

Conduits Characterization for Fractured Reservoirs Using Sub-Seismic Faults Convergence Intensities Mapping*

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Search and Discovery Article #41129 (2013)

Posted June 17, 2013

*Adapted from extended abstract prepared in conjunction with poster presentation at AAPG Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013

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Abstract

The main objective of this study is to characterize the structurally related conduits in fractured reservoirs using 3D seismic data. These conduits are identified and mapped by a three dimensional adaptive, multi-directional, multi-component logical operator seismic attribute. This operator is designed using total geologic concept, it is based on outlining the convergence of the sub-seismic faults as the main components of the damage zone that is distributed around the slip direction. This operator calculates gradients of the seismic abrupt change in amplitude values along 72 detection directions. It searches for the pattern where two sub-seismic faults angularly meet at a point. At these points the fluid and gas flow through the fracture network is most favorably integrated and focused. It is a decision-supported operator. It recognizes the presence or absence of successive linear points sets on the detected sub-seismic faults and those that meet angularly at a convergence point. Mapping structurally related conduits will lower exploration and development cost. It will help avoid the irreparable loss of recovery factor and the abnormal response in secondary recovery. It will help us drill only necessary in-fill wells and conduct more accurate assessment of economic prospects.

In this study examples are demonstrated for structurally related conduits characterization. The produced conduits map resolution depends on the seismic data grid size and velocity sampling interval. It shows different distribution and texture from one lithology to another. The conduits map will help understand the behavior and geometry of the faults damage zones, as will their distribution and impact on fluid flow and the possibilities for compartments existence. Continuous and discontinuous connectivity of the conduits network can be identified. This technique cannot detect primary sedimentary structures and random noises. It provides an output related to the variation of dual porosity and permeability, and it can be considered a supporting input for more realistic reservoir simulation. The difference in conduits distribution in intensities, different texture coarseness, equally spaced, or specific trends are adding remarkable knowledge for characterizing stress distribution, fluid flow directions and intensities. It is a good tool for reservoir top-seal fracturing evaluation, and sweet spots in fractured reservoirs delineation.

Introduction

As hydrocarbon reserves become depleted and the oil industry has become more competitive, the importance of cutting costs by minimizing well numbers, optimizing production and predicting the occurrence of subtle traps have shown the need for information on the means by which faults and fractures affect fluid flow. It is important to determine the effect of natural fractures in our reservoirs as early as possible so that our evaluations and planning can be done correctly from the beginning. Understanding the effects of faults and fractures on fluid flow behavior and distribution within hydrocarbon provinces has therefore become a priority. To model fluid flow in hydrocarbon reservoirs, it is essential to gain a detailed insight into the properties of faults, fractures and related conduits. Fault zones are surrounded by rock volumes and can as such be described as fault envelopes with a highly complex geometries, with strain being accommodated not just on a single fault plane but within a complex array of faults. This three-dimensional fractured rock body is best described as fault damage zones (Kim et al., 2004). The lack of data on the accurate characterization of fault zones and fault properties has resulted in the adoption of a number of assumptions about faults which are not always applicable and which have resulted in the exclusion of a number of important factors from risk evaluations. In this study, the three dimensional seismic data is used for fault-zones-related conduits mapping. The importance of characterizing damage zones arises from the pivotal role that fractures play in governing fluid flow through fractured, low-permeability reservoirs (Johri et al., 2011)

The sub-seismic faults convergence location points and their densities can provide considerable information about fault damage zones delineation and their associated conduits for fluid flow. These points of sub-seismic faults convergence are suitable indicators for structurally related conduits mapping. The local flow conditions along fracture intersection can strongly influence solute dispersion and channeled transport (Park et al., 2003). Fracture intersections can integrate and focus the flow of liquid within a fracture network (Glass et al., 2002; LaViolette et al., 2003). The presence of local flow cells in fracture networks, at fracture intersections, can result in an overall retardation of all particles and an additional strong tailing in the residence time distribution caused by the relative time delays of orders of magnitude for some particles. The connectivity of fracture networks is generally measured in terms of fracture intersections, because circulating flow in local flow cells arises from the interplay between distributed hydraulic potential along fracture intersections and no-flow fracture edges. Flow and transport in 3-D fracture intersections may contribute to the distribution of solute (Park et al., 2003). In this research, we demonstrate distribution and trends of conduits intensities to characterize stress distribution and to support the identification of probable fluid-flow intensities, continuity, and directions.

Problem Statement

The main problem is that faulted reservoirs are complex to drill, they are difficult to produce, and the behavior of fluid flow is hard to predict. For that reason, an efficient means of identifying and characterizing the intensities and distribution of the dual porosity and permeability in naturally fractured reservoirs is greatly needed.

Method

The technique in this study relies only on seismic data. Traditionally, faults have been divided into seismically resolvable faults and sub-seismic faults. Large faults, where a change in time, dip, and amplitude are expected, can be easily observed visually (Badley, 1985). Large

faults cannot give enough information about their damage zones behavior, distribution and geometry. The fault damage zone is developed by smaller faults and fractures branching during propagation. The complex array of the damage zone is small faults surrounding the fault core. In this study, the number of small-scale faults convergence at a point can be a good estimate for the damage zone. The main interest is in the sub-seismic faults where fault throw decreases and observable time changes disappear. This is followed by dip changes, leaving only amplitude anomalies present where throws are at their smallest (Badley, 1985; Townsend et al., 1998).

A three dimensional adaptive, multi-directional, multi-component detector is used to detect sub-seismic faults and their convergence points intensities, for fault damage zone conduits mapping using a three dimensional seismic data volume (El Fouly, 2012, 2013a, 2013b). This detector confirms the presence of a point on the sub-seismic fault from amplitude abrupt changes, recognizes linear sets of the detected points, and identifies at least two linear arrangements that converge at a point. It is composed of 9 symmetrical planes ([Figure 1a](#)) sharing the same center of the cube. Each of the symmetrical planes has eight detection directions ([Figure 1b](#)) and each of the detection direction is divided into two detection segments with a total of 114 detection segments. Each of the detection segments is controlled by an amplitude-abrupt-change-linear-arrangement detector.

Detection segments are locations where all points that show amplitude abrupt changes are detected, recognition of linear patterns of the detected points, and decisions for convergence point presence or absence with existence of at least two recognized linear patterns are taking place. Each detection segment is composed of a seven one dimensional amplitude-abrupt-change detectors perpendicular to the main direction of the detection segment. The detection is confirmed with true or false at the center of the amplitude-abrupt-change detector. The detection segment can provide controlled adaptive lengths for the recognized linear arrangements. It can recognize 3, 5 and 7 units of fixed lengths and ≥ 3 , ≥ 5 and ≥ 7 units with open upper range lengths.

The point of convergence is recognized when two linear arrangements of any 16 detection segments on any of 9 symmetrical planes are confirmed true. Two linear arrangements should have an angular relationship and meet at the center of any of the 9 symmetrical planes for the convergence point to be recognized. The convergence point is presenting a joint relationship between a couple of small faults propagated around the main fault within its damage zone, and it is considered a favorable location for focal continuous fluid flow. Three dimensional moving counter sums the number of convergence points at its center. The size of the moving counter is specified according to the structural nature of the area. The output volume is the intensities of the produced convergence points.

Examples

Cross section examples of the three dimensional output volumes produced by the three dimensional adaptive, multi-directional, multi-component logical operator (El Fouly, 2012, 2013a, 2013b), are used in this sections. These examples are for fault damage zone conduits maps for the detect intensities of the sub-seismic faults and their convergence points. Three dimensional seismic data volume is the only input used to exhibit frequent cases for damage zones for this logical operator. A conduit is identified in this study as a closely arranged cluster of high to moderate intensities of isolated number of sub-seismic faults convergence points. These conduits are directly related to dual porosity and their extension and connectivity to dual permeability. They can be characterized by their volume, spatial distribution, changes in intensities, connectivity, coarseness, and trends, for selected sub-seismic faults lengths.

[Figure 2](#), [3](#), and [4](#) show the original amplitude seismic in-lines, the detected points of the sub-seismic faults convergence, and the calculated intensities of these points. In [Figure 2 a3](#), we can observe the variation in conduits intensities and distribution of fractures within each rock unit. It demonstrates high intensity in a highly fractured rock unit around 3850 ms to moderately fractured around 4100 ms and absent, as seen in the black colored parts of the section. This technique can help map conduits of all types of damage zones. In [Figure 2 b3](#), an example of a wall fault damage zone, the convergence of the small scale faults associated with the main faults are restricted around them and in their cores. [Figure 4 a3](#) shows an example of fault damage zone with less intensity and more volume. [Figure 4 b3](#) displays continuous and discontinuous connectivity of the conduits network. The locations for conduit network connectivity and intensity can be visualized and assessed.

The spatial relations of conduits with each other can provide information related to displacements within the damaged zones and the country rocks identify potential compartments and help assess cap rock integrity. In cases where faults do not have a considerable surrounding damage zone, they will show very low to no intensity. The conduit trends provide the faults dynamic directions, because they are usually arranged along and around the slip direction. [Figure 3 a3](#) displays the behavior of the fault damage zones in a sedimentary section. The high intensity and a wide area of the fault damage zone are observed between 3200 ms and 4900 ms, with less damages along the main fault trend, above 3000 ms. The displacements are clear and can be measured for the fault zones in different parts and their effect on the fractured lithology around 3400 ms. Primary sedimentary structures are not detected in [Figure 3 b3](#), but they are observed clearly in the seismic amplitude time slice of [Figure 3 b1](#). As a matter of fact, sedimentary rock that does not have reasonable amount of fractures is considered invisible to this technique. It is detecting damage zones around and within the main fault zones ([Figure 3 b3](#)).

The currently used logical operator extracts conduits intensities and demonstrates their behavior for different ranges of small scale faults and their relation with the main fault by detecting the points where small scale faults branch during propagation. The sub-seismic faults length ranges of ≥ 28 ms ([Figure 5 c](#)) and the 6 ms ([Figure 5 b](#)) options are used. The convergence points intensities in [Figure 5 c](#) show clear variations in intensities along the fault cores and the changes in intensities reflect the variation of dual porosity and permeability. This range of specific lengths of small faults is restricted and characterizes the country rocks of this area and is absent in the fault cores ([Figure 5 b](#)). The provided examples ([Figure 5 b, c](#)) show that small scale fault lengths increases as the fault core is approached. [Figure 6. b, c, d](#) show sub-seismic faults convergence maps for ≥ 12 ms, ≥ 20 ms, and ≥ 28 ms length ranges. The seismic x-line is a sand and shale stratigraphic section example ([Figure 6 a](#)). The sub-seismic faults convergence intensities and trends show variations within the same rock units for each of the three ranges ([Figure 6](#)). Intensity change and distribution of the conduits for natural fractures vary for each rock unit, and some of them show minimal to no conduits. The presence and absence of connectivity between conduits is a good indicator for the dual permeability pathways behavior.

Conclusion

This study helps with the introduction of key aspects that characterize structurally related conduits in fractured reservoirs. The three dimensional adaptive, multi-directional, multi-component logical operator is employed to map the sub-seismic faults convergence densities. The output accuracy of the seismic data depends on the survey resolution. With this application, continuous and discontinuous connectivity of the conduits network and fluid flow can be located. The structurally related conduits map can be considered a supporting input for more

realistic reservoir simulation. It cannot detect primary sedimentary structures and random noises. It helps provide faults' dynamic directions, allows the measurements of the damage zones dimensions, and supports good understanding for the behavior and geometry of the damage zones. With this technique, the possibilities for the existence of fracture-based compartments and top-seal fracturing can be evaluated. The output conduits map is directly related to dual porosity and permeability. It helps delineate sweet spots in fractured reservoirs. Optimum well locations and well performance with time under a variety of potential completion and development scenarios can be predicted.

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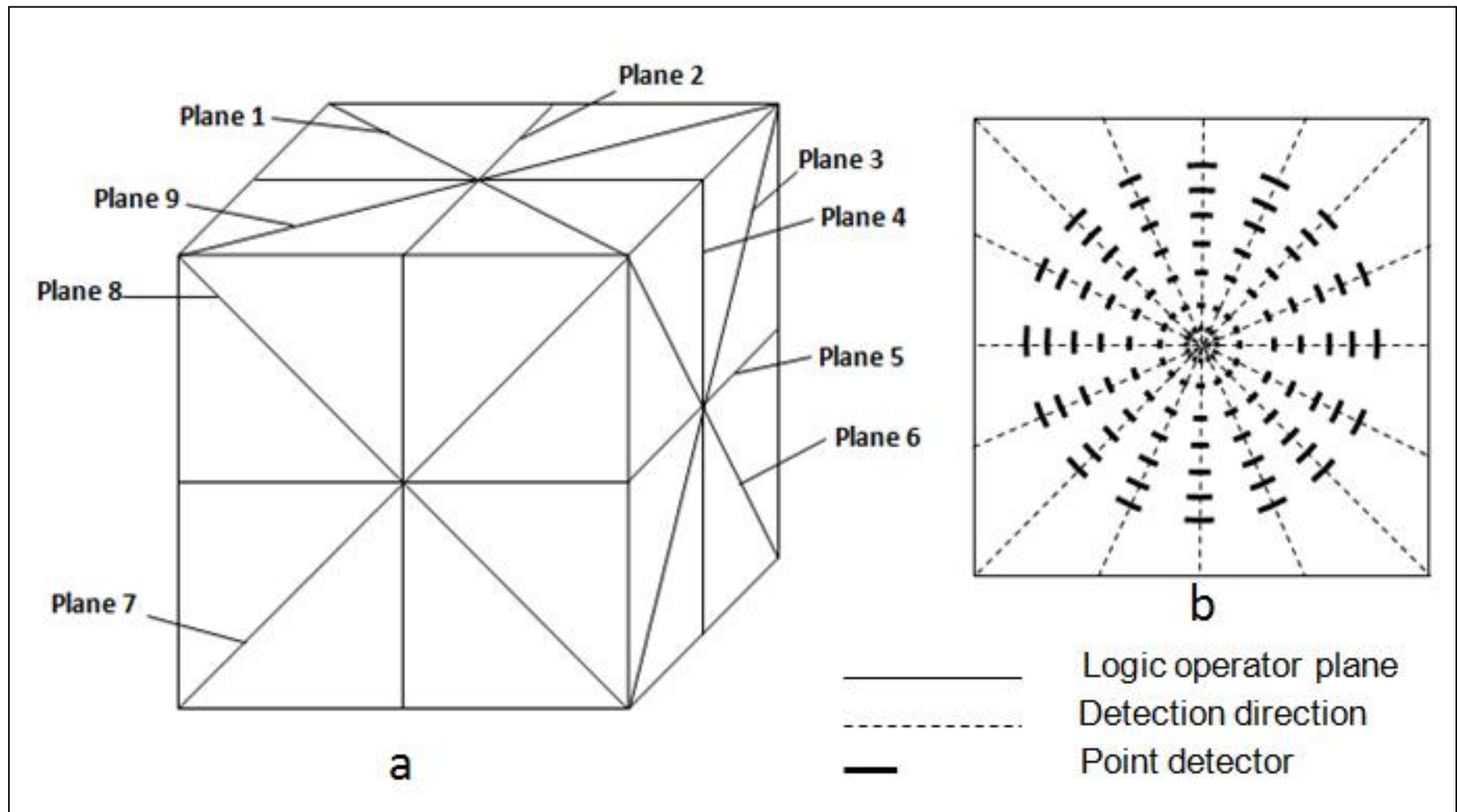


Figure 1. a. Location of the nine symmetrical planes composing the three dimensional adaptive, multi-directional, multi-component logical operator. b. One symmetrical plane of the logical operator with 16 detection segments along eight detection directions and the associated point detectors.

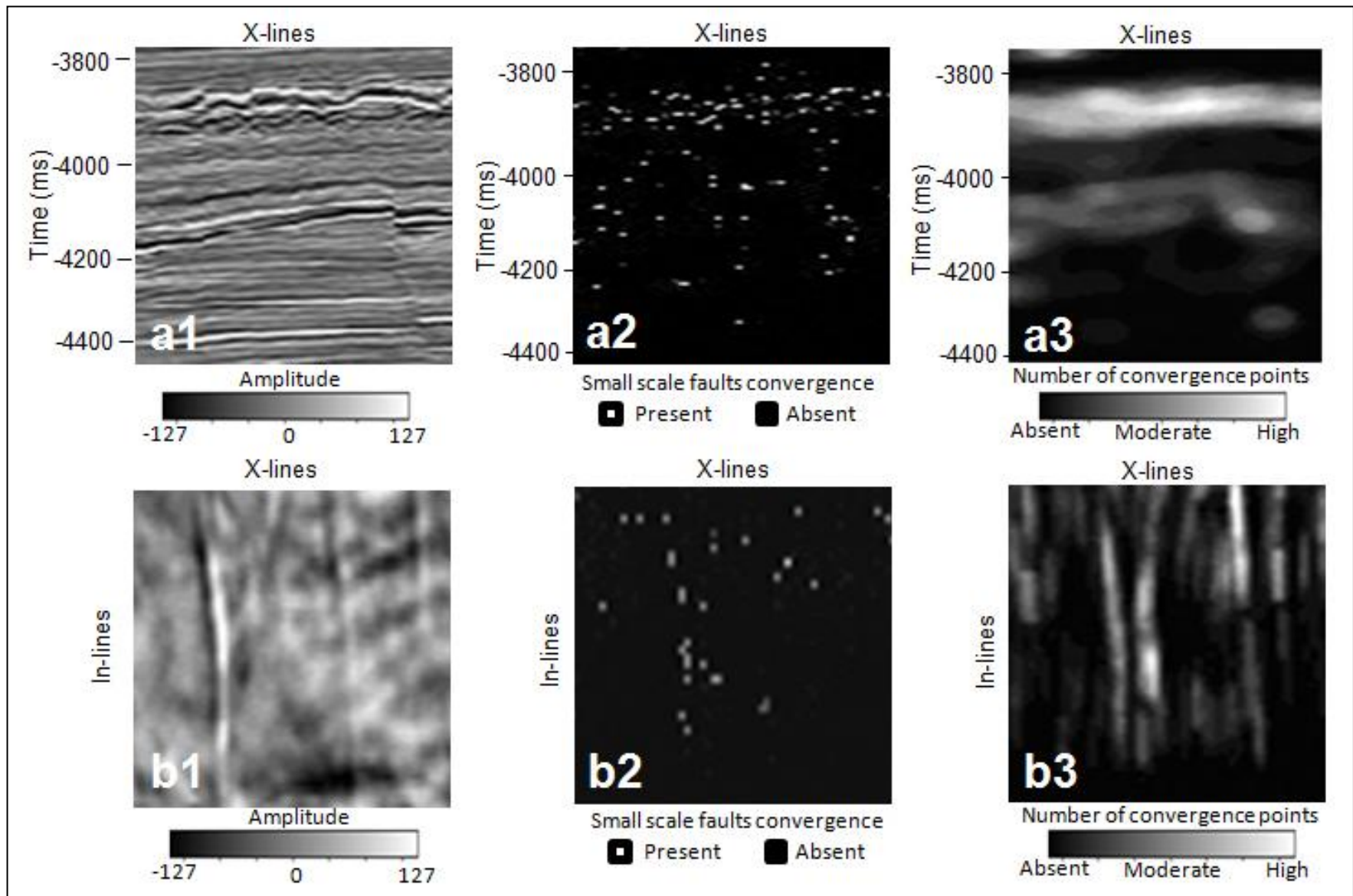


Figure 2. a1 and b1 are amplitude seismic in-lines. a2 and b2 are the detected points for the sub-seismic faults convergence. a3 shows the variation of conduits intensities and distribution of fractures within each lithologic unit. It displays high intensity in the fractured rock units around 3850 ms to moderately fractured around 4100 ms. b3 shows a wall damage zone where the convergence of the small scale faults associated along the main faults are restricted around them and in their core.

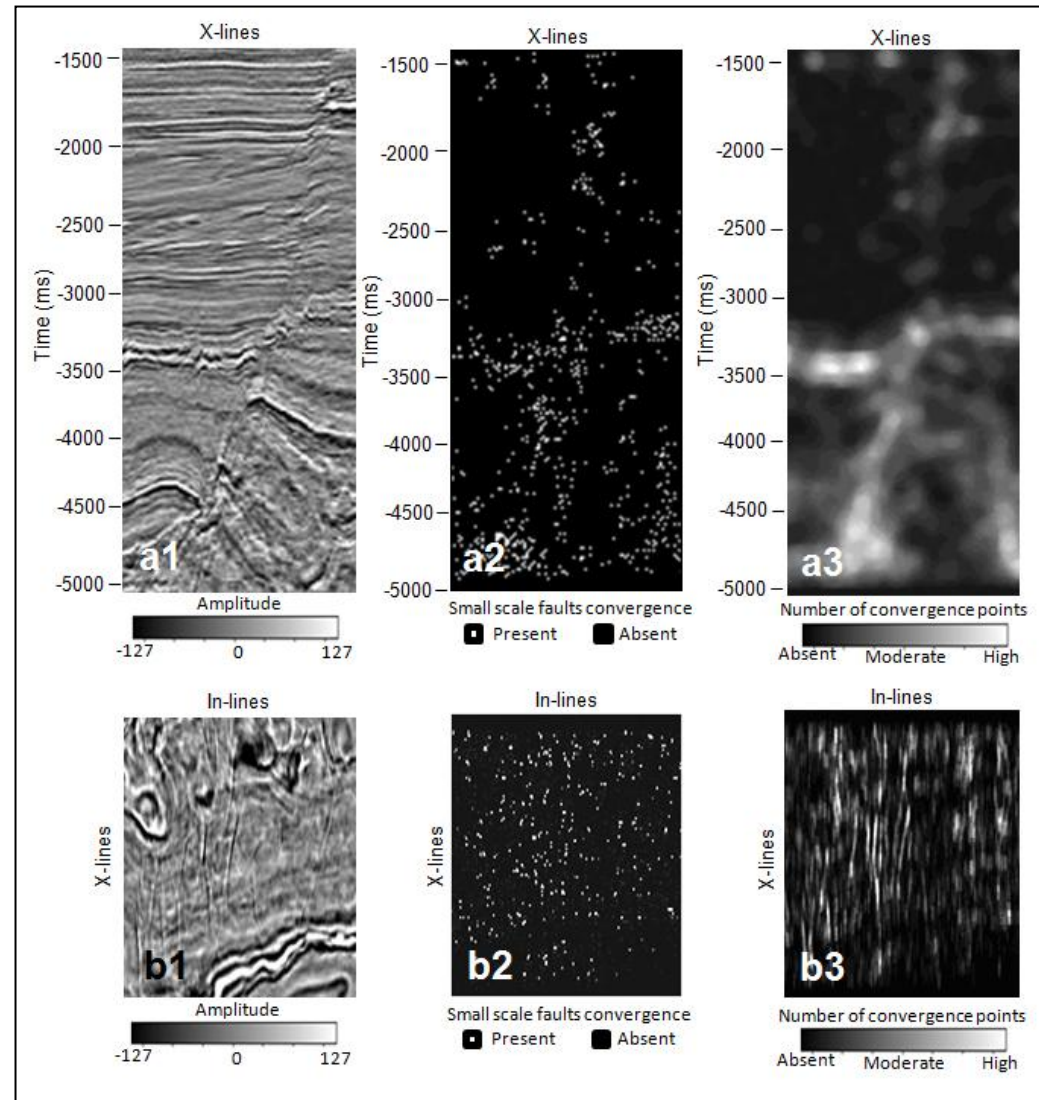


Figure 3. a1 and b1 are amplitude seismic in-lines. a2 and b2 are the detected points of the sub-seismic faults convergence. a3 displays the behavior of the fault damage zone along a sedimentary section. We can observe the high intensity and wider area of the fault damage zone between 3200 ms and 4900 ms and less damage is seen along the main fault, above 3000 ms. The displacements can be observed and measured for the fault zones in different parts and its effect on the fracture lithology around 3400 ms. Figure 3 b3 demonstrates that this technique did not detect primary sedimentary structures that is observed in time slice of Figure 3 b1. It detects damage zones around and within the main fault zones.

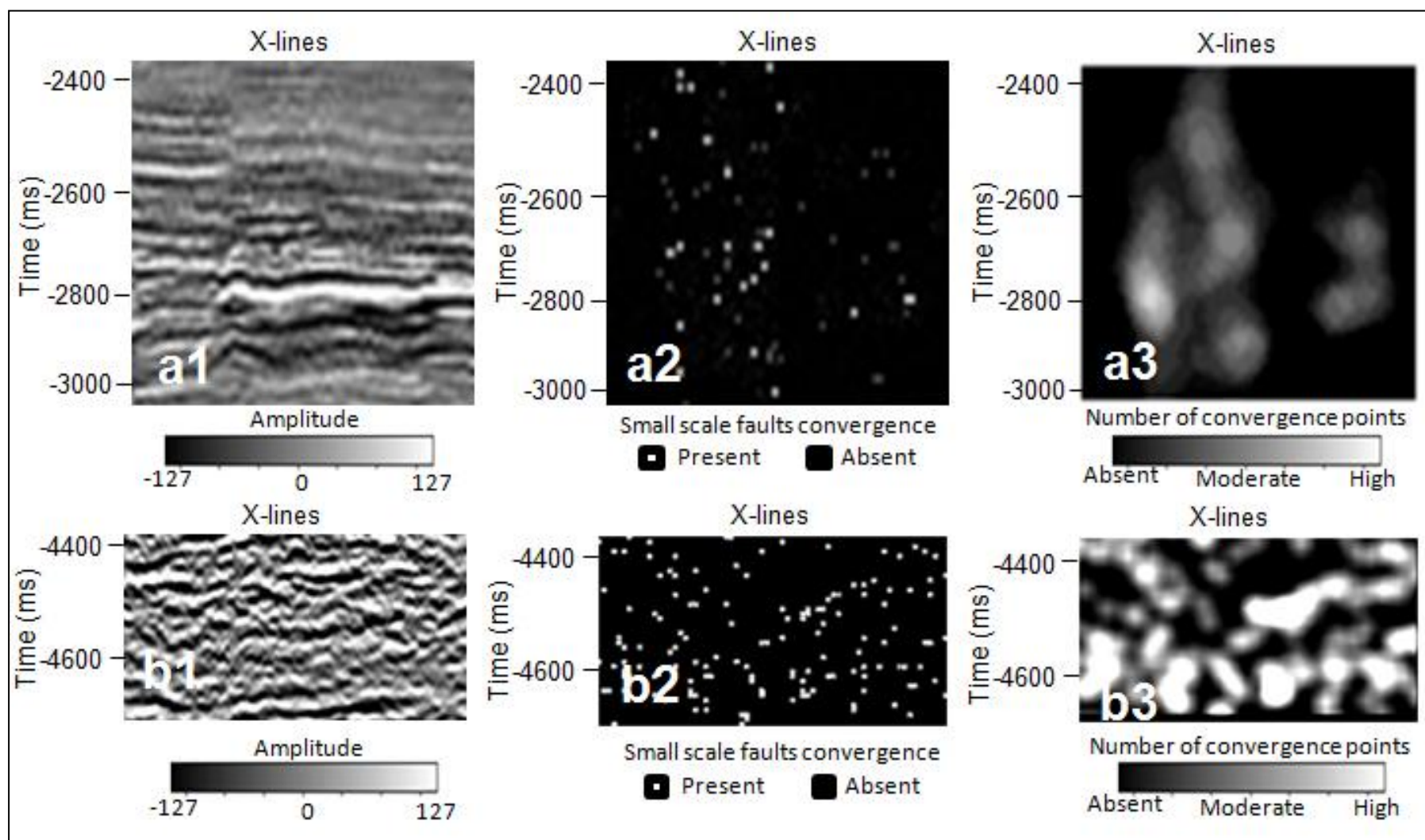
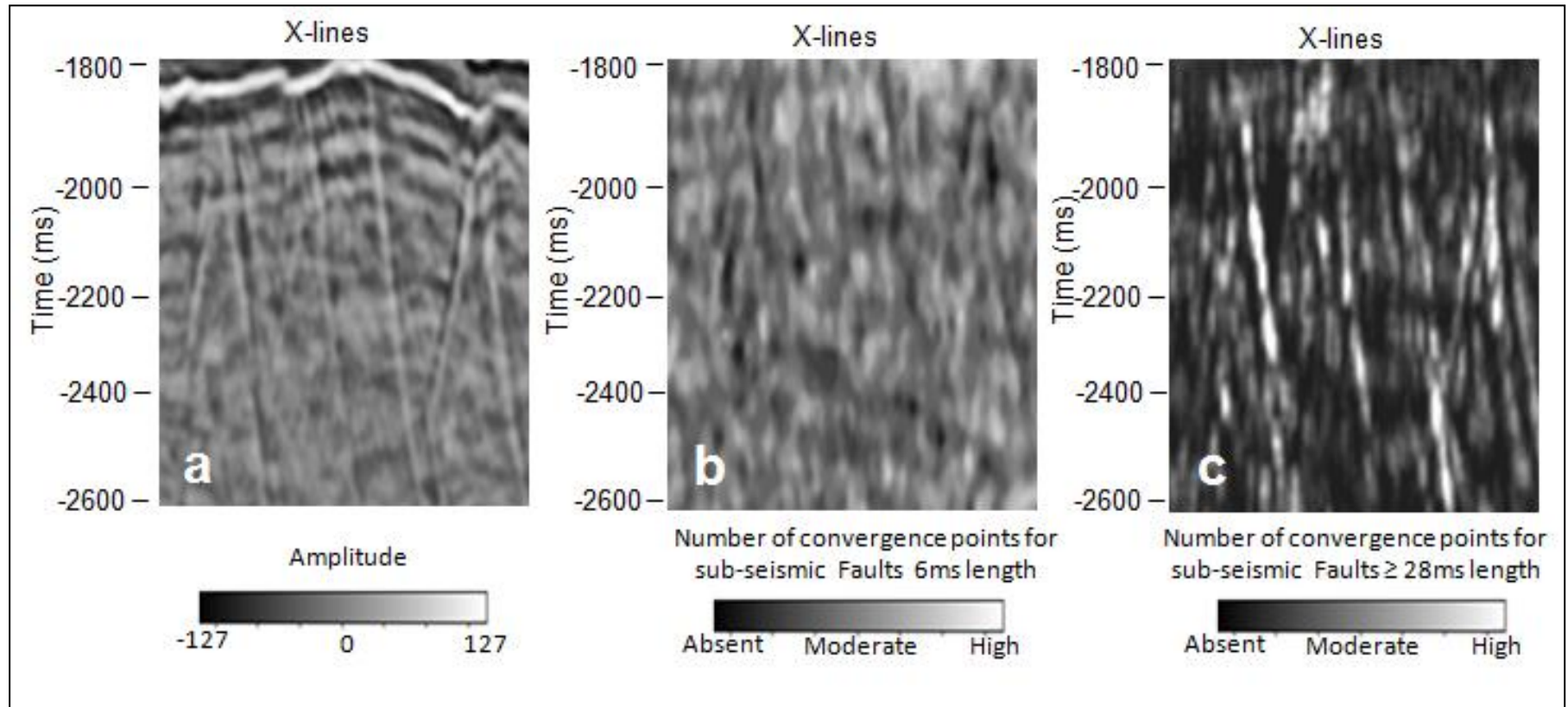


Figure 4. a1 and b1 are amplitude seismic in-lines. a2 and b2 are the detected points of the sub-seismic faults convergence. In Figure 4 a3, the fault damage zone shows less intensity and more area and volume. Figure 4 b3 displays an example of continuous and discontinuous connectivity of the conduits network. Conduits associated with fractured rocks can be assessed.



Figures 5. a shows the original amplitude seismic in-line for a faulted area. b and c are 6ms and ≥ 28 ms sub-seismic faults lengths, respectively. The convergence point intensities in 5c show clear variations in intensities of the converged small scale faults along the fault cores and the changes in intensities to reflect the variation of dual porosity and permeability. The 6 ms sub-seismic fault lengths of small faults are restricted, characterize the country rocks of this area, and are absent in the fault cores.

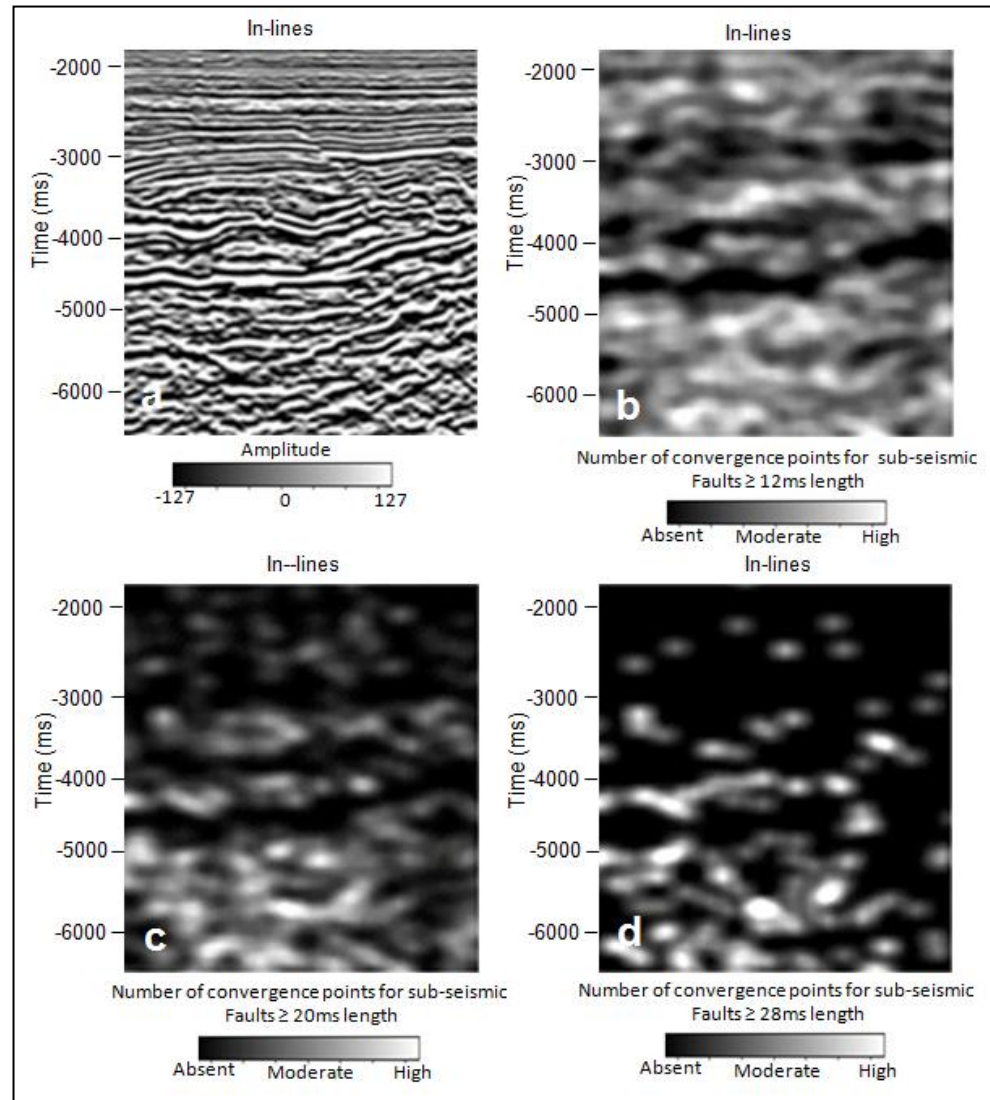


Figure 6. a shows a seismic x-line for a sand and shale stratigraphic section. b,c, and d are sub-seismic faults convergence maps for ≥ 12 ms, ≥ 20 ms, and ≥ 28 ms length ranges, respectively. b shows all densities of sub-seismic faults convergence for ≥ 12 ms length range to detect all possible length ranges. c demonstrates densities of sub-seismic faults convergence for ≥ 20 ms length ranges to detect lengths that are larger than 20 ms and that will include those that are larger than 28 ms as well. d shows densities of sub-seismic faults convergence for ≥ 28 ms length ranges--to detect only lengths greater than 28 ms. Observe that the conduits intensity change and distribution of the natural fractures vary for each rock units and some of them show minimal to no conduits.