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Characterisation of interactions between a pre-existing polygonal fault system and sandstone intrusions and the determination of paleo-stresses in the Faroe-Shetland basin

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ABSTRACT

Detailed analysis of 3D seismic data shows how hundreds of large scale conical sandstone intrusions interact with a polygonal fault network in the Faroe-Shetland basin. The intrusions were injected upwards during the Late Miocene through polygonally faulted claystones of Eocene–Oligocene age. Three types of interactions are recognized: (1) intrusions that are unaffected by polygonal faults, (2) intrusions partially or fully intruded into fault planes, and (3) intrusions arrested by polygonal faults. Type 2 intrusions are generally thinner, taller and wider, whereas those unaffected by faults are thicker and characterized by low dips of intrusive limbs (wings). It was found that Type 2 intrusions preferentially intruded into faults striking NW–SE, whereas Type 3 intrusions were arrested by faults striking NE–SW. Comparison of structural data and simple mechanical predictions allows paleostresses to be reconstructed at the time of intrusion. We have established that the basin was undergoing anisotropic horizontal stresses at the time of intrusions in which σ_H and σ_h were oriented N145°E and N055°E, respectively. Intrusion depth, polygonal fault dips and strikes have been used to quantify paleostress intensity and to give a σ_H/σ_V ratio close to 0.95 and a σ_h/σ_H ratio of 0.8. These ratios support the conclusion that sandstone intrusion emplacement occurred just after a Mid-Late Miocene SSE–NNW (N145°E) compressional phase when the compression direction had decreased in intensity and became smaller than lithostatic stress (σ_v).

1. Introduction

Sandstone intrusions have a long history of field-based research (Murchison, 1827; Newson, 1903; Jenkins, 1930; Parize, 1989; Boehm and Moore, 2002; Scott et al., 2009; Vétel and Cartwright, 2010). In the past decade, research has intensified on this subject principally because reservoir-scale sandstone intrusions have been identified in petroliferous basins using high-resolution three dimensional (3D) seismic data (Lonergan and Cartwright, 1999; MacLeod et al., 1999; Molyneux et al., 2002; Huuse and Mickelson, 2004; Shoulders et al., 2007) combined with well core data (Duranti et al., 2002; Duranti and Hurst, 2004) and represent potential reservoir units. Sandstone intrusions have been recognized at a variety of scales ranging from millimetres to kilometres (see Hurst and Cartwright, 2007). They are hosted in sediments from a wide range of sedimentary environments and occur in many basins world-wide (see Jolly and Lonergan, 2002; their Fig. 2). Sandstone intrusions would necessitate pore fluid pressure build-up in a parent sand body, fracturing of the overburden and liquefaction of parts of the parent body to fill the fracture network (Jolly and Lonergan, 2002; Hurst and Cartwright, 2007).

This paper focuses on a specific class of reservoir-scale sandstone intrusions which display a downward-tapering conical geometry (Molyneux et al., 2002). The Mid-Faroes Ridge area in the Faroe-Shetland basin was selected for structural analysis because earlier descriptive studies suggested that the intrusions interacted with polygonal faults that were widely developed in the Eocene–Miocene slope succession in the basin (Shoulders et al., 2007). A number of previous studies have noted that polygonal faults and conical sandstone intrusions have similar dimensions and dip and that intrusion occurred along polygonal fault planes (Lonergan and Cartwright, 1999; Lonergan et al., 2000; Gras and Cartwright, 2002; Molyneux et al., 2002). In contrast, crosscutting relationships between conical intrusions and polygonal faults have also been observed (Huuse and Mickelson, 2004; Shoulders and Cartwright,

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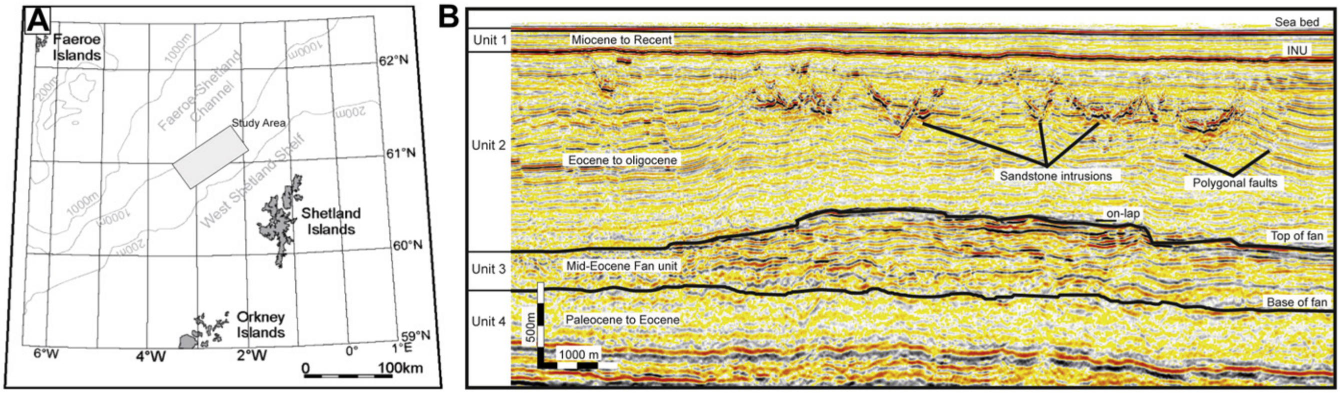

Fig. 1. A: Location map. Study area located within area of three-dimensional seismic data (grey box). B: Seismic section showing stratigraphy of Paleocene to Holocene strata divided in different units. V-shaped high amplitude reflections in the Eocene–Oligocene sequence are interpreted as conical sandstone intrusions within a polygonally-faulted interval, overlying the Middle Eocene fan unit. INU = Intra Neogene Unconformity.

2004; Shoulders et al., 2007). Hence the relationship between polygonal faults and sandstone intrusions is unclear. It appears therefore that intrusions can achieve their gross final geometry irrespective of the presence of polygonal faults within the section. The similar dimensions and dips of conical intrusions and polygonal faults are conceivably due to a common control of the rheology of the host medium of fine-grain mudstones. However, none of these previous studies attempted a rigorous geomechanical analysis of the interactions between faults and sandstone intrusions, which is therefore the main motivation for this study.

The observation that some polygonal fault planes are intruded whilst others are not suggests that the paleostress field acting during the emplacement of the intrusion is likely to act as a primary controlling mechanism. To explore this possibility and to clarify and classify relationships between sandstone intrusions and polygonal faults, we firstly decided to conduct a quantitative analysis of the different types of interactions between faults and intrusions using a study area where there is exceptional imaging quality of a large number of sandstone intrusions into a polygonally faulted host medium. Secondly, we wished to constrain orientation and intensity of paleostresses at the time of emplacement by analysing fault orientations for faults that were preferentially intruded.

In this paper we firstly classify geometrically the different intrusion types as a function of their interactions with polygonal faults in the Mid-Faroes Ridge study area. Then we characterize intrusion types quantitatively using a large set of structural measurements made from the extremely well imaged intrusions in this area. After reviewing the theoretical considerations of hydraulic fracturing in a host sequence that contains pre-existing fractures under a range of stress boundary conditions, we debate the likely stress conditions extant at the time of intrusion and use the intrusions and their interactions with pre-existing faults as a method for paleostress analysis. Using analytical models, we finally constrain the orientation and relative intensity of paleostresses at the time of intrusion.

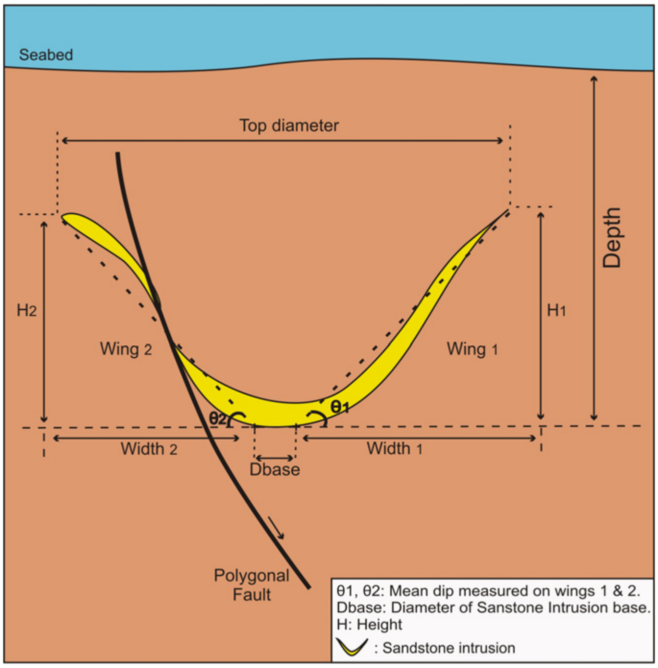

Fig. 2. The notation used for sandstone intrusion characterisation.

2. Geological setting and background

2.1. Tectono-stratigraphic evolution in the Faroe-Shetland Basin

2.1.1. Tectonic evolution

The Faroe-Shetland Basin (FSB), a major Cretaceous-Cenozoic depocentre, is located between the West Shetland Platform and the Faroe Islands (Fig. 1). It contains a series of NE–SW trending sub-basins, which formed as a result of a complex tectonic history (see Shoulders et al. (2007), their Fig. 1) involving multiple phases of extension and volcanism (Carr and Scotchman, 2003). The principal tectonic phases are (1) superposition of successive rift events from the Permo-Triassic to the Paleocene, (2) post-rift subsidence (largely in the Cenozoic), (3) Paleocene magmatic events associated with continental break-up and (4) Late Cenozoic basin inversion.

The last rifting episode continued into the Early Paleocene as a precursor to break-up in the Early Eocene (Skogseid, 1994). Significant rift flank uplift occurred involving the Scottish Massif, and subsequent erosion caused an increase of clastic input to the FSB, and the deposition of large, sand-rich deep-water fans during the Early-Middle Eocene (Robinson et al., 2004). This final rift phase was followed by a period of subsidence produced by movement of the area away from the dynamic support provided by the Icelandic plume (Jones et al., 2001). This period of subsidence was interrupted by a basin inversion phase during the Oligocene–Miocene, believed to result from oblique interaction between Alpine