FractVis: Visualizing Microseismic Events

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Abstract. We present our efforts of applying information visualization techniques to the domain of microseismic monitoring. Microseismic monitoring is a crucial process for a number of tasks related to oil and gas reservoir development, e.g., optimizing hydraulic fracturing operations and heavy-oil stimulation. Microseismic data has many challenging features including high dimensionality and uncertainty. We present a brief introduction to the domain of microseismic monitoring, and derive a set of tasks and data abstractions that can establish common ground between microseismic monitoring domain experts and visualization researchers. We then present FractVis, a prototype for visual analysis of microseismic data, describing the ongoing process of iteratively refining FractVis through close collaboration and consultation with domain experts. FractVis is designed to offer microseismic monitoring experts with visual analytic tools that allow investigation of the 3D spatial distribution of microseismic events, time-varying analysis and interactive exploration of high-dimensional parameter spaces, extensively complementing the existing tools in their disposal.

1 Introduction

The increasing global demand for energy motivates the oil/gas industry to invest in tools that can help domain experts make better-informed decisions. Recently microseismic monitoring has emerged as one of the most important processes to support such decisions. However, making informed decisions about improving reservoir modeling based upon microseismic data is a challenge for expert analysts. These difficulties arise due to the inherent features of the microseismic data: intrinsic complexity, high-dimensionality, and a high degree of uncertainty. Currently these difficulties are intensified by a lack of visual analytic tools to support interactive visual interpretation of the dataset. To address these difficulties, domain experts are demanding efficient interactive visualization tools that can help them as they explore their data.

Microseismic data is comprised of events, each representing an extremely small earthquake [1]. These events are the result of fractures created and/or activated to allow oil and gas trapped in rock pores to flow more easily. The fracture information is captured by sensors (e.g. geophones) and structured as continuous raw ground-motion records. Following, the raw data is pre-processed resulting in an event catalog containing tabular information with many attributes per event. The data inherents high abstraction and uncertainty from the measurements and the preprocessing [2, 3]. Once gathered and processed, microseismic data is generally analyzed by several domain experts such as geophysicists, geologists and reservoir engineers, each representing a different skill set, and often having different interests. The analysis consists of several tasks; expert interpreters need to know the locations of the events in relation to the wells in the reservoir, to be able to filter out noisy events, and perform correlations between various attributes within the large, high-dimensional microseismic dataset. Some important high-level tasks performed by the experts include: understanding hydraulic fracture geometry, estimating the stimulated reservoir volume (SRV), and optimizing long-term field development [1]. These tasks could benefit dramatically from an interactive visualization tool that converts the microseismic data into efficient and effective visual representations. Such a tool should be designed to better reflect and express the available information, the level of uncertainty and other pertinent data details from different stages of oil/gas exploration and production.

The primary contribution of our work is the characterization of the microseismic domain challenge, outlining the potential benefit of applying information/scientific visualization techniques to this problem domain, and sharing our insight based on the design and evaluation of our current implementation FractVis. We describe the data exploration tasks involved in microseismic monitoring, and the common domain abstractions in order to highlight and share our insights of the domain challenges and needs. From these we derive our prototype design requirements, encoding choices and interaction techniques. The secondary contribution of our work is the design, development and preliminary evaluation of FractVis; an interactive visualization prototype that enable exploration and analysis of microseismic events. FractVis is being developed and refined iteratively with feedback and consultations from domain experts. FractVis combines and extends existing and novel visualization techniques to help experts to explore their data and make informed decisions We conclude with our reflections and lessons we have learned during the design of FractVis.

2 Related Work

Many visual analytic systems and visualization techniques applied to reservoir geoscience and engineering have been developed through the recent years [4–7]. Although these tools assist people in their decision making process, there is still lack of visual analytic systems of geophysical data in the microseismic domain. The majority of the work in the domain of microseismic engineering and geosciences has been in the area of developing mathematical methods for microseismic monitoring [1, 2]. Limited research has been done in the area of microseismic visualization and many of the microseismic scientific papers use commercial tools that lack the support of visual interpretation and analysis of microseismic data. In this section, we summarize some of the key related works that have inspired our implementation.

A scatterplot matrix [8] can visually represent multidimensional data by creating a matrix of N^2 scatterplots arranged in N rows and N columns. However, the resolution of each scatterplot in the scatterplot matrix is limited when the data contains high dimensionality. Elmqvist et al. proposed a starplot-like system titled DataMeadow [9], which is a visual canvas designed to support analysis of large-scale multivariate data with flexible visual queries.

One important component of our visualization tool involves the use of parallel coordinates (PC) [10]. This is a well-known technique for visualizing highly dimensional data that represents every dimension as vertical axis parallel to other dimensions on a 2D plane. Heinrich and Weiskopf [11] presents a survey of the current state of the art of visualization techniques for parallel coordinates. While we know that PC suffers from data cluttering, we employed some strategies to alleviate this problem including brushing [12] and axis ordering [13]. PC have also been applied in many different visual analytic systems. Steed et al. presented a system for analyzing weather data using an enhanced PC's implementation [14]. Other visualization techniques have been combined with PC to provide better visualizations tools. For example, Yuan [15] presented a system that scatters the data points within PC. Martin et al. [12] discussed high dimensional brushing for exploring multivariate data with focus on PC. These brushing methods have been integrated in XmdvTool [16] which is a system that combines many multivariate visualization methods. Also, evaluation of PC [17] have shown that the people who performed the tasks with PC found them more effective than other methods.

Roberts [18] provided a discussion of the state of art on using coordinated multiple views, and discussed many systems that support this technique. Similarly to other systems (e.g. Bowman et al. [19]) that provide coordination of different representations of the data, we also make use of multiple coordinated views. Wang-Baldonado et al. [20] provided a set of guidelines for using multiple views in information visualization while Andrienko et al. [21] provided a critical examination of multiple coordinated views.

3 Microseismic Characterization

Microseismic monitoring offers unique information visualization challenges and potential. In this section we briefly characterize the microseismic monitoring domain to motivate our own design, and in hope that this characterization would allow future information visualization efforts to address the various domain challenges. We describe the typical structure of microseismic monitoring datasets, and highlight its important attributes. We present the data abstractions experts are using when approaching the datasets and the high-level tasks they are pursuing, along with the processes and the challenges they are facing. The raw data we present was gathered during continuous meetings, contextual inquiries [22] sessions, and semi-structured interviews with domain experts.

Microseismic Background: Hydraulic fractures are created by injecting water or other specially developed fluids such as cross-linked gels into the rock formation. The injection is performed under high pressure through a chamber in the well causing the formation to crack or fracture, thus generating micro-earthquakes (also called microseismic events). A multi-stage hydraulic fracturing is created by multi-chamber, illustrated by spheres with different colors in Fig. 1. These multi-stage hydraulic fracturing techniques are designed to expose a larger amount of drainage area to the wellbore as compared to a single-stage fracture. Receiver systems (i.e. geophones) are placed in locations near the (fracturing) process to detect the energy generated by the events, and then providing geometric information.

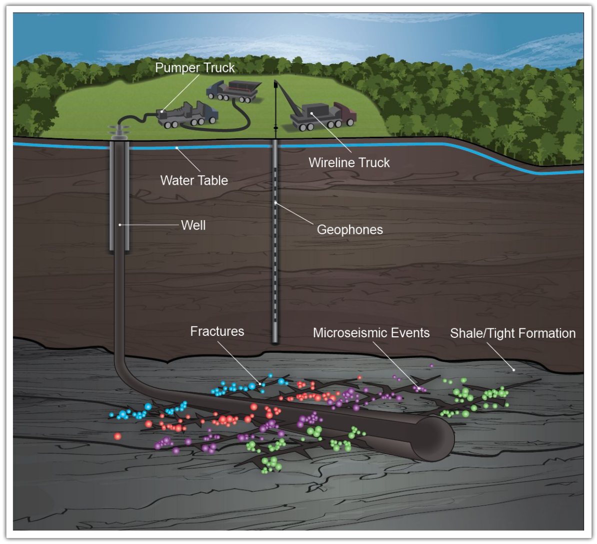

Fig. 1. Hydraulic fracture schematic overview showing multi-stage fracturing (four different colors for the spheres of each microseismic events stage) along with a single well [23].

Microseismic events' locations are calculated using a velocity model [2]. The velocity model describes the propagation of elastic waves (P and S) from the fracture to the detection system. Specifically, this model incorporates the acoustic wave-speed and thickness of rock layers between the source and the receiver locations. Combined with limited acquisition geometry, the uncertainty is inherent in this model and within the calculated locations of the microseismic events. In addition recorded microseismic events typically have noise associated with them, and this may come from many sources including even a truck moving on the surface. Thus the microseismic data events, in addition to their ambiguity, also contain noise and inaccuracies that make them highly uncertain.

Data Description: Microseismic dataset is composed of many layers, but in our work we focus on three because they fit our exploratory goals. The first layer is the microseismic "Events Catalog" which describes each event along with its attributes. The second layer is the "Monitoring and Treatment" wells information. A third component comprises the engineering data and pumping curves. All of these data layers usually exist within a single dataset.

The microseismic data employed in our design of FractVis was a highly multidimensional time varying point cloud dataset. According to experts, some of the most important microseismic attributes are **Time**, **Location**, **Distance**, **Magnitude**, **Noise-Level**, and **Energy**. They also expressed that some of these attributes are independent while others are dependent on each other. For example, the attributes *distance* and *magnitude* are independent and are usually used as standard test for initially checking the validity of the data. In contrast, the attribute *noise level* is dependent on the *signal-to-noise ratio* attribute.

The engineering data layer represents the different characteristic of the fracture growth and the events population with time. For example, pumping curves provide correlation between time and pressure in the injection process. By examining these real-time plots, experts can confirm that microseismic events start to be generated when the pressure reaches its peak with the fluid injection causing the rock to break or fracture. Visualizing the engineering data layer curves and linking them with 3D visualization of the events is important for better understanding of the fracture geometry. The current version of FractVis does not address this second layer of the dataset and we are planning to integrate it in our future prototypes.

Task Analysis and Challenges: Microseismic experts perform different tasks while exploring the data. First, domain experts mentioned that estimating the stimulated reservoir volume (SRV) is one of the most common tasks in microseismic engineering. The goal of this task is to generate a bounding volume which defines subsets of the data events as initial estimations of the production volume. The locations of the events are important in this calculation. However, these locations are estimated due to the inherit uncertainty of the measurements. Experts consider the inclusion of uncertainty in SRV calculation an important future challenge [3]. Various methods are applied to the events prior to calculating the SRV in an attempt to filter out the unimportant events and analyze the data attributes [24]. The ability to filter the data and make decisions regarding the events is greatly affected by the insight and understanding of the dataset; and the expert's ability to extract relations among its attributes. Additionally, experts are analyzing dataset outliers manually. They believe that this manual component can benefit greatly from applying interactive or semi-automatic interactive visualization data correlation techniques. Secondly, since the microseismic data is a time-varying point-cloud, there is a room for supporting time-based visualization and analysis. Microseismic experts consider the *time* attribute as one of the most important independent variables. They expressed that it is common to analyze the correlation between the *time* and many other attributes. Thirdly, analyzing fracture growth over time (i.e. measurements of fracture azimuth, width, etc.) could be spatially visualized to obtain an understanding of fracture geometry and the fractures' interactions, understanding that can be crucial when analyzing the dataset. Finally, domain experts expressed that the ability to see the data from different perspectives at the same time is important. For instance, the synchronized: visualization of the 3D events, visualization of the attributes, and the visualization of the engineering curves would be useful if represented intuitively.

Attempting to analyze the microseismic monitoring dataset involves several challenges. First, although some of the data attributes have dependency, the dimensionality of the independent data attributes is still quite high. Potential techniques for reducing this high dimensionality will certainly aid in the analysis of the data. Second, the data inherently contains uncertainty due to the inaccurate measurements and the noise associated with them. Noise in the data comes from many sources and can not be completely removed. In fact, many techniques have been attempted recently in order to reduce the noise, but the processed data still contains noise which can be quantified for each event [3]. Finally, the microseismic data is highly abstract. The data could have different interpretations and it can often be difficult to validate which of them is the most accurate one. Experts explained that some of the attributes may have different meanings in different contexts, and that applying domain insight is still a crucial part of the process. Overall, the domain experts we consulted thought that visual-analytic tools would be very effective in helping them interactively and effectively explore the dataset. For instance, domain experts said that they sometimes do not fully understand the relationship between many of these attributes and were hoping to be able to intuitively spatially correlate various data attributes in order to learn more about the potential effect of each of them.

4 Design Rationale

We adopted an iterative design approach, we built our first prototype, and we modified our system iteratively based on the requirements and the feedback of our domain collaborator. We decided to focus on supporting the simple tasks of ”data filtering” and ”attributes correlation”. We analyzed the high-level tasks of ”data filtering” and ”attributes correlation” then we identified the following concrete tasks: *Find Anomalies*, *Associate*, *Correlate*, *Identify*, *Filter*, and *Categorize*; by following the taxonomy of [25]. As a result, we designed our prototype to support these tasks.

We chose to represent every microseismic event as sphere centered at its 3D spatial location with radius proportional to any of the attribute values. The color of any sphere event and its corespondent PC line is defined by correlating a color map with some attribute. Among the color maps that FractVis supported, we also supported a rainbow (jet), which may not be recommended for usage in visualization systems [26], but domain experts are familiar with this color map. Our domain collaborators acknowledged our choices of mapping the radius/color of each event sphere relative to some attributes. They considered this mapping to be natural to them, powerful for showing much information at once, and comparable to many existing commercial tools.

Why Parallel Coordinates? First, the technique of PC supports exploration of data trends and attributes correlation without affecting the scale and the dimensionality of the data, which is not the case for the other projective and non-projective techniques. Second, PC is a widely used technique and supports extensibility. Indeed, we extended the PC by integrating dynamic magic lenses and embedding them with it. Furthermore, experts can dynamically recolor the content of the PC according to some attribute to examine attributes correlation without the need to reorder the axes of the PC. Third, the study performed by Siirtola and Räihä [17] revealed that who performed their tasks with PC found it more effective than those who used other methods. Finally, we think that if we extended our visualization and provided interactively embedded visuals (e.g. scatter plot) within our PC, then it would be easier for the experts to familiarize themselves with it and learn interacting with it quickly, interaction which would empower the experts with rich visuals without the need to show additional visualization windows.

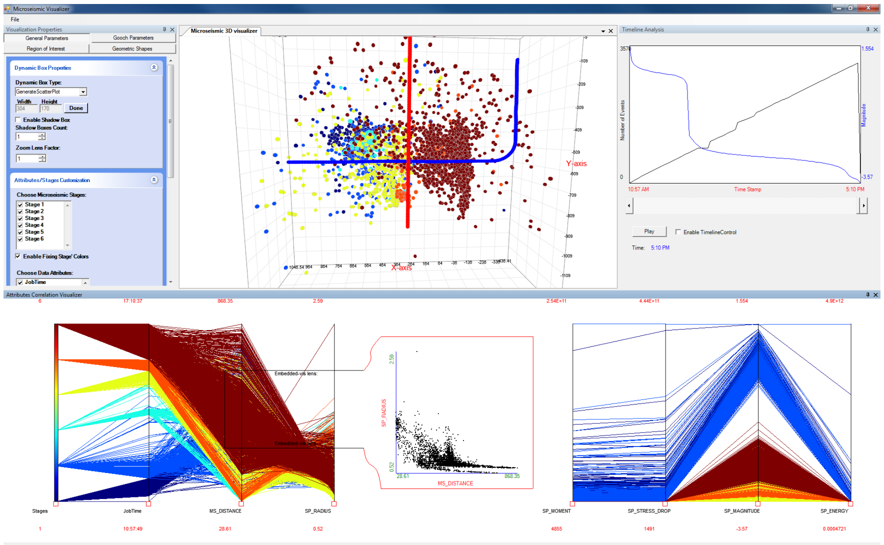

Fig. 2. System overview showing the synchronization of the PC view (bottom) with the other data visualization components: (top center) 3D microseismic events' point cloud, (top right) the time-based visualization and (top left) the GUI view for controlling the visualization parameters.

5 FractVis

Our implementation follows the multiple coordinated views approach [18]. We considered this approach because, we think, it is important to have different representations of the data, at the same time, for achieving simultaneous data analysis. Our system, FractVis, supports two primary coordinated views (Figure 2). The main 3D view enables visual exploration of the microseismic events in the reservoir space with well integration. The second view supports flexible interaction and correlation though an improved PC visualization. Each view presents the data in a different way, allowing experts to link and relate the meanings gained from one view with the others.

The technique of PC [10] can be used to visually explore the main trends and/or relations of a multidimensional data. The standard PC consists of n-parallel lines typically vertical and equally spaced, where 'n' is the number of dimensions (attributes) of the data. Each data sample is represented as a polyline intersecting each attribute at the corresponding relative value. In fact, we extended the PC by introducing and integrating two novel extensions. The first extension describes the integration of magic lenses over the PC to enable intuitive interactions such as data filtering and scaling. In the second extension we present our idea of visual correlation through the use of visual legends.

We extended the implementation of PC through the concept of dynamic boxes (similar to magic lenses [27]) blended over the PC plot. Once a dynamic box is created, all the visible attributes' axes that intersect this dynamic box will be considered for achieving the corresponding effect. We support two types of dynamic boxes where each of

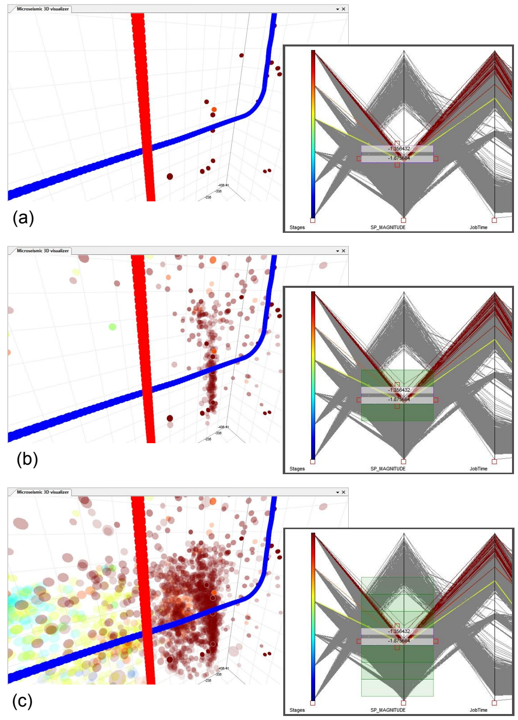

Fig. 3. The effect of filtering over the PC with and without keeping the context: (a) show the normal filtering with a single filter box, (b) show the effect of two shadow boxes and how they result in a small partial context, and (c) show the effect of activating six shadow boxes to increase the partial context.

them is being represented using different color and shape to utilize the cognitive power of the users and facilitate interactions. The first dynamic box causes data filtering (Figure 3 top). Such a filter box will constrain the events to only those who fall within its limits (range), similar to data brushing [12]. Additionally, our visualization shows the filtered out events as transparent 3D spheres and/or gray polylines within the PC to make it easier to identify them. The user can create many filter boxes to achieve complex filtering. This idea is similar to iterative brushing [9] where composite filters are created in order to focus on a refined subset of the data. The second type is a dynamic box which causes embedding custom visuals within the PC visualization. For instance, the user could embed scatter plot within the PC similar to the work of Holten and van Wijk [28]. However, in our implementation, we support such integration interactively. Figure 2 (bottom) shows a dynamic box that caused a scatter plot visual to be generated (and embedded) within the PC.

Shadow boxes (Figure 3) are other novel visual elements that can be attached with filter boxes to enable: (1) range/cluster navigation; by gradually fading all the events before and after the range of the current active filter box, and (2) partial contextualization. This feature is inspired by the work of Doleisch and Hauser [29], where the authors used smooth brushing to reflect the smooth nature of features in their flow simulation data. The number of shadow boxes as well as their properties can be controlled through the GUI of FractVis. For example, in Figure 3 (b and c), the effect of shadow boxes is shown. We can see that although we are strictly filtering the data events (using our filter box), the (synchronized) 3D view shows other (transparent) events representing the partial context.

We introduce a new forms of interactive-based correlation through the concept of ”visual legends”. The basic idea is about placing visual maps (i.e. color map) over any attribute’s axis to update the data representation relative to this attribute. This idea is similar to ”gradient color brush” introduced by Matkovic et al. [30] but we extended this idea by allowing it to represent different visual variables such as color and size. In our implementation, we support two visual legends (maps) in order to perform color correlation and/or size correlation. First, a color map can be placed over any attribute to (associate and) enforce (re)coloring all the PC’s polylines, as well as the 3D spheres, according to the distribution of the values of the selected attribute. Second, a size map can be placed over any attribute to (re)size all spheres of the 3D events accordingly. This could help in identifying the spatial geometric location of events relative to the well. Furthermore, it can be also useful for analyzing the 3D location of the possible events outliers and confirm if they are outliers or not. Our implementation also supports the feature of axes reordering to analyze the relation between any non-sequenced attributes, but we believe that our dynamic legend-based correlation (for instance using color) can be useful for quickly identifying such relations without the need to reorder the attributes.

6 Discussion and Lessons Learned

Given the relatively recent emergence of microseismic monitoring methods, the number of domain experts is limited. Clearly, having access to a limited number of domain experts may not be suitable for conducting detailed formal evaluation, but it does suggest other benefits. The repeating sessions with the same experts allowed for continuous and coherent feedback and refinement of the prototype. Having repeated access to the same experts allowed us to confirm that the system features meet their expectations. We conducted informal evaluation by demoing our visualization prototype to the domain experts and also to visualization researchers. The goal was to gather their reaction about our prototype.

Most of our participants provided positive feedback about many of the system’s features. One of the highly experienced domain experts discovered a very interesting issue with the data calculation using our visualization. He analyzed the relation: *Magnitude* vs. *Distance*, and he specifically expressed: *”When I look at this, I can see there is a problem with the data ... because it is not physically feasible ... So this just highlights some problem with the data”*. Another feedback that shows some limitations and weaknesses in our tool has been provided by some of the participants as well. One domain expert expressed her opinion about our feature of having embedded visuals within the PC as confusing. She specifically expressed: *”I like it popped up in the middle, but what it did is just disconnected the way I am looking into the data so I have to go back”*. We also received many suggestions for improving our tool. For instance, one domain expert suggested that integrating additional types of data (i.e. engineering curves) would be important.

During some of the assessment sessions with the domain experts, they commented about having different visualization and interaction possibilities in our system. Some of them considered that to be confusing and they just preferred simple visualization, while others considered it to be a form of flexibility. Regarding the PC, one expert expressed: *"The parallel coordinates is very unique, and you've just showed me that it can be more powerful... when I become a good user with it, it will be tremendously useful"*. On the other hand, when we asked an expert participant about the idea of having multiple dynamic (filter) boxes, and whether it is easier or not, she specifically said: *"That would be something that I have to use for some time to know if it would be easier or not, but for now I think the concept is useful. I think it can be a very good idea"*. These comments suggest that our prototype may be a good start for microseismic visual-analysis, though a detailed and formal evaluation is needed to fully confirm that feedback and guide future development.

Generally, throughout the process we felt that domain experts are resisting considering and learning new tools and new ways of thinking about analyzing their datasets. While we understood this reaction, it was one of the main challenges that we were facing. Indeed, it inspired us to think about simplifying our design in order to provide experts with simpler tool that will provide new insight while still feeling familiar. One such experience had to do with introducing PC to them as new visualization tool. Our experts were not familiar with PC, and they seem to resist understanding or using it in our early sessions with them. Following this initial resistance we provided the experts with additional visualizations which were more familiar to them, such as scatterplot, integrated with the PC visualization. Our approach was that embedding the new visualization side-by-side with familiar ones would allow users to explore it while retaining a known baseline context, allowing them to learn the new technique. The feedback that we received (from most of the participants) confirmed that our approach was useful and helpful. Overall, we wanted to empower the PC visualization by adding the flexibility to see additional (embedded) visuals which would lead to enhancing the data analysis experience.

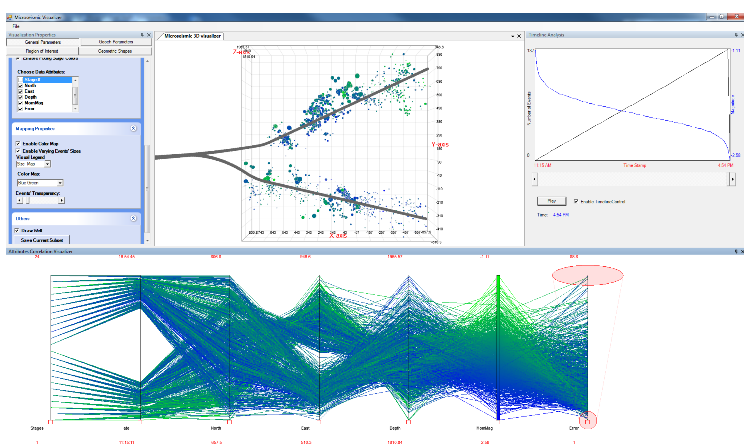

Fig. 4. Visualizing another microseismic dataset using FractVis. The 3D visualization shows that the events from well A (top) are systematically higher than those from well B (bottom).

7 Conclusion & Future Work

In this work, we detail a characterization of the microseismic domain including data abstraction and description. Based on that, we also explain a set of design requirements and visual representation choices specific to the development of microseismic visualization. We developed a prototype, FractVis, for visual exploration of microseismic data. FractVis is composed of a set of coordinated visualizations that resulted by combining and extending different techniques through an iterative collaborative process with the domain experts. Our implementation is flexible and can adapt to any new microseismic data file. Indeed, we visualized another microseismic dataset using our system (Figure 4) and initial insight has been found.

Since it is an ongoing project, there are many improvements to follow. As future work, we are considering the suggestions provided from the feedback regarding improving the prototype and adding additional important features. Furthermore, we plan to conduct a formal detailed user study in the near future. We are planning to conduct ethnographic sessions with the microseismic domain experts to refine our understanding of their processes and practices.

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