Marine and Petroleum Geology 61 (2015) 39–55

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Salt on the move: Multi stage evolution of salt diapirs in the Netherlands North Sea

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A R T I C L E I N F O

Article history:
Received 30 May 2014
Received in revised form
4 December 2014
Accepted 8 December 2014
Available online 16 December 2014

Keywords:
Salt tectonics
Sedimentation
North Sea
3D seismic

A B S T R A C T

After more than half a century of research, the dynamics of salt tectonics in the North Sea remains a contentious issue with unresolved questions regarding triggering and driving mechanisms. The North Sea is now covered by high-quality 3D seismic datasets which allow new insights into the interplay between salt tectonics and sedimentation. These insights are of both regional geological, societal and exploration interest as well as more widely applicable as analogues for salt tectonics in frontier regions such as the South Atlantic salt basins. A high quality 3D seismic volume from the Netherlands North Sea is used to show the thick and mobile Zechstein halite sequence of Late Permian age remobilized in several phases into complex salt structures. Early stage structural evolution was dominated by Triassic NNE–SSW and NW–SE trending salt ridges. Salt tectonic reorganization was triggered by regional shortening in the Campanian. Salt was transferred both laterally and vertically, creating salt anticlines and tall asymmetrical salt diapirs. Vertical growth of the tallest salt diapirs continued in pulses in the Plio-Pleistocene likely driven by increased sediment input from southern North Sea delta systems. The most recent deformation affects Late Pleistocene and Holocene sediment and could have impacted on the landscapes of Meso-Lithic human occupied sites. The recent activity of some salt domes should be considered when planning repositories for gas and nuclear waste.

1. Introduction

During the Late Permian, Zechstein evaporites including halite and gypsum were deposited in the Southern Permian Basin (Ziegler, 1990; Glennie, 1998). The evaporites later became remobilized to form salt structures across the southern and central North Sea (Jenyon, 1984, 1985, 1988; Remmelts, 1995, 1996; Stewart and Coward, 1995; Davison et al., 2000; Rank-Friend and Elders, 2004; Geluk et al., 2007; Stewart, 2007; ten Veen et al., 2012). This remobilization has affected all elements of the petroleum play within the North Sea (trap, seal, hydrocarbon migration routes, reservoir quality) and therefore has been of interest to the hydrocarbon industry since first investigated by Trusheim in the 1950's (Trusheim, 1960).

The availability of high quality 3D seismic data and hundreds of borehole penetrations of the entire evaporite sequence make the North Sea basin a type area for the study of salt tectonics. The North Sea can be used to gain insights transferrable to frontier margins and basins. In the South Atlantic salt basins, for instance, salt tectonics plays a key role in generating trapping geometries above the salt and forms an extensive and effective seal to world class hydrocarbon accumulations (Beglinger et al., 2012a,b; Borsato et al., 2012).

Salt structures in NW Europe are a potential target for nuclear waste deposition due to the impermeability of the Zechstein salt (Bornemann, 1991; Remmelts, 1995; Koyi, 2001; Stewart, 2002). Understanding the controls of salt movement in the past can inform predictions of whether salt structures in the North Sea are likely be active in the future. Salt tectonics in the North Sea also has interest for human history as salt diapirs were influencing topography of inhabited areas such as Doggerland in the Meso-Lithic (Holford et al., 2007).

Despite this interest, questions remain regarding the mechanisms controlling salt mobility in the North Sea. The purpose of this study is to use high resolution 3D seismic data to elucidate the timing and evolution of a complex salt diapir in the south of the Netherlands North Sea using the seismic stratigraphic record of salt–sediment interactions. This case study highlights the

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http://dx.doi.org/10.1016/j.marpetgeo.2014.12.003
0264-8172/

importance of successive thickness maps in understanding past salt movements and the use of supra salt faulting to determining whether salt diapirs were in an active or passive phase.

1.1. Salt tectonics

Salt structures are unlikely to develop spontaneously from a tabular layer of evaporites due to buoyancy alone; initiation of salt movement is attributed to regional extensional deformation (Trusheim, 1960; Kockel, 1995; Koyi et al., 1993; Vendeville and Jackson, 1993; Jackson and Vendeville, 1994) or gravity spreading (Fort and Brun, 2012).

Phases of salt diapirism are described as 'Reactive', 'Active' and 'Passive', in an extensional regime, by Jackson and Vendeville (1994). Reactive diapirism occurs in response to extension of the brittle overburden and is the chief initiator of salt diapirism (Vendeville and Jackson, 1993). The process can operate regardless of original overburden thickness and strength (Koyi et al., 1993; Vendeville and Jackson, 1993). The extension creates space above the salt layer, which allows the salt to emplace into overlying normal fault bound grabens (Hudec and Jackson, 2007). Reactive diapirism creates triangular pointed crest geometries and is generally associated with the creation of early stage salt walls.

The transition to active diapirism occurs when the reactive diapir has gained sufficient vertical extent and the overburden has been thinned by extension. Differential loading is the main driving force behind vertical movement in this phase. The salt diapir will actively intrude into the overburden (Schultz-Ela et al., 1993) lifting the overburden 'roof' above regional datum, rotating and shouldering it aside (Jackson et al., 1994).

The progression to passive diapirism occurs when the diapir has intruded and pushed aside the overburden to the point of salt emergence at the sedimentation surface (Hudec and Jackson, 2007). The crest of a passive salt diapir remains at the surface whilst sediments subside around the diapir.

Regional shortening can amplify existing salt structures, or create salt anticlines where halokinesis has not disturbed the salt layer previously (Koyi, 1988; Stewart and Coward, 1995; Koyi, 1998; Sans and Koyi, 2001). The salt layer is mechanically weaker than the surrounding sediments. This enables amplification of original salt structures undergoing lateral compression, as the underlying salt flows into the core of the anticline (Hudec and Jackson, 2007).

Salt structures amplified by shortening have typical characteristics including episodic growth, allowing thick sets of strata to be deposited above the diapir in between growth periods. They also are characterized by narrower or pinched off conduits from the salt layer and strata adjacent which are little deformed, as the deformation is taken up within the salt layer (Warren, 2006).

1.2. Regional geology

The geology of the Netherlands North Sea is characterized by the interaction of E–W trending structural elements of the Southern Permian Basin and the NW–SE and NNE–SSW elements of the Mesozoic sub basins (Ziegler, 1990; Glennie, 1998; Duin et al., 2006).

The area of study is on the southeastern border of the Late Kimmerian (154–140 Ma) Terschelling Basin (TB) with the Ameland Block (AB) (Fig. 1). NNE–SSW trending faults separate the Terschelling Basin from the Ameland Block (Duin et al., 2006). The Late Carboniferous Hantum Fault Zone bounds the basin to the south. The Hantum Fault Zone is made up of WNW–ESE trending synthetic strike slip faults and NW–SE antithetic strike slip faults (De Jager and Geluk, 2007).

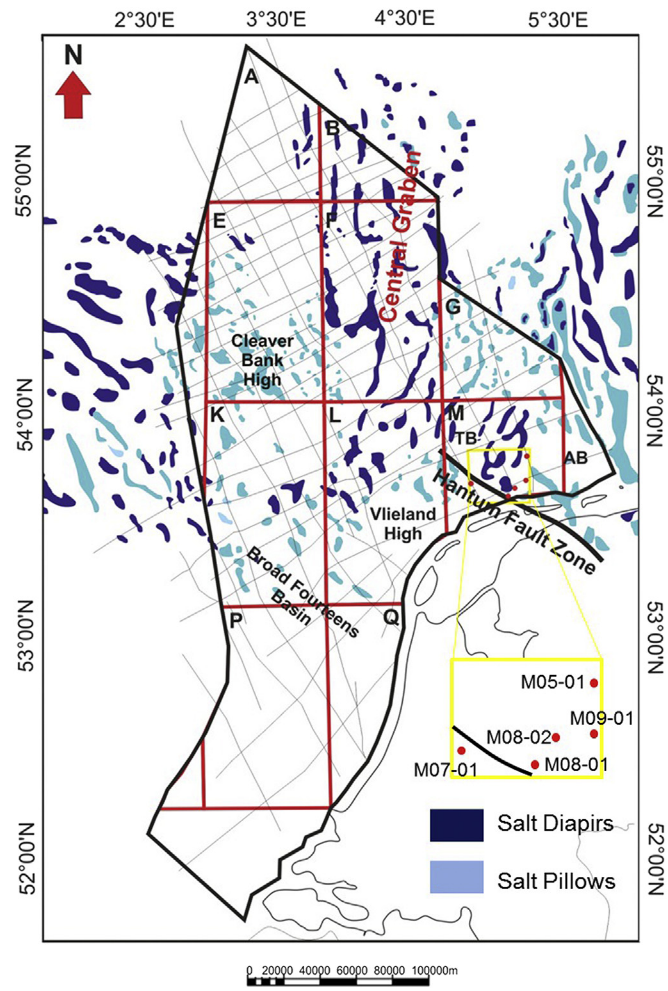

Figure 1. Location and dataset map. Map adapted from Doornenbal and Stevenson (2010); Netherlands North Sea License Quadrants and main structural elements labeled. Yellow Box indicates location of 3D seismic survey *Z3NAM1996A*. Well data used labeled in red. AB = Ameland Block; TB = Terschelling Basin. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

A major extensional phase in the Early Triassic was associated with the reorganization of tectonic plates in the Late Permian to Early Triassic (Ziegler, 1990). Jurassic uplift and extension (Mid to Late Kimmerian 178–140 Ma) is correlated with thermal doming in the North Sea followed by rifting associated with the continental break up of North-West Europe and North America (Glennie, 1998). Tectonic phases and lithostratigraphy are detailed in Figure 2.

The Terschelling Basin was moderately inverted during the Late Cretaceous and Early Paleocene, the consequence of the Subhercynian (86–72 Ma) and the Laramide (~61 Ma) tectonic phases (De Jager, 2003). The inversion was mainly accommodated by transpressional movement in the Hantum Fault Zone in the south west of the study area. The area again was under a contractional tectonic regime in the Late Eocene to Oligocene associated with the Pyrenean–Savian tectonic phase (Knox et al., 2010) whilst sediment loaded subsidence became dominant from the Late Miocene (Duin et al., 2006).

1.3. North Sea salt tectonics

Previous studies of salt tectonics in the North Sea have used regional 2D and individual 3D seismic surveys to study the