Interactive Stratigraphic Structure Visualization for Seismic Data

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Abstract

Underground flow path (UFP) plays a significant role in illustrating seismic data and revealing stratigraphic structures presented in the data. It is challenging to interactively illustrate the UFP due to the well-known characteristics of seismic data, i.e., noisy, discontinuous, and low resolution. In this paper, we propose a novel interactive visualization approach to illustrate the seismic data, which employs a bit-array based 3D texture to organize different types of interactions. There are three major merits of the organization scheme: It enables to switch different types of interactions flexibly. It allows to perform progressive seed point tracing to get more accurate UFP structures, and supports different stratigraphic display modes and their flexible switching. The feedback from the domain experts suggests that the proposed approach is capable of better revealing the UFP structure and distribution compared with the existing approaches in this field.

Keywords: seismic visualization tools, interactive exploration, progressive visualization, underground flow path

1. Introduction

According to the report "International Energy Outlook 2016" [1], released by the U.S. Energy Information Administration (EIA), total world energy consumption rises from 549 quadrillion Btu (British thermal units) in 2012 to 815 quadrillion Btu in 2040, with an increase of 48%. By 2040, almost two-thirds of the worlds primary energy will be consumed in the non-OECD economies. According to the report, liquid fuels, natural gas, and coal account for 78% of total world energy consumption in 2040. Petroleum and other liquid fuels remain the largest source of energy. 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. Obtaining accurate and comprehensive interpretation results of underground data can reduce the cost of petroleum exploration, especially the cost of drilling engineering.

In the field of oil and gas exploration, seismic data analysis can help to explore the distribution of petroleum or gas. Seismic refraction method utilizes seismic waves traveling through different parts of the subsurface. The basis of seismic refraction investigation is in the measuring of the time taken for a seismic wave to travel from one location to another location [2]. A seismic source is used to generate compressional waves, which is measured by a seismograph and a series of evenly spaced sensors. Seismic refraction is a quantitative method as it produces depths of various geological layers, as well as the seismic velocities of these various layers. Seismic refraction data can assist in the interpretation of geological layers. In this paper, kinds of seismic refraction data are abbreviated as seismic data.

Visualization has strong advantages and good potentials in complex data analytics, such as seismic data, ground penetrating radar data, oil reservoir data, etc. They provide a visual encoding to get insight into revealing more information and feature presented in the data. It assists users perform effective analytics by means of various human-computer interactions. Seismic visualization, especially for the seismic volume visualization, plays an indispensable role in exploring oil and gas [3].

Compared with the traditional volume data, e.g., CT scanning volume data, medical volume data, the seismic data has three intrinsic characteristics as follows,

- *Noisy. Limited by the state-of-the-art seismic ex-*

ploration technology, the collected seismic reflection data are noisy. Besides, the seismic wave will reflect or transmit in the stratigraphic structure.

- *Discontinuous. The seismic data is discontinuous because the stratigraphic structure is complex. It consists of substantially various stratigraphic objects such as rocks, sands, glutenite, etc.*
- *Low resolution. The resolution of seismic data is much lower than the traditional CT scanning data or other traditional imaging data.*

Therefore, it is challenging to interactively illustrate the seismic data due to the above characteristics, which often result in failures that most traditional methods do not work well for seismic data. For example, transfer function design, volume cut, graph cuts based segmentation, are often difficult to be applied in exploring and visualizing the features the domain experts are interested in.

The domain experts are the geologists in the Northwest Branch, Exploration and Development Research Institute, PetroChina. One of the domain experts is also coauthored in this paper.

According to the domain knowledge provided by the geologists in cooperation with us, underground flow path (UFP) plays a significant role in understanding of stratum structure. Because the UFPs are closely related with the migration and the deposition of the oil and gas. Therefore, it is quite meaningful to reveal the distribution and structure of UFP in oil or gas exploration.

The cooperative geologists expressed that the existing illustrative visualization methods for seismic data still have some weakness in the interactive exploration. The current issues are summarized as follows:

First, the illustrative process is tedious, including the 2D slice illustration and the 3D seismic illustration. It often takes hours for them to illustrate a seismic slice or a 3D seismic volume.

Second, the existing UFP extraction methods are still time-consuming. The volume cut based approach [3] can help them extract the UFP through interactive cut and volume eraser, however, it is semi-automatic. It still needs users' involvements, which will reduce the extraction accuracy and exploration efficiency.

Third, they require types of interactions and various stratigraphic display modes in 3D volume illustration. For example, armchair display mode, palisade display mode, sometimes need a combination of them, i.e., the cross-shaped display mode. They also require the integration of UFP results and a combination of various of stratigraphic display modes, even the integration of other basic interaction results, which are brushing, erasing, lassoing, picking, sketching, drawing, etc. Besides, they also need to switch different stratigraphic display modes efficiently. Different stratigraphic display modes can assist them explore the seismic stratum with different angles and scales. A traditional and straightforward method is to design various stratigraphic display modes independently. Different modes have different data structures and development framework. However, this method is neither scalable for new display modes, nor scalable for the combination of multiple modes. Moreover, the development cycle of this method is also relatively tedious. Because different stratigraphic display modes require to design different data structures.

In this paper, we propose a novel interactive approach to illustrate 3D seismic data, which can help the geologists or other oil exploration experts get better understanding of the structure and the distribution of UFP. We design a data structure, i.e., bit-array based 3D texture, to organize all the interactions conducted on the seismic data. There are many benefits of the designed organization scheme, which are listed as follows:

- *It enables users to switch different types of interaction flexibly.*

  All interaction operations, including different volume cut interactions and kinds of user sketching operations, can be fused together by bit set and bit reset operations. The GPU built-in data structure, i.e., 3D texture, ensure that the rendering on GPU is efficient.

- *It enables users to perform progressive visualization for seed point tracing.*

  We first design a new seed point tracing strategy to trace the UFP automatically, then propose a progressive approach, which make the UFP be traced more complete and with less noise. The bit-array based 3D texture enables to fuse and separate each step of progressive results by simple set and reset operations.

- *It supports different stratigraphic display modes and enables to switch them efficiently.*

  Parametric equation of surface is used to describe various stratigraphic layer structures, which supports users to change the starting position, the interval, and the depth of each stratigraphic layer. The bit-array based 3D texture together with the parametric equations enables users to switch different stratigraphic display modes or get their arbitrary combination flexibly.

In the reminder of the paper, we firstly review the background of this work in Section 2, and introduce the approach in Section 3, which including the detailed descriptions of three main parts of our method: the illustration of interaction organization and switching in Section 3.1, the introduction of progress seed point tracing to extract UFP in Section 3.2 and the description of different stratigraphic display modes in Section 3.3. In Section 4, we show the results and give some discussions, respectively. For the result part, the domain experts have given us many valuable feedback. Most of the feedback are positive. Finally, we make a conclusion in Section 5.

2. Related Work

We review the related work on seismic data illustration, interactive volume cut visualization and progressive visualization to show the background of our work.

2.1. Seismic Data Illustration

The seismic data illustration falls into three categories, horizon extraction, fault detection and seismic data interpretation.

Horizon extraction often uses surface detection techniques to detect horizons in 3D seismic data. Seismic horizons indicate change in rock properties and are central in geoscience interpretation [4] . For example, fragments of horizons can be detected by automatic horizon picking algorithm. Then they can be combined into form full horizons by 6-connectivity [5]. Besides, Hollt [6] et al. introduce a combination of 2D and 3D minimal cost path and minimal cost surface tracing for extracting horizons with very little user input. Furthermore, sketch can be helped to extract geological horizons from raw seismic volume data [7, 8].

3D seismic discontinuities or faults have important applications for the analysis of 3D structure and stratigraphy. Seismic coherency or faults operate on the seismic data itself and is therefore unencumbered by interpreter or automatic picker biases [9]. Conventional amplitude time slices are often useful for viewing faults that run perpendicular to strike [10]. Then a more robust semblance-based coherency algorithm [9] that reduces mixing of overlying or underlying stratigraphic features is presented. Automatic faults detection algorithms are also developed through highest confidence first (HCF) merging strategy [11] and double hough transform [12], respectively. A more efficient seismic fault detection system is further developed by using graphics processors [13]. Moreover, coherence- and texture-based attribute volumes can significantly improve the efficiency and quality of 3D GPR interpretation [14], especially for complex data collected across active fault zones.

Seismic interpretation is significant in revealing the structure information presented in the data. In order to improve the annotation of seismic structures, Patel et al. [15, 16, 17] exploited deformed texturing, line transfer functions, texture transfer functions and kinds of illustration approaches are employed to trace the horizons and interpret the seismic data. They further presented novel techniques for knowledge-assisted annotation and computer-assisted interpretation of seismic data for oil and gas exploration [18]. Domain knowledge about the structure and topology of geologic features in seismic data can also be used to steer dynamic surfaces into those features [19]. Sketch-based approach can largely improve the illustration interaction. For example, Natali et al. [20] proposed a sketch-based approach to create the 3D illustrative models in geological text books. Furthermore, they also designed an approach [21] based on the composition of two synchronized data structures for processing and rendering.

One of the most frequently used method to interactively illustrate the seismic data is volume rendering. It can bring more continuous information on the subsurface, and provide more traces and more diverse statistics [22]. The gradient vectors are used in many illumination model, gradient-based methods are sensitive to high-frequency noise, a realtime gradient-free method [4] is presented to render results similar to high-quality global illumination. Zhou et al. [23] uses a slice-based method to extract the upper channel and salt dome from the seismic data. Besides, Liu et al. [3] proposed a volume cut based approach to extract the UFP through interactive cut and volume eraser, however, it is semi-automatic. It still needs users' involvements, which will reduce the extraction accuracy and exploration efficiency.

2.2. Interactive Volume Cut Visualization

Volume cut is the process of cutting volume data into several semantic units. It is a fundamental procedure which is required to obtain useful information from the volume region, such as its shape, topology, and various measurements [24]. A GPU-based volume segmentation method [25] allows interactive visualization on anatomy for medical imaging data. Yuan et al. [26] presented a volume cutout method to categorize voxels into foreground set (objective materials) or background

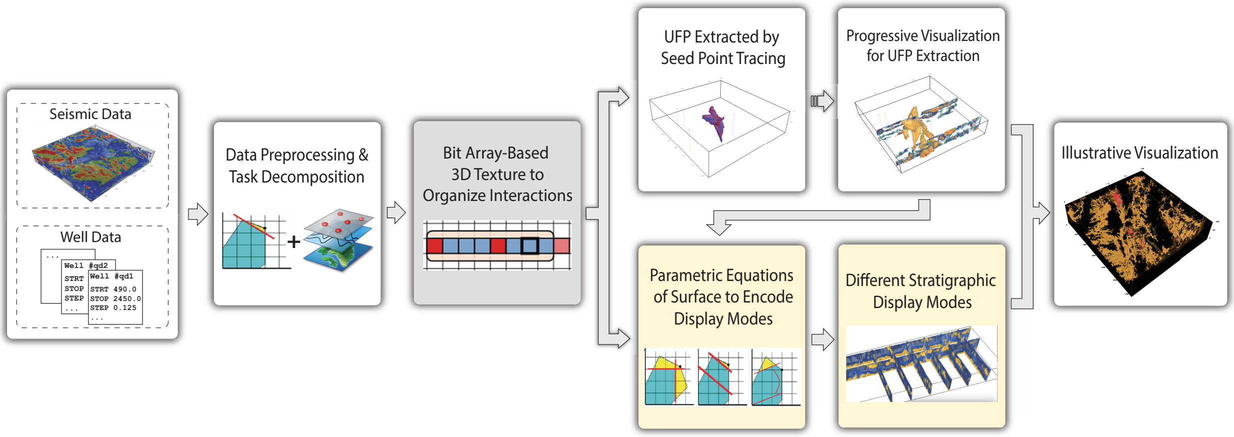


Figure 1: Pipeline of the proposed approach. The seismic survey data and the well data are preprocessed. Then the seismic volume data will be rendered by volume rendering on GPU. Types of interactions can be performed onto the volume and the slice data. The UFP can be further extracted by progressive seed point tracing. Different stratigraphic display modes or their arbitrary combinations can be obtained. Finally, all the illustrative results can be blended to better reveal the structure and the distribution of UFP.

set through graph cuts [27] algorithm. A graph cuts based algorithm was also proposed to classify skeleton structures in medical data [28]. In order to increase the interaction experience, a direct manipulation system [29] with augmented reality techniques is presented to achieve complex volume segmentation of CT/MRI data by using two-handed interface [30]. However, these methods work well for the classic volume data, e.g., CT/MRI data. They are often time-consuming or even infeasible to cut a noisy and discontinuous volume data such as seismic data, because they are sensitive to data noise and data continuity. Furthermore, a volume cut based approach [3] was designed to extract the UFP structures through interactive cut operations.

2.3. Progressive Visualization

Visual data analysis is an interactive and iterative process where users must frequently switch between a wide range of distinct but interrelated tasks. While the specific set of tasks that recur in visual data analysis, as well as the tools that support them, are relatively well understood [31, 32]. When using data-mining tools to analyze big data, users often need tools to support the understanding of individual data attributes and control the analysis progress. This requires the integration of data-mining algorithms with interactive tools to manipulate data and analytical process [33]. Progressive systems are well known in the graphics domain and widely used on websites to improve user experience when loading high-resolution images [34]. They are characterized as incrementally computing results over increasingly larger samples in order to provide more accurate results to the user over time [32]. A general progressive visual analytics workflow was proposed. It enables an analyst to inspect partial results of an algorithm as they become available and interact with the algorithm to prioritize subspaces of interest [35]. Besides, a dynamic model to optimize the efficiency of flexible progressive rendering in visualization is proposed [36]. Specially, Callahan et al. [37] present a progressive approach for the exploration of large datasets stored on a remote server with a thin client that is capable of rendering and managing full quality volume visualizations.

3. Interactive Seismic Data Illustration

In this paper, we propose a novel interactive approach to illustrate the 3D seismic data, together with some other survey data, which can help the geologists or other oil exploration experts get better understanding of the distribution of UFP. Specifically, we design a data structure, i.e., bit-array based 3D texture, to organize all the interactions conducted on the seismic data. It enables to switch different types of interactions flexibly. It also allows to perform progressive seed point tracing to get more accurate UFP structures, and supports different stratigraphic display modes and their flexible switching.

Figure 1 shows the pipeline of the proposed method. Initially, we get the seismic survey data and the well data from the oil exploration experts. Then we preprocess the data, the raw seismic survey data are organized by slices. The reflection time between slices is one millisecond. The well data will be extracted and formatted by reflection time. All the raw data will be preprocessed

Algorithm 1 `rendering_with_interaction_assignment()` function.

function RENDERING_WITH_INTERACTION_ASSIGNMENT(seismic_volume, 3D_texture, img_position_xy)
  volume_rgba_xy = 0 ▹ *RGBA value initialization for the image position (x, y)*
  for volume_ray$_z$ = 1 *to* Z_max **do**
    rgba_xyz ← get_rgba_from_volume(seismic_volume, img_position_xy, *volume_ray$_z$*)
    interaction_type_rgba_xyz ← get_interaction_type_rgba_along_ray (3D_texture, img_position_xy, volume_ray$_z$)
    rgba_xyz ← color_blend (interaction_type_rgba_xyz, transfer_function) ▹ *Color blending by interaction type and the transfer function of volume rendering.*
    volume_rgba_xy += rgba_xyz
  end for
end function

into a volume according to their reflection time and position. The seismic volume data will be rendered by volume rendering on GPU. The interaction tasks will be decomposed into two parts, i.e., CPU part and GPU part. The CPU part task comprises of kinds of interactions. The GPU part task involves interaction type fetching from CPU, and rendering of volume data and well data. Different interactions, i.e., brushing, erasing, lassoing, picking, sketching, drawing, can be performed onto the volume or the slice data. A bit-array based 3D texture will be exploited to organize and switch all the interactions. Besides, it is beneficial for the progressive seed point tracing and supporting different stratigraphic display modes. In order to reduce illustration time and improve the completeness of UFP extraction, we propose a progressive seed point tracing to extract UFP. In detail, a seed point tracing algorithm is proposed to perform progressive visualization based on the 3D texture data organization. Then different stratigraphic display modes are used to visualize the extracted UFP, well, or other feature. The final blending of multiple illustrative results is employed to reveal the structure and the distribution of UFP.

3.1. Interaction Organization and Switch

All the seismic survey data are provided by the the geologists in cooperation with us. The original slice-based survey data will be organized into volume data by the refraction time. The well data will also be integrated into the volume data according to the slice refraction time.

After the data are preprocessed and integrated, all the data will be rendered on GPU. A solution to better reveal the distribution of UFP is to allow users perform kinds of effective interactions. According to the discussion with our domain experts, the existing interactive methods to extract UFP is too tedious and the extraction results are often not accurate enough. Moreover, the domain experts require types of interactions and various stratigraphic display modes in 3D volume illustration, e.g., armchair display mode, palisade display mode, cross-shaped display mode, sometimes need a combination of them. They also require the integration of UFP results into various of stratigraphic display modes, even the integration of other basic interaction results, e.g., the results of brushing, erasing, lassoing, picking, sketching, drawing, etc.

We summarize some general interaction design from the experts' feedback, which requires that the system should satisfy two requirements. First, different interaction types performed onto different stratigraphic layers or different voxels simultaneously. Second, different interaction results can be assigned onto a given voxel.

In this paper, we use a bit-array based 3D texture to organize different interactions, which allows different interaction operation results integrated into one volume. Technically, different interaction type values can be assigned to a voxel of the seismic volume. All interaction types will be associated with a given unsigned value, i.e., the interaction type value. A 3D texture is designed to organize all the interaction types assigned onto all the voxels of the seismic volume. Figure 2 shows the data structure illustration of 3D texture. We use power-of-2 as the type values. The dimension size of the 3D texture is identical to the size of seismic volume. Each voxel of the 3D texture can be assigned with different interaction type values.

For the GPU rendering part, we can get the RGBA value for the final rendered result for its given image position (x, y). The final rendering result for each image position is dependent on the original seismic volume ray (if they are integrated by ray-casting), interaction types of all the voxels along the ray and the transfer function. Algorithm 1 shows the rendering process for each ray. The interaction type values of each voxel, which organized by the 3D texture, are converted into

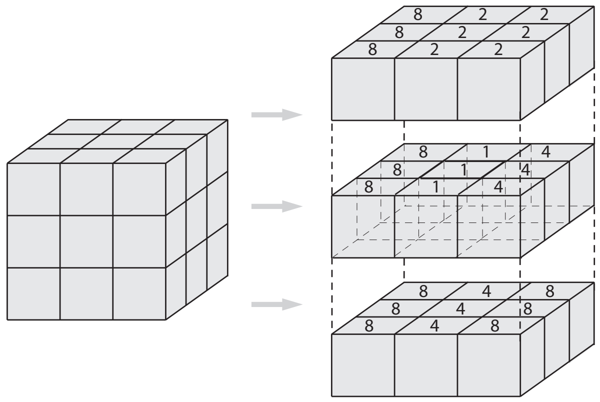


Figure 2: 3D texture of interaction volume. The interaction types of each voxel are organized and saved into the 3D texture.

RGBA values and are blent into the final rendering results. For example, the interaction type value of erasing is 0, brushing is 1, sketching is 2, volume cut is 4. The type value of UFP extraction by the first seed tracing is 64, the second seed tracing is 65 and the third one is 66, etc. The type values of different stratigraphic display modes are 128, 129, 130, etc. If there are multiple interactions conducted on a voxel, the type value can be set as the "logic or result of their maximum bit position of each type value. It is worth mentioning that most of voxels are with a single interaction type except for a small part of overlapping areas. Therefore, we simplify the blending scheme. The blending weight of an on-going or a newer interaction type is assigned to be a maximum value 1.0 by default, although users can also adjust the weight by parameter tuning.

Different interaction types may result in different color assignment results for their interacted voxels. The RGBA values for each interaction type can be defined by the user. For example, the erasing will set alpha value as 0. The brushing will set RGB value by the users' brushing color. The RGBA values of the voxels on the extracted UFP are also defined by the user definition color. Different stratigraphic display modes will set the alpha value of the empty part as 0, then set the RGBA values for non-empty part.

3.2. Progressive Seed Point Tracing for Underground Flow Path Extraction

The current using UFP extraction method by the domain experts is volume cut-based method [3]. As mentioned above, the existing method to extract UFP is too tedious. It includes two steps of cut operations: (1) convex-hull cut and (2) concave-hull cut. It needs users to cut volume step by step. Every step involves several cut interactions. Each cut needs users to perform multiple sketching or drawing interactions. Worse still, the extraction results are often neither complete nor accurate because it is difficult for the users to sketch or draw an optimal curve boundary. According to the feedback of the domain experts, the drawbacks of their current using method can be concluded as follows:

- *The UFP structures extracted by volume cut is relatively noisy.*
- *It just allows users to extract only one UFP at one illustration time, which is quite inconvenient.*
- *The UFP extraction by convex-hull cut and concave-hull cut are time-consuming.*

In order to solve these problems, a seed point tracing method is designed to extract the UFP. The principle of the tracing method is a little similar to that of the horizon growing method [4]. However, they are different due to their characterization of objectives and application scenarios. The horizons are the interfaces between material layers, which are the earth subsurface with distinct mineral densities and porosity characteristics [4]. The UFP is different from the horizon. From the data processing point of view, a UFP is a sub-volume instead of a seismic surface. There are often many non-UFP regions lie within a UFP. A UFP consists a set of points in some space, it groups together points with similar characteristics that are closely packed together, which lie alone in high-density regions. The noise points that lie alone in low-density regions, whose nearest neighbors are too far away.

On the basis of these characteristics, we employ a slightly improved algorithm DBSCAN [38] to acquire seed point tracing. However, the original DBSCAN is computationally intensive due to repeated time-consuming searching. It is almost unaffordable for large-size seismic volume data. Specifically, we improve the efficiency by narrowing the searching radius for our special volume data stored in the regular grids. The user just need to place a seed point on the slice extracted from a volume. The seed point tracing algorithm will trace UFP automatically. However, the seed point tracing is sensitive to seed point placement. It is quite difficult to find an optimal seed point to trace UFP. Besides, the parameters of DBSCAN are hard to tune. Every data mining task has the problem of parameters. Every parameter influences the algorithm in specific ways [38]. The densities of the points on a UFP often varied from regions. It is generally difficult to trace a

UFP completely through placing one seed point. Because the seismic data are often noisy and their resolutions are often low. Therefore, we propose a progressive visualization to perform multi-seed tracing, in order to trace a more complete UFP.

Progressive visualization can refine the tracing results significantly, because the previous tracing results can be used to assist users to find a new optimal seed point to trace UFP more completely. In order to better refine the results, the UFP regions traced by all previous seed tracing should be marked.

As claimed in the Section 1, the bit-array based 3D texture, is beneficial for achieving progressive seed point tracing. In our approach, we consider the tracing processes with different seeds as different interactions. In the 3D texture, different seed point tracing results are assigned with different interaction type values. It is convenient to illustrate each single seed point tracing process, any combination of the multi-seed tracing, e.g., their union, intersection or complement, even the integration of multi-seed tracing and other basic interactions.

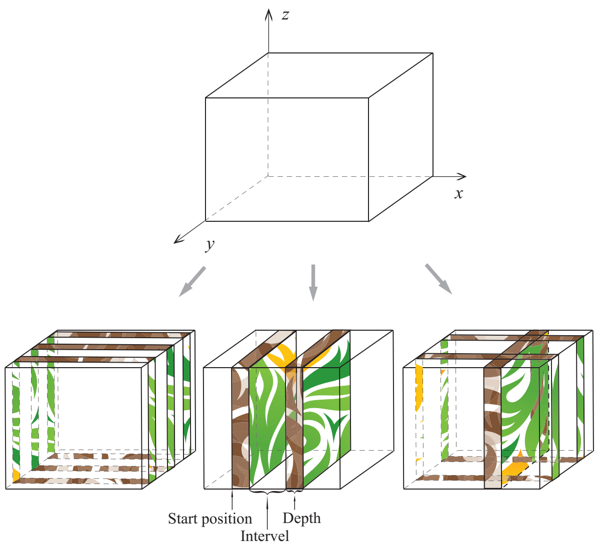


Figure 3: The illustration of three stratigraphic display modes. The original volume (top), the armchair stratigraphic display mode (bottom left), the palisade stratigraphic display mode (bottom middle), and the cross-shaped stratigraphic display mode (bottom right).

3.3. Different Stratigraphic Display Modes

According to the requirements provided by the domain experts, the visualization system should support different stratigraphic display modes, i.e., armchair display mode, palisade display mode, cross-shaped display mode, sometimes need a combination of them. Figure 3 shows three stratigraphic display modes. The start position of a group of stratigraphic layers, the depth of a single stratigraphic layer, and the interval between the stratigraphic layers should be adjusted by the users. Through the adjustment, the visualization can better reveal the distribution of the UFP and other objects the users are interested in. Furthermore, they also require the integration of UFP results into various of stratigraphic display modes, even the integration of other basic interaction results.

A straight-forward solution to visualize the seismic data with different stratigraphic display modes is to cut the original volume data before rendering. However, it is tedious and inefficient because it should process the data frequently. The worst case is that the data should be pre-processed frame by frame while rendering. However, it is not flexible, and it is difficult to switch between different stratigraphic display modes, because the results of different display modes are highly different, as shown in Figure 3.

In order to increase the flexibility and customizability of visualizing the seismic data with different stratigraphic display modes. We propose a novel approach, i.e., which employs parametric equations of surface method to encode the surface of each stratigraphic layer. Especially, the surface of the armchair, the palisade and the cross-shaped stratigraphic display mode are planes. Therefore, the three types of modes can be encoded by the equation of the plane, the depth of each stratigraphic layer, and the interval between stratigraphic layers. The equation of a plane can be determined by four plane equation parameters (A, B, C, D), as shown in Equation (1). It is worth mentioning that the plane equation is the general form after transformation. It just specifies the norm of the plane group. Users can perform interactions of different stratigraphic display modes by changing the parameters of sub-volume slicing. For example, the start position of sub-volumes, the interval of sub-volumes, and the depth of each sub-volume.

$$Ax + By + Cz + D = 0 \tag{1}$$

As claimed in the Section 1, the bit-array based 3D texture, is beneficial for supporting different stratigraphic display modes. In our approach, different stratigraphic display modes results can be considered as different interaction results. The armchair stratigraphic display mode, the palisade stratigraphic display mode and the cross-shaped stratigraphic display mode will be assigned with different interaction type values. Algorithm 2 shows the encoding algorithm for three stratigraphic display modes. The bit value of 3D texture can be set

Algorithm 2 `Stratigraphic_display_modes_encoding()` function.

```
function STRATIGRAPHIC_DISPLAY_MODES_ENCODING(plane_param_set[4], start_position, depth, interval)
    stratigraphic_layers[3] ← get_voxels_from (plane_param_set[4], start_position, depth, interval)    ▷ get voxels located inside the stratigraphic layers of three types of stratigraphic display modes
    for x = 1 to X_max do
        for y = 1 to Y_max do
            for z = 1 to Z_max do
                if voxel_xyz in stratigraphic_layers[ARMCHAIR] then
                    3D_Texture[x, y, z] | = ARMCHAIR_INTERACTION_TYPE    ▷ Set the 3D texture bit value by logic OR operation
                else if voxel_xyz in stratigraphic_layers[PALISADE] then
                    3D_Texture[x, y, z] | = PALISADE_INTERACTION_TYPE    ▷ Set the 3D texture bit value by logic OR operation
                else if voxel_xyz in stratigraphic_layers[CROSS_SHAPED] then
                    3D_Texture[x, y, z] | = CROSS_SHAPED_INTERACTION_TYPE ▷ Set the 3D texture bit value by logic OR operation
                end if
            end for
        end for
    end for
    volume_xyz ← color_blend (3D_Texture_xyz, transfer_function)    ▷ Color blending by the bit-based 3D texture data structure and the transfer function of volume rendering
end function
```

by a logic or operation with its corresponding interaction type values. With the designed data structure, all stratigraphic display modes can be easily to switch, and the integration of display modes and other basic interaction are also easily to be implemented. Besides, the start position of the stratigraphic layer group, the depth of stratigraphic layers, and their intervals can be easily adjusted by the users.

4. Results and Discussion

In our experiments, we test our method on two seismic data provided by the domain experts. The experiments are performed on a workstation. The workstation is with the configuration of Intel Core i5-6500 CPUs operating at 3.30GHz and 16 GB RAM. Two datasets provided by the domain scientists, i.e., dataset I and dataset II are used to test the proposed approach.

4.1. Illustration Results by Basic Interactions

The seismic data can be illustrated by types of interactions, including basic interactions and the interactions we designed in this paper. All different interaction types can be associated with different interaction type values for the 3D texture. Figure 4 shows the illustration result of river delta. It is illustrated just by some basic interactions provided by the system, i.e., brushing, erasing, color mapping, sketching, drawing, are used to illustrate the seismic data. According to the domain experts' feedback, the results illustrated by the basic interactions in this paper are in accordance with their domain knowledge.

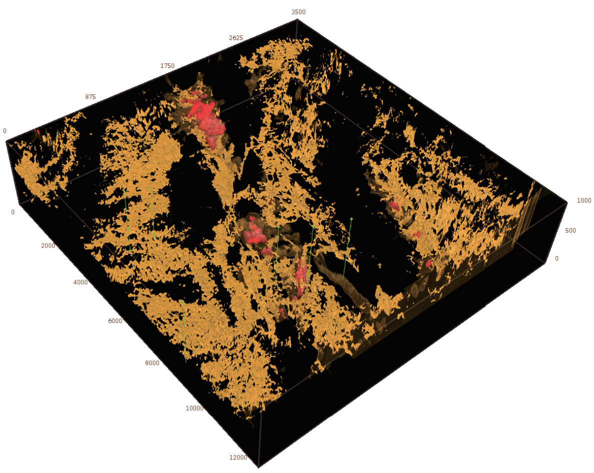


Figure 4: The river delta illustration result by basic interactions: brushing, erasing, and sketching. The green curves are the illustration results of wells.

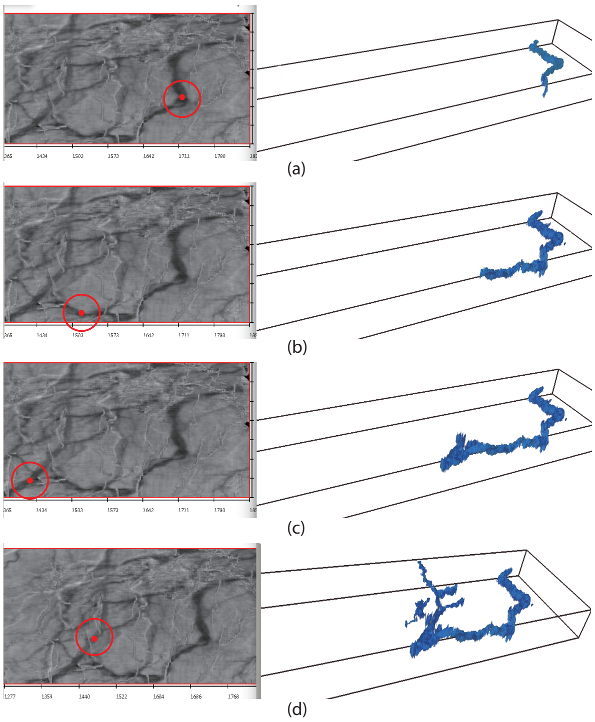


Figure 5: Progressive visualization results of UFP extraction. The users just need to place four seeds step by step. Every seed is placed by the users according to the previous visualization results (the right part of each sub-figure). The seed placement of each step is performed by the users in the slice view (the left part in each figure). After that, the UFP extraction of each step is performed by automatic seed tracing.

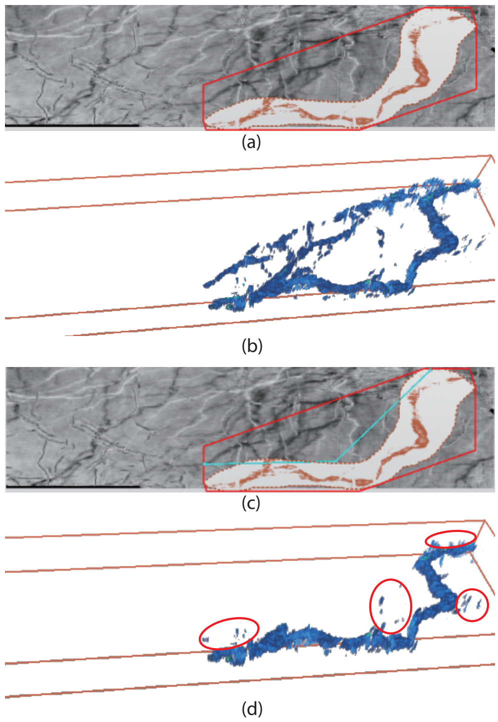


Figure 6: UFPs extracted by the existing volume cut-based approach [3]. Some noisy is still hard to be excluded (in red circle in (d)) by convex-hull cut and concave-hull cut, respectively. (a) Convex-hull cut operation. (b) concave-hull cut operation. (c) UFP structure extracted by convex-hull cut. (d) UFP structure extracted by convex-hull cut.

4.2. Progressive Seed Point Tracing

The existing UFP extraction method [3] is too tedious because it needs users to cut volume step by step. Every step involves several cut interactions. Furthermore, each cut needs users to perform multiple sketching or drawing interactions. Besides, the extraction results are often not accurate enough because it is difficult for the users to conduct an optimal sketching operation.

Compared with the existing volume cut-based method, the seed point tracing method just needs users to place one seed. Then the algorithm will trace the UFP automatically. However, the existing method is difficult to trace complete and accurate UFPs by only one seed point tracing. Thus, it is hard to place an optimal seed point in such condition.

The proposed novel progressive seed point tracing approach is based on the well designed 3D texture. As mentioned above, it is characterized as incrementally computing results in order to provide more accurate results to the users over time.

In our experiments, we find that the proposed progressive seed point tracing approach is not sensitive to the parameters. We place each seed with small perturbation, and find the system can also trace similar UFP structures. After several experiments, we found the parameter setting of DBSCAN-based tracing algorithm is as follows, the searching radius (SR) of the tracing is 2.5, which works fine in all UFP extractions in our experiments. The minimal point size (MPS) within each trace stage is 30.0. We find this parameter setting can get reasonable results in all of the tested datasets. If the domain experts find there are too much noise points in the results, they can decrease the value of MPS slightly; otherwise, they can increase it until they find a reasonable result according to their domain knowledge.

The proposed progressive approach can assist users to provide more accurate UFP distribution. Figure 5 shows the progressive visualization results of UFP extraction. During the analysis and exploration, the users just need to place seeds step by step. Every seed is placed by the users according to all the previous visualization results. According to the illustration results and the feedback provided by the domain experts, there are three

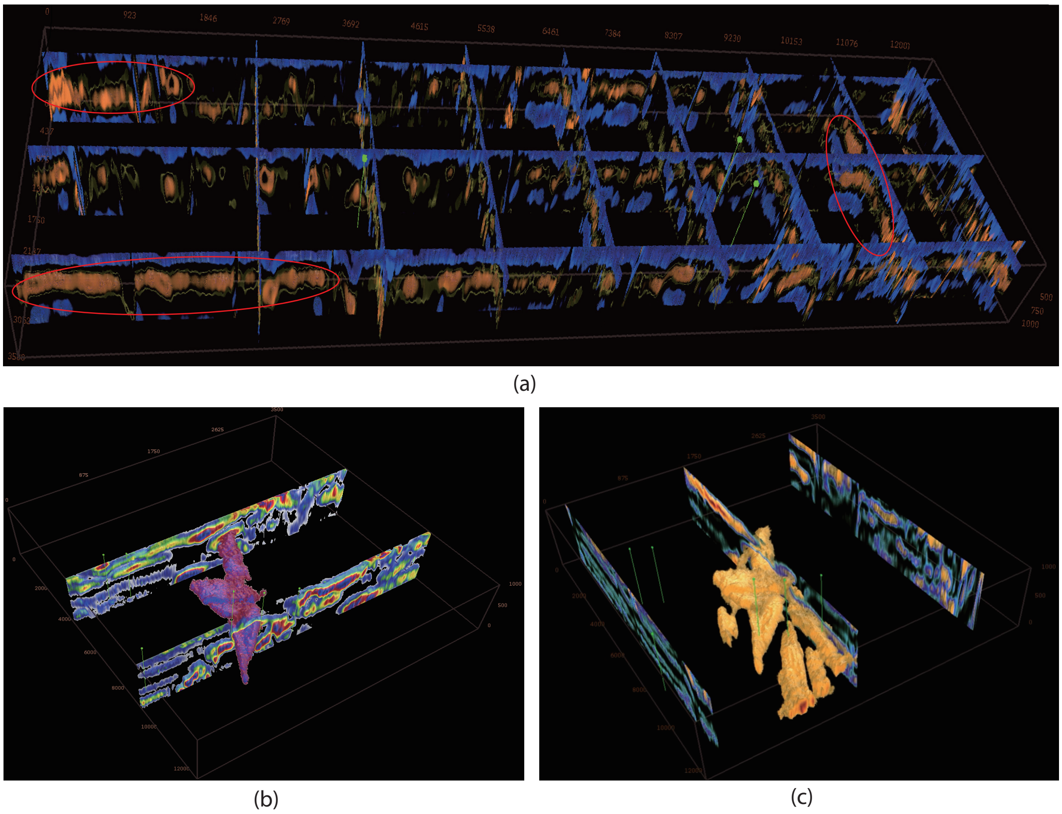


Figure 7: (a) Stratigraphic display mode for dataset I; (b) The armchair stratigraphic display mode for dataset II; (c) The palisade stratigraphic display mode for dataset II.

strengths of the proposed progressive method compared with their current using volume cut-based method:

- *There is much less noise of UFP structures traced by the proposed progressive approach.*
- *The traced result is more complete because the volume cut-based method just allows users to extract only one UFP at one illustration time, which is quite inconvenient according to the feedback of domain experts*
- *The performance of UFP extraction is better. In volume cut method, the illustration of UFP extraction by convex-hull cut and concave-hull cut are time-consuming.*

Figure 6 shows the extracted UFP structures by their current using method, i.e., the volume cut-based approach [3], which includes two steps of cut operations: (1) convex-hull cut and (2) concave-hull cut.

First, it is easy to find that some noisy is still hard to be removed by the volume cut method, neither through convex-hull cut nor by concave-hull cut, as shown in Figure 6d. In our approach, the noise can be easily removed by adjusting the above-mentioned parameter MPS.

Second, it is easy to find that the UFPs extracted by the proposed approach in Figure 5d is more complete than that of volume cut-based method in Figure 6d. The volume cut-based method can only extract one UFP structure at one illustration time. Different UFP structures at different locations cannot be visualized simultaneously. Because all the points outside the convex-hull and the concave-hull will be removed by volume cut operations. It means users need to restart the system and restart the illustration to extract other UFP structures in an identical dataset. It is quite inconvenient according to the feedback of domain experts.

Third, it often takes one or several minutes for the users to extract just one UFP structure when using their current using approach, according to the feedback provided by the domain experts. Because it is hard to manipulate concave-hull cut to get an optimal result. However, it takes only 0.11 seconds in average to extract UF-

P structure for one seed point in dataset I. Although it takes about 5.3 seconds averagely for the extraction in dataset II, as shown in Table 1, it is obviously less than volume cut-based method according to the feedback. From the timing results, we can find it takes much more time to conduct UFP extraction algorithm on dataset II than dataset I. The reason is that the traced point number in dataset II is obviously larger than that of dataset I. Besides, in our approach, we trace UFP structures in individual working threads, which do not interfere main thread working, i.e., the graphical user interface (GUI) rendering. Therefore, users can perform other interaction operations when they start a seed point tracing thread.

Dataset	# Seed Points	# Traced Points	Total Time	Avg Time
Dataset I	9	146,039	0.98	0.11
Dataset II	16	2,478,118	84.82	5.30

Table 1: Timing results (in seconds) for UFP progressive visualization. "# Seed Points" and "# Traced Points" represent the number of seed points and the number of UFP points have been traced, respectively, "Avg Time" is the averaging tracing time of each seed point.

4.3. Stratigraphic Display Modes

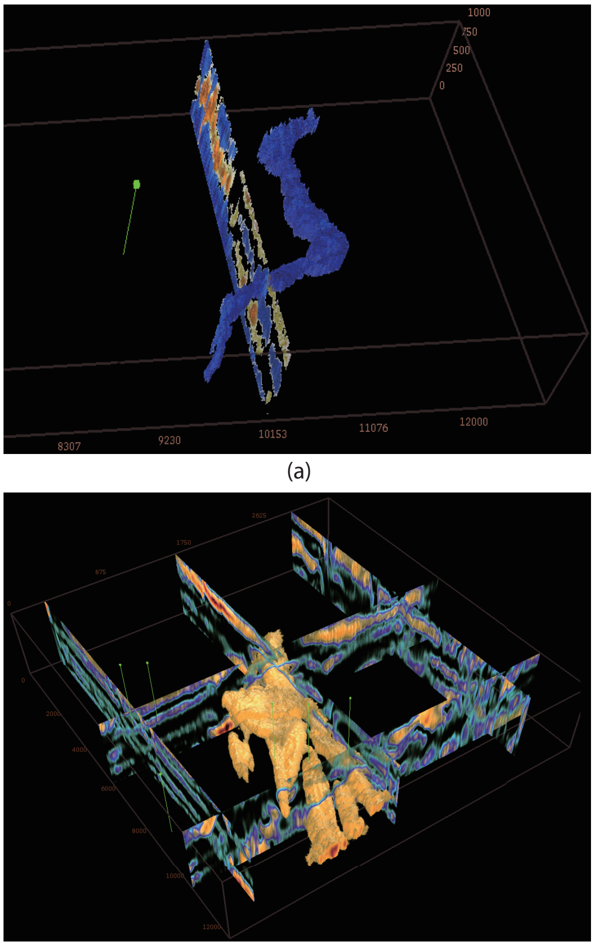
The domain experts claim that the visualization system should support different stratigraphic display modes. Figure 7 shows the stratigraphic display mode to visualize the seismic dataset I, the armchair and the palisade stratigraphic display mode for dataset II, respectively. The stratigraphic display mode and their flexible switching can help users get a better acquaintance of the spatial distribution of seismic materials.

Figure 8 shows the integration result of progressive seed point tracing results and the stratigraphic display mode for the dataset I and the dataset II.

For all the stratigraphic display modes, the users can easily change the start position, the interval, and the depth of each stratigraphic layer, which make the users get better understanding of the spatial distribution of UFP, as shown in Figure 9. The blending weight of cross-shaped display mode will be assigned to be 1.0 in this case, because the users are adjusting the parameters of cross-shaped display mode. The newer interaction type is stratigraphic display mode changing or the parameters tuning of it.

4.4. Domain Experts Feedback

The domain experts have given us many valuable feedback. They are the geologists in the Northwest Branch, Exploration and Development Research Institute, PetroChina. The major feedback is listed as follow:

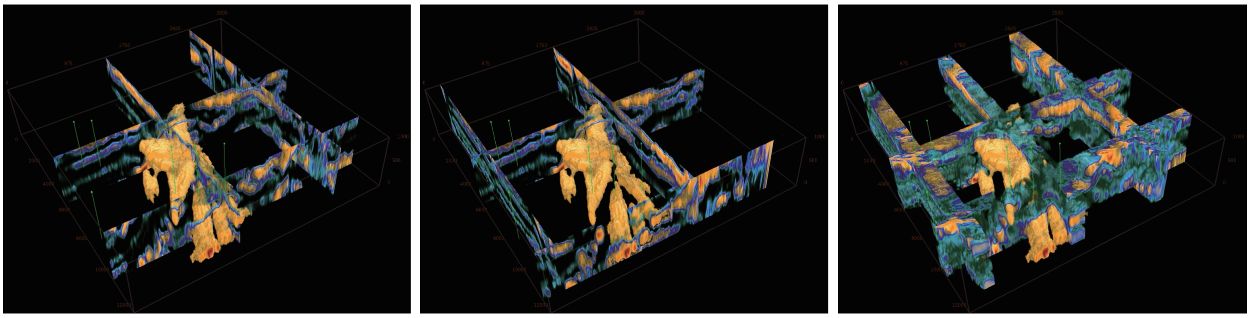


(a)

(b)

Figure 8: The integration result of progressive seed point tracing results and the stratigraphic display mode for the dataset I (a) and the dataset II (b). The users can switch different stratigraphic display modes flexibly.

- *"It often takes tens of minutes for us to get the whole UFP structures through the current using method by multiple times of illustrations. The multi-seed tracing (progressive seed point tracing) is quite more efficient."*
- *"The display modes switching and the slice gesture changing can help us reveal the feature and structures of underground seismic materials."*
- *"The flexible changing of the start position, the interval and the depth for each stratigraphic layer can help us explore the UFP with more detailed information."*
- *"The slice illustration results are also significant during the oil and gas exploration. The current*



(a) (b) (c)

Figure 9: Users can change the start position, the interval, and the depth of each stratigraphic layer or each slice.

version of the slice analyzer still need to be improved. The current slice analyzer is simple and straight-forward."

The domain experts said that the illustration results in this paper are in accordance with the domain knowledge provided by them. It often takes tens of minutes for them to get the whole UFP distribution through the traditional methods, while it just takes about one minute in average for them to perform progressive seed point tracing to get the whole UFP for their providing datasets. More importantly, the existing method, i.e. the volume cut method is not accurate enough. Because the cut result is often a rough UFP structures with a large number of noisy points or subregions. The results of stratigraphic display modes, e.g., the changing of the start position, the interval and the depth for each slice can help them explore the UFP in detail, as shown in Figure 7a. The distribution of the objects in red circles can be easily explored on the slice. The slice depth changing helps them explore spatial feature along the slice or within a stratigraphic layer effectively.

According to their feedback, the biggest issue they are most concerned about is that the current version of the slice analyzer still need to be improved, because the slice illustration results are also significant during the oil and gas exploration. The slice analysis is just used to place seeds, which is simple and straight-forward. It would be better if it provided visual cues of seed placement.

4.5. Discussion

The proposed bit-array based 3D texture can be exploited to organize the interaction types conducted on the seismic data, which assists the domain scientists get a better understanding of the distribution of UFP or other seismic materials they are interested in. We received a lot of positive feedback from the domain scientists. However, there are still some limitations.

First, the progressive seed point tracing still requires the users to place multiple seeds according to their knowledge, although it reduces many interactions compared with the exist methods. In the progressive seed point tracing, the users need to place one or several seeds on the slice view, then the algorithm will trace the UFP automatically.

5. Conclusions

In this paper, we present a novel interactive approach to illustrate 3D seismic data, which can help the geologists or other oil exploration experts get better understanding of the distribution of UFP. We design a data structure, i.e., bit-array based 3D texture, to organize all the interactions conducted on the seismic data. The designed 3D texture enables users to switch different interaction types efficiently. Besides, it enables users to perform progressive visualization for seed point tracing. The progressive seed point tracing can reduce many tedious interactions compared with the existing method. Finally, it supports different stratigraphic display modes and enables to switch them efficiently. The bit-array based 3D texture together with the parametric equations enables users to switch different stratigraphic display modes or get their arbitrary combination efficiently.

In the future, we plan to develop some further work according to the current limitations. First, we plan to design a visual analytics tool to show visual cues about how to place seeds. The goal of the visual cues is to reduce the total number of seeds while keep the traced materials (i.e., UFP) as complete as possible. Second, the slice illustration results are quite significant during the oil and gas exploration, however, the interactions of the slice analysis still need to be improved. For example, the foreground and background of seismic materials should be further extracted and visualized. Third, it still needs the users to tune the parameters of seed point tracing. However, the parameters of seed point tracing within a data are approximate in different sub-region, because the density of the interested materials in one data are similar.

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