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Sketch-Based Slice Interpretative Visualization for Stratigraphic Data

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Abstract. *In this article, the authors propose a stratigraphic slice interpretative visualization system, namely slice analyzer. It enables the domain experts, i.e., geologists and oil/gas exploration experts, to interactively interpret the slices with domain knowledge, which helps them get a better understanding of stratigraphic structures and the distribution of the geological materials, e.g., underground flow path (UFP), river delta, floodplain, slump fan, etc. In addition to some domain-specific slice edit manipulations, a sketch-based sub-region partitioning approach is further presented to help users divide the slice into individual sub-regions with homologous characteristics according to their domain knowledge. Consequently, the geological materials they are interested in can be extracted automatically and visualized by the proposed geological symbol definition algorithm. Feedback from domain experts suggests that the proposed system is capable of interpreting the stratigraphic slice, compared with their currently used tools.* © *2019 Society for Imaging Science and Technology.*
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1. INTRODUCTION

The U.S. Energy Information Administration released the report "International Energy Outlook 2016" [1]. According to the report, liquid fuels, natural gas, and coal will account for 78% of the total world energy consumption in 2040. Petroleum and other liquid fuels remain the largest source of energy.

Stratigraphic data visualization and analysis can help domain scientists to study the distribution of petroleum or gas. The stratigraphic data in this article is seismic data. The basis of seismic reflection investigation is measuring the time taken for a seismic wave to travel from one location to another [2]. Planning of reservoir valorization usually starts by creating a model of the subsurface structures, the seismic interpretation [3]. Seismic interpretation and visualization are beneficial to the discussion and knowledge dissemination among peer experts.

Visualization has strong advantages and great potentials in complex data analytics, such as seismic data, ground penetrating radar data, oil reservoir data, etc. It provides a visual encoding to help users get further insight into revealing more information presented in the data. It assists users in performing effective analytics by providing means of various human–computer interactions. Seismic visualization, especially for the stratigraphic volume visualization, plays an indispensable role in exploring oil and gas [4].

The seismic data have three intrinsic characteristics [5], i.e., it is noisy, discontinuous, and with low resolution. It is challenging to interactively illustrate the seismic data due to the above characteristics, which often result in that most traditional methods do not work well for seismic data [5]. For example, transfer function design [6, 7], volume cut [4], and graph-cuts-based segmentation [8, 9] are often difficult to be directly applied in exploring and visualizing the features the users are interested in.

Users of this work are the geologists in Research Institute of Exploration and Development, PetroChina. According to their domain knowledge, slice interpretation can provide a professional view about the distribution of the stratigraphic structures, e.g., the under-ground flow path, river delta, crevasse splay deposits, floodplain, raided river channel, slump fan, shore-shallow lake, etc. These materials are closely related to the distribution of oil and gas. Besides, slice view can better reveal the pattern and shape of an individual geological material, compared with the three-dimensional (3D) view seismic visualization. The reason is that the occlusion effect in 3D environments has a detrimental impact on tasks involving discovery, access, and spatial relation of objects in a 3D visualization due to in-depth perception [10].

According to the discussion with the domain scientists, their currently used approaches to extracting and visualizing individual geological materials are cumbersome; the designed interactions are hard to manipulate. It either often takes more than one hour to interpret a slice or the interpreted result is not professional enough due to some inherent data characteristics. According to the descriptions presented by domain scientists and the inherent characteristics of seismic data summarized in the existing work [4, 5, 11], the seismic data are often noisy and discontinuous and with low resolution. The data characteristics are illustrated as

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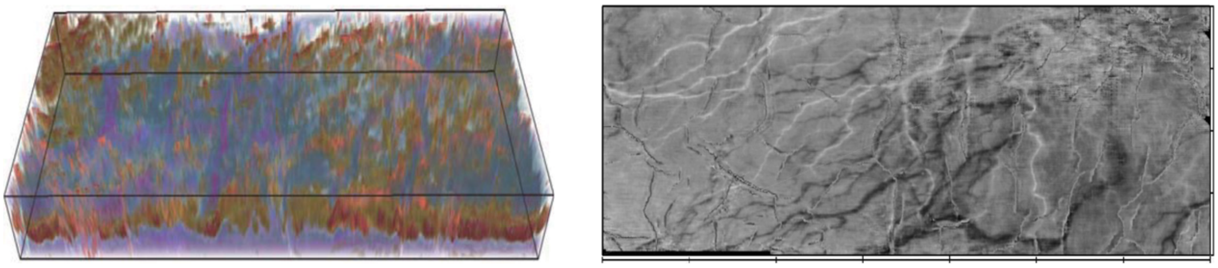


(a) (b)

Figure 1. The seismic data are often noisy and discontinuous and with low resolution and feature locality [5, 11]. (a) A 3D rendering result of a raw stratigraphic data and (b) a 2D slice of a general stratigraphic data. It is easy to find that the stratigraphic data are noisy and discontinuous compared with the traditional medical volume data scanned by CT/MRI devices.

shown in Figure 1. The intensity range, density gradients, and feature point distribution pattern varied among individual UFP structures in one stratigraphic data.

Furthermore, the existing stratigraphic partition approach is also not user-friendly. In this article, therefore, we design a stratigraphic slice interpretation system, namely slice analyzer, to edit the raw stratigraphic data into professional slices, which can be further analyzed by the users. The results interpreted by the slice analyzer are beneficial to their discussion and knowledge dissemination among peer experts. The feedback from domain experts suggests that the proposed system is capable of better interpreting the stratigraphic slice into professional results.

2. RELATED WORK

The most related work can be categorized into two types, such as the interpretative visualization and sketch-based seismic visualization. The work on interpretative visualization can be further categorized into two types, horizon visualization and faults visualization. The work on sketch-based seismic visualization can be further classified into sketch-based illustration and geological storytelling.

2.1 *Interpretative and Illustrative Visualization*

Seismic interpretation is an error-prone and complex task, which often results in hours of work and needs to be manually repeated [3]. It needs advanced techniques to interpret the seismic data. Interpretation automation is different from automated interpretation. The goal of the former is to build a tool to improve the quality and turn-around time for interpretation, while the latter implies a promise of providing an interpretation without human intervention [12].

Most of the existing seismic data visualization works [3, 13–16] lay emphasis on the extraction and visualization of horizons and faults. In geology, faults and horizons are central subsurface structures. The layer-like structures and horizons are the surfaces of the earth. They separate one layer from another under the surface of the ground [17, 18]. These vertical discontinuities of layers are well-known as faults in geology [17, 18]. Using the capabilities of the graphics processing units, 3D horizons and faults can be visualized through efficient volume rendering algorithms based on a pre-integration of the transfer function, which makes it possible to visualize iso-surfaces interactively [19]. Geological illustrations in text books try to convey horizons, faults, and other stratigraphic structures of the Earth by using different artistic expression techniques. Patel et al. [17] propose an approach to render faults, horizons, and other structures of the earth illustrated in text books. They further propose a series of approaches [20–22] to illustrate the seismic data, e.g., the deformed texturing, line transfer function, the texture transfer functions, etc. Hollt et al. [3] proposed an interactive workflow for horizon interpretation based on well positions, which include additional geological and geophysical data captured by actual drillings.

Nevertheless, few works focus on specific stratigraphic structure extraction and visualization. Stratigraphic structures, i.e., underground flow path, river delta, crevasse splay deposits, floodplain, braided river channel, slump fan, shore-shallow lake, etc., are different from seismic horizons and seismic faults as mentioned above. For example, underground flow paths are ancient underground flow paths in geological formation. They play significant roles in the understanding of stratum structure and exploring the distribution of oil/gas because they are closely related to migration and deposition of the oil/gas [4, 5].

For the design of the interactive illustration platform and workflow, collaborative visualization would make multiple users share large datasets and exploration results, simultaneously view visualizations of the data, and interact with multiple views while varying parameters. Such a system would support the collaborations and discussion in both the problem-solving phase and the review phase of design tasks [23]. Collaborative visualization systems are complicated by challenges inherent in the multi-user nature of these applications. Geological storytelling is a typical application of collaborative visualization. It provides an illustrative workflow from the ideas and knowledge in the mind of the geologists. It is beneficial to the discussion and knowledge dissemination among peer experts [24]. Moreover, a data-centric collaborative visualization architecture [25–27] is proposed. It combines the storage of the raw data with the storage of the interpretations produced by the visualization of features for multiple user sessions.

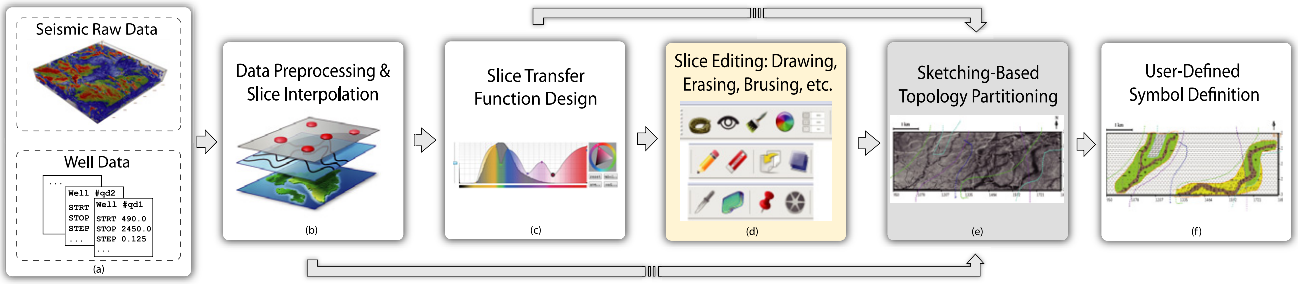


Figure 2. System workflow. (a) The stratigraphic data are provided by the domain scientists. (b) The raw data are pre-processed and re-organized into a volume. The well data are aligned to the volume data. (c) The slice can be illustrated by the slice transfer function. (d) Edited by kinds of basic manipulations. (e) The sketch-based topology partitioning algorithm is designed to divide the slice into individual topology parts. (f) The user-defined symbol definition is used to interpret the stratigraphic data into professional illustration.

2.2 *Sketch-Based Seismic Visualization*

Interaction design of seismic interpretation is vital to the user experience. Sketching is a straightforward and efficient interaction scheme. There are a large number of works in interactive modeling of terrains [28]. However, there are few works that address sketch-based modeling for the geological domain.

For example, Natali et al. [29] proposed a sketch-based approach to create the 3D illustrative models in geological text books. They designed sketching operators for expressing folding and faulting processes. For communicating layer properties such as rock type and grain size, the system allows associating user-defined texture to each layer which can be deformed with a few sketch strokes. Furthermore, they also designed an approach [30] based on the composition of two synchronized data structures. In our slice analyzer system, users can use a sketch-based partitioning scheme to partition the slice into several parts according to domain knowledge and then apply a texture replacement algorithm to define texture for non-rectangular texture.

Besides, Lidal et al. [24] presented a sketch-based geological storytelling. Users can create faults and horizons with texture deformation through some sketching operations. They also proposed two approaches to accomplish rapid 3D geological modeling [31]. The ad hoc approach is based on a composition of many specialized modeling functions, while the generic approach provides one powerful, generic modeling function.

3. OUR METHOD

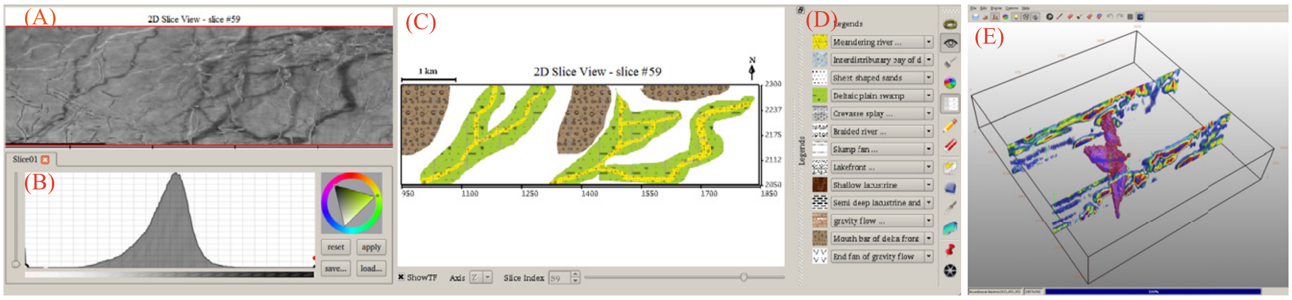
We propose a visualization system, slice analyzer, to interpret stratigraphic data by slice illustration in this article. We design some domain-specific manipulations to edit the raw stratigraphic data into professional slice, which can be further analyzed by the users, e.g., petroleum geologists, gas geologists, prospectors, etc.

Figure 2 shows the pipeline of the proposed method. First, the stratigraphic data are provided by the domain scientists. The stratigraphic data include raw slice data and well data. The raw slice data are pre-processed by re-organizing them into a 3D volume, as shown in Fig. 2b. The well data will be matched onto the stratigraphic volume data according to the slice refraction time. The slice at any position with any angle will be interpolated by the raw slice data. The slice can be edited by the slice transfer function roughly, as shown in Fig. 2c. Different pixels can be encoded into different colors according to the intensity values on the slice. In order to further interpret the slice with more specialized details, the slice analyzer provides basic manipulations including brushing, drawing, sketching, slice transfer function design, and some domain-specific interpretation interactions (Fig. 2d). Then a sketch-based topology partitioning is exploited to segment the slice into individual parts according to domain knowledge (Fig. 2e). Finally, a user-defined symbol definition scheme is proposed to accomplish professional results, as shown in Fig. 2f.

The system consists of a two-dimensional (2D) slice dual view and a 3D stratigraphic view, as shown in Figure 3. 2D slice dual view can provide the original seismic reflection values for reference. Users can edit the slice in the workspace view in the right part. The domain scientists often discuss their projects based on the interpreted slice. During the process of discussion among peer experts, they can analyze the data by exploring the edited professional stratigraphic structures while viewing the original data for reference, as shown in Fig. 3a. The goal of dual view design is to help users rectify the result while interpreting. Uncertainty may exist in the entire visualization. On one hand, as data is transformed, the uncertainties are propagated and aggregated. On the other hand, the uncertainty of the derived data and its sources are mapped to visual representations, which finally populate the view used by the analyst [32]. The design of the dual view just follows the idea initially proposed by Liu et al. [4].

3.1 *Slice Interpretation with Basic Manipulations*

The interactions in the slice analyzer follow overview-to-detail visualization technique, which includes two steps. The first step is to generate a Gaussian-like transfer function by a simple mouse pick-up. For example, the intensity value the user picked up from the view A is I. The function in slice transfer function follows the Gaussian-like distribution $N(\mu, \sigma^2)$, and $\mu = I$. The function will be truncated when x is between $\mu - 2\sigma$ and $\mu + 2\sigma$. That is to say, the



(a) (b)

Figure 3. System overview. The system comprises two views: (a) a 2D slice dual view. The dual view has two parts: the left part shows the original seismic reflection values, which is used for reference, while the right part is the workspace view. (b) A 3D stratigraphic view.

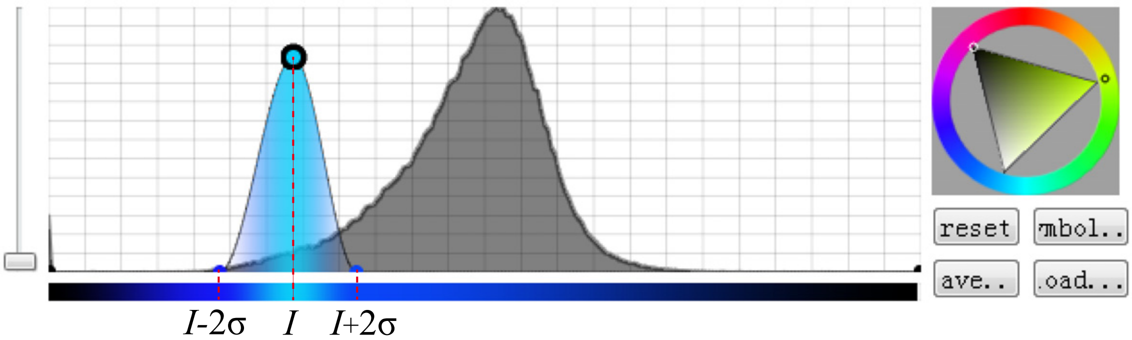


Figure 4. Gaussian-like slice transfer function generation. The slice transfer function can be assigned automatically by a simple click on the left view of the slice dual view. The vertical axis of the slice transfer function is the opacity value of each node.

intensity values between $I - 2\sigma$ and $I + 2\sigma$ are considered as stratigraphic structures in which the users are interested, as shown in Figure 4. The x-axis of the transfer function represents the intensity of the seismic reflection values, while the y-axis represents the alpha value, which shows the opacity value of the transfer function nodes. The background line chart filled with gray is the histogram of seismic reflection values. The histogram bins are utilized to compute the distribution of the intensity values. The Gaussian fall-off values of the transfer function are used to exclude the background pixels. Only the intensity values within the two fall-off values can be kept, which are considered the foreground pixels. The design of the slice transfer function follows the design of volume transfer function [6]. The second step is to adjust the control points to edit the slice transfer function. Users can assign color and alpha value (y-axis) for each control point. That is to say, the Gaussian-like transfer function assignment is an "overview" (coarse-grained) step while the transfer function editing is a "detail" (fine-grained) step.

3.2 *Sketch-Based Sub-Region Partitioning*

According to the requirements of the users, the slice needs to be partitioned into several topological sub-regions. The geological characteristic of each sub-region is varied because different sub-regions are partitioned according to domain knowledge. Therefore, different interactions or specialized symbols should be designed to illustrate the sub-regions.

A straightforward method to partition the slice is to design a lasso selection like the existing approach [4]. However, there are two drawbacks to this approach. First, it may produce many overlaps between different sub-regions because it is hard for the users to draw an exact boundary, as shown in Figure 5a. Second, it will take too much time for the users to partition when there are too many sub-regions.

In order to better partition the sub-regions, we design a sketch-based approach. The sketch allows multiple drawings to intersect with each other, as shown in Fig. 5b. It is more intuitive and efficient for users to do sketching than lasso selection. A modified flood-fill algorithm [33] is employed to compute the topology sub-regions of the stratigraphic slice. Each sub-region corresponds to an individual geological material area. Each geological material area may be illustrated by different interactions.

3.3 *User-Defined Symbol Definition*

After the sketch-based sub-region partitioning, the slice can be divided into several individual sub-regions. Users can define different geological symbols for each sub-region. In the slice, the geological materials which the users are interested in are considered as the foreground, e.g., underground flow path, river delta. The corresponding pixels are foreground pixels. The rest can be considered as the background pixels, respectively. The foreground symbol is different from the background symbol. The foreground should be mapped by its corresponding foreground sym-

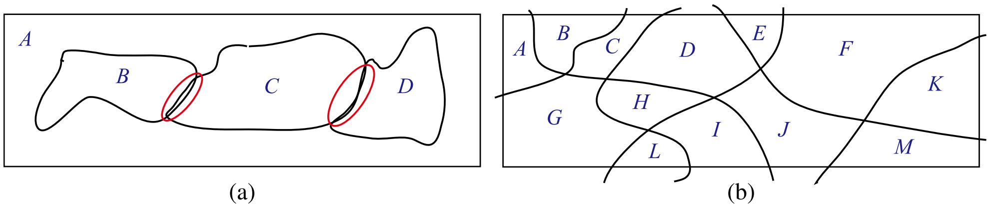


Figure 5. Two partition approaches. (a) The lasso selection to partition the seismic slice into different sub-regions in the existing approach [4]. However, it is difficult for users to draw neighboring boundaries without overlaps. The red circles show the overlapping areas between two lasso selected boundaries. (b) The proposed sketch-based partition approach.

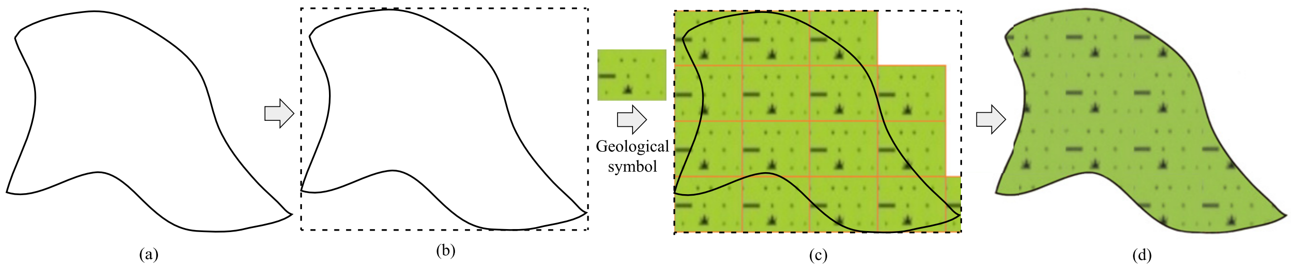


Figure 6. Steps of non-rectangular geological symbol definition. (a) Define a non-rectangular sub-region by sketching. (b) Compute the convex rectangle of the sub-region. (c) Geological symbol definition within the convex rectangle. (d) Keep the pixels within the sub-region.

bols. Similarly, rest of the regions are considered as the background. Generally, the foreground symbols are some professional textures that the users defined, while the background parts can be also filled with a single color.

After the partitioning, all pixels in a slice can further be marked as corresponding sub-region numbers by the flood-fill algorithm. The flood-fill algorithm can pack the topologically connected pixels together. All marked pixels can be replaced with the pixels on user-defined geological symbols. Users can specify any symbol for all sub-regions. For each sub-region, users are required to define its foreground symbols and its background symbols. Then users can get many non-rectangular sub-regions. For a given non-rectangular sub-region shown in Figure 6a, its convex rectangle can be computed as shown in Fig. 6b. The selected new symbol will be mapped onto each sub-region within its convex boundary, as shown in Fig. 6c. Finally, the symbol pixels within the sub-region boundary are kept, while all the outside pixels are removed, as shown in Fig. 6d.

According to the requirements of users, they need to define foreground symbols and background symbols for each topology sub-region. Obviously, a topology sub-region is a boundary with non-rectangular shape. Each non-rectangular sub-region can be considered as a polygon. One solution to define the symbol for all non-rectangular sub-regions is texture mapping. However, there are two drawbacks of texture mapping approach in this scenario. First, it is hard to map rectangular textures onto a non-rectangular boundary. Second, it is difficult to pre-define textures with all scales of color. In this article, we proposed a non-rectangular texture scheme to support user-defined symbol definition by topological partition.

Algorithm 1 shows the user-defined symbol definition algorithm. During the symbol definition process, one of the most important issues is to distinguish the foreground pixels from the background pixels. We propose a convolution-based method to separate the foreground pixels from all the pixels. Specifically, we use a convolution mask with 3×3 neighborhood size to compute the percentage score of foreground pixels, i.e., the score of foreground pixels in the slice. Since we just want to get the average intensity score, all the weights in the convolution mask are assigned to be one by default. If the HSV (hue, saturation, value) distance between a pixel within its neighborhood and the user selected seed point is smaller than a given value HSV_DISTANCE, its foreground percentage score of the center pixel can be increased by 12.5% because there are eight weighted elements in the convolution mask. Furthermore, if the percentage score of the center pixel is smaller than a given value FOREGROUND_SCORE, the current center pixel can be classified into the foreground pixel.

4. EXPERIMENTS AND RESULTS

In our experiments, we test the method on two stratigraphic data provided by the domain scientists. The two testing data in the experiments are ground truth data. The users are familiar with them because they know the distribution of stratigraphic structures in advance. The users can interpret the slice not only by the designed basic interaction operations (e.g., brushing, drawing, sketching) but also through sketching-based sub-region partitioning and user-defined symbol definitions.

Algorithm 1 `symbol definition()` function.

```
function SYMBOL_DEFINITION(subregion_boundary, fore_symbol_img, bkg_symbol_img)
    rect = get_convex_rect(subregion_boundary) ◁ compute the convex rectangle of the topology subregion
    for j=rect.bottom to rect.top do    ◁ From sub-region boundary's bottom to its top
        for i=rect.left() to rect.right do    ◁ From sub-region boundary's left to its right
            if position(i, j) inside the polygon subregion_boundary then
                foreground_score = get_foreground_score(position(i, j), 3, 3)    ◁ Get the average intensity score of each foreground pixel from its 3×3 neighborhood of convolution mask
                if foreground_score ≤ FOREGROUND_SCORE then    ◁ If average intensity score of foreground pixels is larger than a given value, the position(i, j) is a foreground pixel
                    RGB(position(i, j))= RGB(fore_symbol_img, position(j%fore_symbol_img.width(), i%fore_symbol_img.height()))
                    ◁ Set color for the foreground pixel, the symbol texture can be mapped repeatedly
                else    ◁ If it is a background pixel
                    RGB(position(i, j))= RGB(bkg_symbol_img, position(j%bkg_symbol_img.width(), i%bkg_symbol img.height()))
                    ◁ Set color for the background pixel, the symbol texture can also be mapped repeatedly
                end if
            end if
        end for
    end for
end function
```

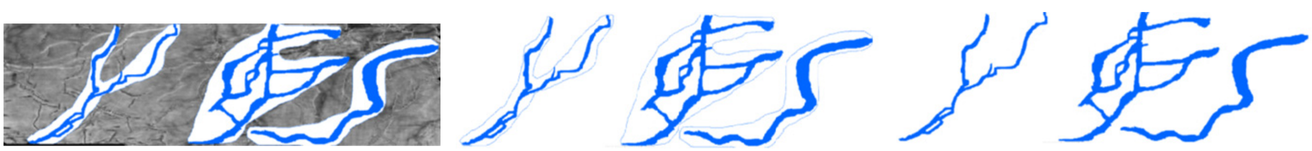


Figure 7. Interpret the slice by some basic manipulations. (a) The foreground underground flow path (in blue) is extracted by slice transfer function, which is auto-generated by Gaussian function $N(I, \sigma^2)$. (b) Edit the background region by changing its alpha value through slice transfer function. (c) Remove the auxiliary lines.

4.1 *Data Description and Experiment Platform*

Two datasets provided by the domain scientists, i.e., dataset I and dataset II, are used to test the proposed approach. The dataset I is 901 × 251 with 21 slices, and the interval between two neighboring slices are 2 ms. The dataset II is 421 × 401 with 90 slices, and the interval between two neighboring slices is also 2 ms. In order to enhance the rendering quality, the datasets will be interpolated in the data pre-processing.

The experiments are conducted on a workstation. The workstation is with the configuration of Intel Core i5-6500 CPUs operating at 3.30 GHz and 16 GB RAM.

4.2 *Slice Interpretation Results by Basic Manipulations*

Generally, users can employ basic manipulations to interpret the slice. For example, users can select some sub-regions by lasso selection and edit it by sketching, erasing, undo, and redo operations, as shown in Figure 7. The slice transfer function can be auto-generated by Gaussian function $N(I, \sigma^2)$. After applying the slice transfer function, the pixels with intensity values between $I - 2\sigma$ and $I + 2\sigma$ will be categorized into foreground sub-regions. After numerous tests, we found that it is optimal to set the σ value as 10. The extracted underground flow paths are shown in Fig. 7c.

4.3 *Results of Sketch-Based Sub-Region Partitioning and Symbol Definition*

The foreground part, i.e., the underground flow paths can be extracted by some basic manipulations provided by the system. However, users are required to draw boundaries of the sub-regions by lasso selection. The sketch-based operations for sub-region partitioning are shown in Figure 8a and Figure 9a. After the sketch-based partitioning, the

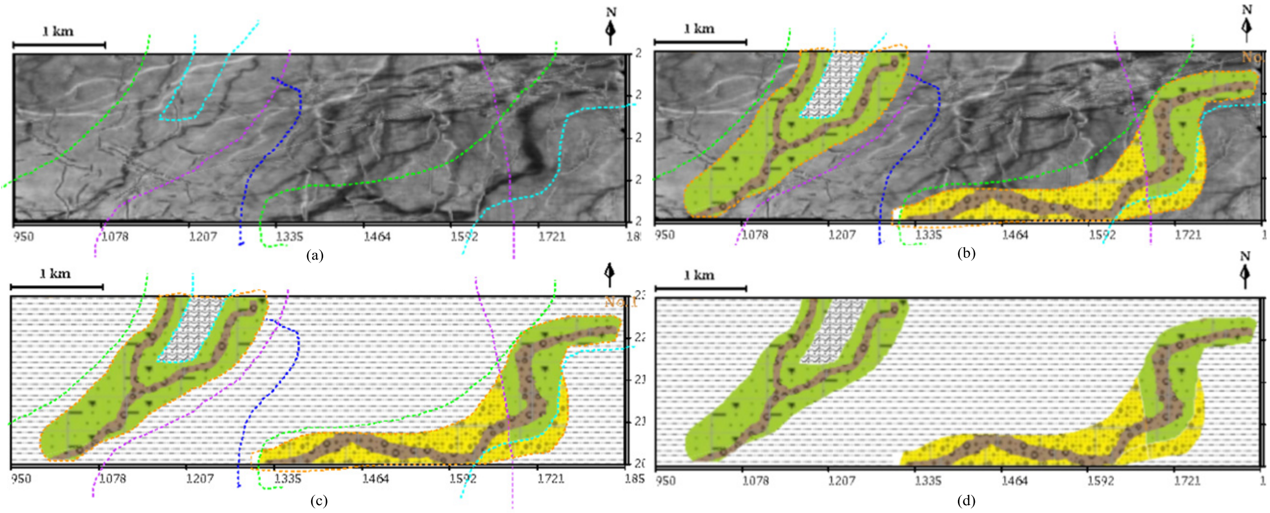


Figure 8. An interpretation process of sketch-based flood-fill sub-region partitioning and symbol definition for dataset I. (a) Sketch-based sub-region partitioning; all pixels in each sub-region are marked as the corresponding sub-region numbers by flood-fill algorithm. (b) User-defined geological symbol definitions for the foreground sub-regions. (c) User-defined geological symbol definitions for the background sub-regions. (d) The final interpretation results with hiding sketching lines.

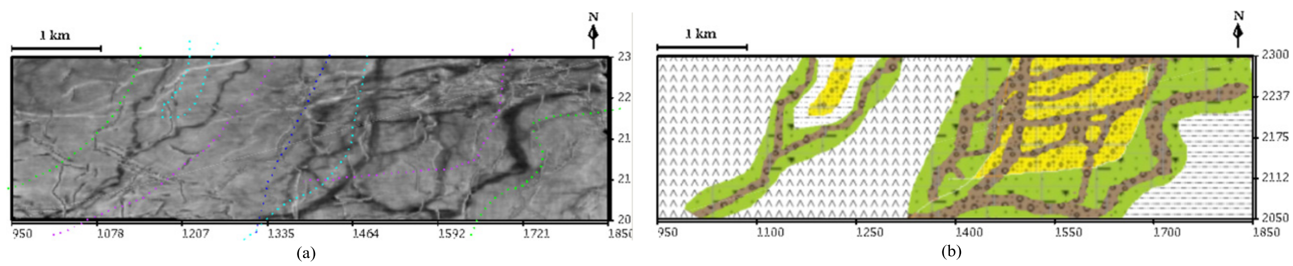


Figure 9. Interpretative visualization results for dataset I. (a) Sketch-based sub-region partitioning. All pixels in each sub-region are marked as the corresponding sub-region number. (b) Geological symbol definitions for the foreground and the background sub-regions.

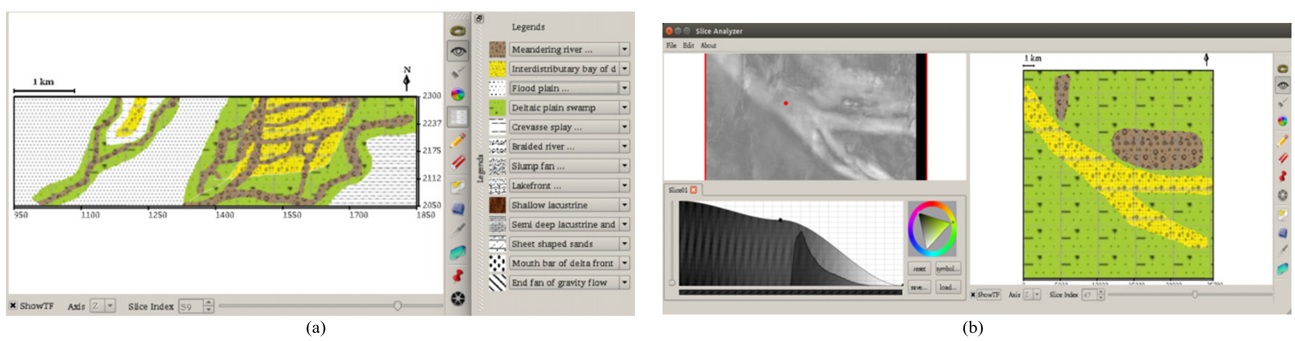


Figure 10. Interpretative visualization results for dataset II. (a) All geological symbols can be defined by the list view in the legend by changing the background symbols. (b) Geological symbol definition.

sub-regions can be achieved by some simple sketching interactions. All the pixels in the slice can further be marked with corresponding sub-region numbers by the flood-fill algorithm. Then all marked pixels can be replaced with pixels of geological symbol textures by user-defined texture replacement. Users can specify any symbol textures for any sub-regions. In each sub-region, it needs to define its foreground symbols and its background symbols, as shown in Fig. 8b and Fig. 8c, respectively. Fig. 8d shows the final interpretation result with hiding sketching lines. In our sketch-based sub-region partitioning scheme, it often takes minutes for users to get a professional result. Therefore, it is much better than the existing approach [4].

Fig. 9 shows another interpretation case of sketching-based sub-region partitioning for dataset I. The users can easily re-define the foreground symbols and background symbols for each sub-region. Figure 10a shows a diverse background symbol compared with Fig. 9b. Furthermore,

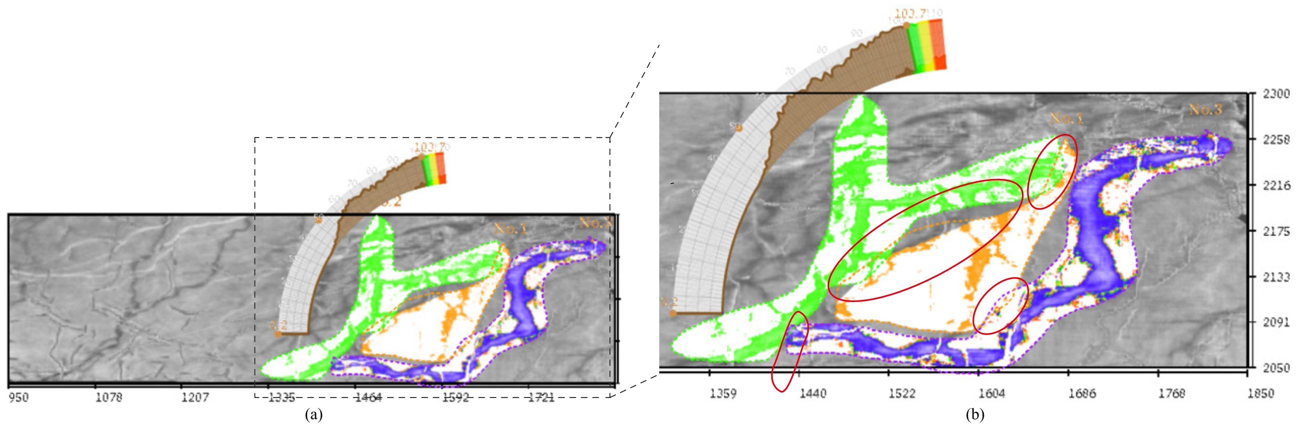


Figure 11. The existing lasso selection approach [4] the domain scientists currently use in illustrating stratigraphic structures, e.g., underground flow paths. (a) It is inaccurate to select the target areas through the lasso selection approach due to the introduced uncertainty. (b) A close-up result. The red circles show the overlapping and holes generated by lasso selection approach, and it will introduce a lot of visualization uncertainty.

Fig. 10b shows the interpretation result of dataset II. It is worth mentioning that the interpretative visualization results in this figure are just some testing examples without domain knowledge.

4.4 *User Assessment*

Most of the existing approaches in seismic visualization can be categorized into two types, i.e., horizon extraction and visualization and fault detection and visualization, as described in Section 2. There is little related work on the visualization of stratigraphic structures, especially for the underground flow paths.

We evaluate the proposed slice analyzer by comparing the results with the existing methods the domain scientists currently use, i.e., the lasso selection method [4]. Figure 11a is the result generated by the existing stratigraphic structure visualization method [4], while Fig. 11b is a close-up of Fig. 11a. It is quite difficult for users to select sub-regions because it is hard to avoid producing overlapping areas and holes, which will introduce too much uncertainty. The red circles in Fig. 11b show the overlapping holes generated by lasso selection. Furthermore, it often takes more than half an hour for users to illustrate the slice through the existing method. The one-curve sketching-based approach and Photoshop-like editing schemes help users save a lot of illustration time.

The users who are the geologists in PetroChina gave us valuable and constructive suggestions. They are experienced and professional in stratigraphic data interpretative visualization. The major feedback is listed as follows:

- "With the help of domain knowledge, the results illustrated by the proposed slice analyzer are professional."
- "The sketching-based 'one-curve' partitioning scheme can save much time for the interpretation."
- "The user-defined symbol definition approach is convenient to interpret the slice and further save much of interpretation time."
- "If the system can recommend several options of sketching paths to choose, it will further save much of interpretation time."
- "It would be better if the system could provide an automatic approach for 3D geological material extraction."

Most of the feedback is positive. The domain scientists think the proposed approach can help them interpret the raw data into professional slices. Additionally, it reduces much of their slice interpretation time. It often takes several minutes, while their existing methods often take tens of minutes. The domain scientists are also concerned about the 3D geological material extraction and visualization.

5. DISCUSSION

The proposed system provides many manipulations to illustrate slices, including sketching, drawing, erasing, brushing, slice transfer function edit, automatic Gaussian-function-based geological materials (foreground pixels) extraction, sketch-based sub-region partitioning, and user-defined geological symbol definition. Nevertheless, there are still some limitations.

First, the slice analyzer still needs the involvement of domain scientists in the analysis process. For example, in the slice transfer function edit, it needs users to pick up a foreground pixel as a seed to generate a Gaussian function to obtain the intensity range. Second, because the stratigraphic data are noisy and discontinuous and with low resolution, the sub-region boundaries are sometimes hard to distinguish for the domain experts, even via the convenient sketch-based partitioning. If the system can recommend several options of sketching paths for users to choose, it would be better to save interpretation time. Third, the 3D stratigraphic visualization is not fully accomplished in this slice analyzer, especially for the 3D geological material extraction. Stratigraphic volume visualization part can be further designed following the WYSIWYG (What

You See Is What You Get) approaches [6, 7] and the stylized volume visualization [34]. The domain-specific language-based approaches [35–37] can be also introduced into the stratigraphic data visualization domain based on some user study.

6. CONCLUSIONS

In this article, we propose a stratigraphic data slice interpretation system, which assists users in interpreting the slices into professional results with domain knowledge and helps them get a better understanding of the distribution of the geological materials they are interested in, e.g., the underground flow path, river delta, crevasse splay deposits, floodplain, raided river channel, slump fan, shore-shallow lake, etc.

The proposed slice analyzer provides many interactions to interpret the slice, including some basic manipulations, such as sketching, drawing, erasing, brushing, slice transfer function edit and automatic Gaussian-function-based stratigraphic structures (foreground pixels) extraction. Furthermore, in order to illustrate the slice with more detailed and professional information, the system further provides sketch-based sub-region partitioning to assist the domain experts in dividing the slice into several sub-regions according to the domain knowledge by some simple sketching manipulations, and then the geological symbol definitions will extract geological materials (foreground pixels) automatically through convolution computation with 3×3 neighborhood size. With foreground pixels and background pixels, users can define geological symbols arbitrarily.

In the future, we plan to develop new features for the proposed slice analyzer. Specifically, we plan to adopt machine-learning algorithms to recommend the best seed point to generate the Gaussian function to define the intensity range in the slice transfer function edit. Moreover, we plan to employ a machine-learning method to recommend several options of sketching paths for users to select.

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