Geological models and their influence on geotechnical investigation

By

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Abstract

Geological models, including maps and 3D models, are used in geotechnical site investigation in order to contribute to the evaluation of an area. A geological map is constructed through a complex, subjective interpretation process and represents both a data set and a conceptual geological model. Uncertainty is associated with the data set, but also with the conceptual geological model. This uncertainty can be considered as potential change to a set of discrete geological interpretations, here called patterns.

Similar to the conceptual abstractions used in architecture and software engineering, geological patterns provide a means of using, organizing and transmitting information. It is possible to recover a set of permissible patterns, a representation of a conceptual geological model, from a geological map alone. The connections between aspects of the geological patterns called parameters and the geotechnical evaluation function can be made explicit. The result can be used to construct a map of the relative uncertainty of the geotechnical evaluation, as a function of the uncertainty associated with the conceptual geological model. It can also be used to map the relative effectiveness of different observation modes for constraining the geological and thus the geotechnical model.

The analysis described here allows unprecedented consideration of where geotechnical models are uncertain and how that uncertainty can be resolved. The generalization of geotechnical evaluation as an evaluation function allows the adaptation of this workflow to other fields of geological decision-making, such as mineral exploration and land use planning.
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Chapter 1

Introduction

1.1 Introduction

Geological maps are created to describe how volumes of rock came to be as they are. They are built using interpretation and interpolation of sparse, widely spaced observations and samples. While inherently complex, their creation using limited and often contradictory information can be understood fundamentally as a way of explaining and interpreting the Earth.

Maps and 3D geologic models are used in geotechnical site investigation as a way of constraining parameterization by simplifying the site into a set of geologic domains with representative engineering properties. This process is illustrated in Figure 1.1. The geological model (B) is constructed as a way of simplifying and abstracting reality (A) through theory-grounded interpretation. Geotechnical domains are derived from the geological model, as a way of putting together rock volumes with similar sets of properties (C). These domains, with generalized properties, are used by an evaluation function of some type in order to inform a decision regarding the geotechnical site (D). Note that the need to reach a different decision using this process would result in different domains with different expected geotechnical behaviour in D. Each step in the process, from initial rock observation to the geotechnical
Figure 1.1: Four steps in the domaining process, showing the abstraction of reality (A) first to geological units (B), then geotechnical ones (C), and finally to decisions (D).
evaluation, is further from direct observation, involves additional judgement, and involves further generalization of field-validated information. The loss of information that results from generalization into domains and the decisions made between choices contribute to geological uncertainty, which manifests as the deviation of the predictions of the model from the reality of what is observed during the geotechnical project. This deviation - the gap between the final model and field observables - is expensive and common to the point of ubiquity. Without generalization, however, the use of geological models to make geotechnical decisions would be intractably complex.

Geological uncertainty refers at least in part to uncaptured, unused or lost information in a model, and thus understanding model creation and structure will help to understand the nature and consequences of uncertainty. The problem of geological uncertainty can at least in part be thought of as a problem of miscommunication. The information leaks throughout the domaining process are part of the communication problem. Improving the understanding of models and their use will suggest ways to prevent or mitigate some of this information loss and misinterpretation of the validity of models.

1.2 Overview of Thesis

This thesis will begin with an examination of the theoretical background to geological modelling, uncertainty and geotechnical evaluation. It will describe scenarios of each part of the process of creating and using geological models, including a formal description of geological modelling in the field, a typology of uncertainty that reflects the modelling process, and a method for recovering design information and reasoning from existing maps. The scenarios are combined and used to develop a method for the collection and use of geological information in geotechnical site investigation intended to reduce the amount of conventionally uncaptured, unused and lost information and partially describe the spatial distribution of uncertainty. A map of geological uncertainty can be used to plan sampling programs and
predict areas that may behave unexpectedly during geotechnical projects. In other words, it helps describe what is known and what is not known about a project area, and how that results from earlier decisions during data acquisition, geological synthesis and geological map use.
Chapter 2

Theoretical Background

2.1 Introduction

This chapter will describe geological models, geological uncertainty and the use of geological models in geotechnical investigations. It begins with a description of a day of field mapping that will be used to help clarify the vague terms geological model and uncertainty as they will be used in the thesis. The theoretical information summarized here will be used to develop descriptions of parts of the modelling process and geological uncertainty in chapters 3 and 4.

2.1.1 A Day in the Field

I will begin the discussion of geological modelling using the example of a geologist’s day in the field, the office and finally when their map is presented to a client. The actual processes in this example are dramatically simplified, but intended to represent the general process of the creation of a geological model based on fieldwork.

Some of the decisions faced by the field geologist are illustrated in Figure 2.1. Beginning her day, the geologist must begin with locating herself on the map. She must then make decisions about what geologic features to look for in the field and where to go. At an
Figure 2.1: A field scene showing some different kinds of uncertainty. The geologist must decide what sort of measurements and observations to make at an outcrop, then decide how they affect her map.
outcrop, the geologist must decide what to look for and what information to record, and what theories to invoke to explain her observations. She needs to identify minerals, estimate their percentages and identify the rock texture. She makes measurements of the attitude of geological features such as the strike and dip of a bed. Once an outcrop has been added to the map, the geologist must think about the relationship between the outcrop and the area as a whole and decide how to change her conceptual model of the area to reflect that new information. Next, she must use the updated conceptual model to plan her next action. Once she decides that enough information has been collected, it is time to return to the office.

Once in the office, tasks are no longer primarily about collecting information but about summarizing the information from the field, synthesizing it, and refining her conceptual model into a coherent, descriptive and spatially accurate geologic representation - a map. As in the field, deciding which theories to invoke is important. At this stage, the main question the geologist must consider is how to describe the properties of unsampled locations in order to fill in the entire map from her discrete stations. She must consider the geological objects in the map - what ones must be added, how should they be shaped, and what trends or units exist in the map area. Geophysical or other data and existing maps of adjacent or overlapping areas must also be considered and possibly integrated or used to modify the map. In addition to high level modelling decisions, relatively simple problems like correctly copying and drawing parts of the map are also important.

The geologist leaves the office with a finished map representing their observation data and their conceptual model of the area. The map embodies her knowledge about the field area, but also encapsulates a great deal of uncertainty. It is presented to a client who must use it to evaluate the area and make decisions about it.
2.1.2 Types of Models

Making a map involves the creation and interaction of several different kinds of models, and as such there are several conceptually distinct usages of the term “geological model” in both the above example and in the literature in general. The most basic type of geological model is a dataset representing the observations and measurements made by a geologist spatially. The dataset is used by the geologist to construct more complex models for reasoning about the field area (the conceptual model) or for delivery to the end user (the descriptive spatial model).

A conceptual geological model is used by the geologist in the field to explain and relate observations and interpretations. It corporates the subjective judgement and experience of the geologist to explain existing observations and suggest where new information would be useful to constrain those explanations. Conceptual models represent an abstract and loosely spatial history of the geology of the field area.

Another use of the term geological model describes the process models used to explain geological phenomena. These models may be theoretical or experimental and are used by the geologist to explain field observations. Process models in turn are part of the geologist’s overall model of how the Earth works.

The most universally relevant use of the term geological model, however, is to describe the descriptive spatial models or maps that are the final product of a mapping project. They are the primary deliverable of the geologist that will be used by others. The geological map shows the distribution of units in space, either in two dimensions as a map or in three as a 3D model.

The different types of geological models that will be discussed in this thesis are summarized in Table 2.1.

In the example above, the geologist’s task in the office is to generalize the data set and their conceptual model into a spatial, descriptive geological map.

In practical geological terms, most geologists make maps in the field. Sometimes a map
Table 2.1: A summary of the different types of geological models I will discuss.

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<th>Type</th>
<th>Description</th>
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<tr>
<td>Data set</td>
<td>A spatial representation of the data collected during mapping.</td>
</tr>
<tr>
<td>Conceptual model</td>
<td>A 4 dimensional description of the geological history of an area. Spatially imprecise. At early stages, it is based on prior experience or particularly sound, universal geological theories.</td>
</tr>
<tr>
<td>Descriptive model</td>
<td>Spatial model of geology summarizing the data and conceptual models. The 2D map, 3D model and accompanying reports. The term “map” in this thesis refers to all descriptive models, including 3D models and other representations.</td>
</tr>
<tr>
<td>Process model</td>
<td>Experimentally or theoretically derived model of a geological process. A theory used to build the conceptual model. Dependent on the scale of investigation.</td>
</tr>
</tbody>
</table>

is extended to depth, with or without data such as drill holes, to become a 3D geological model. These are instances of descriptive geological models because they describe the geology for other users. Both formats implicitly capture the geological history, part of the conceptual geological model. Processes in that history make units or rock masses and then act to modify those units. Units are represented on a map as bounded polygons, or in a 3D geological model as volumes. To simplify, I will focus on the case of the geological map, but in reality all geological representations are about volumes of rocks, not flat polygons.

Considerable research has been devoted to understanding spatial representations of data, the formation and evaluation of process models, and the nature and relationships between the conceptual model and the descriptive model. The next section will examine some of this work in order to further refine the above typology.

### 2.2 Geological Interpretation and Modelling

#### 2.2.1 Introduction

Geology is unique amongst the sciences for its use of historical information to build models and make predictions about the Earth (Frodeman, 1995). It has been the subject of philosophical inquiry since its inception (Baker, 1999) and inherently involved in parts of
the development of the philosophy of science (Kuhn, 1968). A fundamental concept in the study of geological reasoning is the interpretation of sparse (in terms of space and time) data in order to produce a geologic history. The geologic history refers to the processes that occurred in the past to produce the modern distribution of rocks in an area. Geological descriptive models, i.e. maps and 3D models, are both ways of representing the complex information contained in an abstract historical model.

2.2.2 Philosophical Background of Conceptual Models

Some of the first philosophical inquiry into the methods of geology was about how different geology was from other sciences, specifically physics. C.S. Peirce was an early geologist and philosopher of science who developed a taxonomy of the sciences in order to explain what seemed to be major differences in their mode of inquiry (Peirce, 1878). He suggested that the use in geology of historical information and the process of interpreting events based on observations of their effect was fundamentally different from the orderly experimental and mathematical models of physics. He developed a theory of the interpretation of signs, called semiotics, largely as a result of his study of geology (Baker, 1999). In the semiotic understanding of geology, signs are observations in the outcrop that suggest events and objects to add to a model. Interpretation of field observations to inform and construct a model can be thought of as a process of reading signs to produce meaning. Although now central to the contextual interpretation of information in the humanities, semiotics remains largely unknown to practicing geologists.

An important outcome of Peirce’s work on geological reasoning was the description of the process of abduction. Logical arguments, for instance in mathematical proofs or scientific inference, can be distinguished based on their mode of reasoning: deduction, induction and abduction.

Deduction refers to reasoning from the specific to the specific. Conclusions reached through deduction are said to follow from their arguments.
The argument that:

All men are mortal
Socrates is a man.
Then Socrates is mortal.

is an archetypal deduction. Deductive arguments are very powerful but difficult to apply in the real world due to the complexity of natural systems and because knowns in the natural sciences are rarely clear, universal or unambiguous.

Induction is reasoning from specific cases to the general. Inductive arguments tend to take the form of proving something is true for a particular case, and then showing that it is also true for every other observed case. Most scientific theories are developed through induction by repeatedly observing a certain thing and then coming up with a rule that explains that observation. The classic example is a person who sees hundreds of white swans, but no black ones. That person can reasonably conclude that all swans must be white.

As Peirce described it, abduction is reasoning that goes from exceptional things to general explanations. Unlike deduction, the outcomes of abduction do not necessarily follow from the observed exceptions. For example, consider the observation of an outcrop where angular fragments of rock are suspended in a fine matrix. Using abduction, a geologist might suggest that it was deposited as part of a submarine slide. It would be incorrect to say that it is necessarily true that it is a slide, given the observation of angular lithic fragments. The slide is just one explanation for the exceptional thing (angular, coarse fragments in a fine matrix) about the outcrop. In geology, abductive explanations tend to take the form of events in the geological history.

Frodeman (1995) examined the idea of a geological history as the framework for geological reasoning. He suggested that the historical nature of geology was fundamental for understanding the nature of geological models. Geology is historical in that it is based on information about events that happened in the past, and also because the fundamental tool
used to reason about those events is a geological history. As Peirce first described, geolo-
gists use abduction to come up with different events as explanations of observed features.
Geological histories help geologists keep track of different events by helping to decide when
an explanation of a newly observed feature is inconsistent with the model.

A geological map must be considered as a geometry but also as a history and is therefore
a four dimensional object that is created through the interpretation of signs or semiosis,
the original signs being features observed in a landscape or outcrop. Baker (1999) formally
described the concept of semiosis in geology, or geosemiosis. Building on the work of Peirce
and Frodeman, Baker defined the four dimensional interpretation of geological signs (geo
+ semiosis) and described the logical tools available to geologists. He described geological
models as a product of a complex reasoning process that is based on historical information.
Models incorporate subjective information from the geologist as part of the connections
between signs in outcrop, their abductive explanations, and the concepts that those expla-
nations suggest.

This process of explanation-suggestion generates further signs to be interpreted and recur-
sively adds meaning into a model. Baker’s work represented a line in the sand for geologists
regarding a longstanding criticism of their method. The subjectivity of geological models
was not a weakness to be apologized for or mitigated, but was the only way to accomplish the
task of the geologist and in fact was the primary source of the rich meaning and explanatory
power of a geological model.

Like Frodeman, Baker emphasized the nature of the geologic model as a text that must
be interpreted by the reader. Thus communicating the meaning intended by the geologist
is a serious challenge and the use of conventional data structures may result in a loss of
information fidelity, either due to the inability to capture important meaning or through the
medium constraining the message. The geometry is the outcome of all the events interpreted
during modelling. A descriptive model, a map, is a representation of the conceptual geological
model to be reconstituted in the mind of the reader. It is easy to lose parts of the conceptual
model when it is translated to a conventional medium like a map or 3D model, and conversely when interpreting a map to understand a conceptual model. Moving beyond the structure of maps and their conceptual underpinnings leads to the question of how they are used.

### 2.2.3 The Use of Geological Models

The study of geologic modelling, especially where it intersects with the study of geologic uncertainty, is typically linked to the development of large-scale social issues that require geologic thought. The impacts of these issues leads decision makers to demand a degree of certainty from models. Much of the early work on the study of model uncertainty was performed as part of the investigations into the Yucca Mountain nuclear repository, and often centered around a theme of verifiability or whether or not a model is “best”.

Oreskes et al. (1994) echoed earlier philosophical works in describing a model as a self-consistent explanation of data that belonged to a larger set of possible explanations. Verifying a model, or even in many cases finding a “best” model, is not a concept that fits with our understanding of what models are. Instead, it may be productive to consider the relative size of that set of alternative models, or to make the reasoning within a model more explicit. Models are both tools of scientific inquiry and communications of meaning. The concept of verifiability of a model relates to its ability to transmit meaning, because a person who completely understands a model has less difficulty grasping the inevitable uncertainties that are built into it.

### 2.2.4 Summary

The most important things to understand from the philosophical work on geological modelling are the nature of abductive reasoning and the historical/process-oriented definition of the geological map as a descriptive representation of a conceptual geologic model. Geologists use abduction when they use observations of peculiar things to interpret an event in terms of a commonly understood geological cause - a process or set of processes. This event serves as
an explanation for the observations, but is not necessarily the only possible event to interpret from them. The event is then added to the geologic history. Descriptive geological models (maps and 3D geological models) are a combination of geometry and historical events. The geometry is the outcome of all the events interpreted during the creation of a conceptual geologic model, as well as an interpolation of observations. The map thus constructed can be considered a historically constrained interpolation. Creating a 3D geological model using a 2D map requires additional constraining information such as drill hole data, but also further reference to the conceptual model used to construct the map to begin with.

The conceptual geological model is stored and communicated as a map or 3D model, a descriptive model, that must be reinterpreted by the user. Conventional data structures result in a loss of information fidelity when the historical, 4-dimensional conceptual model is committed to paper or its digital equivalent.

To build a descriptive spatial model in the field example, the geologist made field observations and developed explanations for them using theories and subjective judgement. Throughout, she made decisions, measurements and observations. Each part of her descriptive model has some degree of uncertainty, either because of the nature of measuring natural phenomena, the use of theories or judgement, or the non-uniqueness of abductive explanations. Parts of the uncertainty of the conceptual model might be understood implicitly by the geologist, especially higher level modelling decisions, but others are not. This link between geological models, especially their non-unique nature, and uncertainty was identified early in the contemporary study of the structure of geological models (Harrison, 1963). Implicit models of uncertainty are difficult to communicate, but a description and quantification of uncertainty is a necessary complement to the descriptive spatial model. In order to approach the problem of communicating uncertainty information, a general description of how uncertainty develops through measurement, observation and modelling is required. The next section will provide an overview of the study of geological uncertainty and how it has developed over time.
2.3 Uncertainty

2.3.1 Introduction

The need for the study and quantification of uncertainty developed in parallel with computational techniques in geology (Mann, 1993). The use of computers for geological modelling and data capture meant that more parts of geological reasoning required explicit, formal representation. Whatever mental strategies experts had for dealing with and evaluating models, they were unable to put them into formal terms without introducing a representation of uncertainty. While groups of geologists were capable of discussing a geological model and reaching a consensus about what was more certain or uncertain about the model, explicit and precise terminology for doing so was lacking. Conversely, computers offered new ways of working with geological information for which prior analogues, and thus strategies, did not exist. In a geological context, uncertainty is used as a kind of error term that includes all the disparate ways that models can be arbitrary, imprecise or incorrect. Once this term was identified as important, study turned towards describing it in detail and working towards its quantification.

This has proven to a complicated process and one that has forced geologists to examine many seemingly disconnected concepts to seek a greater understanding of their own methods, most of which were previously informal. The development of models of uncertainty is hampered by a lack of shared terminology and methodology, which is a hallmark of a pre-paradigm science (Kuhn, 1968). Pre-paradigm sciences are subject to common reintroduction and drift of terms, as well as the formation of conceptual camps who use similar words differently. This in part reflects the vagueness and generality of the term uncertainty, but also a lack of shared understanding of its sources and nature. In addition, there is a lack of precision about what fieldwork, synthesis and geological model construction are and how they work.
2.3.2 Classes of Uncertainty

It is necessary for any project related to geological uncertainty to clearly define what aspect of uncertainty is being studied and how it relates to other kinds of uncertainty. The scope and lack of a clear definition of the problem of uncertainty has led to a historical tendency to study specific types of uncertainty in isolation and without explicitly acknowledging other types.

Uncertainty is associated with every decision, measurement and description the field geologist makes, and the total uncertainty of a geological map is a function of all those component uncertainties. The sources of geological uncertainty can be summarized into four main classes based on their relative complexity and relationship to other classes. These relationships are illustrated in Figure 2.2, and example decisions for each are given in Table 2.2.

Table 2.2: Example decisions and their classes

<table>
<thead>
<tr>
<th>Decision</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of minerals</td>
<td>Objective</td>
</tr>
<tr>
<td>Attitude of plane</td>
<td>Objective</td>
</tr>
<tr>
<td>Rock type</td>
<td>Subjective</td>
</tr>
<tr>
<td>Texture</td>
<td>Subjective</td>
</tr>
<tr>
<td>Is this a dyke?</td>
<td>Model</td>
</tr>
<tr>
<td>What unit is oldest?</td>
<td>Model</td>
</tr>
<tr>
<td>Where to next?</td>
<td>Goal</td>
</tr>
<tr>
<td>What should I look for?</td>
<td>Goal</td>
</tr>
</tbody>
</table>
Measurements, including positions, measurements of strike and dip, mineral percentages, and the description of color are examples of objective properties. Their numerical and attribute value is a reproducible quantity. Careful measurement and repeated trials are sufficient to reduce objective property uncertainty. Measurements form the base data for many subsequent interpretations. As such, although their uncertainty is relatively straightforward to model, its effects propagate upwards to affect other observations and decisions.

Most field observations, including rock type, texture, relationships between geologic objects, and the description of lithology are not measurements. They are interpretations based on simpler, objective properties. Subjective properties are observations that cannot be measured directly and require the use of theory and interpretation. A community of experts would agree in general on most subjective observations, but valid theoretical cases could be made against them as well. An example of a subjective property is rock type, which is not a natural property that is directly measurable. The choice of a rock type involves the use of theories to explain observed minerals and textures.

Measurements and subjective observation are the foundations on which a geologist builds and constrains a conceptual geological model. A conceptual geologic model is not a set of rock type observations, but includes different events that help the geologist describe and explain the subjective properties of sampled areas and predict those of unsampled ones. Geologic explanations form a narrative, 4D conceptual model of the geological history of a map area. The choice of those geological explanations is associated with model uncertainty. It includes the selection, appropriateness and correctness of geological explanations and theories in a conceptual model.

In addition to making measurements and observations and deciding how to integrate those observations with a conceptual model, a geologist must decide how to most efficiently and effectively go about the work of observing and interpreting in the field. These planning decisions are related to the reasons the model is needed, as well as the components of the model itself. Goal seeking, observation and description decisions made by the geologist
involve an interaction between observations, the requirements of the spatial model, and the expertise of the geologist. They belong to the class of goal uncertainty, which is affected by all the simpler types as well as outside factors like client demands.

The relative impact of each class of uncertainty varies depending on the progress of the modelling process. In the field, all four classes are important. When a geologist develops a spatial descriptive model in the office, only model and decision uncertainty are relevant, with the possibility of reinterpretation of subjective properties possible as well. When the final map is presented, only goal uncertainty remains.

This typology is one way of relating the disparate sources of geological uncertainty. In the following sections, I will describe some of the existing literature on geological uncertainty and how different parts of this typology of have been studied and captured.

2.3.3 Studies Of Uncertainty

Geostatistics

The field of geostatistics began as a way of spreading numerical variables through space and quantifying geological uncertainty in mining contexts (Matheron, 1963). It uses a model of spatial variability called the variogram to estimate the value of a particular variable at each point on a map. The variogram describes the variance of the change in the value of a variable as a function of distance between two samples. It combines spatial information with quantity information to develop a model of a geological property across an area. While many additions and modifications have been made to Matheron’s original model, the variogram is still at the heart of geostatistics.

The tools used by geostatisticians to spread values through space also includes a spatial model of uncertainty called the estimate error. This term is primarily a function of the spacing between samples (Matheron, 1963). It is equivalent to the idea that it is difficult to predict the attributes of part of the map that is far from any samples, which in turn is based on the idea that, locally, nearby things are related and their properties normally change in
a deterministic way.

Geostatistics offers a model of uncertainty that is easy to calculate and described in terms of the variable that users are interested in. Treating lithology as a spatial variable allows estimation of the uncertainty at each point in a descriptive model. The estimation of a geological property at an unsampled point is important in building a geological model, but the variogram is a simple description of geological variability and geologists construct much more complex models that are based on many different sources of information.

The geostatistical model of uncertainty is sufficient when geological variability can be adequately and unambiguously explained by a simple variogram. In that scenario, the conceptual geological model is represented solely by the choice of variogram to use, and thus the descriptive model is a direct product of that single interpretation. There are some geological scenarios where this is true, but for the most part models of uncertainty must be more complex than a function of sample spacing.

Mann’s Typology

Responding to the need for more complete models of uncertainty due to the increased use of computers in the geosciences, Mann (1993) described geological uncertainty in detail by breaking it into three categories. The categories were determined by how each could be quantified. The simplest is type 1 uncertainty, which includes measurement imprecisions, error and bias. This type can be quantified by classical statistics. Type 2 uncertainty is more complicated and includes unit anisotropy and inhomogeneity. It can be quantified by geostatistics, as it is primarily dependent on the spatial continuity of unit properties for which the variogram is well suited. The final category is type 3 uncertainty. It includes everything that could not be quantified using either classical statistics or geostatistics.

In Mann’s typology, type 3 uncertainty is created by the need for generalization of models and our lack of knowledge and has to do with the relationships between the parts that compose a model. Building geological models creates type 3 uncertainty because of the
use of imperfect process models (understandings of geologic environments) and the need to pick a single feature or process model to use, which in turn means discarding both known alternatives as well as those that the modeller could not have conceived of. Mann described type 3 uncertainty as theoretically unknowable and therefore requiring estimation using expert knowledge. He posited that collecting and using good information from experts will be difficult and may require the use of non-quantitative probabilities or fuzzy information.

The problem with this typology is that there are components of types 1 and 2 that are affected by knowable elements of type 3. Parts of the geologic model described by type 3, such as unit definitions, determine the value of type 1 and type 2 components through their influence on sample observation and geostatistical constraints. Therefore any model of type 1 or 2 uncertainty must necessarily incorporate information that falls into the unknowable type 3 category. Because type 3 is defined as parts of uncertainty that we don’t have the tools to quantify, Mann’s typology suggests that without understanding type 3, we can’t really understand type 1 or 2 either.

Types 1 and 2 uncertainty provide a working model of uncertainty in areas with simple geology or where interpretation is otherwise constrained to correctly identifying units and drawing their contacts. A combination of classical statistics (to describe measurement uncertainty) and geostatistics (to describe spreading observations through space) is sufficient to describe uncertainty in this situation. Type 3 is not a useful category because it is too vague and includes many different aspects of geological uncertainty including subjective property, modelling and planning uncertainties. Quantification of type 3 uncertainty requires further division to isolate and study its different components.

**Simulation and Modelling**

More recent work on uncertainty has focused on quantifying uncertainty further using Mann’s typology in several contexts, including oil and gas, mining, geophysical inversion, hydrology and engineering. In petroleum and mining development, the focus is on quantifying uncer-
tainty as a range of possible values for some variable instead of a mean. The need for multiple possible models, usually of potential petroleum reservoirs, led naturally to the development of simulation techniques (Gerritsen and Caers, 2013). These techniques capture part of model uncertainty by simulating some modelling decisions to repeatedly build alternative descriptive models, such as 3D block models. The set thus generated describes the range of possible models, given an uncertain decision. The theories used to build the models are constant, but the choice of relationships and placement of geological objects are simulated. Experimentally-derived process models of fluid flow or sediment deposition can be used to directly simulate the target system multiple times according to constraining observations in order to estimate a range in possibilities. Other techniques automatically construct models that fit observation data using a set of prototypical geologic objects or shapes that a geologist might add to a model.

The quantification of uncertainty has also been examined within the context of geologically constrained geophysical and structural inversion. As with reservoir analysis, quantifying the uncertainty of a geologically constrained inversion usually involves constructing a range of possible geological models. One technique to evaluate many possible models was to simulate measurement uncertainty by randomly perturbing the input structural measurements used to automatically construct a 3D geological model (Wellmann, 2010). The set of models generated quantified the effects of measurement uncertainty in terms its effects on the final model. Methods for visualizing the outputs of these simulations were developed by adapting information theory to produce information entropy maps as a representation of geological uncertainty (Wellmann and Regenauer-Lieb, 2012). Although these experiments effectively described objective property uncertainty and its propagation, subjectivity of geological interpretation was identified as a factor that could confound any simulation-based study (Jessell et al., 2010). Interpretations about the conceptual model would affect subsequent steps in the modelling process, and the range and complexity of those possible interpretations are presently difficult to quantify and include in the inversion process. Geological maps and 3D
models could constrain inversion, but information about conceptual uncertainty, subjectivity and the nature of interpretation itself is difficult to include with current tools.

The British Geological Survey has conducted several studies of uncertainty with a particular focus on the problems of geological modelling. In one experiment (Lark et al., 2014), several geologists were tasked with modelling an area given a set of data points. Each geologist saw a different set of observations, and the results were compared with a control section. Uncertainty was measured as the variability of depth to a target layer across the study area. A statistical analysis was then performed to determine what aspects of the data and modellers best determined the value of uncertainty. Distance to nearest observation borehole was identified as one of the most important parameters for the uncertainty model, which supported a geostatistical model of uncertainty that primarily reflects the distance from observation data points. The modelled area was of very simple geology, however, and the only interpretation required of the geologists was to interpolate nearly horizontal contacts. Later studies in more complex Scottish rocks suggested a different set of parameters as most important for estimating uncertainty (Randle et al., 2015). Geological complexity, as represented by the number of units encountered in an observation borehole, was identified as a particularly important factor. Contrary to the geostatistical model of uncertainty, distance to nearest observation was a poor predictor of uncertainty. These results suggest that for simple geology, the geostatistical model of uncertainty is valid. When geology is complex and interpretation required, model uncertainty dominates and the interpolation uncertainty becomes less important. In addition, model uncertainty varies spatially as a function of geology.

2.3.4 Summary

Geological uncertainty remains a concept that is difficult to define and quantify. It is a complex product of the poorly understood interpretation process and confounded by measurement and observation uncertainty. There are many approaches to quantifying or even
understanding its parts, but a consistent holistic model remains unresolved. While some parts of uncertainty can be modelled and quantified, many aspects of geological uncertainty remain undescribed.

In particular, model uncertainty remains difficult to quantify. The problem of selecting objects to add to a model has been described as conceptual uncertainty (Bond et al., 2007). In that study, a synthetic seismic section was given to a large group of geologists and geophysicists who were asked to interpret geologic objects from it. Most workers could identify the same main features in the seismic section itself, but gave many different descriptions of what objects those features represented. By providing objective data, without the ability to acquire more, the problem of modelling the synthetic geology was reduced to a purely model-based one.

In this study, I will investigate geological modelling in order to understand model uncertainty as described in my typology. I will follow the same methodology as Bond et al. (2007) and consider only the question of adding different features to a conceptual geological model, not the quality of the observations used or the planning process for collecting them. Experiments with model uncertainty suggest that it varies spatially according to geological complexity (Randle et al., 2015). I will develop a model of geological complexity by studying the geological modelling process, and in turn use it to estimate the spatial distribution of model uncertainty. Improved understanding of geological modelling will also help improve communication of meaning between geologist and the model user. The improved connection between the conceptual geological model and evaluation will allow the expression of model uncertainty in terms of the variable of interest for the evaluation such as rockmass strength.

2.3.5 Delivering a Model

In the field example, the geologist constructed a geological map to represent her conceptual, abstract model of the field area’s history and geometry. Her conceptual model includes an understanding of the model’s uncertainty, parts of which she might represent through de-
scriptions in a report accompanying the map or through cartographic features like dashed lines or color variations. Most of the uncertainty information remains implicit. Also implicit is the information that was generalized to construct the descriptive model. Upon delivering the descriptive model, the implicit information is lost. The effects of lost information are further exacerbated by the generalizations, such as domaining, used by the descriptive model’s client. The lost information creates a kind of uncertainty distinct from that developed during the modelling process. In addition, uncertainty information must be propagated forwards and put in terms useful to the client if it is to be used to help make decisions. A description of the flow of information, from the geologist who creates a geologic map to the client who uses it, is required in order to properly use uncertainty information and to mitigate the effects of information loss.

In this thesis, I have chosen to study the information flow of geotechnical investigations for several reasons. Geotechnical evaluations depend strongly on geological properties and are affected by the modelling decisions of the geologist. It uses domaining to generalize the descriptive geological model in a way that is easy to describe, and the geotechnical parameters used are often conceptually simple to connect to geology. The technical aspects of geotechnical site investigation, as well as the potential for immediate and substantial benefits, make it an ideal model problem for studying uncertainty in geology.

2.4 Geotechnical Modelling

2.4.1 Introduction

Geological descriptive models are created or obtained by engineers during the site investigation process. Geotechnical engineers are primarily interested in the distribution and properties of units and the nature of geological structures at a site. These properties are studied in order to help predict ground behaviour during the proposed work at the site. Groundwater is typically studied as part of the site investigation, and the properties and
distributions of rocks and structures are important in terms of their hydrological behaviour. Background measurements of hydraulic head are performed as part of the site investigation and help to constrain hydrologic models. Both hydrologic and geotechnical behaviour models usually contribute to more complex geotechnical models further down the line.

Surface geotechnical investigations use the features and properties of geologic materials at the surface and in the shallow subsurface in order to understand their behaviour. Information about the nature and distribution of units is relatively inexpensive to collect and access. While some of this information takes the form of geotechnical measurements associated with units, it also includes information about geological history that is difficult to express in a geometric model. For instance, the behaviour of Leda clay (Gillott, 1971) is a product of its depositional history, and the nature and behaviour of a fault last active during the Precambrian is different from one with an active scarp today.

Geotechnical investigations that are concerned with the subsurface must work with a different sort of data set. Subsurface information is much more expensive to collect than shallow information and generally takes the form of drill core. Subsurface investigations will generally involve much more prediction of the distributions and properties of units because data is much more sparse. The relationships between units are much more complicated to observe in drill core than when exposed at the surface.

2.4.2 Evaluation

Geologists create maps according to a subjective reasoning process in order to explain the current disposition of a volume of rock as a product of a geologic history. The conceptual model used by a geologist to understand and relay the geological history and then used to predict and understand geologic properties and features in the face of sparse data is difficult to communicate. There is a loss of information fidelity as the conceptual model is reduced to the form of maps or 3D models.

Geotechnical engineers use geological models to evaluate situations. They may want to
determine if a particular area is prone to landslides, or what the support requirements will be for a tunnel, or how pollutants will move through the subsurface. The evaluation process can be generalized as an abstract function that depends in some way on the geological map or 3D model and outputs an evaluation of the site.

Geotechnical models may be numerical or analytical, but both share a need for parameters that describe the system being studied. These parameters are derived from the available geological map in some way, perhaps as simply as using geological units to spread measured parameter values through space. These parameters affect the output of the geotechnical model, which is used along with other geological information as input by the evaluation function. The transformation of geological information to geotechnical parameters is a subjective process that incorporates information and assumptions about how parameters are related to geology. Due to the complexity of how parameters relate to geology, information about the geologic history and its context may more important than the geographic information included in a traditional geological map. Numerical models have a complex, non-linear relationship to the parameters used and therefore to geology. The behaviour models that underpin numerical models are theoretical explanations of complex processes and thus contribute their own uncertainty to the process.

2.4.3 State of Practice

The terms natural heterogeneity or geological variability are used to describe the deviation of geotechnical evaluation functions from reality. These factors are cited as one of the largest sources of cost overruns in large excavations like tunnels (Efron and Read, 2012). As a result, users of geotechnical models are interested in a measurement or factor for geological uncertainty that represents the degree of how right or wrong a geologic map is. Communication between geologists and engineers is difficult, and neither side effectively communicates why they do the things they do and how their work incorporates various assumptions. In other words, there is a loss of meaning or information fidelity when geologists deliver models
to engineers and when engineers commission geological models.

Straightforward, obvious geotechnical problems may be caught during evaluation. Other, more complex problems may be caused by multiple properties and geologic features that are not represented well on a traditional geologic map. Prediction and mitigation of these problems requires more information about the conceptual geological model.

2.5 Chapter Summary

Engineers generalize descriptive geological models to develop domains with homogeneous geotechnical parameters and to identify specific features like faults that may affect a project. Descriptive geological models are themselves generalizations of the conceptual models created by geologists during a field investigation. Conceptual models are sets of interpretations that represent the geological history of an area. Uncertainty is built into models through observations and modelling decisions and also from the loss of information associated with generalization. Model uncertainty, related to geological reasoning and the generalization process, is poorly understood. By considering a conceptual model in its abstract, interpretative form, it may be possible to evaluate model uncertainty.

The problem of selecting objects to add to a model has been described as conceptual uncertainty (Bond et al., 2007). In that study, a synthetic seismic section was given to a large group of geologists and geophysicists who were asked to interpret geologic objects from it. Most workers could identify the same main features in the seismic section itself, but gave many different descriptions of what objects those features represented. By providing objective data, without the ability to acquire more, the problem of modelling the synthetic geology was reduced to a purely model-based one.

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model, not the quality of the observations used or the planning process for collecting them. Experiments with model uncertainty suggest that it varies spatially according to geological complexity (Randle et al., 2015). I will develop a model of geological complexity by studying the geological modelling process, and in turn use it to estimate the spatial distribution of model uncertainty.

The propagation of model uncertainty from descriptive geological model to the geotechnical model must be understood in order to quantify model uncertainty in terms of the evaluation function. Beyond the quantification of uncertainty, it may be possible to improve the information fidelity between the conceptual geological model, the descriptive model, the geotechnical model and finally the evaluation function itself in order to bring more geological information to bear on complex geotechnical problems.
Chapter 3

The Structure of Geological Models

3.1 Introduction

In this chapter, I will explore parts of the geological evaluation process by drawing on the available research in geological modelling and uncertainty. I will also examine the connections between conceptual and descriptive geological models, including maps and 3D models, and geotechnical ones. For ease of presentation, I will consider only the 2D case of the geological map here.

The goal of this chapter is to lay the foundations for a new workflow to integrate more geological information during the geotechnical evaluation process and ultimately to support delivery of geological uncertainty information to decision makers. To begin, I will consider the format of traditional descriptive geological models and how they reflect the underlying conceptual geological model. I will describe the nature of the connection between geological and geotechnical models, as well as the propagation of uncertainty from the conceptual geological model to the geotechnical evaluation function. Together, these components will be used to build a workflow to process existing, traditional geological information in order to deliver more information about uncertainty and its effects on geotechnical investigations.
3.2 Revisiting Geological Models

3.2.1 Modelling in the Field

I will begin by returning to the earlier example of the field geologist. After walking across fairly monotonous outcrops of siltstones and shales, the geologist passes a covered, boggy area and then clammers up a steep slope. On top she finds some blocky outcrops of resistant rock. It is a medium-grained crystalline rock made up mostly of feldspar with some quartz, biotite and hornblende. She remembers having seen this mineral assemblage many times before, so much so that she begins thinking about it as a granite even before carefully examining the mineralogy.

She considers how to represent this new outcrop in her model. The contact with the shales was not exposed, but perhaps it occurred within the boggy area. She remembers another area from previous mapping where discrete bodies of intrusive rocks were found throughout a sedimentary rock sequence and caused contact metamorphism. She decides that the intrusive rock is best handled as being part of a similar intrusive body that intrudes the sedimentary rocks, bringing to mind what she knows about intrusive rocks in general from both academic and work experience. She has not observed any evidence of contact metamorphism yet, which may help to constrain the contact relationship if she fails to find any other direct evidence.

She considers its relationships to the sedimentary sequence, noting that the intrusive must be younger than the sediments if her idea makes sense. Her conceptual model for the area now includes an intrusive event and an accompanying body of intrusive rock that postdates whatever event created the shale. On her map, she adds a dashed line through the boggy area that delineates the approximate near side of the intrusive body. She decides to continue on to see if the intrusive continues, and if its contact is exposed. When she finds more shales later on, she looks for dykes and contact metamorphism: she is looking at new outcrops in the context set by her evolving conceptual model. To summarize, she is using
process models of geological events and their consequences to build a conceptual model of the field area in terms of a geological history that, in addition to observation data, helps to constrain and build a consistent geological map.

### 3.2.2 Aspects of Geological Descriptive Models

The conventional view of a geological map describes it as space-filling interpolation developed from sample observations, which in turn represents an image of the earth. In other words, units are polygons based on observed stations that envelop observation points and end at contacts that are rarely directly traced. This assumed process is shown schematically in Figure 3.1.

This concrete map view contrasts with the philosophical description of geological models as sets of interpretations, developed through abductive reasoning and represented as both a historical conceptual model and a spatial descriptive model. As discussed earlier, a conceptual model is a spatially imprecise, abstract and historical description of an area. An important part of a conceptual model is a geological history, which serves both to organize information and as an explanatory mechanism for observations. Descriptive models summarize the observations made by a geologist and the information organized in the conceptual model in a spatial format such as a map.

In the field example above, the geologist’s descriptive map is a projection of the abstract conceptual model and thus of a history. She located the outcrop of intrusive rock on her map and approximated its boundary. The outcrop’s location is part of her observational data set, but the identification of the rock as intrusive and especially the overall geometry of the proposed body is part of the conceptual model that is represented symbolically in the descriptive model. The map must be considered as information-poor compared to the conceptual model, which contains the totality of the geologist’s observations and interpretations about an area and which is grounded in an understanding of geological processes based on experimental or observational science.
Figure 3.1: A figure showing the traditional view of a map as a space-filling interpolation or image of the earth. A is an image of the area as an air photo. In B, a set of observations are made across the area. A boundary between the samples is delineated in C, and the area in between the observations is filled in D.
Figure 3.2: A figure showing the historical, interpretation-based view of geological maps. Observations are plotted in B as in the conventional view of models, but these observations are used to infer events and objects in C. The events and objects suggest the interpolation in D and are represented externally to the interpolation.
The geological history and the conceptual model is thus developed using a network of inferences and interpretations. The conceptual model created during the process of mapping is then imperfectly communicated using the map as a projection, including the legend and possibly an accompanying memoir, to show both specific, spatial observations that underpin and constrain the history and the interpreted geological objects, the actors and events, from the conceptual historical model. This view is demonstrated in Figure 3.2.

The need for an explicit, unambiguous representation of the geological history alongside a geologic descriptive map was described by Harrap (2001), along with a graph-based language for the representation of a history described as a legend language. The legend language could be used along with a geological map to communicate more information about the underlying conceptual (historical) model.

There are several unique consequences of the historical, interpretation-based view of geological maps: map incommensurability, the importance of contextual information, and complex sample value distribution. The first consequence is that maps on their own are incommensurable. That means that two maps of the same area cannot be directly compared if they represent two different conceptual models. This is illustrated in Figure 3.3. Though the maps in Figure 3.3 are broadly similar geometrically, the boundaries of their respective geological objects cannot be compared or meaningfully averaged. They represent the products of two different and mutually exclusive histories consisting of geological events acting on and creating geological objects. Deriving a “best estimate” or average value from several alternative models implies that the models are commensurable with each other. In cases where interpretation of the geological history is required in order to infer the distribution of units, this is not true and would lead to significant errors in any work based on subsequent use of a map based on averaging different conceptual models.

The second consequence of the historical view of geological descriptive models is the importance of contextual information. The projection of the conceptual model, the map and its geometry, might be the least important or meaningful output of major interpretations or
Figure 3.3: Two maps from the Ballachulish highlands area of Scotland (Pattison, 2013). (A) shows a map developed using the interpretation that deformation occurred prior to metamorphism. (B) was developed using the opposite interpretation.
re-interpretations. These interpretations may change significantly but still leave the same basic map geometry. This is illustrated in Figure 3.4. The Portrush sill in Ireland was the site of a major argument between Neptunist and Plutonist geologists in the early 19th century (Ledevin et al., 2012). Neptunists believed that the diabase, and all such crystalline rocks, had formed through crystallization from an ancient ocean. Plutonists argued that the diabase had intruded the mudstone while at a high temperature, causing it to become hornfelsed. In either interpretation, the overall geometry of the outcrop, the descriptive model, is similar. What differs is the interpretation of the nature of the contact, and especially of the geological processes at work.

This consequence, a result of the complex relationship between map geometry, underlying process and conceptual models, and human reasoning was also described by Bond et al. (2007). In that study, an identical seismic section was sent to many geoscientists to interpret. Most respondents correctly identified the major feature geometry, but there was considerable
variation in describing what the feature was. The difference between those interpretations would have major impacts on the exploration for petroleum in the simulated basin. As at the Portrush sill, geometry was only a projection of a much more information rich conceptual model.

Conceptual geological models have interpretative ambiguity for many reasons, including the imperfect and incomplete nature of field data, the subjective application of theories to explain observations, and the presence of cryptic features that are not explained by current knowledge. Conceptual ambiguity is difficult to represent in the descriptive model because the only brush available to the geologist is to demonstrate changes in units and discrete geological features like faults or folds, in other words using only geometry at map scale.

These consequences occur because descriptive geological models like maps are a representation of conceptual models. In the Ballachulish example (Figure 3.3), two maps that look somewhat similar have important differences topologically. They represent two different conceptual models. In the Portrush sill example (Figure 3.4), two different conceptual models result in the same descriptive model. In Figure 3.5, two different maps of the same area are the products of the same conceptual model. Despite some further definition of units in Figure 3.5B, the maps are conceptually consistent. Both maps are more or less refined and constrained representations of the same conceptual model.

Together, these three examples demonstrate the three possibilities for maps of the same area. They can be conceptually different and descriptively different, as in Ballachulish. They can be geometrically similar but conceptually different, as for the Portrush sill. And finally two maps can share a conceptual model, while looking different from each other, as in Figure 3.5. A descriptive model or map is a drawing that represents a conceptual model. Its topology is determined by the relationships between units in the conceptual model. A conceptual model has a unique topology, which can be represented by any number of descriptive models.

The third consequence of the view of maps as representations of a conceptual model is
Figure 3.5: Two maps showing the area north of the Takhini river and Whitehorse, YT. A is an older map (Wheeler, 1961) and B is a newer representation (Colpron, 2011). Both maps share a very similar conceptual model, even though the shapes of the polygons are different.
that the relative value of new observations across a descriptive model is complex. If a map was a purely interpolation-based construction, then the most valuable sample sites could be determined using geostatistics. Conversely, the most valuable sample sites in a descriptive model that represents a projection of an abstract, conceptual model would be determined by the structure of the conceptual model itself. The most valuable sample would be the one that helps constrain the history or discern between multiple valid histories as much as possible. When many interpretations are possible, the most valuable observations help rule out the most alternatives. This could be completely unrelated to the distribution of existing sample points. Figure 3.6 shows a 1:50000 scale map segment with part of the area removed (A) and then added back in (B). This segment is much more informative of the geology of the area than what was left behind. Clearly the observations that constrained the conceptual model for the area were concentrated in the removed area and had appropriately high value. Because the map is a projection of the historical model, the conceptual model structure is a far greater determinant of the spatial value of observation than the unit geometry. The unit geometry is dependent on the conceptual historical model and constrained by the observation data set.

3.2.3 Uncertainty and Conceptual models

This raises the question of how the conceptual model that underlies a map affects uncertainty. If a geologist making observations with some knowledge of geological processes builds a constrained geological history that is consistent with theory and observations, how do issues with observations, process understanding, and choices during conceptual model construction affect uncertainty?

The geological conceptual model introduces a new, significant type of uncertainty that is poorly addressed by existing methods. A more thorough look at the components of the conceptual model is required in order to effectively describe model uncertainty. The descriptive model cannot be used to describe model uncertainty on its own because it is ultimately
Figure 3.6: A segment of a geological map from the Mendocina creek area, Yukon Territory, showing the effect of removing interpretation-dense map areas (Westberg, 2009)
a projection of the conceptual model. It is useful to consider a descriptive model such as a map as the product of an abstract conceptual model, which is in turn made up of discrete interpretative objects. The form and nature of those objects must be described in order to approach model uncertainty. Figure 3.7 shows what a descriptive map designed to represent more information about the conceptual model might look like. The descriptive model is represented as the projection of a set of discrete interpretations which are linked to the spatial geological objects they produce. Explicitly describing a set of discrete interpretative objects (3.7A) expresses incommensurability by representing the interpretations as a linear order. Contextual information about the events that produced the geological objects in the descriptive model can be stored with reference to both the conceptual model (3.7B) and the map. The value of adding new information at a particular point can be estimated by the number and importance of the interpretations connected with the point. In addition, model uncertainty can be considered as a potential change in the set of interpretations that make up the conceptual model (3.7B).

The conceptual model structure and its relation to the map is an important factor in both the delivery of more geological information to users as well as the description of model uncertainty. Conceptual models include a set of interpretative objects that form the geologic history. The interpretative objects used by geologists to make sense of observations are a conceptual shorthand or abstraction that encapsulates knowledge and judgement. The next section will describe parallel ideas in other disciplines and how they can be adapted to the problem of the components of a geological conceptual model.
Figure 3.7: A hypothetical map based on representing interpretations first, and the geometry as a product of those interpretations. Conceptual information (A) is explicitly connected to its map representation. Alternative conceptual models are represented as different sets of interpretations (B).
3.3 Patterns

3.3.1 Introduction

In this section, I will examine the conceptual abstractions that form discrete interpretations in geology. The interpretations in a conceptual model pertain to the processes that make and modify units (such as sedimentation and metamorphism) and their geometry and topology (such as faults and folds). Other disciplines have described similar abstractions as ways of capturing knowledge, making sense of new situations, and making decisions.

Alexander (1979) described a design language for architecture where good design practices were captured as descriptive patterns. The patterns have a rigorous form, where a problem and associated context are stated, the problem is discussed, a solution is presented. Patterns describe the introduction or modification of elements into an environment in order to have an effect. Each pattern also has links that connect it to and from other patterns. Architectural concepts like “window box” or “promenade” were captured as a set of instructive qualities that could be used to inform their design. Those qualities were based on the distilled experience of many other instances of the architectural concept.

Alexander used a literary style with a rigorous form to describe patterns. Each pattern begins with a set of links to predecessor patterns that suggest its use. The analysis of the architectural problem follows, then a short sentence describing a solution. The pattern ends with a set of links to successor patterns that it invoked, representing an early example of a hypertext. An example pattern for a beer hall is shown in Table 3.1, summarized from Alexander et al. (1977).

The idea of capturing good design technique and reusing it for similar situations appealed to software designers as well. The “quality without a name” described by Alexander (1979) was equivalent to the idea of elegant programming. Software designers developed pattern languages for many different programming situations, especially object-oriented programming (Johnson et al., 1995), as a way to capture common complex problems and their
Table 3.1: A representation of the beer hall pattern from Alexander et al. (1977).

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title</td>
<td>Beer hall</td>
</tr>
<tr>
<td>Predecessors</td>
<td>Neighbourhood boundary, promenade, night life</td>
</tr>
<tr>
<td>Problem summary</td>
<td>Where should people go to drink?</td>
</tr>
<tr>
<td>Analysis</td>
<td>Holds a crowd, mixes crowd, large tables, alcoves, beer and wine, music, activities</td>
</tr>
<tr>
<td>Solution summary</td>
<td>A big place, with open alcoves and large tables, that serves beer and wine and encourages mixing</td>
</tr>
<tr>
<td>Successors</td>
<td>Alcoves, fire, ceiling height, building complex</td>
</tr>
</tbody>
</table>

proposed solutions. Their application of Alexander’s ideas was more technical and pragmatic, but the idea of considering a complex thing like a computer program or town square as a set of discrete conceptual objects was demonstrably effective for both the encapsulation of knowledge and the description of the design process. Complex experience, judgement and knowledge could be represented as patterns with associated parameters that describe when to use them, what problems to consider, and aspects of their implementation.

In addition to their storage and transmission, the application and choice of pattern-like structures has been studied in the context of expert decision-making. Klein et al. (2006) used a framework called the data/frame model to describe how experts use observations to recognize a useful frame that guides and helps filter out further observations. The expert goes through elaboration and reframing cycles to fill in and possibly a choose a different frame to make sense of a situation. This process is distinct from simple hypothesis testing, although parts of it can be viewed that way. The data/frame model is about the larger scale process of fitting observations to a pre-existing conceptual model and guiding further actions. The frame in the data/frame model is equivalent in many ways to the patterns used in software design and architecture.

In the case of architecture and software design, patterns represent distilled experience with relationships, consequence, and underlying justifications. An architect might build an urban setting by “playing” a series of patterns. Another architect might attempt to understand the particular charm - or flaws - of a space by looking in a forensic sense at
what sequence of patterns was used in its construction and what that says about the goals of its designer, whether deliberate or otherwise.

It is also significant that patterns are applied as a sequence or narrative. Making sense of a complex narrative is central problem in parts of the field of artificial intelligence. One approach to this problem is the use of pattern-like objects called scripts (Schank and Abelson, 1977). Scripts were originally described as part of a project to help artificial intelligence software to understand stories. They are bundles of meaning with headers or triggering conditions and outcomes that store extra information so it does not need to be repeated. Most of what happened during a story is not made explicit, but is filled in by the reader as they understand it. For example, a story about someone getting stuck in traffic does not always include the information that the person was in a car. It seems trivial to a human, but software interpreting the story requires everything to be explicit and formalized and thus would have difficulty filling in the part about the car. A script can be considered a form of stored meaning that helps to make sense of a story or portion of a story. A consequence of this is that systems based on scripts and patterns are possible to process using a computer, which could lead to the development of new tools to plan and understand parts of the design process like uncertainty.

The formal specification of patterns and their sequences has implications for teaching as well. Constructing a teaching curriculum around conceptual abstractions like patterns has been proposed for software design (Meyer, 2006). It has been suggested that a case-based format, within which students could develop their own pattern collection, is an efficient way to engage students in “geologic style” thinking (Goldsmith, 2011).

### 3.3.2 Geological Patterns

Like architects or software designers, geologists need a way to capture effective judgement and knowledge in a reusable form. Geologic explanations take the form of objects and events drawn from prior observation or experience and laboratory studies. In order to understand
conceptual models and deliver more information to map users, this process must be made explicit. I propose that the form of these explanations is analogous to the pattern languages of architecture and software design. Geologic patterns encapsulate conditions for their application, relevant observations to make to help constrain them, suggestions for further investigation, and information about the conditions during their formation. A geological model can elegantly explain the history and structure of an area in the same way that a well-designed building improves the use of a space or that a computer program runs efficiently.

Returning to the example of the field geologist, by the end of her day in the field she has observed intrusive rocks of varying textures, as well as some porphyries. She has found volcanic rocks as well, but shale outcrops were rare. She decides that the area fits the pattern of a shallow intrusion that intrudes its coeval volcanic pile. This interpretation allows her to reconcile the disconnected intrusive bodies, their textural variation, the presence of porphyrytic dykes, and the volcanic rocks. The pattern suggests that she should consider alteration patterns in the area, look for more dykes in order to constrain the contact relationships, and map volcanic textures to understand the stratigraphy of the pile. In addition, the use of absolute geochronology would be helpful in unravelling the different intrusives and volcanics. The pattern she chose serves both to explain her observations, as well as suggest new ones to help form and constrain the geologic history (and thus her conceptual model) of the area. The pattern used by the field geologist is shown in Table 3.2 in a similar format to that used by Alexander et al. (1977).

Geological judgements are made in the face of uncertainty. Geological patterns help geologists make sense of an area and make effective decisions by drawing on previous experience and using it to develop a framework for existing and new observations. In the field example above, the geologist knows to look for dykes and evidence of contact metamorphism to help elaborate her story or suggest when it requires a change. The lack of an exposed contact requires her to adapt her pattern of an intrusive body, but enables her to immediately understand the new information and move forward with her investigation.
Table 3.2: A description of the shallow intrusion pattern used by the geologist in the field example.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title</td>
<td>Shallow intrusions</td>
</tr>
<tr>
<td>Predecessors</td>
<td>(Sub)volcanic rocks, intrusives, alteration, texture variation</td>
</tr>
<tr>
<td>Problem summary</td>
<td>How can the textural variation of the intrusives and the presence of volcanic rocks and dykes be explained?</td>
</tr>
<tr>
<td>Analysis</td>
<td>Shallow intrusion, fluid flow, heat, alteration, intruded volcanic pile, mineral growth, textural destruction, brecciation, multiple bodies</td>
</tr>
<tr>
<td>Solution summary</td>
<td>Disconnected intrusive bodies related to a distal pluton, usually intruding their own volcanic pile, often associated with mineralization and alteration</td>
</tr>
<tr>
<td>Successors</td>
<td>Minerals, alteration patterns, cross-cutting, age dating, dykes, volcanology</td>
</tr>
</tbody>
</table>

Geologic histories are a story. They contain a lot of information that is explicit, but also a considerable amount that the reader must interpret for themselves. As a geologist constructs a conceptual historical model, they are telling a story. Instead of having to think about all the causes and effects of something like a pluton intruding, they can add that pattern to the story as a shorthand. They can think of many consequences for the conceptual and descriptive models that are a result of that pluton without writing them all down. Conversely, anomalous observations (such as contact metamorphism) can be used to call up the pluton pattern and use it to guide investigation, even without any locally observed exposures of intrusive rocks.

Just like a complicated story made up of well-understood scripts, the geologic history is just a sequence of more familiar objects and story components. This history eventually constrains the interpolation of observations to create the descriptive geological model or map. Both understanding a map and constructing it requires the use of these fundamental units of meaning. Viewing interpretative objects as geological patterns, and ultimately as units of meaning, has important consequences for understanding model uncertainty as well as information flow from the geologist to the map user.

In the philosophical sense, the application of a pattern is an abduction. The observations are the exceptional things to be explained and the object created does not necessarily follow
from them. Each pattern represents an event in the geologic history. Patterns are the means by which the observations are explained in terms of a series of geologic events. Patterns have a set of observations that suggest when to apply them. Some of these observations are required for the pattern to be used, and others may support it but are not required. Triggering information might include certain sample/observation geometries, particular pieces of evidence in outcrops, or information about the conceptual model and map themselves.

The application of a pattern to form part of the conceptual model usually results in the addition of an object such as a fault line, a deviated contact, or other map feature to the descriptive geological model. In addition to the object that represents the pattern in the descriptive model, patterns contain a whole set of parameter information. For geologic patterns, the parameters are all the associated but implicit pieces of information relevant to a pattern and its place within the geologic history. For example, some of the parameters for the shallow intrusives pattern are heat, fluid flow, and exposure depth.

Patterns also suggest other things for the geologist to consider. Adding the pluton pattern to the map suggests the possibility of dykes or multiple intrusion phases. Along with the parameters of a pattern, these suggestions are gateways to the rest of the geosemiotic web as described by Baker (1999). In finer detail, parameters can assume values, such as depth or temperature. Parameter values describe the conceptual model in absolute terms, and their determination requires field or laboratory data.

Choosing patterns involves considering the terms and conditions for the descriptive model as well as the rest of the conceptual model. Schank and Abelson (1977) described a similar process where high level goals help to decide on which scripts to apply in a story.

While geological patterns can be represented as in Table 3.2, they can also be considered as a paired set of observations and a set of parameters. In this way, the observations that lead to the pattern’s application are more obvious, and the parameters of the pattern are grouped with its successors. This format is shown in Table 3.3.

The view in Table 3.3 is simpler to use with other parts of the workflow that I will propose.
in this thesis, and still captures the relevant information about patterns.

### 3.3.3 Patterns and Maps

Patterns represent the individual components of a conceptual model, and their application usually results in a change to the map. The changes produced by patterns are often in terms of units and their geometries. Maps represent rocks by grouping them according to a homogenous property of interest, such as lithology, age, chemistry, or a combination of properties. The application of a pattern results in changes to the relationships and shapes of units, represented by topology and spatial geometry respectively. Analogically, patterns can be thought of as verbs to the units’ nouns. The creation of units can be considered another kind of pattern, and unit definition is a major component of geological uncertainty because it affects how the conceptual model evolves and how it is translated to a descriptive model. Unit definition includes aspects of subjective property uncertainty (classifying observed rocks within a unit) as well as model uncertainty (the definition of units). In this thesis, I will assume that units represent natural types that can be unambiguously identified given a set of observations. I will also assume that they are discrete, homogeneous, and uniquely defined. The unit attribute will be considered as a real property of a rock.

Patterns can be distilled from anecdotal experience but much of this process is probably about forgiving misfits between new field areas and well-understood old ones (Brodaric and Gahegan, 2007). Like describing a new field area by using stories about an old one, patterns have only a loose spatial context. This is helpful in trying to break down the patterns used
Figure 3.8: The syncline on the map. The interpretation of a fold is represented by measurements (strike and dip) and lithologic contacts, as well as an explicit symbol for a syncline. (Wheeler, 1961)

Table 3.4: The description of the syncline pattern.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title</td>
<td>Syncline</td>
</tr>
<tr>
<td>Observations</td>
<td>Fold signs, varying orientation of bedding, young rocks in core of area, bedding/cleavage relationship</td>
</tr>
<tr>
<td>Parameters</td>
<td>Stress changes, fluid flow, deformation along axis, groups of folds, thrust faults</td>
</tr>
</tbody>
</table>

to build a descriptive model because it means that they can be considered without a need for spatial precision. A conceptual model in the 4D sense can be thought of as a sequence of patterns, and the descriptive model a representation of that sequence. Part of reading a descriptive model such as a map is interpreting the patterns used to construct it, and thus part of the conceptual historical model.

3.3.4 Example Pattern Analysis

Figure 3.8 shows an example geological object, a syncline, from a regional scale map. The pattern information is summarized in Table 3.4.

While it is useful to consider patterns in the form of tables of information, it is more illustrative to consider them as conceptual maps. Conceptual maps are freeform and allow
Figure 3.9: A captured pattern as a conceptual map. It describes the types of observations that lead to the abduction of the syncline. The right side of the figure shows some of the parameters of the syncline. Parameters must be interpreted as they are not shown explicitly in the map representation of the syncline (Figure 3.8).

the explicit illustration of the paths of thinking used to choose and evaluate a pattern. They emphasize the connections between parameters, the loose conceptual framework of a pattern and how they can be considered as part of a network of concepts. An example for the syncline pattern is shown in Figure 3.9.

In this example, the pattern makes sense of many different observations across the map area. It suggests other things to look for to constrain the parameters of the syncline and strengthen the case for its existence. The syncline pattern includes information from other field areas, perhaps those with better exposure that more clearly show the structure of a syncline. It also includes knowledge from laboratory experiments such as centrifuge modelling. Its structure and parameters are justified by its use in many other geological models, strengthening the argument both for its existence and its use on this map. The syncline's clear representation in the descriptive model, the map, represents field observations, a part of the geological history and the geologist’s knowledge and interpretation.
3.4 Summary

Geologists use conceptual abstractions, here called patterns, to help store and communicate knowledge, make decisions under uncertainty, and construct geological histories to understand field areas. The description of geologic pattern is the key to understanding the structure of conceptual models and thus model uncertainty. Patterns encapsulate much more information than can be represented using descriptive geological models like maps. In order to communicate more information about the conceptual model to the end user, some means of making patterns and their parameters more explicit is required. In order to understand the “hidden” information and the model uncertainty of a conventional map, a way of enumerating the set of patterns used by the geologist to construct the map is needed.
Chapter 4

Using Geological Patterns

4.1 Design Recovery

4.1.1 Introduction

It is impossible to directly deliver a 4-dimensional, pattern-based conceptual model using conventional data structures like a paper map. Instead, the geologist must use the map medium to create a descriptive model that captures the information represented in their conceptual model. When a map user reads the map, they must reconstruct the conceptual model mentally using the information available from the map, booklet and legend, as well as their own experience.

This section will explore the interpretation of part of the conceptual, historical model from a descriptive model like a map. In other words, given a map, it will describe how a user can recover a possible underlying conceptual model and the patterns within it in an explicit form. As noted above, geologists do this implicitly when they use an existing map. This project is concerned with making part of this process explicit. Understanding map interpretation is an opportunity to draw on a different field from geology, but one with similar challenges.

One of the tasks in software design is to understand what legacy source code is supposed
to do. The source code is usually very difficult to understand especially in the wider context of the program, and the challenge is to use this low-level information to recover the high-level conceptual plan for the program. One of the ways software designers accomplish this design recovery is through the use of high-level conceptual abstractions like patterns to find clues in the code to understand the bigger picture (Biggerstaff, 1989). For example, given the source code for an online shopping program, the engineer would need to see what section does checkout, what one controls the security, and what one manages the item view. Some of these tasks might be straightforward, but putting them all together to recreate the high-level plan for the program is difficult. There are many techniques in design recovery, but at its most basic it works by using the conceptual abstractions or patterns used in a discipline to help interpret the low-level code.

In geology, geologic patterns represent conceptual abstractions. By fitting known software design patterns to source code, engineers are able to recover meaning and the high-level model. In the same way, fitting a set of geologic patterns to a map allows the recovery of more of the conceptual model.

4.1.2 Recovery of Geologic Patterns

The goal of design recovery is to successfully recover the set of patterns that were used to build a particular descriptive model or map. The mapping geologist chooses the patterns they use as a response to their field observations, interpretations, and information on the evolving map. The outcome of the application of a pattern usually includes the addition of a geologic object or relationship between objects to the descriptive model. In the earlier mapping example, the application of the shallow intrusion pattern resulted in the addition of several igneous bodies with intrusive relationships to the host sedimentary rocks.

The key to later recovering patterns is the examination of the objects represented in the map and the interpretation of what patterns - geological concepts - could have been applied to create them.
It is important to note that the map itself might be inconsistent, and that it is possible to make mistakes when interpreting the intentions of the mapper. If geologic understanding has changed, the necessity for reinterpretation is critical. As noted earlier, the theory of sign interpretation called semiotics was at least partly developed in order to describe geology. Geological map reading is another interpretation process, and one that is subject to the same relationships between the symbol and interpreter as subjective description of geological history.

The legend and booklet that accompany the map might help constrain what patterns are involved and suggest ones that are not obvious from the explicit map geometry. Other sources of local and regional geology might be called on as well. More generally, background theoretical and historical geology knowledge might also be relevant to understanding a conceptual model, including knowledge of how the conceptual structures in geology have changed over time.

Once a permissible set of patterns is recovered, it is possible to estimate what observations may have been made and most importantly the parameter information used in the model. Note that maps that explicitly show field data or reports that condense it in some form, may help in this process as well.

4.1.3 Design Recovery Example

From the map depicted in Figure 4.1, it is possible to infer the use of at least six geological patterns using the descriptive map objects represented. These include the mixed siliclastic and carbonate sedimentary package pattern, the pluton pattern, the normal fault pattern, and the shear zone pattern. The map also depicts relationships between the objects that instantiate those patterns. The legend language, as described by Harrap (2001), can be used to unambiguously represent the inferred geological history, and thus the permissible contact relationships as shown in Figure 4.1.

The pattern set can be used to generate a sketch map that preserves only the pattern
and relationship information from the original map. An example is shown in Figure 4.2. The recovered pattern set is shown in Figure 4.2A. A valid map generated from it is shown in Figure 4.2B. Figure 4.2B looks different from the original map, however, because it lacks explicit correspondence to the field area and data. After rotating, moving and distorting the shapes, the map in Figure 4.2C more closely resembles the original source map (4.2D).

As in Figure 3.5, the two different maps in Figure 4.2 represent the same conceptual model, but with different geometries. They are descriptive representations of the same conceptual model, preserving its topology while altering the shape of units. The topology of the map captures the field observation or interpretation of relationships.

The inferred pattern set represents part of the conceptual model used to create the geological map. The pattern set can be expanded by estimating the parameters of each pattern as described in the legend and booklet, but also by incorporating knowledge from other geological sources such as experiments, previous studies, and experience. This set is a minimum example, showing only what is clearly represented on the map and so directly required. It is also possible to infer patterns such as regional metamorphism and strain gradient whose map expressions are more cryptic. In principle, a conceptual model inferred from a map could be much more detailed, but here the focus is on the recovery of explicit map-scale patterns.
Figure 4.1: An example of design recovery. A set of patterns is recovered from the map and their relationships, as expressed on the map, are captured using the graphical geological Legend Language (Harrap, 2001). F = fault relationship, I = intrusive relationship. Map of the Mendocina creek area after Westberg (2009).
Figure 4.2: A sketch map generated using the pattern information from Figure 4.1. A: The patterns recovered from the original map. B: The patterns used and the relationships between their representative objects are the same as in the map depicted in the original. Note that this representation is non-spatial and features have different shapes and orientations than in the original map. C: By shifting the orientation, shape and area of the objects in the map, it becomes very similar to the original (D).
4.2 Model Uncertainty

4.2.1 Introduction

With a description of geological patterns and their use in mapping and the technique of design recovery for existing maps, I am ready to introduce a description of model uncertainty. As previously described, model uncertainty is related to the choice of patterns used in the conceptual model. This model is not intended to supplant geostatistical or otherwise quantitative models of other kinds of geologic uncertainty, including objective and subjective property uncertainty. While the quality of measurements and observations affects modelling decisions, my description of model uncertainty focuses on the consequences of the choice of patterns when building a conceptual model. It is designed to deal with the specific problem of model uncertainty in a qualitative way that can be linked back to quantitative models. It specifically deals with how the existence of different permissible maps has outcomes in terms of uncertainty.

4.2.2 Model Uncertainty

Geologists must make decisions about what patterns to add to their conceptual model, as well as their properties and relationships. These decisions are represented by the choice of geological patterns to apply. The choice of patterns is driven by interpretation of observations but is usually not well constrained. The alternative patterns that could have been applied to explain the same data set in a permissible way interact to generate a set of possible conceptual models, which in turn correspond to sets of different resulting maps. Map scale is also a factor, which essentially sets a window within which map alternatives can be compared. If information at a finer detail than the mapper uses were available, it would be possible to eliminate some valid alternatives. Conversely, valid alternatives may look identical at a larger scale. The choice amongst these models, whether or not the alternatives are known, represents an uncertain decision. It is never completely determined by the available obser-
vations, although the ability to tightly constrain the conceptual model as much as possible is the essence of good fieldwork. This is an aspect of the geological modelling process called underdetermination.

4.2.3 Underdetermination

Conceptual geological models are underdetermined because they are created from sparse data by using theories to suggest historical events (Kleinhans et al., 2005). Underdetermination means that even with an impossibly complete set of observations, there would still be too little information to totally constrain the conceptual model and thus there will be other ways of explaining the field observations. The situation may get better or worse when indirect data such as geophysics is added, as well as when the map scale and expense of collecting information are considered.

Underdetermination is a significant component of the total geological uncertainty associated with a descriptive model because it means that all the other possible explanations for the observed information introduce a form of uncertainty that must be represented. These different explanations might result in changes to the descriptive model geometry, or more subtle aspects of what is represented by the descriptive model objects. For example, in the example of the field geologist mapping out a pluton, the obscured contact may have been intrusive or a fault. Given the information available, either possibility might be valid and thus the conceptual model is underdetermined, even though one interpretation may be strongly preferred based on, for example, regional information. Both interpretations could result in the same map geometry, but the decision may have consequences in terms of the economic value of a package of rocks or their degree or type of alteration. The legend of the map, and the underlying geological history, would be significantly different.
4.2.4 Evaluating Underdetermination

This leaves the question of how to actually determine the amount of underdetermination at a given point. There are two approaches to this. One is to construct a series of alternative models that indirectly capture a measurement of interpretative uncertainty according to how it affects the output. This requires collecting alternative conceptual model information from the geologist, which is time consuming and difficult. It also does not capture or estimate models that we don’t know enough to build - the unknown unknowns (Bowden, 2004). In order to consider the unknown unknowns and avoid the problem of eliciting many alternatives, the relationship between unmade observations and the choice of patterns must be considered.

Geologists choose (from their personal pattern set) the patterns they will apply to build a conceptual model. Their personal pattern set is developed through education and experience, both in the field and in the laboratory. No geologist has a complete set of patterns, because such a thing would mean that they understand everything there is to know about geology. When a geologist chooses a pattern to apply, they use the observations made, as well as the other patterns and relationships in their conceptual model, to pick a pattern that best fits their evolving model. A pattern might even be so uniquely constrained by the available information that it appears to be the only option. If, however, more information were available about the field area, there is a chance that the pattern would no longer be the only option, either because another one made more sense or because the geologist was forced to create a new theory about the area. Alternatively, the science behind the geologic interpretation might change.

It is impossible to completely sample or observe a volume of rock without destroying it (Oreskes et al., 1994). Thus the geologist is always limited in what information they can collect, and the possibility of further observations always exists. It is always possible that one of those as-yet unmade observations would force the geologist to choose a different pattern to apply, or possibly make an entirely new conceptual model.

For any set of patterns, no matter how self-consistent and well constrained by existing
observations, the possibility of change exists. All patterns belong to a large set of alternatives for both the pattern in general and for that particular map area, including those that are known by some geologists but not the mapper, but more importantly there are those patterns that are simply unknown. Without complete knowledge of geology, all that can be said about the size of that set of unknown alternatives is that it can be very large for each pattern.

Each pattern belongs to a set of valid alternatives, some of which are known but many of which are not. Each area of a map, the product of a conceptual model, has model uncertainty that is in some complex way proportional to the number of patterns that could be used to describe it.

A spatial model of underdetermination can then be defined as simply the number of patterns each point on a map is implicated in. Such a model is shown in Figure 4.3. A set of patterns was interpreted from a geological cross section through a copper porphyry deposit and the resulting density map is shown. The interpretative density map shows the relative density of “how many interpretations” (and thus how many sets of possible alternatives) a cell is subjected to. The outer edges are the products of very little interpretation as the geology is simple and the geologists who made this cross section were not particularly interested in it. It is notable that even in this example the map already has a strong bias, in this case against further study of sedimentary rocks.

In the core of the deposit, the zoned alteration system, fault, fluid channel and dyke patterns overlap, making it a conceptually complex area subject to more varied interpretation. The most complex area is the deep skarn horizons at the base of the deposit, where all of the above patterns overlap with the skarn and hornfels patterns.

The numerical value shown has no direct, practical application in the uncertainty function because it does not mean anything tangible in the real world. We know there are many alternatives, but not how they vary from each other. While it is clear the faults will be important from a geotechnical standpoint, it less clear if uncertainty about the existence and shape of alteration systems or skarn horizons will be relevant.
Figure 4.3: A cross section showing the distribution of patterns and the resulting pattern density map. Areas with many patterns have higher density of interpretation, especially the center of the cross section.
As in the earlier example of the field geologist and the pluton boundary, the result of changing which pattern is applied - what the geological history was - is often not represented by the map geometry. Instead, the change is in terms of the abstract patterns used, their parameters, and their interrelationships. It could also manifest as a change in contact types or event sequences, rather than lithology. The parameters of the intrusive contact pattern are different from the fault contact pattern, while their descriptive model representation is identical except for the symbology of a line. The potential effects of model uncertainty must be considered as a potential change in the set of patterns and their pattern parameters.

To represent this using the interpretative density model, patterns are considered as a set of parameters and a different density map is built for each parameter. Figures 4.4 and 4.5 show two such models. Each parameter uncertainty map has a different distribution of uncertainty as estimated by the density of patterns with the relevant parameter at a particular point. In other words, some pattern choices strongly affect parameters such as fluid flow, while others do not.

Figure 4.4 shows the interpretative density map for the fluid flow parameter. Faults and fluid channels are more uncertain with respect to fluid flow, with the skarn system and porphyry dykes also potentially uncertain. The right side of the cross-section contains the volcano-sedimentary sequence pattern, where fluid flow may have occurred in relation to its deposition.

In Figure 4.5, the variability vector parameter is modelled. The variability vector refers to whether or not a pattern has a principal axis of variability with respect to geologic properties. For example, a sedimentary sequence has a vertical variability vector as within unit variability is low. A zoned alteration system has a variability vector across its zones, which defines the broad trend of Figure 4.5. The variability vector is a useful parameter to consider because it helps suggest how to describe the spatial continuity of geological properties in an intuitive way.

Models for the relative spatial value of different observation modes could also be con-
Figure 4.4: An uncertainty map of the “fluid flow” parameter. The geometry reflects the interpreted locations of faults, as well as the alteration system represented on the geologic cross section.

Figure 4.5: An uncertainty map of the “variability vector” parameter. The anisotrophy of geological features is associated with the alteration system and especially the skarn horizon near its base.
structured from the pattern set of a map, such as in Figure 4.6. These models show the relative value of different kinds of observations for constraining the model. Figures 4.6a and 4.6b show two similar but distinct models for the gouge and breccia and sharp contacts observations respectively. Gouge and breccia observations are most important for constraining the fault pattern, and so its map parallels the shape of the fault pattern set. However, the hydrothermal breccia pattern is also constrained by the observation of breccia, so the most valuable location for gouge and breccia observations is in the area where the fault and breccia pattern overlap. In Figure 4.6b, the sharp contacts observation helps to constrain the same patterns as gouge and breccia, but also the porphyry dyke patterns as well. This suggests that paying attention to the existence of sharp contacts will be useful to constrain the porphyry and fault patterns, especially where they overlap.

Together these models represent spatial distribution of interpretation for the map in general and specific terms. They allow the visualization of conceptual model structure as well as complex spatial information about parameter and observation information. The previous sections, from the description of conceptual models and patterns to the idea of parameter uncertainty, have made a possible workflow for a geologist explicit and thus computationally accessible.
Figure 4.6: Two observation models, showing the relative value of observing gouge and sharp contacts in constraining the model. The observation of gouge and breccia is most important for constraining the locations of faults, while sharp lithologic contacts support the interpretation of porphyry dykes as well.
4.2.5 Applying the Underdetermination Model

The question of my thesis concerns uncertainty information and its effects on geotechnical evaluations. The pattern approach allows the description of model uncertainty through its effects on geological parameters, but the parameter uncertainty models are still not expressed in the terms of the geotechnical evaluation function. This comes back to the problem of defining useful units of uncertainty. Some deeper connection must be made between the parameters and meaning of patterns and the geotechnical model in order to express the possible variation of a concept like “heat” in terms of useful values. This connection would allow the description of uncertainty in terms relevant to the geotechnical models and in terms of relative value of observations to assist with sample selection and planning.

The underdetermination map is not applicable to geotechnical investigation on its own. Certain aspects of the geotechnical model are going to be affected differently by underdetermination. In order to understand how, a description of how geological features affect geotechnical properties is required. It will help describe how uncertainty flows from the geological map to the geotechnical model. In order to define the effects of conceptual uncertainty on the geotechnical model, models of how the geotechnical model’s input properties are affected by geology are required. The result will describe how each pattern parameter affects each geotechnical property, which allows the propagation of uncertainty information from a conceptual geological model to a geotechnical one.

In order to use this information and understand its impacts, geological uncertainty needs to be put in terms of an evaluation of interest. The evaluation must be considered separately, as a function of its parameters, in order to describe the propagation of geologic uncertainty due to underdetermination. Once that is defined, the terms of the uncertainty analysis will be clear, as will the impacts. The study of geological uncertainty must link up with the study of the geotechnical model and its parameters.
4.3 Evaluation Functions

4.3.1 Introduction

Evaluation functions generalize the concept of a geotechnical or other evaluation of an area using a geological map as a primary input. They help answer the question of how geologic maps are used in a particular domain. Evaluations take the form of some simple or complex function that uses properties to calculate a value. Those properties are derived from specialized sampling and the use of a geologic map to constrain their spatial variability.

4.3.2 Description

Evaluation functions may be simple, such as the Rock Mass Rating (RMR) system, or complex, as in Finite Element Analysis. Evaluation functions vary spatially as a result of the variation in the geotechnical properties used for the evaluation. Geotechnical properties include things like the uniaxial compressive strength or density of a rock and the number and quality of joint sets present. Properties are measured at different locations and then spread through domains of rock determined to have similar properties. The geological objects used to constrain the spreading of properties are part of the descriptive model, and therefore correspond to patterns in the conceptual model. This spreading of values describes how geologic information (unit or alteration type) affects the properties and how the distribution of different geological units determines the distribution of property values.

4.3.3 Relationship With Uncertainty Model

The geologic unit to which a point location belongs is usually the most important determinant of its properties in an evaluation model. When model uncertainty is considered as the potential change in geological patterns, it may not result in a change in the geological unit at a point. Instead of the unit attribute at a point, model uncertainty effects are usually related to the parameters of the patterns at a point.
Figure 4.7: A schematic conceptual diagram of how geological features affect a geotechnical property. The interpreted impacts of each geological feature are qualitative estimates without absolute values.

In order to connect a map of model uncertainty to the geotechnical properties and thus the evaluation function, a description of how all sorts of geological parameters actually affect parameter values is required. It will be a qualitative description of how geologic features and aspects of the geological history as represented by pattern parameters might affect geotechnical properties.

Figure 4.7 shows an example of such a description. It starts with high level concepts of fluid flow and change in stress field on the left, then shows how those things contribute to physical processes, and finally how those processes affect the uniaxial compressive strength. The result is a more complete link between the geotechnical model and the conceptual geological model and its representative map by going beyond the use of only lithology or alteration units to define geologic parameters for each pattern. The qualitative description of how geologic parameters, and thus patterns to which those parameters belong, affect properties may not be a better predictor of parameter values (although it should be at least as good as using lithology and alteration), but it is required in order to connect the effects of conceptual geological model uncertainty to the geotechnical model.

Defining how geological parameters affect the evaluation function enables the extraction of more meaning from a map than just geological units. It is possible to express model uncertainty, which is about a potential change in patterns and their respective parameters,
in terms of a potential change in the evaluation function.

4.3.4 Summary

The use of descriptive geological models can be generalized as using evaluation functions that take a geological map or 3D model as input and produce some value describing it for another purpose. This suggests how to formally connect descriptive geological models like maps to evaluation functions and enables the analysis of effects of a wide range of geological features, even those not actually on a map, on the evaluation.

The best way of representing the description of the effects of geology on parameters is to use a fuzzy framework because of its ability to accommodate qualitative descriptions of effects. For example the statement “vein infill tends to increases the quality of joints” can easily be translated into a fuzzy statement. In addition to their use in uncertainty analysis, these statements are transparent, shareable and participatory. They enable discussion of geotechnical assumptions and make them explicit.

4.4 Summary of Models Developed

The geologic modelling process uses fundamental units of meaning called patterns, each representing an interpretation of observation data to construct a conceptual model. Patterns are discrete conceptual abstractions used by geologists to store and communicate knowledge, facilitate decision-making, and make sense of observations. They are similar to patterns used in architecture or software design.

Patterns consist of sets of observations and parameters. Observations are geologic features that suggest the application of the pattern, as well as constrain its existence. For example, the volcanic pile pattern includes volcanic rocks and flow textures as observations. Parameters are aspects of the pattern that are relevant to its interpretation and use. The volcanic pile pattern would include the heat, near surface, and alteration parameters. Pa-
Parameters are the things about a pattern that make its addition to a conceptual model more than just the addition of a body of rock or an event. At a more detailed level, each parameter can have a value, for instance a temperature range, depth or intensity. Together, the set of patterns, their parameters, and their respective values constitute part of the conceptual geological model of an area.

The conceptual model, and thus the pattern set, determines how the geologist will create a descriptive geological model, a geologic map. The map describes field observations as well as representing the conceptual model of the mapping geologist. It is possible to use the fingerprints of different patterns as interpreted from the descriptive model to reconstruct part of the conceptual model using a technique called design recovery.

Design recovery of maps using patterns is possible by considering them as the output of a discrete set of interpretations, each of which results in the addition of an object to the map. Searching for the patterns in a map improves the comprehension of the conceptual model and the meaning gained by looking at a map. The patterns interpreted through design recovery can be used to build an interpretation density map, which in turn can be used to map the uncertainty associated with different parameters.

In order to use uncertainty information in a geotechnical model, the evaluation function, its input properties, and their dependence on geological parameters must be formalized. The effects of geologic parameters on geotechnical properties can be described qualitatively and used to connect the interpretative uncertainty model to the evaluation function.

Design recovery, model uncertainty analysis, and the description of the effects of geological features on geotechnical properties will be used to construct a workflow for the quantification the effects of model uncertainty on a geotechnical evaluation model. They also suggest ways to improve the transmission of meaning and prevent information loss when geologists commit a 4D conceptual model to paper or digital file as a descriptive model.
Chapter 5

Pattern Analysis and Model Uncertainty Case Study

5.1 Introduction

This chapter will demonstrate the use of ideas developed in the previous chapters to describe some of the uncertainty within a geotechnical evaluation at a mine site. It begins with the design recovery of patterns from a geological map, then describes the parameters of those patterns and their effects on geotechnical properties. This information is used to build a map of the uncertainty of the evaluation function.

The case study will evaluate only a limited aspect of geological model uncertainty regarding the density of interpretation and effect of patterns on geotechnical properties. Conceptual geological models can be represented as a set of patterns, which in turn have parameters that may have absolute values. This case study considers only the possibility of changing the patterns and thus the parameters that make up a conceptual model. It does not consider what alternative patterns might be used, nor does it assign parameters values and evaluate the effects of changing those values. It is a test case for the use of an interpretative density map as a proxy for geological underdetermination in terms of patterns and their parameters.
The study area is part of a copper porphyry deposit. At the deposit, a sequence of volcanic rocks and tuffs hosts porphyrytic dykes and an associated alteration system. The proposed mining method is an open pit. The deposit is cut by several high angle faults and its complex alteration system affects both the economics of the deposit as well as its geotechnical requirements. The data used is extracted from actual site data but explicit references have been removed in the interest of confidentiality.

5.2 Geological Map and Design Recovery

The available geological information is the cross section shown in Figure 5.1, along with a brief geological report. The geological cross section was created by slicing through a 3D geological model of the evaluation site. Like a map, the cross section represents both field data and the conceptual model of the geologists who created it. The cross section involves more model uncertainty than most maps, however, as only drill hole data is available from most of the volume it covers and thus large scale interpretation is required to define geological bodies. In order to describe model uncertainty, information about that conceptual model is required. Design recovery allows the recovery of a possible pattern set by examining the objects depicted in the cross section.

Some patterns are obvious from their representations in the cross section. Faults, porphyry dykes and a skarn horizon are marked on the section and in the legend. There are also patterns related to the choice of units, such as the presence of a volcano-sedimentary sequence and a tuff sequence. Other patterns are more cryptic, but are revealed by how the geometry of different units was modelled. A zoned alteration system is depicted, as is a fluid channel. The recovered patterns are shown in Figure 5.2 and summarized in Table 5.1.

Note the overlap between pattern polygons in Figure 5.2. The overlap is the result of sketching in potential patterns, but it helps to represent the tendency for the boundaries in a map to be areas of influence for multiple patterns. This is a direct consequence of the
Table 5.1: The pattern set represented in Figure 5.2 and derived from the map in Figure 5.1.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault</td>
<td>Steep faults imbricate the rocks into thrust panels</td>
</tr>
<tr>
<td>Porphyry dyke</td>
<td>Porphyrytic intrusions form discontinuous dykes</td>
</tr>
<tr>
<td>Hydrothermal breccia</td>
<td>Breccias occur along the fluid channel and are not caused by the faults directly</td>
</tr>
<tr>
<td>Volcano-sedimentary sequence</td>
<td>The older host rocks are conformable sequence of volcanics and sedimentary rocks</td>
</tr>
<tr>
<td>Tuff sequence</td>
<td>A mixed sequence of andesitic &gt;dacitic tuffs host the bulk of the deposit</td>
</tr>
<tr>
<td>Skarn horizon</td>
<td>Sedimentary units were metasomatized by the porphyry system at a counter trend to the main channel</td>
</tr>
<tr>
<td>Fluid channel</td>
<td>The main pathway for alteration, controlled by the geometry of the main faults</td>
</tr>
<tr>
<td>Zoned alteration system</td>
<td>The deposit is marked by distinct zones of alteration roughly parallel to main channel</td>
</tr>
</tbody>
</table>
Figure 5.2: A set of patterns for the map in Figure 5.1 created using design recovery. The geometry reflects the geologic cross section, but the presence of many overlapping patterns in certain areas is represented as well.
representation of a conceptual model and a data set as a 2D or 3D geological model - a contact must be placed somewhere, so the crisp boundaries represented may not reflect an actual discrete separation between geological features. Some patterns, such as alteration haloes, explicitly overlap other boundaries, but most are similar to mapped unit boundaries.

5.3 Patterns and the Interpretative Density Map

The pattern set derived from the geological cross section can be used to build a map showing the density of interpretation for the site as in Figure 5.3. Each cell in Figure 5.3 shows the number of patterns, and thus interpretations, that cell is involved in. Interpretation density is an estimate of the degree of underdetermination of the conceptual geological model because it relates to the number of interpretations, and thus uncertain modelling decisions, used to explain observations there.

In order to consider the impacts of model uncertainty, a set of parameters for each pattern is required. As noted earlier, this study is concerned with the potential impacts of the addition or removal of different patterns to the cross section, not the description of alternative patterns. The impacts of changing the patterns in the conceptual model manifest as changes to the parameters for different areas of the cross section. Parameters are the geological aspects of different patterns that define their characteristics and relationships with other patterns. For example, “hydrothermal” is a parameter of the porphyry dyke pattern because they are associated with hydrothermal systems. A potential impact of changing the porphyry dyke pattern, of model uncertainty, is the removal of its parameters, such as its hydrothermal aspect. Model uncertainty impacts investigations primarily through changes to things about the conceptual model, rather than changes to the lithologic cross section created from it.

Using information from the geological report for the area as well as personal experience and geological references, I described the main parameters of each pattern. Many parameters
Figure 5.3: The interpretation density model for the recovered pattern set and the descriptive geological model. Areas with many overlapping patterns are the most “interpretation dense”, suggesting that information about those areas is of higher value for constraining the overall conceptual model.
are shared by several patterns, defining families of patterns with similar geological histories and modes of formation. For example, heat and fluid flow especially are related to the formation of the deposit itself. There are also parameters that belong to a single pattern, such as welding, branching, and silica content effect. Descriptions for all patterns can be found in the Appendix.

Figures 5.4 and 5.5 illustrate the parameters and observations associated with the porphyry dyke and tuff sequence patterns respectively. Both demonstrate the schematic nature of patterns, as well the associated observation/parameter information not captured by the geological cross section.

The parameters can be combined with the interpretation density map to visualize the effects of model uncertainty in terms of parameters as shown in Figure 5.6.
Figure 5.5: The parameters and observations associated with the tuff sequence pattern.
Figure 5.6: An uncertainty map of the heat parameter. The interpretation of the presence of porphyry dykes and alteration systems implies information about the heat conditions of the rock mass at some point in the geologic history. Changing the conceptual model by removing or reinterpreting the dykes would therefore have consequences for evaluations where geothermal history is an important property.
Figure 5.7: A cross section showing how the relative constraining value of the textural destruction observation changes across the area. Textural destruction is an important piece of evidence for interpreting the presence of hydrothermal alteration systems, so the cross section mirrors the represented extent of the skarn and alteration systems.
Figure 5.6 shows the density of interpretations that involve the parameter “heat” across the cross section. Unlike Figure 5.3, which shows the density of all interpretation across the cross section, Figure 5.6 counts only patterns with the heat parameter.

In the top left of Figure 5.6, hydrothermal breccias, porphyry dykes, and a tuff sequence all overlap. The interpretative uncertainty for the heat parameter is high here because it is an important aspect of all three patterns. Changing information about heat, whether the thermal history of the rocks or absolute values of temperature in the past, could strongly impact the conceptual geological model in this area.

This visualization can also be used to study the spatial variability of the importance of different observation modes. Each pattern has a set of observations that help constrain it, and thus the utility of different observation types varies with patterns across the study area. An example for the textural destruction observation is shown in Figure 5.7.

Figure 5.7 shows how important the observation of textural destruction is at different areas in the cross section in terms of constraining the conceptual geological model. It shows that textural destruction is an important observation throughout the alteration system, but is particularly concentrated in the skarn horizon at the base of the deposit. It suggests that in these areas, observation of textural destruction in drill core supports the interpretations represented in the geological cross section.

5.4 Evaluation Function Analysis

The interpretative density map and the derived maps for parameters and observations lack reference to the geotechnical evaluation function. They do not reflect how the nature of the evaluation function might shift the relative impacts of different patterns. In this case study, the evaluation function is the rock mass rating system, or RMR (Bieniawski, 1989). RMR uses information about joints, ground water, intact rock strength and fracture spacing to evaluate the support requirements, stand up time, and other geotechnical aspects of a
rockmass. The classification criteria and evaluation information for RMR are shown in Figure 5.8.

In this study, I will consider intact strength, the rock quality designation (RQD), and joint spacing, condition, and orientation. Intact strength is the uniaxial compressive strength of a sample as measured through point load or laboratory tests. RQD is a measurement of the quality of drill core taken by adding up the length of recovered core segments longer than 10 cm, then dividing that length by the total length of drilled core. Joint spacing, condition and orientation are measured and categorized according to the RMR specifications as shown in Figure 5.8.

For each parameter listed above, I estimated the magnitude of its effect on each input property of the RMR function. The qualitative, relative estimated values were intended to capture “how much” each geotechnical property might be affected by each geological parameter. For example, the brecciation parameter is expected to have a strong effect on rock strength and RQD, a medium effect on joint spacing, and a low effect on joint condition and orientation. This method is qualitative and subjective, but the estimate is explicit and thus subject to consideration by other experts. The complete set of parameter impact estimates can be found in the Appendix.

The impact values for parameters were used to estimate the effect of each pattern on the geotechnical properties used to calculate RMR. The property totals for each pattern were summed to represent the pattern’s impact on RMR. The impacts of each pattern on the geotechnical input properties are shown in Figure 5.9. The axes of Figure 5.9 show the estimated impact of each pattern in terms of each geotechnical property.

5.5 Mapping Evaluation Function Uncertainty

Each pattern polygon from Figure 5.2 was assigned its corresponding RMR impact value as shown in Table 5.2.
### A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of values</th>
<th>For this low range - uniaxial compressive test is preferred</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength of intact rock material</td>
<td>&gt;10 MPa</td>
<td>4 - 10 MPa</td>
</tr>
<tr>
<td>Uniaxial compressive strength</td>
<td>&gt;250 MPa</td>
<td>100 - 250 MPa</td>
</tr>
<tr>
<td>Rating</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>Drill core Quality RQD</td>
<td>90% - 100%</td>
<td>75% - 90%</td>
</tr>
<tr>
<td>Rating</td>
<td>20</td>
<td>17</td>
</tr>
<tr>
<td>Spacing of</td>
<td>&gt; 2 m</td>
<td>0.6 - 2.0 m</td>
</tr>
<tr>
<td>Rating</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Condition of discontinuities (See E)</td>
<td>Very rough surfaces</td>
<td>Not continuous</td>
</tr>
<tr>
<td>Rating</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Inflow per 10 m tunnel length (l/m)</td>
<td>None</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Groundwater pressure</td>
<td>None</td>
<td>0.1 - 0.2</td>
</tr>
<tr>
<td>General conditions</td>
<td>Completely dry</td>
<td>Damp</td>
</tr>
<tr>
<td>Rating</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>

### B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

<table>
<thead>
<tr>
<th>Strike and dip orientations</th>
<th>Very favourable</th>
<th>Favourable</th>
<th>Fair</th>
<th>Unfavourable</th>
<th>Very Unfavourable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnels &amp; mines</td>
<td>0</td>
<td>-2</td>
<td>-5</td>
<td>-10</td>
<td>-12</td>
</tr>
<tr>
<td>Foundations</td>
<td>0</td>
<td>-2</td>
<td>-7</td>
<td>-15</td>
<td>-25</td>
</tr>
<tr>
<td>Slopes</td>
<td>0</td>
<td>-5</td>
<td>-25</td>
<td>-50</td>
<td></td>
</tr>
</tbody>
</table>

### C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

<table>
<thead>
<tr>
<th>Class number</th>
<th>Description</th>
<th>Average stand-up time</th>
<th>Cohesion of rock mass (kPa)</th>
<th>Friction angle of rock mass (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Very good rock</td>
<td>20 yrs for 15 m span</td>
<td>&gt; 400</td>
<td>&gt; 45</td>
</tr>
<tr>
<td>II</td>
<td>Good rock</td>
<td>1 year for 10 m span</td>
<td>200 - 400</td>
<td>35 - 45</td>
</tr>
<tr>
<td>III</td>
<td>Fair rock</td>
<td>1 week for 5 m span</td>
<td>100 - 200</td>
<td>25 - 35</td>
</tr>
<tr>
<td>IV</td>
<td>Poor rock</td>
<td>10 hrs for 2.5 m span</td>
<td>&lt; 100</td>
<td>15 - 25</td>
</tr>
<tr>
<td>V</td>
<td>Very poor rock</td>
<td>30 min for 1 m span</td>
<td>&lt; 10</td>
<td>&lt; 15</td>
</tr>
</tbody>
</table>

### D. MEANING OF ROCK CLASSES

<table>
<thead>
<tr>
<th>Average stand-up time</th>
<th>Cohesion of rock mass (kPa)</th>
<th>Friction angle of rock mass (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 yrs for 15 m span</td>
<td>&gt; 400</td>
<td>&gt; 45</td>
</tr>
<tr>
<td>1 year for 10 m span</td>
<td>200 - 400</td>
<td>35 - 45</td>
</tr>
<tr>
<td>1 week for 5 m span</td>
<td>100 - 200</td>
<td>25 - 35</td>
</tr>
<tr>
<td>10 hrs for 2.5 m span</td>
<td>&lt; 100</td>
<td>15 - 25</td>
</tr>
<tr>
<td>30 min for 1 m span</td>
<td>&lt; 10</td>
<td>&lt; 15</td>
</tr>
</tbody>
</table>

### E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY conditions

<table>
<thead>
<tr>
<th>Discontinuity length (perpendicular)</th>
<th>Rating</th>
<th>Separation (aperture)</th>
<th>Rating</th>
<th>Roughness</th>
<th>Rating</th>
<th>Infilling (gouge)</th>
<th>Rating</th>
<th>Weathering</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1 m</td>
<td>6</td>
<td>None</td>
<td>6</td>
<td>Very rough</td>
<td>6</td>
<td>None</td>
<td>6</td>
<td>Unweathered</td>
<td>6</td>
</tr>
<tr>
<td>1 - 3 m</td>
<td>4</td>
<td>&lt; 0.1 mm</td>
<td>4</td>
<td>Rough</td>
<td>5</td>
<td>Hard filling &lt; 5 mm</td>
<td>5</td>
<td>Slightly weathered</td>
<td>5</td>
</tr>
<tr>
<td>3 - 10 m</td>
<td>2</td>
<td>0.1 - 1.0 mm</td>
<td>2</td>
<td>Slightly rough</td>
<td>3</td>
<td>Hard filling &gt; 5 mm</td>
<td>3</td>
<td>Moderately weathered</td>
<td>3</td>
</tr>
<tr>
<td>10 - 20 m</td>
<td>1</td>
<td>1.1 - 5 mm</td>
<td>1</td>
<td>Smooth</td>
<td>1</td>
<td>Soft filling &lt; 5 mm</td>
<td>1</td>
<td>Highly weathered</td>
<td>1</td>
</tr>
<tr>
<td>&gt; 20 m</td>
<td>0</td>
<td>&gt; 5 mm</td>
<td>0</td>
<td>Slickensided</td>
<td>0</td>
<td>Soft filling &gt; 5 mm</td>
<td>0</td>
<td>Decomposed</td>
<td>0</td>
</tr>
</tbody>
</table>

### F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

<table>
<thead>
<tr>
<th>Strike perpendicular to tunnel axis</th>
<th>Strike parallel to tunnel axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive with dip - Dip 45 - 90°</td>
<td>Drive with dip - Dip 20 - 45°</td>
</tr>
<tr>
<td>Very favourable</td>
<td>Favourable</td>
</tr>
<tr>
<td>Drive against dip - Dip 45-90°</td>
<td>Drive against dip - Dip 20-45°</td>
</tr>
<tr>
<td>Fair</td>
<td>Unfavourable</td>
</tr>
</tbody>
</table>

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly. ** Modified after Wickham et al (1972).

Figure 5.8: The RMR system, after Bieniawski (1989).
Figure 5.9: A graph showing the estimated effects of each pattern in terms of the input properties for RMR. Impact values are a unitless, qualitative representation of the relative potential effect of adding or removing a pattern from the conceptual model.
Table 5.2: A summary of the impacts of each pattern on geotechnical properties and the corresponding effect on the RMR evaluation.

<table>
<thead>
<tr>
<th>Name</th>
<th>About</th>
<th>Intact strength</th>
<th>RQD</th>
<th>Joint spacing</th>
<th>Joint condition</th>
<th>Joint orientation</th>
<th>RMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid channel</td>
<td>Main pathway for alteration, controlled by main faults</td>
<td>13</td>
<td>9</td>
<td>7</td>
<td>12</td>
<td>3</td>
<td>44</td>
</tr>
<tr>
<td>Zoned alteration system</td>
<td>The porphyry model has distinct zones roughly parallel to main channel</td>
<td>12</td>
<td>6</td>
<td>7</td>
<td>9</td>
<td>0</td>
<td>34</td>
</tr>
<tr>
<td>Skarn horizon</td>
<td>Porphyry system at a counter trend to the main channel</td>
<td>14</td>
<td>9</td>
<td>5</td>
<td>15</td>
<td>2</td>
<td>45</td>
</tr>
<tr>
<td>Porphyry dykes</td>
<td>Porphyry intrusions form discontinuous dykes</td>
<td>18</td>
<td>12</td>
<td>8</td>
<td>10</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>Porphyry dykes</td>
<td>Porphyry intrusions form discontinuous dykes</td>
<td>18</td>
<td>12</td>
<td>8</td>
<td>10</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>Volcano-sedimentary sequence</td>
<td>The older host rocks are conformable sequence of volcanics and sedimentary rocks</td>
<td>10</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>29</td>
</tr>
<tr>
<td>Tuff sequence</td>
<td>A mixed sequence of andesite dacite tuffs host the bulk of the deposit</td>
<td>15</td>
<td>10</td>
<td>8</td>
<td>9</td>
<td>3</td>
<td>45</td>
</tr>
<tr>
<td>Hydrothermal breccias</td>
<td>Breccias occur along the fluid channel and are not caused by the faults directly</td>
<td>18</td>
<td>15</td>
<td>15</td>
<td>13</td>
<td>12</td>
<td>73</td>
</tr>
<tr>
<td>Fault</td>
<td>Steep faults imbricate the rocks into thrust panels</td>
<td>11</td>
<td>19</td>
<td>16</td>
<td>17</td>
<td>12</td>
<td>75</td>
</tr>
<tr>
<td>Fault</td>
<td>Steep faults imbricate the rocks into thrust panels</td>
<td>11</td>
<td>19</td>
<td>16</td>
<td>17</td>
<td>12</td>
<td>75</td>
</tr>
<tr>
<td>Fault</td>
<td>Steep faults imbricate the rocks into thrust panels</td>
<td>11</td>
<td>19</td>
<td>16</td>
<td>17</td>
<td>12</td>
<td>75</td>
</tr>
<tr>
<td>Fault</td>
<td>Steep faults imbricate the rocks into thrust panels</td>
<td>11</td>
<td>19</td>
<td>16</td>
<td>17</td>
<td>12</td>
<td>75</td>
</tr>
<tr>
<td>Skarn horizon</td>
<td>Porphyry system at a counter trend to the main channel</td>
<td>14</td>
<td>9</td>
<td>5</td>
<td>15</td>
<td>2</td>
<td>45</td>
</tr>
</tbody>
</table>
Figure 5.10: A cross section showing the spatial variability in the uncertainty of the RMR evaluation as a function of the conceptual model uncertainty. The cross section summarizes the interpreted set of patterns and their estimated impact. It highlights areas where the choice of interpretation has a potentially critical effect on the RMR evaluation.

A grid was created across the pattern set. Because the pattern polygons overlap, some grid cells contained more than one estimated property impact value. In other words, more than one pattern was predicted to impact the property within the grid cell. In order to capture this information, each grid cell was assigned the sum of each property value for all the patterns it contained. The result was a set of five maps, one for each input property of RMR, that summarized the relative uncertainty of each property. These uncertainty maps can be found in the Appendix. The property uncertainty maps were then summed to create an uncertainty map for the RMR function itself. The result was Figure 5.10.

It shows the relative spatial variation in the uncertainty of the RMR evaluation as a function of the uncertainty associated with the conceptual geologic model.
5.6 Discussion

Design recovery produces a set of patterns and a map showing part of the inferred conceptual model for an area. Parameters for the patterns were estimated using subjective judgement and knowledge, the information in the report accompanying the geological map or 3D model, and reference information. Some patterns were obvious, but others were more vague. Recovery of patterns could continue to a high level of detail, but it would also become much more subjective. Parameters were either almost universal, such as heat and fluid flow, or unique to certain patterns, such as welding and the tuff sequence pattern. This suggests that certain parameters and observations might be more useful in constraining the conceptual model as a function of how many patterns they belong to.

The interpretative density map (Figure 5.3) shows that model uncertainty is highest in the core of the deposit, where the porphyry dykes, fluid channel and alteration system overlap. Interpretative density correlates to the geological complexity of an area. The highest density was in the skarn horizon, but that area may not be relevant for the site investigation. The effect of overlapping patterns tends to produce artifact cells with higher interpretative density than their surroundings. This effect reflects the nature of digital representations of uncertain geological contacts, but also may falsely reflect a relatively certain boundary as being uncertain. It is not clear if sharp edged polygons or deliberately “feathered” polygons are more representative of the areas where patterns and geologic features overlap and come into contact. This may depend on the geological control provided by the source data set, but this is often not available or difficult to visualize.

Maps of the relative uncertainty of different parameters such as Figure 5.6 are interesting, but without connection to the evaluation function it is unclear how significant they are. Maps of observation value such as Figure 5.7 represent a visualization of what information is most useful to constrain the conceptual model, and since they relate to the pattern set itself, they are useful without reference to the evaluation function. A more constrained conceptual model represents a less uncertain source of information for geotechnical analysis, regardless
of what evaluation function is used.

In this case, the evaluation function is known and can be connected explicitly with the geological uncertainty model. RMR is a simple evaluation function to analyze because of its explicit dependence on its input properties. More complex functions may require the use of sensitivity analysis or a first order approximation or estimate such as the point estimate method (Rosenblueth, 1972).

The description of the impacts of geological parameters on the evaluation function’s input properties is based on intuition and experience, and is thus subjective. However, the estimates are explicit and can be discussed with other experts, making them subject to the approval of a group and the benefits of collaboration. It may be more effective to perform a regression analysis of some kind in order to determine the relationship between property variability and the presence of different patterns.

As shown in figures 5.9 and 5.2, there are two families of patterns in terms of their effects on the input properties for RMR. Most patterns are related to fluid movement and alteration at the deposit, with strong effects on rock strength and joint condition. The fault pattern comprises the other family. The fault pattern has a low impact on intact strength but a much higher one on joint spacing and orientation. In general, intrusions and alteration tend to affect the strength of a rock by travelling along, creating and altering joints. Faults are expressed in the rock as changes to the RQD, joint orientation and spacing values. They have a lower associated strength effect because they are not directly related to alteration events. This description is just one way of looking at the effects of geological features on geotechnical properties, and equally valid estimates could be constructed.

The final combination of pattern information and the RMR function results in a set of pattern polygons attributed with their estimated impact on RMR. These can be sampled to create a raster showing the value of RMR uncertainty for each cell in the cross section. The result in Figure 5.10 looks very similar to the interpretative density map in Figure 5.3, with subtle differences along fault traces and in the core of the deposit. It is possible that
interpretative density alone is sufficient for a “first pass” estimate of the spatial distribution of the effects of model uncertainty on an evaluation.

The uncertainty map suggests that the most uncertain areas are along the faults on the left side of the cross section and especially their extent at depth, where they overlap with the alteration, fluid channel and skarn horizon patterns. It also suggests that the right pit wall, where faults cut multiple lithologies, intrusions, skarn and the roots of the alteration system may be a problem area as well. This contrasts with a first glance appraisal of the cross section that suggests the area on the right side is relatively uninteresting.

Another useful aspect of the evaluation uncertainty map is that it can be used to map the value of different observation types.

The observation value map for the sharp contacts observation is shown in Figure 5.11. The value is highest where the porphyry dyke, breccia and fault patterns overlap. Elsewhere, the value maps the fault pattern and is high at depth where a second porphyry body occurs. Figure 5.11 contrasts with Figure 5.12, showing the value of the mineral growth observation. The observation of mineral growth is important for constraining the widespread zoned alteration system, and its value increases where the fluid channel pattern occurs. The geophysics value map in Figure 5.13 is similar to the sharp contacts map. Geophysical contrast is associated with the faults and the alteration zones related to the porphyry intrusions.

The different observation value maps can be summarized to show the most valuable observation at each point as in Figure 5.14. The most valuable observation is the one that constrains the patterns with the highest impact on the evaluation function, in this case RMR. In the geologically complex area in the top left of the cross section, the observation of sharp contacts and of gouge and breccia is most important. In the core of the deposit, constraining the alteration system becomes more important, and thus mineral growth becomes a more important observation. Faults, constrained through geophysics and the observation of gouge and breccia, are important where they are mapped along the left and right sides of the cross section.
Figure 5.11: A cross section showing the value of the sharp contacts observation at different areas in the study area. The observation of sharp contacts helps to constrain the interpretation of faults, dykes and hydrothermal breccia.
Figure 5.12: A cross section showing the value of the mineral growth observation at different areas in the study area. Unlike Figure 5.11, where the geometry reflects the interpreted locations of faults, mineral growth is associated with the envelope of the alteration system.
Figure 5.13: A cross section showing the value of the geophysical contrast observation at different areas in the study area. Faults and the boundaries of the interpreted porphyry dyke bodies are particularly constrained by the observation of a geophysical contrast such as resistivity.
Figure 5.14: A cross section showing the most valuable type of observation in terms of constraining the combined geological and RMR model. It summarizes the type of information represented by Figures 5.11 to 5.13.
In terms of observation value, Figure 5.14 indicates that geophysics may be useful to constrain the shapes and distributions of faults and porphyry dykes. The observation value map also underlines the importance of alteration mapping to constrain fluid channels, which suggests that spectral mapping and the collection of samples that retain important textural relationships (such as core samples over chip samples) are important in certain areas.

The observation value map could be combined with information about the relative costs of different investigation techniques to strengthen cost-benefit models of sampling such as that described by Rojas and Cáceres (2011).

Observation maps are most useful when they incorporate information about the evaluation function because they imply observation value relative to the evaluation itself. Figure 5.15 shows the most valuable observation type, as determined by the number of patterns constrained by each type, without consideration of the evaluation function.

It is subtly different from Figure 5.14, which includes the pattern RMR values. Figure 5.15 visualizes the observation values for the geological conceptual model itself, where each pattern is as valuable to constrain as any other.

The process of building an uncertainty map for an evaluation function and its accompanying observation value map is shown in Figure 5.16. A geological map was used for the recovery of a pattern set, which was attributed using the evaluation function properties and used to create uncertainty and observation value maps. These maps can be used to visualize interpretative uncertainty in terms of its effects on the evaluation function and identify the observations most valuable for constraining evaluation function uncertainty as a result of geological interpretation.

5.7 Summary

The pattern-derived map of evaluation uncertainty identified areas that are uncertain as a result of the interaction between the evaluation function and the conceptual geological
Figure 5.15: A cross section showing the most valuable observation for different areas, irrespective of the impact of each pattern on the evaluation function. Unlike Figure 5.14, it does not incorporate weighting information from the evaluation function.
Figure 5.16: The main processes and outputs from the evaluation function uncertainty analysis.
model (Figure 5.10). It also suggests ways of resolving that uncertainty in an efficient way, informed by the geological model itself (Figure 5.14). The subjective information used to build the uncertainty map is explicit and can be discussed and reviewed as new information and expertise becomes available.
Chapter 6

Further Work and Conclusions

6.1 Project Summary

Geological maps are the products of a complex interpretation process. Geologists collect field data such as rock descriptions, structural measurements, and geologic relationships. This information is used to build a conceptual geological model, including a geologic history. A descriptive geologic model, like a map or 3D model, is a representation of the field data, constrained by the conceptual model, and usually with only a small subset of the field data directly shown. Each part of the mapping process, from simple positioning in the field to the interpretation of regional features such as metamorphic trends, is to some degree uncertain.

Uncertainty associated with modelling decisions has historically proven difficult to isolate and study. Model uncertainty describes the uncertainty of each interpretation used to construct the conceptual geological model. One aspect of model uncertainty is due to the underdetermination of geologic interpretations. In order to study model uncertainty, a conceptual geological model must be separated from its map representation and considered as a set of interpretations.

Individual interpretations can be represented as geologic patterns. Patterns are conceptual abstractions that are used to store, transmit and apply geologic knowledge based on
laboratory studies, field work, and experience. Patterns have features called parameters that describe their geological characteristics in detail. The construction of a conceptual model, and thus of a map, is a design process where the geologist must choose which patterns to use, both to explain existing observations and guide the collection of new information.

It is possible to recover a permissible set of patterns from a geologic map using a technique called design recovery. In design recovery, the geologic representations on a map are used to infer a set of permissible patterns and thus a representation of the conceptual model used to create the map. The pattern set allows consideration of the uncertainty particular to the conceptual model itself by representing the model as a set of interpretations, each subject to change.

The impacts of interpretative uncertainty might not be in the form of changing the geometry of geological units on a map. It might manifest as a change in the parameters of the different patterns used, either because of alternative pattern descriptions or the use of different patterns entirely. The effect of each geologic parameter on the input properties of the evaluation function must be determined in order to evaluate model uncertainty in useful terms.

A case study demonstrated the use of the above techniques to map the potential geological underdetermination on a cross section and integrate geotechnical information to describe the impacts of underdetermination in terms of the geotechnical evaluation function. Pattern information was also used to compare different observation types in terms of their efficiency in resolving the uncertainty of the conceptual model, and thus of the evaluation function. These applications are innovative methods for the visualization and interpretation of geologic maps that allow unprecedented communication of geological meaning to map users.
6.2 Further Work

The analysis of geological patterns provides a framework for future studies of the different aspects of conceptual model uncertainty, geological data representation, and estimation of geotechnical impacts of uncertainty.

In terms of implementation, a streamlined workspace for design recovery, pattern elicitation and property impact estimation is required instead of the tedious mix of GIS and manual entry used for this project. In other words, for these methods to be applied in practice, an operational implementation as tools is needed. Such a workspace would encourage the increased study of model uncertainty and would simplify the process of experimentation with its different aspects.

Alternative patterns and their effects could be studied by creating a set of alternative conceptual models for a single data set. Normally, this would require a geologist to manually reinterpret the available information. However, pattern analysis provides a set of possible observations that were used to construct the conceptual geological model. These observations are artificial raw data that could be used to identify other possible patterns that share those observations. It may be possible recover a single pattern set, then use the observations for each pattern to interpret a set of base information. The base information could be used to suggest a set of alternative patterns with the same observation information. To realize these possibilities, a study in the domain of artificial intelligence would likely be needed.

Each form of underdetermination could be studied in a similar way to the case study here, by using a geotechnical evaluation as a measurement of the real impact of conceptual geological uncertainty. The idea of an evaluation function is general, and may be used to apply this research to any field that uses geological maps to make decisions - mineral exploration, land use planning, geohazard maps, etc.

The evaluation of the choice of observations and parameters ascribed to each pattern would allow the study of the difference in supposedly shared concepts between geologists. Consideration of the different conceptual maps used to create maps of the same area could
have applications in the field of generalization, as geological surveys move to aggregate map
datasets into more coherent wholes and create derived modelling products from them.

The estimation of the values for different parameters could be used to define a more ex-

cplicit link between the conceptual geological model and physical models such as geotechnical
ones. Statistical regression and sensitivity analysis could be used to refine the estimates
of how geologic parameters affect geotechnical properties, perhaps allowing the use of the
pattern set itself to estimate geotechnical property values instead of just their uncertainty.

The process of creating a geological map to represent field data and respect the relation-
ship and history information stored in the conceptual geological model is important to
understand in order to develop alternative visualizations of geological information that might better communicate meaning to map users.

Geological patterns could also provide a useful teaching tool for understanding the process
of geological modelling and the nature of conceptual uncertainty. Explicit representations of
concepts as patterns makes interpretive choices visible both to the mapping geologist and to
others. As a result, established patterns could also form part of the curriculum of a mapping
course to help teach mapping as a design process. The idea of generating new patterns
and invalidating old ones would also provide a chance to discuss theory change and research
issues in geology.

The implementation of a pattern workspace that allows efficient design recovery, parame-
ter elicitation and exposes the parameter-property impact estimate to statistical study would
provide a foundation for the necessary experiments to understand model uncertainty and its
effects on geotechnical site investigation. One such study would investigate the correlation
between interpretative density and model uncertainty, specifically its impacts in terms of
geotechnical properties. Property measurements from across a site area would be classified
according to their degree of deviation from their predicted value (based on lithology and
alteration, for example). The spatial distribution of anomalous samples could be compared
to the interpretative density map to see if interpretative density is a good predictor of the
occurrence of anomalous samples. The process would be repeated for many sections and samples in order to help constrain the absolute impacts of underdetermination. This experiment would put the estimations described in the case study here into real terms, and allow the evaluation of the interpretative density model as a proxy for model uncertainty.

6.3 Conclusions

Geological maps integrate field data and a conceptual geological model in order to describe the geological geometry and history of an area. As a result, they encapsulate the uncertainty that results from observation and interpretation in the field, as well as the interpretation of a geological history and the creation and representation of a map. Methods of uncertainty quantification to date describe forms of uncertainty particular to the geologic map or field data, but not to the conceptual geological model.

Geological pattern analysis provides a way of recovering and describing a conceptual geological model and the consideration of its uncertainty. By expressing model uncertainty in geotechnical terms, a pattern set can be used in a site investigation in order to predict the distribution of model uncertainty and suggest efficient observations to reduce it.

Further study of geologic patterns and their relationships with the evaluation functions and field observations is required in order to describe the effects of model uncertainty and integrate it with other uncertainty quantification methods. Geologic patterns may also provide a useful tool for geoscience education, geological visualizations, and the development of geologic data structures and modelling methods.


Appendix A

Appendix

A.1 Patterns, Parameters, and Observations

Porphyry dykes
Description: Porphyry intrusions form discontinuous dykes
Parameters: Branching, Dykes, Fluid flow, Fracturing, Grain size variation, Heat, Hydrothermal, Magma, Sheets, Volcanism
Observations: Chilled margins, Cross cutting, Fine-medium grained, Geophysical contrast, Igneous contact, Igneous rock, Porphyrytic texture, Sharp contacts

Tuff sequence
Description: A mixed sequence of andesitic-dacite tuffs host the bulk of the deposit
Parameters: Explosive, Extensive, Heat, Hydrothermal, Reworking, Sedimentary, Silica contact effect, Subaerial, Variable lithology, Welding
Observations: Massive, Pumice/ash, Tephra/glass, Variability vector, Variability/grading, Volcaniclastic textures, Volcanics, Welding

Hydrothermal breccias
Description: Breccias occur along the fluid channel and are not caused by the faults directly
Parameters: Explosive, Fluid flow, Heat, Megaliths, Mineralizing, Movement, Pore space,
Shallow/free surface, Variability vector, Very poor sorting

Observations: Cross cutting, Fluid source, Gouge and breccia, Grain size variation, Local alteration, Sharp contacts

**Fault**

Description: Steep faults imbricate the rocks into thrust panels

Parameters: Barrier, Brecciation, Brittle/ductile, Failure, Fluid flow, Lineament, Movement, Offset, Open space, Stress change

Observations: Geophysical contrast, Gouge and breccia, Lineaments, Offset, Sharp contacts

**Zoned alteration system**

Description: The porphyry model has distinct zones roughly parallel to main channel

Parameters: Alteration, Extensive, Gradient, Heat, Mineralizing, Textural destruction

Observations: Diffuse and sharp boundaries, Extensive, Mineral growth, Systematic mineral change, Textural destruction, Variability vector

**Fluid channel**

Description: Main pathway for alteration, controlled by main faults

Parameters: Alteration, Controlling feature, Fluid flow, Mineralizing, Textural destruction

Observations: Controlling feature, Diffuse and sharp boundaries, Mineral growth, Permeability gradient, Textural destruction

**Skarn horizon**

Description: Sedimentary units were metasomatized by the porphyry system at a counter trend to the main channel

Parameters: Alteration, Fluid channel, Fluid flow, Skarn minerals, Textural destruction, Variability vector

Observations: Carbonates, Fluid channel, Fluid source, Skarn minerals

**Volcano-sedimentary sequence**

Description: The older host rocks are conformable sequence of volcanics and sedimentary
rocks
Parameters: Energy level, Extensive, Fluid flow, Heat, Reworking, Variability vector, Volcanism
Observations: Conformable contacts, Paleosurface asperities, Sedimentary rocks, Similar ages, Volcanically derived sediments, Volcanics
Table A.1: Impact of parameters on evaluation properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Strength</th>
<th>RQD</th>
<th>Js</th>
<th>Jc</th>
<th>Jo</th>
</tr>
</thead>
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<td>1</td>
<td>3</td>
<td>0</td>
</tr>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>Branching</td>
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<td>1</td>
<td>0</td>
<td>0</td>
</tr>
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<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
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<tr>
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<td>3</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Controlling feature</td>
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<td>3</td>
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A.2 Uncertainty Maps

Process for creating uncertainty maps

1. Use design recovery to create a pattern set for the map.
2. Identify a set of parameters for each pattern (Section A.1).
3. Estimate the impact of each parameter in terms of the input properties of the evaluation function. (Table A.1).
4. Assign each pattern an impact value for each input property by summing the impact values of its parameters.
5. For each input property, create a raster map showing the sum of the pattern impact values within each cell. (Figures A.1 to A.5)
6. Sum the raster maps together to create a map of evaluation function uncertainty (Figure A.6).
Figure A.1: Relative uncertainty of the uniaxial compressive strength property of RMR.
Figure A.2: Relative uncertainty of the rock quality designation (RQD) property of RMR.
Figure A.3: Relative uncertainty of the joint spacing property of RMR.
Figure A.4: Relative uncertainty of the joint condition property of RMR.
Figure A.5: Relative uncertainty of the joint orientation property of RMR.
Figure A.6: A cross section showing the spatial variability in the uncertainty of the RMR evaluation as a function of the conceptual model uncertainty.