

# PHASE CONGRUENCY FOR IMAGE UNDERSTANDING WITH APPLICATIONS IN COMPUTATIONAL SEISMIC INTERPRETATION

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## ABSTRACT

Phase Congruency (PC) can highlight 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 and context. In this paper, we propose a new method based on PC for computational seismic interpretation with an application to subsurface structures delineation within migrated seismic volumes. We show the effectiveness of the proposed method as compared to the edge- and texture-based methods for salt domes boundary detection. The subjective and objective evaluation of the experimental results on the real seismic dataset from the North Sea, F3 block show that the proposed method is not only computationally very efficient but also outperforms the state of the art methods for salt dome delineation.

**Index Terms**— Image Understanding, Labeling, Computational Seismic Interpretation, Phase Congruency, Salt domes, Fourier Transform.

## 1. INTRODUCTION

Phase Congruency (PC) originally proposed by Morronne *et al.* [1] and modified by Kovesi [2] is an edge detection approach based on the observation that the pixels along edges have Fourier components that are maximally in phase. PC is superior to gradient-based methods due to the fact that PC is a dimensionless quantity that is not affected by the changes in image illumination and contrast thereby making it practicable for images with dominating and inconspicuous edges. PC has been successfully applied to various fields which require access to the minute details of intensity and texture variations in image content. Among many, few examples of such applications include noise removal [3], detecting blood vessels in retinal images [4], detecting lung diseases in chest radiographs [5] and detecting defects in textile fabric images [6]. In

seismic interpretation, Russell *et al.* [7] and Kovesi *et al.* [8] showed the efficacy of PC by detecting seismic discontinuities and velocity anomalies in migrated seismic volumes, respectively. However, to the best of our knowledge, PC has not been utilized for segmenting geophysical images that have chaotic structures and varying textures in seismic volumes such as salt domes.

The evaporation of water from the geological basins gives rise to the depositions of salt evaporites. Over the long periods of time, these evaporites because of their low density 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 the seismic traces near salt dome boundary 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 based on edge detection [9–11], texture [12–14], active contours [15, 16], saliency [17, 18] and different image processing techniques [19–21] to delineate salt domes within migrated seismic volumes. In this paper, we present a novel approach for salt dome delineation based on an attribute map obtained from phase congruency. The

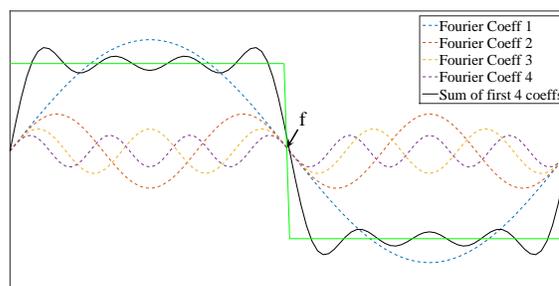
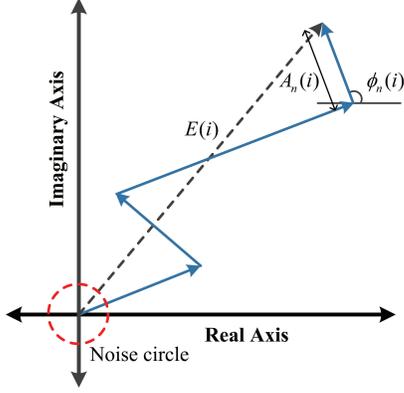


Fig. 1: Phase congruency in Fourier components.

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**Fig. 2:** Phase Congruency: Fourier coefficients addition.

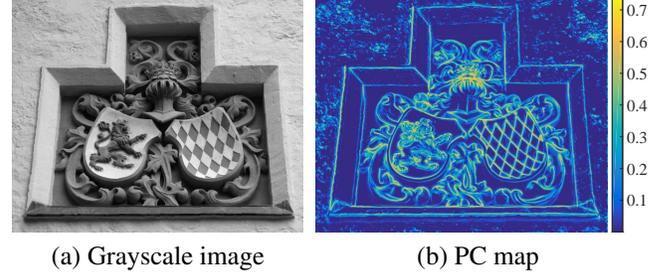
proposed method leads to improved salt dome delineation by accurately and efficiently detecting the presence of strong and weak seismic reflections using the PC attribute map. The rest of paper is organized as follows: a brief theoretical background of PC is given in section 2, the details of the proposed method and computational seismic interpretation are discussed in section 3, the experimental results and their discussions are presented in section 4 followed by the conclusions in section 5.

## 2. PHASE CONGRUENCY

Morrone *et al.* [1] proposed phase congruency, which defines image features as the points at which the phase of all the Fourier components are maximally in phase. Figure 1 illustrates a square waveform labeled in solid green color, its first four Fourier components in dashed color lines, and the summation of Fourier components in solid black line. The point  $f$ , defined as edge, in Fig. 1 depicts an instant at which the phases of all Fourier components are maximally equal. To understand the concept of phase congruency, let 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 Fig. 2, we get the local energy,  $|E(i)|$ , that is the magnitude of the resultant vector from the origin to the end point. Mathematically, PC can be written as

$$PC = \frac{|E(i)|}{\sum_n A_n(i)}. \quad (1)$$

PC varies between 0 and 1 corresponding to no and perfect phase coherence, respectively. In perfect coherence, all the complex Fourier components align together to form  $E(i)$  that results in PC equal to 1. However, PC defined in (1) is highly sensitive to noise because of vector normalization and becomes ill conditioned if Fourier components are very small. Kovési [2] developed a modified form of phase congruency



**Fig. 3:** Typical image and its PC map.

that not only produces a more localized response but is also more robust to noise. The modified PC measure by Kovési [2], which incorporates multiple filter orientations and robustness to noise is given by

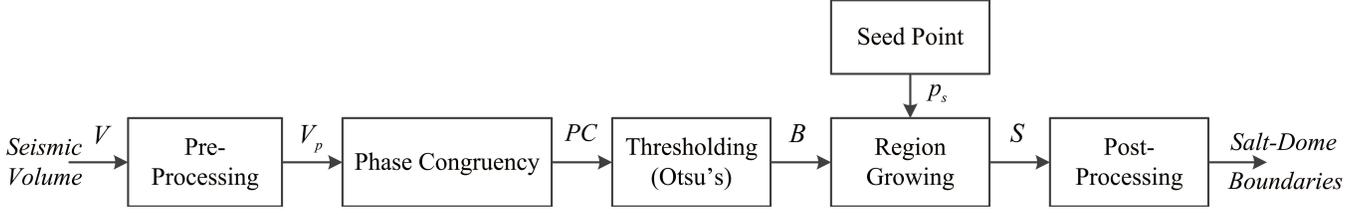
$$PC = \frac{\sum_o \sum_n W_o(i) [A_{no}(i) \Delta \Phi_{no}(i) - T_o]}{\sum_o \sum_n A_{no}(i) + \epsilon}, \quad (2)$$

where  $o$  represent different orientations,  $A_{no}(i)$  and  $\Phi_{no}(i)$  represents the amplitude and phase of Fourier components at different instants and orientations, respectively.  $\epsilon$  is small positive real number in the neighborhood of zero to avoid division by zero,  $T_o$  is the estimated noise influence at each orientation  $o$ ,  $\Delta \Phi_{no}(i)$  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 at orientation  $o$  constructed by applying the sigmoid function to the filter response spread value. A typical grayscale image and its PC map are shown in Fig. 3a-b, which show that the PC map effectively highlights the texture, edges, and corners in the image.

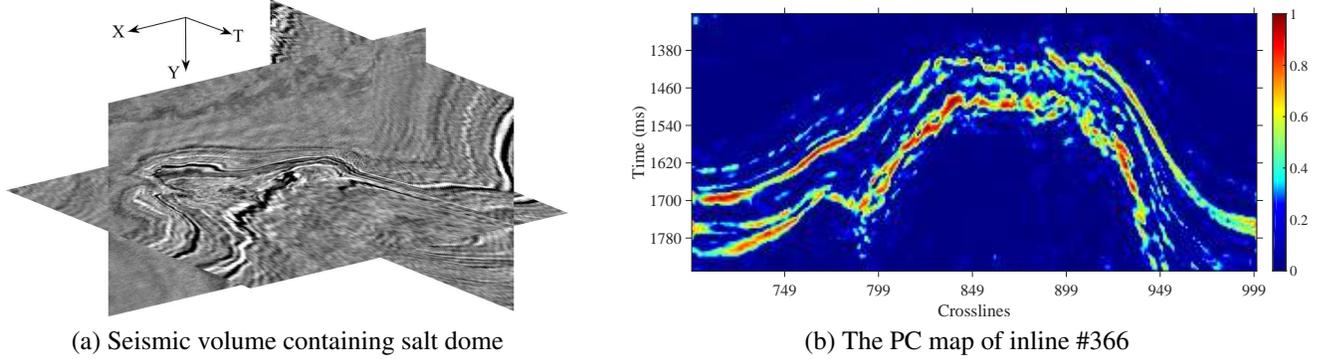
## 3. COMPUTATIONAL SEISMIC INTERPRETATION

In this paper, we propose a novel process for the computational interpretation of salt domes as shown in Fig. 4. Given a 3D seismic volume  $V$  of size  $X \times Y \times T$ , where  $X$  represents crosslines,  $Y$  represents inlines and  $T$  represents time depth, we apply pre-processing operations such as noise removal and image enhancement to yield a 3D seismic data volume  $V_p$  for better seismic comprehension and features detection. We then compute the PC attribute map, which highlights the salt dome edges and different geological features in a seismic image. To highlight the boundary regions of salt domes, we assume that the histogram of points in the PC map follows a bimodal distribution and we optimally divide all these points into two classes. We then determine the adaptive threshold  $T_h$  by maximizing the inter-class variance using the Otsu's method [22] as

$$\arg \max_{T_h} \left\{ \left( \sum_{i=0}^{T_h-1} p(i) \right) (\mu_1(T_h) - \mu_2(T_h)) \right\}, \quad (3)$$



**Fig. 4:** Proposed process for the seismic interpretation of salt domes.



**Fig. 5:** Seismic volume and PC attribute map.

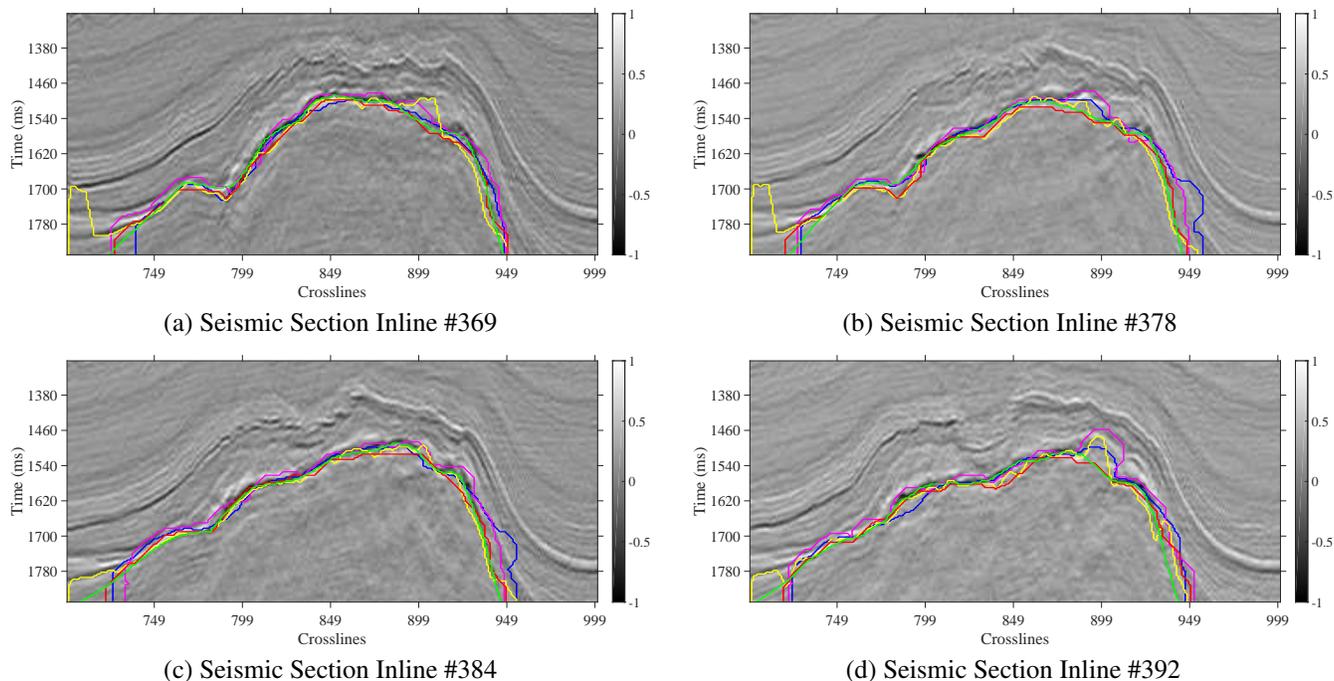
where  $p(i)$  represents the probabilities of points with gray value  $i$ . We assume there are  $K$  quantized gray-levels of PC attribute map, and  $\mu_1(T_h)$  and  $\mu_2(T_h)$  represent the mean values of first and second classes, respectively. The adaptive threshold,  $T_h$ , when applied to PC map as shown in (4) yields a binary volume  $B$  of same size as that of  $V$  and the white regions in  $B$  highlight the salt dome boundaries.

$$B[x, y, t] = \begin{cases} 1 & PC[x, y, t] \geq T_h \\ 0 & \text{Otherwise} \end{cases} \quad (4)$$

The salt domes are complex geological structures and it is inevitable that  $B$  contains noisy and disconnected parts. To get rid of the noise and detect a salt body  $S$  from binary volume  $B$ , we apply region growing method by randomly selecting an initial seed point,  $p_s$ , and grow it pixel-wise until it hits the salt dome boundary. The seed point for region growing can be selected either manually by the seismic interpreter or automatically by centroid, directionality or tensor-based methods. In manual  $p_s$  selection, the seismic interpreter can interactively choose either one seed point, or multiple seed points to speed up the region growing, provided all the selected seed points lie inside salt body. Given the computational complexity and the error rate of automatic seed point selection methods, we have selected the initial seed point manually in this paper. The region growing method yields a binary volume of salt body,  $S$ , and in order to extract the salt dome boundary from binary volume  $S$ , we apply post-processing operations that include dilation and perimeter extraction to label the boundary on top of seismic section inline.

#### 4. EXPERIMENTAL RESULTS

In this section, we present the effectiveness of the proposed method for seismic interpretation, specifically for salt dome delineation on the real seismic dataset acquired from the Netherlands offshore, F3 block in the North Sea [23]. 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 original seismic volume containing salt dome and the PC attribute map of seismic section inline #366 are shown in Fig. 5a and Fig. 5b, respectively. It can be seen from the Fig. 5b that PC map effectively highlights the salt dome boundary. Figure 6a-d show the results of proposed method, labelled in red, as compared to the other salt dome delineation methods, with the ground truth manually labeled in green. The magenta, yellow, and blue color lines depict the output of methods proposed by Aqrabi *et al.* [10], Berthelot *et al.* [12], and Shafiq *et al.* [13], respectively. Subjectively, it can be observed that the proposed method, which computes the image features based on signal phase and Fourier components that makes it independent of image illumination and contrast performs best among all other methods. The proposed method highlights the salt dome boundary very close to the ground truth as compared to the other methods. To objectively evaluate the similarity between the detected salt dome boundaries and the ground truth, we have used the Fréchet distance based similarity index, *SalsIM* [14]. The *SalsIM* index varies between 0 and 1,



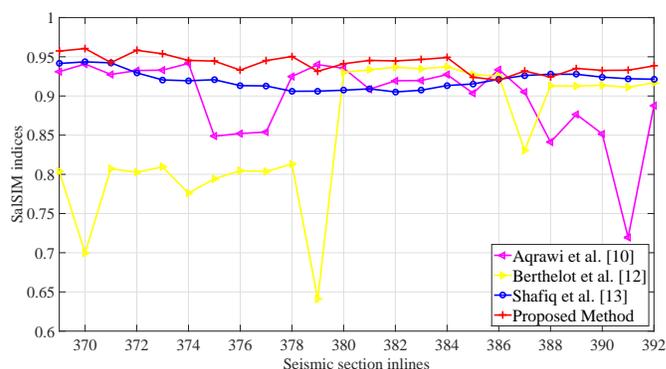
**Fig. 6:** Experimental results on different seismic section inlines. Green: Ground Truth, Magenta: Aqrawi *et al.* [10], Yellow: Berthelot *et al.* [12], Blue: Shafiq *et al.* [13], Red: Proposed Method.

indicating the minimum and maximum similarity between the two curves, respectively. The *SalSIM* indices of the detected salt dome boundaries for different seismic section inlines are depicted in Fig. 7, which illustrates that the proposed method outperforms other methods in delineating seismic structures and yields output very close to the ground truth. The mean and standard deviation of *SalSIM* indices from inline #369 to #392, and the computation time of a seismic inline for different delineation methods are summarized in Table. 1, which illustrates that the proposed method not only yields better delineation results but is also computationally very efficient as compared to the other methods for salt dome delineation.

## 5. CONCLUSIONS

In this paper, we have proposed a novel approach based on the congruency of phase for salt dome delineation. The proposed method is suitable for segmenting seismic volumes having weak seismic reflections, varying illumination and contrast. This paper outlines the process for salt domes delineation which can be modified to capture other geological structures such as chaotic horizons and faults in Earth’s sub-surface as well. The subjective and objective evaluation of the experimental results on the real seismic dataset show that the proposed method not only outperforms the state of the art methods for salt dome delineation but is also computationally less expensive. The proposed method is expected to

not only reduce the time for seismic interpretation but also become a handy tool in the interpreter’s toolbox for delineating geological structures within migrated seismic volumes.



**Fig. 7:** *SalSIM* indices of different delineation methods.

**Table 1:** Objective assessment of different methods.

Delineation Methods	Mean	Std. Dev.	Time (s)
Aqrawi <i>et al.</i> [10]	0.8981	0.0509	0.2464
Berthelot <i>et al.</i> [12]	0.8533	0.0823	33.5447
Shafiq <i>et al.</i> [13]	0.9201	0.0114	63.3162
Proposed Method	<b>0.9412</b>	<b>0.0110</b>	<b>0.2408</b>

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