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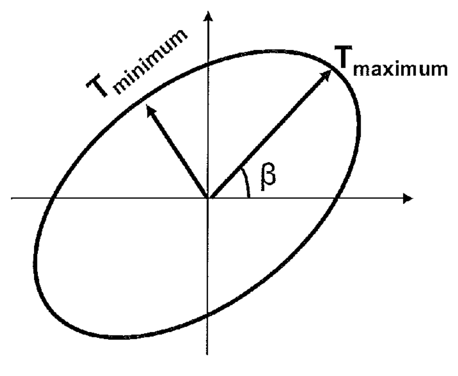
[Continued on next page]

(54) **Title**: TARGET-ORIENTED PROCESS FOR ESTIMATING FRACTURE ATTRIBUTES FROM SEISMIC DATA

Figure 1B

$$T = T_0 + \alpha \cos 2(\theta - \beta)$$

Anisotropic



T_0 = isotropic travel time

β = fracture strike (Vfast direction)

θ = source-receiver azimuth

α = fracture magnitude

(57) Abstract: Method for characterizing a subterranean formation includes: obtaining azimuth-dependent observed travel-times from measured seismic data; inverting observed travel-times to calculate a fracture attribute selected from the group consisting of: magnitude and orientation; identifying presence of fracture based on calculated fracture magnitude; identifying fracture direction based on calculated fracture orientation; calculating predicted travel-times; calculating differences or residual errors between observed travel-times and predicted travel-times; identifying potential fault locations based on residual errors; inverting fracture magnitude and orientation using travel-time differences between a shallower horizon to a deeper horizon of interest to minimize overburden artifacts.

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TARGET-ORIENTED PROCESS FOR ESTIMATING FRACTURE ATTRIBUTES FROM SEISMIC DATA

FIELD OF THE INVENTION

[0001] The present invention relates generally to oil and gas exploration. More particularly, but not by way of limitation, embodiments of the present invention include tools and methods for estimating seismic anisotropy.

BACKGROUND OF THE INVENTION

[0002] In recent years, seismic anisotropy has become an increasingly important topic in geophysics. Seismic anisotropy refers to a directional dependence of seismic wave properties (e.g., velocity) in rock medium. When seismic waves propagate during seismic data acquisition, velocity of the waves may be faster in one direction while slower in another direction. This directional variation can indicate certain structures in the rock that are on the scale of the seismic wavelength. Rocks can exhibit anisotropic properties for a number of reasons including, but not limited to, the presence of fractures, preferred orientation of mineral grains, shape of isotropic minerals, and thin bedding of isotropic layers. In particularly, fracture characterization is a key attribute in optimizing hydrocarbon recovery. Understanding fracture distribution and orientation helps identify sweet spots, especially for unconventional resources and shale plays.

[0003] Seismic data can provide indirect measure of fracture attributes. Velocity variation with azimuth (VVAZ) is a fracture detection method used to characterize fractures by measuring velocity response of seismic waves against varying azimuth (e.g., variation of stacking velocities with source-receiver azimuth). Typically, VVAZ uses prestack primary wave (P-wave) travel times from various azimuths and offsets to reconstruct normal moveout (NMO) velocity ellipse along the time dimension. Long axis of the NMO velocity ellipse corresponds to the P-wave traveling along a fracture strike direction (fast P-wave velocity) while the short axis corresponds to the P-wave traveling perpendicular the fracture strike direction (slow P-wave velocity). Some studies have suggested that relative ratio of the long and short axes of the ellipse is proportional to fracture density while fracture orientation is related to rotation of the ellipse. (Grechka and Tsvankin, 1998, Jenner, 2010, and Stein et al., 2010).

[0004] Conventional techniques for estimating seismic anisotropy can suffer from one or more technical challenges. For example, seismic anisotropy estimation can be expensive, labor-consuming and/or computationally-intensive, particularly when determining azimuthal velocities in all three dimensions of prestack seismic data. In addition, fracture-attribute estimations also tend to be less reliable when prestack seismic data have significant coherent and background noise. In general, an improper understanding of seismic anisotropy can lead to a number of issues including incorrect positions of exploration targets and improper estimations of petroleum reservoir.

[0005] Recently, a target-oriented VVAZ method (Chiu et al, 2012) was proposed, which directly inverted horizontal transverse isotropy (HTI) magnitude and orientation in a fracture layer. This target-oriented VVAZ method requires picking travel times between the top and base of the fracture layer. The advantage of this method minimizes the overburden effects and produces more accurate fracture estimations. Use of differential travel times between the top and the bottom of the target may lead to a more robust inversion result, even for a relatively thin fracture layer.

BRIEF SUMMARY OF DISCLOSURE

[0006] The present invention relates generally to seismic exploration. More particularly, but not by way of limitation, embodiments of the present invention include tools and methods for estimating seismic anisotropy.

[0007] One example of a method for characterizing a fracture in a subterranean formation, the method comprising: obtaining azimuth-dependent observed travel-times from measured seismic data; inverting observed travel-times to calculate a fracture attribute selected from the group consisting of: magnitude and orientation; identifying presence of fracture based on calculated fracture magnitude; identifying fracture direction based on calculated fracture orientation; calculating predicted travel-times; calculating differences or residual errors between observed travel-times and predicted travel-times;

[0008] identifying potential fault locations based on residual errors; inverting fracture magnitude and orientation using travel-time differences between a shallower horizon to a deeper horizon of interest to minimize overburden artifacts.

[0009] Another example of a method for characterizing a subterranean formation, the method comprising: obtaining observed travel-times from seismic data; inverting, via computing processor, observed travel-times to calculate a fracture attribute selected from the group consisting of: magnitude and orientation, wherein presence of fracture is identified using calculated fracture magnitude and fracture direction is determined using calculated fracture orientation; calculating predicted travel-times; calculating differences or residual errors between observed travel-times and predicted travel-times; identifying potential fault locations based on residual errors; inverting fracture magnitude and orientation using travel-time differences between a shallower horizon to a deeper horizon of interest to minimize overburden artifacts.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] A more complete understanding of the present invention and benefits thereof may be acquired by referring to the follow description taken in conjunction with the accompanying drawings in which:

[0011] Figure 1A-1B is an embodiment of the present invention: physical interpretation of azimuthal travel-time inversion.

[0012] Figure 2A-2B is an embodiment of the present invention: an example of elliptical fitting of picked travel times.

[0013] Figure 3 is an embodiment of the present invention: an example of fracture-magnitude map.

[0014] Figure 4 is an embodiment of the present invention: an example of fracture-orientation map.

[0015] Figure 5 is an embodiment of the present invention: an example of residual-error map.

[0016] Figure 6A-6B is an embodiment of the present invention: an example of comparing fracture-magnitude maps with and without overburden effects

DETAILED DESCRIPTION

[0017] Reference will now be made in detail to embodiments of the invention, one or more examples of which are illustrated in the accompanying drawings. Each example is provided by way of explanation of the invention, not as a limitation of the invention. It will be apparent to those skilled in the art that various modifications and variations can be made in the present invention without departing from the scope or spirit of the invention. For instance, features illustrated or described as part of one embodiment can be used on another embodiment to yield a still further embodiment. Thus, it is intended that the present invention cover such modifications and variations that come within the scope of the invention.

[0018] The present invention provides a fast, target-oriented method for estimating seismic anisotropy. While conventional methods typically rely on 3D prestack data to determine azimuthal velocity variation, the present invention directly estimates seismic anisotropy without having to compute NMO velocity ellipse on the 3D prestack data. Instead, travel times from a targeted horizon of azimuthal (migrated or unmigrated) sectored stacks are used to directly derive physical attributes of the fracture via an inversion process.

[0019] Some of the advantages of the present invention include, but are not limited to:

- increasing signal-to-noise ratio of data to give more reliable fracture estimations
- reducing data dimension from 3D to a few targeted travel-time surfaces
- decreasing the processing time considerably to produce fracture estimations because of reducing data dimension
- producing horizon-consistent facture estimations
- reducing or removing overburden effects by using the travel-time difference or residual between azimuthal stack horizons from a shallower horizon to the horizon of interest
- identifying potential fault locations from residual-error map.

Other advantages will be apparent from the disclosure herein.

[0020] Equation (1) can be used to estimate seismic anisotropy:

$$T = T_0 + \alpha \cos 2(\theta - \beta) \qquad (1)$$

where T = azimuthal travel time,

T_0 = isotropic travel time,

α = anisotropic magnitude,

θ = source and receiver azimuth,

β = fracture direction (maximum travel time).

The parameters T_0, α, and β can be solved by a least-squares inversion. This inversion produces at least three output maps: facture magnitude, fracture direction, and residual fitting error.

[0021] Some embodiments provide a method for characterizing a subterranean formation, the method comprising: obtaining observed travel-times from seismic data; inverting observed travel-times to calculate a fracture attribute selected from the group consisting of magnitude and orientation, wherein presence of fracture is identified using calculated fracture magnitude and fracture direction is determined using calculated fracture orientation; calculating predicted travel-times; calculating differences or residual errors between observed travel-times and predicted travel-times; identifying potential fault locations based on residual errors; inverting fracture magnitude and orientation using travel-time differences between a shallower horizon to a deeper horizon of interest to minimize overburden artifacts.

[0022] Figure 1A-1B illustrates how azimuthal velocity variation in travel time may relate to the presence of seismic anisotropy or fractures. In particular, Figure 1 shows how equation 1 can be used to model the fracture attributes of the rock formations. If the rock is homogeneous without any fractures, α is zero. Thus the travel-time surface is a circle (Figure 1A). However, if fractures are present in rock formations, the fractures cause the travel-time surface to become elliptical (Figure 1B). This method derives the fracture attributes, α and β, by modeling the observed travel-time surface. Since α and β directly connect to fracture magnitude and direction, the mapping of both parameters from a data set provides a spatial map showing how the fractures change locally with rock formations.

[0023] In an illustrative example, the present invention uses picked travel times of a common-image gather obtained from azimuthal sectored stacks (Figure 2A) to compute the fracture attributes, α and β. Table 1, below, shows the inversion result. The average residual error is only 0.4 msec which is below the 2 msec sampling rate of this data set. Figure 2B also shows a graphic comparison between observed travel times and travel times predicted from equation 1. The match between observed and predicted values is remarkably similar.

Table 1

Source-receiver azimuth (°)	Input travel time (msec)	Predicted travel time (msec)
27	2686.6	2687.1
57	2685.7	2685.0
87	2685.9	2686.3
117	2689.5	2689.6
147	2692.0	2691.6
177	2690.3	2690.4

Computed fracture strike (β) is 151 degree from the North.

Computed fracture magnitude (α) is 0.24.

Average residual travel-time error is 0.4 msec.

[0024] Faults generally exist in rock formations. If a fault plane is present in rock formations, it causes discontinuity of travel-time surface as a function of azimuths within a common-image gather or a common midpoint gather obtained from azimuthal sectored stacks. The discontinuity of travel times, in turn, creates large residual errors between the observed travel times and travel times predicted from equation 1. The large residual errors from the inversion are the key to be used in identifying potential fault locations. Table 2, below, illustrates an example of inverting travel-time picks across a fault plane. The travel-time discontinuity, for example, occurs between source and receiver azimuths of 57^0 and 87^0. As a result, the travel-time discontinuity creates an average large residual error of 14.6 msec when comparing with a much smaller residual error of 0.4 msec in Table 1. The residual-error map is an effective way to be used in identifying the presence of fault locations.

Table 2

Source-receiver azimuth (°)	Input travel time (msec)	Predicted travel time (msec)
27	2340.6	2351.9
57	2340.9	2346.2
87	2373.1	2351.6
117	2339.2	2361.4

147	2372.6	2367.1
177	2373.5	2362.3

Computed fracture strike (β) is 148 degree from the North.

Computed fracture magnitude (α) is 10.4.

Average residual travel-time error is 14.6 msec.

EXAMPLE 1

[0025] Figures 3-5 illustrate an example of mapping inverted fracture magnitudes (Figure 3), fracture orientations (Figure 4) and residual fitting errors (Figure 5). These maps can be used to highlight the fracture attributes. Fault locations can be best seen in Figure 4 (black lines). As illustrated, the residual-fitting-error trends (Figure 5) followed closely with fault locations in Figure 4. The identification of fault locations helps to reduce drilling risk and to optimize reservoir production.

[0026] This invention also addresses how to minimize the overburden effect that affects the result of travel-time inversion. The seismic waves have to travel through the overburden layers first to reach a deeper target horizon. If the travel times of overburden layers are not corrected, the overburden will impose a footprint on the deeper horizon. The invention also adopts a similar approach as the target-oriented VVAZ method that uses differential travel times between the top and the bottom of the target horizon. However, the invention here employs a completely different mathematical model and input data when compared with the target-oriented VVAZ method. The approach of using differential travel times in equation 1 minimizes the overburden effect and produces more reliable fracture-attribute estimations. The overburden artifacts may be minimized using travel-time differences between a shallower horizon to a deeper horizon of interest. In some embodiments, the overburden artifacts are minimized using travel-time differences between the top and bottom of a target layer.

[0027] In one embodiment, fracture magnitude and fracture orientation within a number of layers are calculated using travel-time differences between a shallower horizon to a deeper horizon of interest. In one embodiment, fracture magnitude and fracture orientation within a target layer are calculated using travel-time differences between the top and bottom of a target layer.

EXAMPLE 2

[0028] Figure 6 shows a comparison of fracture-attribute maps derived from a travel-time surface of a horizon (Figure 6A) vs. the differential travel times between the top and the bottom of the target horizon (Figure 6B). The fracture map derived from differential travel times significantly reduces the overburden footprint and provides more reliable fracture estimations that are related to the fractures of the target horizon but not the overburden artifacts.

[0029] According to one embodiment, the present invention can be used to scan for potential fault locations. If the azimuthal travel-time surfaces change abruptly across a fault plane, the travel-time changes also create large residual fitting errors associated with a fault location.

[0030] Azimuthal velocity variation in travel time can be a good indicator of the presence of seismic anisotropy or fractures. According to one or more embodiments, the present invention provide a method that utilizes travel times from target horizons of azimuthal sectored stacks to invert for fracture attributes.

[0031] The target-oriented travel-time inversion provides a fast, target-oriented method for estimating seismic anisotropy by using azimuthal (migrated or unmigrated) sectored stacks instead of prestack seismic data. Since this method bases on picking travel times on seismic horizons, it produces horizon-consistent facture estimations. The residual error map derived from this invention provides an alternative way to identify potential fault locations. In addition, this invention also addresses how to minimize the overburden effect that affects the result of travel-time inversion. It utilizes the differential travel times between the top and the bottom of the target horizon to estimate fracture attributes. The fracture map derived from the differential travel times gives more reliable fracture estimations that are related to the fractures of target horizon but not the overburden artifacts.

[0032] Although the systems and processes described herein have been described in detail, it should be understood that various changes, substitutions, and alterations can be made without departing from the spirit and scope of the invention as defined by the following claims. Those skilled in the art may be able to study the preferred embodiments and identify other ways to practice the invention that are not exactly as described herein. It is the intent of the inventors that variations and equivalents of the invention are within the scope of the claims while the description, abstract and drawings are not to be used to limit the scope of the invention. The invention is specifically intended to be as broad as the claims below and their equivalents.

REFERENCES

[0033] All of the references cited herein are expressly incorporated by reference. The discussion of any reference is not an admission that it is prior art to the present invention, especially any reference that may have a publication data after the priority date of this application. Incorporated references are listed again here for convenience:

1. Stephen K. Chiu, Jason A Stein, Jack Howell, Samik Sil, Michael Davidson, and Jeff Malloy, 2012, Validate target-oriented VVAZ with formation microimaging, SEG Technical Program Expanded Abstracts: pp. 1-5.
2. Grechka, V., and I. Tsvankin, 1998, 3-D description of normal moveout in anistropic inhomogeneous media: Geophysics, 63, 1079-1092.
3. Jenner, E., 2010, Modelling azimuthal NMO in laterally heterogeneous HTI media: First Break volume 28, No. 9, 89-94.
4. Stein, J., A., R. Wojslaw, T. Langston, and S. Boyer, 2010, Wide-azimuth land processing: Fracture detection using offset vector tile technology: The leading edge, Nov., 1328-1337.

CLAIMS

1. A method for characterizing a subterranean formation, the method comprising:

a) obtaining azimuth-dependent observed travel-times from measured seismic data;

b) inverting observed travel-times to calculate a fracture attribute selected from the group consisting of: magnitude and orientation;

c) identifying presence of fracture based on calculated fracture magnitude;

d) identifying fracture direction based on calculated fracture orientation;

e) calculating predicted travel-times;

f) calculating differences or residual errors between observed travel-times and predicted travel-times;

g) identifying potential fault locations based on residual errors;

h) inverting fracture magnitude and orientation using travel-time differences between a shallower horizon to a deeper horizon of interest to minimize overburden artifacts.

2. The method of claim 1 wherein the fracture magnitude (α) and fracture orientation (β) are calculated using equation $T = T_0 + \alpha \cos 2 (\theta - \beta)$, wherein T is azimuthal travel time, T_0 is isotropic travel time, and θ is source and receiver azimuth.

3. The method of claim 1 wherein the observed travel-times were obtained from a common-image gather from azimuthal sectored stacks.

4. The method of claim 3 wherein the azimuthal sectored stack is migrated or unmigrated.

5. The method of claim 1 wherein the predicted travel-times are calculated using equation $T = T_0 + \alpha \cos 2 (\theta - \beta)$.

6. The method of claim 5 wherein the fault location is indicated by largest residual difference between observed and predicted travel-times.

7. The method of claim 1 wherein the fracture magnitude and fracture orientation within a number of layers are calculated using travel-time differences between a shallower horizon to a deeper horizon of interest.

8. The method of claim 1 wherein the fracture magnitude and fracture orientation within a target layer are calculated using travel-time differences between the top and bottom of a target layer.

9. The method of claim 7 wherein overburden artifacts are minimized using travel-time differences between a shallower horizon to a deeper horizon of interest.

10. The method of claim 8 wherein overburden artifacts are minimized using travel-time differences between the top and bottom of a target layer.

11. A method for characterizing a subterranean formation, the method comprising:

a) obtaining observed travel-times from seismic data;

b) inverting, via computing processor, observed travel-times to calculate a fracture attribute selected from the group consisting of: magnitude and orientation, wherein presence of fracture is identified using calculated fracture magnitude and fracture direction is determined using calculated fracture orientation;

c) calculating predicted travel-times;

d) calculating differences or residual errors between observed travel-times and predicted travel-times;

e) identifying potential fault locations based on residual errors;

f) inverting fracture magnitude and orientation using travel-time differences between a shallower horizon to a deeper horizon of interest to minimize overburden artifacts.

12. The method of claim 11 wherein the fracture magnitude (α) and fracture orientation (β) are calculated using equation $T = T_0 + \alpha \cos 2 (\theta - \beta)$, wherein T is azimuthal travel time, T_0 is isotropic travel time, and θ is source and receiver azimuth.

13. The method of claim 1 wherein the observed travel-times were obtained from a common-image gather from azimuthal sectored stacks.

14. The method of claim 13 wherein the azimuthal sectored stack is migrated or unmigrated.

15. The method of claim 1 wherein the predicted travel-times are calculated using equation $T = T_0 + \alpha \cos 2 (\theta - \beta)$.

16. The method of claim 15 wherein the fault location is indicated by largest residual difference between observed and predicted travel-times.

17. The method of claim 11 wherein the fracture magnitude and fracture orientation within a number of layers are calculated using travel-time differences between a shallower horizon to a deeper horizon of interest.

18. The method of claim 11 wherein the fracture magnitude and fracture orientation within a target layer are calculated using travel-time differences between the top and bottom of a target layer.

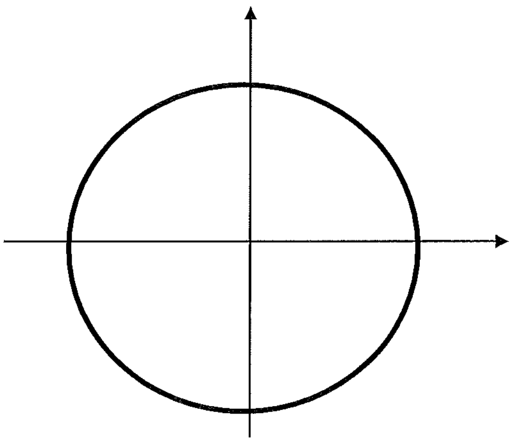
19. The method of claim 17 wherein overburden artifacts are minimized using travel-time differences between a shallower horizon to a deeper horizon of interest.

20. The method of claim 18 wherein overburden artifacts are minimized using travel-time differences between the top and bottom of a target layer.

Figure 1A

$T = T_0$, $\alpha = 0$

Isotropic

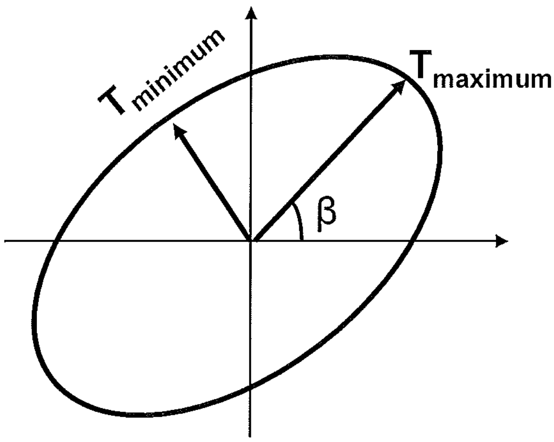


Fracture magnitude (α) = 0

Figure 1B

$T = T_0 + \alpha \cos 2(\theta - \beta)$

Anisotropic



T_0 = isotropic travel time

β = fracture strike (Vfast direction)

θ = source-receiver azimuth

α = fracture magnitude

Figure 2A

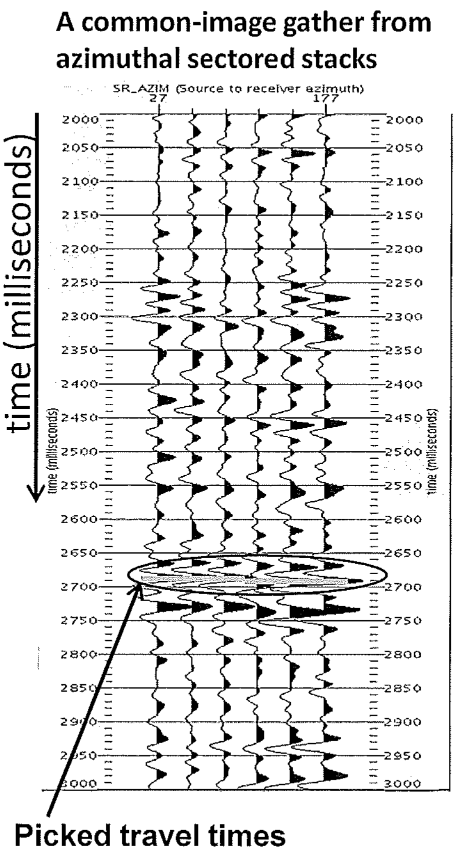
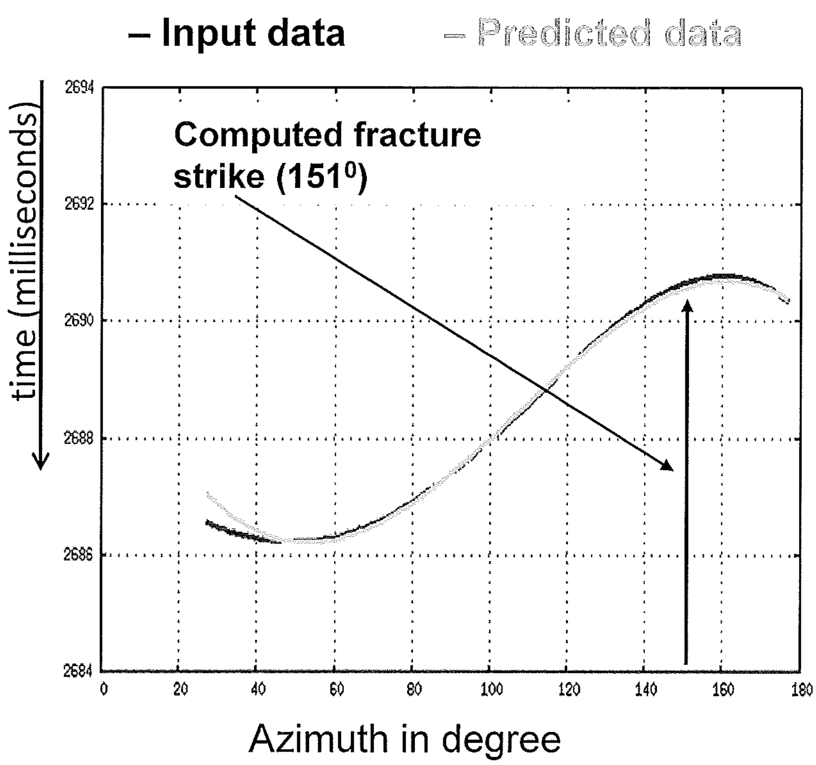


Figure 2B



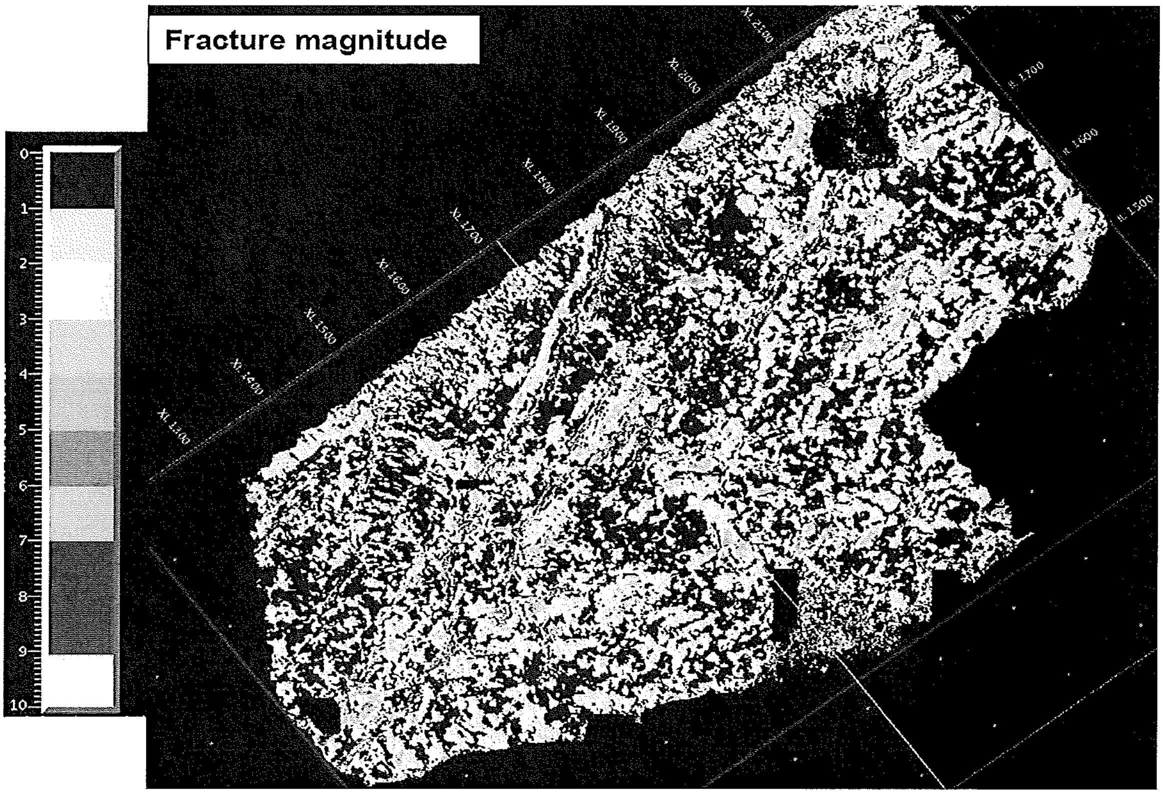


Figure 3

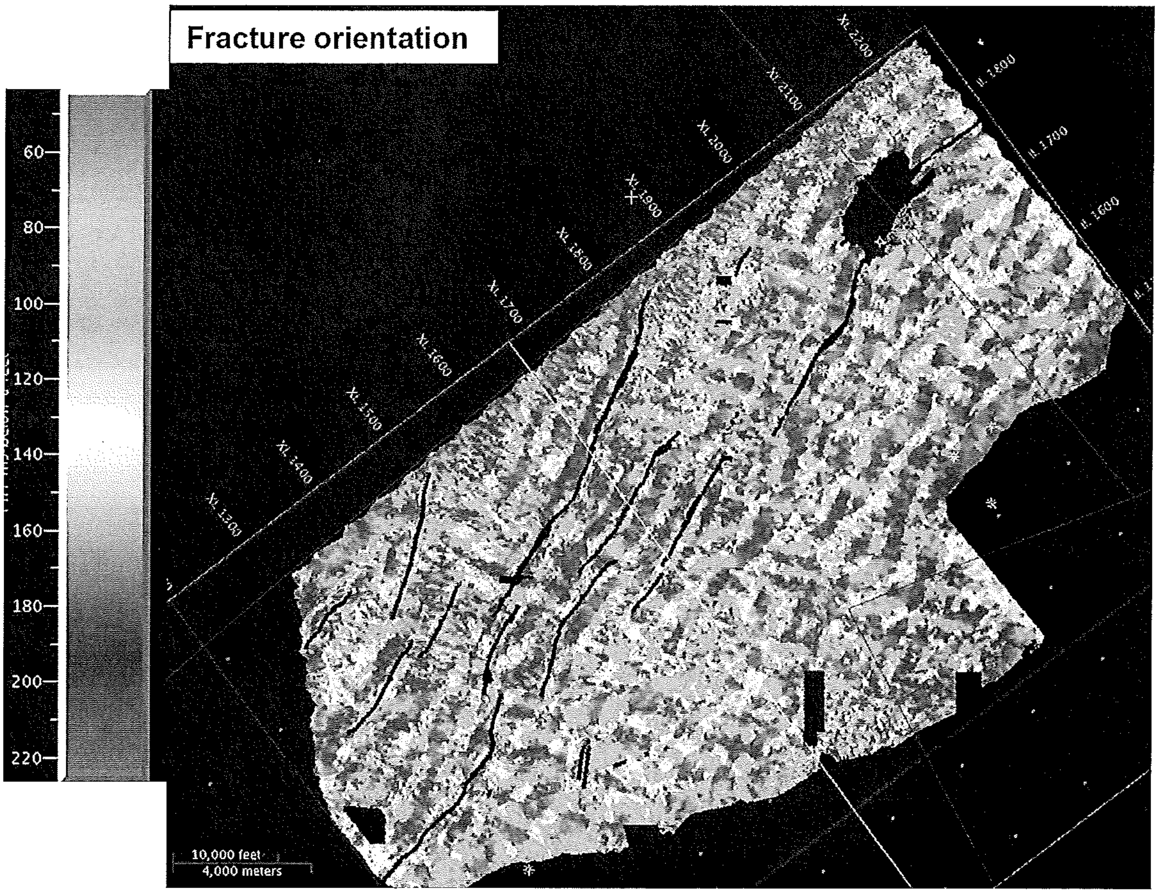

Fracture orientation
60
80
100
120
140
160
180
200
220
10,000 feet
4,000 meters

Figure 4

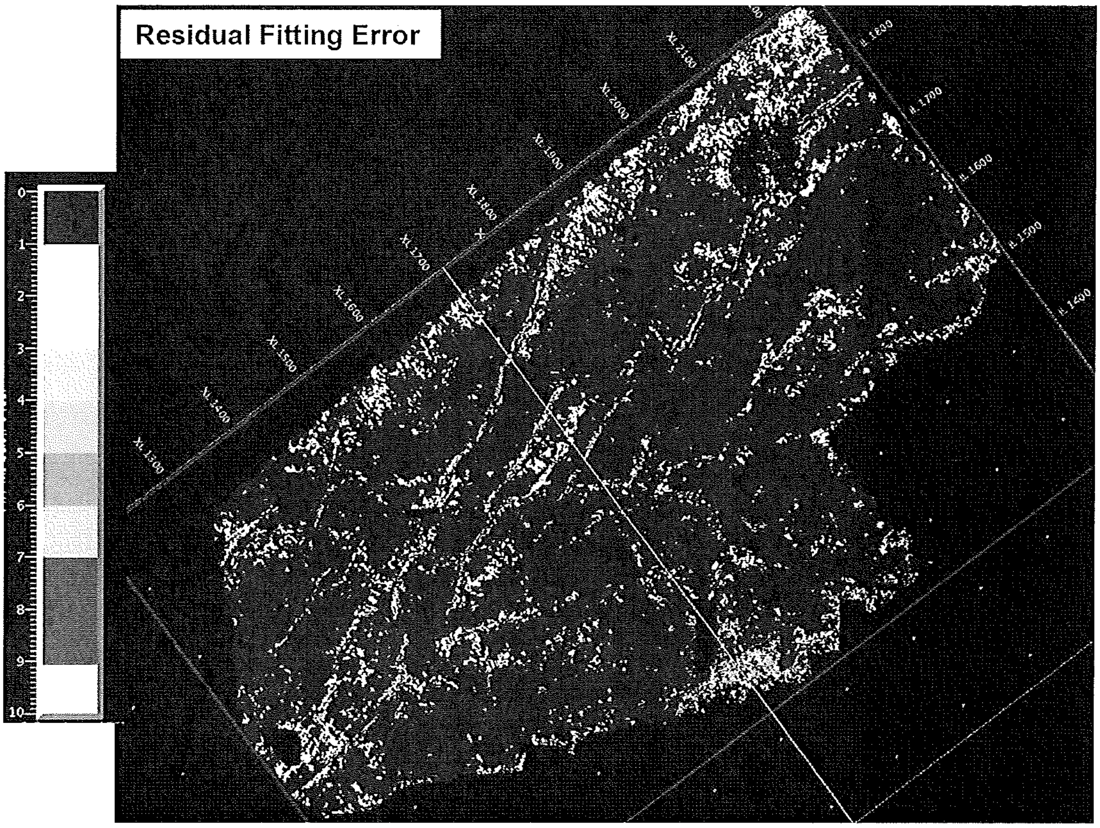


Figure 5

Figure 6A

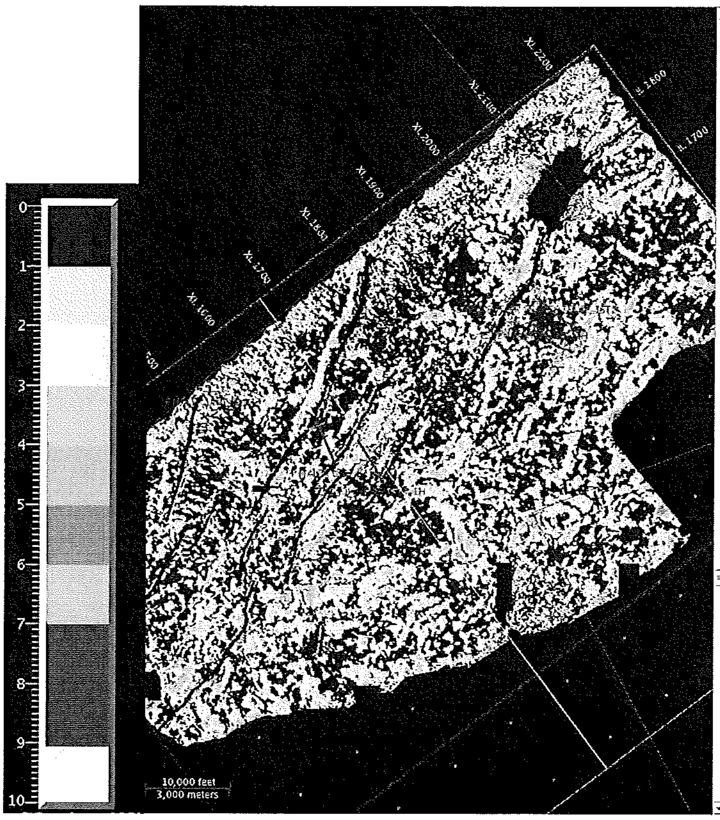
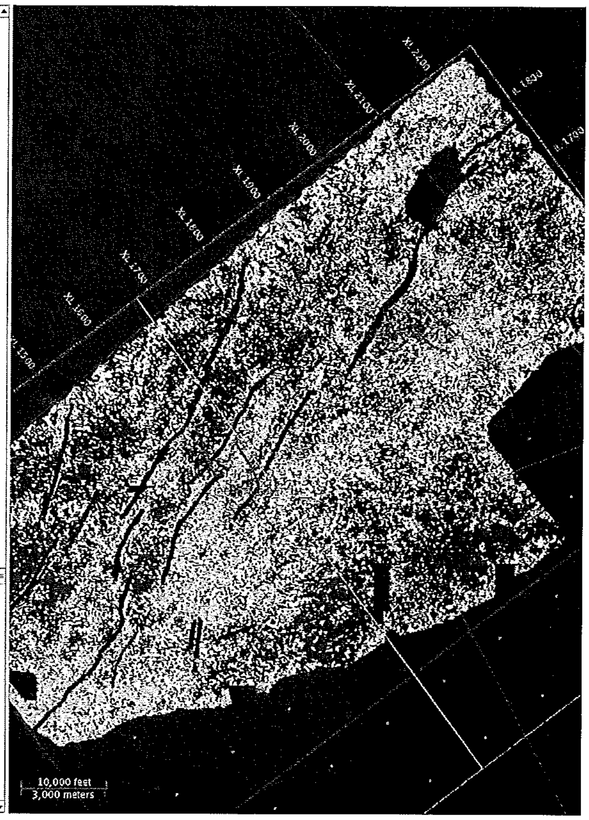


Figure 6B



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US15/42088

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G01V 1/00, G01V 1/50, G01V 1/04 (2015.01)
CPC - G01V 1/50, G01V 1/303, G01V 1/28, G01V 1/288
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8): G01V 1/00, G01V 1/50, G01V 1/04 (2015.01)
CPC: G01V 1/50, G01V 1/303, G01V 1/28, G01V 1/288

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data); Google Scholar; EBSCO; Proquest
Keywords : Seismic, Azimuth, "Travel Time", Invert, Fracture, Orientation

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2010/0220895 A1 (KOREN, Z et. al) 2 September 2010, paragraphs [0008], [0009], [0025].	1-20
A	US 2011/0255371 A1 (JING, C et. al) 20 October 2011, Claim 18, paragraphs [0037], [0040].	1-20
A	US 2009/0010105 A1 (SICKING, C et. al) 8 January 2009, Entire Document.	1-20
A	US 2003/0167126 A1 (HORNE, S et. al) 4 September 2003, Entire Document.	1-20

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 September 2015 (16.09.2015)	15 OCT 2015

Name and mailing address of the ISA/	Authorized officer
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774