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Application of Pyrenean Fractured Carbonate Outcrops for Subsurface Reservoir Characterisation

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SUMMARY

Appraisal and development of fractured hydrocarbon or geothermal reservoirs including tight carbonates, sandstones and basements remains a significant challenge because of the generally high degree of heterogeneity in the intensity and distribution of the open fracture system. Well penetrations are 1-dimensional samples of a complex system. Seismic attribute mapping offers hope for defining domains of high open fracture intensity (sweetspots) but remains a tool in development and may never fully characterise the sub-seismic fracture domain. This presentation describes how outcrop observations in the Catalonian Pyrenees support and extend the interpretation of well and seismic data with respect to fracture typing, scaling, attributes and distributions.

Introduction

The Pyrenean foldbelt is a superb natural laboratory for the study of faults and fractures due to the multi-phase structural history, near-complete stratigraphic sequence from Variscan basement to Mesozoic and Tertiary carbonates and clastics, and high degree of exposure. These factors enable almost any combination of lithology, mechanical anisotropy and structural setting to be examined. The presentation will describe outcrops which shed light on two highly relevant themes for hydrocarbon reservoir appraisal: i) discrimination of fracture types and their attributes; ii) prediction of fracture distributions and orientations away from well control.

Both themes are discussed below using outcrops in the Tremp area, and the application of outcrop observations to fracture model development is described. For example, outcrop data can bridge the so-called 'seismic gap' (Fig. 1), the length scale where joint 'corridors' (linear zones of high fracture intensity) are commonly found.

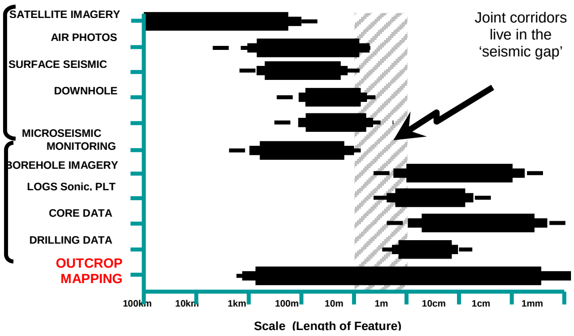

***Figure 1**: Data types used for reservoir fracture studies, and the length scale they observe.*

Structural Setting

The Pyrenees are an Alpine fold-thrust belt formed from Late Cretaceous to Neogene as the result of the convergence of the European and Iberian plates. The high chain (Axial zone) is an antiformal stack of Hercynian rocks flanked by both northward- and southward-directed thrust units (Fig. 2). Most of the outcrop locations are in the northern thrust sheet (Bóixols) of the South-Central thrust unit, a piggy-back imbricate sequence of east-west-trending thrust sheets detached above Triassic salt and strongly controlled by previous extensional faults. The southern Pyrenees provide good analogs for structures in similar foldbelts where hydrocarbons are known to occur (eg the Zagros).

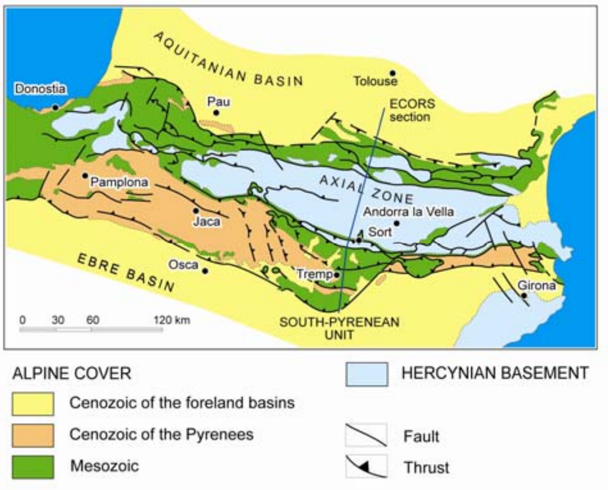

***Figure 2**: Tectonic map of the Pyrenees.*

The Bóixols thrust sheet is made of a 5000-m-thick mostly carbonate section with highly deformed strata from Triassic to Santonian. Field mapping is in progress to better understand the structure and deformation patterns seen at each outcrop, and construction of structural cross sections together with reinterpretation of the Erinyà 1 well data has led to a new interpretation of the northern part of the South-Central thrust unit. This unit bounds with the antiformal stack through a Triassic belt, structure classically interpreted as a passive-roof backthrust (Muñoz, 1992). We suggest that this contact is the result of Mesozoic evaporitic diapirism later affected by the Pyrenean compression, in the line proposed by Canérot et al. (2005). In broad terms, the diapir occupies the core of a large antiformal structure (blind thrust sheet?) that would be responsible for the generation of a southern foredeep where more than 2000m of Upper Cretaceous turbidites were accumulated, likewise a model comparable to productive slope basins where the growth of salt diapirs and turbidite sedimentation are closely linked.

Fracture Types

The term 'fractures'embraces a wide range of geological discontinuities with a wide range of physical properties and scale. For example, granulation seams (minor faults) and extensional joints are 'fractures' with very different permeability properties (sealing versus open respectively). In reservoir appraisal it is therefore very important to discriminate fracture types. One way to do this is to consider their "Mode of Opening" coupled with subsequent sealing or reactivation history through time. Mode 1 fractures (Fig. 3) are pure extension joints, while Modes 2 and 3 (Fig. 4) include shear, hybrid shear-extension joints, and all scales of faults. Mode 4 (Fig. 5) are contractional structures.

Fractures formed in extension (Mode 1) and especially in hybrid shear/extension (Modes 2/3) are the most likely to host fracture porosity and effective permeability as wallrock surfaces separate. Finding planar and barren fractures, for example in core, suggests joint formation during uplift or exhumation. However, Mode 1 to 3 porosity is destroyed by hydrothermal mineralisation or matrix-derived precipitates, for example at greater depth, or by thermochemical or mechanical processes associated with fault propagation. Mode 4 fractures are the result of pressure dissolution mechanisms acting on the rock matrix, resulting in material loss and shortening on planes normal to the maximum stress. They usually act as flow baffles due to the presence of residual clays.

***Figure 3**: A family of Mode 1 extensional joints and joint corridors developed in a sequence of inter-fingering Santonian calcarenites and rudist build-ups, near Aramunt. Note different spacings in the different units.*

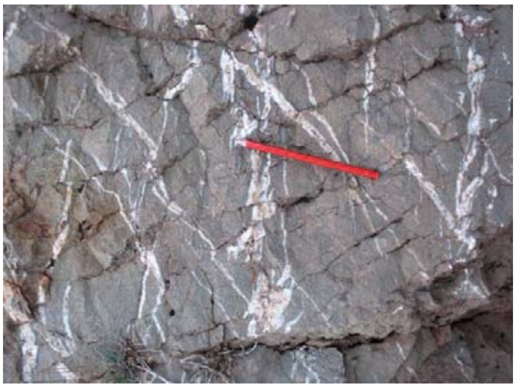

Figure 4.

Figure 5.

Figure 4*: A network of Mode 2 / 3 mineralised shear fractures in the footwall of the Bóixols thrust plane at Bóixols. They record high pore fluid pressures developed ahead of the propagating thrust fault and are cut by near-vertical stylolites.*

Figure 5*: A network of Mode 4 stylolites with near-perpendicular carbonate veins (Mode 1), in Aptian shelly carbonates at Senterada dam. If widely distributed they can cause 'reservoir damage'.*

Fracture prediction

Arguably the three main controls on fracture distribution are fold mechanism and geometry, hostrock mechanical properties and anisotropy, and proximity to faults.

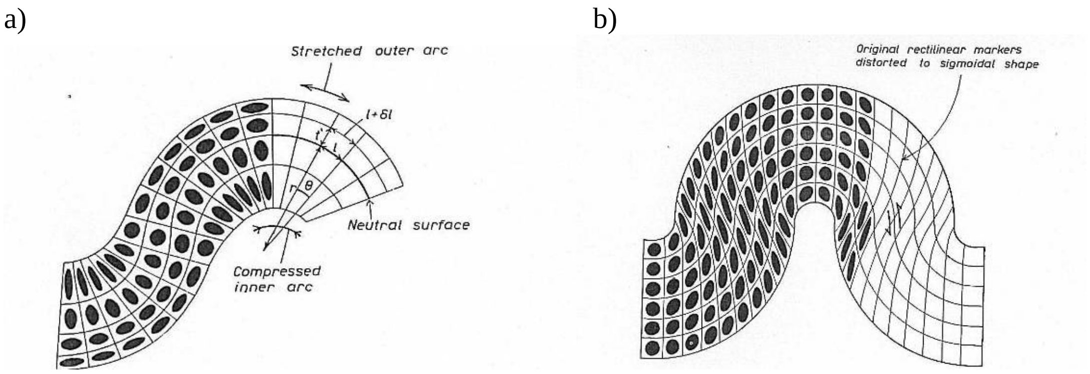

Figure 6*: End-member strain distributions in folds formed by tangential longitudinal strain (a) and flexural slip / flow (b). Note the contrast between high strains at the crest and inner arc in a) but on the limbs in b).*

Prediction of fracture densities across folds is often undertaken by curvature analysis methods because it is a possible proxy for fracture distribution. In reality however, it is necessary to consider both the folding mechanism and the mechanical anisotropy which can lead to radically different strain distributions (Fig. 6). In outcrop many folds display fracture distributions that indicate outer arc extension / inner arc compression (Fig. 7), however the presence of domains of high fracture intensity on the limbs suggests formation by a hybrid folding mechanism. This is often due to the role played by bed boundaries acting as transient mechanical boundaries during folding as well as strong mechanical contrasts between formations.

The prediction of fracture corridor distributions below seismic resolution remains an industry challenge. However, analysis of outcrops such as Aramunt (Fig. 3) enable empirical relationships to be established between spacing, mechanical unit thickness and fault proximity.

***Figure 7**: An asymmetric anticline in strongly layered carbonates with fracture distributions related to a hybrid fold mechanism (Alinyà).*

Static Fracture Models for Hydrocarbon Reservoirs

Outcrop data should be used to help interpret well data and build conceptual static fracture models (Fig. 8) that underpin reservoir simulation, volumetric estimations and well planning. Such models are accompanied by fault and fracture parameters which are used to constrain software modelling of, for example, permeability modifiers.

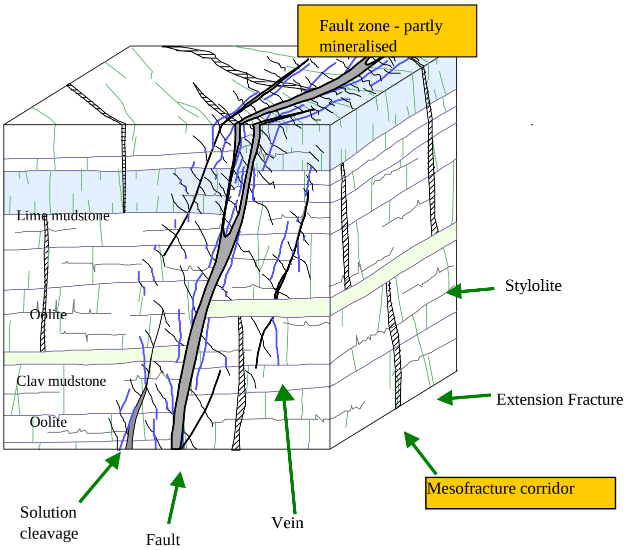

***Figure 8**: A conceptual static fracture model (UK carbonate).*

References

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