Multiscale Seismic Signature of a Small Fault Zone in a Carbonate Reservoir: Relationships Between V_P Imaging, Fault Zone Architecture and Cohesion*

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Abstract

Although fault zones represent a very small volume of the crust, they highly influenced the crust's mechanical and fluid flows properties. The knowledge of their structural, mechanical and hydraulic properties is one of the major issues in the earth science. It is currently observed that the hydraulic and mechanical properties of faults are strongly related to the fault zones architecture (Caine et al., 1996; Lunn et al., 2008; Faulkner and Rutter, 2001; Cappa et al., 2007; Guglielmi et al., 2008; Matonti et al, submitted). Faults are thick corridors (cm to km wide depending on the slip magnitude) with a complex structure that is classically described as composed of three mechanical and hydraulic zones; (1) a single or multiple core zone generally filled with gouge where most of the fault throw is accommodated, (2) a fractured damage zone surrounded by (3) the protolith, also called country rock or host rock (Chester et al., 1993; Caine et al., 1996; Mitchell and Faulkner, 2009).

Here, the seismic (P-waves velocity, V_P) signature of a small fault zone intersecting carbonate reservoir layers with contrasted properties of the Southeastern French sedimentary basin was studied from the micro-scale to the fault zone pluri-meter scale architecture. The studied area is located in a horizontal gallery of the National Underground Research Laboratory (LSBB) at 250-m depth. The gallery is set in porous carbonate layers of lower Cretaceous age. These carbonates are of platform type with grainstone textures (Urgonian facies). The gallery crosses almost perpendicularly the unaltered segment of a small 10-to-20 m thick fault zone. On site, the outcropping gallery wall and three cored boreholes were used to conduct the fault zone studies. We took advantage of one gallery geometry N170 oriented to explore in details the seismic signature of an unaltered volume of about 35-m x 4-m x 26-m across

this fault zone. The main questions that we address are: (1) what is the seismic signature of the contrasted deformation zones that characterize the complex fault zone architecture, and (2) which information can a seismic survey provide on the fault zone strength properties?

Discussion

P-wave velocity measurements were performed with a Pundit apparatus (Pundit EO643) connected to an oscilloscope and to two acoustic sensors set on the rock surface. One sensor is a transmitter that sends an acoustic wave of 54 kHz dominant frequency through the rock that the other sensor, the receiver, captures. The acoustic P-waves arrival time is picked on the first wave arrival using the oscilloscope to visualize the full waveform of both the source and receiver signals. By measuring the length of a straight line connecting the transmitter and the receiver locations, it is possible to estimate the P-waves velocity across the rock. Measurements have been carried out at different scales:

1) at the meter scale on 35 stations set across the fault zone;
2) at the decimeter scale from either sides of joints along the whole fault zone;
3) at the centimeter and micrometer scale on “plug” samples of one inch diameter and 1-2 inches in length.

Results were compared to the fault rock mechanical properties and to a V_P tomography at the reservoir scale that was conducted between the ground surface and the laboratory galleries highlighted some V_P anomalies potentially correlated to the studied fault (Maufroy, 2010).

The rock mass properties characterization was conducted through an adaptation of the Q-value geomechanical method. The Q value describes the rock quality, it is defined according to the fracturation degree and the joint properties (roughness, filling, joint set). Estimations of the compressive strength of the rock (σ_c) were performed in-situ with a Schmidt hammer (on the outcrop and on cores). A measure of σ_c has been achieved every 10-cm along a line intersecting perpendicularly the fault zone. An average σ_c value was established every meter. The microscopic properties were studied by porosity measurements with a helium porosimeter performed on the same samples used for the VP measurements and by observations on thin sections.

Our investigations indicated that P-wave velocities variations across the fault zone are strongly correlated to some key parameters: (1) the intact rock porosity, (2) the fractures density figured with the RQD, (3) the fractures properties (joint filling and joint roughness), and (4) the rock mass compressive strength.

The seismic visibility of the fault zone depends on the contrasts between the porosity and the fracturation density of the sedimentary layers. In porous layers, the fault-induced deformations are mainly accommodated at the micro-scale (grain scale) (Figure 1a). A significant porosity reduction and a modification of the pore types were observed to control the V_P velocities variations towards the fault core with only few macroscopic fractures, the damage zone appears thin leading to a high V_P contrast with the fault core. In the low-porosity layers where deformations are mainly accommodated through brittle fractures, the seismic visibility of the fault is moderate, characterized by a decrease in the V_P value which remains within the magnitude of the V_P variations within the layers outside the fault zone (Figure 1b). Interestingly, the fault seismic signature in the highly fractured layers appears clearly in the frequency domain at three dominant frequencies (2,000, 9,000 and 28,000 Hz), each of which exhibiting different spectral amplitudes for each components of the fault zone. Finally, the seismic signature of a relatively small fault zone included in a layered sedimentary series appears discontinuous, characterized by more or less thick high velocity patches more or less extended within the stratigraphic layers (Figure 1c). This model could be generalized to all sedimentary formations composed of several sedimentary layers with highly contrasted properties (Figure 1d). These variations lead to different mode of deformations, which will have different impacts on the P-wave velocities. Such seismic signature of a fault zone can be expected within layered sedimentary basins where a strong initial contrast between mechanical units is observed.

We also showed that the V_P variations across the fault zone are related to its architecture, and this can help to estimate the fault zone cohesion evolution. Logarithmic correlations were found between V_P and the fault core's cohesion, and the cohesive component of the damage zone. In the fault core, the P-waves propagation depends mainly of the surfaces conditions, like the cohesion, between numerous blocks, whereas in the damage zone the cohesion is mainly influenced by the fracturing degree of the rock mass.

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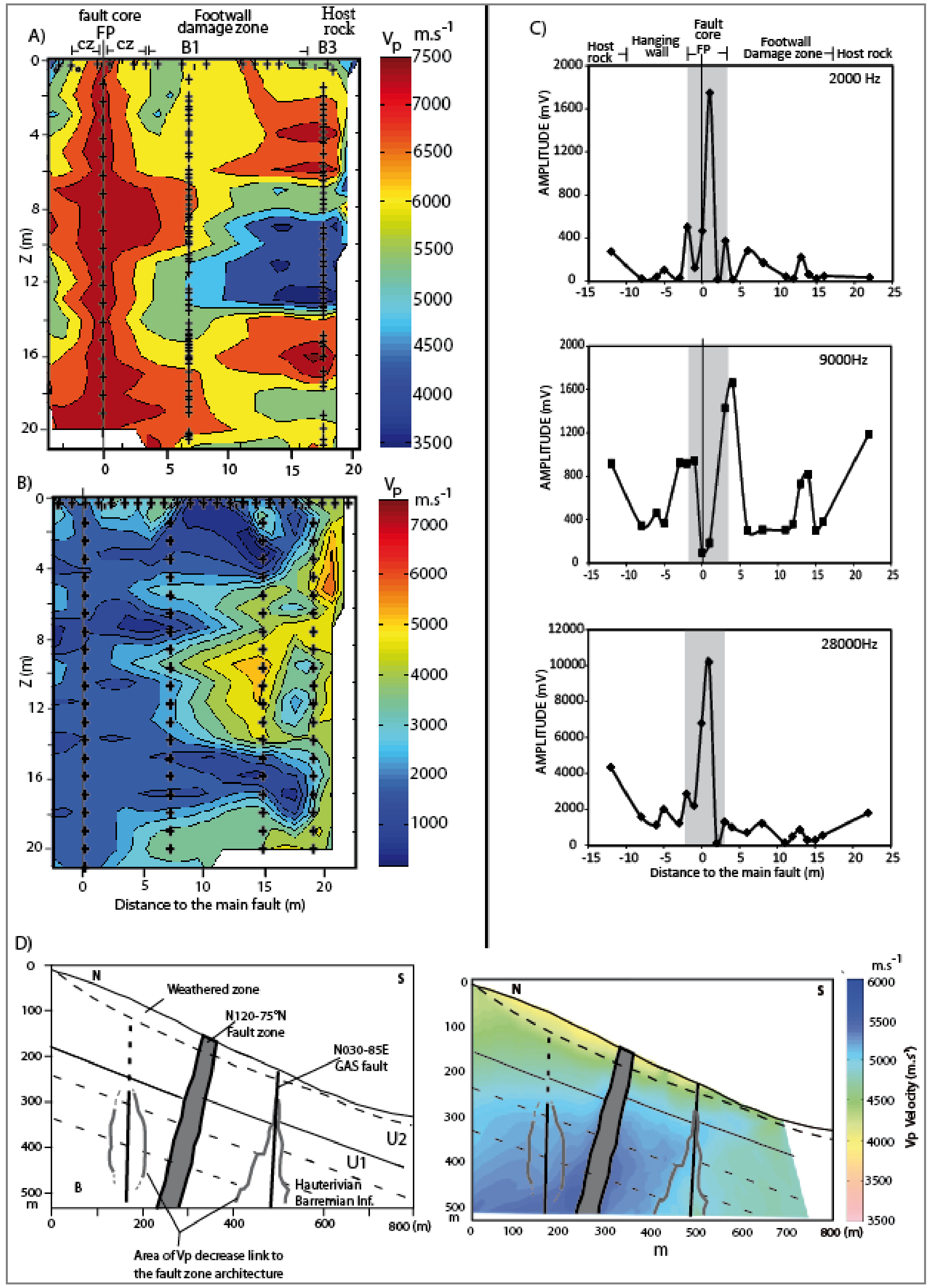

Figure 1. Fault zone seismic signature (A) in the frequency domain, (B) at the matrix scale, (C) at the decameter scale and (D) at the reservoir scale.