Visual Exploration of Seismic Volume Datasets

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ABSTRACT

This paper introduces a novel method supporting the interactive exploration of volumetric subsurface data. To facilitate better insights into the datasets we propose the application of focus and context visualization metaphors. Using these metaphors users can emphasize arbitrary parts of a dataset or remove occluding information interactively to focus on the region of interest. In addition to these visualization issues we will explain how the focus and context metaphors can be combined with VR-based interaction techniques to allow the efficient exploration within more immersive VR environments. In particular, we will discuss how to control the focus and context metaphor to highlight the region of interest in combination with the usage of visual bookmarks to track potentially interesting parts within large volumetric subsurface datasets.

Keywords
Subsurface Exploration, Seismic Volume Data, Focus and Context Visualization, VR.

1 INTRODUCTION

With decreasing availability of fossil fuels such as oil and gas, the demand for efficient techniques to locate the remaining reservoirs is rising. Drilling for these resources is a very cost intensive process, e.g., according to the Joint Association Survey on Drilling Costs drilling one well can cost up to several million US dollars. Hence, the oil and gas industry tries to reduce drilling costs, by using extensive computer-aided analysis and exploration to make better predictions regarding the location of subsurface reservoirs. Also more precise predictions of natural disasters such as earthquakes can be obtained by computer aided subsurface analysis. The most common approach to perform this subsurface analysis is interactive 3D exploration of subsurface structures on the basis of seismic datasets.

Seismic datasets are acquired indirectly. Detonating explosives emit sound waves, which are propagated through the subsurface. The reflections of those sound waves are measured with special receivers located at the surface. Thus geological layers, which reflect the sound waves, can be identified based on the time elapsed before a signal is received as well as the signals attenuation. The resulting information is encoded in a 3D volume composed of discrete samples, each represent-

ing the amplitude reflected beneath the surface. This usually very large 3D volume is often stored as a SEG-Y dataset [SEG02], and the acquired amplitudes can be visualized using different transfer functions to represent the geological structure.

Although the idea of 3D GIS has been proposed [KLR+03], most current 3D GISs adapt the concepts of polygonal representations for visualizing geographic information and are therefore not sufficient for analyzing volumetric seismic datasets. For these reasons GISs supporting volumetric methods have been developed, which are highly specialized applications designed for the purpose of exploring seismic datasets [Geo06, VGe06, Fle06]. In conjunction with these systems, virtual reality (VR) systems support exploration of seismic datasets. VR systems provide three major advantages compared to desktop-based visualization systems. By using stereoscopic projection techniques, spatial perception is improved and thus aids visual comprehension. Furthermore, by using appropriate tracking technologies, the user can perform intuitive 3D interactions, whereas desktop-based systems usually support only 2D input devices.

To benefit from these capabilities provided by VR systems, the developer of a visualization application has to consider VR design issues, e.g., the interactions which can be performed have to be adapted to VR-based interactions. To grant an efficient exploration of seismic datasets it is important to obtain interactive frame rates within the application in order to give immediate visual feedback when the user has performed an interaction. In the context of this paper we faced three major challenges all leading to a reduced frame rate: (1) seismic datasets are usually very large; (2) the high screen resolutions of current displays; (3) for

stereoscopic viewing in VR systems the scene has to be rendered twice, i.e., once for each eye. Therefore it is important to use state-of-the-art volume rendering techniques which exploit the features provided by current graphics hardware to achieve interactive frame rates.

In this paper we propose a novel method for VR-based exploration of seismic datasets. Our approach supports efficient exploration of seismic volume datasets by using focus and context visualization metaphors in combination with intuitive and efficient VR-based interactions. By using these interaction concepts the user can emphasize the region of interest inside the dataset interactively. This region of interest is specified by a *lens volume*, which has an arbitrary convex 3D shape. Inside the region of interest a different visual representation is used for visualization and thus aids comprehension of the dataset without loosing the contextual information outside the region of interest (see Figure 1). By using specialized 3D interaction metaphors the user can switch between different lens shapes as well as visual representations. Furthermore, it is possible to set *spatial visual bookmarks* at certain points of interest, which can be accessed later on using a guided VR-based exploration-metaphor. For visualizing the datasets we use GPU-based ray-casting [RGWE03, KW03] which enables interactive frame rates while rendering the scene stereoscopically and with a high resolution. To use different visual representations within the region of interest we have extended the GPU-based ray-casting technique to support different rendering modes when visualizing a volume dataset.

This paper is structured as follows. In the next section we discuss related work while Section 3 briefly outlines our extension of GPU-based ray-casting and the kinds of visual representations we have found helpful for exploring seismic datasets within our prototype system. In Section 4 the VR-based interaction techniques used to alter the region of interest are explained in detail. The paper concludes in Section 5 by giving a short overview of the presented concepts.

2   RELATED WORK

Visualization techniques for representing volumetric phenomena have advanced in the past years. While most of the proposed techniques have been developed for medical applications, Ma and Rokne [MR04] present a good overview of visualization techniques used to visualize seismic volume datasets. Furthermore, various software applications, e.g., Fledermaus[1], VoxelGeo[2], and GeoProbe[3], that use seismic data to compile and process subsurface visualizations are

available. With these applications, geo-scientists are able to process and visualize seismic data on commodity hardware. However, even with these highly evolved applications and the incorporated visualization techniques the information contained in volumetric data can be overwhelming during exploration.

In medical visualization a lot of work has been done to support the generation of focus and context visualization [HMBG01, VKG05, BGKG05]. In 2005 two software systems have been presented, which allow interactive generation of illustrative visualizations of medical volume data [BG05, SES05]. Both systems incorporate recent focus and context visualization techniques. A general approach to support focus and context visualization by applying the magic lens metaphor to volume datasets can be found in [WZMK05]. Furthermore, Diepstraten et al. [DWE03] have proposed a set of guidelines for generating cutaway illustrations, which can be used to provide the observer insights to an otherwise opaque object.

Immersive visualization and interaction technologies, allowing multidisciplinary teams to explore the subsurface data in a more intuitive and efficient manner, help to increase the value of such enormous amounts of volumetric datasets. A wide range of visualization systems and input devices, which have originally been developed for applications outside of the geo-scientific industry, have been adapted to support users when exploring seismic datasets. Among others, these systems include immersive projection-based VR system environments such as the CAVE, curved and flat-wall displays, desk- or workbench-type systems as well as head-mounted devices ([HBP+02],[CNSD+92]). The best choice of a certain visualization system depends on the task to be accomplished within the system. However, especially the semi-immersive responsive workbench ([KBF+95]) has proven its potential as table-top metaphor for the exploration of geo-spatial data ([FBZ+99], [KHJ00]). The capability to mount the workbench in a horizontal position allows to visualize geo-spatial data in an intuitive way. Although the visualization of seismic datasets within immersive VR systems enables an advanced exploration of the datasets and improves the information retrieval, interaction with the data within current systems is usually limited to mouse, keyboard and/or joystick-type devices, and often requires an experienced navigation expert to pilot other viewers through the visualization. However, since semi-immersive and immersive VR systems allow to explore and process a huge amount of data, recent research approaches review innovative interaction technologies to enable an intuitive exploration and manipulation of geo-spatial data ([MEH+99]).

Fröhlich et al. ([FBZ+99]) have shown, how the exploration of seismic datasets can benefit from the use of volumetric lenses. However, their approach supports

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[1] http://www.ivs3d.com/products/fledermaus/
[2] http://www.paradigmgeo.com/products/voxelgeo.php
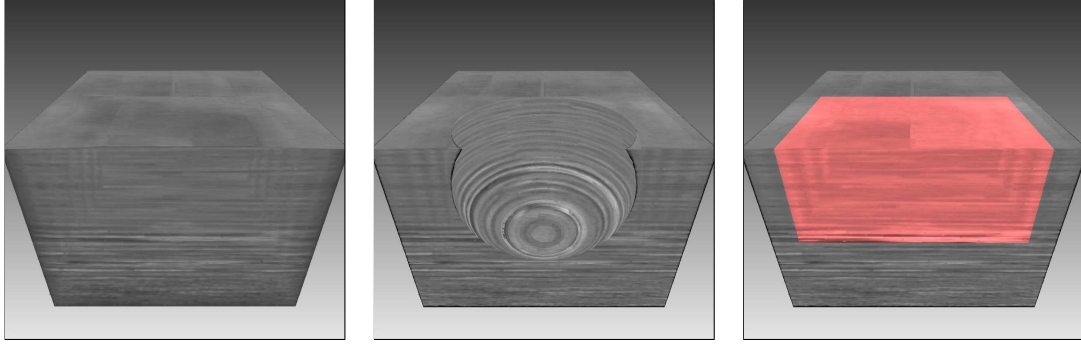[3] http://www.magic-earth.com/geo.asp

Figure 1: Application of focus and context visualization metaphors to a seismic volume dataset. Seismic dataset rendered without using a lens (left), with a spherical clipping lens applied (middle) and with a cuboid lens altering the used transfer function (right).

only lenses having cuboid geometries. Because the surfaces of a cube are given by orthogonal planes, the visualization is similar to the common slicing approach where multiple clipping planes are used to reveal inside structures ([CGH86]). Therefore the technique introduced by Fröhlich et al. can be considered as a generalization of this slicing approach.

However, due to the huge amount of volumetric datasets tracking of the regions of interest is often difficult. Once found regions may get lost since no VR techniques support the geo-scientist when accessing such already explored regions. Concepts for storing regions as well as positions in 3D environments have previously been introduced for guided navigation tasks ([SGLM03], [Döl05]). These approaches allow the user to store certain positions and to define camera paths leading through these so called *bookmarks* placed in the virtual environment. For volume exploration no comparable approaches exist.

3 VISUALIZATION OF VOLUMETRIC SUBSURFACE DATA

In this section we shortly summarize our extension to the GPU-based ray-casting technique [RGWE03] to support different visual representations of the region of interest within a volume dataset. A more detailed explanation of our extension can be found in [RSH05].

GPU-based ray-casting supports very efficient volume rendering on commodity graphics hardware by casting rays through the volume dataset which is represented by a 3D texture.

To apply a different visual representation for the region of interest inside the lens volume, the voxels contributing to a pixel in image space need to be distinguished whether they are inside or outside the lens volume. We determine this voxel classification before rendering the dataset, since it results in better performance, because less per-fragment operations are needed during rendering compared to an alternative approach where the regions are distinguished during rendering. Therefore, in our approach a ray cast through a volume
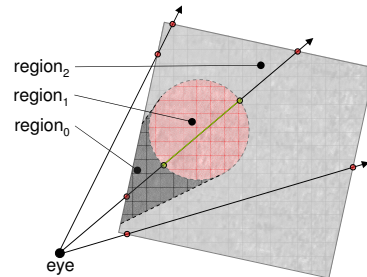

Figure 2: Scheme showing the three regions defined by the lens volume.

dataset which is intersected by a convex lens volume is split into at most three different sections, i.e., one section in front of the lens, one inside the lens and one behind the lens (see Figure 2). This leads to the three view-dependent regions $region_0$, $region_1$ and $region_2$.

Our algorithm renders these view-dependent regions in three subsequent rendering passes starting with $region_0$. Because the view-dependent regions of the volume dataset are determined before accessing the dataset itself, rendering can be performed very fast, since only the usually simple shaped lens geometry and the bounding box of the volume dataset are considered during this computation. In the next subsections we are going to discuss concrete lenses which are useful for 3D exploration of seismic datasets.

3.1 Occlusion Lens

One problem occurring in the visualization of information associated with volumetric data is that usually no insight view can be provided. Especially when navigating through a dense volume dataset the view of the camera will always be occluded. To avoid this problem we propose an *occlusion lens* which renders those parts of the volume dataset transparently that occlude the region of interest (see Figure 3). Therefore when rendering $region_0$ we set the degree of transparency proportional to the amount of volume data occluding the region of interest, i.e., the number of voxels encountered by the ray. This effect does not result in any
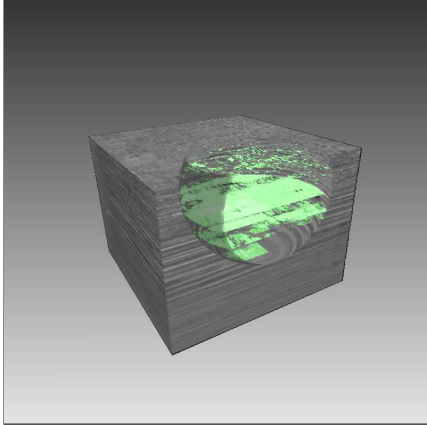
Figure 3: Application of an occlusion lens which renders the parts occluding the region of interest transparently. Inside the lens subsurface structures having a certain intensity are highlighted.

performance penalty compared to direct volume rendering, because during ray traversal instead of setting the voxel's alpha value based on the corresponding scalar value simply the number of samples already processed is used to determine the alpha value.

Another lens type, which we also classify as occlusion lenses is the clipping lens, since it assists in exploring the information on the surface of the lens volume which would be occluded otherwise. Such a lens is shown in Figure 1 (middle) where a spherical clipping lens is used to reveal information hidden inside the dataset. For an easier identification of the clipping region its silhouette edges are enhanced.

3.2 Slicing Lens

A *slicing lens* incorporates clipping-based rendering of slices as visual representation (see Figure 4 (right)). When applying slice rendering surfaces sliced through the volume dataset are displayed. In our prototype application the number of slices and the distance between the slices can be chosen interactively and the visualization provides immediate visual feedback. Thus, it is possible to visualize certain structures based on this rendering technique. As shown in Figure 4 (left) when applying slice rendering to the entire dataset it is difficult to comprehend spatial relationships. Because parts of the dataset are invisible to the user it is difficult to visually comprehend the structure of the dataset and thus the location of the slices. In Figure 4 (right) this spatial relationships can be detected more easily because contextual information is maintained outside the lens. Furthermore the cross-section displayed on the surface of the lens gives an important cue to localize the visualized slices in relation to the rest of the dataset.

3.3 Object Emphasizing Lens

Another lens which improves interactive exploration of seismic volume datasets allows to emphasize objects of

interest by applying image-based silhouette highlighting in combination with a different transfer function. Although in most volume visualization applications the same transfer function is used for the entire dataset, it may be desirable to use different transfer functions in different parts of the dataset, e.g. to identify special regions of interest [SML+99]. Thus, it is possible to reveal structures within the data without changing the context, since in the parts outside the lens volume the original transfer function is retained. In Figure 5 (right) an example is shown where the parts of the dataset lying outside the lens are rendered using direct volume visualization techniques, whereas the parts inside the lens are displayed using a different threshold value as well as a different transfer function to highlight certain objects. In the shown example we use a 1D transfer function inside and outside the focus region, but it would also be possible to combine 1D and 2D transfer functions. Furthermore, the color used for edge-enhancement, the threshold value as well as the transfer function used inside the lens volume can be exchanged interactively. Hence, geo-scientists can either start with a preset threshold and explore the highlighted structures, or they can alter the threshold interactively to find an adequate value for identifying certain structures. By combining the edge-enhancement technique with the altered transfer function objects of interest and their structure can be identified more easily. It can be seen in Figure 5 (left) that using the technique for the entire dataset results in more difficult spatial comprehension.

3.4 Level of Detail Lens

In addition to applying the visual representations as described above, the introduced algorithm allows to further enhance rendering performance. This may be necessary when dealing with datasets having dimensions greater than the maximum dimensions allowed for 3D textures on certain graphics hardware. To enhance performance, a different level of detail (LoD) is used inside the region of interest compared to the LoD outside the region. This is achieved by using a different sampling rate. Figure 6 shows the application of a lens with a different transfer function used for the visualization inside the lens. In Figure 6 (left) the same LoD is used inside and outside the lens, whereas in Figure 6 (right) the LoD outside the lens is coarsened by using half the sampling rate compared to the visualization inside the lens. Usually geo-scientists are interested in details within the region of interest; the parts outside the region of interest are not in focus and may therefore be rendered using a lower sampling rate. Furthermore the LoD outside the lens can be increased adaptively over time when rendering is idle.

In addition to the lenses described in this section several other lenses and even combinations of differ-
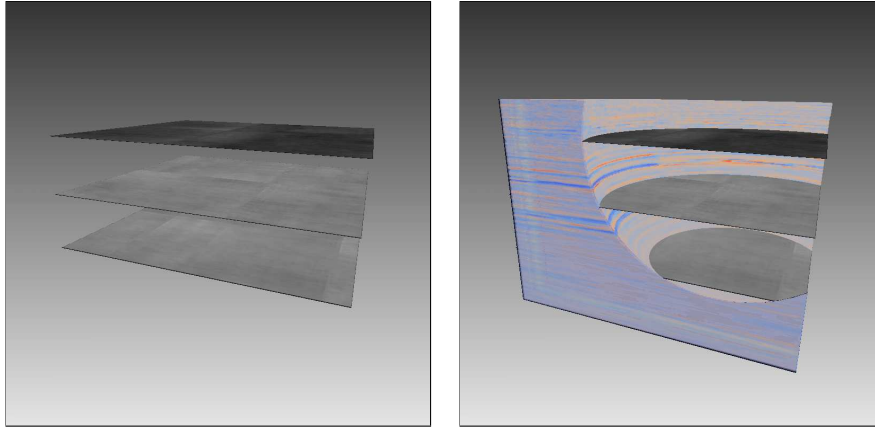
Figure 4: Slice rendering of a seismic volume dataset (left). Slice rendering only applied within the lens volume aids to comprehend spatial relationships (right).
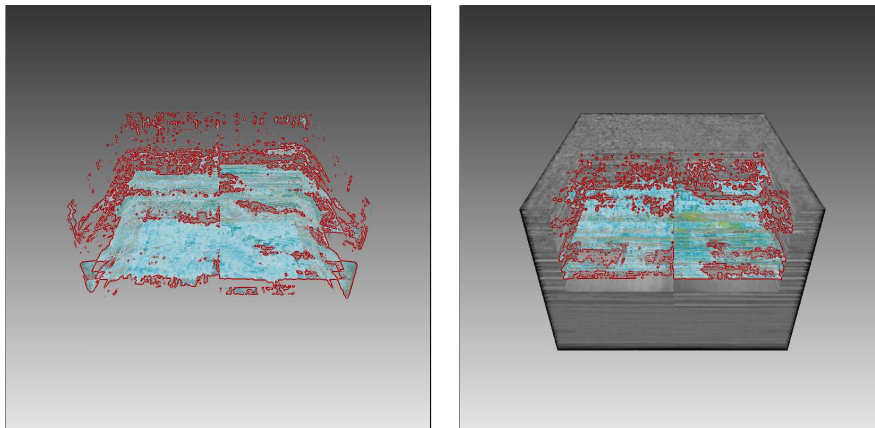

Figure 5: Seismic dataset rendered with image-based edge-enhancement and different transfer function (left) and with edge-enhancement and different transfer function only within the region of interest (right).

ent visual representations inside the lens are possible, e.g., isosurface rendering of translucent surfaces can be combined with regular volume rendering techniques. However, the lenses presented in this section provide a good understanding of the possibilities when applying focus-based visualization techniques to seismic volume datasets.

4 INTERACTION TECHNIQUES FOR VR-BASED EXPLORATION

Although VR technologies provide an excellent alternative to allow more immersive and advanced exploration of large datasets, when using seismic exploration software interaction is often restricted to standard desktop interaction concepts, i.e., interactions are performed via mouse or keyboard devices. This leads to a loss of immersion, since geo-scientists have to accomplish 3D interaction using 2D devices. In this section we propose a VR-based interaction technique that enables users to explore volumetric subsurface data in a very intuitive and efficient way.

4.1 Visualization in a Responsive Workbench Environment

Due to the horizontally mountable projection screen, the semi-immersive workbench has been proven to be advantageous for the exploration of geo-spatial data. We stereoscopicaly display subsurface data in our workbench environment by assigning a *negative parallax* such that the seismic dataset appears on top of the projection screen (see Figure 7). Thus, it is possible to inspect the dataset from all sides. If the height of the dataset exceeds the maximum height that can be visualized above the projection screen, parts of the dataset have to be displayed with *positive parallax*, i.e., below the projection plane.

To enable interaction with surface and subsurface datasets projected on the responsive workbench an optical tracking system determines the position and the orientation of the user's head and input devices. Tracking of the position and orientation of the input devices enables users to interact with the virtual scene. Manipulations can be performed by using *virtual hand metaphors* ([Min94]), i.e., users can directly pick and manipulate objects with the hand or they can move the described
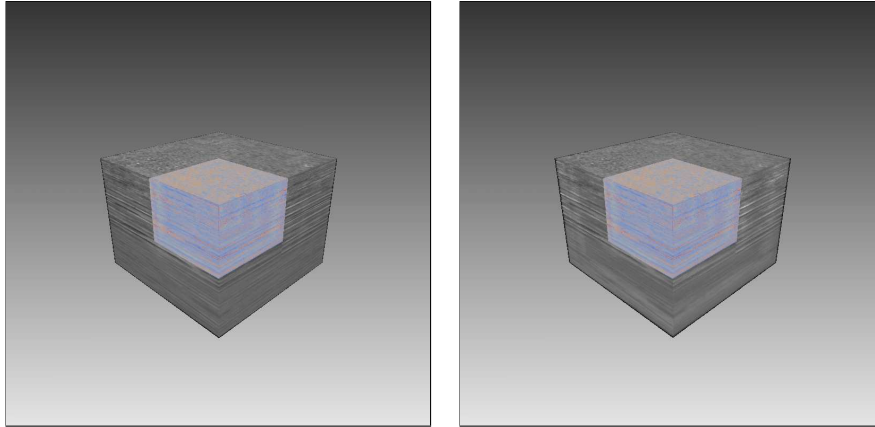
Figure 6: A lens applying a different transfer function. The same LoD is used inside and outside the lens (left). The LoD is coarsened outside the lens by using half the sampling rate (right).
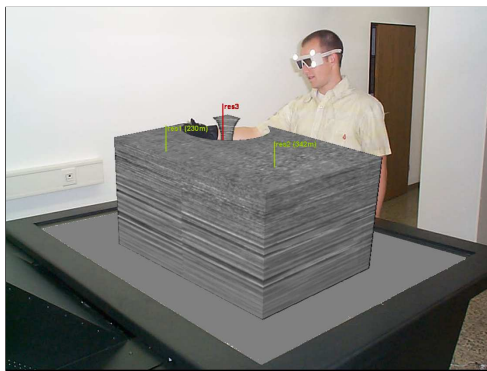

Figure 7: User controlling a spherical clipping lens applied to a seismic volume dataset in a responsive workbench environment. The visual bookmarks have been aligned to the image plane of the observer camera.

lens volume attached to an input device through the subsurface data.

Virtual hand metaphors are not sufficient to allow interaction with parts of a seismic dataset displayed below the projection screen, therefore different strategies must be applied in this context.

4.2 Controlling the Lens

The described lens metaphor offers a comfortable way to explore seismic datasets by visually intruding into the volume. Especially in combination with a stereoscopic projection the user experiences an immersive visualization of complex structures, which improves the cognition of spatial data. To support this immersion, we provide a very intuitive and efficient VR-based control of the lens. The position and orientation of a tracked input device, e.g., a user's hand, are used to move the lens accordingly. Thus, a very intuitive and natural mechanism for controlling the lens through the volumetric dataset is ensured. However, the usage of this interaction metaphor has its limitations. In regions where the seismic data are displayed below the projection screen, distant object interaction, i.e., interaction with data po-

sitioned outside the immediate reach of the user, must be guaranteed.

To enable moving the lens into the aforementioned regions, which are not accessible to the user, we provide the concept of changing the control/display (C/D) ratio. The C/D ratio controller adjusts the ratio determining the relationship between input device movements and the motion of the controlled virtual object, i.e., the lens volume. This adjustment is determined by the input device's position relative to the projection plane, i.e., the closer the hand is to the projection plane the higher this ratio is set. Thus, it is possible to make the movements of the virtual input device less sensitive compared to the user's hand movement or to scale the movements of the user's hand, e.g., for distance object manipulation [BJH01]. Hence in our setup a translation transformation is applied as offset between the real input device and the lens volume depending on the depth of the seismic volume dataset displayed below the projection screen. Thus, an intuitive and efficient distant control of the lens volume is possible.

However, when displaying subsurface data below the projection screen, a side view onto the seismic dataset is not possible due to physical constraints of the hardware setup. Therefore, we have implemented a mechanism to lift the seismic dataset out of the workbench frame to make the lower portions of the volume visible from the side. If the height of the dataset exceeds the maximum height that can be visualized above the projection screen this may result in truncation of the upper parts of the volume dataset.

4.3 Spatial Visual Bookmarking

Since, usually the amount of seismic data acquired for an arbitrary area is very large, localization of regions of interest can be a difficult task. Therefore, we provide a mechanism to support the user by guiding him during the exploration, i.e., the geo-scientist is assisted in locating regions of interest. Once such a region is iden-

tified, the geo-scientist can mark this region and make it accessible later on. Regions of interest can be stored by bookmarking them with a visual hint. In order to support an easy identification by the user textual information about the regions of interest can be attached to the bookmarks.

Individual bookmarks are markers positioned within the seismic dataset, which are easily accessible. When the lens is moved by the user through the dataset emphasizes a special region of interest, an individual bookmark can be defined, e.g., by pressing a button of the input device, and the user gets a visual hint about the marker's position. This approach ensures, the management of bookmarks, e.g., bookmarks can be created, deleted or repositioned.

4.4 Accessing the Bookmarks

Once the bookmarks are defined we use the so called *improved virtual pointer (IVP)* metaphor ([SRH05]) to select a bookmark to position the lens at the appropriate location. The IVP metaphor is a ray-casting-based selection and manipulation metaphor. With ray-casting techniques a selection can be performed when the ray extending from the user's input device hits a selectable object. When attempting to access a spatial visual bookmark geo-scientists benefit from the usage of the IVP metaphor since it provides a very efficient mechanism to aim at small distant objects, such as spatial visual bookmarks. In contrast to other pointer metaphors ([Min94]) selection of a certain object does not require an exact hit of that object with the ray. Thus, the user roughly points the input device to a visual bookmark, and the IVP metaphor determines the bookmark closest to the ray. When using the IVP metaphor distant objects are easy to select and access to bookmarks deep inside the seismic dataset is ensured.

In Figure 7 a user is exploiting the explained interaction concepts in our responsive workbench environment. The seismic dataset is projected onto the projection screen of the workbench, and the user defines and accesses several individual bookmarks within the dataset.

5 CONCLUSION AND FUTURE WORK

In this paper we have presented a novel method allowing interactive VR-based exploration of volumetric seismic datasets. We have proposed the usage of focus-based visualization techniques to ease the identification of certain structures within seismic dataset. Furthermore, we have introduced interaction techniques developed to control the used visualization metaphors intuitively within VR environments. By allowing geo-scientists to set spatial visual bookmarks the user is guided during exploration and can backup previously discovered results.

In the future we will define a taxonomy of lenses used in volumetric visualization applications to assist application developers to choose the optimal lens for their purposes. Furthermore, we are going to conduct a user study with a formal statistical analysis to determine usability as well as efficiency of the proposed concepts.

6 ACKNOWLEDGMENTS

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