Seismic amplitude analysis reveal new volcanic and basement related petroleum plays in the Faeroes

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Introduction

Since the discovery and continued development of fields containing large quantities of hydrocarbons in both the UK (Claire & Lancaster) and Norway (Johan Sverdrup) interest has grown on how seismic can better detect hydrocarbon filled porosity in Naturally Fractured Basement - be it crystalline/metamorphic or basaltic see e.g. the NFR inventory (de Beukelaar et al., 2011) and most recent examples presented (Tracey, 2016; Vosgerau et al., 2016). In the present study we have focused on seismic amplitude analysis related to wrench faulting (that had always been overlooked) as well on other seismically detectable geometric features with internal architecture (e.g. basaltic flows and sills) with volcanic origin and related sedimentary processes with qualitative and quantitative measurements from recently re-processed seismic data. It had been demonstrated that not only old basement highs and transfer faults perpendicular to the oceanic spreading ridge should be considered, but in particular wrench faults and fractured zones that are associated with the opening of the Atlantic and reactivation of earlier tectonic fabrics.

If the seismic response bears essential information about present subsurface geometry, we had been motivated to further exploit the information contained in the variation of amplitudes both post-as well pre-stack seismic data as support to further develop established ideas of geological processes that had taken place with underlying hope and counting on serendipity that this could lead to the development of new play types of the regional complex syn- and post rifting phenomena and associated volcanic history. This work had been strongly motivated by the need of unveiling new ideas from old re-processed and new broadband seismic data and grown Industry interest as a preparation of the 4th licensing round of the Faeroe Islands starting May 2017 with more areas to be opened on the Faroese continental shelf at the 5th licensing round in 2019 and the 6th in 2021 (Eidesgaard, 2016).

Geological framework

Along the length of the divergent boundary of the Atlantic Mid Ocean Ridge, the spreading center is offset by regularly spaced transform boundaries (Ridge Transform Zones). These can be traced shoreward as deep seated crustal fracture zones beneath the sediment cover, as described in the South Atlantic offshore Angola and offshore Gabon (Perry, 2011). In deepwater Nigeria the extension of the Chain Fracture Zone is imaged by modern 3D seismic and forms a very prominent oceanic crust/basement feature, which influences the overlying deepwater sedimentation. Differential compaction related-faulting over the crest of this feature provides migration pathways for hydrocarbons to escape from deep source rocks into the shallower section (Figure 1a, South Atlantic Fracture Zones. Figure 1b, Chain Fracture Zone - Deepwater Niger Delta).

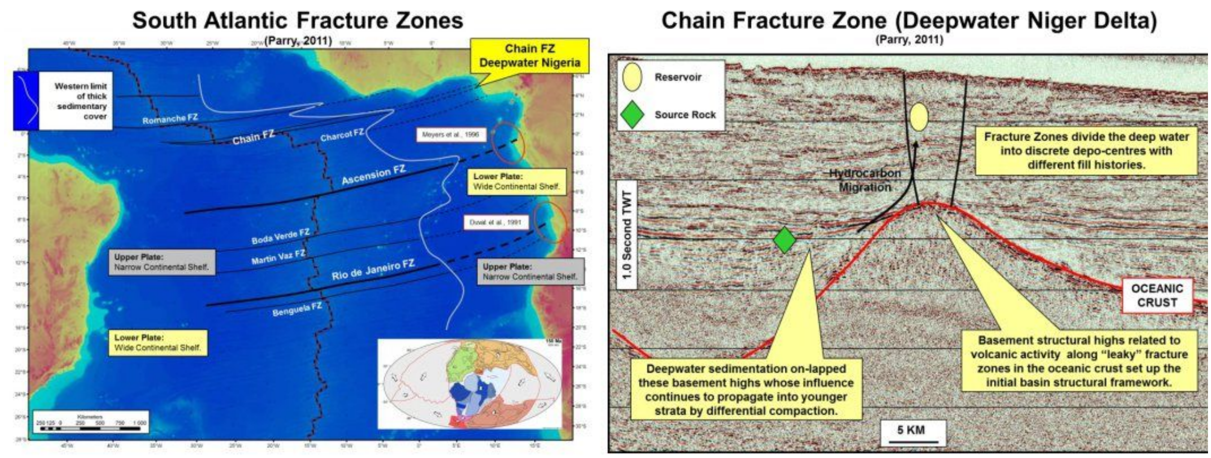

Figure 1 *a) South AtlanticFracture Zones , b) Chain Fracture (Deepwater Niger Delta)*

In the North Atlantic (Figure 2a) similar offsetting fracture zones are clearly evident and can be linked to the onshore geology, where they are related to long lived basement related fractures, as seen both onshore Greenland and on the opposite side of the mid-ocean ridge spreading centre in the Lewisian Gneiss Complex of mainland UK. On the offshore NW European continental shelf, the flower structures associated with the strike slip movement along these features – the Ymir and Wyville-Thompson Ridges is clearly evident (Figure 2b, North Atlantic Fracture Zones). Onshore mapping of the Lewisian Gneiss Complex has shown that the earliest formed basement fractures (earliest Proterozoic) formed weak foliation planes, which were reactivated in all subsequent tectonic episodes, during the two Wilson Cycles of the North Atlantic (Pless et al., 2010; Parry, 2016).

Sills, dykes and lava-delta conduits

Regional faulting and large scale fracture zones with primary and secondary porosity might have influence on conventional and unconventional basement related play types. Sills and dykes might have formed conduits for further intrusive magmatic as well as possible hydrocarbon flows further unlocking the future petroleum potential of the Faroe- Shetland Basin (Hansen et al., 2016; Schofield et al., 2017). Early Cenozoic igneous activity in the North Atlantic Igneous Province generated widespread sill complexes in sedimentary basins at the NW European margins and also various intrusive systems in the contemporaneous basaltic lava pile of the Faroe Islands. The largest sills are exposed as partly saucer-shaped bodies in the three uppermost formations, where inner gently dipping basal sill sections gradually give way to more steeply inclined discordant outer rims that commonly cut several hundred meters into overlying lava flows. Numerous subvertical and moderately inclined dykes intersect the areas affected by sill intrusion, but only inclined dykes, sheets and lava-deltas have been positively identified as sill feeders. Locally controlled rotations of least principal stress axes (measured in outcrops, from wells and if appropriate also from seismic data) during initial sill intrusion or propagation may have been an important contributing factor in determining the overall geometry of the investigated intrusions and how they could have been possible conduits for migration of deeply formed hydrocarbons.

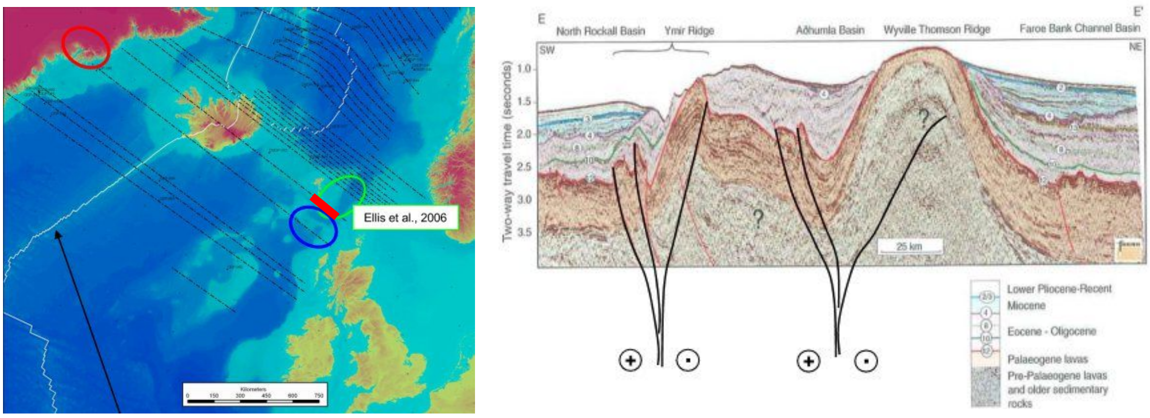

Figure 2 *a) North Atlantic Fracture Zones, b) Flower shaped Wrench Faults and Fractures*

Seismic interpretation and data analysis

The seismic interpretation of "geometric features" like fault blocks and clinoforms in large 2D or 3D data sets formed a first step in the reconstruction of macro scale structural and related sediment fill geological history. Updates from older interpretations (Fruehn et al., 2001) were made using re-processed 2D Flare and more recent 2D/3D broadband data (appr. positions are the NW-SE red bar respectively the green+blue ovals in Fig. 2a). The post-stack amplitude variations represent "the character" of reflectors, the impedance as derived seismic attribute and selected fracture sensitive attributes (Chopra and Marfurt, 2007; Khromova, 2011) are important for the geological history reconstruction as AVA of pre-stack shots and CMP´s showed increased value for lithology and fractured zone determination.

For the offshore Faroese sector in the adjacent UK West of Shetlands Basin see Figure 2a regularly spaced NW-SE trending transfer zones were previously recognized (Ellis et al., 2009). These zones were controlling both igneous and sedimentary activity, as well as sediment accommodation space throughout the Paleocene, and into the Eocene. These seismically mapped zones of weakness also acted as conduits for magmatic activity and in some cases also as conduits for hydrocarbons from deeply underlying sediments. Seismic interpretations of lower shaped wrench faults and fractures are illustrated in Figure 2b. (Ritchie, 2008) makes clear how the understanding of different tectonical regimes might be of influence for the correct seismic interpretation, making it less ambiguous for example to recognize an extensional or transtensional fault system (Figures 3a and b). Basement related highs along these deep seated features (Figure 4) and sills emanating from volcanic conduits were typically identified by their tendency in crosscutting stratigraphy and being laterally discontinuous. Identification and seismic analysis needed taking into account resolution, detectability and S/N ratio, measurements of e.g. reflection strength, fault and fracture sensitive seismic attributes for post-stack data, but also anticipating on further investigation of e.g. AVA and Vp/Vs ratios in pre-stack gathers.

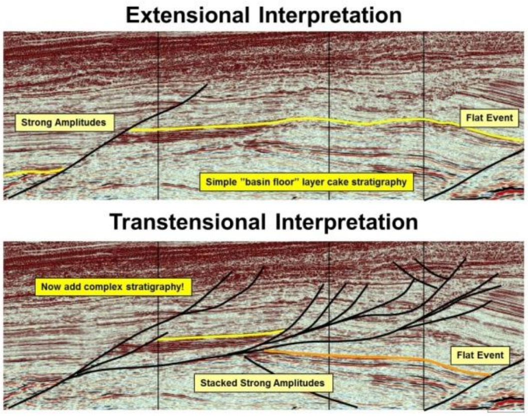

__Figure 3__ a) Extensional and b) Transtensional interpretations

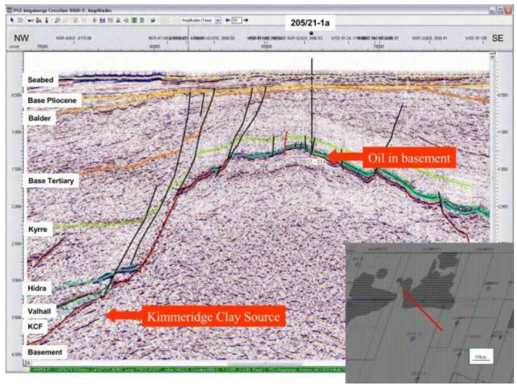

__Figure 4.__ Seismic interpretation of the Lancaster field: a basement high in a proven petroleum play

Seismic amplitudes reworked to impedances covered a wide range of values, but the individual volcanic bodies identified in the seismic mostly appear as strong bright hard reflectors. If carbonates are not involved, a basalt body could be traced by its significantly higher Vp/Vs ratio compared to other lithology types. This is especially important when we deal with weathered basalts which show a lower density and therefore lower impedance. Our interpretation is also confirmed by the occurrence of typical volcanic geometries which are found in the specific tectonic context of wrench faults in a rift basin. Some of the individual bodies could be misinterpreted as the top of a carbonate cemented delta or terminal lobe or are reminiscent of fluvial channels. But the sum of the observed features within the given tectonic setting, including chimneys, craters, stacked lava flows, sills and dykes gives us confidence in classifying these geometries as being volcanic in nature.

Added value by use of pre-stack data conditioning and velocity-density log upgrades

If also state-of-the-art pre-stack data conditioning is applied to the seismic data and an upgrade of calibration logs were made as well, even more accurate and reliable results could be obtained.

We computed attributes to analyze the flatness of specific events associated to seismic horizons and assessed seismic health with recent pre-stack analyses software running on a high-performance hardware platform. Beyond more accurate interpretation of the tectonic setting and seismic (basaltic) facies for better imaged (recently re-processed) data after stack, as demonstrated, we might still have the potential of considering the full data content, including the preservation of full wave propagation phenomena and/or elastic/ fluid parameters hidden in the amplitudes and associated noise that otherwise would have been lost in the stacking process. Analyzing also pre-stack gathers shots and CMP´s added more value to our interpretation. Special attention had been given to an overall upgrade of the seismic data quality of CMP gathers by checking velocity consistency (flattening), various filtering and muting beyond a certain angle. Data conditioning was essentially an amplitude correction per trace computed from the CMP real and modelled AVA that was derived from the computed smoothed AVA model curve for each CDP. Where needed well data quality was improved according to regression curves from petrophysical data as previously carried out (de Beukelaar et al., 2001) in similar cases before modelling of synthetics, seismic inversion and accurate basement mapping.

Conclusions

We used post-stack data for geometric and seismic amplitude interpretation, fine tuned by pre-stack data-analyses (on filtered shots, supergathers and conditioned CMP gathers) together with dense and accurate velocity screening and AVA characterisation for a better understanding of the underlying geology. By studying reflection amplitudes and their azimuthal variations in CMP gathers it was attempted to identify regionally extending fractured zones and on a local scale also relate the least principal stress axes to rotations. Due to the anomalously high Vp/Vs ratio of intra volcanic reflectors when compared with reflectors from other lithologies, acoustically hard volcanic layers usually show amplitude strengthening with offset.

Acknowledgments

We are grateful to Óluva Eidesgaard, Jana Ólavsdóttir and Uni Petersen of Jarðfeingi, Faroese Geological Survey for provision of seismic 2D and well data. Dong and various seismic contractors for providing us with useful samples of Pre/Poststack broadband 2D/3D seismic data. Sharp Reflections in providing us with a PreStackPro software license for analysis, visualisation and interpretation of prestack and poststack seismic data.

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