Seismic attribute characterization of fractured basement reservoirs

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Abstract

The fractured basement reservoirs found around the world can be quite thick, where the bulk of the porosity, and permeability consists of fractures and faults. Basement reservoirs occur in both igneous or metamorphic rocks and occur in structurally higher parts of the basement, to allow lateral migration of hydrocarbons from deeper sedimentary source rocks. Sustained production from such reservoirs requires mapping the fault and fracture patterns, lateral changes in brittleness, and if possible, estimating the maximum horizontal stress in the area. In many cases 3D seismic data provide a good image of the top basement. However, often the basement marker may not be well imaged, so that the critical fault/fracture patterns are more difficult to map. We suggest the application of novel techniques and workflows which could make a big impact in better characterizing the fractured basement reservoirs. The application of voice components to improve the tracking of a difficult-to-pick top-basement reflector. Once picked, coherence, multispectral coherence, Euler curvature, short-wavelength curvature, aberrancy, and fault likelihood often delineate subtle basement fractures. In the absence of sufficient well control, attributes can also aid in constructing the low-frequency velocity model necessary for accurate impedance inversion. Attributes that estimate brittleness help define geomechanical properties of basement reservoirs and their seal. We illustrate these ideas with examples from North America and New Zealand.

Introduction

The first recorded production from fractured basement was in Venezuela’s La Paz field in 1953, where the basement reservoir was laterally charged by the La Luna source rock. In the same year, Walters (1953) showed production from 16 wells from fractured quartzite basement reservoirs laterally charged from Cambro-Ordovician sediments. During the last decade or so, a surprising number of commercially viable basement reservoirs have been discovered in Argentina, Brazil, Canada, China, Egypt, India, Russia, USA (Southern California, Morrow County-Ohio, Texas Panhandle, Central Kansas), Vietnam, and Myanmar. Hung and Le (2004) report that Vietnam’s Cuu Long Basin Bach Ho (White Tiger) giant oil field has recoverable reserve of 1.0-1.4 billion barrels. Such discoveries have resulted in many oil and gas companies taking fractured basement plays seriously.

Both well data and production data show that fractured basements are highly heterogeneous. Usually, the seismic data exhibit a strong velocity contrast between the younger sediments above and the older and harder (granitic) basement below. In cases, where high velocity Paleozoic sediments overlay the top basement, and the velocity contrast is low, careful processing of the data

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may be required to improve the basement top reflections (e.g., Ha and Marfurt, 2017a, b). Most basement reservoirs were at one time exposed, subjecting them to weathering and alteration of preexisting fractures. Depending on the present-day depth and lithology of the basement rocks and the overlying seal, the seismic response may be weak or vary spatially and thus require enhanced imaging.

Basement faults and fractures occur on a variety of scales from regional to sub-seismic and vary with depth into the reservoir. If the velocity of the basement is significantly higher than the overlying and laterally adjacent sediments, accurate mapping of faults and fractures requires prestack depth migration. If the seismic data are well imaged, prestack impedance inversion and a wide variety of seismic attributes provide a means to map the orientation, dip, and intensity of the fracture networks (Mai et al., 2010). Given the need to map faults, the diagenetic alteration of the basement and of the presence of large faults and fractures result in strong and rapid lateral velocity changes, making the seismic datasets good candidates for prestack depth migration to address the lateral variation in velocity and superior imaging (Pham et al., 2008; Tan et al., 2016)).

Finally, the higher cost and risks of drilling fractured basement reservoirs, especially for offshore wells, motivates the development of workflows to better delineate the intensity and orientation of the target features.

**Characterization of basement reservoirs**

To better characterize a basement reservoir, we need to answer the following questions:

(i) Is the basement granitic? If it is not granitic, then we need to determine its lithology and susceptibility to fractures.

(ii) What is the configuration of the basement? Where are the current structural highs and lows, was it uplifted/unloaded and subjected to fracturing, was it exposed subaerially and subjected to diagenesis?

(iii) What are the orientations and intensity of faults or fractures in the basement?

(iv) What is the degree of weathering or erosion of the basement, and how does it vary laterally and vertically?

(v) What lithologic units overlie the basement? Do we have a good seal, and is one or more of these younger laterally deeper units a good source rock?

(vi) Can we estimate the maximum horizontal stress in the area, where the past horizontal stress associated with weathered joints, and where open cracks will depend on the present-day horizontal stress? Such information is important in orienting horizontal wells.
Accurate characterization of basement reservoirs requires not only 3D seismic data, but also borehole and core measurements of porosity, permeability, fluid type, and mineralogy. Several of the basement reservoir characterization objectives can be addressed using seismic attributes to map:

(A) the top-basement marker in view of the low seismic frequency content and low signal-to-noise ratio at deeper levels. For depth-migrated data, a high velocity contrast basement will result in longer wavelength images. For time-migrated data, internal basement features may appear to have similar resolution to those of the lower velocity sedimentary overburden, but velocity pull ups will distort the orientation of dipping faults.

(B) faults and fractures (including their areal extent, depth, intensity, orientation, and network connectivity) and their corroboration with image logs,

(C) fracture porosity and brittleness at the basement level, and

(D) integrate the results to generate a model of the basement interval, including an estimate of the stress regime, to guide drilling and production and estimate the overall economic value of the prospect.

Suggested seismic attribute applications and workflows

Any workflow adopted for characterization of fractured basement reservoirs will need to deviate from the conventional attribute applications for any case study in hand. Some deviations could be in terms of newer technology ideas, which we discuss below.

(a) Use of voice components to aid in difficult-to-pick horizons

The top-basement horizon is usually an unconformity and may not provide a simple single-polarity reflector that can be auto-picked. Rugose basement tops will give rise to a change in reflectivity pattern from the broadband, conformal reflections in the overlying sedimentary section to a lower frequency, relatively unlayered basement, where the primary coherent seismic events are steeply dipping fault planes, diagenetically altered fractures/joints, and (in some cases) igneous dikes. A horizon representing the basement marker is essential to exhibit displays for interpretation not only at that level, but below it. In such cases we propose the innovative application of voice components (Chopra and Marfurt, 2016) that could help with the horizon tracking. Adopting this step will help in generating more accurate attribute displays at the basement level and below it for interpretation and well planning. Coherence run on voice component data may also exhibit higher fault/fracture detail (Figure 1). Not only for this purpose, but such a voice component application can also help track difficult-to-pick horizons which could be used for constraining the impedance inversion process better. Figure 2 shows how the horizons difficult to pick on seismic data (Figure 2a) were picked on the voice components are overlaid on the same seismic section (Figure 2b).
Figure 1: Time slices at t=1322 ms through coherence volumes generated on (a) input seismic data, (b) input data after spectral enhancement, and voice components at (c) 75 Hz, and (d) 85 Hz. Notice the crisp definition of the lineaments seen on the voice component coherence. (Chopra and Marfurt, 2016)

(b) Employing new coherence and curvature attribute techniques for determination of faults and fractures

Most interpretation workstation software packages offer the application of coherence based on a semblance algorithm. We propose the use of more advanced algorithms such as the energy ratio coherence as well as multispectral coherence (Chopra and Marfurt, 2019). Multispectral coherence is a newer coherence algorithm that utilizes the individual voice components within the spectral bandwidth of the input seismic data, and its application on 3D seismic data volume usually exhibits the accrued advantages (Figure 3).
Curvature, acoustic impedance, and coherence are currently the most effective attributes used to predict fractures in the post-stack world. Rather than map the intensity of the strongest attribute lineaments, a better strategy is the application of these attributes in specific directions. It has been found that if the azimuthal direction is set to the inline, then the curvature computation would ignore
the crossline directions, and this would reduce the acquisition noise. Euler curvature (Chopra and Marfurt, 2014) is determined from the most-positive and most-negative curvature magnitudes as well as their strikes in different azimuthal directions. Figure 4 shows a corendered Euler curvature image exhibiting detail for the different fault sets.

![Figure 3: Equivalent stratal slices above a marker at roughly t=1400 ms through (a) broadband coherence, and (b) multispectral coherence volumes. Notice, the improved definition of faults (indicated with yellow, cyan, and green arrows), and the paleo channels (indicated with magenta arrows) on the multispectral coherence display. (Chopra and Marfurt, 2019)](image)

In those cases where the basement markers are trackable and faults exhibit little vertical offset, broadband coherence fails to image discontinuities. In the Anadarko Basin, Oklahoma, US, Patel et al. (2021) have found that small offset basement faults which may extend into the shallower sedimentary formations, and may pass unmapped in most instances, can be illuminated with curvature and aberrancy attributes. In many instances, at depths of basements, due to loss of frequency and hence resolution, faults whose offsets fall below seismic resolution may appear as flexures (Patel and Marfurt, 2019). This is especially true for areas where the basement faults were reactivated one or more times.
Figure 4: (a) Co-rendering three images of long-wavelength Euler-curvature attribute with strikes of ±90°, -30°, and +30° together using a modern 3D viewer and thus generating a composite display amenable to extracting more detailed interaction between three hypothesized fault sets. (b) Equivalent coherence attribute display for comparison. More precise lineaments are seen on the co-rendered Euler curvature display. (Chopra and Marfurt, 2016)

(c) Enhancing fault/fracture interpretation with likelihood attribute

Once fault or large fracture images are created, they can be used for extracting fault segments first, which can then be merged into fault surfaces using image enhancements methods such as ant tracking. Other ways of automatically enhancing fault surface interpretation have been developed, and commercial software packages are also keeping pace with such developments. One such development is the fault likelihood attribute (Hale, 2013; Machado et al., 2016; Chopra and Marfurt, 2017). An examination of the results after this step usually exhibits the crisp fault likelihood lineaments coinciding with the faults on the seismic data. Alternatively, the likelihood images can be filtered in the inline and crossline directions and the two could be co-rendered as well. Figure 5 shows the co-rendered the seismic and fault likelihood attribute image.
Figure 5: Segment of a section from the seismic data volume co-rendered with fault likelihood attribute. (Chopra and Marfurt, 2021)

(d) Aberrancy attribute

Aberrancy is the 2\textsuperscript{nd} lateral derivative of the reflector dip vector, or alternatively, the 1\textsuperscript{st} lateral derivative of the structural curvature tensor. For this reason, aberrancy (often called "flexure") better delineates the fault trace and is useful in both interactive and voxel-based machine learning interpretation (Verma and Bhattacharya, 2019).

Figure 6a shows a segment of an inline seismic section from a 3D seismic volume. The equivalent stratal slice displays along the basement top marker seen in Figure 6a from the curvature, aberrancy and fault likelihood attribute volumes are shown in Figure 6b to h. Notice how more lineament detail is seen on short-wavelength curvature attributes, both most-positive and most-negative. The aberrancy attribute volumes, as well as the fault likelihood attribute show even better definition of lineaments as indicated with the help of coloured arrows.
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Figure 6: (a) Inline section through a 3D seismic amplitude volume acquired in the Taranaki Basin, New Zealand. Equivalent stratal slices at the basement marker through (b) most-positive curvature (long-wavelength), (c) most-positive curvature (short-wavelength), (d) most-negative curvature (long-wavelength), (e) most-negative curvature (short-wavelength), (f) aberrancy total magnitude (long-wavelength), (g) aberrancy total magnitude (short-wavelength), and (h) fault likelihood attribute volumes. More lineament detail is seen on short-wavelength most-positive and most-negative curvature images, whereas the aberrancy attribute volumes, as well as the fault likelihood attribute show even better definition of lineaments as indicated with the help of coloured arrows. (Data courtesy of New Zealand Petroleum and Minerals)

(e) Accurate low-frequency model generation for effective impedance inversion and brittleness determination

An accurate impedance inversion is mandatory for carrying out quantitative interpretation of elastics parameters in the zone of interest. In the context at hand, not only the P- and S-impedance at the basement level and below, but the further computation of attributes therefrom needs to be determined accurately. Besides adequate conditioning of the input seismic data, a reliable velocity model which honours well data and captures spatial variation without introducing any artifacts associated with interpolation/extrapolation is required. The usual methods used for velocity model building could produce artifacts in the form of artificial tongues of sharp impedance changes that may not be geologic, and thus should be used with caution. We suggest the approach for velocity-model building as discussed in Roy and Chopra (2015) that utilizes both the well log data and seismic data for building low-frequency model. In this workflow, first a velocity field is generated using a single well and then the target log is modeled as its linear combination with seismic driven velocity and other attributes. By doing so, we build an integrated velocity model that honours well-log data.
as well as spatial variation of seismic velocity, which will be especially useful for brittleness computation.

(f) Advanced attributes for determination of brittleness

Hermana et al. (2015) have demonstrated the delineation of fracture zones based on elastic properties by way of average brittleness estimation. The average brittleness determination is done with computation of brittleness index defined in terms of normalized Young’s modulus and Poisson’s ratio using the following equation given by Rickman et al. (2008).

\[ BI = 0.5 \left\{ \frac{E - E_{\text{min}}}{E_{\text{max}} - E_{\text{min}}} + \frac{\nu - \nu_{\text{max}}}{\nu_{\text{min}} - \nu_{\text{max}}} \right\} \]

where \( E \) is the Young’s modulus and \( \nu \) is the Poisson’s ratio. \( E_{\text{min}}, E_{\text{max}} \) and \( \nu_{\text{min}}, \nu_{\text{max}} \) are the minimum and maximum values of Young’s modulus and Poisson’s ratio, respectively.

Such a measure or a combination of high Young’s modulus and low Poisson’s ratio as a measure of brittleness may not be true for all basement levels, as they could exhibit different characteristics based on their mineralogy. We propose the application of two new attributes that make use of strain energy density and fracture toughness, the two basic properties sought for determination of brittleness. While the former controls fracture initiation, the propagation of fractures is governed by the latter (Sharma et al., 2020). Core data, well log curves, along with mud logs can be used to authenticate the proposed attributes. Finally, computation of the new attributes can be implemented on seismic data to obtain encouraging results. More details can be picked up from the cited reference.

(g) Merging discontinuity information using some machine learning techniques

The manual interpretation of discontinuity attributes can be a laborious task, and therefore underscores the need for employing computer-assisted tools for the purpose. The drawbacks in following such a traditional approach are that faults, and large fractures are seen but the immersed in noise or other artifacts. Alternatively, many of the main discontinuities are seen but the small ones are not detected. The generation of fault-likelihood mentioned above is only one step in the direction of automated computation. The application of machine learning tools to the different generated discontinuity attributes such as dip-azimuth, semblance, variance, Sobel-filter, edge-detection, and energy ratio coherence volumes can help uncover fault and large fracture detail in the data.

For starters, the use of unsupervised (principal component analysis, independent component analysis, self-organizing mapping) machine learning tools for fault classification could be the way to go.
(h) Limitations to the workflows

After the elaborate description of the different attributes and their applications described above, it may be mentioned that a complete characterization of the fractured basement reservoirs will still require answers to the questions that have been listed under the earlier heading ‘Characterization of basement reservoirs’. If the information on the type of basement rocks is known, the tectonics in the area under investigation is understood, and the quality of the seismic data is reasonably good (as seen in Figure 6a), then the above attribute workflows could be attempted for more accurate interpretation of the fractured basement reservoirs. As responsible geophysicists, we are expected to understand the input parameters to any given interpretation problem, and then attempt the characterization exercise. Mindless interpretation of any sort, coupled with problems of missing input data and cutting corners for making up for it, is only going to spoil the broth, and lead to wasteful expenditures. There are also geologic pitfalls. An interpreter focussed on finding steeply dipping basement faults to a basement reservoir may misinterpret steeply dipping igneous dikes to be a potential target (Chopra et al., 2018b).

Conclusions

The suggested applications characterization of basement reservoirs are the voice components as an aid in horizon tracking and generation of coherence attribute, use of multispectral coherence, Euler curvature, or short-wavelength curvature, fault likelihood, and making use of a superior workflow for low-frequency velocity modeling for more accurate impedance inversion and finally the application of two new attributes for brittleness determination. We are confident that such applications are promising and should be adopted for meeting basement reservoir characterization objectives, subject to the limitations mentioned above.

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Satinder Chopra has 37 years of experience as a geophysicist specializing in processing, reprocessing, special processing, and interactive interpretation of seismic data. He has rich experience in processing various types of data such as vertical seismic profiling, well-log data, seismic data, etc., as well as excellent communication skills, as evidenced by the many presentations and talks delivered and books, reports, and papers he has written. He has been the 2010–2011 CSEG Distinguished Lecturer, the 2011–2012 AAPG/SEG Distinguished Lecturer, and the 2014–2015 EAGE e-Distinguished Lecturer. He has published eight books and more than 500 papers and abstracts and likes to make presentations at any beckoning opportunity. His work and presentations have won several awards, the most notable ones being the 2021 Roy O. Lindseth CSEG Medal Award (2021), AAPG Distinguished Service Award (2019), EAGE Honorary Membership (2017), CSEG Honorary Membership (2014) and Meritorious Service (2005) Awards, 2014 APEGA Frank Spragins Award, the 2010 AAPG George Matson Award, and the 2013 AAPG Jules Braunstein Award, SEG Best Poster Awards (2007, 2014), CSEG Best Luncheon Talk Award (2007), and several others. His research interests focus on techniques that are aimed at the characterization of reservoirs. He is a member of SEG, CSEG, CSPG, EAGE, AAPG, and the Association of Professional Engineers and Geoscientists of Alberta (APEGA).
Kurt J. Marfurt joined The University of Oklahoma in 2007 where he serves as the Research Professor of Geophysics within the ConocoPhillips School of Geology and Geophysics. Marfurt’s primary research interest is in the development and calibration of new seismic attributes to aid in seismic processing, seismic interpretation, and reservoir characterization. Recent work has focused on applying coherence, spectral decomposition, structure-oriented filtering, and volumetric curvature to mapping fractures and karst with a particular focus on resource plays. Marfurt earned a Ph.D. in applied geophysics at Columbia University’s Henry Krumb School of Mines in New York in 1978 where he also taught as an Assistant Professor for four years. He worked 18 years in a wide range of research projects at Amoco’s Tulsa Research Center after which he joined the University of Houston for 8 years as a Professor of Geophysics and the Director of the Allied Geophysics Lab. He has received the SEG best paper (for coherence), SEG best presentation (for seismic modeling), as a coauthor with Satinder Chopra best SEG poster (one on curvature, one on principal component analysis) and best AAPG technical presentation, and as a coauthor with Roderick Perez Altimar, SEG/AAPG Interpretation best paper (on brittleness) awards. Marfurt also served as the EAGE/SEG Distinguished Short Course Instructor for 2006 (on seismic attributes). In addition to teaching and research duties at OU, Marfurt leads short courses on attributes for the SEG and AAPG, and currently serves as Editor in Chief of the AAPG/SEG Journal Interpretation.

Ritesh Kumar Sharma received a master’s (2007) degree in applied geophysics from the Indian Institute of Technology, Roorkee, India, and an M.S. (2011) in geophysics from the University of Calgary. He works as an advanced reservoir geoscientist at Arcis Seismic Solutions, TGS, Calgary. He is involved in deterministic inversions of poststack, prestack, and multicomponent data, in addition to amplitude variation with offset analysis, thin-bed reflectivity inversion, and rock-physics studies. Before joining the company in 2011, he served as a geophysicist at Hindustan Zinc Limited, Udaipur, India. He has won the best poster award for his presentation titled “Determination of elastic constants using extended elastic impedance” at the 2012 GeoConvention held at Calgary. He also received the Jules Braunstein Memorial Award for the best AAPG poster presentation titled “New attribute for determination of lithology and brittleness,” at the 2013 AAPG Annual Convention and Exhibition held in Pittsburgh. He has received the CSEG Honourable Mention for the Best Recorder Paper award in 2013. He is an active member of SEG and CSEG.
Ravi Kant Pathak is a reservoir geophysicist having 32 years of Professional experience from India, Middle East and Malaysia. He acquired his master’s degree in Applied Geophysics from Indian School of Mines Dhanbad, India and Ph. D. degree from Indian Institute of Technology, Kharagpur, West Bengal India. He has wide experience in all gamuts of seismic technology and its application from exploration to reservoir management in diverse geological regimes; clastic, carbonates and deep water. Dr. Ravi has wide experience in time lapse (4D) and multi-component seismic technology. His research interests include advanced seismic application in reservoir characterization, Seismic QI, 4D and multi component seismic and seismic application for unconventional reservoir development. He is an active member of SEG and a Registered Foreign Geologist with Board of Geologists, Malaysia.

Anil Kumar Shrivastava received his M. Sc. in Physics and Ph. D. in Applied Physics from University of Allahabad and joined ONGC in 1983 as Geophysicist. He served in ONGC for 35 years, holding various positions and superannuated as Group General Manager in November 2017. He has acquired vast experience in hydrocarbon exploration and development activities. His areas of interest are reservoir characterization using seismic attributes, stratigraphic inversion and AVO. After superannuation he is providing his services in hydrocarbon exploration and management as a consultant. He has contributed a number of technical papers in national and international conferences and journals. He is a member of SEG, USA and SPG, India.

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