"Point it, Split it, Peel it, View it": Techniques for Interactive Reservoir Visualization on Tabletops

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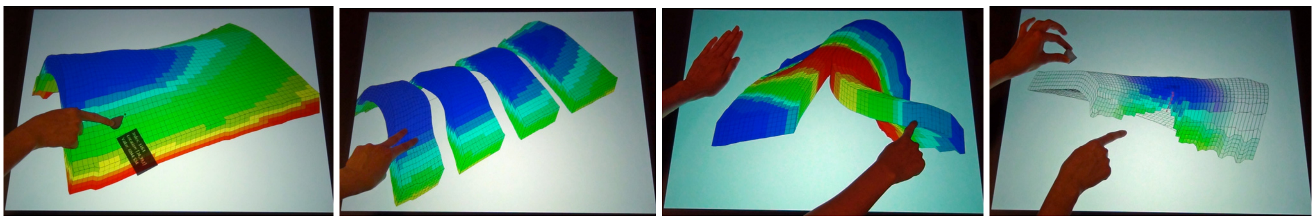


Figure 1: Illustrations of our 4 interactive visualization techniques applied to a reservoir model, on tabletop. From left to right: (1) cell probing; (2) splitting; (3) peeling; (4) focus and context for wells.

ABSTRACT

Reservoir engineers rely on virtual representations of oil reservoirs to make crucial decisions relating, for example, to the modeling and prediction of fluid behavior, or to the optimal locations for drilling wells. Therefore, they are in constant pursue of better virtual representations of the reservoir models, improved user awareness of their embedded data, and more intuitive ways to explore them, all ultimately leading to more informed decision making. Tabletops have great potential in providing powerful interactive representation to reservoir engineers, as well as enhancing the flexibility, immediacy and overall capabilities of their analysis, and consequently bringing more confidence into the decision making process. In this paper, we present a collection of 3D reservoir visualization techniques on tabletop interfaces applied to the domain of reservoir engineering, and argue that these provide greater insight into reservoir models. We support our claims with findings from a qualitative user study conducted with 12 reservoir engineers, which brought us insight into our techniques, as well as a discussion on the potential of tabletop-based visualization solutions for the domain of reservoir engineering.

ACM Classification: H5.2 [Information interfaces and presentation]: User Interfaces. - Graphical user interfaces.

General terms: Design, Human Factors

Keywords: Tabletop, interactive 3D visualization of reservoir models, scientific visualization, reservoir engineering.

INTRODUCTION

Oil and gas reservoir models depict phenomena occurring hundreds to thousands of meters below the earth's surface, and their effects for the exploration and production. They can, for example, represent how oil flows up a certain well, and how its saturation values decrease in surrounding regions, or how a geological fracture might be blocking the fluid flow at a key location. Since assessment of actual reservoirs occurs only indirectly, and is bound by intrusive and limited sensors, with similarly limited range – such as monitoring devices attached to drilled wells – awareness of what is actually occurring within the three-dimensional (3D) reservoir space is inherently lacking. Reservoir flow simulation models, thus, embody the closest depiction of the reservoir, and the most efficient tools for gaining awareness and analyzing its production-related phenomena.

However, depicting 3D, multi-layered reservoir representations with multiple properties can be quite challenging, as well as including useful exploratory mechanisms that would help users gain awareness and reveal production phenomena, as mentioned earlier. With the time dimension to account for, this set of tasks becomes even more difficult. How does one know where to look at first, and when? And after a location of interest is determined, how should elements related to a specific phenomenon be emphasized? How should contextual information be balanced to potentially provide broader perspectives and consequently increase the reservoir engineer's awareness?

Another important factor influencing the ability to effectively interpret the results of reservoir simulation is collaboration, sharing the reservoir awareness. Enabling group access to the reservoir representation can allow for reservoir engineers with different expertise to examine the model simultaneously, and improve chances of gaining correct awareness of the related phenomena. Tabletop interfaces, with their direct physical manipulation and inherent adequacy to collaborative environments, have been recently introduced to the domain within a preliminary exploratory framework [20]. Our work attempts to examine whether the combination of tabletops and interactive visualization techniques can potentially improve awareness and better inform decisions related to oil and gas reservoirs. We also wonder whether tabletop interactive visualization techniques can inspire creativity and insight in the reservoir engineering decision-making process.

We created a set of visualization and manipulation resources for reservoir models on a tabletop interface, attempting to address these questions. In this paper, we present four novel 3D interactive reservoir visualization tools we designed for tabletops (Figure 1): a *tangible cell probe*, reservoir *splitting* and *peeling* techniques, and a *focus and context* visualization resource for wells. We present a user study we conducted with 12 expert reservoir engineers to evaluate our interface, and report our findings reflecting on the validity of our proposed approach and possibilities for improvement. This paper is divided as follows: first, we briefly present instances of related research and development efforts, as well as visualization techniques related to our designed tools; then, we detail each of our four interactive visualization tools, preceded by a brief description of relevant characteristics of the data in focus; then, we describe the methodology of our user studies, as well as obtained results, and discussion of emerging trends and higher level sense-making; finally, we conclude with closing remarks and perspectives for future work.

RELATED WORK

Extensive research attention has been given to mapping 3D visualization techniques to the exploration of scientific data. An overview of the domain is beyond the scope of this paper, and below we touch only on a few key instances which informed our efforts. We also argue that while our work benefited by these and other past efforts, it is still, as far as we know, the first attempt to implement and evaluate a comprehensive set of reservoir engineering techniques on tabletop interfaces.

Perspectives on exploration of scientific and engineering data refer to fundamental efforts in interactive computational visualization and virtual reality [3,15]. More recently, novel interactive technologies are being mapped to advances in 3D and scientific visualization [18,27] and to improvements in scientific workflows [12]. Below, we highlight a few examples that relate more closely to our research.

In terms of visualization techniques, our work was largely inspired by the extensive work that has been made in facilitating the visualization of scientific volumetric data. McGuffin *et al.* [16] and Correa *et. al.* [5] explore a series of deformation techniques applied to medical datasets inspired by real surgical manipulations, such as peeling and dilating. Islam *et al.* [10] describe several approaches for splitting, as well as potential applications in different scenarios. In the realm of focus and context techniques – mechanisms in which an object of interest is always highlighted, while the surrounding context information is rendered in a subtler fashion – Viola *et al.* [25] propose the adjustment of the rendering according to the viewpoint and to importance levels of each object in a dataset; Taerum *et al.* [21] propose a high resolution focus and context lens approach, operating in a multi-resolution framework. Bruckner [2] explores illustrative rendering techniques for visualization, including volume splitting and focus and context techniques. All these techniques focus on volumetric data (*e.g.* CT scans), which are defined by Cartesian, regular grids coming directly from the acquisition device. Our work is, to our knowledge, unique as it specifically focuses on the manipulation and deformation of reservoir simulation grids – formed by 3D cells with irregular geometry and topology – and their static and dynamic attributes (geological and flow simulation properties, respectively).

In the larger domain of petroleum engineering and geosciences, there is growing attention to initiatives of incorporating novel technologies for visualizing geological models and monitoring oil and gas production. Tateosian *et al*. [22] propose a geospatial modeling visualization system that allows manipulation of a terrain directly through a miniature clay surface. Couture *et al.* [6] present a tangible user interface for geophysics, for the analysis of seismic data. The commercial solution *Petrotrek* [17] offers a tabletop version for the Microsoft Surface for complementing oil production monitoring, with the ability to geographically locate and monitor oil production plants in an interactive multitouch map.

In reservoir engineering, more specifically, early efforts include specialized visualization rooms [24, 28], haptic devices [28], stereoscopic view [11] and virtual reality environments [12]. As part of more recent explorations, Harris *et al.* [8] proposed a tangible user interface designed to support oil well path planning; however, this solution focuses merely on well related interactions, not addressing the manipulation of the reservoir model itself. Sultanum *et al*. [20] propose that tabletop interfaces can benefit the domain of reservoir engineering as means and facilitator of collaboration; they also explored basic manipulations of reservoir models on tabletop, but they are still limited in terms of interactive and exploratory visualization resources. Our current work complements these previous efforts by providing a set of extensive interactive tabletop techniques for reservoir exploration, followed by a thorough user evaluation and discussion.

EXPLORATORY TOOLS FOR 3D RESERVOIR MODELS

In this section, we describe four 3D reservoir visualization tools, inspired by previous work [20] and by extensive brainstorming sessions with domain experts. They were implemented in C# and XNA, for the Microsoft Surface. Our efforts focus on post-processing of 3D reservoir flow simulation models. The structure of the 3D reservoir model consists of a grid of cells with irregular geometry that represent the geological layers, but are regularly distributed in 3 directions (i, j and k). They depict both spatial continuities among adjacent cells as well as discontinuities due to the presence of geological faults. Each cell represents a portion of the earth's subsurface, and corresponding rock and fluid properties are associated to them (e.g. rock porosity, permeability, and oil and water saturation values). Fluid properties also change over time; for instance, when oil is extracted, oil saturation values around the reservoir wells tend to decrease. Wells, together with geological features, are important internal elements in the model, often surrounded by interesting and critical events that, nonetheless, can remain hidden if no appropriate mechanisms are used to uncover, depict and highlight them.

Considering the complex characteristics of the data, and the need to explore it in as many perspectives as possible, we developed a set of interactive tools on tabletop to facilitate unveiling its hidden attributes, while allowing users direct access to intrinsic reservoir information. Tools include (1) a cell probing device; (2) the possibility to split pieces of the reservoir and (3) peel them out to reveal correlations between adjacent section; and (4) highlighting wells with a focus and context technique. This set emerges as both (a) satisfying current needs of reservoir engineers – needs that are not fully addressed by current WIMP tools – and (b) taking advantage of the unique properties of the tabletop interface. With this, we attempted to give specialists the possibility to hopefully reveal new aspects of the data.

In this prototype, apart from the visualization tools described in the following subsections, we provide means to translate, rotate and zoom in/out the model through touch, as well as mechanisms to change the currently depicted property and time step (as inspired by previous work [20]). These interactions were designed so as to be aligned with standard multitouch techniques, providing an easy to grasp, familiar interaction, and around which our new manipulation techniques were built.

Firstly, orbiting is performed using a single touch, and it rotates the model in three dimensions about a single point in space. Panning, zooming and rotation are performed using two or more touches: panning is performed when the touches are translated on the screen; two-dimensional rotation of the model happens when touches are rotating around a point in the screen; and zooming is the scaling of the model based on the relative distance between the touches. These gestures are directly supported by the Microsoft Surface SDK, and thus are aligned with standard gestures in other multitouch applications.

Time step navigation can be performed through a widget similar to a media player, with buttons for starting and pausing the animation, as well as step-by-step transitions. And finally, properties are changed through individual tangible cards which are placed on the surface to display the corresponding property.

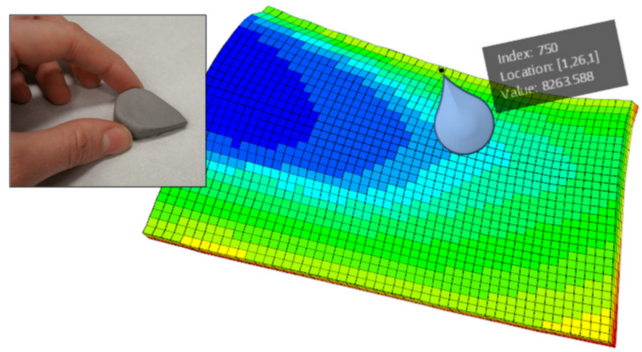


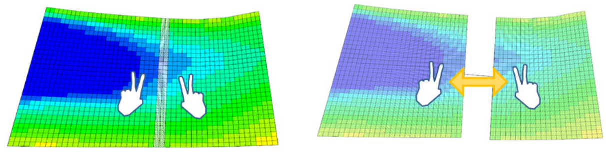
Figure 2: The Cell Probe: (Top left) our tangible clay prototype; (Right) the information panel and probe pointer.

Cell Probe

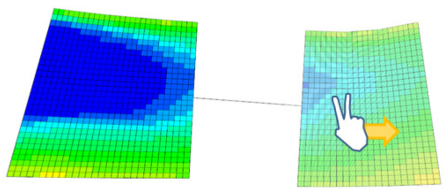
Being able to pinpoint a certain cell and display its specific information is considered by many as an essential tool, and is found in many commercial solutions. It is an important tool for technicians to have more precise awareness of finer-grained data variations. Therefore, we decided to provide a similar function, mapped to the tabletop environment. Considering that pinpointing precision could be compromised by 'fat fingers', a tangible device in the shape of an arrow was designed instead (Figure 2), and attached to a Microsoft Surface byte tag. The screen displays a small point at the tip of the probe, indicating exactly where the selection is happening. A small information panel is also displayed beside the device, containing specific cell information (namely, its location and the value of the currently selected property, which are canonical cell-based pieces of information.).

Splitting

A fundamental operation for exploring and manipulating 3D reservoir models is to access its internal structure. A common strategy is to provide a single cutting plane that splits the model in two [20]. We devised a more flexible 'splitting' metaphor, in which two fingers of each hand define a perpendicular cross section, located at the midpoint between them; the prospective layers to split are highlighted, providing visual feedback of cutting position, which can also be changed by moving both hands together along the layer divisions. When the hands are moved away from each other, the reservoir is split in two at the highlighted cross section mark, and each pair of fingers controls the position of the section below it (as illustrated in Figure 3a). Further splitting can be applied to any subsection of the reservoir. Sections move along a rail perpendicular to the cut (like the beads of an abacus), controlled by each pair of fingers, and can also be re-selected in the same fashion (Figure 3b). Rails provide translation constraints



(a)



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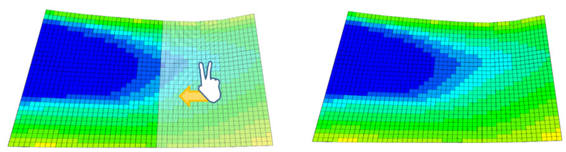


(c)

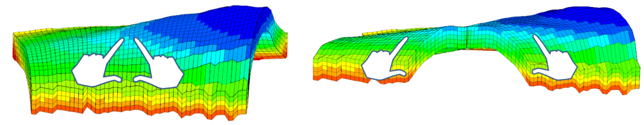
Figure 3: The splitting technique, step-by-step: (a) sectioning, spreading apart two fingers on each hand; (b) repositioning a section with two fingers of the same hand; (c) merging by repositioning a section against a neighbor section.

for facilitating manipulation and favouring spatial organization; rail lines are also displayed, giving the perception of direction and connectivity. A selected section might be repositioned, as well as merged with a neighboring section by making them collide (Figure 3c). Initial cuts can be made in any of the IJK directions; however, for the sake of simplicity, consecutive cuts can be made only in the same direction. This allows for several parallel layers to be visualized at once (examples in Figure 1b and Figure 7).

Peeling

With the splitting technique, adjacent cross sections cannot be seen simultaneously, since one of them is always facing away from the user. A peeling technique was offered to fill in this gap, similar to the way a book is opened [4, 9]. It operates by curling internal faces outwards, in opposite direction, as shown in Figure 4. This curling effect is simulated by rotating the vertices of the target section around a directional axis, as if wrapping the reservoir layers around a virtual cylinder (a similar approach to the ‘peeler’ tools in [5,16]).

A pinching gesture with two hands performs the deformation on two sides of the model, and allows for correlation on both layers (Figure 4a); a palm plus 1-finger deforms only one side (Figure 4b), and when applied on the edges, it peels out the top layer (Figure 4c). Since these operations introduce deformations to the model, sections were programmed to automatically return to their original position as soon as the user interrupts the interaction. However, the



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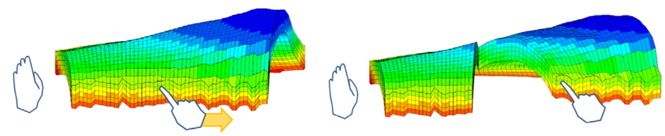

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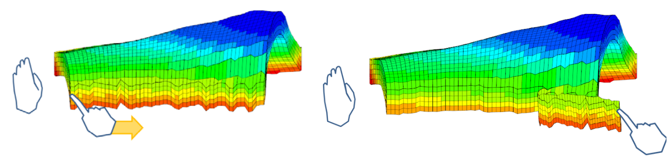

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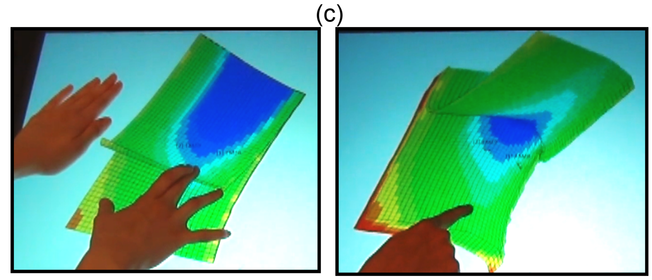


(d)

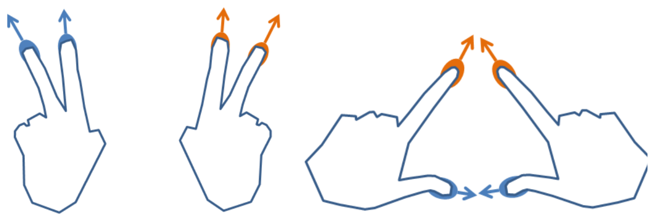
Figure 4: Peeling techniques: (a) double peel, two fingers on each side; (b) palm plus 1-finger, peeling one section only; (c) front layer peeling, palm plus 1-finger on the edges. (d) front layer peeling, palm plus 1-finger pinning the peeled layer and then rotating to visualize cell property correlation with second layer.

user might choose to fix a certain view by placing more fingers on the tabletop, which will pin down the curled sections to allow for free rotation (Figure 4d). For unpinning, the user just needs to signal the beginning of a new peeling operation, e.g. by placing one palm down on the surface.

In order to differentiate between the splitting and the peeling gestures, we used touch orientation. For a cluster of two touches, if the orientations are similar, we characterize it as a splitting operation (Figure 5a); otherwise, it is considered a peeling operation (Figure 5b).

Focus and Context for Wells

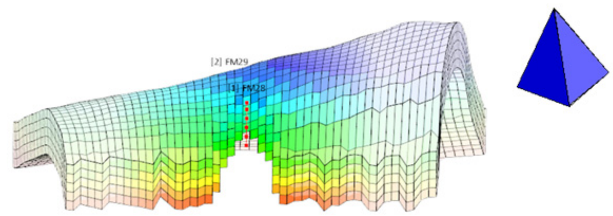
In a reservoir model, wells are entities of critical importance. Analyzing existing wells and their surrounding regions is an essential activity to reservoir engineers, at several stages of exploration and production. We provided thus a mechanism for a well to be visualized at all times, using the concept of focus and context rendering technique, which consists in highlighting an object of interest while also keeping the surrounding context in perspective, thus complementing the perception of the object in focus. This is accomplished with two modes. The first mode allows the



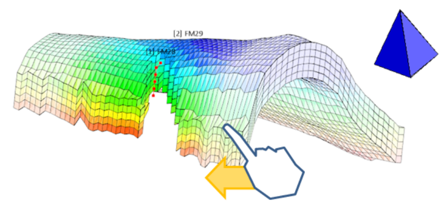
(a) Splitting (b) Peeling

Figure 5: Different touch orientations are used to distinguish between splitting and peeling gestures.

user to select a well through a touch tap on its approximate location (located by their respective well labels displayed on the screen), while the second mode activates the focus and context rendering through the placement of a tagged tangible object on the screen (Figure 6a). This rendering involves both (1) the removal of cells between the viewpoint and the chosen well, and (2) a gradual increase in transparency on the rest of the displayed cells as the distance from the well increases (Figure 6a). In our implementation the region surrounding the focus are dynamically adjusted based on the view point; after the user rotates the model, the cutaway view is also updated, in order to keep displaying the well (Figure 6b). The user can also rotate the tangible device, resulting in an opening or closing of the cutaway angle, giving an extra mechanism of control (Figure 6c).



(a)



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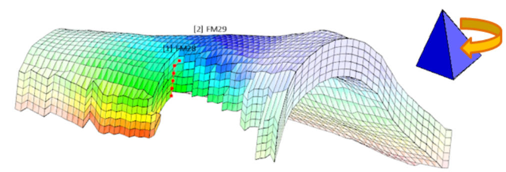

(c)

Figure 6: Focus and Context for wells. In (a) with the pyramid-shaped tangible device down, cells are removed between the well and the viewpoint; (b) the cutaway view is updated after rotation; (c) rotation of the tangible device increases the viewing angle from the well.

EVALUATION

We evaluated our interfaces in a series of formal user evaluations. We conducted 2 pilot sessions with expert reservoir engineers affiliated with our research group (but whom were not involved in the design of the interfaces), and followed with 10 sessions with external reservoir engineering experts. Each of these 12 evaluation sessions lasted around 60 to 90 minutes each. Participants volunteered to join after receiving our study recruitment email sent to research mailing lists at the petroleum engineering department and related laboratories in our university. Participants were paid CAD 15 (aprox. US$15) for their participation in the study.

Sessions started with a brief introduction to the goals of the study – the subjective evaluation of the interactive visualization tools to be presented – and a brief interview to better delineate the participant's fields of expertise, as well as previous experience within the domain. They were followed by a demo session, in which we introduced the four tools one at a time, in the same order as presented in this paper: (1) cell probing, (2) splitting, (3) peeling and (4) focus and context. For each, we invited the participants to try out the visualization tool in focus, while thinking aloud to provide us with insight on each of the tools and their functionality. Participants were allowed some time to get familiar with the environment as well, in order to be able to use each tool independently. 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 the four tools were introduced, we also asked them to rate the tools based 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, finalizing with an invitation for additional comments if there were any. Sessions were recorded, for posterior qualitative analysis [19].

Although the proposed techniques apply to reservoir models of any size, due to hardware limitations of the employed tabletop platform, we used a relatively small model (30x50x5 cells, 7500 cells total) for the studies, so as to allow for a more efficient system feedback.

Participants

Among the 12 participants, 1 was female and 11 were male. Participants' ages were 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 – Master's or PhD – 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 [6]). We believe that factor did not compound our 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. In the next subsections, we present and discuss some of the results.

RESULTS

Cell Probe

When inquired about the usefulness of the tangible cell probe, we received mixed opinions. Many participants (7 out of 12) 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. 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 the multiple users. 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, to display a small graph by the information panel showing the variation trends in that cell over time, for a selected property.

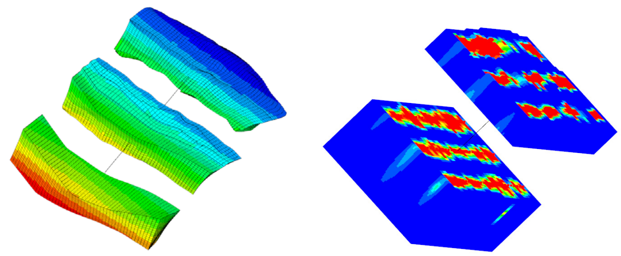

Figure 7: Some instances of splitting depicting variations of (a) Pressure and (b) Temperature between parallel layers.

Splitting

Users were generally supportive (10 out of 12) 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 once in a 2D mode) some pointed out the splitting technique could benefit the visualization, by being able to visualize many parallel layers at once, while also keeping the external perpendicular layers in view (Figure 7).

When inquired about problems and limitations with the current technique, almost all users (11 out of 12) attempted to split in different IJK directions at the same time. Some pointed out the need for more flexible cuts (8 out of 12), *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 to the grid; it is so confusing now"*. A few explicitly stated otherwise (2 out of 12), however: "*it's interesting that I can see the well since it's not moving*". One user reflected on a 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 we 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 it if the deformations could stay in place rather than spring back, and if they were able to decide when to send the section back into its 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 plus 1-finger' modality for peeling received more positive comments. 2 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 (7 out of 12) 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."*). 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"*), users seemed to find it simpler to perform the function with this gesture instead; this might have similarly helped in making it better accepted than 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 (e.g. 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.

Focus & Context

The majority of the users (8 out of 12) found the focus and context tool to be useful, whereas the remaining 4 said that it did not provide any extra insight. The ability to visually highlight a well from any viewpoint was appreciated with comments such as *"I would use this feature for sure"* and *"As you turn you always have a view of your well, you don't have to try and find it again and again"*. Additionally, users reflected on this being a new functionality that does not exist in current non-tabletop software packages. One person explicitly reported liking the idea of being able to control the view angle. All participants stated the need to be able to select more than a single well for the focus; in this case, we also heard about the need to visualize intermediate regions between selected wells, hinting a need for correlation and 'trends'.

Regarding the balance between focus and context, although one of the participants supported the use of transparency to better highlight the focus, two other participants felt it was not very apt in the domain, since information on the surrounding blocks would be lost. Another two participants also mentioned the fact that we might lose some potential information in the cutaway region, although one of them indicated they believe this is a reasonable trade-off between clear visibility and importance of information in that region.

Suggestions for improvement of this tool included being able to select multiple wells for the focus, possibly using filtering mechanisms or sketch based selection. Three people suggested including streamlines [23] in the cutaway region, to depict flow movement and behavior around the focused well. One participant suggested restraining the camera freedom around the focus, so that it rotates around the focused region in a circle, as opposed the current full sphere orbiting. One user also suggested being able to 'peel' out the walls of the cutaway view, to expose layers further back.

DISCUSSION

The following discussion is framed in three topics: firstly, we approach observations related to the participants and their background; then, we comment on the interaction techniques in a more high-level perspective; finally, we briefly discuss the environment in which our tabletop techniques could prove useful, as well as other multitouch platforms to be explored in the future.

On Participants

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. We believe that this variation and individual uniqueness in terms of specific expertise helped us gain insight and better reflect on the advantages and limitations of our tabletop interactive techniques.

The majority of the participants was new to tabletop technology, and was impressed by the Microsoft Surface capabilities. We are aware that the novelty effect might be adding a confounding factor to our results. However, we also believe that since our evaluation sessions were extensive and lengthy (longer than an hour of interaction) the core of the results are fundamentally valid and could offer insight beyond the novelty effect of interaction with a tabletop.

As previously mentioned, each participant came from a different background – such as reservoir simulation, reservoir management, drilling engineering, and so on – and hence each of them had different needs. For instance, the majority rated the splitting tool to be of great importance to them; but the focus and context tool was considered more relevant by those who are regularly working with wells. This fact sheds 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.

On the Techniques

The splitting and peeling tools we provided were frequently compared to a similar function offered by commercial desktop tools, which offers a 2D perspective of the reservoir layers. Many of the participants agreed that the tools we offered could provide further insight when compared to a simple 2D view; however, we still perceived that a lot of the participants' suggestions 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, we also believe that these reflections should be used as incentive to adapt our 3D tools, and make them feel as easy and convenient as their existing 2D counterparts, as 3D spatial awareness is an important component for a reservoir's understanding. 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 required by our interface). Making a vocabulary of gestures as familiar and usable as a simple GUI menu is a fundamental challenge of surface interfaces and we believe that our current set of gestures, while satisfactory as an evaluation test bed, should definitely be further enhanced and improved. This might reflect the need to balance the power of tabletops with the traditional computational paradigms that permeates the environment of oil and gas professionals.

In general, possibilities for improvement on the techniques gravitated around two main concepts. Firstly, participants requested more preciseness and control within the multitouch environment (an issue recently explored by Wigdor *et al.* [26]), a reflection of the meticulous nature of their work. Secondly, we perceived a recurrent pattern of data correlation among the suggestions, in the most varied renditions: *e.g.* being able to compare two or more properties, visualize several layers or reservoir models at once, among others. We considered these two points – *control* and *correlation* – as important aspects to bear in mind when designing future versions of our system.

Finally, apart from the cell probe (which was a very well known function to our participants), splitting, peeling and the focus and context were generally considered as novel functions. Participants were engaged by these tools, and seemed to be interest in, and to want to share a range of different thoughts regarding each of them. Our 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 be an indicative of how a creative environment can add and facilitate the thought and problem-solving process, as quoted by one of our participants: *"It actually brings some new ways of analysis (...) it brings some creativity for sure".*

On Contextual Perspectives

The techniques we present in this paper do not represent a full work tool; rather, we introduce a set of useful exploration strategies for a novel interaction environment, to be integrated into a more complete reservoir visualization system. They are, therefore, in line with the visualization needs of reservoir engineers, and fit the reservoir interpretation workflow.

In this applicability context, we have foreseen a few usage scenarios for our techniques. Firstly, the tabletop environment for visualization could be used for technical meetings among reservoir engineers, in an exercise of collaborative discussion and validation following a reservoir engineer's individual analysis. It could also be used in the context of a presentation, providing an interactive environment for a smaller group of managers and stakeholders to interact and discuss results (an exercise often performed within traditional presentation environments and passive content). Overall, these are some of the collaborative interchange scenarios for which the tabletop could be particularly relevant and useful, extending the current environment with more interactivity, better engagement and potentially facilitating discussion. Additionally, the exploration of vertical multitouch displays could also be considered, as a complementary data channel for a broader audience (similarly to [17], for instance).

On a broader perspective, however, there is room for exploration with other touch surfaces, as multitouch technology is becoming more and more widespread. During the experiments, a few participants also hinted that they would be interested in having access to the multitouch technology on their desktops, for instance. With this, we envisioned possibilities for the investigation of interactive reservoir visualization for a personal usage, through multitouch mobile environments such as tablets and phones. From an interaction perspective, mobile environments would most likely require a redesign of our techniques, accounting for a reduced number of touches and screen space. The limited hardware would also severely constrain model sizes, which require considerable computational power to be loaded and displayed. In this case, a client-server architecture could make the interaction feasible [1], with the personal device serving as an input/output device while communicating over the network with a powerful processing station responsible for loading, rendering and manipulating the models.

CONCLUSIONS AND FUTURE WORK

In this work, we describe the development of a set of novel techniques for supporting 3D representation and exploration of reservoir flow simulation models on tabletops. We report findings of a qualitative user study with domain experts, conducted in order to evaluate these new tools, as well as a follow-up discussion inspired by our findings.

Parts of our short-term future work will focus on making improvements to the proposed visualization tools, revisiting the gesture vocabulary and coming up with more insightful resources.

Much of the results presented in this research pertain to needs of individual reservoir engineers. We are planning to expand our perspectives and conduct user studies in a collaborative, task-oriented approach. We believe this would bring many of the tabletop environment strengths into light, and help with further insight into how digital tabletops and visualization affect the collaborative aspects of the reservoir engineering domain.

Other directions that we are planning to explore are the use of vertical interactive surfaces for interaction with reservoir models, the augmentation of the tabletop reservoir environment with mixed-reality entities, the usage of multiple tabletops to support remote collaboration, and the integration of a more rich vocabulary of TUIs to support the interactive environment.

We would like to believe that our humble efforts can inform beyond the specifics of the reservoir engineering problem domain, and can help reflect on how powerful and valid the tabletop and surface interaction environments are, and on their potential to transform the ways humans explore scientific data.

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REFERENCES

1. Abraham, F., Celes, W. "Distributed Visualization of Complex Black Oil Reservoir Models." *Eurographics 2009 Symposium on Parallel Graphics and Visualization*, 2009, 87-94.
2. Bruckner, S. *Interactive Illustrative Volume Visualization*. PhD Thesis, TU-Vienna, 2008.
3. Bryson, S. "Virtual Reality in Scientific Visualization." *Communications of the ACM*, 39(5), 1996, 62-71.
4. Chiu, P., Liao, C. and Chen, F. "Multi-touch Document Folding: Gesture Models, Fold Directions and Symmetries." *ACM Conference on Human Factors in Computing Systems (CHI '11),* 2011.
5. Correa, C., Silver, D. and Chen, M. "Feature Aligned Volume Manipulation for Illustration and Visualization." *IEEE Transactions on Visualization and Computer Graphics*, 12(5), 2006.
6. Cosentino, L. *Integrated Reservoir Studies*. Technip, 2001.
7. Couture, N., Rivière, G. and Reuter, P. "GeoTUI: A Tangible User Interface for Geosciences." In *Proc. of 2nd international Conference on Tangible and Embedded interaction (TEI '08)*, 2008. 89-96.
8. Harris, J., Young, J., Sultanum, N., Lapides, P., Sharlin, E. and Sousa, M.C. "Designing Snakey: A Tangible User Interface Supporting Well Path Planning." In *Proc. of 13th IFIP TC13 Conference on Human-Computer Interaction (INTERACT '11),* 2011 (to appear).
9. Hong, L., Card, S. and Cheni, J.D. "Turning Pages of Electronic Books." *In Proc. of The 3D User Interfaces (3DU'06)*, 2006.
10. Islam, S., Silver, D. and Chen, M. "Volume Splitting and its Applications." *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 2007.
11. Johnson, A., Leigh, J., Morin, P. and Keken, P.V. "GeoWall: Stereoscopic Visualization for Geoscience Research and Education." *IEEE Computer Graphics and Applications*, 2006.
12. Keefe, D.F. "Integrating Visualization and Interaction Research to Improve Scientific Workflows." *IEEE Computer Graphics and Applications,* 30(2), 2010, 8-13.
13. Lidal, E.M., Langeland, T., Giertsen, C., Grimsgaard, J. and Helland, R. "A Decade of Increased Oil Recovery in Virtual Reality." *IEEE Computer Graphics and Applications*, 2007.
14. Loftin, R.B., Bavinger, B.A., LeRoy, S.D. and Nelson Jr., H.R. "Advanced Visualization Techniques for Exploration and Production." *Offshore Technology Conference*, 1997.
15. McCormick, B.H. "Visualization in Scientific Computing*". SIGBIO Newsletter,* 10(1), 1988, 15-21.
16. McGuffin, M.J, Tancau L. and Balakrishnan R. "Using Deformations for Browsing Volumetric Data." *Proc. 14th IEEE Visualization (VIS'03)*, 2003.

17. Petrotrek for the Microsoft Surface. The Information Store and Infusion Development. www.istore.com

18. Song, P., Goh, W.B., Fu, C., Meng, Q. and Heng, P. “WYSIWYF: Exploring and Annotating Volume Data with a Tangible Handheld Device.”*ACM Conference on Human Factors in Computing Systems (CHI ‘11),* 2011.

19. Strauss, A., Corbin, J. *Basics of Qualitative Research.* Second Edition. Sage Publications, 1998.

20. Sultanum, N., Sharlin, E., Sousa, M.C., Miranda-Filho, D.N and Eastick, R. “Touching the Depths: Introducing Tabletop Interaction to Reservoir Engineering.” In *Proceedings of ACM International Conference on Interactive Tabletops and Surfaces (ITS ‘10)*, 2010.

21. Taerum, T., Sousa, M.C., Samavati, F., Chan, S. and Mitchell, J.R. “Real-Time Super Resolution Contextual Close-up of Clinical Volumetric Data”. *Eurographics/IEEE-VGTC Symposium on Visualization*, 2006.

22. Tateosian, L.G., *et al*. "TanGeoMS: Tangible Geospatial Modeling System." *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 2010.

23. Thiele, M.R., Batycky, R.P. and Fenwick, D.H. “Streamline Simulation for Modern Reservoir-Engineering Workflows.” *Journal of Petroleum Technology*, 2010.

24. Thomson, J.A. and Poupon, M.N. “*Special Sessions on Petrotechnical Visualization: A Point of (3D) View on Visualization.*” *Offshore Technology Conference (OTC)*, 2004.

25. Viola, I., Kanitsar, A. and Gröller, E. G. “Importance-Driven Volume Rendering.” In *Proceedings of the Conference on Visualization (VIS '04)*, 2004.

26. Widgor, D., Benko, H.,Pella, J., Lombaro, J. and Willams, S. “Rock & Rails: Extending Multi-touch Interactions with Shape Gestures to Enable Precise Spatial Manipulations.” In *Proceedings of the 2011 annual conference on Human factors in computing systems (CHI’11)*, 2011.

27. Yu, L., Svetachov, P., Isenberg, P., Everts, M.H., Isenberg, T. “FI3D: Direct-Touch Interaction for the Exploration for 3D Scientific Visualization Spaces.”. In *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 2010.

28. Zamel, N.M, Pita, J.A. and Dogru, A.H. "Next-Generation Visualization Technologies for Exploration and Production." *SPE Middle East Oil Show*, 2001.