

Seismic attribute-assisted seismic fault interpretation

Bo Zhang^{1, 2}, Yanghua Wang¹

¹ Centre for Reservoir Geophysics, Imperial College London, London, UK, SW7 2BP

² Department of Geological Sciences, the University of Alabama, Tuscaloosa, AL, USA, 35406

E-mail: bzhang33@ua.edu, yanghua.wang@imperial.ac.uk

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Abstract

Fault mapping is one of the main tasks of 3D seismic interpretation, and seismic discontinuity attributes are often used to support fault mapping in the vertical sections and time slices. The most commonly used fault mapping procedure usually involves three passes/generations. First, the approximate positions of the faults (generation I) on some vertical sections are interpreted manually. Second, generation I faults are projected on some time slices, and the individual fault traces (generation II) are picked on time slices. Finally, generation II faults are projected onto the vertical sections and fault sticks (generation III) are picked in the vertical sections. To speed up the fault mapping process, we propose to automatically extract the generation III faults in the vertical sections under the mapping conditions of generation I and II faults by using the seismic discontinuity attribute as input. A quality control (QC) step is essential to improve the accuracy of the automatically generated fault sticks. To reduce the time required for QC, we propose to output the fault sticks on the seismic vertical sections defined by the interpreters. The workflow is applied to a real seismic survey to demonstrate its effectiveness.

Keywords: seismic attribute, fault interpretation

Introduction

During the past three decades, seismic geometric attributes have become a key component in assisting 3D seismic structure interpretation, stratigraphy analysis, and quantitative reservoir characterization. Seismic fault mapping is one of the two main tasks in 3D seismic structure interpretation and is a time-consuming task. The seismic fault attribute (coherence) is commonly used to highlight the potential fault locations and can be classified into three generations. The first generation compares the local similarity of seismic waveforms (Bahorich and Farmer, 1995). The second generation compares the similarity of seismic waveforms along with the local dip of seismic reflections (Marfurt et al., 1998). The third generation is based on analyzing the eigenstructure of seismic data (Gersztenkorn and Marfurt, 1999). To better highlight the fault locations, researchers have applied enhancement approaches to seismic coherence to improve the spatial continuity and robustness to noise. The commonly used enhancement approaches include edge-preserving filtering (e.g., Nagao and Matsuyama 1979; AlBinHassan et al. 2006), ant tracking (Pedersen et al. 2005), and skeletonization (Qi et al., 2016, 2017). Recently, deep learning technologies are showing great potential and promising results in generating seismic fault attribute (Wu et al. 2019).

There are hundreds of publications about seismic fault attribute. However, there are few publications about generating seismic fault sticks/surfaces from fault attribute. Zhang et al. (2014) noticed that seismic fault attribute shows better continuity on time slices and proposed a semi-automatic workflow for fault surface extraction. The workflow proposed by Zhang et al. (2014) consists of two main steps: generating fault sticks on time slices and manually grouping the fault sticks to form a fault surface. Wu and Hale (2016) first enhanced the fault attribute and then generated fault surfaces using a linked data structure from 3D seismic images. Wu and Fomel (2018) generated fault

surfaces by using an optimal surface voting algorithm. Lou et al. (2021) first produced fault sticks on time and vertical slices from seismic fault attribute and then generated fault surfaces by analyzing the spatial connectivity between the fault sticks. Those semi-automatic/automatic fault surface algorithms have been successfully applied to real seismic datasets. Unfortunately, those methods either need sophisticated algorithms for fault attribute enhancement or a complex workflow with a set of user-defined parameters.

This paper is organized as follows. First, we briefly overview a typical workflow for 3D seismic interpretation. Then, we present various insights into how seismic fault attribute can aid in the process of seismic fault interpretation: (1) the seismic fault attribute helps to highlight potential locations of faults and can be used to accelerate the process of fault mapping, (2) prior information (e.g., interpreted fault sticks on a coarse grid) about the fault surface is critical for seismic attribute-assisted seismic fault mapping, (3) a QC step is necessary no matter which algorithm is used. Next, we show a workflow of seismic attribute-assisted seismic fault interpretation. The workflow can generate fault sticks in the user-defined vertical sections under the constraints of interpreted fault sticks. We illustrate our workflow step by step by applying it to a real seismic survey.

Review of a typical 3D seismic interpretation procedure

Figure 1 shows a typical workflow of 3D seismic interpretation for a faulted framework (Schroeder, 2016). The workflow consists of five parts: performing reconnaissance, large-offset faults interpretation, horizon interpretation, and small-offset faults interpretation. In this paper, we will concentrate on fault interpretation with the aid of a seismic fault attribute.

Fully automatic seismic fault mapping is not a practical solution

Fully automatic seismic fault mapping should be the ultimate solution that can “liberate”

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interpreters from this time-consuming task. Currently, automatic seismic fault mapping algorithms extract fault surfaces from fault attribute. However, almost all algorithms need a set of steps and corresponding parameters for fault mapping. It is well-known that seismic data's signal-to-noise ratio (SNR) determines whether the seismic fault attribute can correctly highlight the fault locations. Usually, different seismic surveys have different SNRs. Thus, interpreters may have to adjust both steps and parameters of the automatic fault mapping for the different seismic surveys.

Figures 2-3 illustrate a real scenario where relying on a computer for fully automatic fault surface extraction is impractical. Figure 2a-c shows three vertical sections (inline 252, inline 272, and inline 292) of seismic amplitude within the F3 seismic survey, Netherlands. The locations of those three sections within the survey are indicated by the red (252), blue (272), and green (292) lines in Figure 3. Note that there is only one major fault in the middle of the inline sections 252 and 292 indicated by red arrows in Figures 2a and 2c. However, there are two faults in the section of inline 272 indicated by red and green arrows. Figures 2d and 2e show two possible interpretation strategies. We interpret a small fault stick (red curve) on the left and a large fault stick (green) on the right shown in Figure 2d. However, it is also reasonable to interpret a large fault stick (red curve) on the left and a small fault stick (green) on the right shown in Figure 2e. Based on the seismic reflection patterns in the inline sections 252, 272, and 292, it is very hard for an interpreter to judge which interpretation strategy is the correct solution. Thus, it would be even more difficult for a computer to perform automatic fault mapping. Figures 3a and 3b show two-time slices of coherence at $t_0=0.324s$ and $t_0=0.364$, respectively. The two-time slices of coherence attribute shown in Figure 3 together indicate that the faults indicated by the red and green arrows in Figure 2 belong to a growth fault zone that contains several normal faults. Thus, the interpretation in Figure 2e is more reasonable than the

interpretation shown in Figure 2d. The phenomenon shown in Figures 2 and 3 demonstrates that it takes time for an interpreter to correctly map the faults. Thus, it is almost impossible for a computer to figure out the correct interpreting strategy.

Figure 4 illustrates a real scenario where it is almost impossible to automatically extract the fault sticks from the seismic discontinuity attribute. Figures 4a-4c show three-time slices of coherence attribute within the F3 seismic survey, Netherlands. Note that the same growth fault has clear seismic coherence anomalies on the time slices at $t_0=0.4s$. The fault trace is still recognizable on the time slices at $t_0=0.68s$. However, it is almost impossible to figure out the fault trace on the time slice at $t_0=0.8s$. Then, we should question the accuracy of the automatically mapped faults at and near $t_0=0.8s$ if there is no intervention from an interpreter. The scenario shown in Figures 3 and 4 illustrates that it is impractical to rely solely on an algorithm performing automatic fault mapping.

Review of a typical seismic fault mapping procedure

For 2D seismic data, we have individual vertical seismic lines to work with. For 3D data, we can view and interpret faults on the vertical sections of inline, crossline, or arbitrary (zig-zag) line that traverse through the data volume. To better view seismic faults, we can view the seismic data that are oriented along structural dip or perpendicular to structural strike. The seismic coherence attribute is commonly used in assisting seismic fault interpretation. Considering that the seismic coherence attribute usually demonstrates better spatial continuity on time (or depth) slices, it is very beneficial to view seismic coherence at the time (or depth) slices for interpreting faults. Linear (or curved) bands of low coherency are possible fault traces. Different interpreters may have different methodologies for fault mapping. In this paper, we adopt the process proposed by Schroeder (2016) that includes three passes/generations at interpreting major faults (Figure 5). The process starts with manually interpreting

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the approximate position of faults (Generation I) on a few vertical sections (coarse interpretation grid). Then, interpreters project the Generation I fault picks on time slices and interpret the fault traces (Generation II) on time slices with the aid of the seismic coherence attribute. Finally, interpreters project the Generation II picks on the vertical sections and refine the fault picks (Generation III).

A fast-interactive process of fault mapping

Figure 6 shows the modified methodology of fault mapping. First, we interpret a few vertical fault sticks (Generation I) in the vertical sections (usually less than three). Then, we pick three fault sticks (Generation II) on three different time slices that should be located at the upper, middle, and lower portions of the fault surface. Speed rather than accuracy is the goal in the process of Generation I and Generation II fault picks. Next, we automatically extract fault sticks in the vertical sections under the constraints of Generation I and Generation II fault picks. The calculated Generation III fault sticks have a constant length and are automatically extracted in the interpreter-defined vertical sections. To reduce QC time, each fault stick is outputted at a user-defined temporal interval (e.g., 50ms). Finally, the interpreter must QC the accuracy of fault sticks by deleting automatically picked points, adjusting automatically picked points, or adding additional picks.

Step one: Picking the Generation I fault sticks in the vertical sections

We recommend a reconnaissance (or recon) to determine the approximate geometry of the fault that we plan to interpret. A few vertical fault sticks (Generation I) in the vertical sections are interpreted to determine the approximate vertical geometry of the fault surface and three fault traces (Generation II) on three seismic time slices of coherence are recommended to determine the approximate horizontal geometry of the fault surface. The three coherence time slices should be located at the upper, middle, and lower portions of the fault surface. The vertical sections should be located in the middle of the

fault surface along the time/depth axis. Figures 7a and 7b show two interpreted Generation I fault sticks in the inline sections 270 and 200 within the F3 seismic survey, Netherlands, respectively. The yellow/red squares in Figure 7 are the manually picked points and the yellow/red curves are the linearly interpolated Generation I fault sticks under the constraints of the yellow/red squares. The minimum and maximum two-way travel time of the interpreted fault sticks will be the minimum and maximum two-way travel time of the Generation III fault sticks that are generated by our workflow shown in Figure 6. Usually, our workflow only needs less than three fault sticks in the vertical sections which is different from the process proposed by Schroeder (2016) that requires the interpretation of the Generation I fault picks in several vertical sections.

Step two: Interpreting the Generation II fault sticks on three-time slices

Figures 8a-c show three-time slices of seismic coherence at $t_0=0.3s$, $t_0=0.7s$, and $t_0=1.2s$, respectively. The purple circles in Figure 8 are the projected Generation I fault mapping on time slices. The red squares in Figure 8 are the manually interpreted seed points that serve as constraints for the linearly interpolated fault sticks shown as the green curves in Figure 8. Note that the green curves generally follow the low coherence trend on time slices and the length of the Generation II fault sticks varies with time slices. The length of the horizontal window equals the length of the longest Generation II fault sticks. Note that the linearly interpolated fault sticks on time slices may fail to be located at the center of the local minimum coherence. To facilitate the Generation III fault sticks extraction, we extract the seismic coherence on time slices using a small window that is parallel with the interpreted Generation II fault sticks and refine Generation II fault sticks using dynamic warping (Wu and Fomel, 2018). Figure 9 shows a 3D review of Generation I (green curves) and Generation II (red curves) fault sticks.

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Step three: Automatically extracting Generation III fault sticks in the vertical sections

The cross symbols in Figure 10a are the projected Generation II fault mapping in the vertical section of inline 200. The green curve in Figure 10a is the linearly interpolated fault stick under the constraints of red cross symbols shown in Figure 10a. The purple “box window” in Figure 10a, which is centered at the red curve, is defined to extract the seismic coherence that is used for the Generation III fault sticks computation. The width of the purple box is defined as 20 pixels. In this paper, we use a modified dynamic time warping (DTW) to compute the Generation III fault sticks. The goal is to find an optimum “path” (fault stick) on which we obtain a minimum accumulation/addition of seismic coherence attribute.

Initially, the DTW was designed to align two temporal signals and consists of three steps: alignment errors computation, forward accumulation, and backward tracking (Sakoe & Chiba, 1978). Wu and Fomel (2018) successfully applied dynamic time programming to condition seismic fault attribute and aid in fault surface extracting. In this paper, the value of an element $error(i,j)$ of the error matrix is assigned using the value of corresponding seismic coherence attribute $seis_cohe(i,j)$ as follows:

$$error(i,j) = seis_cohe(i,j), i = 1:M, \quad j = 1:N, \tag{1}$$

Where i and j are the vertical and horizontal sample index, M and N are the sample number of the coherence matrix along the vertical and horizontal axis, respectively. Note that the projected points of Generation II fault sticks in the vertical section (Figure 10a) are approximately or accurately located at the fault locations. Thus, the computed fault stick is close to or passes through those three cross symbols in shown Figure 10a. Then, the fault stick extracting process becomes a constrained optimization problem. The original DTW is designed to find an optimal path that has minimum

accumulated errors without any constraints. To add constraints, we can set a set of “barriers” in the error matrix to ensure the optimal path passing through the picked point of Generation II fault sticks. The barriers are implemented by replacing the value of seismic coherence with a high value/error (e.g., 999). As a result, the error of the defined barrier is higher than the sum of the coherence of one seismic trace. The low coherence value samples, which are located at or nearby the picked points of Generation II fault sticks, look like a “tunnel” that has the function of a water tunnel within a hydro-power station. Based on the above discussion, the error matrix is modified as follows

$$error(i,j) = \begin{cases} 999, & \text{if } i = jt_k, j \in [(1:x_k - 2), (x_k + 2:M)] \\ seisc_{cohe(i,j)}, & \text{Otherwise} \end{cases}, \quad i = 1:M, \quad j = 1:N, \quad (2)$$

where jt_k and x_k are the projected vertical coordinate and horizontal coordinate of the k^{th} picked Generation II fault stick on the analysis vertical section, respectively. Figure 10b shows the conditioned seismic coherence attribute.

Then, we recursively accumulate the error matrix from the lower left side to the upper right side as follows

$$\begin{aligned} accu_error(1,l) &= error(1,l) \\ accu_error(i,l) &= accu_error(i,l) + \min \begin{cases} accu_error(i-1, l-1) \\ accu_error(i-1, l) \\ accu_error(i-1, l+1) \end{cases} \\ \text{for } i &= 2, 3, \dots, M \end{aligned} \quad (4)$$

Finally, the optimal path is obtained by a backtracking step as follows (Sakoe & Chiba, 1978):

$$\begin{aligned} d(L) &= \arg \min_{l=1:N} accu_error(M, l) \\ d(i-1) &= \arg \min_{l \in \{d[i]-1, d[i], d[i]+1\}} d[i-1, l] \\ \text{for } i &= 0, L-1, \dots, 2 \end{aligned} \quad (5)$$

Figure 11a shows the computed fault stick under the constraints of picked Generation II fault sticks. Note the computed fault in Figure 11a has picked points at every time index and each fault stick may have up to hundreds of points. It would be time-consuming to manually improve the accuracy of a

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fault stick with hundreds of points. Thus, we propose to output computed points at a user-defined temporal interval (e.g., 50ms) (Figure 11b). We also suggest outputting the fault sticks on the user-defined vertical sections (e.g., every 10 inline in the paper) to reduce the time of QC process from the interpreter. Figure 12 shows the computed fault sticks with a spatial interval of 10 inline and a temporal interval of 0.05s.

Step four: QC by the seismic interpreter

The final step is the QC from an interpreter. We suggest interpreters screen each extracted fault stick using interpretation software. The interpreters need to judge if the extracted fault sticks on vertical sections are the proper interpretation of fault surfaces. We may need interpreters to shift, add, or delete some of the extracted fault points on vertical sections according to the discontinuity features of seismic amplitude. Figure 13a shows one representative inline section overlaid with a computed Generation III fault stick. Note that most of the extracted fault points are correctly located on the fault surface. However, the points indicated by the purple and blue arrows in Figure 13a fail to locate on the fault surface. Three possible reasons are responsible for the inaccurate points: (1) inaccurate window that is illustrated by the purple dash curve in Figure 10a, (2) artifacts of seismic discontinuity attribute, and (3) there is more than one fault surface within the defined window shown in Figure 10a and the pixels with lower values of the discontinuity attribute belong to other fault surfaces. The low signal-to-noise ratio of seismic data produces the discontinuity artifact indicated by the purple arrow in Figure 13a. The chaotic reflections associated with the salt dome produce the discontinuity artifact indicated by the blue arrow in Figure 13a. In the demonstration shown in Figure 13, we simply delete the inaccurate points and find that the remaining fault points shown in Figure 13b are exactly located on the fault surface. The QC process is implemented section by section until interpreters are satisfied with the fault

sticks. Figure 14 shows the final Generation III fault sticks after editing the fault sticks shown in Figure 12.

A summary of the time cost

Our workflow consists of a quick reconnaissance of the seismic data and four steps. The reconnaissance is needed to set the approximate locations of the vertical section and three-time slices. It usually takes less than one minute to set the location of sections and slices in which Generations I and II fault sticks are interpreted. It also takes less than one minute to pick one vertical fault stick and three horizontal fault traces. It takes less than one second for a computer to calculate the Generation III fault sticks shown in Figure 12. The QC step varies from case to case. It takes us around two minutes to QC all the fault sticks shown in Figure 12. Compared to the manual interpreting process, our workflow is superior in terms of time cost. Although our workflow is not a fully automatic process, our method should generalize better fault surfaces than the fully automatic picking algorithms that need to consist of a set of steps and corresponding parameters in terms of generality.

Application

We have illustrated an interactive process of fault mapping from a fault attribute volume. Under the constraints of manually picked fault sticks, the proposed process is robust for seismic fault mapping from seismic attribute volume. This section demonstrates the fault mapping process with the seismic coherence attribute.

Kerry 3D Seismic Survey (Kerry-3D)

The Kerry 3D seismic survey was acquired over the North Sea, Netherlands. Figures 15a and 15b show the chair display for the 3D seismic amplitude and seismic coherence attribute, respectively. Figures 16a and 16b show the manually interpreted fault sticks (Generations I and II) and computed

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Generation III fault sticks, respectively. The spatial and temporal intervals of the calculated fault sticks are set as 10 and 0.05s, respectively. Figures 17a and 17b show one representative seismic section (Inline 615) with computed fault sticks before and after the QC step, respectively. The white arrows in Figure 17a indicate representative computed picks that need to be edited in the QC step. Figure 18 shows the final Generation III fault sticks. The manually interpreted fault sticks shown in Figure 16a belong to 35 fault surfaces. It takes us around one hour to generate the fault sticks shown in Figure 16a. It takes the computer approximately 30 seconds to generate the Generation III fault sticks shown in Figure 16b on a single-core computer. The QC process is implemented by using Petrel software of Schlumberger and takes one interpreter approximately one hour to edit the computed Generation III fault sticks of 35 fault surfaces.

Discussion

The seismic coherence attribute is a seismic edge-detection attribute commonly used for fault interpretation. Seismic volumetric curvatures are also widely used to depict faults. Chopra and Marfurt (2015) point out that the seismic coherence and curvature attributes are complementary attributes in assisting seismic interpretation. In this section, we will discuss the role of seismic curvature attributes in fault mapping. In some cases, seismic curvature attributes at short wavelengths can better highlight the locations of faults with small offsets (Chopra and Marfurt, 2015). Chopra and Marfurt (2015) point out that the most negative and positive curvatures provide better illumination of faults and fractures than other curvature attributes. Thus, our discussion is based on the comparison of seismic coherence, the most negative curvature, and the positive curvature.

An optionally complementary step to the process of fast-interactive fault mapping

Figure 19a shows one inline section (inline 250) of seismic amplitude within the F3 seismic

survey, Netherlands. Figures 19b and 19c show the vertical section of seismic amplitude overlaid with the most positive curvatures at short and long wavelengths, respectively. Figures 19d and 19e show the equivalent vertical section of seismic amplitude overlaid with the most negative curvatures at short and long wavelengths, respectively. Note that the red color in Figure 19 correlates to both the anticline/dome and the upthrow sides of the faults while the blue color correlates to both the syncline/basin and the downthrow sides of the faults. Figure 20 shows a comparison of time slices ($t_0=0.4s$) through seismic amplitude, seismic coherence, the most positive curvature at short and long wavelengths, and the most negative curvature at short and long wavelengths. Given the strong positive curvature pattern indicated by the black arrows in Figure 20, we have confidence that the fault should be further extended southwest. Figure 21 shows the final fault surface in which a few more sticks are interpreted (indicated as white arrows) according to the curvature anomaly. Figures 19-21 together illustrate that seismic curvature is a complementary attribute to seismic coherence in assisting seismic fault mapping. However, we must point out that this optional step is not always needed for every fault.

The process of mapping faults with small offsets

Figure 22a shows a cropped vertical section of seismic amplitude (inline 3389) within the Great South Basin, New Zealand. The red arrows in Figure 22a indicate a fault whose offset is smaller than one-half of the wavelength. Figure 22b shows the equivalent vertical section (inline 3389) of seismic amplitude and a time slice ($t_0=1.35s$) of coherence. Note that the fault is not visible (indicated by red arrows) on the coherence time slice. Figure 22c shows the equivalent vertical section (inline 3389) of seismic amplitude and a time slice ($t_0=1.3s$) of the most negative curvature at the short wavelength. Figure 22d shows the equivalent vertical section (inline 3389) of seismic amplitude and another time slice ($t_0=1.4s$) of the most negative curvature at the short wavelength. By examining the trend of fault

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anomalies indicated by the green arrows in Figures 22b and 22c, we are confident that the lineaments indicated by the green arrows in Figures 22b and 22c belong to the fault indicated by the red arrows in Figure 22a. Note that we cannot observe notable fault offset in the section of seismic amplitude at the location indicated by the blue arrow in Figure 22c. Based on the observation shown in Figure 22, we propose the following mapping process for the faults with small offsets. First, a reconnaissance is needed on the slices through seismic amplitude and curvature attributes at the short wavelength. Then, interpreters should pick Generation I fault sticks in a few vertical sections (Figure 23a) through seismic amplitude. Next, interpreters pick Generation II fault sticks on a few time slices of curvature attribute at short wavelength (Figure 23b) under the guidance of Generation I fault sticks. We propose to use time slices through the curvature attribute to identify the time window of the fault surface. Finally, interpreters interpret the Generation III fault stick (Figure 23c) under the guidance of Generation II fault sticks (the red cross symbols in Figure 23c) and obtain the final fault sticks (Figure 24). Note that the proposed process of mapping faults with minor offsets is like that proposed by Schroeder (2016). The only difference is that we use the curvature attribute to generate the Generation II fault sticks on time slices through the curvature attribute at the short wavelength.

Artifacts of seismic fault attribute may affect the accuracy of extracted fault sticks

Faults usually have low values of the coherence attribute. However, a low value of coherence attribute does not mean the existing of faults. For example, the seismic coherence attribute tends to have low value at the boundary of two strong seismic events. Other incoherent noise in the seismic data may also result in low coherence values. Figures 25a and 25b show one seismic and corresponding coherence section. The yellow arrows in Figure 25 indicate the zone of low coherence value that is not related with a fault. The green curve in Figures 25c and 25d show the extracted fault sticks. The yellow

arrow in Figure 25c indicates the portion of the extracted fault stick that is affected by the pixels with low coherence value. As a result, our algorithm extracts an inaccurate fault stick. The red curve in Figure 25d shows the manual interpretation. Figure 25 demonstrates that the accuracy of the extracted fault sticks is affected by the quality of seismic fault attribute. Thus, we do not recommend using any automatic or semi-automatic methods if interpreters cannot visually observe any faults in the seismic faults attribute sections.

Conclusion

We conclude that it is impractical to perform 100% automatic seismic fault mapping without intervention from interpreters. The proposed interactive fault mapping process is designed for faults that can be seen in the seismic discontinuity attributes. The experiment demonstrates that algorithms can generate high-quality seismic fault sticks under the constraint of a few manually interpreted seismic fault sticks. The Generations I and II interpretation only include four or five fault sticks in our application. However, we may need an interpreter to pick more than five fault sticks if a fault surface has strong variation in azimuth and dip. We want to emphasize that our method is designed to replace the procedure of third phase of seismic fault interpretation.

Both seismic coherence and curvature attributes are useful in assisting seismic fault mapping. Samples with low coherence anomalies are assumed to be correlated to potential fault locations. The applications demonstrate that curvature can better highlight the locations of faults that have small offsets. Thus, we can use curvature anomalies to manually extend the interpretation of faults beyond the resolution of the seismic coherence attribute if needed. Considering that the curvature attribute illustrates anomalies on the upthrow/downsides of the faults if the fault has sufficient fault offset (e.g., greater than one wavelength), it is impractical to have a seismic curvature attribute as the input to

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compute fault sticks/surfaces.

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Appendix

The fault offset of a fault is measured using the time duration of wavelet (Schroeder, 2016) (Figure A1). It is a large-offset fault if the fault throw is equal to or greater than time duration of a peak/trough. It is a moderate-offset fault if the fault throw is between half ($\frac{1}{2}$) to one (1) duration of a peak/trough. It is difficult to identify the fault in the seismic section if the fault throw is smaller than half ($\frac{1}{2}$) of the duration of a peak/trough.

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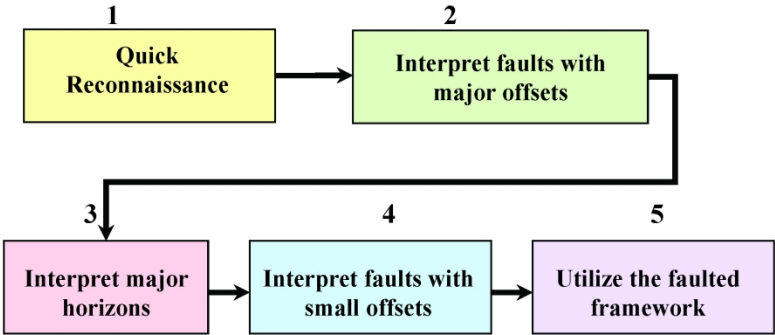


Figure 1.

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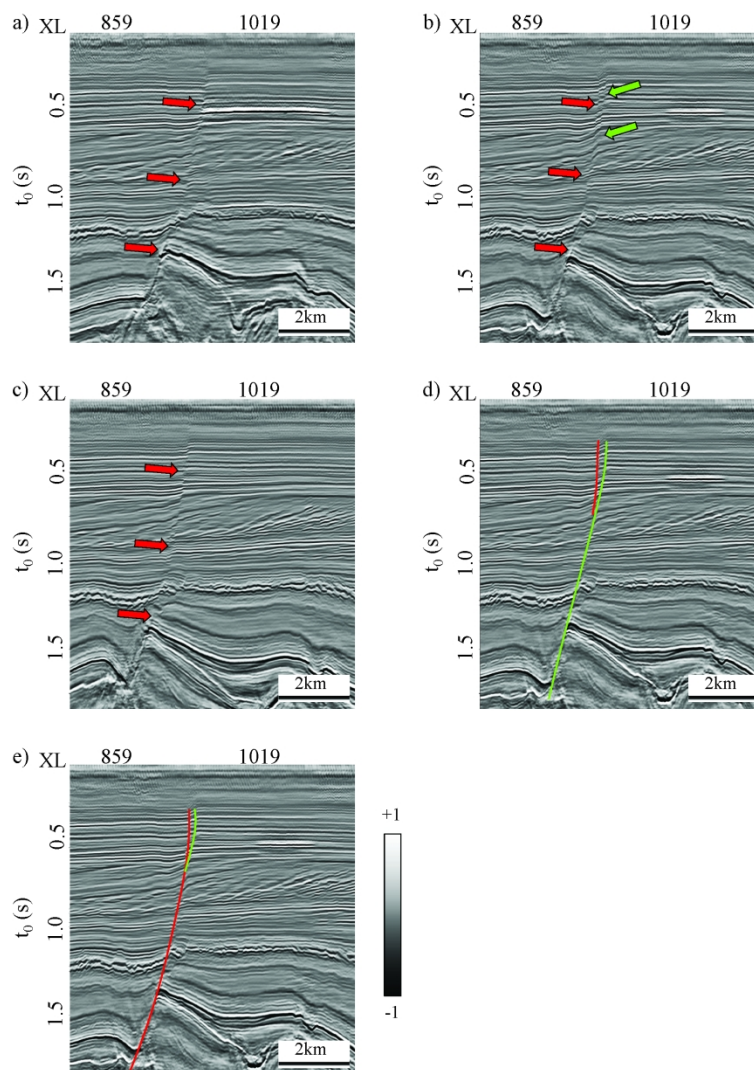


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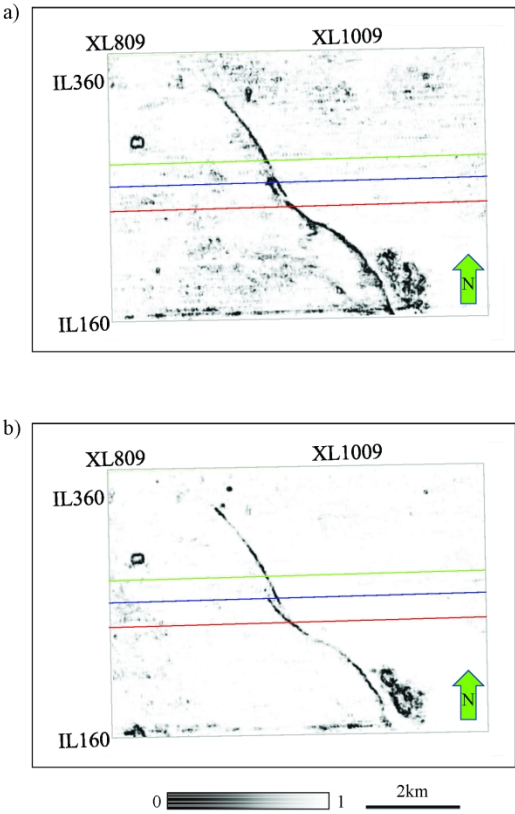


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215x279mm (300 x 300 DPI)

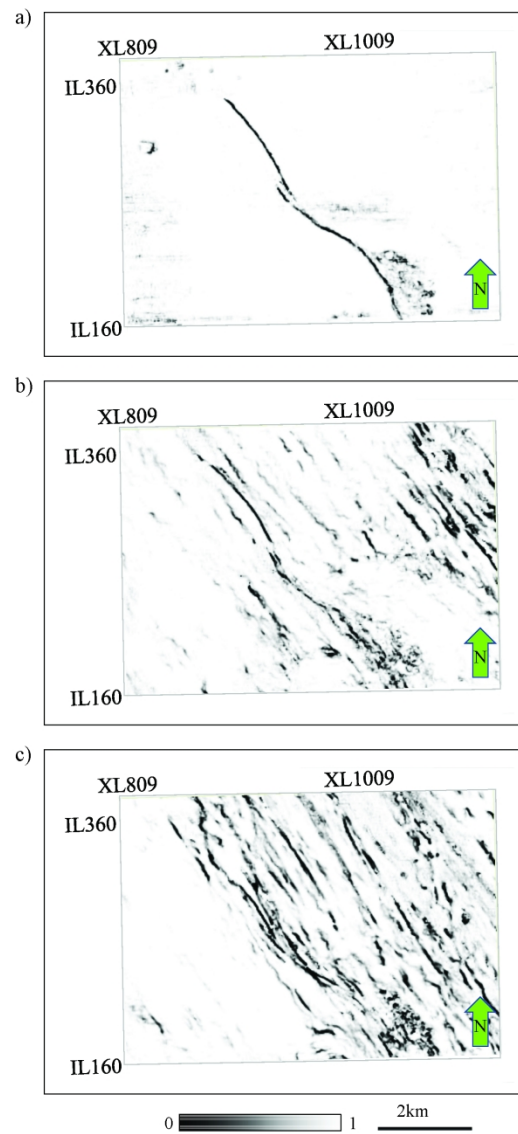


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215x279mm (300 x 300 DPI)

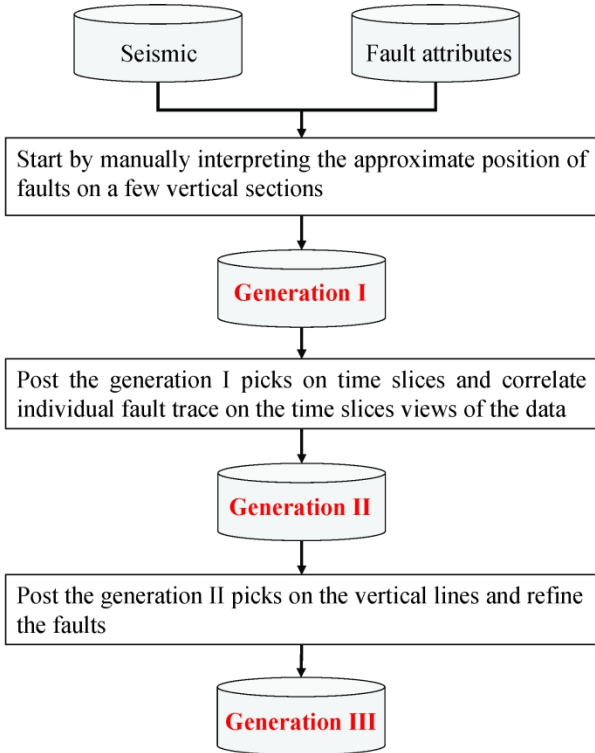


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Figure 5. A typical workflow of 3D seismic fault interpretation.

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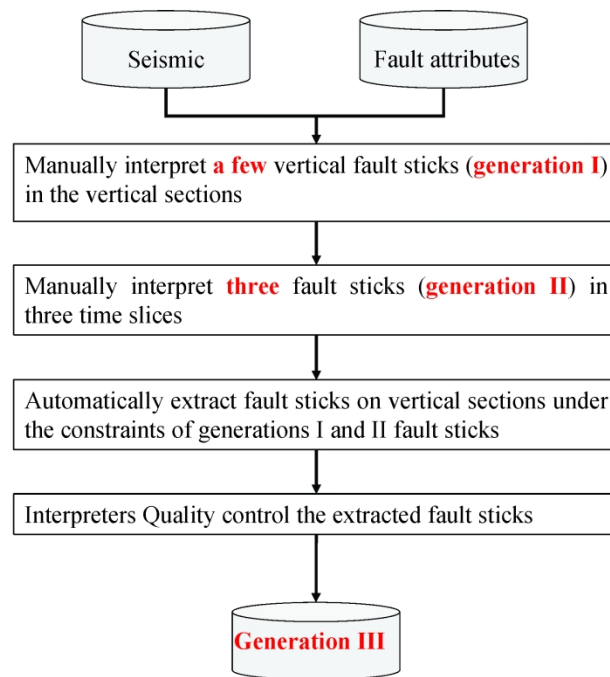


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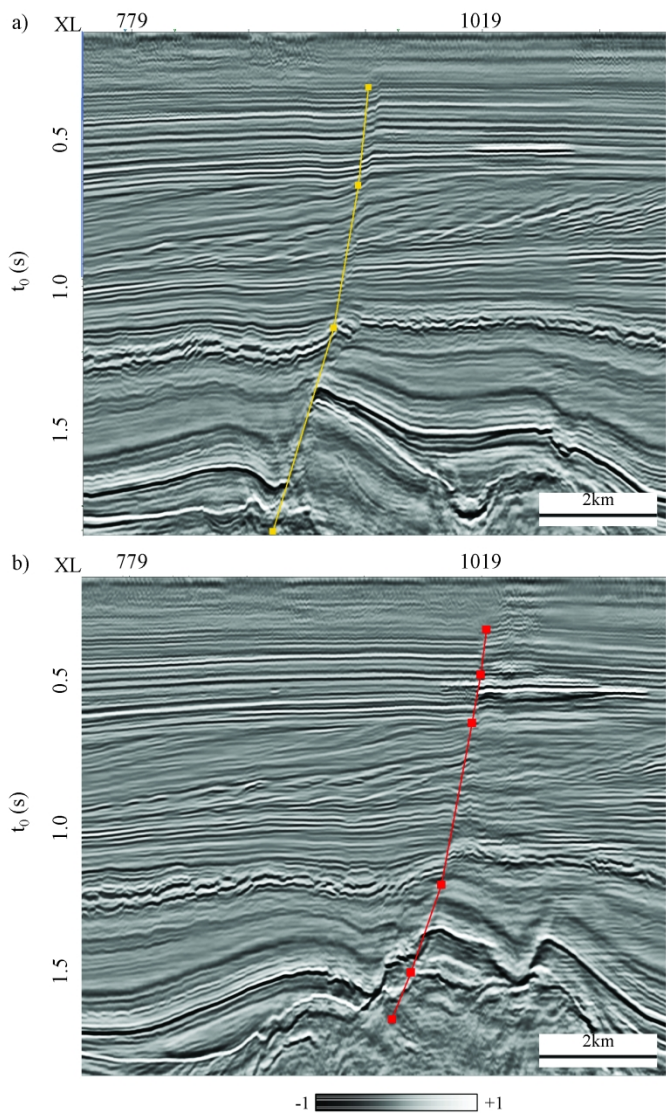


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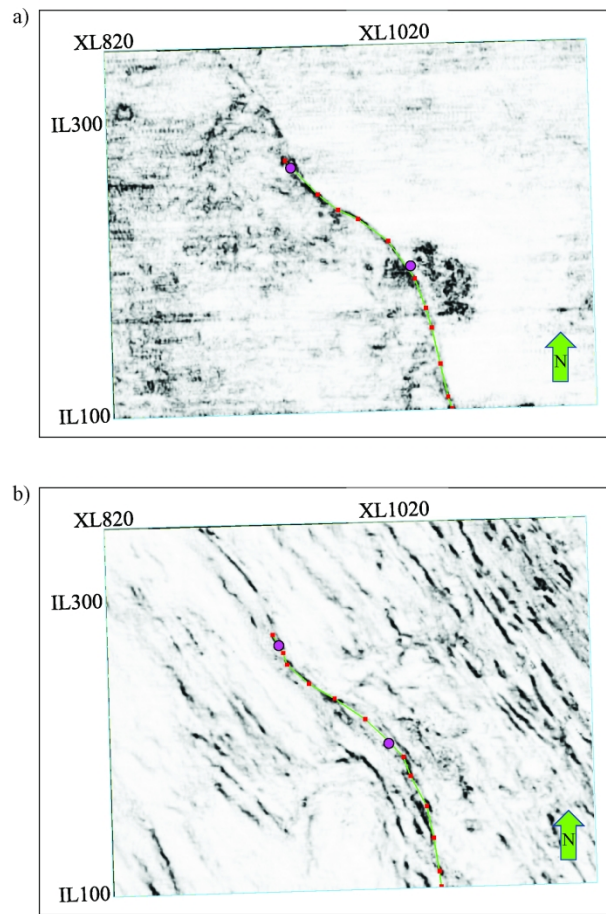


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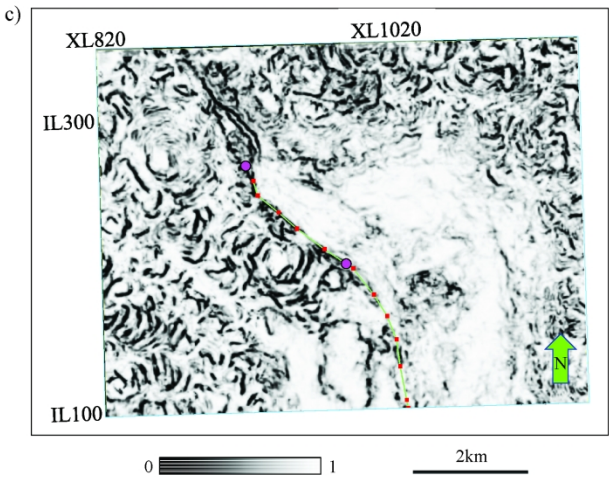


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215x279mm (300 x 300 DPI)

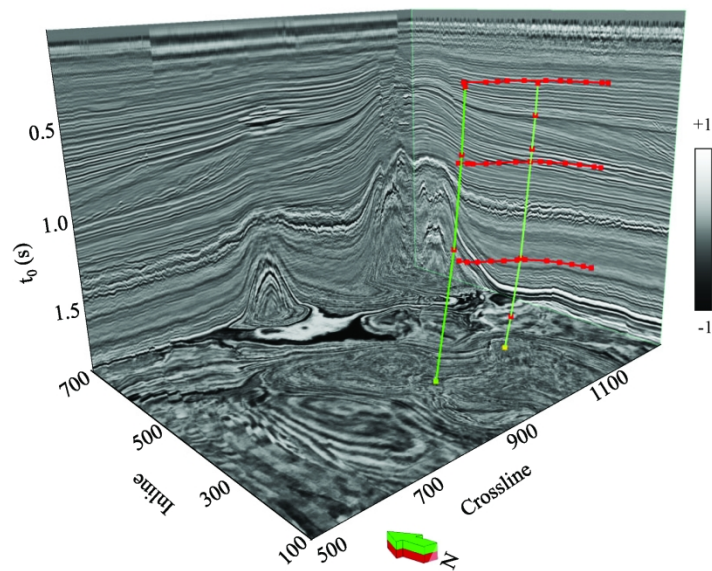


Figure 9.

Figure 9. A 3D view of the Generation I and Generation II fault sticks.

215x279mm (300 x 300 DPI)

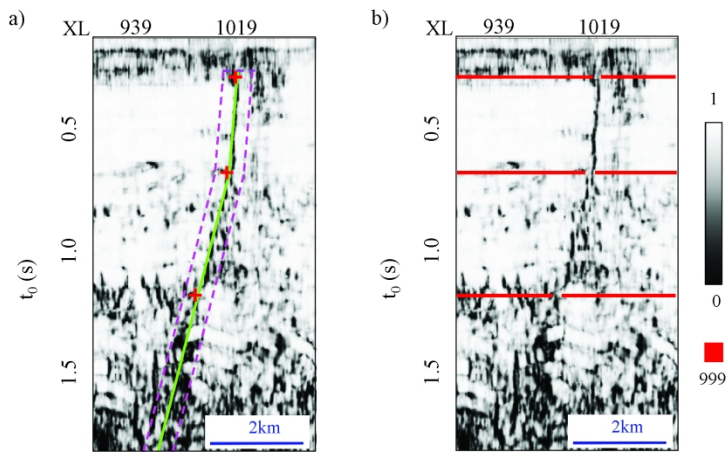


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215x279mm (300 x 300 DPI)

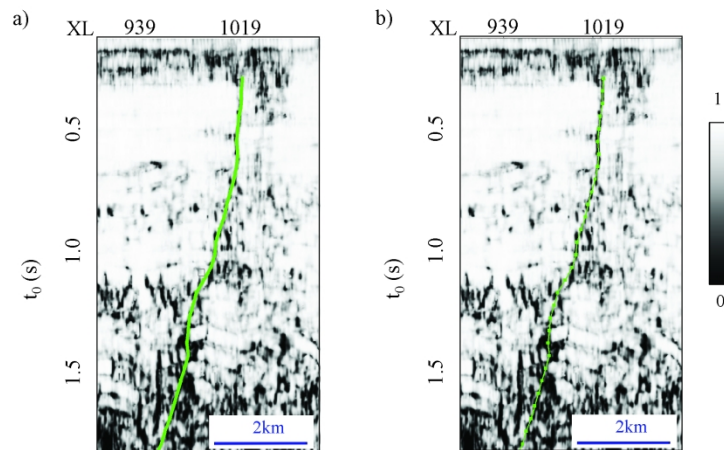


Figure 11.

Figure 11. The computed fault stick with a temporal interval of (a) 4ms and (b) 50ms.

215x279mm (300 x 300 DPI)

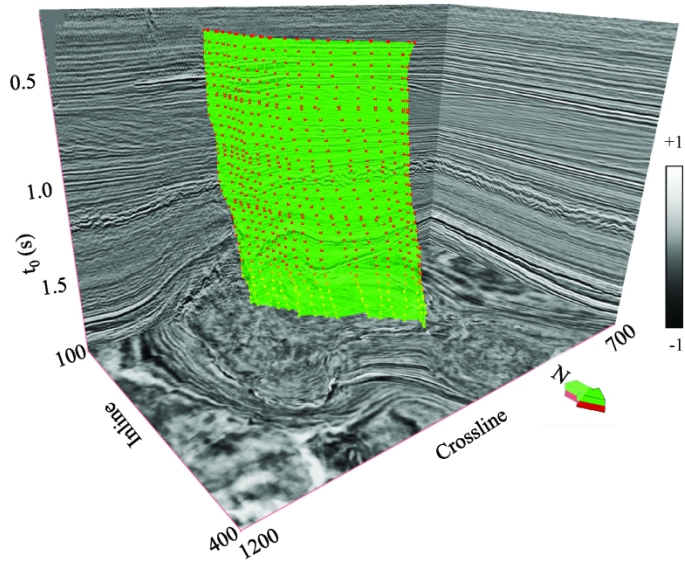


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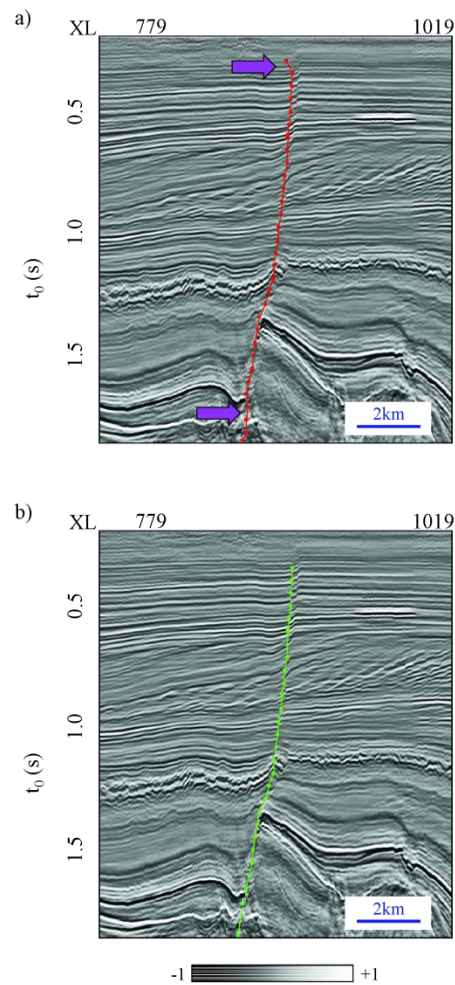


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215x279mm (300 x 300 DPI)

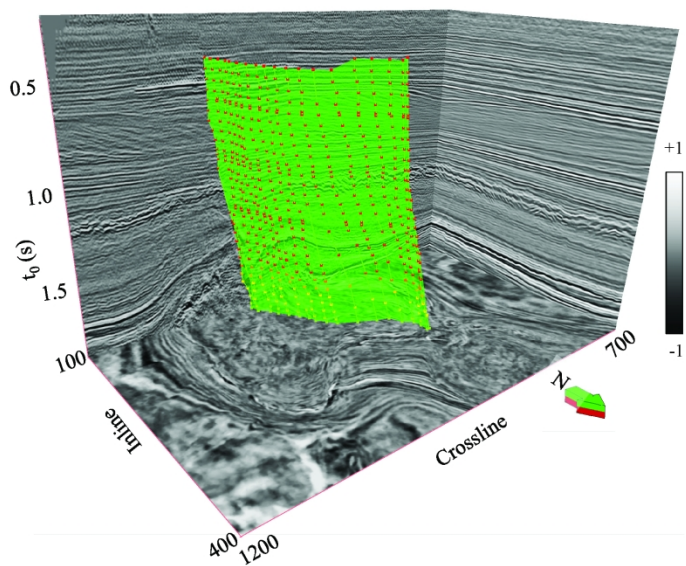


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215x279mm (300 x 300 DPI)

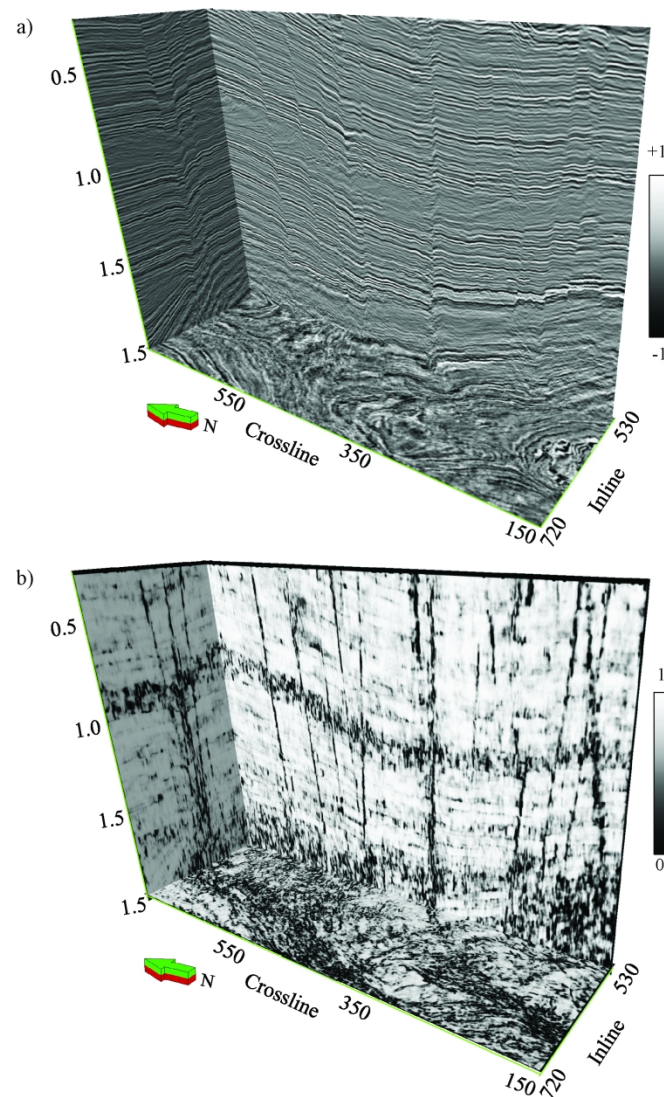


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215x279mm (300 x 300 DPI)

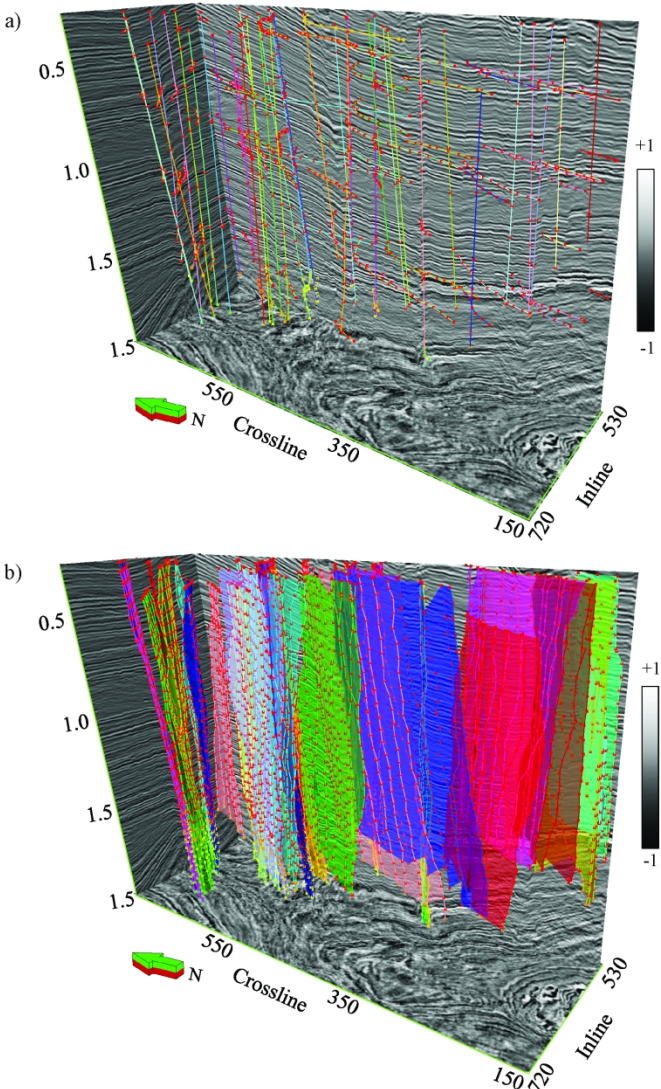


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215x279mm (300 x 300 DPI)

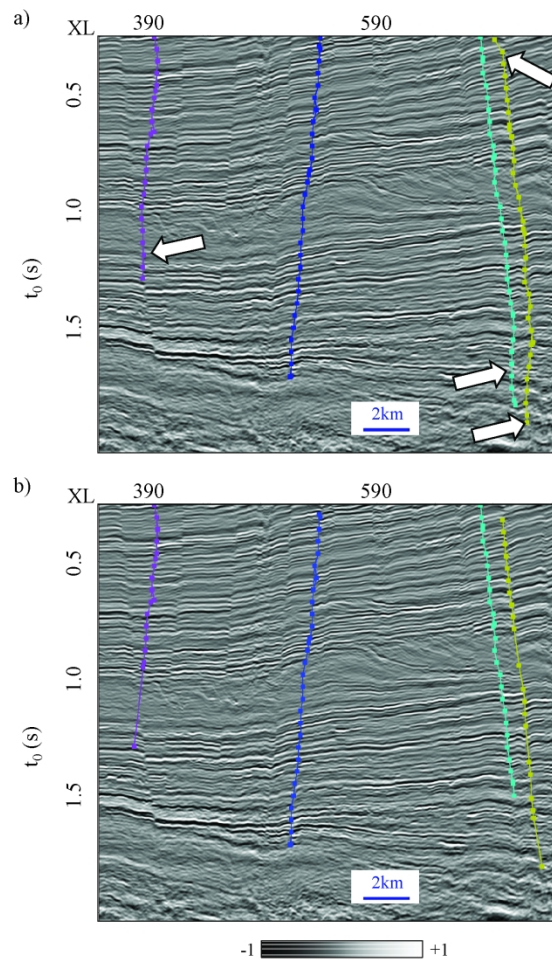


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Figure 17. Representative fault sticks (a) before and (b) after manually editing in the vertical section. The white arrows indicate picks that need to be deleted by the interpreter.

215x279mm (300 x 300 DPI)

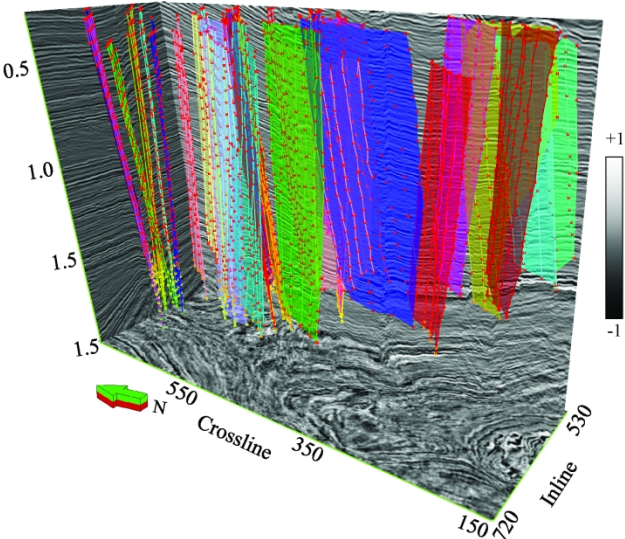


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215x279mm (300 x 300 DPI)

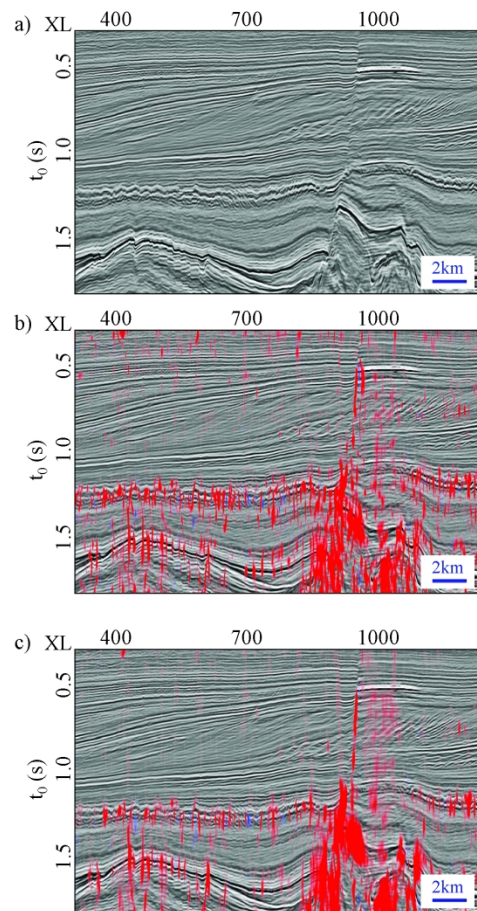


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215x279mm (300 x 300 DPI)

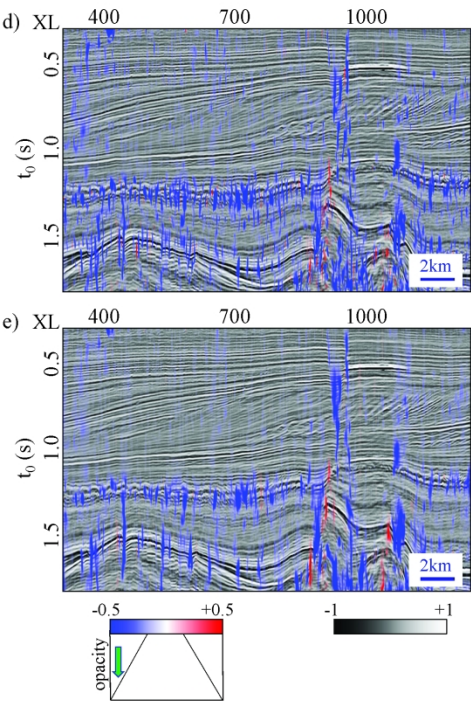


Figure 19.

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215x279mm (300 x 300 DPI)

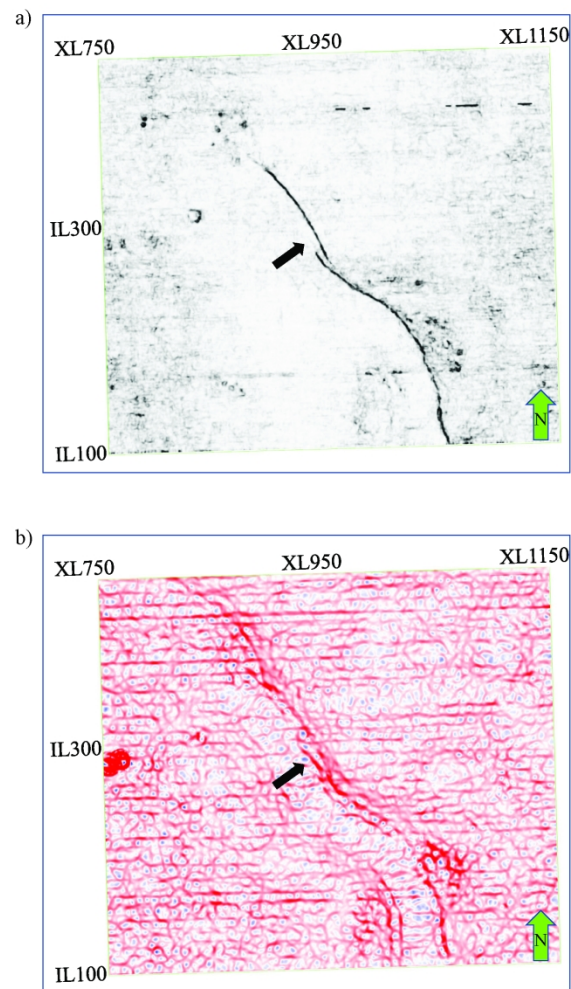


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215x279mm (300 x 300 DPI)

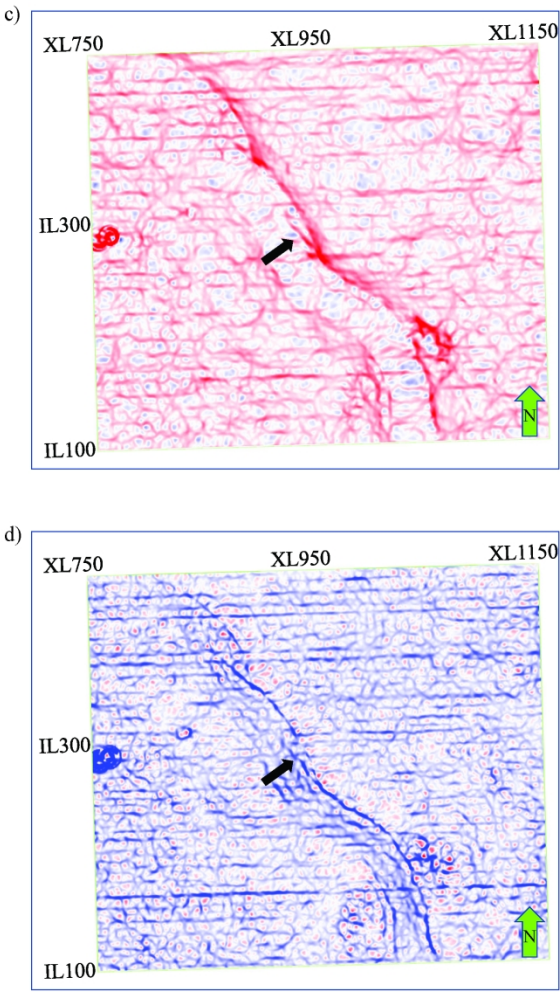


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215x279mm (300 x 300 DPI)

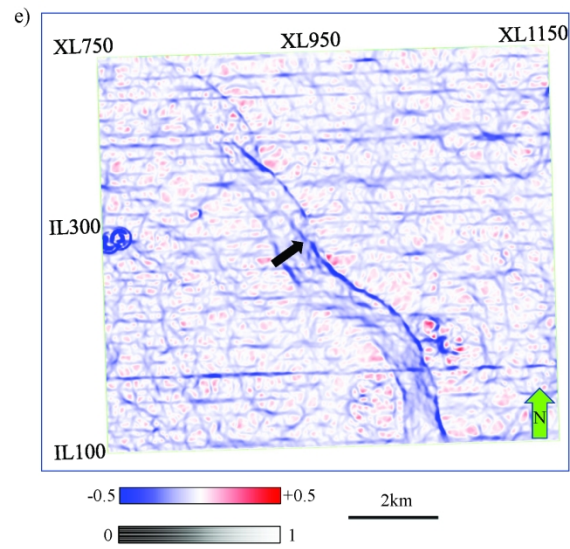


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215x279mm (300 x 300 DPI)

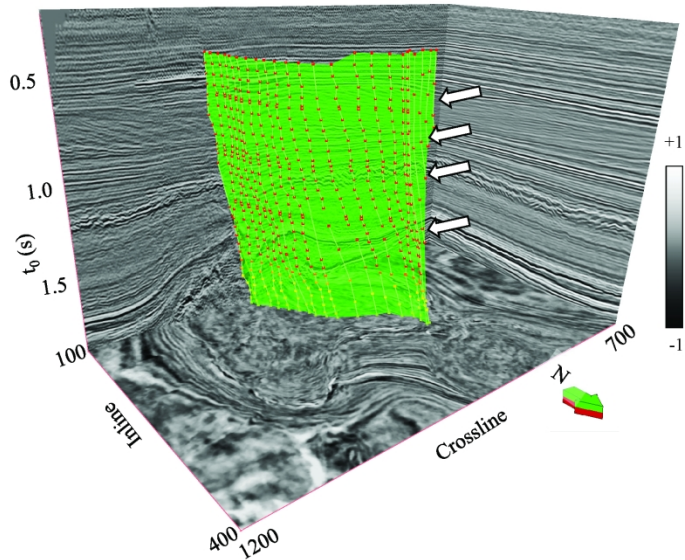


Figure 21.

Figure 21. Extended fault surface based on the coherence and curvature anomaly patterns. The white arrows indicate additionally manually interpreted fault sticks.

215x279mm (300 x 300 DPI)

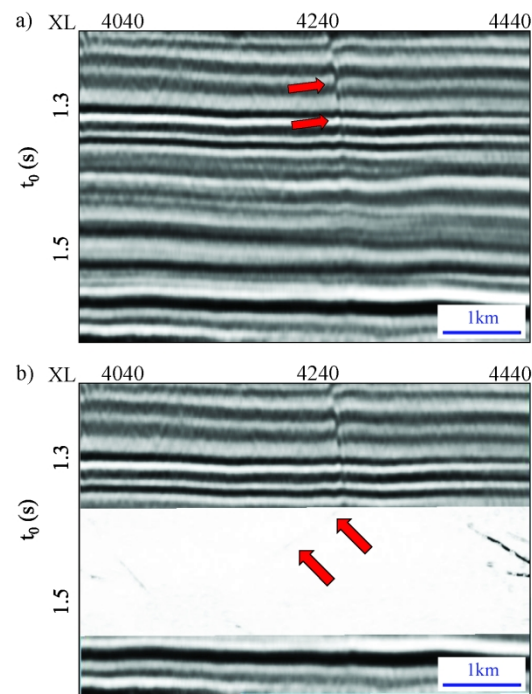


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215x279mm (300 x 300 DPI)

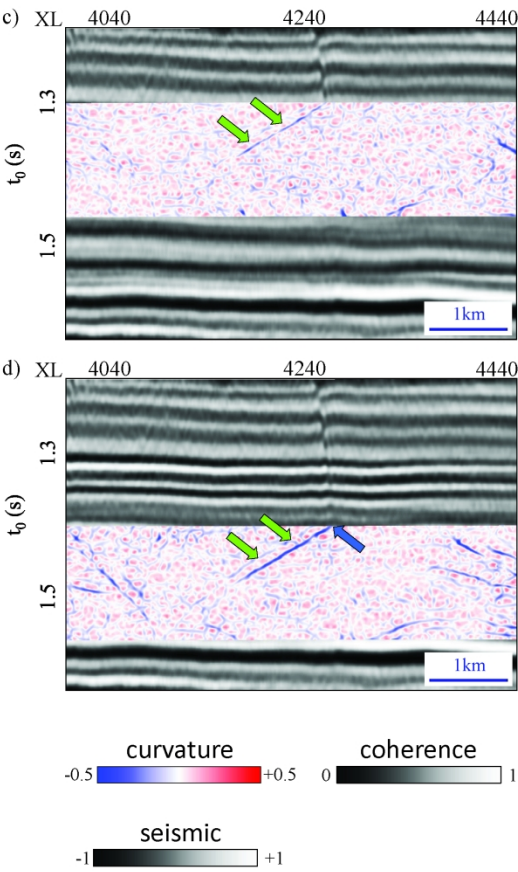


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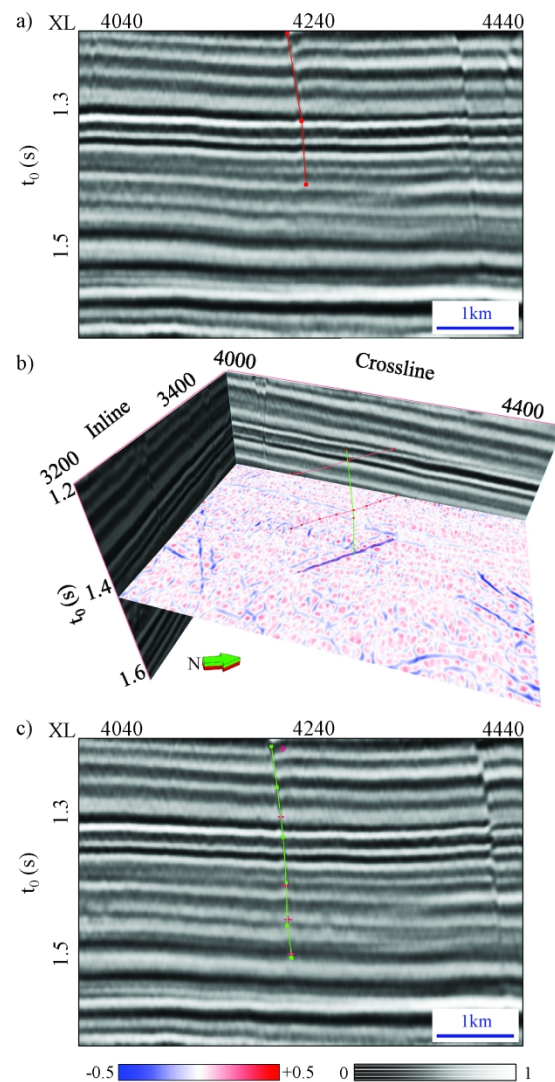


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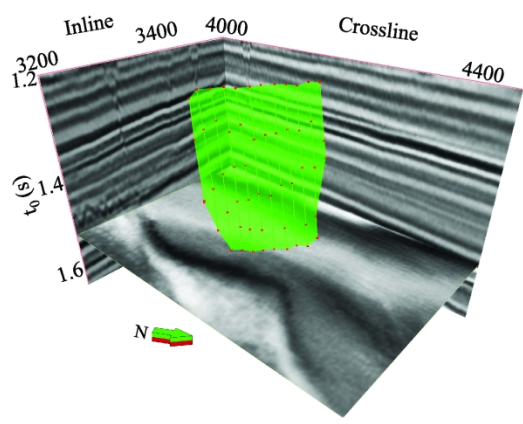
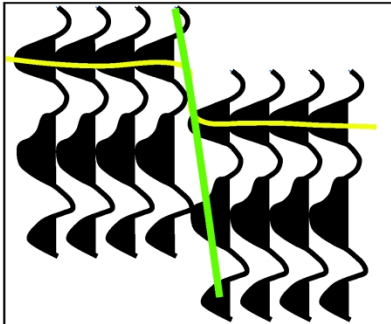


Figure 24.

Figure 24. The 3D view of interpreted Generation III fault sticks of a fault surface that have small offsets.

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Large-Offset Fault
One (1) peak or trough or more



Moderate-Offset Fault
Between half ($\frac{1}{2}$) and one peak or trough

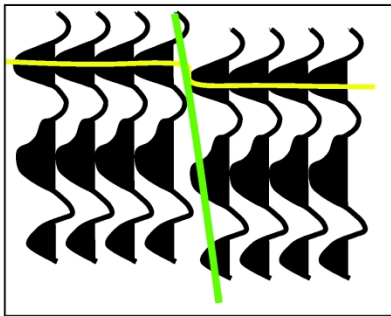


Figure A1.

Figure A1. Cartoons shown the definition of faults with large and moderate fault throw

215x279mm (300 x 300 DPI)