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Application of Pyrenean Fractured Carbonate Outcrops for Subsurface Reservoir Characterisation

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SUMMARY

The so-called ‘seismic gap’ remains a major challenge in the appraisal and development of fractured hydrocarbon reservoirs which are generally very heterogeneous in terms of open fracture intensity and connectivity and therefore also in reservoir quality. Acceptable and sustainable well rates largely depends on finding the fracture ‘sweetspots’, but much of the fracture system exist at scales too small to be mapped seismically and too large to be fully determined from well data (ie in the seismic gap). Excellent km-scale exposures of carbonates in the Spanish Pyrenees enables this problem to be tackled head on by studying fractures from micro to macro-scale; their dimensions and distributions provide data for use in reservoir simulation and for guiding well and seismic interpretations. In addition, the influence of mechanical properties and anisotropy on fracture distribution can be examined in detail. The results and principles should be used to underpin and calibrate sub-surface reservoir characterisation.

Introduction

Fractured reservoirs where storage and / or well performance are dependant on a well-connected open fracture system (Types 1 and 2 of Nelson 2001) are a 'broad church' that includes tight carbonates and dolomites, clastics especially cleaner sandstones and Palaeozoic quartzites, volcanics, and also igneous or metamorphic basement formations. However, most fractured reservoirs show rapid variations in open fracture intensity and orientation, and this heterogeneity can have a big impact on the distribution of reservoir quality and sustainability of production.

Other important fracture attributes are aperture and dimension. Regarding the latter, the term 'fracture' is often unhelpfully used in reservoir appraisal to embrace everything from micro- to meso- or even macro-scale structures (see Table below). It is important to be more precise in defining both fracture type and associated dimension because longer length and wider aperture tend to correlate (eg in master joints, or fracture corridors, defined below), and also because longer dimensions increase connectivity of the smaller-scale ('background') fracture system.

Length m.	Hierarchy term	Fracture type examples	Most relevant data type
< 0.5	Micro-scale	Most stylolites, tension gash veins, 'hairline' fractures	Core
0.5 to 10	Meso-scale	Regional or fold-related joint systems, fault-related fractures	Core, image logs, full waveform sonic
10 to 200	Meso to macro-scale *The 'seismic gap'*	Fracture 'corridors' and sub-seismic faults	High resolution seismic especially multi-azimuthal
200 to 1000	Macro-scale	Seismic scale faults	3D seismic and other geophysical datasets

Fracture types and their key attributes which impact on reservoir performance and should be considered for simulations should be fully described during reservoir appraisal. However both well and seismic data have their own limitations when it comes to deterministic mapping of meso-scale to macro-scale fracture intensity variations and fracture dimensions. For example, joint or fracture 'corridors' (linear zones of high fracture intensity) commonly exist at the meso- to macro-scale; these are generally below the limit of seismic resolution and also difficult (but not impossible) to identify and characterise in well data.

Outcrop studies can provide excellent insights into the 'sub-seismic volume' and thus mitigate these problems by helping to calibrate both seismic and well data and also generate parameters to control reservoir modelling. This article describes some specific outcrops in Mesozoic carbonates of the South Pyrenean thrust unit (Figure 1) where useful insights can be made for those working in fractured reservoir appraisal.

The Pyrenean fold and thrust belt reveals a near-complete stratigraphic sequence from Variscan basement through to Mesozoic and Tertiary carbonates and clastics. Due to a high degree of exposure in the Catalan Pyrenees it is possible to study many combinations of lithology, mechanical anisotropy and structural setting. Two highly relevant themes for reservoir appraisal and modelling will be discussed: firstly the challenge of capturing fracture heterogeneity in the sub-seismic volume, and secondly the importance of evaluating the relationship between mechanical anisotropy and fracture development and distribution.

Structural Setting

The Pyrenees are an Alpine fold and thrust belt formed from the Late Cretaceous to Neogene due to the convergence of the European and Iberian plates. The high mountains of the Pyrenees Axial zone are formed by an antiformal stack of Hercynian rocks which is flanked by both northward- and southward-directed thrust units within the Mesozoic sequence (Figure 1) which are detached above

Triassic salt and strongly controlled by previous extensional faults. The South Pyrenean thrust unit provides good analogs for structures in similar fold and thrust belts where hydrocarbons are known to occur (eg the Zagros).

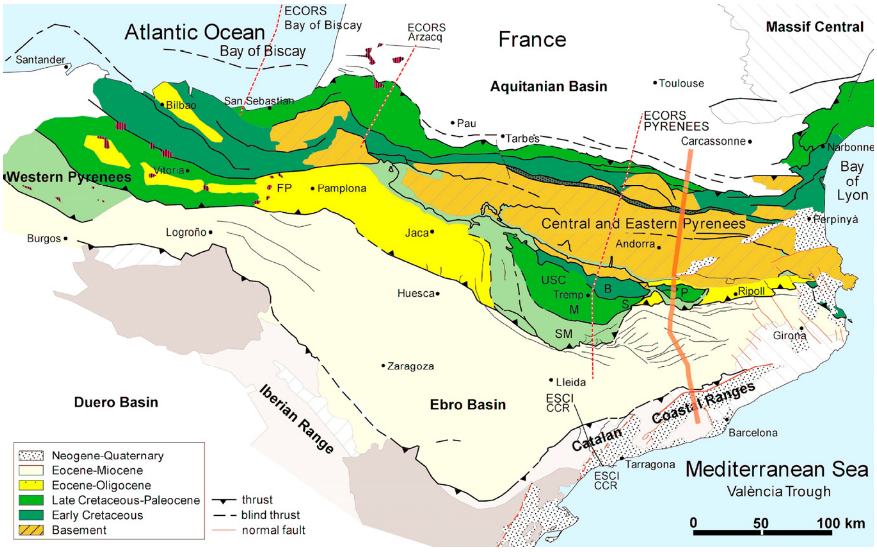

Figure 1 *Tectonic map of the Pyrenees. B = Boixols thrust sheet.*

The outcrops discussed here are located within the uppermost, and oldest, of three 'piggy-back' thrust sheets which constitute the South Pyrenean thrust unit. Known as the Bóixols thrust sheet, it contains a 5000m thick mostly carbonate section with highly deformed strata from Triassic to Santonian and is in contact with the Axial zone antiformal stack along a narrow line of Triassic rocks which has been classically interpreted as a passive-roof backthrust (Muñoz, 1992). However, based on significant new fieldwork, we suggest that this contact is the result of Mesozoic evaporitic diapirism later affected by the Pyrenean compression, similar to the ideas of Canérot *et al*. (2005).

The Vilanoveta location is in the north-dipping backlimb of the St Corneli anticline, a structure which is bounded to the south by the Bóixols thrust and has been described in a number of previous studies (eg Tavani *et al* 2011). The Hortoneda location is further north and revealed by an erosional window within the thick syn- to late-orogenic gravels that blanket the southern Pyrenees.

Vilanoveta: The Sub-Seismic Volume

In the north limb of the St Corneli anticline the E-W striking Vilanoveta canyon wall (Figure 2) exposes interbedded units of Coniacian to lower Santonian rudist carbonates, calcarenites and marly limestones along more than 2km of strike-parallel section and ~100m of vertical section. The rudist carbonates are relatively thick, massive and competent. The calcarenites are also competent and strong but have much internal layering including foresets, and the marly limestones are in comparison relatively weak and ductile. This range of lithologies introduces a significant mechanical anisotropy to the section which has a direct influence on the fracture system observed. The exposure is cut by fractures and faults ranging from meso- to macro-scale but as Figure 2 indicates much of the fracture pattern is well below seismic scale. In fact, it is likely that only faults F2 and F3, spaced approximately 600m apart, would be seen on seismic, with perhaps a suggestion of 'features' or 'lineaments' associated with the sub-seismic faults that occur between F2 and F3. At sub-seismic scale there is a network of meso-scale joints and meso- to macro-scale fracture corridors whose vertical connectivity is governed by the mechanical layering. In a fracture model these structures could constitute a connected network of fractures draining the matrix, with the fracture corridors acting as high k pathways. However, obtaining reliable data on the spacings and distributions of both of these model elements is difficult from well data and impossible from seismic data unless lineaments and similar edge features in high resolution seismic processing, or from application of techniques such as ant-tracking, are assumed to be fracture corridors or sub-seismic faults.

Vilanoveta thus provides key conceptual insights on the typical nature and distribution of fractures in the sub-seismic volume, and can also generate specific parameters on attributes such as length, height and spacing that may be used in support of reservoir models. It is also instructive to discuss what would be the appropriate grid cell size to capture the fracture heterogeneity seen at sub-seismic scale (perhaps 50 to 100m laterally?) as well as the rapidly varying matrix properties between layers (perhaps 2m thickness?). A further approach would be to apply domainal fracture models.

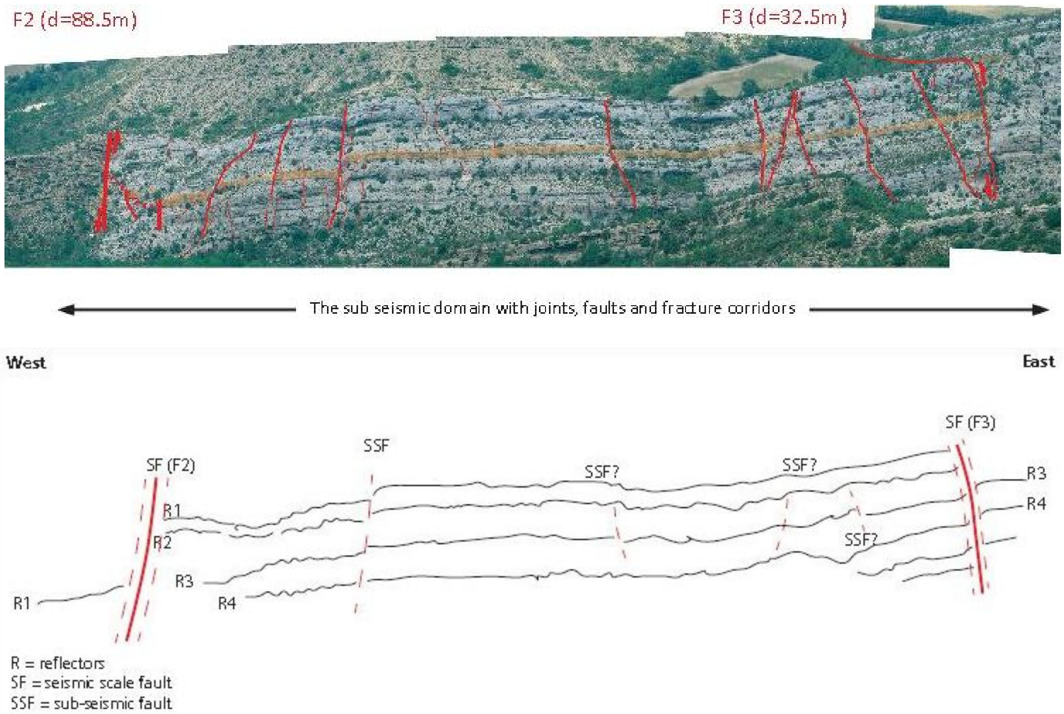

Figure 2 *Upper picture is a panoramic view of Vilanoveta canyon looking north with seismic to sub-seismic scale faults marked. Lower picture shows a pseudo-seismic profile of the exposure.*

Hortoneda: Mechanical Anisotropy and Fracture Distribution

The main control on fracture distribution within folds is the interplay between formation mechanical properties, including degree of anisotropy, and the fold mechanism. Further controls are likely to be the deformation depth, and fault proximity. At Hortoneda, a Coniacian sequence is deformed by a large scale E-W striking anticline but the upper massive carbonate has responded very differently to the lower, well-bedded carbonate. An interval of marly facies separates the two.

The fracture sequence in the upper block (Figure 3) comprises i) early bed-parallel carbonate vein networks with vertical growth fibres ii) a system of N and S-directed (opposite verging) low angle semi-ductile thrusts iii) a system of sub-vertical, irregular joints with axis-parallel, oblique and normal trends which indicate dip-slip and strike-slip movements and iv) late normal faulting. This farcture paragenesis indicates that the massive limestone accommodated Pyrenean N-S compression by intial layer-parallel shortening and vertical uplift (i above), followed by thrusting (ii above). Subsequent brittle jointing was probably associated with tectonic relaxation and / or uplift and exhumation (iii and iv above).

In contrast, below the marly interval which acted as a decollement, the well-layered carbonate responded with a more classical fold mechanism probably dominated by flexural slip. A quasi-radial axial fracture pattern is observed, although complicated locally by the presence of faults and their damage zones (Figure 4). There appears to be a higher degree of shortening in the lower carbonate than in the upper, and this is assumed to be partly accommodated by the decollement.

Hortoneda provides insights about the importance of mechanical control in fracture development. Prediction of fracture intensity distributions across folds is often undertaken by curvature analysis based on seismic data because rate of curvature is often assumed to be a proxy for fracture distribution. In reality however, structures with similar geometry in seismic mapping may have very different strain and therefore fracture distributions due to the influence of rock properties and anisotropy on the fold mechanism (see Ramsay 1967). In reservoir appraisal, construction of geomechanical models using wireline log data can go a long way towards understanding these issues and predicting the likely strain distribution in specific structures and formations.

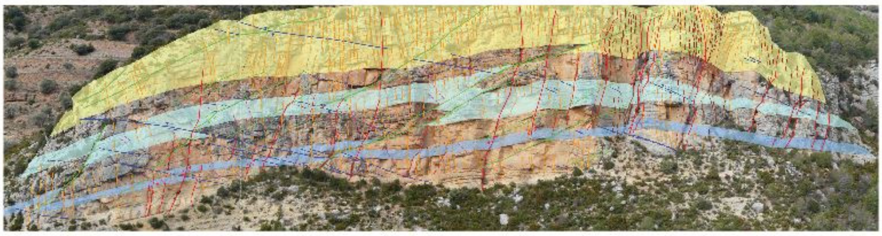

Figure 3 *Fracture pattern in the upper massive carbonate unit.*

Figure 4 *Fracture pattern in the lower, well-layered carbonate unit.*

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