Using corrected phase to localize geological features in seismic data

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ABSTRACT

We consider the time-frequency analysis method, basis pursuit, as a method to extract spectral information from seismic data. We look specifically at the phase attribute produced from the results of running basis pursuit on various data sets. We explore the numerical results of derivative of the corrected phase attribute proposed in (Han et al., 2015) on other geological data sets. We consider the phase attribute provided by other spectral decomposition methods, continuous wavelet transform and synchro-squeezing transform, and apply the derivative of the corrected phase process to these attributes. We end with a comparison of the results for basis pursuit to those of continuous wavelet transform and synchro-squeezing transform.

INTRODUCTION

Time frequency analysis, or spectral decomposition, characterizes seismic signals with respect to frequency and time. From this information, we can derive seismic attributes for the purposes of localizing geological features in seismic data. Popular time-frequency analysis methods include the continuous wavelet transform (CWT) and the short-time Fourier transform (STFT) as well as other spectral decomposition methods include the synchro-squeezing transform (SST) and basis pursuit (BP).

In (Han et al., 2015), the authors apply all four of these methods to seismic data and compare the results experimentally. They found that basis pursuit provided the most promising results. Specifically, they discussed the amplitude and phase attributes. They also proposed a derivative of corrected phase attribute which we will discuss in a later section. In this paper, we will focus on the time-frequency analysis method, basis pursuit, and consider applications of the derivative of the corrected phase attribute to more data sets than are considered in Han et al. (2015) in order to extend the work of the authors. We will also compare these results to the results provided by other time-frequency methods when considering the derivative of the corrected phase method.

In the next section, we describe the time-frequency analysis method, basis pursuit. In the following section, we provide the data sets on which we tested basis pursuit and the corrected phase method. Next, we examine the data sets and focus on the phase attribute and the corrected phase attribute. In the penultimate section, we analyze the results of the derivative of the corrected phase method on other time-frequency analysis methods. Finally, we discuss future research and conclude.

BASIS PURSUIT

The spectral decomposition method basis pursuit decomposes the signal from seismic data into individual atoms of a predefined dictionary. In time-frequency analysis, atoms are elementary waveforms which are discrete and populate a given dictionary (Tary et al., 2014). Specifically, the signal can be represented in series or matrix notation.

For a series representation, the signal is a convolution of the predefined wavelet family $\Psi(t,n)$ and the coefficient series $a(t,n)$ of these wavelets:

$$s(t) = \sum_{n=1}^{N} [\Psi(t,n) * a(t,n)] \tag{1}$$

where N represents the number of atoms, t is time, and n is an index to the dilation of the atom $\Psi(t,n)$ which determines its frequency. For the matrix representation of the signal, we have

$$\mathbf{s} = D\mathbf{a} + \eta = (\mathbf{\Psi_1}\ \mathbf{\Psi_2}\ \cdots\ \mathbf{\Psi_N}) \begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_N \end{pmatrix} \tag{2}$$

where D is the wavelet dictionary, η is the noise, $\mathbf{\Psi_n}$ is the convolution matrix of $\psi(t,n)$ with the dilation index n. As such, basis pursuit relates the time-frequency distribution to the set of weights $\mathbf{a}$ associated with the set of atoms $\psi(t,n)$ in the dictionary D.

Basis pursuit involves the following two steps:

1. a minimization term used to reduce the number of retrieved atoms as well as their magnitude, and
2. simultaneously identifying all the atoms by applying a single inversion problem.

In particular, the method used in this paper involved basis pursuit denoising. The object was to minimize the cost function:

$$J = \frac{1}{2}||\mathbf{s} + D\mathbf{a}||_2^2 + \lambda||\mathbf{a}||_1 \tag{3}$$

where the first term is the least-squares difference between the observed data and the predicted data, and the second term is the regularization term where λ controls the relative strength between the data misfit and the number of non-zero coefficients of $\mathbf{a}$.

This algorithm is guaranteed to converge eventually to a local optimum. The success of basis pursuit depends heavily on the predefined dictionary; however, while a larger wavelet dictionary provides better results, it also causes a longer computation time of the algorithm.

DATA

We apply the derivative of the corrected phase method to the following two seismic data sets. Note that the two seismic data sets are post-stack data.

In Fig. 1, the geological structure circled is a valley. This particular data set is from the CREWES Blackfoot data; however, we will refer it as the valley data set based on the geological feature we are interested in locating.

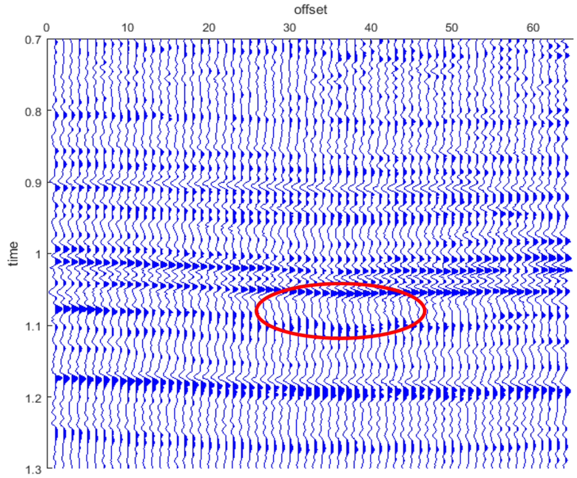


FIG. 1. The valley lies between offsets $30 - 40$ and time $1.05s$.

In Fig. 2, the goal is to identify the hydrocarbon reservoir circled in red. We call this data set the reservoir data set.

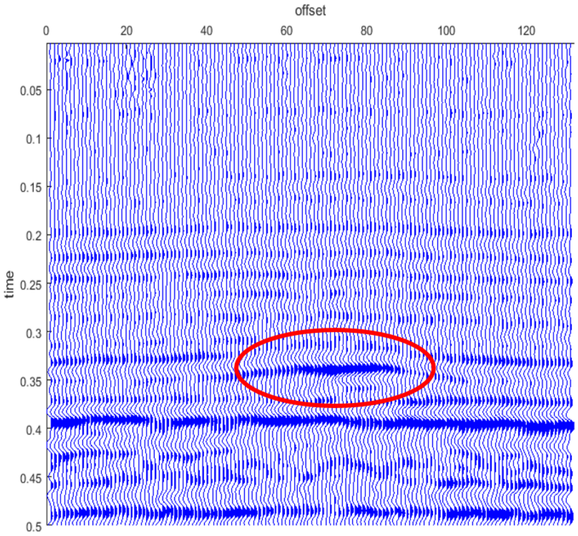
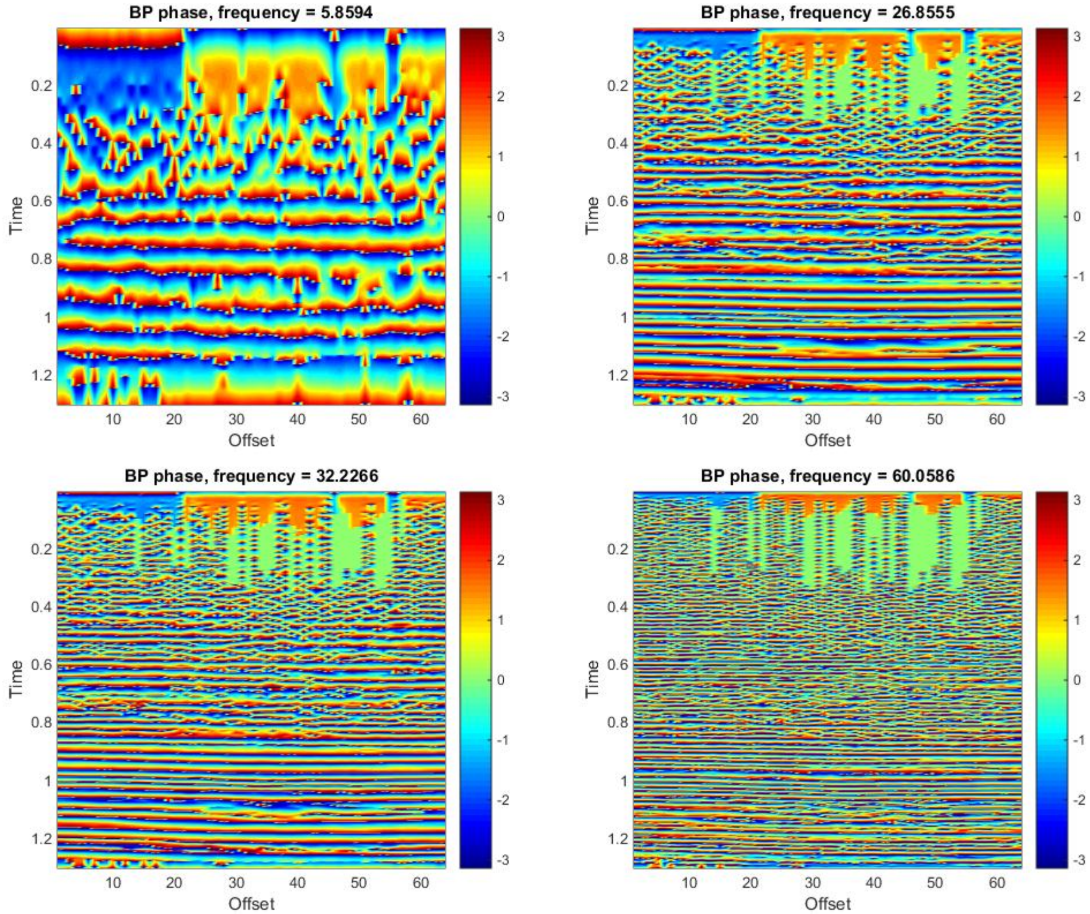


FIG. 2. The hydrocarbon reservoir lies at around offsets $60 - 85$ and time $0.34s$.

PHASE ATTRIBUTE RESULTS FROM BASIS PURSUIT

We begin by applying basis pursuit to the geological data sets mentioned in the previous section and consulting the phase attribute. First, we consider the valley data set.

The images in Fig. 3 are the phase attribute of the valley data set at specific frequency slices. Recall that the valley is located between offsets 30 and 40 and time $1.05s$. Referring to Fig. 1 (upper left), it is evident that at lower frequencies basis pursuit does not provide a clear image of the valley. At about 26 Hz, distinguishing the valley becomes much easier as seen in Fig 1 (upper right). As the frequency increases to 32 Hz, the valley is still


BP phase, frequency = 5.8594

BP phase, frequency = 26.8555

BP phase, frequency = 32.2266

BP phase, frequency = 60.0586

FIG. 3. Phase attribute for valley post-stack data: Constant frequency slices obtained by applying BP to the valley data set at frequencies approximately 5 Hz, 26 Hz, 32 Hz, and 60 Hz.

relatively clear to locate; however, as the frequency continues to increase, it is more difficult to localize the valley once again. Given the ability to locate the valley over a range of frequencies, we can see that basis pursuit performs well on this data set.

Now, consider how well basis pursuit performs on the reservoir data set with regards to the phase attribute.

In contrast to the valley data set, basis pursuit provides better localization of the hydrocarbon reservoir at higher frequencies. In particular, these frequencies range from approximately 40 Hz to 60 Hz as seen in the bottom row of Fig. 2. At the lower frequencies, locating the reservoir proves more difficult as seen in the top row of Fig. 2. Despite being able to find the reservoir at approximately 40 Hz and 60 Hz, it is not as visible as BP's results for the valley data set.

DERIVATIVE OF THE CORRECTED PHASE METHOD

Some of the difficulty in localizing the valley and hydrocarbon reservoir using the phase attribute from basis pursuit arises from the arbitrary coherent lines in the image which do not provide any information. In (Han et al., 2015), an attempt was made to remove these lines in a process called the corrected phase method.

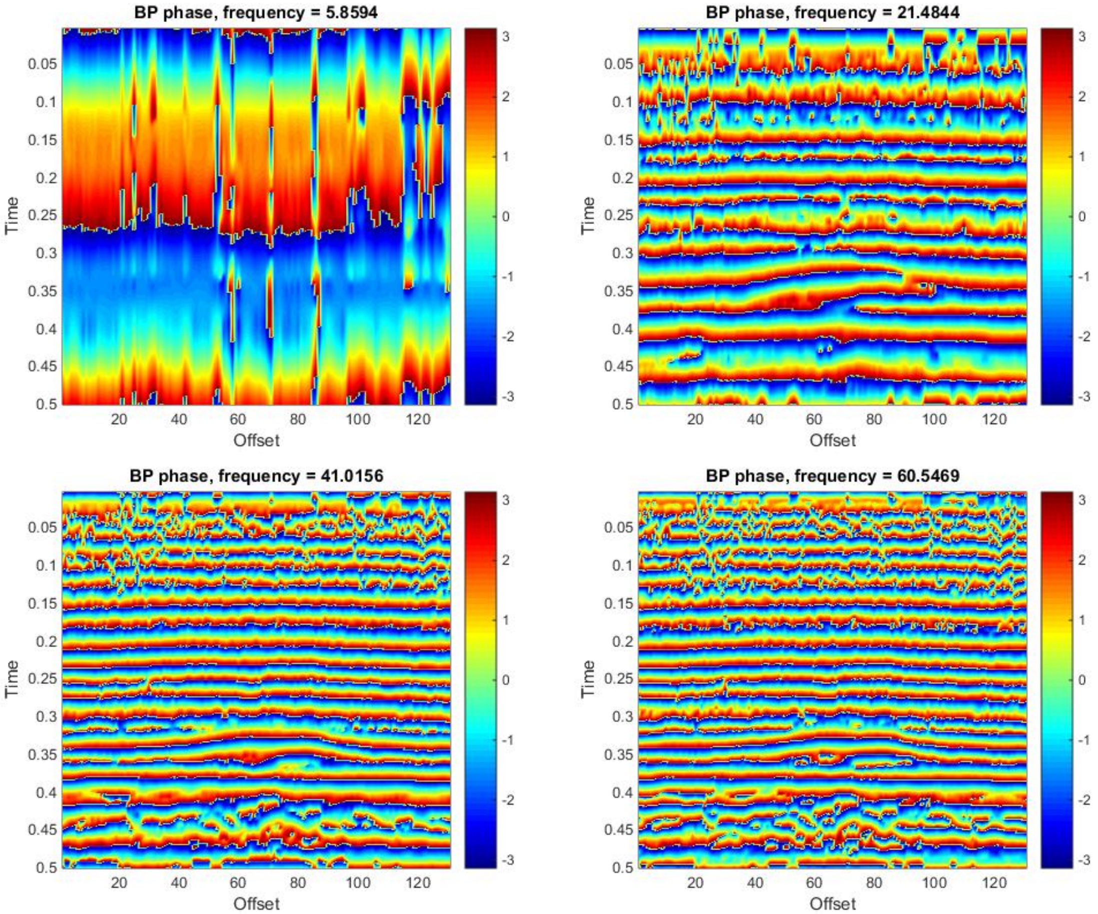


FIG. 4. Phase attribute for reservoir post-stack data: Constant frequency slices obtained by applying BP to the reservoir data set at frequencies approximately 5 Hz, 20 Hz, 40 Hz, and 60 Hz.

This method involves unwrapping the time-dependent curve in the phase attribute and fitting it to a quadratic equation. Then, the quadratic is subtracted from the original curve. The resulting curves are plotted in Fig. 5.

In Fig. 5, the top row shows the phase attribute on left and the corrected phase on the right for the valley data sets at approximately 26 Hz. The bottom row shows the phase attribute on the left and the corrected phase on the right for the reservoir data set at approximately 40 Hz. While this method removes the coherent lines from the phase attribute, little extra information is provided. In fact, this method provides less information than the original phase attribute. As such, another approach is necessary.

The authors in (Han et al., 2015) take the process a step further by taking the derivative of the residuals and plotting these results. The derivative of the residual phase curves should highlight the change in phase which means the boundary of the geological structure will be evident. Note that these results are being produced from the information provided by running basis pursuit on the seismic data sets.

A study of Fig. 6 shows this is the exact result achieved with regards to the valley data set. At the location of the valley, the boundary of the valley is evident at approximately 26 Hz and 32 Hz. This outline of the boundary enhances the ability to localize the valley.

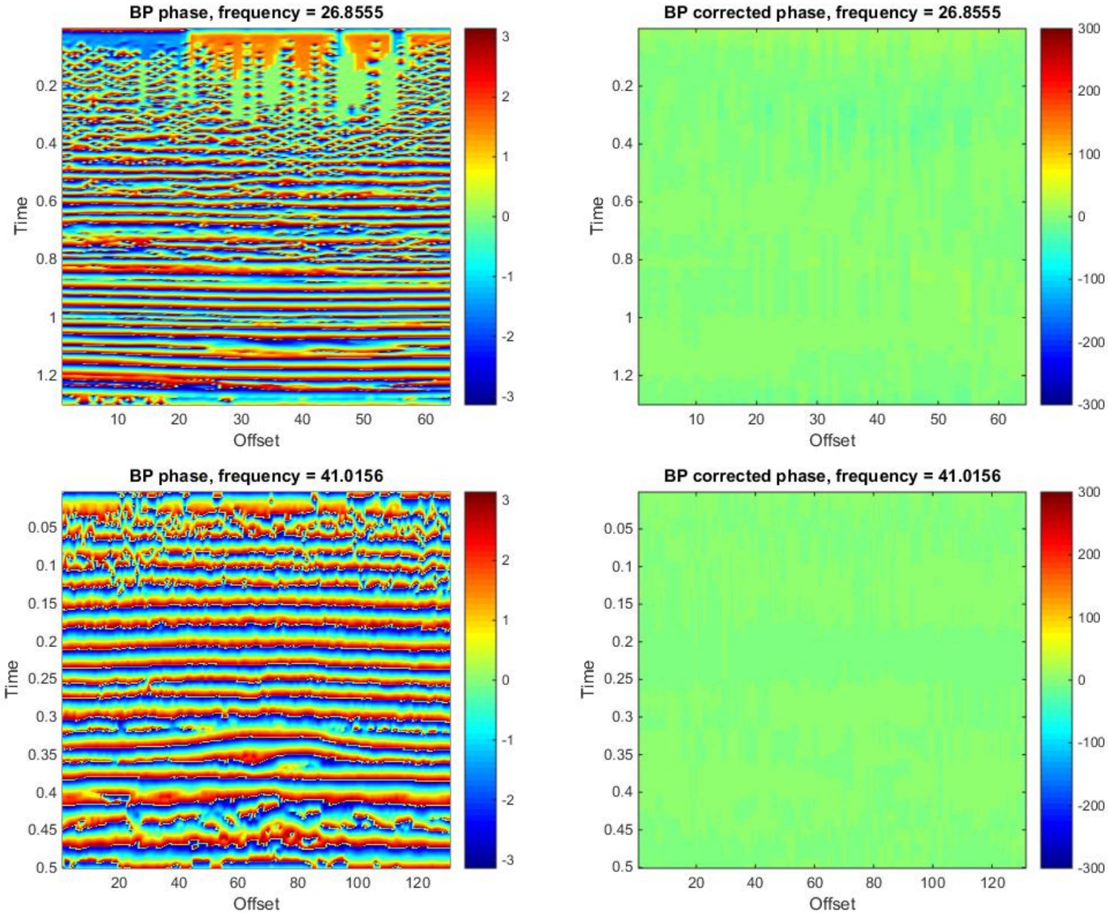


FIG. 5. **Top row**: Compares the phase attribute for the valley on the left to the corrected phase method on the right. **Bottom row**: Compares the phase attribute for the reservoir on the left to the corrected phase method on the right.

In Fig. 7, the results for the reservoir data set are also promising; however, it is not as easy to locate the boundary of the reservoir as it was to localize the valley in Fig. 6. The derivative of the corrected phase attribute is considered at approximately 40 Hz and 60 Hz since the reservoir was the most evident at the frequencies when considering the phase attribute. Notice in left column of Fig. 7 that we can locate the reservoir; however, the shadowing at its location is not as dark as it was for the valley data set. This lack of shadowing potentially explains the absence of a clear boundary in the derivative of the corrected phase images in the right column of Fig. 7 for the reservoir set. Despite this fact, the derivative of the corrected phase plots still produce a better localization of the hydrocarbon reservoir than the phase attribute. As seen in the right column of Fig. 7, there is a distinct line located in the position of the reservoir outlining the bottom of it at both frequency slices: 40 Hz and 60 Hz.

The derivative of the corrected phase attribute holds promising results for localizing geological features in seismic data. In both seismic data sets, the geological structure was evident when this method was applied to it. While the derivative of the corrected phase method provided a better localization of the valley than the reservoir, it provided better results than the phase attribute in both cases.

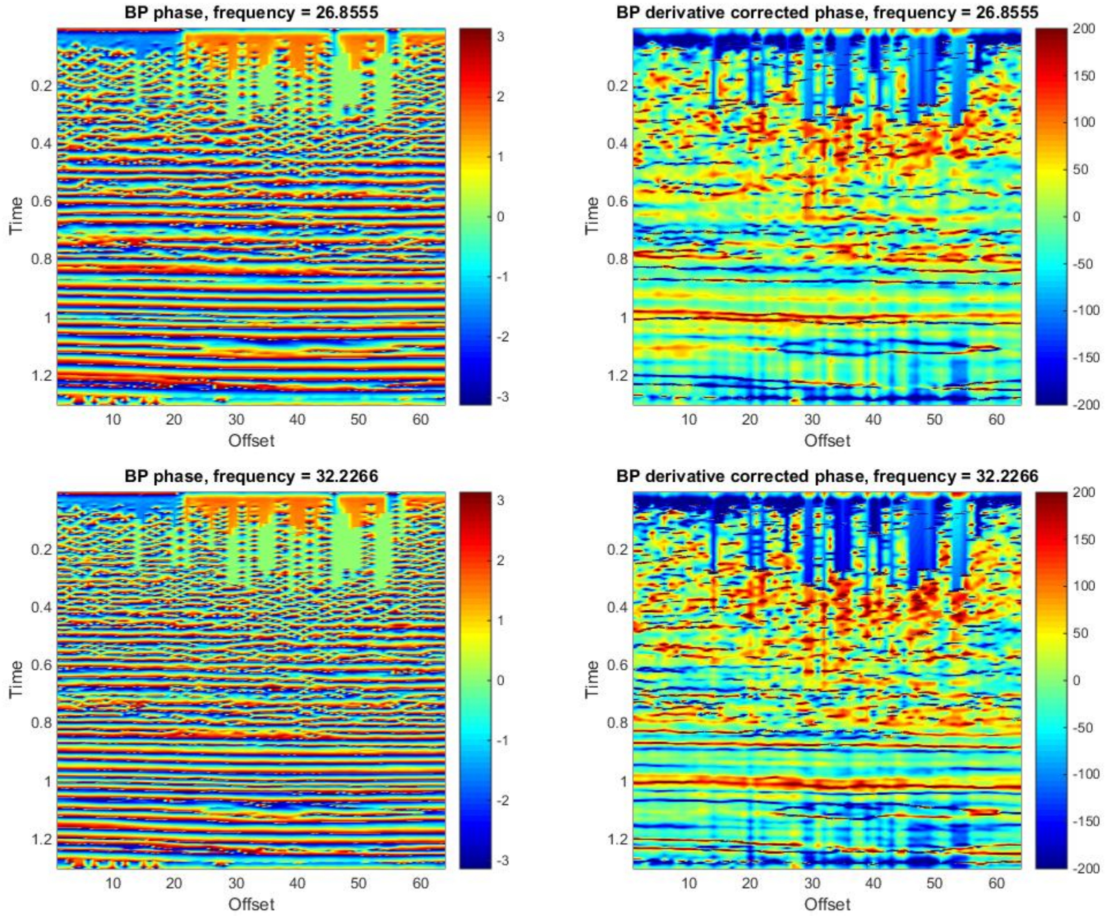


FIG. 6. **Left column**: Phase attribute of the valley data set at about 26 Hz and 32 Hz. **Right column**: Derivative of the corrected phase method of the valley data set at about 26 Hz and 32 Hz.

APPLICATION OF OTHER TIME FREQUENCY ANALYSIS METHODS

In this section, we consider the phase attribute produced by applying other time-frequency analysis methods to the valley and reservoir data sets. We also apply the derivative of the corrected phase method to these attributes and compare the results to those of basis pursuit in a later section.

We will discuss the results of two spectral decomposition methods: continuous wavelet transform (CWT) and synchro-squeezing transform (SST). For both methods, we choose the Morlet wavelet to be the mother wavelet. We start by considering the continuous wavelet transform.

In (Han et al., 2015), the authors experimentally found that basis pursuit worked the best of the time-frequency methods they considered; however, CWT also showed promise. In Fig. 8, the image on the left is the phase attribute produced by running CWT on the valley data set. The valley in this case can be localized with relative ease between 30 and 55 offset and at 1.01 secs. In fact, the image looks very similar to the results of BP; however, it should be noted that the frequency slice is much lower at about 6 Hz than that of basis pursuit. The image on the right in Fig. 8 are the results of the derivative of the corrected phase method applied to the phase attribute pictured on the left. As with BP, the

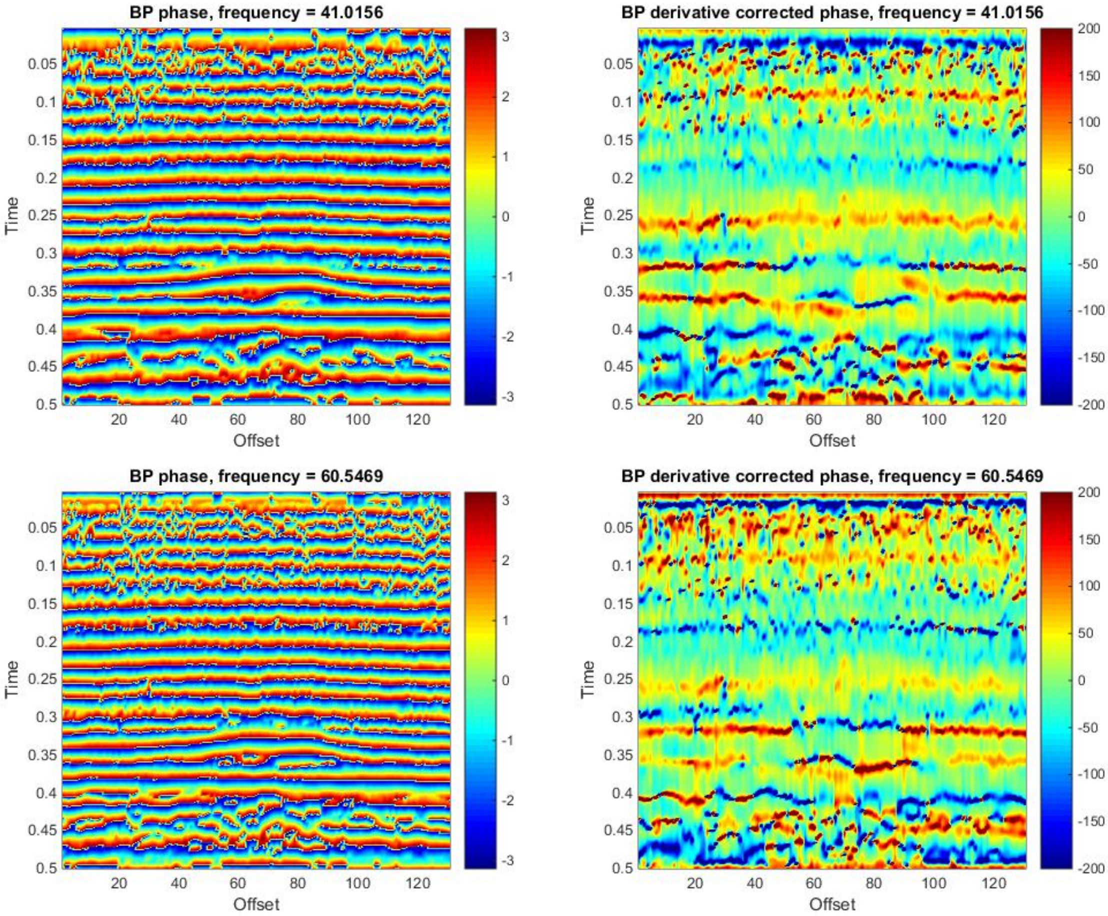


FIG. 7. **Left column**: Phase attribute of the reservoir data set at about 40 Hz and 60 Hz. **Right column**: Derivative of the corrected phase method of the reservoir data set at about 40 Hz and 60 Hz.

boundary of the valley can be identified.

Fig. 9 shows similar results for the reservoir data set. While the reservoir can be localized in the phase attribute pictured on the left, it is not as easily located as the valley. This is similar to the results of basis pursuit. Considering the derivative of the corrected phase method, there is an outline of where the reservoir, similar to the BP case; however, the outline is not as clear as it was when applying BP to the data set. While basis pursuit with the derivative of corrected phase method performed better on the reservoir data set, CWT is still a viable option as the derivative of the corrected phase method still provides better results than simply considering the phase attribute.

In (Han et al., 2015), the authors found that the syncrho-squeezing transform was the least helpful in located geological features in seismic data. As such, SST provides a study of how well the derivative of the corrected phase method works in identifying geological structures when produced from phase attributes where localizing the feature is difficult.

Fig. 10 shows the phase attribute and derivative of the corrected phase results for the valley data set. On the left, the valley can be localized to some extent; there is a shadow between 30 and 55 offset and at 1.02 seconds. However, the valley is not as clear as the

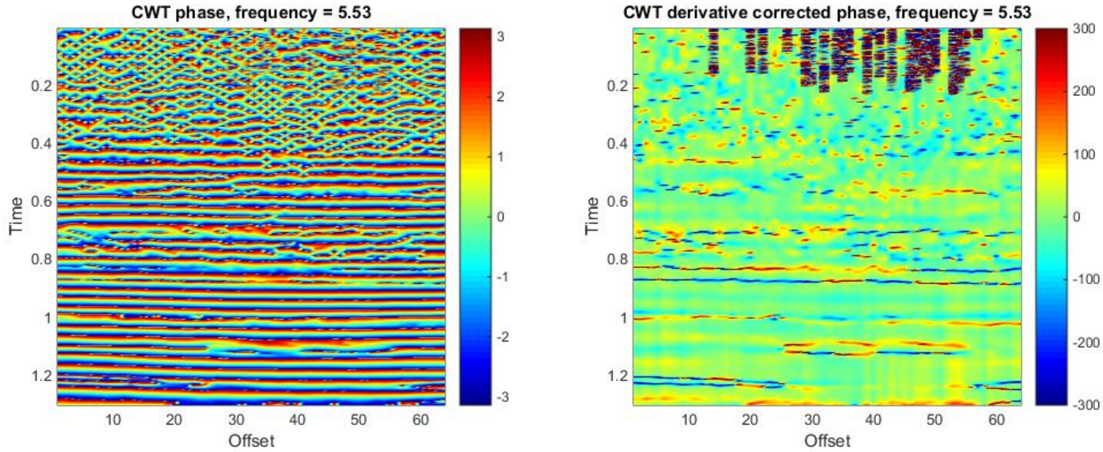


FIG. 8. **Left**: Phase attribute of the valley data set at about 6 Hz using CWT. **Right**: Derivative of the corrected phase method of the valley data set at about 6 Hz using CWT.

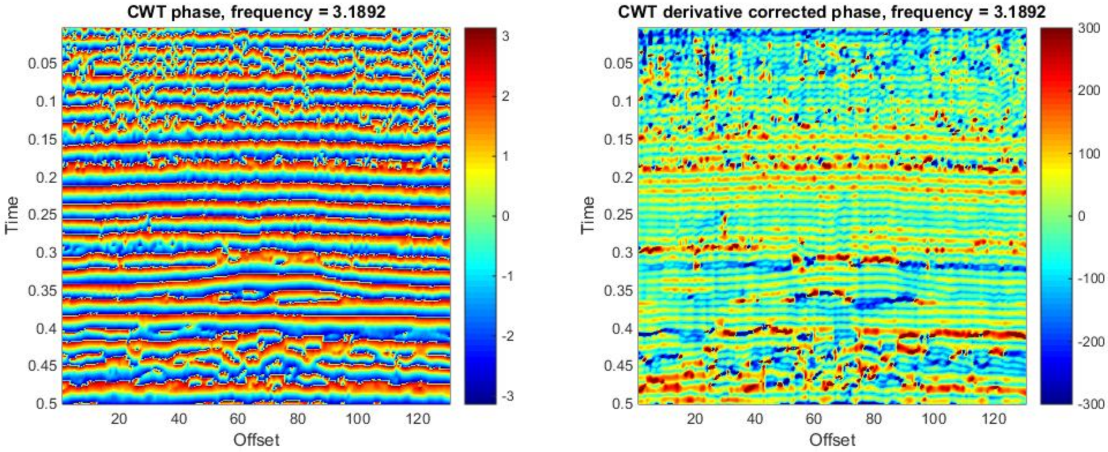


FIG. 9. **Left**: Phase attribute of the valley data set at about 3 Hz using CWT. **Right**: Derivative of the corrected phase method of the valley data set at about 3 Hz using CWT.

results of BP and CWT. From the derivative of the corrected phase method pictured on the right in Fig. 10, the valley remains relatively difficult to locate. In fact, the corrected phase method does not remove the coherent lines as adequately for the phase attribute produced from SST as it does for BP and CWT. As a result, locating the reservoir in the derivative of the corrected phase proves difficult. This suggests that the success of the derivative of the corrected phase method depends to a degree on the success of localizing the geological feature in the phase attribute.

As with BP and CWT, SST has a more difficult time localizing the reservoir with regards to the phase attribute. Also, the corrected phase method does not remove the arbitrary lines from the phase attribute with respect to this data set as effectively as it did for BP and CWT. Consulting Fig. 11, the image on the left shows the phase attribute produced from the results of SST at about 33 Hz. It is possible to locate the reservoir in this image; however, in the derivative of the corrected phase method pictured on the right, it is difficult to localize the reservoir. The method fails to highlight the change in boundary of the reservoir when using SST. As with the valley data set, there is a shadow present in the derivative of corrected phase image; however, identifying the hydrocarbon valley relies heavily on the

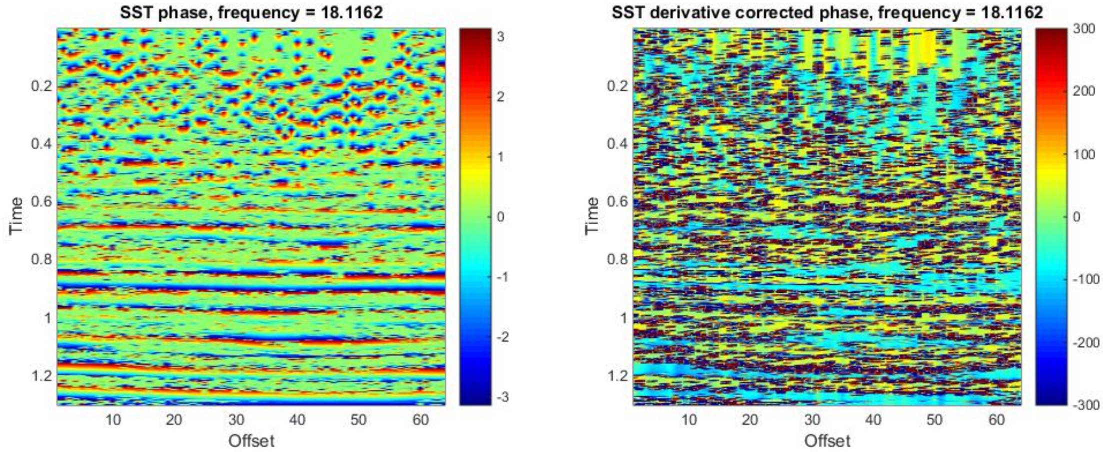


FIG. 10. **Left**: Phase attribute of the valley data set at about 18 Hz using SST. **Right**: Derivative of the corrected phase method of the valley data set at about 18 Hz using SST.

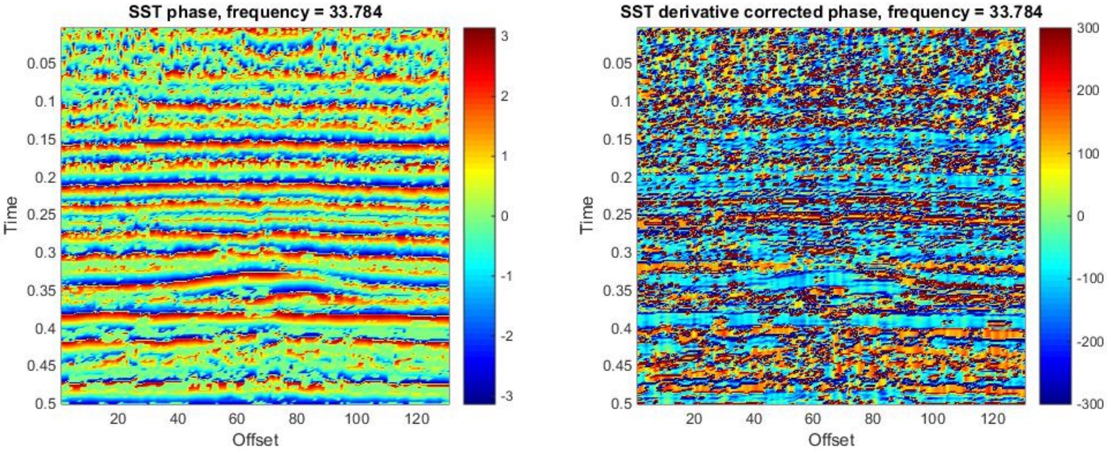


FIG. 11. **Left**: Phase attribute of the reservoir data set at about 33 Hz using SST. **Right**: Derivative of the corrected phase method of the reservoir data set at about 33 Hz using SST.

reader's knowledge of its presence. As such, SST with the derivative of the corrected phase method is not a promising combination for localizing geological features in seismic data.

FUTURE WORK

Our next step is to apply the derivative of the corrected phase method to pre-stack data. We should also consider applying this new method to 3 component data. Another step in extending these results would be to consider how well the derivative of the corrected phase attribute performs on data sets which contain more noise.

CONCLUSIONS

We demonstrated the effectiveness of basis pursuit in localizing geological features when consulting the phase attribute. We also exhibited the extended capabilities of locating geological structures in seismic data once the phase is corrected and we considered the derivative of the corrected phase. We observed that to some degree the success of the derivative of the corrected phase method is dependent on how clearly the phase attribute localizes the geological feature. This result is evident with all time-frequency analysis methods we considered in the paper. As in (Han et al., 2015), basis pursuit performed the best with respect to the phase attribute as well as the derivative of the corrected phase method. The continuous wavelet transform performed adequately for both data sets and both methods whereas the synchro-squeezing transform struggled to identify the valley and hydrocarbon reservoir.

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