

# 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.*

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications—

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## 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. [BGSJ07]. 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

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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.

## 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 [GP01] and scientific visualization [MLF\*12]. Wohlfart and Hauser [WH07] 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 [JKM01] 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 [MAB\*97]. 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 [HS05]. Hoeben and Stappers [HS05] 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 [Nak06] and Johnson et al. [JGHY07] present other tools for sketch-based prototyping, such as the ART019 work by Yamamoto [YNNA06] or "The Electronic Cocktail Napkin" by Gross and Yi-Luen Do [GD96]. 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. [WFR\*10] 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 [SFC07] presented by Silva et al., uses provenance as a 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 [KNS04]. 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. [PGT\*08] 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 [Tur05], 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 work-

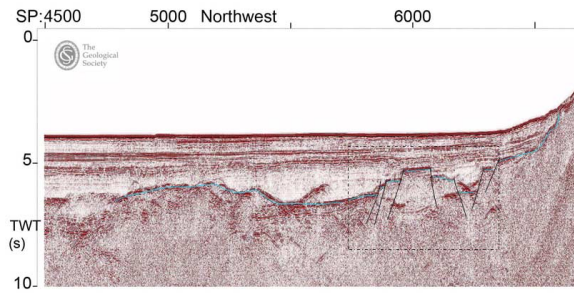


Figure 1: An example of a 2D seismic slice with an interpretative sketch. Such an interpretation is the starting point for an early-stage geological model. The example was made in Microsoft PowerPoint by one of our collaborating geologists. The seismic slice is called "WESTLINE shotpoints 4500-8500" and it is public available through the Virtual Seismic Atlas [Vir11]. We use this seismic slice as an example throughout this paper.

flows in oil and gas exploration can for instance be found in [Cos01].

### 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 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 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.

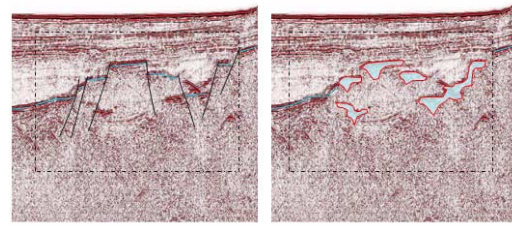


Figure 2: Close-up images of two very different interpretations from the exact same position on the seismic slice. These interpretations will result in two very different geological models. Also made in Microsoft PowerPoint by one of our collaborating geologists.

Domain specific modeling software packages, such as Petrel [Pet11], 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. Other 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 [Cor11] 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.

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.

#### 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

#	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.

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 story*. We call the individual geological events in story for *story nodes*, similar to the terminology used by Wohlfart and Hauser [WH07]. 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*.

#### 4. Telling Geological Stories

Our concept of geological storytelling consists of three main components:

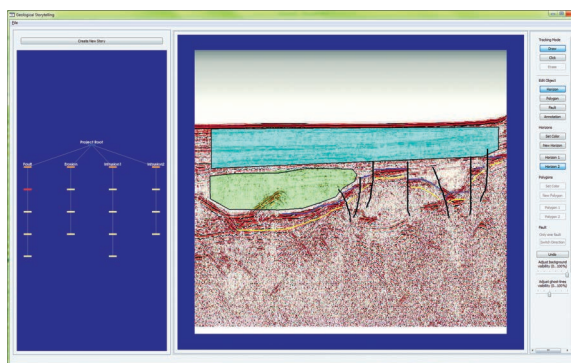


Figure 3: The main window of our geological storytelling prototype. To the left is the StoryTree depicting alternative stories. In the middle is the canvas sheet where story nodes can be sketched. The canvas is a virtual flip-over, providing unlimited number of sheets.

**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.

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.

#### 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 drawing 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 [Wac11]. 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 be seen in our supplementary video. The user can

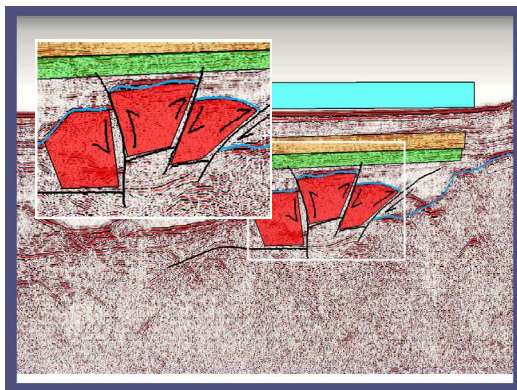


Figure 4: A screen shot showing examples of all the drawing primitives available in our prototype.

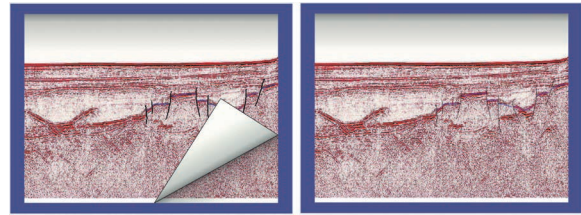


Figure 5: *Left:* When the geologist has completed a story node she flips over the canvas to get a new sheet for the next story node. *Right:* To aid the author, the sketches from the previous story node is visible as faint, ghost lines on the new story item canvas.

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.

#### 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 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.

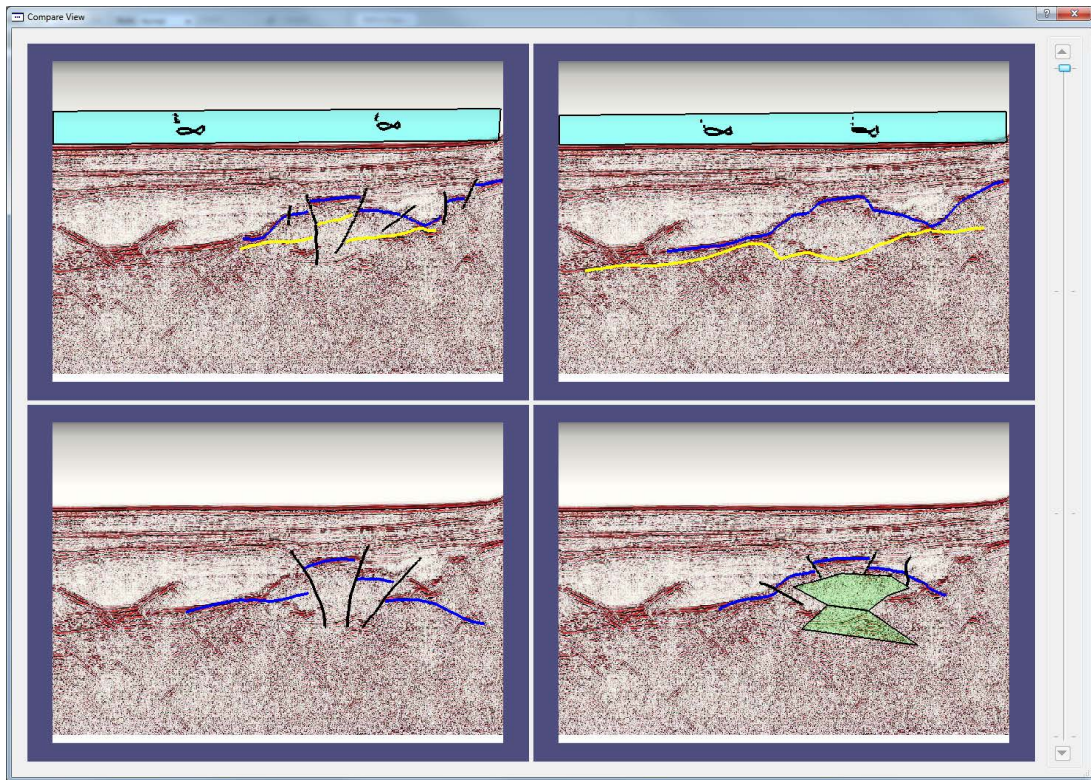


Figure 7: A screen shot of the InspectView comparing four distinct geological stories. All the views are synchronized with the time step slicer on the left hand side. In this view the geologist can visually compare, side-by-side, different geological stories to find the most plausible ones.

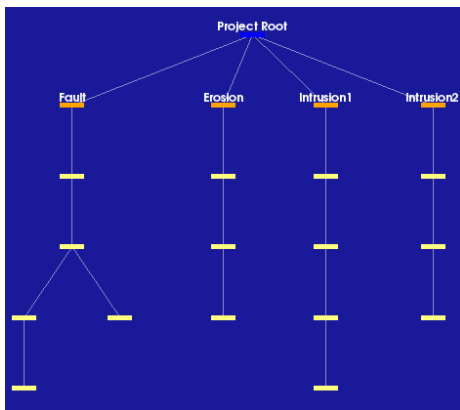


Figure 6: The StoryTree with four stories of different story length and with branches. A branch indicates that different geological event-trails may lead up to the same, later story node.

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.

#### 4.3. Evaluating Geological Stories

The InspectView is our proposed solution to the requirements presented in Section 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.

#### 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.

#### 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 [Vir11]. Note that the stories are only examples and not necessary reflecting geological

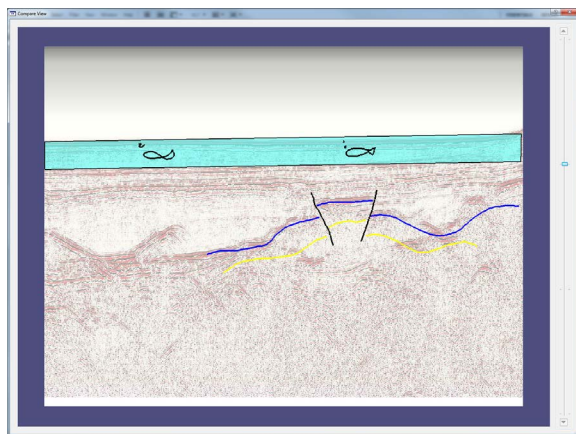


Figure 8: A screen shot of the InspectView playing a single geological story. From the time line slider to the right we see that the view now shows story node number two of a total of four story nodes. In this view the geologists can visually evaluate the geological soundness of the sketch.

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.

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 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

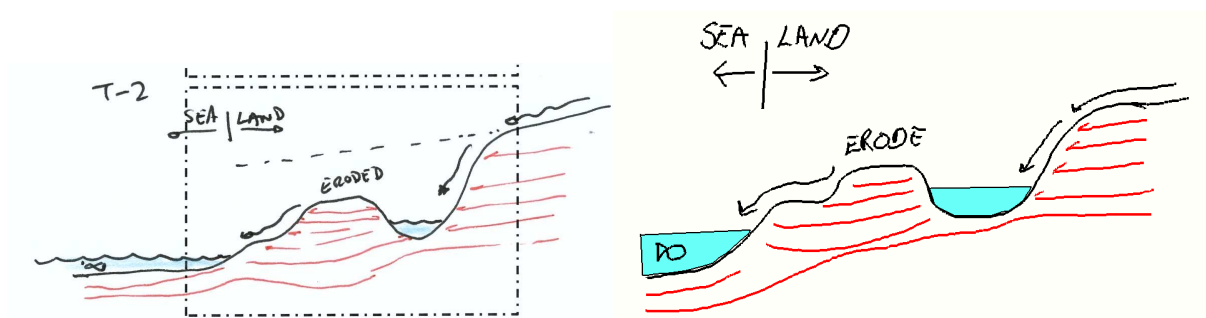


Figure 9: To the left: A hand drawn sketch showing one story node from a longer story about an erosive geological model. It was made by one of our collaborating geologists. To the right: The same story node, but this time reproduced in our geological storytelling prototype.

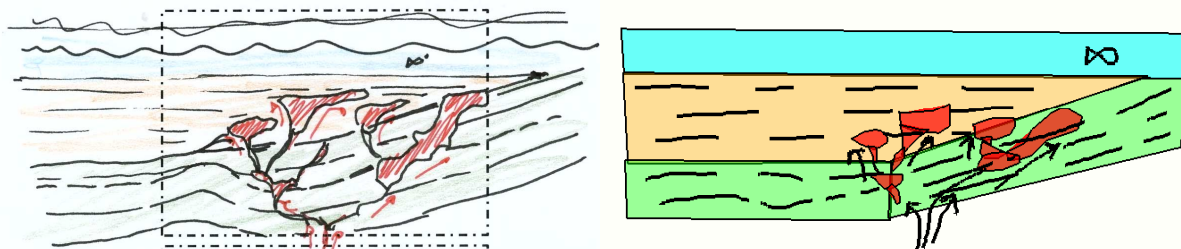


Figure 10: To the left: A hand drawn sketch showing one story node from a longer story about an intrusive geological model, also made by one of our collaborating geologists. To the right: The same story node, but this time reproduced in our geological storytelling prototype.

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 [Dec] 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.

## 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.

## 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. [BMa10], 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.

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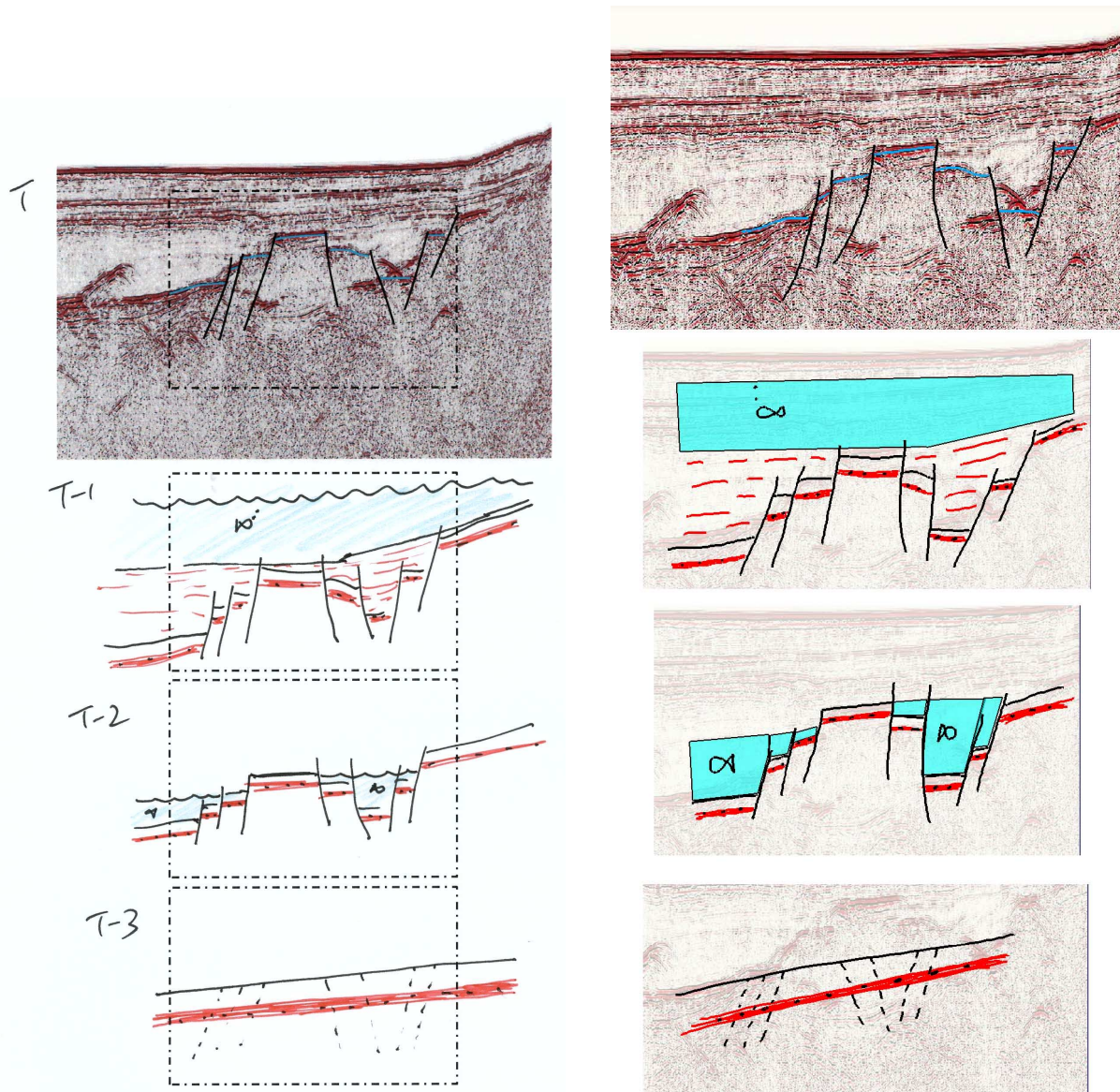


Figure 11: The hand drawn sketch to the left was made by one of our collaborative geologists after we explained our concept of a geological story. It shows an imagined geological story of the seismic slice shown in the top of the figure (Today). This particular story shows how a fault system has evolved 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.

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