Accurate seismic dip and azimuth estimation using semblance dip guided structure tensor analysis

Yihuai Lou¹, Bo Zhang¹, Tengfei Lin², Naihao Liu³, Hao Wu¹, Rongchang Liu¹, and Danping Cao⁴

ABSTRACT

Seismic volumetric dip and azimuth are widely used in assisting seismic interpretation to depict geologic structures such as chaotic slumps, fans, faults, and unconformities. Current popular dip and azimuth estimation methods include the semblance-based multiple window scanning (MWS) method and gradient structure tensor (GST) analysis. However, the dip estimation accuracy using the semblance scanning method is affected by the dip of seismic reflectors. The dip estimation accuracy using the GST analysis is affected by the analysis window centered at the analysis point. We have developed a new algorithm to overcome the disadvantages of dip estimation using MWS and GST analysis by combining and improving the two methods. The algorithm first obtains an estimated “rough” dip and azimuth for reflectors using the semblance scanning method. Then, the algorithm defines a window that is “roughly” parallel to the local reflectors using the estimated rough dip and azimuth. The algorithm next estimates the dip and azimuth of the reflectors within the analysis window using GST analysis. To improve the robustness of GST analysis to noise, we used analytic seismic traces to compute the GST matrix. The algorithm finally uses the Kuwahara window strategy to determine the dip and azimuth of local reflectors. To illustrate the superiority of this algorithm, we applied it to the F3 block poststack seismic data acquired in the North Sea, Netherlands. The comparison indicates that the seismic volumetric dips estimated using our method more accurately follow the local seismic reflectors than the dips computed using GST analysis and the semblance-based MWS method.

INTRODUCTION

The seismic volumetric dip and azimuth, which together reflect the orientations of seismic events, are important geometric attributes in assisting 3D seismic data interpretation. Four main categories exist for calculating seismic volumetric dip and azimuth. The first category is based on crosscorrelation. Bahorich and Farmer (1995) calculate the seismic volumetric dip by comparing the crosscorrelation of a set of windowed seismic data, which was generated using time lagging between nearby seismic traces. The second category uses a complex trace analysis to calculate volumetric dip. Barnes (1996) and Luo et al. (1996) estimate seismic dip using the partial derivative of the instantaneous phase obtained from 3D complex trace analysis. To improve the stability of seismic dip estimation, Barnes (2000) smooths the instantaneous phase using a weighted average window. Barnes (2007) further estimates seismic dip by using the ratio of smoothed instantaneous wavenumber to smooth instantaneous frequency. The third category is based on the semblance-based multiple window scanning (MWS) method. Marfurt et al. (1998) first calculate the semblance between the windowed seismic traces along a set of preset dips and azimuths and then treat the dip and azimuth pair that has the highest semblance value as the local reflector’s dip and azimuth. Marfurt (2006) improves the accuracy of dip and azimuth estimation by using Kuwahara’s multiple window search. The fourth category is based on the gradient structure tensor (GST). The seismic volumetric dip and azimuth was estimated by using the eigenvector that corresponds to the largest eigenvalue (Bakker et al., 1999; Fehmers and Höcker, 2003).
The GST resulted in inaccurate dip estimation when the sampling window encountered faults and other discontinuous structures. To improve the accuracy of the dip and azimuth estimation, Luo et al. (2006) use a data-adaptive weighting function to reformulate the GST. Wang et al. (2018) estimate the dip and azimuth by combining the GST analysis and Kuwahara’s multiple window search strategy. Wu and Janson (2017) use directional structure tensors to estimate the seismic structural and stratigraphic orientations. Other methods, such as plane-wave destruction (Fomel, 2002), predictive painting (Fomel, 2010), and globally consistent dip estimation (Aarre, 2010), have been proposed to compute volumetric dip and azimuth.

The volumetric dip and azimuth are widely used to compute other geometric seismic attributes such as curvature and similarity/coherence. The volumetric dip and azimuth can be used to improve the accuracy of the dip-steered coherence near steep structures (Marfurt et al., 1999). Barnes (2003) uses the shaded relief seismic attribute, which combines the reflector dip and azimuth, to depict small-scale geologic structures. Al-Dossary and Marfurt (2006) use a partial derivative of the reflector dip to calculate the seismic curvature and further correlate the seismic curvature with fracture density. Lomask et al. (2006), Wu and Hale (2015, 2016), and Lou and Zhang (2018) use the reflector dip and azimuth to flatten the seismic reflection events and then generate a relative geologic time volume based on the flattened seismic volume. Wu and Fomel (2018) use reflection dips together with multigrid correlations to calculate least-squares horizons. In addition, the seismic volumetric dip and azimuth are used for edge-preserving smoothing to detect sharp edges in seismic data, such as faults and other discontinuous structures (Luo et al., 2002; Qi et al., 2014; Lou et al., 2019; Wu and Guo, 2019). Structure-oriented filtering uses the volumetric dip and azimuth to suppress noise of poststack and prestack seismic data and preserve edges of geologic structures (Hoecker and Fehmers, 2002; Zhang et al., 2016; Wu and Guo, 2019). Qi et al. (2016) use a structure-oriented Kuwahara filter for seismic facies analysis. The reflector dip and azimuth are also used to incorporate structural constraints in geophysical inversion problems (Clapp et al., 2004; Wu, 2017).

Multiple window Kuwahara scanning and GST are the most successful methods to estimate the dip and azimuth of seismic reflectors. The Kuwahara window search was developed by Kuwahara et al. (1976) to suppress random noise of image interior textures and preserve texture edges. However, the MWS methods need users to define a set of dips and azimuths for the dip and azimuth scanning. Unfortunately, the user-defined increment of discrete candidate dip and azimuth may affect the accuracy of the dip and azimuth estimation. Computation costs increase with decreasing the interval of dips and azimuths. However, the accuracy of dip and azimuth estimation may decrease with increasing the interval of dips and azimuths, especially for the dip reflectors. Thus, it is very difficult to define a suitable interval of dips and azimuths for the whole seismic survey. GST-based methods treat the eigenvector (usually the first eigenvector) corresponding to the largest eigenvalue as the dip and azimuth of the local reflector. However, the correlation between the first eigenvector and dip and azimuth of local reflectors depends highly on the anisotropy of the windowed seismic image. The anisotropy of the seismic image is defined as the reflection patterns varying with different directions. An accurate dip and azimuth estimation can only be obtained if the extracted seismic events are the dominant linear feature within the analysis window. Thus, it is imperative that the seismic events within the defined window correspond to the most “dominant” linear feature (usually the first eigenvalue and eigenvectors) prior to the estimation of dip and azimuth using GST analysis. In this paper, we present a new method to estimate the seismic volumetric dip and azimuth robustly by integrating multiple window Kuwahara scanning and GST analysis. We begin with generating a set of searching windows centered as the analysis point by rotating the analysis window along a user-defined dip and azimuth. Then, we calculate the semblance of seismic data in each analysis window. The window with the highest semblance value is the best window for the following GST analysis. Using the best window, we extract the seismic data and use GST analysis to compute the dip and azimuth of seismic data. Finally, we use the Kuwahara window search to determine the dip and azimuth of local seismic reflectors. Our method is applied to the poststack seismic survey in the F3 Block acquired in the North Sea, Netherlands.

**DIP ESTIMATION USING MWS**

Marfurt et al. (1999) propose to estimate the dip of seismic reflectors using MWS, which begins with defining inline and crossline dip increment. We also need to define the minimum and maximum inline and crossline dips for scanning. Figure 1 shows the schematic diagram for a 2D dip estimation of the seismic reflector (Marfurt et al., 1999) with the yellow dot (the intersection of the yellow lines) as the analysis point. First, we extract the seismic data using a user-defined window centered at a set of discrete candidate dips (shown in orange, green, and blue) and compute the coherence for the extracted seismic data. In this example, we obtain the maximum coherence along the dip shown in green. Then, we pass an interpolation curve through the coherence measures estimated by the peak value and two or more neighboring dips. The peak value of this curve gives an estimate of coherence, whereas the corresponding dip value of the peak coherence gives an estimate of instantaneous dip.

To improve the robustness of dip and azimuth estimation to noise (Marfurt et al., 1999), we use the complex seismic trace $F(t, x, y)$ in the following analysis. The complex seismic trace $F(t, x, y)$ is defined as

$$F(t, x, y) = f(t, x, y) + if^H(t, x, y),$$  \hspace{1cm} (1)
where $f^H$ is the Hilbert transform of the real seismic trace $f$, $t$ is the two-way traveltime, and $x$ and $y$ are the inline and crossline coordinates, respectively. We calculate the coherence $S(k,l)$ for the analysis point in every analysis window using semblance-based coherence (Marfurt et al., 1998)

$$S(k,l) = \frac{\sum_{m=-M_k}^{M_k} \sum_{n=-M_l}^{M_l} \left[ \sum_{l=1}^{N} f(t_0 + m, x, y) \right]^2 + \left[ \sum_{n=1}^{N} f^H(t_0 + m, x, y) \right]^2}{N \sum_{m=-M_k}^{M_k} \sum_{n=-M_l}^{M_l} \left[ \left( f(t_0 + m, x, y) \right)^2 + \left( f^H(t_0 + m, x, y) \right)^2 \right]},$$

where $M$ is the half-window size in number of samples, $k$ and $l$ are the dip indexes in the inline and crossline directions, respectively, $N$ is the number of seismic traces in the analysis window, and $t_0$ is the time index corresponding to $t_0$. We use $(X)$ to represent $(t, x, y)$ in the following analysis.

Figure 2 shows a representative inline seismic section within the F3 seismic survey. Figure 3a and 3b shows the computed crossline dip varying with the increment of discrete scanning dips at the analysis points marked by the red and blue crosses, respectively, in Figure 2. The size of the time window is nine samples centered at the analysis points. The minimum and maximum scanning dips are 0.32 and 0.32 ms/m. The increment of the discrete scanning dips ranges from 0.016 to 0.08 ms/m. Figure 3a illustrates that the increment of the discrete scanning dips has negligible effect on the dip estimation for the reflectors with gentle dip angles. Figure 3b shows that there is a noticeable variation of the estimated dips varying with the increment of scanning dips. The phenomenon in Figure 3a and 3b demonstrates that the effect of the increment of discrete scanning dips on the dip estimation for the reflectors increases with the increasing dip angle of the seismic reflectors.

### DIP ESTIMATION BY APPLYING GST ANALYSIS TO ANALYTICAL SEISMIC TRACES

In Figure 4a, the red window shows the extracted traces (the red dots) used for dip estimation using GST analysis. We obtain the dip of the reflectors by analyzing the eigenvector of the gradient tensor computed using the extracted seismic traces. Unfortunately, the dip estimation accuracy highly depends on the anisotropy of the seismic image. As a result, the dip of the reflectors may affect the accuracy of the dip estimation using GST analysis. To demonstrate this issue, we first extract the seismic data using time windows along a discrete number of candidate dips (Figure 4b and 4c) and then we compute the dip of the extracted seismic data using GST analysis. The reflectors dip $\theta$ at this analysis point is

$$\theta = \theta_1 + \theta_2,$$

where $\theta_1$ and $\theta_2$ are the dips of discrete window used to extract the seismic data and the estimated dip of the reflectors of the extracted seismic data, respectively.

To improve the stability of the dip estimation using GST analysis to noise, we use analytical seismic traces to construct the structure tensor. First, we generate the gradient vector $V_i(X)$ for each sample of the seismic traces by using the partial derivatives $\partial F(X)/\partial t$, $\partial F(X)/\partial x$, and $\partial F(X)/\partial y$:

$$V_i(X) = \left[ \frac{\partial F(X)}{\partial t}, \frac{\partial F(X)}{\partial x}, \frac{\partial F(X)}{\partial y} \right]^T,$$

$$\frac{\partial F(X)}{\partial t} = 0.5 * f(t_0, x, y) * (f^H(t_0 + 1, x, y) - f^H(t_0 - 1, x, y)) - 0.5 * f^H(t_0, x, y) * (f(t_0 + 1, x, y) - f(t_0 - 1, x, y)),$$

Figure 2. A representative inline seismic section with two analysis points (the red and blue crosses). Computed dips of the red and blue crosses are shown in Figure 3a and 3b, respectively.

Figure 3. The computed dip varying with the increment of discrete scanning dips at the analysis points indicated by (a) the red cross and (b) the blue cross in Figure 2.
Figure 4. The computed dip as a function of discrete candidate analysis windows. (a) The discrete candidate window along the 0° (the traditional GST window). (b) The discrete candidate window along the minimum scanning degree. (c) The discrete candidate window along the dip approximately parallel to the local seismic reflectors. (d) The computed dip for the analysis point.
\[
\frac{\partial F(X)}{\partial x} = 0.5 \cdot f(\tau_0, x, y) \cdot (f^H(\tau_0, x + 1, y) - f^H(\tau_0, x - 1, y)) \\
- 0.5 \cdot f^H(\tau_0, x, y) \cdot (f(\tau_0, x + 1, y) - f(\tau_0, x - 1, y)),
\]
(4c)

\[
\frac{\partial F(X)}{\partial y} = 0.5 \cdot f(\tau_0, x, y) \cdot (f^H(\tau_0, x, y + 1) - f^H(\tau_0, x, y - 1)) \\
- 0.5 \cdot f^H(\tau_0, x, y) \cdot (f(\tau_0, x, y + 1) - f(\tau_0, x, y - 1)).
\]
(4d)

The GST(X) at the analysis point (X) is given by

\[
\text{GST}(X) = \frac{\sum_{m_x=-M_x}^{M_x} \sum_{m_y=-M_y}^{M_y} \sum_{m_z=-M_z}^{M_z} W(X + M) \ast \mathbf{V}_s(X + M) \ast \mathbf{V}_s^T(X + M)}{V_s(X + M)},
\]
(5)

where \(M_x\) and \(M_y\) are the half-size of the analysis window along inline and crossline directions, \(M\) represents the \((m_x, m_y, m_z)\), and \(W(X)\) is the weighting factor to enhance the signal-to-noise ratio (Luo et al., 2006). Then, we calculate the eigenvalues and eigenvectors of the structure tensor

\[
\text{GST}(X) = \lambda_u(X)u(X)u^T(X) + \lambda_v(X)v(X)v^T(X) \\
+ \lambda_w(X)w(X)w^T(X),
\]
(6)

where \(\lambda_u(X), \lambda_v(X), \text{ and } \lambda_w(X)\) are the eigenvalues satisfied \(\lambda_u(X) \geq \lambda_v(X) \geq \lambda_w(X) \geq 0\). The terms \(u(X), v(X), \text{ and } w(X)\) are the corresponding normalized eigenvectors. The dominant eigenvector \(u(X)\) corresponding to the largest eigenvalues is perpendicular to the local reflectors. Therefore, the inline dip \(p(k, l)\) and the crossline dip \(q(k, l)\) of the seismic reflector within the analysis window are defined as

\[
p(k, l) = \frac{u_x(X)}{u_y(X)},
\]
(7)

\[
q(k, l) = \frac{u_y(X)}{u_x(X)}.
\]
(8)

If the inline dip and crossline dip of the discrete search window are \(\theta_k\) and \(\theta_l\), respectively, then the inline dip \(P(k, l)\) and crossline dip \(Q(k, l)\) of the seismic reflector at the analysis point are defined as

\[
P(k, l) = p(k, l) + \theta_k,
\]
(9)

Figure 5. The computed (a) inline dip and (b) crossline dip at analysis point indicated by the red cross in Figure 2. The computed dips are a function of discrete candidate analysis windows.

Figure 6. The computed (a) inline dip and (b) crossline dip at the analysis point indicated by the blue cross in Figure 2. The computed dips are a function of discrete candidate analysis windows.
\[ Q(k, l) = q(k, l) + \theta. \] (10)

Figure 4a–4c shows three discrete windows used to extract the seismic traces needed for the construction of the structure tensor. Figure 4a shows a traditional time window for the GST analysis. The estimated dip \( \theta_2 \) for the extracted seismic traces in Figure 4a is the dip of the reflector at the analysis point. The dip of the window used to extract the seismic traces in Figure 4b has an opposite dip with the dip of the seismic reflection. Thus, the dip angle \( \theta_2 \) of the extracted seismic traces is larger than the dip of the seismic reflection at the analysis point. The dip of the window used to extract the seismic traces in Figure 4c is approximately the same as the dip of the seismic reflection. Thus, the dip angle \( \theta_2 \) of the extracted seismic traces in Figure 4c is approximately equal to 0 m/\( m \). Figure 4d shows the computed dip \( \theta \) at the analysis point labeled by the blue cross shown in Figure 2 varying with dips of the analysis window. The dip value labeled by the green dot in Figure 4d is estimated using an analysis window, which is approximately parallel to the local seismic events. The dip value labeled by the red dot in Figure 4d is estimated using an analysis window, which has a 0 m/\( m \) dip angle (the traditional window). Ideally, the estimated dip \( \theta \) at the analysis point should be a constant value for all analysis windows if the anisotropy value of the seismic images is zero. However, Figure 4d illustrates that we obtain different dip estimations if we use different analysis windows. Thus, the reflector dip estimated using GST analysis is highly dependent on how seismic data are extracted. Figure 4d also illustrates that there is negligible variation of dip values if the analysis windows are approximately parallel to the dip of the local reflectors. Figures 5 and 6 show the dips estimated using GST analysis as a function of discrete candidate analysis windows indicated by the red and blue crosses, respectively, in Figure 2. The \( x \)- and \( y \)-axes in Figures 5 and 6 are the inline dip \( \theta_1 \) and crossline dip \( \theta_2 \) of the analysis window, respectively. Figure 5a and 5b shows the computed inline dip \( P(k, l) \) and crossline dip \( Q(k, l) \) at the analysis point marked by the red cross in Figure 2. Figure 6a and 6b shows the computed inline dip \( P(k, l) \) and crossline dip \( Q(k, l) \) at the analysis point marked by the blue cross in Figure 2. At these two analysis points, the estimated inline and crossline dips are a function of the analysis window parameters \( (\theta_1, \theta_2) \) used for extracting the seismic data. The rate of estimated dips varies with the parameters of the analysis window, indicating that the way we extracted the seismic data affects the dip estimation result. The white dots in Figures 5 and 6 indicate the analysis windows that are approximately parallel to the surface of the local reflectors.

**DIP ESTIMATION BY INTEGRATING DISCRETE WINDOW SCANNING AND GST ANALYSIS**

Figure 7 shows the workflow of our method. Our method begins with rotating the analysis window along a set of user-defined dips and azimuths. Then, we calculate the semblance in every analysis window. Considering that the GST analysis may result in inaccurate dip estimation when the analysis window does not follow the local reflector, we select the window that is approximately parallel to the local seismic events as the analysis window for GST analysis. In this paper, we use the semblance scanning strategy to find the window that is approximately parallel to the local reflector. Then, we compute the dip and azimuth of the seismic events within the selected window using GST analysis. Finally, we output the dip, azimuth, and coherence of the analysis point using Kuwahara searching (Marfurt, 2006).

**REAL DATA EXAMPLES**

To illustrate the effectiveness of our method, we apply it to a post-stack seismic volume (F3 block) acquired in the North Sea, Netherlands. The F3 block seismic data consist of 400 inline and 700 crossline sections. The inline and crossline interval is 25 m, and the time increment of the seismic traces is 4 ms. We compare the volumetric dip computed using our method with the other two methods.

Figure 8 shows a representative inline seismic section within the 3D seismic survey. The red line AA’ in Figure 8 indicates the location of the inline section within the seismic survey (rectangle in

![Seismic data](Image)

**Figure 7.** Workflow for the dip estimation by integrating discrete window scanning and GST analysis.

![Output seismic dip and azimuth](Image)

**Figure 8.** The representative inline seismic section depicting a salt dome in the black rectangle.
the upper right corner of the figure). Figure 9a–9c shows the computed crossline dips using MWS (Marfurt, 2006), GST analysis, and our method, respectively. The increment of the discrete scanning candidate dips is 0.016 ms/m for inline and crossline dip estimation. We choose two representative reflection features in Figure 8 to illustrate the superiority of our method. Steep crossline dip angles are present for the seismic reflections within the black rectangle and “sinusoidal” shapes and chaotic features within the blue rectangle (Figure 8). Figure 10a–10c shows the magnified seismic amplitude (Figure 8, blue rectangle) corendered with the crossline dip computed using MWS, GST analysis, and our method, respectively. In Figure 10a, the dip computed using the scanning method smears across discontinuous zones is indicated by the white arrows. In Figure 10b, the estimated dip using GST analysis has abrupt changes (color changing from red to dark blue) for the seismic reflection indicated by the red arrow, indicating that the GST-based method may give us an inaccurate dip estimation of seismic reflectors. However, our method accurately estimates the reflector dip near discontinuous zones indicated by the red and white arrows (Figure 10c). Figure 11a–11c shows the magnified seismic amplitude (Figure 8, black rectangle) corendered with the crossline dip computed using MWS, GST analysis, and our method, respectively. In Figure 11a, inaccurate dip estimations are indicated by the white arrows and artifacts are indicated by the red arrows. The estimated dip using GST analysis (Figure 11b) is overall smaller than that shown in the upper right corner of the figure. Figure 9 overlays the magnified estimated dip in the blue rectangle in Figure 9a on the magnified seismic section in the blue box in Figure 8. Dip estimations based on (a) semblance scanning method, (b) GST analysis, and (c) our proposed method. The white arrows in Figure 10a indicate estimated dip smears across discontinuous zones. The red arrow in Figure 10b indicates the inaccurate dip estimation. The red and white arrows in Figure 10c indicate that our method accurately estimates the reflector dip near discontinuous zones.
Figure 11a for the reflections on the salt dome flank (steep angle structures). The two reflection events indicated by the white arrows in Figure 11b are visually parallel to each other. Thus, we should have almost the same color (dip angle) for those two reflection events. However, in Figure 11b, seismic reflections indicated by the lower white arrow have a deeper red color than seismic reflections indicated by the upper white arrow. In Figure 11b, the seismic reflections indicated by the purple arrow are parallel to each other. They should have the same color (dip angle) for all seismic reflections. However, we have slightly different colors for different samples within the seismic reflections. By comparison, our method

Figure 11. The magnified estimated dip in the black rectangle in Figure 9 overlay on the magnified seismic section in the black box in Figure 8. Dip estimations based on (a) the semblance scanning method, (b) GST analysis, and (c) our proposed method. The white and red arrows in Figure 11a indicate inaccurate estimated dips and artifacts, respectively. The purple and white arrows in Figure 11b indicate the seismic reflections should have the same color, and almost the same color, respectively. The arrows in Figure 11c indicate that our method accurately estimates the reflector dip.

Figure 12. The representative time slice seismic data set at 1650 ms.

Figure 13. Time slice at 1650 ms from the crossline dip volume (equivalent to the time slice in Figure 12). Dip estimations based on (a) the semblance scanning method, (b) GST analysis, and (c) our proposed method. The white and black arrows indicate steep reflections and locations with noise, respectively.
accurately estimates the reflector’s dip for both structures with a steep dipping angle and other seismic reflections indicated by the arrows in Figure 11c.

Figure 12 shows a representative time slice of the seismic amplitude across the salt dome along the yellow line BB’ in Figure 8. The seismic amplitude corendered with crossline dips is shown in Figure 13a–13c and with inline dips in Figure 14a–14c computed using multiple window semblance scanning, GST analysis, and our method. The inline and crossline dips computed from MWS have more noise (zones indicated by the black arrows in Figures 13a, 13c, 14a, and 14c) when compared to that computed using our method. In Figures 13 and 14, the white arrows indicate locations where there are steep reflections. The dip angle computed using GST analysis is smaller than that computed using both of the other two methods.

Then, we illustrate the superiority of our method by comparing the structure curvatures (Al-Dossary and Marfurt, 2006) that are computed from the estimated dips accordingly. Figure 15a–15c shows the time slices of the most positive curvature derived from dips computed using semblance (Figures 13a and 14a), GST analysis (Figures 13b and 14b), and our method (Figures 13c and 14c), respectively. The black arrows in Figure 15a–15c indicate representative locations at the salt dome boundary. The smeared curvature anomalies across the salt dome boundary are indicated by the black arrows in Figure 15a and 15b. However, the curvature anomalies in Figure 15c illustrate sharp features at the salt dome boundary. The white arrows in Figure 15a–15c show the representative locations where the curvature computed from new dips shows more continuous anomalies at the salt dome boundary than those computed from

Figure 14. Time slice at 1650 ms from the inline dip volume (equivalent to the time slice in Figure 12). Dip estimations based on (a) semblance scanning method, (b) GST analysis, and (c) our proposed method. The white and black arrows indicate steep reflections and locations with noise, respectively.

Figure 15. Time slice at 1650 ms from the most positive curvature volume (equivalent to the time slice in Figure 12). The most positive curvature based on the dip computed using (a) the semblance scanning method, (b) GST analysis, and (c) our proposed method. The white and black arrows indicate representative locations at the salt dome boundary.
the dips estimated using semblance and GST analysis. In this paper, we only compare the most positive curvatures computed from the three different dips; however, we can obtain similar results by comparing other curvature measurements, such as the most negative curvature.

CONCLUSION

In this paper, we propose a new method to improve the accuracy of volumetric dip estimation. A proper increment of discrete candidate angles is one of the most important parameters for the dip estimation using MWS. The dip estimated using GST analysis is usually smaller than the dip of seismic reflectors. Our workflow avoids the inaccurate dip estimation near discontinuous and steep structure zones by integrating the advantages of the MWS and GST analysis. We improve the accuracy of dip estimation by applying GST analysis to the window, which is approximately parallel to the local seismic reflector. We use the MWS method to find the window that is approximately parallel to the local seismic reflector. Field data examples show that our method precisely estimates the reflector dip near steep structures. The field data application also demonstrates that the dip estimated using our method has better antinoise performance, and the structure curvature generated using our method precisely highlights the boundary of the salt dome.

ACKNOWLEDGMENTS

The authors thank the Netherlands Organization for Applied Scientific Research (TNO) for providing the seismic data used in this study to the general public.

DATA AND MATERIALS AVAILABILITY

Data associated with this research are available and can be accessed via the following URL: https://wiki.seg.org/wiki/Open_data.

REFERENCES


Luo et al.