Scalable and interactive visual computing in geosciences and reservoir engineering

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Abstract: Visual computing technologies enable more intuitive data modelling, visualization and analysis, facilitating these processes by real-time interactive visual interfaces. These technologies are essential for software in the oil and gas industry, allowing users to gain insights and actionable information when dealing with increasingly complex, multidisciplinary datasets and processes. In the context of the oil and gas industry, interactive visual computing should also scale well with the growing data size and other components of a data analytics pipeline. We present key problems and challenges motivating the research and development of scalable and interactive visual computing systems, followed by a classification of the most important research themes and related topics. Eleven case studies developed with the industry are also presented, highlighting the main cutting edge findings, limitations and achievements.

Oil and gas exploration, development and production (E, D&P) involve complex tasks comprising workflows with pipelined processes that require the processing of a large volume of variables related to multidisciplinary data sources (Fig. 1). Designing software and hardware solutions to ensure that users gain insightful and actionable information over industry data is a challenging problem. *Interactive visual computing* technologies play a critical role in such applications. The fundamental goal of interactive visual computing is to provide technological tools for users, supporting the rapid manipulation, visualization and analysis of data. The outcome of the interactive visual computing process is the transformation of raw data into processed information, and ultimately into knowledge (Plaisant *et al.* 2003; Thomson & Poupon 2004; Bertini & Lalanne 2009).

We present our experience in the investigation and development of scalable and interactive visual computing (software and hardware) technologies and their application to a variety of problems in geoscience and reservoir engineering. Much of this work involved collaboration with practitioners in the oil and gas industry. We begin by outlining the key problems and challenges motivating the research and development of novel scalable and interactive visual computing technologies, followed by a categorization of scalable and interactive visual computing into research themes and topics. We present some of the scalable and interactive visual computing examples, the resulting prototypes we designed, and how these were applied to actual industry challenges. Each example addresses one or more topics related to each of the three main visual computing research themes presented. Finally, we discuss and reflect on our findings and their implications to the domain (field of interest).

Challenges

Interactive visual computing was established in the oil and gas industry as early as the 1980s, with the introduction of interpretation workstations, later progressing towards 3D voxel-based visualization and interpretation technology in the early 1990s (Pajon & Rainaud 1992; Cairns & Feldkamp 1993; Sousa & Miranda-Filho 1994). Dramatic advances in the fields of scientific visualization (Hansen & Johnson 2011), computer graphics (Gomes *et al.* 2012), human–computer interaction (Shneiderman & Plaisant 2009), and high-performance computing (Hager & Wellein 2010) have enabled a significantly broader range of interactive reservoir visualization tasks, with many of the industry processes relying on computerized tools and commercial software packages.

In parallel with this progress, interactive visual computing in the oil and gas industry faces major challenges and prospects. They are attributed to both the immense technological progress in scalable and interactive visual computing technologies as well as the industry technologies driving data growth at an exponential rate. The large volumes of industry data require novel methods for data management and analysis. This challenge can be divided into two aspects: technology driven and user

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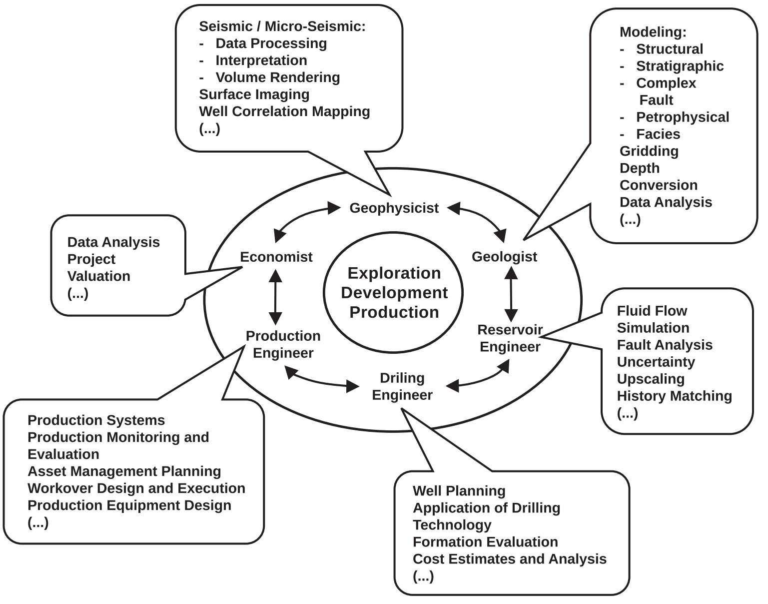

Fig. 1. Various tasks across exploration, development and production (E, D&P) present opportunities for research and development of novel interactive visual computing tools.

driven. The technology-driven aspect approaches the challenge by seeking novel scalable and interactive visual computing technologies for more efficient handling of data complexity, availability and uncertainty, with better adaptation to the oil and gas business processes and stages. The user-driven aspect attempts to support multidisciplinary approaches to facilitate efficient interaction and collaborative decision-making. We examine these two aspects in more detail below.

Technology driven

The growing challenges of data complexity, availability and uncertainty vary according to the business

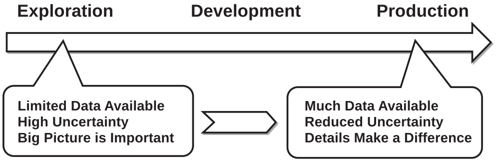

Fig. 2. Three key factors that interactive visual computing (software and hardware) technologies should address in the oil and gas industry: large data volume; level of uncertainty; and interactive modelling, visualization and analytics techniques required to allow the depiction of the 'big picture', progressing toward the depiction of details (Giertse 2009).

stages (Fig. 2). Ideally, novel scalable and interactive visual computing technology can address these challenges by applying:

- Interactive visual analytics techniques, establishing a coherent workflow through complex processes, indicating the level of uncertainty in a range of features, visually highlighting data interpretations as well as anomalies (Giertse 2009; Seemann *et al.* 2013);
- Scalable data management frameworks, handling the exponential increase in the volume of industry data, enabling information handling and analysis via different modalities, spatial densities and scales;
- Leveraging existing workflows and industry-standard commercial and in-house software packages;
- Integration of reservoir modelling and characterization with automated analysis of essential dynamic patterns (e.g. flow, mechanics and seismics).

User driven

In the oil and gas industry, it is necessary to communicate with an assorted group of individuals who are involved in different stages of field development and decision-making (Fanchi 2002; Giertse 2009). Geologists, geophysicists, engineers, business and project managers, accountants and public relations individuals as well as many others are involved. All of these individuals need an effective process to share information with each other. Ideally visual computing tools would provide a dissemination method that everyone can understand regardless of background. The challenge is to determine the appropriate visual interaction and representation of the information for the user, their experience and their role/task. Overall, an effective visual computing system needs to be based on the targeted users and their specific intended use of the systems, as well as supporting multidisciplinary collaborative decision-making (Tyson & Williams 1993; Thomson & Poupon 2004; Love & Purday 2008).

In summary, these new challenges require research of novel scalable and interactive visual computing technologies and solutions to provide:

(1) Visual representations and analytics that reflect and express the available information, the level of uncertainty and visualization requirements for processes at different business stages (Fig. 2);
(2) Linked static and dynamic reservoir modelling, visualization and analytics reflecting on all the business stages;
(3) Improved communication between professionals and stakeholders involved in field development and decision-making;
(4) Guidance for complex processes reflecting and expressing the level of data uncertainty during model building, interpretive visualization and analysis of reservoir datasets;
(5) Leverage of existing work processes, expressing the level of uncertainty over a range of features from visual anomalies to detailed interpretations and reservoir dynamics.

It is important to note that the problems and challenges mentioned above are present in other disciplines in science and engineering. In essence, these challenges arise whenever there is a hybrid data modelling and analysis (i.e. performed by both humans and computational models), pipelined from concept to development to full implementation, and based on various processes that rely on human interpretation. Within these commonalities, the oil and gas industry provides its own distinctive set of challenges and requires an innovative tailoring and adaptation of the technological solutions.

Research themes and topics

We classify *interactive visual computing* applied to the oil and gas industry as embodying three main research themes rooted in the discipline of computer science, as listed below. This three-theme classification and related topics have been identified jointly with the oil and gas industry partners and collaborators as key components for the next generation of software systems supporting visual computing technologies. In addition, these three research themes (RT) and topics are closely related to the main structure of the software systems that apply interactive data modelling, visualization and analytics techniques to reservoir data. At the core of these software systems, RT-3 is applied to RT-2 and RT-1; RT-2 is applied to RT-1. All three RTs are applied to the input data of the software system.

Research theme 1: Visual data modelling and knowledge representation

This research theme focuses on reservoir data modelling (i.e. techniques for visually constructing and editing the geometry and topology of 2D and 3D reservoir models) and knowledge representation (i.e. techniques to visually encode interpretive and analytical reasoning in the reservoir data modelling process), both facilitated by interactive visual interfaces. Topics include: modelling (geometry and topology) approaches for 2D and 3D reservoir models; reservoir data collection, management and integration; surface-based and grid-based reservoir modelling; sketch-based reservoir modelling (Amorim R. *et al.* 2012*a*); ‘Big Data’ analytics (Seemann *et al.* 2013) and infrastructure for reservoir data analysis; and scalable reservoir data representation for (a) data acquired and/or computed at different stages of the oil and gas business and (b) synthesis of information from diverse reservoir data sources.

Research theme 2: Data visualization and analytics

This research theme focuses on reservoir data visualization (i.e. techniques for visualizing 2D, 3D and high-dimensional reservoir data and models) and analytics (i.e. analytical reasoning about the reservoir data), both facilitated by interactive visual interfaces. Topics include: visualization and analytics of different reservoir data types (scalar, vector and tensor fields); grids; multi-{dimensional, scale, field, modal} data; numerical data streaming from sensors (e.g. drilling-rig sensors) and visualization techniques and approaches, including scalar, flow, partial differential equations, uncertainty (Potter *et al.* 2012), collaborative (Isenberg *et al.* 2011) and distributed (Abraham & Celes 2009); topology/geometry-based visualization techniques; and hardware for visualization and analytics of reservoir data, including the following topics:

hardware acceleration, graphics processing units (GPUs) and multi-core architectures, distributed, grid and cloud environments, and distributed, parallel or multi-threaded approaches.

Research theme 3: Visual data interaction techniques and technologies

This research theme includes: user interfaces and interaction design for reservoir data modelling, visualization and analytics; innovative methods for understanding and interacting with reservoir data; collaboration and co-design of data analysis with domain users; interactive visual steering of reservoir simulation runs and well-test simulations; interactive reservoir data manipulation and editing for validation; display and interaction technology, interactive tabletops and surfaces; immersive and virtual environments, and augmented and mixed reality; gesture-based interfaces; tangible and physical interfaces; and hardware, including sensing and input technologies with novel capabilities.

Projects, prototypes and results

Each project we develop in collaboration with the oil and gas industry includes one or more topics related to each of the three main visual computing research themes outlined in the previous section. We present the following project examples:

(1) Interactive and intuitive geometric and topological modelling of reservoir structures;
(2) Stimulated reservoir volume (SRV) reconstruction and exploratory visualization;
(3) Interpretive visualization of fused hydrocarbon microseep and reservoir data;
(4) Interactive post processing of reservoir simulation results:
   - (4.1) Interactive display surfaces for collaborative exploratory visualization and analysis of reservoir simulation post-processing,
   - (4.2) Interactive and tangible 3D modelling and visualization of well configurations and trajectories in reservoir simulation post-processing;

(5) Exploratory visualization and analytics of high-dimensional data:
   - (5.1) Uncertainty quantification in history matching,
   - (5.2) Microseismic event monitoring,
   - (5.3) Petrological databases;

(6) Interactive computational steering framework for reservoir flow simulators.

Example 1: Interactive and intuitive geometric and topological modelling of reservoir structures

Reservoir models are built incrementally using available knowledge, including: (a) the reservoir data (geophysical, geological, reservoir engineering and production engineering data); and (b) the expert interpretation of those data from multidisciplinary teams. Building a reservoir model involves the integration of both of these sources (Cosentino 2001; Fanchi 2002; Love & Purday 2008).

A fundamental problem during early geological model development is the lack of computational tools to develop a prototype framework model that supports early-stage interactions, intuitive visual interpretation and integration (Geiger *et al.* 2009; Patel *et al.* 2009). Such a prototype model typically consists of a network of horizons and faults, providing the basis for subsequent model refinement and integration with other data and applications.

This example highlights three challenges: (a) the sparseness and inaccuracies present in the data, and the high degree of uncertainty and different interpretations from domain experts; (b) the difficulty of encoding traditional, manual, hand-drawn techniques currently used by geophysicists and geologists for interpretation; and (c) the need to establish direct and intuitive manipulation of the geometry and topology of complex heterogeneous features representing the geology of the reservoir.

The main objective of this example was to develop interactive visual computing software tools applying direct manipulation approaches, such as sketch-based interface and modelling (SBIM) techniques on industry data (Olsen *et al.* 2009; Vital Brazil 2011). The method would then enable a more intuitive, interactive modelling of both the geometry and topology of reservoir structures using sketches extracted directly from user input.

SBIM is an established research field in interactive computer graphics with practical applications in different fields and industries, including automobile, entertainment, botany and architecture (Olsen *et al.* 2009). The three main applications of SBIM are to create 2D and 3D digital models, augment the model by adding geometric detail and use the input sketches for user interface operations. In addition to speed and intuitive user interfaces that support a faster learning curve, the sketch paradigm also provides tools that are more appropriate for brainstorming and prototyping. In scenarios of concept model design, the intention in most cases is to create approximations of the intended conceptual model, to facilitate discussion and thinking, rather than strong commitment. Experts can use SBIM during their conceptual discussions to express lack of certainty and precision, which are often inherent in the early analysis. A further key aspect of the sketch paradigm is the manner in which SBIM tools for the oil and gas industry can interface with high-end modelling tools already in use. The goal is to *complement* existing modelling systems with novel SBIM tools and capabilities.

SBIM techniques have recently been investigated and applied to reservoir modelling (Amorim R. *et al.* 2012*a*, *b*, 2014; Lidal *et al.* 2013; Sultanum *et al.* 2013). In our group, we are developing and integrating SBIM methods and tools to support the construction, manipulation and editing of completely new and/or existing reservoir models in different E, D&P stages, data types and modelling tasks. We are currently involved in five different case study projects, briefly described below.

Case study 1: Seismic horizons. As a first step, we load a given seismic volume and a set of horizons automatically extracted from this volume (Patel *et al.* 2010). The datasets are then pre-processed (i.e. filtering, optimizing/mapping to different representations) in order to make it more appropriate for SBIM operations. Our first SBIM prototype (Amorim R. *et al.* 2012*a*) enables the user to sketch over the seismic volume and pre-segmented horizons in order to rapidly adjust the geometry of their interior regions (i.e. curvatures) and boundaries (Fig. 3). For this prototype, we used large, interactive tablet displays using a stylus for the sketch input.

Case study 2: Geocellular grids. In this example, the user selects layers from a given geocellular grid, which are then converted to a surface-based representation suited for SBIM operations. After this, the user edits specific regions of the surfaces using SBIM operators adapted from the tool set used in the previous example for seismic volumes (Amorim R. *et al.* 2012*a*). Afterwards the edited surfaces are converted back to the grid representation, preserving the original grid cell indices and information. Regions where re-gridding is required are also indicated (Fig. 4). This prototype was deployed in the same hardware configuration of case study 1.

Case study 3: Digital outcrop models. In this example, we developed an SBIM prototype system to enable users to interactively model fracture surfaces from LiDAR (light detection and ranging) derived digital outcrop models represented as point clouds (Fig. 8). This prototype was developed and deployed in interactive multitouch tabletop displays with custom input devices built for the sketch input. The reason was to meet requirements to allow multiple users to work simultaneously when

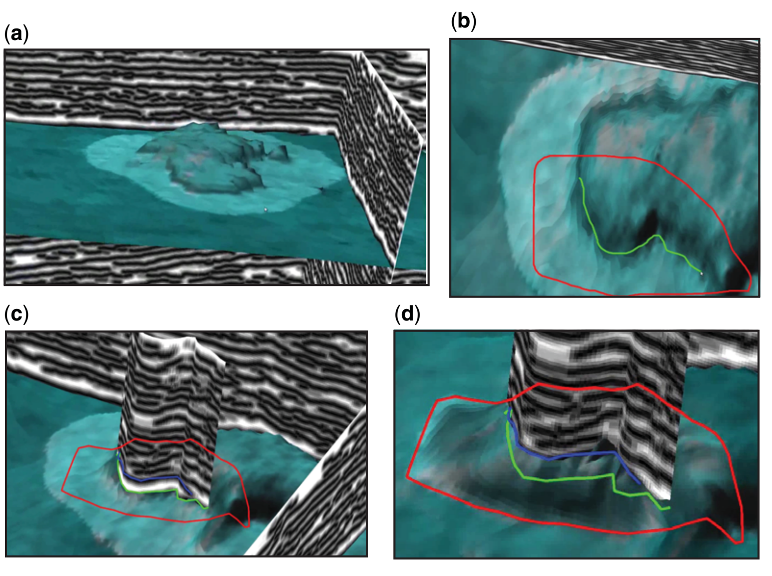

Fig. 3. Example of steps to edit the geometry of a horizon surface: (**a**) the specific region on the horizon selected by the user; (**b**) user sketches a region of interest (red) over the horizon surface; user then sketches a green stroke specifies the path for a free-form cross-sectional cut in the seismic volume; (**c**) the resulting sectional slice of the seismic volume established by the green stroke; user then sketches a blue sketch defines the path for adjusting the geometry of the underlying horizon surface; and (**d**) the final geometry automatically adjusted by the system after the blue stroke. Please refer to Amorim R. *et al.* (2012*a*) for more details.

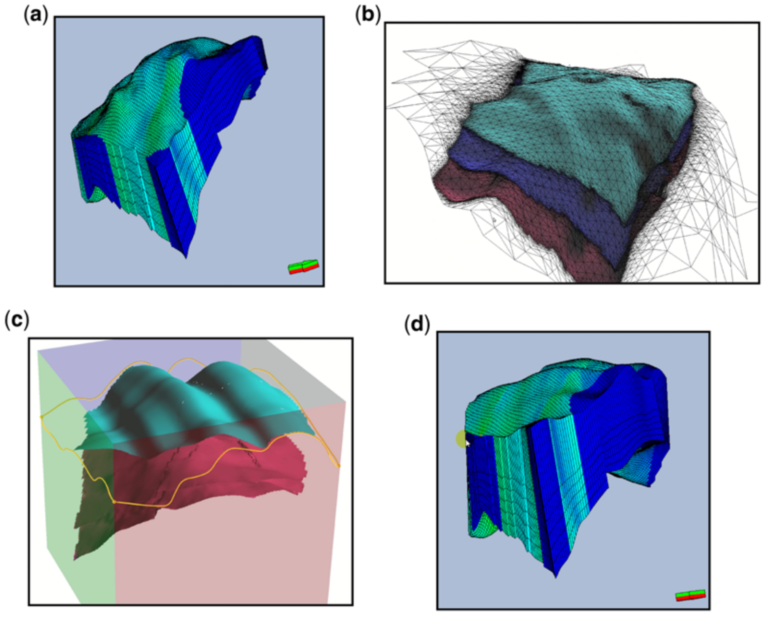

Fig. 4. Editing the geometry of reservoir models using sketch-based interfaces and modelling (SBIM) techniques: (**a**) a given geocellular grid model is loaded in the SBIM system; (**b**) the geocellular grid model is then converted to a surface-based representation (i.e. adaptive mesh structure); (**c**) the user applies specific SBIM editing operators (in the example to edit the boundaries of the surface of the topmost layer); and (**d**) the edited surfaces are then converted back to the geocellular grid representation.

exploring and modelling the fracture surfaces. Please refer to Sultanum *et al.* (2013) and to example 4.

Case study 4: Geological maps. In this example, we developed SBIM tools to enable users to interactively model geological structures inspired by traditional geological map view sketches and conventional symbols and annotations. In our system, the user sketches the geological structures and symbols in 2D map view. Our SBIM algorithms then interpret and convert the user-input sketches and symbols, generating a 3D model. The user can then manipulate in real-time the 3D model, go back and edit the 2D map view sketches for updating the 3D model, and so on. This provides a coordinate-view and modelling (2D and 3D) environment. This prototype was deployed in the same hardware configuration as case study 1 and also for mobile tablet devices. Please refer to Amorim R. *et al.* (2014) for more details.

Case study 5: SRV. The SBIM prototype for this example is part of a software system we developed for reconstructing SRVs from microseismic point-cloud data (example 2, Fig. 5). The goal was to allow multiple users to work simultaneously when exploring and visualizing the SRV. The users can sketch directly over the 3D SRV in coordination with the automatic SRV reconstruction algorithms we developed. This creates a hybrid approach (i.e. automatic and interactive) for modelling SRVs, allowing users to quickly experiment with different reconstruction results. Please refer to Amorim R. *et al.* (2012*b*), to example 2 and to Figure 5. This prototype was deployed in the same hardware configuration of case study 2.

Preliminary system and usability evaluations related to the practical use of our prototypes developed for the five case studies were encouraging, suggesting that our SBIM tools will improve experts' turnaround times in industry data interpretation and subsequent model construction and editing. One key observation is that domain experts traditionally make sketches and annotations while interpreting industry data. Our SBIM tools preserve this legacy and build on expert users' practices and at the same time provide completely new 3D digital modelling capabilities, as well as the underlying power of computation that is obviously lacking when using paper and pencil. This ensures a faster learning curve when using the new SBIM tools, thus improving the productivity on generating complex digital reservoir models. We are

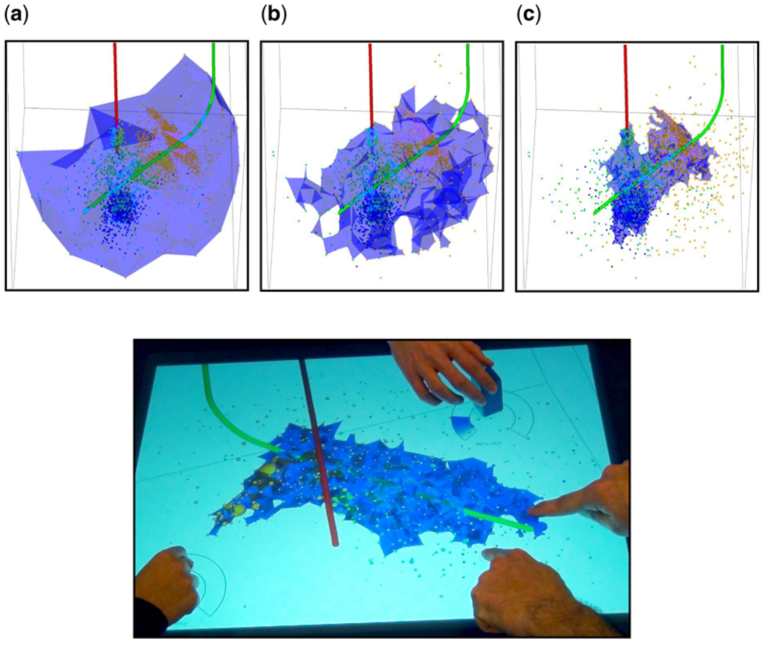

Fig. 5. Top row: the microseismic point cloud with the horizontal well (green) and the monitor vertical well (red). The figure illustrates the progression of the stimulated reservoir volume (SRV) reconstruction at different resolutions: (**a**) coarser SRVwrapping all data points in the microseismic cloud; (**b**) medium SRV resolution with less points wrapped; and (**c**) fine SRV resolution with fewer event points wrapped in the reconstructed volume. Bottom row: three experts working in the reconstructed SRV using a collaborative work environment (tabletops) as part of our software prototype (Amorim R. *et al.* 2012*b*).

progressing to new phases of investigation and development in the five case studies presented in this section as well as in new projects involving SBIM applied to reservoir modelling.

Example 2: SRV reconstruction and exploratory visualization

Unconventional resources have received strong attention from energy companies. In these settings, hydraulic fracturing is commonly applied to stimulate the near-well region owing to the low permeable nature of these resources. Fractures propagate away from the wellbore as fluid pressure increases during fluid injection. Microseismic events may be triggered by this process. The distribution of microseismic events can provide insight into the geometry of the resulting fracture network. Thus, the monitoring of such events has become an important tool to better understand hydraulic fracture geometry, to estimate the SRV, to refine fracture treatment and to optimize long-term field development. The SRV refers to the volume of rock affected by the stimulation and is a concept introduced by Mayerhofer *et al.* (2010). It represents a 3D volume that is approximated by measuring the spatial extent of the microseismic event point cloud (Fig. 5). Production data (production rates, volumes, fluids) can be compared with the total SRV and field observations to determine well performance and plans for future field development.

This example involves surface and volume reconstruction from a given microseismic point cloud. It fits mainly within research theme 1: visual data modelling and knowledge representation. In our first prototype (Amorim R. *et al.* 2012*b*), we proposed two different approaches to estimate the SRV that integrate spatio-temporal correlations to obtain more accurate volume estimations. The first approach is called *alpha-shapes* (Akkiraju *et al.* 1995), which is a generalization of the well-known *shrink-wrap* algorithm (van Overveld & Wyvill 2004). The shrink-wrap algorithm generates a triangular mesh to approximate an iso-surface. It starts with a triangulation of a sphere and next applies a series of deformations to this triangulation to transform it into the required iso-surface. Both algorithms create a hull for a point cloud using some sample original points to describe the boundary, but the alpha-shapes algorithm can result in non-convex shapes.

The second approach we explored is the density-based region reconstruction, which considers the density of the microseismic samples in the 3D space to reconstruct the SRV. The density-based approach uses a radial basis function with Gaussian kernels to account for uncertainty in microseismic events. In addition to these two methods, we also developed a sketch-based (SBIM) tool to assist users in interpreting and filtering microseismic events directly as well as manipulating the resulting 3D SRV model for exploratory visualization and analytics tasks (Amorim R. *et al.* 2012*b*).

We integrated these two approaches to allow direct user changes to the final volume through sketch-based tools, thus giving the expert the ability to guide the SRV estimation and to explore alternative 'what-if' scenarios for a better understanding of the microseismic data. We also integrated the tools developed in this work with an interactive tabletop, multitouch display to create a collaborative work environment for the experts (Fig. 5).

Ongoing and planned research include the development of novel techniques to calculate the SRV, taking into account the geological information and using data from microseismic event simulation models as ground truth. We are also integrating the SRV reconstruction prototypes into our tools for microseismic visual analytics (as described in example 5).

Example 3: Interpretive visualization of fused hydrocarbon microseep and reservoir data

Hydrocarbon microseeps (HM) refer to the active vertical migration of analytically detectable hydrocarbon molecules through microscopic fractures, pore spaces and along mineral grain boundaries from subsurface reservoirs to the Earth's surface (Brown 2000).

Detailed, high-resolution HM surveys complement geological and seismic methods, offering a flexible, low-risk, low-cost and environmentally friendly technology to find hydrocarbon accumulations. HM surveys give no explicit information about reservoir depth, thickness or permeability, but can provide insight into the probability of favourable petroleum-trapping conditions. Raw HM data include a large number of samples representative of the levels of hydrocarbon concentrations breaching the Earth's surface. Airborne sensors are used to identify the surface location of seeps and enable rapid collection of data over significantly large areas. This results in more scalable HM survey result in more scalable HM survey and data integration scenarios. Large clusters of HM values may indicate the location of discrete structural or stratigraphic trapping conditions within the survey area for future exploratory drilling targets. Consequently, there is a strong motivation for advanced visual computing tools that properly integrate data from HM surveys with subsurface geological/geophysical datasets. This combination of surface/subsurface data can (a) significantly reduce exploration risk by focusing on the areas with the greatest petroleum potential and (b) provide an effective method to detect bypassed oil and determine the productive limits of a field. These two aspects would lead to the addition of new reserves, the drilling of fewer dry or marginal wells and the optimization of the number of developments or secondary recovery wells.

For this example, the main challenges involve integrating multimodal, multiscale data from different disciplines (geophysics, geology, geochemistry, GIS) in 2D and 3D, allowing fast throughput and interactive exploratory visual analysis. Additional requirements included interaction techniques that would allow users direct manipulation with the data (e.g. SBIM techniques as described in examples 1 and 2), collaborative visual analysis, data exploration and decision-making. The main objective is twofold: (a) to explore and develop different strategies to integrate characteristics of multiscale, heterogeneous datasets from surface geochemistry data (HM surveys) and subsurface data from geology and geophysics; and (b) to develop different exploratory visualization tools deployed in different display technologies to efficiently access and retrieve 2D and 3D maps at different scales, probing regions of interest, overlaying different map attributes and annotating maps.

The first software prototypes we developed integrated multiscale 2D maps from the geochemical surveys, including the HM footprint data, geochemical data contour lines, geological and topographic maps, oil migration pathways and geophysical seismic lines and sections. The core functionalities allowed the user to composite layers of different maps and to filter and correlate specific data attributes. These tools were deployed using different multitouch, calligraphic display technologies, allowing a number of users to simultaneously interact with the same dataset for collaborative visualization and analytics tasks (Burns *et al.* 2012; Seyed *et al.* 2013; Fig. 6). Preliminary system and usability evaluations reflecting on the practical use of our prototype involved domain experts who stated that the proposed new approach would help them improve turnaround times in interpreting HM-related data. We are currently expanding our HM tools to support new sets of HM data.

Example 4: Interactive post-processing of reservoir simulation results

Reservoir simulation results are typically visualized using a single simulation *post-processing*

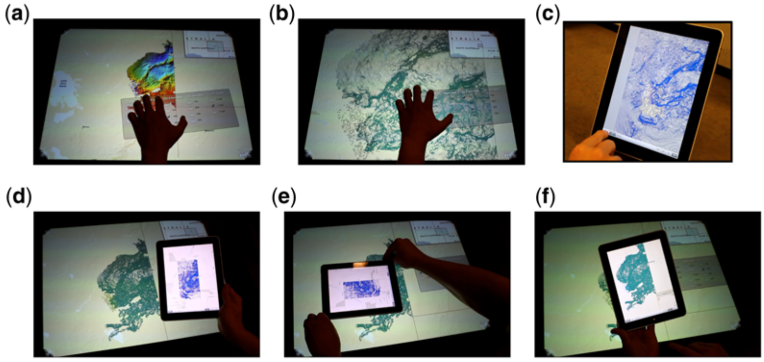

Fig. 6. Example illustrating two users interacting with our multisurface software prototype for visualization and analytics of hydrocarbon microseep (HM) (Burns *et al.* 2012; Seyed *et al.* 2013): (**a**) one user selects a particular geological map over an interactive tabletop display surface; (**b**) another map is selected for visualization; (**c**) in parallel, the second user is interacting with the same data in a mobile display surface (tablet device); this second user decides to import the visualization result from the tabletop device. This is achieved by placing the tablet device over the tabletop device as shown in (**d**, **e**); (**f**) the visualization result of the tabletop device is automatically transferred in real-time to the tablet device. This setup allows collaborative local and/or remote data visualization and manipulation across different interactive display devices.

visual computing tool, in which the dataset is first created from numerical simulations and then used as input to a visualization system for graphical output and interaction (Sousa & Miranda-Filho 1994; Zamel *et al.* 2001; Caers 2005). There are no interactions with simulation parameters and/or images generated during the simulation execution. The main advantage of post-processing is that data can be examined repeatedly using different mapping techniques. The next generation of post-processing reservoir visualization technology faces great challenges owing to (a) the growing scale and complexity of reservoir simulations, (b) the need to integrate, visualize and explore a broader range of data fused with the post-processing simulation, and (c) the industry need for tools supporting multidisciplinary collaborative decision-making (Cosentino 2001; Zamel *et al.* 2001; Fanchi 2002; Thomson & Poupon 2004; Dopkin & James 2006; Giertse 2009).

Most high-end post-processing commercially available visualization tools, as well as proprietary tools developed internally by various oil and gas companies, enable visualization of a 3D reservoir grid. The purpose of these tools is to depict the reservoir's geometry, topology and static and dynamic property values per each grid cell and support conventional visualization methods. These models include colour mapping of cell properties, isosurfaces and WIMP-based (Windows, Icons, Menus, Pointing device) interfaces, transparency control, conventional cutting planes and time-step animation for cell properties. We identified with our collaborators from the oil and gas industry a need to step beyond these functionalities and to provide effective new interactive visualization and analytics solutions addressing four key challenges: (a) visualizing multiple aspects of the reservoir model integrating data from other disciplines and workflows; (b) determining a better understanding of the hidden dynamics in the reservoir; (c) defining how to interact directly and intuitively with the data in a 3D workspace; and (d) efficiently handling large simulation files and multiple datasets.

Our main goal was to develop and integrate a unified simulation that will provide interactive visualization tools and tackle specific problems related to the four main challenges stated above. Our solution was realized via a set of interactive visual computing techniques, of which we detail two examples in the next subsections.

Example 4.1: Interactive display surfaces for collaborative exploratory visualization and analysis of reservoir simulation post-processing. We designed a novel user interface for collaborative, exploratory visualization and analytics of reservoir models with different levels of complexity using the new medium of large interactive displays, surfaces and tabletops. We deployed our interface on interactive surfaces supporting multitouch and tangible interfaces (Figs 5–8). Tangible interfaces couple physical representations (e.g. spatially manipulable physical objects) with digital representations (e.g. graphics and audio). The physical objects are used as both representations and controls for interacting with the computational media (Ullmer & Ishii 2000; Shaer & Hornecker 2010). The key

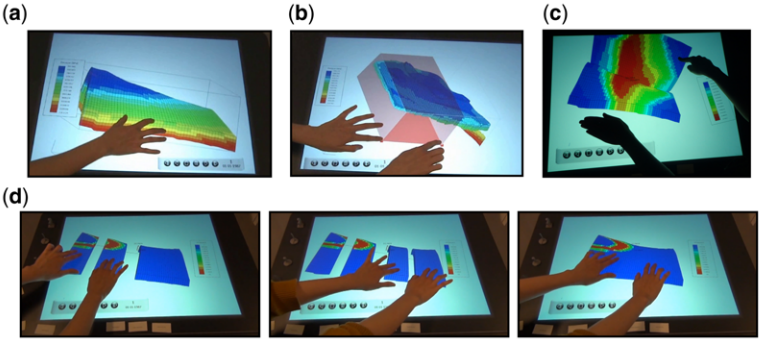

Fig. 7. A number of multitouch operators applied to reservoir post-processing models using interactive tabletop surface displays. The model is manipulated by fingers of either one hand or both hands pointing at any region of the grid model displayed on the tabletop surface. These operators allow the user to intuitively manipulate, visually explore and analyse the 3D reservoir grid model: (**a**) panning the 3D reservoir model using one hand; (**b**) manipulating the corners of the reservoir bounding box allows block-cutting operations; (**c**) flipping layers of the reservoir model for visual inspection of internal grid cells; and (**d**) splitting the reservoir model in different regions. Please refer to Sultanum *et al.* (2010, 2011) for more details.

steps we took in the design process include (a) user observations and expert interviews to identify visualization requirements and tasks that best fit the face-to-face collaborative, interactive tabletop modality, (b) the development of prototypes for different collaborative and exploratory visualization tasks using tabletop devices and (c) usability evaluations via design critiques.

A prototype for a multitouch tabletop has been developed and evaluated with direct involvement of engineers from several oil and gas companies (Sultanum *et al.* 2010, 2011; Fig. 7). Our work was the first to use tabletop technology for interactive 3D visualization of reservoir simulation post-processing. We are currently expanding the set of interactive visualization tools and functionalities that our tabletop interface provides, enabling easier exploration of the reservoir models internal regions and construction of cross-sectional structures. We are also planning to conduct formal usability tests in order to provide deeper insight into the impact that our interactive tabletop approach has on these collaborative, exploratory reservoir engineering visualization tasks.

In the future we hope to see full integration of our interactive tabletop approach with the existing computing infrastructure of oil and gas companies. For example, the new tabletop devices and software systems will need to be integrated seamlessly with existing desktop hardware and software. Outstanding research challenges relate to the scalability of current interactive visualization and analytics infrastructure and functionalities to cope with tasks involving a large number of possibly remote users, high dimensions and volumes of data, and a large spectrum of interactive visual analytics goals. For instance, a particular collaborative visual analytics task could involve teams of users located at different physical locations (e.g. offices, laboratories, field locations). In this case, the visual analytics tool may require integration with additional tabletops, display walls, mobile computers (Burns *et al.* 2012; Seyed *et al.* 2013) and immersive virtual reality environments, such as CAVE systems (Lidal *et al.*

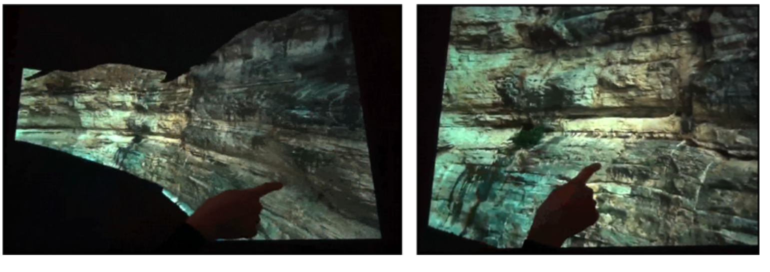

Fig. 8. The same interface device (multitouch tabletop surfaces) from Figures 5–7, but now applied to outcrop analogues reconstructed from LiDAR data. In the figure, the user is exploring one particular outcrop section by panning it with a single finger touch. Please refer to Sultanum *et al.* (2013) for more details.

2007) or collaborative mixed-reality environments (Li *et al.* 2014).

Another future effort we pursue is the integration of our interactive tabletops tools and techniques in other interactive, collaborative visual analytics tasks and datasets from the oil and gas industry, including hydrocarbon-microseep (presented in example 3, Fig. 6), microseismic event monitoring (example 5.2, Fig. 11) and point-based/surface-based LiDAR datasets (example 1, Fig. 8).

Example 4.2: Interactive 3D modelling and visualization of well configurations and trajectories in reservoir simulation post-processing. A critical task in the reservoir engineering workflow consists of creating and/or modifying well placement in reservoir post-processing simulation models for fine-tuning subsequent reservoir simulation runs of the same model (Cosentino 2001; Caers 2005). Currently, this task involves numerous manual steps, creating an intensive and often cumbersome workflow that requires high expertise of manipulating the well using WIMP-based CAD (computer aided design). Our goal was to develop novel interactive tools that provide direct and more intuitive ways for the reservoir engineer to create and manipulate 3D flexible well configurations and trajectories.

The steps we took to pursue this research goal were to: (a) develop tangible, physical interfaces in conjunction with SBIM methods to specify and manipulate flexible, multilateral well configurations defined inside Cartesian and corner-point hexahedral grid structures (Harris *et al.* 2011; Sultanum *et al.* 2011); (c) develop specific visualizations to correlate different well trajectories, cross-sections and focus + context depiction (Sultanum *et al.* 2011); (c) integrate SBIM tools from step (a) with the visualization tools from step (b); and (d) integrate engineering and geological constraints over the interactive well visual manipulation prototype from stage (c).

An initial prototype integrating these steps was developed with a physical interface for direct 3D manipulation of flexible wells (Harris *et al.* 2011; Sultanum *et al.* 2011) (Fig. 9). The prototype is integrated with visualizations of cross-sections of the reservoir in which well trajectories can be mapped onto spatial data for flow properties and their related uncertainties. We are currently integrating this prototype with an interactive visual steering system to enable coordinated visualizations of reservoir flow patterns and behaviour as the user manipulates the wells in real time. Visual steering systems aim to enable users to control (or steer) simulation and visualization parameters during the run-time of the simulation (see also example 6).

Example 5: Exploratory visualization and analytics of high-dimensional data

As discussed above, industry data are exponentially increasing in volume and complexity, representing diverse information, high dimensionality and varying levels of uncertainty. The data are acquired and structured in different modes (e.g. grids, surfaces, volume data, point clouds) and scales, based on the various data sources – for example, multiple simulation runs generating large parameter spaces and sensors that are used to probe and gather the data. All of these factors represent interesting challenges for the research and development of interactive reservoir visualization and analytics tools. In this section, we focus on one particular factor listed: the high dimensionality of industry data. In this context, high-dimensional data refers to a large number of data samples, in which each individual sample contains dozens or hundreds of attributes. Analysis of high-dimensional data typically takes the form of extracting correlations between data samples, discovering meaningful information in data, clustering data samples and finding efficient representations of clustered data, classification and event association. Since the volume (and

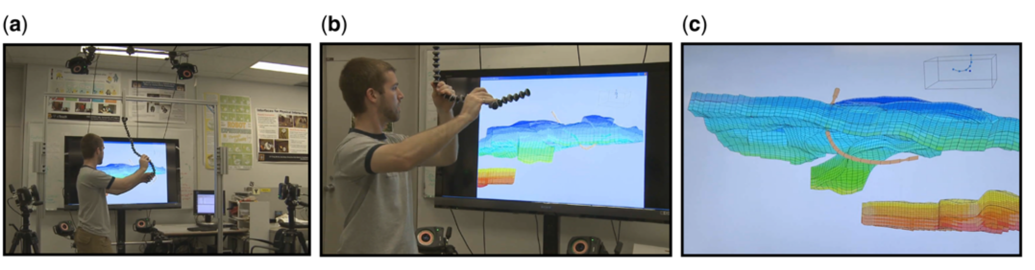

Fig. 9. Well-manipulation and planning framework (Harris *et al.* 2011; Sultanum *et al.* 2011) allowing direct manipulation of physical interfaces. (**a**) The user with the hardware setup including the physical interface representing the flexible well, the six tracking cameras and the large display device; (**b**) a close-up view showing two of the six cameras tracking the physical well as the user manipulates it; (**c**) The digital well's shape and position are updated in real time in the 3D digital model of the reservoir model, in sync with the camera tracking.

dimensionality) of data is typically large, the emphasis for new algorithms must be on efficiency and scalability to large datasets. In addition, interactive visualization techniques and tools are critical components to the analytics of high-dimensional data. Another important requirement is to ensure that the new visual computing solutions (e.g. data analytics algorithms and interactive visualization techniques) are integrated with any existing visual analytics methods and tools being used. In our projects, such integration has proven to be critical in our projects along two fronts: (a) reducing the learning curve over understanding and interacting with a new visual analytics technique; and (b) allowing the user to have different insights over the same dataset, by coordinating and complementing the results of existing, familiar methods with the results of novel ones. Four interactive visual computing examples applied to the oil and gas industry are described in the following subsections.

Example 5.1: Uncertainty quantification in history matching. History matching cases are fundamentally a high-dimensional problem, where many unknown variables are adjusted during the process. The challenge in this process is twofold: (a) our limited ability to visualize high-dimensional spaces; and (b) the computational aspects of sampling in high dimensional spaces – that is, the curse of dimensionality (Bengtsson *et al.* 2008). In the case of history matching, each uncertain variable can be viewed as a dimension. The models in an assisted history matching framework using an optimization (sampling) algorithm can be viewed as vectors placed in a *n*-dimensional space.

We investigated and developed multidimensional projection algorithms, integrating them in visual analytics software prototypes to enable users to gain insights into the sampling performance of population-based algorithms and comparing multiple runs in history matching (Hajizadeh *et al.* 2012).

Multidimensional projection provides a way to overcome this challenge by reducing the dimensionality of data and projecting the resulted points into a lower-dimensional space (1D, 2D, 3D). This mapping aims at maintaining the distance relationship between the data points in the original space.

In our first experiment, we tested three projection methods, the least square projection (LSP), projection by clustering and principle component analysis, to examine the relationship between the exploration of the search space and the uncertainty in predicting reservoir production (Hajizadeh *et al.* 2012). We performed the tests on a synthetic reservoir model, parameterized using five layers and nine homogenous regions per layer, resulting in 45 porosity values that were adjusted using five population-based algorithms (ACOR, DE-Rand, DE-Best, PSO and NA) applied for history matching the reservoir model. All of the history-matching runs contain 3000 models.

Figure 10 shows the results of the ensembles of the 3000 history-matched models projected on a 2D surface using the LSP algorithm and the Euclidean distance measurement. These projections summarize the performance of the five population-based sampling algorithms in navigating the 45-dimensional search space in the reservoir model. We used colour as an indication of the iterations of algorithms, providing insights about the start and end points of the sampling in time.

One important finding in our experiment is that the resulting visualization of the overall pattern or shape of the projected points provided a completely new insight concerning the performance of population-based sampling algorithms during history matching. A dense collection of points on the 2D projection indicates convergence of the algorithm towards a specific region of the parameter space in higher dimensions. As shown in Figure 10, each of the five population-based algorithms generate different patterns for a single multidimensional projection method and corresponding distance measure. This visual cue provides a quick and useful tool to compare various ensembles of history-matched models and to understand their differences. This can be a valuable tool in selecting the ensemble that better fits in the scope of the project for decision making. Please refer to Hajizadeh *et al.* (2012) for additional results using other multidimensional projection methods and distance measurements. Our main conclusion is that multidimensional projection algorithms are valuable diagnostic tools for assisted history-matching workflows, as a way of evaluating their performance and comparing ensembles of history-matched models. In addition, our experiment demonstrated that exploration of the search space is also a critical element in the uncertainty quantification workflow that can be monitored with multidimensional projection schemes.

We are currently investigating and developing novel mathematical models and algorithms for multidimensional projection. Our main goal is twofold: (a) to allow real-time user interaction with the projected samples for exploratory visualization and analytics; and (b) to allow the user to interactively sample a new data point in the projected space and project the new sample back to the high-dimensional space. We are testing the new algorithms in various high-dimensional datasets. Preliminary results and evaluations are very encouraging (Amorim E. *et al.* 2012, 2014). We are also working on the integration of these new multidimensional projection methods with other high-

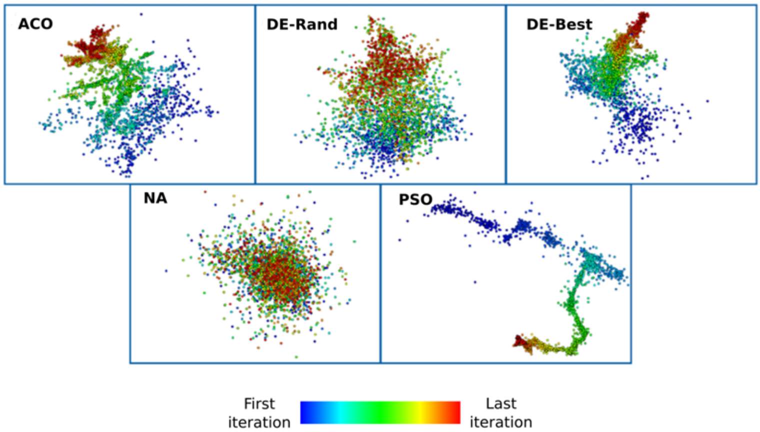

Fig. 10. Examples of 3000 history-matched models (represented as points) projected on a 2D surface by the least square projection (LSP) algorithm. These projections summarize the performance of five population-based algorithms (ACOR, DE, PSO and NA) in navigating a 45-dimensional search space of a reservoir model. Colour indicates the iterations of the algorithms, providing insight over the start and end points of the sampling in time (Hajizadeh *et al.* 2012). Copyright 2012, Society of Petroleum Engineers Inc. Reproduced with permission of SPE. Further reproduction prohibited without permission.

dimensional data visualization techniques, including parallel coordinates (examples 5.2 and 5.3)

Example 5.2: Microseismic event monitoring. Microseismic event monitoring datasets have been considered as a high-dimensional data visualization and analytics problem. Microseismic raw data (P- and S-waves) are captured by geophones on the ground or inside monitoring wellbores. This raw data is pre-processed, resulting in an event catalog containing tabular information describing the microseismic *cloud* of events for each fracture stage. This cloud is represented as a set of time-varying 3D points with each point representing a microseismic event and containing many attributes per event. Some of these attributes include the time in which the microseismic event occurred, the distance from the event position to the monitoring sensor, its signal-to-noise ratio, magnitude, among other derived attributes from the P- and S-waves (Daku *et al.* 2004; Ulrich 2011). Once gathered and processed, microseismic data is generally analysed by several domain experts, including geophysicists, geologists and reservoir engineers, commonly pursuing different objectives during the pre-processing phase. The analysis consists of several tasks, including: locating the miscroseismic events in relation to the wells; filtering out noisy events; performing correlations; understanding hydraulic fracture geometry; estimating the SRV; and optimizing long-term field development (Warpinski 2009). These tasks could benefit significantly from collaborative, interactive visualization and an analytics tool that will convert the microseismic data into efficient and effective visual representations.

To address some of these challenges, we developed *FractVis*, an interactive visualization and analytics prototype (Mostafa *et al.* 2012, 2013*a*), providing a multiple coordinated views approach using parallel coordinates (Inselberg 1985) and interactive 3D visualizations (Fig. 11). The typical visualization of parallel coordinates represents each data attribute as parallel spaced lines (axes/columns) where each line is represented by its name, and the minimum and maximum values of all the samples. The main goal of *FractVis* is to provide different coordinated visual data representations – that is, 3D time-varying microseismic point-cloud visualization, attributes correlation (via parallel coordinates) and flexible filtering and selection, with simultaneous data analysis. These features aim at enabling better microseismic point-cloud filtering and selection, which can be used, for example, as input to the SRV estimation and reconstruction system described in example 2.

The *FractVis* prototype supports three coordinated visualization windows (Fig. 11). The main 3D view allows exploration and visual analysis of the microseismic events in the reservoir space with well integration. The second view supports improved interactive parallel-coordinates visualization, allowing the user to intuitively interact with various analytics options. The third view aims to support time-based analysis of the data. Each view presents the data in a different way, allowing the user to link and compare the different insights

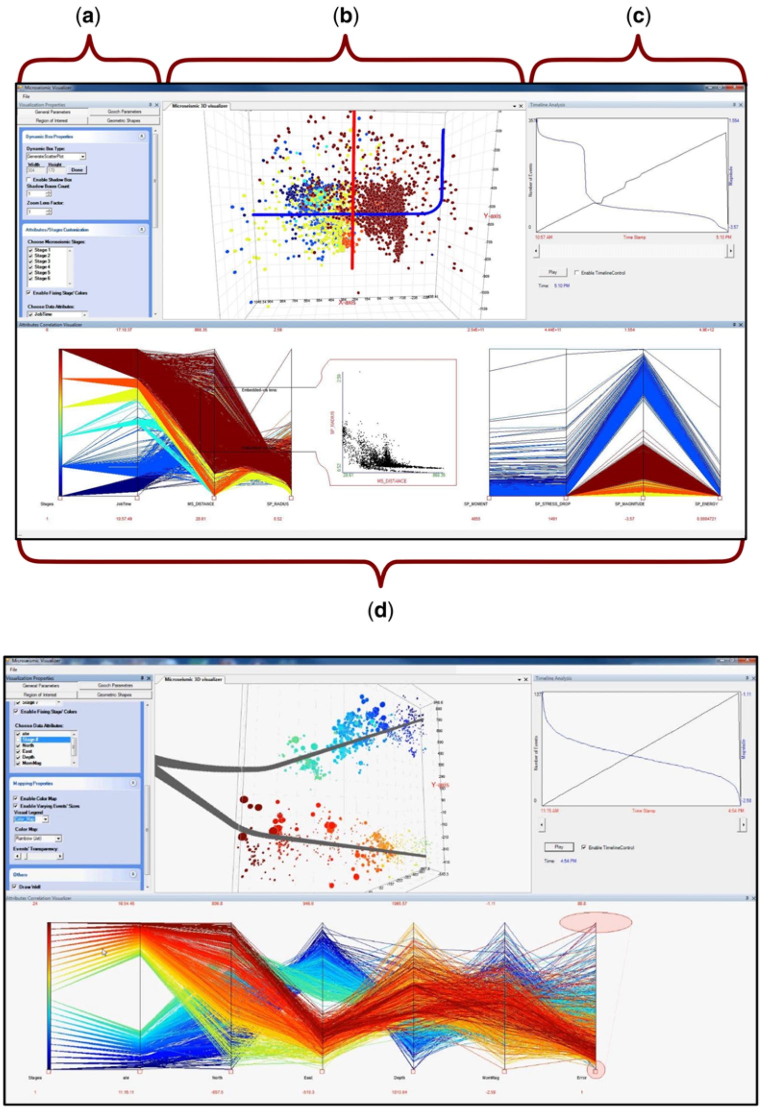

Fig. 11. Examples of our interactive microseismic visualization and analytics tool (Mostafa *et al.* 2012, 2013*a*). Key interface and visualization components include: (**a**) attributes and parameters selection; (**b**) 3D point-cloud visualization; (**c**) time-varying attribute of the point cloud; and (**d**) parallel coordinates with each vertical axis corresponding to one out of *n* existing attributes and each coloured line corresponding to an event (point sample) from the microseismic point cloud. Some of these attributes include the time at which the microseismic event occurred, the distance from the event position to the monitoring sensor, its signal-to-noise ratio and magnitude.

gained from different visualizations of the same data. For instance, we placed the classic scatter plot alongside the parallel coordinates representations, allowing experts to gain insights on how to best explore the parallel coordinates technique that they were often less familiar with. Such combinations of well-known visualization techniques with novel ones have helped to accelerate learning and provide new visual cues and insights during the data analysis process.

Example 5.3: Petrological databases. Petrographic datasets are usually represented as a high-dimensional database detailing the characteristics of rock samples from an outcrop or cores and cuttings from the subsurface. Petrographic analysis may be site- or well-specific or involve comparisons between multiple sites and/or wells. Routine petrographic analyses commonly involve basic characterization through microscopic observations and geochemical analyses. Basic statistical methods are used to identify clusters in the data as preliminary indicators of petrofacies. While the expert knowledge is needed to acquire and interpret the data, better computational tools are needed to facilitate the automation and integration of routine petrographic analyses (e.g. combined image analysis, basic and advanced statistics) with novel computational tools supporting interactive visualization and analytics of high dimensional petrographic data.

In our work (Cevolani *et al.* 2013; Mostafa *et al.* 2013*b*), we designed and developed *PetroVis*, a software prototype to support interactive, high-dimensional petrographic data visualization and analytics. We tested *PetroVis* with three petrological databases of compositional data from different sedimentary basins. These databases include 280 thin sections collected from core recovered from 30 wells. The rows of the database tables correspond to attributes observed in the thin sections through microscopic analysis, and the columns correspond to a single thin section from the cored wellbores. In the database tables, the name of the samples is composed of the name of the well and a number representing the sample according with the depth where the thin-section was collected.

PetroVis consists of a set of visualizations organized through two analysis modes. The first aims to assist experts in the visual analysis of data and correlation of various petrographic attributes. As with the *FracVis* prototype (example 5.2), we used parallel coordinates as the key visualization technique in *PetroVis* prototype. The second analysis mode provides advanced data correlation by coupling statistical methods to extend the parallel coordinates visualization technique. For instance, the experts can classify the attributes using standard deviation or quartile ranges. Our choice to visualize the petrographic data was influenced by the structure and the dimensionality of the data. In addition, domain analysts are usually familiar with scientific tools such as *Matlab* and they are familiar with cross-plotting techniques for correlating two or three data attributes. Accordingly, we decided to use and extend the technique of parallel coordinates (Inselberg 1985) to support the exploration of the high-dimensional petrographic data. By using parallel coordinates, experts can gain insights about the main rock properties that generated a cluster. Such information supports the classification of clusters. For instance, this first prototype helped an expert to qualify a field dataset with more than 100 thin sections in about 3 hours instead the usual 2 days.

The parallel coordinates visualization component in the *PetroVis* prototype is illustrated in Figure 12. Each data element (in this case a rock sample from a well or a thin section) is represented as a polyline intersecting every visible data axis at a position proportional to its value for that dimension. Although parallel coordinates suffer from data clustering, we tried to address this by adopting certain strategies such as data filtering and axis reordering. There are other important features that we are still integrating in the *PetroVis* prototype: (a) extending the scatter plots by including statistical features within the visualization and improving the synchronization with the other visual elements of the interface; (b) automating more of the *PetroVis* operations by integrating our visualization with existing statistical packages to enable the manipulation of data clusters on the fly; and (c) developing more intuitive interaction techniques to allow the manipulation and exploration of the data, for example by allowing the user to visually manipulate the samples within a cluster, as well as to visually refine one or more clusters.

Example 6: Interactive computational steering framework for reservoir flow simulators

As the scale, complexity and computational costs of reservoir simulations grow (Dogru *et al.* 2008; Abraham & Celes 2009), reservoir engineers must be able to monitor the progress of the simulation and control or steer them during the run-time (Parker *et al.* 1997; Kreylos *et al.* 2002). The utility and cost-effectiveness of these reservoir simulations is increased by transforming the traditional post-processing visualization and analysis of simulation results into integrated, interactive solutions (Dopkin & James 2006). The goal is to tightly integrate the interactive visualization techniques with the reservoir simulation systems and algorithms, allowing efficient and effective guidance during the reservoir analysis as the simulations occur (Johnson *et al.* 1999; Kurc *et al.* 2005; Matkovic *et al.* 2008). By ‘closing the loop’ between the user and the simulations, engineers can drive the reservoir simulation, visualization, analysis and discovery process by observing intermediate results. They would be able to change the parameters, resolution or representation, and visualize the effects by experimenting with ‘what-if’ scenarios (Mulder *et al.* 1999). This new process would provide an effective way to detect and verify uncertainties, correct unstable situations and readily terminate uninteresting runs. Computational steering frameworks have been proposed for various scientific and engineering domains (Kreylos *et al.* 2002; Kurc *et al.* 2005; Matkovic *et al.* 2008). Our team is addressing this challenge by designing a generic visual steering

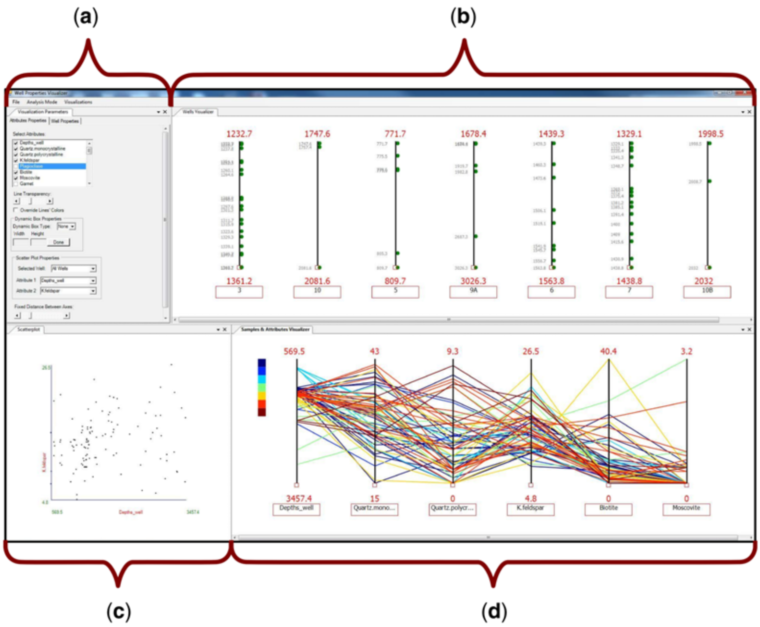

Fig. 12. Interactive visualization and analytics tool for petrological databases (Cevolani *et al.* 2013; Mostafa *et al.* 2013*b*): (**a**) attributes and parameter selection; (**b**) all of the samples present in each well of the basin (represented as a vertical line) are positioned according to the depth where they were collected in the core; (**c**) scatter plot correlating two attributes selected by the user; and (**d**) parallel coordinates with each vertical axis corresponding to one out of *n* existing attributes scaled to the range of values for that attribute present in the database. Each well is represented by one colour (in the figure we have seven wells) and each line represents one sample. Each line is going to cross one coordinate in the point that represents the value of this attribute for this specific sample. These attributes are the values that the analyst found from the analysis of the thin section in the microscope.

framework that can be promptly integrated with existing high-end commercial reservoir simulators for black oil, compositional, thermal, streamline and experimental/case-specific simulation studies.

Current high-end reservoir simulators do not allow the user to visually interact with both the ongoing simulation and visualization parameters. These simulators only provide the traditional post-processing visualization and analysis of simulation results. The current practice of monitoring the simulation runs, interrupting them, visualizing the results, changing parameters, re-starting and re-running the simulation repeatedly is requiring the user to rely on different software packages, and to go through numerous manual steps, creating a non-streamlined and less effective workflow.

We are developing an interactive visual steering framework for integrating the input and output of existing high-end commercial reservoir simulators to provide a more intuitive control of parameters and tools options for both the simulation and visualization processes. We are working in collaboration with the oil and gas industry on developing this new software framework and on designing different case studies to test the visual steering prototype (Moghadam *et al.* 2012). Our software framework follows an iterative approach (Fig. 13) in seven key steps. Initially, using the simulation and visualization tools, the user creates, respectively, the initial simulation (base case) and visualization models (steps 1 and 5). The steering process will follow in three phases. In the first phase, using the simulation tool, the user specifies the initial simulation control parameter values and produces the first simulation results (steps 2 and 3). In the second phase, simulation results are integrated with the visualization model (steps 4 and 5), generating the visualization results (step 6). In the third phase, the user can proceed, refining the control parameter values and manipulating specific simulation time steps (step 7), generating new simulation results (using the current simulation model) and then returning to the second phase for subsequent new visualization results and exploratory visual analysis.

One important requirement is to provide an efficient exchange of control parameters and access to results as the simulation progresses, without degrading the overall performance of the simulator.

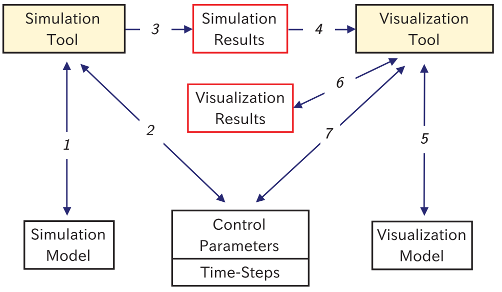

Fig. 13. The reservoir visual steering framework with seven iterative steps. Please refer to the main text in example 6.

Preliminary system and usability evaluations related to the practical use of the prototypes we developed were encouraging, suggesting that our interactive visual steering framework: (a) will improve experts' turnaround times in reservoir simulation studies; (b) will provide a more intuitive control of parameters and tools options for both the simulation and visualization processes; and (c) will provide flexibility to compare different alternatives, to correct an unacceptable reservoir dynamic behaviour or to seek improved development alternatives.

Conclusions

The challenges driven by large amounts of data with different modalities, scales and uncertainties and the requirement for multidisciplinary decision making are found in many fields. Possible solutions can be found with interactive, scalable, visual computing (SVC). SVC has been a key technology supporting different workflows, disciplines and stages in oil and gas exploration, development and production. Interactive scalable visual computing has been a key technology supporting different workflows, disciplines and stages in oil and gas exploration, development and production. SVC design, implementation and evaluation of new interactive visual computing tools can help to provide more efficient analysis and new insight to reservoir models. In this article we presented a number of examples of novel visual computing tools and technologies we developed to support existing E,D&P processes via new computational and interactive visualization techniques.

Our article has discussed a wide spectrum of some of the interactive visual computing tools and solutions our group investigated and developed, including: (a) tools that allow the handling, management, visualization and analysis of integrated, multidisciplinary workflows and datasets smoothly and efficiently; (b) tools that help to provide visual representations that give a deeper, fuller reflection on all the available information acquired from E, D&P; (c) tools that improve the communication between technical professionals and decision-makers; and (d) tools that help to guide complex work processes to express the level of uncertainty during analysis and interpretations of multidisciplinary reservoir datasets.

The examples presented fit our three main visual computing research themes: (a) visual data modelling and knowledge representation; (b) data visualization and analytics; and (c) visual data interaction techniques and technologies. We see great growth potential for the domain as the industry practitioners are introduced to and adopt more novel interactive visualization techniques into their existing practice. Please refer to our group's website at http://ires.cpsc.ucalgary.ca for additional information.

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References

Abraham, F. & Celes, W. 2009. Distributed visualization of complex black oil reservoir models. *In*: *Proceedings of the 9th Eurographics Conference on Parallel Graphics and Visualization (EG PGV'09)*. Eurographics Association, Aire-la-Ville, Switzerland, 87–94.

Akkiraju, N., Edelsbrunner, H., Facello, M., Fu, P., Mucke, E. P. & Varela, C. 1995. Alpha shapes: definition and software. *In*: *Proceedings of the 1st International Computational Geometry Software Workshop*, Minneapolis, MN, USA, 63–66.

Amorim, E., Vital Brazil, E., Daniels, J., II, Joia, P., Nonato, L. G. & Sousa, M. C. 2012. iLAMP: Exploring high-dimensional spacing through backward multidimensional projection. *In*: *IEEE Conference on Visual Analytics Science and Technology (VAST'12)*. IEEE Computer Society, Washington, DC, 53–62.

Amorim, E., Vital Brazil, E., Nonato, L. G., Samavati, F. & Sousa, M. C. 2014. Multidimensional projection with radial basis function and control points selection. *In*: *Proceedings of the 7th IEEE Pacific Visualization Symposium (PACIFICVIS'14)*. IEEE Computer Society, Washington, DC, 209–216.

Amorim, R., Vital Brazil, E., Patel, D. & Sousa, M. C. 2012*a*. Sketch modeling of seismic horizons from uncertainty. *In*: *Proceedings of the 9th International Symposium on Sketch-Based Interfaces and Modeling (SBIM'12)*. Eurographics Association, Aire-la-Ville, Switzerland, 1–10.

Amorim, R., Boroumand, N., Vital Brazil, E., Hajizadeh, Y., Eaton, D. & Sousa, M. C. 2012*b*. Interactive sketch-based estimation of stimulated volume in unconventional reservoirs using microseismic data. *In*: *13th European Conference on the Mathematics of Oil Recovery (ECMOR XIII)*. European Association of Geoscientists and Engineers (EAGE), Poster Session, Biarritz, France.

Amorim, R., Vital Brazil, E., Samavati, F. & Sousa, M. C. 2014. 3D Geological modeling using sketches and annotations from geologic maps. *In*: *Proceedings of the 11th International Symposium on Sketch-Based Interfaces and Modeling (SBIM'14)*. Eurographics Association, Aire-la-Ville, Switzerland.

Bengtsson, T., Bickel, P. & Li, B. 2008. Curse-of-dimensionality revisited: collapse of the particle filter in very large scale systems. *In*: *IMS Collections. Probability and Statistics: Essays in Honor of David A. Freedman*. Institute of Mathematical Statistics, **2**, 316–334, Beachwood, OH, USA, http://dx.doi.org/10.1214/193940307000000518

Bertini, E. & Lalanne, D. 2009. Surveying the complementary role of automatic data analysis and visualization in knowledge discovery. *In*: *Proceedings of the ACM SIGKDD Workshop on Visual Analytics and Knowledge Discovery: Integrating Automated Analysis with Interactive Exploration (VAKD'09)*. ACM, New York, 12–20.

Brown, A. 2000. Evaluation of possible gas microseepage mechanisms. *AAPG Bulletin*, **84**, 1775–1789.

Burns, C., Seyed, T., Bradley, K., Duncan, R., Balasch, A., Maurer, F. & Sousa, M. C. 2012. Multi-surface visualization of fused hydrocarbon microseep and reservoir data. *In*: *CSEG/CSPG/CWLS GeoConvention 2012:Vision*, Calgary, Alberta, Poster Session.

Caers, J. 2005. *Petroleum Geostatistics*. Society of Petroleum Engineers, Richardson, TX.

Cairns, J. L. & Feldkamp, L. D. 1993. 3D visualization for improved reservoir characterization. *SPE Computer Applications*. Society of Petroleum Engineers, Richardson, TX, **5**, 13–24 (SPE-24269-PA).

Cevolani, J. T., Mostafa, A. E., Vital Brazil, E., Costa de Oliveira, L., Goliatt da Fonseca, L. & Sousa, M. C. 2013. Computational methodology to study heterogeneities in petroleum reservoirs. *In*: *EAGE Annual Conference & Exhibition incorporating SPE Europec*. Society of Petroleum Engineers, Richardson, TX. Conference Paper (SPE-164865-MS).

Cosentino, L. 2001. *Integrated Reservoir Studies*. Technip, Paris.

Daku, B., Salt, J. & Sha, L. 2004. An algorithm for locating microseismic events. *In*: *IEEE Canadian Conference on Electrical and Computer Engineering (CCECE/CCGEI'04)*, Niagara Falls Ontario, Canada, **4**, 2311–2314, http://dx.doi.org/10.1109/CCECE.2004.1347708

Dogru, A. H., Fung, L. S. K., Al-Shaalan, M. & Pita, J. A. 2008. From mega-cell to giga-cell reservoir simulation. *In*: *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers, Richardson, TX. Conference Paper (SPE-116675-MS).

Dopkin, D. & James, H. 2006. Trends in visualization for E&P operations. *First Break*, **24**, http://fb.eage.org/

Fanchi, J. R. 2002. *Shared Earth Modeling: Methodologies for Integrated Reservoir Simulations*. Elsevier Science, New York.

Geiger, S., Matthäi, S., Niessner, J. & Helmig, R. 2009. Black-oil simulations for three-component, three-phase flow in fractured porous media. *SPE Journal*, **14**, 338–354 (SPE-107485-PA).

Giertse, C. 2009. Applications of illustrative methods for oil & gas exploration and production. *In*: *First Interdisciplinary Gathering on Illustrative Visualization (IllustraVis'09)*. University of Bergen, Norway. Panel Session.

Gomes, J., Velho, L. & Sousa, M. C. 2012. *Computer Graphics: Theory and Practice*. CRC Press, Boca Raton, FL.

Hager, G. & Wellein, G. 2010. *Introduction to High Performance Computing for Scientists and Engineers*. Chapman & Hall/CRC Computational Science, CRC Press, Boca Raton, FL.

Hajizadeh, Y., Amorim, E. & Sousa, M. C. 2012. Building trust in history matching: the role of multidimensional projection. *In*: *SPE Europec/EAGE Annual Conference*. Society of Petroleum Engineers, Richardson, TX. Conference Paper (SPE-152754-MS).

Hansen, C. D. & Johnson, C. R. 2011. *The Visualization Handbook*. Academic Press, New York.

Harris, J., Young, J., Sultanum, N. B., Lapides, P., Sharlin, E. & Sousa, M. C. 2011. Designing Snakey: a tangible user interface supporting well path planning. *In*: *Proceedings of the 13th IFIP TC 13 International Conference on Human-Computer Interaction – Volume Part III (INTERACT'11)*. Springer, Berlin, 338–354.

Inselberg, A. 1985. *The Plane with Parallel Coordinates. The Visual Computer*. Springer, Berlin, **1**, 69–91.

Isenberg, P., Elmqvist, N., Scholtz, J., Cernea, D., Ma, K-L. & Hagen, H. 2011. Collaborative visualization: definition, challenges, and research agenda. *Information Visualization Journal*, Special Issue on Information Visualization: State of the Field and New Research Directions, **10**, 310–326.

JOHNSON, C., PARKER, S. G., HANSEN, C., KINDLMANN, G. L. & LIVNAT, Y. 1999. Interactive simulation and visualization. *Computer*, **32**, 59–65.

KREYLOS, O., TESDALL, A. M., HAMANN, B., HUNTER, J. K. & JOY, K. I. 2002. Interactive visualization and steering of CFD simulations. *In*: *Proceedings of the Symposium on Data Visualisation 2002 (VISSYM'02)*. Eurographics Association, Aire-la-Ville, Switzerland, 25–34.

KURC, T., CATALYUREK, U. *ET AL.*. 2005. A simulation and data analysis system for large-scale, data-driven oil reservoir simulation studies. *Concurrency and Computation: Practice and Experience*, Special Issue: High-Performance Computing in Geosciences, **17**, 1441–1467.

LI, N., SHEKHAR NITTALA, A., SHARLIN, E. & SOUSA, M. C. 2014. Shvil: collaborative augmented reality land navigation. *In*: *CHI'14 Extended Abstracts on Human Factors in Computing Systems (CHI EA '14)*. ACM, New York, 1291–1296.

LIDAL, E. M., LANGELAND, T., GIERTSEN, C., GRIMSGAARD, J. & HELLAND, R. 2007. A decade of increased oil recovery in virtual reality. *IEEE Computer Graphics and Applications*, **27**, 94–97.

LIDAL, E. M., NATALI, M., PATEL, D., HAUSER, H. & VIOLA, I. 2013. Geological storytelling. *Computers & Graphics – Special Section on Expressive Graphics*, **37**, 445–459.

LOVE, F. & PURDAY, N. 2008. 3D Visualization technology, reducing cycle time and improving performance, from basin scale assessment through prospect identification to optimal drill site selection. *In*: *Offshore Technology Conference: 'Waves of Change' (OTC'08)*, Houston, TX, Conference Paper (OTC 19596).

MATKOVIC, K., GRACANIN, D., JELOVIC, M. & HAUSER, H. 2008. Interactive visual steering —rapid visual prototyping of a common Rail injection system. *IEEE Transactions on Visualization and Computer Graphics*, **14**, 1699–1706.

MAYERHOFER, M. J., LOLON, E. P., WARPINSKI, N. R., CIPOLLA, C. L., WALSER, D. & RIGHTMIRE, C. M. 2010. What is stimulated reservoir volume? *SPE Production & Operations*. Society of Petroleum Engineers, Richardson, TX, **25**, 89–98 (SPE-119890-PA).

MOGHADAM, A. K., SULTANUM, N., MARTINS FILHO, Z., MIRANDA-FILHO, D. N., HAMDI, H., CHEN, J. & SOUSA, M. C. 2012. Interactive visual steering for reservoir geoscience and engineering. *In*: *CSEG/CSPG/CWLS GeoConvention 2012:Vision*. Calgary, Alberta, Poster Session.

MOSTAFA, A. E., AMORIM, R., VITAL BRAZIL, E., EATON, D., CARPENDALE, S., SHARLIN, E. & SOUSA, M. C. 2012. Exploratory visual modeling and analysis of microseismic events. *In*: *CSEG/CSPG/CWLS GeoConvention 2012:Vision*. Calgary, Alberta, Oral Presentation.

MOSTAFA, A. E., CARPENDALE, S., VITAL BRAZIL, E., EATON, D., SHARLIN, E. & SOUSA, M. C. 2013*a*. FractVis: visualizing microseismic events. *In*: *Proceedings of the 9th International Symposium on Visual Computing (ISVC'13)* – 'Advances in Visual Computing', Lecture Notes in Computer Science, Springer, Berlin, 384–395.

MOSTAFA, A. E., CEVOLANI, J., VITAL BRAZIL, E., SHARLIN, E. & SOUSA, M. C. 2013*b*. PetroVis: exploratory visualization for petrographic characterization. *In*: *IEEE VISWeek 2013, Poster and Extended Abstract, Electronic Conference Proceedings*.

MULDER, J. D., VAN WIJK, J. J. & VAN LIERE, R. 1999. A survey of computational steering environments. *Future Generation Computer Systems*, **15**, 119–129.

OLSEN, L., SAMAVATI, F., SOUSA, M. C. & JORGE, J. A. 2009. Sketch-based modeling: A survey. *Computers & Graphics*, **33**, 85–103.

PAJON, J.-L. & RAINAUD, J.-F. 1992. Interactive visualization of 3D complex geological structures. *European Petroleum Computer Conference*. Society of Petroleum Engineers, Richardson, TX. Conference Paper (SPE-24268-MS).

PARKER, S. G., JOHNSON, C. J. & BEAZLEY, D. 1997. Computational steering: software systems and strategies. *IEEE Computational Science & Engineering*, **4**, 50–59.

PATEL, D., STURE, Ø., HAUSER, H., GIERTSEN, C. & GRÖLLER, M. E. 2009. Knowledge-assisted visualization of seismic data. *Computers & Graphics*, **33**, 585–596.

PATEL, D., BRUCKNER, S., VIOLA, I. & GRÖLLER, M. E. 2010. Seismic volume visualization for horizon extraction. *In*: *Proceedings of the 3rd IEEE Pacific Visualization Symposium (PACIFICVIS'10)*. IEEE Computer Society, Washington, DC, 73–80.

PLAISANT, C., CHINTALAPANI, G., LUKEHART, C., SCHIRO, D. & RYAN, J. 2003. Using visualization tools to gain insight into your data. *In*: *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers, Richardson, TX. Conference Paper (SPE-84439-MS).

POTTER, K., ROSEN, P. & JOHNSON, C. R. 2012. From quantification to visualization: a taxonomy of uncertainty visualization approaches. *In*: *Uncertainty Quantification in Scientific Computing*. IFIP Advances in Information and Communication Technology Series. Springer, Berlin, **377**, 226–249.

SEEMANN, D., WILLIAMSON, M. & HASAN, S. 2013. Improving reservoir management through big data technologies. Society of petroleum engineers. *In*: *SPE Middle East Intelligent Energy Conference and Exhibition*. Society of Petroleum Engineers, Richardson, TX. Conference Paper (SPE-167482-MS).

SEYED, T., TANG, T., MAURER, F. & SOUSA, M. C. 2013. SkyHunter: a multi-surface environment for supporting oil and gas exploration. *In*: *Proceedings of the 2013 ACM International Conference on Interactive Tabletops and Surfaces (ITS '13)*. ACM, New York, 15–22.

SHAER, O. & HORNECKER, E. 2010. Tangible user interfaces: past, present, and future directions. *Foundations and Trends in Human-Computer Interaction*, **3**, 1–137.

SHNEIDERMAN, B. & PLAISANT, C. 2009. *Designing the User Interface: Strategies for Effective Human-Computer Interaction*, 5th edn. Pearson Addison-Wesley, Reading, MA.

SOUSA, M. C. & MIRANDA-FILHO, D. N. 1994. 3D scientific visualization of reservoir simulation post-processing. *In*: *SPE 9th Petroleum Computer Conference (SPE-PCC'94)*. Society of Petroleum Engineers, Richardson, TX. Conference Paper (SPE-28247-MS), 255–264.

Sultanum, N. B., Sharlin, E., Sousa, M. C., Miranda-Filho, D. N. & Eastick, R. 2010. Touching the depths: Introducing tabletop interaction to reservoir engineering. *In*: *Proceedings of the 2010 ACM International Conference on Interactive Tabletops and Surfaces (ITS '10)*. ACM, New York, 105–108.

Sultanum, N. B., Somanath, S., Sharlin, E. & Sousa, M. C. 2011. 'Point it, split it, peel it, view it': techniques, evaluation and design heuristics for interactive reservoir visualization on tabletops. *In*: *Proceedings of the 2011 ACM International Conference on Interactive Tabletops and Surfaces (ITS'11)*. ACM, New York, 191–201.

Sultanum, N. B., Vital Brazil, E. & Sousa, M. C. 2013. Navigating and annotating 3D geological outcrops through multi-touch interaction. *In*: *Proceedings of the 2013 ACM International Conference on Interactive Tabletops and Surfaces (ITS'13)*. ACM, New York, 345–348.

Thomson, J. A. & Poupon, M. N. 2004. Special sessions on petrotechnical visualization. A point of (3D) view on visualization. *In*: *Offshore Technology Conference (OTC'04)*. Houston, TX. Conference Paper (OTC-16763-MS).

Tyson, S. & Williams, B. 1993. Visualization of oil reservoirs over a large range of scales as a catalyst for multi-disciplinary integration. *In*: *Proceedings of the 4th Conference on Visualization (VIS'93)*. IEEE Computer Society, Washington, DC, 366–369.

Ullmer, B. & Ishii, H. 2000. Emerging frameworks for tangible user interfaces. *IBM Systems Journal*, **39**, 915–931.

Ulrich, Z. 2011. Calculating stimulated reservoir volume (SRV) with consideration of uncertainties in microseismic-event locations. *In*: *Canadian Unconventional Resources Conference (CURC'13)*. Society of Petroleum Engineers, Richardson, TX. Conference Paper (SPE-148610-MS).

van Overveld, K. & Wyvill, B. 2004. Shrinkwrap: an efficient adaptive algorithm for triangulating an iso-surface. *The Visual Computer*, **20**, 362–379.

Vital Brazil, E. 2011. *On sketches for modeling*. PhD dissertation, IMPA – Instituto de Matemática Pura e Aplicada (Pure and Applied Math Institute), Rio de Janeiro.

Warpinski, N. 2009. Microseismic monitoring: inside and out. *Journal of Petroleum Technology*, **61**, 80–85 (SPE-118537-JPT).

Zamel, N. M., Pita, J. A. & Dogru, A. H. 2001. Next-generation visualization technologies for exploration & production. *In*: *SPE Middle East Oil Show*. Society of Petroleum Engineers, Richardson, TX. Conference Paper (SPE-68099-MS).