Title:

Interpreter-assisted tracking of subsurface structures within migrated seismic volumes using active contour

Author(s):

Muhammad Amir Shafiq* and Ghassan AlRegib

Center for Energy and Geo Processing (CeGP),

School of Electrical and Computer Engineering,

Georgia Institute of Technology,

Atlanta, GA, 30332

**amirshafiq@gatech.edu*

Summary:

This paper presents an active contour based tracking work flow for delineating salt domes within migrated seismic volume. The proposed work flow requires minimum intervention and parameter tuning from the interpreter that makes it very advantageous for semi-automated seismic interpretation. The proposed tracking frame work starts by projecting the salt dome boundary detected at the initialized seismic section inline in both negative and positive inline directions, respectively. The tracking frame work continues to project detected salt dome boundaries from each inline on neighboring inlines until results starts to deviate from the desired results. The proposed work flow for interpreter-assisted salt dome segmentation implements an edge-based active contour with an arc length penalty using level sets to dynamically move the curve at salt dome boundary. The experimental results on real seismic dataset show that active contour tracking outperforms other methods for salt dome delineation and require initialization at only four seismic sections to track salt domes in 53 consecutive inlines of migrated seismic volume.

Introduction

The water evaporation from basin over long periods of time and geological formation of surrounding rock strata determine distinctive appearances of diapir shaped structures called salt domes. The salt domes may span tens of kilometers in Earth's subsurface and because of salt impermeability, they effectively form seals for petroleum and gas reservoirs. Experienced interpreters can manually delineate the salt domes by comparing the intensity and texture variations between salt and non-salt regions. Over the last few years, researchers have proposed several methods, which include edge-based detection methods by Zhou et al. (2007), Aqrawi et al. (2011) and Amin and Deriche (2015b), texture-based methods by Berthelot et al. (2013), Hegazy and AlRegib (2014), Shafiq et al. (2015b) and Wang et al. (2015), graph theory based methods by Shi and Malik (2000) and Felzenszwalb and Huttenlocher (2004), active contours by Haukas et al. (2013) and Lewis et al. (2012), and different image processing techniques by Lomask et al. (2007), Guillen et al. (2015), Amin and Deriche (2015a) and Shafiq et al. (2016) to delineate different structures within seismic volume. More recently, an active contour based method proposed by Shafiq et al. (2015a) requires contour initialization near salt dome boundary by interpreter at each seismic section inline that makes the seismic interpretation time consuming and labor intensive. Salt domes are complex geological structures and their shape and size vary across the seismic volume. In order to accurately detect salt dome changes, interpreters have to fine tune algorithm parameters because accuracy and efficiency of various salt dome delineation algorithms are sensitive to parameter selection. The interpreter-assisted algorithms which require frequent tuning although help to maintain a false positives rate low, but on the other hand increases the time required for seismic interpretation. In this paper, we propose a method for tracking salt domes within seismic volume using active contour which require minimum manual intervention and parameter tuning.

Theory

The proposed tracking work flow is shown in Fig. 1. Given a seismic volume, we randomly select a seismic section inline and perform salt dome delineation using the method proposed in Shafiq et al. (2015a), which requires an active contour initialization near salt dome boundary. We then project the detected salt dome boundary to the neighboring inlines where we treat it as an initial curve for salt dome boundary detection using active contour energy minimization. The projection step eliminates the need of active contour initialization at each seismic section and we continue this *project and detect* process as long as tracking is yielding very good delineation results. The interpreter can re-initialize or fine tune active contour parameters if delineation results start to deviate from the desired output. The process of

Figure 1: Active contour tracking workflow

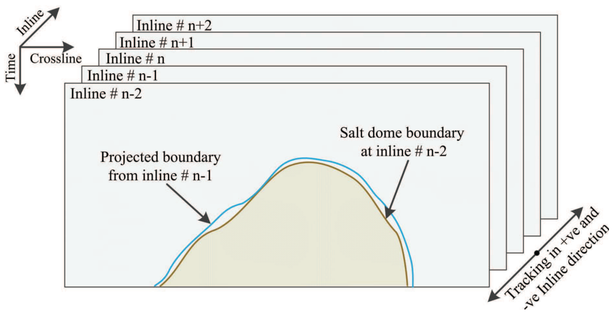


Figure 2: Boundary projection

Table 1: Mean and Std Dev. of *SalSIM* indices

Methods	*SalSIM* Mean	*SalSIM* Std Dev.
Aqrawi et al. (2011)	0.8781	0.0672
Berthelot et al. (2013)	0.8360	0.0714
Shafiq et al. (2015b)	0.9203	0.0115
Tracking (Proposed)	0.9387	0.0122

boundary projection is illustrated in Fig. 2. We start tracking process from a randomly selected seismic section inline #n. The interpreter initializes the active contour at inline #n and after delineation using active contour, the result of inline #n is projected in -ve inline direction on inline #(n-1). At inline #(n-1), we treat projection as a initialized active contour because the shape and size of salt dome changes slowly across inline direction. The salt dome delineation result at inline #(n-1) is then projected on inline #(n-2) and we continue tracking in negative inline direction. Similarly, we repeat *project and detect* process in positive inline direction by projecting the boundary detected at inline #n on inline #(n+1) and so on. The proposed tracking work flow not only preserves the active contour from local minimas and parameter tuning but also makes the delineation fast and eliminates the need of initialization at each step.

To track the salt domes in seismic volume, we have to design an energy function that not only ensure salt dome delineation but also ensure small length and smoothness of the curve. To achieve this goal, we define an energy function given by (1) that explicitly defines an external energy by 1st term and internal energy by 2nd term such that the former will converge the curve towards salt dome boundary and the latter will keep the curve small and smooth.

$$E(C(p,t)) = \int_0^L \Phi dp + \int_0^L \frac{1}{2}\lambda \|C_p\|^2 dp, \tag{1}$$

where $C(p,t) \in \Re^2$ is a parameterized curves of Euclidean arc length L at instant t and parameterization p. The external energy is driven by the edge detection function $\Phi(x,y)$, whereas the internal energy will be governed by the curve length and the smoothness penalty λ. To derive a partial differential equation (PDE) independent of parametrization, we define the energy function using arc length parameter s by (2) and its energy minimization using gradient descent is given by (3).

$$E = \int_0^L (\Phi + \frac{\lambda}{2}) ds, \tag{2}$$

$$C_t = (\Phi + \frac{\lambda}{2})\kappa N - (\nabla\Phi.N)N, \tag{3}$$

where $\nabla\Phi$ is the gradient of edge function, κ is curvature and N is normal to curvature. The edge function $\Phi(x,y)$ is the crux of active contour tracking that will dynamically move the contour towards the salt dome boundary. For active contour tracking, we have used the same function $\Phi(x,y)$ proposed in Shafiq et al. (2015a), given by

$$\Phi(x,y) = \frac{1}{(\varepsilon + \|\nabla I\| * G_\sigma)^p}, \tag{4}$$

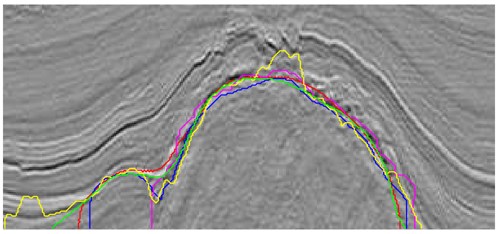
where I is input seismic image, p is positive integer and ε is small positive real number in the neighborhood of zero. We have used epsilon in $\Phi(x,y)$ function to avoid division by zero that would result in infinite energy if the gradient of image is zero. G_σ is the Gaussian kernel with standard deviation σ and $\|\nabla I\| * G_\sigma$ produces a smooth and denoised version of I so that the active contour don't stuck in local minima. We have also normalized the image and its edge function to obtain same results for the different seismic images of varying intensities. The function $\Phi(x,y)$ is positive in the homogeneous regions of I whereas approximately zero at the salt dome boundary. The derivation of level set evolution, Ψ_t, from (3) is fairly simple and straight forward.

$$\Psi_t = \widehat{\nabla\Phi}.\nabla\Psi + (\widehat{\Phi} + \frac{\lambda}{2})\nabla.(\frac{\nabla\Psi}{\|\nabla\Psi\|})\|\nabla\Psi\|, \tag{5}$$

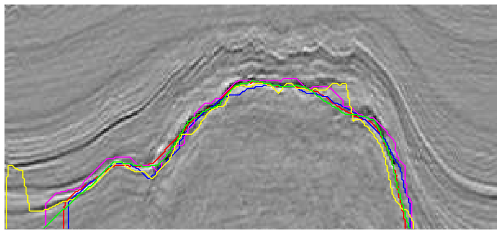
where $\widehat{\Phi}$ and $\widehat{\nabla\Phi}$ are the extensions of edge function and the gradient of edge function, respectively. For numerical implementation, we have used upwind forward time difference scheme given as

$$\Psi(t+\Delta t) = \Psi(t) + \Delta t(\widehat{\nabla\Phi}.\nabla\Psi + (\widehat{\Phi} + \frac{\lambda}{2})\nabla.(\frac{\nabla\Psi}{\|\nabla\Psi\|})\|\nabla\Psi\|), \tag{6}$$

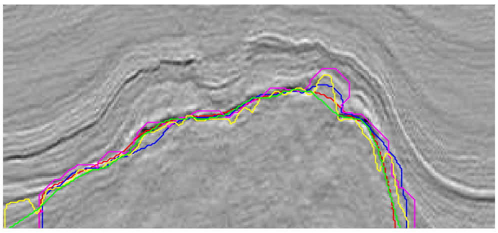
where Δt is time step and $\nabla.(\frac{\nabla\Psi}{\|\nabla\Psi\|})\|\nabla\Psi\|$ is the geometric heat equation.



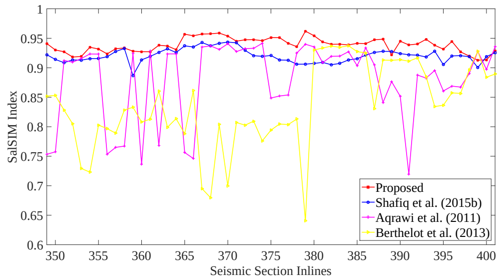
(a) Seismic Section Inline #349



(b) Seismic Section Inline #369



(c) Seismic Section Inline #392



(d) *SalSIM* indices

Figure 3: Experimental results on different seismic section inlines. Green: Ground Truth, Magenta: Aqrawi et al. (2011), Yellow: Berthelot et al. (2013), Blue: Shafiq et al. (2015b), Red: Active Contour Tracking.

Experimental Results

In this section, we present the effectiveness of active contour tracking on the real seismic dataset acquired from the Netherlands offshore, F3 block in the North Sea by dGB Earth Sciences (1987). The seismic volume that contains the salt dome structure has an inline number ranging from #151 to #501, a crossline number ranging from #401 to #701, and a time direction ranging from 1,300ms to 1,848ms sampled every 4ms. The results of active contour tracking as compared to the other delineation methods are shown in Fig. 3a–c, with the ground truth manually labeled in green. The Fig. 3a-c show the delineation results on three different seismic inlines in which magenta, yellow and blue lines represent the boundaries detected by Aqrawi et al. (2011), Berthelot et al. (2013) and Shafiq et al. (2015b), respectively, whereas the red line represents the boundary detected by active contour tracking. Subjectively, it can be observed that the boundaries detected by active contour tracking are closest to the ground truth as compared to other methods and yield best results for salt dome segmentation. To objectively evaluate the similarity between the detected boundaries and the ground truth, we have used the Fréchet distance based similarity index, *SalSIM* by Wang et al. (2015). The *SalSIM* index close to one indicates that the detected salt dome boundary and the ground truth are close to each other, whereas indices close to zero show a dissimilarity between the two curves. The *SalSIM* indices for different salt dome delineation algorithms from seismic section inline #349 to #401 are shown in Fig. 3d, which show that active contour tracking yield best results for salt dome delineation. The mean and standard deviation of the *SalSIM* indices from inline #349 to #401 are shown in Table .1, which also show that active contour is best method for delineation among other methods. In the experimental results shown, we have tracked salt domes in 53 consecutive inlines without any parameter tuning, and re-initialization at only four inlines #349, #380, #384 and #388 respectively.

Conclusions

In this paper, we have proposed an active contour based tracking of subsurface structures such as salt domes within migrated seismic volumes. The experimental results on real seismic dataset show that active contour tracking outperforms the state of the art methods for salt dome delineation. The proposed framework has minimal manual intervention and parameter tuning which makes active contour tracking very suitable for semi-automated seismic interpretation.

Acknowledgements

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

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