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Interactive Sketch-based Estimation of Stimulated Volume in Unconventional Reservoirs Using Microseismic Data

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SUMMARY

The development of unconventional reservoirs has received tremendous attention from energy companies in recent years. Due to the low permeability nature of these resources, a hydraulic fracturing is often applied to stimulate the near-well region to enable economic production. The injection pressure, as it propagates, creates fractures that generate microseismic events. The monitoring of such events has become an important tool to better understand hydraulic fracture geometry, to estimate stimulated reservoir volume, to refine fracture treatment, and to optimize long-term field development.

In the estimation of Stimulated Reservoir Volume (SRV) from microseismic data, recent literature highlights the importance of using time and uncertainty to achieve a more accurate estimation, as well as the influence of more complex geometries in understanding the microseismic event cloud. However, the current methods do not take any of these factors into consideration.

In this work, we propose two different approaches to estimate the SRV that integrate spatial correlation together with time to obtain more accurate volume estimations. The first method is called alpha-shapes which is a generalization of the well-known shrink-wrap algorithm. The second approach is the density-based region reconstruction which considers the density of the microseismic samples in the space to reconstruct the SRV. The density-based approach uses 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 tool to assist the users in filtering microseismic events that are visibly wrong.

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

1 Introduction

Microseismic events generated during an induced hydraulic fracture treatment are caused by shear slip-pages due to pore pressure changes and altered stresses near the fracture tip (Warpinski et al. (2004)). The distribution of events can provide insight into the geometry of the resulting fracture network. In particular, the location of the microseismic events reveals regions in which the rock has been fractured by the injection of high-pressure fluids. Stimulated Reservoir Volume (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 cloud. In principle, SRV can then be related back to total injected volume and well performance (Mayerhofer et al. (2010)). In conventional reservoirs with high permeability and/or liquid based reservoirs, the microseismic activities exhibit themselves as wide clouds, though the actual stimulated rock is likely much smaller. Single planar fractures and conductivity are mainly the key drivers to stimulation performance in these types of reservoirs (Mayerhofer et al. (2010)). Whereas shale reservoirs have been observed to produce more complex fracture networks and multiple fracture planes. The concept of SRV is therefore useful to describe stimulation performance in these types of reservoirs.

A fracture plane can have a vertical or horizontal orientation which propagates away from the point of origin, e.g. a perforation along a wellbore, and inevitably develops height, length and propagates along a preferred azimuth. In extremely tight reservoirs such as shale, microseismic events typically do not locate very far from the fracture plane. This is especially the case when the reservoir contains a compressible fluid such as gas. Therefore, if a large microseismic event cloud is observed, then the actual fracture network size and geometry can be approximated to be roughly coincident with the volume of the cloud. Thus an estimate of the SRV for an ultra-low permeability reservoir can be directly made from the extent of the microseismic event cloud.

Ultimately, production data is compared to the total SRV and field observations to determine well performance and future field development. Since total SRV is ultimately important for analysis, in this paper we propose two different approaches to estimate SRV which enables the user to account for uncertainty Zimmer (2011) and/or more complex shapes. Current methods do not take these factors into consideration, thus the two presented approaches propose novel techniques for reconstructing the SRV to obtain more accurate volume estimations. Each of the two proposed methods has different properties and can be more suitable for a specific scenario or rock formation being stimulated. Both methods reconstruct the SRV, using different approaches, based on the spatial distribution of the microseismic events and allow more complex geometries to be reconstructed. Besides, one of the described methods is able to include the uncertainty on its formulation.

For calculating the actual volume occupied by the reconstructed SRV we introduce a new method, based on a discrete form of Gauss' theorem, that is both efficient and accurate. Besides, we present a sketch tool to allow the expert to visually filter microseismic events that are outliers. In addition, the system is ported to a multitouch tabletop system to provide a collaborative work environment for the experts.

In Section 2 we describe the proposed methods for reconstructing the SRV and the volume calculation method. Section 3 presents examples of use of the proposed techniques and their behavior. Section 4 presents the discussions about the reconstruction methods and their usage in different scenarios. Finally, Section 5 presents the conclusions.

2 Method and Theory

The methods commonly mentioned in the literature nowadays to reconstruct and estimate the SRV are the binning method and the shrink-wrap method. The binning method maps a set of discrete parallel bins of constant width along the principal fracture direction. The height of these bins are then calculated based on the height of the deepest and shallowest microseismic event within each bin (Mayerhofer et al.

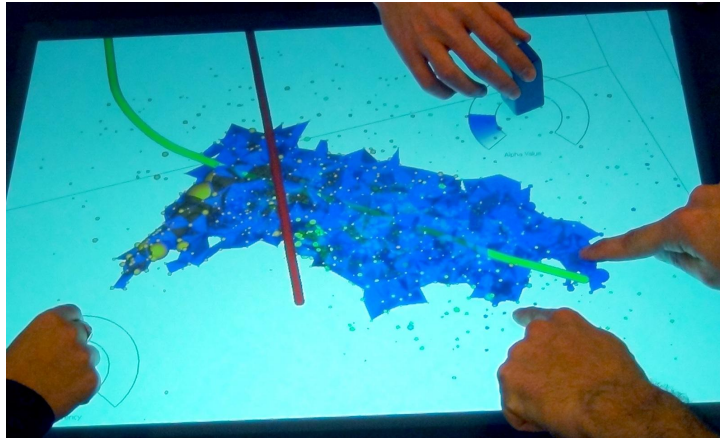


Figure 1 Our system ported to a multi-touch interactive tabletop with three users collaborating in a SRV reconstruction.

(2010)). The shrink-wrap method is basically a convex-hull computation, i.e., it computes a convex polyhedron where all vertices are microseismic events in such a way that all microseismic events are enclosed by this polyhedron. Both approaches have limitations on the geometric shape they are able to reconstruct. The binning method, in its standard implementation, and the shrink-wrap method are only able to represent shapes that are *homeomorphic* to spheres, that means they cannot represent other topologies, e.g., torus like shapes. Furthermore, the shrink-wrap method is only able to represent convex shapes.

In order to solve the aforementioned limitations of the existing methods, we propose a novel way to estimate the SRV. We first define a volume exploiting the user's expertise with visual feedback, then we triangulate this volume boundary and finally use this triangulation to obtain the volume of this reconstructed geometry. The triangulated volumes are constructed using one of the two methods we propose in this work: the first method is called alpha-shapes (Edelsbrunner and Mücke (1994)) which is a generalization of the well-known shrink-wrap method; the second method is called density-based region reconstruction (Vital Brazil and de Figueiredo (2009)) and takes into account the density of the samples (microseismic events) in the space for reconstructing the SRV.

The microseismic data is full of uncertainties and the expert plays an important role filtering the data by removing events. Sometimes, filtering events based on data attributes is not an intuitive task and can become a cumbersome process. Allowing the expert to directly interfere in the SRV reconstruction is also an important aspect. Such interaction can allow the expert to directly remove microseismic events that are visibly wrong. To support these functionalities, we developed a visual selection and removal of microseismic events based on sketches. Besides, such visual filtering of events can be more effective in a collaborative environment where experts can work together as a team discussing and making decisions. With this in mind, we ported our system to a collaborative multi-touch interactive tabletop (Microsoft Surface) Sultanum et al. (2011). The tabletop environment allows the experts to work in a collaborative way sharing insights and manipulating and visualizing the data together. Figure 1 presents three users collaborating in a tabletop using our system.

The following sections describe the SRV reconstruction methods implemented in our system. Section 2.1 presents the Alpha-Shapes method while Section 2.2 presents the other method entitled Density-Based Region Reconstruction. Finally Section 2.3 presents the proposed method for computing the actual volume of the SRV based on a discrete form of Gauss theorem. It is important to notice that this volume calculation method is efficient (linear complexity on the number of faces of the reconstructed SRV) and also accurate.

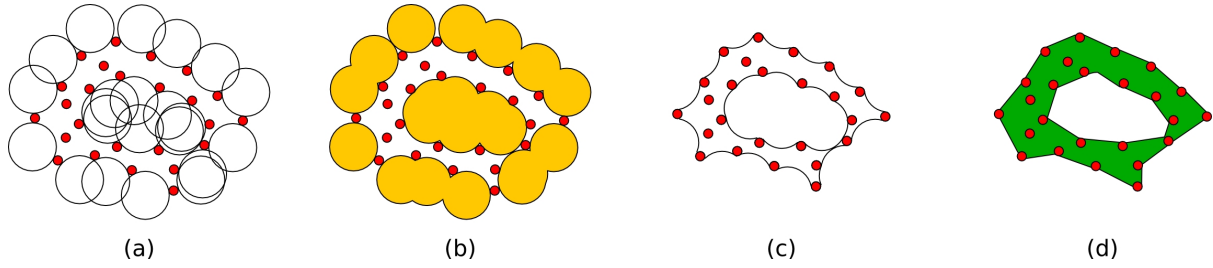


Figure 2 Constructing alpha shapes for a 2D set of points. In (a) the set of 2D points (in red) with the circles not containing the points. In (b) the union of the circles defines the carved areas. In (c) the round boundaries created by the circles are shown. Finally, in (d) the round boundary elements are straighten to create the alpha-shape.

2.1 Alpha-Shapes

Alpha-shapes (Edelsbrunner and Mücke (1994)) is a generalization of the shrink-wrap method (convex hull), which allows non-convex shapes depending on the parameter α . When $\alpha = \infty$ the alpha-shape is the shrink-wrap method. Intuitively, imagine a sphere of radius α carving the whole 3D space where it does not enclose any of the microseismic events. The non-carved volume defines regions that are inside the SRV. Finally, we straighten the boundary where the carving created the spherical shape by creating faces between the boundary vertices (microseismic events). Figure 2 depicts this process in 2D.

The alpha-shapes allows us to create more general shapes with different topologies. Besides that, the geometric shape is intuitive, because it interpolates the points, and is controlled by a single parameter α . However, the alpha-shapes method has some problems such as the generation of non-closed surfaces (depending on the alpha parameter value), sensitiveness to noisy data, and when implemented using weights the results are not intuitive. Depending on the alpha parameter we can have edges that are not shared by two faces constituting an opening in our surface or even an isolated face. To ensure that we have always a closed surface we need to exclude singular faces, i.e., faces that do not belong to any solid. Besides that, it is also interesting to find a minimum alpha parameter that gives a solid with all points either on the boundary or in the interior of SRV. In our system we use the CGAL library implementation of Alpha-Shapes Da and Yvinec (2012). The CGAL implementation provides means of removing singular faces and calculating this minimum alpha value.

2.2 Density-Based Region Reconstruction

This method uses the density of the points (microseismic events) to create an implicit surface that defines the SRV. Given a function $f : \mathbb{R}^3 \rightarrow \mathbb{R}$, an implicit surface is defined as the pre-image of a regular value. We are defining our implicit surface as $S = \{x \in \mathbb{R}^3 \mid f(x) = 0\}$. This implicit surface is defined on \mathbb{R}^3 by summing up a Radial Basis Function (RBF) (with Gaussian kernels) contribution for each microseismic event. The radii of these RBFs are computed based on the density of our microseismic data. More specifically, an iterative process computes the minimum radius for each event to enclose other n events until a given n results in a standard deviation of less than 0.25 for the radii. When this requirement is met the global radius r used for all RBFs will be the average of the radii. The sum of all RBFs will define a function on all \mathbb{R}^3 but we want to give more control to the user of how to define the inside and outside of the volume. For this reason, parameters A_{coeff} and B_{coeff} specify thresholds to define a new function given by the piecewise function:

$$\chi(x, y, z) = \begin{cases} -1 & \phi(x, y, z) \leq A, \\ 2 \frac{\phi(x, y, z) - A}{B - A} - 1 & A < \phi(x, y, z) < B, \\ 1 & B \leq \phi(x, y, z), \end{cases} \quad (1)$$

where $A = cA_{coeff}$, $B = cB_{coeff}$ and $c = \frac{2max\phi(x,y,z)}{\log(N)}$ and N is the total number of microseismic events. The ϕ function will be defined in the next set of equations. The RBF kernel is responsible to include the inverse of uncertainty ζ of the microseismic events in the SRV computation. The following equations define all necessary steps to compute the function:

$$\phi(x, y, z) = \sum_{i=1}^N K_i(x, y, z), \quad (2)$$

$$K_i(x, y, z) = \psi \left(\frac{\|(x, y, z) - (x_i, y_i, z_i)\|}{r} \right) \gamma(i), \quad (3)$$

$$\psi(u) = e^{-u^2/2} \quad \text{(Gaussian Kernel)}, \quad (4)$$

$$\gamma(i) = \frac{\zeta_i - \zeta_{min}}{\zeta_{max} - \zeta_{min}} (\beta - \alpha) + \alpha, \quad (5)$$

where i defines a specific microseismic event, ζ_{min} and ζ_{max} the minimum and maximum values of the inverse of the uncertainty, respectively. The function γ maps and defines the importance of the uncertainty in the volume reconstruction. The α and β parameters are responsible for controlling the influence of the uncertainty in the SRV reconstruction. Equation (5) basically states that the higher the value of α the more important is the uncertainty and the higher the difference $(\beta - \alpha)$ the more important are the events with less uncertainty.

To create a surface that encloses the volume we sampled the space with a GPU (CUDA NVIDIA (2012)) implementation of the described implicit model and used the marching tetrahedra algorithm (Doi and Koide (1991)) to create a surface. The density-based region reconstruction method is robust to noise and naturally maps the uncertainty on the space. Moreover, it is always a closed surface and allows the user to control the final volume using intuitive parameters. A drawback of the method is that its final volume shape could not be intuitive because it relies on the events spatial density. For this reason, our system allows the user to sketch regions where he/she wants to reduce the density of the events. Besides, the reconstruction of the volume using this method can be expensive depending on the number of events. For reconstructing the volume the space has to be sampled in a grid and the evaluation of each sample depends on all microseismic events.

2.3 Volume Calculation

Our SRVs are represented by triangulated closed surfaces. For this reason, an efficient and straightforward method for calculating the the volume occupied by this surface is using the method described in Hughes et al. (1996). This method uses a discrete form of Gauss' theorem for measuring a volume. This theorem relates the outward flux of a closed surface to the volume integral of the divergence of the region inside the surface. The theorem is stated as:

$$\iiint_V (\nabla \cdot \mathbf{F}) dV = \oiint_S (\mathbf{F} \cdot \mathbf{n}) dS, \quad (6)$$

where V is the volume we are interested in, and S is the closed surface bounding V . If we assume the vector field \mathbf{F} to be $F(x, y, z) = (x, 0, 0)$ we will have the following:

$$\iiint_V (\nabla \cdot (x, 0, 0)) dV = \oiint_S ((x, 0, 0) \cdot \mathbf{n}) dS, \quad (7)$$

where the divergence $\nabla \cdot (x, 0, 0)$ is equal to 1, thus:

$$V = \oiint_S ((x, 0, 0) \cdot \mathbf{n}) dS. \quad (8)$$

If we can find a parametrization $s(u, v)$ for S we have:

$$V = \iint_A \mathbf{F}(s(u, v)) \cdot \left(\frac{\partial s}{\partial u} \times \frac{\partial s}{\partial v} \right) dudv. \quad (9)$$

Since we have a triangulated surface we can find a parametrization $s_{T_i}(u, v)$ for each triangle and calculate the volume as a summation of the above integral for each triangle:

$$V = \sum_{i=1}^N \iint_{A_i} \mathbf{F}(s_{T_i}(u, v)) \cdot \left(\frac{\partial s_{T_i}}{\partial u} \times \frac{\partial s_{T_i}}{\partial v} \right) dudv, \quad (10)$$

where, N is the number of triangles of our surface. A triangle T_i can be parametrized based on its vertices \mathbf{p}_0^i , \mathbf{p}_1^i and \mathbf{p}_2^i as follows:

$$s_{T_i} = \mathbf{p}_0^i + u(\mathbf{p}_1^i - \mathbf{p}_0^i) + v(\mathbf{p}_2^i - \mathbf{p}_1^i), \quad \forall u, v \mid 0 \leq u \leq 1 \text{ and } 0 \leq v \leq u.$$

It is important to notice that the vertices \mathbf{p}_0^i , \mathbf{p}_1^i and \mathbf{p}_2^i should define the triangle in a counter-clockwise sequence in order to represent the correct orientation of the triangle, i.e., defining the correct normals of the surface. Using this parametrization in Equation (9) we have:

$$V_{T_i} = \int_0^1 \int_0^u (\mathbf{p}_{0x}^i + u(\mathbf{p}_{1x}^i - \mathbf{p}_{0x}^i) + v(\mathbf{p}_{2x}^i - \mathbf{p}_{1x}^i))((\mathbf{p}_{1y}^i - \mathbf{p}_{0y}^i)(\mathbf{p}_{2z}^i - \mathbf{p}_{1z}^i) - (\mathbf{p}_{1z}^i - \mathbf{p}_{0z}^i)(\mathbf{p}_{2y}^i - \mathbf{p}_{1y}^i)) dv du, \quad (11)$$

where the subscripts x , y and z correspond to the components of the point \mathbf{p} . Solving this integral we have that the volume contribution of the triangle V_{T_i} is:

$$V_{T_i} = \frac{1}{6}(\mathbf{p}_{0x}^i + \mathbf{p}_{1x}^i + \mathbf{p}_{2x}^i)((\mathbf{p}_{1y}^i - \mathbf{p}_{0y}^i)(\mathbf{p}_{2z}^i - \mathbf{p}_{1z}^i) - (\mathbf{p}_{1z}^i - \mathbf{p}_{0z}^i)(\mathbf{p}_{2y}^i - \mathbf{p}_{1y}^i)). \quad (12)$$

Which finally give us the volume of our closed surface:

$$V = \frac{1}{6} \sum_{i=1}^N (\mathbf{p}_{0x}^i + \mathbf{p}_{1x}^i + \mathbf{p}_{2x}^i)((\mathbf{p}_{1y}^i - \mathbf{p}_{0y}^i)(\mathbf{p}_{2z}^i - \mathbf{p}_{1z}^i) - (\mathbf{p}_{1z}^i - \mathbf{p}_{0z}^i)(\mathbf{p}_{2y}^i - \mathbf{p}_{1y}^i)). \quad (13)$$

3 Examples

In this section we present the sketch functionalities that include deleting selected, non-selected, and deleting events based on a percentage value to decrease the density of events in a region. We also present the two proposed SRV reconstruction methods including their strengths and weaknesses.

The deletion of points in a sketched region can be useful for the expert to, based on his/her knowledge, remove events that are outliers. Figure 3 presents the region sketching for removing selected events. Sometimes it can be easier to remove points that are not selected. For this reason, we provide means of sketching a region where all points will be kept while all others will be removed. Figure 4 presents the region sketching for removing non selected events. A different method for removing events can be useful for the SRV reconstruction using the Density-Based algorithm. In this method the user sketches a region and defines a probability of removing points. This method will reduce the density of points in the sketched region and will change the reconstruction of the SRV. Figure 5 presents the sketching of a region for removing about 85% of the events. In addition, we allow the expert to filter the data specifying a range of values of a given attribute of the microseismic events.

When the expert is satisfied with the set of microseismic events, the SRV can be reconstructed using one of the two methods described in this work. Figure 6 presents the reconstruction of the SRV using

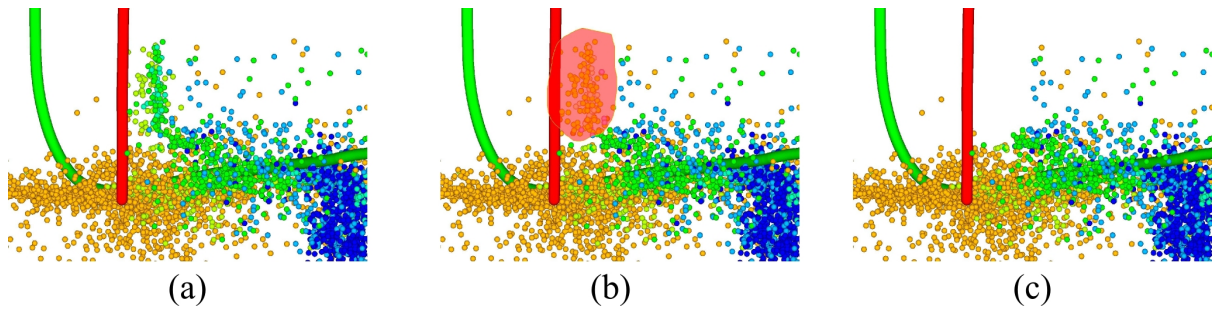


Figure 3 Sketching a region to remove events. In (a) all events before deleting. In (b) region sketched (in red) to remove events. In (c) the final result after removing selected events.

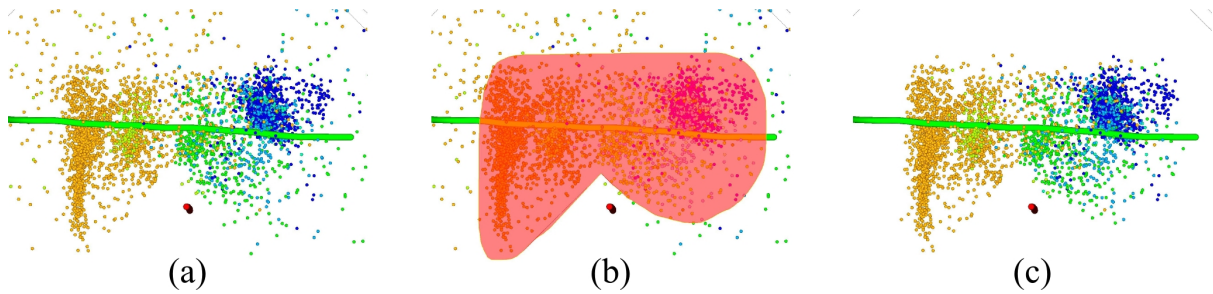


Figure 4 Sketching a region and removing events outside this region. In (a) all events before deleting. In (b) region sketched (in red) to keep events and delete the others outside this region. In (c) the final result after removing non selected events.

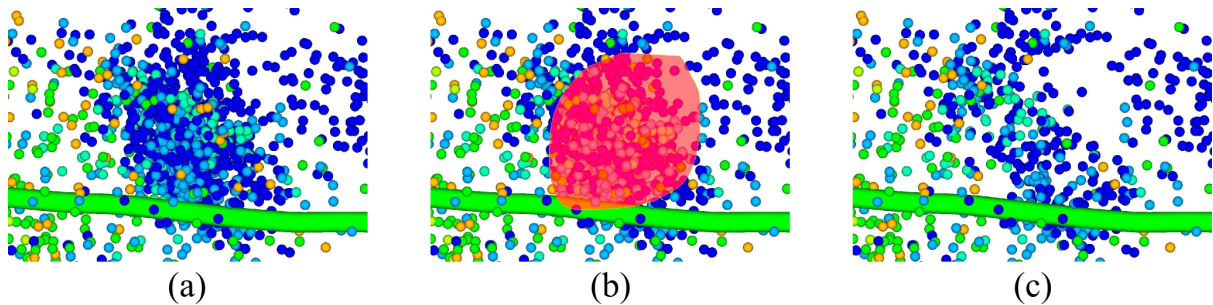


Figure 5 Sketching a region to reduce the density of events. In this example we are removing 85% of the events in the sketched region. In (a) all events before deleting. In (b) region sketched (in red) to remove 85% of events. In (c) the final result after reducing the density of selected events.

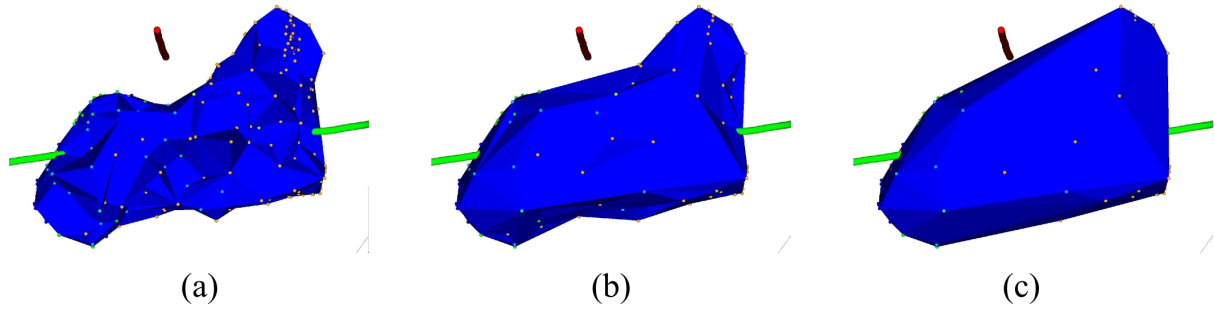


Figure 6 Reconstructing the SRV using the alpha shapes method with different alpha values. In (a) using alpha value of 8699.93 with a reconstructed volume of $7.052 \times 10^7 \text{ m}^3$. In (b) using alpha value of 80385.30 with a reconstructed volume of $1.020 \times 10^8 \text{ m}^3$. In (c) using alpha value of 7.81627×10^8 (which is equivalent to the shrink-wrap method or convex hull) with a reconstructed volume of $1.230 \times 10^8 \text{ m}^3$.

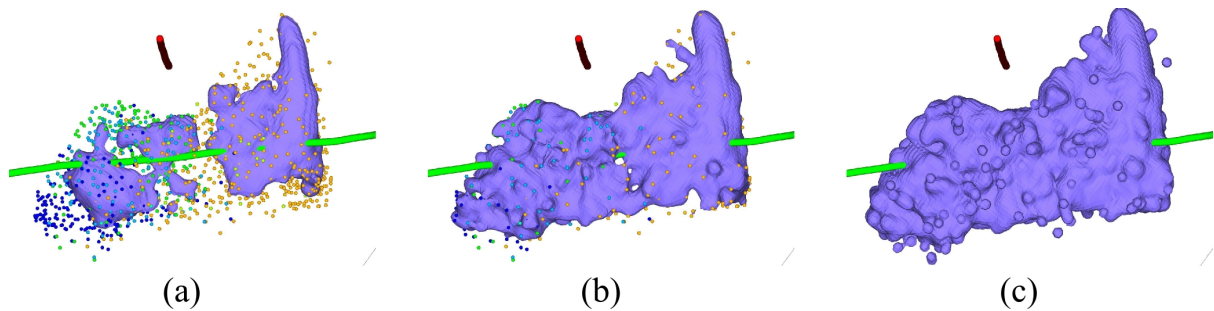


Figure 7 Reconstructing the SRV using the Density-Based method with different values for A and B without considering the uncertainty. In (a) with $A = 2.191$ and $B = 6.467$ with a reconstructed volume of $1.065 \times 10^7 \text{ m}^3$. In (b) with $A = -0.579$ and $B = 3.696$ with a reconstructed volume of $2.531 \times 10^7 \text{ m}^3$. In (c) with $A = -1.520$ and $B = 2.756$ with a reconstructed volume of $4.313 \times 10^7 \text{ m}^3$.

the alpha shapes method. Different alpha parameter values are shown. The first alpha parameter Figure 6(a) is the minimum value that creates a closed surface representing the SRV for the given set of microseismic events. In Figure 6(c) the alpha parameter chosen is the minimum to create the convex hull or shrink wrap of the set of events. The Density-Based method results are presented in Figure 7 without considering the uncertainty. The first example presented in Figure 7(a) is the reconstructed SRV using higher values for A_{coeff} and B_{coeff} . The method is based on the density of the microseismic events and according to Equation (1), the greater the values of A_{coeff} and B_{coeff} the more important is the density for the SRV reconstruction.

The expert is able to guide the SRV reconstruction by sketching regions to remove events. The changes in the microseismic events distribution by this filtering can create different topologies on the reconstructed SRVs. Figures 8 and 9 present the behavior and ability to represent different topologies for the alpha-shapes and density-based region reconstruction methods, respectively. In particular, the results of the reconstruction of the SRV using the alpha-shapes method presented in Figure 8 show its capability of representing general topologies and how this method produces more intuitive results in terms of geometric shape than the density-based method presented in Figure 9.

Despite the fact that the alpha-shapes method produces more intuitive results, the density-based region reconstruction method easily encodes the uncertainty in its formulation. The uncertainty is included in the SRV reconstruction as described in Equations (3) and (5). Figure 10 compares a SRV reconstruction with and without uncertainty using different values for α and β for Equation (5). In Figure 10(a) the

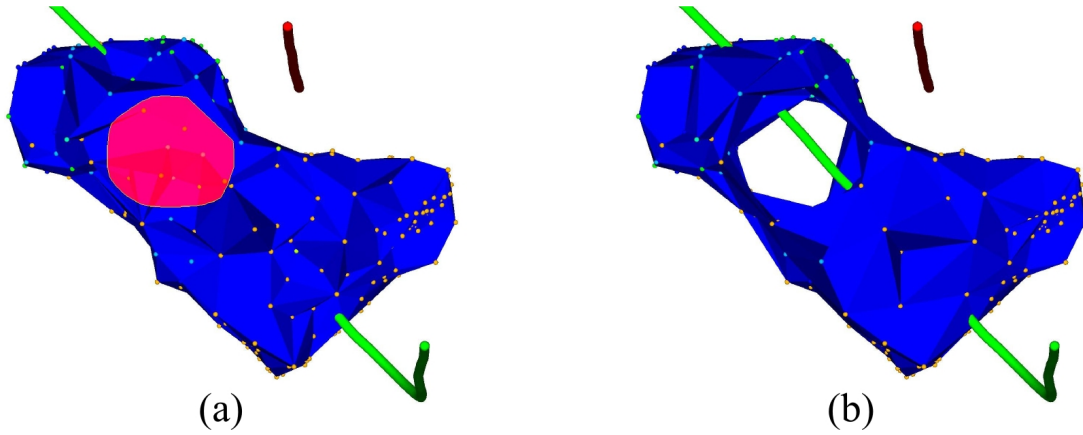


Figure 8 Behavior of the alpha shapes method when removing events. The final SRV reconstructed in (b) has a different topology of the SRV reconstructed in (a). In (a) all events before deleting with a region sketched in red to remove events in that region. The volume of this reconstruction is $7.052 \times 10^7 m^3$. In (c) the final SRV reconstruction after removing the selected microseismic events. The final volume is $6.288 \times 10^7 m^3$.

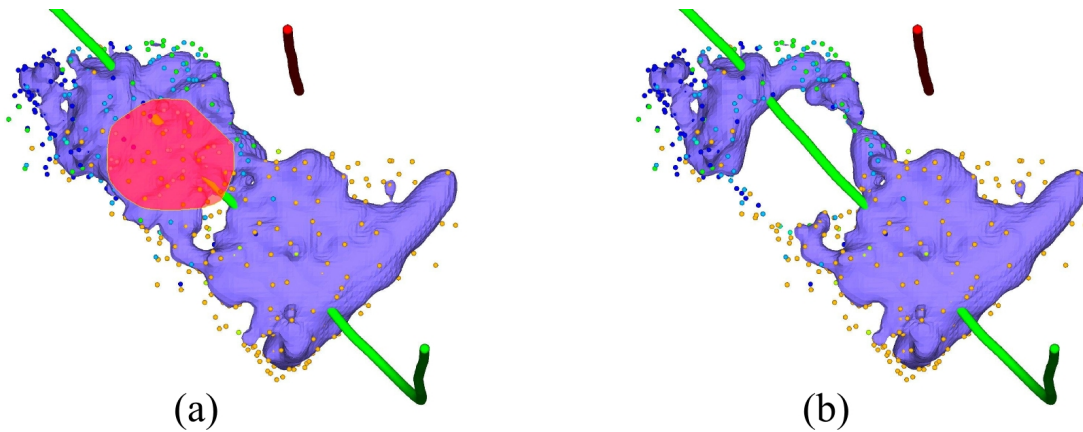


Figure 9 Behavior of the Density-Based method when removing events. In (a) all events before deleting with a region sketched in red to remove events in that region. The volume of this reconstruction is $1.965 \times 10^7 m^3$. In (c) the final SRV reconstruction after removing the selected microseismic events. The final volume is $1.502 \times 10^7 m^3$.

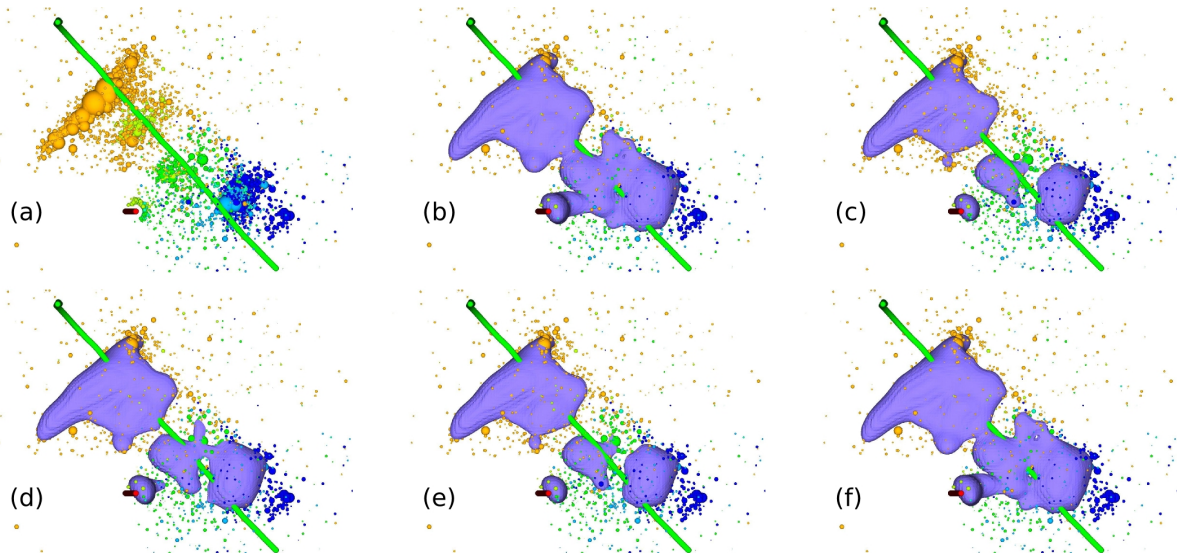


Figure 10 Effects of mapping the uncertainty when reconstructing the SRV using the Density-Based Method. In (a) all events before reconstructing the SRV. Where the smaller the radii the higher the uncertainty of a microseismic event represented as a sphere. In (b) Density-Based Method reconstruction without considering the uncertainty. The volume for this reconstruction is $1.866 \times 10^7 m^3$. In (c) considering the uncertainty with parameters $\alpha = 0$ and $\beta = 1$. The volume for this reconstruction is $1.295 \times 10^7 m^3$. In (d) considering the uncertainty with parameters $\alpha = 1$ and $\beta = 10$. The volume for this reconstruction is $1.522 \times 10^7 m^3$. In (e) considering the uncertainty with parameters $\alpha = 1$ and $\beta = 90$. The volume for this reconstruction is $1.330 \times 10^7 m^3$. In (f) considering the uncertainty with parameters $\alpha = 70$ and $\beta = 90$. The volume for this reconstruction is $1.841 \times 10^7 m^3$.

SRV is reconstructed without considering the uncertainty for comparison purposes. When uncertainty is considered the SRV reconstructions tend to consider more regions with lower levels of uncertainty and leave regions with high uncertainty outside the volume. The values chosen for the α and β parameters would make the uncertainty more or less important for the SRV reconstruction as presented in Figure 9(c,d,e,f).

4 Discussions

Two different approaches for reconstructing SRV were presented. Depending on the level of deformation and amount of stimulated reservoir rock, one method may be more suitable than the other based on the objects they are able to reconstruct and on the interpretability of the microseismic map. However, in order to facilitate the construction of the stimulated volume a certain level of knowledge about the reservoir is required, such as its physical characteristics, geomechanical behaviours and structural properties. Since microseismic events exhibit themselves differently in different reservoir environments, it is important to understand what drives microseismic development especially in gas versus fluid filled reservoirs. For instance, in shale gas formations all events are usually considered for the SRV reconstruction. For this reason, the alpha-shapes reconstruction method would be more appropriate. For the case of sandstone gas formations some microseismic events far from the main fracture are not considered. In such a case, the density based method would give better results for the SRV reconstruction. There are many parameters that control SRV and like any interpretive tool, it is in the users hand to understand not only the strengths and limitations of the data, but of the two methods presented here.

5 Conclusions

In this paper we presented two novel methods for reconstructing the SRV, interactive sketch tools to allow the expert to filter the microseismic events based on his/her knowledge and the system was ported

to a collaborative tabletop environment. The first method, alpha-shapes, takes into account the geometric shape of the event cloud distribution. The second method, density-based region reconstruction, is based on the density of the microseismic events and is able to include the uncertainty of the data in the SRV reconstruction. Both methods, differently from the existing ones in the literature, are able to reconstruct concave shapes with different topologies. To help in the SRV reconstruction our system provides a sketch-based filtering of microseismic events to allow the expert to easily remove events that are visually wrong. Besides that, the system was ported to a tabletop environment which provides means of collaboration between experts working on the same dataset.

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