Evidence of early halokinesis in the Zechstein Group suggests the formation of Permian-Triassic carbonates build-ups offshore UK (Quad. 20-21)

Paolo Esestime[1], Peter Browning-Stamp[1] and Ashleigh Hewitt[1] demonstrate, through the use of 3D seismic, the presence of untested Permian-Triassic facies, controlled by early halokinesis of the Zechstein evaporites.

The Upper Permian Zechstein Group comprises sequences of carbonate and evaporites, which extend over most of the onshore areas in North-West Europe, from Britain to Poland, and across the central and southern North Sea, bringing important economic value to hydrocarbon exploration. The nature and distribution of the evaporitic facies are key factors influencing the deposition, thermal evolution and the trapping mechanism in the overburden section, as well as the sealing of the Early Permian-Carboniferous units underneath. The Zechstein Group includes source rocks from anoxic shale and microbialites, reservoirs from shallow water carbonate and several levels of seals from anhydrites and halite (Karnin et al., 1992; Cooke-Yarborough 1994; Slowakiewicz et al., 2013).

The early salt movements have been tracked back to the Triassic and Jurassic (Glennie and Higham, 2003 and references therein), under different tectonic regimes between the Jurassic-Cretaceous rifting, to the Paleogene inversion, active in the remote foreland of the Alpine Orogeny.

The lateral facies distribution has been largely described as a result of different subsidence rates and climatic fluctuation in the Zechstein Basin (Figure 1). Well data confirms the complex architecture of this basin at different scales (Geluk, 2000).

This paper is based on the detailed structural and stratigraphic interpretation of about 4500 km^2 of 3D seismic from the Blakeney Cube, which was shot in 2011 in Quadrants 20 and 21, of the central North Sea (Figure 1). We focus on defining the sedimentary patterns and seismic facies of the Zechstein section, confined within the pods or mini-basins generated during the earliest phases of salt movements. The Upper Permian section has been widely overlooked in this 3D seismic by past drilling campaigns, and to obviate the limited well control, the Zechstein has

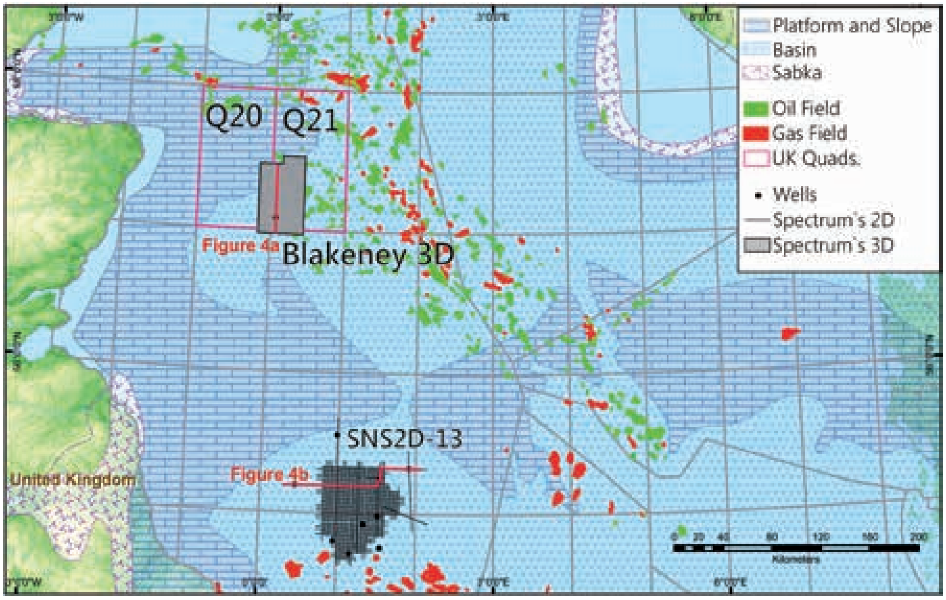

Figure 1 *Map showing the seismic surveys and the wells available. In background, the paleogeography of the Zechstein Basin, Z2 cycle, (Slowakiewicz et al., 2013).*

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been calibrated on an additional 4000 km of 2D seismic (SNS2D-13) acquired in 2013 in the southern North Sea (Figure 1).

Zechstein paleogeography and stratigraphy

The Zechstein Group was deposited over approximately six million years, during the Upper Permian (Lopingian Period), in an intra-continental basin characterized by restricted circulation in arid condition, with a discontinuous supply of minor clastic deposits.

The Group has been subdivided into a number of formations and sequences, which allow regional stratigraphic correlation, based on the relationships between faces and sea-level fluctuations. These formations are also correlated on a regional scale from Britain to Central and Eastern Europe, in Germany and Poland (Tucker, 1991; Strohmenger et al., 1996; Wagner and Peryt, 1997) (Figure 2). The carbonate and evaporites sequences show variable thicknesses and facies from shallow to deep water. This subdivision is based on several cycles, each one containing an interval of carbonate, halite and anhydrite, separated by regional unconformities (Figure 2), which are commonly present at the top of the halite and at the base of the carbonate intervals (Tucker, 1991).

The Z1 sequence defines the basal transgression of the Zechstein Basin. The event is marked by a few metres of black shale and conglomerate, followed by shallow water carbonate. This interval covers the previous landforms exposing Carboniferous-Devonian units, under arid conditions and extensive erg-type deposits of Aeolian dunes, (Rotliegend Sandstones).

The lateral distribution of shallow and deep water facies in both carbonates and evaporites remains mostly constant during the several cycles (Figure 3), suggesting a tectonically quiescent period and a stable paleogeography. The sedimentary cycles might be related to repeated 'crisis' in the water circulation and sediments supply, with erosion and consequent deposition of halite and anhydrites intervals.

Regional studies suggest that the maximum thickness of shallow water carbonate is along the edges of the Zechstein Basin, while evaporites are thickest in the depocentre, where stagnant conditions may have been temporally persistent (Peryt et al., 2010).

From the Lower Triassic the evaporites were replaced by siliciclastic deposits, several hundred metres thick, mostly fine grained (Bunter Shales Fm. sl.). Clastic deltaic deposits continued during the Triassic, infilling the pods and mini-basins formed by the halokinesis, which controlled both sediment thickness and dispersal patterns within the sandstone and siltstone intervals.

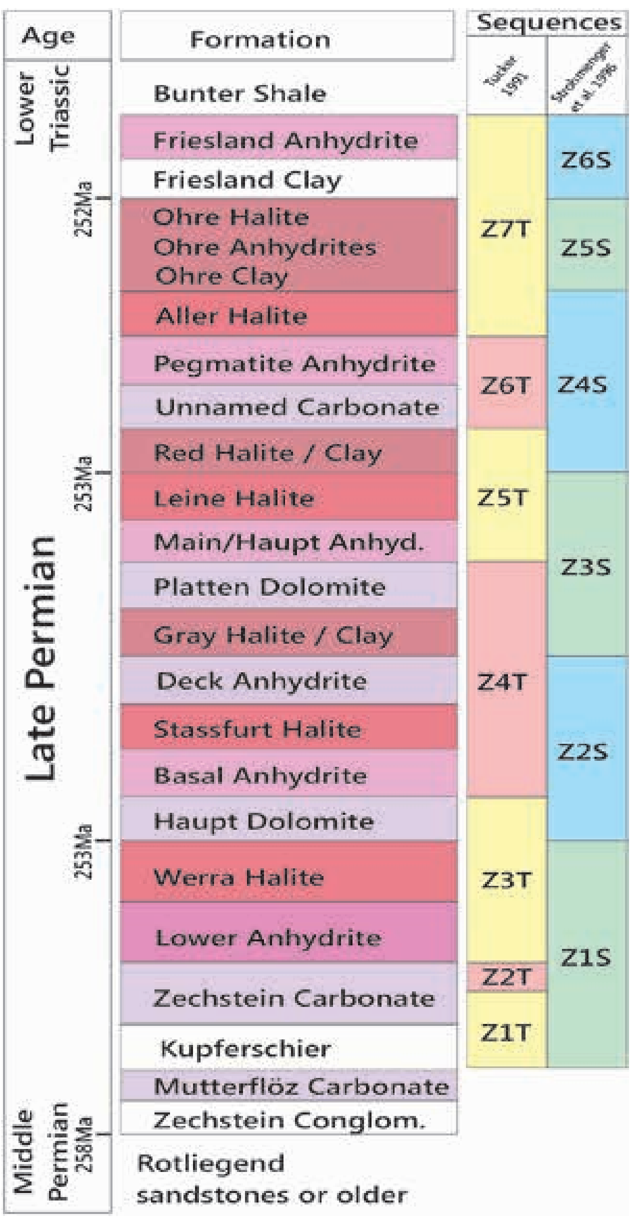

Figure 2 Stratigraphy of the Zechstein Group (modified from Tucker, 1991; Stromenger et al., 1996).

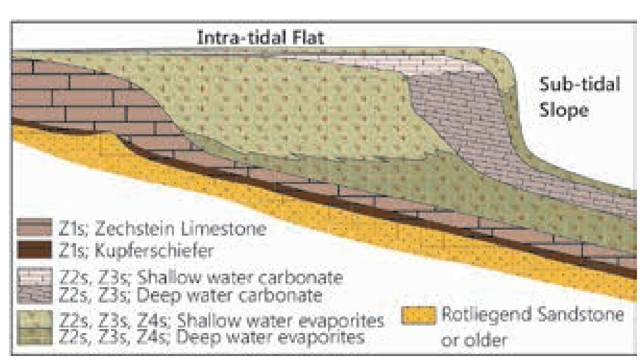

Figure 3 Regional depositional Model for the Zechstein Group (modified from Stromenger et al., 1996).

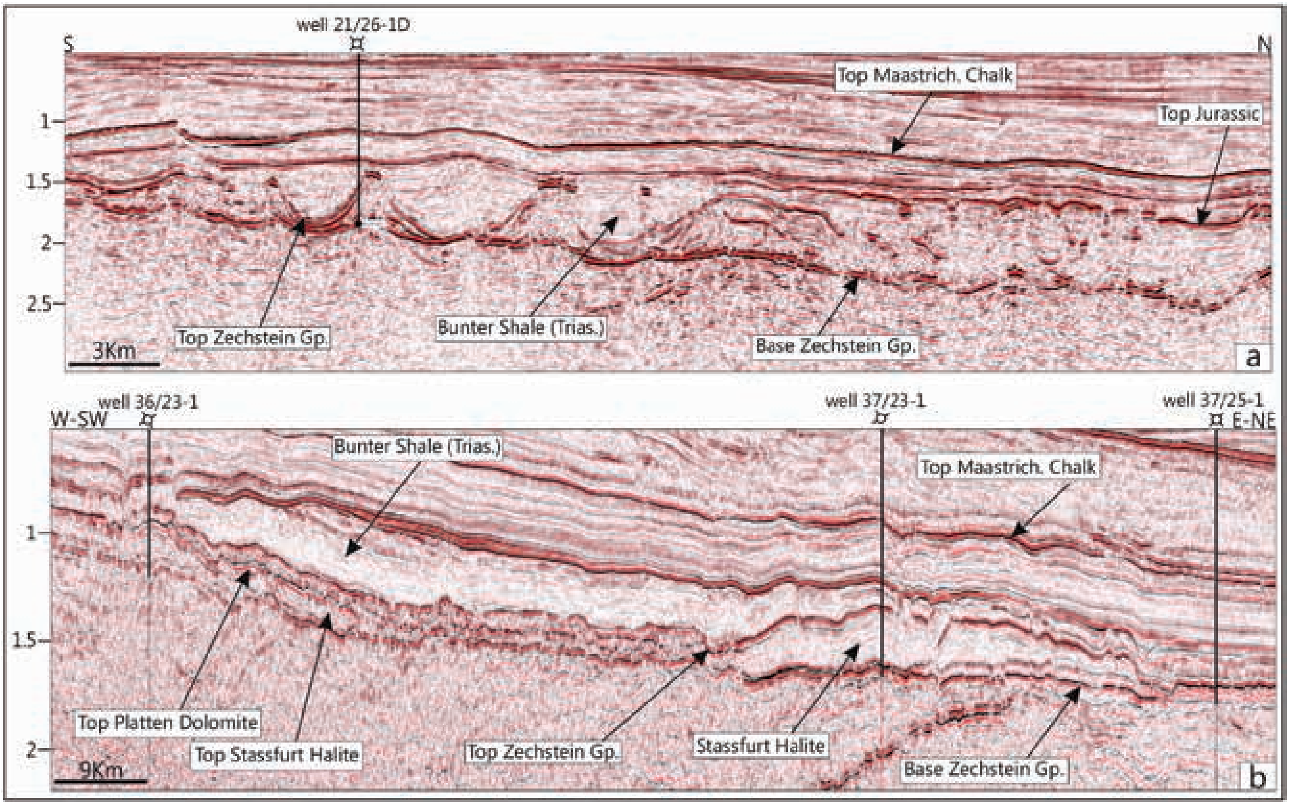

Figure 4 *Calibrated sections showing the main facies in the Zechstein Group.*

Seismic calibration

Only well 021/26-01D was made available to calibrate the 3D seismic cube. The well encountered 2390 ft of the Zechstein Group at 5763 ft and 950 feet of Triassic shales (Bunter Fm.) above. The base Cretaceous chalk was separated from the Triassic by Aptian-Albian sandstones. The well encountered mostly halite; the basal carbonate of the Z1t cycle is about 70 feet thick and only a layer of dolomite and anhydrite is present between 7391-7453 ft, possibly related to the Platten or Haupt. Dolomite (Figure 2). However, the well is not representative of the survey area, because it was drilled within a highly remobilized section on the side of a steep diapir (Figure 4a).

Nine wells have been tied to an additional 2D seismic grid in the nearby sector of the southern North Sea (Figure 4b). The basal carbonate in the cycle Z1t has been clearly calibrated, enabling a good correlation on the 3D survey of the main carbonate units of the interval Z2t-Z4t (Figure 2). In addition, the base of the Bunter Shale is marked by a major unconformity in both the 3D and 2D seismic, and represents a good constraint for correlating the age of the halokinetic structures active during the Triassic (Figure 4b).

The cycles Z1t-Z3t are relatively thin isochrons (50-100 ms TWT), while the Z4t-Z6t have the thickest halite intervals (Stassffurt and Leine Fms.). These later cycles have a characteristic chaotic low amplitude seismic facies, interrupted by strong reflectors generated by the acoustic contrast between carbonates and anhydrites, in particular the Platten Dolomite.

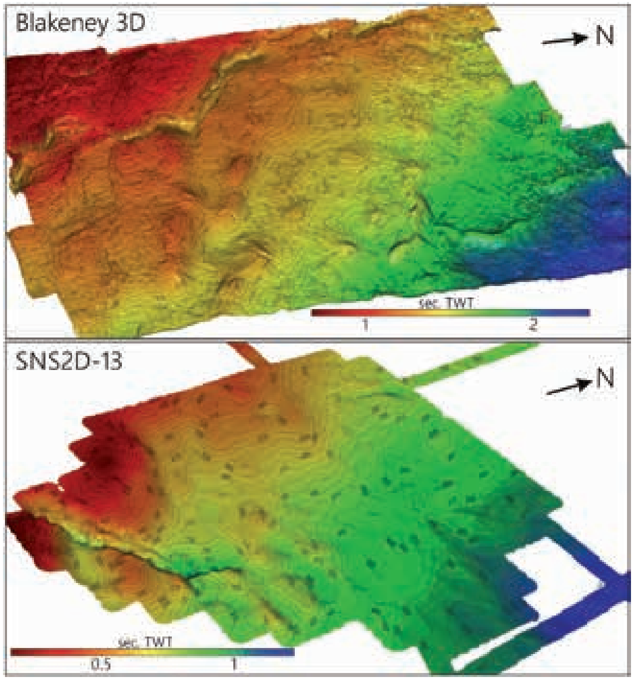

Figure 5 *TWT horizon maps at the Top Maastrichtian Chalk, from the Blakeney 3D (above) and SNS-13 2D seismic (below).*

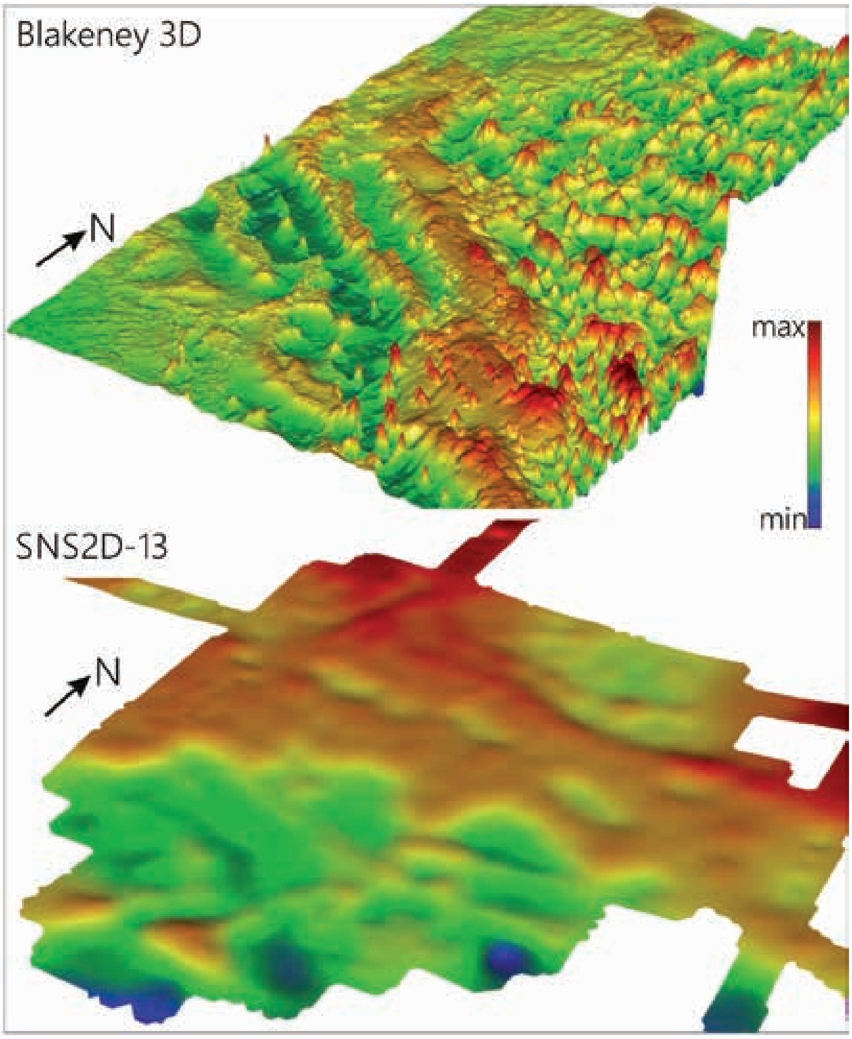

Figure 6 *Maps showing the vertical thicknesses in TWT of the Zechstein Group in the Blakeney 3D (above) and SNS2D-13 (below).*

Halokinesis and structural evolution

In both 3D and the 2D surveys the effect of late compressional phases in the Paleogene are clearly visible. The pre-Permian substratum is involved in regional buckling resulting in large anticlines in the overburden, which are detached within the Zechstein evaporites, and frequently rejuvenate pre-existing salt dome or diapirs (Figures 4a, 4b and 5). Normal faults are present locally and accommodate minor collapses due to salt withdrawal (Figure 5).

The structural styles of the Jurassic-Neogene overburden are very similar between the central and southern North Sea, and the latest deformation was controlled mostly by the regional tectonics regime (Figures 4a and 4b).

The halokinesis is mostly confined to the Permian-Triassic units, and the Jurassic is locally affected by minor salt withdrawal. This evolution can be seen in both the survey areas, irrespective of differing resolution between 3D and 2D seismic, but the style of the halokinetic structures appear very different (Figure 6).

In the southern North Sea survey, salt diapirs can be seen occasionally, and the main halite intervals are inflated and deflated, forming large domes, which control the thickness of the Triassic Bunter Shale above (Figures 4b and 6).

The Blakeney 3D area can be subdivided into three structural domains from southwest to northeast: a relatively flat stable area, devoid of relevant salt movements, adjacent to a narrow sector of large ridges separated by wide pods of Triassic sediments (Figure 7), which, to the north east abruptly changes into numerous small salt diapirs that are chaotically distributed (Figure 6).

The wells tied to the 2D seismic allowed the interpretation of the halokinetic structural style with the lateral stratigraphic variations, and the consequent changing in the rheology of the salt (Figure 4b). Highly reflective continuous seismic facies are associated to less mobile Zechstein units, because the increasing amount of carbonate within the halite and the anhydrites reduces their halokinesis. This seems to present a reasonable explanation for the relatively flat area

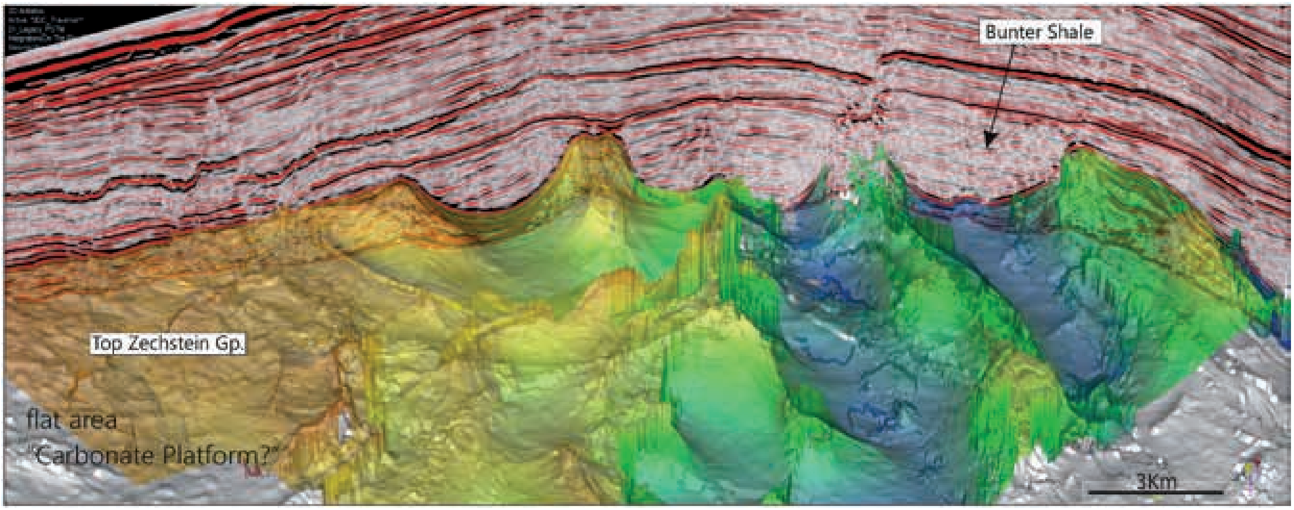

Figure 7 *Three-dimensional view of the horizon calibrated at the top Zechstein in the southern sector of Blakeney 3D.*

observed in the southwest corner of the Blakeney 3D, where the salt diapirs are almost absent (Figure 7).

When comparing the deformation present in the carbonate intervals of the Zechstein Group, a notable difference exists between the study 2D and 3D seismic data areas. The southern North Sea exhibits tabular carbonate bodies (ie. Platten and Haupt Dolomite), fragmented and floating within the salt, which suggest the deformation occurred after the deposition. In the Blakeney 3D, however, carbonate bodies cannot be identified within the salt, but these may be present in the reflective facies that extends above and laterally along the major ridges (Figures 7 and 8). These

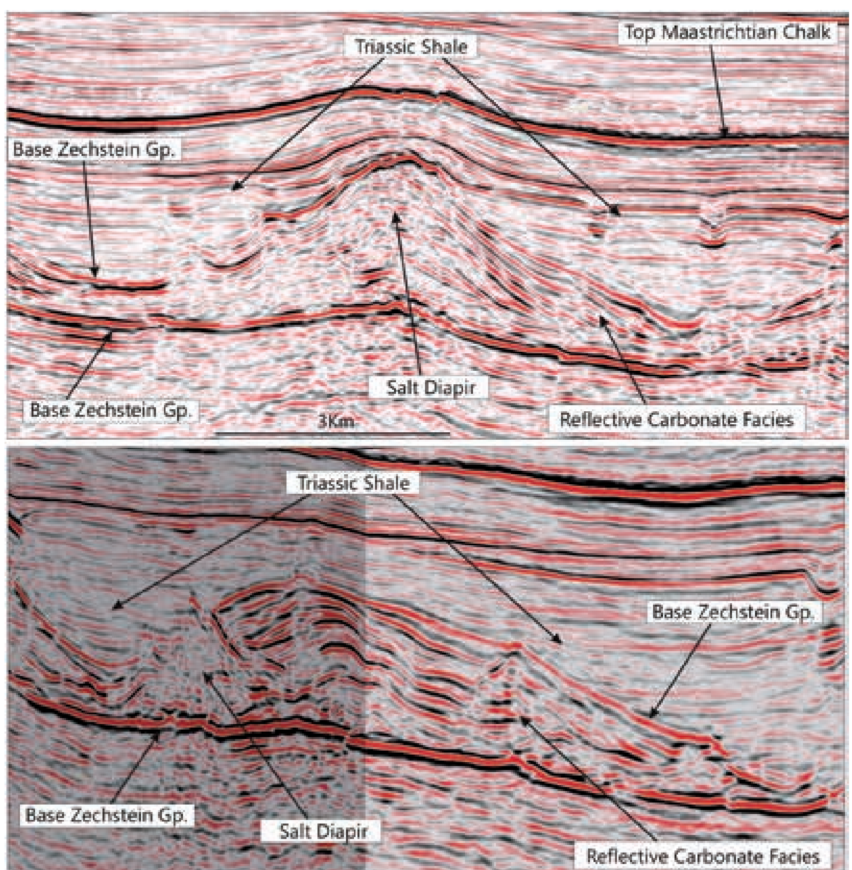

Figure 8 *Seismic section (above) and three-dimensional view (below) of the seismic facies and sedimentary patterns characterizing the Zechestein Group along the main halite ridges. Note the reflective horizons interpreted as carbonate.*

reflective bodies mimic the syn-depositional pattern of a progradation, which moves from the core of the salt ridge to the adjacent mini-basins, and eventually forms a turtle-type structure and welds, where a complete salt withdrawal occurred afterwards. This interpretation is compatible with a single long-lasting phase of halokinesis, on which the pods and the diapirs continue growing from the Permian to the Triassic (Figure 8). Only one set of salt ridges can be observed, and its activity is gradually terminated by Triassic shale. Therefore, the reflective bodies should have preserved their syn-depositional pattern, resulting in only a minor rotation and deformation during the late phases of salt movements.

Salt related carbonate build-ups

The large salt-related diapirs in the Blakeney 3D show sedimentary patterns in sets of bright horizons, which prograde from the ridges in the mini-basin. This interpretation is highly compatible with the carbonate build-ups in salt diapirs observed in the Mexican onshore areas of La Popa Basin (Figure 9). This area is an Upper Cretaceous-Paleogene siliciclastic basin, in the foreland of the Sierra Madre Oriental, which show the halokinesis of deep evaporites, mainly gypsum, active during the deposition of pelagic marls, shales and sandstones.

Diapirs and salt-related structures in La Popa Basin triggered the formation of local carbonate reefs, surrounded by massive calciturbidites. The evolutionary model of these local carbonate platforms has been described by Giles et al. (2008), as the effect of morphological reliefs developed in the salt ridges during halokinesis (Figure 9). When the carbonate reefs develop, the erosion creates the progradation of massive limestone similar to a small carbonate platform, which extended from the salt ridges into the surrounding mini-basin.

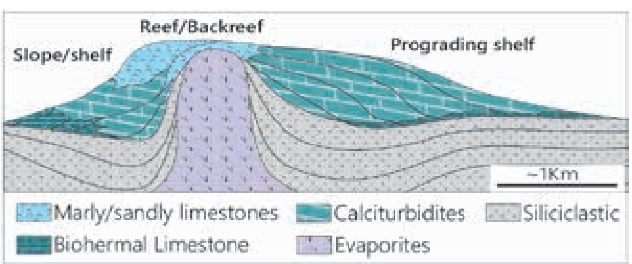

Figure 9 Sedimentary model for carbonate lentils related to salt diapirs (Papalote Diapir) in the outcrops of la Popa Basin (Northern Mexico) (modified from Giles et al., 2008).

The salt diapir of Las Ventanas (Figure 10) represents a potential analogy for the structures interpreted in the Blakeney 3D. In these large outcrops, the massive detrital limestone rest above and laterally of the main gypsum bodies. These local carbonates create sharp peaks that stand out from the flat morphology of the pelagic limestone and the shale (Indidura Fm. and Parras Shale Fm.) (Figure 9b).

Conclusion and potential new hydrocarbon play

We have briefly described the evidence of untested carbonate facies developed as build-ups on of the Permian-Triassic

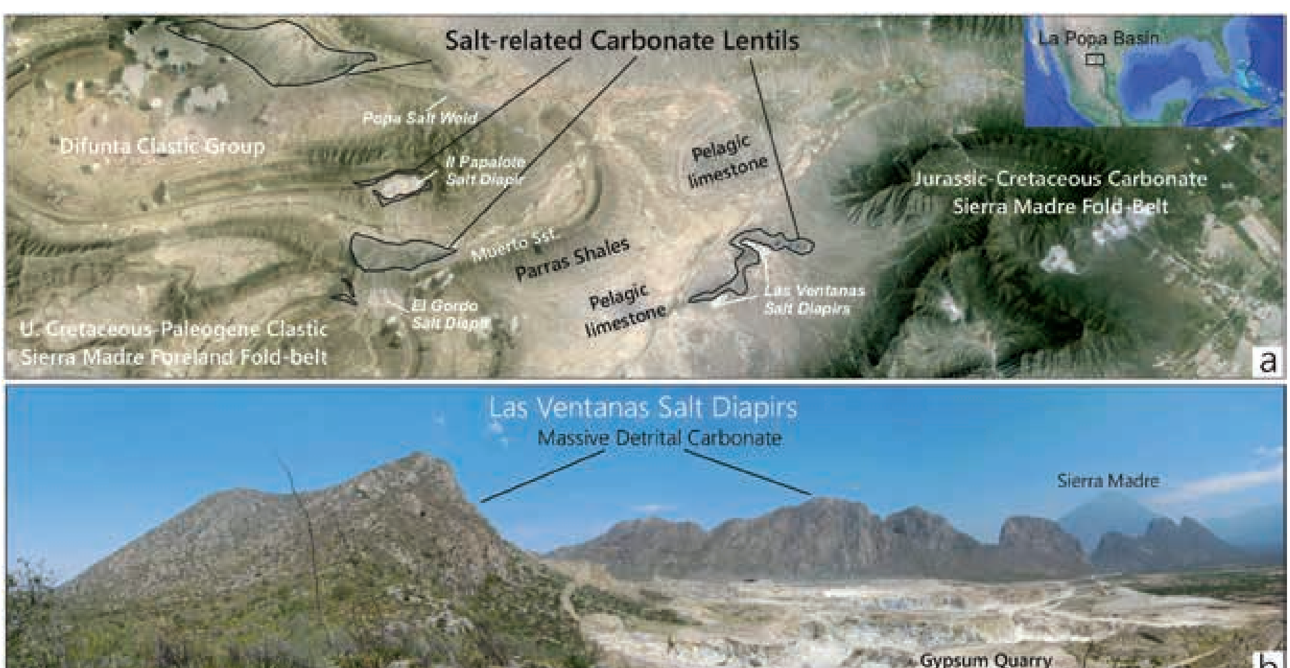

Figure 10 (Above) Regional view of la Popa Basin (Northern Mexico) and the several carbonate lentils associated to halokinetic structures and salt-diapirs. (Belove) Detailed pictures of the Gypsum Quarry in Las Ventanas diapirs, surrounded by massive lentils of calciturbidites.

salt-ridges of the Zechstein units. The use of 3D seismic shows that the carbonate bodies may extend for more than 10 km, forming local carbonate platforms and shelf, active during the early halokinesis. Potentially, these represent a local equivalent of more regional carbonate intervals, already known in the Zechstein Group, i.e., Platten-Haupt Dolomites.

More detailed studies are required to test this preliminary interpretation, from which could be developed a new hydrocarbon play. The size of these carbonate prospects may be commercial, with good reservoir properties and an effective seal of Triassic shale.

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