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Exploring Novel Interfaces for 3D Visualization of Reservoir Simulation

Post-Processing Data

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Exploring Novel Interfaces for 3D Visualization of Reservoir Simulation Post-Processing Data" submitted by Nicole Barbosa Sultanum in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE.

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Abstract

Oil and gas reservoir flow simulation models are computational models that converge reservoir data collected from several sources into a single entity. They are used by reservoir engineers to forecast reservoir behaviour, a fundamental activity for better understanding of the underground reserves; they are also analyzed and discussed by a team of experts in related fields, ultimately attempting to find optimal solutions to the exploration of oil and gas reservoirs. We believe that well designed interactive visualization systems can facilitate this interchange with a clearer awareness of the reservoir while fostering teamwork, and can positively impact the decision-making process. Novel interactive technologies, with the potential for leveraging such aspects, are prone to provide a new, rich and collaborative experience for the task of reservoir visualization analysis.

In this thesis, we thus undertake the task of designing with novel interactive technologies for reservoir visualization, through a set of novel digital tabletops and tangible interfaces for reservoir engineering. We discuss the domain and the importance of visualization in the field, including findings of an observation study we conducted in order to obtain insight on the work of these professionals. Following, we present our research, encompassing three prototypes we designed, implemented and evaluated: *Snakey*, a tangible interface for exploratory 3D well planning; *Touching the Depths*, a tabletop interface for visualization of reservoir simulation data; and a set of direct reservoir manipulation techniques, applied to a multitouch tabletop environment. We conclude by presenting design heuristics for the development of interactive reservoir visualization systems, synthesizing crucial lessons learned throughout this research.

Publications

Some of the materials, ideas and figures in this thesis have previously appeared in the following publications:

- N. Sultanum, E. Sharlin, M. Costa Sousa, D. Miranda-Filho, R. Eastick. *Touching the Depths: Introducing Tabletop Interaction to Reservoir Engineering.* Proceedings of ACM International Conference on Interactive Tabletops and Surface (ACM ITS '10), November 2010, Saarbrücken, Germany.

- J. Harris, J. Young, N. Sultanum, P. Lapides, E. Sharlin and M. Costa Sousa. *Designing Snakey: A Tangible User Interface Supporting Well Path Planning.* Proceedings of 13th IFIP TC13 Conference on Human-Computer Interaction (INTERACT 2011), September 2011, Lisbon, Portugal. *(to appear)*

The following work was recently submitted, and is currently under review.

- N. Sultanum, S. Somanath, E. Sharlin and M. Costa Sousa. *"Point it, Split it, Peel it, View it": Techniques, Evaluation and Design Heuristics for Interactive Reservoir Visualization on Tabletops.*

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Chapter 1

Introduction

Oil and gas resources are currently among the world's most fundamental commodities, with its numerous uses ranging from energy generation to plastic production. While the use of oil dates back thousands of years ago, its exploration only consolidated in the 19th century, with the discovery of kerosene for generating energy. Since the first commercial well drilled in 1859 [30], oil and gas reservoirs have been thoroughly studied as an attempt to cope with their complexity and uncertainty, and to improve oil retrieval in a commercially and environmentally viable exploration.

As the knowledge about oil and gas fields grew vaster and more complex, specializations in geosciences and engineering have been created to focus on sub-tasks of the general effort of oil/gas exploration and production (E&P), including the field of *Reservoir Engineering*. Reservoir engineers are responsible for capturing the essence of an oil/gas reservoir, in terms of its containing fluids, and the appropriate mechanisms that can be leveraged for extracting these resources. For this purpose, *reservoir flow simulation models* are created, to depict a reservoir's flow behaviour. Reservoir visualization systems represent the principal means to access and analyze these data, and are, therefore, essential to their work. Similarly, when these tools provide better means for interacting with the model, as well as facilitate collaborative analysis, they are also fostering better awareness, and consolidating understanding of a reservoir. With this in mind, several interactive systems operating on alternative interfaces – such as collaborative visualization rooms [80, 10] and immersive environ-

ments [55, 78, 20, 48] – have been explored over the years, as an attempt to provide more powerful, insightful and intuitive interaction and potentially enhance the overall experience of the analysis as well as fostering better decisions.

In this thesis we follow this trend, and explore the incorporation of novel, "beyond the desktop"' interaction platforms and visualization techniques to the task of visualizing reservoir simulation models. We present some of our efforts in this direction, featuring the use of digital tabletop devices and tangible user interfaces (TUIs). We also present insights gathered from domain experts through diverse experiments, including design critiques, an observation study and a user evaluation.

The remainder of this chapter encompasses a brief overview of the domain addressed by this thesis – interactive visualization for reservoir engineering – followed by thesis goals, approach, contributions, and finally concluding with an overview of the remaining components of the thesis.

1.1   Reservoir Engineering and Interactive Visualization

As oil and gas E&P became a solid, highly profitable activity, many enterprises emerged as a result, creating a strong competition. Consequently, a constant pursue for knowledge in the oil/gas E&P process was necessary to consolidate one's position in the field; and as the body of knowledge accumulated, technical branches have grown more and more segmented, following a trend of specialization. Consequently, many areas of expertise have emerged as branches of engineering and existing sciences – such as Geology, Chemistry and Physics – however maintaining a strong correlation between the disciplines, and consolidating oil/gas E&P process as a true collaborative

effort. Reservoir engineering is one of the many emerging fields.

The reservoir engineer is responsible for setting up a development project attempting to optimize the hydrocarbon recovery as part of an overall economic policy [17]. In other words, given a reservoir description, a production strategy must be created that will seek to maximize extracted resources and minimize exploration costs. It is a complex activity, which involves a good understanding of rock properties, knowledge on the motion of fluids inside a reservoir, and how to make use of proper retrieval mechanisms in a profitable way. For this purpose, reservoir simulation models – virtual three-dimensional, multi-property, time-varying representations of oil reservoirs – are used by reservoir engineers to converge the knowledge acquired about a certain oilfield, and also incorporate physically-based simulations for forecasting possible outcomes of production scenarios. This entity, when depicted in a rich, relevant, and engaging manner, can greatly improve awareness and allow for more informed decision making, consolidating interactive reservoir visualization as an essential tool for the domain.

Over the years, with the gradual depletion of the 'easy' oil reserves – that is, the more technologically accessible sites, with higher levels of recoverability – there has been an increasingly high demand for the research and development of innovative, open-minded solutions, to allow more intuitive visual exploration of the massive data scales and complexities that are very characteristic of oil/gas E&P. Research has thus been comprehensively conducted in the field, including not only technical issues but also human aspects. The process of analysis and decision making, despite the aid from automated tools, still relies on the analysis and interpretation of a series of professionals, who are the true driving force behind oil/gas E&P. In this perspective,

(a) (b)
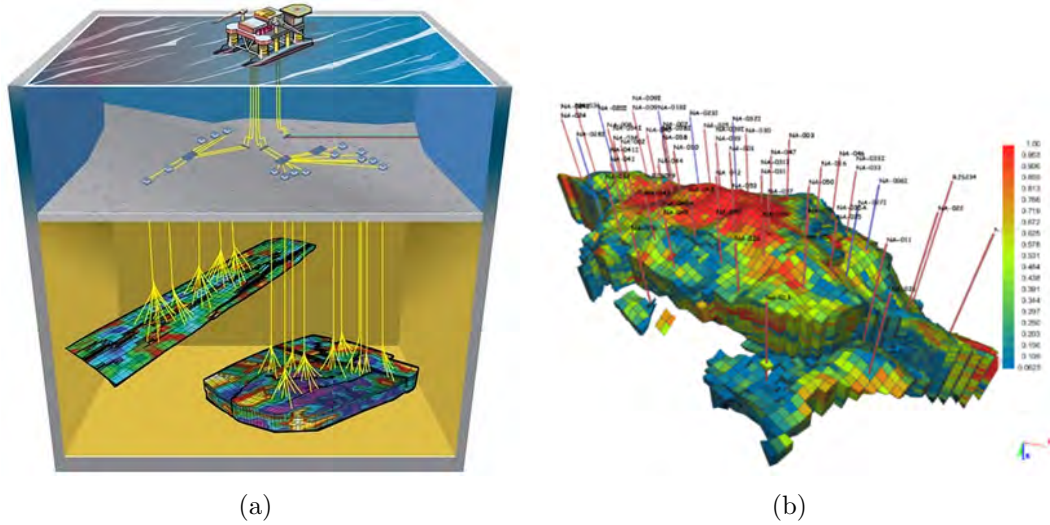
Figure 1.1: Two examples of reservoir depictions: (a) a man-made illustration, depicting two reservoirs at the bottom, and the respective production facilities on top (schematic illustration from Halliburton); (b) an example of a 3D reservoir flow simulation model, depicting the distribution of oil saturation over the reservoir (from [4]).

interactive visualization systems are probably one of the most high-impact tools in the domain, since it is through them that the experts gather additional knowledge and make more well informed decisions.

Given the importance of the "human element" on interactive reservoir visualization for the oil/gas E&P, efforts should be made in terms of better enabling and enhancing perspectives; for that, advances in computational media and visualization techniques are invaluable, in a sense that, when properly used, they can facilitate faster and more accurate analysis and interpretation.

1.2 Goals

The main goal of this thesis is to investigate and engage in the design, implementation and evaluation of new ways of performing interactive visualization, through the use of novel interaction platforms – *digital tabletops* and *tangible user interfaces* – targeted at the potential improvement of the reservoir's awareness and the overall user experience and insight for the domain of reservoir engineering.

These efforts include both human and technical aspects of interactive reservoir visualization, and require a multidisciplinary approach to create and concretize ideas in a more comprehensive manner. Therefore, in this thesis, the reader will find elements from the domains of reservoir engineering, human-computer interaction, scientific visualization and computer graphics.

1.3 Approach

In order to constitute an exploratory endeavour, *several* initiatives must be considered. In this thesis, we present and discuss the design, implementation and evaluation of *three* prototypes with distinct approaches and complementary objectives:

1. *Snakey*, a flexible tangible interface for well planning tasks in reservoir engineering, that represents a new approach for the manipulation of well trajectories;

2. *"Touching the Depths"*, a tabletop interface for the visualization of reservoir flow simulation models;

3. A set of visualization manipulation techniques making use of multitouch and tangible elements on a tabletop environment.

Tabletops and tangible devices were chosen due to their power and flexibility as interaction media, with affordances for direct manipulation and potential for collaboration. In terms of a broader, long-term goal of ideal interaction paradigm – which would be making the reservoir model a graspable, intuitively manipulable entity in the hands of the reservoir engineer – these platforms also represent, as far as we observed, the best of what current technology has to offer for attaining a glimpse of this vision. Adding to this, these are virtually unexplored technologies within the domain of reservoir visualization, which makes them particularly suitable choices from a research point of view.

With the awareness that the interests and needs of the field play a central role in such domain-specific applications, an active participation and constant feedback of domain experts was maintained throughout the progress of this research, motivating and evaluating each effort through design critiques, evaluation and observation studies. This proved to be extremely positive, both in terms of validating the technologies as well as indicating potentially interesting directions to pursue.

1.4   Contributions

The main contributions of this thesis are:

1. **A set of user investigations focused on the visualization needs of reservoir engineers**, including an in-situ observation, design critiques and a formal user evaluation;

2. **A tabletop interface and related visualization techniques applied to visualization of reservoir flow simulation models**, being, to the best of

our knowledge, the first attempt to map a valid set of reservoir engineering tasks to a tabletop interface;

3. **A novel tangible interface for well planning in reservoir engineering**, addressing the problem of inputting spatial 3D curves with an original TUI solution, as well as exploring its validity to the task of well planning for reservoir engineering and simulation studies;

4. **A set of heuristics for the design of novel visualization interfaces applied to reservoir engineering**, synthesizing key concerns emerging from the comprehensive expert feedback gathered throughout the research.

1.5   Thesis Overview

The remaining components of this thesis are organized as follows:

- In *Chapter Two*, we provide an overview of the reservoir engineering field, reflecting on the importance and evolution of reservoir visualization tools for the domain. We also report a few highlights of an user observation conducted in order to obtain more awareness of more tacit, hands-on aspects of the field;

- In *Chapter Three*, we present and discuss a few relevant past efforts in reservoir visualization and related fields, with a focus on novel interactive techniques;

- In *Chapters Four*, *Five* and *Six*, we detail the design, implementation and evaluation of three prototypes, making of novel interfaces for providing new ways of visualizing reservoirs: (1) *Snakey*, a well planning tangible interface; (2)"Touch-

ing the Depths", a tabletop visualization tool, and (3) a set of visualization techniques for direct reservoir manipulation.

- In *Chapter Seven*, we list a set of design heuristics for reservoir visualization applications on beyond-the-desktop interfaces, which emerged from the user evaluation and critiques performed throughout this research and touch base on fundamental aspects of the domain and its users;

- And finally, in *Chapter Eight*, we conclude, with final remarks and general perspectives for future work;

Chapter 2

Reservoir Engineering

This chapter presents an overview of the key processes and disciplines present in the oil and gas E&P life-cycle, emphasizing the role of reservoir engineers and the importance of visualization technologies to their work. We start with a brief overview of the oil/gas E&P, citing the high-level stages and related fields of expertise. Next, we follow with a more in-depth description of the reservoir engineering field, including the importance and evolution of visualization technology in the domain. Finally, we conclude with highlights of a 1-week observation study, conducted to complement the knowledge about the reservoir engineer's work commonly found in the literature with a more hands-on perspective, attempting to gain insight on tacit aspects of the domain.

2.1   Oil/Gas E&P: a Multidisciplinary Effort

Oil and gas E&P is a complex endeavour. The main reason for this is the fact that oil/gas reservoirs are unseeable entities, located hundreds to thousands of meters below the surface; their physical access is limited, making the collection and modeling of data very challenging, and with results often wrapped in uncertainty and subject to various interpretations.

The only way to directly access the reservoir subsurface and physically collect data is by drilling wells. Samples gathered during drilling, sensors sent down a well, and

many other assessment techniques help increase expert's knowledge about a certain field, and provide better awareness of the reserves. It comes, however, with restrictions. First of all, wells have limited range of accessibility, and cannot 'see' much from the regions further away from their drilling trajectory. Secondly, drilling wells is a costly and difficult activity; therefore, their locations must be well chosen, which is particularly hard at the beginning of exploration when so little is known about the reservoir.

Complexity also lies in the process itself, involving the extraction, production and management of oil/gas reserves. Drilling wells and establishing a production installation is expensive, dangerous, and difficult. After a field is settled, there is still much to be done, in terms of monitoring the resources, dealing with unexpected events, and gathering more knowledge about this inherently encapsulated entity that is the oil/gas reservoir. External factors – such as economic trends and changes in legal and environmental policies – also have a direct impact on the E&P standards, and must be taken into account. In summary, oil/gas E&P is an intricate and multi-faceted undertaking, requiring multidisciplinary teams operating in coordinated actions with smooth communication, and in a timely manner.

In a high-level perspective, the oil and gas E&P lifecycle encompasses four main stages [38]:

1. The *exploration* stage involves identifying potential areas for exploration, by assessing the likelihood of petroleum reserves in the subsurface. Field assessments made by the *geologists*, and seismic surveys interpreted by *geophysicists*, are some of the efforts performed in this stage. Specialists attempt to select can-
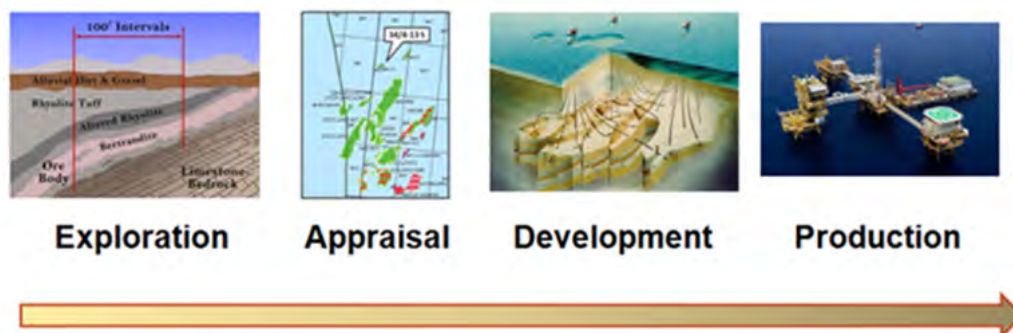
Figure 2.1: Four main stages of oil and gas E&P.

didate regions for further examination, where exploration wells can be drilled to allow for more information on the subsurface.

2. During the *appraisal* stage, experts aim on gathering more knowledge about the field and reducing uncertainty, by confirming the existence of underground reserves in economically profitable amounts, as well as attempting to delineate the reservoir boundaries.

3. If the prospects are favourable, the *development* stage will follow, with thorough planning on deciding the strategies to use for the reservoir in focus; well drilling, production facilities, and considerable investment.

4. In the *production* stage, oil and gas production is established, requiring constant monitoring of the reservoir, as well as active intervention for maintaining desired production rates.

Throughout these stages, experts in distinct (but related) fields will perform several activities, which are often closely related to, and have direct impact on, other expert's work. Figure 2.2 shows a diagram of the many professionals involved in the
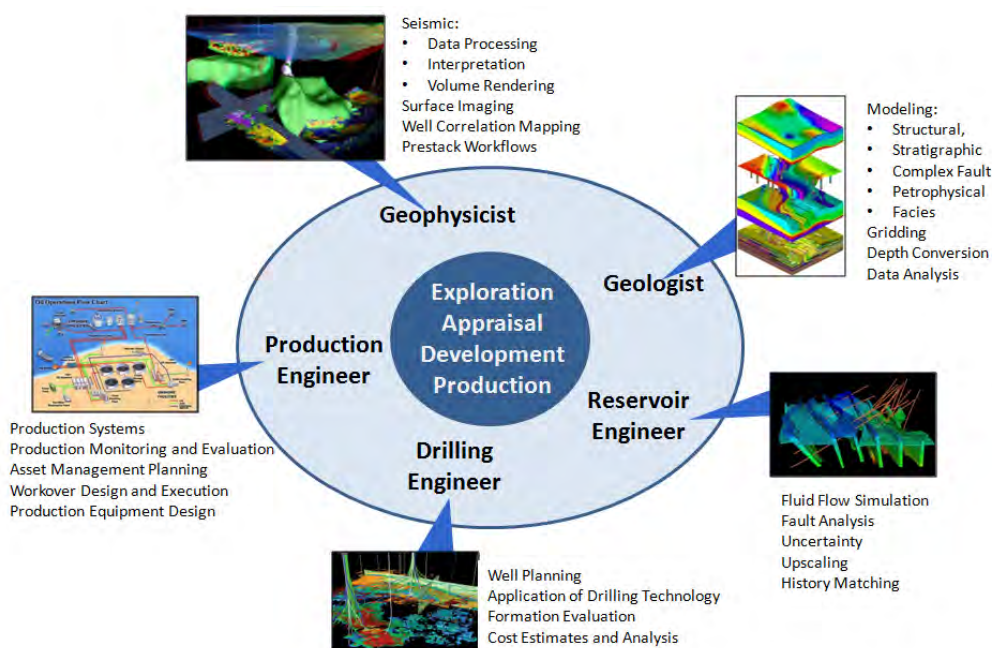
Figure 2.2: A few of the professionals and tasks involved with the oil/gas E&P life–cycle.

oil and gas E&P.

Firstly, the *geologists* are responsible for finding locations of probable oil sources, making field assessments, and gather information about the reservoir, *e.g.* its dimensions, structure, soil composition, and so on. *Geophysicists* participate in the process, being responsible for interpreting seismic data depicting the structure of the reservoir. *Seismic data* are depictions capable of portraying structural cues of geological layers underneath the surface, and are used when little or no information is known about the field; they are generated with the help of potent sound waves – such as a strong stomp by a thumper truck, for instance (Figure 2.3(a))–, which are then reflected by the rock layers and captured by geophones, generating rough cross section images of the underground structures (Figure 2.3(b)).
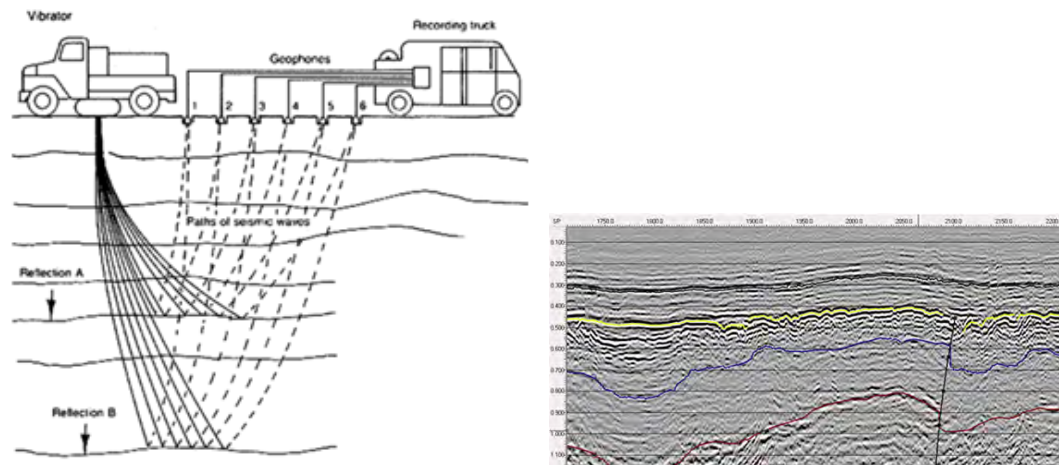
(a) A diagram illustrating how seismic readings are collected

(b) An example of a seismic cross sectional reading

Figure 2.3: Seismic surveys.

With this knowledge at hand, a computational model is created, representing the oil reservoir from a geological perspective. The output is a high-resolution model, containing both the structural description (shape and fault configuration) and estimated rock property values (such as porosity, permeability, and so on). This model is sent to the *reservoir engineer*, whose responsibility involves using the provided data to estimate the amount of resources in place, and coming up with a good strategy to extract them (studying drive mechanisms, proposing enhances recovery methods, and so on). In order to do so, fluid related properties – such as estimated oil, water and gas saturation levels – are added to the static geological model. As they are dynamic and time-dependent, many extra data dimensions are created, which greatly increases the size of the reservoir description, often making it impractical to work with the models in their original resolution. Therefore, a coarser version is created, a process known as *upscaling* [16] (Figure 2.4). The extended upscaled model – commonly called the *flow simulation model* – represents the reservoir behaviour as a whole (with both its

(a) A high resolution geological model

(b) A coarser, upscaled version
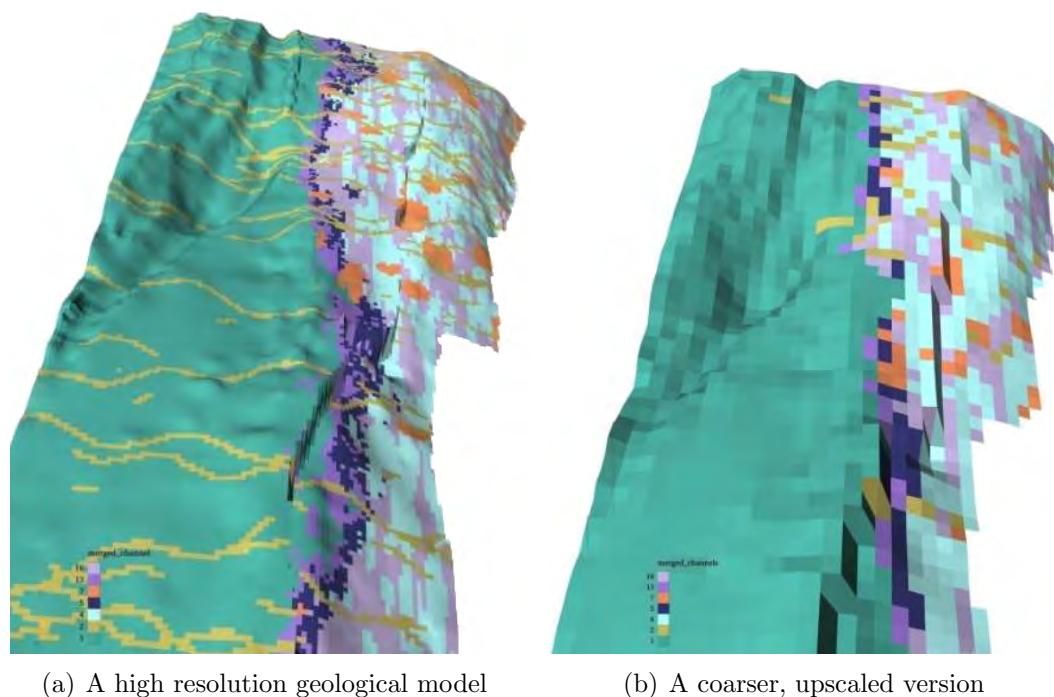
Figure 2.4: An example of upscaling (images from Saudi Aramco). On the left, a high resolution geological model is depicted, showing refined details; on the right, an upscaled resolution version of the same geological model, with reduced resolution for use in reservoir simulation.

structural and flow information) and is used for forecasting and planning.

Drilling engineers are assigned for the well planning, which involves well path design, the selection of appropriate techniques and materials, all in a cost-effective manner; *production engineers* are responsible for the production installations and equipment, and production monitoring. Every drilled well brings more information and awareness of the reservoir: geologists and reservoir engineers gather the new bits of knowledge and revise their records accordingly. As initial estimates for the reservoir model are often incomplete due to the lack of information at initial stages, the reservoir engineer has the responsibility of updating the reservoir models, as soon as more data from the production stage is available – a process called *history matching*

[57]. With this, the virtual representation of the reservoir gets gradually closer to its physical counterparts, allowing for more grounded, well informed decisions.

Finally, the involvement of these professionals and communication between them is hardly a uni-directional process: a lot of interchange happens between the described fields, as revisions and improvement go back and forth throughout the workflow, with the reservoir engineer playing a fundamental role.

2.2   The Reservoir Engineer

As mentioned in the previous section, the reservoir engineers are the professionals responsible for defining how oil and gas reservoirs are to be explored, through the definition of a production plan that attempts to maximize extracted resources (and minimize production costs). Creating an optimal production plan, though, is not an easy task. Reservoirs are complex entities, with unique history, formation and idiosyncrasies, ultimately requiring the reservoir engineer to consider a multitude of factors. With this intricacy to be taken into account, better solutions are not always obvious. Thus it is fundamental to be able to expand a tree of possible production scenarios, and then project the consequences of prospective decisions onto the future, so that more promising options can be selected.

Fortunately, forecasting tools – known as *simulators* – exist for this purpose. They are numerical computational modules, implemented to solve physical equations describing fluid movement inside a reservoir, and are able to predict how they would flow in a certain production scenario configured by the reservoir engineer. *Pre-processing tools* are used to prepare these scenarios for simulation, allowing the reservoir engi-
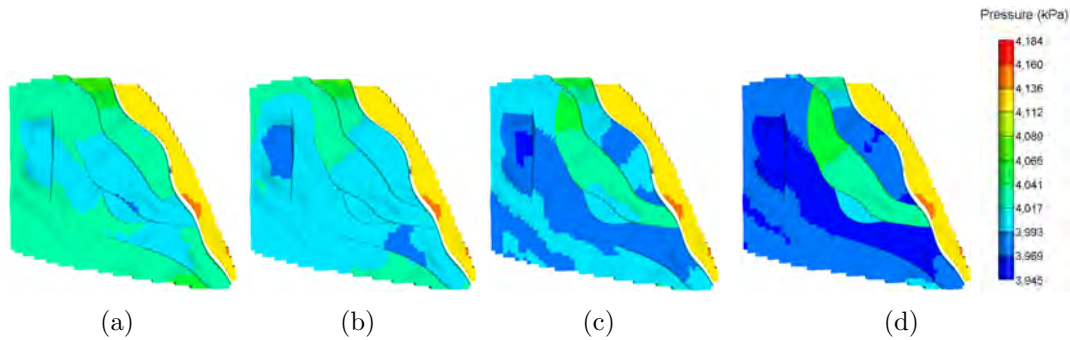
Figure 2.5: Top view samples of a reservoir flow simulation model, depicting variations in pressure simulated for a period of 20 years.

neer to merge the reservoir descriptions provided by the geology and geophysics, as well as configure production parameters and place wells.

The output of the simulator is an extension of the geological reservoir model – often called a *reservoir flow simulation model* – containing forecasted fluid property variations over time, which change according to a production scenario specified by the reservoir engineer. A series of reservoir characteristics are simulated this way, such as the migration of oil when wells are producing, changes in pressure (see Figure 2.5) and temperature, and so on.

The output of the simulators is interpreted and analyzed with the help of *post-processing tools*. They can be 2D tools (such as plot, graph and table builders) as well as 3D visualization tools. The latter provides an intuitive three-dimensional representation of the reservoir, corresponding to its actual estimated physical shape, and is used to spatially depict the property changes occurring in the model (e.g. Figure 1.1(b)). The simulation workflow is depicted in Figure 2.6.

The described computational resources have already become part of the essential toolkit of reservoir engineers, and although field visits are not uncommon, most of

Figure 2.6: The simulation workflow in reservoir engineering.

their time is frequently spent with their desktop computers.

Nonetheless, however powerful these tools might be, there is still a high degree of uncertainty to cope with, due to the inescapable incomplete nature of the provided data. Being found so deep down the earth, direct investigation of the reservoir is limited to what can be assessed from wells, being thus a partial portrayal at best; meanwhile, indirect assessment is limited, often doubtful. In addition to that, the provided reservoir description might contain errors and inconsistency, not to mention the imprecisions that might be introduced by numerical errors in the simulation, or accidental errors introduced by the reservoir engineer him/herself. And most of them are hard to detect and verify, for the reservoir – albeit physical and concrete – is an *ungraspable and invisible entity*. This predicament is well described by Cossé [17] in the following quote:

"(...) the reservoir specialist works on a system to which he enjoys virtually no material access. He has to be satisfied with partial data, furnished by the wells, and therefore incomplete and insufficient. Consequently, he must extrapolate these local data over kilometers in order to compile a synthetic image of the reservoir, enabling him to make production forecasts that are fairly reliable for the near future, and much less so for a more distant future."

As an attempt to cope with the consequences of this uncertainty, it is common

practice to submit one's work to the judgement of other professionals in the field. Upper management (often with a technical background), fellow reservoir engineers and other experts in related areas have the chance to discuss a certain scenario, aiming to find flaws and possibilities of improvement. Within this context, visualization tools play a fundamental role in exploring and analyzing the data in question. The next section is dedicated to give the reader a perspective of how visualization found its way into the domain of reservoir engineering and finally settled as an indispensible tool.

2.3 The Evolution of Reservoir Visualization in Reservoir Engineering

The development of 3D visualization tools represented a real breakthrough in reservoir geosciences and engineering, in particular for visualizing reservoir flow simulation results [76, 79, 8, 7, 22, 67, 6]. Nowadays, several high-end commercial software packages are available for reservoir simulation and visualization [50, 64, 28, 27], and they became an integral part of the reservoir engineering daily work. Conventional tools available in commercial packages allow for 3D visualization and manipulation operations that greatly facilitate understanding and analysis of the model, as well as illustrating and communicating ideas to other team members.

However, this scenario used to be quite different. In the early 80s, computational reservoir simulation already existed, but its output was manually interpreted by reservoir engineers, in its raw form of computer printouts produced by mainframes [12, 11] such as illustrated in Figure 2.7(a). Changes began with the greater accessibility of

desktop computers and the appearance of 2D visualization tools [34], that were able to display planar views of reservoir layers and respective simulation events. Austin *et al.* [8] provides an informative report on this transition period:

"Prior to the arrival of graphic terminals on every reservoir simulation engineer's desk, the majority of the simulation analysis and interpretation was done by examining stacks of 'green-bar' computer printouts. Interpretation was time-consuming and after several months of examining countless simulation runs, many good reservoir engineers decided that reservoir simulation wasn't for them.

As graphics terminal began to arrive on the desktops of the simulation engineer, others continued to question the need for 2D graphics. 'Why aren't array printouts good enough for you?' and 'You're going to use the numbers eventually, so why be bothered with generating complicated graphics?' were a couple of the typical questions asked during this time period. Today, nearly everyone expects a simulator to generate the expected 2D graphic output."

With the introduction of 3D graphics-enabled workstations (Figure 2.7(b)), the first 3D visualization tools for post-processing simulation data were also introduced [76, 79, 8, 7, 22, 67, 6] (Figure 2.7(c)), as described by Thomson and Poupon [73]:

"3D visualization has gradually been introduced into E&P workflows since the late 80s. At first, there was a bit of reluctance from the E&P community to take up the new technology, in part due to a change in interpretation habits (pioneers were sometimes seen as video-game interpreters). An additional reason that 3D visualization was slow to catch on was the severe performance limitations of the early hardware/software platforms. At that time, interactivity could only be obtained with compromises in display resolution and/or dataset size."
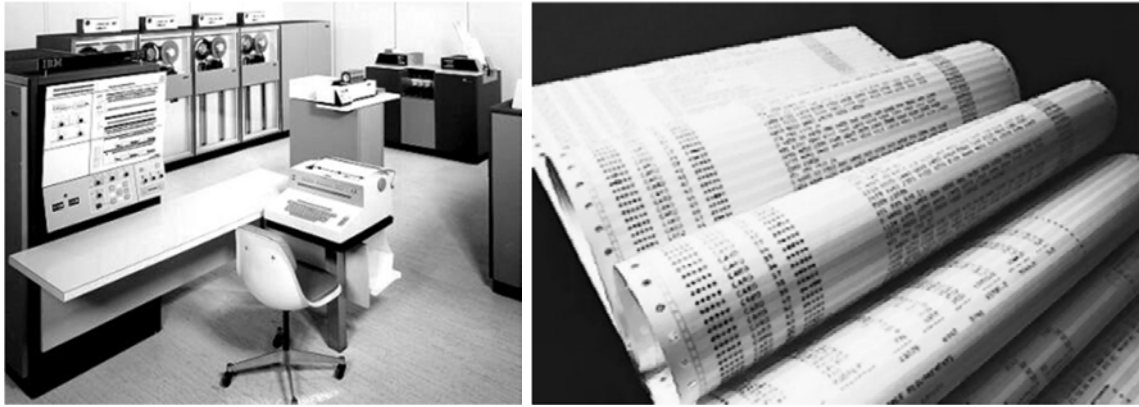
(a) An IBM mainframe – a common simulation platform in the early 80's– and example of computer printouts where simulation results were outputted.

(b) A Silicon Graphics desktop computer, with 3D capabilities
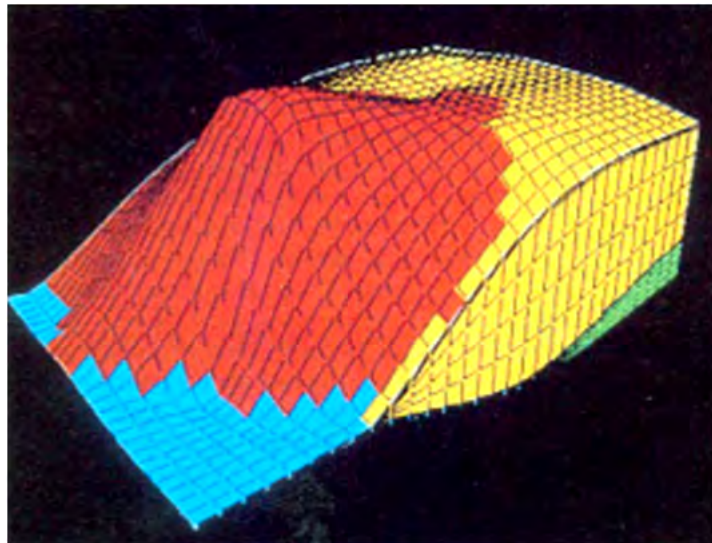
(c) An early 3D reservoir model visualization [76]

Figure 2.7: Early technologies for the interpretation of reservoir simulation data.

Indeed, interactivity and model size were severely limited by the hardware available. But despite the initial technical limitations, 3D visualization consolidated its presence in the reservoir engineering working environment, as technological evolution eventually allowed more complex structures to be modeled, progressively leading to desktop computers powerful enough to run visualization software: reservoir engineers could then have their own workstations. This last technological evolution is two-edged however, as Thomson and Poupon [73] reflect on the transfer of the reservoir engineer to the desktop environment:

"(reservoir engineers) were spending more and more time in front of their monitor... and less and less time directly interacting with their colleagues. The days of leaning over a large work table covered with seismic lines, maps and well logs are long gone... even though these work sessions were developing true multi-disciplinary approach and promoting different perspectives."

Collaboration is very important in this field, widely acknowledged to be an essential aspect of an oil/gas E&P life-cycle [26, 72]; improved access to post-processing data can greatly improve common understanding of the reservoir, thus facilitating collaborative analysis. With that in mind, a few initiatives appeared, applying technology as an attempt to better address collaborative aspects of the reservoir visualization analysis and provide a shared awareness of the reservoir (*e.g.* visualization centers [10, 80]). Despite the general understanding of the importance of collaboration for the domain, more formal investigations of its social aspects in the area are sparser. The work of Corbett [13] is a relevant instance, focusing on personality aspects that affect teamwork, with specific implications to E&P teams; Corbett et al. [14] also conducted a study evaluating the performance of teams of "reservoir

evaluation and management" students, and establishing correlations with individual and team personality profiles.

With a focus on visualization technology for reservoir engineers, it would be desirable to gain greater insight into their work and dynamics. To have a glimpse of how the reservoir engineer uses current computational tools, we conducted a brief observation study in a customer support office of a company that develops computational tools for the domain [50]. The methodology and results are described in the following section.

2.4   In-Situ Observation Study

Seeking greater insight into the work and the environment of reservoir engineers, we observed for a week the activities of the customer support office of CMG Ltd.[1], a company that commercializes computer tools for the domain.

The observed group was composed of 4 trainees, 2 of which had recently joined the team (two to three weeks), while the remaining had one year of experience in the function. The latter group performed the trickiest support requests, and also served as mentors for the new interns in their free time. All of them were engineering students seeking a specialization in the petroleum industry. Their work consisted in solving issues users encounter when operating any of the companys tools. The final users are actual reservoir engineers working in real world E&P projects, who request help from the customer support office when facing difficulties interacting with any of the tools. The trainees, provided with user data and error description, try to replicate the user's scenario in order to find the root of the problem. Additionally, the office

was also regularly visited by reservoir engineers (who perform outsourcing services for real E&P projects from external oil companies), and their feedback and opinion was also gathered when possible.

A customer support environment was chosen instead of regular reservoir engineer office, mainly due to time restrictions. A real E&P project in an oil company may last for many months, even years, requiring a long term commitment to observation, analysis and evaluation. Also, having access to such an environment would require longer negotiations, possibly causing delays to the studies. Finally, in the customer support office, reservoir engineering tasks could be collected in greater number and range than from a real oil project, within the same time frame. Several requests are received and solved every day in the customer support office, making it a prolific observation environment. The main computational components utilized by the users are illustrated in Figure 2.8, and are as follows:

1. *Builder*® is the pre-processing tool that allows the reservoir engineer to converge the necessary information onto a single dataset, the geological model with the rock properties, plus estimated fluid reserves in place, production parameters, and so on;

2. *IMEX*®, *STARS*® and *GEM*® are the simulators, each with specific simulation purposes and suited for different oil production processes and scenarios. That is, they will be chosen by the reservoir engineer depending on the specific phenomena he or she is attempting to examine.

3. The *Results* suite comprises tools for accessing the output of the simulators. Results Report® is used for displaying data in tabular form; Results Graph®,
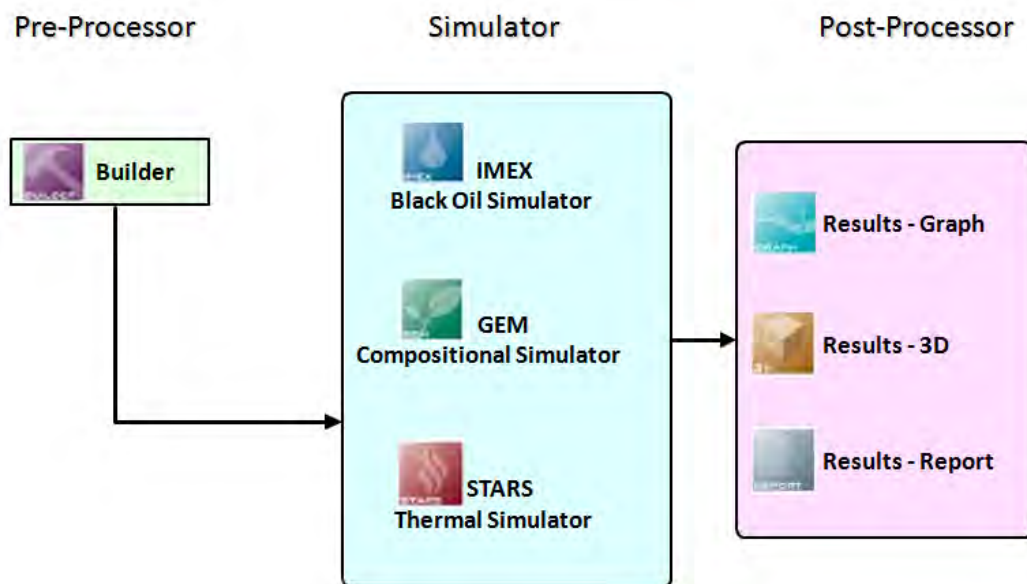
Figure 2.8: CMGs suite of reservoir simulation systems. Used by permission from Computer Modelling Group.

as the name implies, is used for generating graphs from the reservoir dataset; and finally, Results 3D® offers a 3D perspective of the reservoir model as well as manipulation tools for browsing, exposing and highlighting the simulated behaviour.

We adopted an open and subjective observation approach, focusing on understanding the environment rather than gathering user requirements (as proposed by Dourish [21]). Notes were taken, reporting and time stamping observed events. Dialogues were transcribed when possible. In the intervals between tasks, interns were inquired about the work they were performing and how the tools helped them achieve their goal, in a way to interfere with their job as little as possible. In the following subsections, the relevant aspects taken from this experience are synthesized.

2.4.1 Tool Usage

A significant amount of time was observed to be spent on pre-processing and simulation tools, as opposed to post-processing tools. Most of the problems faced by users (and sent over to the customer support office) are related to the simulators, or to reservoir configuration prior to simulation. These tasks represent a substantial part of the reservoir engineer work performed on desktop, and their respective tools are made to support a wide variety of configurations, with a great – and hardly manageable – amount of available functions. A dialogue extract illustrates this:

Observer: *"What are the tools that most commonly require customer support?"*
User: *"The simulators, frequently. (...) People are usually pushing the limits on the simulator, plus, they are more complex pieces of software to begin with. "*

2.4.2 The Role of Visualization Tools

Visualization resources are embedded in both pre and post-processing tools, and although they are essential for depicting the 3D structure and property distribution of the reservoir, in many instances the users bypassed the post-processing tool and browsed specific simulator output straight from the text files. It was quite common among the senior trainees who had solid experienced in the environment, since they could find the desired information directly from the raw output without the need to load a computationally demanding tool.

One of the reservoir engineers was asked about his experience with visualization tools for the domain. He mentioned that time and experience made his use of visualization tools sparser. According to him, they are more useful for presentation

purposes, such as creating videos and illustrating reports, with depictions well suited for people who do not have a deep technical background and need more explicit visual cues. However, he highlighted that they were still an essential tool for his work, despite not exploring its resources to the fullest when generating results to himself.

2.4.3 On Integration

This particular toolset offered by the company is comprised of several separate tools, that have specific functions and produce outputs for other tools in the same set. While this is an acceptable strategy on a business and modular point of view (shared by practically all the similar solutions in the market), the lack of user interface integration can be very disruptive. A reservoir model is modified in tool A (pre-processing), sent to simulator B, and which output is visualized in tool C (post-processing); this process is manually repeated every time changes and adjustments are made to the original dataset. In the customer support office, the computers were equipped with double displays, which somehow mitigates the overwork, but is not a definitive solution.

Likely, the reason for this lack of integration lies on technical issues as well. Reservoir flow simulation is a very time-consuming process, often requiring several hours to be finished, imposing an inescapable interruption to the workflow. There is long ongoing research on *reservoir steering* – that is, visualizing output data while simulation is running [54, 39, 2, 24]– but it is indeed a complex endeavour and currently it is still far from being adopted at a corporate level. Nonetheless, even without faster, near real-time simulation runs, a more seamless approach – possibly taking parallel tasks into account – would certainly benefit the users.

2.4.4   On Tool Expertise and Interactivity

The complex nature and large number of features in reservoir engineering tools can be overwhelming for both novices and experts. Due to this, there is a strong coupling between a reservoir engineer's performance and familiarity with related programs: the work of this professional depends heavily not only on actual field knowledge, but also on operation skills of their specific computational tools. Due to that, usage often requires long and extensive training, a fact that was particularly evident among the less experienced interns who were just beginning to interact with these tools. A lot of their time was observed to be spent reading the manuals and browsing for functions. Similarly though, even seasoned professionals might fail and stumble when interacting with unfamiliar tools.

On the other hand, GUI-based interfaces added to conservative design leads to user restraining, with operations requiring many interaction steps – menu selections, dialog boxes, parameter adjustments, and so on. While the purpose of this observation study was not on meticulously inspecting the user interface of the mentioned tools, we were convinced that there is room for improvement in terms of interactivity. With a more careful re-design, novices could have an easier time finding the functions that they need, and experts could benefit from more efficient usage.

2.4.5   Cooperation and Teamwork

Numerous cases of collaboration and interaction were observed in the study. It was naturally recurrent among the trainees, due to the learning environment established for the new interns; they would often ask questions to their seniors on how to access a specific function in the programs. However, it was also frequent for graduated

reservoir engineers to come help the veteran trainees on particularly complicated support cases. We also observed the opposite happening, when reservoir engineers came to consult the interns relating to tool usage. It reflects not only the mentor-mentee relationship of the internship, but also the inherently intricate nature of their job. Although from a different nature than mentioned in the literature, we were convinced of the strong potential for collaboration in the environment.

2.5 Summary

In this chapter, a general background of the domain this thesis addresses is provided, summarizing some of its fundamental aspects – the complexity, the multidisciplinarity and the uncertainty. A historical perspective is also provided, on how visualization evolved to become an essential element in the reservoir engineer's toolbox.

Findings of an observational study were reported, conducted with a goal of obtaining insight into the work of reservoir engineers. The main conclusion to be taken from the study is that although important in a personal workspace, visualization tools are particularly valuable in presentation environments and multi-user analysis. With this, the validity of exploring new visualization solutions for reservoir engineering seems clear, with a focus on collaborative environments and improved interactivity for promoting better communication and understanding among team members.

Chapter 3

Novel Interfaces and Reservoir Visualization

Following up on the historical background on reservoir engineering visualization provided in Section 2.3, this chapter aims to discuss following efforts in reservoir visualization, as well as research conducted in human-computer-interaction for oil/gas visualization. It starts by outlining past and current work in reservoir engineering visualization, and follows with some of the alternative interfaces developed for visualization tools in the greater domain of geosciences and engineering, aiming to propose new concepts in terms of interaction and visualization.

3.1   Visualization Technologies for Reservoir Engineering

This section outlines some of the main established visualization environments for reservoir simulation data, and includes both research initiatives in academia and industry, as well as commercially available solutions. Among the latter, the GUI-based desktop systems are the most pervasive visualization tools available for reservoir data, and there is a multitude of solutions available, from different enterprises. Petrel® [64] from Schumberger, Results® [50] from CMG, and 3DView® [28] from Halliburton are among some of the most popular systems, with an extensive list of features available (see Figure 3.1).

With the need to provide means for project presentations and facilitate group analysis, collaborative visualization environments were introduced. Visualization rooms
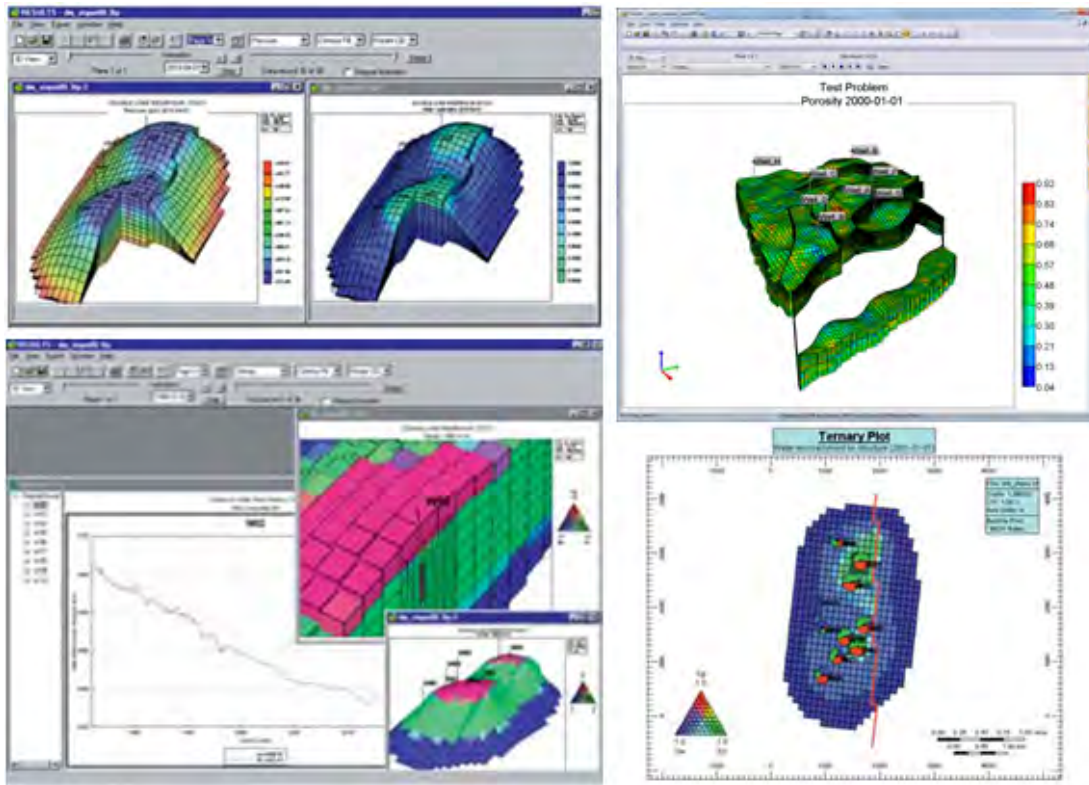
Figure 3.1: Screenshots of a GUI-based reservoir simulation visualization system (CMG Results 3D [50]).

[80, 10] with large displays and stereoscopic view have transcended internal industry research initiatives [66] and are now commercially offered (see Figures 3.2(a) and 3.2(b)).

Immersive virtual reality (VR) systems were also vastly explored in the domain. Among some of the early investigations, Mello *et al.* [55] proposed a VR system composed by a large stereoscopic display, and input through voice commands (limited to a single user) and gesture detection using an overhead camera. Williams [78] investigated the use of a head-mounted display for reservoir simulation visualization, and established comparisons between a non VR environment.
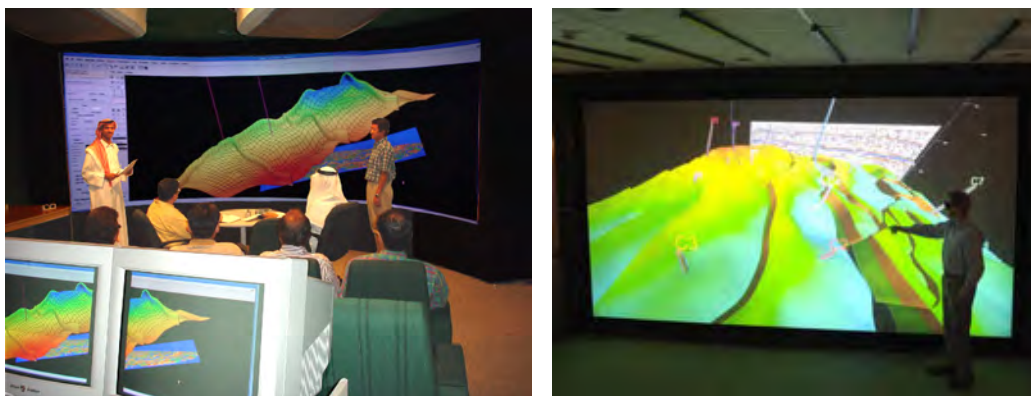
(a) Visualization room at Saudi-Aramco [80]

(b) Stereoscopic view in a visualization room from Mechdyne (http://www.mechdyne.com/)
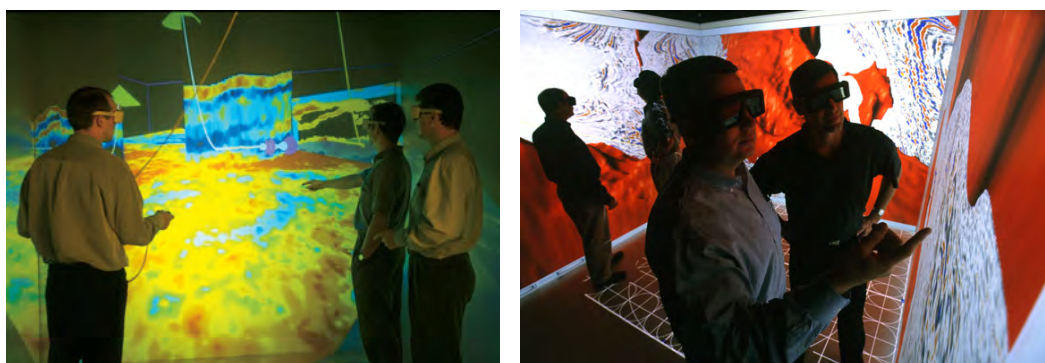
(c) HydroVR, A CAVE environment for well planning [48].

(d) A stereoscopic immersive environment from Mechdyne (http://www.mechdyne.com/)

Figure 3.2: Visualization rooms and virtual reality environments in reservoir engineering visualization.

The CAVE [19] – a walk-in, immersive VR environment – was also employed in many explorations (*e.g.* Figures 3.2(c) and 3.2(d)). Among them, Loftin *et al.* [49] propose a CAVE visualization environment for the visualization of geophysical data. Also, Lidal *et al.* [48] describe ten years of development and extensions for HydroVR, another CAVE environment applied to oil/gas E&P (Figure 3.2(c)), encompassing three main development milestones and highlighting the importance of taking collab-

oration and multidisciplinarity into account; the first initiative focused on providing means to support well planning; the second milestone focused on enabling remote collaboration; and the third effort focused on the implementation of data integration and correlation techniques for enriching possibilities of analysis.

Research efforts of the VRGeo group [32, 31], involved with VR exploration applied to the oil/gas domain, include: a curved display for enabling collaboration for larger groups (Figure 3.3(a)); a two-viewer stereoscopic display, that provides corrected 3D perspective for each tracked user through the use of two stereo projectors (Figure 3.3(b)); and integration with mobile devices such as PDAs and tablet PCs, as personal environment controllers (Figure 3.3(c)).

| (a) | (b) | (c) |
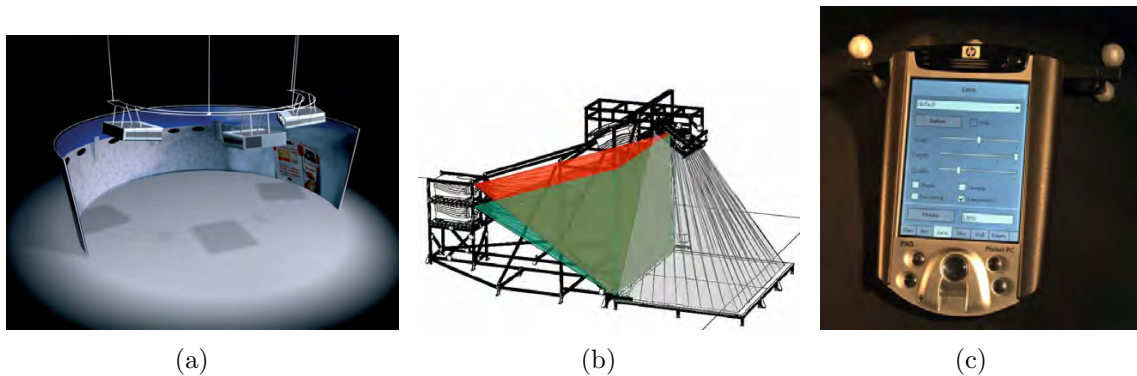
Figure 3.3: Virtual reality tools and environments for reservoir visualization from the VRGeo group.

Dorn [20] reviews a few of the technologies used for oil/gas visualization, including large-scale visualization screens (Figure 3.4) and personal visualization environments and workbenches; he also describes efforts in implementing an immersive environment for drilling planning.

Haptic devices have also been explored in reservoir visualization [80], with the PHANToM pen [35] (Figure 3.5); it provides sensory feedback from physical properties

(a) Large flat.

(b) Multi-panel.

(c) Cylindrical curved.

(d) Immersive room.
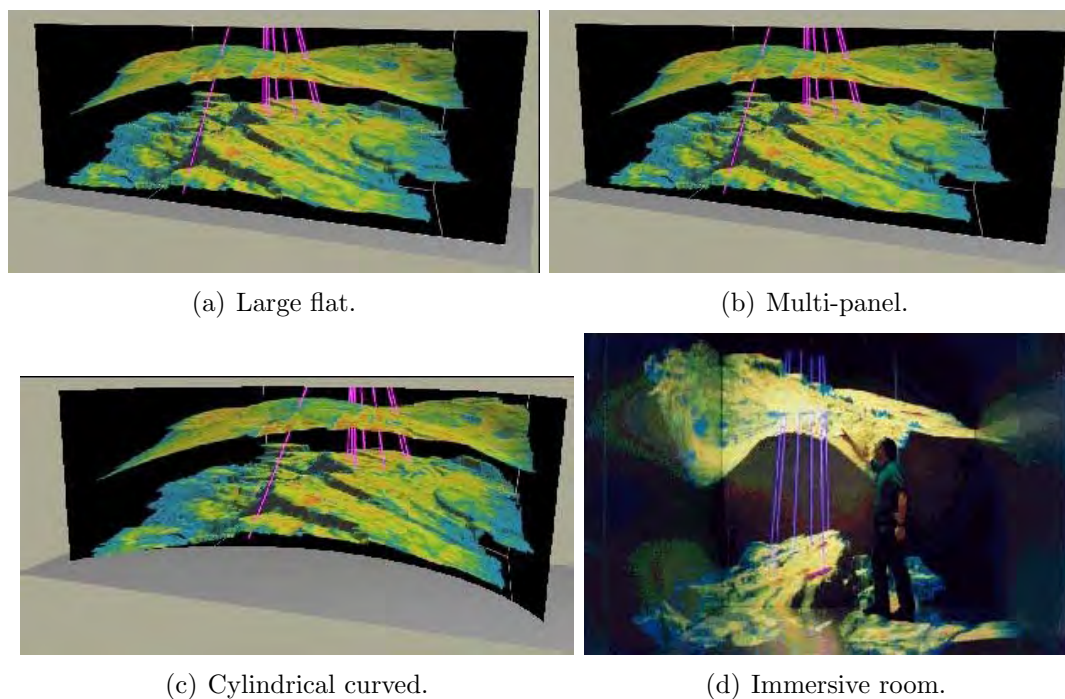
Figure 3.4: Dorn [20] reviews some of the screen types used in oil/gas visualization environments.

while navigating through tridimensional reservoir data. Haptic and sound have also been explored as alternative perception channels in MuSE [60]; they work by mapping vibration intensities, and sound pitches/tones to data variations in the reservoir, in a similar way a color scale is assigned to represent data values.

3.2 Novel Interfaces and Techniques applied to Oil/Gas E&P

Apart from reservoir engineering, many interactive systems have been developed for different stages and disciplines of the geosciences and oil/gas E&P lifecycle, focusing on enhancing the way people work by making use of novel interfaces and visualization approaches.
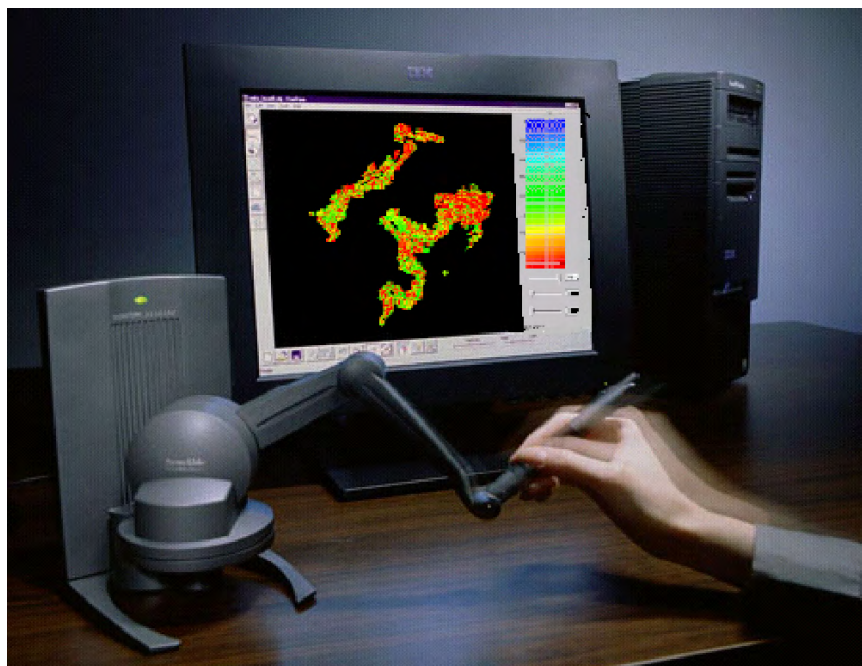
Figure 3.5: Haptic PHANToM pen [35] applied to 3D reservoir visualization (from Teneo Computing) [80].

Within the oil production monitoring, an application called Petrotrek was released with an extension for the Microsoft Surface [69] (Figure 3.6), designed to monitor oil production plants. It was designed as a higher-management tool, providing corporative information in many levels of detail, while harnessing the multitouch resources of the tabletop interface for a more intuitive use. Through touch browsing, users can locate productions installation on a world map, and display more detailed related data on a secondary vertical screen; it also provides functionality for video conferencing directly on the tabletop.

Lee *et al.* [46] proposed a query-based approach for constructing reservoir visualizations, providing power and flexibility with an approach that is relatively simple to use – provided the user has received proper training: it allows the addition of elements

(a) Navigating a map

(b) Locating a region of interest

(c) Listing available colleagues

(d) Remote collaboration through video
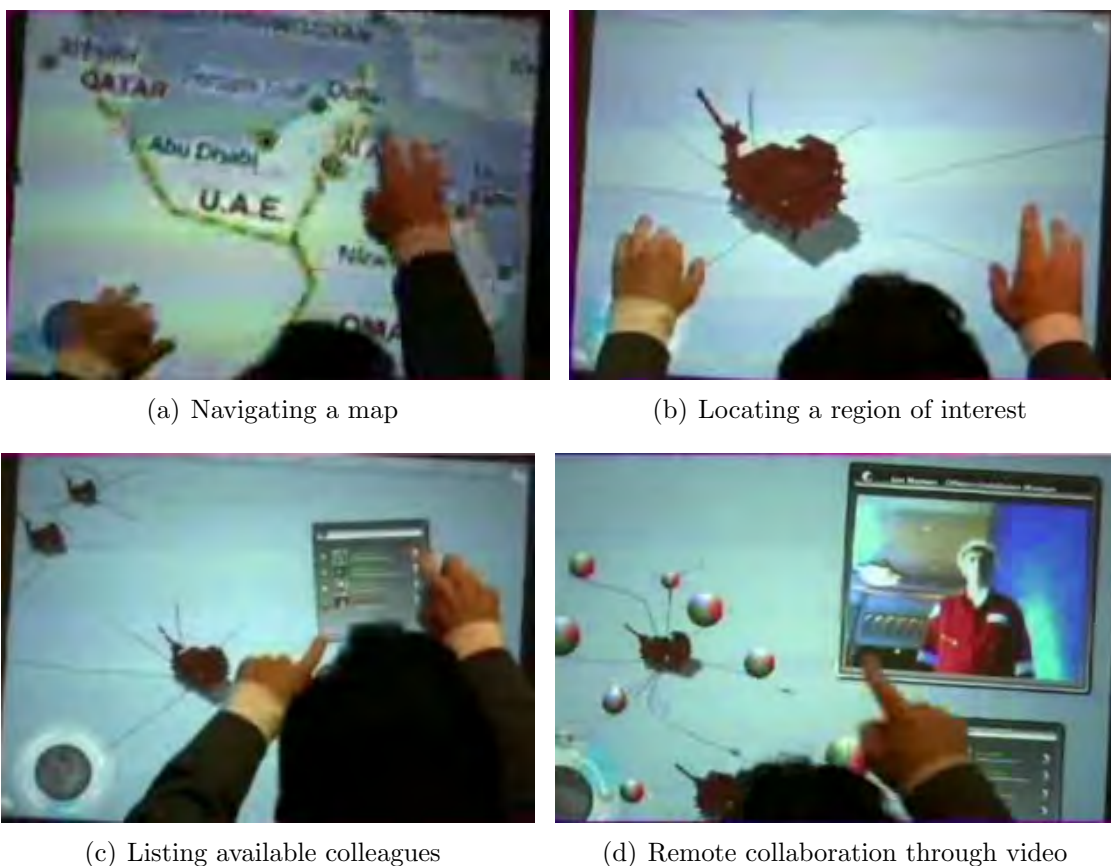
Figure 3.6: A demo sequence on Petrotrek for the Microsoft Surface [69].

onto a visualization, as well as comparison between different properties. Figure 3.7 shows an example of usage.

For the domain of geophysics, Couture *et al.* [18] designed GeoTUI, a tangible user interface for the creation of seismic cross sections in a 3D seismic volume. The system consists of a 2D geological map, top projected onto a table, from which cutting planes can be defined to reveal the underlying perpendicular seismic cross section. Several interaction modes using tangibles were developed and compared, as they aimed to understand which modality would perform better in terms of speed and reliability for defining the cross sections – a problem analogous to the definition of lines on a 2D

```
Show Vis {
        For Section_21 and Layer_2 in Reservoir_LH,
        show 3D Volume of Oil Saturation.
        Show Cube of Well.
        Show Line of Well Pipe.
        Show Cylinder of Water Injection.
}
```
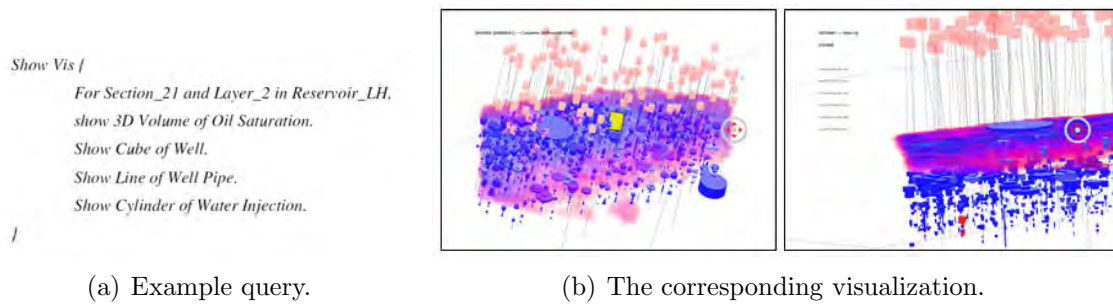
(a) Example query.   (b) The corresponding visualization.

Figure 3.7: A query-based system for reservoir visualization [46]. The query on the left determines which reservoir visualization elements are to be displayed; on the right, the view produced from the example query is displayed.

map: a mouse, one tangible puck, two pucks, and a ruler (Figure 3.8). A button box was included to complement the interaction. Experiments revealed the two-puck and the ruler options outperformed the mouse in terms of satisfaction and speed.
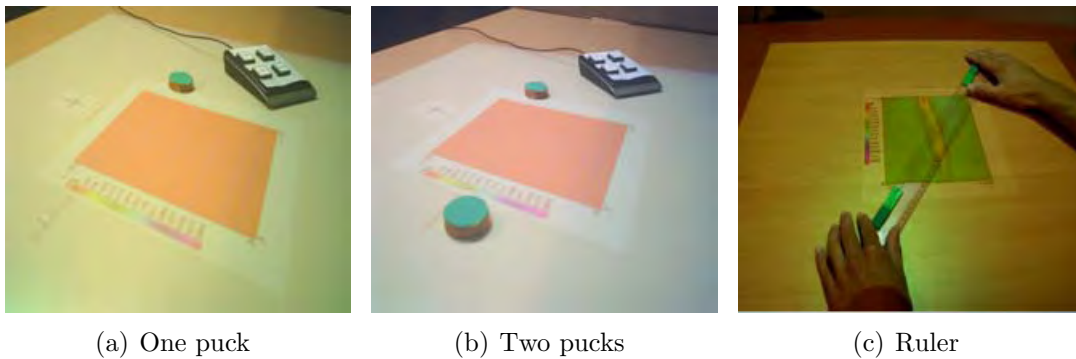
(a) One puck   (b) Two pucks   (c) Ruler

Figure 3.8: Tangible modalities developed for GeoTUI [18].

Tateosian *et al.* [70] proposed a tangible interface for direct manipulation of terrain data through a flexible physical miniature model based on a modeling clay – a work based on a sculpting interface conceived by Ishii *et al.* [36], and adapted to a geospatial context. A laser scanner equipped on top of the map enables real time input; a projector, also mounted on top, provides feedback on the impact of the changes made on the model, calculated with the help of a geospatial information

system (GIS). As changes are made to the clay model, the impact of these changes is calculated on the GIS, and the consequences are displayed directly onto the physical model. Props can also be added to the scene, to represent buildings and dams (Figure 3.9(b)) that might impact the simulated results.
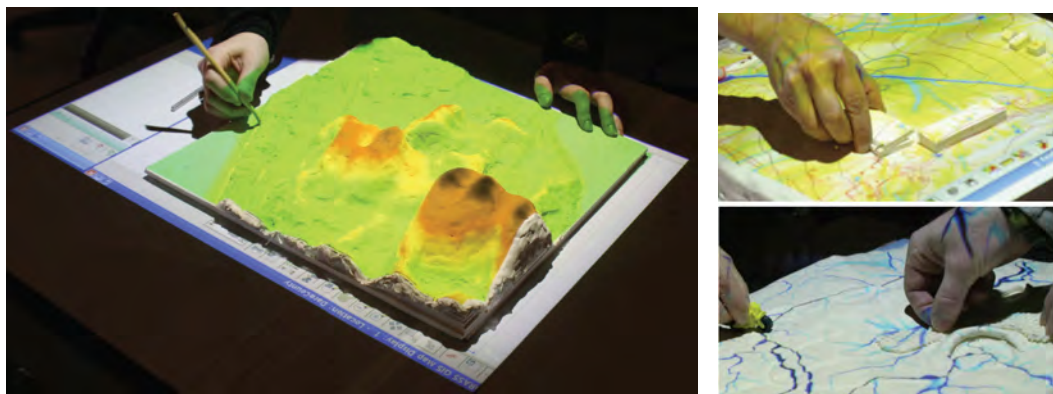
(a) An user makes changes on the physical model. (b) Added props.

Figure 3.9: Using TanGeoMS [70].

3.3   Summary

This chapter focused on reviewing relevant efforts in interactive visualization systems for oil/gas E&P and geosciences, including solutions not only for reservoir simulation – the focus of this work – but also research incorporating novel interfaces and techniques to the more general problem of analyzing and interacting with geological data. The latter is mostly a collection of instances of out-of-the-box thinking, which in one way or another served as inspiration for the work presented in this thesis. The following three chapters describe the design, implementation and evaluation of three visualization prototypes for exploring and analyzing reservoir simulation data using

digital tabletops and tangible devices; they represent our efforts on attempting to understand the potential of novel interfaces, and how they might bring additional value to the field.

Chapter 4

Snakey: A Tangible Interface for Manipulating Flexible Wells

4.1 Introduction

Drilling a well is a very costly operation, each often requiring no less than several millions of dollars. It is also a very complex undertaking, influenced by numerous factors: the type of operation the well is to perform, the current state of the fluids in the reservoir, the region's geology, potentially dangerous areas to avoid, available equipment and materials – among many other factors pertaining to many different expertises – must be considered for a successful performance. Therefore, a lot of thought is put prior to their realization.

Designing the well trajectory is one of the many important tasks in the afore-mentioned process, one that is often done with the aid of CAD solutions. These tools attempt to solve a fundamentally difficult problem, that is defining a three-dimensional trajectory within an intrinsic two-dimensional space embodied by the desktop monitor and mouse. As a result of this less-than-ideal mapping between interfaces and task, plus the critical nature of the well planning process, computational tools for defining well trajectories require very detailed input from the user. However, in earlier stages, this time-consuming level of detail might actually be restricting, preventing potentially interesting options to be explored due to the cumbersomeness

of their manipulation. Therefore, the well planning process could benefit from an alternative, quicker way of manipulating these trajectories, with a more exploratory approach to potentially bring new solutions to light and afford better spatial mapping.

Motivated by this, we envisioned *Snakey*, as a 3D tangible user interface (TUI) for the manipulation of wells and exploration of reservoirs to provide an unique, intuitive, collaborative, exploratory manipulation of tridimensional well paths. The well is represented by a physical flexible and manipulable proxy, which directly reflects trajectory readjustments while providing input and output from and to its virtual counterpart (Figure 4.1). The following sections describe how we designed Snakey, followed by results of a preliminary evaluation of the prototype, and concluding with closing remarks and perspectives of future work.

4.2   Design and Implementation

A few design goals were considered. First of all, the TUI should allow for (1) intuitive and simple 3D curve manipulation, with changes applied in real time. Nonetheless, unless manipulated by the user, (2) the device should be able to keep its shape, and serve as a constant representation of the well. As a secondary goal, it should also be able to (3) improve 3D perception of the represented well path. Additionally, we also envisioned the (4) incorporation of other physical properties into the device – such as visual and haptic feedback – allowing for richer sensorial awareness of the well directly onto the device (such as indicating fluid flowing through the well, or highlighting regions that require further attention). Finally, we also wanted to (5) create an environment that allowed for collaborative manipulation, accounting for the
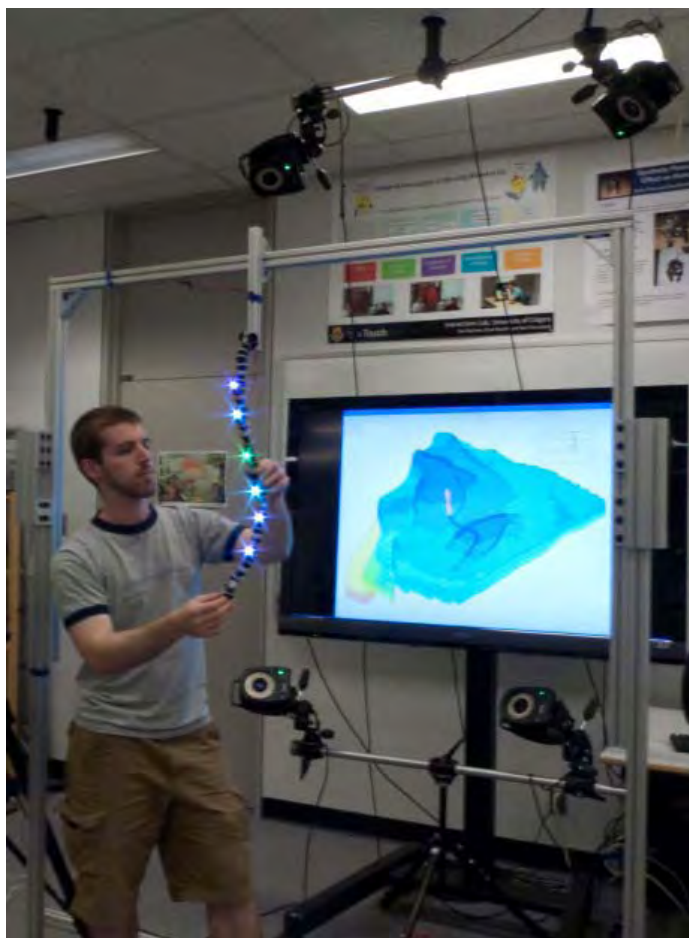
Figure 4.1: The Snakey interface.

multidisciplinary nature of the oil & gas E&P processes.

One of the main challenges in Snakey's development was creating an appropriate physical proxy for the well, an entity flexible enough to be manipulated by hand, but also able to keep its shape when the user finished the manipulation, and is no longer holding or supporting it. While several materials have failed these pre-requisites [37], a solution was found using Joby's GorillaPod™, a flexible camera tripod (Figures 4.2 and 4.4(left)). The GorillaPod consists of modular plastic units connected to each other in a series of ball and socket joints, which are able not only to maintain

their own shape but can sustain even heavier loads (Figure 4.2); it is also modular, allowing freedom in the configuration of the tangible device: pieces can be taken apart and reattached with considerable ease, and branching nodes allow for the creation of multilateral well configurations (Figure 4.4). The device is mounted on the top of an aluminum frame (Figure 4.1), freeing the surrounding space for the user to freely inspect the tangible device in different perspectives, as well as inviting multiple users to join the 3D well trajectory inputting session.
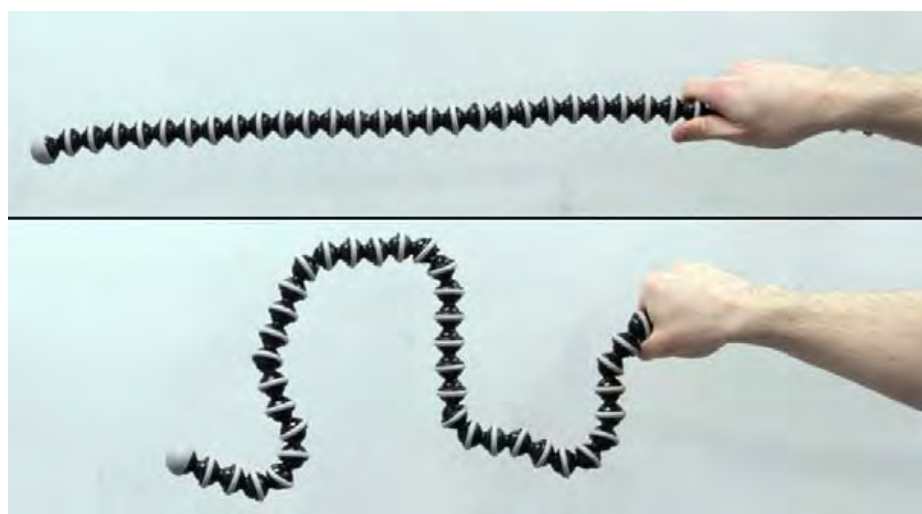
Figure 4.2: Illustration on the GorillaPod's ability to hold its shape, and to be easily manipulated into complex shapes.

The Snakey interface also features a large display reflecting the effects of the tangible device on a reservoir model (Figure 4.3). The reservoir model is rendered with partial transparency, as to be able to display the well trajectory within it. An optical solution was chosen to track the changes on the flexible device – the Vicon™ system – which consists in a set of infrared cameras set up around a space, which can perceive motion of physical objects through special infrared reflective markers attached to

them, allowing for a virtual 3D reconstruction and continuous tracking. Due to its high throughput, it allows for real time tracking, as well as permitting more flexibility in terms of possible shapes of the flexible device (*e.g.* branched configurations). LED lights and vibration motors were also embedded onto the flexible body of Snakey, in order to provide additional haptic and visual feedback and complement the monitor visualization of virtual well and its effects on the reservoir model.
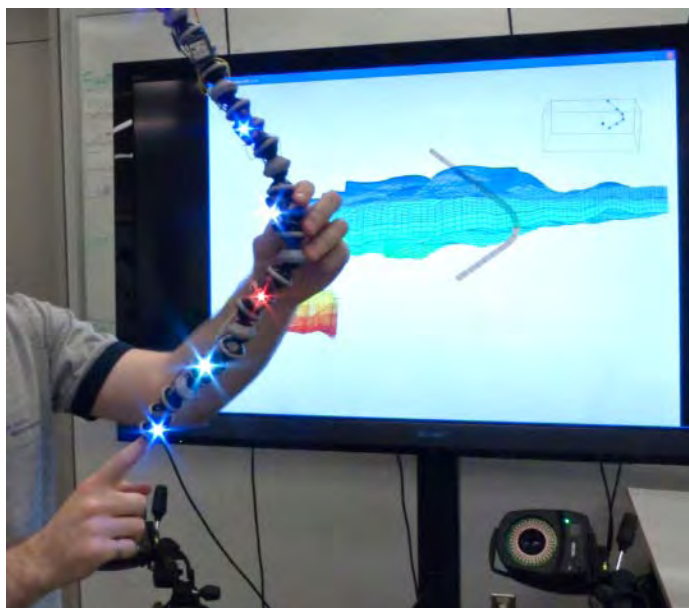
Figure 4.3: Detail showing the physical Snakey, and its virtual counterparts on the monitor screen

4.3 Preliminary evaluation

When designing domain-specific solutions, it is compulsory to solicit feedback from domain experts and invite their participation in the design. Therefore, a design critique session was conducted with two senior professionals who are domain experts, and engaged them in a subjective, brainstorming session with the design team in
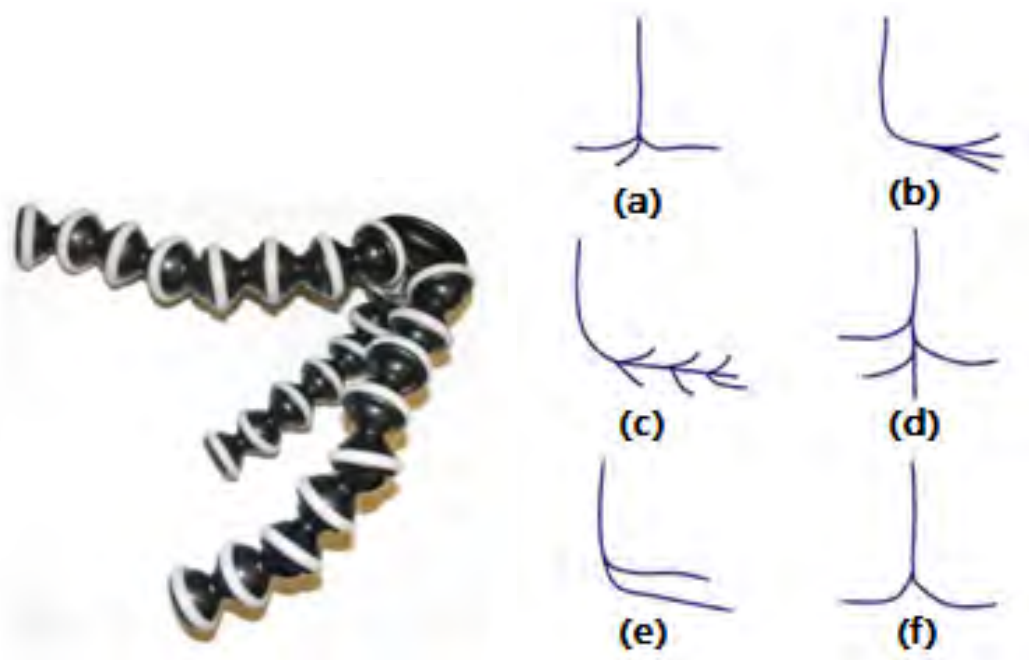
Figure 4.4: On the left, a multibranched configuration for the GorillaPod. On the right, common multilateral well path configurations (a) multibranched, (b) forked, (c) laterals into horizontal hole; (d) laterals into vertical hole; (e) stacked laterals; (f) dual-opposing laterals.

order to evaluate the concept of tangible manipulation for wells, gain more insight into its potential usefulness and come up with ideas on how it can be leveraged to provide further awareness. The session started with a presentation of the concept of Snakey and a demo, followed by open discussion; meanwhile, notes were taken, registering important points emerging during the session. In the next paragraphs, some highlights are presented and briefly discussed:

4.3.1 On Physical vs. Virtual Worlds

While users were able to view the physical device from any angle simply by walking around it, they pointed out that rotating the reservoir simulation data on the display

with a mouse was not ideal, taking attention away from the TUI and disrupting the workflow. They suggested mounting a manipulation device on Snakey's frame, so as to minimize the inconvenience. Another related issue is scale. As the current interface maps the physical probe to the entire well, together with the relatively low resolution of the flexible proxy, precision might be lacking. For that, a possible solution would be allowing Snakey to be able map to smaller segments of the well, as opposed to a whole path. The anchoring point was also discussed, with the possibility of fixing Snakey at the bottom – as opposed to the top – allowing for the freedom of movement in the upper parts of the well.

4.3.2 Additional Feedback on the Physical Well

The components attached to the flexible device – i.e. the LED lights and the vibration motors – were considered valuable, and many possible usages were suggested. The LEDs, for instance, are capable of varying color and brightness, allowing for many variations on visual cues (such as flashing and scrolling the lights). One potential use was displaying the attributes of the geology or the simulation along Snakey's path, e.g. pressure or porosity, or indicating portions of the well that are producing oil. The lights and the vibration motors could also be used to indicate constraint errors, for instance highlighting specific locations in which the turning angle is too high. The experts also suggested further control to be provided by the tangible interface, with a functionality for controlling attributes along the length of Snakey by using the hands. For example, indicating where an operation might take place by squeezing a specific region of the device, or sliding the hand along a region to mark and select a segment – which would require additional sensors.

4.3.3   Saving and Storing Context

A major request relates to the ability to store configuration shapes and compare to other stored alternatives. Additionally, users would also like to be able to load the shape and resume editing it with the tangible device. Ideally, Snakey would be equipped with some form of actuation to be able to autonomously restore to a previous configuration. However, in awareness of related technical difficulties, suggested workarounds involved active user input for restoring a shape, with possible aid from the LED lights for indicating how well the tangible device matches the desired path by displaying green or red colors.

4.3.4   Potential as a Visual Exploratory Tool

Users suggested extending the functionalities of Snakey and using it as a more general exploratory visualization tool. They suggested displaying a cross section view of the reservoir, by taking the vertical projection of the input trajectory as a curtain, cutting the reservoir and displaying internal data; in the well planning process, for instance, this could allow the visualization of areas around prospective well locations.

4.4   Discussion

With the immediate and intuitive nature of this interface, the experts saw the potential of this approach for bringing in new possibilities in the well planning workflow. It could allow for faster and broader explorations, with results of many possible outcomes quickly analyzed. Due to its inherent collaborative nature, it could also better engage team members, allowing anyone to step in and manipulate the physical curve and pro-

vide meaningful input. Also, the many suggestions related to embedded haptic and visual feedback, as well as possible use in exploratory visualization, highlight Snakey's potential beyond its basic goal of designing well paths. Its powerful metaphor easily lends itself to many meaningful input and output channels augmenting user's power and awareness.

Some interesting reflections can be raised concerning the disconnection of the physical and virtual worlds. As mentioned earlier, the current prototype allows for independent change of viewpoint on the display; so how disruptive is the separation from the physical and the virtual representation, when both are independent? Does it significantly affect perception, or are people easily able to adapt to different orientations? How could the physical *vs.* virtual association be strengthened, while still providing considerable freedom for changes in perspective?

The optical tracking option chosen for this prototype offers crucial advantages, namely, speed and flexibility. However, it also introduces other problems such as the occlusion of the reflective markers embedded onto the device, which occasionally get covered by the hands performing manipulations; with more people around Snakey, occlusion issues only increase. Point redundancy and interpolation methods were implemented, but managed to solve this problem only partially. Overall, a new tracking strategy should be sought.

4.5 Future Work

Snakey, albeit a rich and interesting approach, is still in its first steps; several design aspects remain open for it to become a full fledged work tool. One of the first aspects

to be approached in its future implementations is on the interaction design itself, for providing a stronger coupling between the physical and the virtual world. Some basic resources should be offered, such as controlling scale and position of the well, further navigation and manipulation resources for the display of the underlying reservoir model, loading previous well configurations for comparison, among others.

Hardware-wise, the tracking needs to be revisited; either by providing a better integration between the physical device and the markers, or by introducing a new tracking solution altogether.

As possible improvements, embedded devices could include touch and pressure sensors, for affording more possibilities in terms of interaction; and actuation on Snakey, beyond loading pre-stored shapes, could also serve as an additional interaction feedback element, reinforcing physical constraints and automatically fixing key locations in a well design.

4.6   Summary

This chapter presented Snakey, a prototype for a tangible user interface with a direct and physical metaphor for manipulating well trajectories in oil reservoirs. Snakey was evaluated by two experts in a design critique session, which provided better insight on its strengths and limitations. Discussion highlights are presented, as well as perspectives for future work.

Snakey is still an early prototype; however, it did manage to achieve its basic goal, which was validating the concept and unveiling directions for future work. Another successful aspect of this effort was defining what it is not meant for: it should not

replace traditional CAD tools, but rather, introduce a complementary resource for initial exploratory stages of the well design. On the other hand, it also demonstrated potential as a more general exploratory tool for the visualization of the reservoir model Since many visualization resources could make use of such tridimensional input device, it could also find its way in other petroleum related tasks in geology and reservoir engineering.

Chapter 5

"Touching the Depths": A tabletop interface for reservoir post processing data

5.1 Overview

Tabletop interfaces are a relatively new media, proposing a distinct interaction paradigm with horizontal displays. Initially born as a fruit of research aiming on a digital approach to the way we traditionally work on tables [77], tabletops have already become successful products and many options are currently available for purchase (for instance, the Microsoft Surface [56], Smart Table [71], Perceptive Pixel [61], among others). Although they are not yet at a stage of end-user pervasiveness, there are many tabletop systems available to the general public – such as in museums and visitor centres [25, 15, 52] – as well as domain-specific applications – such as scientific visualization [65, 23, 74], art and music [45, 40], therapy and medicine [29, 9, 81, 59], among others. These few samples of the numerous efforts in tabletop development represent the great interest both academia and industry have in its affordances and features: a fostering environment for collaboration, allied to a potentially large display area, comfortable and natural setup for multitouch interaction and possible integration with tangible objects. Figure 5.1 shows some existing application.

These assets are very much aligned with the points made in Chapter 2, regarding the advantages of collaboration and interactivity applied to visualization in a reservoir

Figure 5.1: Examples of tabletop systems. From left to right, top to bottom: Smart table in a school [71]; a walk-up-and-use tourist information application [52]; a very large, custom made tabletop installation in a museum; a visualization system for genome browsing [65]; a multi-display molecular visualization environment including a tabletop device [23]; retail store application for cell phones [56]; the Reactable [40]; a tabletop system for managing meeting content [62].

engineering environment. Combining reservoir visualization with tabletop interfaces could thus potentially ease data exploration and help facilitate discussions between team members, management and customers. They could also enhance the repertoire of interaction capabilities of reservoir model manipulation, through touch and tangible devices. With this in mind, a reservoir visualization prototype was developed with a set of essential reservoir manipulation tools, in order to demonstrate and validate the concept of this novel interface to the domain.

This chapter presents the implementation of a tabletop prototype for the visualization of reservoir flow simulation models. This is followed by a brief discussion of highlights obtained from two design critique sessions, conducted to evaluate the relevance of the concept of tabletops to the domain, as well as assess its strengths and weaknesses. We finally conclude describing a few possibilities for future work, motivated by the design critiques.

5.2 Implementation

The prototype was developed for the Microsoft Surface (MS) [56] in C#, using XNA for graphics rendering and the Microsoft Surface SDK for handling interaction (touch and marker detection). A general view of the interface and its components is provided in Figure 5.2. Reservoir datasets were generated using CMG's family of simulators (IMEX, GEM and STARS), which are directly loaded into the program through a given .NET library that provides access to the many data items of a reservoir model.

Manipulation of the reservoir model is done through touch, with 2D gestures detected by the MS SDK – such as pinching and spreading – which are interpreted and
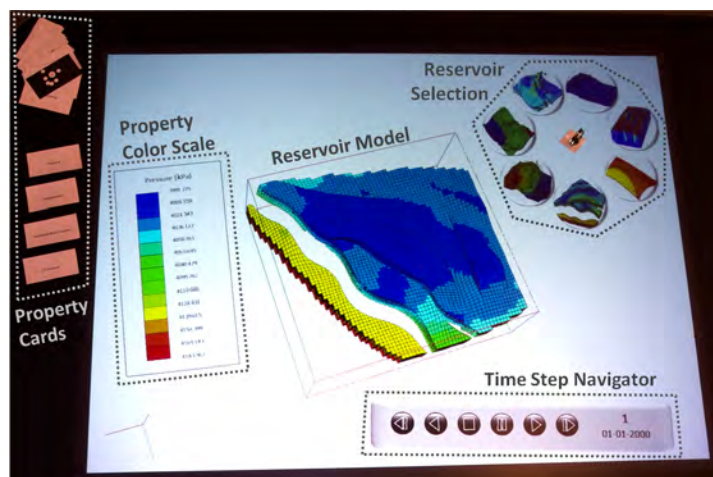
Figure 5.2: General view of the created reservoir visualization tabletop interface, with its main components.

mapped to fundamental 3D transformations for manipulating models. The following subsections will detail each of the basic gestures and interactive devices.

5.2.1 Manipulating the reservoir model

The most basic reservoir manipulation is the 3D rotation, also know as *Orbiting*, and is performed with one touch. Screen (x,y) delta translations of the touch are mapped to spherical camera rotations. The center of this sphere is initially located inside the reservoir, and finger displacement makes the camera be displaced in the corresponding direction (see example in Figure 5.3).

Other operations, such as *zooming*, *rotation*, and *panning* are achieved with two or more touches, and can all be performed simultaneously. Zooming is mapped to relative distance variations between touches; rotation is performed when touches rotate around a single pivot point; and panning, when touches are equally displaced. Figure 5.4 illustrates each of the described gestures.

(a) Initial position   (b) Reservoir after orbiting   (c) Illustration on spherical camera rotations
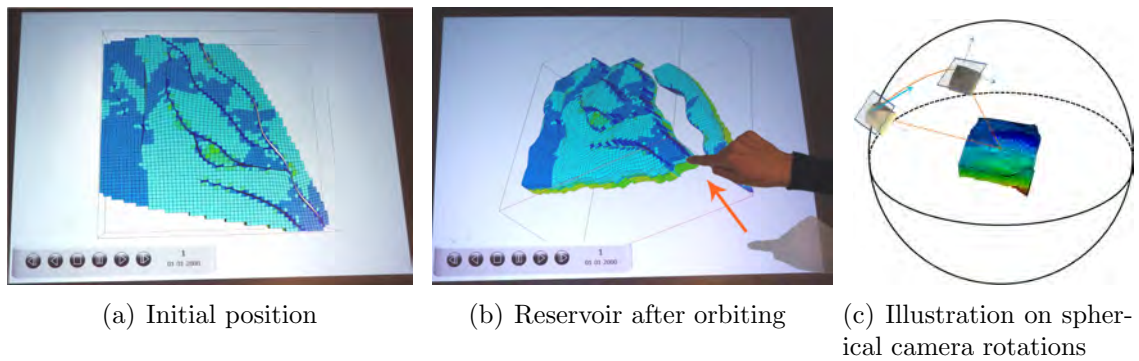
Figure 5.3: An example of orbiting. On the right, a 3D perspective on the spherical rotation the camera performs, according to a certain screen direction.

(a) Initial position   (b) Zooming

(c) Rotating   (d) Panning
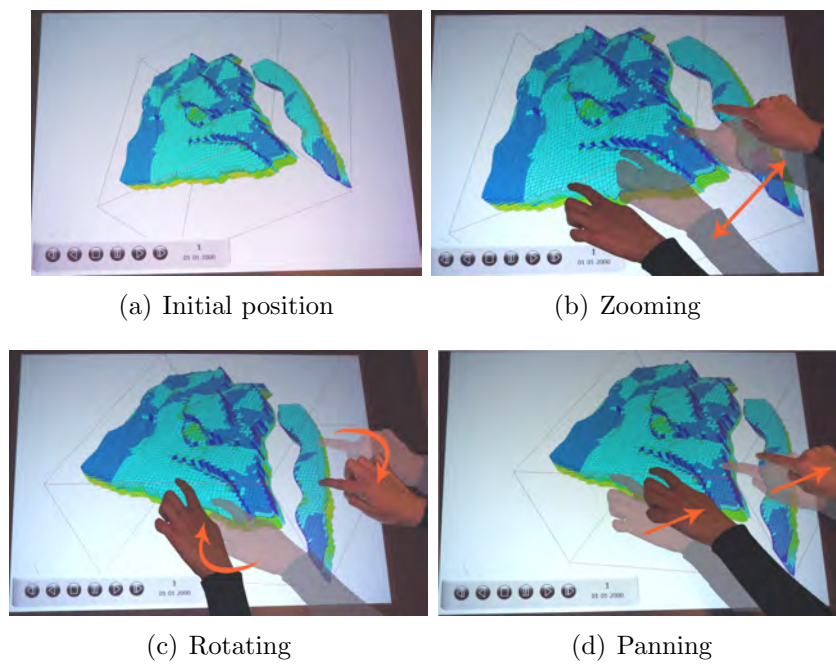
Figure 5.4: Various successive "2+ finger" manipulations being performed on a reservoir model.
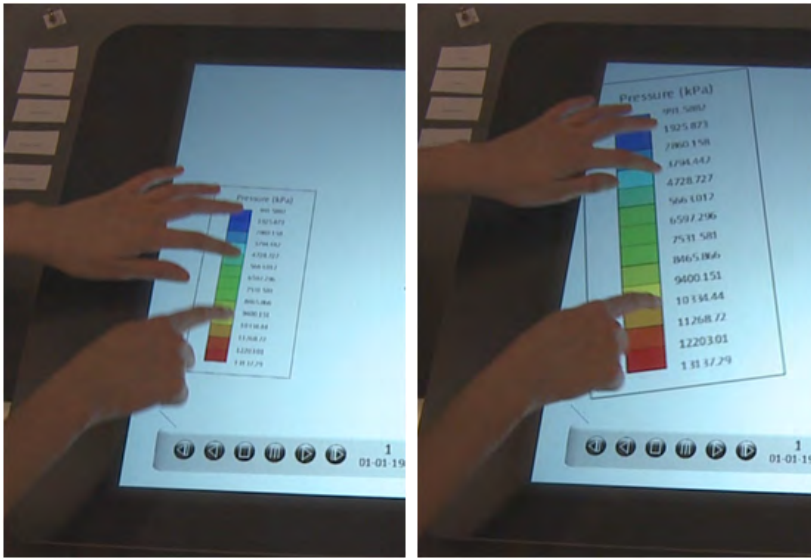
Figure 5.5: Manipulation of the color scale.

5.2.2 Widgets

The color scale (Figure 5.5) is a movable and resizable component that displays color codes associated to the value range of the selected property. Manipulation is performed in a similar fashion to the reservoir model: one touch performs rigid translation, and two or more touches perform simultaneous translation, rotation and scaling.

The time step navigator is a widget similar to a media player, allowing visualization of property changes through time, for all dynamic properties. Component manipulation (rotation and translation only) is achieved with the same gestures described for the color scale (Figure 5.6). Button functionality is depicted in Figure 5.7.
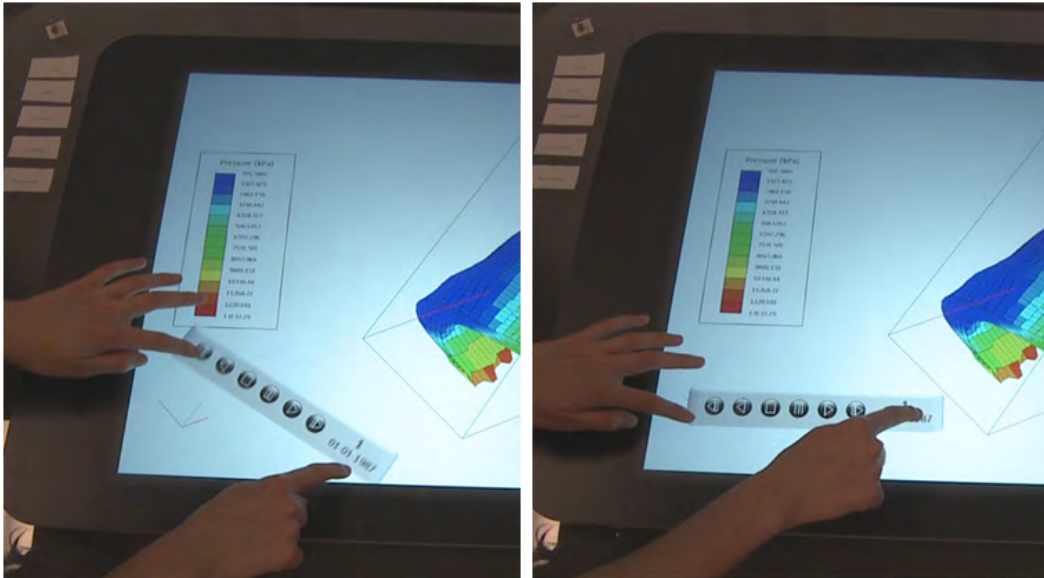
Figure 5.6: Manipulation of the time step navigator.
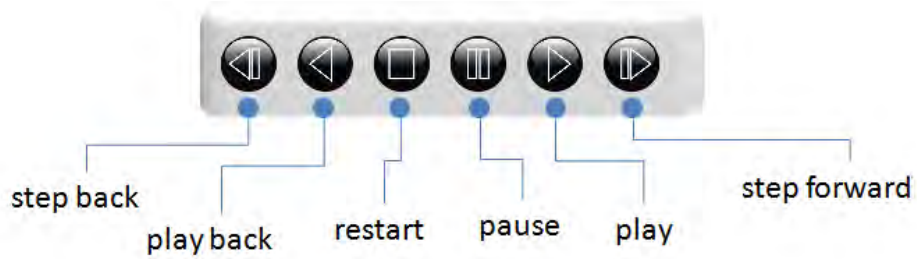
Figure 5.7: The time step navigator and its functions.

(a) Property cards and byte tags   (b) Temperature is selected   (c) Pressure is selected
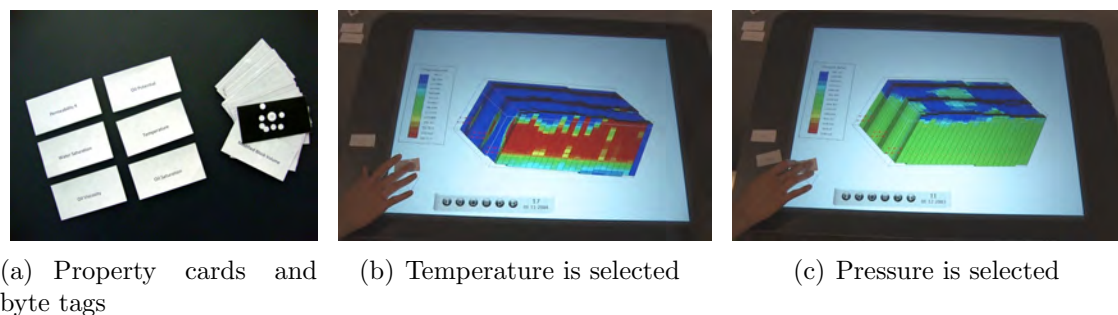
Figure 5.8: Property Cards, and examples of usage.

5.2.3 Tangible devices

For each of the given datasets, the available properties were listed. A tagged property card was assigned to each one the 36 properties found, as a mechanism to visualize the different available properties (such as oil, gas and water saturation, porosity, pressure, etc.). Each card contains the title of a property, associated to an unique Microsoft Surface byte tag at the back (Figure 5.8(a)). By placing a card on the screen, the whole model displays its corresponding property values (Figures 5.8(b) and 5.8(c)). This format was conceived to provide more user flexibility for selecting properties as well as allowing a quick shift between them, which facilitates correlation.

A tangible tool is also provided for users to select other models for visualization (Figure 5.9). A tagged object brings up a circular menu with a set of available datasets, and the corresponding model can be selected with a one-touch tap.

5.2.4 Reservoir Grid Sectioning

A basic mechanism to display internal parts of the reservoir (such as well paths and property values inside the reservoir) was implemented, which works by specifying a
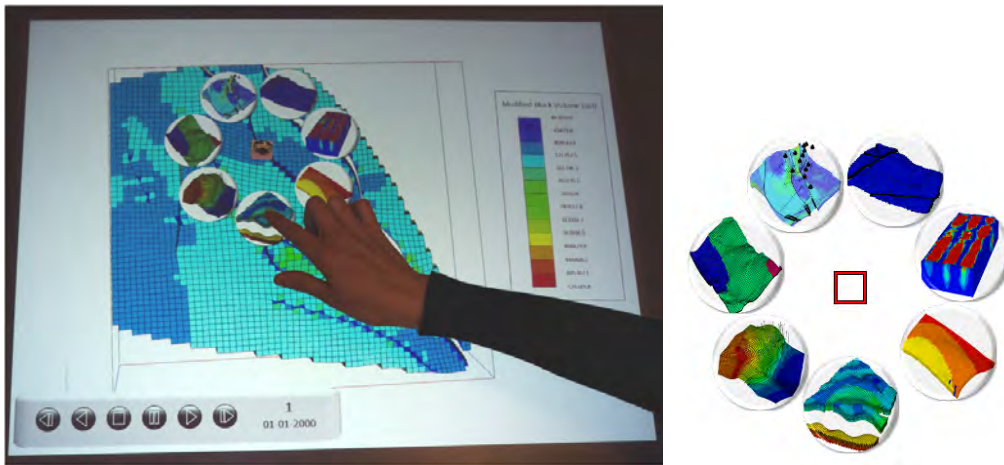
Figure 5.9: Model selection view.

'cutting' section through a manipulable bounding box (Figure 5.10(a)). The simultaneous selection of two adjacent corners of this box defines the cutting axis (Figure 5.10(b)), which can be adjusted through "corner dragging" to restrict the selection volume (Figures 5.10(c) and 5.10(d)). Visual cues are provided during this operation, showing where the cut will be performed. When the touches are released, the visualization is adjusted to display only the cells inside the defined sub-partition (Figure 5.10(e)).

The corner detection algorithm works at a 2D level: the corners of the bounding box are projected onto screen space, and then a simple 2D distance verification checks whether a touch is close enough to trigger a corner selection. While it is probable that a corner gets mistakenly selected in this fashion, it takes two successful adjacent corner selections to start a sectioning operation, thus being very unlikely to accidentally enter this mode. Also, visual cues on the corners indicate when they are being selected, allowing the user to avoid an erroneous manipulation.

(a) Initial configuration (b) User selects two adjacent corners (c) Surrounding bounding box is adjusted

(d) Final desired position (e) Fingers are releases and cut is performed
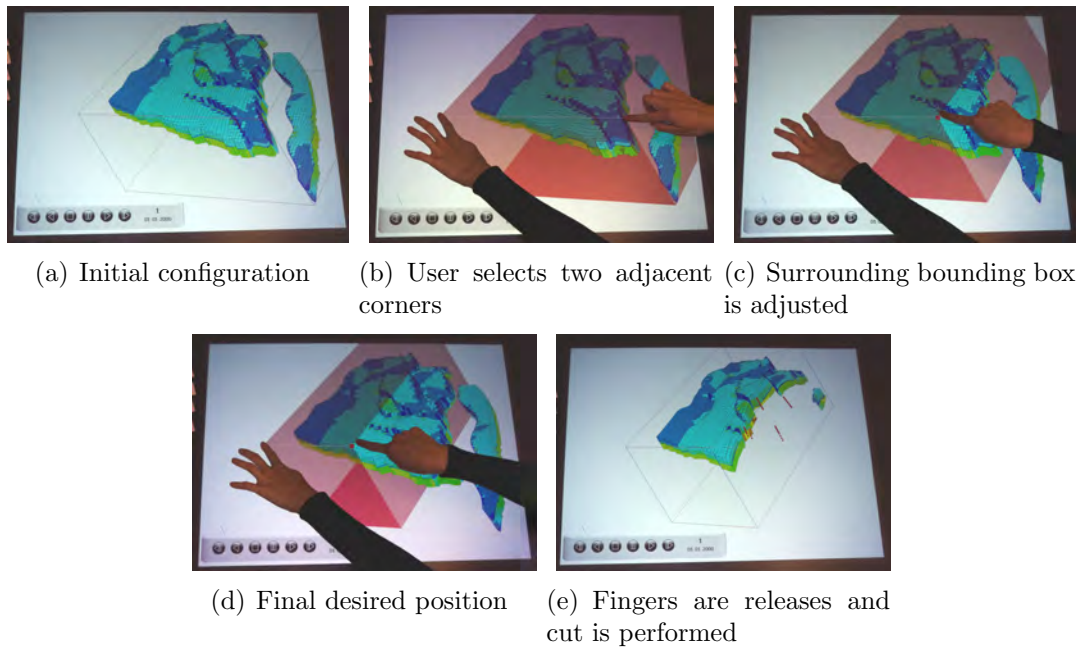
Figure 5.10: Sequence depicting a sectioning operation.

5.3 Design Critique and Discussion

In a domain-specific application such as the one presented here, considering feedback from actual users is crucial. Therefore, we hosted three design critique sessions, lasting from 1 to 2 hours each, with a total of around 15 expert practitioners from the oil industry. The prototype was presented, and the participants invited to interact and provide informal feedback. The goal was to expose the users to the concept of digital tabletops and discuss its potential to their work environment, as well as brainstorming ideas for future development.

Both groups were very satisfied and excited with the concept, and also offered many suggestions for improvement. Below, we present some relevant themes of discussion, originated from the feedback gathered through the sessions.

5.3.1 Team Engagement

Very positive feedback was received, concerning the collaborative potential of the tabletop environment. Some of the comments were related to team focus and engagement, as well as favouring interaction amongst complementary disciplines (i.e. *"Everyone has ideas, but it is hard to convey and converge them in a group"*). Also, it was stated that a more inviting work environment is not only pleasing, but it also stimulates and fosters collaboration; users want a *"place where people will enjoy going to"*, but also having an *interactive* collaborative work environment, more than just a room to look at end results in 3D (i.e. Visualization rooms).

5.3.2 Remote Collaboration

As company offices and teams are frequently spread around the world, they brought to our attention the importance of providing means for remote collaboration, such as distributed manipulation of the reservoir model, plus voice/video conferencing.

5.3.3 Tangible User Interface

The participants liked the idea of property cards, but commented that they found cumbersome to flip through all the cards to find a single property. They proposed selecting 5 or 6 more relevant properties and associating each of them to a special tangible object, with a differentiable and intuitive shape for quick recognition. Another suggestion was to let the user decide which properties are relevant, by allowing an interactive association of properties to a set of wild cards.

5.3.4   Enhancing the Visualization

Participants provided interesting ideas for interactive visualization resources that would nicely fit in a tabletop environment, including: (1) intuitive ways for spatially manipulating geological layers of the reservoir model; (2) synchronized exploratory visualization between layered 2D view and 3D views of the reservoir; (3) selecting regions of interest to allow further inspection, and present more detailed property information about them.

5.3.5   Ergonomics

One of the participants commented it was uncomfortable to sit around the table for a long period of time. Considering the prolonged interaction that such a tool might require, this was considered a very relevant remark. While the chosen platform – the Microsoft Surface – is more casual and less aimed for continuous extended use, height adjustments of the table and surrounding chairs could help reduce the fatigue even with the current setup.

5.3.6   Training

Due to the collaborative factor and the ease of operation, training was also highlighted as an interesting use of our interface. Additionally, participants suggested its exploration as a mean to better communicate ideas and technical aspects between individuals with varied levels of expertise.

5.4   Future Work

This section presents some possibilities for future work, as motivated and inspired by the previous design critique sessions. It includes possible solutions for issues highlighted during the sessions, as well as interesting topics to develop further.

5.4.1   Redesigning the Property Selection

Our previously proposed property cards had the main disadvantage of being cumbersomely numerous, requiring them to be selected beforehand. Also, they were more likely to be lost in such format, making them more unappealing for a real-life scenario. Additionally, even though the possible number of distinct properties easily surpasses 200, a very reduced set of them is made available on each dataset, rendering a great percentage of the cards useless for a particular visualization task. However, property swap was performed very quickly and straightforwardly during usage, mostly compensating for the initial selection effort. A solution was sought in order to improve on the outlined disadvantages, but also retaining this swapping efficiency as much as possible.

The brainstormed design features two tangible devices associated to circular menus, which we called *property baskets*. The first one would be the *general basket*, which would contain the list of all available properties in the currently displayed model. As mentioned before, although the number of possible rock and fluid properties is extensive, the average total is in the range of 50 properties per dataset. It is still a large number of properties to be displayed at once; and thus, it would benefit from a tree-like, hierarchical organization, featuring high level property categories such as

(a) The *general basket*　　　　　　(b) The *work basket*
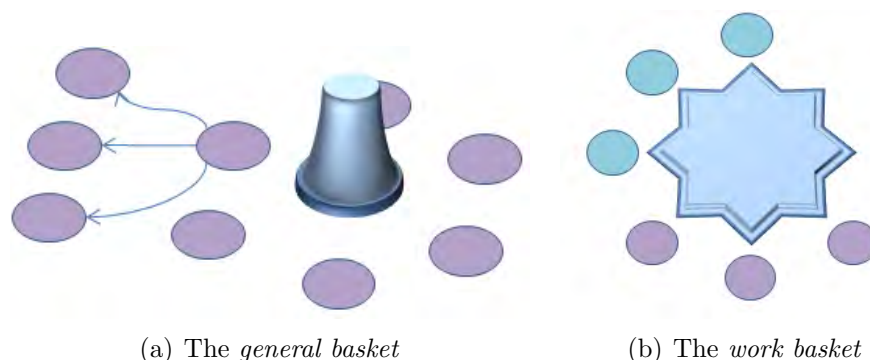
Figure 5.11: A possible replacement for the property cards: two collections of properties (represented as blobs in these diagrams).

"Fluid Characterization", or "Rock/Fluid Interaction" in the first ramification level (as roughly illustrated in Figure 5.11(a)); categories and properties could be selected by a simple tap.

The second element created is the *work basket*, which would keep a reduced set of user-selected properties currently in use, in an attempt to provide swapping efficiency – very much like a 'Favorites' property list. For the physical representation, the idea was creating a star-shaped design in which each of the star-ends (Figure 5.11(b)) would represent a slot in which to allocate a property; associating the property slots to physical constraints would help reinforce the idea of a reduced, manageable set, the true purpose of this feature. The ideal maximum number of properties was advised to be around 10. For populating an initially empty work basket, users could drag and drop properties from the general basket to one of the slots; also, if empty slots are available, properties recently selected through the general basket – although not allocated by the user to any slot – could appear automatically in the work basket.

The labeling of these properties leads to further discussion. With their enormous variety, an iconic representation would most likely be unfeasible; however, undiscrim-
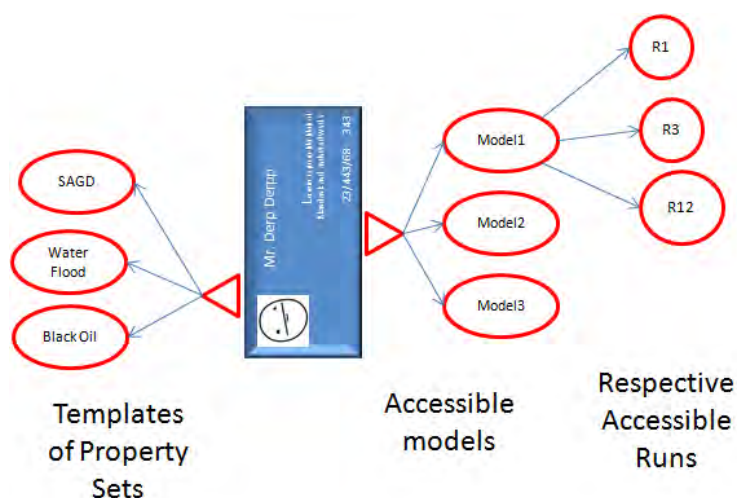
Figure 5.12: A redesign for the model selection, taking into account personal projects and preferences, which would be triggered from a user's identification card.

inated use of text can quickly turn into a verbose mess. Alternatives could be sought with a balance between the use of abbreviated text and colors, for quicker differentiation; however, more thought and investigation needs to be put into this particular question.

5.4.2 Redesigning the Model Selection

While the model selection menu in this tabletop prototype was offered mainly for demo purposes, the discussions also encompassed a possible redesign taking into account a corporative scenario. Considering that reservoir engineers are, in general, in charge of specific projects within a company, each of them would have their own collection of reservoir models to work with; a personal identification card with an unique identifier could be placed on the tabletop surface, bringing up a selection of reservoir models, with the respective simulation runs associated to them (Figure 5.12).

Another suggestion, pertaining the previously presented topic of property selec-

(a)   (b)
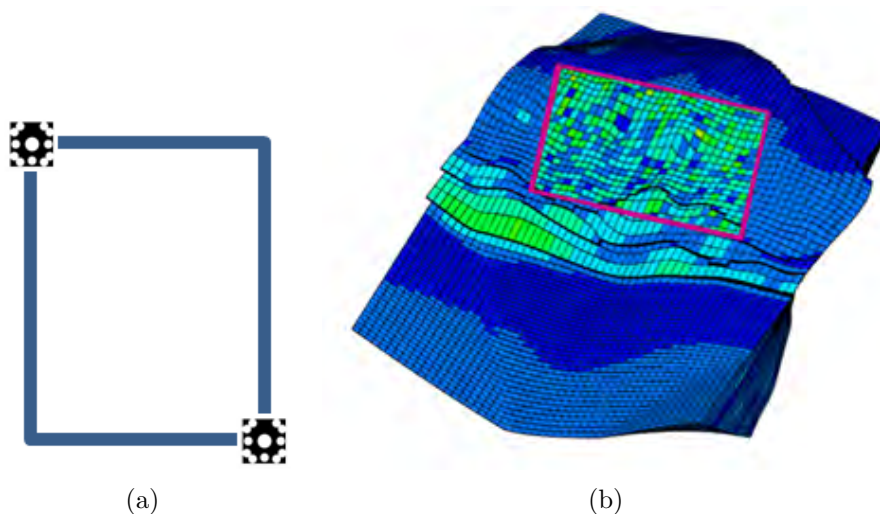
Figure 5.13: Concept for a tangible frame, to be placed on the tabletop surface and reveal secondary properties for comparison; 2D graphs were also suggested.

tion, would be displaying pre-selected sets of properties defined by the user, grouping properties according to specific tasks; the work basket would fill up with the properties of a selected set, saving up on property selection time.

5.4.3   Visualization Lenses

Alternative visualization windows were considered for facilitating correlation, in the form of tangible frames, a concept already explored in past tabletop research [42, 43, 68]. Two designs were proposed: (1) a fixed rectangular frame, which could be used to display 2D graphs and additional information, as well as secondary properties for comparison (Figure 5.13); also, (2) an adjustable tangible lens in the shape of a drafting compass was suggested, for physical flexible resizing of the lens (Figure 5.14) and minimal occlusion around the borders of the lens.
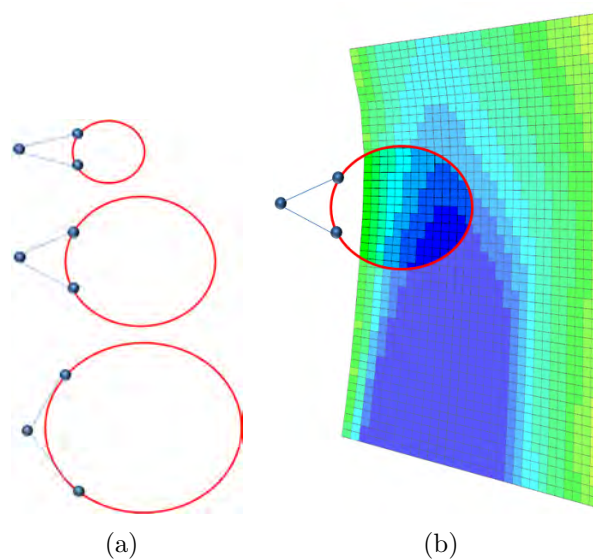
Figure 5.14: Concept for a tangible adjustable lens, in the shape of a drafting compass.

5.4.4 Saving Context

The possibility of saving context would consist in, at any given moment in the inter-
action, be able to save the current state of the visualization (angle of view, selected
property, current model, and so on). A context could be associated to a tangible puck
or a button displayed on the screen, which could feature a thumbnail of the stored
visualization for identification. It was considered an useful feature for two possible
occasions: first of all, it would allow users to store views of interest and compare
them, looking for correlations and trends; another use would be for storing relevant
views in advance, for posterior presentation and discussion with other groups.

5.4.5 Reservoir Grid Manipulation Techniques

Finally, discussions also encompassed techniques for manipulating the reservoir grid,
allowing for the exposure of internal layers. Taking advantage of the tabletop affor-
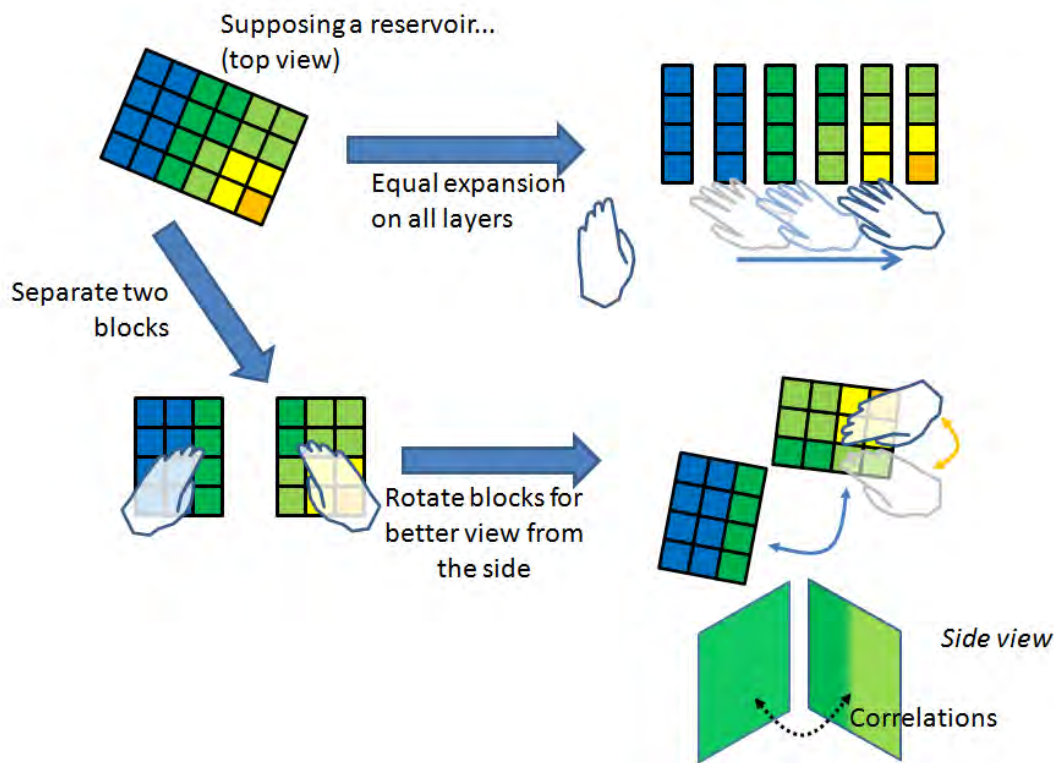
Figure 5.15: A few possibilities for reservoir grid manipulation, aiming for exposing internal layers of the reservoir.

dances for direct manipulation through multitouch interaction, intuitive interaction metaphors were considered, such as splitting layers apart with opening and spreading gestures of the hand. To instantiate this general concept of internal layer exposure, suggested strategies involved splitting reservoir sections, as well as introduce an equal spacing between all layers in a specific direction (Figure 5.15).

This particular effort was carried forward and reached a prototype stage, which will be described in Chapter 6.

5.5 Summary

This chapter motivated the creation and presented details of a reservoir engineering visualization system on tabletops, making use of its unique capabilities. Design critique sessions were conducted with invited practitioners from the industry, who provided very positive overall feedback and encouraged our efforts to be continued. Provided ideas and suggestions also motivated several instances for future work. And so, the upcoming chapter reports on follow up work on tabletop, focusing on extending the basic reservoir manipulation features offered by introducing new visualization tools for inspecting internal parts of the reservoir.

Chapter 6

Reservoir Visualization Tools for a Multitouch Environment

Commercial applications for visualization of reservoir flow simulation data provide resources to access additional information about the reservoir models, as well as visualizing and exploring its internal parts (such as cross section cuts, transparency, and so on). Some of them, however, are often not intuitive, or easy to use enough to be evenly matched with the strong need to obtain insightful perspectives and support analysis.

Here, we propose the exploration of intuitive approaches for interactive visualization and structural manipulation of the reservoir model. These approaches make use of the multitouch capabilities and tangible devices on tabletops, due to their ability of enabling complex tasks through a much more meaningful interaction than found on traditional desktop setups. Three main tools were investigated and developed, which are:

- **The Cell Probe**: a tangible device that displays cell-specific data;

- **The *Splitting***: an approach for fractioning and rearranging reservoir cells;

- **The *Peeling***: a technique used to curl reservoir sections in order to expose and correlate adjacent reservoir layers;

Motivation and a few ideas for these techniques emerged from previous discussions

(see Section 5.4), and represent follow-up work of the tabletop effort presented in the previous Chapter 5. In this chapter, we present the design and implementation for each of the tools above, as well as an user evaluation study conducted with a total of 12 domain experts which provided great insight into the relevance of the proposed tools, their strengths and weaknesses, and suggestions for improvement. Following, perspectives for future work are presented and discussed, inspired by feedback gathered from the user studies.

6.1 Cell Probe

The focus here was creating a mechanism that would allow users to visualize more detailed, cell-specific data, by designating a cell and viewing its respective information. Similar functions are available in commercial tools (e.g. CMG Results® 3D [50]), and most users consider them helpful and worth providing.

6.1.1 Design

In a multitouch environment, one of the most immediate way to pinpoint things is through touch. Adding up to the previously implemented prototype (Chapter 5), with a specific probing mode on, the user could drag one finger over the reservoir to specify the desired cells and the system would provide updated information on the screen. There are two issues with this strategy, however. One of them is the act of overriding a gesture that already has an assigned function (in this case, reservoir orbiting), and thus requiring a specific mode to be turned on for probing. The other issue is particular to the touch environment: finger touches cover larger areas, and

the point immediately below it ends up being occluded, thus lacking on precision. Therefore, we decided on a different strategy, that consists in using a tangible object as a pointing device, that would both: (1) free the one-finger gesture to its original intent, and waive the necessity of a specific user mode for probing; and (2) address the lack of precision from "fat fingers" by transferring the pointing duties to a more accurate entity – a tangible device designed for the task.

(a) The concept design   (b) A clay prototype   (c) The probe in use
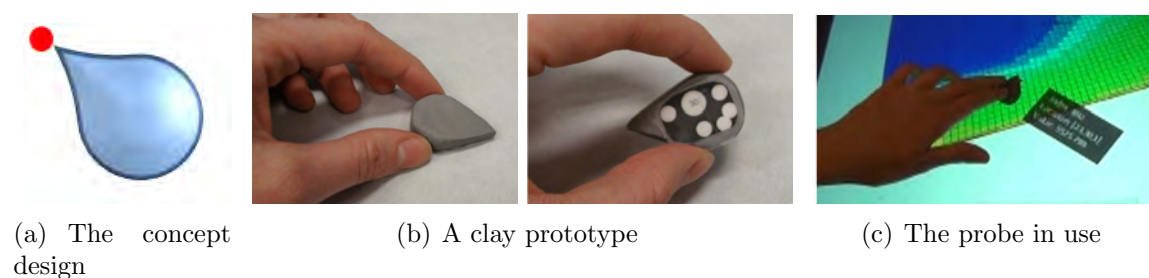
Figure 6.1: The cell probe.

Our envisioned proxy was designed in an arrow-like shape, with a pointer that indicates the selection spot (Figure 6.1(a)). A Microsoft Surface byte tag attached to the bottom provides tracking of position and orientation (Figure 6.1(b)). On the display, a small probe is drawn at the tip of the pointer – to provide an extra cue of where the device is pointing at – as well as a small widget beside the device with detailed cell data (Figure 6.1(c)). Parallel exploration would be possible by having more than one probe at a time; however, for simplicity, we experimented with a single probe only.

Alternative formats were considered. One of them was the 'thimble', a pointer similar to the arrow design, but which would serve as a wearable extension of the finger (Figure 6.2(a)). Between this and the chosen pointer however, the latter allowed for more freedom in rotation and collaborative sharing. Another option was the 'hook', a

curved device perpendicular to the surface which could allow for an unobstructed view of the areas surrounding the point of interest (Figure 6.2(b)). Concerns were raised regarding the stability of the device, and since the disk design was more compact, the 'hook' was also put aside. However, the concept seems promising in its premises, and it would be an interesting research effort to further analyse its assets in the future.

(a) The 'thimble'   (b) The 'hook'
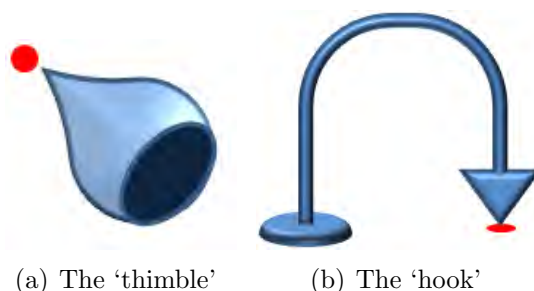
Figure 6.2: Alternative designs

6.1.2 Implementation

In order to determine which cell is being selected, a *cell picking* algorithm was implemented. It uses a ray-casting technique, which consists on performing ray-triangle intersections [5] between (1) a ray leaving the pointing device towards the 'inside' of the screen, and (2) the triangles that form cell faces, outputting (3) the cell corresponding to the closest face-intersection value (Figure 6.3).

Since a brute-force ray testing against all cell triangles would be unfeasible considering the large number of cells, an octree [5] was used to narrow down possible intersection candidates and speed up spatial search. An octree is a tridimensional axis-aligned bounding box built around a compound object containing many parts. The box is recursively subdivided into 8 sections, until each subsection contains only a pre-defined maximum amount of object parts within it (Figure 6.4). Originally used

(a) User perspective　　　(b) 3D Side view
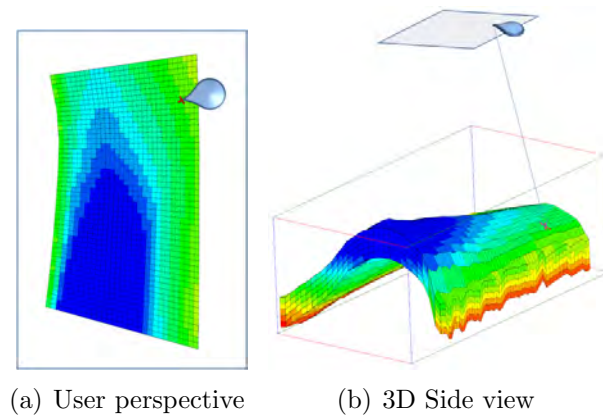
Figure 6.3: Cell 'picking'.

to store and search for *triangles* in ray tracing algorithms [63], this octree is used to store *reservoir cells*. If a cell is located in more than one partition, duplicate references to this block are made. For searching objects in this octree, intersections are tested first against the partitions of this octree, and then linearly against the reduced set of blocks inside the final leaf subpartition. Considering no structural changes happen to the reservoir model, the octree construction can occur in pre-processing stage, allowing for real time cell search during probing.
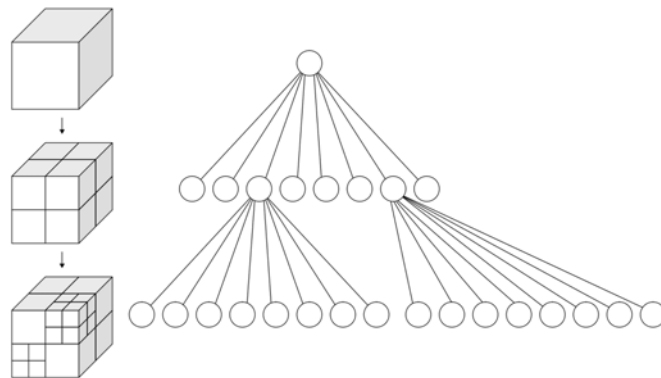
Figure 6.4: An octree. On the left, the spatial partitions, and on the right, the underlying data structure (an 8-nary tree).

6.2 Reservoir Splitting

The most common depictions of 3D reservoir datasets show renderings of their external cells with their respective property values. Nonetheless, reservoir models are volumetric entities, and there are many important events happening inside them that should be properly highlighted and visualized. Therefore, visualization techniques that are able to somehow portray internal structures of volumetric datasets are extremely useful (e.g cross sections, exploded diagrams, cutaway views, and so on). A few examples are depicted in Figure 6.5.

(a) Geological cut   (b) Cutaway view (from [58])   (c) Fence Diagrams
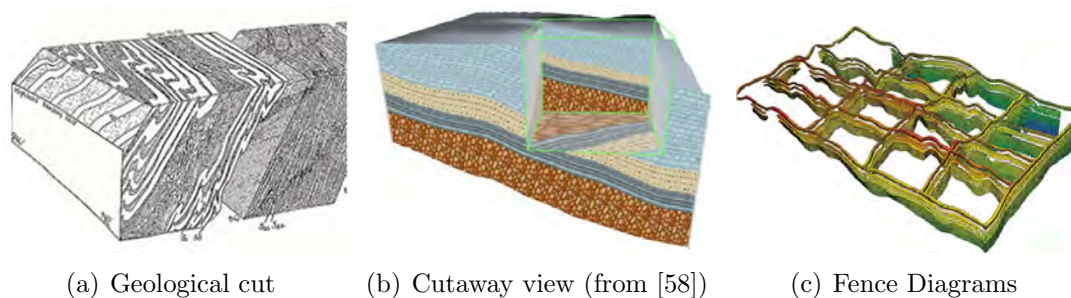
Figure 6.5: Examples of illustrations depicting internal structures of geological models, through cuts and cross sections.

In this section we introduce a technique that uses multitouch interaction to allow the examination of internal parts of the reservoir. Through intuitive manipulation, it operates in a similar fashion to the way we commonly handle and tear apart compound physical objects in the real world to see how they look inside. It consists on the ability of *slicing* the reservoir into subsections to expose internal cells, *reposition* them in a convenient location, and also *merging* them back together to restore its original shape (as exemplified in Figure 6.6).
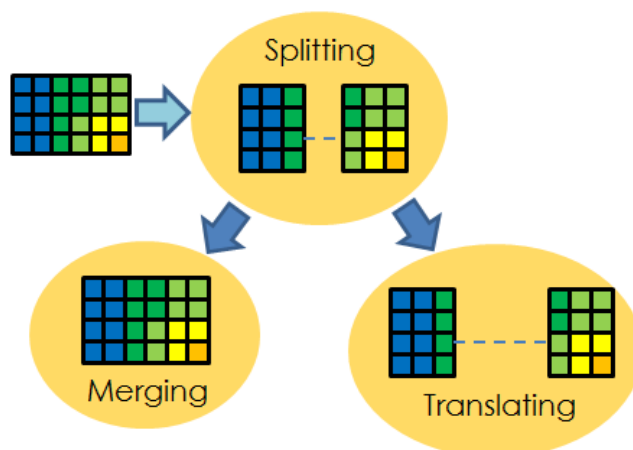
Figure 6.6: Slicing, repositioning and merging of reservoir layers.

6.2.1 Design

'Slicing' operations make sense on reservoir models, due to their discrete structure and layered organization: reservoir models are represented as 3D grids of irregular cells, and are organized in an (i,j,k) indexing, with the (i,j) coordinates roughly representing the horizontal position, and the (k) coordinate relating to depth. However, unconstrained slicing could potentially lead to confusing visualizations. Therefore, aiming for a more manageable manipulation of these sections, a few restrictions were applied. First, in order to facilitate spatial intuition, slicing was made available only along one of the (i,j,k) coordinates at a time, as opposed to arbitrary cuts. Another restriction is that the sections can only be repositioned along a 'rail', roughly perpendicular to the performed cut. The resulting effect resembles operating an abacus, with the beads moving along a fixed trajectory (see Figure 6.7).

There are three main operations involved in this visualization technique, already partially illustrated in the previous Figure 6.6:

1. **Sectioning**, representing the splitting of the reservoir into smaller sections;
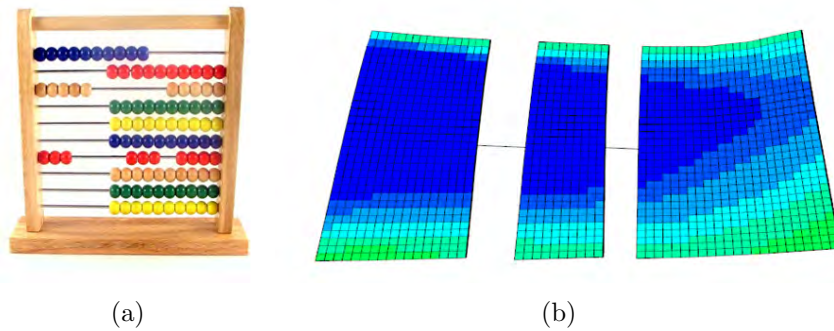
Figure 6.7: On the left, a real abacus; on the right, our 'reservoir splitting' technique, that follows similar principles.

2. **Translation**, when sections are selected and moved from a certain position to another;

3. **Merging**, when two sections are rejoined together forming a larger section.

Reservoir sectioning was designed to resemble an 'opening' gesture. With two or more fingers of each hand, the user can position them so that the desired cross section remains in between (Figure 6.8(a)). When hands are moved apart from each other, the reservoir is split in two, and each section follows the movements of the corresponding hand in the perpendicular trail reserved for the performed cut (Figure 6.8(b)). *Rail lines* are displayed between adjacent sections, indicating the direction in which the sections are allowed to be relocated. The same two-finger stance, with one hand, can be used to re-select and reposition previously cut sections (Figure 6.8(c)). Merging is also performed in the same fashion, and happens after a certain section is positioned to collide with one of its neighbours (Figure 6.8(d)). As soon as the corresponding touches are removed, they are joined and turn into a single partition (Figure 6.8(e)).

(a) Selecting a cross section   (b) Splitting the reservoir

(c) Selection followed by translation

(d) Sections collide   (e) Sections are merged
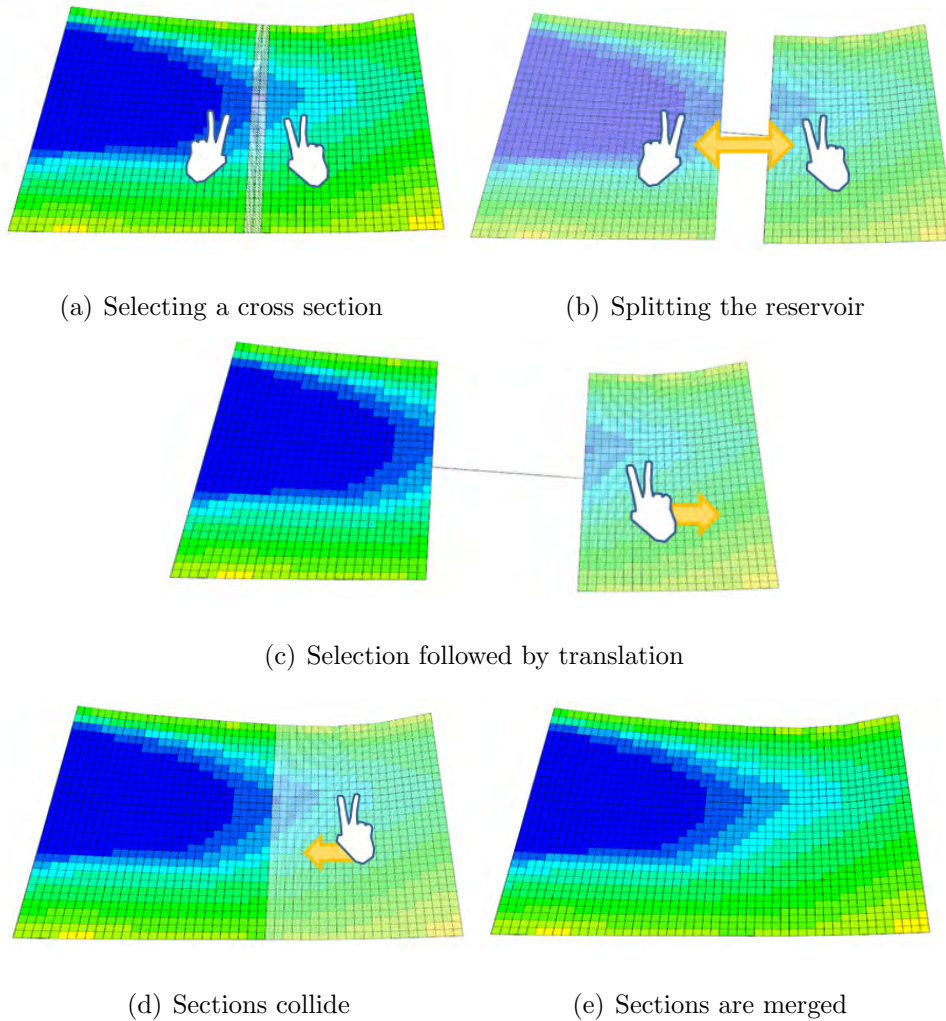
Figure 6.8: Gestures for splitting, translation and merging.

6.2.2 Implementation

A linked list was chosen to store the reservoir partitions. It starts as a single node, representing the whole reservoir. As soon as it is split, the root node is transformed into a lower indexed section, and a new node is created to represent the higher indexed section. Additionally, when intermediate partitions are sectioned, the higher indexing section inherits the previous section's children, keeping the indexing order in the tree.

By maintaining this indexing order, it is possible to access all sections through the root node, and it also facilitates section merging: as detailed before, collision events are interpreted as merging commands, and this ordering maintains all potentially colliding sections next to each other in the data structure. Figure 6.9 depicts examples on how this data structure grows and adapts to the manipulation of sections.

| (a) Initial State | (b) Splitting | (c) Splitting | (d) Merging | (e) Merging |
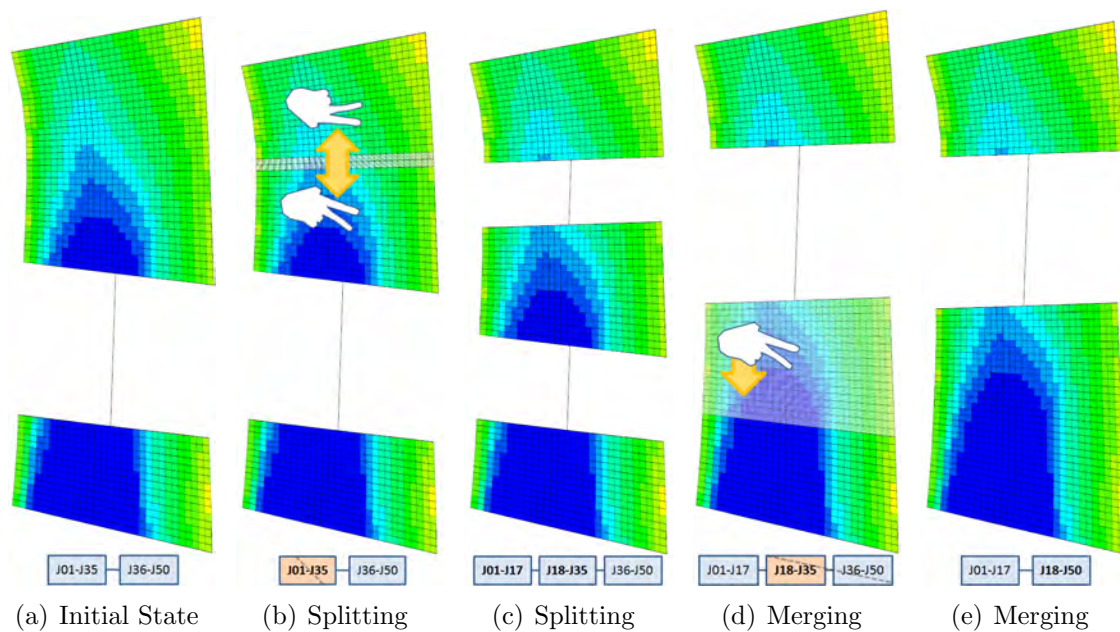
Figure 6.9: Depiction of splitting and merging on the J direction, with respective changes on the underlying data structure. In this example, 'J' varies from 1 to 50.

For rendering the original reservoir model, only the outer shell is tessellated and displayed – *i.e.* the visible faces of the external cells of the model. When internal parts of the reservoir are made visible, they need to be rendered as well. So, the outer shell is generated for each new section, and is updated every time a structural change (i.e. splitting or merging) is made. Individual translation components are kept for each section, allowing for simple collision detection and efficient displacement through translation matrices. When a certain partition is moved, its intended displacement

(a) Pressure (b) Oil Saturation (c) Temperature
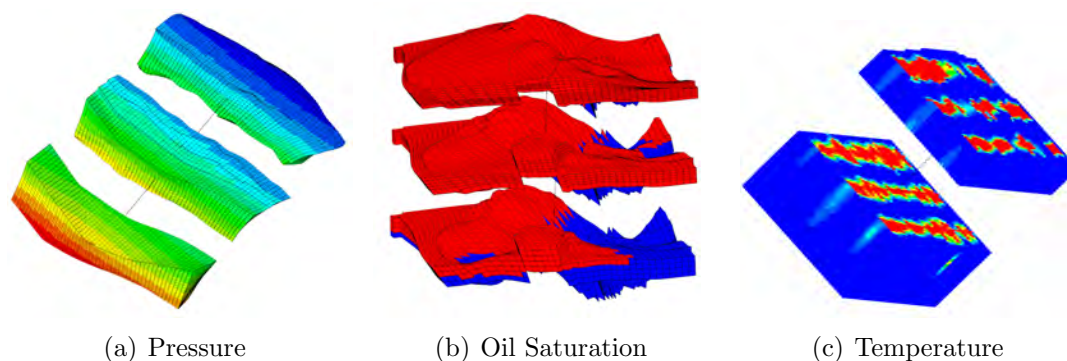
Figure 6.10: A few practical examples of reservoir splitting on several models.

is checked against its neighbours to avoid overlapping, and ultimately merging two sections if contact is still maintained at the end of the manipulation.

With cells being spatially repositioned, it was necessary to make a few adjustments to the *cell-picking* algorithm. Since it would not be efficient to update all grid cell coordinates to the new translation values, the 2D screen coordinates of users' touch and objects' tags are recalculated instead, reflecting an "inverse translation". It is done by projecting a 3D point representing the 2D coordinate on the imaginary rail line of the section, applying the inverse translation along the line, and then re-projecting this point back onto the screen. It represents where the cell probe would be pointing if the prospect cell had not been translated. For each section, these new coordinates are used for searching the pre-calculated octree with original coordinates in place.

6.3 Reservoir Peeling

When flipping the pages of a book, as shown in Figure 6.11, it is possible to see parts of the content from both pages. A similar visualization would also be useful
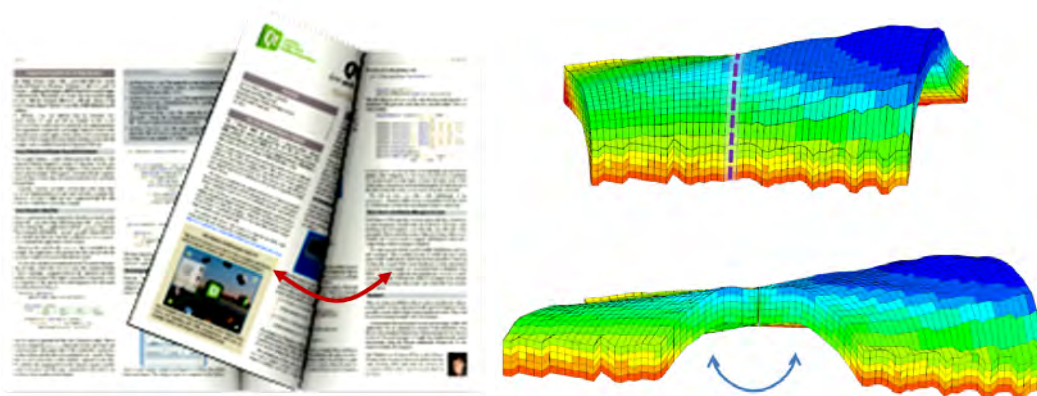
Figure 6.11: The flipped pages of a book, and the presented technique for reservoir flipping

in reservoirs, and is the main motivation for the feature we called *peeling*: an easy visualization for correlation of phenomena appearing in adjacent internal cells (Figure 6.11, on the right). It improves on the *splitting* technique, in the perspective that it is possible to see both internal faces at the same time. Instead of merely rotating the sections of interest outwardly, we opted for a "curving and bending" strategy that would allow for more natural results, in particular for partial exposures. A curling technique introduced for pages of virtual 3D books [33] was analysed and adapted to reservoir models, more thoroughly described in the remainder of this section.

6.3.1 Design

Since the peeling action relates to the idea of 'opening up, exposing the reservoir', its equivalent gesture should be able to convey similar touch and gesture intuition. A two-hand, 4-finger gesture was conceived for the purpose, as illustrated in Figure 6.12: with thumb and index finger of both hands in an L-shape and positioned close to one another, the reservoir would split in two along the midsection between both
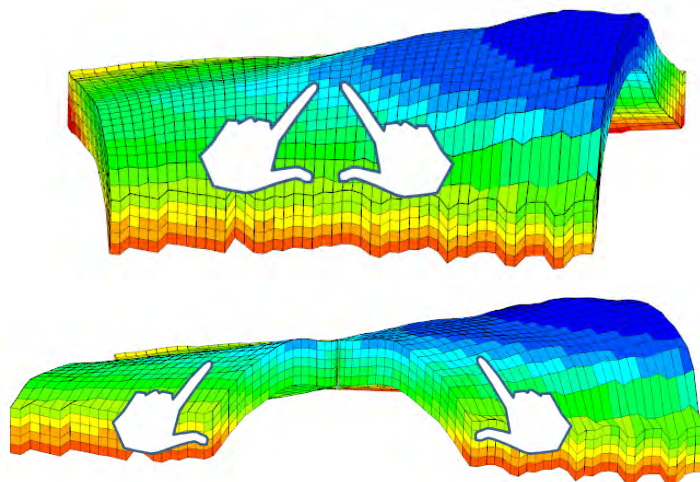
Figure 6.12: 4-finger gesture depicting the curling of two reservoir sections at once.

hands, and as hands are spread apart, each section would follow the hands and curve outwardly from the initial splitting section. For further control, the curving should track the user's movements as closely as possible, but still maintaining a minimum level of shape integrity.

In order to avoid misdetection with the sectioning gesture (which also consists in putting down four fingers, with pair of fingers close to each other), the *orientation* of the touches was taken into account. If two touches in a touch cluster have similar orientations, then they are very likely to belong to the same hand (splitting). Otherwise, it is detected as a peeling operation. The differences between both gestures are depicted in Figure 6.13.

A different modality was also envisioned, as a more informal and direct way of surveying the internal layers. With a hand palm down on the surface (as a metaphor for holding the visualization on the current position) the user can use a one-finger dragging gesture to curve a single section outwards from the initial touch point. The

(a) Splitting   (b) Peeling
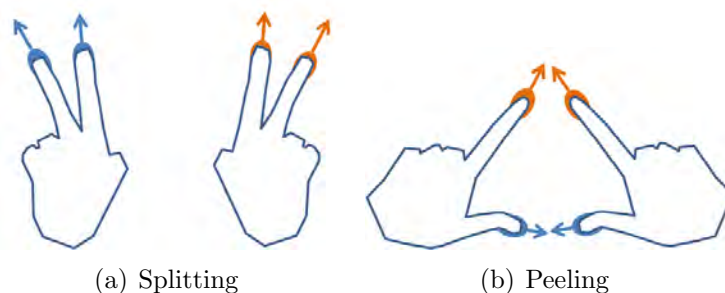
Figure 6.13: Differences in orientation between the gestures for the splitting and the peeling techniques

direction of the cutting and curving are defined by the direction of the gesture itself. Figure 6.14 depicts examples of 1-finger peeling in two different directions.

A slightly different approach was adopted for the edges on the boundaries of the model, since it wouldn't make sense to "cut outside an edge". If an edge is picked, and the gesture direction is perpendicular to it while pointing towards the inside of the reservoir, then the topmost visible layer is folded towards the user and then to the gesture direction, as if 'peeling' the reservoir. Figure 6.15 show some examples.

And finally, the inspiration and idea for this technique came from discussions and brainstorming with an invited senior reservoir engineer, as a novel resource for exposing internal reservoir layers in a very straightforward, intuitive way. As the process of curving the reservoir would introduce deformations, it was decided to make it a more transient interaction. The solution we found was, as soon as the user finished interacting, the reservoir would gently, and automatically, return to its original state. Nonetheless, a mechanism was also devised to deliberately fix the peeled section, to view it from different angles, if the user wishes so. In both techniques, putting extra fingers down will "pin down" the reservoir, which is signaled by a 'pin' icon on one corner of the screen (Figure 6.16). To 'unpin' and make the reservoir go back to

(a)

(b)
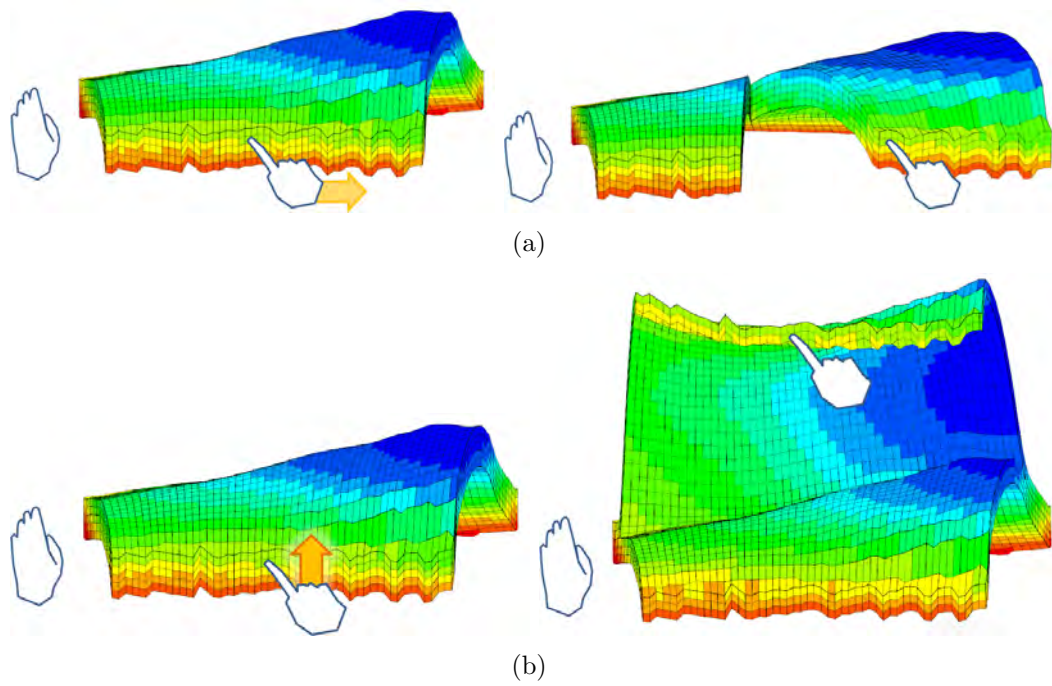
Figure 6.14: Palm plus 1-finger gesture depicting peeling for one reservoir section, in two different directions for the same view point.
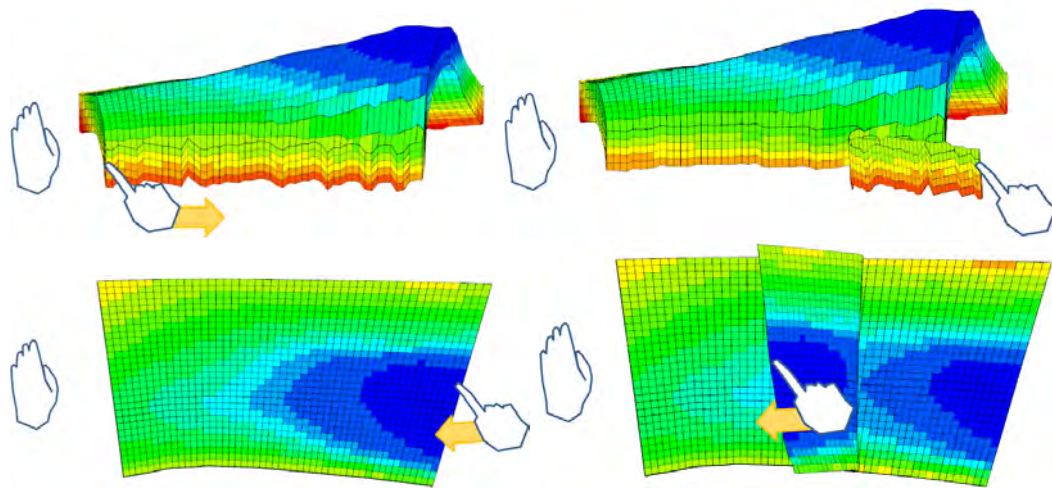
Figure 6.15: Examples of edge peeling.

its original unbent state, the user just needs to signal the start of another flipping operation, by either putting one palm down, or placing four finger in the previously defined configuration.

(a) Reservoir is pinned down   (b) The same cut, in a different view
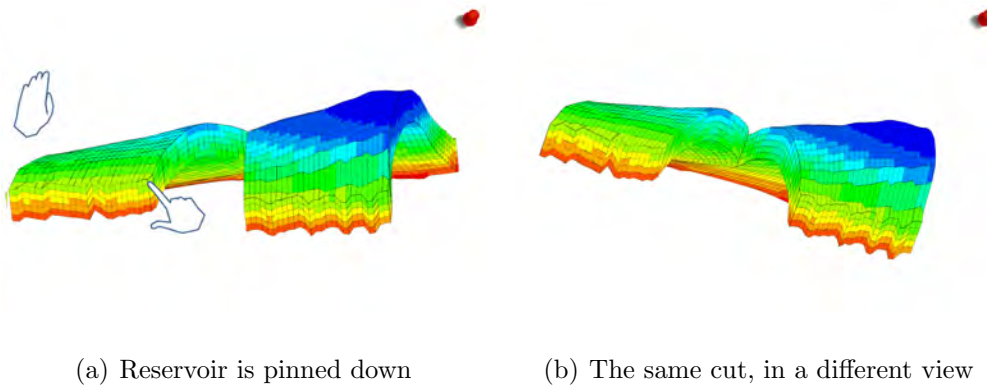
Figure 6.16: Palm plus 1-finger gesture depicting flipping for one reservoir section, in two different directions for the same view point.

6.3.2 Implementation

As mentioned earlier, we were inspired by a curling technique used for page flipping in electronic 3D books [33], which displaces vertices of a mesh to simulate the effect of wrapping them around a virtual cone resting on a plane representing the page to be curled.
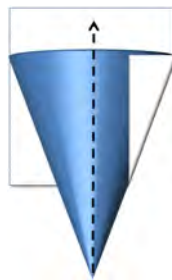
Figure 6.17: Cone curling around a page.

The algorithm consists in finding, for each 2D point P, its respective 3D point T, located on the cone (as depicted in Figure 6.17). It does so by rotating the point S – an equivalent point in the arc defined by P and the cone apex – around the cone cross section, and then another rotation to account for the cone tilting (Figure 6.18(b)). More details on this technique can be found in the original paper by Hong et al. [33].

(a)   (b)
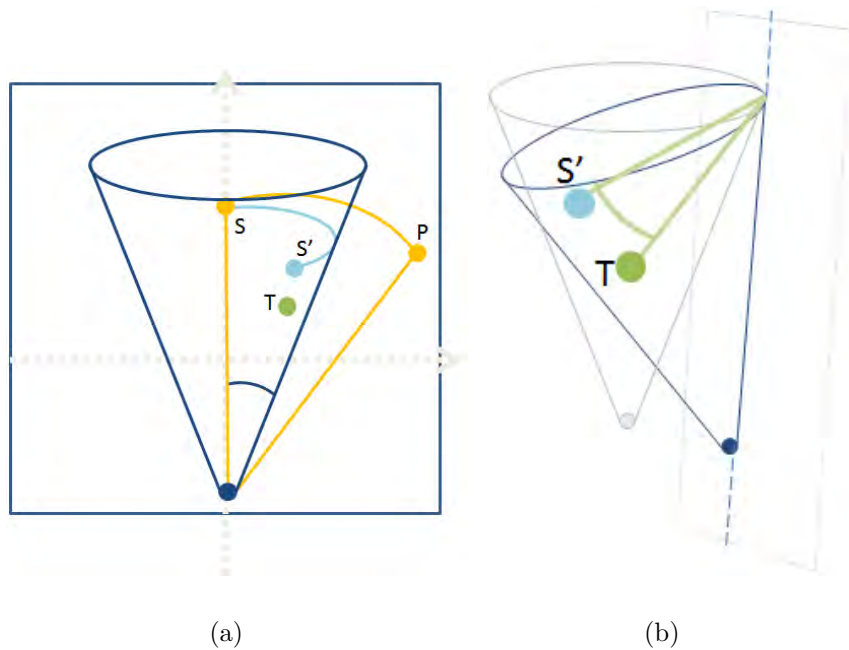
Figure 6.18: Diagrams depicting the cone curling algorithm described in Hong et al [33]. For a point P, the equivalent curled point T on the cone is reached by finding and intermediate point S on the vertical origin, and perform a rotation around the cone radius (generating S') (a), followed by another rotation to account for the cone tilting (b).

A separate program was implemented to replicate the described results, and also to test important generalizations necessary to apply the technique to arbitrary 3D reservoirs points, instead of 2D book pages. For the generalization, instead of bending

along the 2D plane (x,y,0), the algorithm was made to consider a generic plane instead (i.e. an arbitrary normal vector); similarly, instead of directing the bending cone up towards the Y direction, a generic cone positioning and direction were also used. Since the technique consists in repositioning vertices, a shader implementation was made possible, with threefold benefits: (1) greatly speeding up the curling deformation, (2) bypassing the necessity of extra data structures to store the new vertices, and consequently (3) being easy to port in the visualization prototype. A pseudo-code for this generalized version of the cone curling can be found in the Appendix A.

In summary, the problem of curling arbitrary objects around a cone was reduced to finding an appropriate cone positioning inside the object's space. However, it proved to be more complicated than initially thought, since it was not yielding desirable results. The curling envisioned for pages always bend more strongly on one edge, not being appropriate for uniform curling when sections are to be bent from within the reservoir. Thus, the overall curling was very hard to control.

Finally, we observed that the cone curling technique was not quite fit for the purpose due to the lack of control, but it inspired a simpler, and yet flexible variation: using a *cylinder* to shape the curling, instead of a cone. A primary advantage would be allowing for more flexible curling configurations, being able to simulate both corner curling or edge curling; another advantage comes from the fact that, for being simpler, this technique requires the input of less parameters, thus being easier to control. Finally, due to its regularity, it yields more structured bending, with more well behaved deformations (Figure 6.19). It was later found out to have similar effects to the work of McGuffin et al. [53], which consists in rotating sections of a volumetric object around a half-cylinder.

(a) Possibilities with cylinder curling

(b) Depiction of the cylinder curling algorithm.
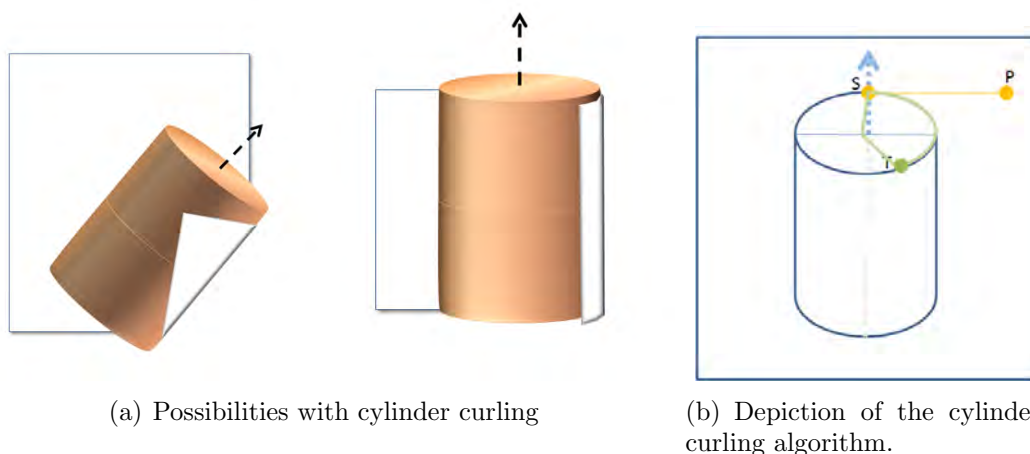
Figure 6.19: Diagrams depicting our cylinder curling.

For a cylinder resting on a plane, it consists on the following: for each point P in the plane, find the equivalent point T that lies on the cylinder (Figure 6.19(b)). Since the cylinder's radius is the same along its length, less calculations are needed. Additional tweaks were added, such as the possibility of restricting the maximum curling angle. It was observed that, for a lateral curling perspective (see Figure 6.14(a), for instance), an empirically defined angle of 80 degrees was able to fully expose internal walls, without any excessive curling on the extremes. For the edge peeling (see Figure 6.15), a wider angle was necessary, since the layer to be exposed is opposite to the user's view; 130 degrees was observed to be a good limit value. As with the previous technique, a shader implementation was also valid, which allowed for great efficiency in the curling, and a pseudo-code for this technique can also be found in the Appendix A.

Finally, the last task is how to employ the described algorithm to perform the desired curling and bending effects, i.e. how to properly manipulate its parameters. The envisioned outcome was conceived as a initial, subtle curving, followed by a

(a) 50 degrees   (b) 90 degrees   (c) 130 degrees
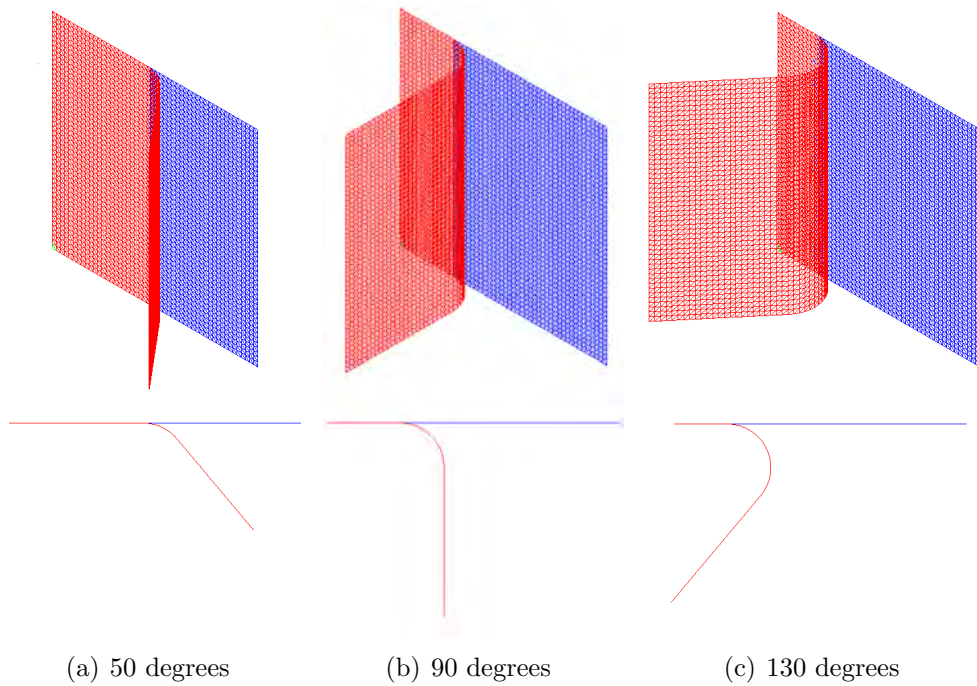
Figure 6.20: Examples of maximum bending angles, top and side view.

wider opening that gradually reveals the innermost parts of the reservoir– just like opening a book from the middle. This can be seen, technically, as two parts of a fluid motion: one that performs the curving until a maximum angle is reached, and another that cuts through the reservoir inwards while bending the cells outwards. To reproduce the effects for the first part, the curling cylinder starts with a very large radius, and gradually reduces to a minimum value(Figure 6.22(a)); meanwhile, a maximum curling angle is reached (i.e. 80 degrees for a lateral curling). The second part maintains the radius and angle, but instead moves the whole cylinder inwards, making more cells enter the curling area (Figure 6.22(b)). The complete sequence is associated to a normalized *animation track*, which maps the whole described sequence to a numeric interval $[0, 1]$ (see the pseudocode in Figure 6.21).

```
//Determines the variations in the peeling animation according to each timestep.
//It consists in changing the parameters of the cylinder along the interval [0:1]
void PeelingStateOnTimestep (float animTimestep [0..1])
{
    //0.3 is an example value. Means that at the stage 0.3 of a normalized animation
    //timestep, the second stage of animation will start (30% of the animation line)
        float transition = 0.3;
        if(animTimestep < transition) {
                //from 0 to transition,
                 DECREASE cylinder radius, from maxRadius to minRadius;
                 INCREASE bending angle limit, from 0 to maxBend;
        }else{
                //from transition to 1
                 cylinder radius = minRadius;
                 bending angle limit = maxBend;
                 INCREASE cylinder's distance from start edge;
        }
}
```

Figure 6.21: Pseudocode describing the peeling animation, in two stages.
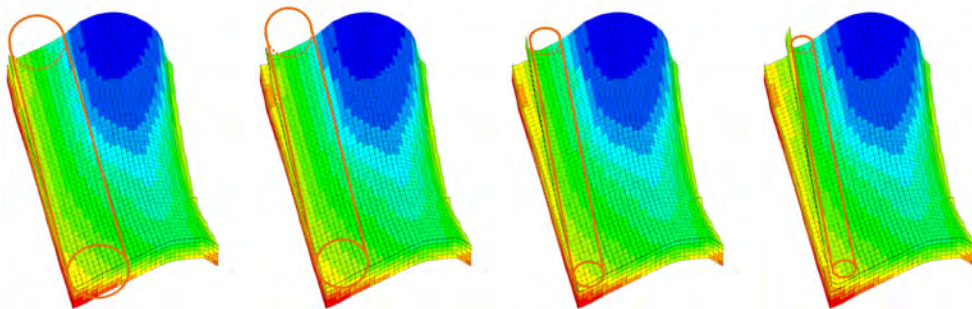
(a) First stage: curving
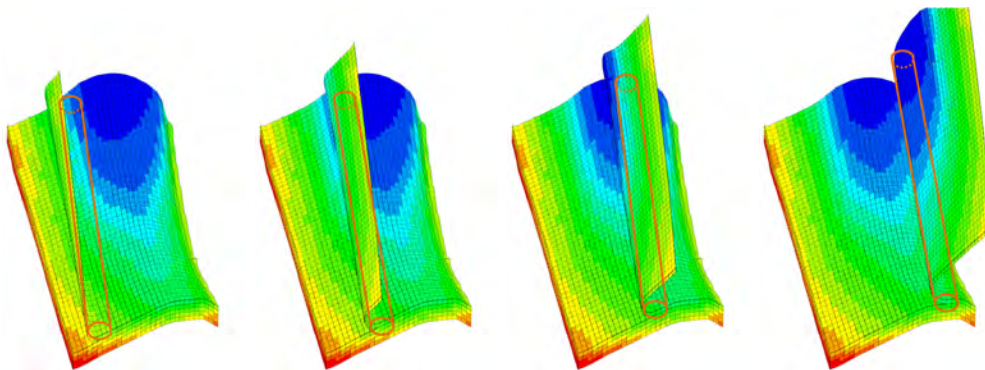
(b) Second stage: in-depth cut

Figure 6.22: Depiction of the two stages of an animation flow.

By the described means, it is actually possible to forecast trajectories of any given point in the reservoir, along the whole span of the animation line. With that, if the trajectory for the first reservoir point selected in a peeling gesture is calculated and stored, then it is possible to use it as a link between animation track positions and screen coordinates of the users touch: all that is required is to find the point in the trajectory that is closest to the screen coordinate. For simplicity, the 3D trajectory points are projected onto screen space, and a simple 2D distance algorithm is used. A few hundred points (namely 300, in this implementation) are calculated at the beginning of each peeling operation, using as reference the centroid of the cell that is immediately below the touch (or cluster) (Figure 6.24(a)). As the gesture continues, the touch/cluster distance is linearly checked against all points in the trajectory (Figures 6.24(b) and 6.24(c)). Many optimization techniques could be applied to this search, however, no performance issues were noticed with the linear search for this number of elements. See the pseudocode in Figure 6.23, describing how the finger trajectories are constructed.

Finally, as previously mentioned in Subsection 6.3.1, after the user finishes the interaction, the reservoir automatically falls back into its original position. In order to provide a more natural and intuitive feedback, this repositioning is displayed as a continuous animation sequence that simply rewinds the curled reservoir section through the same track until it is back to its original state, when it is re-merged with its adjacent section.

```
//Finds the curled path trajectory from a start point.
private Point2D[] GenerateCurledTrajectory(Point3D startPoint)
{
    int n = 300; //the number of points in the trajectory
    Point2D[] fingerTrackTrajectory = new Point2D[n];
    for (float i = 0; i < n; i++)
    {
        //normalizing the timestep
        float t = 1 / (n - 1) * i;
        //sets curling parameters for current timestep
        PeelingStateOnTimestep(t);
        //performs cylinder curling according to
        Point3D curledPoint = CurlPoint(startPoint);
        //Projects 3D curled point onto screen space (2D)
        Point2D screenPoint = Project3DPointOntoScreen();
        fingerTrackTrajectory[i] = screenPoint;
    }
    return fingerTrackTrajectory;
}
```

Figure 6.23: Pseudocode describing the generation of animation trajectories.
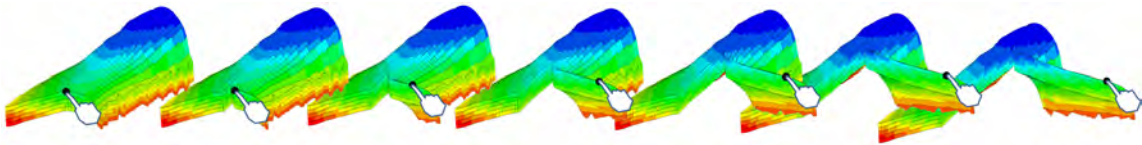
(a) An animation sequence, with the projected points composing the finger tracking trajectory.
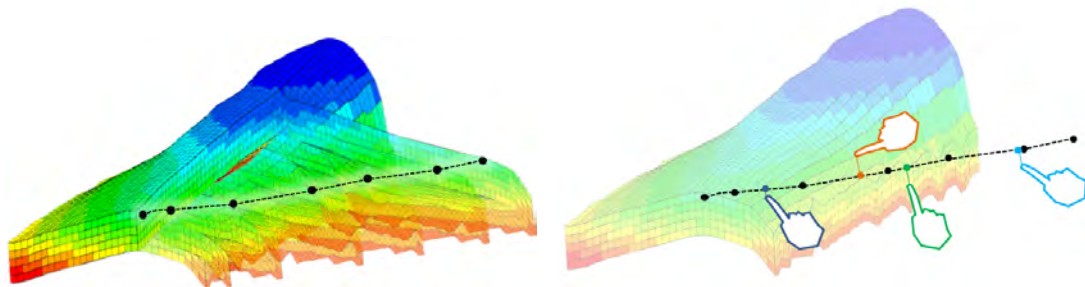
(b) A complete animation trajectory

(c) Touch positions associated to animation track values

Figure 6.24: Diagrams depicting animation trajectories and finger tracking.

6.4 User Evaluation

The three components presented here were evaluated in a series of formal user studies. They encompass 2 pilot sessions with expert reservoir engineers affiliated with our research group (but who were not involved in the design of the interfaces), and a full study which involved individual sessions with 10 external reservoir engineering experts. Each of these 12 evaluation sessions lasted around 60 to 90 minutes each. Participants volunteered to join via a study recruitment email sent to research mailing lists at the petroleum engineering department and related laboratories in our university. Participants were paid $15 for their participation in the study.

Sessions followed a closed protocol and started with a brief introduction to the goals of the study – the subjective evaluation of the interactive visualization tools to be presented – through a preset script. Participants were asked to fill a consent form, determining whether they would allow video recording and picture taking, for purposes of posterior qualitative analysis; 10 participants authorized video recording, while one agreed on audio recording. One person did not wish to be videotaped, and a thorough description of the discussion and comments was made instead.

A brief interview was conducted with each participant, to better delineate their respective fields of expertise and previous experience within the domain. Following the interview came a demo session, in which the three tools were introduced by the study administrator, one at a time, in the order: (1) cell probing, (2) splitting, (3) peeling. For each, participants were invited to try out the visualization tool in focus, while using a *think aloud* qualitative evaluation technique [47]. Participants were allowed some time to get familiar with the environment as well, in order to be able to

use each tool independently. The experimentation was not task oriented, attempting to invite free, subjective feedback. After this, users were prompted on their opinion on the tool in focus, reflecting on usefulness of the presented features, potential problems and suggestions for improvement. After all tools were explored and reflected upon, one by one, participants were also inquired on the most and least relevant tool in their opinion, and asked for suggestions for other potentially useful functionalities in the realm of 3D visualization for reservoir flow simulation models. The session was finalized with an invitation for additional comments, if there were any. Apart from video recording, notes were also taken during the sessions, registering important points emerging in the discussions and facilitating posterior analysis.

The detailed evaluation procedure, including questionnaire and themes of discussion, can be found in the Appendix B, together with the respective email recruitment lettter and the consent form.
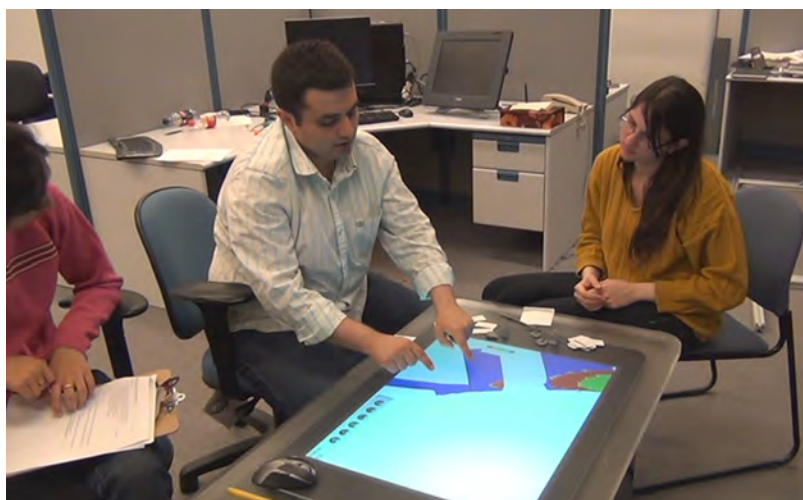
Figure 6.25: One of the user sessions.

6.4.1 Participants

Among the 12 participants, 1 was female and 11 were male. Participants' ages ranged from 23 to 50 years old. All participants had at least a bachelor's degree in a petroleum related field, and 11 of them either had a post-graduate degree (masters or doctorate level) in reservoir engineering or a petroleum-related field, or were currently pursuing one; 11 of them reported having some past industry experience in their field, either as interns or as a full-time employee; 2 of them reported currently holding a position in the industry. Although all participants were familiar with the specific reservoir models in focus, they had slightly different backgrounds (such as specializations in reservoir simulation, oil production history matching, drilling engineering, geophysics, and so on [16]). We believe that this factor did not compound the evaluation, but rather, contributed in allowing reflections on different point of views, and helped in diversifying and enriching the possible usage perspectives of our proposed tools. Despite of this variety, we were still able to perceive many common trends, which we collected and analyzed for each of the tools.

6.4.2 Results

A qualitative approach was taken for the analysis of the results, based on grounded theory [3]. For each of the user sessions, a written summary was created, highlighting pertinent points of discussion; these summaries were created from notes taken during evaluations, plus a revisit to the recorded sessions. Then, for each of the tools, points were categorized and grouped by similarity. As relevant topics were surfacing, the videos were once more revisited for collecting illustrative quotes that could meaningfully summarize the concepts at hand. The results of these efforts follow below, in

separate subsections for each of the tools.

Cell Probe

When inquired about the usefulness of the tangible cell probe, we received mixed opinions. Many participants commented that it was useful (*e.g.* *"I use it all the time"*) and fundamental (*"it has to be there"*); however, a few participants (3 out of 12) said that information from a single cell was not very relevant, since they were more interested in the "general trend" as opposed to specific values, *e.g.*: *"(...) in terms of the big picture of the reservoir, maybe a single grid is not important, maybe a group of grids is important"* and *"I am looking through specific trends and not through one specific value"*. This was pointed out to be particularly true in managerial presentations: *"(Managers) don't care about (cell-specific values), they just want to know 'where is the oil', 'what is it doing there', 'how is it gonna cost us to get it out'(...)"*.

In terms of interaction and the use of the TUI, a considerable number of people (4 out of 12) spontaneously stated they preferred fingers over the tangible object: *"I prefer fingers for sure"* and *"If you could do everything with the hand it is going to be more interesting"* were some of the related replies; one person recommended using a stylus, and another suggested a wearable probe instead – coincidentally, a very similar approach to the 'thimble' design we discarded (see Section 6.1.1). In terms of the tangible's usage in collaborative settings, one person mentioned that the information display should be adjusted to other participants around the table, by displaying the text with adequate orientations for multiple users around the table (a concept already explored in tabletop research [44]). Another person also suggested

having more tangible devices available – one for each participant – allowing for parallel browsing.

For further improvement, half of the users suggested the ability to view two or more property values for a cell at a time, a function already offered by commercial desktop tools (*e.g.* *"(...) it's now showing porosity, and at the same time you want other property also displayed..."*). One of the participants also suggested the possibility to display 'delta' values alongside the current one for comparison, *i.e.* the property value for the cell on the previous and the next time step; another one proposed a similar, but more powerful approach, by displaying a small graph by the information panel showing the variation trends in that cell over time, for a selected property.

Splitting

Users were generally supportive of the splitting function in terms of usefulness, stating it was very important to see internal parts of the reservoir (*"There are lots of things that you need to see inside of a reservoir, that is natural to a reservoir engineer."*). Comparing it to the common way it is performed with commercial tools (viewing one layer at a time, in a separate 2D mode) some pointed out the splitting technique could enhance awareness and provide insight, by being able to visualize many parallel layers at once, while also keeping the external perpendicular layers in view (Figure 6.10).

When inquired about problems and limitations with the current technique, almost all users (11 out of 12) attempted to split in different (i,j,k) directions at the same time. Some pointed out the need for more flexible cuts, *e.g.* cutting along a geological fault, or the path of a well. Additionally, 4 participants commented that, as the

reservoir is sectioned, all the wells contained in a section should move together with it: *"you guys should really make the well touch the grid; it is so confusing now"*. A few stated otherwise, however: *"it's interesting that I can see the well, since it's not moving"*. One user reflected on the need to further manipulate the now separated partitions individually, a function not supported by our current splitting interface: *"can you maybe rotate the sections?"*. Finally, possible suggested improvements included the aforementioned need to create more flexible cuts, *e.g.* through sketch-based techniques. One participant suggested being able to move sections "out of the rail"; one person suggested being able to select a region in which all layers are automatically split in a specified direction, and equally spaced.

Peeling

We presented and evaluated both peeling strategies (4-finger and palm plus 1-finger), and received interesting feedback on each.

Opinions on the usefulness of the 2-section peeling (performed with 4 fingers in a pinching gesture) function were not as positive as initially expected. Although 3 participants could see some potential in it, 8 stated they did not get anything new when compared to the previous splitting function. One of participants justified this by saying that differences between adjacent layers are often not expressive, and correlations between them carry little extra information (*"If you see two consecutive layers, I don't think it's that useful... there won't be that much variation between adjacent cells"*). One person also commented that "opening from the center does not feel natural". Additionally, 5 people mentioned they would prefer the deformations to stay in place rather than spring back, to be able to decide when to send the section

back into place (*e.g.* *"I think it should stay there automatically, and if we want to take it out, we put the hand down"*). We also noticed that, in general, the participants encountered difficulties in using the function with the 4-finger gesture, which might have also contributed to reduce the overall satisfaction.

On the other hand, the 1-section, palm/1-finger modality for peeling received more positive comments. Two out of 12 mentioned it could be a good way to perform quick explorations (*e.g.* *"Of the others you showed me, this is more of a searching tool"*); one of them also mentioned that, for this particular purpose, it would be better if the layers returned automatically to their place after manipulation. Similarly, with the 'edge' peeling, many people expected to be able to peel through more layers than just the top one (*e.g.* *"(...) but you are only able to flip only the very top or very bottom layer, right? If I had control over what set of layers I want to do (peeling) for, it would be nice for me."*). Although two users were bothered by having to place one palm down (*e.g.* *"First I learned to work just with my fingers, now you're telling me to put 1 hand down and work with other fingers. I prefer to work just with my fingers"*), in general, users seemed to find it simpler to perform the function with this gesture instead; this might have similarly helped in improving receptiveness when compared to the previous one.

As possibilities for improvement, one user suggested being able to show further details in the correlation of adjacent cells by using the previously introduced cell probe (for example, displaying a connection line between adjacent cells). Another user suggested being able to make annotations in a certain internal cell, associated to the current time step.

6.4.3 Discussion

The majority of the participants was new to tabletop technology, and was impressed by the Surface capabilities. While being aware that the novelty effect might have added a confounding factor to the results, evaluation sessions were extensive and lengthy (often longer than an hour of interaction), making us believe that the core of the results is fundamentally valid and could offer insight beyond the novelty effect of interaction with a tabletop.

As mentioned before, although all the participants were from the petroleum engineering domain, each participant had unique views and requirements due to the varying nature of their expertise and specializations – such as reservoir simulation, reservoir management, drilling engineering, and so on [16]. Their varied opinions on the usefulness and potential improvements of the cell probe function, for example, were very much related to particulars of their field – people with drilling background spontaneously requested displaying actual depth coordinates for a cell, while people more involved in simulation aspects and behaviour of fluids wanted to see correlations between property values. Anecdotes like this one shed light onto the multidisciplinary aspects of the domain, present in various stages of oil and gas exploration and production, thus evincing the need to reach out to a broader range of experts in related subfields of expertise within reservoir geosciences and engineering.

The splitting and peeling tools were frequently compared to similar functions offered by commercial desktop systems, which offer a 2D perspective of the reservoir layers (Figure 6.26). Many of the participants agreed that the offered tools could provide further insight when compared to a simple 2D view; however, a lot of the

participants' suggestions still involved the visualization of a pure 2D perspective for reservoir layers. On one side, this can be viewed as a reflection of how immersed our participants are in the visualization paradigms they were trained at, and are used to. On the other hand, these reflections should be used as incentive to adapt the current 3D tools, and make them feel as easy and convenient as their existing 2D counterparts.

(a) Top layer's 2D view   (b) 3D view
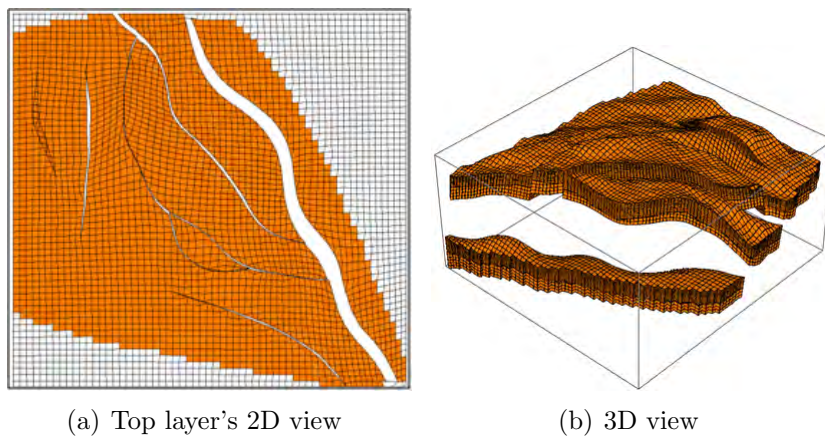
Figure 6.26: A reservoir model, seen both in 2D and 3D perspective, as provided by a commercial tool.

Some of the participants' suggestions were directed at the gesture vocabulary. A few participants suggested that the need to learn a new gesture for every tool would require training, which could potentially hinder ease of use. Some reported that their experience is based on choosing options from several menus, and hence they would probably prefer a menu selection approach than one that requires them to learn a set of completely new ideas (as expressed by the set of gestures used in this interface). Making a vocabulary of gestures as familiar and usable as a simple GUI menu is a fundamental challenge of touch interfaces and we believe that our current set of gestures, while satisfactory as an evaluation test bed, should definitely be further

enhanced and improved. However, it is also important to consider gestures that require a learning effort but turn out very efficient with time, specially considering conditions of very repeated use.

Finally, apart from the cell probe (which was a very well known function to our participants), splitting and peeling were generally considered novel functions. Participants were engaged by these tools, and seemed at ease to share a range of different thoughts regarding each of them. The overall impression is that the inherent strengths of the tabletop environment combined to novel, unconventional set of interaction techniques may perhaps have influenced and fostered the insightful and inspiring ideas our participants provided us with. This might also be an indicative of how a creative environment can encourage and facilitate the thought and problem-solving process, as stated by one of our participants during her evaluation session: *"It actually brings some new ways of analysis (...) it brings some creativity for sure"*.

6.5   Future Work

In this section, some directions for future work are highlighted, based on the feedback obtained by the presented techniques through the user evaluation.

6.5.1   Enabling Correlations with the Cell Probe

A good part of the suggestions received by the users concerning the cell probe involved enabling access to further data, related to the region in focus: displaying the value of other properties to compare with the current one in the appointed cell, and also displaying variations of that property over time. Another possible use that we could

foresee for the cell probe is using it in conjunction with the peeling to indicate position and correlation info of adjacent cells (Figure 6.27), as the perception of continuity can be somewhat difficult at times.
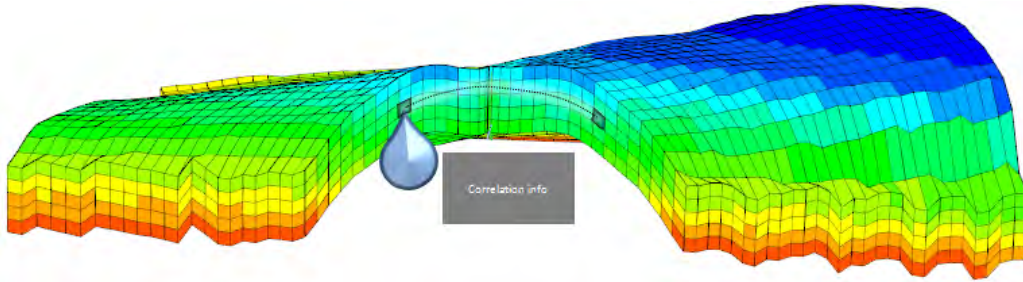
Figure 6.27: A possible extension for the cell probe, displaying correlation between adjacent cells in the peeling.

6.5.2 Flexible splitting

As internal events in the reservoir do not necessarily follow the structure of the layers, cuts were suggested to be more flexible. Free-form cuts would probably satisfy most of the users; however, the complexity that follows might be difficult to address, from an interaction perspective – considering, for instance, the creation of partial cuts that cut out a shallow piece of the reservoir, as opposed to a simple slicing operation that cuts through the whole depth. Also, most of the time, users mentioned specific features of the reservoir to be observed, in which a free-form sketch selection would be inexact. They wanted, for instance, to see the cells surrounding well paths (Figure 6.28(a)), or view property values along a geological fault. Interval slicing was also suggested, which is somehow supported by the current version of the prototype through manual splitting, but it could be extended to operate automatically, and also allow for directions other than the ones defined by the (i,j,k) layers (Figure 6.28(b)).
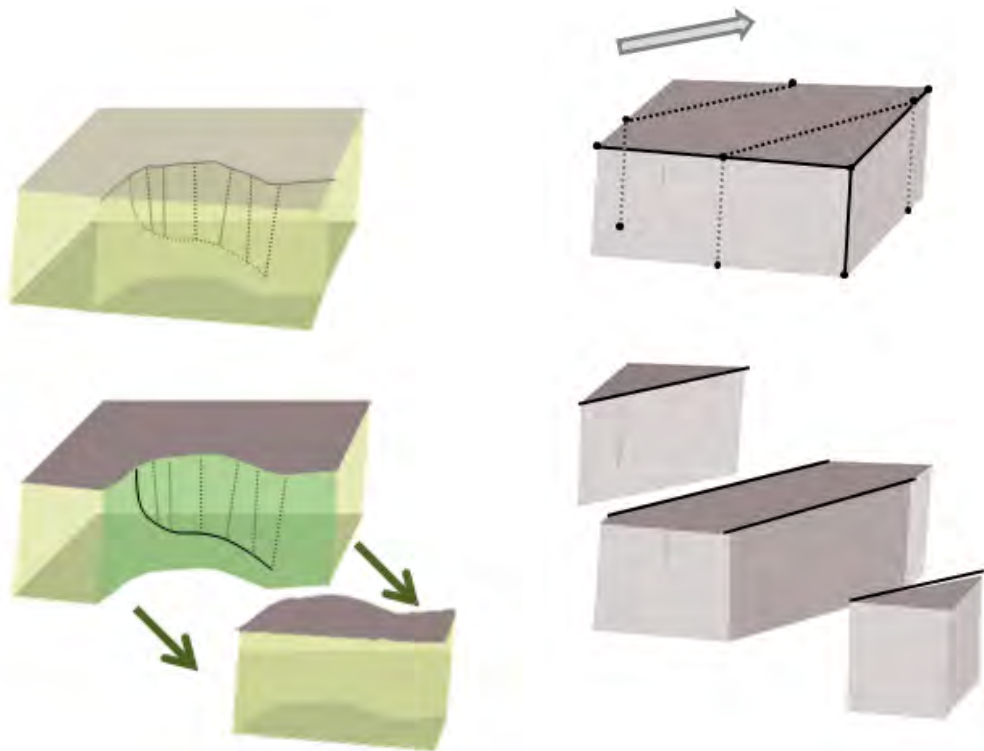
(a) Splitting along the trajectory of a well path.

(b) Several equal splits in a customized direction.

Figure 6.28: A few possibilities for improvement on the splitting function, following high-level constraints.

6.5.3 Exploratory tools for Layer navigation

The edge peeling, and the palm/1-finger peeling had a reasonably good acceptance due to its interaction simplicity and the strong metaphors it evokes from the real world gesture of flipping through pages of a book. Also, as many have highlighted the importance of navigating through 2D layers, the efforts on peeling could be redirected to ideas for supporting this exploratory avenue. For that, it should offer very quick, efficient mechanisms for layer browsing, flipping and restoration, possibly relying on 2D inspirations. For instance, a fanning gesture to expose the layers as if it was a

hand of playing cards could allow for a partial view of all layers, which could the be individually browsed, or compared against another opposite layer (Figure 6.29).

(a) Distributing the layers.   (b) Selecting and comparing individual layers.
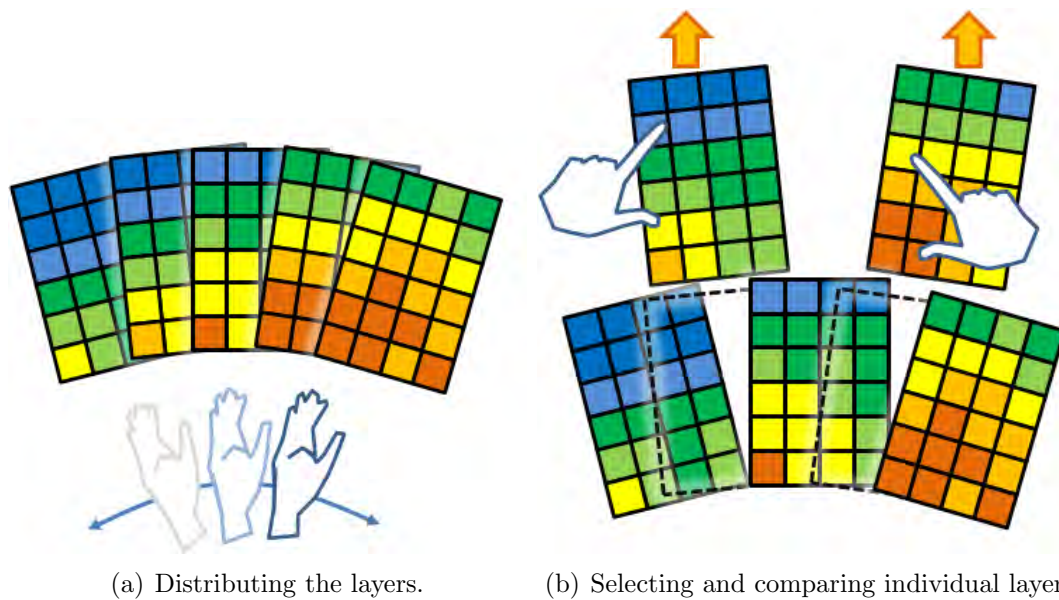
Figure 6.29: One possible approach for exploratory layer browsing, relying on a 2D metaphor for the layers as playing cards.

6.6   Summary

In this chapter we presented the design, implementation and evaluation of three reservoir visualization tools for tabletops: the *tangible cell probe*, the *splitting*, and the *peeling*. Results obtained from a qualitative formal user study involving 12 domain experts are also presented and discussed, which represented a fundamental effort in delineating the strengths and weaknesses of the proposed strategies. Many possibilities for improvement also emerged, as well as potentially relevant directions to take for future development.

Chapter 7

Heuristics for the Design of Interactive Visualization Tools for Reservoir Engineering

This chapter discusses a set of heuristics for the design of interactive visualization environments for the domain of reservoir engineering. 'Heuristics' represent lessons learned from experience; here, we thus present a summary of what we believe are important highlights which emerged throughout the design, implementation and evaluation of the work presented in this thesis. The focus of this chapter is not to provide a comprehensive compilation, as there might be many other relevant concerns that apply; however, we think that the themes discussed here are valuable, as they embody fundamental concerns for the design of applications for the visualization of reservoir models, transcending particularities of implementation and providing more general, broader perspectives. Our design heuristics are:

H1. *Facilitate 3D exploration and awareness*;

H2. *Provide freedom and control*;

H3. *Facilitate correlation*;

H4. *Share the power*;

H5. *Design for diversity*;

H6. *Consider the GUI legacy.*

The remainder of this chapter includes a description of each of the cited items, followed by an evaluation of reservoir engineering visualization interfaces using our heuristics (including our own prototypes); we do so in order to reflect on the designs of reservoir visualization environments, as well as validate the effectiveness of the proposed heuristics for evaluating future efforts in the domain.

7.1 Heuristics

H1. *Facilitate 3D Exploration and Awareness*

The need to easily access and investigate internal regions of the reservoir model must be a primary concern for the interaction designer. On the other hand, with reservoir models being 3D entities, external navigation and situational awareness must be supported at all times as well; this is particularly true for visualization on displays, which are 2D environments by nature. The interaction designer should be conscious of the need to properly balance between the reservoir's internal interaction mechanisms and its external navigation and manipulation tools. For instance, when a layered 2D view of the reservoir is necessary, it is important to at least keep awareness of where that layer is located in the whole volume (for example, displaying the 3D view in a separate window, indicating the location of the selected layer). Having a quick and effective mechanism to access and explore hidden data is an invaluable resource in attempting to understand a reservoir's behaviour, but ideally should not undermine the user's overall awareness of the reservoir and ability to manipulate and navigate it.

H2. *Provide Freedom and Control*

Due to the depth and multidimensionality of reservoir data, there are inumerous ways it can be manipulated. Naturally, in the perspective of interface design, particular effort must be put into making these manipulations easy to perform, which often means that a few constraints are applied in order to simplify the interaction; nonetheless, the interface should provide users with enough power to perform more generic, precise operations. A very simple case would be, for instance, a redesign of the splitting function (Section 6.2) to allow for more general directions, giving the opportunity to perform cuts following particular trends of the geology or the reservoir properties, and thus allowing for a different view of the data that more conveniently and clearly presents a particular phenomenon – even if it requires a slightly more complicated interaction to be performed, *e.g.* defining a region by sketch. In summary, the presented trade-off must be well balanced, having in mind that an over restraining interface that is easy to use will more likely fail to uncover important aspects of the data.

H3. *Facilitate Correlation*

Designers should provide tools that directly support flexible comparisons and correlation of data within the reservoir environment. The interactive environment should facilitate exploratory and non-restrictive comparison of its various elements. Throughout the study evaluation (Section 6.4), for instance, we observed many references to comparison and association, in the most varied renditions. Users wanted to compare properties, looking for possible correlations that might make one affect the other; they also sought to compare a set of parallel layers to better understand the movement or expansion of fluids in a tridimensional perspective; users wanted to observe trends in a property's behaviour over time, for a cell, a region, or the whole

model, and so on. Supporting such comparison mechanisms is an essential element for experts to gain knowledge about a reservoir, and visualization tools should aim at providing and simplifying these processes.

H4. *Share the Power*

Oil and gas exploration and production is a multidisciplinary effort, bringing together experts from many fields of expertise for collaborative decision making. Collaborative visualization tools play a major role in this process, since it is often through them that alternative scenarios are presented, scrutinized and critiqued. Visualization rooms with stereoscopic view [80] and virtual reality environments [48], for instance, were created with this philosophy, and allow for a shared view of the reservoir. However, control of the interface is always in the hands of a single user, which limits interactivity and automatically imposes a hierarchy of command. For presentation purposes, this might be an adequate setup, as most of the interaction is performed by a single presenter; however, for collaborative analysis, a more 'democratic' access to the interface would be truly empowering. Digital tabletops, for instance, don't necessarily require the control to be monopolized by a single user, giving team members more equal chances to contribute, and can encourage more active participation.

H5. *Design for Diversity*

As a result of the complexity of the oil and gas exploration, a whole myriad of specializations emerged to deepen understanding of the process. These disciplines, however, are often overlapping, which makes the interchange of ideas between professionals a necessity. For this interchange to work effectively, it is necessary to have a common base of knowledge, and reservoir flow simulation models establish intersections with many related disciplines. For example, apart from reservoir engineers,

other professionals (such as geologists, geophysicists and upper management) also need to visualize and understand the behaviour of reservoir flow simulation models, under the perspectives relevant to their own field of expertise; providing the option of visualizing geophysical and geological data superimposed on the reservoir flow model (where they apply) can make it potentially easier for these professionals to relate to the scenario and provide meaningful input related to their background. Designers should have in mind that their interface can, and should, emerge as a point of convergence for the several disciplines, a touchstone that should allow all its users to have a voice and relate to the task at hand.

H6. *Consider the GUI legacy*

The routine of a reservoir engineer traditionally includes many thousands of hours of work with a desktop computer, running simulations, updating datasets and visualizing models, through domain-specific computational solutions using WIMP inspired interfaces. Reservoir engineers have traditionally used GUI-based interfaces, with an overwhelming number of functions distributed in several menus and icons. Although complex and time-consuming, these tools are essential to their work. As necessity brings reservoir engineers to use a tool for an extended period of time, they become so comfortable with them that upcoming novel and arguably better solutions can be met with prejudice, if they seem to clash directly with the paradigms these users are accustomed to. With novel interactive environments, their inherent freedom and power can - and should - be used to provide a different experience. However, the interaction designer should also acknowledge the GUI heritage when designing these tools, as to better understand the users' technological background in attempting to provide an easier transition from the more conservative approaches pervading the

environment. For a classical literature example, Mackay et al. [51] explore an augmented reality system for extending functionalities based on the everyday tasks of air traffic controllers based on paper. In our context, we could analyze, for instance, the 'pointing' metaphor: as a deeply ingrained interaction paradigm in desktop environments, it frequently induces the use of index finger for touch interaction. It denotes that, depending on the case, such gesture might a good candidate for reuse with the help of user-selected modes, as opposed to the creation of more sophisticated gestures to address distinct functions; this way, simplicity and power can be attained by relying on users' previous interaction background.

7.2 Interface Evaluation with the Proposed Heuristics

In this section, we use the heuristics presented in this chapter to evaluate three interfaces for reservoir visualization: (1) CMG Results 3D, a commercial desktop tool for 3D reservoir visualization of flow simulation models [50]; (2) *Snakey* (Chapter 4); and (3) *Touching the Depths* and the related tabletop visualization techniques (Chapter 5 and 6, respectively). In the process, we also seek to evaluate the heuristics themselves, and their validity for gaining insight, for the design of visualization applications for the domain.

Heuristics will be referenced throughout the section by their respective codes, as presented in the previous section:

H1. *Facilitate 3D exploration and awareness* **H4**. *Share the power*

H2. *Provide freedom and control* **H5**. *Design for diversity*

H3. *Facilitate correlation* **H6**. *Consider the GUI legacy*

7.2.1 CMG Results 3D

Considering that CMG Results 3D is a single-user desktop application, a few of the heuristics presented here do not apply (**H4**, **H5**, **H6**); still, it is representative of a canonical class of visualization tools for the purpose, and therefore deserves at least a brief overview.

Commercial desktop systems for reservoir engineering visualization are, in general, very comprehensive, and this one is no exception; it provides many visualization tools that allow for different perspectives on the reservoir (**H2**): property and time step browsing, layer cutting for exposing internal cells, directional vectors for displaying fluid flow, isosurfaces for spatial/temporal depiction of changes in property values, and many others. It also offers useful mechanisms for data correlation (**H3**), providing, for instance, a way to calculate equations based on the combinations of two or more properties, and displaying this compound value in color for every cell; it also allows for the simultaneous display of multiple independent views, allowing for visual comparison. Nonetheless, 3D navigation is lacking (**H1**), as the operations of rotating, zooming and panning can only performed one at a time, by a manipulation mode selection through a button menu or keyboard; 2D layer views are available through a menu item selection, which however offers no cues to where that layer is spatially located, except for the layer number of the current 2D view.

7.2.2 *Snakey*

Snakey excels at providing 3D awareness of a well path (**H1**); with an actual physical representation of the tridimensional trajectory, users get an immediate and natural perception of shape and position. The embedded devices – LED lights and vibration

motors – can be used for displaying additional information in parallel with the monitor screen, which aids in data correlation in the regions around a well (**H3**). Since the interface is always readily available, users have the freedom to grab and manipulate it if no one is doing so at the moment (**H4**).

However, Snakey, as a proof-of-concept prototype, has limited functionality beyond well design and well exploration (**H5**). Due to its preliminary stage, it is still limited on what can be done in terms of well path design (**H2**): it is necessary to provide further control in terms of the well position and scale in the virtual realm of the reservoir model, as well as appropriate functionality for well saving and loading, well comparison (**H3**), and so on. Finally, the intuitiveness of the manipulation indicates no major problems in the apprehension of its manipulation, there might be some resistance regarding lack of preciseness when putting Snakey together with other well path design tools (**H6**). However, it is important to have in mind that Snakey isn't meant to replace traditional tools, but rather to complement them with a new exploratory work stage, and therefore lends itself to little comparison with previous tools for the purpose.

7.2.3 *Touching the Depths*, and Reservoir Manipulation Techniques

Firstly, similarly to Snakey, the tabletop environment is capable of fostering real multi-user interaction (**H4**), due to its format factor, shared view and multitouch capabilities. It provides relatively good 3D perception (**H1**), as the rotation and orbiting of the reservoir model operate quickly and directly; 2D layer visualization operates within the 3D environment with the splitting and the peeling, and there is always a clear perception of where they are located.

Mechanisms of comparison, nonetheless, are scarcely available, and the user will find it difficult to establish correlations (**H3**). Data integration with other datasets is not provided, which could help experts in similar fields better relate to the visualization (**H5**). Screen components (color scale, time step navigator, tangible menus) and reservoir rotation are greatly inspired in traditional interfaces, and offer little difficulty for the novice user (**H6**); nonetheless, a few of the gestures for direct reservoir manipulation – such as the variations for peeling – may perhaps have crossed the threshold of comfort in its innovation, although part of the difficulties and frustration faced by the users was related to eventual touch misdetections by the tabletop platform itself. Finally, this prototype provides a fair amount of control (**H2**) with the reservoir manipulation tools, although there is much that could be improved in terms of freedom (as highlighted by comments and suggestion in the user evaluation on Section 6.4.

	H1	H2	H3	H4	H5	H6
CMG Results 3D	☹	☺	😐	N/A	N/A	N/A
Snakey	☺	😐	😐	☺	☹	😐
Tabletop	☺	😐	☹	☺	☹	😐

Table 7.1: A chart summarizing the performances of each of the evaluated tools according to our heuristics.

7.3   Summary

In this chapter we presented and discussed six heuristics for the design of interactive reservoir visualization systems, representing high level considerations, general enough to be applied to any interactive platform. We also inspect some domain interfaces using our proposed heuristics (also including the prototypes presented in this thesis) with the goal of demonstrating the effectiveness of these heuristics for evaluating reservoir visualization systems.

Our heuristics reflect on specific aspects of the domain and its users and, we believe, can be useful to anyone designing related applications. They can also, to a smaller extent, be generalized to the visualization of other datasets that share similar traits with reservoir simulation models – namely, temporal tridimensional multi-property structures. Nonetheless, the best contribution these guidelines offer – and the best way of making use of them – is not to take them as a strict checklist, but use them to gain a better perspective of intrinsic, tacit aspects of the domain. In the end, the interface designer is the one ultimately deciding how, and to what extent, the items presented apply to his or her specific case.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

In this thesis we presented our research efforts in the exploration of recent beyond-the-desktop interfaces to the activity of reservoir visualization and analysis. Through the implementation, design and evaluation of three prototypes – *Snakey*, a tangible interface targeted for well planning; *Touching the Depths*, a tabletop interface for reservoir simulation visualization; and visualization techniques for direct manipulation of reservoir models – we gained insight on the potential of these new technologies to provide an improved user experience, and potentially foster better decision making. A set of heuristics is also presented and evaluated, completing this research effort with a broad perspective encompassing several points of relevance. With this, we revisit the main contributions of this thesis, as follows:

1. **A set of user investigations focused on the visualization needs of reservoir engineers**: in Chapter 2, Section 2.4, as well as in the user critiques and evaluation on Chapters 4, 5, and a detailed formal user study presented in Chapter 6, we report results reflecting on many aspects of reservoir visualization, which bring insight into its importance, usability, limitations and possibilities of improvement.

2. **The first tabletop interface applied to visualization of reservoir simu-**

lation models: In Chapters 5 and 6, tabletop efforts for reservoir visualization were addressed, with detailed design, implementation and evaluation of each component;

3. **A novel tangible interface for well planning**: In Chapter 4, *Snakey*, a flexible tangible interface for direct manipulation of 3D well trajectories was described, with a prototype implementation and preliminary evaluation by domain experts;

4. **A set of heuristics for the design of novel visualization interfaces applied to reservoir engineering**: The collection of design heuristics contained in Chapter 7 is the result of a high level perspective of several recurring issues emerging from the many user interventions as well as design efforts in the course of this research. They represent what we believe is a practical toolset for future designers of interactive visualization tool for reservoir engineering, informing the community of the insights we gained and how similar design efforts can be approached in the future.

8.2 Perspective for the Future

In previous chapters 4, 5 and 6, immediate follow-up work was discussed, pertaining to each individual effort. In this section, more general instances of future work are presented, and briefly discussed.

8.2.1 Collaborative, In-The-Wild User Studies

User participation in this work was frequent, and fundamental. Among the observation study, the design critique sessions and the user evaluation, valuable feedback was gathered in terms of interactivity, relevance, problems to address and potential avenues for improvement. Collaboration was a recurring topic in the process – a natural subject considering its importance in the domain, as well as being one of the main issues our prototypes attempted to undertake – and its relevance and general aspects were made clear.

However, it is still unknown to us how the proposed systems would perform in a real-life collaborative scenario: would it be able to engage team members, foster new ideas and stimulate participation? How would collaboration unfold? We believe that a collaborative, task-oriented user evaluation would be truly valuable in order to unveil some of these aspects, and many more. However, it is clear to us that further design efforts would be needed to better facilitate collaboration.

8.2.2 Simulation Steering and Its Implications to Reservoir Visualization

Being computationally intensive, simulation runs are widely assumed to be an 'offline' stage, that happens prior to, and separately from the visualization of its output. This situation, however, has consequences that go beyond technical concerns. Firstly, it introduces a disconnect between the simulation and the visualization, when ideally one could use the visualization as both input and output, while directly displaying the consequences of the user changes. Secondly, it imposes restrictions to exploration, since the extensive simulation cycles limit the number of possibilities to feasibly analyze.

Being aware of these limitations, and still haven't yet reached a near real-time performance for reservoir simulation, research has been conducted in order to investigate strategies for running the simulation in parallel, and continually displaying the outcome of ongoing calculations, as well as allowing for changes in between – simply put, reservoir simulation steering [54, 39, 2, 24]. While further reviewing technicalities of reservoir simulation steering would be out of the scope of this work, it would be of interest to understand and investigate it implications for the design and use of reservoir visualization tools.

8.2.3 Multiscale, Multi-Disciplinary Dataset Integration

The need for interchange between experts in different fields of oil and gas E&P was extensively presented and discussed in this work, with implications for collaboration, efficacy and efficiency for decision-making processes. In terms of collaboration between members of multidisciplinary teams, the next level would be the creation of an integrated, unified reservoir visualization, incorporating data from the diverse disciplines – geology, geophysics, economics, and reservoir, drilling and production engineering – onto a single entity, allowing for a vast potential in correlation and the visualization of the problem in different levels of detail (see example in Figure 8.2.3). A few research initiatives have been made onto this high level goal of integration [75, 41], but explorations joining this paradigm with collaborative interactive visualization systems still deserve further attention.
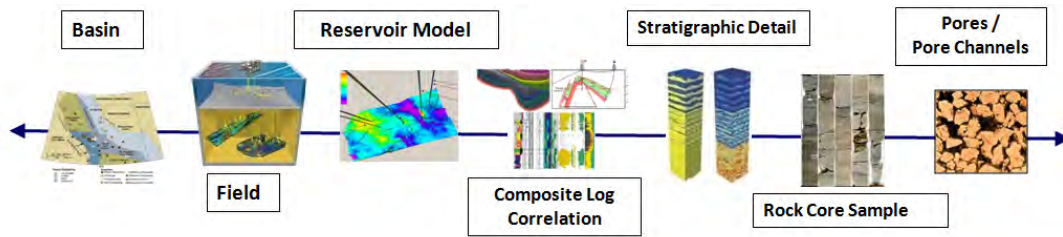
Figure 8.1: An example on how a few of the field-specific reservoir datasets could be incorporated as different levels of detail in the reservoir: starting from the left, the "big picture", descending to the microscopic pore level of the reservoir rocks.

8.3 Closing Remarks

This thesis presented our exploratory research, with experimental designs of tangible and tabletop interfaces applied to the task or reservoir simulation visualization. Our efforts encompass three novel prototypes that were designed and implemented with the input and guidance of senior professionals, followed by evaluations and critiques from more experts from the domain. Insights obtained from these three efforts materialized into a concise, but powerful and relevant set of design heuristics, guiding future designers and providing practical insight on key concerns in the design of reservoir visualization systems. We believe that there are vast possibilities for improvement within this rich, multi-faceted field of application, which we hope this work can prove useful in inspiring and guiding future endeavours towards new solutions for the domain.

Appendix A

Reservoir Peeling Techniques

Contains pseudo-codes for a shader implementations of the curling techniques described in Section 6.3, namely:

1. the generalized cone curling;

2. the cylinder curling;

A.1   Generalized Cone Curling

```
//Given parameters
vector3 p;
vector3 coneApex;
vector3 restingPlaneNormal;
vector3 coneUpDirection;
float coneAngle;
//Calculating the radius of the circle passing on P, with origin on the
//cone apex.
float bigR = distance(p,coneApex);
//Finding the point S, lying on the cone direction with same distance to
//the cone origin than P.
vector3 s = coneApex + (coneUpDirection*bigR) + transl;
//Finding the radius of the cone cross section passing on S.
float lilR = bigR * sin(ConeAngle);
//Finding the angle between S and the desired point T, in the cone cross
//section
vector3 projPA_SA = projection(p - coneApex,Up);
float alpha = acos(length(projPA_SA) / bigR);
float beta = alpha / sin(ConeAngle);
vector3 right = cross(coneUpDirection,PlaneNormal);
//1st Rotation: around the cone cross section
vector3 s_ = s + (restingPlaneNormal * lilR)
            + rotate(restingPlaneNormal * lilR, coneUpDirection, beta);
//2nd Rotation: A tilting, accounting for the inclination of the cone
//resting on the plane.
vector3 t = s + rotate(s_ - s, right, ConeAngle);
```

A.2 Cylinder Curling

```
//Given parameters

vector3 p;

vector3 cylinderNormal;

vector3 cylinderOrigin;

vector3 cylinderDirection;

float cylinderRadius;

//Finding the center of the cross section, by projecting P onto the

//cylinder line direction

float3 crSCenter = projection(p - cylinderOrigin, cylinderDirection)

                + cylinderOrigin;

//Finding S, the tangent point between cylinder and plane, within

//P's level

float3 s = crSCenter - (cylinderNormal * cylinderRadius);

//Finding the equivalent rotation angle which arc length corresponds

//to the distance between SP

float rotAngle = length(s - p) / cylinderRadius;

//Rotating s_ around cylinder, by the calculated angle

float3 t = rotate(s_ - crSCenter, cylinderDirection, rotAngle)

        + crSCenter;
```

Appendix B

User Evaluation

Contains the components used for conducting the user evaluations described on Section 6.4 of this thesis. It includes, respectively:

- the ethics approval for user studies;

- an amendment to the ethics approval, allowing for a monetary compensation to be provided for participation in the studies.

- the recruitment letter;

- the consent form;

- description of the procedures of the study;

To: Mario Costa Sousa
Computer Science

From: Dr. Kathleen Oberle, Chair
Conjoint Faculties Research Ethics Board (CFREB)

Re: **Certification of Institutional Ethics Review:** Exploring Novel Interfaces and Visualization
Techniques Applied to Reservoir Engineering

The above named research protocol has been granted ethical approval by the Conjoint Faculties Research
Ethics Board for the University of Calgary. Enclosed are the original, and one copy, of a signed
Certification of Institutional Ethics Review. Please note the terms and conditions that apply to your
Certification. If the research is funded, the sponsor should be notified, and the original certificate sent to
them for their files. The copy is for your records. The Conjoint Faculties Research Ethics Board will
retain a copy of the Certification on your file.

Please note, an annual/progress/final report must be filed with the CFREB twelve months from the date
on your ethics clearance. A form for this purpose has been created, and may be found on the "Ethics"
website, http://www.ucalgary.ca/research/cfreb

In closing let me take this opportunity to wish you the best of luck in your research endeavor.

Sincerely,

Russell Burrows
For:
Kathleen Oberle, PhD
Chair, Conjoint Faculties Research Ethics Board

Enclosures(2): Dr. Ehud Sharlin, Nicole Sultanum

UNIVERSITY OF CALGARY
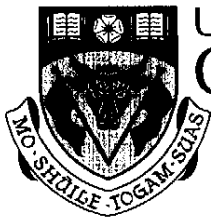
CERTIFICATION OF INSTITUTIONAL ETHICS REVIEW

This is to certify that the Conjoint Faculties Research Ethics Board at the University of Calgary has examined the following research proposal and found the proposed research involving human subjects to be in accordance with University of Calgary Guidelines and the Tri-Council Policy Statement on *"Ethical Conduct in Research Using Human Subjects"*. This form and accompanying letter constitute the Certification of Institutional Ethics Review.

File no:	**6660**
Applicant(s):	**Mario Costa Sousa**
	Ehud Sharlin
	Nicole B. Sultanum
Department:	**Computer Science**
Project Title:	**Exploring Novel Interfaces and Visualization Techniques Applied to Reservoir Engineering**
Sponsor (if applicable):	**CMPF**

Restrictions:

This Certification is subject to the following conditions:

1. Approval is granted only for the project and purposes described in the application.
2. Any modifications to the authorized protocol must be submitted to the Chair, Conjoint Faculties Research Ethics Board for approval.
3. A progress report must be submitted 12 months from the date of this Certification, and should provide the expected completion date for the project.
4. Written notification must be sent to the Board when the project is complete or terminated.

Kathleen Oberle, PhD
Chair
Conjoint Faculties Research Ethics Board

NOV 0 3 2010
Date:

Distribution: (1) Applicant, (2) Supervisor (if applicable), (3) Chair, Department/Faculty Research Ethics Committee, (4) Sponsor, (5) Conjoint Faculties Research Ethics Board (6) Research Services.

UNIVERSITY OF CALGARY

MEMO

To: Dr. Mario Costa Sousa
Department of Computer Science
Faculty of Science

Date: June 16, 2011

From: Dr. Kathleen Oberle, Chair
Conjoint Faculties Research Ethics Board

Re: Approval of Modification for: Exploring Novel Interfaces and Visualization Techniques
Applied to Reservoir Engineering
Original Approval Date: November 3rd 2010
File No: 6660

The Certificate of Institutional Ethics Review issued on November 3rd 2010 continues in force and extends to the modifications as set out in your email/memo dated June 16th 2011. Your request to provide your study participants with $15 CAD by way of remuneration, having suitably amended the consent instrument to reflect this payment, is approved as described.

You should attach a copy of the documentation you provided in order to request the modification, together with a copy of this memorandum, to the original Certification in your files.

Sincerely,

Kathleen Oberle, PhD
Chair, Conjoint Faculties Research Ethics Board

Cc: Dr. Ehud Sharlin & Nicole Sultanum (Co-applicants)

Study Recruitment Email Letter

Dear colleague,

We are part of Illustrare*, the Scalable Illustrative & Scientific Visualization Group (SISV) located at the* Graphics Lab *and* Interactions Lab *at the University of Calgary (6th floor, Math Sciences building, room 625A). We are currently developing a reservoir 3D post-processing visualization tool on digital tabletops, an emerging technology that leverages interaction and collaboration to new levels in computational applications, and only recently has been finding its way into oil reservoir systems.*

We are looking for volunteers to take part in the design and evaluation of our developing prototype, and share your thoughts, critics and suggestions on how we could better attend the needs of potential users. We are looking for candidates who have experience working with visualization and analysis of reservoir flow simulation models.

Sessions will begin by a quick demo on the tabletop device and our application, followed by an open discussion. The whole process should take no more than 1 hour. With your consent, we might record or videotape the sessions, for later analysis. Additionally, if possible, we would also like to have another separate follow up meeting. We will be offering $15 per session for the participants, as a token of appreciation for your time.

Please reply to **Nicole Sultanum** *(nicole.sultanum@gmail.com or call (403) 220-7041) letting us know whether you are interest in volunteering to participate on this research. We will do our best to accommodate for the timeframes you are available, within the 1-week period of the study, approximately from* **June 20 to June 24***.*

Thank you for your time!
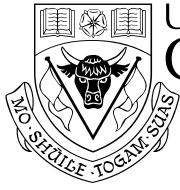
Name of Researcher, Faculty, Department, Telephone & Email:

Nicole B. Sultanum, Faculty of Science, Department of Computer Science, 403-220-7041, nbsultan@ucalgary.ca

Supervisor:

Mario Costa Sousa, Department of Computer Science
Ehud Sharlin, Department of Computer Science

Title of Project:

Exploring Novel Interfaces and Visualization Techniques applied to Reservoir Engineering

Sponsor:

Natural Sciences and Engineering Research Council

This consent form, a copy of which has been given to you, is only part of the process of informed consent. If you want more details about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

The University of Calgary Conjoint Faculties Research Ethics Board has approved this research study.

Purpose of the Study:

We would like to better understand the needs and thoughts of reservoir engineers concerning the use of domain-specific tools, and thus, we are conducting user sessions to have greater insight into the reality of these professionals and how the respective computational tools can be improved.

What Will I Be Asked To Do?

In general, participants will be asked to use reservoir engineering tools on our tabletop platform (using the Microsoft Surface) and provide their feedback. There will be a 10 minute introduction to the device and its particular forms of interaction, followed by an introduction on the reservoir engineering tool to be evaluated. Participants will be free to experiment with the tools, as well as coming up with fictional tasks while interacting and discussing with other participants, for as long as the participants would like. However, we ideally expect at least 10 minutes of free interaction. Afterwards, participants are interviewed by the researchers about their experience with the tool, their opinions on its usefulness and adequateness, and what could be improved in it. This discussion should take at least 10 minutes.

Participants might agree to have their photo taken, or be videotaped. The photos and videos collected from the experiment may be used in publications, presentations, or videos and may be used in the public domain for academic purposes only. Only the participant's physical likeness will be used in this media. The participant's name or any other identifying information will be kept confidential.

Participants may withdraw from the study at any time. If either participant wishes to withdraw, the session will be stopped immediately and the participant will be thanked. Possible questions of the participant will be answered. The data collected from that participant will be destroyed and not be included in the analysis of the study.

Please note that non-participation or withdrawal will have no impact on your continuing relationship with either CMG or the University of Calgary.

What Type of Personal Information Will Be Collected?

All participants' private information that happens to be collected during the study will be kept anonymous. However, a participant's physical likeness may be used in academic publications or presentations, or in the public domain. Please be aware that absolute anonymity cannot be guaranteed when participating in group sessions, since your individual participation will be widely known to other participants. Similarly, your participation on this study will also be known to CMG, the company hosting these experiments. Your affiliation (either being CMG or any other company) might also be cited.

To take part in this study, you might agree to have your photo taken and to be videotaped. In this case, you allow the researchers to use your physical likeness in publications or in the public domain (both in photo and video form). Please be aware that, for these cases, there is no way to guarantee full confidentiality. Also, if intended reporting of photographed or videotaped images includes public display, the researchers will have no control over any future use by others who may copy the images and repost them in different formats or contexts, including online.

I agree to have my photo taken during this experiment	☐
I DO NOT agree to have my photo taken during this experiment	☐
I agree to be videotaped during this experiment	☐
I DO NOT agree to be videotaped during this experiment	☐

Initial: _____

Are there Risks or Benefits if I Participate?

There are no foreseeable risks, harms, or inconveniences to the participants.

What Happens to the Information I Provide?

The information collected here will be integrated into a Masters Degree project, as well as related academic presentations or publication of results in journals and conference papers. Dialogues between participants or between the researcher and participants may be used; pictures taken by the computer or video recorded by the camera may also be used, with the participant's authorization. The data collected for these studies will be stored for three years on a computer hard drive, at which time, it will be destroyed.

Participation is completely voluntary. A monetary compensation of *CAD 15.00* might be provided for participation in this study. You are free to discontinue participation at any time during the study.

Signatures (written consent)

Your signature on this form indicates that you 1) understand to your satisfaction the information provided to you about your participation in this research project, and 2) agree to participate as a research subject.

In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) _____

Participant's Signature _____Date: _____

Researcher's Name: (please print) **_____**

Researcher's Signature: _____Date: _____

Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

<div align="center">

Nicole B. Sultanum,
Department of Computer Science
403-220-7041, nbsultan@ucalgary.ca

Mario Costa Sousa
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If you have any concerns about the way you've been treated as a participant, please contact the Senior Ethics Resource Officer, Research Services Office, University of Calgary at (403) 220-3782; email rburrows@ucalgary.ca.

A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

01 – Introduction: Presentation and Structure

Thank you for your participation. We invite you to take part in the evaluation of this tabletop visualization prototype for reservoir post-processing data. We have been working in collaboration with reservoir engineers in trying to shape this new experience as a very meaningful one for the users.

Imagine a world in which you could have your reservoir model, at hands reach... and you could easily, and intuitively, manipulate it freely, directly, and you could feel it, tear it apart, see the tiny bits and the big picture, remodel wells... anything you can imagine. Technologically, it is still very challenging to have such a thing happening, but we are going to present you some of our current efforts towards this vision, with this tabletop prototype. It is a very different way to see reservoir models, for a very different experience, and (hopefully) a positive one. So we would invite you to 'think out of the box' as well... "go crazy, let your imagination go wild", and always reflecting on the possible implications for the domain. There is no right and wrong, so express yourself freely. Tell us what you think about it. Your opinion is very valuable to us, and criticism is very welcome too. We are also seeking constructive ideas on how to improve and evolve our ideas.

We developed a few tools for the exploration of reservoir flow simulation models on tabletop, and we would like to hear your subjective insight on them. This is not a commercial tool, it is an evolving prototype, so it might crash and behave unexpectedly. But we believe it brings across the concepts we are trying to propose – our main goal – while also reflecting on the specifics and the mechanics of the 'how to's.

This study is not task or goal oriented. You will not be asked to perform a specific task but rather to use a set of tools, and to brainstorm with us about them. This section will be divided as follows:

1) *First, we would like you to fill out this consent form (explain about the consent form);*
2) *We have also prepared a simple questionnaire, to know a bit more about you and your experience.*
3) *Then, we will present the tabletop environment, and explain the features of our prototype. Meanwhile, we invite you to use the system. We will ask you to "think aloud" while doing so, which is basically constantly verbalizing your thoughts. Your ideas will be recorded for later evaluation and consideration, and provide us with further insights... and, there is no right and wrong, so please express yourself freely, whatever you are thinking. What might seem a trivial thought to you might be insightful to us. We will also ask you a series of questions about your vision and opinion on the presented system.*
4) *Finally, we conclude, while welcoming any additional comments if there are any.*

02: Questionnaire

1) Name:

2) Age:

3) Current professional/academic title:

4) Professional background/education and experience (include no. years):
   a. Academic training (degrees, specializations):

   b. Professional training (w/professional positions):

5) Res. engineering software tools used in the past, for how long and for which role.

6) Previous experience/use of reservoir simulation models?

03: Demo and Discussion: Procedure

For each feature (cell probe, splitting and peeling), respectively:

1) Demonstrate a feature:

Cell probing
Show and explain tangible device; show how it works.
Splitting
Show how cells are split; Show how to select partitions; Show how to merge them; Show that it can be done in any IJK direction
Peeling
Show palm + finger approach; Show + 4 finger approaches; Show edge peeling; Show that it can be done in different IJK directions

2) Ask the user to repeat the action until they confirm they understood it. Allow the users considerable time with the interface, to "mess" around and think aloud. Address any question they may have (e.g. if they forgot something)

3) Address questions while user interacts with the prototype.
   a. *Can you tell us how and when you think this feature might be useful?*
   b. *Do you see any potential problems with the way it currently works?*
   c. *Would you have any ideas on how this could be made better?*
   d. *What do you think about this function?*
      i. *Intuitive / Not intuitive? To what degree?*
      ii. *Easy to use / Cumbersome? To what degree?*
      iii. *Useful / Useless? To what degree?*
      iv. *Relevant / Disposable? To what degree?*

After all features are introduced and individually discussed:

4) *What do you think about the two strategies for curling? Which did you like better? More comfortable? Makes more sense?*
5) *Of all visualization functions here presented, which do you see as having more potential (if you think that's the case), and why?*
6) *Which do you think is weaker, and why?*
7) *Can you think of features that you think would be important to offer, in terms of reservoir visualization and manipulation?*
8) *Any additional comments that you think have not been addressed yet?*

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