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doi: 10.1144/SP363.23
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Abstract: Most of the information on subsurface evaporitic structures comes from 3D seismic data. However, this data only provide limited information about the internal structure of the evaporites, which is known from salt mines and salt diapir outcrops. Brittle intra-salt layers (carbonate, anhydrite, clay) of at least 10 m thickness form good reflectors in evaporites, but the structure and dynamics of such ‘stringers’ in the salt movement are poorly understood. In this study, we investigate the intra-salt Zechstein 3 (Z3) stringer from 3D seismic data in an area offshore the Netherlands. Observations show complex deformation including boudinage, folding and stacking. Reflections from thin and steep stringer parts are strongly reduced, and we present different structural models and tests of these. We compare our observations to structural models from salt mines and analogue/numerical models of intra-salt deformation. A smoothed representation of the upper surface of the stringer fragments follows the shape of Top Salt, but smaller-scale stringer geometries strongly differ from this and imply boudinage. The imaged disharmonic patterns of constrictional folds provide evidence for the complexity of the intra-salt, in agreement with observations in salt mines. This may be explained by interaction of the layered salt rheology, complex three-dimensional salt flow, different phases and styles of basement tectonics and movement of the overburden.

The Southern Permian Basin in NW Europe is a classic area of salt tectonics (Ziegler 1990; Taylor 1998; Mohr et al. 2005; De Jager 2007; Geluk et al. 2007; Hübscher et al. 2007; Littke et al. 2008). Its evolution regarding salt tectonics strongly differs from what can be observed in passive-margin settings (e.g. Nigeria, Gulf of Mexico; Hübscher et al. 2007; Littke et al. 2008). The Dutch offshore part of the basin, where the study area is located (Fig. 1a), contains at least the lower four of the evaporitic cycles of the Late Permian Zechstein Group with a total thickness of 400–1000 m in c. 1.5–3 km depth (Z1–Z4, locally maybe Z5; Fig. 1b). The thick and dominant Z3 cycle contains a relatively brittle layer of anhydrite, carbonate and clay, which is fully encased in massive halite (‘stringer’). Whereas the Z1, Z2 and Z4 are also local reflectors, Z1 and Z2 are mechanically coupled to the underburden and the Z4 (+Z5) to the overburden. However, the Z3 stringer reflectors are mechanically decoupled from the sub- and supra-salt sediments (van Gent et al. 2011; Fig. 1b). According to Taylor (1998) salt movement is mainly accommodated by flow of Z2 salt, whereas the Z3 and Z4 salts are more or less ‘passively’ displaced. Halokinesis strongly influenced the geometry of the Z3 stringer (Geluk 1995; Burliga 1996; Behlau & Mingerzahn 2001; Bornemann et al. 2008; van Gent et al. 2011). The Z3 stringer in the Dutch offshore further shows a large variety of locally restricted and strongly varying deformation features, such as boudinage and folding associated with compression or shearing and extension or shearing, respectively (in the sense of Zulauf & Zulauf 2005; Zulauf et al. 2009). These features have been associated with the formation of salt domes, walls and pillows (Geluk 2000b; Geluk et al. 2007; van Gent et al. 2011) as well as extensional Z2 and Z3 salt thinning and supra-salt sediment basin growth (compare to data in e.g. Mohr et al. 2005). Similar structures have been observed in salt mines (e.g. Fulda 1928; DeBoer 1971; Richter-Bernburg 1972; Schléder & Urai 2005; Schléder 2006; Alsop et al. 2007; see also Fig. 2d). Field data is given by salt diapirs outcropping, for example, in the Iranian Dasht-e-Kavir (Jackson et al. 1990) and Zagros Mountains (Kent 1979) in Oman (Reunig et al. 2009; Schoenherr et al. 2009) and in the Spanish Pyrenees (Wagner et al. 1971), which may represent analogues for buried salt structures (Geluk 2000b).

Nevertheless, the structure of the intra-salt is still poorly understood in comparison to the external shape of salt structures. Field observations show complex folding and rupturing of an initially more or less continuous stringer, while modern
Fig. 1. (a) Location map of the study area (red dot) and main structural elements after De Jager (2007; image courtesy of the Nederlandse Aardolie Maatschappij) and Z3 palaeogeography (after Geluk 2000a) in its vicinity offshore Dutch, modified after van Gent et al. (2011). (b) Zechstein stratigraphy in the Netherlands (after Geluk 2007; based on Van Adrichem-Boogaert & Kouwe 1993–1997; Geluk 2000; TNO-NITG 2004). The red dot marks the projected position of the study site. In the right column the position of the seismically imaged stratigraphic units is indicated. Note that only the Z3 stringer is visible in seismic reflection data and is fully encased in Z2 and Z3 + Z4 halite.
Fig. 2. Depth maps of Top Salt (A), Z3 top stringer (B) and top pre-salt/Base Salt (C) in the study area modified after van Gent et al. (2011). (a) Interpolated interpretation surface of the Zechstein Top Salt. Prominent features are the SSW–NNE-trending salt wall in the centre, the adjacent deep rim syncline at the wall’s eastern flank and several larger salt domes and pillows mainly in the NW and SE area (see also Fig. 3a). (b) The interpreted Z3 stringer surface is a highly fragmented (‘floaters’) and seismically invisible in large parts, especially in the area of the central N–S salt wall as well as in other areas of prominent salt structures. In contrast, the stringer is well-imaged and smoother in, for example, the south-western area. (c) Interpolated interpretation surface of the top pre-salt corresponding to the Base Salt. Note the dominance of SE–NW-trending graben and upthrown blocks and some minor faults trending approximately SSW–NNE. (d) Example of the saltminer’s view on the internal structure of salt: schematic profile through a salt dome after Seidl (1921). Note the complexity of folding of a continuous stringer layer (black).
high-resolution 3D seismic data display a strong fragmentation of stringers (van Gent et al. 2011). Consequently, commercial drilling through the Zechstein is seriously hindered by unexpected stringers and related pressure kicks form major drilling hazards (Williamson et al. 1997; see also data in Kukla et al. 2011). In this study we aim to understand the complex geometries of the highly deformed Z3 stringer in the western Dutch offshore. We discuss our interpretation and the potential to (1) identify and trace the highly deformed intra-salt stringer in 3D seismic data and (2) quantify part of its deformation pattern compared to what is known of salt flow regimes both inside and outside major salt structures and intra-salt observations in salt mining. The results contribute to an understanding of 3D intra-salt structures and to novel non-destructive prediction methods of intra-salt structures before the creation of underground openings.

**Methods**

We used the seismic interpretation package Petrel 2007 and 2009 (Schlumberger) to study a PSDM (pre-stack depth-migrated) 3D seismic volume of c. 20 × 20 km² area and 3.5 km depth (Fig. 2). The lateral and vertical minimum resolution is of the order 20 m. Because of a high acoustic impedance contrast between the Z3 stringer (carbonate, anhydrite, clay) and the Z2 and Z3 salts above and below, the double-reflector Z3 stringer is reasonably well imaged in the seismic data. However, there are important imaging limitations related to the seismic quality and resolution (frequency content, noise level, processing details), but also regarding steeply dipping, thin parts of the stringer (Sleep & Fujita 1997; van Gent et al. 2011). Hence, if the thickness of the stringer is much below the tuning thickness of c. 30–35 m, it is not visible or has weak contrast and a careful interpretation is required. This also concerns the internal structure of the stringer, as the boundary between anhydrite (top) and carbonate (base) is mostly below the resolution of the data. Furthermore, the Base Salt and Top Salt are both strong reflectors and can locally lead to mistakes in interpretation of stringers in areas where they are close to the top or the bottom of the salt.

To trace the Z3 stringer we combined different interpretation techniques comprising manual horizon interpretation, 3D autotracking and surface interpolation. In areas of intense folding and overlapping (stacking) of stringer fragments (see Fig. 2b), additional horizons were implemented. Alternatively, a ‘fault interpretation’ routine was carried out allowing for doubled z-values, which are not allowed using conventional surface interpretation. Based on the resulting high-density point cloud, we interpolated the top stringer fragments to a surface ‘A’ (Fig. 3b) and smoothed it to a surface ‘B’ (Fig. 3c). Surface B is similar to the concept of an enveloping surface (Park 1997) whereas in this case it cuts through the stringer and does not cover it. The surfaces then enable a comparison of the local (surface A) and the regional (surface B) stringer geometry to that of the Top Salt (e.g. Fig. 3b). As proposed by van Gent et al. (2011) we adopt the concept of differences in thicknesses, geometries and structural styles of the bottom and the top reflector being associated with the Z3 carbonate (ZEZ3C) and the anhydrite (ZEZ3A), respectively.

**Study area**

The study area is located in the Dutch offshore (area introduced by van Gent et al. 2011 as ‘western offshore’; Fig. 2) on the Cleaver Bank High, directly north of the Broad Fourteens basin, and is in close proximity of the Sole Pit Basin and the Central Graben (Fig. 1a). Although these basins were inverted in the Cretaceous and Tertiary, the study area is located outside the area of erosion and thus appears less affected by those features (e.g. Geluk 2000a, 2005; de Jager 2003, 2007). During the Late Carboniferous, the Cleaver Bank High was tectonically active and uplifted. Between the Permian and the Middle Jurassic the Cleaver Bank High experienced no significant tectonic activity, but during the Late Jurassic–Early Cretaceous the Cleaver Bank High was uplifted and deeply eroded (Ziegler 1990). For more details of the regional settings, the stratigraphy and rheology of the Dutch offshore Zechstein, refer to de Jager (2003) and Geluk (2000a, 2005, 2007).

**Pre-salt and Top Salt**

On a regional scale, mapping of the reflector that represents the base of the salt section or the top of its
underburden displays SE–NW-striking graben structures and upthrown blocks, which have been associated with the Mesozoic tectonic inversion of the Broad Fourteens basin (van Gent et al. 2011; Fig. 2c). Furthermore, subordinate faults striking ESE–WNW and SW–NE are present (de Jager 2003; Schroot & De Haan 2003; van Gent et al. 2011; Fig. 2c). These structural features have been associated with multiple phases of tectonic movements in the pre-salt (e.g. Geluk 2000a, 2005). Dominant structural features of the Top Zechstein (Figs 2a & 3a, b) are a large NE–SW-striking salt wall which has a listric fault and asymmetric graben at its crest, an asymmetric salt withdrawal area below the downthrown block and accumulation below the upthrown block. In addition, several salt domes or pillows can be identified, of which the largest occur in the NW and SE of the study area (Figs 2a & 3a). Comparing Figure 2a and Figure 2c, salt thicknesses and Top Salt geometry at regional scale show no clear connection to tectonic features in the pre-salt units.

The Z3 stringer at regional scale

The study by van Gent et al. (2011) has already shown that the on average 40–50 m thick Z3 stringer (Figs 2b & 3b) has a complex structure dominated by boudinage and folding, frequently offset vertically over more than half of the total Zechstein thickness (Figs 4 & 5). On average the Zechstein salt thickness above the stringer is less than that below (Figs 4 & 5), and hence the stringer mostly occurs close to or at the Top Salt. However, single stringer fragments also occur locally in the central to lower salt section and can be of thickness above average (i.e. up to c. 70 m in this study area; Fig. 5, left side). For a concept of ‘thicker zones’, see van Gent et al. (2011).

In general, surface B (see section 2) displays large-scale folding that follows the Top Salt (white, dashed lines in Figs 4a & 5a) since all structures in the stringer are dislocated to the Top Salt are removed due to the smoothening (see Fig. 3c). On the smaller scale, the surface A (black, dashed lines in Figs 4a & 5a) images superimposed patterns of complex, constrictional and open to isoclinal folds with mean wavelengths of 400 m and fold amplitudes less than 200 m, disharmonic to surface B (see also Fig. 3c). This images a stringer geometry similar to salt mines (Fig. 2d). In many areas there is no continuous reflector even when the stringer is shallow-dipping (Figs 2b, 4b & 5b). This is interpreted as representing a disruption of the stringer into individual isolated fragments, especially in

![Fig. 4. (a) East–West seismic profile (for location see Fig. 2a) through the study area with the stringer interpolation surface A (black, dashed line) and the smoothed surface B (white, dashed line) and (b) its interpretation figure. In (b), blue represents the Z2–Z4 salt section between the pre-salt, brown the Basal Zechstein, Rotliegend and Carboniferous and yellow the sedimentary overburden. Note the differences in Z3 stringer geometry west and east of the central salt wall related to structural features of the Top Salt.](http://sp.lyellcollection.org/ at RWTH Aachen on February 19, 2013)
areas of the central salt wall (Fig. 2b) and salt domes in the NW and SE study area. We assume here that the investigated evaporitic sequence was a smooth and closed layer (Geluk 2007) prior to its deformation, disregarding other effects on its continuity (e.g. non-deposition, erosion, etc.).

**Observations and results: folding v. complex offsets of the stringers on a local scale**

Given the geometrical complexity of the Z3 stringer in the investigated area, an accurate tracing of the stringer is not always possible. This especially applies for areas where stringer thickness is below the resolution of the seismic data (i.e. <20 m) and/or the stringer is very steep. Hence, from the 3D seismic data there is no clear evidence that gaps between visible stringer fragments are connected by thin and steep stringer parts.

Building on the results presented by van Gent *et al.* (2011), we focus on a small example area (c. 400 × 400 m; Fig. 6) in the south-westernmost study area (for location see Fig. 2b). Surface A (Fig. 6a) images a complex pattern of smooth, open to tight folds. Since our stringer interpretation (dark areas in Fig. 6b) does not fully support a connected stringer, folding cannot be accepted as the only structural process. By comparing the seismically resolved stringer fragments (Fig. 6b) with gradient measurements of surface A (Fig. 6c), we see that locally steeply inclined (i.e. up to 70°) stringer parts are imaged. Furthermore, parts that are expected to be gently inclined (i.e. <30°) are not visible. These areas can therefore be interpreted as ‘real’ gaps most likely representing tectonic boudinage (with respect to an initially continuous Z3 evaporites layer).

Tracing such geometries across some selected seismic profiles with spacing of 250 m (Fig. 7; profiles B–D) clearly shows abrupt vertical offsets of up to 450 m in the stringer (Fig. 7; profile C). Two conceptual end-member models of this setting are shown in Figure 7e. Differentiation between these types of stringer deformation is not possible at this point. The intra-salt structure is much more complex than it would be expected from the relatively smooth Top Salt and surface B geometry in places (see e.g. Fig. 3b). Consequently, such offsets provide additional complexity to the stringer and show that the overall stringer geometry cannot be...
explained by simple models of either folding or boudinage.

Discussion

Regarding intra-salt stringers and their implication for evaporite deformation, the factors and processes of great importance for the internal tectonics and deformational style inside salt structures are (according to Geluk 2000b): rheology and mechanics of the evaporites; their thicknesses and spatial distribution; the types of salt structures; and the local and regional stress field history. We have shown that the structure of the stringer in the studied part of the Dutch Zechstein section cannot be easily associated with the Top Salt geometry. Consequently, our data and interpretation imply that the deformation in the salt can be locally much higher than it would be expected based on homogeneous salt rheology and Top Salt geometry. Furthermore, low (salt layers and pillows) and high (domes and diapirs) degrees of halokinesis do not necessarily correlate with the amount of deformation of the stringer (see also examples from Brazilian salt basins by Gamboa et al. 2008; Fiduk & Rowan 2012).

Local scale

Starting from our interpretation of the Z3 stringer folding and disruption (Fig. 3b), detailed observations of the order 10–100 m scale (Figs 6 & 7) imply that complexity of deformation cannot be explained by models of either (1) folding associated with thinning and steepening of parts of the stringer or (2) tectonic boudinage. The first is a likely model based on observations from salt mines (Fig. 2d) showing connected and complexly folded layers. The second is imaged in seismic data, but also shown from some salt mine examples (e.g. Schléder & Urai 2005). Regarding the first model, isolated, highly offset stringer fragments observed in both the lower and upper parts of the salt section may represent syncline- and anticline-type fold hinges. Seismically fuzzy areas between the stringer fragments may then be interpreted as the non-imaged, steep and thin fold limbs (see Fig. 7e; right side). Some of these thin and steep stringer parts intersecting seismically imaged fragments have been proven by hydrocarbon wells.

They favour a model of complex, superimposed patterns of folding being part of the seismically invisible stringer. On the other hand, the fuzzy areas between stringer fragments may represent real gaps related to tectonic boudinage, locally offset by vertical throws in the salt (Fig. 7e; left side).

Compared to prior studies investigating stringer occurrences in salt mines and outcrops, which show that intra-salt layer deformation likely combines both folding and boudinage on different scales (e.g. Schléder 2006), the connectivity of a stringer is most likely much higher than expected from seismic data interpretation. However, the models (i.e. boudinage v. folding) cannot be separated at this stage. Based on our interpretation, we assume that the overall folded shape of the investigated Z3 stringer, regardless of whether this may represent a continuous or fragmented layer, displays complex folding of the salt at different scales (compare Figs 2d & 3b). Furthermore, it implies that the deformation in the salt is not necessarily coupled to deformation in the underburden and the overburden.

Regional scale

At the regional (kilometre) scale, the central salt wall and the large, elongated rim syncline east of it are dominant drivers of salt drainage. Surrounding salt structures in the NW and SE may be also important, leading to superimposed salt flow regimes (e.g. Geluk 1995, 2005). Common models of simple salt flow towards salt structures (e.g. Chemia et al. 2008) do not match the observed stringer’s vertical throws also found in areas that appear to be less affected by lateral salt flow (e.g. Figs 5 & 7a–c). More complexity is introduced by the different orientations of stringer offsets (i.e. mainly parallel to the central salt wall but also NW–SE, N–S and NE–SW). We therefore hypothesize a vertical component in salt flow much larger than expected, in accordance to what is shown in salt mining literature (e.g. Fulda 1928; Bornemann 2008; Fig. 2d).

To provide a test for some of the hypotheses of how the Z3 stringer geometry came to be, we first anticipate possible impacts of structures in the underburden (i.e. graben and upthrown blocks) as well as rim syncline development in the overburden. Comparing our measurements of offsets in the underburden to those of stringer fragments in the salt column (e.g. Figs 4 & 5 and comparing Fig. 2b, c),

Fig. 6. (a) Interpolated surface (surface A) generated from the Z3 stringer interpretation, implying a superimposed complex pattern of open to tight folding of the stringer (for location see Fig. 2b). (b) A comparison of the interpolated stringer surface (a) to the basic stringer interpretation from seismic data: neither folding of a connected stringer surface nor strict breaking of the stringer to fragments is finally resolved for this area, while a combination of both is most likely. (c) Gradient map of the interpolated stringer surface showing that, compared to (b), the stringer can also be interpreted in very steep parts. With respect to the resolution of the seismic data, these gaps most likely represent boudins.
impacts of tectonics in the underburden are not likely first-order mechanisms of intra-salt deformation on the larger scale. On a local scale, offsets in the underburden likely contribute to locally restricted complex 3D salt flow. For example, upthrown blocks and graben structures may result in complex ‘corner flow’ with increased intensity of the stringer’s folding and breaking (e.g. Fig. 5).

If comparing structural features in the overburden to the overall stringer geometry (surface A), we propose that the development of rim synclines (Fig. 3a) in areas of a less-deformed stringer provide strong impacts on its deformation. The resulting large-scale salt depletion may provide a cut-off of the salt section preventing further drainage of salt (and stringer) to domes and diapirs (as it may apply for the salt structure in Fig. 5; right side). We therefore conclude that the deformation of the overburden most likely had an impact on the intra-salt structure on the large scale, while deformation in the underburden can be associated with some local impacts on the smaller scale (i.e. ‘corner flow’). In other words, although pre-salt tectonics and overburden sedimentary history and tectonics may have had first-order impacts on the structural features over a regional (kilometre) scale, the complexity of the stringer may only be explained by much more complex salt flow patterns. This may be related to rheological stratification in the salt body, which includes highly mobile potassium–magnesium salt layers in the upper part of the Z3 salt with bischofite, kieserite, carnallite and sylvite (see data in Williamson et al. 1997; Geluk et al. 2007; Urai et al. 2008). The internal mechanical stratigraphy of the Zechstein salt section is therefore proposed as having had a much larger effect on controlling the subsequent patterns of the internal structure than previously proposed by Urai et al. (2008).

Another possible mechanism to discuss is gravitational sinking of single isolated stringer fragments in the salt section (e.g. Koyi 2001; Chemia et al. 2008) as it may be interpreted, for example, for the highly offset stringer in Figure 7c. However, keeping in mind that the main phases of halokinesis in the studied area are Mesozoic and Cenozoic deformation (Geluk 2000a, 2005), and with respect to average sinking velocities of intra-salt bodies proposed from numerical (e.g. Chemia & Koyi 2008; Li et al. 2012) and analogue models (e.g. Koyi 2001; Callot et al. 2006), all the physically separate stringer fragments would have grounded since then (van Gent et al. 2011). Based on our seismic data we suggest that there is no conclusive evidence for sinking after the end of salt movement. Rather, we propose a model of non-cylindrical synclinal folds formed during salt flow, and both seismically invisible fold limbs and real gaps due to boudin fragments can be expected in between the seismically resolved fold hinges. The resulting pattern of stringer fragments finally results from superposed, polyphase folding and boudinage in the sense of Zulauf & Zulauf (2005), with negligible contribution by gravity-induced sinking.

Conclusions

The investigated Zechstein 3 stringer in the Dutch offshore part of the Southern Permian Basin shows a complex 3D structure as expected from salt mines and outcrops with a wavelength much shorter than that of Top Salt and an amplitude much larger than expected based on homogeneous salt rheology. This is in agreement with the expected rheological layering in the salt, further enhanced by the large contrast with the stringer and corner flow around upthrown blocks in the pre-salt. Polyphase superimposed patterns of brittle and ductile stringer deformation suggest very different behaviour in extension and shortening. Our data show no conclusive evidence for significant gravitational sinking of stringer fragments after the end of halokinesis. Interpretation of our data is limited by the fact that thin parts of the stringer in steep orientation are often not well imaged. Further work comparing well with seismic data is required to quantify this effect.

We thank the Nederlandse Aardolie Maatschappij (NAM), a Shell operated 50–50 joint venture with ExxonMobil for providing the high-resolution seismic data, and especially M. DeKeijzer and J. Verbeek for fruitful comments. We would also like to thank S. Becker and L. Reuning (RWTH Aachen University) for discussion. We thank reviewers G. Zulauf and M. Geluk for their comments and suggestions which greatly improved the quality of the manuscript.

Fig. 7. (a) Interpolated stringer surface (surface A; for location see Fig. 2b) with an E–W slicing seismic section showing examples of steep stringer offsets deeply incising the surface; (b) (c) and (d) depict a sequence of NW–SE seismic profiles with 250 m spacing showing details (interpretation in white boxes) of the observed steep and deep offsets in the stringer. (e) Sketches of possible end-member scenarios for the offsets in (d) explaining how such ‘offsets’ may look in nature. The first (left) deals with a breaking of the stringer and a subsequent offset of a fragment by vertical flows in the salt. The second (right) images a continuous stringer with a steeply inclined fold that is seismically not resolved because of the thin and steep fold limbs. Based on observations in salt mines (e.g. Fig. 2d), the second model may be favoured for parts of the stringer not imaged in seismic data.
References


