Journal of Structural Geology 30 (2008) 854–867

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

The geometry and emplacement of conical sandstone intrusions

Joe Cartwright [a,*], David James [a], Mads Huuse [b], William Vetel [a], Andrew Hurst [b]

[a] 3DLab, School of Earth, Ocean and Planetary Sciences, Cardiff University, Main Building, Park Place, Cardiff, CF10 3YE, Wales, UK
[b] University of Aberdeen, Department of Geology & Petroleum Geology, Kings College, Aberdeen, AB24 9UE, UK

ARTICLE INFO

Article history:
Received 23 July 2007
Received in revised form 20 March 2008
Accepted 27 March 2008
Available online 11 April 2008

Keywords:
Sandstone intrusion
Emplacement
Seismic
Conical

ABSTRACT

Conical sandstone intrusions with a geometry comparable with that of many igneous sills have been identified using 3D seismic data from large areas of the North Sea and Faeroe–Shetland Basins. These intrusions are of reservoir scale, ranging from 100 to 2000 m or so in diameter, 50–300 m in height, and 1–80 m in thickness (aperture). They are concentrated in specific stratigraphic intervals in the Cenozoic fills of both basins. Two geometrical end members are recognised and defined here: 'apical cones' and 'flat-based bowls'. The former consist of inward dipping conical inclined sheets meeting at a prominent apex and the latter of similarly dipping discordant margins climbing from the edges of a concordant sheet. Both end members are associated with domal folds that are interpreted as resulting from the hydraulic elevation of the overburden during intrusion, and which are analogous to similar structures associated with bowl-shaped igneous sills. Measurements of aperture (ω) versus distance exhibit systematic relationships with the structural relief of these folds, offering a potentially predictive method for estimation of sandstone intrusion aperture and reservoir volume prior to drilling. A growth model for these end-member geometries is presented, drawing on existing theory for igneous sill emplacement. Aperture versus distance plots (ω –X) are used to illustrate two contrasting models for aperture inflation during propagation, but these require much further data before any specific growth model can be adopted.

1. Introduction

Sandstone intrusions have been recognised in the outcrop record since the early 19th century, with the vast majority of recorded examples being dykes and sills with apertures (thickness) of less than a metre (Taylor, 1982 and references therein). Most studies of sandstone intrusions have been field-based and descriptive, with only limited attempts made to discuss the processes involved in their emplacement. Notable amongst studies that have explicitly sought a process-based understanding are those presented by Newsom (1903) and Jenkins (1930). More recently, greater effort has been expended on developing a rigorous process framework for the phenomenon of sand intrusion in general (Jolly and Lonergan, 2002; Gallo and Woods, 2004; Jonk et al., 2003). However there is still only a limited treatment of the emplacement mechanics of sandstone intrusions, with emphasis being focused on the conditions necessary for hydraulic fracturing (Cosgrove, 2001; Jolly and Lonergan, 2002).

The lack of a more rigorous mechanical analysis of the process of sandstone intrusion undoubtedly derives from the complex nature of the processes involved. Intrusions of any size require pressure build-up and release in a parent sand body, fracturing of the overburden under generally Mode I conditions, liquefaction and fluidized flow of the sand/fluid mixture from the parent sand body, and multiphase flow to fill the mode I fracture sets (sandstone dykes and sills) (Jolly and Lonergan, 2002; Hurst and Cartwright, 2007). From a mechanical perspective, the occurrence of sandstone dykes and sills provides unequivocal evidence of pure tensile failure and opening at a range of formation depths in the subsurface. Gretener (1980) was the first to recognise the significance of this, correctly identifying their origin as due to hydraulic fracturing, and drawing an analogy with artificial hydraulic fractures induced in wellbore stimulation. His analogy drew on the pioneering theoretical analysis of artificial hydraulic fracturing by Hubbert and Willis (1957), who had suggested that igneous dykes and sills were natural examples of hydraulic fracturing induced by high pressure fluid injection.

Until fairly recently, sandstone intrusions have not generally been considered to have any significance for resource geology such as hydrocarbons, water or minerals, and have therefore been generally overlooked in the large subsurface databases (wells and seismic) that exist in sedimentary basins. In the past decade, the wider availability of 3D seismic data coupled to high resolution well log data has led to the increasing identification of sandstone intrusions in a number of

* Corresponding author.
E-mail address: joe@ocean.cf.ac.uk (J. Cartwright).

0191-8141/$ – see front matter
doi:10.1016/j.jsg.2008.03.012

petroliferous sedimentary basins (Dixon et al., 1995; Lonergan and Cartwright, 1999; MacLeod et al., 1999; Lonergan et al., 2000; Molyneux et al., 2002; Hurst et al., 2005; Huuse et al., 2004) (Fig. 1). These sandstone intrusions range from a few centimetres up to several kilometres in dimension and exhibit a range of geometries from dykes and sills to lensoid bodies with interconnected sill-like protrusions termed 'wings' (Huuse et al., 2003).

The largest truly intrusive sandbodies thus far recognised are of reservoir scale, i.e. with thicknesses of >40 m, and lateral extents of >1 km. In some cases, recent drilling has indeed shown sandstone intrusions to be acting as hydrocarbon reservoirs in an intrusive form of hydrocarbon trap (Lonergan and Cartwright, 1999; MacLeod et al., 1999), thus highlighting the need to improve our understanding of their genesis to aid in predictive reservoir modelling (Hurst and Cartwright, 2007).

This paper focuses on a specific class of sandstone intrusion, commonly observed on 3D seismic data. This class of conical or bowl-shaped intrusion was first described by Molyneux et al. (2002), but they were previously identified in unpublished reports by geologists for Fina (UK) Ltd. (M. Cope and R. Laver, personal communication, 1992). They have subsequently been identified within Cenozoic successions throughout the North Sea and Faeroe–Shetland Basins (Løseth et al., 2003; Huuse et al., 2004; Shoulders and Cartwright, 2004; Shoulders et al., 2007). Unlike the much steeper dykes, they are exceptionally well imaged by 3D seismic data because they tend to dip at less than 40°.

Recent studies based on 3D seismic imaging of these types of conical or bowl-shaped intrusions have described their basic three-dimensional geometry (Molyneux et al., 2002; Huuse et al., 2004, 2007; Shoulders and Cartwright, 2004; Shoulders et al., 2007). The main aims of this paper are: (1) to refine the existing description of the geometry of conical and bowl-shaped intrusions, (2) quantify their dimensions, and (3) examine their relationship with the host strata, all with an underlying goal of explaining their emplacement. Frequent use is made of analogy with igneous sills of comparable geometry, and the established theoretical framework for igneous sill emplacement is adapted to present a qualitative model for the emplacement of conical sandstone intrusions.

The discussion focuses on differences between two commonly observed end-members of a geometrical spectrum of conical sandstone intrusion types, the apical cones and the flat-based bowls. The paper closes with a discussion of the implications of the intrusions for basin hydrodynamics, as a stimulus for future theoretical analysis of these extraordinary structures.

2. Background and basinal context

Large scale conical or bowl-shaped sandstone intrusions have thus far only been described from the North Sea and Faeroe–Shetland Basins where they are widely distributed in both slope and basin floor environments (Fig. 1). In both basins they are intruded into the fine-grained slope successions of the Palaeocene to Miocene (Molyneux, 2001; Shoulders and Cartwright, 2004). These sediments are clay-rich (typically >50%), dominated by smectite, have extremely low permeability (Yang et al., 2004) and are presently slightly overpressured (Teige et al., 1999). Their pore fluid pressure at the time of intrusion is unknown.

The typical seismic expression of these sandstone intrusions is shown in Fig. 2, as irregular, high amplitude reflections, exhibiting an obvious discordant relationship to the host stratigraphy. When mapped using 3D seismic, these discordant reflections are found to exhibit a spectrum of geometries that differ from any known depositional geometry. This spectrum has two end members: (1) *apical cones*, consisting of smooth to irregular, concave upwards or inverted cones, with fairly sharp, downward facing apices, and (2) *flat-based bowls*, defined by a concordant central sheet and peripheral inclined margins or 'wings' (Fig. 3). This latter end member is similar to the geometry exhibited by many bowl-shaped igneous sills (Smallwood and Maresh, 2002; Hansen et al., 2004; Cartwright and Hansen, 2006). The conical intrusion end member has several possible natural analogues (see Section 6), and similar geometries have also been produced experimentally in laboratory simulations of artificial hydraulic fracturing (Hubbert and Willis, 1957, their Fig. 24; Chang, 2004).

The slope and basin floor sediments that host the intrusions are intensely deformed by polygonal fault systems (Cartwright, 1994;

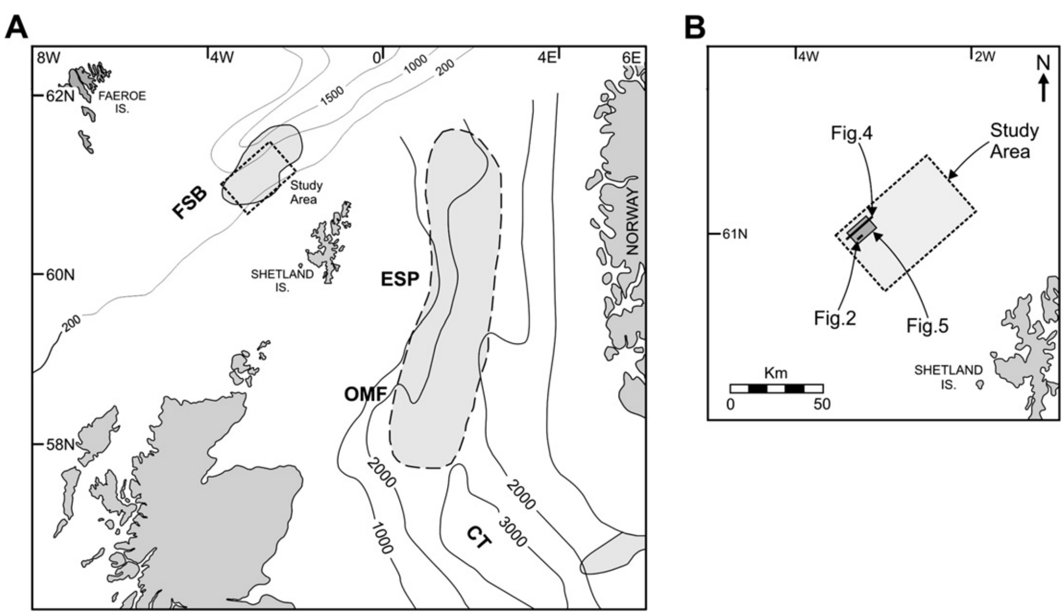

Fig. 1. (A) Location map and distribution of large-scale intrusions in the Faeroe–Shetland Basin (FSB), and North Sea Basin (from Huuse and Mickelson, 2004; Shoulders et al., 2007). Areas in grey tone are regions in which large numbers of conical sandstone intrusions have been observed on 3D seismic data. Rectangular dotted area in FSB is study area from which most of the seismic examples in this paper are taken. Contours in FSB are bathymetry in metres. Contours in the North Sea region are depth in metres to the Top Chalk. ESP , East Shetland Platform ; OMF , Outer Moray Firth ; CT , Central Trough. (B) Location map of study area in Faeroe–Shetland Basin, with location of other figures marked.