Detection of Salt-dome Boundary Surfaces in Migrated Seismic Volumes Using Gradient of Textures

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SUMMARY
Salt domes, an important geological structure, are closely related to the formation of petroleum reservoirs. In many cases, no explicit strong reflector exists between a salt dome and neighboring geological structures. Therefore, interpreters commonly delineate the boundaries of salt domes by observing a change in texture content. To stimulate the visual interpretation process, we propose a novel seismic attribute, the gradient of textures, which can quantify texture variations in three-dimensional (3D) space. On the basis of the attribute volume, we apply a global threshold to highlight regions containing salt-dome boundaries. In addition, with region growing and morphological operations, we can remove noisy boundaries and detect the boundary surfaces of salt domes effectively and efficiently. Experimental results show that by utilizing the strong coherence between neighboring seismic sections, the proposed method can delineate the surfaces of salt-dome boundaries more accurately than the state-of-the-art detection methods that label salt-dome boundaries only in two-dimensional (2D) seismic sections.

INTRODUCTION
The evaporation of sea water leads to the deposition of salt. Because of the lower density, salt grows upwards and commonly penetrates into surrounding rock strata, which forms an important diapir structure, salt domes. Salt domes are mostly impermeable and can seal petroleum and natural gas with surrounding strata. To localize petroleum reservoirs around salt domes, experienced interpreters need to accurately label salt-dome boundaries in migrated seismic data. With the dramatically growing size of collected seismic data, however, manual interpretation is becoming time consuming and label intensive. To speed up interpretation efficiency, in recent years, interpreters have been utilizing computer programs to interactively delineate salt-dome boundaries. With the supervision of interpreters, the computer-assisted interpretation is feasible.

Since the formation process determines the textures of geological structures in migrated seismic data, salt domes and their surrounding strata commonly have distinctive textures. To characterize the texture difference between the two sides of salt-dome boundaries, current computer-assisted salt-dome detection methods were proposed based on graph theory and image processing techniques. Lomask et al. (2004) represented seismic sections as weighted undirected graphs by defining vertices and edges as pixels in seismic sections and the connections of arbitrary two pixels, respectively. The weights of edges are determined based on intensity and position difference of pixels. Using the normalized cut image segmentation (NCIS) method, seismic sections can be partitioned into two parts along detected salt-dome boundaries. The NCIS-based method was later enhanced in Lomask et al. (2007) and Halpert et al. (2009). However, the main disadvantage of NCIS-based methods is their high computational complexity. Therefore, Halpert et al. (2010) employed a more-efficient graph-based segmentation method, referred to as “pairwise region comparison” (Felzenszwalb and Huttenlocher, 2004), in the detection of salt-dome boundaries.

Edge detection methods have also become a powerful tool for the detection of salt-dome boundaries. Zhou et al. (2007) and Agrawi et al. (2011) convolved 2D and dip-guided 3D Sobel filters with seismic data, respectively, and acquired gradient maps containing distinctive boundaries. To refine boundaries obtained from gradient maps, authors proposed to apply post-processing techniques. Similarly, based on the supervised Bayesian classification model, the method in Berthelot et al. (2013) extracts the boundaries of salt domes from the combination of multiple seismic attributes: gray-level co-occurrence matrix (GLCM) attributes, frequency-based attributes, and dip and similarity attributes. Since salt bodies have homogeneous textures in migrated seismic sections, Hegazy and AlRegib (2014b) proposed to combine three texture attributes (directionality, smoothness, and edge contents) to detect salt regions.

Except for the gradient map derived from 3D Sobel filters in Agrawi et al. (2011), all methods and attributes above are proposed to detect salt-dome boundaries in 2D seismic sections, which fail to utilize strong coherence between neighboring seismic sections. To improve the accuracy and the efficiency of salt-dome detection in seismic volumes, we propose a new attribute, the gradient of textures, which describes the change of textures along the three dimensions. By adaptively determining a global threshold, we highlight the regions of salt-dome boundaries in binarized volumes. Finally, we apply region growing to extract salt volumes and morphological operations to refine detected salt-dome boundaries.

PROPOSED METHOD
On the basis of the various formation processes of salt domes, we can broadly classify salt boundaries into two types. The first type is where salt bodies are adjacent to strong reflectors (e.g., caprock), while the second type of boundaries can be only characterized through the change in textures. A single salt-dome structure may have a mixture of both boundary types. Although traditional edge detection methods are suitable for the first type of boundaries, they fail to accurately delineate the second type. Our proposed method is designed to detect both boundary types. Figure 1 illustrates the block diagram of the proposed salt-dome detection method. In the following subsections, we introduce each block in detail.

Gradient of Textures (GoT)
The growing of salt domes commonly intrudes into surrounding strata formed by other sedimentary rocks such as limestone and shale. Since different rocks have distinctive textures in migrated seismic data, to characterize the change of textures
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Thresholding

Seismic Volumes

Computing Gradient of Texture (GoT)

Region

Thresholing

Morphological Operation

Salt-Dome Boundaries

Figure 1: The block diagram of the proposed salt-dome detection method.

between salt and non-salt regions, we propose a new 3D seismic attribute, the gradient of textures (GoT). For a given point, its GoT represents the texture dissimilarity between two neighboring cubes that share a square face centered around the given point. Figure 2 introduces the definition of the GoT along the x-direction, in which dotted and stripe textures are separated by a green dashed vertical boundary. In the following, we explain how the GoT profile changes along a single line and how the GoT attribute is extended to the whole 3D space. To evaluate the GoT in the x-direction, we move the center point and its two neighboring cubes, denoted $W_{x-1}$ and $W_{x+1}$, in the x-direction along the blue line. By evaluating the texture dissimilarity along the blue line using the function $d(\cdot)$, we yield the GoT profile as the curve shown at the bottom of Figure 2. The greatest GoT value is reached when the center point falls exactly on the texture boundary, as in this case two neighboring cubes contain completely different texture contents. Therefore, the point with a greater GoT value has a higher possibility of falling on a boundary surface.

In Figure 2, we slide the center point only along the x-direction and calculate the corresponding GoT component for illustration purposes. However, in the 3D space each point has a GoT attribute with three components in the x, y, and t axes, which correspond to the crossline, inline, and time directions, respectively. Therefore, by combining the three components, the GoT value of each point can be calculated as follows:

$$G_i = d (W_{x-1}, W_{x+1}), \quad i \in \{x,y,t\}, \quad (1)$$

$$G = \sqrt{G_x^2 + G_y^2 + G_t^2}, \quad (2)$$

where $G_i, i \in \{x,y,t\}$, represents the GoT component on each direction and $G$ defines the combined GoT value. Figure 3 illustrates the positions of neighboring cubes in the calculation of the GoT components on the x, y, and t directions. Because of the complicated structures of salt domes in the subsurface, we need to carefully choose the size of neighboring cubes in the calculation of the GoT. However, depending only on cubes with fixed sizes is not enough to capture texture variations along salt-dome boundaries. Therefore, to improve the robustness of the proposed method, we introduce the weighted multi-scale GoT, which is the weighted average of GoT values calculated based on various cubes. The components of the weighted multi-scale GoT is calculated as follows:

$$\tilde{G}_i = \sum_{n=1}^{N} \frac{o_n}{\sum_{n=1}^{N} o_n} \cdot d (W_{x-1}^{n}, W_{x+1}^{n}), \quad i \in \{x,y,t\}, \quad (3)$$

where $n$ determines the size of neighboring cubes and $o_n$ represents the corresponding weight. $W_{x-1}^{n}$ and $W_{x+1}^{n}$ denote the neighboring cubes with edge length $(2n+1)$. Figure 4 illustrates the cross-sections of the smallest $(3 \times 3 \times 3)$ and largest $(11 \times 11 \times 11)$ neighboring cubes around a blue labeled salt-dome boundary.

In the framework of the weighted multi-scale GoT, we attempt to propose a measure of texture dissimilarity that is consistent with interpreters’ perception. Hegazy and AlRegib (2014a) introduced an similarity assessment index on the basis of 2D fast Fourier transform (FFT) that can efficiently evaluate variations between images. We derive the 3D version of the assessment index using 3D FFT and employ it in function $d(\cdot)$. The defi-
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Definition of 3D FFT is expressed as follows:

\[ F[u,v,w] = \frac{1}{L} \sum_{x=0}^{L-1} \sum_{y=0}^{L-1} \sum_{z=0}^{L-1} f[x,y,z] e^{-2\pi i (ux+vy+wz)/L}, \]  

where \([x,y,z]\) and \([u,v,w]\) represent the coordinates of the spatial and frequency domains, respectively, and \(L\) defines the edge length of a cube-shaped data volume. Based on the 3D FFT, derived function \(d(\cdot)\) applies two concatenated 3D FFT magnitude operations to the absolute difference of neighboring cubes and averages the result as follows:

\[ d(W_-, W_+) = E(|\mathcal{F}(|\mathcal{F}(abs(W_- - W_+))|)|), \]  

where \(\mathcal{F}\{\cdot\}\) represents the 3D FFT and function \(abs(\cdot)\) calculates the absolute values of all elements in the difference of neighboring cubes \(W_-\) and \(W_+\). In addition, function \(E(\cdot)\) indicates the average operation. Since the dissimilarity measure in Hegazy and AllRegib (2014a) has been proved to comply with human’s perception, its extended version in seismic volumes can also help simulate the labeling strategies of interpreters. Therefore, by applying Equations 3 and 5 on all points of the seismic volume, we can obtain the corresponding GoT volume that describes the change of textures in the 3D space.

**Thresholding**

To highlight the boundary regions of salt domes, we apply threshold \(T\) to the GoT volume as follows:

\[ B[x,y,t] = \begin{cases} 1 & G[x,y,t] \geq T \\ 0 & \text{Otherwise} \end{cases}, \]  

where \(B\) and \(G\) represent the binary and GoT volumes, respectively, and white regions in \(B\) indicate likely salt-dome boundaries. To adaptively select threshold \(T\), we extend Otsu’s method (Otsu, 1975) from images to volumes. In contrast to other regions, salt-dome boundaries commonly have higher GoT values. Therefore, we assume that the histogram of points in the GoT volume follows a bimodal distribution shape. To optimally divide all points into two classes, we determine threshold \(T\) by minimizing the intra-class variance as follows:

\[ \arg\min_T \left\{ \sigma_1^2(T) \sum_{i=0}^{T-1} p(i) + \sigma_2^2(T) \sum_{i=T}^{K} p(i) \right\}, \]  

where \(K\) is the number of the quantized gray-levels of GoT values and \(p(i)\), \(i = 0, \ldots, K - 1\), represents the possibility of points with gray value \(i\). In addition, \(\sigma_1^2\) and \(\sigma_2^2\) define the individual class variances, which can be calculated as follows:

\[
\begin{align*}
\sigma_1^2 &= \sum_{i=0}^{T-1} \left( i - \frac{T-1}{2} \right)^2 \frac{P(i)}{P_1}, & P_1 &= \sum_{i=0}^{T-1} P(i) \\
\sigma_2^2 &= \sum_{i=T}^{K-1} \left( i - \frac{K-1}{2} \right)^2 \frac{P(i)}{P_2}, & P_2 &= \sum_{i=T}^{K-1} P(i)
\end{align*}
\]  

Therefore, on the basis of Equation 7, we can adaptively identify threshold \(T\) by exhaustively searching between 0 and \(K - 1\).

**Region Growing and Morphological Operation**

Before we introduce post-processing steps, we explain two basic morphological operations, dilation and erosion, which can enlarge and shrink the regions of salt-dome boundaries in a binary volume with 3D structural element \(H\). The mathematical expressions of dilation and erosion are expressed as follows:

\[
\begin{align*}
\text{Dilation:} & \quad M \oplus H = \bigcup_{z \in M} H_z, \\
\text{Erosion:} & \quad M \ominus H = \{ z \in H, \subseteq M \}
\end{align*}
\]

where \(M\) and \(H\) represent the binary volume and the structural element centered at 3D point \(z\), respectively. The dilated volume can be understood as the locus of the points covered by \(H\) when the center of \(H\) moves inside \(M\). In contrast, the eroded result represents the locus of points reached by the center of \(H\) when \(H\) moves inside \(M\). Since we apply all morphological operations on binary volumes rather than binary images, the smoothness and continuity of detected salt-dome boundary surfaces can be guaranteed.

As we mentioned in the previous section, we employ threshold \(T\) to highlight salt-dome boundaries in GoT volume \(G\). However, because of complicated structures in the subsurface and the using of global threshold \(T\), it is inevitable that binary volume \(B\) contains noisy or disconnected boundary regions. The cross-sections of which are illustrated by the dashed and solid boxes in Figure 5. To bridge gaps between disconnected boundary regions and ensure that detected boundaries can enclose the entire salt body, we apply the closing operation to \(B\), which first dilates and then erodes \(B\) with the same structural element. Since noisy regions commonly exist in non-salt structures, we can eliminate the influence of noisy regions by detecting the boundary surface of the sealed salt body. Inside the salt body, we arbitrarily select an initialization point and grow it in the 3D space until dilated boundary regions are hit. Finally, on the basis of the definition of the GoT attribute, to more accurately delineate the boundary surfaces of salt domes, we utilize the sphere structural element to dilate the extracted salt body.

**EXPERIMENTAL RESULTS**

In this paper, we apply the proposed method to detect the boundary surfaces of salt domes in the real seismic dataset acquired from the Netherlands offshore F3 block with the size of \(24 \times 16\) km\(^2\) in the North Sea. The local volume that contains a salt-dome structure has an inline number ranging from \#151 to \#500, a crossline number ranging from \#401 to \#701, and a time direction ranging from 1,300ms to 1,848ms sampled every 4ms. Figure 6(a) illustrates the tested local volume and one of its seismic section Inline #269.
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To obtain the weighted multi-scale GoT attribute, for each point, we define various neighboring cubes on three directions with the edge length ranging from 3 to 11 and evaluate their dissimilarity using Equation 5. Since larger cubes are more sensitive to texture variations, to compensate for this bias, we define weights $\omega_n$ inversely proportional to edge length $n$. Figure 6(b) shows the GoT volume and the GoT map of Inline #269. Furthermore, by adaptively selecting global threshold $T$, we can highlight the boundaries of the salt dome. By applying the closing operation with a diamond shape, the highlighted boundary regions can seal entire salt body as Figure 6(c) illustrates. Furthermore, we manually select the initialization point and grow it to detect the salt body shown in Figure 6(d). Finally, we dilate the extracted salt body with a sphere shape and obtain the labeled salt-dome boundary with high accuracy.

Figure 6: The intermediate results of the proposed salt-dome detection method.

In this paper, we compare the proposed method with the detection methods in Berthelot et al. (2013) and Aqrawi et al. (2011). Figures 7(a) and (b) compare salt-dome boundaries detected by different methods in Inline #265 and #269 with the ground truth manually labeled in red. The magenta, yellow, and green curves represent boundaries detected the Berthelot’s, Aqrawi’s and proposed methods, respectively. In contrast to jagged boundaries detected by Aqrawi et al. (2011), although in Figure 7(a) the boundary detected by Berthelot et al. (2013) has comparable accuracy with that detected by the proposed method, in Figure 7(b) Berthelot’s method seriously degrades and the detected boundary deviates far from the ground truth. To objectively evaluate the similarity between detected boundaries and the ground truth, we normalize the Fréchet distances (Alt and Godau, 1995) in the similarity index, and Figure 7(c) shows the similarity indices of salt-dome boundaries detected in Inline #259 to #269. We notice that in almost all sections the proposed method has the best performance. To verify the robustness of the proposed method, Figure 8 illustrates the detected boundary surfaces of the salt dome in the tested volume.

Figure 7: (a) and (b): the comparison between boundaries detected by various methods with the ground truth in Inline #265 and #269, and (c): similarity indices of boundaries detected in Inline #259 to #269.

Figure 8: 3D salt-dome boundary surfaces detected by the proposed method.

CONCLUSION

In this paper, we proposed to detect the boundary surfaces of salt domes in seismic volumes using the 3D attribute, the gradient of texture, which can describe the changing of textures along salt-dome boundaries. With adaptively selected threshold, likely salt-dome boundaries can be highlighted. By applying region growing and morphological operations, we can delineate boundary surfaces with high accuracy. Experimental results show that the proposed method outperforms the state-of-the-art method on salt-dome detection.

ACKNOWLEDGEMENTS

This work is supported by the Center for Energy and Geo Processing (CeGP) at Georgia Tech and by King Fahd University of Petroleum and Minerals (KFUPM).
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