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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 UFP visualization approaches in this field.

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 exploration 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

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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 straight-forward 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 the work.

2.1. Seismic data illustration

The seismic data illustration approaches 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 full horizons by 6-connectivity [5]. Besides, Hollt et al. [6] introduced 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. [15–17] used 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