Physiography of the NE margin of the Permian Salt Basin: new insights from 3D seismic reflection data

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Three-dimensional seismic reflection data from the Egersund Basin, offshore Norway image geomorphological features that record mid-Permian footwall degradation of basin-bounding fault systems. This ancient landscape was subsequently flooded during the pan-European, Late Permian transgression of the North Permian Salt Basin and was fossilized beneath Zechstein Supergroup evaporites. We provide the first conclusive evidence for pre-Zechstein normal faulting in the Egersund Basin, indicating that extensional strain was shared between Permian and Late Jurassic–Early Cretaceous rift events.

Supplementary materials: Uninterpreted versions of the seismic sections shown in Figure 2 are available at www.geolsoc.org.uk/SUP18678.

The Zechstein Supergroup is a pan-European, evaporite-dominated unit that documents repeated flooding and desiccation of a restricted marine sea during the Late Permian (the Permian Salt Basin). The present-day extent of and lithological variability within the Zechstein Supergroup reflect both the depositional extent of the unit, which was controlled by the syndepositional basin physiography, and subsequent erosion and dissolution. Previous studies in the UK sector of the North Sea have shown that the Zechstein Supergroup was deposited on an overall ramp-like margin, and is halite-rich in the basin centre, and anhydrite- and carbonate-rich at the basin margin (e.g. Tucker, 1991; Smith et al. 1993; Clark et al. 1998; Cartwright et al. 2001). However, the role of pre-Late Permian, rift-related normal faulting had on the primary geometry and extent of the Zechstein Sea is contentious, principally owing to a lack of studies that have unequivocally determined the morphology and evolution of pre-Zechstein faults. Where faults are identified, they are associated with relatively rapid, across-fault changes in evaporite thickness and lithology, although it is unclear if fault movement occurred before, during or after deposition (e.g. Høiland et al. 1993; Penge et al. 1993; Dickinson 1996; Clark et al. 1998; Stewart & Clark 1999; Cartwright et al. 2001). Furthermore, because large parts of the NW margin of the Permian Salt Basin are covered by only vintage, regional 2D seismic data, the identification of geomorphological features (e.g. fault-scarp degradation complexes) that might help differentiate between pre-, syn- and post-Zechstein faulting is challenging (see discussion by Clark et al. 1998).

Motivated by these previous studies and uncertainties, we aim to determine if pre-Late Permian normal fault systems controlled the location of the NE margin of the Permian Salt Basin. This first requires accurately defining the present-day structure of the margin, before seismic-stratigraphic relationships and geomorphological features can be used to assess the temporal and spatial evolution of key structures. To fulfil these objectives, we used 3600 km² of modern, high-quality, pre-stack time-migrated, 3D seismic reflection data that have a line spacing of 12.5 m and a vertical resolution of c. 40–60 m within the stratigraphic interval of interest (i.e. based on an interval velocity of c. 4200 m s⁻¹ and a peak frequency of 20 Hz). Constraints on the age and lithology of the mapped seismic packages are provided by four boreholes that contain wireline log and biostratigraphic data (see Jackson & Lewis 2012; Jackson et al. 2013; Lewis et al. 2013).

Tectonostratigraphic framework of the Egersund Basin. The Egersund Basin is located offshore Norway (Fig. 1a) and is interpreted to have initiated during Carboniferous–Permian rifting, although geophysical or geological data to support this inference have, up to now, been lacking (Sorensen et al. 1992; Glennie 1998). During the Late Permian, repeated flooding and desiccation of a restricted marine sea (the Permian Salt Basin) resulted in deposition of the thick, pan-European, evaporite-dominated succession (Zechstein Supergroup, Fig. 1b). This unit, which forms the major mechanical detachment across much of the southern part of the North Sea Basin, pinches out to the NE onto the immediate footwall of the basin-bounding Stavanger Fault System (line labelled ‘X’ in Fig. 1c). During the Triassic, regional extension and activity on basin-bounding fault systems triggered flow of the Zechstein Supergroup, controlling deposition of a non-marine succession (Smith Bank and Skagerrak formations; Fig. 1b) (Jackson et al. 2013; Lewis et al. 2013). Regional extension and salt flow continued into the Middle Jurassic–Early Cretaceous, when normal faulting, coupled with a eustatic rise in sea level, caused relatively rapid subsidence that resulted in the deposition of an upward-deepening marine succession (Bryne, Sandnes, Egersund, Tau and Sauda formations; Fig. 1b) (Sorensen et al. 1992). Extension rates decreased during the late Early Cretaceous and basin inversion occurred in the Late Cretaceous (Jackson & Lewis 2012; Jackson et al. 2013).

Basin structure and seismic stratigraphy. The Stavanger Fault System forms a NNW–SSE-striking, 40 km long, WSW-dipping normal fault system. It has up to 1 km of throw at the NW end of the seismic survey, and this decreases towards its SE and NW tips (Fig. 1c). The Stavanger Fault System is basement-involved and offsets the top Rotliegend Group, although its upper tip is located at the base of the Zechstein Supergroup, and does not breach post-salt strata (Figs 1c and 2). Early Permian strata thicken across the fault, indicating that the fault was active during the Early Permian (Fig. 2d). In contrast, Triassic strata immediately above the upper tip of the Stavanger Fault System are broadly isochronous and are folded into an SW-facing monocline that formed as a result of forced folding above the underlying, upward-propagating fault; thinning of the Triassic further towards the north is related to structural attenuation across a number of salt-detached normal faults (Fig. 2d) (Lewis et al. 2013). Jurassic and Cretaceous strata thin across the monocline, implying that the structure was growing at this time and
that the underlying Stavanger Fault System was active (Fig. 2d). In the footwall of the Stavanger Fault System, a series of broadly NW–SE-striking, SW- and NE-dipping, low-throw (<50 m) normal faults are developed below the salt; these offset the top Rotliegend Group and tip out upward into the salt. A number of faults of similar orientation and attitude are developed above and tip out downward into the salt; these are larger than the sub-salt faults (up to 500 m throw) and formed in response to thin-skinned extension associated with salt-influenced forced folding (Lewis et al. 2013). Early Cretaceous strata thicken across these faults, suggesting that they were active at broadly the same time as the Stavanger Fault System and the overlying forced fold (Fig. 2d).

Intra-Permian seismic geomorphology and seismic stratigraphy. At top Rotliegend Group level, the footwall of the Stavanger Fault System dips gently (<5°) towards the south and a series of broadly NE–SW-trending erosional features are identified along the top of the Rotliegend Group (Fig. 2a). These features are up to 6 km long, at least 60 m deep, 0.5–1 km wide and are best developed to the south of the pinch-out of the overlying Zechstein Supergroup (Fig. 2a). The erosional features are restricted to the footwall of the Stavanger Fault System; the adjacent basinal areas are planar and subhorizontal at the same stratigraphic level (see hanging wall location in Fig. 1c). Owing to the relatively limited frequency content and vertical resolution of our seismic data, we are unable to image discrete stratal onlap of the Zechstein Supergroup onto top Rotliegend relief in the footwall of the Stavanger Fault System. However, it is clear that this relief results in subtle but seismically resolvable thickness changes in the Zechstein Supergroup (Fig. 2b and c). In addition, the Zechstein Supergroup increases in
of the Stavanger Fault System. (See (a) and Fig. 1c for location.) The location of (a) and Fig. 1c for location.) The location of (a) is shown. (e) Seismic section illustrating detailed geometry of erosion features in the footwall of the Stavanger Fault System. Location of section is shown in (b). (d) Fault-perpendicular (north–south) seismic section illustrating the structure and seismic-stratigraphic architecture of the Stavanger Fault System. (See (a) and Fig. 1c for location.) R, top Rotliegend; Z, top Zechstein; T, top Triassic; J, top Jurassic (see Fig. 1b).

Thickness from the footwall to the hanging wall of the Stavanger Fault System and Fault B; in the hanging wall of the fault system the unit forms a fault-parallel salt wall and displays an apparent downlap relationship with underlying Rotliegend Group (Fig. 2d).

**Interpretation and discussion.** We note that erosional features at top Rotliegend level have an irregular plan-view geometry, do not have the same morphology as any features in the overburden, and are clearly not consistently parallel to the inline (NE–SW) or crossline (NW–SE) direction of the seismic dataset. These observations suggest that these features have a geological origin and are not seismic artefacts related to multiples or a seismic survey acquisition footprint. Furthermore, we do not think that these features are a velocity-related artefact (i.e. velocity pull-up) related to very high-frequency lateral changes in salt velocity, as both halite and deeply buried, lithified carbonates, an important constituent of the Zechstein Supergroup at basin margin locations (Tucker 1991; Clark et al. 1998), have similar acoustic velocities (>4000 m s⁻¹).

A further key observation is that the erosional features are restricted to the footwall of the Stavanger Fault System, and they truncate and are overlain by Early Permian and Late Permian deposits, respectively, thus indicating that they are ‘middle’ Permian in age. Based on these observations, our preferred interpretation is that this suite of erosional features documents middle Permian subaerial degradation of the footwall of the Stavanger Fault System (Fig. 3a) (cf. Elliott et al. 2012). We interpret that the linear, north–south-elongate, erosional features are fluvial valleys, which were cut by the same fluvial systems that deposited the underlying Rotliegend Group. It is possible that these systems drained the Stavanger Platform, and fed sediment into the Egersund Basin at the southeastern tip of the Stavanger Fault System (Fig. 1c). A corollary of this interpretation is that the Stavanger Platform was exposed and created fault-bounded structural relief along this part of the NE margin of the Permian Salt Basin; the basin was therefore locally bound by a normal fault system, which was either dormant and simply inherited from the Early Permian rift event or active during deposition of the salt during the Late Permian (Fig. 3a). Subsequent flooding of the basin margin during the Late Permian resulted in sealing and ‘fossilization’ of this ancient landscape below evaporites of the Zechstein Supergroup (Fig. 3b and c). We interpret that the present-day extent of the Zechstein Supergroup, which pinches out onto these fault-bound structural highs, thus broadly reflects the depositional limit of this unit rather than a remnant related to subsequent, Jurassic–Cretaceous rift-related footwall uplift and erosion (Fig. 3a). We note that the Lista Nose is at a similar elevation at the present day to the outer edge of the Stavanger Platform, but appears to lack well-defined erosional features (Fig. 1c). This may simply reflect poorer seismic imaging of these subtle features in this location. An alternative interpretation is that the Lista Nose is a slightly younger structural feature (i.e. intra-Late Permian–Jurassic), thus its crest was not exposed and eroded prior to flooding of the Permian Salt Basin and deposition of the Zechstein Supergroup.

Based on the observations that Triassic strata are folded, but display no change in thickness across the fault tip, and that Jurassic and Cretaceous strata thin across the fault-tip monocline (Jackson et al. 2013; Lewis et al. 2013), we interpret that the Stavanger Fault System was dormant during the Triassic, but was reactivated during the Late Jurassic–Early Cretaceous rift event. The amplitude of the fold above the Stavanger Fault System is similar to the throw on the underlying structure (Fig. 2d), suggesting that most of the throw observed on the fault system was accrued during the Late Jurassic–Early Cretaceous rift event; however, sufficient throw was accrued during Early Permian rift-ting to create a topographic feature at the basin margin (Fig. 3).
Because of the increasing availability of modern, high-quality, 3D seismic reflection data across the margins of the Permian Salt Basin, future research should focus on detailed structural mapping and seismic geomorphological analysis adjacent to Zechstein Supergroup-related normal fault systems; this may not only provide further insights into the physiography of the Permian Salt Basin, but also will allow us to better understand how strain was shared between Permian–Triassic and Late Jurassic–Early Cretaceous rift events in the North Sea Basin. The approach outlined here would complement lower resolution methods (e.g. flexural backstripping and forward modelling) that have been applied elsewhere would complement lower resolution methods (e.g. flexural backstripping and forward modelling) that have been applied elsewhere.

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References

CARTWRIGHT, J.A., STEWART, S.A. & CLARK, J.A. 2001. Salt dissolution and salt-related deformation of the Forth Approaches Basin, UK North Sea. Marine and Petroleum Geology, 18, 757–778.

CHRISTIANSSON, P., FALÉIDE, J. & BERGE, A.M. 2000. Crustal structure in the northern North Sea: an integrated geophysical study. In: NØTTVEDT, A. (ed.) Dynamics of the Norwegian Margin. Geological Society, London, Special Publications, 167, 15–40.

CLARK, J.A., STEWART, S.A. & CARTWRIGHT, J.A. 1998. Evolution of the NW margin of the North Permian Basin, UK North Sea. Journal of the Geological Society, London, 155, 663–676.

DICKINSON, B. 1996. The Puffin field: the appraisal of a complex HP–HT gas-condensate accumulation. In: HEUST, A., JOHNSON, H.D., BURLEY, S.D., CANHAM, A.C. & MACKERTICH, D.S. (eds) Geology of the Humber Group: Central Graben and Moray Firth. UKCS. Geological Society, London, Special Publications, 114, 299–327.

ELLIOTT, G.M., WILSON, P., JACKSON, C.A.-L., GAWTHORPE, R.L., MICHIELSEN, L. & SHARP, I.R. 2012. The linkage between fault throw and footwall scarp erosion patterns: An example from the Bremen Fault Complex, offshore Mid-Norway. Basin Research, 24, 180–197.

GLENNIE, K.W. (eds) 1998. Petroleum Geology of the North Sea: Basic Concepts and Recent Advances. Blackwell Science, Oxford.

HØILAND, O., KRISTENSEN, K. & MONSEN, T. 1993. Mesozoic evolution of the Jaren High area, Norwegian Central North Sea. In: PARKER, J.R. (ed.) Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Geological Society, London, 1189–1195.

JACKSON, C.A.-L. & LEWIS, M.M. 2012. Origin of an anhydrite sheath encircling a salt diapir and implications for the seismic imaging of steep-sided salt structures, Egersund Basin, Northern North Sea. Journal of the Geological Society, London, 169, 593–599.

JACKSON, C.A.-L., CHUA, S.T., BELL, R.E. & MAGEE, C. 2013. Structural style and growth of early-stage inversion structures: Insights from 3D seismic reflection data, Egersund Basin, offshore Norway. Journal of Structural Geology, 46, 167–185.

LEWIS, M.M., JACKSON, C.A.-L. & GAWTHORPE, R.L. 2013. Salt-influenced normal fault growth and forced folding: The Stavanger Fault System, North Sea. Journal of Structural Geology, 54, 156–173, http://dx.doi.org/10.1016/j.jsg.2013.07.015.

PENG, J., TAYLOR, B., HUCKERBY, J.A. & MUNNS, J.W. 1993. Extension and salt tectonics in the East Central Graben. In: PARKER, J.R. (ed.) Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Geological Society, London, 1197–1209.

ROBERTS, A.M., YELLING, G., KUSZIN, N., WALKER, I. & DORN-LOPEZ, D. 1995. Quantitative analysis of Triassic extension in the Northern Viking Graben. Journal of the Geological Society, London, 152, 15–26.

SMITH, R.L., HEDDON, N. & FULTON, M. 1993. Salt control on Triassic reservoir distribution, UKCS Central North Sea. In: PARKER, J.R. (ed.) Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Geological Society, London, 547–557.

SORENSEN, S., MOREZOT, H. & SKOTTHEIM, S. 1992. A tectonostratigraphic analysis of the southeast Norwegian North Sea Basin. In: LARSEN, R.M., BRIEKE, H., LARSEN, B.T. & TALLERAS, E. (eds) Norwegian Petroleum Society: Structural and Tectonic Modelling and its Application to Petroleum Geology. Proceedings of the Norwegian Petroleum Society Workshop, 19–42.

STEWART, S.A. & CLARK, J.A. 1999. Impact of salt on the structure of the Central North Sea hydrocarbon fairways. In: FLEET, A.J. & BOLDY, S.A.R. (eds) Petroleum Geology of NW Europe: Proceedings of the Fifth Conference. Geological Society, London, 179–200.

TUCKER, M.E. 1991. Sequence stratigraphy of carbonate-evaporite basins: models and application to the Upper Permian (Zechstein) of northeast England and adjoining North Sea. Journal of the Geological Society, London, 148, 1019–1036.

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