Tectonophysics 674 (2016) 76–88

Contents lists available at ScienceDirect

Tectonophysics

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

A Late Paleozoic sill complex and related paleo-topography in the eastern North Sea analyzed using 3D seismic data

Ole Rønø Clausen *, Katrine Juul Andresen, Jens Andreas Rasmussen [1]

Department of Geoscience, Aarhus University, DK-8000 Aarhus C, Denmark

ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form 11 January 2016
Accepted 5 February 2016
Available online 16 February 2016

Keywords:
North West European Craton
Ringkøbing-Fyn High
Paleozoic volcanism
Sill Intrusions
3D seismic

ABSTRACT

In this paper, we utilize large igneous intrusions as a key to a detailed analysis and understanding of the late Paleozoic evolution of the Ringkøbing-Fyn High, an important structural element in the North West European Craton. The study takes advantage of high-quality 3D seismic data and boreholes to map the geometry and lateral distribution of intrusive sills cross-cutting the sedimentary strata at a low angle (transgressive sills). Our analysis shows that the transgressive sills most likely sourced the vast extrusion of volcanics, which covered most of the Early Permian Northern Basin and which is associated to the Skagerak-Centered Large Igneous Province (SCLIP). Furthermore, a geometrical analysis of the sills demonstrates that the magmatic source for the sills was located SE of the studied area, suggesting a correlation with geophysically inferred lower crust intrusions. Hence, we are in this study able to constrain the full magmatic system from the lower crust intrusions to the surface volcanics. Intrusion of the sills occurred prior to an Early Permian faulting event, which created rotated fault blocks outlining the present Ringkøbing-Fyn High. The sills exposed for erosion at the crest of the footwall in turn controlled the Late Permian paleo-topography and the distribution of the Zechstein evaporites due to the fact that they are harder to erode. Hence, we are able to demonstrate a topography controlled thickness variation of the Zechstein evaporites. The study furthermore emphasizes that an understanding of the deepest parts of the North Sea Basin is crucial when evaluating the potential for yet unrecognized hydrocarbon plays.

1. Introduction

Recognizing and mapping both magmatic and sediment intrusions in sedimentary basins has been the subject of studies in the last century (e.g., Newsom, 1903; Tweto, 1951). The commencement of 2D seismic data as well as state-of-the-art 3D seismic data in sedimentary basins and along passive margins have increased the geometrical and dynamical understanding of intrusive magmatic sill complexes in the subsurface significantly (e.g., Løseth et al., 2009, Magee et al., 2013). This understanding enables us to use the occurrence of intrusions and their geometry in the deep subsurface to unravel the early evolution of deep basins or the sedimentary succession lying beneath the basins. The present study is focused on the pre-Zechstein succession, i.e., below the top pre-Zechstein surface, which often is referred to as the "seismic basement" because of the poor resolution of the units below. However, in the present study area the investigated units are relatively shallow and it is possible to resolve the geometry of the pre-Zechstein succession.

The eastern North Sea comprises the eastern part of the northern Permian Basin, the Ringkøbing-Fyn High and parts of the Southern Permian Basin (Fig. 1), which are parts of the Northwest European Craton. The Southern Permian Basin has historically been intensely investigated because of the presence of commercial hydrocarbon discoveries (Breunese et al., 2010), in contrast to the Northern Permian Basin and the Ringkøbing-Fyn High, which have been deemed economically uninteresting and consequently lesser intensely explored outside of the Central Graben and Viking Graben fairway. The top pre-Zechstein (TPZ) constitutes the flooding surface in the Permian Basins, initializing the Late Permian sedimentation. In the central and eastern North Sea, volcanoclastic sediments and volcanic rocks are observed in deep wells and constitute a significant portion of the Lower Permian succession (Aghabawa, 1992; Stemmerik et al., 2000, Glennie et al., 2003). Heeremans and Faleide (2004) interpreted the presence of transgressive sills (intrusions which cut the sedimentary bedding at a low angle) in the eastern North Sea area using 2D seismic data (their Fig. 4); however, due to the locations of the seismic lines, it was not possible to map these in detail. They merely stated that intrusions are present in the area. 3D seismic data are an optimal tool for identifying and mapping the geometry of intrusive bodies in sedimentary successions (D.M. Hansen et al., 2004; Hansen and Cartwright, 2007). However, due to the absence of productive hydrocarbon plays east of the Siri Canyon (Hamberg et al., 2005), there is only a single 3D seismic survey available in the easternmost North Sea. The AG9801 survey is located at the northern flank of the Ringkøbing-Fyn High, in an area where

* Corresponding author.
E-mail address: ole.r.clausen@geo.au.dk (O.R. Clausen).
[1] DONG Energy, Kraftværksvej 53 DK-7000 Fredericia.

http://dx.doi.org/10.1016/j.tecto.2016.02.010
0040-1951/

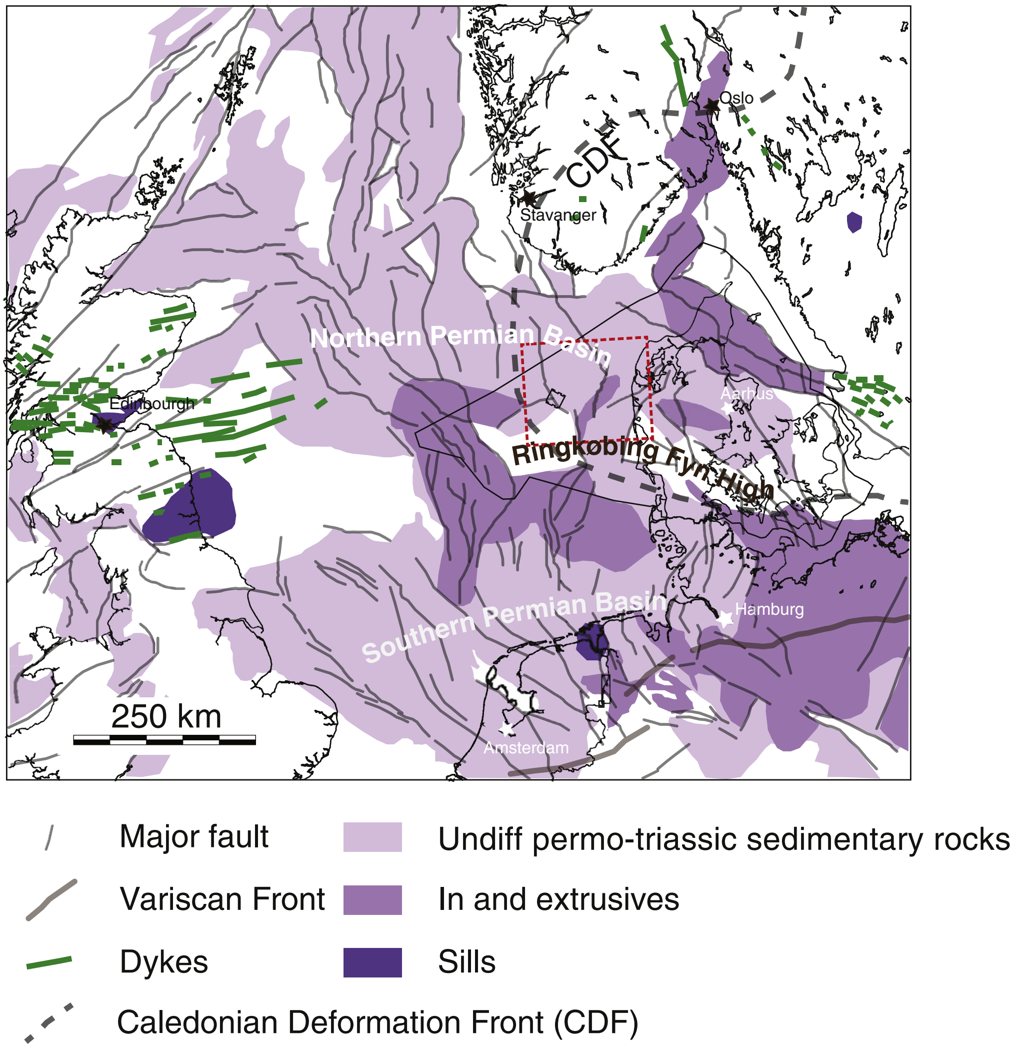

Fig. 1. Map of the greater North Sea area with the extent of Permo-Triassic sediments, as well as the major structures, outlining the shape of the Northern and Southern Permian basins. The basins are separated by the Ringkøbing-Fyn High and the Mid North Sea High. Extrusives and intrusives (sills and dykes) of the area are also indicated. The studied area for this paper is indicated by the small black outline of the 3D seismic survey AG9801 within the larger dashed red box which shows the location of the maps in Fig. 2. Apparently, no intrusives or extrusive occur within the study area. The identification of the intrusives and extrusives is however until now primarily identified from well information. CDF (dashed line) indicates the position of the Caledonian deformation front. Modified from Heeremans and Faleide (2004) and Abramovitz and Thybo (2000).

volcanics have been reported (Heeremans and Faleide, 2004) (Fig. 1), and the Paleozoic succession is encountered at very shallow depth. Thus, the 3D seismic imaging of the shallow Paleozoic succession is of relative high resolution, which enables a detailed interpretation of sills.

The objectives of this study are to use the high-quality 3D seismic data to analyse in detail the spatial distribution of Late Paleozoic intrusions and to unravel the structural and stratigraphic interactions and implications of the intrusions within the Ringkøbing-Fyn High.

1.1. Geological setting

The Paleozoic evolution of the eastern North Sea is dominated by an interaction of the Caledonian orogeny and the Variscian orogeny overprinted by Late Carboniferous–Early Permian rifting associated with extensive igneous activity (e.g., Coward et al., 2003; Ziegler, 1990). Thermal subsidence following the Late Carboniferous–Early Permian rifting created the Northern and Southern Permian basins separated by a number of structural highs striking approximately E–W constituting the Mid North Sea High and the Ringkøbing-Fyn High (Fig. 1) (Vejbæk & Britze, 1994). Vejbæk (1997) concluded that the highs were formed due to lesser stretching causing initial lesser subsidence, but also due to the crustal architecture with the Moho located deeper under the Ringkøbing-Fyn High than in the adjacent basins, partly controlling the later subsidence. Geophysical modelling and deep reflection and refraction seismic lines confirm this interpretation (Gemmer et al., 2002; Frederiksen et al., 2001; Abramowitz and Thybo, 2000). Lassen and Thybo (2012) presented a near-top crystalline basement map of the area (see Fig. 2a) as well as a thickness map of the Paleozoic succession (see Fig. 2b). Their study indicated a number of Paleozoic fault-controlled depositional centers (Fig. 2a) with adjacent areas probably containing thick successions of pre-Zechstein Paleozoic sediments (Fig. 2b).

Early Permian basalts interpreted as intrusive sills are observed within Silurian sediments in deep exploration wells onshore Denmark (Fig. 3) (Larsen, 1971; Vejbæk, 1997). Volcanics and volcanoclastic are furthermore encountered in a number of offshore wells in the easternmost Danish North Sea (Fig. 3) typically below the base of the Upper Permian (Zechstein) if present or if absent directly below younger sediments (Aghabawa, 1992; Vejbæk, 1997; Nielsen and Japsen, 1991). In the wells C-1, D-1, R-1, and L-1 adjacent to the study area, igneous rocks are encountered (Fig. 3). The igneous rocks (basalts and rhyolites) in these wells are interpreted as volcanic flows (Aghabawa, 1992) and are dated to be of Early Permian age (Fig. 3; Larsen, 1971; Aghabawa, 1992; Stemmerik et al., 2000). Onshore Denmark in a structural location