Sketch-based Modelling and Conceptual Visualization of Geomorphological Processes for Interactive Scientific Communication

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Abstract

Throughout this dissertation, solutions for rapid digitalization of ideas will be defined. More precisely, the focus is on interactive scientific sketching and communication of geology, where the result is a digital illustrative 3D model. Results are achieved through a sketch-based modelling approach which gives the user a more natural and intuitive modelling process, hence leading to a quicker definition of a geological illustration.

To be able to quickly externalize and communicate ones ideas as a digital 3D model, can be of importance. For instance, students may profit from explanations supported by interactive illustrations. Exchange of information and hypotheses between domain experts is also a targeted situation in our work. Furthermore, illustrative models are frequently employed in business, when decisional meetings take place for convincing the management that a project is worth to be funded.

An advantage of digital models is that they can be saved and they are easy to distribute. In contrast to 2D images or paper sketches, one can interact with digital 3D models, and they can be transferred on portable devices for easy access (for instance during geological field studies). Another advantage, compared to standard geological illustrations, is that if a model has been created with internal structures, it can be arbitrarily cut and inspected.

Different solutions for different aspects of subsurface geology are presented in this dissertation. To express folding and faulting processes, a first modelling approach based on cross-sectional sketches is introduced. User defined textures can be associated to each layer, and can then be deformed with sketch strokes, for communicating layer properties such as rock type and grain size.

A following contribution includes a simple and compact representation to model and visualize 3D stratigraphic models. With this representation, erosion and deposition of fluvial systems are easy to specify and display. Ancient river channels and other geological features, which are present in the subsurface, can be accessed by means of a volumetric representation.

Geological models are obtained and visualized by sequentially defining stratigraphic layers, where each layer represents a unique erosion or deposition event. Evolution of rivers and deltas is important for geologists when interpreting the stratigraphy of the subsurface, in particular because it changes the landscape morphology and because river deposits are potential hydrocarbon reservoirs.

Time plays a fundamental role in geological processes. Animations are well suited for communicating temporal change and a contribution in this direction is also given.

With the techniques developed in this thesis, it becomes possible to produce a range of geological scenarios. The focus is on enabling geologists to create their subsurface models by means of sketches, to quickly communicate concepts and ideas rather than detailed information.

Although the proposed techniques are simple to use and require little design effort, complex models can be realized.

Publications

This thesis is based on the following publications:

Paper A: **Mattia Natali**, Ivan Viola and Daniel Patel. Rapid Visualization of Geological Concepts. In *Proceedings of SIBGRAPI Conference on Graphics, Patterns and Images*, 2012, pp. 150–157.

Paper B: **Mattia Natali**, Tore Grane Klausen and Daniel Patel. Sketch-Based Modelling and Visualization of Geological Deposition. In *Computers & Geosciences 67C*, 2014, pp. 40–48.

Paper C: **Mattia Natali**, Julius Parulek and Daniel Patel. Rapid Modelling of Interactive Geological Illustrations with Faults and Compaction. In proceedings of *Spring Conference on Computer Graphics (SCCG)*, 2014.

The following publications are also related to the dissertation:

Paper 1: **Mattia Natali**, Endre Mølster Lidal, Julius Parulek, Ivan Viola, Daniel Patel. Modeling Terrains and Subsurface Geology. In *Proceedings of Eurographics 2013 (STARs).*

Paper 2: Endre Mølster Lidal, **Mattia Natali**, Daniel Patel, Helwig Hauser, Ivan Viola. Geological Storytelling. In *Computers & Graphics 37*, 5 (2013), pp. 445–459.

Moreover, the following articles on non-related topics were published during my Ph.D. studies:

Paper I: **Mattia Natali**, Silvia Biasotti, Giuseppe Patané, Bianca Falcidieno. Graph-based Representations of Point Clouds. In *Graphical Models 73*, 5 (2011), pp. 151–164.

Paper II: **Mattia Natali**, Marco Attene, Giulio Ottonello. Steepest Descent Paths on Simplicial Meshes of Arbitrary Dimensions. In *Computers & Graphics 37*, 6 (2013), pp. 687–696.

I am the main author of all the papers listed above except for Paper 2, where I contributed with implementation and a description of the automatic generation of 3D illustrative animation from 2D animated sketches. Paper 2 was co-authored with Endre Mølster Lidal, who was my fellow PhD student in the GeoIllustrator project at the time the paper was written.

My thesis is based on Paper A, Paper B and Paper C. The research conducted to produce these three papers was guided by both Daniel Patel and professor Ivan Viola, respectively my main supervisor and my co-supervisor. They also contributed to the writing of Paper 1 and Paper 2.

Tore Grane Klausen, who received his PhD in geology in 2013 as part of the GeoIllustrator project, contributed in Paper B with regard to the geoscientific domain motivation of our research. He also provided valuable feedback for developing the prototype we used to create our results.

Julius Parulek co-authored Paper C and Paper 1. In Paper C, he contributed with his expertise on GPU programming and wrote parts of the text describing this.

Thesis Structure

The thesis consists of two parts. Part I gives an introduction to the problems that are addressed in the thesis, a short overview of related work, and summarizes the main contributions we achieved in five chapters. Chapter 1 introduces our research topic and our main contributions. We give an overview of related work in geological modelling in Chapter 2. In Chapter 3, we introduce the methods we developed in our scientific work, which are detailed in the papers of Part II. Results and demonstration cases are shown in Chapter 4, while conclusions and future work are stated in Chapter 5.

Part II presents the three papers that form the basis of this dissertation, reformatted and with a common bibliography.

Contents

Part I

Overview

Chapter 1

Introduction

Geological models are generally abstract simplifications of natural systems, that aim to represent essential processes and properties. They provide a controlled environment in which geologists can work on, especially for interpretations or simulations.

Before the digital era, subsurface *geomorphology*, the study of geological shapes and the processes that originated them, was studied either in the field or in laboratories. Unfortunately, not every question can be answered with such approaches. One of the reasons is that the temporal scale of observation is completely different from the temporal scale of many geological processes. Direct observation is limited to years or decades, while geology, such as a stratigraphic rock layer, evolves over millions of years. For "short-term" geological events such as meandering rivers (in the order of centuries), this limitation can be partially overcome through the use of archived historical observations. Modelling can help geologists to address some of these issues and provide a complementary way of gaining insights into geological processes. Controllable and repeatable analyses can be conducted on models. Geomorphological modelling is a growing discipline. Many models have been developed for academic and commercial purposes, which are often quite different in their aims, assumptions and capabilities.

An important branch of geomorphology is structural geology. Structural geology is the study of the three-dimensional distribution of rock units (*lithostratigraphy*) with respect to their deformational histories. In this dissertation, we define how to create digital 3D models that express structural geology, as well as depositional and erosional processes in an illustrative manner. Several geological modelling operators are introduced to achieve our aim which is a quick and intuitive approach to geomodelling. Each geological operator is performed by sketching the essential shape that identifies the geological process or the subsurface configuration to be illustrated. That is, fast creation of illustrations is achieved by adopting sketch-based techniques tailored for expressing various geological configurations.

1.1 Problem Statement

Imagine we are in an important meeting. There is a group of participants that have to make a decision with respect to, for instance, the existence of natural resources. The existence of natural resources at an unexplored area is dependent on its geological configuration. An example is the Barents Sea and its subsurface lithostratigraphy, which is believed to contain hydrocarbons.

The oceanic crust of the Barents Sea presents some complexities in its sedimentation structure. In this meeting, geologists gathered to discuss possible interpretations of the field area. The geologists have collected any kind of data at their disposal about the area and use any relevant information to converge into a global picture. An example of data at disposal in a qualitative manner is given by analogues from Svalbard [67, 53]. The island of Svalbard can be considered as being a part of the sea ground that has risen to above sea level due to tectonic forces, exposing an example of subsurface layering at one sample point at the Barents sea. Much research on the revealed geological structures at Svalbard has been performed prior to and independently of this meeting. Geologists can use this qualitative information to create hypotheses about the structure elsewhere in the Barents sea. There is an interpretation and discussion process, where it is important for everyone to be able to interact with the model to explore different alternative scenarios and their consequences. Subsurface geology consists of several shapes and, in most of the cases, it is not easy to say what kind of process has led to the current configuration. For that reason, a team of geologists is employed to share different expertises and opinions. Some of them are experts on folding processes, others in faults or fluvial systems. A common discussion on the same scenario brings a broader knowledge and increases the chances to develop the right interpretation of the involved processes.

In this first phase, it is important to externalize ideas and show them to the others. Moreover, it is also desirable that everyone can interact with what has been externalized by one person. In this way, such as when using a blackboard, weak points or mistakes can more easily be detected (by the presenter herself or by the listeners).

A geologist, with a specific expertise in the situation being examined, wants to express a point of view regarding the interpretation of a plausible process that generated the current configuration. Based on her experience on the subsurface, she wants to figure out ancient configurations of the area and the processes that were involved. And most important, the geologist needs to convince the others by explanations that have to be visually supported. Her initial thought is followed by comments and suggestions which most likely lead to an improved model. She may not have noticed the role of an ancient river channel which deposited in the Barents Sea area and contributed to accumulate sandstone and natural energy resources. Therefore she leaves the word to an expert in these fluvial system evolutions, who adds to the initial model all the channels and related deltas that may have contributed to the geomorphology development. Once all the involved geological features are placed in the model and a common view of the geomorphological history in the Barents Sea has been achieved, the geologists have another aim: they need to convince the management board that they have the right model on which to invest.

In this following meeting, the approach is quite different from the previous meeting, where peer experts were discussing together. Now one of the geologists speaks on behalf of all of them, bringing their common model to the board. This form of communication is one-directional, the leading geologist presents their ideas in a simple form, such that non-experts understand the essential concepts behind the natural processes and their consequences. The management will make a decision based on the opinions of the geologists, which have been condensed into illustrative models. The leading geologist cannot show field measurements to non-experts, because they would not understand, and cannot give the measurements to an algorithm that automatically produces a communicative animation of the geological event, because qualitative decisions must be taken when creating the result; neither can she show a set of existing template illustrations that in some way could be related to the actual real situation, because they would be to general. She does not create the illustration with a professional 3D modelling software, as this takes too much time and requires detailed expertise in the modelling software. Moreover, for time reasons, she cannot generate an image that recreates the 3D perspective, illumination, textures and complex shapes with a 2D drawing software or with her hand-drawing abilities (which might not be too well developed). A physical representation of the event would be another option, but it is not realizable in practice. A feasible option would be to take a piece of paper and quickly draw to approximatively reproduce an abstract illustration of the model she has in mind. However, a digital representation would help the quality and the communicative power of the illustration. In addition, a digital representation is reproducible and editable, and the illustration that the geologists created as a common model can be proposed again to the board, possibly with minor modifications.

1.2 Requirement Analysis

In our hypothetical meetings, the person who explains processes concerning the Barents Sea would benefit from a rapid modelling technology, for prompt interaction, and a 3D illustrative visualization, to produce a simple abstraction which maintains the relevant information.

In general, scientific illustrations should fulfil different requirements, depending on the target audience:

1. When communicating towards peer experts, illustrations should be:
    - **technically correct**: small approximations are tolerated, but geological constraints cannot be discarded;
    - **quickly modelled**: when different points of view are needed, abstract ideas must be interactively shared;
    - **reproducible**: such that research can be spread in different venues.
2. For the scope of management decisions, illustrations should:
    - **be perfectly refined**: no space for weaknesses in the model, critical decisions are based on it;
    - **sell message**: benefits shall show through visual interpretation;
    - **impress viewer**: feelings are often the basis for a decision.
3. Illustrations that aim at students for teaching purposes should:
    - **be educational**: conceptual information enables a generalization of the model that can be used for similar cases, while peculiarities of the studied case extends student experience;
    - **include animation of processes**: time dominates geology and if it is reflected in the illustration, processes are more easily understood;
    - **aid in remembering material**: a visual picture of an event is more powerful for our mind than written words.

In category (1) we classify all the situations where the common scope is to produce a representation (or several alternatives) of a studied case that is a joint work of peer experts. The preliminary meeting carried out by the geologists discussing the Barents Sea geomorphology is an example of category (1).

The following meeting, where one geologist presents a common interpretation to the management board, falls into category (2).

We have not given an example of the third category in the previous section, however illustrations for teaching purposes are broadly used by teachers in their courses or by geologists in educational seminars. A typical usage of type (3) is for displaying definitions of geological processes or for modelling of real cases that can be explored in classes when going to the field is not an option, or for illustrating what has been observed in the field. It can be argued that animations do not only fit into this category.

An illustration, can have parts based on measured points or interpreted data. In such cases, the modelling is constrained. The focus in this thesis is on unconstrained conceptual sketches which may be influenced by qualitative knowledge of the area (for instance from analogues). Approaches for creating models, when sparse or dense measurements in the area exist, are described in the next related work chapter.

That is, there is a balance between detailed realistic models and simple-to-read abstract illustrations. As, for example, between photo-realistic and cartoon-like illustrations. By realistic conceptual illustrations, we refer to illustrations which are enhanced by shadows or rock-like textures, while abstract conceptual illustrations are enriched with symbolic textures and other non-realistic symbols, which geologists know and use. Realistic illustrations are good for communicating to those who do not understand the geological symbols and textures. On the other hand, symbolic illustrations can more clearly communicate different aspects and properties to geologists. The results of this thesis are more oriented towards geologist usage and non-photorealistic visualization, however we provide some examples of realistic visualizations in Paper A, where we have used non-symbolic textures which are photos of rocks that have been made tileable. In geological illustrations, the geometric aspect is central, but other characteristics help to improve the expressibility of a model or to achieve different results in order to highlight different properties. In this perspective, illustrations may be enhanced with colours, textures, text or symbols. The geometric aspect is tackled in the first part of the modelling process through procedural or sketch-based techniques, as defined in the next chapter. The visualization aspect is introduced in the latest stage of the illustrative modelling and consists of the utilization of colours, textures, text or symbols to mainly convey non-geometric properties.

Summarizing the requirements of all scopes (1), (2) and (3), we can conclude that a rapid modelling technology is desired to gain interaction in the communicative process.

In the next chapter, we introduce the reader to related work on modelling terrains and geology in the subsurface. Few of the aforementioned requirements are satisfied by existing techniques. This thesis attempts to satisfy most of the remaining ones.

Chapter 2

Modelling and Visualization in Geology - State of the Art

Illustrating by means of pen and paper is still a common practice for geologists who want to externalize their ideas. The digitalization of this process has not evolved enough to fulfil the requirements raised in the previous section. One currently employed approach is to draw 2D pictures with drawing software, forfeiting all the benefits of a 3D representation, such as interaction, rotation, depth information and cross-sectional views. On the other hand, there are rapid model generation techniques, described in the next sections, where modelling is not performed with an intuitive sketch-based modelling procedure, but rather through procedural modelling.

Procedural modelling covers some of the requirements of the previous section, however it cannot be employed for interactive discussions requiring quick modifications of the model. Procedural modelling is mainly currently used for creating the top surface of a geological model, i.e. the terrain, as described in this chapter. Moreover, procedural modelling is hard to control due to limited and often non-intuitive parameters when producing real case scenarios.

Sketch-based modelling, on the contrary, has quickly grown in the last ten years to support intuitive design in several fields, including geology. In general and not specifically for digital applications or for geology, drawing sketches helps:

- the process of developing new ideas;
- to explain ideas to others.

A sketch-based approach is useful to create models from scratch or to show an interpretation based on sparse data when this is available.

This chapter gives a broader overview on the state of the art concerning geometric modelling in geology, going through both procedural and sketch-based approaches.

Several modelling methods have been introduced to build terrains and subsurface geology. We classify previous work into a data oriented taxonomy, consisting of approaches not building on measured data, which we call *data-free*, approaches making use of sparsely sampled data, which we call *sparse-data* scenarios and approaches making use of densely sampled data such as volumetric measurements, which we call *dense-data* scenarios.

2.1 Geomodelling in Computer Graphics and in Geosciences

Realistic appearance of natural sceneries has been a key topic in computer graphics for many years. The outcome of this research primarily targets the film and gaming industries. The modelling is often procedural and can be constructed with little user intervention. In most cases, only the top surface is the final product of the modelling process, even if subsurface features have been taken into account during the modelling.

Parallel to this development, the modelling of geological structures has been developed from the geological domain. This modelling process usually requires heavy user involvement and substantial domain knowledge. The model creation can often take up to one year of intensive work. The modelling process also includes data acquisition from the site which is to be modelled. The result is usually a complex 3D model, consisting of a number of different subsurface structures.

The needs of the entertainment industry and the geoscientific domain are substantially different, although they represent similar natural phenomena. While the former one puts emphasis on interactive realistic visual appearance, the latter one focuses on structural realism, i.e. the correctness from the geoscientific point of view, while discarding rapidity. In recent years, research in geosciences have identified the importance of rapid prospects, i.e., fast geoscientific interpretations at early stages in exploration. For such a use, the extensive development period of a typical geological model becomes a severe limitation. Rapid prospects raise a need for rapid modelling approaches that are common practice in computer graphics terrain modelling.

While the terrain synthesis for entertaining industries is a product of content creation carried out by artists, the geoscientific models are created based on qualitative expert knowledge or actual measurements, and are done by geologists and other geoscientists based on a substantial level of background knowledge and experience. Moreover, when modelling based on measurements, the input data are either densely covering a certain spatial area, for instance by means of large-scale acoustic surveys, or consist of sparse input data that are completed by extrapolating known values over the areas where no measurements are taken. There is a multitude of approaches to sample geology, for instance from seismic surveys (2D cross-sections, 3D volumes or 4D time varying volumes), boreholes (1D curves) or virtual outcrops from LIDAR scans (3D textured surfaces) [112].

2.2 Geological Objects

The study of structural geology divides the subsurface into geo-bodies [58] of different categories. Central objects are layers, horizons, faults, folds, channels, deltas, salt domes and igneous intrusions.

Much of the research in geomodelling explores how to represent geological feature such as horizons, folds, faults and deposition. Deposition occurs when eroded particles of rock are brought by wind, water or gravity to a different place, where they accumulate to form a new rock layer. The subsurface is composed of a set of layers with distinct material composition. The surface which delimits two adjacent layers is known as a *horizon.* Deposition does not modify the structure of the existing horizons, but gives origin to a new rock layer instead. Two fundamental geological phenomena involve modification of the original structure of horizons: the process of folding and the process of faulting. A fold is obtained when elastic layers of rock are compressed. It is defined as a permanent deformation of an originally flat layer that has been bent by forces acting in the crust of the Earth. Faults originate when forces that act on a specific layer are so strong that they overcome the rock's elasticity and yield a fracture. A horizon is therefore displaced and becomes discontinuous across a fault. Channels are remains of buried river depositions.

2.3 Modelling of Geological Objects

Geological models can be divided into two different categories, *layer-based models* and *complex models* [133]. The layer-based models, built of multiple horizontal oriented surfaces, are typically created to model sedimentary geological environments for the purpose of ground-water mapping, or oil and gas exploration. In regions with complex geological structures or where the layering is not dominant, for instance when modelling igneous and metamorphic terrains, a more complex terrain model is needed. These complex terrains are modelled when exploring for metal and mineral resources. In this dissertation, we focus on the layer-based models.

In two viewpoint articles, Turner [133, 132] provides a thorough introduction to the challenges of creating computer tools for modelling and visualization of geological models. The articles formulate the essential domain needs and the capability to interactively model and visualize: geometry of rock and time-stratigraphic units; spatial and temporal relationships between geo-objects; variation in internal composition of geo-objects; displacement and distortions by tectonic forces; and the fluid flow through rock units.

Furthermore the following characteristics of the geo-bodies are highlighted: complex geometry and topology, scale dependency and hierarchical relationships, indistinct boundaries defined by complex spatial variations, and the intrinsic heterogeneity and anisotropy of most subsurface features. These characteristics are, according to Turner, not possible to satisfy with traditional CAD-based modelling tools. Thus, dedicated geological modelling and visualization tools are necessary. Marroquim et al. [80], for instance, propose a representation that is particularly suitable for geological models, where they use tetrahedra to describe the subsurface geology.

In geological modelling there are often scenarios that lack sufficient data. In order to build a meaningful model, the creator must interpolate between the sparse sampled or derived data available, or can sketch from imagination in case of no data. Traditional interpolation schemes for discrete signal reconstruction are not sufficient as the process needs to be guided by geological knowledge, often through many iterations, to produce a successful result. A plausible geological scenario has to follow certain geo-physical constraints. Caumon et al. [23] describe specific structural modelling rules for geological surfaces defining boundaries between different lithological layers. Geo-bodies exhibit spatial continuity, therefore abrupt geometric variations such as sudden change of normal orientation on the surface, and abrupt changes within a fault are not common. This implies that a structural model may be validated via reconstructing its depositional state.

In Section 2.4 we will briefly categorize previous works in terms of the type of data that is being addressed (see Figure 2.1).

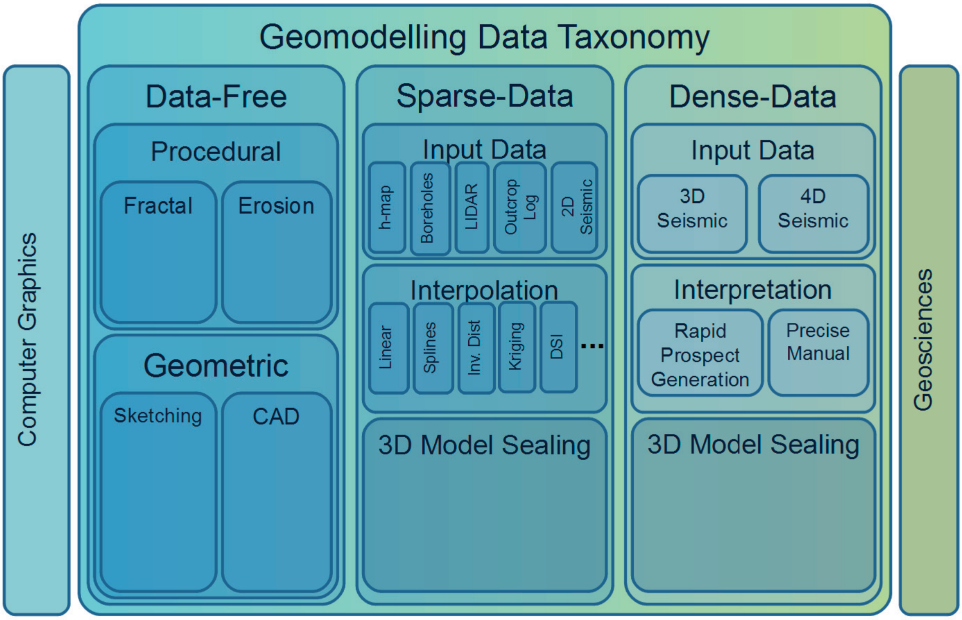


Figure 2.1: Geomodelling methods are classified according to which type of data they use and from which domain they originate (computer graphics to the left or geosciences to the right).

2.4 Geomodelling Data Taxonomy

We have decided to divide the literature of geologic modelling into three categories (see columns in Figure 2.1) according to how much measured data the model is based on. The *data-free* scenario represents current and future trends in rapid modelling, while the other two categories (*sparse-data* and *dense-data* scenario) are mostly faced with modelling that is constrained by acquired data. In the first category (no data) very little work has been done in geosciences, whereas computer graphics has contributed here due to the purely aesthetical need for creating realistic looking models for use in animations and games. Also general methods for sketching and modelling has been developed in the field of computer graphics. For sparse data, there are contributions from both computer graphics and geosciences. For instance, for interpolating scattered points there are Spline methods from computer graphics and mathematics, whereas the Kriging interpolation originated in the geosciences. For dense data, most of the research has been performed in the geosciences.

In the workflow where no measured data is required as input (data-free), some papers focus on surface creation, other general papers describe different mathematical surface representations. Several sketch-based papers describe different ways of fast sketching and assembling of solid objects and some focus on compact representations and fast rendering of complex solid objects. For the case where data is being used (sparse or dense-data), the workflow follows the columns in Figure 2.1 from top to bottom, beginning with measuring data, interpreting relevant structures, interpolating these into higher-order objects and representing these in some appropriate mathematical way. The structures are then assembled into solid geometry describing the subsurface.

2.4.1 Data-Free Scenario

This section describes works that do not rely on any measured or sampled input data, and where the models are created from scratch, driven by imagination or concept ideas and domain knowledge.

The *data-free* scenario has no ground truth information and therefore the geometric synthesis relies entirely on *procedural* and *geometric* modelling. The typical computer graphics research agenda proposes methodologies that alleviate the user from labour-intensive tasks by automating parts of the modelling. Procedural modelling offers the modeller specific, easy to handle, input parameters which control the process of geometry generation. The geometry typically represents terrain surfaces. Procedural techniques in modelling has been facilitated mainly through *fractal* modelling [121, 9]. Simple *erosion* models [68, 57] are utilized to create dynamic and realistic landscapes [113, 59].

The shortcoming of procedural modelling is usually the lack of direct control over the landscape development. The modeller has a rough idea of the landscape, but implicit parameter settings do not guarantee a match with a modeller's idea of an intended shape. Therefore a combination of explicit geometric modelling, to represent the modeller's expectations, with procedural modelling, to add realism, is a preferred strategy. On the other hand, geometric modelling can be a labour-intensive task. For rapid modelling scenarios, various forms of *sketching* metaphors [48, 105, 138] or modelling by example [18] provide fast ways to express the rough structure of a terrain or, more general, of a stratigraphic model.

Procedural Modelling: Fractal and Erosion Surface Creation

Currently there seems to be three approaches to generate synthetic terrains: fractal landscape modelling, physical erosion simulation and terrain synthesis from images or sample terrain patches. Before the work by Olsen [93] (2004), it was mostly common to use simple fractal noise to obtain terrain surfaces, as computers were not fast enough to simulate erosion processes in real-time. Olsen proposes a synthesized fractal terrain and applies an erosion algorithm to this. His representation of terrains is a two-dimensional height-map. To simulate erosion, he considers the terrain slope as one of the main parameters: a high slope results in more erosion, a low value produces less erosion. Starting from a noisy surface, called the *base surface*, erosion occurs to simulate weathering on a terrain.

The ability to model and render piles of rocks without repetitive patterns is one of the achievements of the work by Peytavie et al. [106]. They focus on rocks and stones, which are found everywhere in landscapes. They provide realism to the scene, reveal characteristics of the environment and hint on its age. Before this paper, the standard way of generating rocks was to produce a few models by artists, which were then instantiated in the scene. To create piles of rocks, collision detection techniques were applied with a high computational cost and low control.

Musgrave et al. [87] describe the creation of fractal terrain models, avoiding global smoothness and symmetry; these two drawbacks arise from the employment of the first definition of fractional Brownian motion (fBm) as introduced by Mandelbrot [79]. Moreover, in their method there is a second stage in which the surface undergoes an approximation of a physical erosion process. Terrain patches are represented as height-maps and the erosion process is subdivided into a thermal and a hydraulic part.

Concerning modelling terrains with rivers, Sapozhnikov et al. state that at the time when their paper [120] was written (1993), it was impossible to simulate the process of natural river network formation without making a substantial approximation; i.e. a simpler model that does not make use of physical laws, but nevertheless reproduces the main geometrical features of a real river network. They use a random walk method to generate a set of river networks of various sizes.

Stachniak et al. [126] point out that fractal methods have been used to create terrain models, but these techniques lack control by the user. They try to overcome this by imposing constraints to the original randomly created model, according to the user's wishes. The method requires two inputs: the initial fractal approximation of the terrain and a function that incorporates the constraints to be satisfied in order to achieve the final shape. As an example, they show how to adapt a fractal terrain to accommodate an S-shaped flat region, representing a road. The constraint function defines a measure that indicates how close a terrain is to the desired shape. The final solution is provided by a minimization of the difference from the current terrain to the desired one.

Another way of combining procedural modelling with user constraints is described by Doran and Parberry [40]. In their work, they procedurally generate terrain elevation height-maps, taking into consideration input properties defined by the user. The model lets the user choose amongst five terrain tools: coastline, smoothing, beach, mountain and a river tool. Together, they can generate various types of landscapes.

A terrain surface is created by fractal noise synthesis in Schneider et al.'s work [121]. They aim to solve the problem that was one of the biggest disadvantages in fractal terrain generation at the time (2006), namely the setting of parameters. They reduce such an unintuitive process of setting parameters by presenting an interactive fractal landscape synthesizer.

Roudier et al. [119] propose a method for terrain evolution in landscape synthesis. Starting from an initial topographic surface, given by a height-map, they subsequently apply an erosion process to obtain the final 3D model. The erosion consists of mechanical erosion, chemical dissolution and alluvial deposition.

Chiba et al. [27] propose a method that overcomes the limitation of previous techniques for generating realistic terrains through fractal-based algorithms. However the method lacks ease of handling, i.e. it is not possible to modify the surface on the basis of the user's suggestions such as introducing ridge or valley lines, which are usually important to characterize a mountain scenery. The topology of the landscape is created by a quasi-physically based method, that produces erosion by taking velocity fields of water flow into consideration. The whole process of erosion, transportation and deposition is derived on the basis of the velocity field. On the other hand, Dorsey et al. [41] focus on the visual effect of erosion on a single stone or rock, represented volumetrically, taking into consideration weathering effects on it.

In the work by Benes et al. [10], a method for eroding terrains is described. A concise version of a voxel representation is utilized, and thermal weathering is simulated to erode the initial model. This new way to represent terrains has the advantage of being able to represent caves and holes. When applying erosion, all the layers, including the ceilings of the caves, are involved in the process.

In a subsequent paper [12], a technique for procedural modelling of terrains through hydraulic erosion is introduced. The purpose is to use a physical-based approach together with a high level of control. Contrary to previous techniques which tend to oscillate during water transportation, they provide a tool for hydraulic erosion that is fast and stable. They overcome oscillation, relying more on physical constraints than was previously the case. The erosion process consists of four independent steps, where each step can run repeatedly and in any order. These four steps are: introduction of new water (simulation of rain); material capture by water (erosion); transportation of material; and deposition at a different location.

Another work by Benes et al. [13] applies a hydraulic erosion fully based on fluid mechanics using the Navier–Stokes equations that describe the dynamics of their studied models. They use a 3D representation provided by a voxel grid and the erosion process leads to a model that can either show a static scene or an animation illustrating the evolution of terrain morphology. At each iteration of the erosion process, a solution to the Navier–Stokes equations is computed to determine a pressure and velocity field in each voxel.

Interactive physics-based erosion is employed by Stava et al. [127] (Figure 2.2). This work is based on hydraulic erosion, and achieves interactivity, which allows the user to take an active part during the generation of the terrain. The technique is implemented on the GPU, and because of limited GPU memory, the terrain is subdivided into tiles, which individually fit in GPU memory. Each terrain is represented as a height-map.

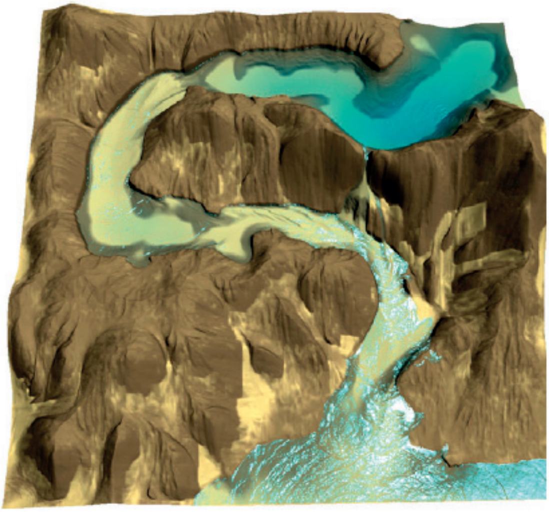


Figure 2.2: The eroded terrain is obtained by simulating the movement of the water flow and transportation of rock particles [127].

Kristof et al. [68] adopt 3D terrain modelling through hydraulic erosion by fluid simulation using a Lagrangian approach. Smoothed Particle Hydrodynamics (SPH) [51, 75] is employed in this paper to solve dynamics that generate erosion. SPH require low memory consumption, acts locally, works for 3D features and is fast enough to work on large terrains.

For Hnaidi et al. [57], the terrain is generated from some initial parametrized curves which express features of the target terrain (see Figure 2.3). Constraints such as elevation and slope angle are assigned to each curve.

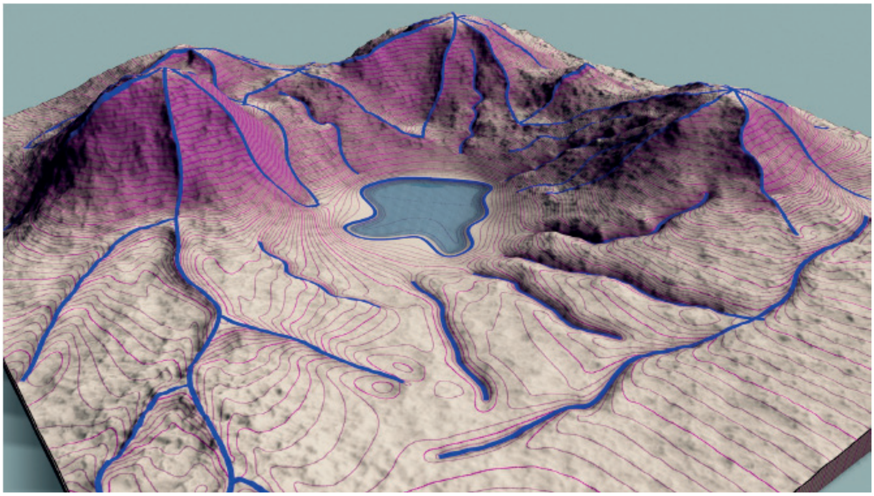


Figure 2.3: Sketches visible in the figure as blue strokes work as constrains during the method proposed by Hnaidi et al. [57].

Prusinkiewicz and Hammel [113] address the problem of generating fractal mountain landscapes, which also includes rivers. They do this by combining a midpoint-displacement method for the generation of mountains with a method to define river paths.

Hudak and Durikovic [59] tackle the problem of simulating terrain erosion over a long time period. They use a particle system and take into consideration that terrain particles can contain water. Discrete Element Method (DEM) is used for the simulation of the soil material and Smoothed Particle Hydrodynamics (SPH) simulates water particles.

Instead of procedural and erosion synthesis, Brosz et al.'s paper [18] introduces a way to create realistic terrains from reference examples. This process is faster than starting the terrain generation from scratch. Two types of terrains are necessary to obtain the final one: a base terrain, used as a rough estimate of the result, and the target terrain that contains small-scale characteristics that the user wants to include in the reconstruction.

Brosz et al. present two ways to generate landscapes represented as a height-map: using brush operations to bring some predefined information or action on the surface; alternatively, simulation and procedural synthesis can be applied to obtain a realistic terrain. One drawback of using simulation is that it can be slow, while in the case of procedural synthesis, expressibility is reduced by a limited set of parameters. De Carpentier and Bidarra try to combine brushing and procedural synthesis in their work [36], an example is shown in Figure 2.4.

Geometric Modelling

Gain et al. present a paper [48] that describes procedural terrain generation using a sketching interface. Their approach aims to gather benefits, such as intuitiveness, and overcome some limitations, such as height definition, of previous methods of sketch-based terrain modelling [29, 141, 147]. Watanabe and Igarashi [141] use straight lines and, even though they yield a boundary for landforms using local minima and maxima of the user's sketch, they do not give the user the possibility to change the proposed

Figure 2.4: Two types of noise as seen on left and right side applied by de Carpentier and Bidarra [36] to achieve a realistic terrain.

shape. Furthermore, they apply noise onto the terrain after surface deformation, hence the obtained surface does not interpolate the user strokes exactly. Whereas landforms rarely follow straight lines, Zhou et al. [147] allow landforms to have more freely shaped paths using a height-map sketching technique as guidance for an example-based texture synthesis of terrain. In contrast to the method suggested by Gain et al. [48], they provide low and indirect control over the height and boundary of the resulting landforms.

Brazil et al. [138] introduce a sketch-based technique to generate general 3D closed objects using implicit functions. They also show how to obtain simple geological landscapes from few user strokes, see Figure 2.5. Several of the fractal and erosional surface creation methods represent the surfaces as height-maps. This is an easy-to-maintain data structure which fits well with erosional calculations. However, the method by Brazil et al. [138] can represent complex surfaces with overhangs or closed objects, using implicit functions defined as a sum of radial basis functions. Based on points with normals as input, a smooth implicit function, interpolating the points while being orthogonal to the normals, is created.

Peytavie et al. [105] represent complex terrains with overhangs, arches and caves. They achieve this by combining a discrete volumetric representation, which stores different kinds of material, with an implicit representation for the modelling and reconstruction of the model.

Bernhardt et al. [14] presented a sketch-based modelling tool to build complex and high-resolution terrains. They achieved a real-time terrain modelling by using both CPU and GPU calculations. To represent large terrains, they use an adaptive quad-tree data structure which is tessellated on the GPU.

In the following text, we consider solid representations as being different from boundary representations in that they are not hollow, but have spatially varying properties. Takayama et al. [130] present diffusion surfaces as an extension of diffusion curves [97] to 3D volumes. The representation consists of a set of coloured surfaces in 3D. A smooth volumetric colour distribution that fills the model is obtained by diffusing colours from these surfaces. Colours are interpolated only locally at the user-defined cross-sections using a modified version of the positive mean value coordinates algorithm. A result of

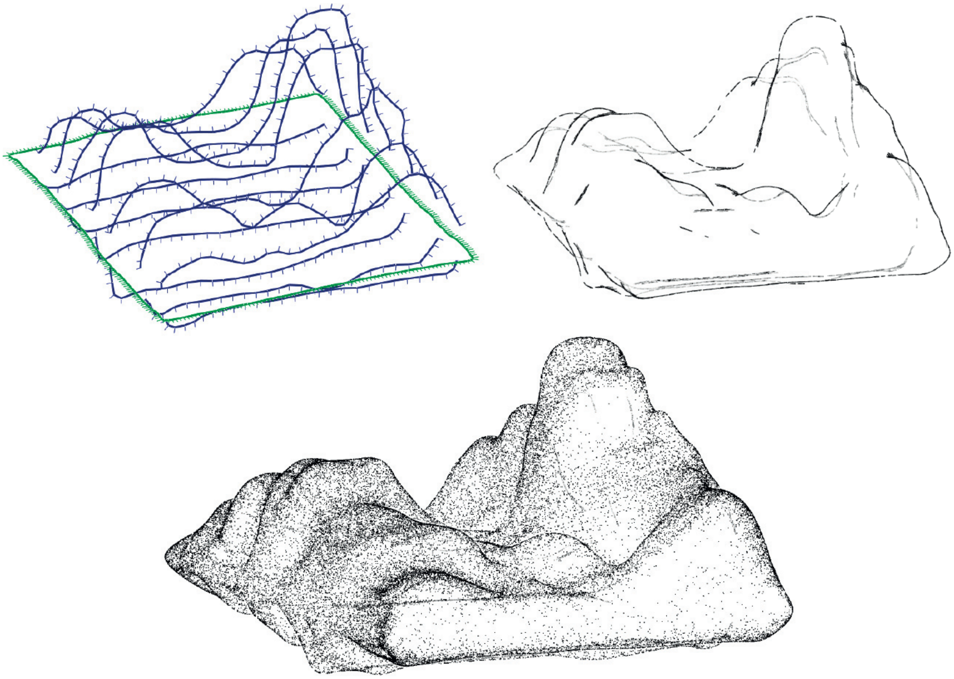


Figure 2.5: Landscape example generated with the sketch-based approach by Brazil et al. [138]. Top left image shows the input curves and their normals. Right and bottom images show resulting landscape in two different rendering styles. The model is represented with Hermite Radial Basis Functions.

the work by Takayama et al. [130] is shown in Figure 2.6.

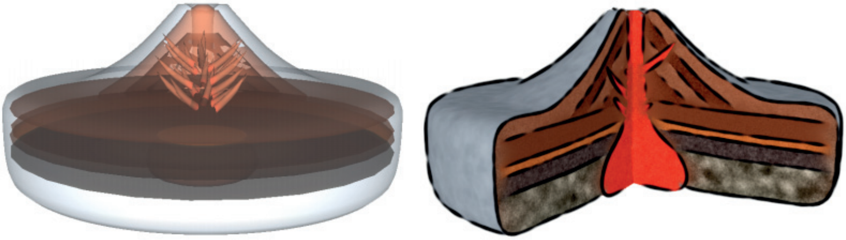


Figure 2.6: A volumetric representation of a geological scenario using diffusion surfaces (Takayama et al. [130]).

In the work by Wang et al. [140], objects are represented as implicit functions using signed distance functions. Composite objects are created by combining implicit functions in a tree structure. This makes it possible to produce volumes made of many smaller inner components. This multi-structure framework lets them produce models irrespective of resolution (see Figure 2.7 for a geological application example).

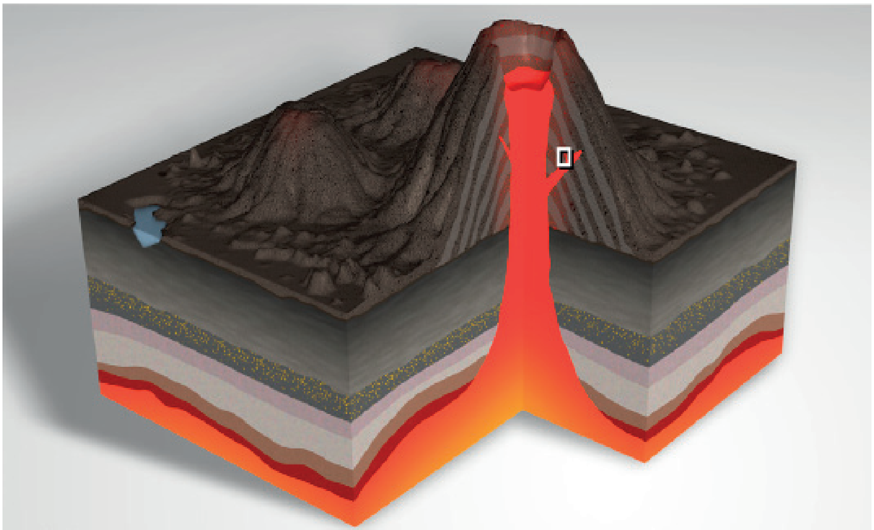


Figure 2.7: A volumetric representation of a geological scenario using an implicit representation (Wang et al. [140]).

2.4.2 Sparse and Dense Data Scenarios

This section describes methods that use sparsely scattered geologically measured data or dense data, such as 3D seismic reflection volumes, for creating a subsurface model. In contrast to data-free modelling, the process is now naturally constrained by values in the data.

The *sparse-data* modelling scenario is the most frequently used in the geoscience domain [52]. Very often data comes from boreholes [69, 65, 84], where the data needs to be interpolated between. Besides boreholes, there are often other acquisition types available, such as surface elevation models [39, 146], obtained through the process of remote sensing. This heterogeneous pool of geoscientific data raises the challenge of data integration and data interpolation. The main interpolating methods are the B-Spline method, the inverse distance method, the Kriging method and the discrete smooth interpolation method [78, 76]. We will briefly discuss them later in this Section. The implicit function interpolator is another increasingly popular interpolation method [82].

Turner [133] demonstrates how to build a typical geological model from a *sparse-data* scenario by firstly interpreting bore-hole logs to construct triangulated surfaces of horizons [8] and then create the geo-bodies [37, 125] in sealed, boundary-representations [24] of the volumes between these surfaces. The modelling of faults [143] is also very important and Turner describes the challenge of modelling the interface between the boundary representation and the fault to avoid unwanted crossings or empty spaces between faults and geo-bodies. Using a structured mesh representation of the boundary surface can result in discretization errors, while using unstructured grid representation [47] adds computational complexity and results in slower model construction.

The *dense-data* scenario is typically based on a single- or multi-attribute seismic dataset. The first challenge is purely of computational character, i.e., how to interactively display large amounts of volumetric data. This was addressed, e.g., in the work of Plate et al. [109]. Utilizing volume rendering, such datasets can be displayed without prior extraction of geo-bodies. Extracting geological structures from such a dataset is necessary for consecutive steps along the workflow, such as reservoir modelling. This process is known as geoscientific interpretation and is a very time-demanding task. Typically the original seismic dataset, consisting of the amplitudes of reflected sound waves, can be used to extract a number of derived attributes. These attributes are not geo-bodies, but their distribution over the 3D domain indicates the presence of certain geological structures. The *SHIVR* system [72] can extract geo-bodies based on scatter plots, as shown by Andersen and van Wijngaarden [6]. Rapid prospect generation can certainly benefit from faster interpretation. Patel et al. proposed methods for rapid horizon extraction in two [102] and three dimensions [101]. Afterwards, once the interpretation is available, 3D visualization can assist in validating the correctness of the extracted horizons with respect to original or derived attribute data [103].

A natural next step after 3D structural modelling is the development of a time-varying structural model. Inverse methods are often utilized in geomodelling to restore hypothetical geological scenario backwards in time [142, 54, 22]. Such an approach aims at restoration of deposited sedimentary layers, for example through unfolding. Restored information about palaeogeography often gives good indication where to search for hydrocarbon reservoirs.

Measured Data

Subsurface data can be collected in several ways, at various effort and expense. Seismic 2D or 3D reflection data is collected by sending sound waves into the ground and analysing the echoes. When the sound waves enter a new material with a different impedance, a fraction of the energy is reflected. Therefore, various layer boundaries of different reflective character are visible in the seismic data as linear edges. Well logs are obtained by drilling into the ground while performing measurements and collecting material samples from the well. Outcrops are recorded by laser scans together with photography (LIDAR) to create a 3D pointcloud of the side surface of geology [112]. This surface can be investigated and visible layer boundaries can be identified and outlined as curves along the surface.

Interpolation

Key interpolating methods for surfaces in geosciences are the B-Spline method, the inverse distance method, the Kriging method, the Discrete Smooth Interpolation (DSI) method [77, 78, 76] and the Natural Neighbor Interpolation method [122]. Kriging is a statistical approach to interpolation that incorporates domain knowledge and is uncertainty-explicit [28, 134]. Kriging, like exemplar-based synthesis, creates a surface that has similar properties to an example dataset.

The Discrete Smooth Interpolation allows for integration of geo-physical constraints into the interpolation process. The interpolator takes as input a set of (x, y) positions, some with height values and others without. After interpolation, all positions have been given height values. Discontinuities between positions can be defined so that certain neighbour points do not interpolate. Typically for a horizon surface, discontinuities would be added across faults. In addition, constraints such as having points being attracted towards other points, having points being limited to movement along predefined lines or on surfaces can also be defined. These constraints are useful for interpolating geologic surface data. However the method might not be well suited for cases with very little or no observation data (as indicated by De Kemp and Sprague [37]), such as in the data-free scenario. Natural Neighbor Interpolation is also based on a weighted average, but only of the immediate neighbours around the position to be interpolated. A Voronoi partition is created around all known points and the weight is related to the area of these partitions around the unknown point.

An interpolation and surface representation system for geology is discussed in the work by Floater et al. [45]. Scattered point measurements can come in many forms, uniformly scattered, scattered in clusters, along measurement lines or along iso-curves. Fitting a surface through the points requires interpolation. Different interpolation methods vary in quality dependent on the distribution of the scatter data. Floater et al. offer interpolation in form of piecewise polynomials on triangulations, radial basis functions or least squares approximations.

Although more of a connectivity algorithm than an interpolation algorithm, the work of Ming and Pan [84] presents a method for constructing horizons from borehole data. Each borehole dataset consists of a sequence of regions. Each region has its start and end depth specified as well as its rock type. One rock type might appear in several layers and also the rock type sequence might vary between boreholes. This results in several possible connectivity solutions. The challenge is to make a suitable matching of layers to create a solid layer for each rock type.

Interpretation

Several commercial tools exist for interpreting 3D seismic data. One example is Petrel [123] where the user sets seed points and the system grows out a surface. The user can change the growing criteria or the seed points until a satisfactory surface is extracted. This can be time consuming. Kadlec et al. [62] present a system where the user interactively steers the growing parameters to guide the segmentation instead of waiting until the growing is finished before being able to investigate it. Fast extraction of horizon surfaces is the focus of Patel et al. [101]. Their paper introduces the concept of brute-force and therefore time-consuming preprocessing for extracting possible structure candidates in 3D seismic reflection volume. After preprocessing, however, the user can quickly construct horizon surfaces by selecting appropriate candidates from the preprocessed data. Compact storage of all surface candidates is achieved by using a single volumetric distance field representation that builds on the assumption that surfaces do not intersect each other. This representation also opens up for fast intersection testing for picking horizons and for high quality visualization of the surfaces. The system allows the user to choose among precomputed candidates, but editing existing surfaces is not possible. Editing is addressed by Parks [99] and Amorim et al. [5]. They present methods that allow to quickly modify a segmented geologic horizon and to cut it for modelling faults.

Free-form modelling is achieved using boundary constraint modelling [16]; this is simpler and more direct than Spline modelling, which requires manipulation of many control points. Discontinuities arising from faults are created by cutting the mesh. Amorim et al. [5] allow for more advanced surface manipulation in their system. Surfaces with adaptive resolution can be altered and cut with several sketch-based metaphors. In addition, the sketching takes into account the underlying 3D seismic so that it can automatically detect strong reflection signals which may indicate horizons.

3D Model Sealing

Solid geometric representations of subsurface structures is important for analysis. A sealed model enables consistent inside/outside tests, providing well defined regions. It is also the first step for producing physical reservoir simulations of liquid or gas flow inside the model at later stages.

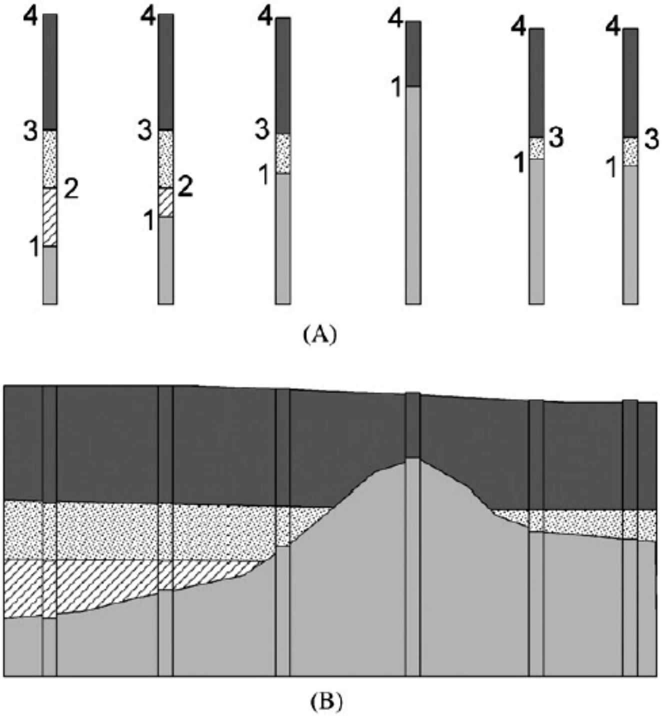
Baojun et al. [8] suggest a workflow for creating a 3D geological model from borehole data using commercial tools and standards. They use ArcGIS for creating interpolated surfaces from the sparse data. They use geological relevant interpolation such as Inverse Distance Weighted, Natural Neighbor, or Kriging interpolation. This approach results in a collection of height-maps which are imported into 3D Studio Max and stacked into a layer cake model. Then Constructive Solid Geometry (CSG) [111] operators are used to create holes (by boolean subtraction) at places where data is missing in the well logs. The model is then saved as VRML enabling widespread dissemination through viewing the model in web browsers.

Lemon and Jones [69] present an approach for generating solid models from borehole data (see Figure 2.8). Boundary points in the borehole data is interpolated into surfaces. For creating a closed model, they state and exemplify that CSG together with set operations can be problematic as the set operation trees grow quickly with increased model complexity. They simplify the model construction by representing horizons as triangulated surfaces and letting all horizon vertices have the same set of (x, y) positions and only varying the z positions (see Figure 2.9). This simplifies intersection testing between horizons and makes it trivial to pairwise close horizons by triangulating around their outer borders.

Complexity increases when models must incorporate discontinuities in the layers due to the faults. Wu and Xu [143] describe the spatial interrelations between faults and horizons using a graph with horizons and faults as nodes. The graph is used to find relevant intersections and bounding surfaces which are Delaunay triangulated to form closed bodies. In a follow-up paper [43], two types of fault modelling techniques are compared (based on what they call *stratum recovery* and *interpolations in subareas*) and a unified modelling technique for layers and faults is presented to solve the problems of reverse faults (i.e. convergent sedimentation blocks), syn-sedimentary faults (when slumping of sedimentary material happens before it is lithified) and faults terminated inside the model (also known as blind faults).

Solid modelling tools in CAD do not easily support subsurface features such as hanging edges and surface patches. Many papers describe data structures for representing the solid blocks that horizons and faults subdivide the subsurface into. Boundary representations are frequently used. Generalized maps, used for describing closed geological models, are introduced by Halbwachs and Hjelle [55].

Implicit surfaces (implicits) provide a suitable way to represent geological solids [82]. Essentially, such solids are described by implicit functions that can be expressed in different forms, e.g., distance based models, analytical functions or interpolation schemes like for instance RBFs. Pasko et al. [100] generalized the above representations, which lead to an inequality, $f \geq 0$, also called *functional representation* of solids. Kartasheva et al. [64] introduced a robust framework to model complex heterogeneous solids, which was based on functional representation. The implicit solid definition is quite broad, and for instance, the terrain modelling using a height-map can easily be represented by implicits [49].



(A)

(B)

Figure 2.8: Borehole data with identified layer boundaries in a) and resulting interpolation in b) from the method by Lemon and Jones [69].

2.5 Illustrative Visualization

Illustrative 3D visualization has mostly been researched in fields such as medicine [137], but not in geology. For a wide overview on illustrative visualization techniques and their application to several fields, we suggest the tutorial by Viola and colleagues [137]. When considering medical illustrations, Sousa et al. [124] present a volume illustration method for interactive simulation sessions. While in geological illustrative visualization, Patel et al. [103] propose an approach to display volumetric seismic data. The level of abstraction provided by illustrative visualizations is used when communicating interpreted or simplified scenarios, e.g. when people with different background are present in the audience.

2.6 Challenges and trends in geological modelling

Geoscience technology on closed model representations and model updating has not progressed at the same speed as in computer graphics. Better knowledge transfer between computer graphics and geosciences would be advantageous. Caumon et al. [23] state that beginners with 3D modelling too often lose their critical sense about their work, mostly due to a combined effect of well defined graphics and non-optimal human-machine communication. It is also important that a structural model can be updated when new

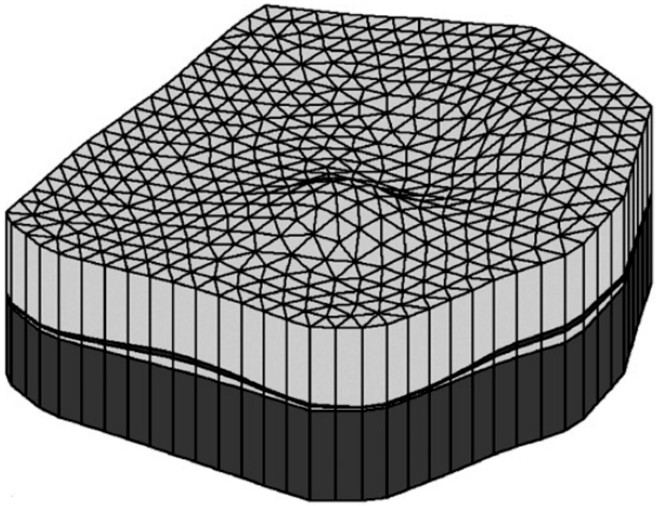


Figure 2.9: Example of model created with method by Lemon and Jones [69]. The shared (x,y) vertex positions can be seen on the side surfaces.

data becomes available or perturbed, to account for structural uncertainties. In other words, with current modelling technology, uncertainty is difficult to express, and models are hard to update.

Researched literature from geosciences emphasizes a strong need for modelling technology for communication and further analysis of the Earth's subsurface. While several matured methods are now in use by the domains of geology and geosciences, all tools require considerable effort to build structural model. Current tools focus on precise modelling in favour of rapid modelling. But rapid modelling is the key for the ability of expertise exchange, especially in the early phases of the interpretation process, which is the focus of the thesis.

In this direction, we contribute to cover missing technology, necessary to fulfil all the requirements highlighted by the meeting on the Barents Sea. In the next chapter, we describe how.

Chapter 3

Modelling and Visualization - Extending the State of the Art

Participants of the meeting are now discussing future strategies for an area of the Norwegian side of the Barents Sea that has not yet been digitized or measured. They need to create a complete geological model and illustration from scratch.

Here we give a description of the methods that we introduced in our work to rapid model and visualize illustrations. All three papers A, B and C are based on producing a layer-cake representation as a final model. The layer-cake model is a typical form for conveying subsurface structures. It is broadly employed by scientists in academia and industry.

The focus of what we model changes a bit through the papers to cover different aspects. In the first approach, Paper A, we create a 3D model by sketching on a cross-section and extruding the curves into surfaces. From the boundary of those surfaces, we seal the volumetric model with a triangulation. One of the advantages of having a mesh representation is that we can easily apply textures on the model. For warping the textures to fit the layer shape, we use conformal mapping, which preserves angles. This is important when deforming an illustrative texture that needs to be recognized (either because of common use amongst geologists or because it has been defined in an accompanying legend).

In the following work, reported in Paper B, we choose a different point of view for the user to sketch, namely from top-view. This is more appropriate when dealing with fluvial systems and their morphological evolution. To be able to encode more details in river and delta deposition processes, a novel concise representation of layers was introduced. Layers are still defined by a boundary representation in the modelling stage, i.e. a heightmap is assigned to each layer of the illustration. During rendering, we treat the model as a volume, obtained by our proposed ray-casting technique on the heightmap representation. That opens up for more versatile rendering and permits to internally inspect generated illustrations.

In our last work, Paper C, we still use the heightmap representation with volumetric rendering, but extend it, so that it can incorporate fault processes as well. We then show that the volumetric model is suited to be internally explored in several ways, depending on the main focus of the viewer. GPU acceleration is exploited to manage a higher computational cost due to the introduction of interactively animated faults.

3.1 Contributions

Our contribution leads to a new approach of designing 3D illustrations, which can be utilized during discussions between experts, for teaching purposes or for industrial strategic decisions. It is suitable for different scopes, but has a common achievement, that is abstraction and modelling (i.e. going from a real case to a virtual model) for simplification and interpretation.

We provide new visualization and modelling methods to digitally express an abstract concept related to subsurface morphologies. With the help of a sketch-based approach, simulating the intuitive way of expressing ideas through pen and paper, and by visualizing obtained models with illustrative techniques, we are able to generate 3D illustrations and animations in little time and less effort compared to alternative techniques.

In this dissertation, we contribute to extend the state of the art in modelling and visualization with the following aspects:

- Rapid Modelling (Section 3.2)
- Illustrative Animated Storytelling (Section 3.3)
- Layered Data Representation for Morphological Evolution (Section 3.4)
- Model Discontinuities and Interactive Illustrations (Section 3.5)

3.2 Rapid Modelling

An example of sketch based solid assembly of geological layer-cake models is presented in Paper A. Here we describe how to obtain a boundary representation of a solid model with the use of a sketch-based technique. Our approach lets a user sketch layers on the side of a bounding box which is extruded to a solid.

To outline our core contribution of Paper A, we show Figure 3.1, which lists three simple actions defining some of the most common processes in geology: folding, faulting and erosion. Folding and erosion events are distinguishable by a different texture deformation.

We compute 3D surfaces as extrusions in the third dimension of the drawn curves and represent them as triangular meshes. Adjacent surfaces are sealed together by triangulating their boundaries, hence creating closed layers. The shape of folded layers is thus given by the shape of the sketched curves. Whereas layer discontinuities are defined by a cross-sectional sketch and a further user input curve. From these curves, we deduce direction and amplitude of displacement. To change the model, the user can select a previously sketched curve and redefine parts or all of it by over-sketching.

The illustrative message of the model is enhanced by textures which are attached to the sides of the layers. Professional illustrators are trained to recognize standardized illustrative textures or non-standard textures together with a texture legend. In either case, the role of a texture is important to convey the types and properties of layers that are present in the model. We automatically adapt a texture to the shape of a layer, using a conformal map, that by definition preserves angles. This latter property is often important because we do not want to alter the illustrative meaning of the input texture. In addition, the texture on each layer can be reshaped independently of the others. The

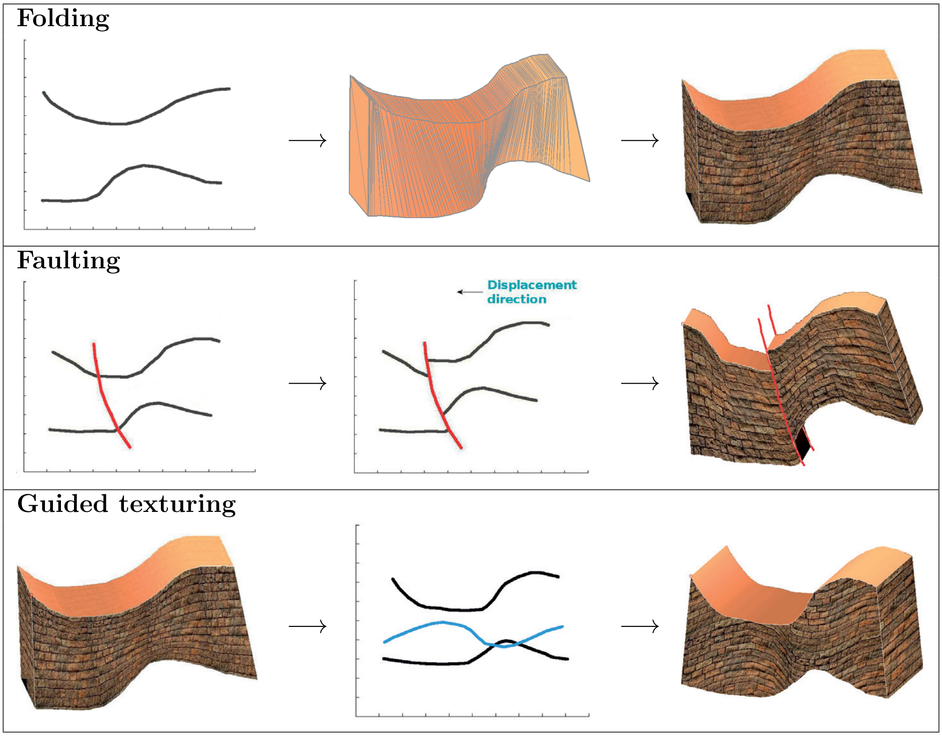


Figure 3.1: Global overview: (top) folding definition with just two strokes that generate the model, which is triangulated and textured on the side; (middle) faulting process after having specified the (red) fault and the direction of forces acting on it; (bottom) guided texturing, changing texture mapping from the default setup by a user-defined stroke (blue).

shape correction is achieved with a sketch-based user guidance, depending on the kind of process to be visualized.

If we consider the two green sketches b_1 and b_2 of Figure 3.2, we can suppose they define one of the layers of an illustration. Our approach automatically maps a chosen texture (in practice, a 2D rectangular image) to the planar region in 3D space delimited by b_1 and b_2. By default, the top and bottom edge of the source texture is mapped to the top and bottom curve of the target layer. Then texture coordinates are assigned to the interior of the layers using conformal mapping which minimizes interior angular deformation. With this procedure, the input texture adapts to the shape of the layer, as in the top-right image of Figure 3.1. In case the user wants the layer texture to deform differently, she can sketch two target curves (s_1 and s_2 in Figure 3.2) differently from the layer borders. A new mapping is then calculated and the texture is cropped to the layer area.

Figure 3.2: Texture obtained on the basis of a user's stroke ($\mathbf{s}_1$ and $\mathbf{s}_2$). $\mathbf{b}_1$ and $\mathbf{b}_2$ are the top and bottom boundary of the layer, whereas $\mathbf{s}_1$ and $\mathbf{s}_2$ are based on the user's stroke that is acquired to guide the behaviour of the texture.

3.3 Illustrative Animated Storytelling

In Paper 2, we extend the method described in Paper A to support animations. The idea is to employ the method described by Lidal et al. [71] to introduce a temporal aspect. In that paper, they emphasize the fact that, in many situations, communicating changes over time is fundamental when interpreting a geological process. They also propose a system that manages alternative interpretations of the same observed structural configuration.

In the same way 2D sketches tell geological stories that then can be compared to discuss feasible alternatives of an event (previous work by Lidal et al. [71]), we can, in Paper 2, automatically reproduce a geological animation that itself tells a story.

An animation is defined by means of sketched key-frame configurations. Intermediate time steps are obtained by interpolating the key-frame curves. Each 2D time step is extruded to a 3D model using the technique defined in Paper A. The conversion is implemented in Matlab and results in an animated film clip which take in the order of minutes to calculate.

When creating animations, the user must separately define the "shape morphing" and the "texture morphing", as the latter results in different meanings (see Figure 3.3).

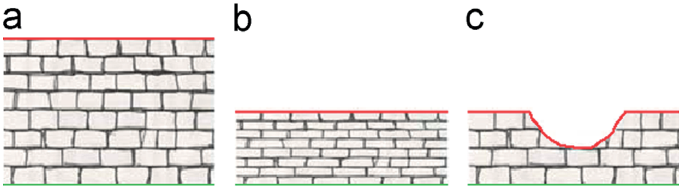


Figure 3.3: (a) Texture on the initial configuration of a layer; (b) compacted layer which is communicated by a compacted texture; (c) eroded layer which is communicated by a cut texture, where no texture deformation is performed. Image courtesy of Endre Lidal [73].

3.4 Layered Data Representation for Morphological Evolution

In Paper B, we give priority to layered structures and develop a representation for that, together with an accompanying volume visualization. The representation of the 3D layer-cake is encoded into heightmaps and volumetric visualization is achieved by ray-casting across the set of heightmaps. All features in a scene are introduced by means of sketched curves on the top surface of the model. Every curve is interpreted and converted to its corresponding heightmap. As shown in Figure 3.4, the interpretation of curves follows few simple rules:

- an open curve is a centreline of a tubular shape;
- a closed curve defines a deposit area when the user assigns a positive height, whereas it defines an erosion area when the user assigns a negative height.

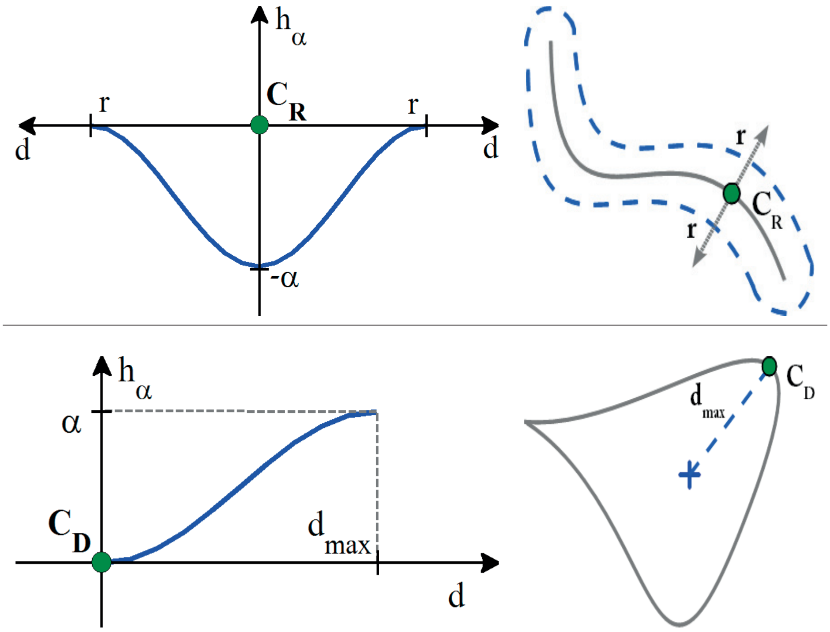


Figure 3.4: Top: the function h_α representing the section of erosion induced by the centreline. C_R is an arbitrary point along the centreline. Bottom: the function h_α defining deposition within a contour. C_D is an arbitrary point along the contour.

In addition, if enabled, interpolation between two curves (either open or closed) facilitates the process of defining a sequence of intermediate stages, that can be interpreted as different time steps of a shape evolution, as shown in Figure 3.5. The user only provides the number of intermediate time steps together with the initial and the final configuration.

From a centreline curve, we compute its region of influence. Within this region, a function that returns a height value for each grid point is defined. The value is inversely proportional to the distance to the closest centreline segment. When a point of the

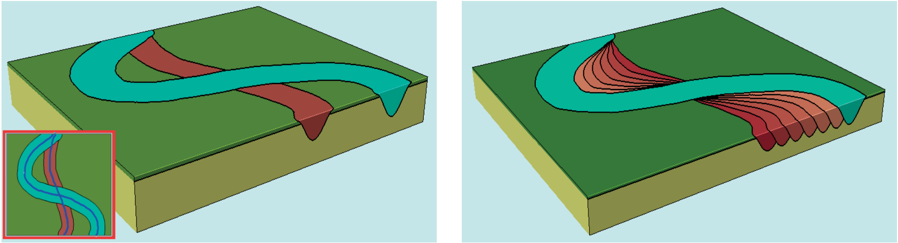


Figure 3.5: River evolution example. Left: first and last configuration of the river are sketched and imprinted. Right: imprint of additional five interpolated stages of the depositional history.

heightmap grid is outside the neighbourhood defined by the centreline, the height is set to zero. Similarly, we need to compute the distance field of the heightmap with respect to a closed curve to get the value of erosion or deposition inside the curve.

As defined in Paper B, relative and absolute layers (see Figure 3.6) are simultaneously kept updated and used during the modelling part (mainly relative) or during the volume visualization (absolute). Basically, they are both heightmaps, the difference lies in the values assigned to the grid points. When we refer to a relative layer, we know that the value at a grid point corresponds to the layer thickness. Therefore it is independent of previous events. The actual height value is instead dependent on the thickness of the layers below. When we refer to an absolute layer, we interpret the value at a grid point as the height of the layer at that point.

An identification number is assigned to each layer, and this number can be associated to a specific colour and volumetric translucency, reflecting specific properties of the layer.

The volume rendering takes place inside a user defined bounding box. For each fragment on the front faces of the bounding box, a fragment shader accumulates the colour along the ray, starting at the front face into the model until the back face of the bounding box is reached. Shading is performed at layer boundaries. When the layer id of the current sample is different from the layer id of the previous sample, we have crossed a boundary. The normal of the crossed boundary is found by calculating the central difference, looking up four samples in the corresponding layer heightmap. For samples that reside on the intersection of the bounding box with the solid model, we also check if the sample above, below, to the left or to the right have a different layer index. If so, the sample is on a layer boundary and we colour it black. This results in a layer separation line as shown in Figure 3.5, also found in hand made illustrations.

3.5 Model Discontinuities and Interactive Illustrations

Using the layered data representation that we introduce in Paper B, we propose an extension of it to represent layer discontinuities in Paper C. Our illustrations result in having independent layer blocks, produced by user-defined discontinuities, that can be displaced interactively with a simple slider. By layer discontinuity, we mean a surface $\mathcal{F}$ that separates the layer into two parts which are then displaced along $\mathcal{F}$. This surface defines where the initial heightmap is cut and how to build the two new heightmaps which encode the displacement.

When $\mathcal{F}$ intersects a layer, the layer is split and saved as two distinct heightmaps.

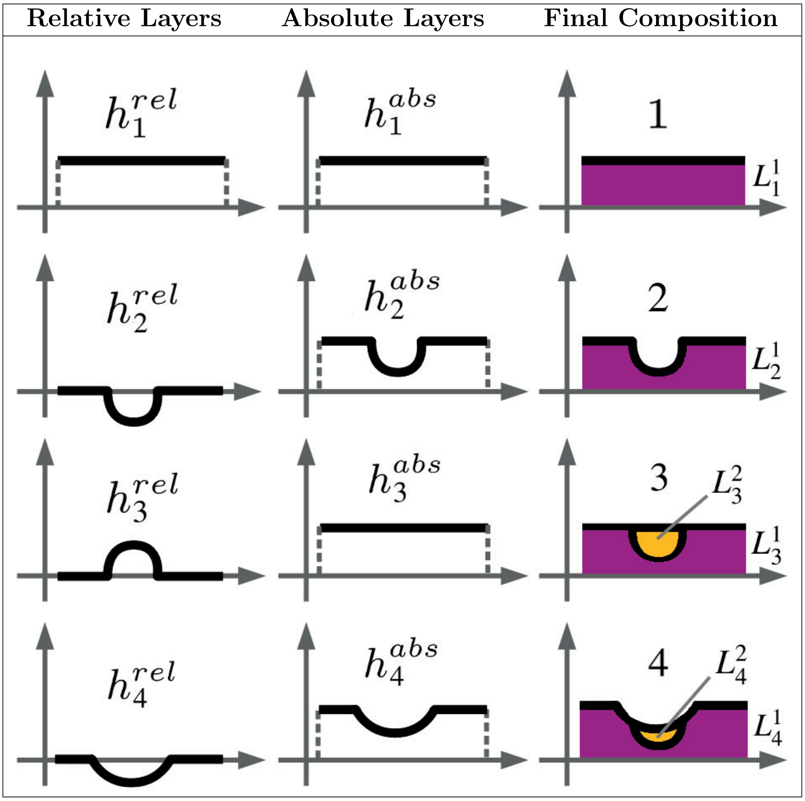


Figure 3.6: Relation between relative layers, left column and absolute layers, middle column. The right column shows the accumulated final model. From top to bottom is shown the adding of new layers, where layers 2 and 4 produce erosion (removal of material).

The displacement that is caused by the discontinuity is defined by the user and assigned to the layers intersected by $\mathcal{F}$ (only one of the two layers obtained by the splitting moves according to the displacement). A layer delimited by a top surface $\mathcal{T}$ and a bottom surface $\mathcal{B}$ that has a discontinuity defined by a surface $\mathcal{F}$, as shown in Figure 3.7, is separated into two parts. Their absolute values are given by

$$h_1^{abs}(i,j) = \begin{cases} h_{\mathcal{B}}^{abs}(i,j) & \text{if } j \leq j_Q \\ h_{\mathcal{F}}^{abs}(i,j) & \text{if } j_Q < j \leq j_P \\ h_{\mathcal{T}}^{abs}(i,j) & \text{if } j > j_P \end{cases}$$

and $h_2^{abs} = h_{\mathcal{T}}^{abs}$.

The process of faulting a model requires the use of both absolute and relative layers, which were introduced in Paper B. For a conversion from one representation to the other, we calculate new values for each grid point of the heightmap in parallel using the GPU. This results in a quicker procedure, allowing interactive animations.

Finally, we suggest and give examples of several visualization techniques that ease the internal inspection of an illustration. In Paper C, we show examples of cut-view, staircase view, exploded view and time-defined view, i.e. where we select a particular

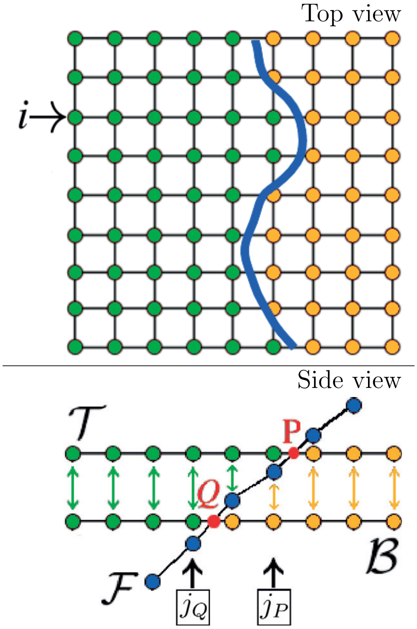


Figure 3.7: Top image: grid of the layer that is traversed by the discontinuity $\mathcal{F}$ (blue curve). Bottom image: cross-sectional view corresponding to the i-th row, where $\mathcal{F}$ intersects the grids $\mathcal{T}$ and $\mathcal{B}$.

time period to display by means of a temporal slider that goes through the time steps of the modelling process.

Chapter 4

Results

This chapter summarizes the principal applications and results obtained with the methods introduced in the papers. Our illustrations have application in geology as communicative support in interactive discussions amongst domain experts, for management decisions and for teaching purposes.

4.1 Folds, Faults and Erosion

Several scenarios may be explored in a meeting with domain experts. One possibility is that the topic is centred on the observation of different rocks and their intrinsic properties. Furthermore, a rock deformation given by folding and faulting processes is studied and discussed. To this aim we contribute with the work in Paper A, where sketches cover the need for folds and faults in the layer-cake, while deformed textures of particular rock types can be assigned to the layers.

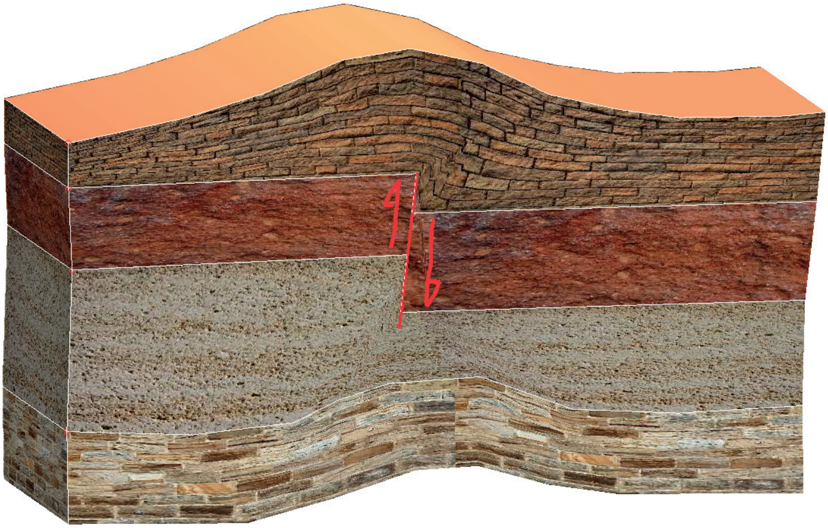


Figure 4.1: Layer-cake illustration obtained with our approach.

For the work presented in Paper A, we studied what information geological illustrations share and salient points they have in common. We also discussed with geologists how they would have proceeded in sketching illustrations. We extrapolated common sketching procedures to achieve intuitiveness in our tool. After we implemented our prototype, we generated a few models, such as the one in Figure 4.1, to show to domain experts. Finally, we asked them to evaluate the speed of our approach.

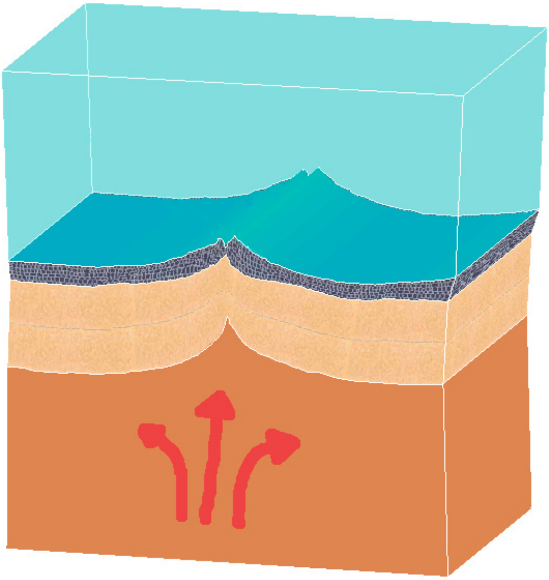


Figure 4.2: Example of the oceanic crust with red arrows suggesting movements of the mantle.

A comparison of times concerning Figure 4.1 and Figure 4.2 is given in Table 4.1, where we place side by side the estimated time used by a geologic illustrator to create a 2D illustration (rightmost column) and the time used to create a 3D model of the same illustration with our approach (second and third column).

Time	User interaction	Processing	Illustrator's estimation
Figure 4.1	∼ 20 sec.	∼ 2 min.	∼ full day
Figure 4.2	∼ 20 sec.	∼ 1 min.	< 1 hour

Table 4.1: Approximate comparison of time using our approach versus manual drawing.

Figure 4.2 demonstrates how to enrich illustrations with simple refinements that help to assign a context which is important to convey scales, environment or other useful information. For instance, layer transparency makes the top layer resemble water and projected drawings, used for notations on the model, show the pressure coming from the mantle.

Introducing animations in our illustrations enables us to present more types of processes. We are able to show geological events such as the forming of a *graben fault*, as in the example of Figure 4.3. In the left column, we sketched the initial and the final time step of the process. Intermediate key-frames are interpolated, extruded in 3D and rendered with the same texture as in the right column of Figure 4.3.

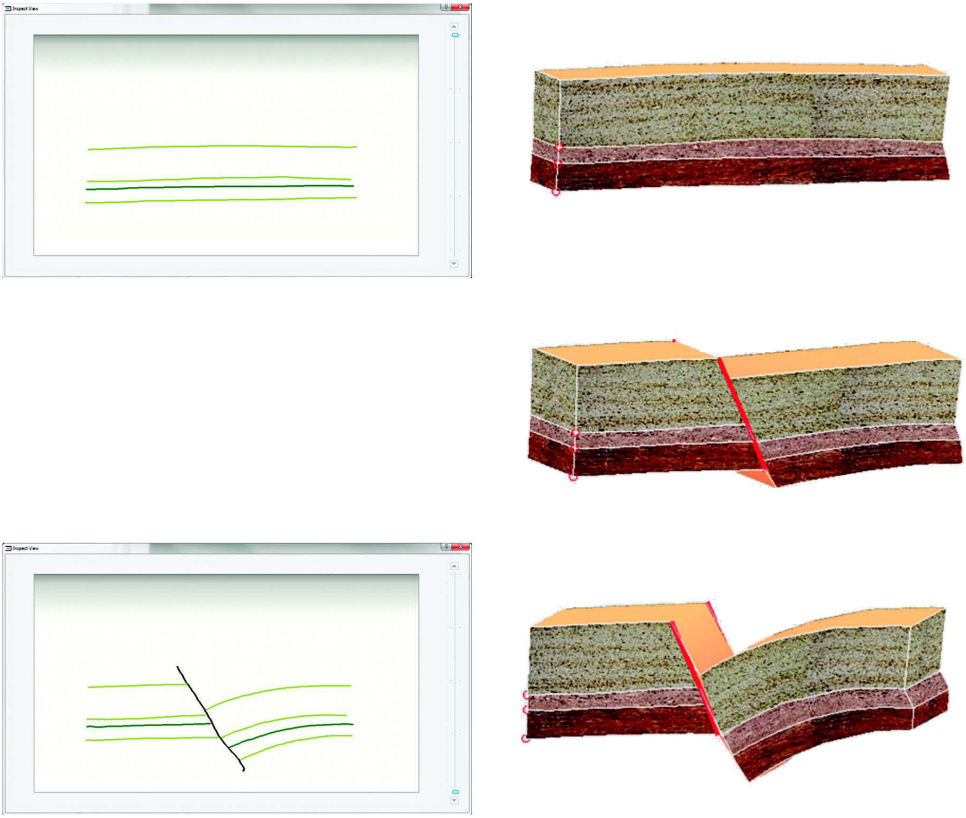


Figure 4.3: Still images of an illustrative animation (right column) and the corresponding initial and final sketched configurations of the geological event (left column). Image courtesy of Endre Lidal [73].

4.2 Stratification and Fluvial Systems

Internal architecture is important in the sense that it tells how a depositional element (e.g. channel or delta) evolved. Our approach offers a new way of producing illustrations by performing interactive erosion and deposition that lets the illustrator mimic processes that she interprets to have been the cause for fluvial system morphology.

One of the interests of geologists are ancient rivers, as they are possibly carriers of hydrocarbons, because rivers had flora located nearby and were visited by fauna. This can cause massive deposits of biomass to accumulate and become buried by successive depositions.

Models of basin stratigraphy, generated by fluvial system development, highlight sub-surface heterogeneity for natural resource exploitation. Furthermore, they can also be employed in the context of palaeogeomorphology, which is a branch of geology that studies ancient erosion surfaces.

A hypothetical meeting concerning a fluvial system development, as depicted in Figure 4.4, would host an expert on river and delta geology. The domain expert would, in short time, sketch the 3D model displayed in Figure 4.4 and, in the meanwhile, tell her story about the formation process and how the meandering river would eventually deposit its transported material particles.

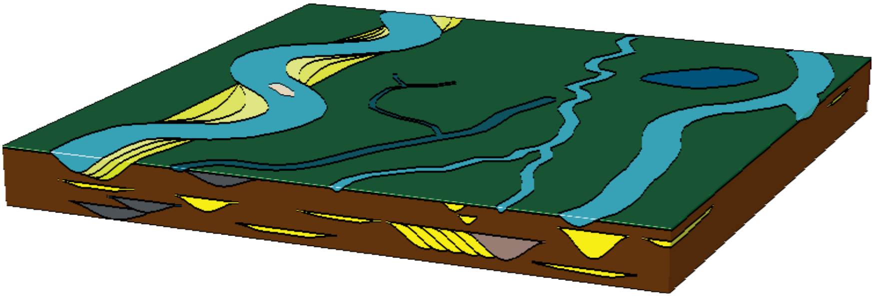


Figure 4.4: This example illustrates a real case analysis from field observations of a river sedimentation process [66]. It was recreated with our technique described in Paper B.

Paper B addresses sketching illustrations of fluvial systems. Their depositional history is important for geologists, because it allows them to detect sandstone formations. Evolution of rivers is characterized by many phenomena that can be considered or addressed in the modelling stage. For instance, there can be an interest in studying river braids (e.g. how and where, along its path, this occurs) to understand the reasons and consequences. One could also focus on the evolution of the shape of a river itself (e.g. curvature of oxbows or width of flow) and on how a river is influenced by, or changes the environment around it. Similarly, there can be an interest in the sedimentation process that is involved in a fluvial system [32]. That is, to model erosion and deposition of the internal and external bank of a meandering river, as well as *clinoforms*, which are subaqueous landforms generated by a delta deposition.

Geological feature are defined by sketching on top of the layers, as shown in Figure 4.5 bottom right.

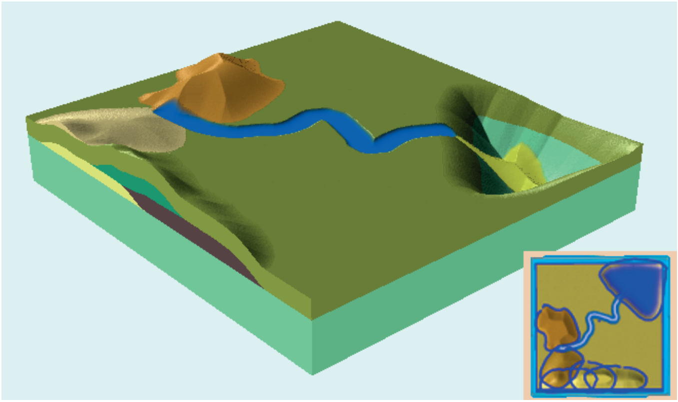


Figure 4.5: A 3D model created using our sketch-based approach to shape surface and subsurface geological features. Bottom right inset shows a map view of the sketched strokes in blue overlaid on the model.

Sketching Rivers. An open curve is interpreted by our system as a river centreline. A river evolution is sketched by defining a start and an end river in addition to specifying how many intermediate rivers the system should create. Each sketch has a user-defined height and width factor associated. For rivers, this defines the depth of the river erosion and the region of influence.

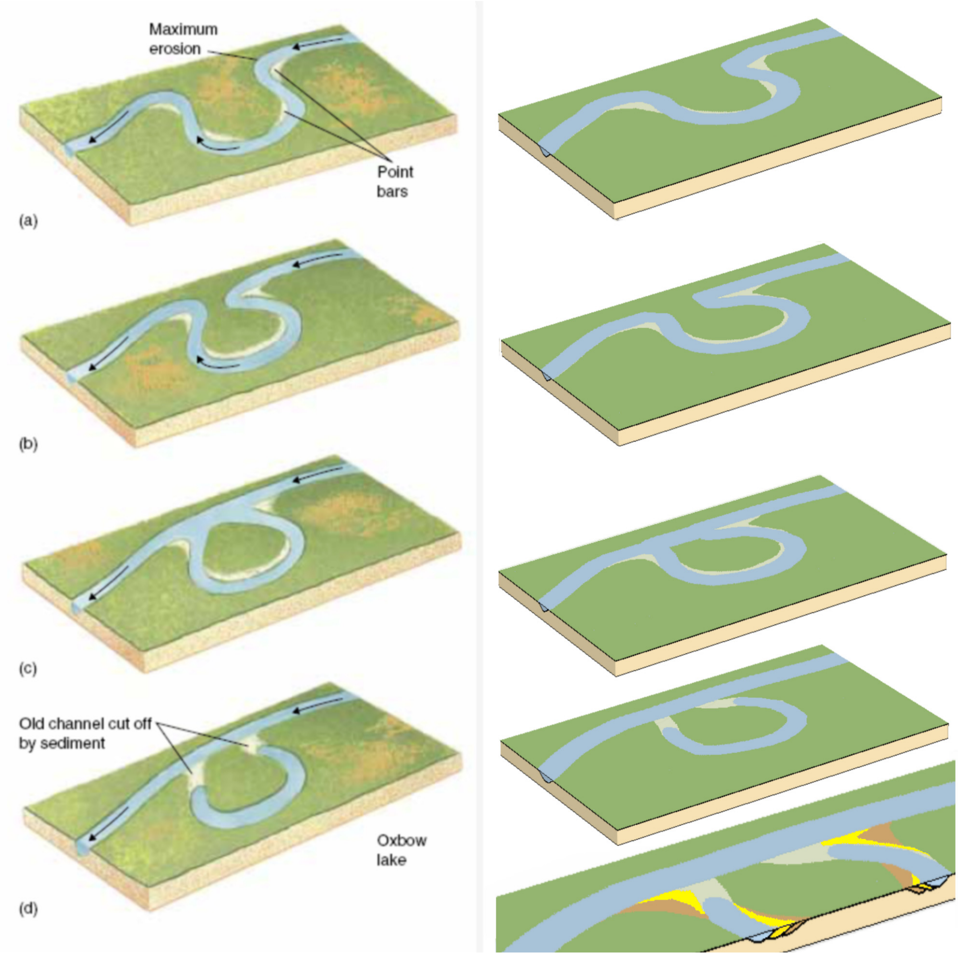


Figure 4.6: Left: sequence of illustrations showing the evolution of a meandering river with oxbow shape by Thompson and Turk [131]. Right: Reproduction with our approach requiring only five strokes. In the enhanced image at the bottom, we added colours to the individual depositions to show them separately.

Sketching Deltas. When sea level is sinking, deltas and shoreface deposits are arranged in successive, seaward-stepping sets, distinguished from each other by brief periods of altered depositional patterns (e.g., storms or sediment supply). Internally, these sets typically show coarsening upwards of grain sizes and therefore high quality reservoir sandstone can be found in the upper part of these sets. Similar effects with opposite trends take place when sea is rising. Due to the successive deposits at varying positions, deltas have a complex internal structure which are tedious to model when defining each layer boundary individually. We propose a simple yet powerful sketching metaphor for modelling deltas including the varying grain size properties of each individual layer. A closed curve defines an area within which the delta deposits.

Sketching Mountains, Lakes, Constant Layers and Sea. Mountains, which are a source for depositional material, can be coarsely sketched with our approach by using the same sketching metaphor as for sketching deltas. This is not geologically correct, because mountains are usually not created directly from sedimentation. However from a modelling point of view, our sketching operators support expressing mountains in this way. Lakes can also be sketched for creating landscape features. Layers of constant thickness can be added to represent a base layer, a top soil layer or a series of layers of different material composition that can be later eroded for modelling outcrops. In addition, the user can define a global sea level where translucent volumetric water will be rendered for describing the subsea volume in which delta deposits are produced.

A property that is appreciated by domain experts is that our 3D sketched models can be easily internally inspected with cutting planes that enable multiple cross-section visualizations. This helps in understanding complex internal layering within the sandstone, otherwise not intuitively apprehensible (Bridge [17]). Sequentially defined models enable interactive discussions, fast hypothesis testing and creation of time-series illustrations, such as the one in Figure 4.6, that demonstrates how to achieve an illustration with our system (right) expressing the same river evolution process as in the manually made illustration to the left.

Our proposed data structure, and the way it is processed to render volumetric models, has advantages compared to a voxel representation. For example it has higher resolution with less storage requirements. This is due to bilinear interpolation of adjacent height values of the grids we use. The difference in resolution can be noticed in Figure 4.7, where voxel artefacts are clearly visible in the zoom in of the left image. When using a volume for storing individual segmentation masks, interpolation between segmentation id's make no sense and must be turned off. This results in staircase artefacts.

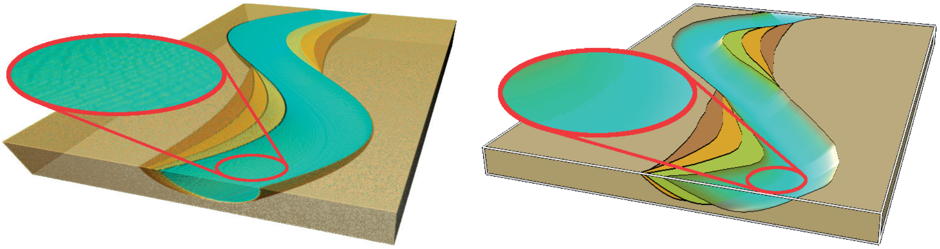


Figure 4.7: In this figure, we show the improvement in resolution from using a voxelization of the model (left image) to using our volume visualization obtained by ray-casting through heightmaps (right image).

Geological features are defined through sketches. Each sketch can generate deposition and erosion processes; in particular, rivers and channels, mountains, basins, deltas and intermediate stages of their evolution. This latter processes of delta deposition and

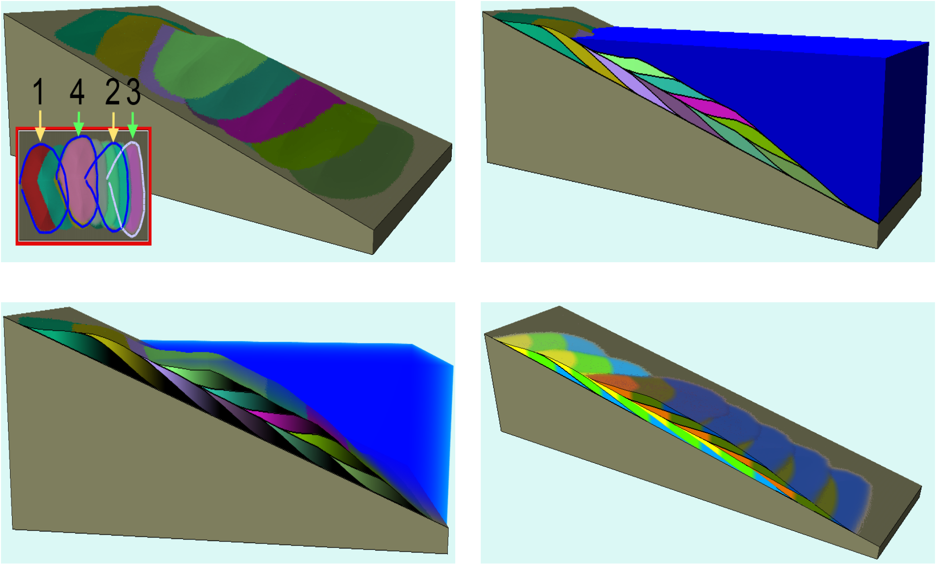
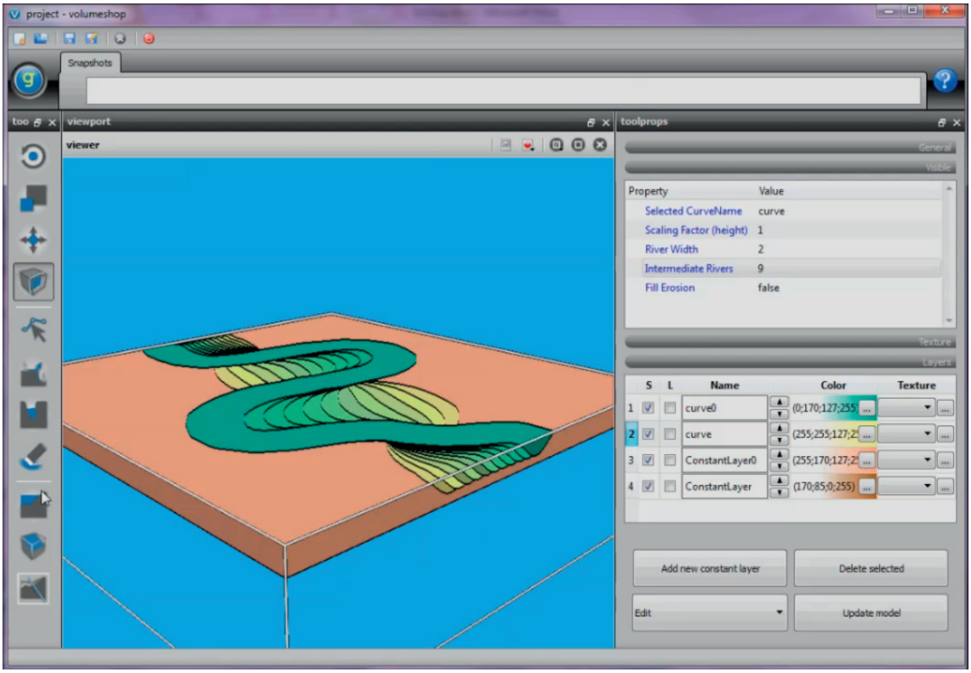


Figure 4.8: Delta stratigraphy example, where only four sketches define the model: sketch 1 and 2 describe the sedimentation process that moves from the shoreline towards the sea; the second sedimentation process accumulates deposits in the opposite direction and is defined by sketch 3 and 4. The two lower images also show different grain sizes for each deposit.

development in time is shown in Figure 4.8, in which more phases of deposition are automatically added by interpolating two curves. Few strokes define the whole model and the cut-views highlight the grain size distribution encoded in the delta deposit colour map.

Grain size of delta depositions is dependent on the distance to the mouth of the river as heavy particles deposit first. Our system allows the user to define this feature and to visually convey it, as represented by Figure 4.8 in the two lower images. The example in Figure 4.8 has been created with just four sketches: the first (in chronological order) sedimentation process goes towards the sea and is defined by sketch 1 and 2 (interpolated with three intermediate steps); the following sedimentation process proceeds towards the shoreline and is defined by sketch 3 and 4 (interpolated with three intermediate steps). Grain size can be expressed by darkening layer colours, as in the bottom-left image of Figure 4.8, or by letting the user utilize customizable colours for each of the depositional layers, as in the bottom-right image of Figure 4.8, where we define three colours for each deposit and, in addition, we chromatically distinguish between the first sedimentation process and the second. As is natural for illustrations, Figure 4.8 is an over-simplification of the complexity of a real situation.

Evaluation. Our prototype is implemented in *Volumeshop* [19]. See Figure 4.9 for a snapshot of the graphical user interface we have implemented. We used our prototype to generate a tutorial video [88] that was shown to geoscientists with different expertises for a user evaluation. In addition, other domain experts directly tried our tool before giving us feedback.



Property	Value
Selected CurveName	curve
Scaling Factor (height)	1
River Width	2
Intermediate Rivers	9
Fill Erosion	false

	S	L	Name	Color	Texture
1	☑	☐	curve0	(0;170;127;255	
2	☑	☐	curve	(255;255;127;2	
3	☑	☐	ConstantLayer0	(255;170;127;2	
4	☑	☐	ConstantLayer	(170;85;0;255)	

Figure 4.9: Image of the graphical user interface which was employed for the user study and to create our examples in Paper B and Paper C.

Details of the results and discussion on the user study can be found in Paper B. Here we list some of the comments we received by the participants:

- "The system seems really useful if you study fluvial systems behaving in a regular way."
- "There is a lot of potential in a piece of software like this. In addition to help visualizing systems in 3D, it could speed up the process of creating illustrations."
- "Great job indeed!"
- "It seems like a nice and easy modelling tool."
- "The program has good potential and can be of great help in visualizing in 3D."
- "The program definitely has good potential. As geologists often deal with 2D outcrop sections and build a picture from many pieces, this program can really be a powerful tool in 3D imaging of geological processes."

4.3 Interactive Faults and Compaction

The process of faulting is, in general, restricted within the first 15 kilometres of the Earth's crust. Faults are important geological features. Their interpretation leads to an understanding of the behaviour of the crust of the Earth. Movements in the crust

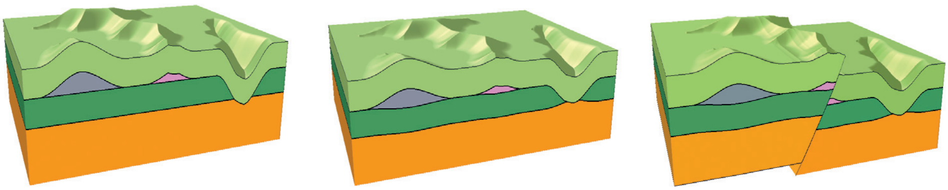


Figure 4.10: To the initial stratigraphic illustration (image to the left) we firstly introduce compaction (middle image) and then we add a fault (right image).

produce faults in rock layers. For instance, a standard approach to derive the direction of two lithospheric plates is to study faults generated by their displacement. A clear manifestation of active faulting is given by earthquakes. Studies on active faults cannot foresee earthquakes, but they can give hints on where to expect seismic activity. Moreover, understanding the types and patterns of faults have other implications on the prediction and reconstruction of ancient landforms. This is because different types of faults tend to form in different scenarios, and, for example, faults at active rifts are different from those along edges of mountain ranges. Another important consequence of faults is that they can change the movement of groundwater, generating a strong influence on the distribution of mineralisation and also on the subsurface accumulation of hydrocarbons.

Compaction contributes to the formation of sedimentary rock by squeezing out air and fluids that exist between sediment particles. The squeezing process is due to the weight of overlying layers of sediment. Faulting and earthquakes shatter rocks that are then compacted to form new aggregate materials, sometimes of economic value.

This section of the thesis is focused on achieving illustrative geological models showing non-planar faults and compaction of layers. Paper C describes in details the steps that are needed to obtain our goal.

Going back to the hypothetical meeting, a geologist which is expert in faulting and compaction takes the word and explains to the audience why the compacted rock layer has yielded hydrocarbon leakage in its upper level. The leakage has gone through passages opened by a fault fracture all the way up, until an impermeable layer has been encountered.

We have extended Paper B to include faults and compaction. We also transfer the most computational expensive tasks to the GPU by implementing computing intensive parts of the code in CUDA. This helps us to maintain interactivity during modelling of faults (which requires more computations than what was needed in Paper B for stratification processes). Parallelization is done on the points of the heightmap grid, therefore every procedure on the GPU consists of computing calculations with a low number of variables corresponding to the number of layers. With our implementation, we are able to quickly create models, such as the ones in Figure 4.10, using few sketches. Figure 4.10 shows a stratigraphic model to the left, a compacted version of the same illustration in the middle (the lower a layer is, the more compacted it is) and finally a fault in the right image. Notice that in the two right images of Figure 4.10, the orange bottom layer does not expand where there is erosion, as it might seem. There is just a relative effect of compaction around it.

Compaction of layers is given by a coefficient which defines material compressibility. The coefficient is dependent on the weight of the material deposited on top. When an

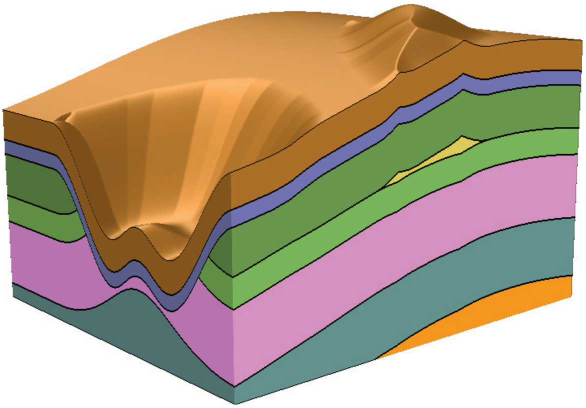


Figure 4.11: A negative coefficient of compression, due to erosion, generates expansion of a layer thickness as can be observed in the centre of the cavity.

erosion is encoded in one of the above heightmaps, we obtain the effect of expansion on the layer below. This effect allows us to obtain an initial stage of intrusion shapes in the illustration, as visible in the example of Figure 4.11.

Our approach differs from other previous techniques when considering the range of faults that can be modelled. Non-planar faults are important in geology and we support them by giving the user the possibility to directly draw the desired shape of the fault surface. Figure 4.12 displays an example of a non-planar fault, where some of the left layers have been set to be transparent to better show the actual internal shape of the fault surface. Although the fault is planar on the side in this example, this is not a restriction in our method.

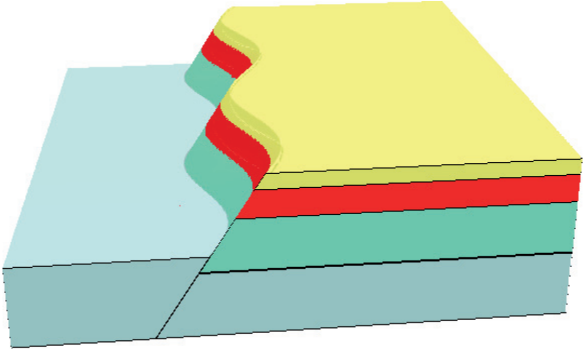


Figure 4.12: In this example we show a non-planar fault. The three top layers of the left block are set to be transparent to reveal the fault shape.

Chapter 5

Conclusions and Future Work

Tools for rapid geological modelling do not exist for subsurface applications, and the idea of rapid model updating and visualization may be an excellent teaching tool and dissemination medium. Our contribution provides this.

We present different ways of defining a 3D layer-cake. Our choice is dependent on what we want to focus on, i.e. the common denominator in our work is given by the exploitation of sketches to obtain intuitiveness and rapidity in modelling; but each geological process or set of geological processes has been treated by us with diverse approaches to best suit domain needs or wishes. For instance, in the first paper (Paper A), we mainly focus on faults and folds. Therefore it is important to be able to draw on a side (cross-section) of the model.

In Paper B, we concentrated our efforts on modelling and visualization of fluvial systems and their depositional history. In this case, sketching on top of the layers, from a top view, turns out to be more convenient for those who design an illustration.

To give the user full control of the modelling and to allow interactivity, we have not incorporated the aspect of physically based simulation of river evolution by simulating matter transport in water. Several existing works already suggest solutions to this.

Depositional processes of rivers and deltas implicitly define internal structures, which require a volumetric representation to display them. The same volumetric representation used in Paper B is employed in Paper C, where internal features are in addition fractured by faults and compacted by gravity.

Coulthard and Wan De Wiel [32] suggest landscape evolution models as a method for modelling river history. Following this line, we propose a layered representation where each layer is a height map of a certain time step.

The simple idea of interpreting height values of a relative layer as amount of deposition or erosion leads to an intuitive definition of a geological process and to basic and parallelizable arithmetic operations during the computations among layers. The various stages of deposition and erosion of a river or a delta are captured by the data structure and rapidly retrieved for visualization.

Geologists, arguing for a feasible interpretation of the stratigraphic configuration of the Barents Sea in the above mentioned meeting, benefit from the contributions that can be found in this thesis. More precisely, the following contributions cover their requirements, but are missing from previous work.

- A rapid sketching tool for creating illustrative visualizations of structural geology, as seen in geology text books which can be beneficial in exploration companies to describe subsurface situations, that includes:

- modelling of a faulting process of a rock layer through simple sketched curves;
- texture shape modification, in order to communicate different geological events, according to user guidance (in the form of strokes);
- application of conformal map for smooth texturing of deformed rock layers (to maintain the meaning of illustrative textures on rock layers);
- animation of 3D synthesized models, to convey geologic processes;
- a volumetric rendering algorithm based on a novel compact representation to interactively obtain illustrative layer-cake visualizations;
- fluvial systems with their history and evolution, together with a visualization of their depositional imprinting (useful to model ancient river channels which are present in the lower stratigraphic layers of the Barents Sea);
- customizable colour distribution to convey the variation of different properties of a deposited material such as grain sizes in a delta deposition;
- support for compaction of subsurface layers;
- support for non-planar faulting processes and their interactive animation;

Although our main application is in a geological environment and our tools target specific geological aspects, we see various fields which could benefit from interactive domain specific sketching. This is true anywhere where a 3D model can be used as an illustration of a process, and when there is a group of people that has to take a decision that is dependent on the configuration of the considered event. For instance, our approach could be adapted for application in archaeology, terrain inspection before laying the foundation during buildings construction, towards geothermal industry, ore extraction or aquifer detection.

Earth science disciplines are increasingly interested in modelling methodologies developed within the computer graphics research. And they are driven by the need for rapid modelling procedures. An interesting research direction can be the consideration of temporal aspects in geology, as investigated in Paper 2. Erosion has been considered in this context, but geological processes are driven by many more phenomena. Here, also the temporal aspect can benefit from user input in the form of sketched information.

Customizable river and delta sections is also a foreseeable extension of this work; the user could sketch the profile of the river section instead of having a fixed analytical function for that as we currently do.

A natural extension of this work could support co-rendering of the model together with an underlying seismic dataset or, in general, any measurements such as well logs or magnetic data, if they exist. In addition, it would be possible to import real landscape heightmaps (*Digital Elevation Models (DEMs)* are a widespread representation for that purpose) and combine them with user defined changes to the initial geomorphology.