3D seismic study of complex intra-salt deformation: an example from the Upper Permian Zechstein 3 stringer in the western Dutch offshore

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Abstract

Most of the information of subsurface evaporitic structures comes from 3D seismic data. However, this data provide only limited information of the internal structure of the evaporites, which is known in salt mines and 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 stringer fragments upper surface follows the shape of Top Salt, but smaller scale stringer geometries strongly differs from this and imply boudinage and disharmonic patterns of constrictional folds imaging 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.
1. Introduction

The Southern Permian Basin in NW Europe is a classic area of salt tectonics (Ziegler 1990; Taylor 1998; Mohr et al. 2005; Geluk et al. 2007; Hübscher et al. 2007; De Jager 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 approximately 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 under- and the Z4 (+Z5) to the overburden, respectively. However, the Z3 stringer reflectors are mechanically decoupled from the sub- and supra-salt sediments (van Gent et al. in press; 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 2008; van Gent et al. in press). 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), which have been associated to the formation of salt domes, walls and pillows (Geluk 2000b; Geluk et al. 2007; van Gent et al. in press) 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 (Schoenherr et al. 2009; Reuning 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 with the external shape of salt structures. Field observations show complex folding and rupturing of an initially more or less continuous stringer, while modern, high-resolution, 3D seismic data display a strong fragmentation of stringers (van Gent et al. in press). 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. (this issue)). 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 (i) identify and trace the highly deformed intra-salt stringer in 3D seismic data and (ii) to quantify part of its deformation pattern compared to what is known of salt flow regimes in- and outside major salt structures and intra-salt observations in salt mining. The results contribute to understanding of 3D intra-salt structures and to novel, non-destructive prediction methods of intra-salt structures before the creation of underground openings.

2. Methods

We used the seismic interpretation package Petrel 2007 and 2009 (Schlumberger) to study a PSDM (Pre-stack depth-migrated) 3D seismic volume of approximately 20 x 20 km and 3.5 km depth (Fig. 2). The lateral and vertical minimum resolution is in the order of 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. in press). Hence, if the thickness of the stringer is much below the tuning thickness of about 30-35 m, it is not visible or has weak contrast, and 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 auto-tracking and surface interpolation. In areas of intense folding and overlapping (stacking) of stringer fragments (see Fig. 2B), additional horizons were implemented or 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) while our surface B 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. (in press) we adopt the concept of differences in thicknesses, geometries and structural styles of the bottom and the top reflector being associated to the Z3 carbonate (ZEZ3C) and the anhydrite (ZEZ3A), respectively.

3. Study area

The study area is located in the Dutch offshore (area introduced by van Gent et al. in press 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 to 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, we refer to de Jager (2003) and Geluk (2000a; 2005; 2007).
3.1 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 to the Mesozoic tectonic inversion of the Broad Fourteens basin (van Gent et al. in press; Fig. 2C). Furthermore, subordinate faults striking ESE-WNW and SW-NE are present (de Jager 2003; Schroot & De Haan 2003; van Gent et al. in press; Fig. 2C). These structural features have been associated to multiple phases of tectonic movements in the pre-salt (e.g. Geluk 2000a; 2005). Dominant structural features of the Top Zechstein (Figs. 2A, 3A and 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 ones occur in the NW and SE of the study area (Figs. 2A and 3A). Comparing Figures 2A and 2C, salt thicknesses and Top Salt geometry at regional scale show no clear connection to tectonic features in the pre-salt units.

3.2 The Z3 stringer at regional scale

The study by van Gent et al. (in press) has already shown that the on average 40-50 m thick Z3 stringer (Fig. 2B and 3B) has a complex structure dominated by boudinage and folding, frequently offset vertically over more than half of the total Zechstein thickness (Figs. 4 and 5). On average the Zechstein salt thickness above the stringer is less than below (Figs. 4 and 5), and hence the stringer mostly occurs close to or at the top salt. However, single stringer fragments locally also occur in the central to lower salt section and can be of thickness above average (i.e. up to ~70 m in this study area (Fig. 5, left side); see concept of ‘thicker zones’ by van Gent et al. (2010)).

In general, surface B (see section 2) displays large scale folding that follows the Top Salt (white, dashed lines in Figs. 4A and 5A), because all structures in the stringer disharmonic 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 and 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 and 5B). This is interpreted representing a disruption of the stringer into individual, isolated fragments, especially in areas of the central salt wall (Fig. 2B) and salt domes in the NW and SE study area. We here assume 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).

4. Observations and results: folding vs. 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. (in press), we focus on a small example area (~400 x 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 only cannot be accepted being the only structural process. Comparing the seismically resolved stringer fragments (Fig. 6B) with gradient measurements of surface A (Fig. 6C) shows 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. Based on this, at least those areas can 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 Fig. 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.

5. Discussion

Today's view on intra-salt stringers and their implication for evaporite deformation comprise factors and processes being of great importance for the internal tectonics and deformational style inside salt structures as summarized by 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 to the Top Salt geometry. Consequently, our data and interpretation imply that the deformation in the salt can locally be 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 to the amount of deformation of the stringer (see also examples from Brazilian salt basins by Fiduk & Rowan (this issue) and Gamboa et al. (2008)).

5.1. Local scale

Starting from our interpretation of the Z3 stringer folding and disruption (Fig. 3B), detailed observation in the order of 10- to 100-m scale (Figs. 6 and 7) imply that complexity of deformation cannot be explained by models of either folding associated with thinning and steepening of parts of the stringer or tectonic boudinage. The first is a likely model based on observations from salt mines (Fig. 2D), showing connected and complexly folded layers. The second one is imaged in seismic data, but also shown from some salt mine examples (e.g., Schléder & Urai 2005; Schléder 2006) and analogue
models (e.g., Zulauf & Zulauf 2005). In accordance to the first model, isolated, highly offset stringer fragments observed in both the lower and the 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, showing that intra-salt layer deformation likely combines both folding and boudinage on different scales (e.g. Schléder 2006, and references therein), the connectivity of a stringer is most likely much higher than expected from seismic data interpretation. But both models (i.e., boudinage vs. folding) cannot be separated at this stage. Based on our interpretation, we assume that the overall folded shape of the investigated Z3 stringer, regardless whether this may represent a continuous or fragmented layer, displays complex folding of the salt at different scales (compare Figs. 3B and 2D). Furthermore, it implies that the deformation in the salt is not necessarily coupled to deformation in the under- and the overburden.

5.2 Regional scale

At regional scale (km-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 found also in areas that appear to be less affected by lateral salt flow (e.g. Figs. 5 and 7A-C). More complexity is further given 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). Based on that, we hypothesise 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 and 5, and comparing Figs. 2B and 2C), impacts of tectonics in the underburden are not likely first-order mechanisms of intra-salt deformation on the larger scale. But on local scale offsets in the underburden likely contribute to locally restricted, complex, three-dimensional 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). Therefore, we 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 to 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 had first-order impacts on the structural features in regional scale (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 1997; Geluk et al. 2007; Urai et al. 2008). The internal mechanical stratigraphy of the Zechstein salt section is therefore proposed having much larger effects on controlling the subsequent
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 for example be interpreted for the highly offset stringer in Fig. 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. (this issue)) 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. in press). 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, while both seismically not imaged fold limbs and real gaps due to boudin fragments can be expected in between. The resulting pattern of stringer fragments then finally results from superposed, polyphase folding and boudinage in the sense of Zulauf & Zulauf (2005), with negligible contribution by gravity-induced sinking.

6. Conclusions

(1) The investigated Zechstein 3 stringer in the Dutch offshore part of the Southern Permian Basin shows a complex, three-dimensional 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;

(2) This is in agreement with the expected rheological layering in the salt, further enhanced by the large contrast with the stinger and corner flow around upthrown blocks in the pre-salt;

(3) Polyphase, superimposed patterns of brittle and ductile stringer deformation suggest very different behaviour in extension and shortening;
(4) Our data show no conclusive evidence for significant gravitational sinking of stringer fragments after the end of halokinesis;

(5) 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.

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References


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Figures:

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 paleogeography (after Geluk, 2000) in its vicinity offshore Dutch, modified after van Gent et al. (in press); B: Zechstein stratigraphy in the Netherlands (after Geluk 2007; based on Van Adrichem-Boogaert and Kouwe, 1993-1997, Geluk, 2000 and 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. (in press); 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 not imaged 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).
3) A: 3-D view from south on the interpreted Top Salt surface (see also Fig. 2A) combined to a z-slice of the investigated seismic volume in approximately 2 km depth. The prominent, N-S-trending salt wall and the adjacent rim syncline in the centre of the study area are most likely responsible for the bulk of the salt drainage in this area. Large salt domes in the NW and SE, and minor salt pillows in the NE and SW area are seen to provide a superimposed, complex salt movement; B: 3-D south-view on the Top Salt (coloured fishnet) and the interpolated Z3 top stringer surface below (surface A). This stringer surface images complex patterns of folds and strictly differs from the Top Salt (see e.g. Fig. 6A); C: interpolated stringer surface A (coloured) and the smoothed surface B (grey), which follows the Top Salt.

Fig.4) E-W seismic profile (A; 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 its interpretation figure (4B). In Fig. 4B, blue colours represent the Z2-Z4 salt section between the pre-salt (Basal Zechstein, Rotliegend and Carboniferous; brown) and the sedimentary overburden (yellow). Note the differences in Z3 stringer geometry west and east of the central salt wall related to
structural features of the Top Salt.

Fig. 5) N-S seismic profile (A; for location see Fig. 2A) slicing through the study area west of the central salt wall (stringer interpolation surface A (black, dashed line) and smoothed surface B (white, dashed line)) and its interpretation figure (B). Note that some parts of complex stringer geometry may be correlated to the occurrence of structures in the pre-salt, for example a graben in the underburden (centre of the profile). Nevertheless, comparing the stringer and the Top Salt and the pre-salt does not show a clear connection of intra-salt deformation to tectonic features in the under- and overburden.
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 (6A) to the basic stringer interpretation from seismic data. It shows that either folding of a connected stringer surface nor strict breaking of the stringer to fragments is finally resolved for this area; C: gradient map of the interpolated stringer surface showing that, compared to Fig. 6B, 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.
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-D: sequence of NW-SE seismic profiles with 250-m spacing (2-times exaggerated; for location see 7D) showing details (interpretation in white boxes) of the observed steep and deep offsets in the stringer (7D); E:
sketches of possible end-member scenarios for the offsets in Figure 7D explaining how such “offsets” may look like 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.