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Seismic Structure Extraction based on Multi-scale Sensitivity Analysis

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Abstract The exploration of geological composition, e.g. underground flow path, is a significant step for oil and gas search. However, to extract the structural geological composition from the volume, neither the classic volume exploration methods, e.g. transfer function design, nor the traditional volume cut algorithms can be directly used due to its three natural properties, various compositions, discontinuity and noise. In this paper, we present an interactive approach to visualize the structural geological composition with the assistance of multi-scale sensitivity of transfer function. We utilize a slice analyzer to interactively obtain the local transfer function for individual structural geological composition with a carefully designed lightweight transfer function interface guided by the multi-scale sensitivity, which can effectively help the users find the cut-off values of target composition. The final transfer function is shared to 3D volume texture on GPU, and then volume cut methods based on algebraic set operators are utilized to extract the corresponding geological composition in the volume.

Keywords Seismic visualization · sensitivity analysis · volume rendering

1 Introduction

The global demand for oil and gas continues to grow due to the driving of economic growth in developing countries, which requires superior techniques and methodology. Seismic visualization plays an indispensable role in exploring oil and gas. The formation and distribution of gas resource correlate closely with structural geological-composition such as underground flow path, which may influence the position of major subsurface folds and faults [12]. The seismic volume data are collected by sending sound waves into the earth, recording and processing the reflection echoes.

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The seismic volume exploration is challenging due to its natural properties, composition-intensive, discontinuous and noisy. The data may generally consist of a variety of different sedimentary deposits. Therefore, we can neither use transfer function design methods nor employ the existing intelligent volume cut algorithms to extract the structural geological-composition from the volume.

In this paper, we propose an interactive approach to visualize the 3D structural geological-composition by a 2D slice analyzer guided by multi-scale transfer function sensitivity. The contributions in this paper are twofold. First, we carefully design a local transfer function guided by visualized sensitivity. In particular, we use a sensitivity-aware lightweight transfer function to guide the user find the cut-off values with some predicted cues. Second, we propose some GPU-based volume cuts methods based on algebraic set operators to extract the target 3D seismic structure. Specially, we use an automatical volume cut method (named convex-hull cut) derived from algebraic union operator on single-step cut. and then utilize an interactive volume cut approach derived from algebraic intersection operator on single-step cut.

2 Related Works

Visualization of seismic data is challenging, and it has been studied for many years. There have been many advanced techniques proposed recently. In general, typical techniques for seismic data visualization are volume exploration.

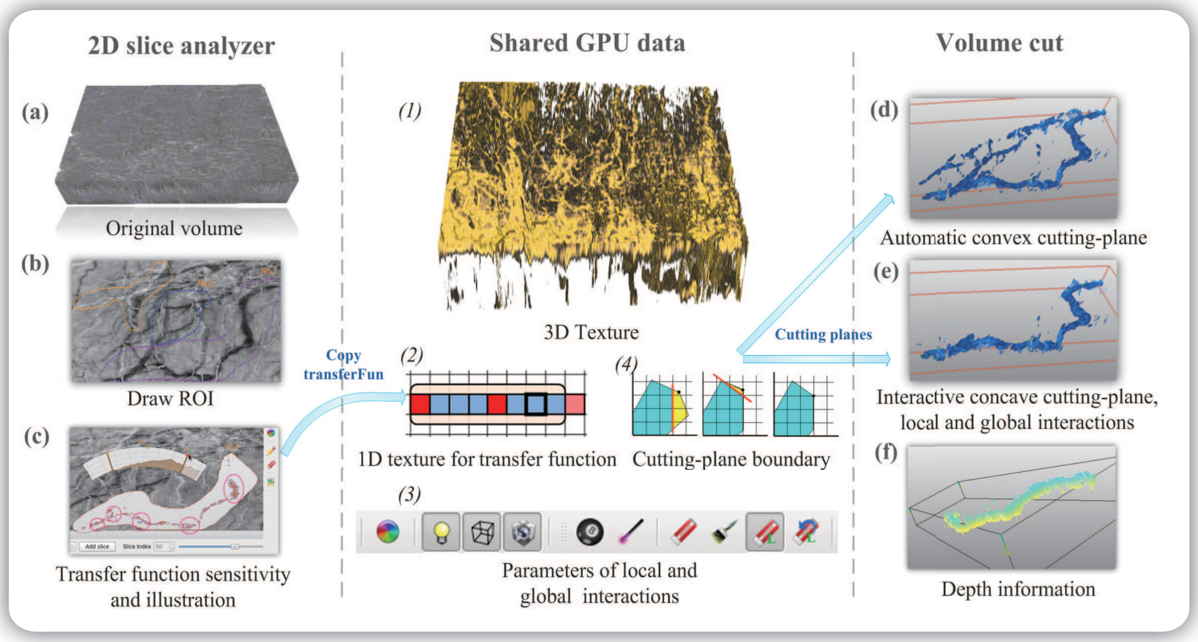


Fig. 1 Exploration workflow and rendering pipeline of our system. (a) Select the axis-aligned slice from the volume. (b) Draw ROI boundary of structural geological-composition. (c) Local light-weigh transfer function adjustment by the guide of multi-scale sensitivity. Some image-based interactions are also allowed to help to obtain the individual transfer function of each ROI boundary, e.g. local transfer function sharing between ROIs or slices. (d) Automatic volume cut with convex cutting-plane. (e) Interactive volume cut with concave cutting-plane to refine the sub-volume. (f) User can also see the depth information after the target is extracted. There are mainly four types of shared GPU data: (1) 3D volume texture, (2) 1D texture for transfer function of the volume, (3) Parameters of volume-based interactions, such as brushing, erasing, lighting etc. (4) Cutting plane parameters.

2.1 Seismic Volume Visualization

Compared to 2D seismic slice analysis, volume rendering can bring more continuous information on the subsurface, and provide more traces and more diverse statistics [2]. As most existing horizon extraction methods only use time-domain data instead of depth-domain ground-truth data, Hollt et al. [8] proposed to real-time compute depth conversion through velocity modeling, and use exploded views to visualize the depth surface deformation. Besides, Amorim et al. [1] developed a system which allows the user to sketch directly over the raw seismic volume to produce some visual simulation results on geological horizons.

Volume cut is the process of cutting volume data into several perceptual or semantic units. The volume cutout approach [13] allows a user to directly interact with rendered images to classify the pixels into foreground set or background set. However, it can be time-consuming and infeasible to cut a noisy volume data such as seismic data because the interactions would be highly ambiguous due to its clutter and discontinuity. Recently, Li et al. [9] proposed an interactive volume cut technique supported by a diffusion equation solver. Their cutout operations are limited to relatively continuous data and need dense sampling when rendering.

Most existing automatic volume-cut techniques are relatively sensitive to the continuity and have limited tolerance of noise. Thus, we can neither use traditional transfer function design methods nor employ the existing intelligent volume cut algorithms to extract the structural geological-composition from the seismic volume.

2.2 Sensitivity-aware Analysis

Sensitivity visualization can imply us some prediction result in advance and guide the user to explore the data efficiently and effectively. The stability of the visualization in data exploration is quite important especially for the case that the visualization require to specify parameter or inputs. Usually, a small change in the parameter values or input can give very different results.

Parameter sensitivity [3] is visualized to allow the user to visually explore how small variations in parameter values affect the output of fiber tracking. Sensitivity can also help analysts to discover local and global trends and find pair-wise correlations between variables in 2D scatterplots. Chan et al. [4] define partial derivatives of two variables in the scatterplot as sensitivity coefficients to predict the positions of interpolated points, and extract a global sense of flow to help analysts discover local and global trends in a 2D projection. But this method has some limitations. The scatterplot only shows the sensitivity with respect to a single variable at a time. Thus, they propose a more scalable version called generalized sensitivity scatterplot (GSS) [5], which compute sensitivity coefficients to provide cues about the way the data scatter in a higher dimensional space.

3 Workflow and Overview

In our work, we use a slice-based analyzer to help extract the structural geological-composition since it is quite difficult to visualize it simply by editing transfer function or performing intelligent volume cut algorithms. Figure 1 shows the exploration workflow and rendering pipeline of our system.

The system consists of two linked views, the *Seismic Volume* view and the *Slice Analyzer* view. The *Seismic Volume* view shows the final volume rendering results and supports some volume-based interactions as shown on the left part of Figure 2a. The *Slice Analyzer* view processes 2D texture based interactions and obtains the transfer function of target geological-composition as shown on the right part of Figure 2.

4 Slice Analysis

2D slice analysis is quite important in seismic visualization. Only 2D data exist in the earliest stage of data collection. When creating illustrations for communication purposes, illustrators make heavy use of 2D slices [11]. Furthermore, it is quite time-consuming and labor-intensive to get a feasible transfer function from the seismic volume when editing the transfer function with try-and-error methods. The initial result of volume rendering with a proper transfer function is shown in Figure 2a. It is pretty hard to find any structural information inside this volume. Thus we carefully design a local light-weight transfer function and visualize the transfer function sensitivity to guide the user find the cut-off value of target geological-composition, the transfer function can be finally shared to the corresponding 3D texture on GPU.

The slice analyzer is mainly composed of a linked dual-widget, raw-data widget (Figure 2b) and working-area widget (Figure 2d). The raw-data widget just shows gray-scale raw data throughout the slice illustration to keep away from introducing uncertainty and distracting the user from the illustration. Moreover, it is also a reference when the user do some interactions in the working-area widget.

4.1 Sensitivity-aware Local Transfer Function

The user can firstly utilize the slider on the interaction control panel (Figure 2e) to select an axis-aligned slice which has a certain region of interest (ROI) for potential structural pattern. Then the user can draw ROI boundary curve with a lasso tool. Each ROI boundary has an individual local transfer function because their valid data ranges vary from place to place, even if their target compositions are identical. The global transfer function widget (Figure 2c) allows to edit the transfer function of the non-ROI area. This widget can be employed to explore the slice in the early stage of illustration and change the contrast between ROI and non-ROI. After ROI boundary is identified, the user can obtain the approximate distribution range of the target geological-composition by simply clicking on the corresponding area in the left raw-data widget. At last, the distribution range of the target geological-composition can be refined through adjusting the light-weight transfer function (Figure 3a). Transfer function is one of powerful visualization components to classify the volume data into several compositions with cut-off value. The local light-weight transfer function here is a simplified version compared to the traditional one. The goal of light-weight transfer function is just to find the cut-off value of target geological-composition within the ROI boundary. Then classify the pixels into two sets, the foreground set and the background set. The highlighted foreground in the ROI shows the extracted target and the transparent background represents other uninteresting geological-composition or noise.

The arc-shaped interface of light-weight transfer function is designed to save space. There are two control points on the outside arc of Figure 3a. The left and the right control points represent the start point and the end point of the cut-off value of the target composition. We can change their values by dragging these two side control points. Follow the operations on multi-touch devices, apart from moving the control point left and right, the light-weight transfer function also supports pinch and stretch operations to narrow and enlarge the range by using the middle mouse button if the mouse is used as controller.

Traditional transfer function adjustment is a typical try-and-error method without any guide. Notice that transfer function design is a quite time-consuming job in volume rendering, especially for the seismic data. The noise and various unknown compositions in the seismic volume will bring much more visual clutter (Figure 2a) compared to traditional volume data (e.g. medical data). So the user may do not know how and where to start the exploration.

For the sake of giving the users guides when adjusting the transfer function, we visualize the cues, which is called multi-scale transfer function sensitivity visualization, to help the user find the cut-off values with a finer granularity. If one of control points of the transfer function is being dragged, the visual changes the user is going to achieve in the next step can be encoded to some specific colors. Figure 4a shows the visualized transfer function sensitivity. The

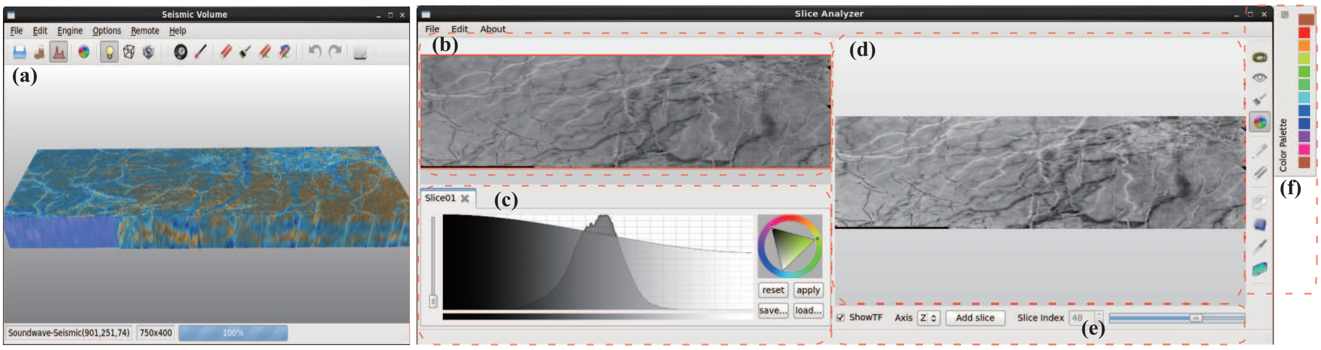


Fig. 2 The overview of the interface. Left: Seismic volume view including interaction toolbar. Right: Slice analyzer view. (a) Original raw-data widget. (b) Global slice transfer function widget. (c) Working-area widget to show slice interpreting results. (d) Interaction control panel to select slice. (e) Image-based interaction toolbar. (f) Color palette.

color stripes outside the right control point consists of three types of colors, each stripe has a span of one, three and five units of intensities, which is so called multi-scale sensitivity. It means if the user further moves the right control point with one unit right, the pixels with green color, whose intensities are between 84.0 and 85.0, will be involved into the foreground set. Likewise, if the user further moves it with three or five units right, the corresponding pixels are rendered as yellow or orange respectively. Again, the color stripes between the two control points in Figure 4b represent that if the user further narrows the range of foreground set with pinch operation on both control points, the pixels with corresponding colors will be removed from the foreground set. The sensitivity also enables sub-pixel adjustment, the changes can be visualized with the support of 2D texture interpolation. Notice that the data is quite discontinuous, the colors in the stripe should be quite different to each other to achieve good perception. With the assistance of multi-scale sensitivity, the user can effectively know when to stop moving the control points without over-adjustment or under-adjustment, and also can predict the cut-off value with a finer granularity.

Meanwhile, the histogram within the arc-shape (Figure 3a) is another statistical information to help to visualize the transfer function sensitivity. It is used to quantize the sensitivity. The bins of the histogram represent the number of involved pixels when the control points are dragged to the corresponding positions. For example, the current value of right control point is 83.0 as shown in Figure 4. If the control point is moved right to get a new cut-off value such as 76, the integral value from the current position to the new position is the total number of pixels would be increased into foreground set of the current ROI. Likewise, if the right control point is moved left to get a new position, the integral value from the current position to the new position is the total number of pixels would be removed from the foreground set. We also employ horizon graphs [7] to render histogram curves to save space as shown in Figure 3a. Both sides of the

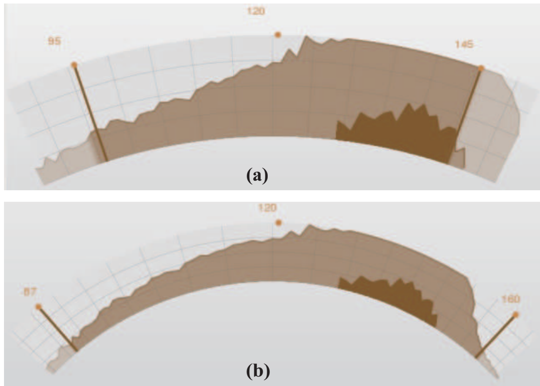
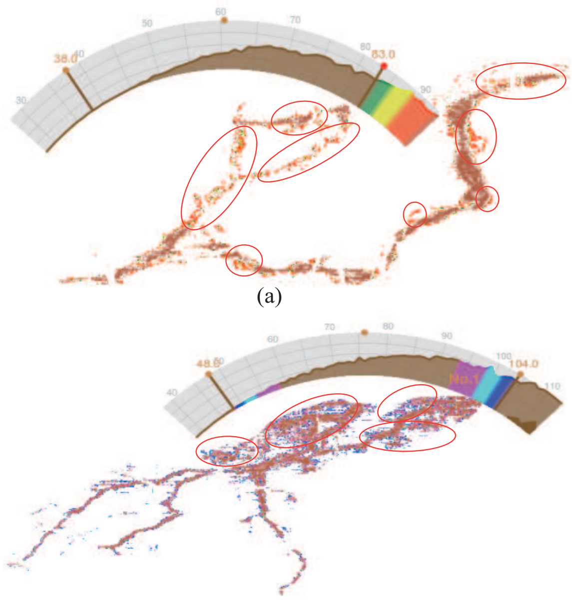


Fig. 3 Local light-weight transfer function for ROI (a) Light-weight transfer function with sensitivity histogram. The histogram within the arc-shaped interface is used to quantize the transfer function sensitivity. (b) Logarithm-based coordinate mapping to enlarge the visual scope of the middle values.

arc-shaped interface are expanded outwards to get enough extra space to show histogram curve around the current control points as shown in Figure 3a. This extra histogram curve can provide the sensitivity information when the user want to enlarge the distribution range of the target composition, for example, move the left control point left, right control point right or stretch two side control points outwards.

Finally, we utilize a logarithm-based coordinate mapping to provide a Focus+Contex effect (Figure 3b) since the middle coordinates should be highlighted and then decrease the operation granularity. From the operation point of view, this coordinate transformation is also a method to decrease the operation sensitivity. In order to specify the ROI boundary to contain potential target pixels as most as possible, we allow the user to edit the ROI boundary points to redefine their boundary.



(a)

(b)

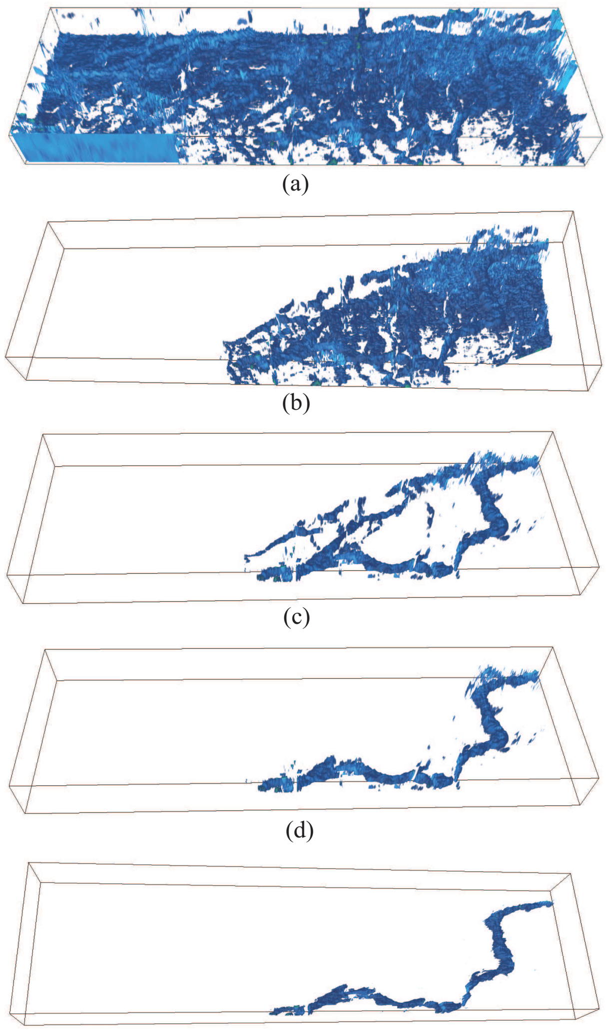
Fig. 4 Transfer function sensitivity: (a) The color stripes outside the right control point encode the corresponding pixels will be involved into foreground set if the user further drags the right control point right to enlarge the range of cut-off value. (b) The color stripes between two control points encode the corresponding pixels will be removed from the foreground set if the user further pinches the two control points to narrow the range of cut-off value.

5 3D Geological-composition Extraction

After 2D slice analysis, the volume transfer function can be achieved from the slice analyzer to specify the cut-off value of target geological-composition. The result of applying the transfer function on the corresponding volume is shown in Figure 5a. We can see little structural information at this stage since there is too much visual clutter due to noise and other uninteresting compositions.

To further remove the other uninteresting composition outside the ROI boundary, we propose four steps to extract structural geological-composition.

Firstly, we use an automatic method, convex-hull cut to cull the volume with limited number of cutting planes. Most sub-volumes containing uninteresting compositions are cut by convex-hull cut as shown in Figure 5b. Nevertheless, the clutter around the target is still too much, thus we secondly perform an interactive method, depth cut to remove the uninteresting sub-volume in depth direction (Figure 5c). The manipulation of this step is quite convenient since the system will guide the user to rapidly detect the depth range of the target by a proper lighting. Thirdly, we design another interactive cut to refine the current sub-volume. The user only need to input three points on the slice to form a fold line, which is used to derive the cutting plane to cull the uninteresting sub-volume around the concave area of the target (Figure 5d). Lastly, we provide a coupled eraser of global-field and local-field (voxel-based) to denoise. The extracted geological-composition structure is shown in (Figure 5e).



(a)

(b)

(c)

(d)

(e)

Fig. 5 3D geological-composition extraction steps. (a) Apply transfer function copied from slice analyzer on the volume. (b) Automatic convex-hull cut to extract the sub-volume. (c) Interactive volume cut: depth cut. (d) Interactive volume cut: denoise. (e) Voxel-based eraser to denoise.

5.1 Volume Cuts

For seismic volume rendering, we use GPU-based pre-integrated ray casting [10] to render the seismic volume. In order to get some relatively complex shaped sub-volume, we propose a GPU-based volume cuts algorithm based on one or multiple single-step cut with the assistance of algebraic set operators. The single-step cut is similar to view frustum culling.

Given n cutting planes $C_1, C_2, \cdots, C_i$ ($1 \leq i \leq n$):

– $\bigcap_1^n C_i$: *Intersection Operator*. Only the fragments outside of all these *n* cutting planes will be culled.
– $\bigcup_1^n C_i$: *Union Operator*. The fragments just outside one of these *n* cutting planes will be culled.

We implement an automatic GPU-based volume cut, the convex-hull cut, which at most result in only eight cutting planes. We first detect the 3D convex hull of the volume from the ROI boundary point set. After the cut, the uninteresting composition outside the ROI boundary can be removed. The small number of cutting planes make the volume exploration smooth when the hardware configuration is relatively poor.

In addition, we provide another interactive cut to refine the sub-volume after above-mentioned two steps. The clutter hidden in the concave area of the target can be eliminated after this interaction process. The user only needs to input three points on the slice by mouse-click to form a fold line (two line segments), which is used to derive the cutting plane to remove the noise around the concave area of the target, the result is shown in Figure 5d. Theoretically, the two line segments represent two single-step cut, which are combined into one cut by *Intersection Operator*.

6 Evaluation and Results

Our domain expert partners have used our slice analyzer to extract the target structural geological-composition. They really appreciate the carefully designed interface of local light-weight transfer function, which helps them rapidly visualize different geological-composition with different local transfer functions, and further illustrate the seismic data for communication purposes. They were able to extract the target structure in a shorter time compared to the manual interpretations. At last, they also suggest we integrate the real-world map into our system for the future work to better assist them to analyze the spatial attribute of the seismic data. We also ask several students in our lab to evaluate this system, they can also efficiently visualize the geological-composition after a brief introduction. Besides, most of the students agree that the visualized transfer function sensitivity can effectively help them edit the transfer function since it give them feedback in advance.

The dataset measures $901 \times 251 \times 74$ voxels and covers an area of roughly 12.7×3.5km. The sampling rate in depth was 10ms. The process of rendering and cut are carried out on DELL T3400, with CPU using a dual-core E4600 at 2.40Ghz, 1.5GB of main memory, and NVIDIA Geforce GTX 275 GPU with 896MB of total memory. The rendering process is smooth enough to provide us with real-time interactions on DELL T3400 due to GPU acceleration.

6.1 Sensitivity-aware Transfer Function

In many cases, it is impossible for the user to predict the cut-off value of transfer function, one possible solution is to find it in try-and-error method, but it is aimless and sometimes may mislead the user.

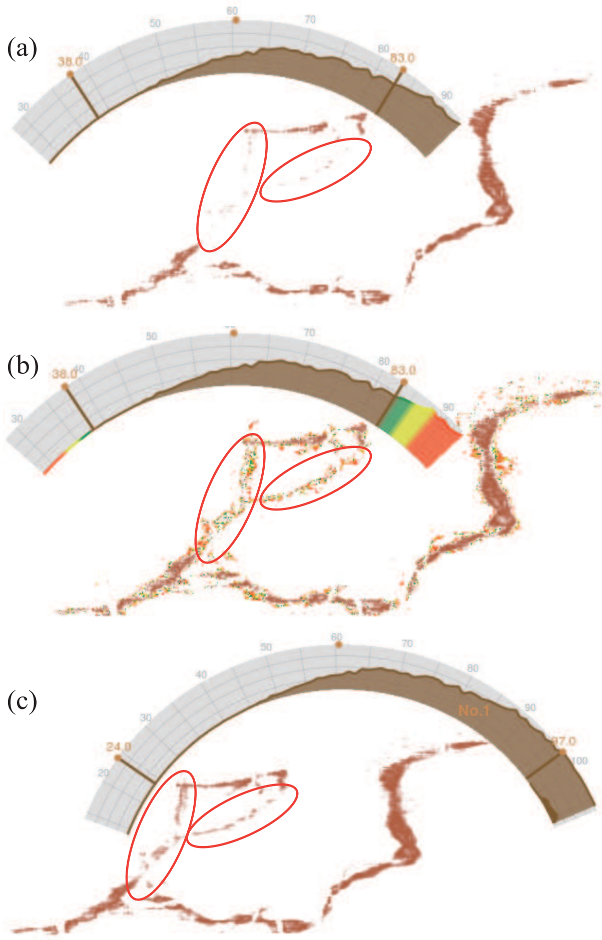


Fig. 6 (a) Transfer function adjustment without multi-scale sensitivity. (b) Stretch operation with multi-scale sensitivity to find implicit cut-off values. (c) Result after the guidance of multi-scale sensitivity.

Figure 6a shows the case of adjusting transfer function without multi-scale sensitivity. The current cut-off value is from 38.0 to 83.0. It is impossible for the user to predict that there are some extra pixels concealed in the red circle should be involved into the foreground set, which may mislead the user that it is already the final result and stop dragging the control points. However, the visualized multi-scale sensitivity can guide the user when to stop moving the control points to find a good result. The multi-scale representation can provide a finer granularity of controlling. The pixels in the red circles in Figure 6b can be involved into foreground set efficiently with the multi-scale sensitivity. It is worth mentioning that the introducing noise can be removed by the eraser

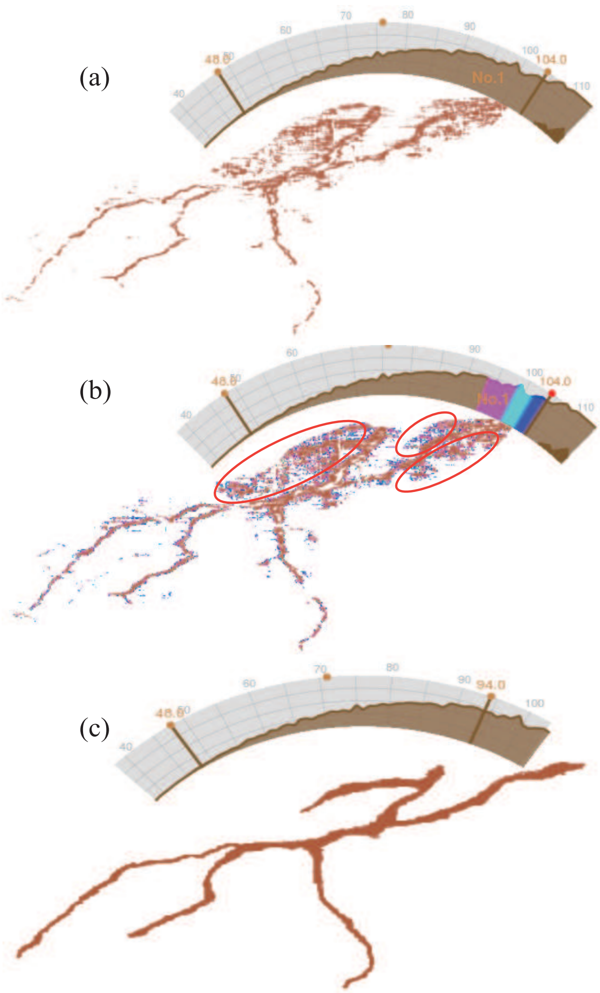


Fig. 7 (a) Transfer function adjustment without multi-scale sensitivity. (b) Move the right control point left to narrow the range of cut-off value to denoise. (c) One possible result after the sensitivity-aware adjustment and some interactions e.g. interpolation and eraser.

when adjusting the transfer function. After further adjusting the control points with stretch operation, the cut-off value from 24.0 to 97.0 in Figure 6c is a more reasonable result compared to Figure 6a since the pixels in the red circles are also the target structural composition according to the domain experts.

Besides, the user can also strike a balance between getting a precise cut-off value and denoising. In many cases, it is hard to find a good cut-off value as shown in Figure 7a due to the noisy seismic data. The user can further move the right control point left to remove the large piece of noise in the red circles in Figure 7b. Figure 7c is a possible result when the user move the right control point from 104.0 to 94.0. It is notice that the result in Figure 7c is refined by interpolation and eraser operation. Thus, with the guidance of visualized multi-scale sensitivity, the user can get a tradeoff between finding a more precise cut-off value and denoising.

After many tests by the students, we can reach an agreement that the histogram in the light-weight transfer function can imply the user to adjust the transfer function with proper granularity and guide the user to move left or right in the initial stage of adjustment. The higher the histogram value is, the more pixels will be involved, and the finer granularity is required.

6.2 Interactive Volume Exploration

A set of global-based volume interactions are integrated into the system WYSIWYG [6]. The limitation of the toolkit WYSIWYG is that most of their interactions are global or topologically global since they just change the transfer function in global field or topologically global field. In this work, we have implemented some global-based interactions following the system WYSIWYG e.g. eraser and brush. In order to make up for the shortcomings of their tools, we also implemented some voxel-based interactions to explore the extracted volume. For example, we implement a local-field eraser to remove some isolated distribution noise after the convex-hull cut and interactive cut. Figure 5e shows the visual result by the refinement of local-field eraser. For the sake of viewing the context information of the extracted geological composition, we use Focus+context technique to further explore the final volume. In particular, we assign the culled volume a controllable opacity to visualize the context structure (Figure 8). This technique may bring users some important information around the focused area.

Some exploration results are shown in Figure 9. The corresponding structural geological-composition are extracted by automatic convex-hull cut and interactive cut, then further refined by local-field eraser and lastly explored by global-field brush.

7 Conclusions and Future Work

In this paper, we propose an interactive approach to visualize the 3D structural geological-composition with the assistance of multi-scale sensitivity to address the natural problems of seismic data. A 2D slice analyzer is used to obtain the cut-off values by a light-weight transfer function interface guided by visualized multi-scale sensitivity. The transfer function sensitivity can effectively and efficiently help the user find the cut-off value. Then we use the analyzer to automatically obtain the convex-hull of the sub-volume to perform volume cut derived from a union operator on single-step cut, and design an interactive volume cut method to refine the sub-volume. The extracted sub-volume can be further explored by local-field and global-field interactions.

However, there are some limitations of this work, which are meantime our future work. Firstly, the extracted 3D struc-

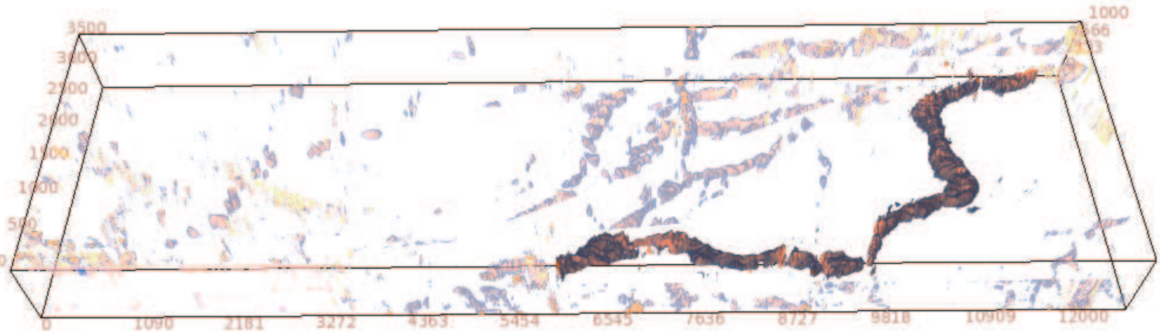


Fig. 8 Volume exploration by Focus+context technique. Brushing is employed in this case to give new colors to the extracted volume.

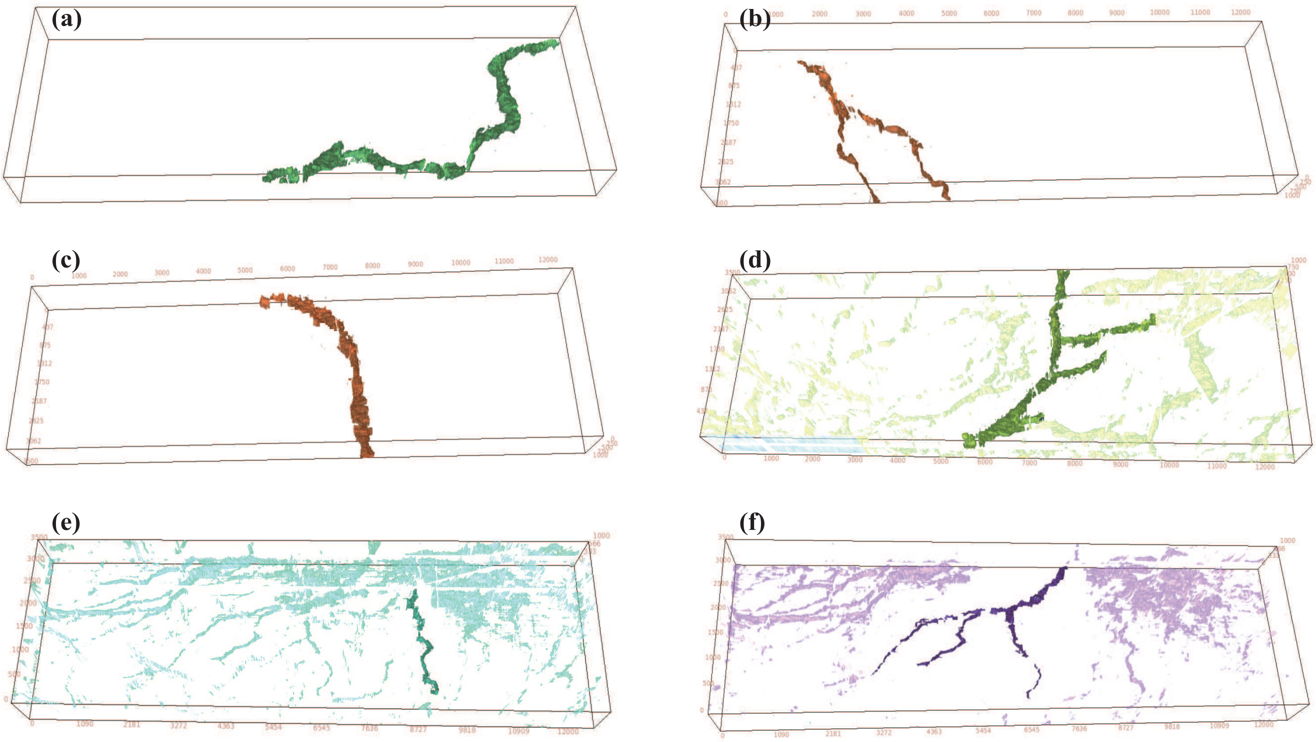


Fig. 9 Six exploration cases of the extracted volume (Coordinate unit: meter). Result without coordinates (a). Results with coordinates (b) and (c). Results with Focus+context techniques (d), (e) and (f).

tures are discontinuous due to the natural properties of the raw data. The surface of the sub-volume should be further smoothed by interpolation and visualized through other visualization techniques. Secondly, it lacks of some automatic methods to guide the user to find ROI area at the earliest stage. In our future work, we will solve these problems through utilizing image processing algorithms and other visualization techniques. Furthermore, we will integrate the real-world map into our system to assist the geological experts to analyze the spatial attribute of the seismic data.

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