Salt dome detection within migrated seismic volumes using phase congruency
Muhammad A. Shafiq*, Yazeed Alaudah, Haibin Di, and Ghassan AlRegib
Center for Energy and Geo Processing (CeGP) at Georgia Tech and KFUPM, School of Electrical and Computer
Engineering, Georgia Institute of Technology, Atlanta, Georgia, 30332-0250. *amirshafiq@gatech.edu

SUMMARY

In this paper, we propose a method based on phase congruency (PC) for computational seismic interpretation with an
application to subsurface structures delineation within migrated seismic volumes. Phase congruency highlights small discontinuities in images with varying illumination and contrast using the congruency of phase in Fourier components. PC can not only detect the subtle variations in the image intensity but can also highlight the anomalous values to develop a deeper understanding of the images content. We show the effectiveness of the proposed method on the SEAM dataset, which models the complex salt structures found in the Gulf of Mexico. Experimental results show that the proposed method effectively delineates salt domes within migrated seismic volumes.

INTRODUCTION

The evaporation of water from the geological basins gives rise to the depositions of salt evaporites. Because of the lower density, these evaporites grow upwards and commonly break through the sediment layers and surrounding rock strata such as limestone and shale to form a diapir shaped structure called salt dome. Salt domes are important geophysical structures that contain hints about petroleum and gas reservoirs. By observing the intensity and texture variations of seismic traces near salt-dome boundaries in migrated seismic volumes, experienced interpreters can manually delineate their boundaries. However, with the striking increase in the size of seismic data over the last few years, researchers in academia and industry have utilized semi-automated seismic interpretation software and tools to overcome the time-consuming and labor-intensive manual interpretation. Researchers have proposed several methods to delineate salt domes which include edge-based detection methods by Agrawi et al. (2011), Zhou et al. (2007), and Amin and Deriche (2015b), texture-based methods by Berthelot et al. (2013), Shafig et al. (2017b), and Wang et al. (2015), active-contour-based methods by Haukas et al. (2013) and Shafig et al. (2015), saliency-based methods by Drissi et al. (2008) and Shafig et al. (2017a), machine-learning-based methods by Guillen et al. (2015) and Amin and Deriche (2015a), and different image processing techniques by Halpert et al. (2009), Lomask et al. (2007), Felzenszwalb and Huttenlocher (2004), Larrazabal et al. (2015), Wu (2016), and Qi et al. (2016).

In this paper, we present a novel approach for salt dome delineation based on an attribute map obtained using phase congruency. The proposed method leads to improved salt dome delineation by accurately and efficiently detecting the presence of strong and weak seismic reflections using the PC attribute map. The experimental results on the SEAM dataset (Fehler and Ke-
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Seed Point

Pre-
Processing

Seismic Volume

Phase Congruency

PC

Thresholding (Otsu’s)

Interactive Editing (Optional)

Region Growing

Salt Dome

Figure 3: Block diagram of the proposed salt dome delineation workflow.

(a) A typical seismic inline section

(b) PC Map

(c) Binary map obtained after thresholding

(d) Interactively edited binary map

(e) Output of region growing

(f) Highlighted salt dome

Figure 4: The intermediate results of the proposed salt dome delineation workflow.
us consider a 1D signal, which has $N$ Fourier components, and at any instant $i$ they are represented by amplitude $A_n(i)$ and phase $\phi_n(i)$, respectively. If we add the Fourier components at any instant $i$ according to the head to tail rule on complex axis as shown in Figure 2, we get the local energy, $|E(i)|$, that is the magnitude of the resultant vector from the origin to the end point. Therefore, PC can be mathematically written as

$$PC = \frac{|E(i)|}{\sum_n A_n(i)}.$$  

(1)

PC varies between 0 and 1 corresponding to no and perfect phase congruency, respectively. In perfect phase coherence, all complex Fourier components align together to form $E(i)$ that results in PC equal to 1. However, PC defined in equation 1 is highly sensitive to noise because of vector normalization and becomes ill conditioned if Fourier components are very small. Kovesci (1999) developed a modified form of phase congruency that not only produces a more localized response but is also more robust to noise. The modified PC measure by Kovesci (1999), which incorporates multiple filter orientations and robustness to noise is given by

$$PC = \frac{\sum_o \sum_n W_o(i)|A_n(o,i)\Delta\Phi_n(o,i) - T_o|}{\sum_o \sum_n A_n(o,i) + \varepsilon},$$  

(2)

where $o$ represents different orientations, $A_n(o,i)$ and $\Phi_n(o,i)$ represents the amplitude and phase of Fourier components at different instants and orientations, respectively. $\varepsilon$ is a small positive real number in the neighborhood of zero to avoid division by zero. $T_o$ is the estimated noise influence at each orientation $o$. $\Delta\Phi_n(o,i)$ defines the phase deviation and $\lfloor \cdot \rfloor$ defines soft thresholding, which means that the enclosed term is equal to itself when its positive, and zero otherwise. $W_o(i)$ is the weighting function for orientation $o$ constructed by applying the sigmoid function to the filter response spread value.

PROPOSED METHOD

In this paper, we propose a novel workflow for the computational seismic interpretation of salt domes as shown in Figure 3. Given a 3D seismic volume $V$ of size $T \times X \times Y$, where $T$ represents time or depth, $X$ represents crosslines, and $Y$ represents inlines, we apply pre-processing operations such as noise removal and image enhancement to yield a 3D seismic data volume, $V_p$, for better feature detection. We compute the PC attribute map, which highlights salt dome edges and different geological features in a seismic image. We then determine the adaptive threshold $T_o$ using Otsu’s method to obtain a binary map of highlighted salt-dome boundaries. The adaptive threshold $T_o$ is the weight region in $B$ and white regions in $B$ highlight the salt-dome boundaries. Salt domes are complex geological structures and it is inevitable that $B$ contains noisy and disconnected parts. After obtaining the binary map using adaptive global threshold, we may apply morphological processing operations, if required, to close the salt body and disconnect the non-salt regions from the salt regions in areas, which have low congruency in phase. To get rid of the noise and detect a salt body $S$ from the binary map $B$, we apply a region growing method by randomly selecting an initial seed point, $p_i$, and growing it pixelwise until it hits the salt-dome boundary. The seed point for region growing can be selected either manually by the seismic interpreter or automatically using centroid, directionality or tensor-based methods. In manual $p_i$ selection, the seismic interpreter can interactively choose either one seed point, or multiple seed points to speed up the region growing, provided all selected seed points lie inside salt body. Given the computational complexity and the error rate of automatic seed point selection methods, we have selected initial seed points manually in this paper. The region growing method yields a binary map of the salt body, $S$, which is superimposed on the original seismic section to highlight the salt dome.

EXPERIMENTAL RESULTS

A seismic inline section from the SEAM dataset and its PC map are shown in Figure 4a and Figure 4b, respectively. It can be observed from Figure 4b that it highlights the salt-dome boundary and different geological structures in a seismic image. The thresholded PC map obtained after adaptive global thresholding using Otsu’s method is shown in Figure 4c, which has some open salt regions as shown in red areas that may cause leakage during the region growing process. Therefore, in order to fix the thresholded binary map, the interpreter may interactively edit these areas to yield a closed threshold binary map as shown in Figure 4d. The output of region growing is shown in Figure 4e, whereas Figure 4f highlights the detected salt dome within the example seismic inline section. The proposed workflow can be interactively supervised by an interpreter who can interactively edit, if required, any areas that are misinterpreted by the algorithm. The proposed workflow is also computationally inexpensive and the time required to detect salt domes using the proposed workflow is merely 1.60 seconds. We further apply the proposed method to detect salt domes from different seismic inline and crossline sections within the SEAM dataset and results are shown in Figure 5. The careful examination of the results show that the proposed workflow not only yields very good delineation of salt dome boundaries but also effectively detects the base of salt domes.

CONCLUSION

In this paper, we proposed a method for delineating salt domes within seismic volumes using the phase congruency attribute. In proposed workflow, we use phase congruency to generate an attribute map of edges in the seismic data and adaptively select a threshold to convert these attribute maps into binary maps. A software tool interactively guided by an interpreter and the region growing method are then used to accurately detect salt bodies within seismic volumes. Experimental results on the SEAM dataset show that the proposed workflow is not only computationally less expensive but also yields very good results for salt dome delineation. The proposed method is expected to not only reduce the time for seismic interpretation but also become a handy tool in the interpreters toolbox for delineating geological structures within migrated seismic volumes.
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Figure 5: Output of the proposed salt dome delineation workflow.

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EDITED REFERENCES
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REFERENCES


