Sketch-based Storytelling for Cognitive Problem Solving

Externalization, Evaluation, and Communication in Geology

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Dissertation for the degree of Philosophiae Doctor (PhD)

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April 2013

To my father
Olav Lidal,
who is so sadly missed

To Linda,
Olav, and August

SCIENTIFIC ENVIRONMENT

UNIVERSITY OF BERGEN
Department of Informatics

ICT

**Research School in
Information and Communication Technology**

GEO
ILLUSTRATOR

ABSTRACT

PROBLEM solving is an important part of all engineering and scientific activities. It is present, for instance, when experts want to develop more fuel-efficient cars or when they are searching for oil and gas in the subsurface. Many alternatives have to be examined and evaluated before the optimal solution is found. Solving such problems is not only performed inside the mind of the scientist, but it is also an interaction between mind and scribbles, sketches, or visualizations on papers, on blackboards, and on computers. For problem solving in expert teams, this externalization through sketches and visualizations also plays an important communicative role.

This dissertation presents research for assisting the problem-solving process on the computer, through novel technological advances in the fields of illustrative visualization and sketch-based modeling. Specifically, it targets problems that are related to evolutionary processes. Firstly, inspired by storytelling, the domain experts can express their ideas for solution as stories. These stories are based on sketches that the experts draw, utilizing a novel temporal-sketching interface inspired by a flip-over canvas metaphor. Further, the dissertation describes a set of sketching proxy geometries, such as the box-proxy geometry, that the experts can take advantage of when drawing three-dimensional (3D) sketches. These proxy geometries support the task of mapping a two-dimensional input (2D), e.g., a mouse or a digitizer tablet, to a 3D sketch. Solving difficult problems require that many different solutions are evaluated to identify the most optimal one. This dissertation introduces the story-tree, a tree-graph data structure and visualization, which manages and provides access to an ensemble of alternative stories. The story-tree also provides an interface where the stories can be evaluated and compared. This playback of the stories is done through automatic animations of the 2D sketches. The third challenge addressed in this dissertation is to communicate the optimal solution to decision-makers and laymen. By combining the animated 2D story sketches with illustrative visualization techniques it is possible to automatically synthesize and animate 3D models. These animations can be combined with new cutaway visualization techniques to reveal features hidden inside such 3D models.

All of these contributions have been investigated in the context of the problem-solving tasks relevant to the early phase of petroleum exploration. This phase is characterized by having very little ground-through data available. Thus, a large solution space needs to be explored. Even so, the geologists need to produce models that can predict if petroleum is present. In addition to working with few data, the geologists also work under heavy time constraints because of the competition between the oil companies exploring the same area. The contributions from this dissertation have created enthusiasm among the domain experts and already, a new research initiative has mate-

rialized from the work described in this dissertation. Based on the feedback from the domain experts, we can conclude that the contributions presented in this dissertation form a valuable step towards better tools for problem solving, involving the computer, for the domain investigated here.

RELATED PUBLICATIONS

This dissertation is based on the following publications:

Paper A: **Endre M. Lidal**, Helwig Hauser, and Ivan Viola, *Geological Storytelling - Graphically Exploring and Communicating Geological Sketches*, in *Proceedings of Sketch-Based Interfaces and Modeling (SBIM)*, 2012

Paper B: **Endre M. Lidal**, Mattia Natali, Daniel Patel, Helwig Hauser, and Ivan Viola *Geological Storytelling*, in *Computers & Graphics*, vol.37,no.5,pp.445-459,2013.

Paper C: **Endre M. Lidal**, Helwig Hauser, and Ivan Viola, *Design Principles for Cutaway Visualization of Geological Models*, in *Proceedings of Spring Conference on Computer Graphics (SCCG)*, 2012

Paper D: **Endre M. Lidal**, Daniel Patel, Morten Bendiksen, Tor Langeland, and Ivan Viola, *Rapid Sketch-based 3D Modeling of Geology*, accepted for *Workshop on Visualization in Environmental Sciences (EnvirVis)*, co-located with EuroVis, 2013

The following publications are also related to the dissertation:

Paper 1: Mattia Natali, **Endre M. Lidal**, Julius Parulek, Ivan Viola, and Daniel Patel, *Modeling Terrains and Subsurface Geology*, State-of-the-Art report accepted for Eurographics, 2013

Paper 2: **Endre M. Lidal**, Tor Langeland, Christopher Giertsen, Jens Grimsgaard, and Rolf Helland, *A Decade of Increased Oil Recovery in Virtual Reality*, in *IEEE Computer Graphics and Applications*, vol.27, no.6, pp.94–97, 2007

Paper 3: **Endre M. Lidal**, Tor Langeland, and Jens Grimsgaard, *When Visualization and Virtual Reality made a paradigm shift in Oil & Gas*, Book chapter to be published in *Novel Visualization Tools in Petroleum and Chemical Engineering*, Springer, 2013

Paper 4: Morten Bendiksen, **Endre M. Lidal**, and Ivan Viola, *Rapid Modeling of Geology*, accepted for Central European Seminar on Computer Graphics for students (CESCG), 2013

Abstract 1: Haakon Fossen and **Endre M. Lidal**, *The visual aspects of teaching geoscience*, presented at "Vinterkonferansen" arranged by Geological Society of Norwegian, 2013

I was the main author and main contributor to all the papers (Papers A–D) on which this dissertation is based, and all the papers were written during my PhD studies. My main supervisor, Professor Ivan Viola, has been co-author on all of these papers, contributing with formulating the ideas and suggesting research approaches during brainstorming sessions and discussions. He also provided motivations and inspirations, and helped me detect weaknesses and flaws through constructive critique and always well justified questions. Viola also contributed to the writing of the papers.

Professor Helwig Hauser has co-authored three of these papers (Paper A, Paper B, and Paper C). He contributed with suggestions, evaluations of my ideas, and valuable guiding when my research got stuck. These three papers are also the result of a good and creative collaboration with researchers at Statoil.

Paper B is an extended journal version of Paper A, including new research such as the animated 2D sketches and the automatic synthesizing of illustrative 3D model animations. We were invited to submit this extended version as one of three out of the papers presented at the SBIM conference in 2012. Paper B is also co-authored by Daniel Patel and my fellow PhD student Mattia Natali. Natali contributed with program code that can automatically synthesize static illustrative 3D models from 2D geological sketches. Natali and I extended this code together to automatically synthesize animated 3D models based on my animated 2D sketches. Both Natali and Patel contributed with fruitful discussions about the paper extension and participated in the writing of the paper.

In Paper D, I was the principle researcher proposing the sketching proxies in what we called the "ad-hoc" modeling method. I got good assistance from the former Masters student Morten Bendiksen, as he implemented my proposals and conducted the preliminary user-study. I was the day-to-day supervisor for Morten. A shortened version of Morten MSc thesis, Paper 4, is accepted for presentation in the 2013 Central European Seminar on Computer Graphics for students. The "general" modeling approach described in Paper D is the work by the co-authors Daniel Patel and Tor Langeland, performed at Christian Michelsen Research.

I was also the main author of Paper 2 and Paper 3, but these papers describe visualization research that was performed prior to my PhD studies. Paper 2 describes work that has provided me with background information about the work procedures and data types of the geoscience domain. The book chapter, Paper 3, was written during my PhD studies and contains a much more thorough presentation of the topics of Paper 2. It is related to my PhD project as the writing process provided me with more information about the geoscience domain and it kept me in close contact with the co-authors Jens Grimsgaard, from Statoil, and Tor Langeland, from CMR, who also participate in the GeoIllustrator project. In this book chapter, we explain, for instance, how the introduction of virtual reality technology in Statoil changed the work procedures of the disciplines involved in oil and gas exploration, from a sequential work process to an inter-disciplinary collaborative process.

For Paper 1, my contributions were in the classification of the works presented in this state-of-the-art report and participating on the writing of it.

Abstract 1 is the first publication from the collaboration between Professor Haakon Fossen at the Department of Earth Science, UiB and myself. Professor Fossen presented the abstract at a conference arranged by the Geological Society of Norway in January 2013.

CONTENTS

Part I

Overview

CHAPTER 1 ⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯

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HUMANS are advanced problem solvers. While most animals solve problems through trial and error, we humans also utilize insight, which we get from reasoning, creative thinking, and an understanding of principles [7]. Our advanced problem solving capabilities has been an evolutionary advantage for us. This has taken us from the times of constructing traps to catch animals for food, to constructing the technologically complex society we have today. Cognitive science is the scientific study of the mind and its processes, and problem solving is one of these cognitive processes. The problem-solving process not only takes place inside our mind, but is actually an interaction between our mind and external artifacts, such as pen and paper, calculators, and more and more often computer-based information and support systems. Visualizations are increasingly important in such cognitive computerized systems [82], because we acquire more information through vision than all the other senses combined. Visualization is not only for single person problem solving. Many difficult cognitive problems are solved by teams of experts and then visualization also plays the important role of communicating ideas between the team members.

During the problem-solving phase, either as a solo task or as a part of a team, the utilization of visualization usually takes the form of sketches. People sketch their ideas and proposed solutions on white-boards, papers, and other drawing mediums. These sketches serve as a cognitive tool to augment memory and information processing by relieving the mind from some of those burdens [78]. In other words, they make us solve the problem more easily, quicker and better.

The work described in this PhD dissertation concerns the creation of computerized visualization tools for accomplishing efficient problem solving.

1.1 Problem Statement

This dissertation has been conducted within the context of the GeoIllustrator project, an interdisciplinary collaboration between informatics, geoscience, and R&D industry. The aim of this project is to develop new visualization technology in order to understand geological geometries and to rapidly model a space-time representation of these geometries.

The domain experts have expressed the need for tools that support rapid geological modeling. The motivation for this need is that the remaining unexplored petroleum resources are increasingly difficult to find, and exploring and evaluating many alternative geological models has become increasingly important. Geologists work under high time constrains; especially the initial screening of a prospect has to be done quickly. The computer tools they have, such as Petrel [69] and GoCad [60], are designed for constructing precise geological models, models that require a large amount of details and that take months to build. These tools are impractical where the domain experts want to express their initial thoughts as basis for discussions about structural arrangements. As a metaphor, they have expressed a vision of "Sketch-Up [76] for geology".

The problem studied in this PhD work is how to investigate new and extend existing illustrative visualization techniques and sketch-based modeling techniques: to enable the geologists to express their model ideas; to let them more easily collaborate and explore model hypotheses; and to communicate the best of these hypotheses to the audience of decision-makers and laymen.

1.2   Contributions

The main contribution in this dissertation is the description of a system pipeline that covers the entire process of externalizing, evaluating, and communicating rapid geological models. Such a system is described on a conceptual level and the dissertation provides new scientific contributions for each stage in this pipeline, to make it easier for the domain users to express, discuss, and communicate their ideas and models. The contributions include new general contributions, such as temporal sketching through the flip-over canvas. Further, they include contributions where the state-of-the-art is not considering applications in domains that share the specifics of geology (cutaway visualization, as example) or where it is a need to specialize the state-of-the-art.

Specifically, the technical contributions are:

▷ Applying storytelling techniques to express and communicate evolutionary processes

▷ The flip-over canvas as an interface for temporal sketching

▷ The box-proxy as an interface for creating 3D geological sketches

▷ The Story Tree as a visual representation and an interface for managing, accessing, and displaying alternative geological models

▷ Domain-based techniques for animating 2D temporal sketches and the synthesizes of animated 3D models, based on these 2D sketch animations

▷ A set of design principles for making illustrative cutaway visualizations for non-canonical models

1.3   Structure

This dissertation is structured in two main parts. Part I, the Chapters 1– 5 provide an overview of the contributions and application of this dissertation and put it in the larger perspective. Part II consists of the individual publications the dissertation is based on, reformatted to the style of this dissertation and with the references in a unified bibliography.

The rest of this overview part is organized the following way: Chapter 2 provides background and context information about sketching and visualization, geology and the petroleum exploration pipeline, and storytelling. Chapter 3 describes, in detail, the contributions, and is followed up by Chapter 4, containing application of the contributions within the target domain. Chapter 4 also contains discussions about the results of this dissertation. The overview part ends with the conclusions and suggestions for future work in Chapter 5.

T HIS chapter provides background information about geology and petroleum exploration to understand the domain challenges that this dissertation addresses. This is followed by an overview of scientific works within the topics of sketching and sketch-based modeling, storytelling, and illustrative visualization that are related to the research presented in this dissertation. Note that this chapter contains margin side-notes for easy references to important terminology used in the other chapters.

2.1 Background: Geology and Petroleum Exploration

2.1.1 Geology

Geology is the scientific study of the solid Earth, its landscapes and rocks, and the processes that shape and change it. Rocks can be classified into three groups: sedimentary, igneous, and metamorphic rocks. Sedimentary rocks are the type of rocks most relevant to this dissertation, as it is within this group most of the petroleum (oil and gas) is created and contained. The study of sedimentary rocks is the expertise of the sedimentologist. Sedimentary rocks are formed by the deposition of mineral *Sedimento-* and organic particles on land and in water, followed by compaction and the subsequent *logist* transformation of the particles into solid rocks through cementation. Sedimentary rocks usually form layered structures at many scales, as seen in Figure 2.1. It is common to separate geological layers by their geological properties, such as grain size, permeability, and porosity; or by the time they were created. Rock layering is called stratification and the vertical stratification column through the layers is denoted strata. Stratification *Strata* is studied in the geological branch called stratigraphy.

External forces (tectonics) push and pull on these sedimentary layers, deforming them by folding and faulting. Figure 2.2 shows some schematic examples of different types of faulting. However, faults are usually not a single, clean fracture along a fault plane, but instead a set of complex fracture deformations associated with the fault plane. The geologists use the term fault zone when referring to the zone of these complex deformations. Within the context of this dissertation, the term geological events is applied *Geological* as a name for all of these Earth deforming processes. Thus, this term includes, among *events* others, folding, faulting, erosion, depositions, and magma and salt intrusion. The study

Figure 2.1: Sedimentary rocks are usually deposited in horizontal layer. A vertical column through all these layers is called the strata and it describes the rock properties for each layer. The image is courtesy of Haakon Fossen.

Structural geologist of deformation of rocks and the interpretation of the geological structures this creates is the expertise of the structural geologist. As further elaborated in the next section, understanding the geological structures is important for locating oil and gas. Many geological processes happen quickly, e.g., landslides, turbidites, debris flow, eruptions, and earthquakes. The changes that take place on the Earth's surface, including the creation and subsequent erosion of mountains and the accumulation of sediments, are slow processes, taking place over millions of years. Deforming the subsurface by folding and the development of fault zones also takes place over long time. When dealing *Geological time* with geological time the geologist often refers to time spans ranging from millions to hundreds of millions of years.

For more information about geology and geological processes, please see the e-learning modules of Fossen [23]. Turner [77] provides a good description of the characteristics of geology for the purpose of computer representations and visualizations.

2.1.2 Petroleum Exploration

The information in this subsection is extracted from the textbook by Gluyas and Swarbrick [29]. There are five factors that need to be present to form a petroleum reservoir. There must exist a *source rock* containing sufficient organic material that, when buried and heated, will produce petroleum. This petroleum migrates upwards until it reaches an impermeable rock that forms a *seal*. If the geometry of this seal is such that it prevents the oil and gas from migrating further, it is called a *trap*. Displacements in the subsurface, such as faulting, can also produce traps. Immediately below the sealing trap, there must be a rock layer, the *reservoir*, with such properties that it can contain the migrated petroleum. The source, reservoir, and seal are, most often, sedimentary rocks formed in a basin. In addition to these four factors, a fifth, temporal, factor is also critical; The *timing* of the construction of seal, trap, and reservoir relative to the migration from a source is very important: Has the source rock been buried deep enough and heated enough to start producing? Is the trap in place before the migration started? These and similar questions can only be answered by reconstructing the geological history of the area under investigation.

The process of finding and producing a petroleum reservoir can be divided into several distinct stages. In petroleum terminology, these stages are denoted *the petroleum*
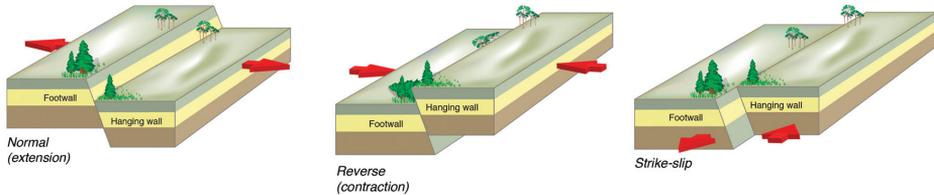
Figure 2.2: External push and pull forces deform the subsurface rocks. Faults are created where these deformations cause fractures. Above is shown examples of different kinds of faults. The image is courtesy of Haakon Fossen.

value chain. This value chain starts with the *exploration* stage, where the geologists need to determine if the four critical factors are present in the area of investigation and that the relative timings are correct. The exploration stage is generally divided into two stages. The first is the *frontier* exploration stage, where the main tasks are to determine the existence of source rocks and to identify the largest basin structures in the area. If the chance of economically viable petroleum in a basin is high enough, then the work transitions to the *basin* exploration stage, where the focus is to explore this basin; to understand how the petroleum system of this particular basin works. The target for this dissertation is mainly the frontier exploration stage, but for completeness, the exploration stage is followed by the appraisal stage, where the size and shape, together with the reservoir quality are determined. Then follows the development stage, where the plans are made for how many wells are needed and where they should be drilled. In the next stage, the production stage, the pre-production basin, the prospect, is turned into a petroleum-producing field. When production is declining, it is time to enter the stage of reserve additions and reserves growth, where this decline in production opens up for exploring new, nearby located, reservoirs. Finally, there is the stage of field abandonment and reactivation, where, for various reasons, the field productions is terminated (abandonment), possibly followed at some later time by a reactivation of the field.

The frontier exploration stage is characterized by having very few data, possibly only regional, long 2D seismic sections (see an example in Figure 2.4), as the acquisition of dense 3D seismic data and the drilling of exploration wells is very expensive and not performed unless the probability of petroleum is high. When the geologists interpret the seismic data in the frontier exploration stage, they look for overall shapes in the seismic section resembling geological shapes that are familiar to them, so-called geological analogies, that can help them to understand the situation at hand. The primary objective of this stage is to create a model for the petroleum system of the area under investigation. Figure 2.3 shows an example of the types of models created during the frontier exploration stage.

Most areas for petroleum production are licensed from the land or sea owner, usually a government, to a single petroleum company or a joint group of companies. The competition between the petroleum companies exploring in a new area prior to licensing, is often high and the work has to be performed under tight time constraints (e.g. licensing round deadlines). The licensing company, or licensing group, that eventually gets the permission to further explore new acreage, continues the exploration work with the aim to locate profitable reservoirs and produce petroleum. Usually, the first

Petroleum value chain

Frontier exploration

Geological analogies
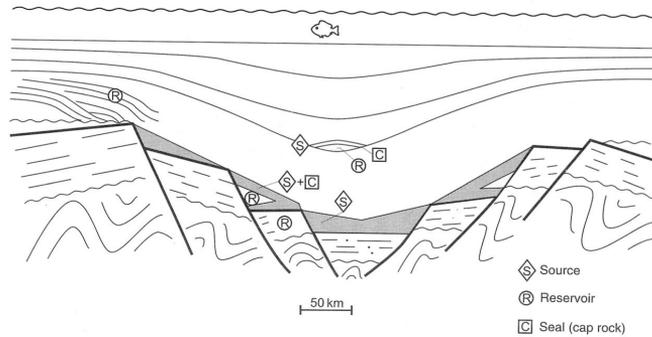
Figure 2.3: This figure shows an example of how the geologists working in the frontier exploration stage would express a geological model. The image is obtained, with permission, from Gluyas and Swarbrick [29], copyright of John Wiley and Sons.

company locates the biggest reservoirs and thus, produces most petroleum. In addition, the company that first builds production and transportation facilities in a new area can profit from these investments in later explorations. Thus, the geologists in the frontier exploration stage often work under tight time constrain and have to quickly construct a range of geological models.

2.1.3   Data Scenarios

Within the GeoIllustrator project three different data scenarios for geological investigations in an area have been identified: the *dense-data* scenario, where the domain experts have access to dense, usually three dimensional, seismic data and ground-truth data through well logs and well cores; the *sparse-data* scenario, where the available data generally is limited to a few 2D seismic sections and, maybe, a few well logs and well cores; and the *no-data* scenario, without any acquisition data from the investigated area. In the no-data scenario, the geologists instead rely on theories and hypotheses of how a particular subsurface has been formed in the past. This dissertation focuses on the sparse-data and no-data scenarios, as these are the most relevant scenarios in the frontier exploration stage. Therefore, many of the contributions from this dissertation relates to 2D seismic and 2D sketching.

2.1.4   Seismic Interpretation, Geological Modeling, and Geological Sketching

Seismic If seismic data is available to the geologist, he or she performs an *interpretation* of this
inter- data and constructs a geological model based on this interpretation. As pointed out in
pretation Section 2.1.2, the interpretation of a 2D seismic section during frontier exploration is a search for geological analogies. Thus, this is a subjective process, highly influenced by the knowledge and prior experiences of the geologist. Bond et al. [5] show in a study how different the same 2D seismic section can be interpreted by different geologists, calling this a "human-biased conceptual uncertainty". An assumption made in this dissertation, to reduce this uncertainty one should explore many alternative geological models, made by many experts, to identify the models with the highest probability, and
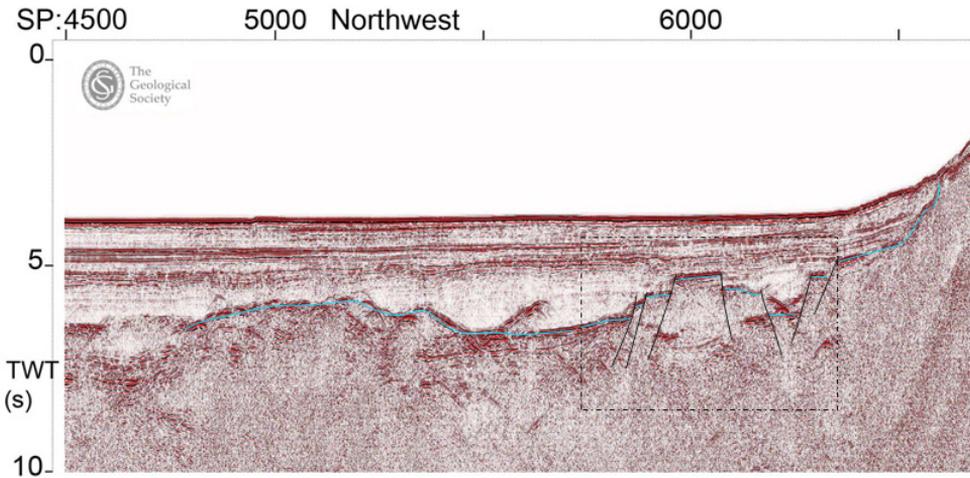
Figure 2.4: The figure shows a 2D seismic section, where the vertical axis is depth (here in time). A seismic section displays the reflections from the various rock types when a pressure wave is shot into the subsurface. Inside the stippled box, one of our collaborating geologist has sketched an interpretation, in this case a fault system, around some of these reflectors. Image is courtesy of the BIRPS survey.

not leave this task relying on a single geologist.

Today, almost all seismic interpretations are performed on computers, in domain specific interpretation software. However, as described in Paper A and Paper B, the geologists in the very early stage of frontier exploration still utilize pen and paper, or very simple computer tools, such as Microsoft PowerPoint, for studying seismic sections and illustrating their geological models. Example of one such interpretation is shown in Figure 2.4. These interpolations and illustrations are difficult to archive, distribute, and present (pen and paper) or not expressive enough (PowerPoint). Our collaborating geologists described that the lack of computerized support tools targeting this stage prevents them from exploring the whole range of potential models.

The term *geological model* may have different meaning and content depending on the value chain stage. In this dissertation, geological model is used as a term describing a rough description of the subsurface, including: the cross-sectional geometric framework, such as the boundaries of the geological layers, the faults and folds, and erosional unconformities; and the rock type description, such as for instance sandstone, siltstone, or shale, for each of the geological layers, i.e., the strata.[1] These models are expressed in a schematic style, such as shown in Figure 2.3. The sedimentologist also creates plan-view schematic diagrams illustrating depositional environments and associated depositional architecture, as shown in Figure 2.5. In this dissertation, such illustrations, both cross-sectional and plan-view (and combinations) are included in the

Geological model

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[1]In the geosciences in general, a geological model may also contain detailed information about the geological properties, such as permeability and porosity, for each layer, and for a detailed reservoir model, also for the individual grid cells. Those components are constructed in later stages of the value chain, outside the scope of this dissertation.
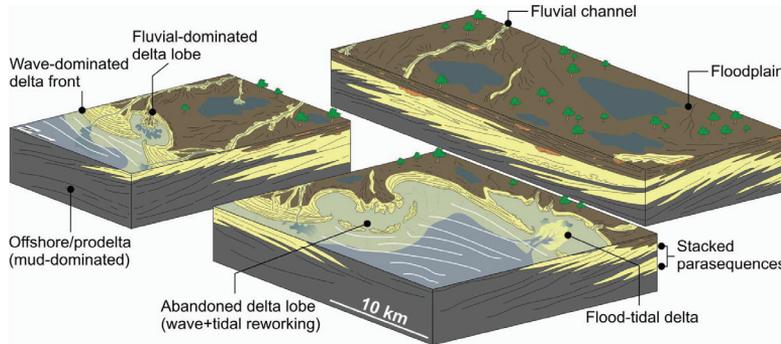
Figure 2.5: Sketches made by sedimentologists contain a combination of terrain modeling and subsurface geological layer modeling. The sketches depict depositional environments and the associated depositional architectures. The illustrations are courtesy of Sten-Andreas Grundvåg, a cooperating geologist within the GeoIllustrator project.

term geological model.

Geologists perform substantial amount of sketching, such as sketches of geological maps and stratigraphic logs made during geological field studies, and sketches while discussing geological models and structural configurations, to name a few. Some of these sketches are meant for individual use, some are meant for communicating with peer experts, some are made for teaching purposes, whereas others are documentation and presentation of results. The geological sketches usually have to include temporal aspects, in addition to the present geometric configuration.

2.2 Related Works in Computer Graphics and Visualization

A large part of research and development on methods for geological modeling and visualization of geological models is performed by commercial software vendors. Their results are treated as trade secrets and are only seldom published. However, our collaborating domain experts claim that no tools exist that target the frontier exploration stage, and this is a main reason for supporting the work described in this PhD dissertation.

2.2.1 Sketching and Sketch-based Systems

Ware [82, pp. 405–407] writes that a sketch can be considered as externalization of mental imagery, i.e., an idea or an image produced in the mind. He further points out that sketching is fundamental to most artists, designers, and engineers, and that sketches are thinking tools primarily composed of rapidly drawn lines. Sketching and sketch-based modeling have been investigated for many years in computer science, especially targeting the design process. The book by Buxton [11] is one example. Olsen et al. [59] provide an extensive overview of the field of sketch-based modeling[2].

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[2]Sketch-based modeling is the computerized process of constructing geometric models from 2D sketches.

They show that the sketch-based modeling techniques provide a rapid and intuitive interface for performing computer-based modeling.

Many sketch-based computer support systems have been proposed. Hoeben and Stappers [33], Nakakoji [56], Johnson et al. [38], and Gross and Do [31] all present tools for sketch-based prototyping. Their focus is on the sketching process for externalizing design ideas and they show that sketch-based modeling facilitates the production of many alternatives. However, none of these systems captures evolutionary processes, nor do they focus on the externalization, or capturing, of the reasoning process behind the sketches. They do not either propose solutions for arranging or comparing alternative solutions. This limits their applicability for the problems addressed in this dissertation.

Natali et al. [58] propose a method of synthesizing 3D models from 2D sketches and the approach for presentation and communicating geological models described in Section 3.4 in this dissertation is partly an adaption and extension of their work. Based on the investigations performed while writing Paper 1 [57], and from the feedback of domain experts, there is not identified any published work on sketching targeting the exploration and communication of multiple geological models.

2.2.2 Illustrative visualization

One of the most comprehensive discussions about Illustrative Visualization is written by Rautek et al. [67]. They define illustrative visualization as: "A computer supported interactive and expressive visual abstraction motivated by traditional illustrations." They state that the goal of illustrative visualization is to utilize visual abstractions to distinguish between the important information and the context information. Further, they identify the key components of illustrative visualization as: a controlling mechanism in spirit of the focus+context and the set of visual abstraction techniques originating from illustrations. It is common to differentiate between *low-level* and *high-level* visual abstractions. Line drawing styles mimicking pen or brush strokes are an example of the low-level abstractions and exploded views and cutaways are example of high-level abstractions.

The majority of the published visualization works targeting geoscience data addresses the management and visualization of (large) 3D seismic data sets. Only a few publications have addressed illustrative visualization of geoscientific data, for instance, the works by Ropinski et al. [68] and Patel et al. [64]. The PhD work of Patel [62] is another important contribution to illustrative visualization of geoscientific data. However, all of these mentioned works address the search process of seismic exploration, and not the visual communication process that is targeted by the cutaway visualization in this dissertation. The results presented in this dissertation, reported in Section 4.3 and in Paper C, show that computerized cutaway visualization addressing other domains, such as the works by Li et al. [45], Burns et al. [10], and Kubish et al. [43], is not applicable to 3D geological models.

2.2.3 Storytelling in Visualization

Storytelling is a powerful technique for communicating knowledge and information. When the ancient humans socialized around the fire and told stories, this was their way

of teaching each other about the world and how to survive. Recently, the visualization research community has shown examples of how applying aspects of storytelling to visualization of data can enhance the understanding, for instance in information visualization [28] and scientific visualization [50]. Wohlfart and Hauser [85] present the first work on applying storytelling aspects to scientific visualization. They observed that visualization for the purpose of presentation and communication has to be both comprehensible and reliable. Instead of only displaying the final visualizations to the viewer, they propose to present a story of how these visualizations were made. These stories should contain animated camera viewpoint changes and animations of transfer-function adjustments. They claim that this makes the visualizations more comprehensible and reliable. Even though their application focused on interactive volume visualization, the storytelling concept presented in this dissertation is inspired by the concept they present. The recent published work by Kosara and Mackinlay [40] summarizes the application of storytelling in visualization today and outline future research directions.

However, all of these approaches mentioned above only apply storytelling to the (final) presentations of data and models. The storytelling concept presented in this dissertation is novel in that it also utilizes stories in the authoring phase.

CHAPTER 3

CONTRIBUTIONS

Tʜɪs chapter contains a presentation of the individual technical contributions from the papers presented in Part II. These contributions can individually, and in combination, be applied to different scenarios. In this dissertation, they are presented in the context of how to improve the work processes involving cognitive problem solving through novel technology.

Firstly, an overall model of the work process needs to be defined. Figure 3.1 shows one possible way of modeling the problem-solving process found in many engineering and scientific disciplines, whether it is designing a new, more fuel-efficient car, or exploring a prospect for natural resources. Most problem-solving processes are run by teams of domain experts, rather than by one single expert. However, the problem solving generally starts with an initial stage of *individual* work, i.e., a personal preparation step, where the individual domain expert investigates the problem on his or her own and tries to come up with one, or more, preliminary solution(s). Many experts accomplish this by externalizing, e.g., drawing, their ideas into sketches and in this sketching process they develop a better understanding of their idea and the problem. This, in turn, makes him or her refine the idea, externalized into new sketches. This iterative loop is a *visual thinking* process [82]. The expert needs at this stage, support technologies that
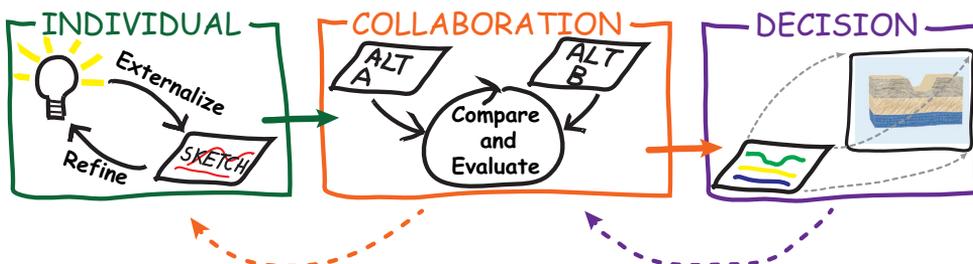
Figure 3.1: The figure shows a model of the cognitive problem-solving process found in many engineering and scientific disciplines: an individual stage (*left*), where ideas for solutions are shaped; a collaboration stage (*middle*), where the alternative solutions are compared and evaluated to find the most optimal one; and a decision stage (*right*), where decisions are made whether the solution is sufficient or more work is needed.
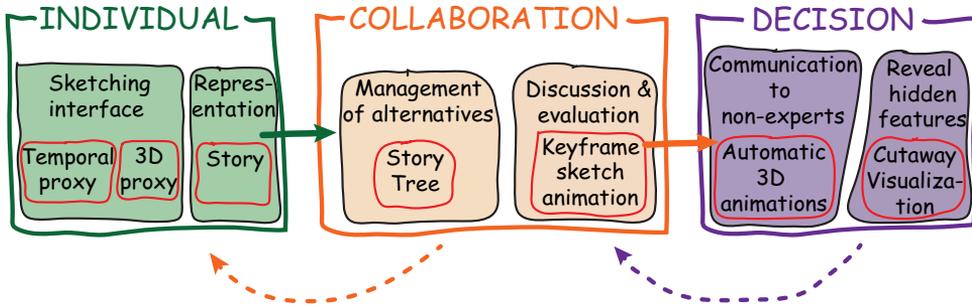
Figure 3.2: The figure shows how the technical contributions presented in this dissertation relates to the problem-solving model.

make it easy to express and refine solution ideas.

The experts then bring their solution suggestions to the next stage, the *collaboration* work session. In this stage, the preliminary solutions are evaluated, compared, and refined. Thus, now there is a need for technology that supports all these tasks. The goal of this stage is to identify the optimal solutions, based on certain domain criteria defining the optimum.

These optimal solutions are then brought to the third stage, the *decision* stage, where decisions are made whether the solutions are good enough, if further investigations are needed, or if the entire project should be terminated. The decision-makers are usually knowledgeable, but not experts, in the target domain. The sketches made by the experts are generally too domain specific and do not provide enough information for the decision-makers. The optimal solutions must therefore be presented in a form that is comprehensible for this audience, thus technology that improves communication is important at this stage. When the audience consists of laymen, such as politicians, then an informative communication form is even more important.

This model is general and it fits many domains, for instance, the domain experts have expressed this model for the petroleum domain. Usually, the process described by this model is iterative, with new decision points (decision gates) after each iteration. In such case, is the model and the technologies proposed in this dissertation especially suited for the first, initial iteration, where the solution space is large, creativity and expressiveness are important, and before domain-specific tools are utilized.

The contributions from this dissertation to these three process stages are illustrated in Figure 3.2. The contributions are individual contributions serving to address the technical needs. They are a mixture of novel visualization and modeling techniques, and improvements to known solutions, improvements optimized for the petroleum exploration domain. For the personal stage, we propose a concept, based on story-telling, as representation for suggested solutions (Section 3.1). This representation is kept throughout the whole work process. We also propose a sketching interface (Section 3.2), for constructing stories and for sketching 2D and 3D models. For the collaboration stage, we propose a tree-graph representation and visualization, to manage the alternative solutions, in addition to provide an interface for comparing the stories. We also propose a domain specific method for animating the story sketches (Section 3.3), for improved evaluation and comparison. For the decision stage, we propose to synthe-
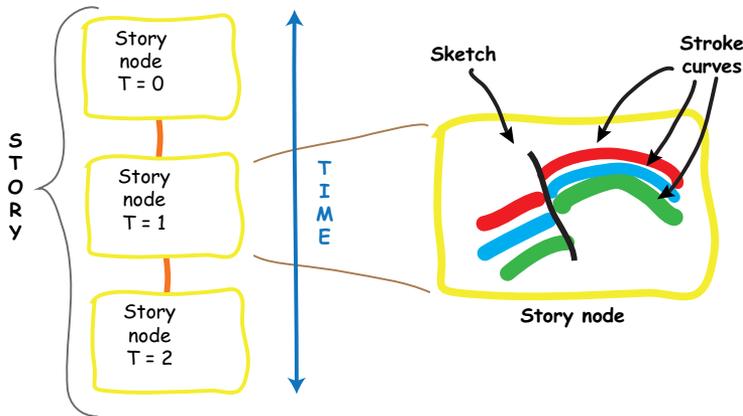
Figure 3.3: A story is defined as a temporal ordered sequence of story nodes (*left*). Each of these story nodes contains a sketch representing a time in an evolutionary process (*right*). Each sketch is described by one or more stroke curves drawn by the author.

size illustrative 3D animations automatically from the sketch animations, to increase the communication of the optimal solutions. We also propose design principles for applying the illustration-inspired cutaway visualization to disclose features located inside 3D geological models (Section 3.4).

Demonstrations of these contributions applied to the geology and petroleum domain is presented in the next chapter, Chapter 4.

3.1 Storytelling – Modeling Evolutionary Processes

One particular cognitive problem-solving task we have studied is the frontier exploration stage of the petroleum exploration pipeline. As described in Chapter 2, many frontier exploration projects start by building a rough geological model based on the interpretation of one (or a few) 2D seismic sections. Working with geologists from the Norwegian oil and gas company Statoil, we have developed a concept suitable for supporting their tasks. Our collaborating geologists have explained that they construct rough geological models that are used to evaluate whether to further explore a prospect or not. Given the high uncertainty when interpreting seismic sections [5], the larger the number of models they can explore, the better this decision will be. However, the time pressure is high and they lack the computerized tools for this task.[1]

We observed that an interpreted 2D seismic section (e.g., Figure 2.4) does not capture the reasoning the geologist makes when building a model. Most of this is left in the mind of the geologist, i.e., the sketched artifact is incomplete and the model has to be explained by the model author in order to be understood. The problem we need to solve is therefore, how to capture the reasoning behind the geological model, *in addition*, to the interpreted 2D seismic section. The solution we propose is based on an important geological principle, *uniformitarianism*, which states that the geological processes that have been shaping the geology in the past are the same that are observable

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[1]These challenges are further explained in Paper A and Paper B.

today. These processes are referred to as geological events, and examples are; sediment deposition, erosion, folding, intrusion, and faulting. The present geology in an area is the result of all the geological events that have taken place there up until present time, thus geology is an evolutionary process.

Based on this domain knowledge, we propose to provide to the geologists the possibility of capturing the geological reasoning behind their models by enabling them to externalize geological event-steps. This externalization is accomplished through sketches. We propose that the geologists represent this reasoning information in the form of an evolutionary *story*. We define a story as a temporally ordered sequence of discrete time events (see Figure 3.3). We denote these discrete time events as *story nodes*, using the terminology introduced by Wohlfart and Hauser [85]. Each story node contains one sketch representing the evolutionary process at one particular time step in the evolution, and when these nodes are connected in a temporal order, they form the story. Authoring, evaluating and playing back these stories, addressed later in this chapter, is what we denote as *sketch-based storytelling*.

As explained in Section 2.2.3, visualization researchers have in the recent years started to apply storytelling for presentation of data, however, our approach is novel in that it combines storytelling with the actual modeling phase, and not only as a post processing stage for communication. One immediate advantage of the story concept is that the author is encouraged to plan his model in these evolutionary steps; this can help him or her producing better models. Another advantage is that the author can utilize the same representation of the model in presentations for communicating with peer colleagues, because the story representation lends itself well for communication. Also, the archival of models in an organization is better supported, because the story contains more information than just a single image of the final model, thus it has potential for being retrieved and understood, even without the model author being available to present it.

We derived the concept of storytelling as a representation for the work process of building rough geological models based on interpreting 2D seismic sections. Our concept, however, is not limited to 2D applications; it is just as applicable to 3D modeling, as long as it is applied to capture an evolutionary process.

3.2   New Sketching Interfaces

As explained, each of the story nodes of a story contains one sketch that is expressing the evolutionary stage at this specific story time. Each sketch is composed of a set of *curves*, and a curve is constructed by sampling one user input stroke, see Figure 3.3 (*right*).

3.2.1   Temporal Sketching Proxy

To author the stories, we need to provide the user with a suitable sketch and story-authoring interface. We propose, in Paper A and Paper B, to base such an interface on a canvas flip-over metaphor, resembling pen-and-paper sketchbook drawing. The author draws each story node sketch on a separate canvas sheet, i.e., each flip-over canvas sheet corresponds to a story node (see Figure 3.4).
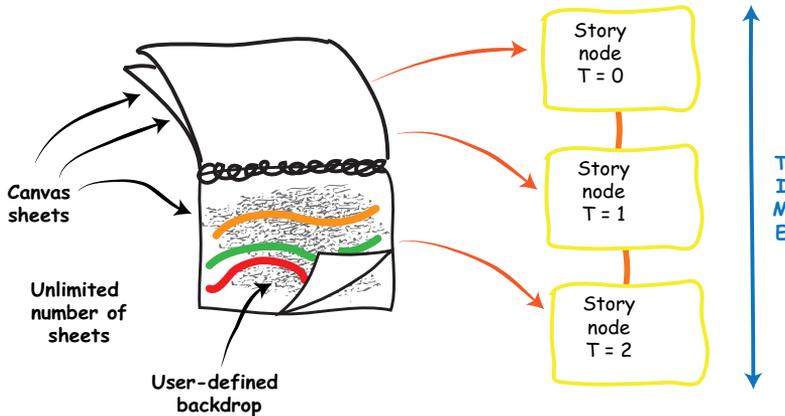
Figure 3.4: The temporal sketching proxy is based on a flip-over canvas metaphor, familiar to sketch book users. Each canvas sheet represents one story node, i.e., the author draws one sketch on each canvas sheet. The temporal sketching proxy provides an unlimited number of sheets, and new canvas sheets can be added between existing sheets.

This familiarity to pen-and-paper drawing makes it intuitive and easy for the user to apply. The virtual flip-over also has some advantages over its physical counterpart; it has an unlimited number of canvas sheets, the order of the sheets can be rearranged, and new pages can be added in between existing pages. Two other important advantages are that, firstly, it is possible to put a user-defined backdrop image on the canvas, being it a 2D seismic section that the user can trace interpretations on (as shown in Figure 3.4) or a paper-like texture for aesthetics. Secondly, as there is often temporal coherency between the sketches on consecutive story nodes, the sketches from the previous canvas can be shown as *ghost-lines* to guide the sketching on the current canvas. We also have added functionality to copy these ghost lines from one sheet to the next to ensure that repeated sketches are duplicated at the correct positions.

The internal representation of a story can be a linked-list (Figure 3.4), where each canvas sheet corresponds to a node in the list and the link preserves the temporal order of the nodes. When the canvas sheet is flipped-over to create a new story node, the new node is inserted as a child node of the story node that was in the canvas before the flipping. However, instead of a linked-list representation we propose to utilize a tree-graph structure, i.e., a linked list with possible branching. We argue for supporting branching so that for a given point in a story there may be reasons for exploring several alternative sub-story tracks. Thus, instead of having to create completely new stories, the branching supports that the common parts of these semi-similar stories are only authored and represented once. Branching is shown in Figure 3.5, where the vertical axis represents the time dimension and story node siblings represent the alternative paths through the story. One example could be that two different story paths (evolutions) can lead to the same, more recent in time, story node. Except for acknowledging the advantage of supporting branching, we have not investigated the roles of siblings any further in our work.

The temporal direction of the story is irrelevant for the sketching. Our flip-over story-authoring concept supports stories drawn both from present time and backwards,
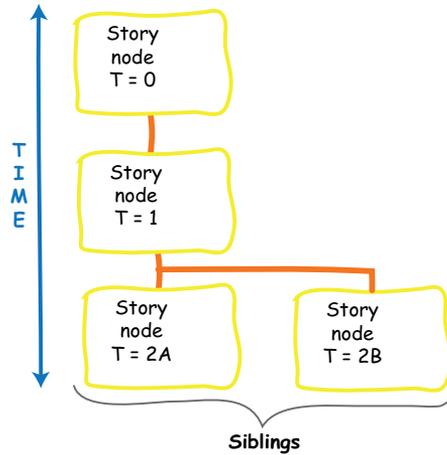
Figure 3.5: A story node can have more than one child node, i.e., this creates a branching. A branch represent a point in the story were there are alternative story paths. This type of story is a *multi-path* story.

and vice versa.

3.2.2   3D Sketching Proxy

So far, the focus has been on 2D sketches, because the domain data studied, 2D seismic sections, have an inherent 2D character. For a more general story-authoring scenario, we do not necessarily have this limitation and thus, sketching directly in 3D views can, and should, be advocated. Sketching directly in 3D has known complications. Firstly, the input devices, both the computer mouse and stylus pen on a digitizer board, operates in a 2D space. Thus, there must be a mapping from this 2D input space to the 3D modeling space, which is non-trivial. Secondly, even if there is a 3D input device, such as a 3D tracked input device in a virtual reality installation, it is a challenge to perceive where in 3D space one draws and how the sketched curves have to be drawn to form the final sketch. Often these problems are solved by providing 2D proxy planes positioned in 3D space, onto which the sketching curves are drawn. One example of this approach is the "Just Draw It"-system [30]. The challenge then is how to position these proxy planes most efficiently in the 3D modeling space. In Paper D, we propose a domain specific solution to this challenge. From geological sketches and illustrations, for instance Figure 2.2 and Figure 2.5, the typical box-like shape of geological illustrations can be observed. Therefore, we propose to utilize a box-shaped proxy-geometry for making the 3D sketching, as shown in Figure 3.6. After the author has sketched on one or more sides of the box, the surfaces are interpolated.

To model details on this interpolated surface, for instance rivers and mountains, we propose to utilize the surface as a second proxy geometry. Sketched curves made when the interpolated surface is active are automatically mapped onto this surface. The sketch author then can define this curve to be a mountain ridge or the central line of a river. For mountain sketching, a third proxy geometry is provided for sketching its height profile. This proxy geometry is a fence-like geometry position perpendicular
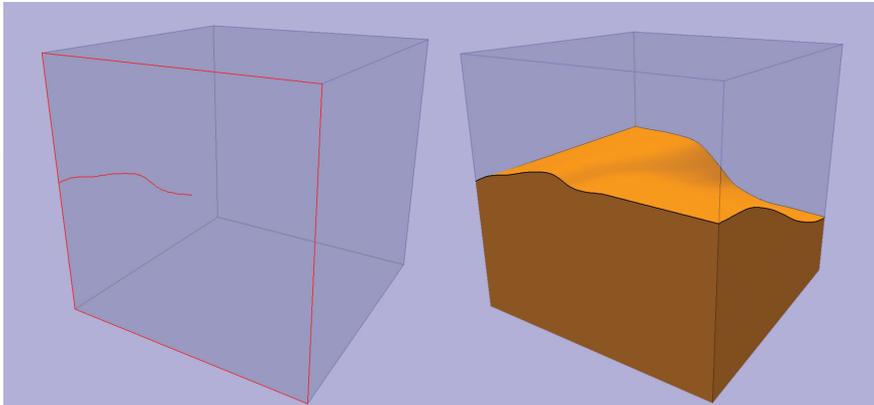
Figure 3.6: Left: We propose a box shaped proxy-geometry to provide a spatial anchor for the 3D sketches. The curves sketched represent the intersection between a layer surface and this box. *Right:* These curves are then interpolated to surfaces and a solid model of the layer is created.

to the surface, and following the sketched curve. This proxy is inspired by the terrain modeling technique described by Gain et al. [27]. Figure 3.7 illustrates the process of sketching a mountain through these additional proxy geometries. The special purpose functionalities for sketching rivers, mountains, etc., are examples of ad-hoc functions that can be added to such a 3D sketching system. Paper D and Chapter 4 in this dissertation present a discussion about the ad-hoc vs. a general modeling approach.

We have also investigated the possibility of combining sketching with procedural modeling. As a test case, we chose to utilize a simple procedural modeling routine for modeling the depositions from rivers into the sea (see Figure 3.8). As this was only a simple experimentation, providing no real scientific contributions, it is not described further in this dissertation. For the interested reader, please refer to the MSc thesis by Bendiksen [4].

Benefits of the box-proxy are that there is no need to position an arbitrary proxy plane in 3D space and that this very simple proxy geometry, combined with the surface and fence proxy geometries, can be utilized to quickly express many common geological scenarios. A limitation is that the sketched geological model has to be layer based. A layered-based approach is applicable for models made during petroleum exploration, but not applicable to geological models for mining or geothermal reservoir modeling. However, the latter scenarios are outside the scope of this work. Although we can model folded layers, the 3D sketching box-proxy currently lacks the support for modeling faults.

3.3 Managing and Comparing Alternatives

When solving cognitive problem tasks, it is generally beneficial to explore many alternative solutions. A computerized tool for exploring many alternatives must provide a mechanism for managing these alternatives, must provide an interface to access the alternatives, and must provide a way of presenting the alternative solutions for evaluation and comparison.
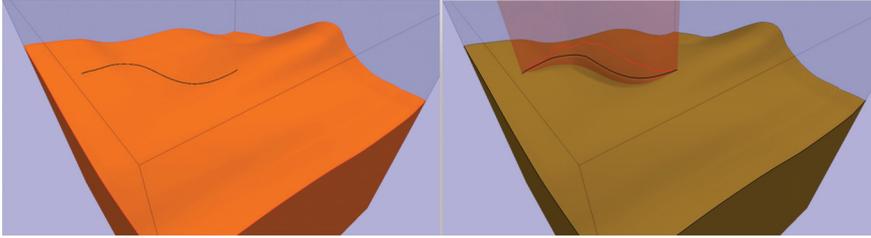
Figure 3.7: Left: When a surface is activated it becomes a proxy geometry. Sketched curves are now mapped to this proxy geometry and they can be utilized to define terrain details. *Right:* The height profile of a ridge or mountain can be specified by sketching a curve on the fence proxy-geometry. Both images are courtesy of Morten Bendiksen.

Our story metaphor for representing a possible modeled solution can easily be extended to also represent an ensemble of possible solutions, by defining each alternative as a parallel story track. We add an additional dimension to our representation, the alternatives dimension (see Figure 3.9). The rest of this section describes how we propose to interact with this representation and how we can improve the playback and comparison of these parallel story tracks.

3.3.1 The Story Tree Interface

The *story tree* interface we propose, shown in Figure 3.10, serves three purposes. Firstly, it provides a visualization of all the alternative stories (orange nodes), and all the individual story nodes (yellow nodes) of each story. The purpose of the blue root node is to show that all these stories are related to the same project, for instance the same 2D seismic section; in addition, the root node also provides a short cut to selecting all the stories.

Secondly, the story tree interface also serves as the interface for navigating to a specific story node within a specific story. When a story node in the story tree is selected, the sketch of this story node is displayed in the flip-over canvas, and the user can author and update this sketch.

The third purpose of the story tree is to provide an interface for selecting stories for playback and evaluation, further explained in the following subsection. If more than one story is selected, these stories are played back side-by-side for easy evaluation and visual comparison.
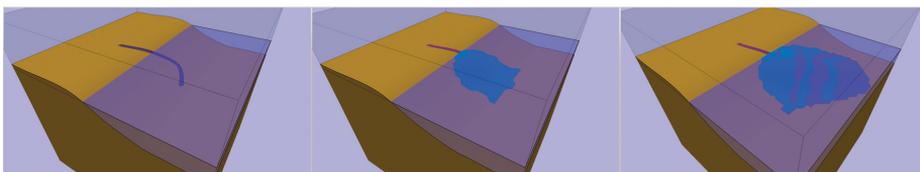
Figure 3.8: This sequence of images shows the procedural modeling of sedimentary depositions from a river into the sea. The images are courtesy of Morten Bendiksen.
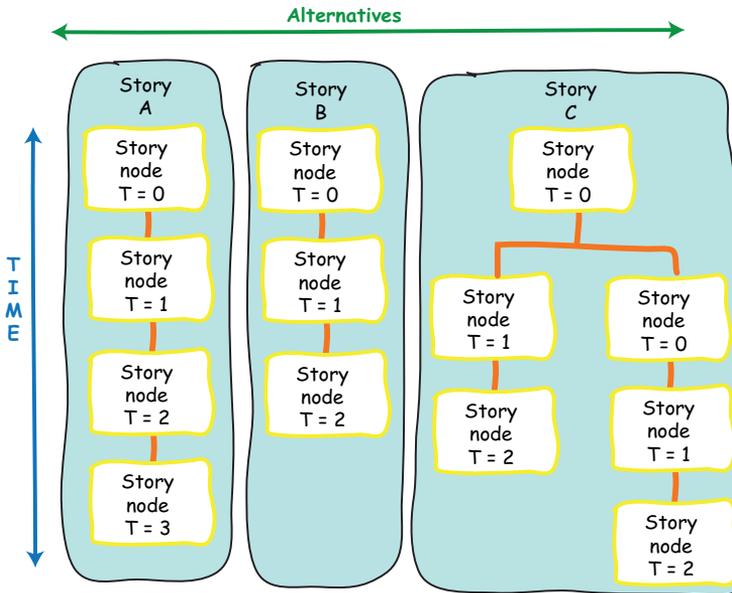
Figure 3.9: To represent an ensemble of alternative stories we add an extra (*alternatives*) dimension to our story metaphor. In this figure, there are three separate stories, Story A, B, and C. Story C contains a branch and is therefore a multi-path story.

3.3.2 Animating Sketches

Playing back a story, communicates the evolutionary process that is modeled. The simplest form of playing a story is by flipping through the stack of story node sketches, as we proposed in Paper A. However, the flipping of these discrete time-snapshots provides in most cases a limited depiction of the continuous evolutionary process they model. For instance in the case of geological stories, it can be difficult to understand the structural movements and to understand the geological changes based on the static sketches only, especially without explanations from the model author. Because of this limitation, we propose in Paper B to extend the playback of the stories by automatically synthesizing 2D animations of the sketches. In short, we treat the story node sketches as animation keyframes. Animation of sketches has been explored to some extent, for instance in the Sketch-n-Stretch [73] system and the K-Sketch [19] system. The solution we present here takes advantage of geological domain knowledge. The main contribution of our solution is that these animations are automatically synthesized, without any additional animation or modeling actions needed from the user.

As the geological sketches consist of curves, such as horizons and fault lines, our proposed automatic animation method focuses on the interpolation of these curves between the keyframes. We need to interpolate a curve c_{from} in one keyframe to the curve c_{to} in the next keyframe. In Paper B, we show that we need to handle the following animation cases:

Curves with unequal number of points – The interpolation $c_{from} \Rightarrow c_{to}$ is usually accomplished by a point-to-point mapping of the vertex points of the curves in each
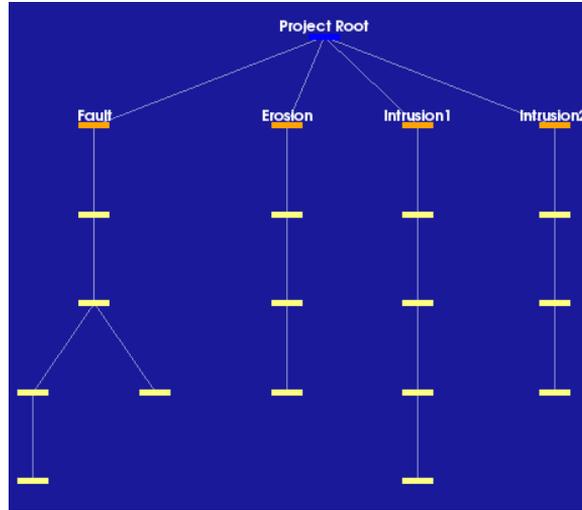
Figure 3.10: This figure shows the visualization of the story tree. The node representing a story is in orange color and the actual story nodes are depicted in yellow. This visualization is also the interface for selecting individual story nodes for inspection and authoring, and the interface for selecting stories for playing and comparison.

consecutive keyframe. For geological sketches depicting structural changing events, such as folding or erosion, it is usually the case that this mapping cannot be done automatically, as it can be a large difference in the number of curve points, see Figure 3.11 a) and b). Traditionally in computer animation, this would require specifying the mapping manually by the animator, something we want to avoid for an automatic method. Instead, we propose a domain-specific automatic method. Super-sampling only the line with the fewest vertex points can produce interpolations that are not geologically sound, as Figure 3.11 c) indicates. The method we propose is to super-sample both curves with the vertex point of the other curve, so that both c'_{from} and c'_{to} have the number of vertex points equal to the sum of the vertex points of the two original curves. Thus, producing an interpolation that is more geologically sound, as shown in Figure 3.11 d).

Curves that appear/disappear between keyframes – For some geological events, such as erosion and deposition, a sketched curve can disappear (complete erosion) or appear (deposits) between two keyframes. Applying domain knowledge, we know that these appearances and disappearances only happen at the top level of the sketches. For erosion, we animate the disappearing curve as an interpolating towards the curve below the disappearing curve. For deposition, we animate the appearing curve as an interpolating from the curve below the appearing curve. This is illustrated in Figure 3.12 for an appearing curve, where the curve c_2 is only present in keyframe k+1. The interpolation for this curve is then, referring to curves in the illustration: $c_{1_{from}} \Rightarrow c_{2_{to}}$.
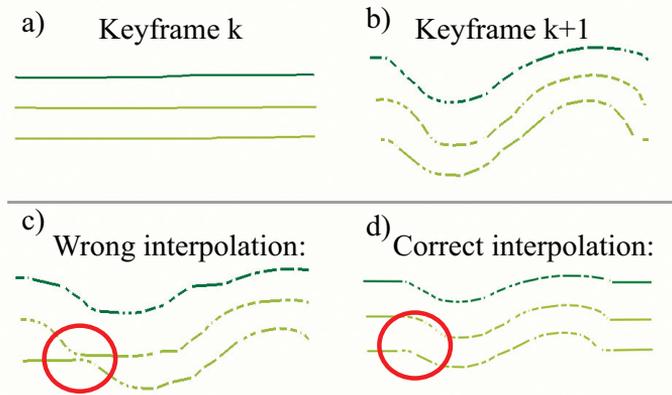
Figure 3.11: a) is showing a sketch of three straight horizon lines. b) shows the same lines in the next keyframe after a folding event has occurred. In c) the highlighted red area shows a geological incorrect interpolation, while d) shows the correct interpolation. The white dots in b), c), and d) convey the position of the curve points.

Splitting of curves between keyframes – Our animation method also has to handle the splitting of curves into one or more disjoint segments, which is case for a geological faulting event, i.e., $c_{from} \Rightarrow \{c_{to0}, \cdots, c_{toN}\}$. If a fault curve is sketched along with the split curve, then we split the c_{from} curve at the intersection with this fault curve and then interpolate the start point of the new curve segments along the fault curve.

3.4   Presenting Stories

The final stage in our proposed work process model (Figure 3.1) is the decision stage, where the best solutions are presented to decision-makers. The challenge here is that the sketches made by the domain experts may not convey enough information to the audience in this stage. This is a problem we picked up in Paper B. Seeking inspirations from illustrations found in geological textbooks and from communicative material made by professional geological illustrators, we propose a method to synthesize illustrative 3D animations automatically based on the animated sketches.
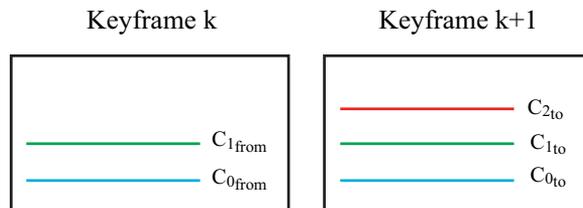
Figure 3.12: The figure is showing two consecutive keyframes. In the animation sequence between these keyframes, the new curve $c_{2_{to}}$ is interpolated from the curve $c_{1_{from}}$.
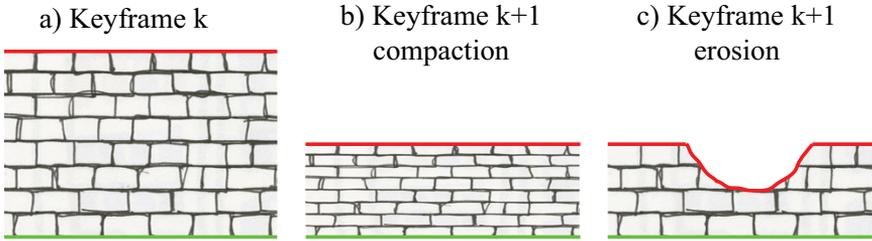
Figure 3.13: a) The geological layer at keyframe k. b) The geological layer of a) after a compaction event, notice the texture is also compacted. c) The logical layer a) after an erosion event, notice that the layer is not compacted.

3.4.1   Animating Automatically Synthesized 3D models

Natali et al. [58] describe a method for automatically synthesizing a static illustrative 3D geometric model from a 2D sketch. They achieved this by tessellating the areas between the horizon curves, extruding the 2D sketch in the third dimension, and applying illustrative texturing. We have adapted and extended their method in the following way, to synthesize *animated* 3D geometric models from our 2D animations automatically:

Animate deposition and erosion events – The texture mapping technique presented by Natali et al. focuses on depicting correct looking compaction and folding deformations events, but it cannot handle an animation sequence that contains erosion and deposition events. Figure 3.13 illustrates the difference between these events. The erosion event cannot be synthesized by merely considering each interpolated 2D animation frame individually. Thus, we extended their method with the following 2-pass extension (please refer to Figure 3.14), to depict that the geological layer is cut into and not just compacted:

1a) Tessellate the area between the initial top curve of the eroding horizon $c_{1_{from}}$ and the horizon below $c_{0_{from}}$

1b) Texture map this area with the layer texture T, apply conformal texture mapping and render this to an image T_{conf}

2)   Tessellate the area between the curves c_{1_n} and $c_{0_{from}}$ and texture map this layer with the image T_{conf}, applying regular texture mapping

   Note, if the horizon line described by the curve $c_{0_{from}}$ is also changed between the keyframes, i.e., $c_{0_{from}} \neq c_{0_{to}}$, then the references to $c_{0_{from}}$ in the algorithm above should instead be to the interpolated curve c_{0_n} as part of the interpolation $c_{0_{from}} \Rightarrow c_{0_{to}}$. The steps for the sedimentary deposition event are similar to the steps for the erosion event, except that the area tessellated in step 1a) is the area between $c_{1_{to}}$ and $c_{0_{to}}$.

Handle temporal coherency – Temporal coherency is important in animations and if not properly handled can result in very visible, temporal artifacts. The texturing method described by Natali et al. only considers the synthesis of static images and we observed temporal artifacts, in the form of texture jittering, when animating our synthesized 3D models. The source of these artifacts was a low tolerance to minor changes in
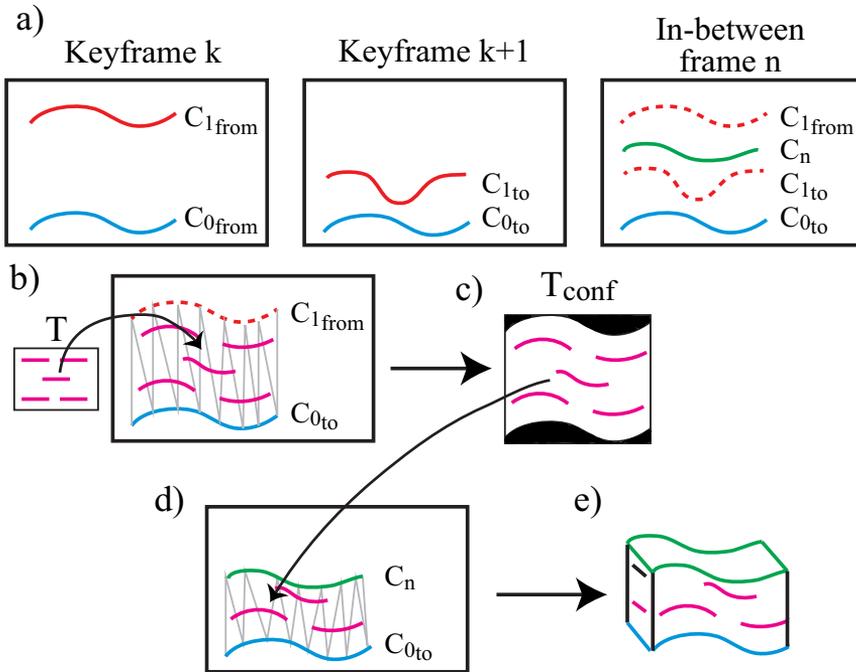
Figure 3.14: a) shows two consecutive keyframes depicting an erosion event and one of the interpolated in-between frames. b) The area between $c_{0_{from}}$ and $c_{1_{from}}$ is conformal texture mapped and c) a new texture, T_{conf}, is extracted. d) The area between c_{1_n} and $c_{0_{from}}$ is texture mapped with T_{conf} to make the final 3D model e). Note that the tessellation in the figure is an illustration.

the horizon curves in the tessellation and conformal texture mapping. These jittering artifacts were only noticeable on geological layers that remained unchanged during an animation sequence, and not on the layers that are deformed by compaction, erosion etc. To solve this issue, we focused on keeping the horizon curves on consecutive key frames, for stable layers, as identical as possible. Our method therefore supports, in the sketching canvas, a copy functionality of the ghost curves(already discussed in Section 3.2, so that the author accurately can duplicate a horizon curve from one keyframe to the next keyframe.

Another temporal artifact we had to address was the seams between tiled textures. For the still images presented by Natali et al., these seams are not very noticeable. However, when the model is animated, these seams become very visible and they are erroneously perceived as structural information, which leads to misinterpretation of the model. The textures used for the animations must therefore be seamless, i.e. they must wrap around both vertically as well as horizontally.

Figure 3.15 shows three frames from an automatically synthesized animation of a 3D illustrative model. This animation depicts an erosion event.
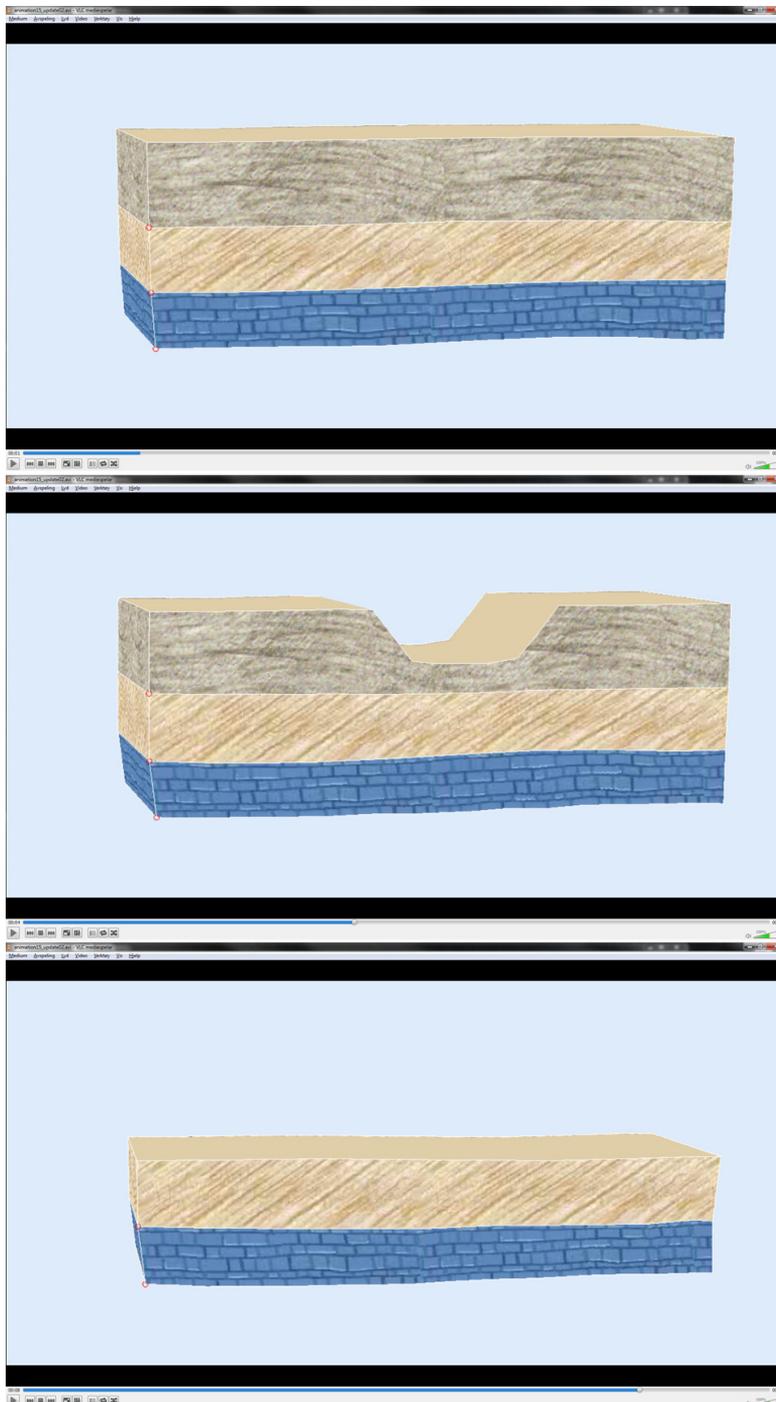
Figure 3.15: Three still images of an illustrative animation made from a geological story about an erosion scenario.

Figure 3.16: The figure shows an example of professionally made geological cutaway illustration. Copyright of Statoil, used with permission.

3.4.2 The oblique, illustrative cutaway visualization

When depicting complex 3D geometric models, such as geological models, there are often important features inside the model that are occluded by surrounding context. Thus, there is a need for occlusion management to show these internal features, while at the same time also to show as much of the context as possible. This is the focus of our investigations in Paper C.

Professional illustrators utilize many techniques for occlusion management, one of these is the cutaway, as seen in Figure 3.16. Computer generated cutaway visualizations have been studied for several years in the visualization field, however as we show in Paper C, the techniques presented so far do not work well applied on geological 3D models. Especially problematic is the low depth perception and this hampers the model understanding with respect to perceiving: the spatial ordering of the focus features, the location of the focus features relative to the cutaway, the shape and topology of the focus features, the spatial relationship between the focus features and the context, and the relationship between the cutaway shape and the model.

Based on the characteristics of geological objects as reported by Turner [77], studying of geological illustrations, as well as discussions with geologists and illustrators, we propose the following design principles for creating cutaway illustrations targeting geological 3D models[2]:

1. Use an oblique viewpoint to the cutaway – From geological cutaway illustrations, such as Figure 3.16, we observe that they have an oblique viewpoint to the cutaway, as opposed to the view-dependent cutaway found in computer visualization literature. The viewer is not looking directly into the cutaway, but rather slanted from one of the sides. This oblique viewpoint increases the depth perception by providing a frame of reference (the cutaway wall). Figure 3.17 illustrates the difference between a view-dependent and an oblique cutaway.

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[2]Please refer to Paper C for further details
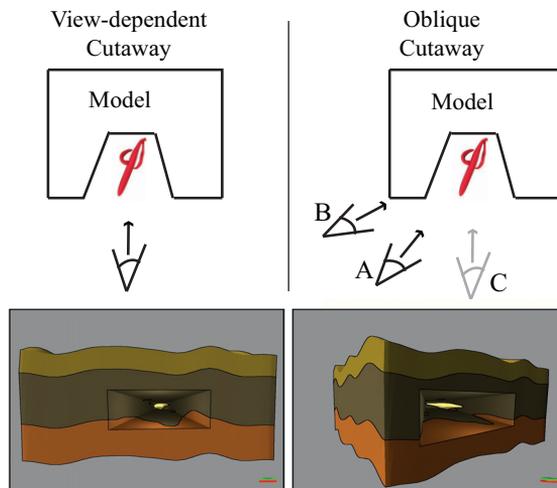
Figure 3.17: Top left: A schematic top view of a cutaway visualization where the camera points directly into the cutaway. *Top right:* The same cutaway, but with an oblique viewpoint. The cutaway proxy geometry is generated from the camera position C and the scene is rendered from the camera position A. Note: with large angles (camera positions B), the focus feature is occluded by the context. *Bottom:* The corresponding cutaway visualizations.

2. Simple cutaway shape for complex models – A simple and easy-to-understand cutaway shape makes it easy to extrapolate the complete model and to understand how deep into the model the cutaway extends. As a general advice, we recommend a rectangular box-shaped cutaway, often found in geological illustrations.

3. Include familiar context – By not cutting away parts of the context that are familiar to the viewer, even if it is partially covering the focus feature, can emphasize this relationship and make it easier to relate the focus feature to the context. See Figure 3.18 for an illustration of this principle.
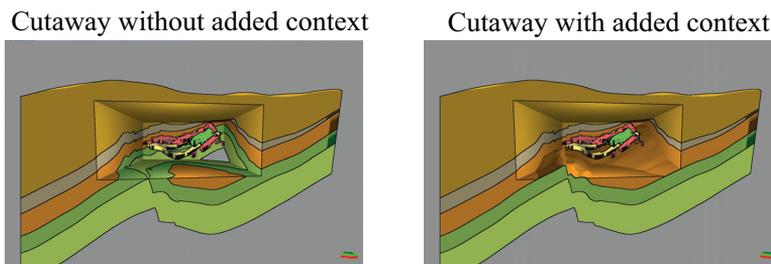
Figure 3.18: This figure shows the visual difference between a cutaway visualization where the cut is made non-context aware (*left*) and where parts of the context is added to the cutaway shape (*right*). It is easier to understand the relationship between the focus features and the context in the context-aware cutaway visualization.

4. Utilize an illumination model that effectively communicates shape, and ordinal and relative distances – We recommend mimicking the lighting and shadows that professional illustrators draw between the focus features and the context, as this emphasizes the spatial distance and the spatial ordering.

5. Take advantage of the motion parallax depth cue – Motion and interaction are mechanisms that can increase depth and shape understanding of 3D models, for instance by the difference in angular velocities between objects at different distances from the viewing position. We recommend taking advantage of interaction and movement in the computer-generated cutaway visualizations. To achieve this effect, however, there must be a fixed frame of reference for measuring this angular velocity difference, thus we need to decouple the cutaway orientation from the viewpoint movements, so that the cutaway provides this frame of reference.

For further details about these design principles and how to implement them in a visualization tool, please refer to Paper C. The next chapter (Section 4.3) demonstrates the design principles applied to real-world 3D geological models.

CHAPTER 4

DEMONSTRATIONS AND DISCUSSIONS

THIS chapter provides demonstrations of how the contributions of this PhD disser-
tation can be applied to solve problems within petroleum exploration and within
geology in general. Section 4.1 presents results of geological storytelling, both for the
sparse-data and for the no-data scenarios. Section 4.2 contains demonstration results
of the box-shaped 3D sketching proxy, followed by Section 4.3, where the results from
the proposed design principles for cutaway visualization of 3D geological models are
demonstrated. Each of these sections ends with a discussion about the contributions.
In addition, this chapter ends (Section 4.4) with a discussion about approaches for de-
signing sketching tools for geology.

4.1 Geological Storytelling

The results reported in this section are a summary of the results presented in Paper A
and Paper B. Please refer to these papers for the complete detail description and for the
supplementary video material for those papers.

We have implemented a proof-of-concept prototype system, targeting the geological
domain, of our contributions presented in Chapter 3. This prototype is called "Geolog-
ical Storytelling" and the images presented in this section are screen-shots of this pro-
totype. As explained, the story node sketches are compounded of curve lines and these
curves are the sampled user strokes. Through our collaboration with geology experts,
we identified that for authoring geological stories, to prove our concept, the geologist
needs to be able to draw curves for the following "primitives":

Horizon lines:	one or more horizontal curve(s) for depicting the borders (a horizon) between different geological layers
Fault lines:	one vertical curve for depicting a fault (displacement)
Polygons:	for depicting the geological layer between two horizons
Arrows:	for indicating directions of movement, for instance, the direction of erosion or the direction of intrusion
Annotations:	for adding labels and highlighting important parts

4

All curves are represented as a set of connected line-segments between the sampled vertex points. When sketching on a 2D seismic section it is important for the geologists that the lines are rendered exactly where they are drawn, therefore, we do not apply any filtering or resampling of the user's strokes. Much research is already published on filtering and resampling, and on simulating artistic effects, such as pen-strokes. Thus, we did not prioritize this and our strokes are quite straightforward.

4.1.1   Sparse Data – 2D Seismic Section Sketching

After describing our concept of expressing geological models as stories to the domain experts that we collaborate with, we encouraged them to draw sample geological stories for us. These stories were intended as input to the design of our prototype, so these sketches were made using pen and paper. Their stories are based on a publicly available 2D seismic section and Figure 4.1(left) shows one of these stories. It describes a faulting scenario in four story node steps. In Figure 4.1(right), we have reproduced this story in our prototype system, utilizing many of the above-mentioned drawing primitives. Visually, it can be verified that this hand-drawn story can be reproduced quite well. Figure 4.2 shows a close-up comparison between a reference story node (left) and the reproduced story node (right), taken from a story about an erosion scenario.

Together with a professor in geology, we have authored two alternative stories of another publicly available 2D seismic section. These stories are shown in Figure 4.3. In Figure 4.4, we show how to perform the side-by-side comparison of these stories.

4.1.2   No-data – 2D Sketching

We have also applied the geological storytelling prototype to the no-data scenario. An application in this scenario is that of producing animated teaching material, for demonstrating geological principles or geological events. In our system, the geological concepts can easily be sketched, utilizing the temporal sketching flip-over canvas with a clean backdrop. Our system then automatically synthesizes a 3D illustrative animation. Figure 4.5 (left column) shows how the story node sketched for a half-graben faulting scenario and Figure 4.5 (right column) shows three screen-shots of the resulting 3D animation.

4.1.3   Discussions

It has unfortunately not been possible for us yet to perform a user-study in a petroleum exploration environment to measure the impact of our proposed technologies. We have though, in many occasions demonstrated our sketching-based storytelling system to domain experts working in the frontier stage of the petroleum exploration pipeline and to professors in geology. The feedback we have received was encouraging and inspiring, and some of the benefits they recognized were:

    ▷ It strongly resembles pen-and-paper sketching, a medium they are familiar with and very often utilize when they explain their interpretations and models.
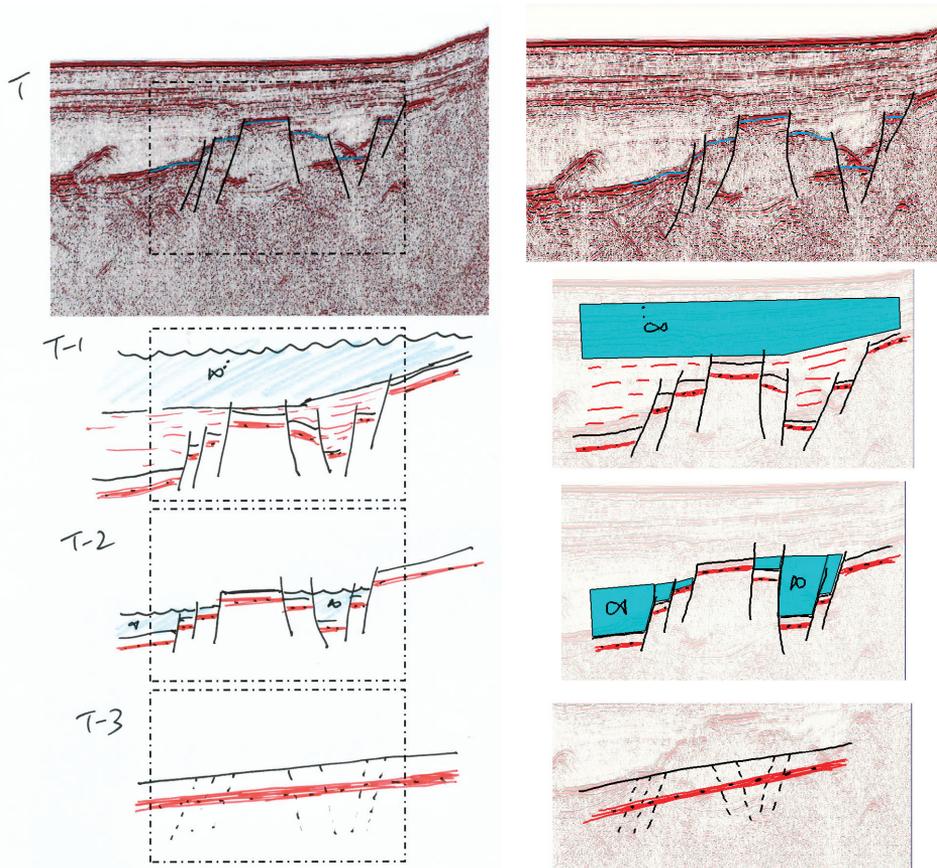
Figure 4.1: The hand drawn sketch to the left was made by one of our collaborative geologists after we explained the concept of a geological story. It shows an imagined geological story of the seismic slice shown in the top of the figure (Today). This particular story shows how a fault system has evolved from a non-fault stage (T_{-3}) through several events of faulting and sedimentary deposits (T_{-2} and T_{-1}). To the right, this geological story is authored in our storytelling prototype. These two visualizations look similar and tell the same geological story.
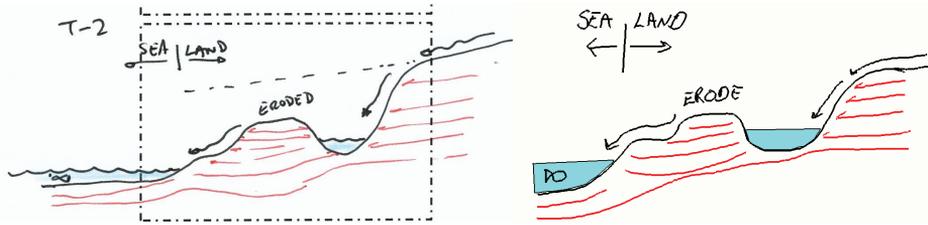
Figure 4.2: To the left: A hand drawn sketch showing one story node from a longer story about an erosive geological model. It was made by one of our collaborating geologists. To the right: The same story node, but this time reproduced in our geological storytelling prototype.

▷ Not all geologists reason in geological events when interpreting seismic, even though this is commonly thought of as a good approach. Our system will encourage them, in an easy way, to adopt this method.

▷ Geologist may agree on an interpretation of a seismic section, however may have different opinion about the presence of, e.g., petroleum. If the geologists express their models as geological stories, they can more easily discuss where their differences are.

▷ Our sketching-based storytelling approach can significantly speed up the time it takes to produce geological animations. Even the creation of the simplest animation, utilizing general-purpose modeling and animation tools, can take a full working day.

▷ In relation, our system, because it is easy to use, can encourage geologist with lesser artistic skills to employ more illustrations and animations in their publications and communications.

Even more encouraging is it that we now have started collaboration with one of the professors in geology to turn our prototype system into a distributable tool for geological storytelling. His motivation is to develop a tool that encourages geologists to utilize sketches and illustrations more to communicate their models and findings.

For the sketch-animations to be understandable and believable, it is important that they are geologically sound. We have anecdotal evidence, based on the feedback we have collected from the domain experts, that our animations are geologically sound. This means that our interpolation scheme does not create geologically impossible constructs. Further investigations, such as formal user studies, are necessary to claim that this holds for all possible geological sketches. Nevertheless, our results show that this is a fruitful approach.

Geologists frequently utilize arrows in their hand-drawn geological sketches, see for instance Figure 4.2. The role of these arrows is purely visual, utilized mostly for depicting movements and dynamics in a still image, such as the direction of eroded particles in Figure 4.2. Whether or not these arrows also can be utilized as animation descriptor for the sketch-animations could be a research question on its own. However, combining these two roles (arrow as a movement depicter and arrow as an animation descriptor) may easily introduce a mismatch, as for example a different arrow specification would be needed to achieve a desired displacement or deposition, than what
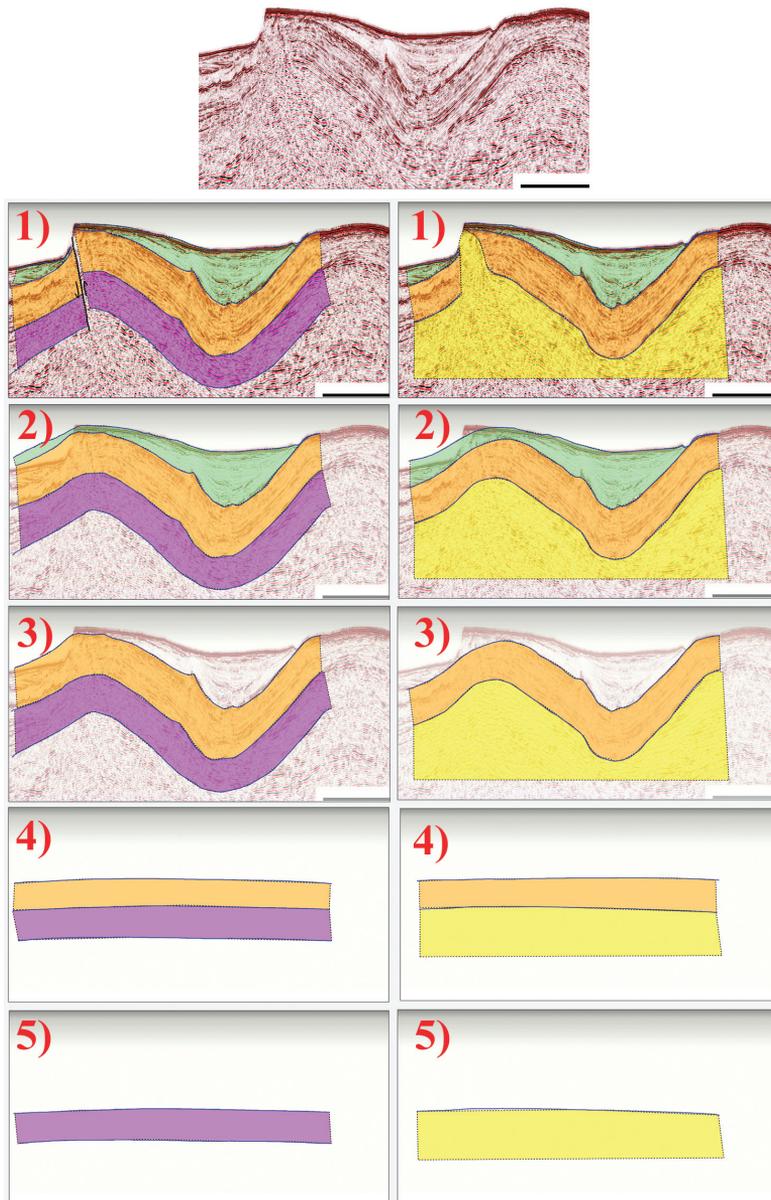
Figure 4.3: The seismic section "Ymir Ridge profile 3" is courtesy of Fugro. The story to the left is telling about geological layers deposited 5), 4) that are folded by tectonically plate movements 3). New sedimentary depositions are made 2) and the construction is then faulted 1). In the story to the right, the geological layers 5), 4) are folded by an intrusive layer 3), this folding also enables sedimentary depositions 2), and in the end, the intrusion breaks through the upper layers 1)
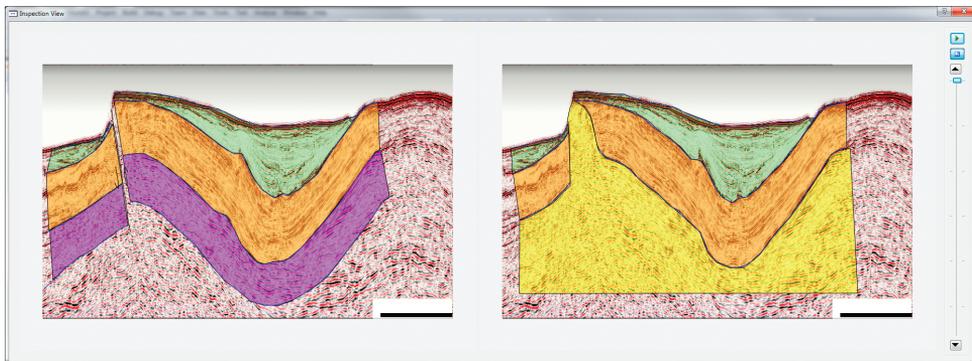
Figure 4.4: The figure shows the side-by-side comparison-view containing one frame of the animation of the stories shown in Figure 4.3.

would be preferred as a visual symbol itself. We have therefore not investigated this any further.

Annotations often accompany structural information in the hand-drawn geological sketches and they are important for the geologists. Our geological storytelling system supports annotations, however we did not add them to the automatically synthesized 3D geometric models for time constrain reasons. Optimizing the layout of labels and annotations on 3D geometric models is a well understood problem, for instance the solution presented in the recent work by Čmolík and Bittner [15].

As a step towards turning our proof-of-concept application into a distributable storytelling tool that the geologist can apply in their daily work, we have returned to our collaborating frontier-exploration geologists and challenged them to draw more complex geological stories. Three story nodes (out of six) of a more complex geological story are shown in Figure 4.6. This story contains geological events such as syn-rifting, where sedimentary deposit are made at the same time as a faulting process (middle figure); and salt intrusions (lower figure). Our goal for the distributable tool is not limited to only being able to express stories such as these, but also to investigate if it is possible to provide new user-interface technology that increases the speed of the sketching process.

4.2 Direct Sketching in 3D Views

This section contains demonstrations of geological 3D sketching utilizing our box-proxy (Section 3.2.2). The box-proxy has been implemented in a prototype application described in Paper D. This application was developed in collaboration with sedimentologists. Important to them is to model the environment, where the depositions occurred, thus, they combine landscape modeling with the typical layer-cake modeling.

4.2.1 Box-proxy Sketching

Figure 4.7 (left) shows a typical geological model that can be made by our prototype application. It shows a subsurface geological layer, combined with a landscape, with
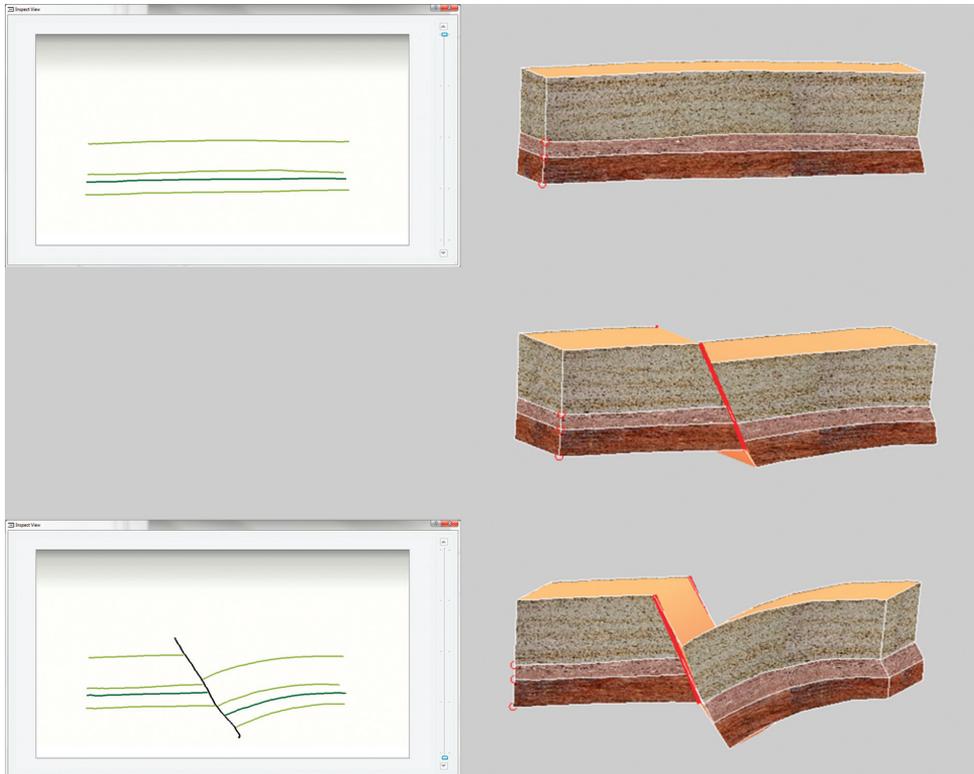
Figure 4.5: Left row: Two example key-frames that constitute a fault animation. *Right row:* Three still images of the illustrative animation made from these key-frames.

rivers and mountains, modeled on top. This model also contains the procedural generated river deposits that occur when a river meets the sea. Figure 4.8 shows a visual comparison between a textbook geological illustration (*left*) and the reproduction sketched in our prototype (*right*), both depicting the eroding effect of a glacier. As the figure shows, our prototype is able to communicate the story of the illustration series, even though it cannot reproduce the smaller glacier branches, or all the illustrative details on the glacier and terrain.

4.2.2 Discussions

We conducted a small, preliminary user-study on four students of geology, at a master-level. After a short introduction to the tool (15 minutes) and an assignment to reproduce a predefined model, they were encouraged to utilize the prototype to make sketches relevant to their geological studies. One of these sketches is shown in Figure 4.7 (right). The users found that sketching with the box-proxy was easy to understand and use. Rotating the cube while sketching, aided this process by providing a good overview of the model. The simplicity of the sketching was praised, but also seen as a limitation, especially when creating complex models. Especially missing was the possibility of sketching and modeling faults.
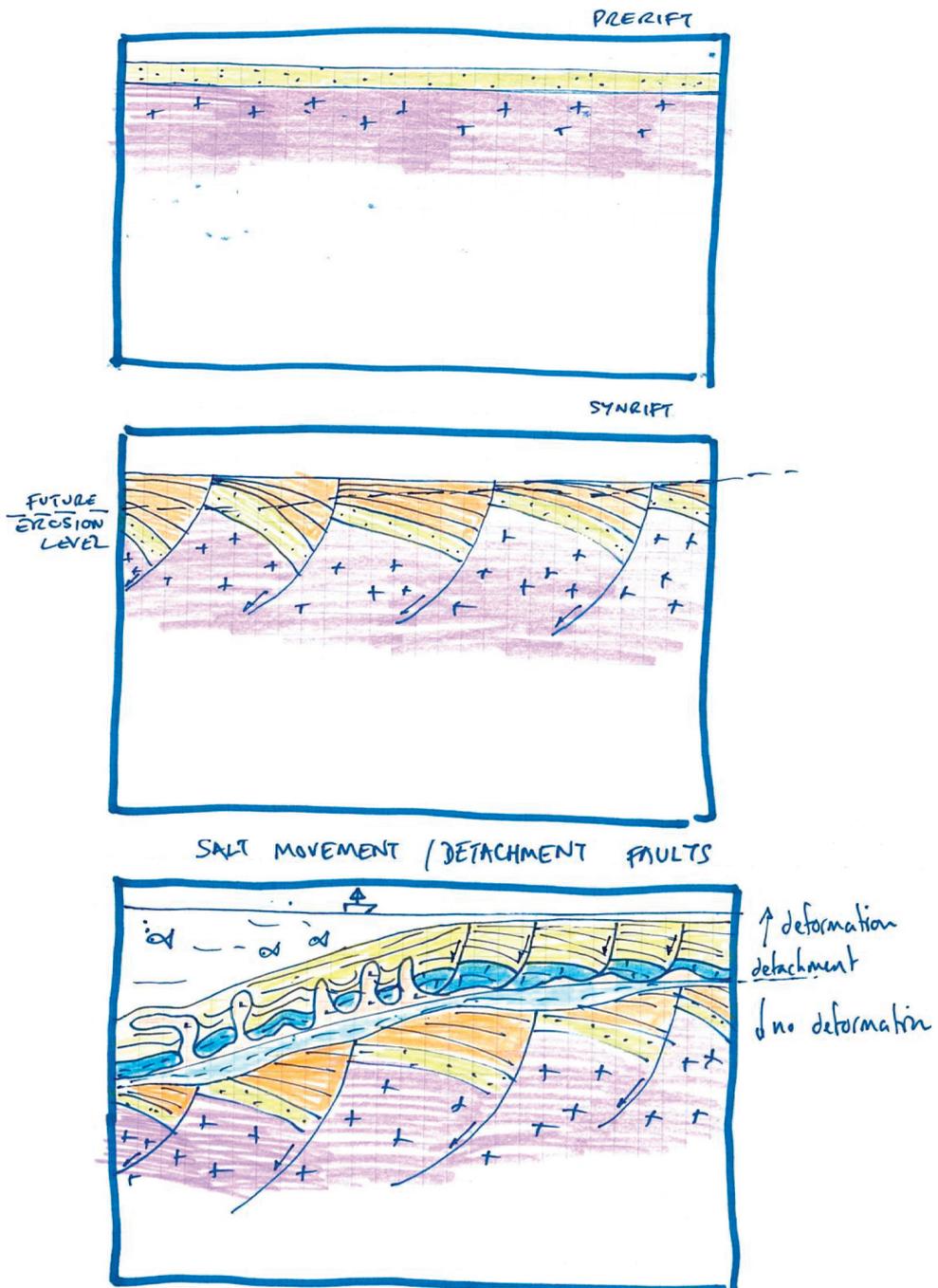
Figure 4.6: This figure shows three out of six story nodes of an advanced geological story. This story contains geological events such as syn-rifts and salt intrusions. The story is sketched by one of our collaborating geologists.
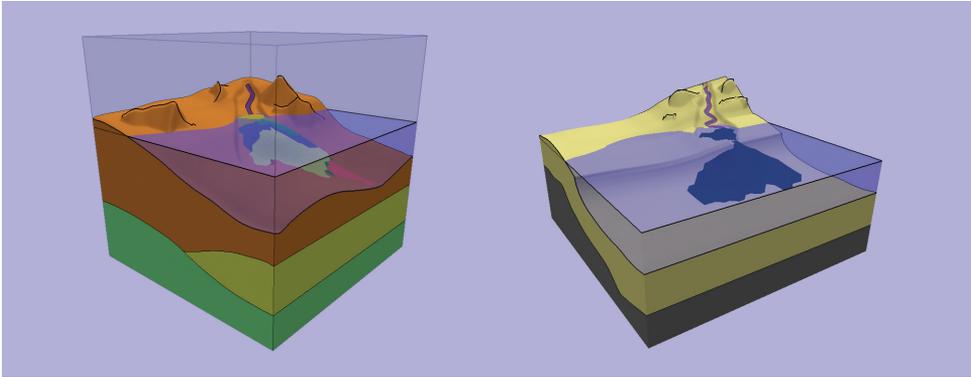
Figure 4.7: The figure to the left demonstrates a geological model containing all the features that can be sketched in this prototype. The figure to the right is the modeling result of one of the participants in the user-study. This figure shows very well the procedural deposition from the river into the sea. Both images are courtesy of Morten Bendiksen.

A domain expert from the petroleum industry that has evaluated this work pointed out the lack of support for sketching faults, which are important if the 3D sketching should be applied to a broader geological sketching audience. In addition, he emphasized that annotations are important and pointed out that they were missing in our reproduction in Figure 4.8. Finally, he asked for the possibility of changing the size of the box-proxy geometry. Our proxy geometry does not support this today. Despite of these drawbacks, he definitely thinks that this approach of sketching 3D models is an approach worth more investigations.

The procedural deposition modeling, as shown in Figure 4.7, was not as much appreciated by the domain experts as we expected. The main reason for this is that the deposition process can be very complicated to describe procedurally and a simplified version may not be able to produce sufficiently good results. They suggested leaving it to the model author to sketch the deposits explicitly. That said, the consensus was that the combination of explicit and procedural modeling could be useful, only that we did not pick the optimal case to show it. As an example, domain experts have recommended us to experiment with shaping the rivers procedurally (straight or winding, narrow or wide) based on the terrain through which they flow.

4.3   Revealing Internal Features in a 3D Geological Model

Last demonstration in this chapter shows how to reveal internal features in a geological model utilizing our oblique illustrative cutaway visualization technique. The demonstration is published in Paper C; please refer to this paper for further details.

The 3D models produced in the prototypes described in Section 4.1 and Section 4.2 do not yet include internal features hidden by the surrounding context. Therefore, the model in this demonstration represents the dense-data scenario and it is obtained from a reservoir model. The model utilized for this demonstration is from the Ness-formation in the Oseberg-field, obtained from our collaborators at Statoil. Its focus features are sand-filled channels, ancient rivers and deltas with excellent reservoir properties, see
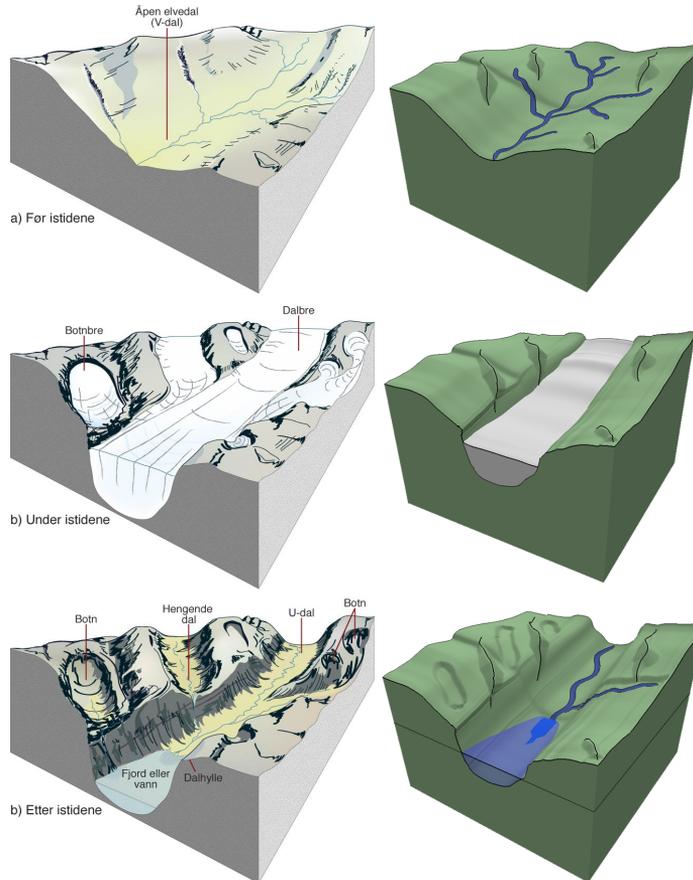
Figure 4.8: This figure shows the comparison of a geological story created by a geology illustrator (to the left) and the same story reproduced in our 3D sketching prototype. Although it is not possible to reproduce the story illustrations exactly, the overall story is reproduced. Images to the left are courtesy of Haakon Fossen. Images to the right are courtesy of Morten Bendiksen.

Figure 4.9 (left). The model is created in the domain application system IRAP RMS. Even though this is a matured tool, the visualizations of such models it provides are very elementary. To study the channels together with the geological layer context, the channels are projected onto the underlying geological surface, as Figure 4.9 (right) shows. Thus, the spatial ordering and actual positions of the channels are lost, and have to be reconstructed in the mind of the viewer.

4.3.1   Cutaway Visualization of 3D Geological Models

The goal of this project was to synthesize geological illustration, such as showing in Figure 3.16, from computerized geological models. The Ness model is very wide and long, compared to the depth. The geological layer-cake cutaway illustrations we want to reproduce, typically have a cube shape. We have therefore, cropped the Ness model around some potentially interesting channel structures and utilize this sub-model to
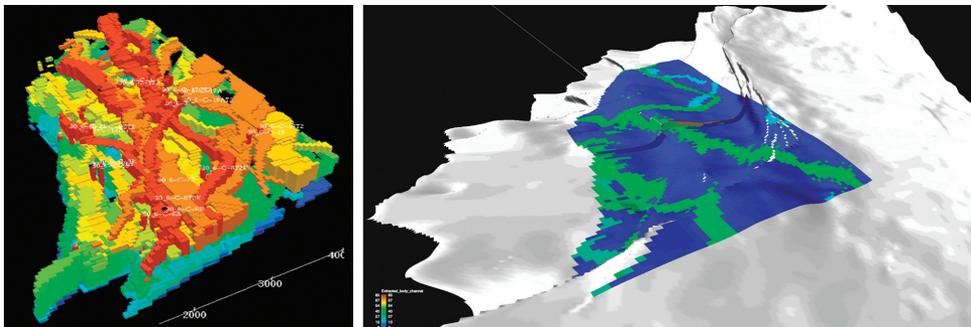
Figure 4.9: The figures show how the Ness formation is visualized in in the domain specific application called Roxar Reservoir Management Software (RMS). The figure to the left shows all the modeled channels in the formation, but this visualization cannot show the context around the channels. The figure to the right shows how the channels are depicted together with the context in this tool. Here the channels are projected onto the horizon surface, thus the spatial information of the channel locations is lost.

illustrate our cutaway method[1].

Applying our cutaway visualization design principles to the Ness geological model produces visualization as shown in Figure 4.10 (right). By comparing this image with the visualization of the same model utilizing our implementation of a previous state of the art method [10], shown in Figure 4.10 (left), reveals that our oblique cutaway visualization offers better communication of: how deep into the model the channels are located; how the channels relate to the bottom surface of the geological layer they reside in (the orange layer); the spatial ordering of the focus features. All this information is difficult, if not impossible, to perceive from the left image.

Our cutaway visualizations are constructed in real-time; and, since it requires a two-pass rendering it runs at approximately 50% of the frame-rate compared to rendering the model without the cutaway visualization.

4.3.2 Discussions

We have demonstrated the cutaway visualizations of the Ness geological model to domain experts. They all emphasize the benefit of showing the focus features together with the context and they confirmed the increased perceptual improvements of our visualization. A formal user-study is needed to confirm properly that this holds for the general case of 3D geological model visualization and whether there are additional design principles that we have not yet discovered.

The fact that we cannot yet produce 3D models with inside "hidden" features with our sketching prototypes, prevents us from demonstrating the power of all our technical contributions on one complete example. However, projecting the sketching-for-geology concept, introduced in this dissertation, towards the future predicts that such synthesized models will be available, and then the illustrative cutaway visualization will be an important occlusion management technique.

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[1]Results from the complete Ness-model are included in Paper C.
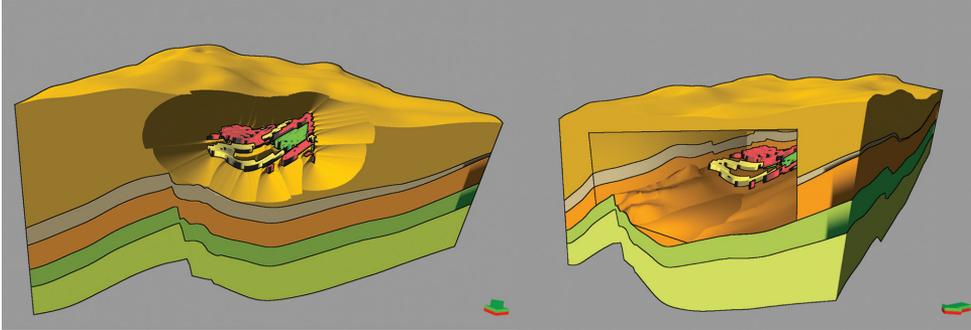
Figure 4.10: The figure to the left shows our implementation of the cutaway method by Burns et al. [10] applied to the Ness geological model. It exemplifies one of the perceptual problems we observed with current cutaway methods; it looks like the geological channels are located in the yellow-colored top layer, while in fact they are all residing in the orange, third layer. The figure to the right shows a cutaway visualization based on our design principles. In this picture we more clearly see in which layer the geological channels resides, how the channel shapes corresponds to the shape of the surrounding context, and the depth of the cutaway.

4.4   Discussions on Sketching Tools for Geology

In Paper D, we present and discuss two different approaches for performing geological sketching directly in 3D views. In the first approach, the *general* approach, the sketching is performed utilizing a general-purpose, highly expressive, surface modeling technique. The geologist sketches curves in 3D views, with normal specification. These curves can then be interpolated, utilizing the Variational Hermite Radial Basis Function method [6], into surfaces. In addition, there are functions that turn these surfaces, or subsections of the surfaces, into solid objects, for instance to construct geological layers. The idea is that every geological feature, layers, channels, salt-diapirs, and so on, can be expressed through this modeling technique and thus, in principle, any 3D geological models can be constructed. Figure 4.11 shows examples of how to sketch a surface representing a salt diapir (left and middle) and a mountain (right). Figure 4.12 shows the final geological model synthesized based on the layer surfaces (left), notice that this synthesizing function can produce an arbitrary cut-section of the model (right). The domain experts that have tested this tool report that this sketching metaphor was easy to use and it was easy to express complex surfaces. In addition, the possibility for creating arbitrary cross-section of the model was appreciated.

The other approach we present in Paper D is the proxy-based approach for 3D geological model sketching that is presented in Section 3.2.2 and demonstrated in Section 4.2 in this dissertation. We denote it the *ad-hoc* approach, as this approach requires adding new, special purpose, sketching proxies for every new geological feature the geologist needs to express. In the prototype, this is currently limited to sketching layers, rivers, mountains, valleys, and the sea level. This feature limitation was one of the drawbacks pointed out in a user-study, where otherwise the simplicity and rapidness were especially appreciated.

Comparing these approaches shows that the ad-hoc approach solves specific problems with specific tools, i.e., one sub-tool for creating mountains, another for creating
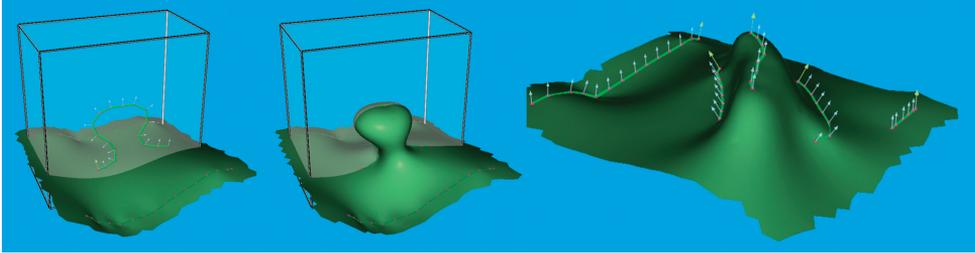
Figure 4.11: Figures modeled according to the general approach presented in Paper D. The salt diapir surface in the middle is created by sketching the outline curve (left). The figure to the right shows how to sketch a terrain with a mountain. The images are courtesy of Daniel Patel.

rivers. These sub-tools make it easy for the geologist to quickly draw geological models, but at the same time, the geologist is limited by the selection of sub-tools and the functions implemented in each sub-tool. The generic approach, on the other hand, has only one way for defining the surfaces, unbound to any semantic. Therefore, a large diversity of shapes can be modeled, but at the cost of increased time and more complex interactions. Combining the ad-hoc with the general approach is possible, creating a set of sub-tools with the expressiveness of the generic approach. However, care should be taken not to end up with the worst of both, a limited set of sub-tools that are slower to use.

The geology domain is large and diverse. Different geologists make different types of sketches, emphasizing different features as vital for a sketching tool. As the domain of sketching tool for geologist is still an under-explored domain, it is important to work closely with the domain experts, as has been done during the work on this dissertation. However, if the research is guided by a few domain experts, this may result in solutions that only fit one group of geologists. On the other hand, involving to many geologists, with a diverse geological background, may result in a list of conflicting requirements, making a realization impossible.

In Paper D, we propose that, if the domain for such a tool is large or of unknown size (geology), it might be advantageous to start with a generic tool and, through a
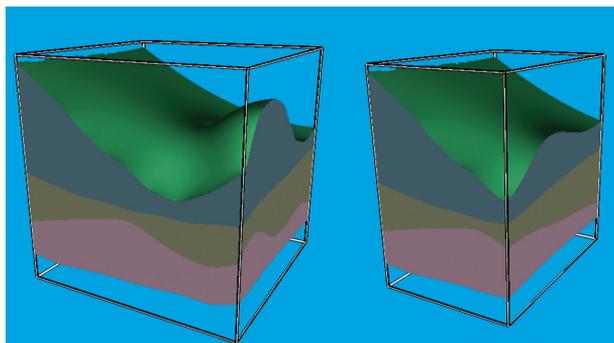
Figure 4.12: The general-approach tool can synthesize layered geological models based on the entire (left) or a cut section of (right) the stacked surfaces. The images are courtesy of Daniel Patel.

dialog with the users, an ad-hoc tools can crystallize out when testing this generic tool. However, based on the experiences obtained through this PhD work, combined with previous experiences[2], the author of this dissertation also recommends considering the following approach:

1. **Start with a selected target group** – Start by identify one target group of geologists and design and develop a sketching tool that improves the work procedures of this group. This reduces the possibility of conflicting requirements and increases the chance of producing a tool that, at least, can be utilized by a limited group of geologists. It is preferably if the selected group represents a large share of the geologists, however this is not essential.

2. **Start with the ad-hoc approach** – The first tools should be ad-hoc based, i.e., a set of special-purpose sub-tools, and the geologists should be involved in the specification of the sub-tools. Starting with the ad-hoc approach limits the expressiveness of the tool, as pointed out above. However, if the user are involved during the specification and development of the sub-tools this will give them ownership to the tool. This ownership can be a contributing factor for them to utilize it more and propose improvements. During development, the collaborating geologists are only trying out the tool now and then. With the ad-hoc approach, it will also be easier for them to try out new functions, as these are easy identifiable and do not have a complex interface that the geologist needs to remember from test to test.

3. **Expand after success** – If this first tool becomes a success, then look for other groups of geologists, starting with the ones with similar requirements, and extend the tool by including their requirements. Thus, this is an expansion in functionality due to adding new user-groups.

4. **Create multiple tools if necessary** – If at some point when adding new groups of geologists, their requirements are conflicting with the existing tool, or there is some limitation in the existing tool that prevents the new requirements to be fulfilled, then this is the point to realize that multiple tools are needed. Depending on the tool design, but this is outside the scope of this dissertation, some of the functionality can be reused in both tools.

5. **Expand in coverage** – The other direction to expand a sketching tool is to extend work procedure coverage of the tool for the target group of geologists. If such a tool is successful, the borders between making a very rough sketch for work meetings and producing a professional-looking illustration will become fuzzy. The users will request to be able to extend the rough sketch into the illustration in the same tool. This has already been investigated in this dissertation. A possible advanced solution is to allow for multiple representations of the same sketch, ranging from a rough sketch to a detailed and expressive 3D geometric model. This is the place where the general-approach will shine, because by taking the rough sketches as input it would be easy for the geologists to add new details, utilizing the general-approach, as these are developed during the work pipeline.

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[2]For instance, from working on the SHIVR project described in Paper 2 and Paper 3.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

W HEN this PhD work started out, the goal was to research new technologies in illustrative visualization and sketch-based modeling to make it easier for knowledge-workers to shape and express their ideas and solutions, to discuss these more efficiently, and to present them convincingly to decision-makers and non-experts. These tasks are common for problem solving in engineering and scientific domains.

This dissertation has presented the concept of sketch-based storytelling, a method for expressing ideas and conceptual models concerning, in particular, evolutionary processes. This is accomplished by expressing the evolutionary process as a temporally ordered sequence of discrete time event sketches, what is called story nodes. These story nodes describe the key steps in the process studied. Two sketch interfaces have been presented: the flip-over canvas, a novel interface for making temporal 2D sketches; and the box-proxy canvas interface, for simplifying the sketching directly in 3D views.

Exploring many possible solutions is a strategy for finding the optimal solution for difficult problems. This dissertation described the story tree, a tree-graph data structure, and visualization, for managing and accessing an ensemble of alternative solutions. The story tree also provides an interface for navigating to specific story nodes and to play the stories, either in a single story mode or in a multi-story, side-by-side, comparative mode. The stories are played as 2D animations. These animations are generated by treating each story node as a keyframe and then applying novel keyframe-animation techniques to interpolate automatically the inbetween-frames.

Regarding the task of presenting the knowledge-workers' optimal solutions to the decision-makers, this dissertation described an approach of automatically synthesizing illustrative 3D animations from the 2D sketch animations. For solutions that include important features hidden and occluded by context information, especially for non-canonical features, the dissertation described five design principles for constructing automatic cutaway visualizations that enhances the depth perception and thus increases the efficiency of communicating the solution.

The PhD work in this dissertation is performed within the scope of the interdisciplinary GeoIllustrator project. This project is primary aiming for better tools for the geology domain. The contributions of this PhD dissertation are influenced by this project and the collaboration with the domain users in the project, in such a way that some of the contributions are domain specific. Based on the experience from this PhD work and

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prior work within visualization for the geology domain, the dissertation also provides a set of recommendations for realizing a sketching tool for the geologists.

5.1 Conclusion

This dissertation presented feedback and evaluations collected from a diverse group of domain experts and this provides anecdotal evidence that the contributions are justified and represent an important first contribution towards sketching tools for geologists. Specifically, based on the anecdotal evidence, the conclusions are:

▷ There is a significant potential in combining sketching-based modeling techniques, storytelling, and illustrative visualization to perform rapid, geological modeling.

▷ Storytelling is a well received and intuitive representation for the group of evolutionary processes, to which geological modeling belongs.

▷ The flip-over sketching interface is a novel and an easy to use approach to make temporal sketches and to build the stories.

▷ Preliminary user-study indicates that the box-proxy is an intuitive and easy-to-use interface for rapidly sketching of simple geological models.

▷ We have shown that a cutaway visualization based on our five proposed design principles provides better depth perception and model communication for geological 3D models than the previously known cutaway visualization methods.

5.2 Future Work

Claiming that the problem addressed by this dissertation is completely solved would require more evidence, e.g., from formal user-studies. However, the acknowledgments and enthusiasm from the domain experts concerning the results of this dissertation have already initialized a new research project with the aim to provide more user-study results.

It follows from the demonstrations and discussions in Chapter 4 that there are many future research topics opened up by the results from this dissertation. These topics can be found in all of the stages in the problem-solving pipeline (Figure 3.1).

5.2.1 Individual Stage – Sketching and Story Authoring

Now that our research has presented a system for externalizing, managing, comparing, and presenting geological sketches, we recommend giving more research focus on the content creation part of geological sketching. One direction is to add new sketching primitives and improve the sketching interface to enable the sketching of stories such as the one shown in Figure 4.6. In addition, investigations of how to include petroleum migration in the sketches and stories are needed.

Although many geological problems can be solved in 2D, there are complex geological problems that require 3D modeling and 3D visualization. Therefore, the second

research direction we recommend is to continue on the work already started regarding rapid construction of 3D geological models. One approach would be to build the geological stories from a series of 3D sketches, made through our proposed 3D proxy geometries. In the work concerning the animation of story-node sketches in this dissertation, we have limited our studies to 2D sketches. In principle, it should also be possible to extend this concept to animate the 3D sketch-based stories. However, the complexity would be higher, as it requires a geologically sound morphing of 3D objects from one story node to the next. For a solution to be really beneficial, this morphing has to be automatic. If the author has to animate each control point manually, then the rapid modeling and ease of use is endangered.

The other approach for constructing 3D models is to take advantage of more than one 2D seismic section, if this is available, when constructing a model. The approach would be to build separate geological stories for all of these seismic sections, preferably by exploring many stories for each seismic section. Afterwards, the system could interpolate 3D geological models based on all of these spatially separated stories. By extending our 2D story tree with a third dimension, we could easily manage these story sets and provide equally easy access to the story nodes as we do today. Regional 2D seismic sections are often sparsely located. Most likely, there would be a need for sketching stories in between the 2D seismic sections, to express geological reasoning where there is no seismic data available. This can be done by providing the author with clean canvas sheets that he or she can position as needed.

5.2.2   Collaboration Stage – Managing and Evaluating Stories

Due to time limitations, we have not been able to explore the story tree concept as much as we would like to. One research topic already mentioned in Section 3.2.1, is the study of branching in the tree and the role of siblings. We also see advantages of performing operations on the individual story nodes, or on subsections of a story. Examples of useful operations are move, copy, merge, and split operators. In addition, the story nodes in the story tree are currently equally spaced, thus, the story with the largest number of story-nodes will be perceived as the story covering the longest geological time span. This may, in many cases, not be the truth, as a story covering a long time span in geological time may be represented with few story nodes, simply because less geological events happen in this story. By assigning a geological time-stamp on each story node, we could improve the layout of the alternative stories in such a way that the distance between the story nodes depends on the distance in the geological time.

Buxton discusses the usefulness of "Sketching On Sketches" [11, pp. 175–200], meaning that sketches can be augmented with meta information, such as evaluation of the sketch, improvements, etc. This is a concept that can be applied in the collaborative stage of the problem-solving pipeline. We do provide the option for the collaborating experts to edit the sketches (and even author new story nodes) during evaluating and comparing stories. However, we do not differentiate between annotations *in* the sketch, i.e., annotations that label and describe the entities in the sketch, and annotations *about* the sketch, i.e., annotations that provides meta information and comments to sketch. The simple solution of adding this feature is to provide the collaborating experts with a "commenting" annotation pen that would draw the comments in a different color than the black color we utilize for the sketch annotations.

5.2.3   Decision Stage – Presenting the Stories

There are some interesting research directions regarding the synthesizing of illustrative animations of the 3D models. Firstly, we have not focused much attention on providing an interface for specifying animation parameters, such as frame-rate, time between keyframes, etc. The goal of the work presented in this dissertation was to show that it is possible, automatically, to construct illustrative 3D animations synthesized from the 2D sketches. Traditional animation software usually provides a time-line editor, for managing the animation settings. Such a time-line would most likely be advantageous in our system, although care should be taken to keep it simple and not overload the users with settings and parameters. Our target audience are mostly novice animators and thus an effort should be made to investigate default settings that can cover most of the situations.

An interface for authoring cutaway visualization in combination with these synthesized illustrative animations has also not been discussed in this dissertation. It is, in fact, a general open research issue regarding creating complex animated sequences of cutaway visualizations. Our cutaway visualizations do support animated viewpoints, we applied this for the design principle number five (take advantage of motion parallax depth cue), but our prototype encourages interactive exploration and contains less support for sequence authoring beyond the basic rotation animations found in most cutaway visualization works. Thus, there is a need to investigate an authoring interface for specifying complex cutaway animations and dynamic parameter adjustments.

If combined with the synthesized illustrative 3D models of Section 4.1, we could address a shortcoming of our cutaway visualization; the visualization could benefit from illustrative layer texturing. In addition, our cutaway visualizations do not presently utilize the faults that may exist in geological models. Visualizing faults as focus objects of a cutaway visualization could provide insight about the relationship between the faults and the geological layer context. Another exiting research topic would be to combine the cutaway geometry with faults existing in the model, such that the faults that are close to the cutaway are included as part of the cutaway geometry. This would provide an even stronger spatial understanding of the location of the cutaway and would relate the focus features to the faults. If rendered with an illustrative, texture based rendering model, it would be possible to separate the parts of the cut-walls that follow fault-planes from the regular cut-walls, by rendering the former in a rough and bumpy style, while rendering the latter in a clean and smooth style.

5.2.4   Storytelling

Kosara and Mackinlay [40] outline many interesting research directions for visualization and storytelling. However, when discussing storytelling and collaboration, they claim that there is no point in creating storytelling if there is no audience. However, as has been shown in this dissertation, creating stories during the individual part of problem solving can also be beneficial. This approach can "force" the researcher to maintain a holistic view of the problem. Further, presenting a solution is an efficient method to verify that one indeed has understood the problem at hand, even if the presentation is only to oneself. The author of this dissertation is convinced that, at least for evolutionary processes, storytelling can be beneficial to the exploration of data and not

only as a presentation technique. In a way, this is storytelling to an audience, although the audience in this case is oneself.

In addition, no work in visualization, including this dissertation, has considered some of the most characteristic aspects of storytelling, such as plot, characters, drama, suspense, non-linear time, etc. It is not intuitive to see where suspense and drama would fit when the task is to locate petroleum. However, as a means for communication, these storytelling aspects should be investigated more than they have been so far. One question that needs to be answered is whether dramatization will be accepted as a means for understanding a problem better or that its close association with fiction will hurt the creditability of the visualization. This creditability problem is constantly dealt with in narrative journalism, the storytelling style of journalism. Nevertheless, expressing evolutionary processes as a story, as proposed in this dissertation, opens up for the research and experimentation on these kinds of ideas.

Part II

Scientific Results

PAPER A

GEOLOGICAL STORYTELLING - GRAPHICALLY EXPLORING AND COMMUNICATING GEOLOGICAL SKETCHES

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Abstract

Developing structural geological models from exploratory subsea imaging is difficult and an ill-posed process. Therefore, in practice several experts generate a larger number of geological interpretations. This leads to the situation that a number of geological sketches are prepared and examined for the next steps in the oil and gas exploration pipeline. In this paper, we present Geological Storytelling, a novel graphical approach for performing rapid and expressive geomodeling of a multitude of model variations. The solution builds on a flip-over metaphor for sketching the individual steps in a story that externalizes the mental steps the modeler performs when developing the model. The stories, through the discrete story steps, are then visualized in a Story Tree for easy access and management. This tree also provides the interface for individual story playback and examination, or comparative visualization of several stories. With our approach, the experts can rapidly sketch geological stories that both visualize the proposed model of today's geology and visualize how the expert derived this model. Presenting the model as a visual story helps the peers to evaluate the geological soundness of the model. We have developed geological storytelling in collaboration with domain experts that work with such challenges on a daily basis. Our focus of this work has been on models derived from single

seismic slices. We have implemented a prototype of Geological Storytelling to demonstrate our concept and to get domain expert feedback.

A.1   Introduction

The early stages of geological exploration in a new area are typically characterized by having little or no ground-truth data, but maybe a few, spatially limited 2D seismic slices. Still, an approximate geological model is needed to make the decision whether this can be an area worth further investigation. The structural geological models made at this point are thus just as much influenced by the experience and prior knowledge of the domain expert as by the measured data. This typically leads to subjective geological models, as shown by the experiment conducted by Bond et al. [5]. They documented that given a geologically sound, but artificial, 2D seismic slice, geological experts produced highly different geological interpretations. This human-biased, *conceptual uncertainty* tells us that many geological models, made by multiple experts, should be explored to identify the models with the highest probability.

It is time-consuming to build these early-stage models with the computer tools the geologists have today, and they require more details than is directly supported by the data. Simpler, more general-purpose computer tools are usually not expressive enough to capture the model correctly. Even more challenging is it to evaluate a model after it is made, since much of the foundation for the model is based on information and ideas in the mind of the geologist who constructed it. Domain experts state that for these reasons too few models are created and analyzed.

In collaboration with two domain experts, we have made an analysis of these problems and derived a set of requirements that a solution must fulfill. These domain experts are geologists holding PhD degrees with more than 4 years of experiences facing these challenges on a daily basis. The problem we solved in this work is two-fold. First, the experts must be able to rapidly create a set of geological models in digital form, and second, we must provide the experts with a way to evaluate the geological soundness of these models and to identify the most probable ones. The solution we present here is *Geological Storytelling*, a novel graphical approach for capturing and visualizing the reasoning process that leads up to the geological model. We utilize a flip-over metaphor, resembling pen-and-paper drawing where sketching the individual steps in a story externalizes the mental steps that the modeler goes through to develop the model. The different stories, through the discrete story key-frames, are then visualized in a Story Tree for easy access and management. This tree also provides the interface for individual story playback and examination, or comparative visualization of several stories. With our approach, the expert can rapidly sketch geological stories that both visualize the proposed model of today's geology and also visualize how the expert derived this model. Presenting the model as a visual story helps the peers to evaluate the geological soundness of the model. In this work we focus on models created from individual 2D seismic slices, see an example in Figure 1.

To summarize, our main contributions presented in this paper are:

▷ a sketch-based interface for rapid modeling and exploration of various geological scenarios.

▷ a concept that handles sketching processed over time.

▷ a novel approach for externalizing the mental reasoning process and enable this process to be presented and evaluated.

A.2   Related Work

Throughout history, storytelling has been an efficient way of conveying information. Recently, the visualization research community has shown examples of how applying aspects of storytelling to visualization of data can enhance the understanding, for instance in information visualization [28] and scientific visualization [50]. Wohlfart and Hauser [85] presented the first work on applying storytelling aspects to scientific visualization. They observed that visualization for the purpose of presentation and communication has to be both comprehensible and reliable. They propose that in addition to presenting the final visualizations, a story of how these visualizations were made, containing animating camera viewpoint changes and transfer function adjustments, improves on these challenges. Even though their application was on interactive volume visualization, we were inspired by the story telling aspects they present when we created Geological Storytelling.

A central aspect of Geological Storytelling is the management of a potentially larger number of alternatives and the relations between them. In related work, Jankun-Kelly and Ma have described visualization spreadsheets [36] which support the management of 2D sets of varied visualizations, e.g., the Cartesian product of a few transfer function variations vs. a few viewpoint variations. Marks et al. described design galleries which are based on the idea of first producing a larger amount of variants and then bringing them up in an organized visualization in order to help the user to find a preferred solution [52]. Both solutions automatically produce a multitude of alternatives, which then are managed, but the alternatives are not related to each other like in a story.

Design support systems also deal with the externalization of ideas, exploring alternatives and rapid prototyping. This is especially the case during the early stages of the design process when the designer explores a range of solutions [33]. Hoeben and Stappers [33] proposes a page based, digital sketchbook without logic for interpreting the sketches. Preliminary results indicate that such a digital sketchbook improves the amount of sketches the designer produces. Nakakoji [56] and Johnson et al. [38] present other tools for sketch-based prototyping, such as the ART019 work by Yamamoto [86] or "The Electronic Cocktail Napkin" by Gross and Yi-Luen Do [31]. These systems all focus on the sketching process to externalize a design idea. However, none of the systems focus on the externalization of the reasoning behind the sketches, nor focus on arranging or comparing them. This limits their application on the problem we are solving.

In the recent work on the World Lines framework by Wasser et al. [83] the authors present an interactive visualization of exploring alternative scenarios for improved decision making. However, World Lines is concerned with simulation steering and producing alternatives through input parameter adjusting. It is not externalizing any thought process that is behind these parameter adjustments, which is the essential target use in our case. The VisTrails approach [71] presented by Silva et al., uses provenance as a
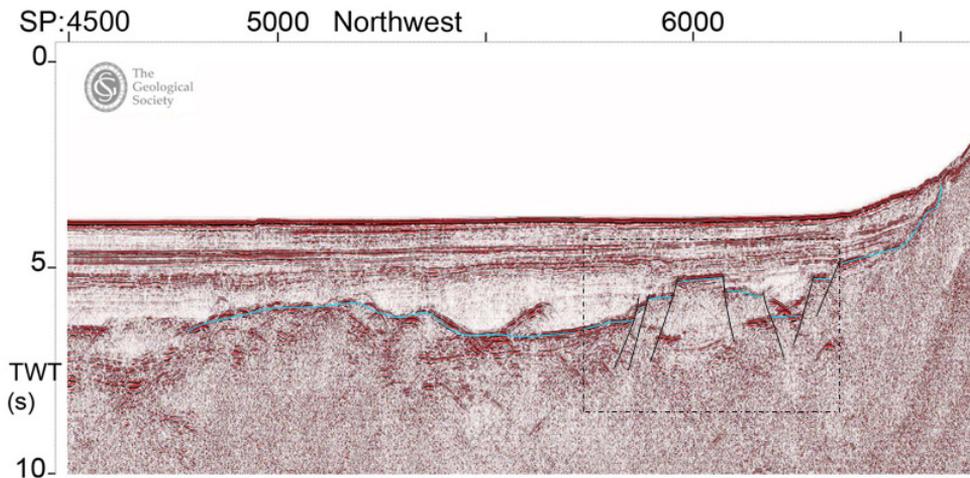
Figure 1: An example of a 2D seismic slice with an interpretative sketch. Such an interpretation is the starting point for an early-stage geological model. The example was made in Microsoft PowerPoint by one of our collaborating geologists. The seismic slice is called "WESTLINE shotpoints 4500-8500" and it is public available through the Virtual Seismic Atlas [72]. We use this seismic slice as an example throughout this paper.

way of capturing the process leading up to a specific data visualization. Kreuseler et al. have also proposed a history mechanism which gives access to provenance information with respect to the creation of a visualization [41]. However, none of these systems are handling artifacts created outside of the data.

A large part of research and development on geological modeling is done by commercial software vendors. The results of this research is typically not publicly available, as it is considered to be intellectual property and treated as trade secrets. Patel et al. [63] made an important contribution related to the interpretation and illustrative visualization of seismic data. Capturing of knowledge has been discussed in earth science academia, for instance in the work of Turner [77], but we are not aware of any publications that discuss the externalization of the reasoning process in the light of early geological modeling. An introduction to workflows in oil and gas exploration can for instance be found in [18].

A.3   Background and Solution Requirements

In this work, we target the geological sketches produced during the first steps in the exploration pipeline of discovering natural resources, such as oil and gas. Collecting high quality, dense 3D seismic data and drilling test wells for collecting ground truth data is very expensive, especially offshore. Thus, the data available for an unexplored area is limited, often there exists no ground truth data and only spatially sparse 2D seismic data. It is up to the geologists, often under heavy time constraints, to create
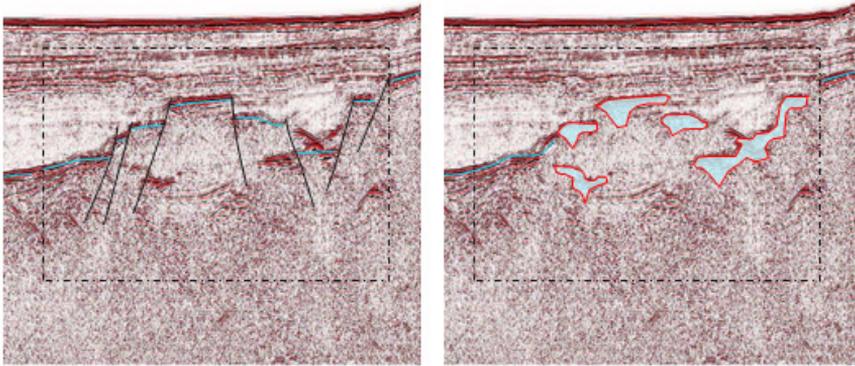
Figure 2: Close-up images of two very different interpretations from the exact same position on the seismic slice. These interpretations will result in two very different geological models. Also made in Microsoft PowerPoint by one of our collaborating geologists.

rough, early geological interpretations to evaluate the possibilities of oil and gas. A 2D seismic slice is shown in Figure 1. Figure 2 shows close-up views of two possible seismic interpretations of this seismic slice. The seismic interpretations form the basis of the geological model.

The oil companies are only willing to spend resources to collect dense, 3D seismic data and drill test wells to map the subsurface in details, if the early geological models indicate possibilities of oil and gas. At this point, other geoscience experts, such as additional geologists, geophysicists, reservoir engineers, and drilling engineers, will become involved in the mapping process. The geologists creating the early models are typically not participating, as they have moved on to model other new, unexplored geographical areas.

As stated in Section A.1, the problem that the geologists are facing is two-fold. First, how can they create many model alternatives within their time limits. Second, how can they communicate and evaluate the geological soundness of these alternatives and select the most plausible ones.

Domain specific modeling software packages, such as Petrel [69], focus on producing high detail models found in the later stages of the exploration pipeline. Applying them when creating the early models takes much time and they are more complicated than is required. Some geologists use pen and paper for sketching their models. Pen and paper use is very expressive and usually quick as well. It is, however, often a challenge to discuss the paper sketches, especially in remote collaboration meetings. In addition, paper sketches are often very large and complicated to scan and archive. The knowledge captured is therefore not accessible. Others geologists are using presentation software, such as Microsoft PowerPoint. Although these tools are suited for presentations, they have very limited drawing capabilities. Expressing a geological sketch in PowerPoint is difficult. General purpose drawing programs, like CorelDRAW [17] are positioned somewhere in-between, more expressive than PowerPoint, but they require more time than pen and paper, and it is difficult to edit the models in work meetings.

#	Requirement
1	Time is limited, so creating the models must be fast and intuitive.
2	Creating models is a creative process, therefore expressiveness should not be limited.
3	The reasoning behind the interpretation must be captured and communicated, in addition to the final proposal.
4	The representation of the model, together with the reasoning, must be in a form so that knowledge can be captured in the organization.
5	The representation must support evaluation of the geological soundness of the interpretation.
6	The representation must support comparison of different geological models to qualitatively rank these according to probability.

Table 1: The table shows the requirements that a solution for improving early-stage geological modeling has to meet. We have identified them based on interviews with geologists who specialize on early-stage geological modeling.

During our discussions with the geologists we uncovered that the model sketches they produce do not capture the mental reasoning behind the interpretation. Without oral explanations from the modeler it is often difficult for another geologist to validate a model. Thus, a key requirement is to capture more information in the produced artifacts. We have derived a set of requirements that need to be fulfilled to solve this problem. The requirements are shown in Table 1 and they are based on our interviews with the two early interpretation specialists.

A.3.1   The Core Idea - Geological Storytelling

Regarding the Requirement 1 and 2 in Table 1: the geologist wants a solution that is as expressive and easy to use as pen and paper, but without the drawbacks. Regarding the Requirement 3, capturing the reasoning behind a model, the question is how much capturing is enough. Clearly, the single image captures too little information, while full detailed 4D models from the geology domain software take unacceptably much time.

One of the important principles in geology, *uniformitarianism*, states that the processes that have been shaping the geology in the past are the same that are observable also today. These processes are referred to as geological events, and they are events such as sediment depositions, folding, intrusion and faulting. Further, the present geology in an area is the result of the geological events that have happened until now. The geologists think in these geological event steps when they produce their geological-interpretation sketches.

The core idea of the solution we propose is then: We provide the geologists with the possibility of capturing, using sketches, the reasoning behind their models by enabling them to externalize the geological event-steps they had in their mind when creating the model. A time series of consecutive geological events is what we call a *geological*
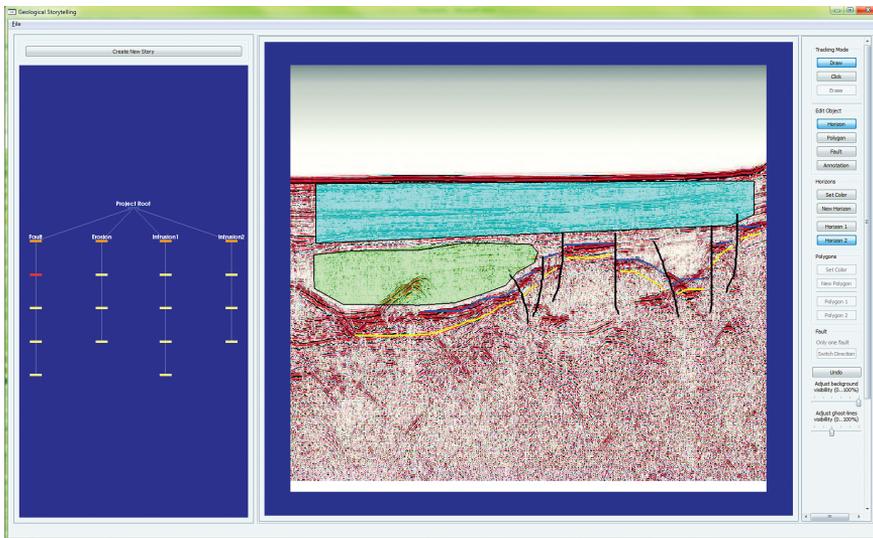
Figure 3: The main window of our geological storytelling prototype. To the left is the StoryTree depicting alternative stories. In the middle is the canvas sheet where story nodes can be sketched. The canvas is a virtual flip-over, providing unlimited number of sheets.

story. We call the individual geological events in story for *story nodes*, similar to the terminology used by Wohlfart and Hauser [85]. We also provide management of the story and its story nodes, together with playback and comparison views. In this way we give the geologists a graphical representation of reasonings made about the geological events they think have happened. Creating, playing and comparing these reasoning processes are what we denote as *geological storytelling*.

A.4   Telling Geological Stories

Our concept of geological storytelling consists of three main components:

The Canvas is the sketching interface where the geologist can sketch the geological story on a 2D seismic slice backdrop, utilizing a pen and paper interaction style. We advocate a flip-over metaphor for indicating a new story node, as this is a method well known to sketch book users.

The StoryTree is a tree graph representation of all the geological stories, each with its own subtree of story nodes. Individual story nodes can be selected for editing in the canvas. One or more complete story trees can be selected for playback or comparative visualization in the inspect view.

The InspectView serves two purposes. First, it is a view where a story can be played and evaluated. In addition, multiple stories can be played synchronized for a side-by-side visual comparison.
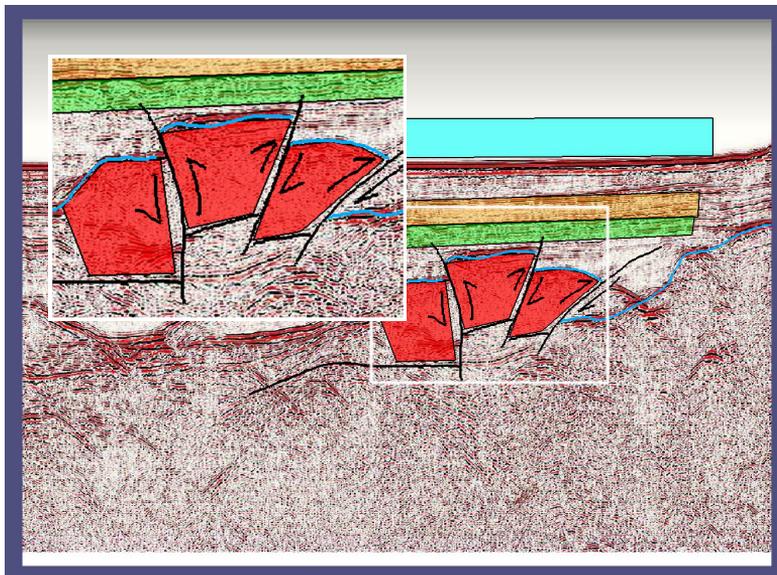
Figure 4: A screen shot showing examples of all the drawing primitives available in our prototype.

In the rest of this section, we describe how to create, manage and visually evaluate the geological stories. Figure 3 and Figure 8 show screen shots of the main windows of our geological storytelling prototype.

A.4.1   Authoring Geological Stories

Inspired by the pen and paper interaction style, we propose a canvas where the geologist can draw the geological story. Each story node is drawn on a separate *canvas sheet*. It is possible to use the data from a seismic slice as a canvas backdrop. The geologist has specified the need for the following drawing primitives:

▷ **Horizon Lines** for drawing the horizons marking the border between the different geological layers.

▷ **Vertical Fault Lines** for drawing faults systems.

▷ **Polygons** for highlighting layers between horizons, to indicate sea-level, and to draw intrusive objects.

▷ **Arrows** for indicating directions of movement, for instance the direction of erosion or the direction of intrusion.

▷ **Annotations** for adding labels and highlighting important areas of the seismic section.

Examples of how geologists apply these drawing primitives can be seen in the handmade sketches in Figures 9, 10, and 11. Figure 4 shows a screen shot from our prototype where we have made an example interpretation illustrating all the available draw-
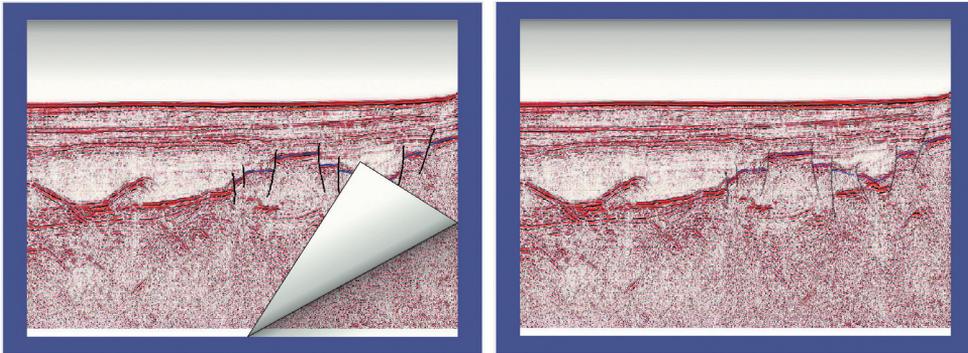
Figure 5: Left: When the geologist has completed a story node she flips over the canvas to get a new sheet for the next story node. *Right:* To aid the author, the sketches from the previous story node is visible as faint, ghost lines on the new story item canvas.

ing primitives. Horizon lines and polygons can be rendered in arbitrary color and opacity. The fault lines are always drawn in opaque black color, as is the common domain practice.

The prototype supports both continuous drawing, and point-and-click drawing. Continuous drawing is best suited for accurate sketching, while point-and-click drawing is best for drawing longer straight lines and for drawing the polygons. It is important for the geologist that the lines are rendered exactly where they were drawn, thus there is no smoothing or subsampling of the points collected during continuous drawing. Drawing the stories can be done with the mouse input device, but a closer feeling of pen and paper can be achieved using a pen display input devices, such as the Wacom Cintiq 21UX [81]. If mistakes are made, the user can simply delete the drawn primitive and start over.

Once the geologist has finished drawing a story node into the canvas, she can flip the page by clicking in one of the bottom corners of the canvas. This provides the geologist with a new canvas sheet, for sketching the next story node. There are usually strong correlations between the sketches on two consecutive story item nodes, as many of the geological objects are the same or slightly modified. Therefore, to aid the geologist the sketches from the previous story node are visible as faint, ghost lines on the new canvas. Figure 5 shows the metaphor of flipping the canvas and the ghost lines. This can also been seen in our supplementary video. The user can adjust the visibility of the ghost lines. The visibility of the backdrop seismic image in the canvas can be adjusted individually for each canvas sheet. The way of sketching the story by starting with interpreting today's seismic and then sketch story nodes backwards in geological time is motivated by the feedback from our collaborating geologists.

A.4.2 The StoryTree

The StoryTree is the structure where all the geological stories are stored. Each story has its own subtree where all the story nodes of that story are laid out in order. Typically, the order of the story nodes are in descending geological time, but this is up to the geologist to decide. The only constraint put on the tree is that when a canvas sheet is
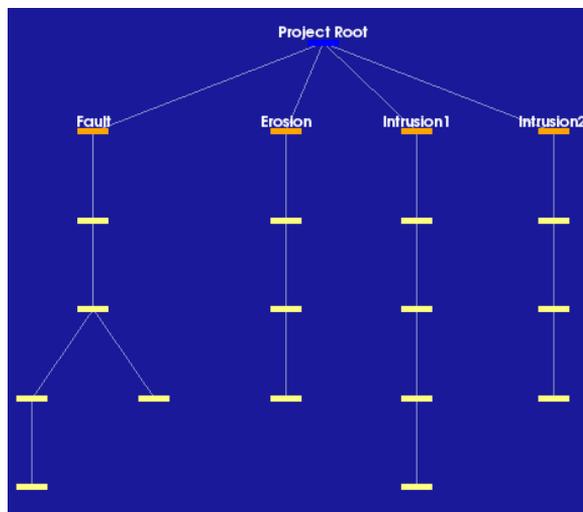
Figure 6: The StoryTree with four stories of different story length and with branches. A branch indicates that different geological event-trails may lead up to the same, later story node.

flipped over to create a new story node, then this new node is inserted as a child node of the story node that was in the canvas before the flipping. Thus, the canvas view and the StoryTree are linked.

If the parent of the new story node is not a leaf node, then the new node will become sibling of the existing nodes. Siblings symbolize in this case a merge in the geological story. One example could be that two different story paths can lead to the same, more recent in geological time, story node. Figure 6 shows a StoryTree populated with four different geological stories. The blue project node serves as a common root node for all the story subtrees and relates to seismic imaging of today's geology. The orange nodes are the story root nodes, and the yellow nodes below are the individual story nodes belonging to this node. As one can see from Figure 6, the first story, "Fault" is a multi-path story, while the stories "Erosion", "Intrusion 1" and "Intrusion 2" are single path stories.

If a story node in the StoryTree is activated, then this story node is displayed in the canvas. This is the second purpose of the StoryTree, i.e., to navigate to a specific story node for review or updates. The third purpose of the StoryTree is to select one or more geological stories, to perform playback or comparison in the InspectView. Nodes in the tree can be selected either individually or as a group. The InspectView is activated through a context menu in the StoryView window.

The StoryTree is initialized with one story and one story node, the latter is the node that represents the empty story sheet visible in the canvas at startup. New stories are created by pressing the push button above the StoryTree. The new story is added as a story root node under the project node. This button approach was selected because we did not want to overload the flip over metaphor with multiple meanings. Thus, the flipping metaphor in the canvas is reserved for new story nodes, which we also find most intuitive.
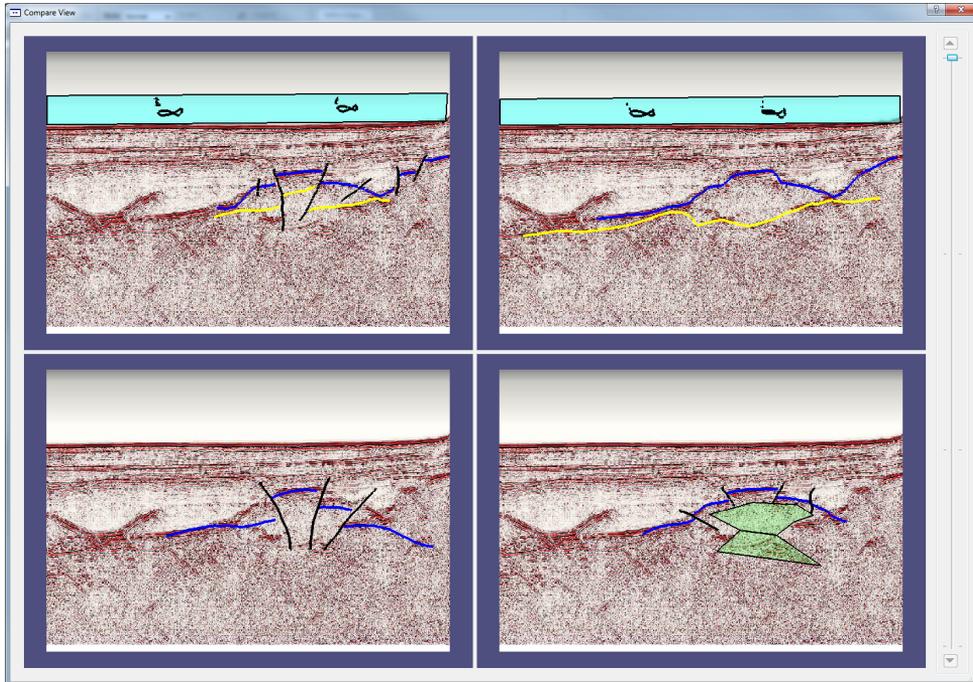
Figure 7: A screen shot of the InspectView comparing four distinct geological stories. All the views are synchronized with the time step slicer on the left hand side. In this view the geologist can visually compare, side-by-side, different geological stories to find the most plausible ones.

A.4.3 Evaluating Geological Stories

The InspectView is our proposed solution to the requirements presented in Section A.3 concerning evaluating geological soundness in models and comparing the geological sketches to identify the most plausible ones. This is done by providing a view where the geological stories can be interactively played.

The InspectView is configured based on the selections made in the StoryTree. If a story branch, or part of a story branch, is selected then all the canvas sheets for this story are rendered in the InspectView. The story can then be played, in chronological order, using a time line slider. The InspectView playing back a single story is shown in Figure 8.

If nodes from more than one story branch are selected in the StoryTree view, then InspectView is showing a side-by-side comparison of these stories. In this configuration, all the views are synchronized with the time line slider, so all views change canvas sheet simultaneously. Figure 7 shows the comparison of 4 geological stories in the compare view.

The InspectView opens as a separate window in our prototype. We chose this configuration because it makes it easier to support a dual screen setup, i.e., having the story authoring and management on one screen and the inspection view on the other screen.
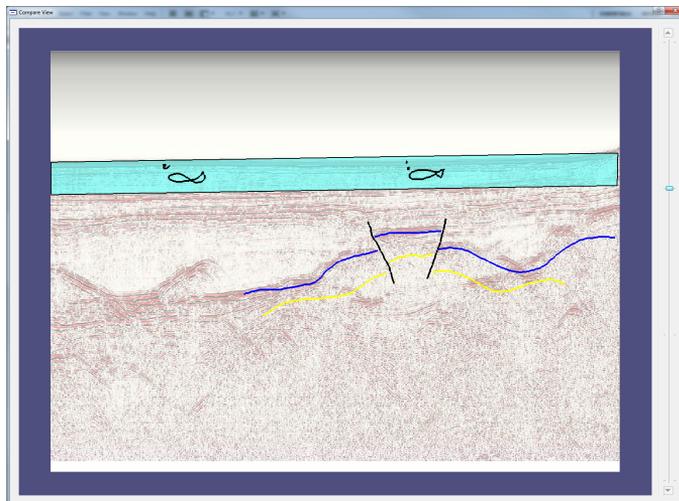
Figure 8: A screen shot of the InspectView playing a single geological story. From the time line slider to the right we see that the view now shows story node number two of a total of four story nodes. In this view the geologists can visually evaluate the geological soundness of the sketch.

A.4.4   Implementation Details

The prototype was implemented in C++ as a plug-in to an application framework for hypotheses exploration that we are currently developing. The graphical user interface is implemented using Qt. The StoryTree is implemented using VTK. We have extended the default VTK interactor styles with our own interactor style. The canvas and the canvas contents are rendered using OpenGL.

A.5   Results

It is challenging to conduct a full case study of geological storytelling directly in the work processes of our collaborating partners. The industry they represent is a highly competitive field, so they want to keep geological interpretation sketches and seismic data secret. Instead, we have performed the evaluation in two parts. First, we got our collaborative geologists to draw three example geological stories on paper. This was performed on a publicly available seismic slice, from the Virtual Seismic Atlas [72]. Note that the stories are only examples and not necessary reflecting geological correct interpretations of the seismic. Our argument is that hand drawn stories represent the level how expressive the geologist wants the story sketching to be. If we can reproduce them in our system we get a verification that the expressiveness is on par with what is expected. Figure 11 shows a complete story of one of these stories that was drawn. The story shows a fault model where sedimentary deposits has happened after the faulting. Figure 11 also shows the same story reconstructed in our prototype. We reproduced the two other geological stories too, and selected story nodes are shown in Figure 9 for an erosive model, and in Figure 10 for an intrusive model. The images show that the pen-and-paper made Geological Stories can be reproduced successfully in our system.
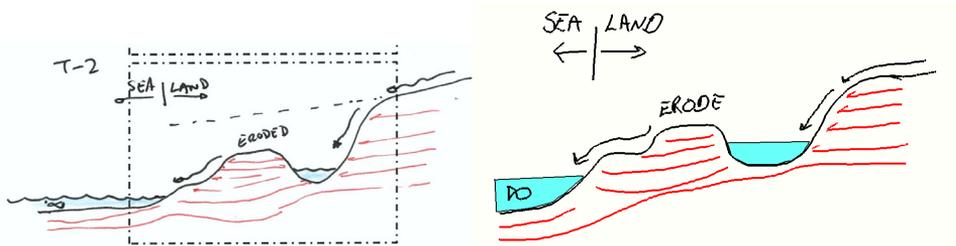
*Figure 9:* To the left: A hand drawn sketch showing one story node from a longer story about an erosive geological model. It was made by one of our collaborating geologists. To the right: The same story node, but this time reproduced in our geological storytelling prototype.
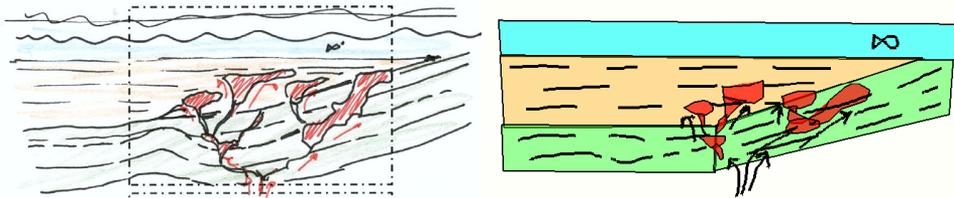
Figure 10: To the left: A hand drawn sketch showing one story node from a longer story about an intrusive geological model, also made by one of our collaborating geologists. To the right: The same story node, but this time reproduced in our geological storytelling prototype.

Secondly and more importantly, we also conducted meetings with several domain-experts to collect expert evaluations. In these meetings we presented the concept of Geological Storytelling and demonstrated our implementation to these experts, which have not been involved in the development. In one meeting we presented geological storytelling to a professor of Earth Sciences at our university, who also has many years of experience from the oil industry. His initial feedback was that he found geological storytelling useful. He described a relevant scenario where two geologists may agree on the interpretation of the seismic image, but they have quite different understanding of the geological scenario that has produced this seismic image, i.e., their geological interpretation differs. Geological storytelling will help them performing geological reasoning about their models and discuss the differences. He further said that geological storytelling also could be very powerful for presentations of geological models to management and decision makers.

We have also had meetings with a group of domain experts involved in early exploration operations from a world-leading oil company. These experts were three geologists with 8–15 years experience, one geophysicist with 20+ years experience, and two visualization experts with 10 and 20+ years experience. They found that Geological Storytelling is a good solution to the problem at hand and that it has not been seen in other software solutions. It strongly resembles hand-drawings on paper, a method they often use when they want to explain their interpretations. The concept of thinking in "complete" geological storylines is not how all geologists do their interpretations. However, a tool based on our concept can encourage all the geologists to make better
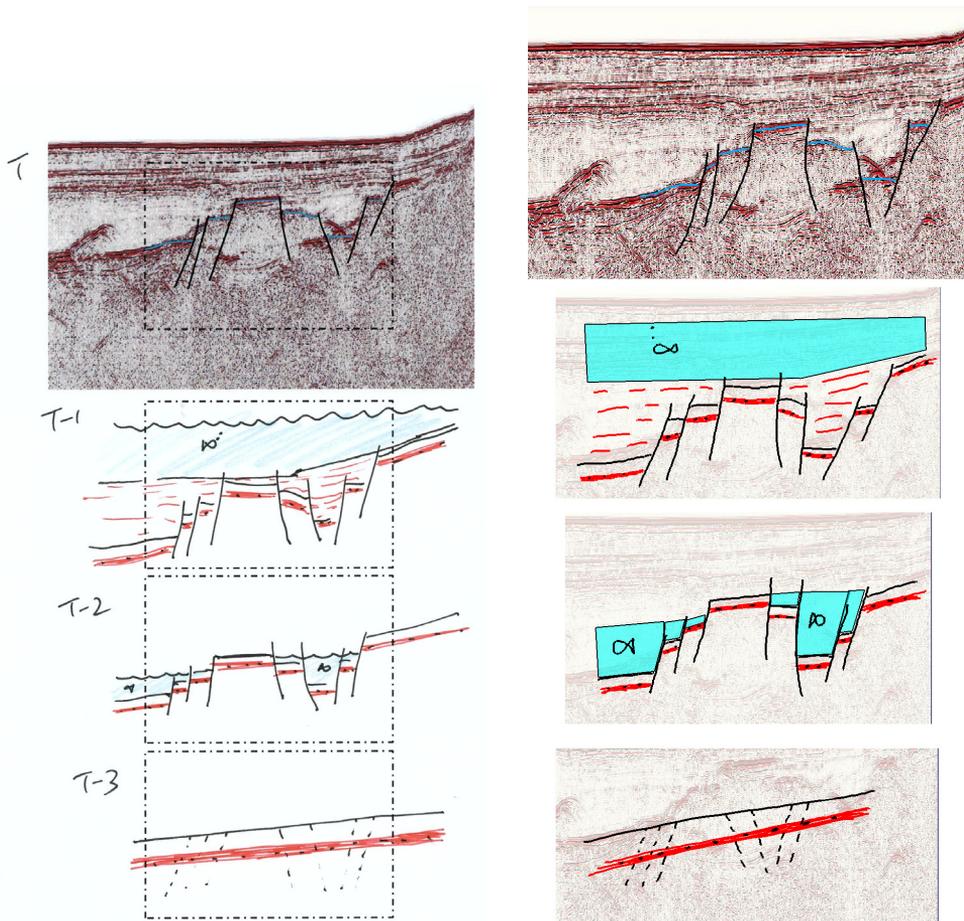
Figure 11: The hand drawn sketch to the left was made by one of our collaborative geologists after we explained our concept of a geological story. It shows an imagined geological story of the seismic slice shown in the top of the figure (Today). This particular story shows how a fault system has evolved from a non-fault stage (T_{-3}) through several events of faulting and sedimentary deposits (T_{-2} and T_{-1}). To the right, this geological story is authored in our storytelling prototype. We see that these two visualizations look similar and tell the same geological story.

geological reasonings, and thus produce better interpretations. They further added that geological storytelling also can be useful for communication upwards in the organization, i.e., to decision makers, mainly because it will be possible to create several stories to present. As a final remark, the geologists agreed that geological storytelling can be useful outside early exploration operations, e.g., it can also be applied in production, to quickly sketch up models/geological ideas in more known areas. The experts also provided suggestions for future developments. These are all related to turning our implementation into a production tool, such as support for specific seismic file formats, exporting the stories to file formats compatible with other petroleum software tools, and copy/paste functionality for the sketched objects.

Regarding scalability, our collaborating geological experts anticipate that there can be up to 10 geological stories for each 2D seismic slice. The rendering and storage of these geological stories only requires little computational resources compared to the graphical capabilities and storage available in today's computers.

The geological storytelling concept and our prototype tool can, with a little engineering work, easily be integrated into the software tool-chain in the oil companies. As one example, tools such as Decision Space Desktop [32] can co-visualize GIF-animation images together with the geoscience data types, so the most probable geological story could be exported to this format and co-visualized directly on the seismic slice.

Please also see more results in our supplementary video demonstrating how to create, play and compare geological stories.

A.6   Limitations

One limitation of Geological Storytelling is that there are no geological semantics build into the sketching of the geological stories – the lines, polygons and arrows drawn on the story node sheets do not have any geological semantics outside of which the user brings in. This is due to a trade-off between semantic objects, that have to be restricted to a finite set, and the full expressiveness which is possible with our free-hand sketching. Even though there can be many different hypotheses behind a seismic interpretation, there is little semantic ambiguity concerning the geological sketches.

A.7   Summary and Future Work

In this paper we have presented Geological Storytelling, an interactive visual approach for constructing and evaluating early geological sketches. We have done an analysis of associated challenges. Our observation is that too little information about the reasoning behind the geological models is captured in the model artifacts, which are currently state of the art, especially since the time limits for modeling are so tight. From interviews with geologists that construct these early geological models we have derived a set of requirements which solutions must satisfy (see Table 1).

Geological storytelling fulfills these requirements by enabling the geologists to externalize their geological reasoning into geological stories through rapid sketching on a virtual canvas. The set of such alternative stories are arranged in a tree representation

for easy access and analysis. Each geological story is the root of a subtree containing all the related story parts. Stories selected in the tree can be played in an inspection view, to be visually evaluated and compared by the peer experts.

In the future, we would like to continue developing the concept of Geological Storytelling. We already have some ideas of how we can enhance the sketches the geologists make with knowledge from perceptual science, and ways of expressing 3D geological sketches into geological stories. Especially interesting is to extend the comparison of the different geological stories. This poses a challenging problem. In contrast to works such as by Bruckner et al. [9], where they used scaled down images of the multiple views when exploring the parameter spaces of computer generated visual effects, our geological stories cannot merely be shrunk. Instead, we hope to develop an abstract representation of the whole story.

Acknowledgments

PAPER B

GEOLOGICAL STORYTELLING

B

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Abstract

Developing structural geological models from exploratory subsea imaging is difficult and an ill-posed process. The structural geological processes that take place in the subsurface are both complex and time-dependent. We present *Geological Storytelling*, a novel graphical system for performing rapid and expressive geomodeling. Geologists can convey geological stories that externalize both their model and the reasoning process behind it through our simple, yet expressive sketch-based, flip-over canvases. This rapid modeling interface makes it easy to construct a large variety of geological stories, and our story tree concept facilitates easy management and the exploration of these alternatives. The stories are then animated and the geologists can examine and compare them to identify the most plausible models. Finally, the geological stories can be presented as illustrative animations of automatically synthesized 3D models, which efficiently communicate the complex geological evolution to non-experts and decision makers. *Geological storytelling* provides a complete pipeline from the ideas and knowledge in the mind of the geologist, through externalized artifacts specialized for discussion and knowledge dissemination among peer-experts, to automatically rendered illustrative 3D animations for communication to lay audience. We have developed geological storytelling in collaboration

with domain experts that work with the modeling challenges on a daily basis. For evaluation, we have developed a geological storytelling prototype and presented it to experts and academics from the geosciences. In their feedback, they acknowledge that the rapid and expressive sketching of stories can make them explore more alternatives and that the 3D illustrative animations assist in communicating their models.

B.1 Introduction

The early stage of geological exploration in a new location is typically characterized by having little or no ground-truth data, and perhaps a few, spatially limited 2D seismic sections. Still, an approximate geological model is needed to make the decision whether this location is worth further investigations. These early geological models are therefore just as much influenced by the experience and prior knowledge of the geologist, as by the measured data. This typically leads to subjective models, as shown by the experiment conducted by Bond et al. [5]. They documented that given a geologically sound, but artificial, 2D seismic section, geologists produced highly diverging geological interpretations. This human-biased *conceptual uncertainty* tells us that many geological models, for one location, made by several geologists, should be explored to identify the models with the highest probability.

Building these early-stage models with the computer tools the geologists have today, is very time-consuming, and these tools require more details than is directly supported by the data. General-purpose computer modeling tools are usually not able to represent the model correctly. It is also challenging to evaluate a model, since much of the foundation for the model is based on knowledge and ideas in the mind of the geologist who constructed it. Domain experts state that for these reasons too few models are created and analyzed.

We have made an analysis of these problems in collaboration with two domain experts. These domain experts are geologists, holding the PhD degree, with more than four years of experience with these challenges on a daily basis. The problem that these geologists face is threefold. First, they need computer tools to be able to rapidly construct varieties of alternative geological models, and secondly, they need a better way to evaluate the geological soundness of these models and to identify the most probable ones. Finally, they need to be able to communicate their models in such a way that they are comprehensible also by non-experts and decision makers.

The approach we present is *geological storytelling*, a novel graphical system for capturing and visualizing the reasoning process that leads up to the geological model, for exploring and comparing a set of such models, and for presenting and communicating the most probable ones. We utilize a flip-over metaphor, resembling pen-and-paper drawing, where sketching the individual steps in a story externalizes the mental steps of the modeler when developing a model. The different stories, represented by these discrete story steps, are then visualized in a story tree for easy access and management. This story tree also provides the interface for individual story playback and examination, or comparative visualization of several stories. By treating the story steps as key-frames, we can play back and compare the stories as an animation, thus providing more information to the viewer than through still images. The most promising geo-
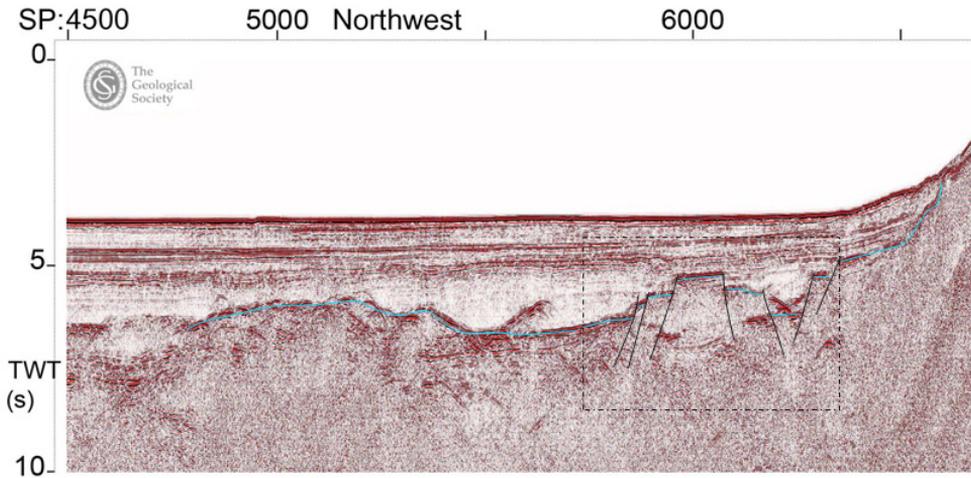
Figure 1: An example of a 2D seismic section showing a seismic profile. This section has been augmented with an interpretative sketch. Such an interpretation is the starting point for an early-stage geological model. One of our collaborating geologists made this example in Microsoft PowerPoint.

logical models can be automatically synthesized into 3D geometrical models and the complete story can be rendered as an illustrative animation, improving the communication towards decision makers and non-experts.

Our contribution is a novel system and a non-trivial integration of techniques from sketch-based modeling, computer animation, and geometric modeling. Its individual components are adapted existing and novel, tailor-made techniques. We justify the utility of the system in several target domain scenarios.

To summarize, the geological storytelling system provides a *complete pipeline* from the conceptual models and ideas in the geologist's mind, via externalized artifacts (the sketches) for alternative solutions exploration and discussions, to the synthesis of animation of 3D models for presentation and communication. This paper is an extended version of an Expressive 2012 SBIM paper by Lidal et al. [47].

B.2   Background and Requirements

The application focus of our work is the early stage of exploring a new location for discovery of natural resources, such as oil and gas. Collecting high quality, dense 3D seismic data and drilling test wells for collecting ground-truth data is very expensive, especially offshore. Before these large investments are made, a pre-screening is conducted. During this process, the data available for the location is limited, often consisting of only spatially sparse 2D seismic data. It is up to the geologists, typically under heavy time constraints, to create rough, early geological models to evaluate the possibilities of oil and gas. A 2D seismic section is shown in Figure 1. This seismic section is called "WESTLINE shotpoints 4500-8500" and it is publicly available through the
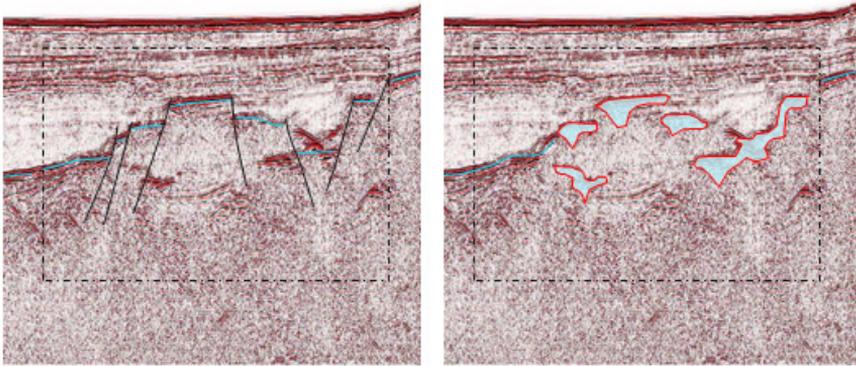
Figure 2:   Close-up images of two very different interpretations from the exactly same position on the seismic section. These interpretations will result in two very different geological models. These close-ups were also made in Microsoft PowerPoint by one of our collaborating geologists.

Virtual Seismic Atlas [72]. We use this seismic slice as a guiding example throughout the paper. Figure 2 shows close-up views of two possible seismic interpretations of this seismic section. Such interpretations often form the basis for geological models.

If the geological models indicate possibilities of oil and gas, and the company is willing to spend the resources needed for mapping out the subsurface in details, then other geoscience experts, such as additional geologists, geophysicists, reservoir engineers, and drilling engineers, will become involved. The geologists who created the early models will typically not participate, as they have moved on to pre-screen other unexplored locations.

Domain specific modeling software packages, such as Petrel [69], focus on producing detailed models based on data only existing in the later stages of the exploration pipeline. Applying such tools when creating the early models is time demanding and they are more complicated than is required. Some geologists use pen and paper for sketching their models. Pen and paper is very expressive and quick. It is however often a challenge to discuss the paper sketches, especially in remote collaboration meetings. In addition, paper sketches are often large and complicated to scan and archive. The knowledge captured is therefore not accessible. Others geologists are using presentation software, such as Microsoft PowerPoint. Although these tools are suited for presentations, they have very limited drawing capabilities. Expressing a geological sketch in PowerPoint is difficult. General purpose drawing programs, such as Corel-DRAW [17] are positioned somewhere in between, being more expressive than Power-Point, but requiring more time than pen and paper, and it is difficult to edit the models in work meetings.

During our discussions with the geologists, we uncovered that the model sketches they produce do not capture the mental reasoning behind the interpretation, only the interpretation itself. Without oral explanations from the modeler, it is often difficult for another geologist to validate a model. Thus, a key requirement is to capture more information in the produced artifacts. We have derived a set of requirements that needs to be fulfilled to solve their problem. The requirements are shown in Table 1 and they

#	Requirement
1	Time is limited, creating the models must be fast and intuitive
2	Creating models is a creative process, therefore expressiveness should not be limited
3	The reasoning behind the interpretation must be captured and communicated, in addition to the final proposal
4	The representation of the model, together with the reasoning, must be in a form so that knowledge can be captured in the organization
5	The representation must support evaluation of the geological soundness of the interpretation
6	The representation must support comparison of different geological models to qualitatively rank these according to probability

Table 1: The table shows the requirements that a solution for improving early-stage geological modeling should fulfill, identified them based on interviews with geologists who specialize on early-stage geological modeling.

are based on our interviews with the two specialists who we collaborate with.

B.3   Related Work

Geology is a visual science requiring substantial spatial reasoning skills from the geologists. Studies have shown that modern visual aids, such as interactive visualization, conveying terrain topography, and 3D geologic block visualizations, increase geospatial comprehension [66]. The first appearance of dedicated software for assisting spatial perception of geological structures for high-school students was Geo3D [39] that claimed credits for drastic improvement of students' performances in structural understanding.

A large part of research and development on methods for geological modeling is performed by commercial software vendors. The results of this research are typically not publicly available, as it is considered to be intellectual property and treated as trade secrets. Patel et al. [63] made an important contribution related to the interpretation and illustrative visualization of seismic data. Natali et al. [58] proposed a method of synthesizing 3D models from 2D sketching and our approach for presentation and communicating geological models adapts and extends their work. The steps in their 3D model synthesis which are relevant for our work are as follows. First, layers on a 2D plane are defined by 2D curves representing the borders between the layers. These curves correspond to the horizon lines described in this article. Then each layer is textured for communicating its rock type. The texture orientation, direction and deformation is specified by assigning texture coordinates on the borders of the layer. Texture coordinates for the layer interior are interpolated from the border values by performing an angle preserving (conformal) parameterization. Angle preservation is important as textures used in geology are symbolic and communicate different rock types. This avoids shearing, in which texture symbols might become unrecognizable and aesthetically disturbing. Their method also supports tiled textures. To express vertically displacements, a fault curve is defined. It partitions any intersecting layer into two, but at the same time

it maintains correct texturing along the cut. Finally a 3D layer cake model is created of this 2D cross section by extruding all curves into the screen plane.

Capturing of knowledge has been discussed in earth science research, for instance in the work of Turner [77], but we are not aware of any publications that discusses the externalization of the reasoning process in the light of early geological modeling. An introduction to workflows in oil and gas exploration can be found in referenced literature [18] and the book by Fossen [25] provides an introduction to structural geology.

Computer graphics research related to animation of geological structures has mostly been focusing on simulating the phenomenon of erosion [34, 42, 53, 74] or simulating natural phenomena occurring on the surface of the earth (e.g., [51]). Although these approaches are fully interactive and perform computation in real-time, they are of limited use, when communicating subsurface geological processes.

Visual-aid tools for science education, including the earth sciences, can be classified as static, animated, and interactive visualizations. Animation has been rated as a very effective visual form for communicating a process or the temporal development of certain structures [3]. Its main disadvantage was reported to be the time-consuming authoring phase and lack of dedicated tools for authoring science animations [46].

Systems that support the design process often deal with the externalization of ideas, exploring alternatives and rapid prototyping. Hoeben and Stappers [33] reports that this is especially the case during the early stages of the design process when the designer explores a range of solutions. They propose a page based, digital sketchbook without any support for interpreting the sketches. Preliminary results indicate that such a digital sketchbook improves the amount of sketches the designer produces. Nakakoji [56] and Johnson et al. [38] present other tools for sketch-based prototyping, such as the ART019 work by Yamamoto [86] or "The Electronic Cocktail Napkin" by Gross and Yi-Luen Do [31]. The focus of all these systems is on the sketching process to externalize a design idea. They show that sketch-based modeling facilitates the production of many alternatives, however, none of the systems focus on the externalization of the reasoning behind the sketches, nor on arranging or comparing them. This limits their applicability for the problem we are solving.

The management of a potentially larger number of alternatives and the relations between them are one part of the problem we want to solve. Jankun-Kelly and Ma [36] describe visualization spreadsheets which support the management of 2D sets of varied visualizations, e.g., the Cartesian product between transfer function candidates and viewpoint candidates. Marks et al. [52] describe design galleries that are based on the idea of first producing a large amount of variants and then bringing them up in an organized visualization in order to help the user to find a preferred solution. Both solutions automatically produce a multitude of alternatives, which then are managed, but there is no support for alternatives that relates to each other.

In the work on the World Lines by Waser et al. [83] the authors present an interactive visualization of exploring alternative scenarios for improved decision making. The work of World Lines is concerned with simulation steering and producing alternatives through adjusting the input parameters. It is not externalizing the thought-process behind these parameter adjustments, which is the essential target use in our case. The VisTrails approach [71] presented by Silva et al., utilizes provenance as a way of capturing the process leading up to a specific data visualization. Kreuseler et al. [41] have also proposed a history mechanism that gives access to provenance information with

The Geological Storytelling System
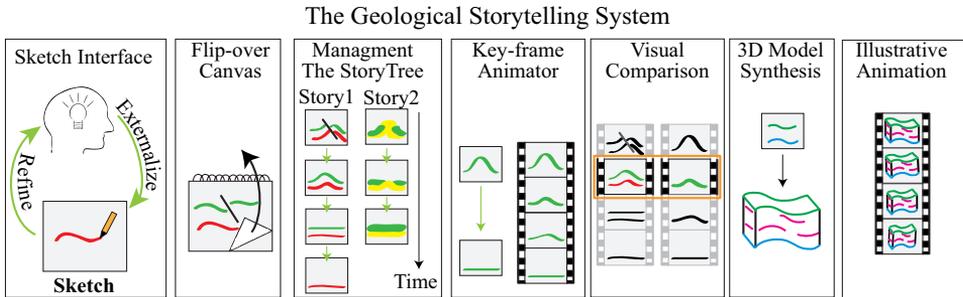
Figure 3: The components of the geological storytelling system are (from left to right): The *sketching interface*, where the geologist rapidly creates the sketches; the *flip-over canvas*, where the reasoning step is sketched as a set of story nodes; the *story tree* where the story nodes are arranged into complete stories; the *key-frame animator*, which turns the story node sketches into 2D animations; the *visual comparison*, where the animations are compared to identify the most plausible geological model; the *3D model synthesis*, which turns the sketches into 3D models; and the *illustrative animation*, an efficient way of communication the model to decision-makers and non-experts.

respect to the creation of a visualization. However, none of these systems can handle artifacts that are created outside of the data.

Throughout the history, storytelling has been an efficient way of conveying information. Recently, the visualization research community has shown examples of how applying aspects of storytelling to visualization of data can enhance the understanding, for instance in information visualization [28] and scientific visualization [50]. Wohlfart and Hauser [85] presented the first work on applying storytelling aspects to scientific visualization. They observed that visualization for the purpose of presentation and communication has to be both comprehensible and reliable. They propose that in addition to presenting the final visualizations, a story of how these visualizations were made, containing animated camera viewpoint changes and transfer function adjustments, improves on these challenges. Even though their application focused on interactive volume visualization, we were inspired by the story telling aspects they present.

B.4   The Geological Storytelling System

We have derived our geological storytelling system by analyzing each of the requirements presented in Table 1. The requirements 1 and 2 state a need for a fast and intuitive, yet at the same time expressive, modeling technique. As we discussed in Section B.3, a sketch-based interface is a well-justified choice to these kinds of requirements. Regarding capturing the reasoning behind a model (requirement 3), the question is how much capturing is sufficient. A single image captures too little information, while creating detailed 3D models through the domain software takes too much time. To identify the correct level of capturing, we looked at one of the important principles in geology, *uniformitarianism*. This principle states that the processes that have been shaping the geology in the past are the same that are observable today. These processes are referred to as geological events, and examples are sediment depositions, erosion, folding, intrusion, and faulting. Further, the present geology in an
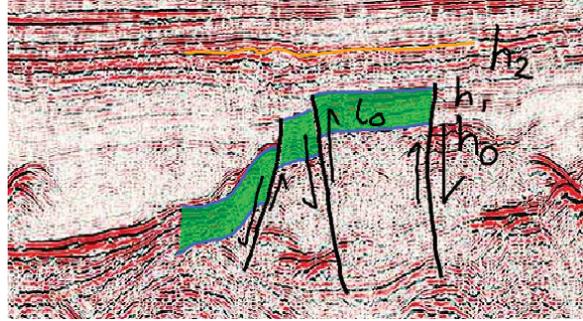
Figure 4: The figure is showing the drawing primitives on a seismic section. The orange horizon h_2 is described by one curve, while the blue horizons h_0 and h_1 are described by multiple, disjoint curves, due to the fault lines. The geological layer l_0, colored in green, is divided into three disjoint polygons because of the same faults.

area is the result of the all the geological events that have taken place there up until now. Geologists usually think in these geological event steps when they produce their geological-interpretation sketches.

Based on this domain knowledge, we propose to provide the geologists with the possibility of capturing, using sketches, the reasoning behind their models by enabling them to externalize the geological event-steps they had in their mind when creating the model. A time series of such consecutive geological event steps is what we call a *geological story*. We name the individual geological events in the story *story nodes*, similar to the terminology used by Wohlfart and Hauser [85].

Our system also covers the management of sets of alternative stories for easy play-back, evaluation, and presentation. The playback and evaluation is enhanced with 2D animations, automatically interpolated from the story nodes. To understand the geological meanings of the 2D animated sketches requires that the viewers have a certain amount of domain knowledge. However, the most plausible geological models also need to be communicated to decision-makers, laymen and other non-experts. For this task, we propose to present the geological stories as animations of illustrative 3D models, inspired by the instructive animations produced by oil companies, when they explain their operations and technologies. In the method we present, these 3D animations are automatically rendered from the frames of the 2D sketch animations. Figure 3 illustrates our system, its components and the data flow.

We provide the geologists with a graphical representation of the reasoning over the geological events they believe have taken place. Creating, animating, comparing and presenting these reasoning processes are what we denote as *geological storytelling*. Our geological storytelling system is novel in that no such complete pipeline has been presented before.

B.4.1   Capturing Sketches and Building Stories

The story nodes are the elements of the geological story and contain sketches of the geological situation at a specific point in geological time. Each sketch is composed by a set of curves and a curve is captured by sampling one input stroke made by the user.
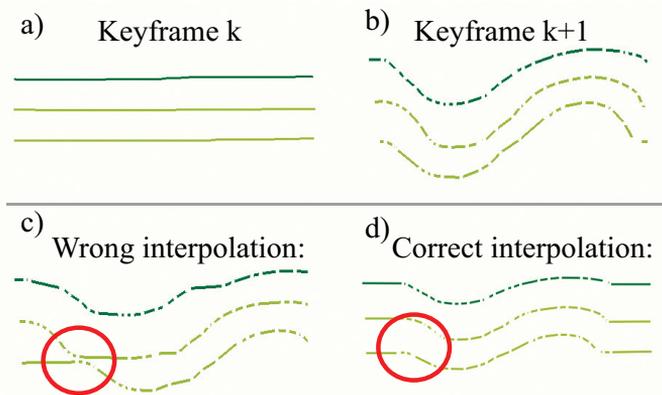
Figure 5: a) is showing a sketch of three straight horizon lines. b) shows the same lines in the next keyframe after a folding event has occurred. In c) the highlighted red area shows a geological incorrect interpolation, while d) shows the correct interpolation. The white dots in b), c) and d) convey the position of the curve points.

The curve is represented as a set of connected line segments from the sampled vertex points. In some sketch-based applications, the raw strokes are filtered and resampled, for instance to remove noise, as described by Olsen et al. [59]. However, when sketching on a 2D seismic section it is important for the geologists that the lines are rendered exactly where they are drawn. Therefore, we propose not to apply any filtering.

The geologists have specified the need for the following drawing primitives: *Horizon lines*, for drawing the horizons denoting the borders between the different geological layers; *Vertical fault lines*, for drawing faults, i.e., discontinuities across geological layers; *Polygons*, for drawing the layers between the horizons, to indicate the sea level, and to draw intrusive objects; And *arrows and other annotations*, for indicating directions of movement, for instance, the direction of erosion or the direction of intrusion, and for adding labels and highlighting important parts in the seismic section. A horizon line is composed of one curve, unless the horizon is faulted, then it is composed of a set of curves. Each fault line is always continuous and thus always represented by one curve. A geological layer is described by one or more polygon, depending on whether the layer is intersected by faults or not. Each of these layer polygons are outlined by one curve. Arrows and annotation can be composed of an arbitrary number of curves. Figure 4 shows an example sketch containing the drawing primitives.

We advocate a flip-over metaphor for specifying a new story node, as this is a method well known to sketch book users. There are usually correlations between the sketches on two consecutive story nodes, as the geology they depicted is only incrementally modified. Therefore, to aid the geologist, all sketches made on the previous canvas sheet are visible as *ghost lines* on the next canvas sheet.

The story nodes are managed by a tree data structure we call the *story tree*. Here, the complete geological story is produced by combining all its story nodes into a geological-time-ordered sequence. The time direction of the geological stories is user-defined, as our system supports stories progressing from the past to the present, as well
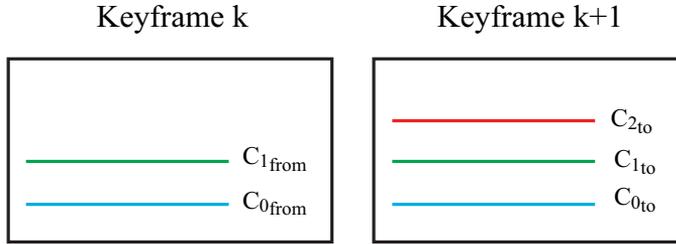
Figure 6: The figure is showing two consecutive keyframes. In the animation sequence between these keyframes, the new curve $c_{2_{to}}$ is interpolated from the curve $c_{1_{from}}$.

as from the present to the past.

B.4.2   Animating Sketches

The simplest form of playing a geological story is by flipping through the stack of story node sketches, as we proposed in Lidal et al. [47]. It can be difficult to see the structural movements and to understand the geological changes from the static sketches only, especially without explanations from the model author. Because of this, we now propose to extend our system with the playback of the geological stories through automatically synthesized 2D animations of the sketches. We treat the story-node sketches as animation keyframes. Since the geological sketches consist of curves, such as horizons and fault lines, our proposed method focuses on the animation of these curves between the keyframes. It is important that the animations are geologically sound, in order to be understandable and believable.

Keyframe animations, as explained in basic computer animation literature, such as by Parent [61], are created by interpolating a curve c_{from} in one keyframe to the curve c_{to} in the next keyframe over a number of in-between frames. The interpolation $c_{from} \Rightarrow c_{to}$ is usually accomplished by a point-to-point mapping of the vertex points of the curves in each consecutive keyframe. If the curves do not have the same number of points, then this mapping usually has to be done manually by the animator. In our case, the consecutive keyframe curves rarely have the same number of points. If c_{from} is a flat horizon line it can be described by very few points and then, due to a transformation such as folding, c_{to} can become very complex with many points, see Figure 5 a) and b). To specify the point-to-point mappings manually would be prohibitively time consuming for the author, and not something that we want in a rapid, sketch-based environment. The naive approach to super-sample the line with the fewest number of points and then do a simple mapping along the line, produces in many cases animations that are geologically wrong, as the still image in Figure 5 c) shows. The main issue in this case, is that part of the curve is interpolated horizontally, due to few curve points. The result is that the lower layer almost disappears in the middle of the animation sequence and then reappears in the end of the sequence. This is not geologically possible. The method we propose instead is to super-sample both curves with each other's vertex points, in this way both curves have the number of points equal to the sum of the points in the original curves. This ensures that the interpolation is geological sound, as shown in Figure 5 d). The total number of points in all the curves of a sketch is still so

a) Keyframe k

b) Keyframe k+1 compaction

c) Keyframe k+1 erosion
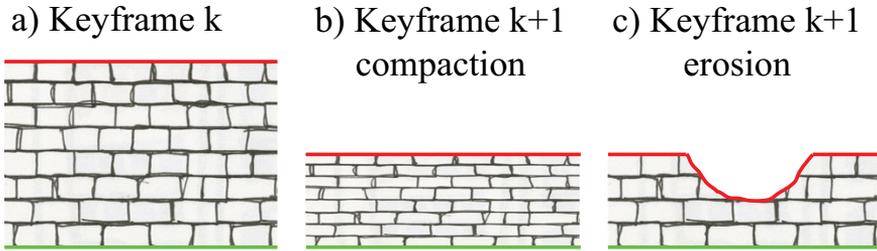
Figure 7: a) The geological layer at keyframe k. b) The geological layer of a) after a compaction event, notice the texture is also compacted. c) The logical layer a) after an erosion event, notice that the layer is not compacted.

low that this super-sampling has no influence on the performance.

In a geological story, we are often confronted with the appearance and disappearance of curves between consecutive keyframes, e.g., in the event of depositions of new geological layers or the complete erosion of geological layers. In computer animation software, these appearances and disappearances have to be animated manually, something we want to avoid. For our sketches we know that the appearances and disappearances only happen at the top of the sketches, thus we can utilize the curve(s) of the horizon line below as starting curve (for deposition) or end curves for the in-between interpolation. This is illustrated for the deposition event in Figure 6. Here the curve c_2 is only present in keyframe n+1. The interpolation for this line is then, referring to curves in the illustration, $c_{1_{from}} \Rightarrow c_{2_{to}}$. For a complete layer erosion event, c_2 is only present in keyframe n, and this gives an interpolation $c_{2_{from}} \Rightarrow c_{1_{to}}$.

Our animation method also has to handle the case of faulting events. This implies that a continuous horizon curve is split into disjoint curve segments in the consecutive keyframe, $c_{from} \Rightarrow \{c_{to0}, \cdots, c_{toN}\}$. The challenge here is to make sure that the split of the horizon is fixed in the sketch, i.e., is not moving, across all the in-between frames. If a fault line is sketched along with the horizon line split, we split the c_{from} horizon line at this fault line and then interpolate the start point of the new horizon segments along the fault line. In the case the fault lines are not sketched by the author, we, ideally, should be able to calculate the arc-length and make the split according to the percentage of the segments $c_{to0} \cdots c_{toN}$. However, because we are advocating sketched curves, and their arc-lengths are usually not equal from keyframe to keyframe, we had to do the split according to the absolute coordinates instead.

We apply *linear interpolation* between the key frames. Linear interpolation can break the smoothness of the animation, because it is not C^1 (tangential) and C^2 (curvature) continuous. However, this is a desired feature, as it emphasizes the key frames as distinct changes in the geological evolution that the author identified as important for understanding the geology.

The annotations and arrow symbols often accompany structural information in hand-made geological sketches. Their role is purely visual, useful mostly for displaying dynamics in a still image. Whether or not these arrows can be utilized as animation descriptor is a research question on its own. Because, combining these two roles might easily introduce a mismatch, as for example a different arrow specification is needed to achieve a desired displacement or deposition, than what would be preferred as a visual
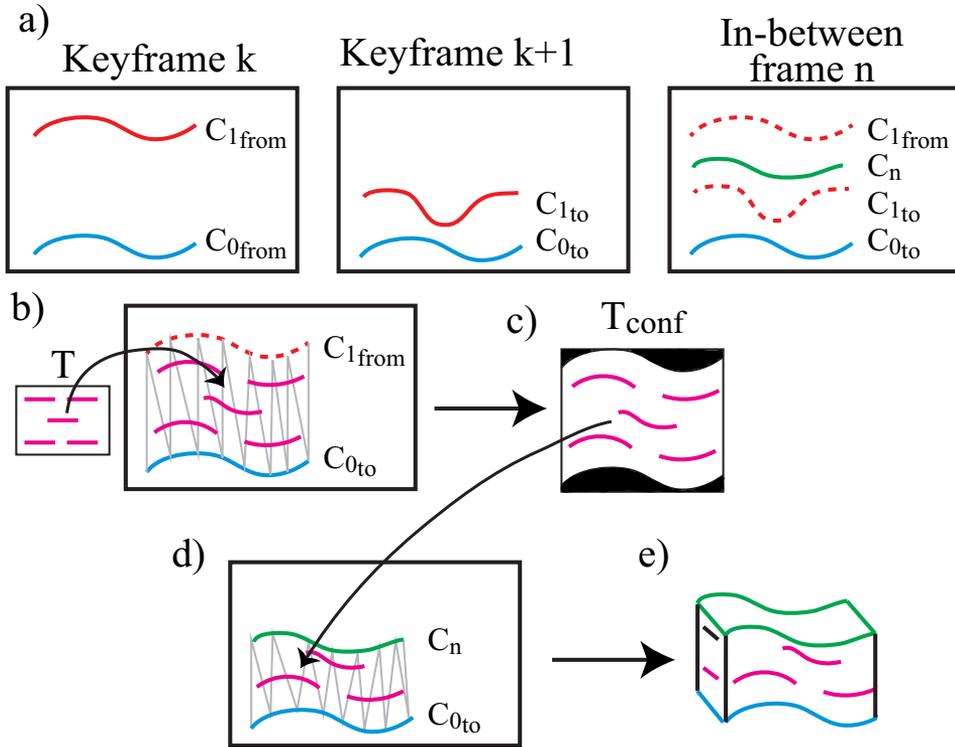
Figure 8: a) Two consecutive keyframes depicting an erosion event and one of the interpolated in-between frames. b) The area between $c_{0_{from}}$ and $c_{1_{from}}$ is conformal texture mapped and c) a new texture, T_{conf}, is extracted. d) The area between c_{1_n} and $c_{0_{from}}$ is texture mapped with T_{conf} to make the final 3D model e). Note that the tessellation in the figure is an illustration.

symbol itself.

The fault curves are interpolated by fading them in or out by utilizing transparency. In order to ensure that the fault is visible when the in-between keyframes animation starts, we use the following formulas, for fading in (1) and for fading out (2), where $f \in [0.0, 1.0]$ is the fraction of the interpolation.

$$c_{to}\alpha = min(0.5 + f, 1.0) \tag{1}$$

$$c_{from}\alpha = max(0.5 - f, 0.0) \tag{2}$$

In the work we present here, the polygonal drawing primitives are not interpolated between the keyframes. The reason for this is that the geological movements are all described by the horizon and the fault curves, and thus this conveys the movements between the keyframes. During story playback, the polygons are only rendered for each keyframe.

B.4.3   Synthesizing 3D Models and Rendering Animations

Presenting the geological stories to non-experts was omitted in our previous work [47], but it was necessary to add to make our storytelling system complete. Although Na-

tali et al. [58] proposed a method for synthesizing 3D models from 2D sketches, we had to adapt it with several extensions to make it fit our need. Firstly, the layer texturing method they propose cannot automatically handle deposition and erosion events, which are very important for geological stories. To adapt their conformal mapping layer texturing to our needs we had to extend it to also support these events.

For the erosion we must make sure that the animation actually depicts that the layer, and thus the texture, gets clipped away and not merely deformed, as would be the case of a compaction or a folding event, see Figure 7. In the work presented by Natali et al., this can be achieved *manually*, however for animations we need a method that can do this automatically. We propose the following 2-pass extension (please refer to Figure 8):

1a) Tessellate the area between the initial top curve of the eroding horizon $c_{1_{from}}$ and the horizon below $c_{0_{from}}$

1b) Texture map this area with the layer texture T, apply conformal texture mapping and render this to an image T_{conf}

2) Tessellate the area between the curves c_{1_n} and $c_{0_{from}}$ and texture map this layer with the image T_{conf}, applying regular texture mapping

Note, if the horizon line described by the curve $c_{0_{from}}$ is also changed between the keyframes, i.e., $c_{0_{from}} \neq c_{0_{to}}$, then the references to $c_{0_{from}}$ in the algorithm above should instead be to the interpolated curve c_{0_n} as part of the interpolation $c_{0_{from}} \Rightarrow c_{0_{to}}$. The steps for the sedimentary deposition event are similar to the steps for the erosion event, except that the area tessellated in step 1a) is the area between $c_{1_{to}}$ and $c_{0_{to}}$.

Secondly, because the method by Natali et al. only considers the synthesis of static images, they did not provide any solution for handling temporal coherency. However, temporal coherency is very important in animations and if not properly handled it can result in temporal visual artifacts. We encountered such temporal artifacts when animating our synthesized 3D models, in the form of texture jittering. This issue was due to a low tolerance to minor changes in the layer borders (the horizon lines) in the tessellation and conformal texture mapping of the geological layers. The source of these minor changes in the layer borders is the sketching interface and the fact that it is difficult and unnatural for the user to re-sketch the same horizon identically on the consecutive keyframe. The jittering artifacts were only noticeable on geological layers that remained unchanged during an animation sequence, and not on the layers that are deformed by compaction, erosion etc. To solve this issue, we focused on keeping the horizon lines on consecutive key frames, for stable layers, as identical as possible. Our method therefore supports, in the sketching canvas, a copy functionality on the ghost lines, so that the author quickly can duplicate a horizon line from one keyframe to the next keyframe. A minor additional benefit is that this also can reduce the authoring time.

Another temporal artifact we had to address was due to the seams between tiled textures on the geological layers. For the still images presented by Natali et al., these seams are not very noticeable. However, when the model is animated, these seams become very visible and they are erroneously perceived as structural information that leads to misinterpretation of the model. The textures used for the animations must therefore be seamless, i.e. they must wrap around both vertically as well as horizontally.

Guides for synthesizing seamless textures can be found in many references, such as [65].

Figure 9 shows three frames from an automatically synthesized animation of a 3D illustrative model. This animation depicts an erosion event. Please refer to the supplementary video material for more examples of 3D animated geological stories.

B.5 Prototype Description

To demonstrate our geological storytelling system we have realized it as a research prototype. It is implemented in C++, using Qt as UI framework. The graphics is rendered through OpenGL and VTK. Figure 10 shows a screen shots of the main window. Our prototype consists of four components: The *canvas*, the *story tree*, the *inspection view*, and the *presentation renderer*.

B.5.1 The Canvas

The canvas is the sketching interface where the geologist authors the geological stories. It is inspired by the pen-and-paper interaction style commonly used by artists. Each story node is drawn on a separate canvas sheet. It is possible to use the data from a seismic section as a canvas sheet backdrop. Examples of sketches authored on a seismic backdrop is shown in Figure 10. Horizon lines and polygons can be drawn in user-defined colors and opacities. The fault lines are always drawn in opaque black color, as this is the common domain practice. The prototype supports both continuous drawing and point-and-click drawing. Continuous drawing is best suited for accurate sketching, while point-and-click drawing is best for drawing longer straight lines and for drawing the polygons.

Once the geologist has finished drawing the sketch for a story-node on a canvas, she can flip the page by clicking in one of the bottom corners of the canvas. This provides the geologist with a new canvas sheet, for sketching the next story node. Figure 11 shows the metaphor of flipping the canvas and the ghost lines of the sketch from the previous canvas sheet. The visibility of the backdrop seismic image in the canvas can be adjusted individually for each canvas sheet. Examples of sketching stories in the canvas are included in our supplementary video.

B.5.2 The Story Tree

The story tree is the visual structure that stores all the alternative geological stories that are derived from the same seismic section. Figure 12 shows a story tree populated with four different geological stories. The blue project root node serves as a common root node for all the story subtrees, and denote that they all are based on the same seismic section. The orange nodes are the story root nodes, representing the starting point of each story. The yellow nodes are the individual story nodes of the stories. When the canvas is flipped-over to create a new story node, then this new node is inserted as a child node of the story node that was in the canvas before the flipping. We allow sibling nodes in our story tree. Siblings symbolize a branching of the geological story and it creates a multi-path story. One example could be that two different story paths
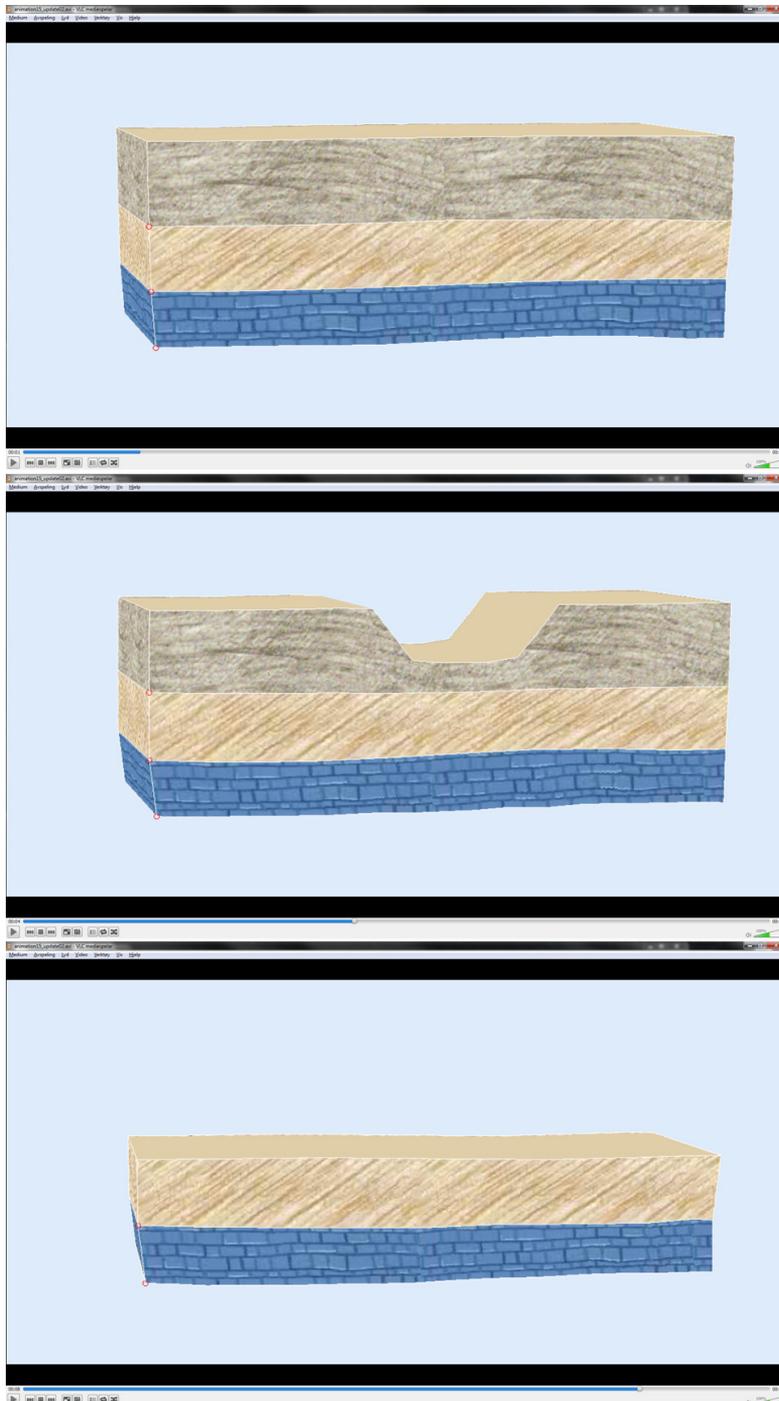
Figure 9: Three still images of an illustrative animation made from a geological story about an erosion scenario.
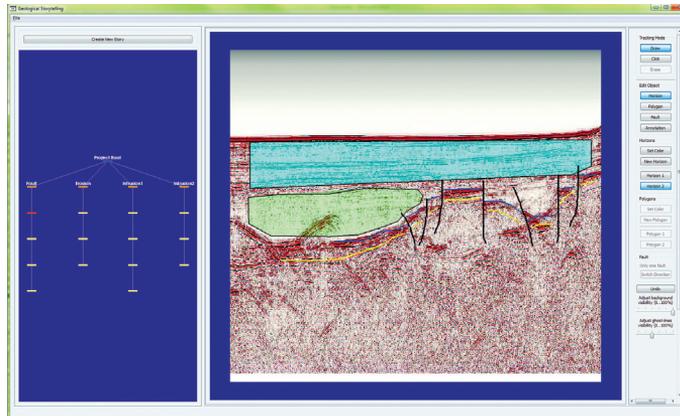
Figure 10: The main window of our geological storytelling prototype. To the left is the story tree depicting alternative stories. In the middle is the canvas where story nodes can be sketched. The canvas is a virtual flip-over, providing unlimited number of sheets.
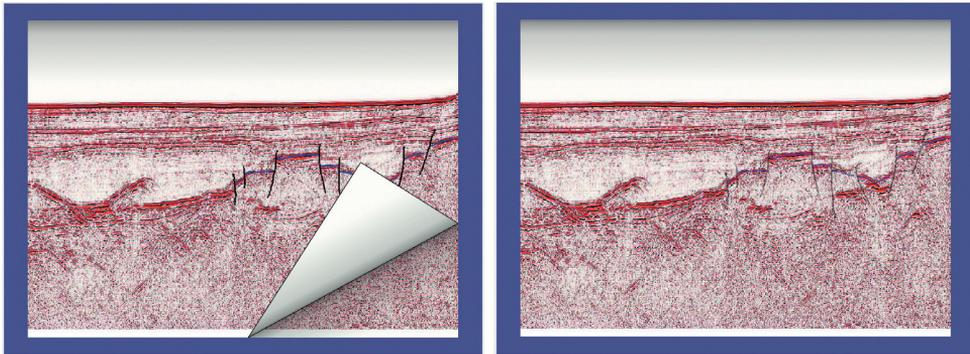
Figure 11: Left: When the geologist has completed a story node she flips over the canvas to get a new sheet for the next story node. *Right:* To aid the author, the sketches from the previous story node are visible as ghost lines on the new story item canvas.

(evolutions) can lead to the same, more recent in geological time, story node. In this work, we have not investigated the roles of siblings any further. As one can see from Figure 12, the first story, "Fault" is a multi-path story, while the stories "Erosion", "Intrusion 1" and "Intrusion 2" are single path stories.

If a story node in the story tree is activated, then this story node is displayed in the canvas. This is the second purpose of the story tree, i.e., to navigate to a specific story node for review or updates. The third purpose of the story tree is to select one or more geological stories, for playback or comparison in the inspection view.

B.5.3   The Inspection View

In the inspection view the geologists can play and compare the geological stories to evaluate geological soundness and judge the plausibility of the story. The playback of the 2D story animations can be controlled through a time slider, providing the users
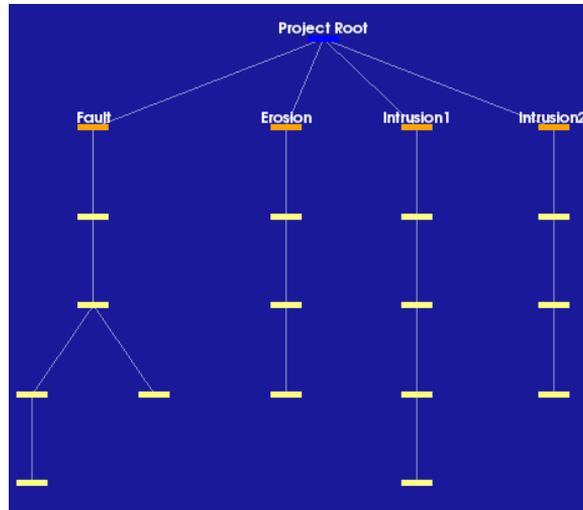
Figure 12: The story tree with four stories of different story length and with branches. A branch indicates that different geological event-trails may lead up to the same, later story node.

with the option to move both forward and backward in geological time. The inspection view is shown as a separate window in our prototype, supporting a dual screen setup with the story authoring and management on one screen and the inspection view on the other. A screen-shot of the inspection view during story playback is shown in Figure 13.

The inspection view is configured based on the selections made in the story tree. If a story, or part of a story, is selected then the 2D animation for this story is rendered in the inspection view. If more than one geological story is selected in the story tree, then these stories are played back side-by-side. This enables the geologist to identify differences between the stories and compare them against each other. The side-by-side playback is synchronized, thus all stories are animated based on the same time-slider. Figure 14 shows the comparison of four geological stories.

B.5.4   The Presentation Renderer

The presentation renderer takes as input all the interpolated frames of an animated geological story. It synthesizes an illustrative 3D geometry model from each of these frames, with a user-specified texture for each geological layer. Each 3D model is then rendered to an image and stored in a buffer. The camera position can be specified individually for each rendered image, enabling camera panning, rotation and zooming during the animation sequence. The rendered images can be compiled and exported as a complete movie file. Alternatively, each individual image can be exported as an image file, in case the animation sequence are to be combined with other video data in a third-party video editing program.
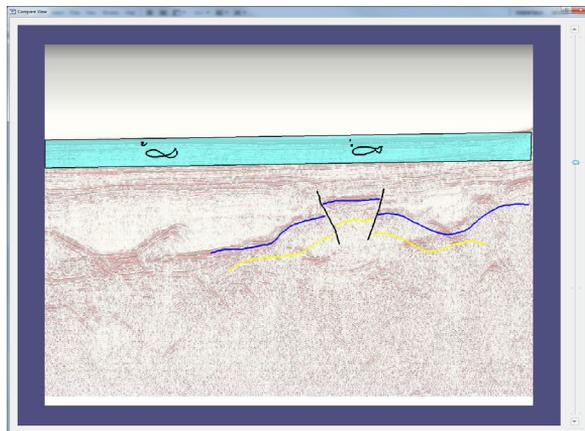
Figure 13: A screen shot of the inspection view playing a single geological story. In this view the geologists can visually evaluate the geological soundness of the sketch.

B.5.5 The No-data Scenario

This far, we have described a usage scenario of geological storytelling based on a 2D seismic section. Sometimes the geologists also want to brainstorm and discuss geological scenarios without referring to specific seismic data. For instance, when they discus geological evolution on a larger scale or when they hypothesize about a location where no seismic yet has been collected. A related example is the teaching of structural geology, where conceptual examples often are utilized. These can all be denoted as *no-data scenarios*.

Geological storytelling can also be applied to the no-data scenarios. Instead of using a seismic section as backdrop, the stories are sketched on a clean canvas sheet. In addition, the geological-time order in which the story is authored, is usually reversed. For the no-data scenario, the story is usually based on knowledge about pre-historic events and the sketching of the story nodes are forward in geological time, hypothesizing how the geology may look like today. See Figure 15 for examples of a no-data geological story of a fault scenario and three still images of the illustrative 3D animation.

B.6 Results

The industry that our collaborating partners represent is very competitive, so they want to keep interpretation sketches and seismic data secret. This makes it difficult to conduct a full case study of geological storytelling directly in their work processes. Instead, we have performed the evaluation in two parts. First, we got our collaborative geologists to draw three example geological stories on paper. This was performed on a publicly available seismic slice, from the Virtual Seismic Atlas [72]. Note that the stories are only examples and not necessary reflecting geological correct interpretations of the seismic. Our argument is that hand drawn stories represent the level of how expressive the geologist wants the story sketching to be. If we can reproduce them in our system, we get a verification that the expressiveness is on par with what is expected.
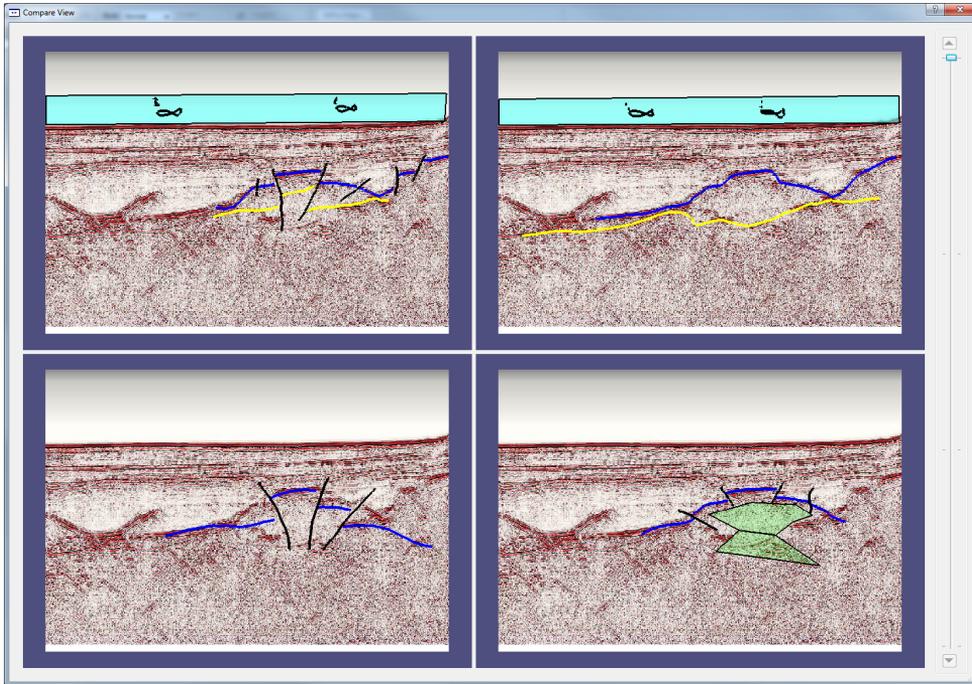
Figure 14: A screen shot of the inspection view comparing four distinct geological stories. All the views are synchronized with the time step slider on the right hand side. In this view, the geologist can visually compare, side-by-side, different geological stories to find the most plausible ones.

Figure 18 shows one of these hand-drawn stories. The story shows a fault model where sedimentary deposits took place after the faulting. Figure 18 also shows the same story reconstructed in our prototype. We reproduced the two other geological stories also, and selected story nodes are shown in Figure 16 for an erosive model and in Figure 17 for an intrusive model. The images show that the pen-and-paper made geological stories can be reproduced successfully in our system. In the supplementary video to this paper, we also show how one of these expert-authored scenarios, the erosive model, is rendered as a 3D illustrative animation. The authored sketches and selected frames of this animation are shown in Figure 19.

Secondly and more importantly, we also conducted meetings with several domain-experts to collect expert evaluations. In these meetings, we presented our geological storytelling system and demonstrated our implementation to these experts, who have not been involved in our project. In one meeting, we presented geological storytelling to a professor of Earth Sciences at our university, who also has many years of experience from the oil industry. His initial feedback was that he found geological storytelling useful. He described a relevant scenario where two geologists may agree on the interpretation of the seismic image, but they have quite different understanding of the geological scenario that has produced this seismic image, i.e., their geological interpretation differs. Geological storytelling will help them performing geological reasoning about their models and discuss the differences. He further confirmed that geological storytelling also could be very powerful for presentations of geological models to
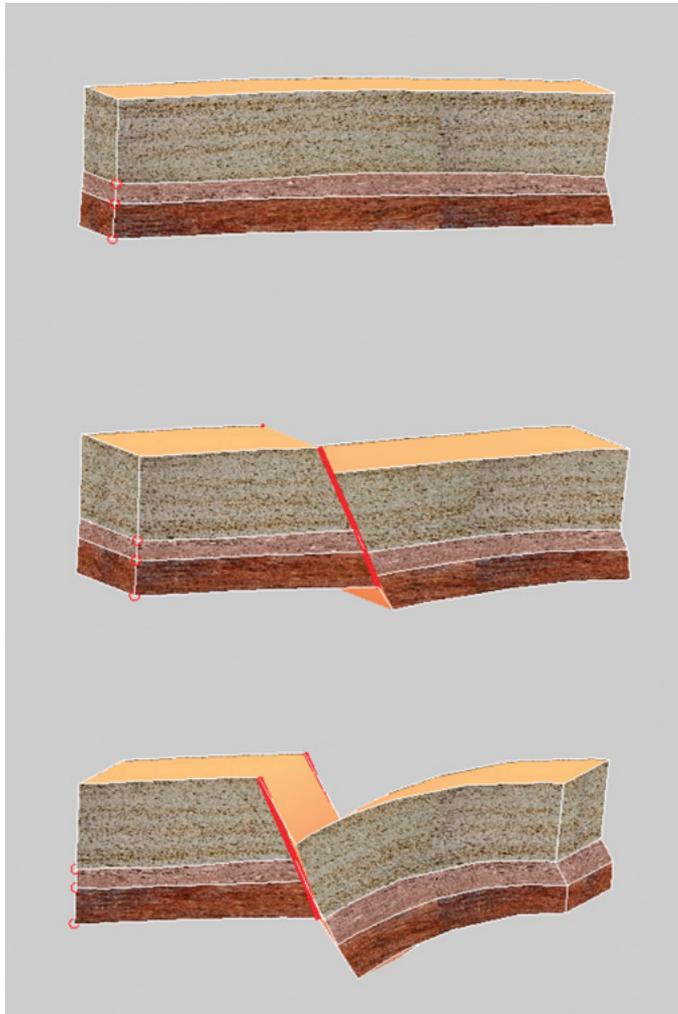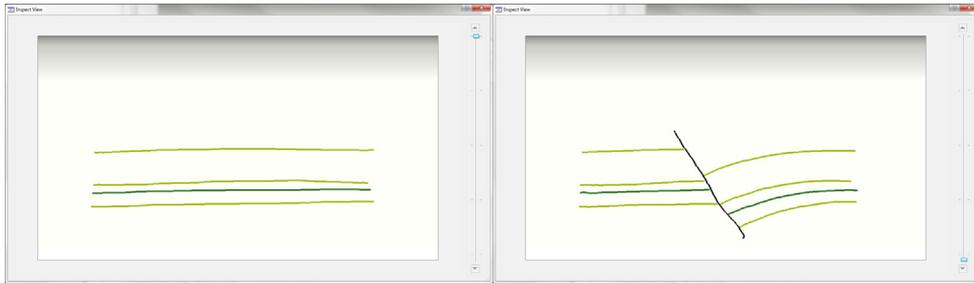
Figure 15: Top row: Two example key-frames that constitute a fault animation. *Bottom:* Three still images of the illustrative animation made from these key-frames.
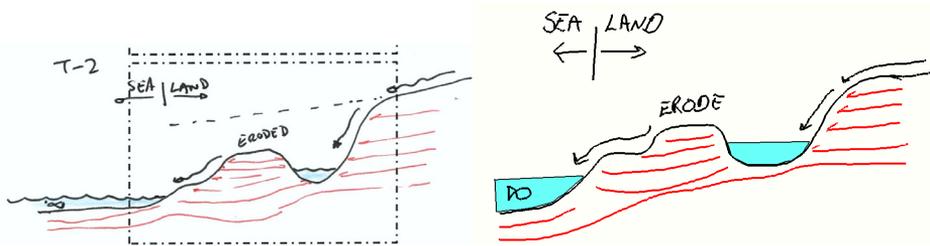
Figure 16: To the left: A hand drawn sketch showing one story node from a longer story about an erosive geological model. It was made by one of our collaborating geologists. To the right: The same story node, but this time reproduced in our geological storytelling prototype.
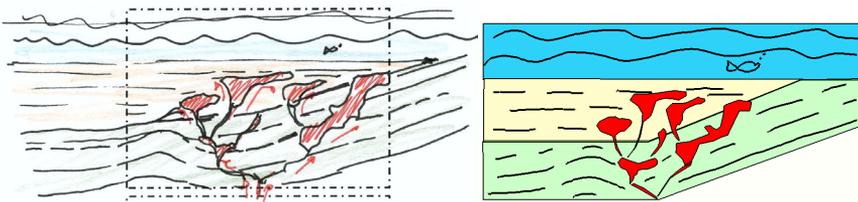

Figure 17: To the left: A hand drawn sketch showing one story node from a longer story about an intrusive geological model, also made by one of our collaborating geologists. To the right: The same story node, but this time reproduced in our geological storytelling prototype.

management and decision makers. In a follow up meeting with this professor, we developed together the geological stories depicted in Figure 20. These stories are based on the seismic section denoted "Ymir Ridge profile 3", seen in the top of the figure. It is also available through the Virtual Seismic Atlas [26]. We chose this seismic section to illustrate other geological event than what we find in "WESTLINE shotpoints 4500-8500", especially folding. The sketches to the left in Figure 20 depict a story of a folding scenario driven by tectonic plate compaction (story node 3), followed by a sedimentary depositions in the top fold (node 4), and finally, a faulting due to tectonic plate extension (node 5). The second story, told through the right side sketches, also tells of folding. The driving force for this folding is the yellow magma layer that pushed the other layers up (node 3), before it breaks through the top layers (node 5). The supplementary video shows a side-by-side comparison of these stories.

We have also had meetings with a group of domain experts involved in early exploration operations from a world-leading oil company. These experts were three geologists with 8–15 years of experience, one geophysicist with 20+ years of experience, and two visualization experts with 10 and 20+ years of experience. They found that geological storytelling is a good solution to the problem at hand and that it has not been addressed in other software solutions. It strongly resembles hand-drawings on paper, a method they often use when they want to explain their interpretations. The concept of thinking in "complete" geological stories is not how all geologists carry out their interpretations. However, a tool based on our system can encourage all geologists to make better geological reasoning, and thus produce better models. They further added that geological storytelling also can be useful for communication upwards in the organiza-
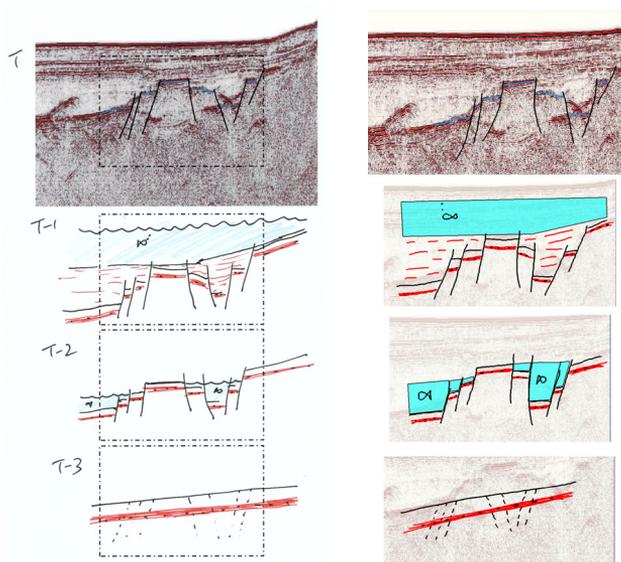
Figure 18: The hand drawn sketch to the left was made by one of our collaborative geologists after we explained the concept of a geological story. It shows an imagined geological story of the seismic slice shown in the top of the figure (Today). This particular story shows how a fault system has evolved from a non-fault stage (T_{-3}) through several events of faulting and sedimentary deposits (T_{-2} and T_{-1}). To the right, this geological story is authored in our storytelling prototype. We see that these two visualizations look similar and tell the same geological story.
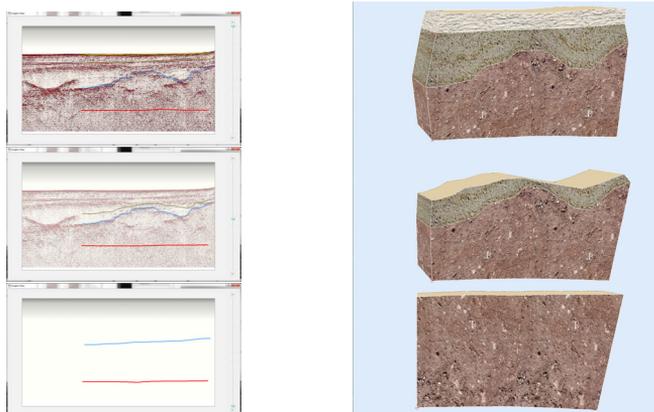
Figure 19: Left: Three of the geological story nodes sketched for a deposit scenario based on a 2D seismic section. *Right:* Our prototype synthesizes illustrative 3D models based on the 2D animation of the geological stories. The three images shows frames from the animation rendered based on these illustrative 3D models.
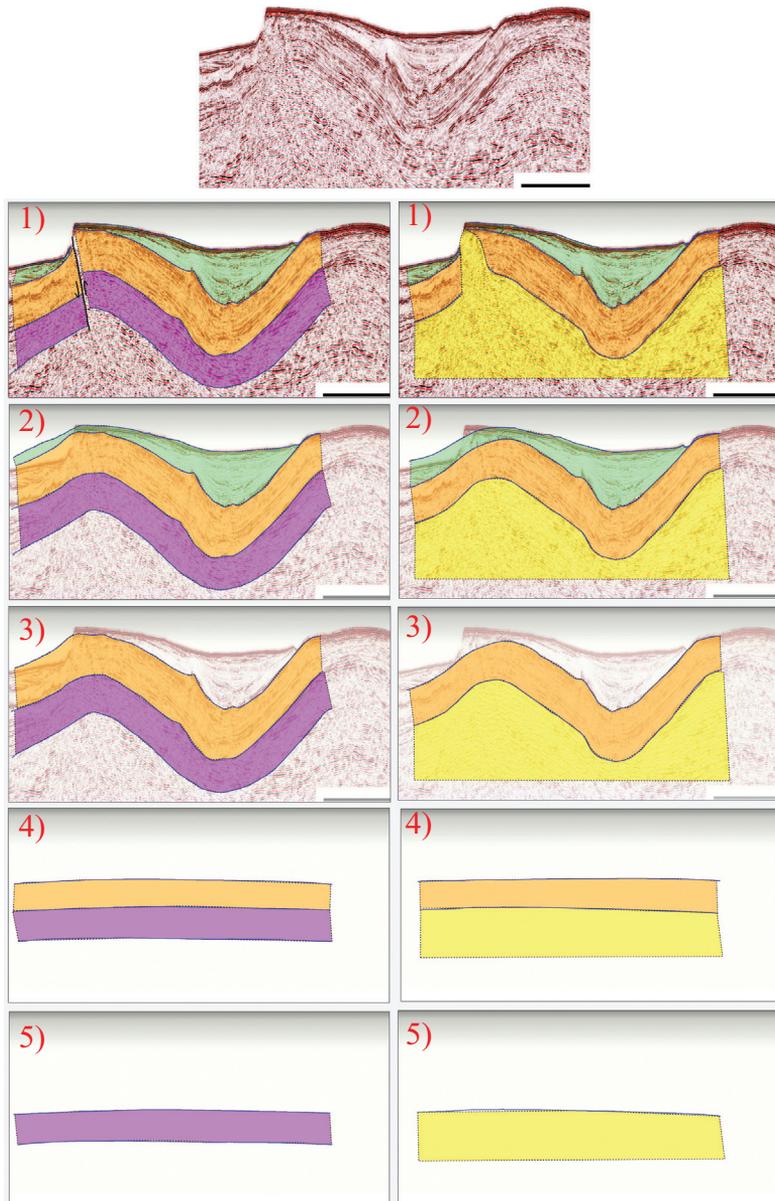
Figure 20: The seismic section "Ymir Ridge profile 3" is courtesy of Fugro. The story to the left is telling about geological layers deposited 5), 4) that are folded by tectonically plate movements 3). New sedimentary depositions are made 2) and the construction is then faulted 1). In the story to the right, the geological layers 5), 4) are folded by an intrusive layer 3), this folding also enables sedimentary depositions 2), and in the end, the intrusion breaks through the upper layers 1)

tion, i.e., to decision makers, mainly because it will be possible to create several stories to present. As a final remark, the geologists suggested that geological storytelling can be useful outside early exploration operations, e.g., it can also be applied in production, to quickly sketch up models/geological ideas in known locations. The experts also provided suggestions for future developments. These are all related to turning our implementation into a production tool, such as support for specific seismic file formats, exporting the stories to file formats compatible with other petroleum software tools, and copy/paste functionality for the sketched objects.

Finally, we have demonstrated geological storytelling to a professor in structural geology and a renowned geological illustrator. He is frequently constructing geological animations for educational and communicative purposes [23], drawing them in Adobe Illustrator [2] and animating them in Adobe Flash [1]. He mostly utilizes the generic Shape Tween Flash function to animate his models, only for the special cases is he resorting to manual animation. He reported that he spends at least a full workday on even the smallest of these animations. He was very positive to our proposed animation pipeline, he appreciated that expressive illustrative animations could be constructed so quickly through our simple sketch-based interface. He emphasized the need for such tools, especially for geologist with lesser artistic skills, to help them use more illustrations in scientific publications, in teaching, and in communication with non-experts. He confirmed to us that our proposed pipeline is a valuable contribution to this goal and he has invited us to collaborate with him to develop our system further. On question about the linear interpolation we utilize for line interpolation he stated that for the animating of horizons from one key-frame to the next, we have shown him, they are perceived as geological sound. For the animations containing faults, it is important that the horizon segments are animated along the fault.

B.7 Discussions and Limitations

We have made the sketching of the story nodes in geological storytelling as free-form and as context-free as possible. The alternative would be a system that could interpret sketches into geological entities, such as objects, events, and processes. The latter would require that we would upfront identifying every possible geological entity that is sketch able, a task we are not sure can be done. With our context-free approach it is up to the geologist, both to sketch the geological events and to make sure that the result of the events is geologically sound. When we have discussed this with the geology experts and the geology illustrator during the presentation we have had, they have all subscribed to our approach, because they value very much the freedom and expressiveness of such an approach. Regarding scalability, our collaborating geological experts anticipate that there can be up to 10 geological stories for each 2D seismic slice. The rendering and storage of these geological stories only requires little computational resources compared to the graphical capabilities and storage available in today's computers.

The set of geological events that we support when creating the animations of synthesized 3D models are not the complete set of all known geological events. For instance, we do not support intrusions. However, with this work our aim was to show the potential of our pipeline, and not to provide a complete tool. Likewise, our implementation is

#	Requirement	Coverage
1	Time is limited, creating the models must be fast and intuitive	Flip-over canvas methaphor and the sketch-based interface
2	Creating models is a creative process, therefore expressiveness should not be limited	The sketch-based interface
3	The reasoning behind the interpretation must be captured and communicated, in addition to the final proposal	The concept of geological stories
4	The representation of the model, together with the reasoning, must be in a form so that knowledge can be captured in the organization	The geological stories and the illustrative presentation animation
5	The representation must support evaluation of the geological soundness of the interpretation	Playing back the geological stories as animations
6	The representation must support comparison of different geological models to qualitatively rank these according to probability	The story tree and the side-by-comparison animation (partially)

Table 2: The table shows how the geological storytelling system covers the requirements we presented in Section B.2.

only a proof-of-concept and thus not optimized for speed or memory usage. Therefore, we have not performed any performance or memory usage measurements.

Merging the role of a visual symbol with the role of an animation descriptor, such as the case of annotations and arrows, could potentially lead to a richer set of modeling interactions. As already mentioned in Section B.4.2, before this can become useful, a dedicated research is necessary to establish the match between the arrow as an animation descriptor and its desired appearance for visually encoding of the motion. We hope that such questions can be addressed in our future collaboration with the geological illustrator.

The geological storytelling system and our prototype tool can, with a little engineering work, easily be integrated into the software tool-chain in the oil companies. As one example, tools such as Decision Space Desktop [32] can co-visualize GIF-animation images together with the geoscience data types, so the geological stories could be exported to this format and co-visualized directly on the seismic slice. The illustrative animations can be included into project presentations and archived together with other digital project documentation.

Based on the feedback from the domain experts, geological storytelling can be extending to application beyond the early steps of geology mapping, for instance for brainstorm meetings and for rapid communication and evaluation of geological ideas also in locations where the oil companies already have obtained detailed information. Geological storytelling tells stories of geological evolution and we anticipate that our system also is equally applicable towards exploring and communicating other evolutionary processes. It is outside the scope of this work to investigate that further.

There are a few limitations to our proposed geological storytelling system. First, the

story tree has no function for arranging the stories according to how probable they are. This sorting has to be manually managed by the users. Secondly, when synthesizing the illustrative animations we are extruding a 2D sketch to create the 3D model. Some geological processes are, however, also reaching into the third dimension, for instance intrusion, and to cover these would require true 3D models. True 3D models could improved rendering of the top surface of the synthesized models, among other provide the illusion of cutting into solid material during erosion animation. Nevertheless, these improvements are not required for proving the value of geological storytelling.

In Table 2, we have summarized how the geological storytelling system covers the requirements from Section B.2. As discussed above, the requirement of ranking the geological stories is only partially covered by the story tree. Except for this, the domain experts have confirmed that the requirements of Table 1 are covered by our system.

B.8 Conclusions and future work

In this paper, we have presented Geological Storytelling, an interactive visual system for constructing, evaluating and communicating early geological sketches. We have performed an analysis of associated challenges and presented these as requirements. Our observation is that too little information about the reasoning behind the geological models is captured in the model artifacts, which are currently state of the art, especially since the time limits for modeling are so tight. Our geological storytelling system fulfills these requirements. The feedback we have received from all the domain experts we have talked to, confirms this.

In the future, we will continue developing geological storytelling and the creation of illustrative animations together with academic staff from the Earth Science Department at our university. Our focus will be in several directions. First, we would like to extend our system to cover all aspects of geology sketching and animation, for instance the automatic animations of geological layers and the sea level. Increasing the range of animations in our system will show if we can apply our linear interpolation scheme also for these animations or if we need to extend it. Secondly, our 3D models are currently based on a time series of 2D sketches. We want to support multiple sketches for each story node, in such a way we can synthesize more complex 3D structural models. Complex 3D models will require the need for occlusion management. There may be interesting features located inside the geological models that we need to expose. Ghosting, cutaway and exploded-view visualizations are examples of occlusion management techniques.

It would also be interesting to extend the comparison of the different geological stories. This poses a challenging problem. In contrast to works such as by Bruckner et al. [9], where they used scaled down images of the multiple views when exploring the parameter spaces of computer generated visual effects, our geological stories cannot merely be shrunk. Instead, we hope to develop an abstract representation of the entire story.

For the oil and gas industry, the structural modeling is only one of the steps in the exploration pipeline. We would like to extend our geological stories to also cover oil and gas migration, so that stories and animations of complete oil reservoir can be generated.

Acknowledgments

PAPER C

DESIGN PRINCIPLES FOR CUTAWAY VISUALIZATION OF GEOLOGICAL MODELS

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[2]Christian Michelsen Research, Norway

Figure 1: Left: A geological cutaway illustration. Image is courtesy of Statoil. *Middle:* Our implementation of the cutaway method by Burns et al. [10] on the Ness geological model. It exemplifies one of the perceptual problems we observed with current cutaway methods; it looks like the geological channels are located in the yellow-colored top layer, while in fact they are all residing in the orange, third layer. *Right:* A cutaway visualization based on our design principles. In this picture we more clearly see in which layer the geological channels resides, how the channel shapes corresponds to the shape of the surrounding context, and the depth of the cutaway.

Abstract

In this paper, we present design principles for cutaway visualizations that emphasize shape and depth communication of the focus features and their relation to the context. First, to eliminate cutaway-flatness we argue that the cutaway axis should have an angular offset from the view direction.

Second, we recommend creating a box-shaped cutaway. Such a simple cutaway shape allows for easier context extrapolation in the cutaway volume. Third, to improve the relationship between the focus features and the context, we propose to selectively align the cutaway shape to familiar structures in the context. Fourth, we emphasize that the illumination model should effectively communicate the shape and spatial ordering inside the cutaway, through shadowing as well as contouring and other stylized shading models. Finally, we recommend relaxing the view-dependency constraint of the cutaway to improve the depth perception through the motion parallax. We have identified these design principles while developing interactive cutaway visualizations of 3D geological models, inspired by geological illustrations and discussions with the domain illustrators and experts.

C.1 Introduction

Presenting and communicating important features in complex 3D geometric models is challenging. Professional illustrators utilize many different techniques for achieving this aim. The cutaway is a technique often used to expose focus features that otherwise would be occluded. The cutaway metaphor has also been adapted to interactive visualization. In this paper, we argue for the need of new, extended design principles to effectively apply interactive cutaway visualizations to models from domains previously not investigated. Our application-side motivation is to use visualization to communicate important features found inside 3D geological models more clearly. We want to provide the experts from the geoscience domain with an authoring tool that they can use to create interactive visualizations for communicating the important features in the geological models they create.

Traditionally, these models were communicated through handcrafted illustrations. Computers and simulations have taken over most of the modeling and rendering of geological models. The 3D computer tools that are currently used in the earth science domain have, however, not adopted its illustrative heritage. Thus, many of the expressive techniques used earlier for communicating the models have been lost in this workflow transition [54].

Our study focuses on sedimentary deposit geological models. These models are made, e.g., during ground-water mapping, or oil and gas exploration. Sedimentary models contain a set of geological layers having different geological properties. Structural changes, such as folding or faulting, can change the direction and shape of these layers, but the models often resemble similarity to the cake-layered model seen in most geological illustrations. Typical focus features in a geological model are sand-bodies, i.e., potential water, oil, and/or gas reservoirs, or structural bodies, like salt. The left image in Figure 1 shows an example of geological focus features depicted in a cutaway illustration. Further examples can be found on the Internet [37]

When we applied known cutaway visualization solutions to geological models, we identified serious depth perceptual problems, as depicted in the middle image in Figure 1. To improve the cutaway visualization we sought inspiration from geological illustrations, from vision and perception sciences, as well as from discussions with geologists and illustrators. Based on this we have formalized five design principles

for creating cutaway visualizations that work well with geological models and other models that share the same characteristics. These design principles, presented in Section C.3, include recommendations of relaxing the view-dependency of the cutaway, to use a simple cutaway shape, and to use an illumination model that effectively communicates the shape and spatial ordering inside the cutaway. The right image of Figure 1 shows the result.

C.2   Related work

Cutaway visualizations were utilized in early works on volume data rendering, e.g., by Levoy [44]. The first work that put cutaway as the main focus was by Feiner and Seligmann [22]. Another early work that resembles an illustrator's cutaway, is the 3D magic lenses by Viega et al. [79]. Diepstraten et al. [20] later proposed a set of requirements for producing *interactive* cutaway illustrations. The work of Coffin and Höllerer [16] extended these earlier publications by proposing a user-defined cutaway that adapts to the occluding geometry. Weiskopf et al. [84] showed how to create both convex and concave interactive cutaways in texture-based volume data visualizations. The publications mentioned above were limited by and specially tuned to the graphics hardware of their time.

Viola et al. [80] introduced *view-dependent* cutaways for volumetric data and coupled this with the integration of important driven techniques. Their cutaways were data-driven, i.e., the cutaway shape was automatically defined from the focus features. Bruckner and Gröller [8] made an interactive implementation of this data-driven, view-dependent cutaways. Burns et al. [10] adapted the data-driven, view-dependent cutaways for polygonal meshes. Their polygonal solution requires double-walled polygons to provide cutaway walls. Kubisch et al. [43] utilize cutaways to expose tumors for surgery planning. They acknowledge the problem of low depth perception inside the cutaway and suggest using shadows and distance markers on the cutaway wall. All these view-dependent cutaways are image-based and thus highly connected to the viewpoint and the camera position. Li et al. [45] gave a thorough overview of cutaways in traditional illustrations and presented an advanced system for creating cutaways. Their implementation is based on CSG models and this is not generally applicable to the complex shapes of geological features. Furthermore, they define cutaways primarily for static viewpoints rather than the dynamic cutaways for interactive viewpoints that we aim for. Elmqvist and Tsigas [21] have created a taxonomy of occlusion management for visualization. They rate the cutaway visualization as *very low* quality when depth cues are considered.

Only a few works on cutaways specifically targeting the earth science domain has been presented. Ropinski et al. [68] introduced a view-independent cutaway for seismic datasets and this work was followed up by the roaming box, also for seismic datasets, by Patel et al. [64]. The focus in both of these papers is on the search process of exploring a dataset of measured samples. This process usually has different requirements and solutions than the visual communication process we target here in our work. Turner [77] presented general characteristics of geological models. This work is especially interesting because Turner uses these characteristics to explain the challenges of building computer representations and performing the visualization of geological models.

In the recent book by Thompson et al. [75] they provide a thorough overview of works and theory from vision science and visual perception in the context of computer graphics. Our design principles are rooted in these sciences.

The 3D geological models we visualize consist of a set of sealed geometric objects defined as polygon surfaces, often used in geological models [12]. Thus, the cutaway algorithms for volumetric data mentioned above are not applicable, unless they can be adapted to polygonal scenes. Burns' adapting of Viola's work is one such example. The cutaway algorithms that seem most applicable to our needs are: Burns et al. [10], Li et al. [45] and Kubisch et al. [43]. We compare these works to our design principles in the next section.

C.3   Geological Model Characteristics and the Design Principles

We observed low depth perception when we applied known cutaway visualization methods to 3D geological models. This low depth perception hampered the model understanding in the following ways:

- ▷ difficulties to perceive the spatial ordering of focus features, i.e., the ordinal distance between focus objects

- ▷ difficulties to understand the relative distance of focus features to the cutaway walls, i.e., the position of the focus features inside the cutaway

- ▷ difficulties to perceive the shape and topology of the focus features

- ▷ difficulties to understand the spatial relationship between the focus features and the context, e.g., within which geological layer is a focus feature residing

- ▷ difficulties to understand the relationship between the cutaway shape and the model

To understand why the known cutaway approaches failed for geological models we turned to Turner [77]. It is common to model the subsurface a set of geological features or units, called *geo-objects*. Turner argues that these geo-objects have characteristics that pose big challenge for the modeling and the visualization of geology, especially compared to visualization of engineering and other man-made objects. He lists, among others, these characteristics: *complex geometry and topology* and *indistinct boundaries defined by complex spatial variations* [77], characteristics we believe are the main reasons why current cutaway visualizations fail. Turner points out that a tool for geology must be capable of efficiently model and visualize: *Geometry of rock- and time-stratigraphic units*, and *spatial and temporal relationships between geo-objects*. These requirements target what we listed as shortcomings of today's computer-generated cutaway visualizations.

According to Thomson et al. [75], *familiarity* with the object's shape contributes to the scene perception. A major difference between the geo-objects and the objects from, for instance, medical illustrations is that of *familiarity*. Sand-bodies, folded horizons, and faults, which result from complex geo-physical processes, vary significantly in structural arrangement from one geological model to another. Therefore, the geological cutaway visualization cannot rely on the viewer's familiarity with a specific model. In

addition, in medical illustration cutaways are predominantly utilized for an *onion-like* structural arrangement. Geological structures have usually a *layer-cake* structure. This difference is an additional challenge in the cutaway design.

With the knowledge from vision and perceptual science, the geo-object characteristics, and the geology visualization requirements in mind, we studied geological illustrations and had discussions with geology illustrators and geology domain experts. From this, we made the following observations and derived design principles for computer-generated illustrative cutaway visualization.

Design Principle 1: *Use an oblique viewpoint to the cutaway.* Studying cutaway illustrations like in Figure 1 and the examples found online at [37], we observed that the viewpoint is rarely ever positioned so that the viewer is looking directly into the cutaway. Instead, the illustrations all have an oblique viewpoint to the cutaway, mostly slanted from the left side. This oblique viewpoint increases the depth perception by providing a frame of reference (the cutaway wall) for perceiving the depth. This makes the cutaway look less flat (more 3-dimensional), analogous to the way how the shape perception of an object is increased by moving a light source from a headlight position to an "over-the-shoulder" position. Note that the oblique cutaway is something different than beveling, proposed by other cutaway methods, such as [45]. Beveling (the cut angle) exposes the cross sectional surface of the cut, providing better depth understanding of the cut surface. The slanted view in oblique cutaway, however, provides visual cues of the depth relations between the focus feature and the context. Oblique cutaway can be combined with beveling.

Design Principle 2: *Simple cutaway shape for complex models.* Because of the complexity in the geological models the illustrators draw the cutaway as a simple shape. They often use a rectangular-based box shape, sometimes similar to the overall shape of the geological model, also pointed out by [45]. A simple and easy-to-understand cutaway shape makes it easy to extrapolate the complete model and to understand how deep into the model the cutaway extends. As a general advice, we recommend a rectangular box-shaped cutaway, like geology illustrators often use.

Design Principle 3: *Include familiar context.* Important relationship aspects between focus features and context are often expressed by keeping some parts of the context, close to the focus features, uncut. The artist can deliberately leave some minor parts of the focus features occluded to emphasize the relationship between the focus and the context. This can be seen in the examples referenced online [37].

Design Principle 4: *Utilize an illumination model that effectively communicates shape, and ordinal and relative distances.* We observed that the illustrations often communicate rock or stratigraphic properties through exaggerated rendering techniques and textures. The illustrators also draw shadows between the focus features and the context to emphasize spatial distance and spatial ordering.

Design Principle 5: *Take advantage of the motion parallax depth cue.* Although we studied mostly static illustrations, it is known to vision science [75] that motion and interaction are mechanisms that can increase depth and shape understanding of 3D models. Thus, it is important to also take advantage of interaction and movement in the computer-generated cutaway visualizations.

Comparing the design principles to previous works, we get:
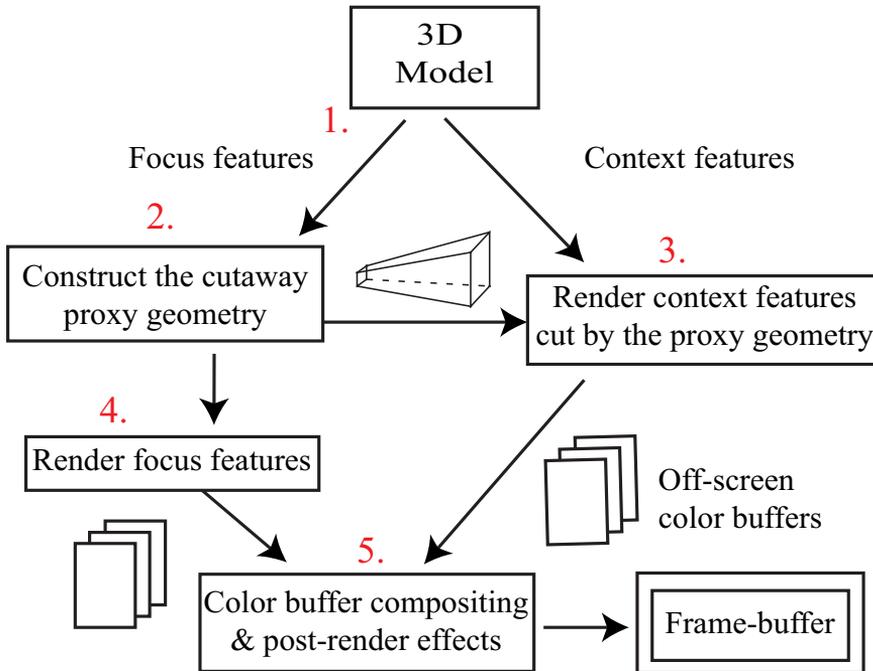
Figure 2: The proposed cutaway visualization pipeline.

Burns et al.: Their cutaway supports neither the oblique cutaway nor motion parallax depth cue. The cutaway shape is too complex for geological model and it is not possible to include context features in the cutaway.

Kubish et al.: Their work acknowledges the depth perception issues inside the cutaway and they suggest some illumination techniques to improve this. It does not support oblique cutaways, motion parallax depth cue, or simple cutaway shape needed for geological models.

Li et al.: Their work is strong on suggestions for lighting models for enhancing shape and topology of cut objects and it supports linking the focus features with the context. However, it requires predefined viewpoints and lacks support for oblique cutaways.

Even though some of the current cutaway algorithms cover some of the design principles, none of them covers all of the principles.

C.4   The Design Principles Realized

The input model to our cutaway visualization is a set of 3D polygonal objects. Our solution uses a *cutaway proxy geometry* for defining the *cutaway-volume*. This proxy geometry has initially the shape of a truncated rectangle-based pyramid with parallel front and back planes. The individual steps of our cutaway visualization solution are described below and also illustrated in Figure 2:
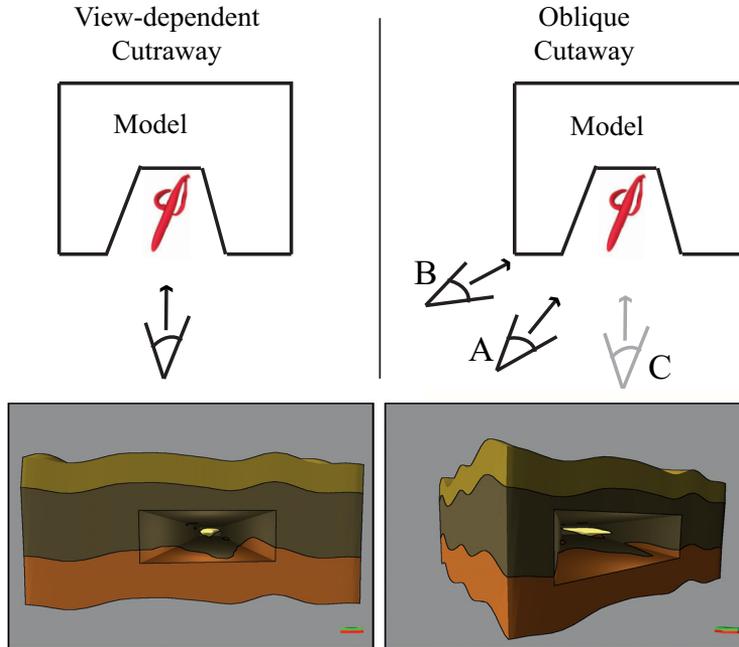
Figure 3: Top left: A schematic top view of a cutaway visualization where the camera points directly into the cutaway. *Top right:* The same cutaway, but with an oblique viewpoint. The cutaway proxy geometry is generated from the camera position C and the scene is rendered from the camera position A. Note: with large angles (camera positions B), the focus feature is occluded by the context. *Botttom:* The corresponding cutaway visualizations.

1. The polygon objects of the model are divided into two groups, one or more *focus features* and the *context*.

2. The cutaway proxy geometry is constructed based on the depth footprint of the focus features.

3. The context objects of the geological model are intersected by the cutaway proxy geometry and the cutaway walls are constructed. For each context object, the cutaway walls and the parts outside the cut volume are rendered to a separate off-screen color buffer. By rendering each feature to separate off-screen buffers, we can add compositing effects when synthesizing the final output image.

4. The focus features of the model are each rendered into separate off-screen color buffers.

5. After all objects are rendered, the off-screen color buffers are composited into one buffer. Compositing effects, such as silhouette rendering, can be applied in this step. In this final step, before copying the image to the frame-buffer, we can also add perception enhancing screen-space post-rendering effects.

In this section we describe in detail how to realize the design principles.
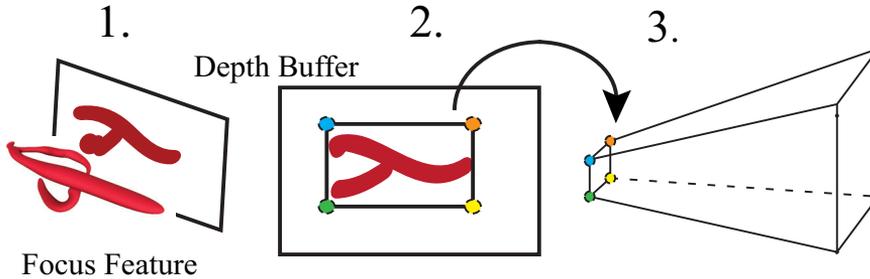
Figure 4: The back plane of the cutaway proxy geometry is constructed from the bounding rectangle around the depth footprint of the focus features (1) – (3)

C.4.1   Oblique Cutaway (DP1)

Thompson et al. [75] writes that a spatial frame of reference is needed to judge shape and distance. For a computer-generated cutaways this reference frame can be provided by drawing the cutaway with an oblique viewpoint. Provided this oblique viewpoint the observer can perceive the shape and depth of the focus objects against the side cutaway walls, something that is difficult with a direct-on cutaway viewpoint.

Constructing the Cutaway Proxy Geometry

To create the oblique cutaway we need to relax the tight coupling between the cutaway and viewing direction found in view-dependent cutaways. We apply one camera transformation to create the cutaway and another transformation to render the scene, see the illustration in Figure 3. Because of the change in view transformation we must create a polygonal model defining the cutaway volume, i.e., a *cutaway proxy geometry*, and this proxy geometry must be defined in model-space.

The proxy geometry we propose is initially frustum shaped, defined by 8 corner points. It is illustrated in Figure 4. The steps to define these 8 points are:

1. Render the depth footprint of the focus features to an off-screen depth buffer, (see (1) in Figure 4).

2. Extract the maximum depth value and the bounding box around the depth footprint, (see (2) in Figure 4).

3. Transform corners to view coordinate space, (see (3) in Figure 4).

4. Define the front plane depth value by finding the point in the model closest to the camera and then use its depth value, with a small offset, for the depth distance of the front plane.

5. The corners of the front plane of the cutaway frustum are calculated using the bevel angles, i.e., the slope of the sidewalls in the frustum. It is possible to specify individual bevel angles for each sidewall.

6. After all 8 corners are calculated, they are transformed to the model coordinate space. This is to enable the decoupling from the camera.

This algorithm is efficient enough to allow the recalculation of the cutaway proxy geometry whenever needed.
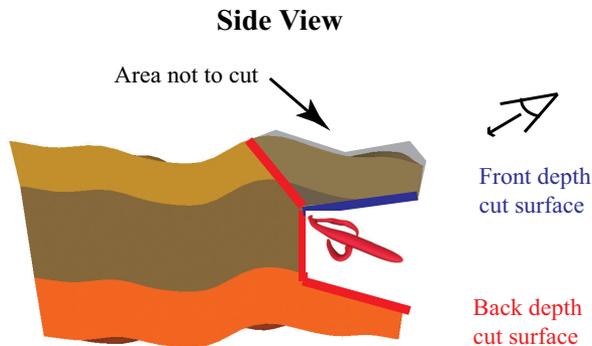
Side View

Figure 5: Side view of a cutaway visualization with a vertical angular offset. To preserve the semi-occluding area between the cutaway and the camera, we introduce the front (in blue) cutaway surface in addition to the back (in red) cutaway surface.

Creating the oblique cutaway

With the proxy geometry defined, cutting the context objects is done in the following three steps:

1) Extract the front and back depth cutaway surface

Current cutaway visualization solutions, such as Burns et al. [10] and Kubisch et al. [43], use only one (back) depth cutaway surface for intersecting the context. This makes it impossible to decouple the cutaway from the viewpoint as required by an oblique viewpoint cutaway, because all context in front is cut away. We introduce an additional (front) depth cutaway surface. With both a front and back cutaway surface, we ensure that only the context residing *inside* the cutaway volume are cut. The context outside, that could potentially occlude the focus features, are left uncut, see Figure 5.

Current graphics hardware does not support multiple depth buffers, thus we have to render to two separate off-screen buffers and perform the depth test in the fragment shader. Figure 6 illustrates the front and back depth buffers according to the following algorithm:

1. One off-screen buffer is attached as a depth buffer attachment to a frame buffer object (FBO) and initialized to minimum depth value (0.0). Depth test is enabled, with depth-function "greater". As the cutaway proxy geometry then is rendered, the surfaces of the geometry furthest away are recorded in the depth buffer. This is the back depth cutaway surface. We also render a diffuse light-map to a separate off-screen buffer during this step. This light-map is later used for shading the cutaway walls.

2. A second off-screen buffer is attached as a depth buffer attachment to an FBO and initialized to maximum depth value (1.0). Depth test is enabled, now with depth-function "less", thus this time the closest surfaces of the geometry are stored in the depth buffer. This is the front depth cutaway surface.

2) Rendering the cutaway walls

Similar to the other cutaway visualizations, we generate cutaway walls to produce the illusion of cutting into solid materials. The cutaway walls also provide a frame of
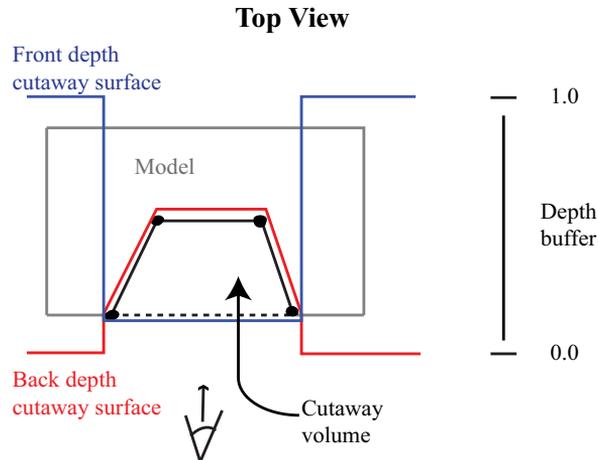
Figure 6: The cutaway volume is the space enclosing depth values that are larger than the front depth cutaway surface and smaller than the back depth cutaway surface.

reference for perceiving the depth inside the cutaway. We modified the stencil-buffer algorithm that Kubisch et al. [43] presented and which they adapted from Coffin and Höllerer [16]. This algorithm renders the context objects correctly without any prior sorting. For each fragment of each context object, we perform a stencil test to see whether the back cutaway surface is inside this context object. If the stencil test passes, we increase the stencil value each time a fragment from a front-facing polygon is rendered and decrease the value for each time a fragment from a back-facing polygon is rendered. We compute this for every fragment that is inside the cutaway volume. With modern graphics hardware, both tests can be done in one rendering pass.

After all polygons of a context object are rendered and if the stencil value is larger than the initial value, then we can conclude that the cutaway surface is inside this context object. We render the fragment to an off-screen color buffer. To resolve the case with context objects completely enclosed by other context objects we use a depth buffer with the depth-test set to "greater". This way we ensure that the fragment color of the context objects closest to the cutaway surface is the final cutaway wall color. The fragment colors are the diffuse material colors of the context object, shaded with the diffuse-light-map generated during the back depth cut surface extraction step.

The stencil buffer is cleared and the depth buffer containing the "greater" depth values is kept between each context object. In addition, we maintain a second depth buffer that stores all the depth values at the cutaway surface for every fragment written. The main difference between our algorithm and the one described by Kubisch et al. [43], is that we intersect with both a front and back cutaway depth buffer, we render to a set of off-screen color buffers, and we maintain a second depth buffer. Kubisch et al. calculate this second depth-buffer in a separate processing step.

3) Rendering the context outside the cut volume
With the depth buffer generated during cutaway wall construction and the front and back depth cutaway buffers, we render the context object again. This time we are

Side View

Cutaway without added context

Cutaway
Proxy
Geometry

Layer 1

Layer 2

Layer 3

Context Structure
Added to Cutaway

Final Back Depth
Cutaway Surface

Cutaway with added context
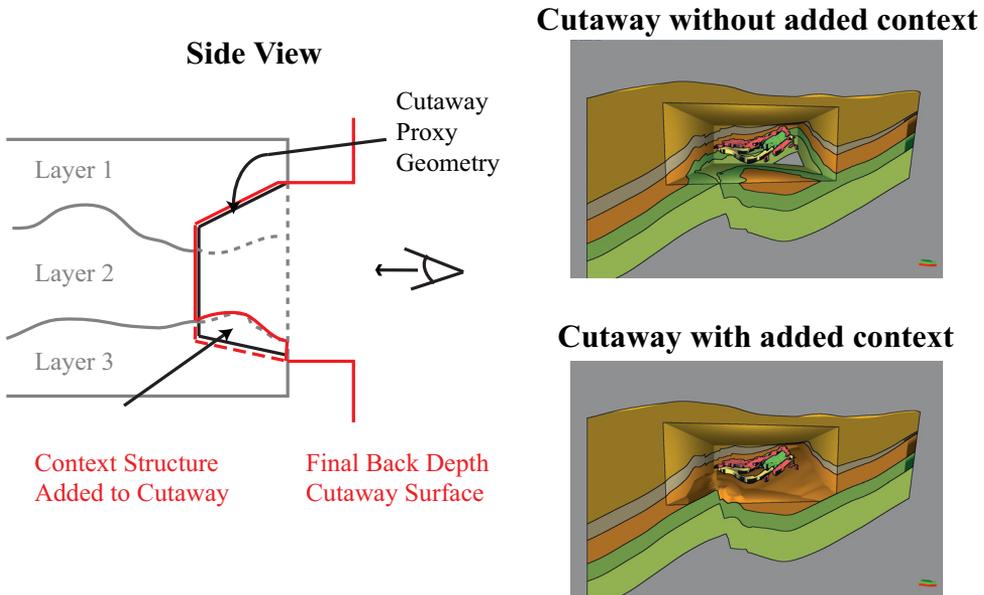
Figure 7: Adding structural parts from the context to the cutaway can be done during back cutaway depth surface generation. Compare the new back cutaway surface (solid red line) with the cut surface without the context structure added (dashed red line).

discarding fragments that either are inside the cut volume defined by the front and back depth cutaway buffers or further away from the accumulated depth buffer. The result is a set of off-screen color buffers, one for each context object.

C.4.2 Cutaway shape (DP2 and DP3)

The frustum shaped cutaway volume utilized so far conforms to DP2, i.e., a simple cutaway shape makes it easy to extrapolate the complete model and to understand how deep into the model the cutaway extends. With DP3, we argue that adding structures from the context to the cutaway volume can improve the understanding of the relationship between the focus features and the context. In addition, identifiable context structures in the cutaway can assist the viewer to understand where in the model the cutaway is made. The context structures are added to the back cutaway surface as part of the preparation step before cutting the context: After we have rendered the cutaway proxy geometry to create the back cut surface, then we render the context structures into the same FBO, now with depth-test set to "nearest". Figure 7 illustrates how the original back depth cutaway surface (in blue) is updated after the context object is rendered (in red). We recommend adding the horizon interface behind the focus features as context structures for the geological models we study, as shown in the result section.

C.4.3   Illumination models (DP4)

Much research has been conducted on shape depiction and inter-object interaction in general computer graphics, but much less attention is paid to objects inside cutaways. The exception is the work by Li et al. [45]. We emphasize that the illumination model applied when rendering the scene should effectively communicate the shape and spatial ordering inside the cutaway, as well as enhancing relationships between the focus features and the context. Some example of enhancing effects that can be realized during the rendering of the scene objects:

Context Connectivity Projection – To emphasize the relationship between the focus features and the context we propose to color parts of the focus features in the same color as the context object it relates to. For geological models, this relationship can for example indicate which geological layer (context) a channel (focus) belongs to. We implement the context connectivity projection as patterns painted on the surface of the focus features in the fragment shader used for the focus feature rendering. Surface color is based on the interpolated model-space coordinate of the fragment. If we consider only one dimension of this coordinate, stripes are produced, for two or three dimensions dots are produced. The user can adjust the frequency and the size of them. See Figure 12 for a demonstration of this effect.

Lighting – Carefully set lighting can enhance shape communication of an object. To communicate the shape and depth of the cutaway walls better we propose to set a point-light source in the opening of the cutaway when rendering the cutaway walls. Adjusting the attenuation factor of this light source enhances the impression of depth. This lighting setup is used on all images of the conceptual model in this paper. To avoid ending up with flat lighting on the focus features, we utilize the lighting from the upper-left hand side when rendering them.

Compositing is a per-pixel operation of copying pixels from the off-screen color buffers to the output color buffer, one color buffer at the time. Only foreground pixels are copied, i.e., the pixels in the color buffers to which the rendering pipeline actually rendered to. The compositing algorithm identifies foreground pixels through the value of the alpha byte of the pixels, as shown in the bottom image in Figure 8. The stencil buffer and the accumulated depth buffer utilization when rendering the context and the focus features ensures that only the visible parts are rendered to the off-screen color buffers. This simplifies the compositing of the buffers, as there is no need for visibility management. The only requirement is that the buffer sets are processed in the order presented above. The output buffer can be sent directly to the frame-buffer for screen rendering or we can apply screen-space post-rendering effects. Examples of compositing and post-rendering effects are:

Silhouette Outlines – Silhouette outlines are important for communicating the shape of an object and to separate overlapping objects. Isenberg et al. [35] give a good discussion of silhouette extraction and rendering techniques. In our implementation, we apply a Sobel-filter that detects the edges between foreground and background in the color buffer while processing the fragments during the merging of an off-screen buffer. If the fragment is on an edge, we draw the fragment in the silhouette outline color (most often black).

Shadows – Illustrators often use shadows to emphasize the distance between two overlapping objects or between an object and the background. Similar to Li et al. [45],
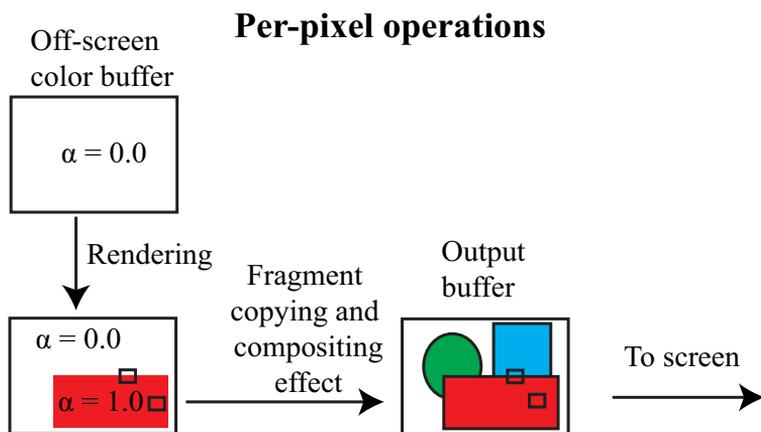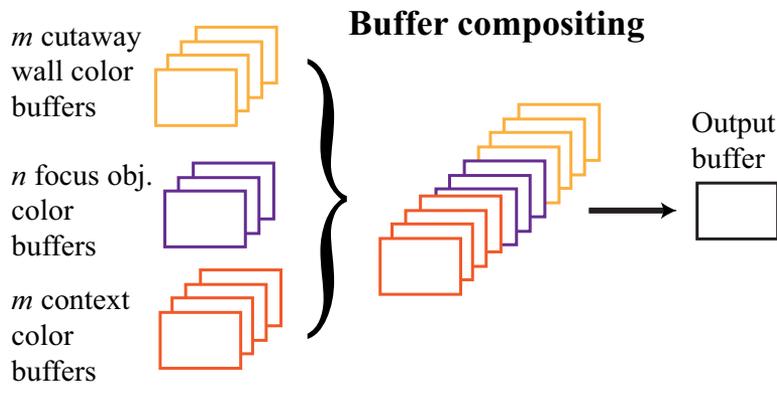
*Figure 8: Top:*The compositing of the off-screen color buffers. No object visibility management is required if the buffers are composited in the order shown. *Bottom:* Compositing is a per-pixel operation, one off-screen color buffer at the time. Only the foreground pixels (alpha value of 1.0) from the color buffers are copied into the output buffer, with possible compositing effects, such as in this example silhouette detection.

we also use the unsharp-masking technique by Luft et al. [49]. This is shown in Figure 12. In our implementation, we apply this effect on the output results from the compositing step.

C.4.4 Motion Parallax Depth Cue (DP5)

The effect of the motion parallax implies that when in motion, objects closer to the viewer seem to move faster than objects further away. This perceived difference in angular velocity can be used to communicate the spatial distance between objects. To take advantage of the motion parallax for cutaway visualizations we need to compare the angular velocity of the focus features against a fixed spatial frame of reference, the cutaway walls. Thus, the cutaway must be decoupled from the camera movements and not move when the camera moves. For the view-dependent cutaway visualizations, the

Top View
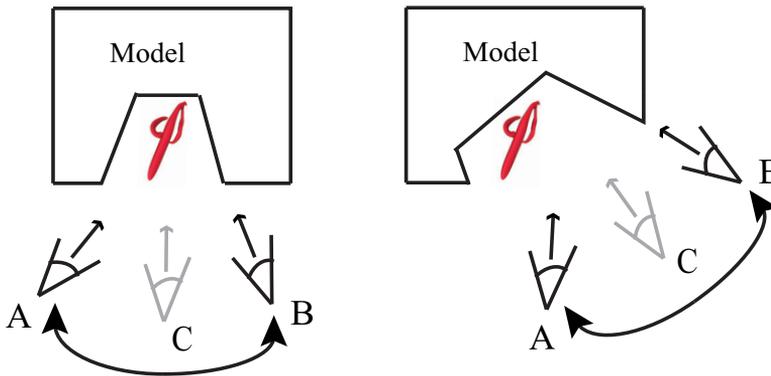
Figure 9: Illustrations of the threshold-based locked cutaways. *Left:* The camera can move between positions (A) and (B) without triggering recreation of the cutaway proxy geometry. *Right:* If the camera moves outside of these thresholds the cutaway automatically follows the camera until the camera moves in the opposite direction again and new thresholds are set.

cutaway will always moves together with the viewer, thus, the cutaway provides no fixed spatial frame of reference and the depth from motion is not well perceivable.

The cutaway proxy geometry is used to create the motion parallax effect. By completely decoupling the cutaway from the camera movements, we freeze the cutaway at a fixed location in the model. When rotating the camera, this fixed cutaway then provides the needed frame of reference. Completely decoupling the cutaway and camera can result in total focus feature occlusion if the camera is rotated too far, see camera position B in right image in Figure 3. This is why we propose a threshold-based fixed frame of reference cutaway. The user defines two angular threshold values and if the camera rotations are within these threshold values, the cutaway proxy geometry is not updated. When the camera rotates beyond these angular thresholds, the cutaway starts to follow the camera like the oblique viewpoint cutaway described in the previous subsection. This will go on until the camera is rotated in another direction, then the cutaway is fixed and the motion parallax is again more visible. Figure 9 illustrates the threshold cutaway.

C.5   Results and Discussion

Our cutaway visualization solution is implemented in the VolumeShop framework [8], because this framework has good encapsulations of OpenGL functions and good polygon-mesh rendering capabilities.

Our geological partners provided us with a geological model from the Ness-formation of the Oseberg offshore-oilfield in the North Sea. The focus features in this model are sand-filled channels. These channels represent ancient rivers and deltas with excellent reservoir properties, thus with high possibilities of containing oil and gas. Note that the voxelized shapes of the channels are caused by the conversion from a reservoir simulation grid. We wanted to preserve this shape in our visualization to
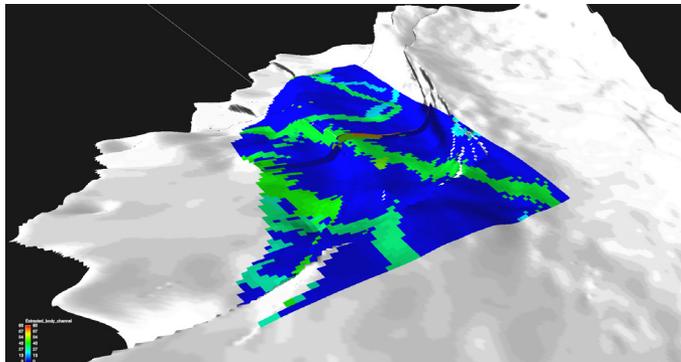
Figure 10: The picture shows how the channels from the Ness-formation are depicted together with the context in the domain specific application called Roxar Reservoir Management Software (RMS).

keep it similar to the way the domain experts visualize them. Figure 10, taken from the petroleum application Roxar RMS, shows a typical visualization of these channels. In order to study the channels together with the context, they are projected down to the underlying geological layer surface, thus losing the spatial ordering and the actual position.

First we selected three of the main channels as focus features and visualized them in the context of the complete Ness formation geology model. The visualization is shown in Figure 11.

Moving to a viewpoint closer to the channels, like the one applied in Figure 12, shows the advantage of adding parts of the context in order to understand the channels better. See for instance in the far end of the picture how it becomes clear why the discontinuities in all three channels are elevated above the main channel parts. Despite the large cutaway of the context in this model, the mapping of context layer color onto the channel (the orange spots) efficiently communicates the relationship between the channels and the geological layer they reside in.

Then we cropped the Ness model around some potentially interesting channel features. This visualization is shown in the right image of Figure 1. One can see the perceptual improvement given by using the simple cutaway shape and the added surface layer below the channels (added context information). For instance, it is easier in this picture to perceive which geological layer the channels reside in. This figure also demonstrates the oblique viewpoint cutaway. Here the depth of the cutaway, i.e., the relative distance from the front of the geological model to the focus features, is clearly communicated.

We also obtained the coordinates of one of the wells in the Oseberg Field and this well is included in Figure 13. Note that this is a different crop-out section of the Ness formation than in the previous images and that the well also continues down to formations below the Ness formation. We think this image demonstrates a big potential for cutaway visualizations during well path planning and verification, which we want to explore in the future.

We have shown our cutaway visualizations to the domain experts, including two geologists and two other experts from our collaborating company in the oil and gas in-
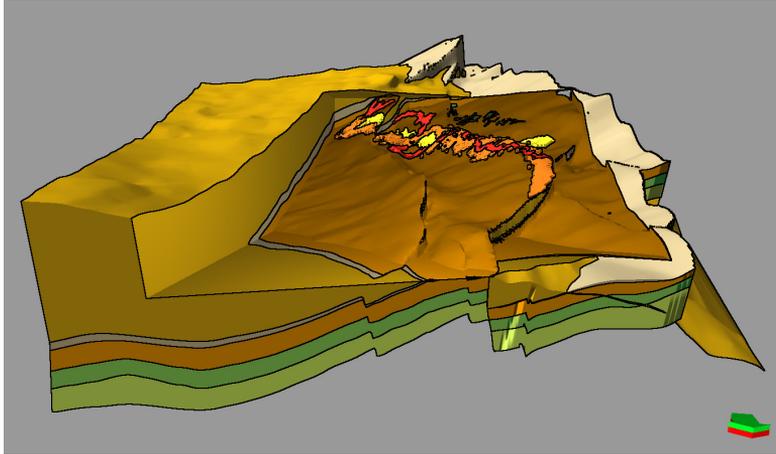
Figure 11: The picture shows the full-field cutaway visualization of the geological model of the Ness formation.

dustry, and three PhD students from the Department of Earth Science at our university. They have all confirmed the increased perceptual improvements in the cutaway visualizations that follow our design principles. They also emphasized the importance of seeing the focus features in relationship with the context. Therefore, they especially appreciated that the cutaway shape can include identifiable context and the projection of context layer color onto the channels.

C.6   Conclusion and Future Work

With this work, we wanted to provide new, expert-authored, interactive visualization of the features found inside 3D geological models. We have shown that the previous computer-generated cutaway visualization methods have limitations when attempting to communicate the focus features visually. Reasons for these problems lie in the complex shape of the features of these models. Based on knowledge from the vision and perception science, inspiration from geological illustrations, and interviews with geological illustrators and domain experts we have formulated five design principles for computer-generated cutaway visualization. We believe that these design principles increase the perception of models from the geological domain when using cutaways as occlusion management method, similar to the illustrators' approach. Domain experts have also confirmed the improvements we claim.

A natural extension to our work is to conduct a larger user study to quantify the benefits and identify the optimal applications of cutaway visualization for models from the geological domain. This will also include adding more geological structure types in the visualization. For instance, we believe that faults could be used to contribute to the cutaway shape. Another possible extension is to perform a systematic analysis of geological work-tasks and types of geological models, and then create a system to automatically select the better depth and shape enhancing cues. This would be similar to the work that Cipiloglu et al. [14] have done for general 3D scene rendering.
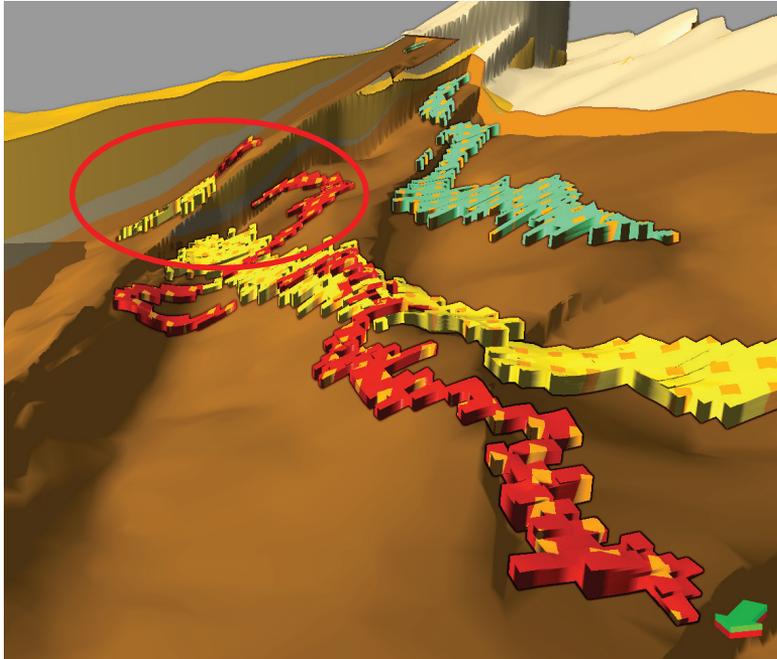
Figure 12: In this close-up of the channels, we see the advantage of adding parts of the context, in this case the layer below the channels, to the cutaway shape. This added context explains why there is a discontinuity and displacement in the far end of the channels (highlighted in red in picture). We are also rendering the color of the context layer as spots on the channels to emphasize the context relationships.
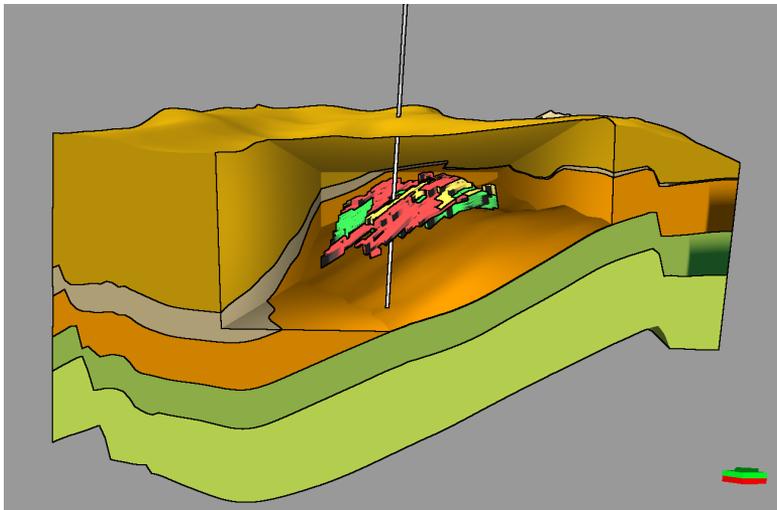
Figure 13: The picture shows a cutaway visualization together with one of the wells from the Oseberg field. This well penetrates the Ness formation before it continues down to other reservoir formations.

Acknowledgments

PAPER D

RAPID, SKETCH-BASED MODELING OF 3D GEOLOGICAL MODELS

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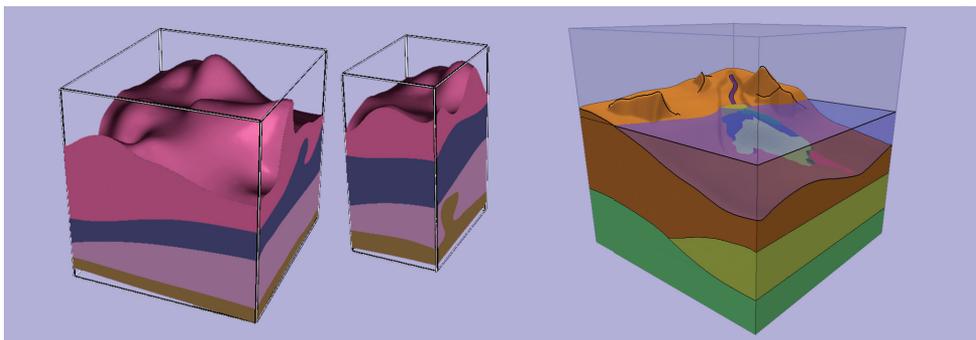
Figure 1: Left: an uncut and a cut solid model made with our generic approach. Right: A model made with our ad-hoc approach.

Abstract

We present and compare two different approaches for performing rapid 3D geological modeling. The ad-hoc approach is based on a composition of many specialized modeling functions, while the generic approach provides

D

one powerful, generic modeling function. Our experiences after developing these two approaches are that the solution space of 3D geological modeling is more extensive than we initially expected and most likely larger than for other modeling domains such as architecture. Further, more research is needed to investigate whether it is possible to find one well defined toolset of sketching metaphors that is able to cover all of geological modeling.

D.1   Introduction

Geometric 3D modeling is an essential technology for a wide range of disciplines. In principle, all objects, from every domain of origin could be modeled by a set of *generic* simple operations, for example operating on vertices and normals of the polygonal mesh. However, such modeling approach would be very time-consuming and the domains express a need for technology that allows for a more rapid modeling process. Therefore, several *ad-hoc* modeling approaches have been developed that simplify and speed-up the modeling process based on underlying rules, constraints, and principles of the particular domain.

In geology, constructing precise models of geological structures takes months and it is a labor-intensive task. This is highly impractical in scenarios where the geologists would wish to express their initial thoughts as a basis for discussion about the structural arrangement of a particular sub-surface zone. This domain therefore calls for rapid 3D geological modeling technology, where precision is traded for speed of modeling. Geologists expressed a vision to have a "Sketchup for Geology" inspired by the popular 3D architectural modeling software [76]. For scientific investigation, this metaphor is helpful for having a clear goal in mind, but surprisingly little can be adopted from it.

Modeling approaches can roughly be categorized into modeling of man-made and of natural objects. Man-made objects often have a simple structure, which can be constructed using three-dimensional geometric primitives. A typical example is architectural modeling, perhaps the most simple modeling scenario, where the modeling process can take advantage of a number of modeling constraints, such as the right-angle constraint between the walls and the floor. A second representative of this category is modeling for manufacturing, where various mechanical parts are on average more complex in shape than architecture, but they typically have distinct boundaries, and models often contain many instances of identical objects. Modeling of natural shaped objects adds another level of complexity, because instances of the same object vary in detail, often important details are present on various scale levels. One complex modeling scenario from this category is geology. Geological objects have complex topology, there is in general little symmetry, and the boundaries between geological bodies are not well defined [77].

In this paper, we present and discuss two different approaches to accomplish rapid 3D geological modeling. One approach contains a set of ad-hoc modeling operations for capturing the typical geological objects, known from hand-made geological illustrations, while the other approach uses a more *generic* technology. Our contributions are: 1) two novel approaches for rapid geological modeling, 2) a comparison of these two complementary approaches.
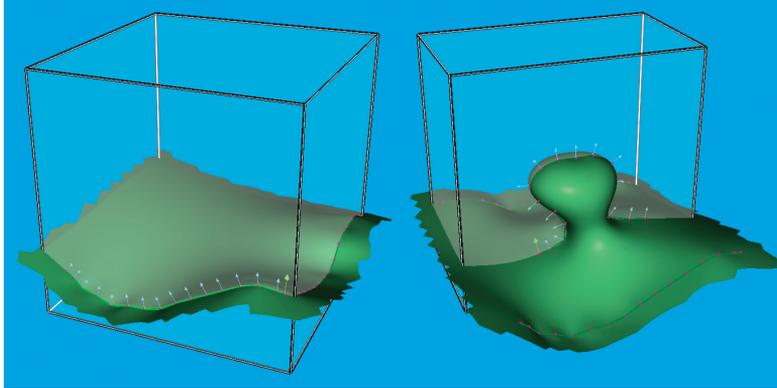
Figure 2: Left: Surface defined by two curves, one on the right side of the bounding box and one in the front shown with normals. Right: A surface with multiple z-values.

D.2 Related Work

Sketch-based modeling techniques have proven to be a rapid and intuitive way of performing computer-based modeling [59]. But, there are few works that address sketched-based modeling for the geological domain. Exceptions are the works by Natali et al. [58] and Lidal et al. [48], however, both of these works base their modeling on 2D sketches, while the focus of the projects we present in this paper is true 3D sketching. There exists a large body of work in modeling of terrains, either through sketching or procedural modeling techniques. Natali et al. [57] provides an overview of these methods. However, as they point out, surface terrain modeling is often only one of several tasks needed to produce 3D subsurface geological models. Our generic approach is based on work by Brazil et al. [6] and the ad-hoc approach is described in more details in [4].

D.3 The Generic Approach

This prototype consists of two properties. The first property is the ability to create a stack of surfaces for defining the boundaries between stratigraphic layers. The second property is the representation of these layers as solids, which can be clipped into by using a bounding box.

A surface is created by sketching interpolative curves in 3D (Figure 2). Each curve is represented as a set of points, where each point has an associated normal. The collection of points with normals from all the curves represent a sparse sampling of the surface. The complete surface is reconstructed by interpolating all the points, while keeping the surface orthogonal to the normals. This is achieved using the Variational Hermite Radial Basis Function method [6]. This method produces an implicit function describing the surface. The implicit function is sampled to find points on the zero-surface, which are then triangulated within the extents of the bounding box and then visualized.

The curves are defined in 3D by drawing them on the sides of the bounding box,
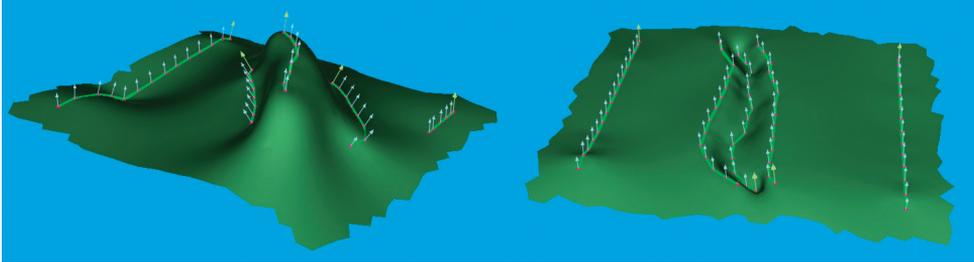
Figure 3: A sketch of a mountain (left) and river (right) with normals on all curves shown.

which acts as a proxy-geometry for projecting the user strokes on the 2D screen into 3D. This box is depicted in Figure 2. Each side of the box can be moved in a direction normal to the side surface. The normals to a curve are in the plane of the proxy surface. These default normals can be overridden by the user by specifying an additional rotation angle around the curve tangent. Figure 3 shows two surface examples, where the three center curves define a mountain and a river, respectively. The three curves are drawn on the top surface of the bounding box at different heights and the normals were rotated around the curve tangent to achieve the intended surface slope.

Defining interpolating curves with normals is a mathematically well defined metaphor. It makes it possible to produce a wide range of complex shapes, including geological features such as mountains, hills, valleys and rivers. The method is also well suited for creating surfaces that match with field measurements, which often consist of curves and the accompanying surface normals. In addition, it is possible to define surfaces with multiple z-values, which is important for modeling for instance salt bodies found in the subsurface (Figure 2, right). Defining certain shapes might be time consuming for the user as it requires the user to define many curves. Also, there are usually several alternative ways to define the curves for creating a specific surface. Fitting the surface to the curves is computationally demanding and the performance depends on the number of input points.

The modeled surfaces ordered in depth, pairwise define a stack of layers. The side surfaces of a bounding box can be adjusted to cut into the model, to reveal its inside features. For each side of the bounding box, intersection with it and all sketched surfaces is calculated using the CGAL library [13]. For each side surface of the cube, each layer will be described by a top and a bottom curve that are triangulated and assigned the layer color. The two left images in Figure 1, show an example of a solid model defined by five surfaces and how the model is cut into by adjusting the size of the bounding box.

The tool was tested by domain experts from a leading oil company. They reported that the surface sketching metaphor was easy to use and easy to create complex surfaces. They found it efficient to create cross sections using the bounding box. Features that were requested was the ability to define faults and more general ways to deform surfaces without having to individually change the curve sketches.
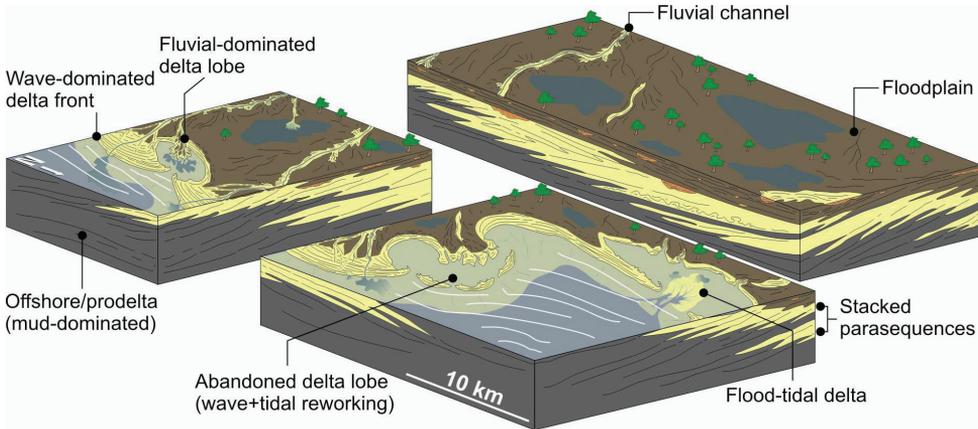
Figure 4: Sketches made by sedimentologists contain a combination of terrain modeling and subsurface geological layer modeling. The sketches depict depositional environments and the associated depositional architectures.(Courtesy of Sten-Andreas Grundvåg.)

D.4 The Ad-hoc Approach

The second research project for rapid sketching of 3D geological models we present has been carried out in close collaboration with sedimentology geologists, including a professor and a master-level student. Figure 4 shows examples of sketches that a sedimentologist would make. The sketches contain a combination of terrain modeling and modeling of subsurface geological layers. From these types of sketches and through discussions with the sedimentologists, we have identified the need for expressing the following geological features: layers, shorelines and sea-level, mountains and ridges, rivers and valleys, vegetation, and sedimentary deposits. Below we describe the system in the light of the discussion of this paper.

To provide an intuitive canvas for performing 3D sketching, we provide the geologists with several proxy geometries onto which they can draw their sketches. The first proxy we provide is the semi-transparent *box-proxy* where curves sketched are projected onto the box (Figure 5, *left*). These curves represent the intersection between a top or bottom surface of a geological layer and the box-proxy. The geologists sketch on one or more of the box sides and a surface is interpolated between these lines and a layer is constructed between two such surfaces (Figure 5, *right*). The surface interpolation method applied is a simple linear interpolation between the opposing sides of the box. We chose this simple interpolation method over more complex methods, such as Inverse Distance Weighting [70], to enable the geologists to easily predict the shape of the interpolated surface. If the geologist wants to update the layer she can over-sketch the box intersection curves. The solution also supports layers that terminate onto other layers, e.g., as shown for the olive-green layer in the right of Figure 1.

The second sketching proxy-geometry we provide is the layer top surface, activated when the user selects it. Sketched curves are now projected onto this proxy-geometry instead of onto the box geometry. For each sketched curve, the user can define it as a river, a ridge/mountain or a valley (Figure 6, *left*). River or valley curves will lower the surface geometry locally, whereas ridge and mountain curves raise the surface locally.
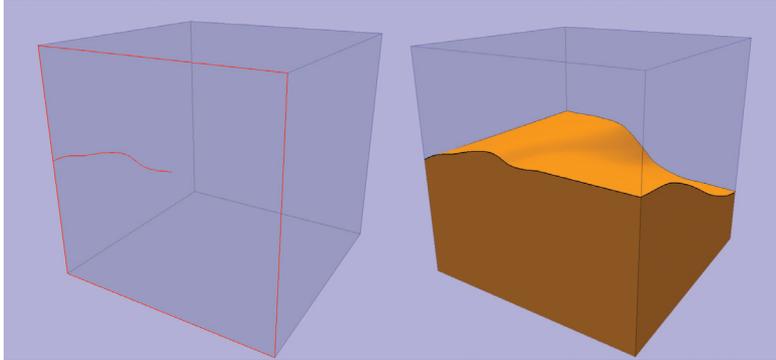
Figure 5: Left: We propose a box shaped proxy-geometry to provide a spatial anchor for the 3D sketches. The curves sketched represents the intersection between a layer surface and this box. *Right:* These curves are then interpolated to surfaces and a solid model of the layer is created.
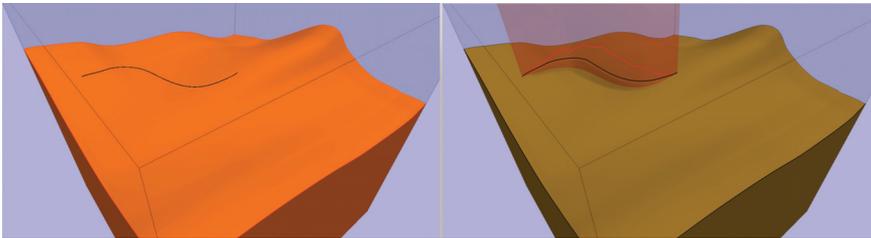

Figure 6: Left: Adding terrain details to a surface utilizing the surface proxy-geometry. *Right:* Sketching the height of a ridge on a fence proxy-geometry.

The third proxy we provide is a fence proxy, utilized when we sketch ridges and mountains (Figure 6, *right*). This proxy is inspired by the terrain sketching work described by Gain et al. [27] where the geologist indicates the height profile.

The features we now have described are sketched through a set of specialized sketching functions. Each feature has been added due to specific needs from geologists. Therefore we denote this rapid 3D modeling approach for *ad-hoc modeling*. Examples of other specialized functions we could add based on user feedback are vegetation, annotations and lines to indicate structures on the surface.

Figure 1 right, shows all the implemented features included in one sketch. Figure 7 shows a comparison of an illustration from a textbook in geology with the result produced in our project. A limitation in our reproduction is that we can only reproduce the glaciers to a limited degree, the smaller glacier arms cannot be modeled. We could add a specialized glacier modeling function, similar to the rivers and mountains, thus extending the functionality *ad-hoc*-ly.

We have run a preliminary user-study of our modeling system on four geology students at a master-level. The feedback from the participants was positive. One user said he never had experienced a tool for creating simple illustrations this easy to use. Even though the potential of our method was noticed, most participants pointed out that the support of more features are needed. These include sketching faults and setting the width of mountains and valleys [4].
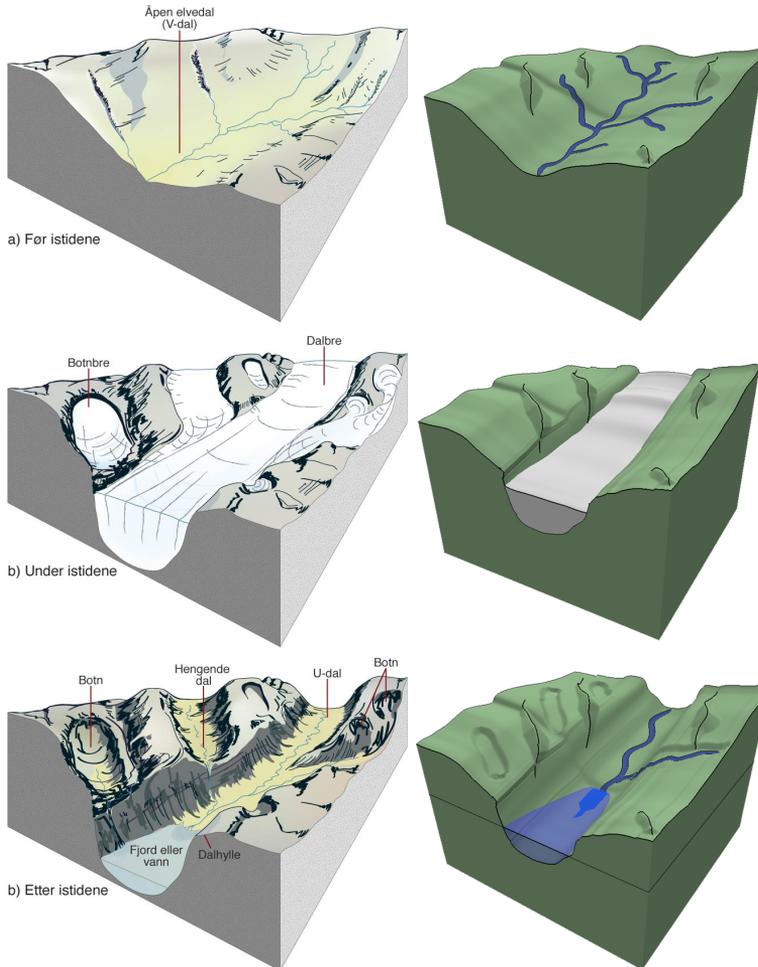
Figure 7: A comparison between illustrations from a textbook [24] (*left*, courtesy of Haakon Fossen) and the reproduction of these sketches in our project (*right*).

D.5   Discussion

The solution space: Our initial goal was to identify and create a tool that addresses the geologists' needs for rapidly producing geological models. The two prototypes we have briefly described are the first attempts to produce such a tool. They are different and show a subset of the possible variations and design choices that exist. The prototypes can be considered two samples in the space of possible solutions. We believe now that this solution space is larger than what we initially considered it to be. One reason for this is that the field of geology has many alternative ways of creating a geological model depending on what it will be used for and on which features that should be modeled.

Collaboration with domain experts: The domain of 3D sketch-based modeling for geology is new and under-explored. Thus, close collaboration with domain experts is vital to secure good solutions. Problems with user guided research in a new domain is

that these (few) domain experts will have a strong influence on the final solution and it can result in a tailor-made solution to subproblems in the domain. This can be avoided by including many different domain experts to get a broader image. However, the diversity in needs from the different branches of geology can produce an incompatible list of requirements, with conflicting wishes, e.g., whether to focus on modeling features on the top surface or not. This makes it hard to converge to one general solution that fits all. Further investigations are needed to verify if a general sketching solution indeed is possible.

Generic versus Ad-hoc approach: The ad-hoc approach solves specific problems with specific tools, i.e., one tool for creating mountains, another for creating rivers. These tools make it very easy for the user to quickly draw structures accurately, but limited to the functions implemented. The generic approach has only one way for defining the surfaces, which is unbound to any semantic. Therefore, a large diversity of shapes can be modeled, but at the cost of increased time and more complex interaction. This represents two different approaches to identifying wanted behavior of a geological sketching tool. For the ad-hoc approach, a use scenario is first identified and then a solution is implemented. For the generic approach, a generic solution is first introduced to users with the intention that they will experiment to identify the use scenarios that have high impact in their domain. Which approach to apply depend on the domain. In a narrow and well defined domain (such as architecture), it can be possible to directly create an ad-hoc tool. If the domain is large or of unknown size (geology or medicine), it might be advantageous to start with a generic tool and through a dialog with the user, ad-hoc tools can crystallize out when testing the generic tool.

D.6   Conclusions and Future Work

We have presented and compared two different approaches for rapid 3D geological modeling. From the experiences we have made we can conclude: The solution space of geological modeling is much larger than we expected at the beginning; This space is much larger than for other modeling domains, such as architecture, thus it is not straightforward to develop a "Sketchup for Geology"; Much research is still needed to investigate if the ad-hoc approach or the generic approach is the most applicable approach for geological sketching and if it is possible to converge to a few sketching metaphors covering all of geology.

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Errata for
Sketch-based Storytelling for Cognitive Problem Solving

Externalization, Evaluation, and Communication in Geology

Endre Mølster Lidal

Thesis for the degree philosophiae doctor (PhD)

at the University of Bergen

(signature of candidate)   _(signature of faculty)_
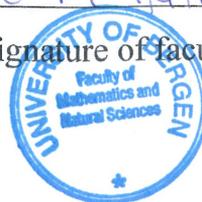
June 3rd 2013

Errata

Page xi "**Paper B:** […], accepted for *Computers & Graphics,* 2013" corrected to: "**Paper B:** […], in *Computers & Graphics,* vol.37, no.5, pp.445-459, 2013"

Page xi "**Paper D:** […], submitted to *Workshop on* […]" corrected to "**Paper D:** […], accepted for *Workshop on* […]"

Page 71(footnote) "This article is accepted for publication in *Computers & Graphics,* 2013[…]" corrected to "This article is published in *Computers & Graphics,* 37(5), 2013[…]"

Page 117(footnote) "This article is submitted to *Workshop on Visualization in Environmental Sciences (EnvirVis),* 2013" corrected to "This article is accepted for *Workshop on Visualization in Environmental Sciences (EnvirVis),* 2013. Note, the version included here is the submitted version of the paper, because the camera-ready version was not available at the time of the dissertation submission."