FRACTURE CHARACTERIZATION IN THE SAN BERNARDO FOLD BELT, SAN JORGE BASIN, ARGENTINA
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Abstract
The seismic sections of Perales anticline show a coherent seismic anomaly in the frontal limb of the structure at the level of Castillo Formation. The outcrop characterization carried in this formation showed that Castillo Formation is intensely fractured and faulted at the steeper or overturned limbs of the anticlines studied.
From the field study it was suggested that the anomaly could be due to dilatational fractures generated as splay fractures at the ends of the reverse/thrust faults.
Two unsuccessful wells corroborated that Castillo Formation was intensely fractured. Although an important water influx confirmed the hypotheses of an open fracture network, the confined character of the influx might evidence a proportion of closed fractures.
The objective of this paper is to combine the information of the outcrops with subsurface information to elucidate the nature of the anomaly. The analysis of fracture directions in the outcrops and well-bore shows an apparent relationship between fracture orientation and the main structures, such as the reverse faults and the strike slips faults that segmented the anticline.
Finally, with the information available from the outcrops and image loggings it cannot be concluded weather open fractures are the reason of the seismic anomaly. Therefore a more detailed study will be needed.

Introduction
Resolving the nature of the anomaly was considered crucial for the development of Castillo Formation as an oil reservoir at the steeper limbs of Perales anticline.
Relaying in the hypotheses that this anomaly is due to fractures, an investigation of potential fractures and faults in the Castillo Formation has been conducted. In this report, we summarize the results of this investigation along with the results of two wells drilled following the surface analog study.

Geological Setting
The San Jorge Basin, located in the central Patagonia of Argentina is a Jurassic and early Cretaceous rift basin that evolved into a sag basin (Figure 1). The sedimentary record of the thermal stage is mainly continental, with deposits ranging from coarse alluvial fans in the flanks to high-sinuosuty meander belts and shallow ephemeral lakes in the central area with significant pyroclastic supply.

Figure 1. Location map (after Homovec et al, 2000).

The eastern part of the basin is characterized by extensional style structures. The San Bernardo Fault Belt, to the west, is a NNW range characterized by wide fault propagation anticlines, with N-S orientation, that were reactivated during the Miocene (due to the subduction along the western margin of South America). The anticlines are often arranged in echelon and fragmented by WNW strike-slip faults.

The Perales Anticline, host of one of the major oilfields in the area (Figures 2), is the southward continuation of the San Bernardo range in the subsurface. The NNW orientation of this range and the subsurface anticlines, contrast with that of the regional extensional faults in WNW orientation.
Figure 2. Perales Anticline and San Bernardo Range locations (after Homovc et al, 2000). 1. Chenque Anticline, 2. Cerro Castillo Anticline.

Although Bajo Barreal Formation (Figure 3) is the main reservoir of the Perales Anticline, the Castillo Formation offers high potential when secondary porosity is enhanced by cement dissolution and fracturing (Strelok et al. 1998).

Seismic Anomaly
Seismic sections of Perales anticline show complex features at the frontal limb along the whole anticline (Figure 4, 5 & 6)

Deep migration studies and velocity analysis conferred geological character to these reflections. In addition, the acoustic velocity of the anomaly is similar to that of the host rock. The nature of these features has been a matter of diverse interpretations.

These features were formerly explained as reflections from beds either overturned or belonging to horse blocks. Later Homovc et al. (1999) interpreted these anomalous reflections as fractures filled with magmatic material. Recently Aydin (2000) suggested that the anomaly could be the effect of dilatational fractures due to splay-fracture mechanism related to high-angle reverse faults. These fractures could be filled with magmatic material, hydrocarbons fluids, or solids such as calcite.

Outcrop Characterization
Aydin (2000) performed an outcrop characterization of Castillo Formation, in San Bernardo Fold belt in order to extrapolate the distribution of fractures associated with folds and faults to the Perales anticline.

The field data consisted of measurements of fracture intensity in the Castillo Formation and characterization of the nature and distribution of fracture and faults. The area of study is located near Canadon Matasiete, where the frontal limb of the Cerro Castillo anticline is exposed (Figure 2), and at Angostura and Chenque Anticline, where fracturing is associated with a reverse fault and a strike-slip fault, respectively.

It was found that the intensity of fracturing is in part controlled by brittleness of the rock layers and by the magnitude of slip along faults at a high angle to the fold axes. Fracture zones with even a small amount of shearing provide significant fracture porosity and permeability and thus are effective flow pathways. However, as slip increases, a brecciated fault rock with a low permeability develops.

The siliceous tuff layers within the Castillo Formation at the frontal limb exhibit a dense fracture network. The number of fractures increases near the faults from a background value of 10-15 per Meter Square to more than twice of this amount.

Lithology
The lithology of the Castillo Formation consists of tuffs, tuffaceous sandstones and sandy and argillaceous tuffs with intercalations of tuffaceous-argillaceous matrix sandstones. The productive horizons have a secondary porosity that ranges between 9 - 12% with permeability values between 3 a 20 mD (Corveleri et al, 1996).
Figure 4. Seismic Section of The Perales Anticline (True Amplitude -Time). BB: Bajo Barreal Fm., CAS: Castillo Fm., D-129: Pozo D-129 Fm.

Figure 5. Top Section Tobacco Time Structure Map
Furthermore, the study showed that the Castillo/Bajo Barreal boundary is faulted. Most likely, the faults associated to this boundary are reverse faults. Although fracture patterns vary from different units inside this formation, two well-connected fractures sets commonly exist. The most common configurations includes strike-parallel and dip-parallel fracture sets but also two oblique sets.

The fracture characterization showed that the majority of the faults associated with the inferred thrust fault at the core of the folded strata are either low-angle and strike-parallel or a few are high-angle faults oblique to the trend of the faults zones.

Fracture orientation was measured in different locations associated with two main structural features, a reverse fault and a strike fault (Figure 7). The principal fracturing directions associated with the reverse faulting are 190°, 290° and 305°. The main directions associated with the strike fault are 310° and 235°.

From the field study it was concluded that the normal frontal limb of the Cerro Castillo anticline has been attenuated to about half of its thickness as measured along the eastern side of Canadon Matasiete. Faulting appears to be the main mechanism of this process as documented by the high-resolution mapping. It is believed that in the later formation of the anticline, the faults take advantage of preexisting joint orientation.

**Borehole data**

Well A (Figure 8) was aimed to target in the conventional plays of Bajo Barreal Formation and the anomalous zone of Castillo Formation. Due to an accidental deviation in Well A, the anomaly was reached laterally.

The Formation Micro Scanner log (FMS) of Well A showed a considerable amount of fractures with maximum density of 14 fractures/m. Although is not possible to discriminate the nature of the filling material, the log image differentiates between filled and opened fractures. The principal filled-fracture directions are 240°, 195° and 280°. For open fractures, the main directions are 275° and 195°.

Castillo Formation was not tested during the completion of Well A, because no significant shows of oil or gas were found. Nevertheless, during the completion of the upper Bajo Barreal Formation (which only produced formation water), oil filtrate from Castillo Formation was found. But Castillo oil potential remains doubtful due to the inconclusive tests.

Well B (Figure 9) was drilled directionally in the northern part of Perales anticline. The objective of
Figure 7. Fracture orientation in outcrop characterization.

Figure 8. Well A sketch.
Well B was the center of the anomalous zone in Castillo Formation.

The Formation Micro Imager (FMI) showed that the beddings dipped to the east. As a result the idea of overturned beds or horse blocks was discarded. The fracture density topped a value of around 12 fractures/m. The principal filled-fracture direction is 185° and for the open-fracture the main directions are 270° and 210°.

Although the FMI log showed that the rocks were extensively fractured, oil or gas shows of hydrocarbons were even poorer than those in Well A. Fracturing was also locally confirmed by the high-rate water influx from some reservoirs of the Castillo Formation.

Moreover, the FMI log registered in Well B was useful to discard the hypothesis that the anomaly was the result of the seismic response of overturned or rotated beds, because the dipmeter orientations show that the beds are dipping 45° to 80° to the SE, opposite to the NW dipping of the reflectors in the anomalous zone.

The analysis of fracture directions in the outcrops and well-bore shows that the occurrence of more oblique fractures near the strike slip faults (235° - 240° and 310°) and more north-south fractures (195°) when the main structure is the reverse faults (Figure 10). A detailed analysis of this issue is critical for the future development of Castillo Formation in different locations of the anticline.

With the information available from the outcrops and well loggings it cannot be concluded weather open fractures are the reason of the seismic anomaly. This assumption could be analyzed through an acoustic impedance modeling.

The same acoustic model would allow checking the feasibility of an anomaly generated through the reflection of shear fractures or small faults at divergent angles from the main faulting.

**Conclusions**

The imaging logs in both wells confirmed the existence of an important network of fractures in the anomalous zone. The important water influx in Well B supports that a fraction of the fracture network is conductive and perhaps responsible for anomalous water production during drilling. The operating problems in Well A leave the door open for further studies to establish the potential productive zones. On the other hand, neither of the wells exhibited a considerable amount of hydrocarbon shows, neither in the mud logging nor in the electrical logs.
Finally, evaluating if the seismic anomaly is related to seismic migration problems in the processing stage would be of high importance.

**Future work**
The next step in this research will be the modeling of the fracture system with synthetic seismograms. This model will generate synthetic seismic responses of the fractured rock filled with different solid or fluid material. This information will be later compared with the actual seismic response of the anomaly in Castillo Formation.

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**References**


