ZEPHYR

Hauptdolomite distribution around the Elbow Spit High

Seismic mapping

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	Harald de Haan – Senior Geologist & Geophysicist, Seismic-to-well ties
Cambridge Carbonates:	Jo Garland – Petrographic Analyses

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We would also like to thank Friso Veenstra (TNO) for is help to crystalize industry interest for new research on the Zechstein play in the Netherlands and across the North Sea.

Finally, we would like to thank TGS for allowing us to show seismic data from the DEF-survey. All seismic examples south of the Elbow Spit High are shown by the courtesy of TGS.

Overview - ZEPHYR

Introduction

- Aim of ZEPHYR & Data used
- Regional Background
- Introduction ZEPHYR study area
- Results Petrographic analyses Cambridge Carbonates*

Methods

- Seismic-to-well Tie
- Seismic mapping
- Facies mapping

Results south of ESH

- Base maps and isopachs
- Seismic results

Discussion south of ESH

- High rugosity zone south of ESH
- Karstification
- Back barrier reef patches/pinnacles

Results north of ESH

- Seismic results

Discussion north of ESH

- Prospectivity ZEZ2C in far north Dutch offshore

Conclusions

- Facies Map
- Recommendations for future work

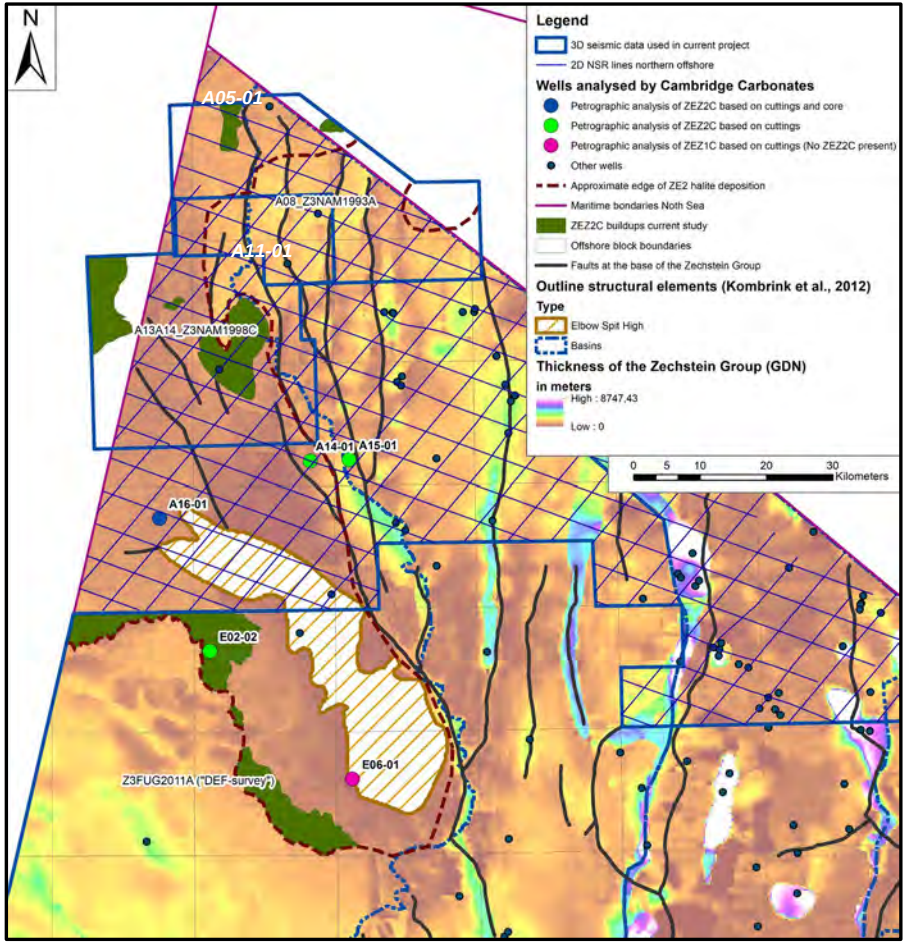
Appendices

- Appendix A: PaleoScan model south of ESH

* Note that *the results of the petrographic analyses conducted by Cambridge Carbonates are described in detail in a separate presentation.*

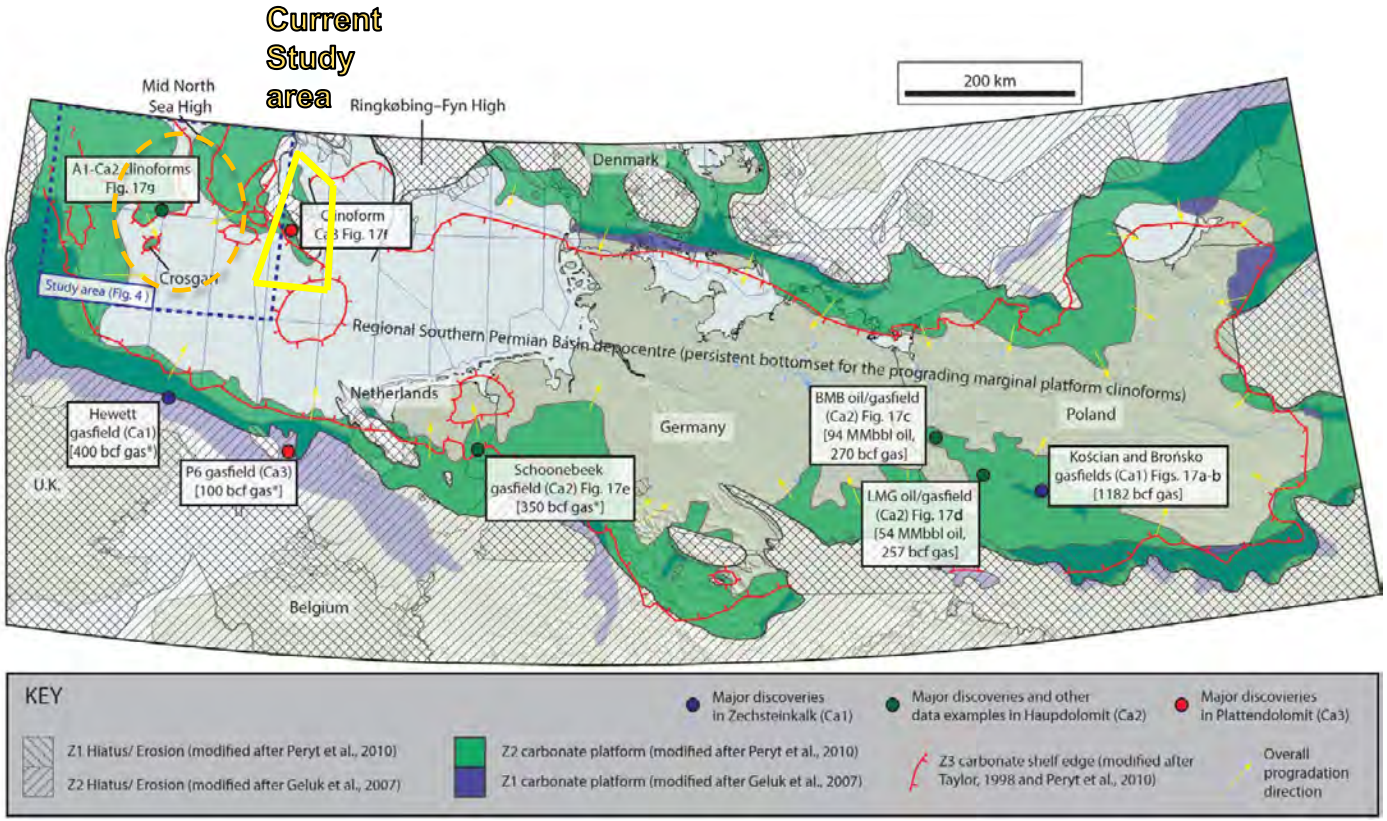
INTRODUCTION – GOALS & DATA USED

- Aim of study:
  - To gain better understanding of the carbonate facies, and distribution of Hauptdolomit (ZEZ2C) platforms in the area around the Elbow Spit High.
    - Achieved by using seismic data and petrographic analyses of ZEZ2C samples from cores & cuttings
    - The current study builds on knowledge from UK side of MNSH and updates the work of Tolsma (2014).
- Wells assessed by Cambridge Carbonates
  - A16-01 (petrographic analysis based on core material & cuttings)
  - A14-01 (petrographic analysis based on cuttings
  - A15-01 (petrographic analysis based on cuttings)
  - E02-02 (petrographic analysis based on cuttings)
  - E06-01(petrographic analysis based on cuttings, only ZEZ1C, no ZEZ2C present)
- Seismic surveys used for interpretation:
  - A08_Z3NAM1993A
  - A13A14_Z3NAM1998C
  - Z3FUG2011A (“DEF-survey”)
  - 2D NSR lines northwest of DEF
- Additional wells of interest
  - A05-01; thick Werra Anhydrite (ZEZ1A) platform, but limited carbonates
  - A11-01; 15m thick ZEZ2C present, but relatively thin ZEZ1A



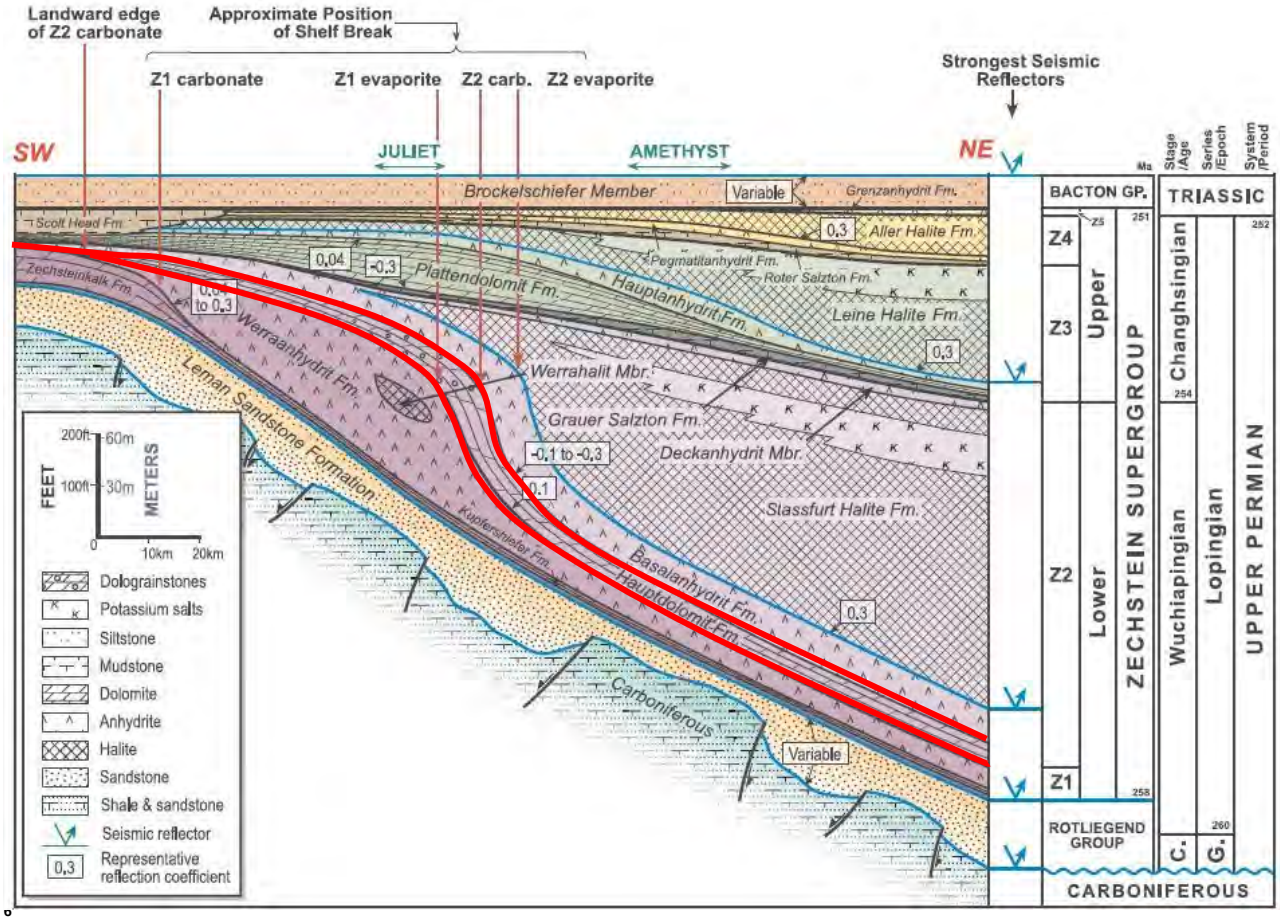
INTRODUCTION – REGIONAL BACKGROUND; ZEZ2C OCCURRENCE

- Zechstein build-ups at the margins of the Southern Permian Basin
- Examples of (recent) ZEZ2C discoveries in the UK sector, south of MNSH highlight the current relevance of this play: Auk, Argyll/Alma, Crosgan, Ossian
- Next couple of slides will focus first on the UK side south of the MNSH to illustrate the stratigraphy and important ZEZ2C play elements.



Patruno et al., 2017

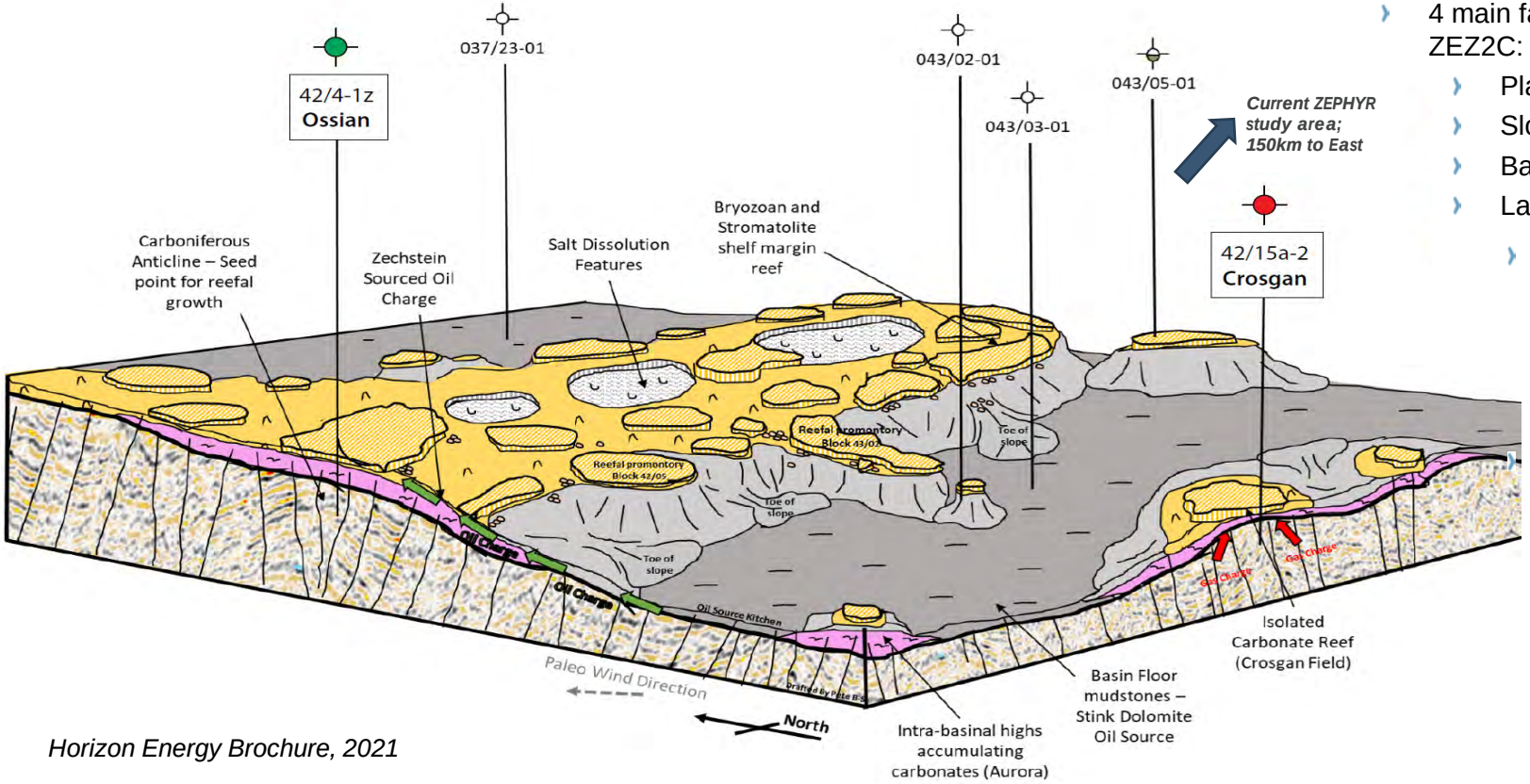
INTRODUCTION – REGIONAL BACKGROUND; ZE STRATIGRAPHY



Modified from Grant et al., 2019

- Upper Permian Zechstein Group comprises a series of marine evaporites and carbonates that were deposited into 4 cycles (Z1-Z4) under warm and arid conditions.
- Each cycle is characterized by an initial transgression, followed by regressive phases.
- The main interest of the present study is the Z2 carbonates (ZEZ2C, Hauptdolomit Fm.)

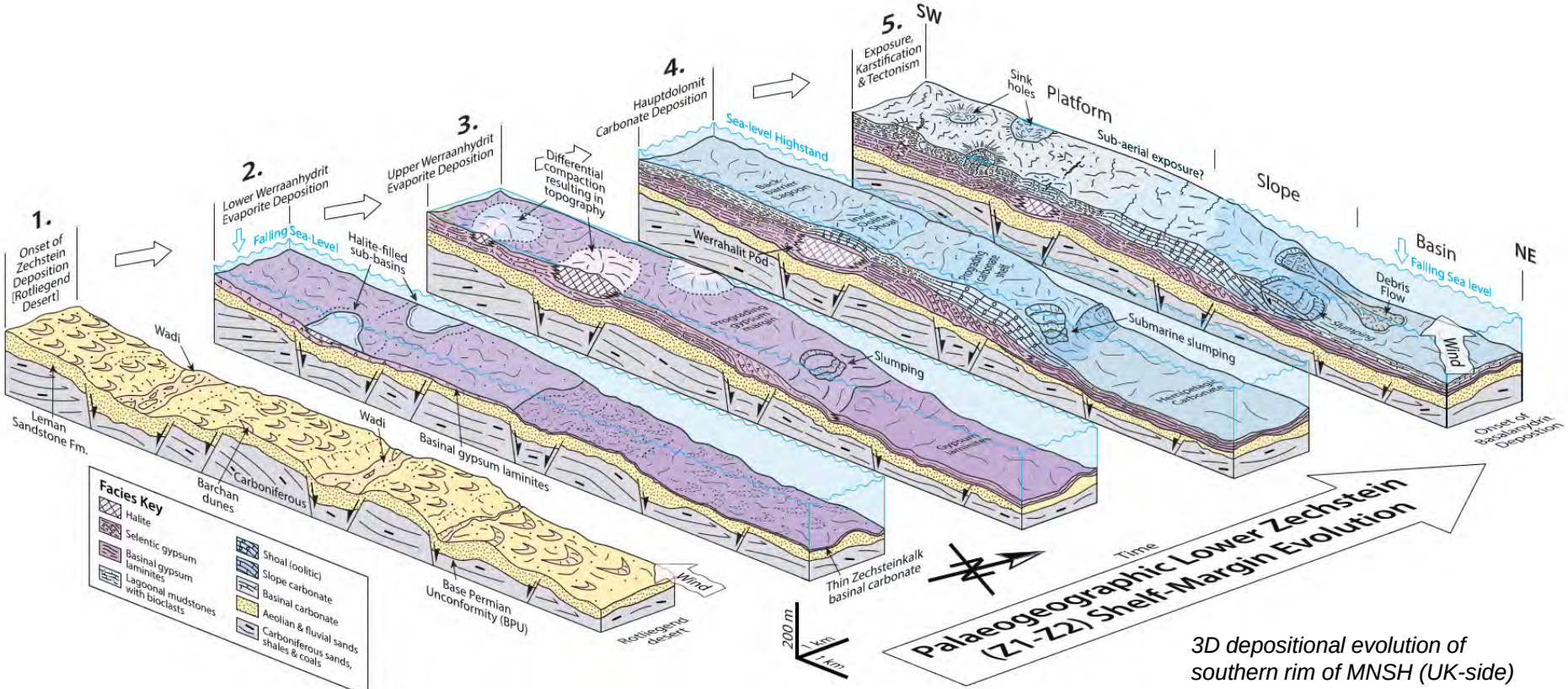
INTRODUCTION – REGIONAL BACKGROUND; DEPOSITIONAL MODEL ZEZ2C



Horizon Energy Brochure, 2021

- 4 main facies types for ZEZ2C:
  - Platforms
  - Slope
  - Basinal
  - Lagoonal/Back barrier
    - Thickest ZEZ2C platforms on top of pre-existing Carboniferous highs and Werra (ZEZ1W) platforms
    - The best reservoirs are expected to be found in the platform-, and possibly slope facies.

INTRODUCTION – REGIONAL BACKGROUND; DEPOSITIONAL EVOLUTION ZEZ2C

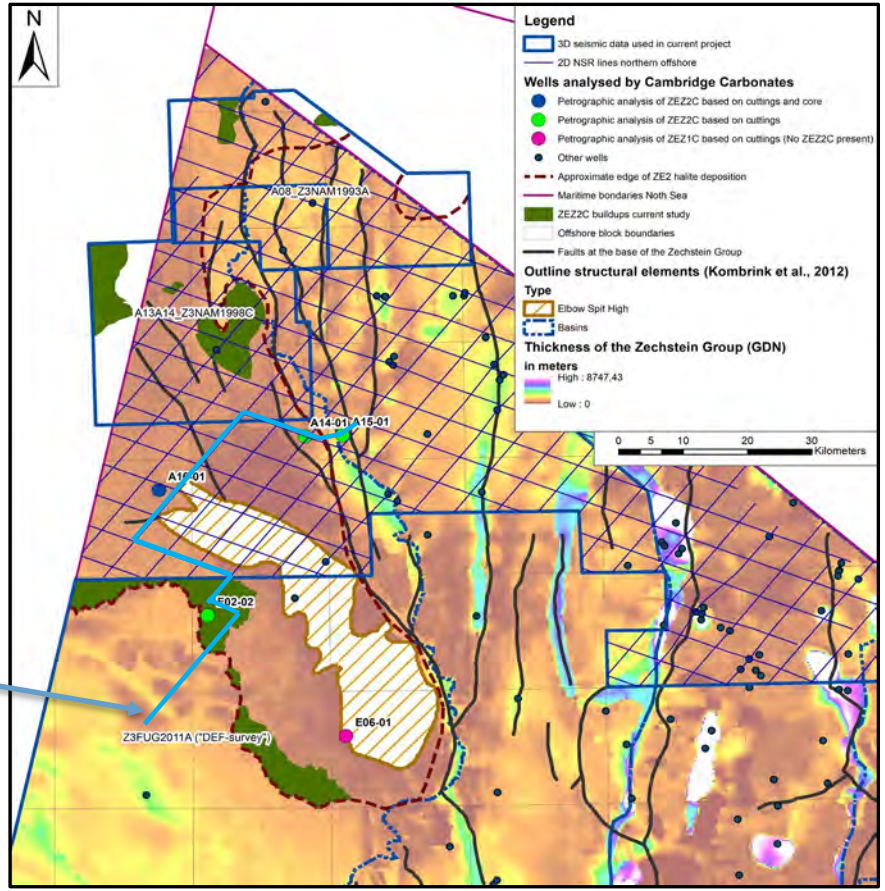


3D depositional evolution of southern rim of MNSH (UK-side) Figure from Grant et al., 2019

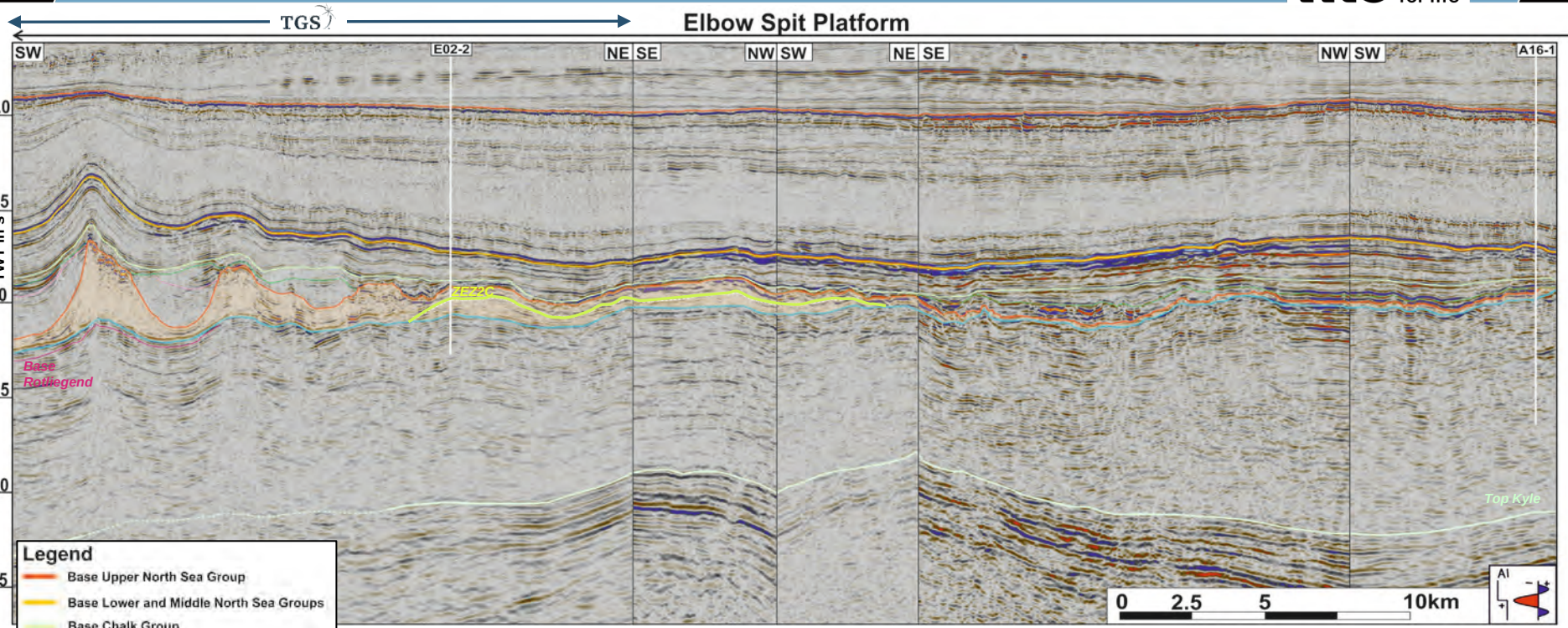
STUDY AREA INTRODUCTION

- Entire Zechstein Group is generally thin around the Elbow Spit High (ESH).
- Halite deposits are generally found towards the east and south (see dashed red line on the map).
- Around the ESH, several ZEZ2C platforms are present in a similar setting as on the UK side.
- Some key-elements of the study area are illustrated by a seismic panel crossing the ESH. This panel is shown on the next two slides.

Location of Seismic panel across ESH shown on next two slides

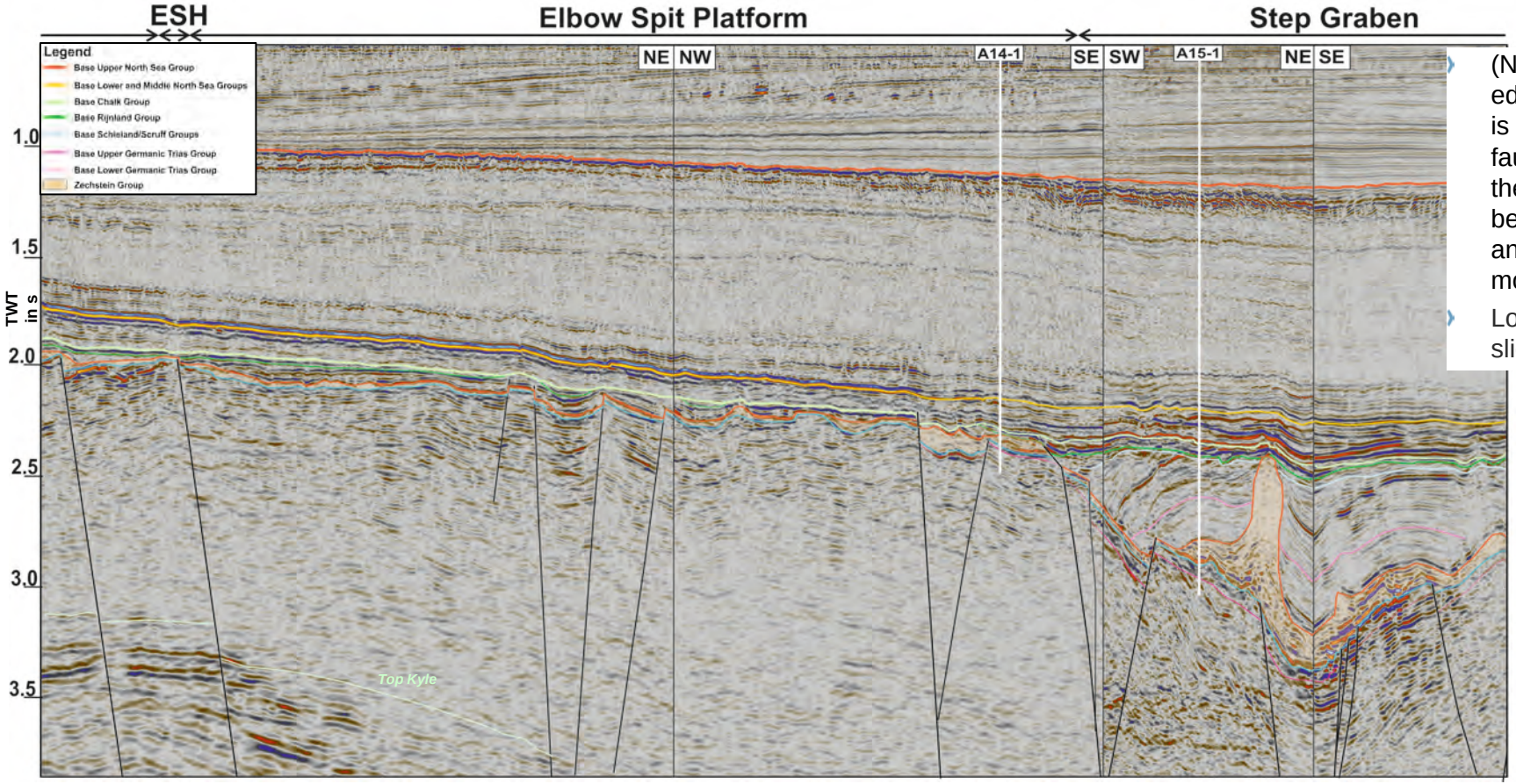


STUDY AREA INTRODUCTION – SEISMIC PANEL



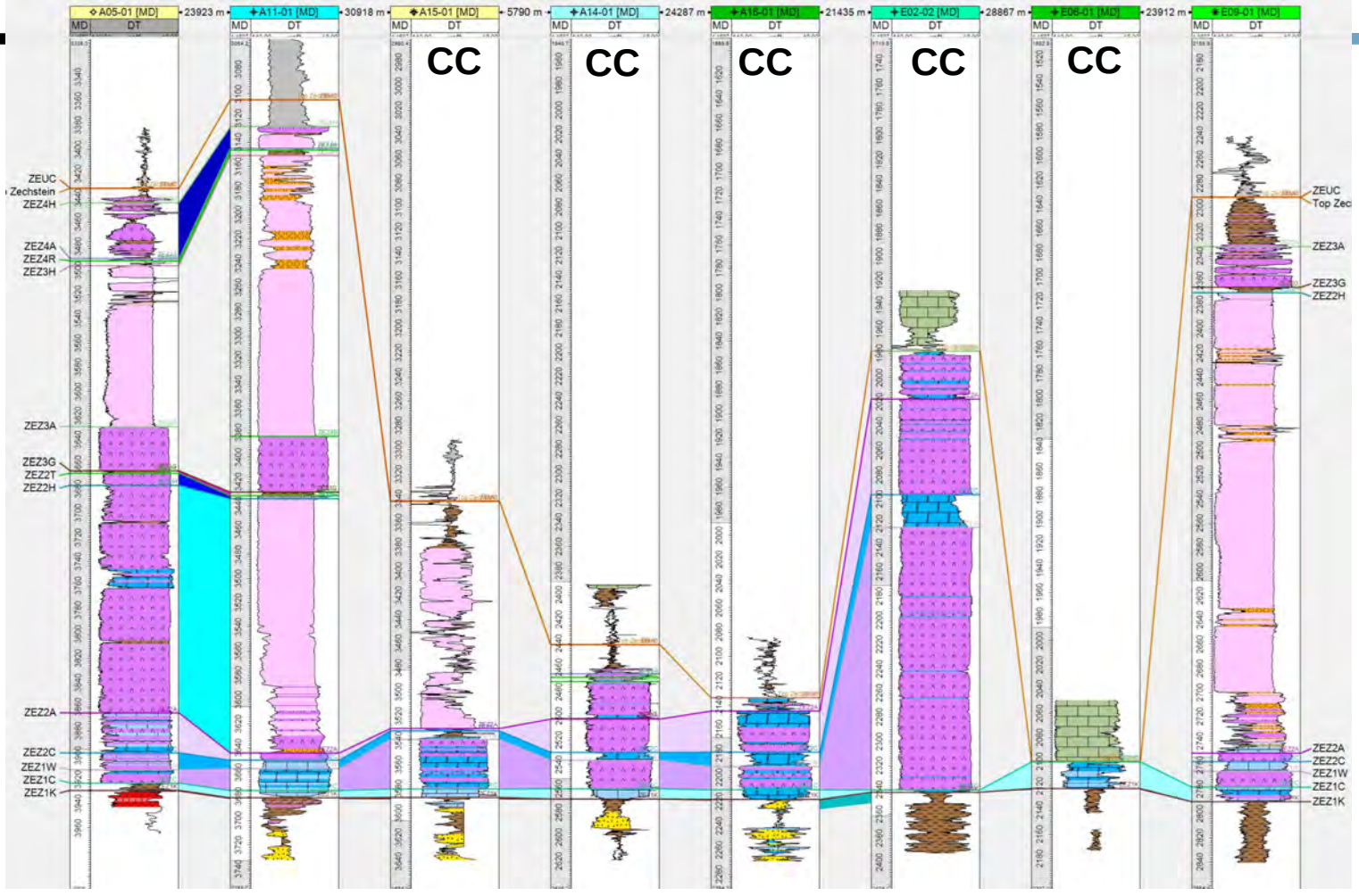
- Southern edge of ESH is characterized by gradual transition between marginal deposits (e.g. platforms) and the deeper basin. Location: see slide 9

STUDY AREA INTRODUCTION – SEISMIC PANEL



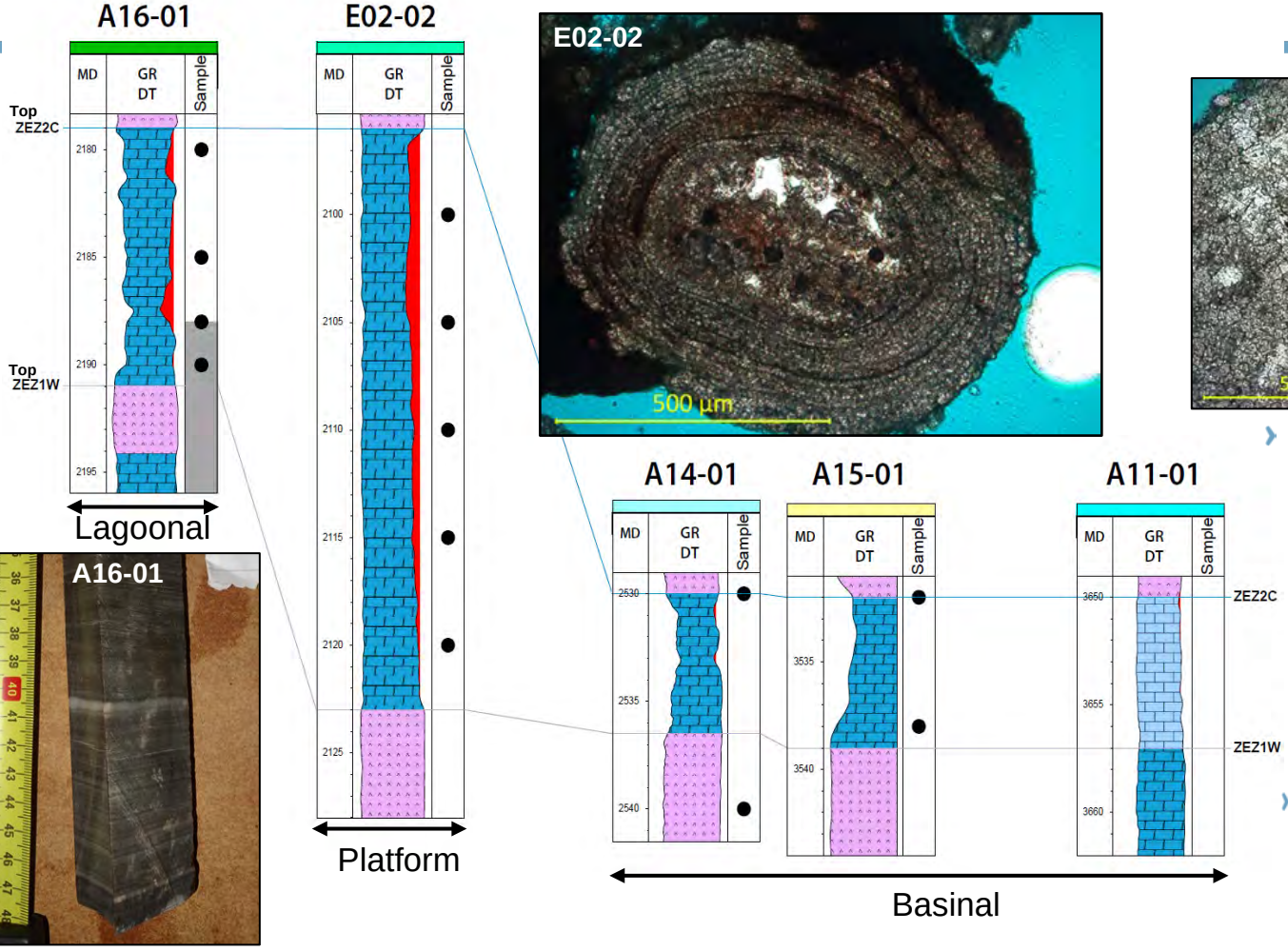
- (North)eastern edge of ESH is heavily faulted and the transition between basin and high is more rapid
- Location: see slide 9

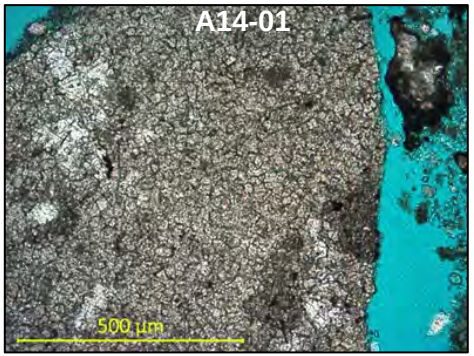
RESULTS PETROGRAPHIC ANALYSES - WELL PANEL



- The ZEZ2C for the CC indicated wells were analysed by Jo Garland from Cambridge Carbonates (CC).
- See next slide for a summary of the results from Cambridge Carbonates.

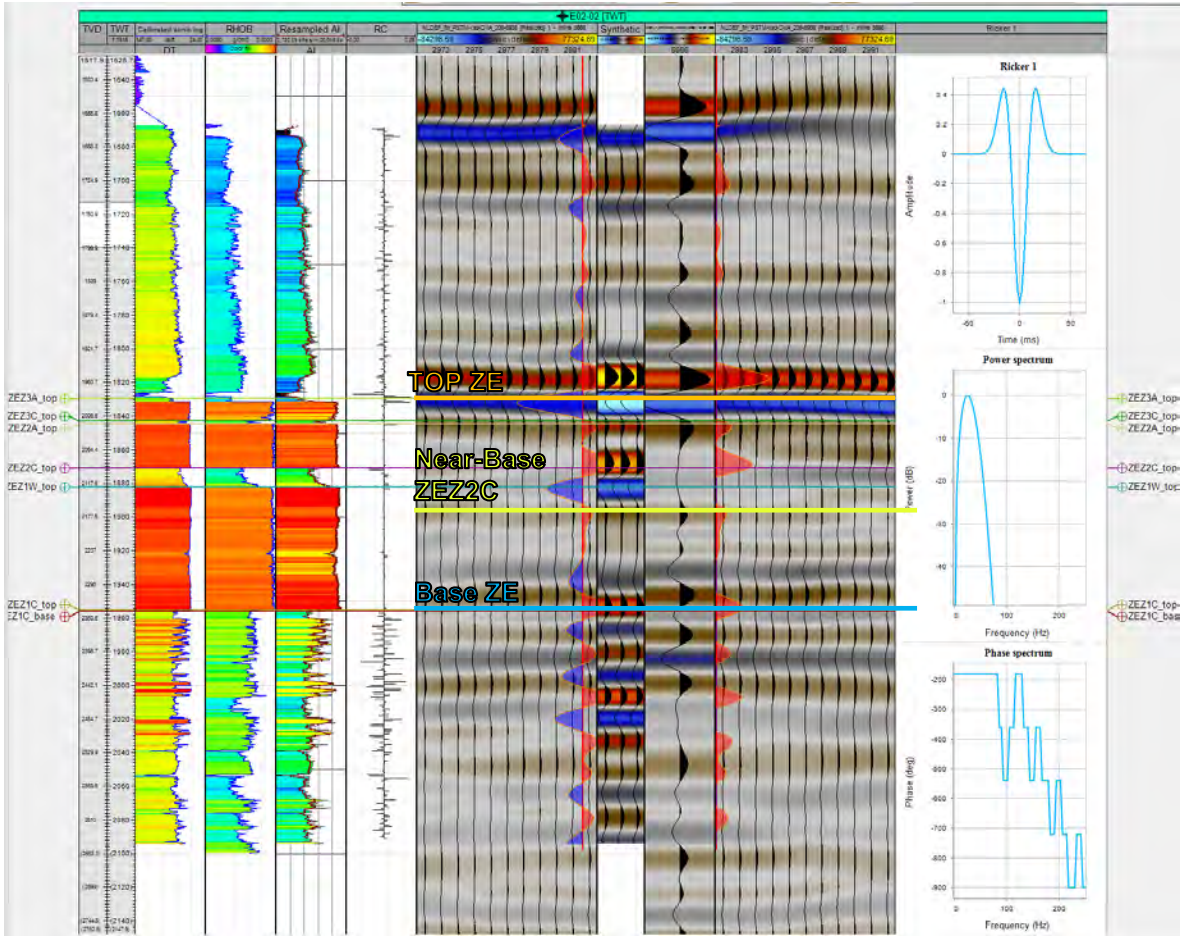
RESULTS PETROGRAPHIC ANALYSES - WELL PANEL

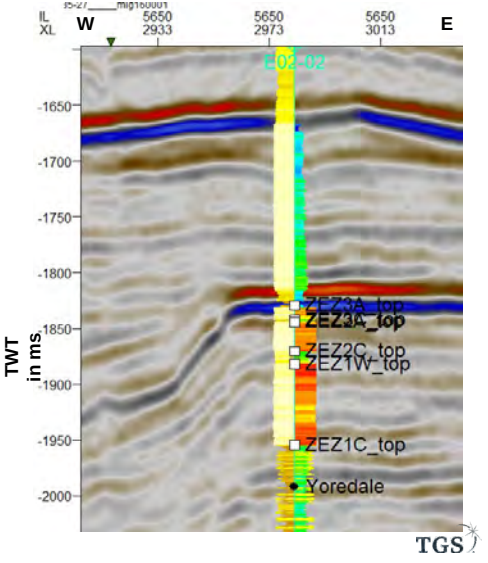




- Following conclusions from petrographic analysis performed by CC:
  - E02-02: Platform facies
  - A15-01 & A14-01: Basinal facies
  - A16-01: Lagoonal facies
- *See separate presentation from CC for the results and discussion of all petrographic analyses that were conducted.*

METHODS: SEISMIC-TO-WELL TIE

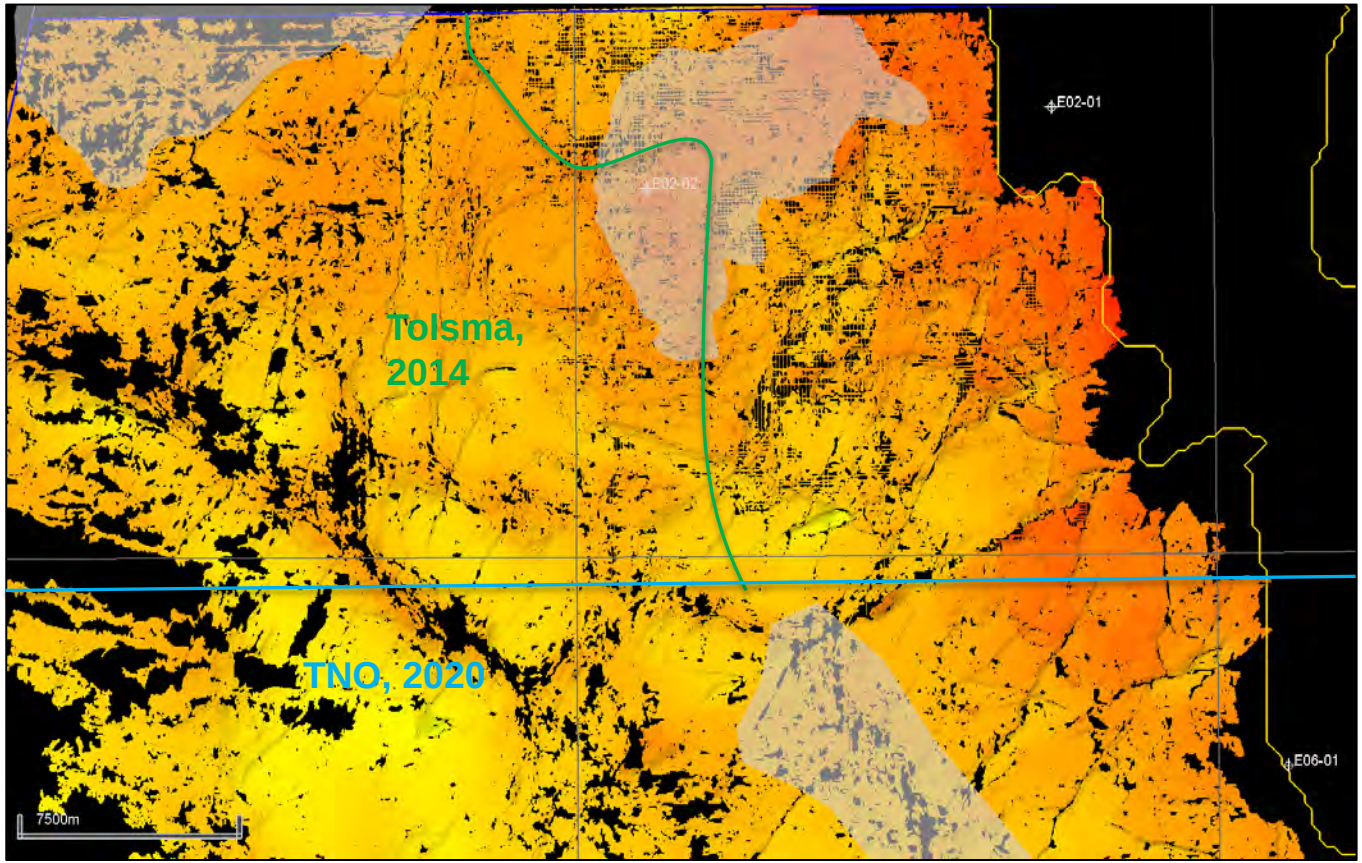




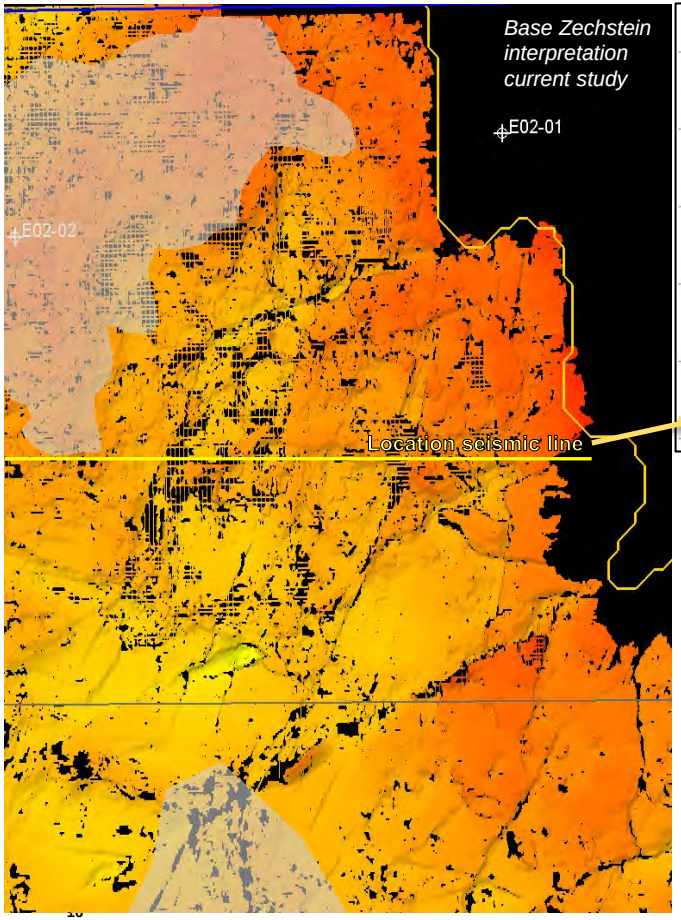
- Synthetic E02-02
  - Top ZEZ3A; Hard kick
  - Top ZEZ2C; soft kick
  - Base ZEZ2C; hard kick
  - Base ZEZ1C; soft kick
- Soft kick slightly underneath Base ZEZ2C was taken as base ZEZ2C

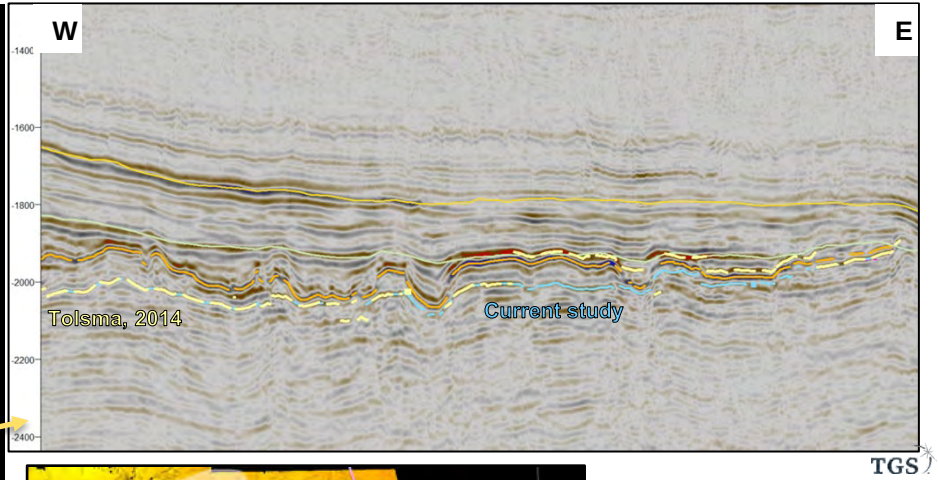
METHODS – SEISMIC MAPPING

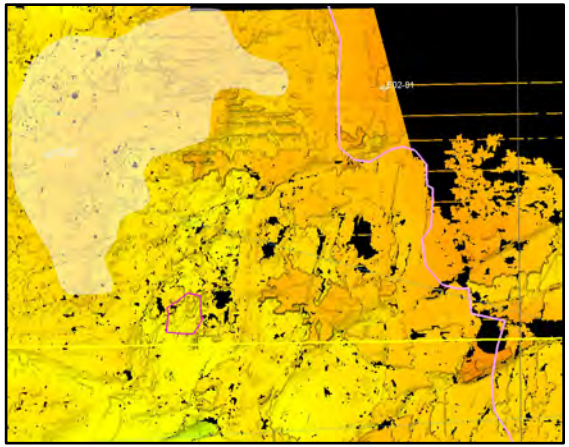
- Seismic mapping performed during the current study on the DEF-survey:
  - Top Zechstein
    - Generally easy to pick with autotracking.
  - Base Zechstein
    - East of green line mapped during current ZEPHYR study
    - West of Green line Base ZE of Tolsma (2014) was used
    - South of blue line Base ZE of TNO (2020) was used
  - Soft kick event slightly underneath base ZEZ2C for the platform areas
- Additionally: PaleoScan model was constructed SW of ESH by using these three horizons as a constraint (See Appendix A for some of the results, including RMS amplitude maps).



METHODS - SEISMIC MAPPING





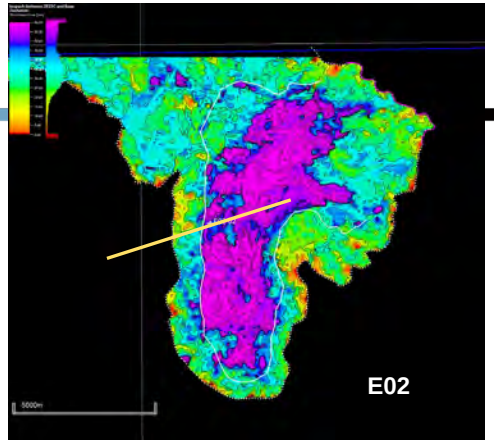


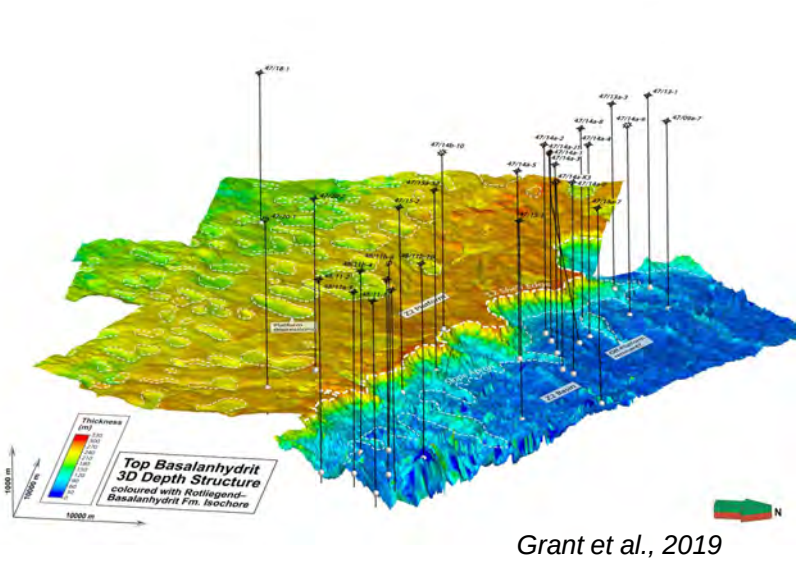
- Proper mapping of Base & Top Zechstein is essential for the understanding of Zechstein platforms
- Update in certain areas was needed

Base Zechstein interpretation, Tolsma 2014

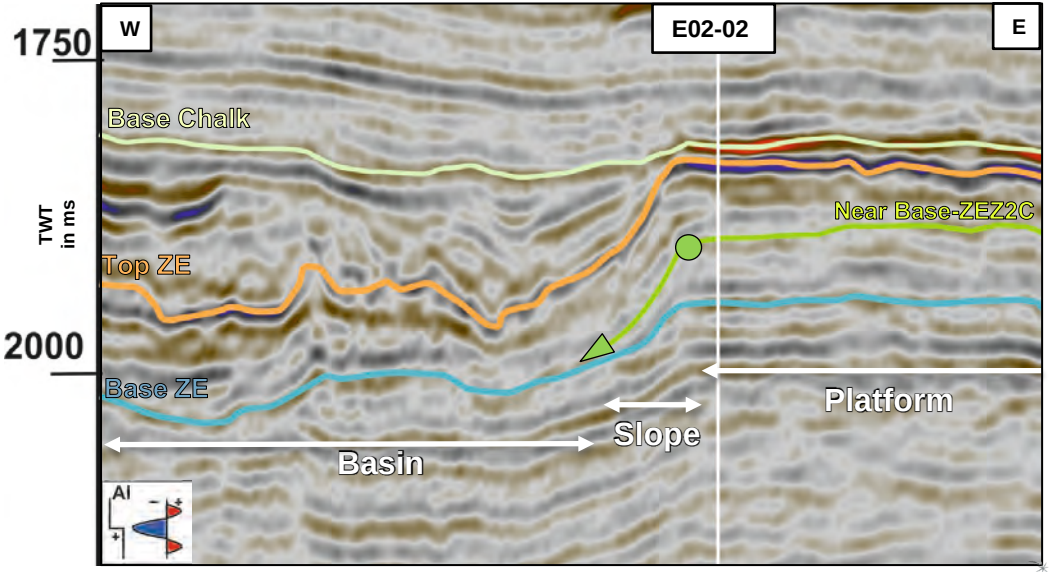
METHODS – FACIES MAPPING

- Mapping was performed of:
  - Base-, & Top Zechstein
  - Soft kick slightly underneath base ZEZ2C
  - the Z2C shelf edge; inflection point of reflector
  - The Z2C slope apron; downlap of reflector



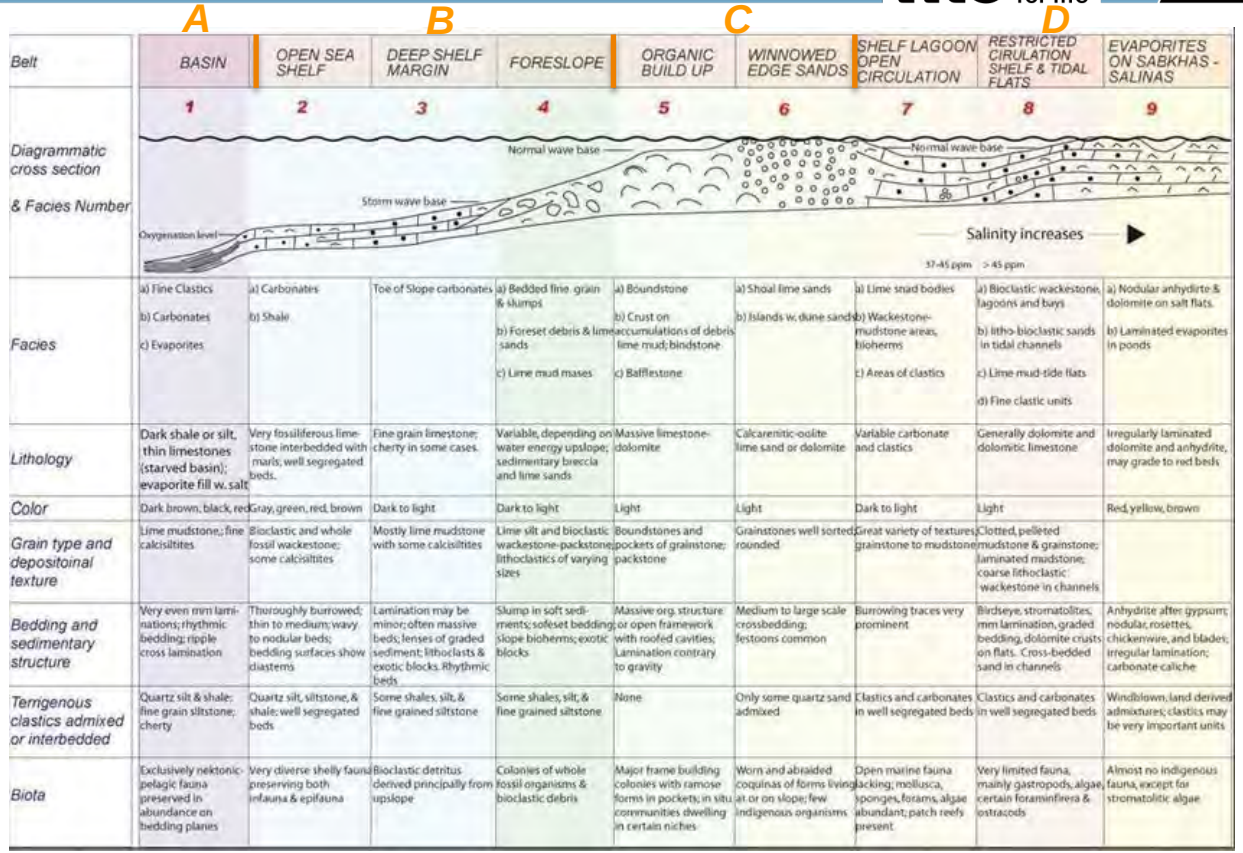


Grant et al., 2019



METHODS – FACIES MAPPING

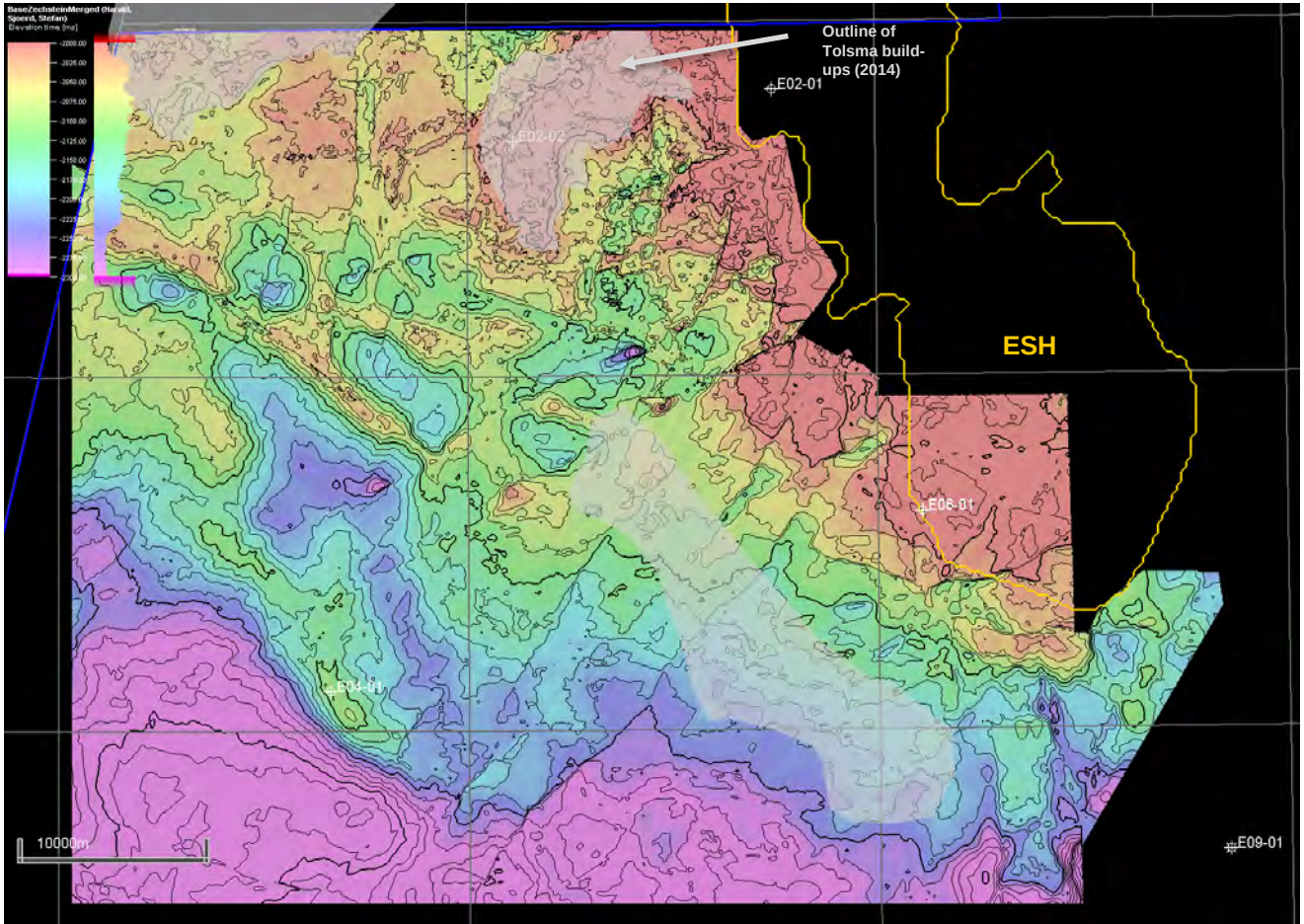
- Mapping was performed of:
  - Base-, & Top Zechstein
  - Soft kick slightly underneath base ZEZ2C
  - the Z2C shelf edge; inflection point of reflector
  - The Z2C slope apron; downlap of reflector
- Based on these seismic observations and the petrographic analysis of some key wells, a facies/depositional environment map was constructed for the ZEZ2C in terms of:
  - A: Basinal facies
  - B: Slope facies
  - C: Platform facies
  - D: Back Barrier/Lagoonal facies



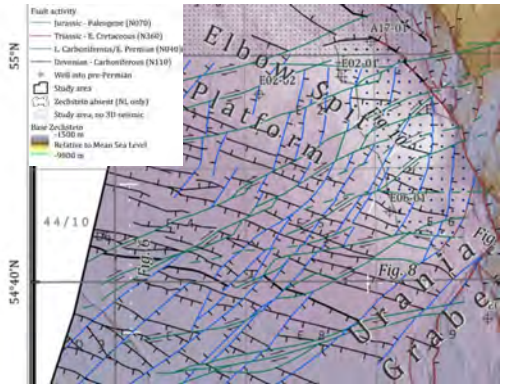
	A		B		C		D		
Belt	BASIN	OPEN SEA SHELF	DEEP SHELF MARGIN	FORESLOPE	ORGANIC BUILD UP	WINNOWED EDGE SANDS	SHELF LAGOON OPEN CIRCULATION	RESTRICTED CIRULATION SHELF & TIDAL FLATS	EVAPORITES ON SABKHAS - SALINAS
	1	2	3	4	5	6	7	8	9
Diagrammatic cross section & Facies Number			Storm wave base	Oxygenation level	Normal wave base		Normal wave base	Salinity increases 37-45 ppm > 45 ppm	
Facies	a) Fine Clastics b) Carbonates c) Evaporites	a) Carbonates b) Shale	Toe of Slope carbonates	a) Bedded fine grain & slumps b) Foreset debris & lime sands c) Lime mud mases	a) Boundstone b) Crust on accumulations of debris lime mud; bindstone c) Baffilestone	a) Shoal lime sands b) Islands w. dune sands	a) Lime snad bodies b) Wackestone-mudstone areas; bioherms c) Areas of clastics	a) Bioclastic wackestone, lagoons and bays b) litho-bioclastic sands in tidal channels c) Lime mud-tide flats d) Fine clastic units	a) Nodular anhydirte & dolomite on salt flats b) Laminated evaporites in ponds
Lithology	Dark shale or silt, thin limestones (starved basin); evaporite fill w. salt	Very fossiliferous lime-stone interbedded with marls; well segregated beds.	Fine grain limestone; cherty in some cases.	Variable, depending on water energy upslope; sedimentary breccia and lime sands	Massive limestone-dolomite	Calcarenitic-oolite lime sand or dolomite	Variable carbonate and clastics	Generally dolomite and dolomitic limestone	Irregularly laminated dolomite and anhydrite, may grade to red beds
Color	Dark brown, black, red	Gray, green, red, brown	Dark to light	Dark to light	Light	Light	Dark to light	Light	Red, yellow, brown
Grain type and depositoinal texture	Lime mudstone.; fine calcisiltites	Bioclastic and whole fossil wackestone; some calcisiltites	Mostly lime mudstone with some calcisiltites	Lime silt and bioclastic wackestone-packstone; lithoclastics of varying sizes	Boundstones and pockets of grainstone; packstone	Grainstones well sorted; rounded	Great variety of textures; grainstone to mudstone	Clotted, pelleted mudstone & grainstone; laminated mudstone; coarse lithoclastic wackestone in channels	
Bedding and sedimentary structure	Very even mm lami-nations; rhythmic bedding; ripple cross lamination	Thoroughly burrowed; thin to medium; wavy to nodular beds; bedding surfaces show diasterns	Lamination may be minor; often massive beds; lenses of graded sediment; lithoclasts & exotic blocks. Rhythmic beds	Slump in soft sedi-ments; soft-set bedding; slope bioherms; exotic blocks	Massive org. structure or open framework with roofed cavities; Lamination contrary to gravity	Medium to large scale crossbedding; festoons common	Burrowing traces very prominent	Birdseye, stromatolites; mm lamination, graded bedding, dolomite crusts on flats. Cross-bedded sand in channels	Anhydrite after gypsum; nodular, rosettes, chickenwire, and blades; irregular lamination; carbonate caliche
Terrigenous clastics admixed or interbedded	Quartz silt & shale; fine grain siltstone; cherty	Quartz silt, siltstone, & shale; well segregated beds	Some shales, silt, & fine grained siltstone	Some shales, silt, & fine grained siltstone	None	Only some quartz sand admixed	Clastics and carbonates in well segregated beds	Clastics and carbonates in well segregated beds	Windblown, land derived admixtures; clastics may be very important units
Biota	Exclusively nektonic-pelagic fauna preserved in abundance on bedding planes	Very diverse shelly fauna preserving both infauna & epifauna	Bioclastic detritus derived principally from upslope	Colonies of whole fossil organisms & bioclastic debris	Major frame building colonies with ramose forms in pockets; in situ communities dwelling in certain niches	Worn and abraided coquinas of forms living at or on slope; few indigenous organisms	Open marine fauna lacking; mollusca, sponges, forams, algae abundant; patch reefs present	Very limited fauna, mainly gastropods, algae, certain foraminifera & ostracods	Almost no indigenous fauna, except for stromatolitic algae

Figure from Wilson, J.L., 1975

RESULTS – SEISMIC MAPPING; BASE ZE

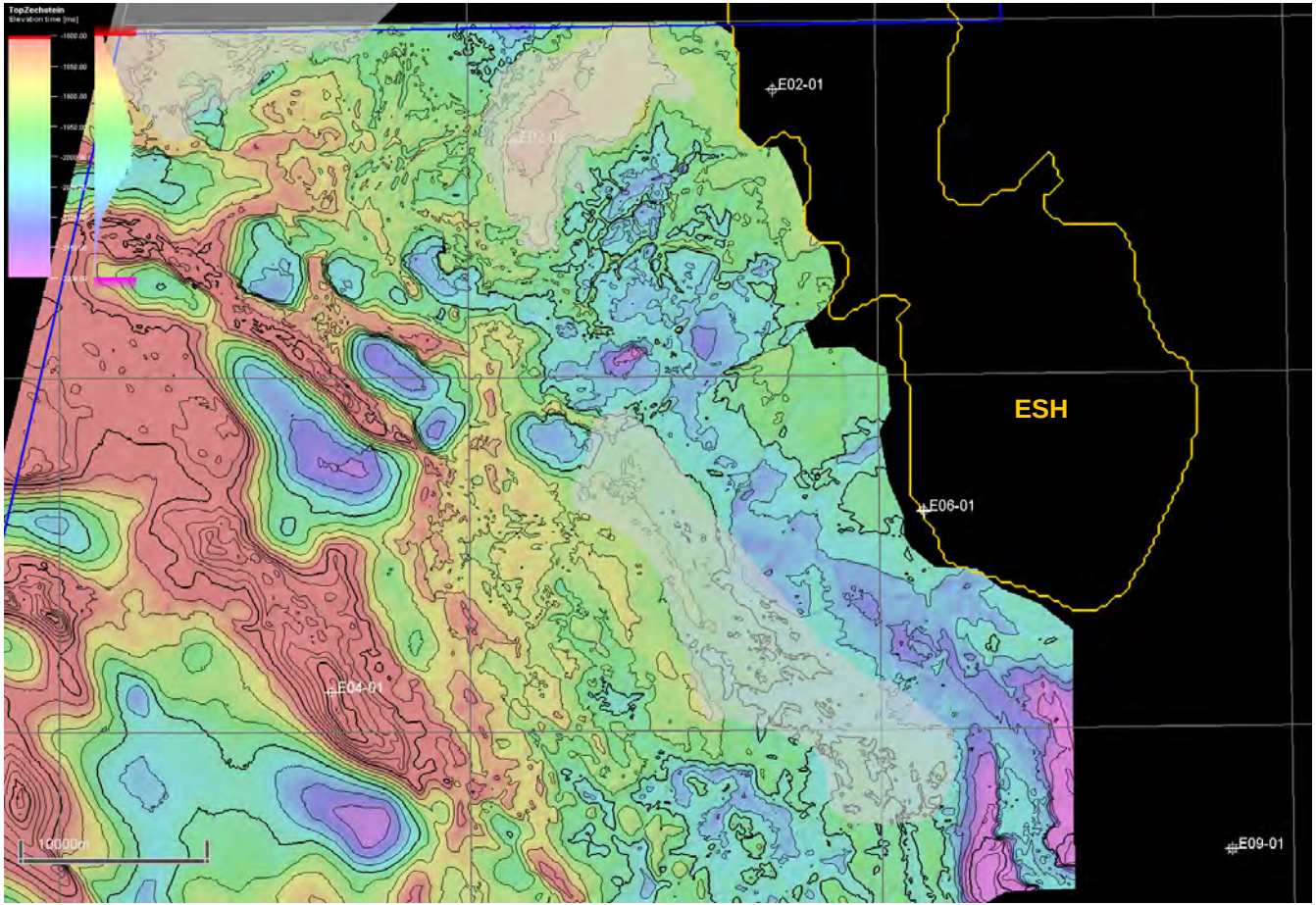


- Base ZE southwest of ESH,
- Elevated base ZE directly around ESH and E02-02 platform
- Note three main fault trends, also recognized by Ter Borgh et al., 2018:
  - SW-NE strike-slip faults (N070)
  - SSW-NNE Late Carboniferous /Early Permian (N040)
  - NW-SE Devonian-Carboniferous faults (N110)



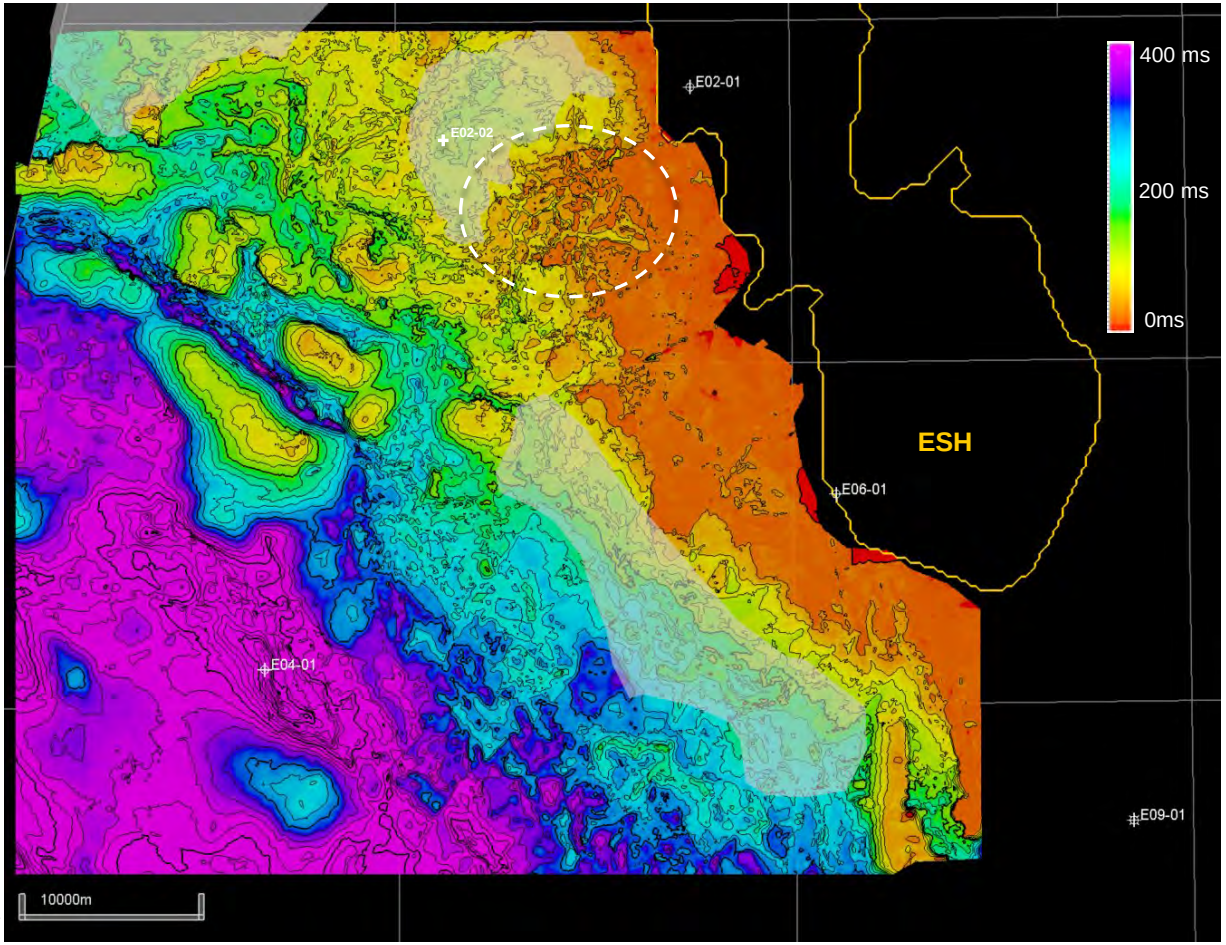
From Ter Borgh et al., (2018)

RESULTS – SEISMIC MAPPING; TOP ZE

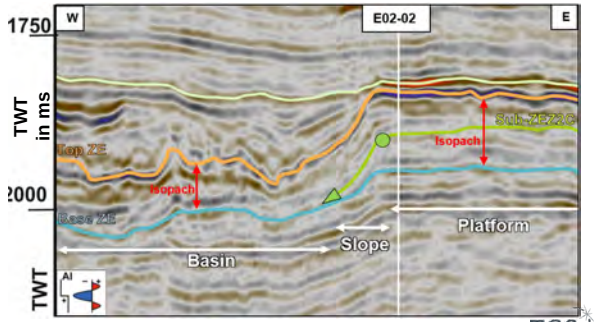


- Top ZE southwest of ESH
- Note Mesozoic pods in the SW part of study area.
- Also note zone of high rugosity at top ZE southeast of well E02-02

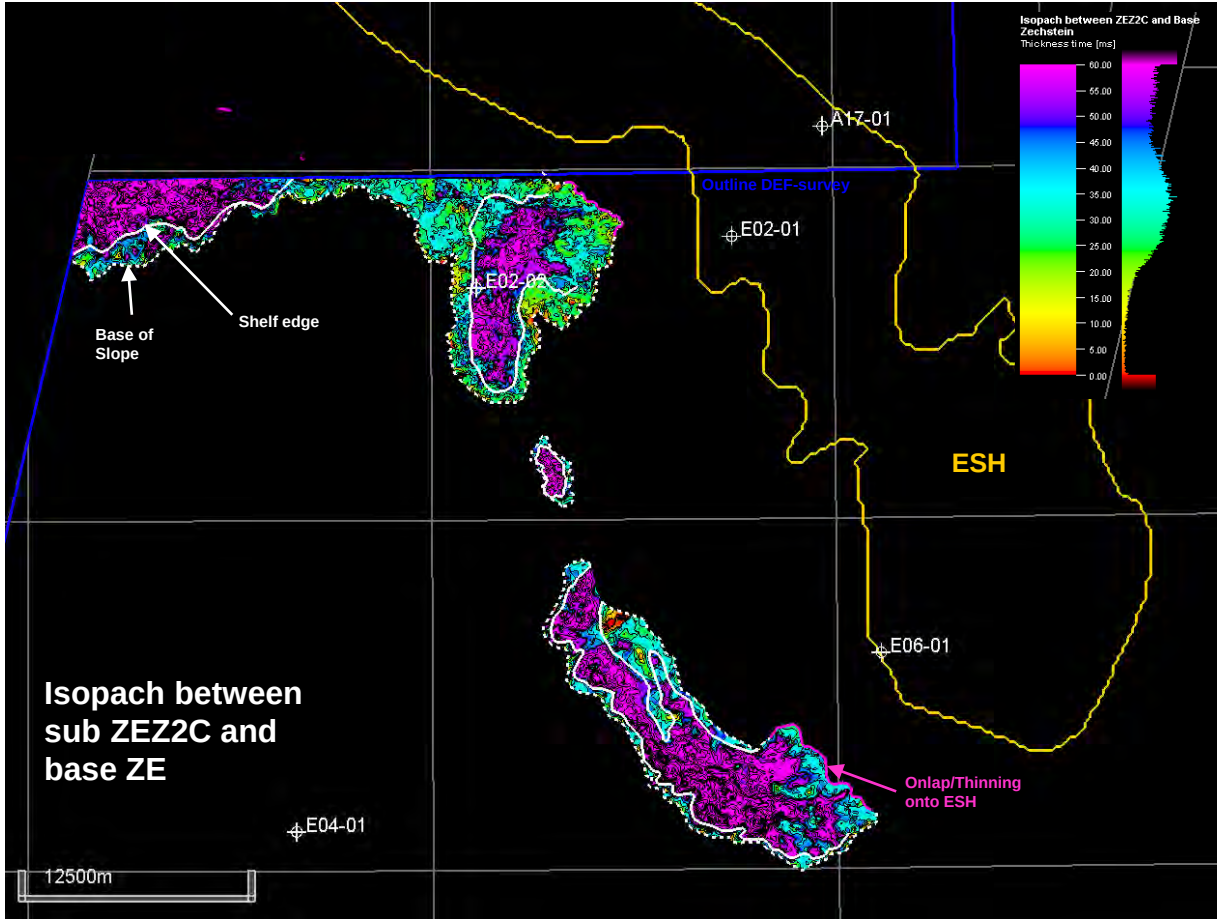
RESULTS – SEISMIC MAPPING; ISOPACH ZE



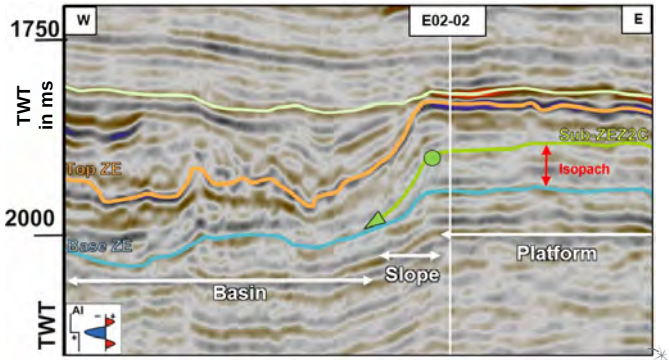
- Isopach ZE southwest of ESH,
- Note complex zone east of the E02-02 platform (indicated within the white dashed circle). Top Zechstein displays high rugosity. Base Zechstein hard to map. Three hypothesis that could cause this seismic signal (more on this in discussion);
  - Karst due to dissolution
  - Isolated reef patches
  - Faulting and related pop-ups



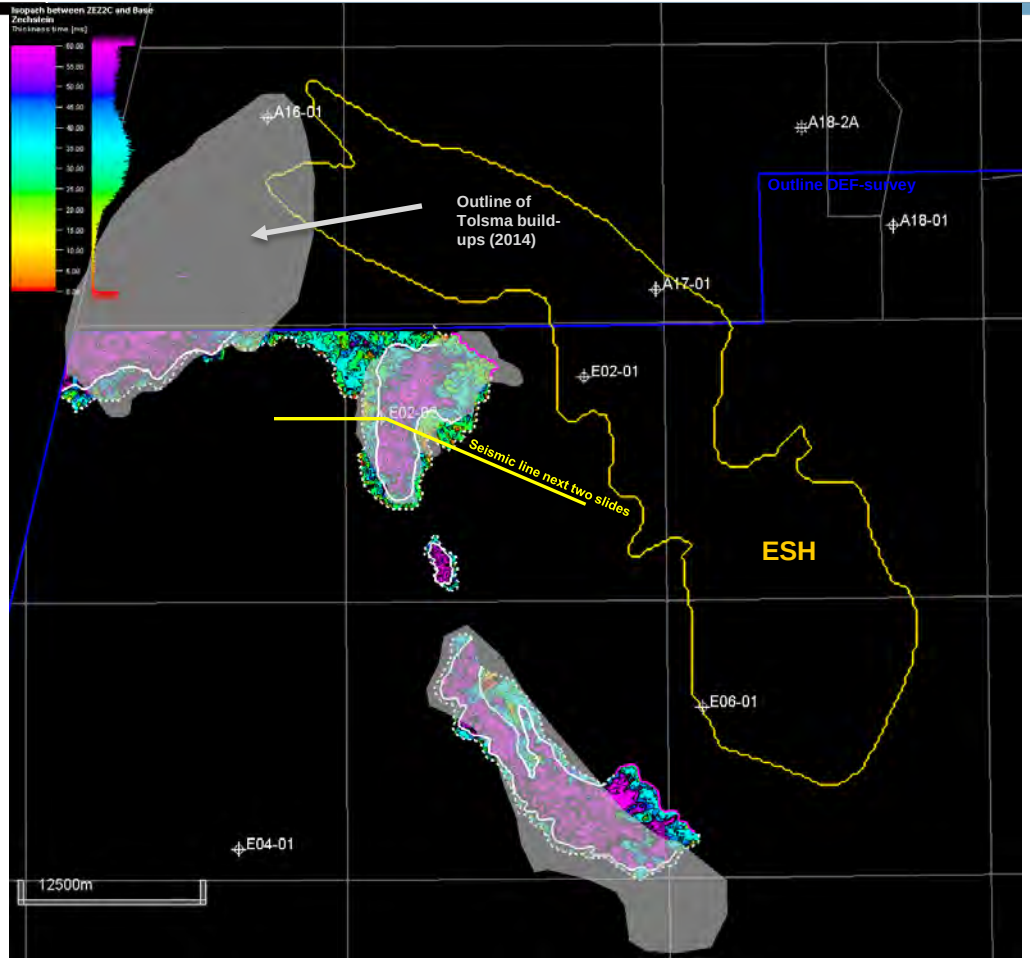
RESULTS – ISOPACH SUB ZEZ2C AND BASE ZECHSTEIN



- Isopach of interval between sub ZEZ2C reflector and Base Zechstein
- White lines: Z2 Shelf edge, represented by inflection point of reflector
- Dashed white lines: Base of slope represented by downlap of reflector
- Pink line: onlaps/thinning against high
- Note: thickest sub ZEZ2C interval in core part of the build-up then decreasing thickness both towards basin-, and lagoonal side

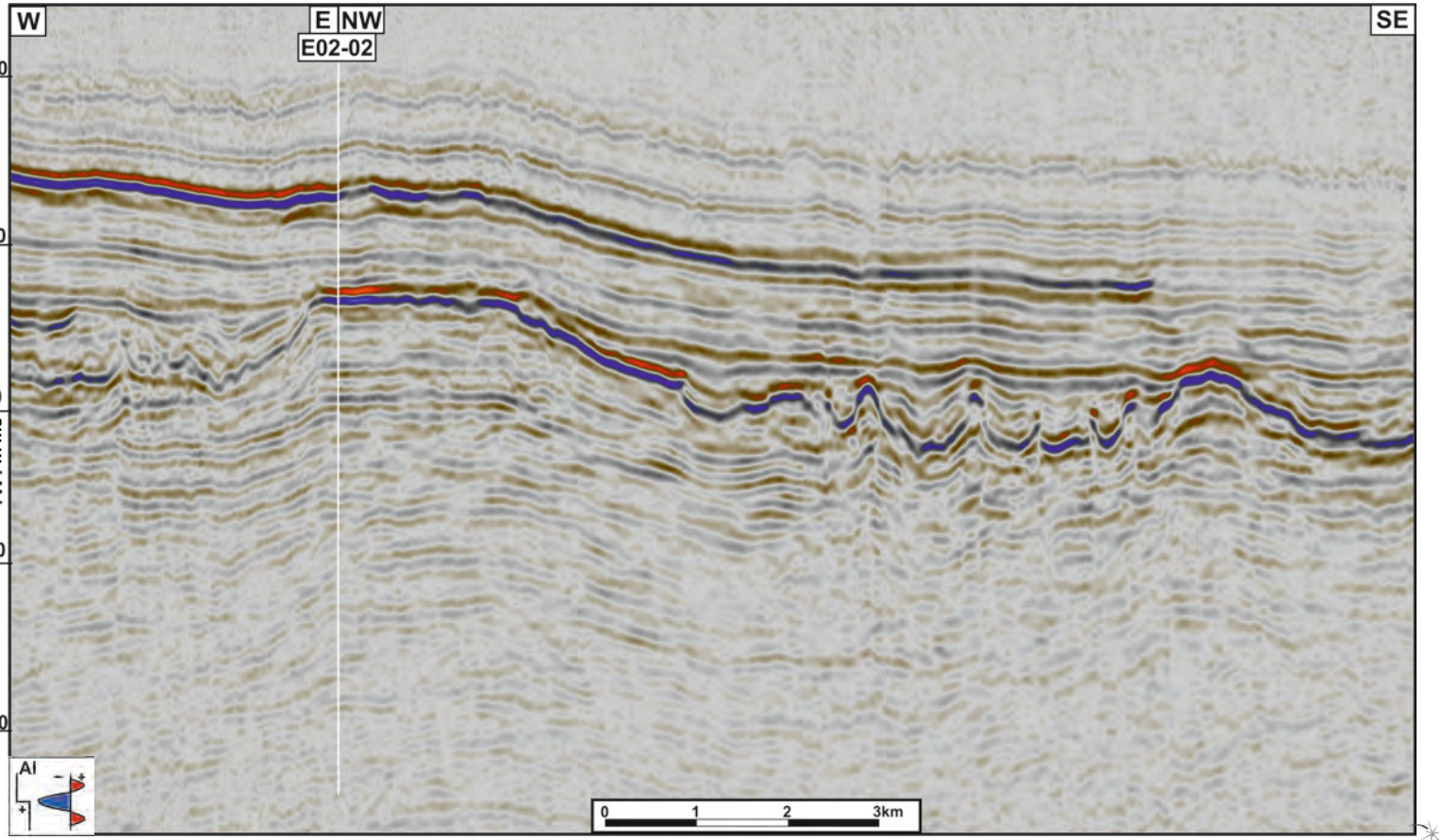


RESULTS – ISOPACH SUB ZEZ2C AND BASE ZECHSTEIN

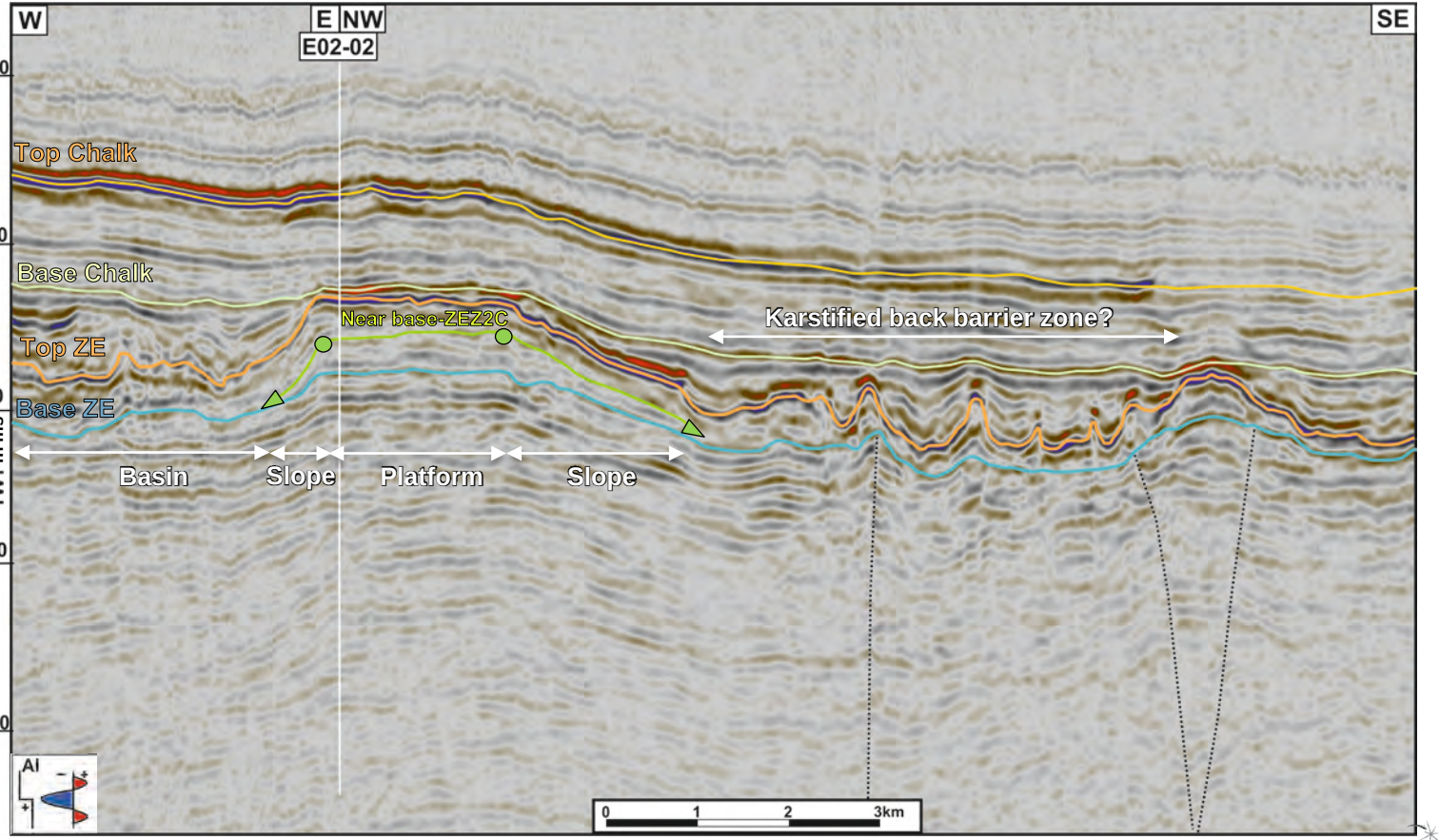


- Transparent polygons: Z2 buildups as mapped by Tolsma (2014)
- Generally: the outlines are roughly the same, but exact build-up configurations are more detailed and somewhat smaller than mapped by Tolsma (2014)
- On the next couple of slides, several seismic lines are shown to illustrate the area south of the ESH. Note that besides the E02-02 well, no build-ups were drilled; hence the position of the ZEZ2C could not be exactly determined and tied to the seismic data. Instead, downlaps and inflection points were mapped to derive the postulated position of the build-ups.

RESULTS – SEISMIC SOUTH OF ESH

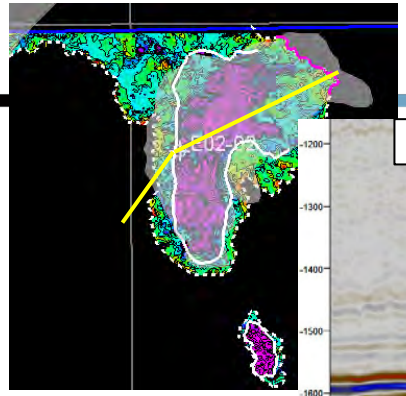


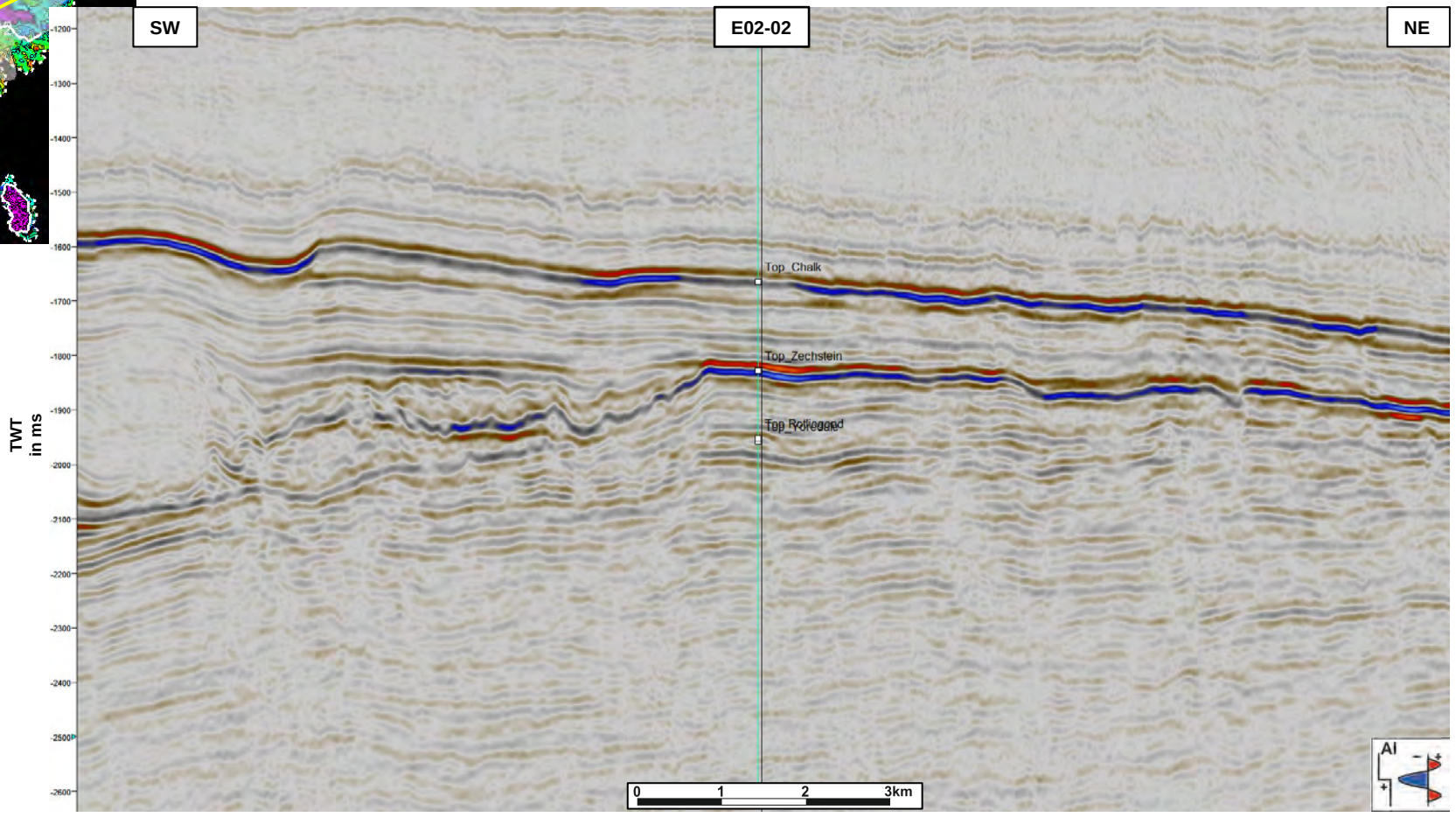
RESULTS – SEISMIC SOUTH OF ESH



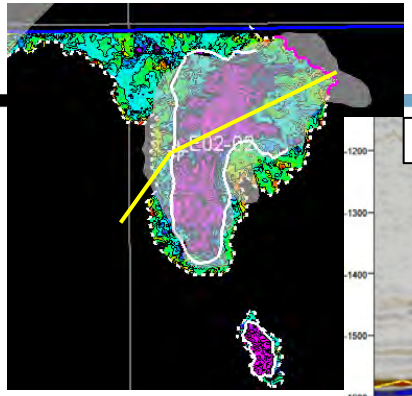
- Platform present on pre-existing Carboniferous anticline/paleo-high.
- Note high rugosity of top Zechstein reflector. Three hypothesis that could cause this seismic signal (more on this in discussion);
  - Karst due to dissolution
  - Isolated reef patches
  - Faulting and related pop-ups

RESULTS – SEISMIC SOUTH OF ESH

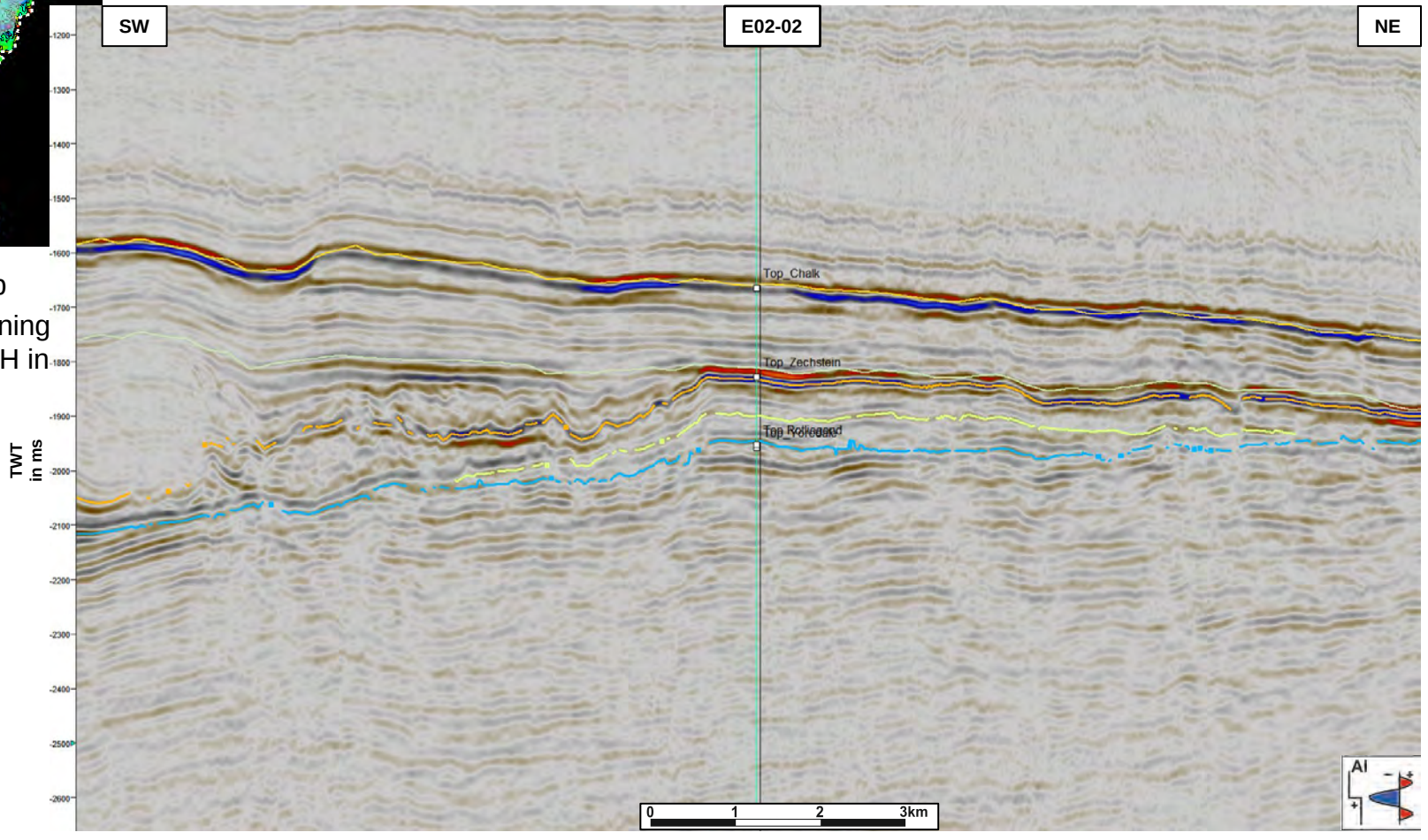




RESULTS – SEISMIC SOUTH OF ESH

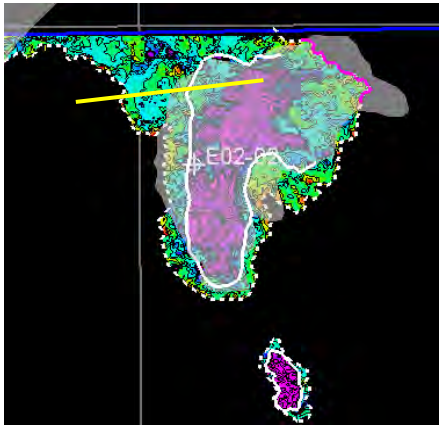


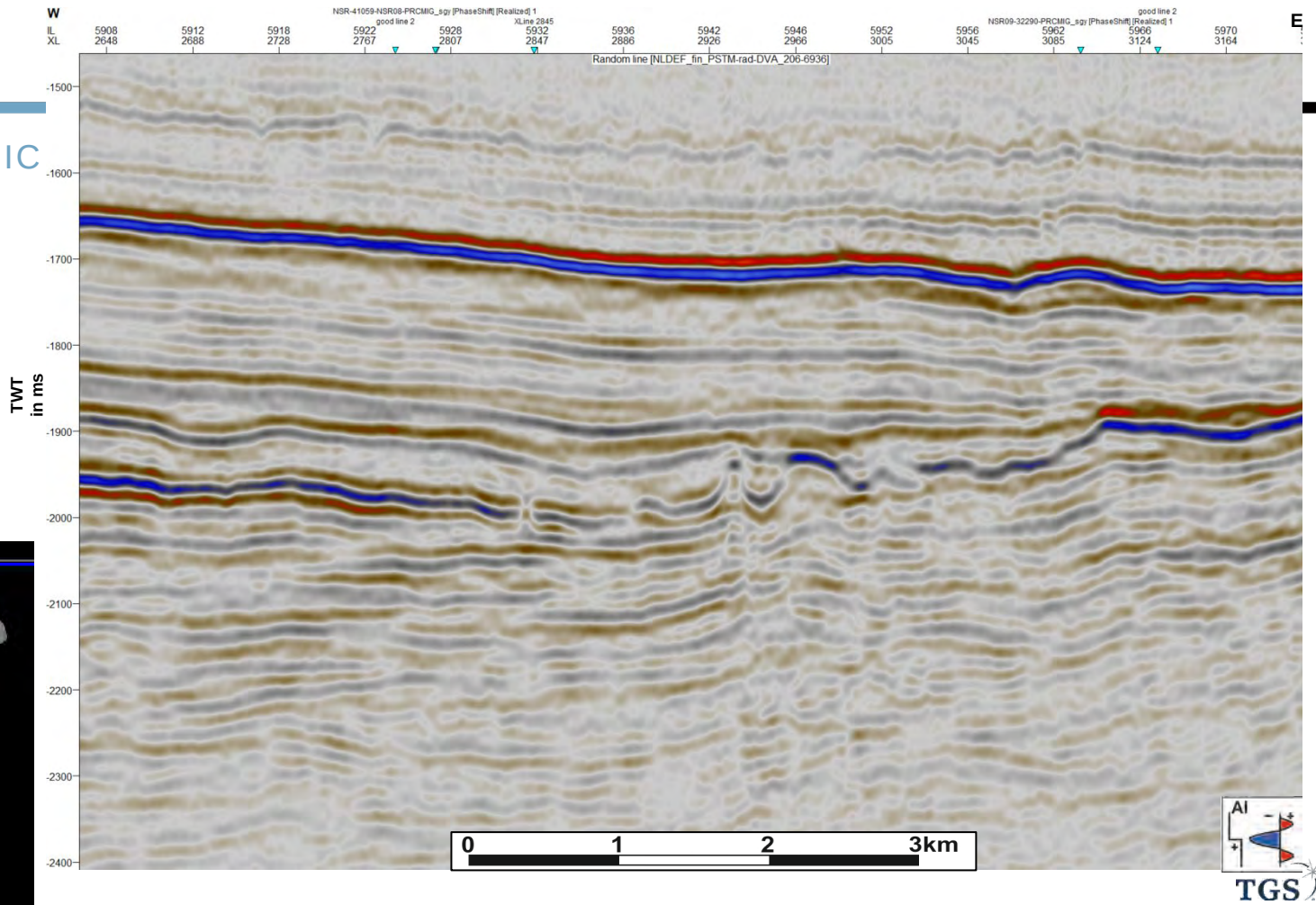
- E02-02 build-up
- Note onlap/thinning towards the ESH in the NE



RESULTS – SEISMIC SOUTH OF ESH

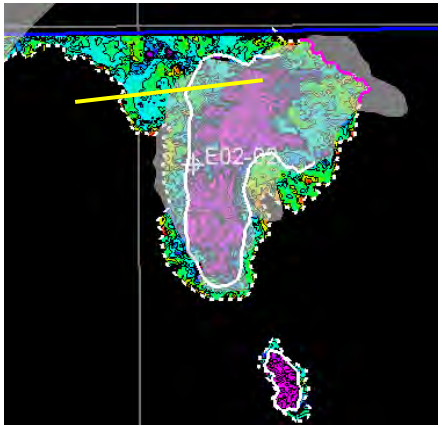
- E02-02 build-up

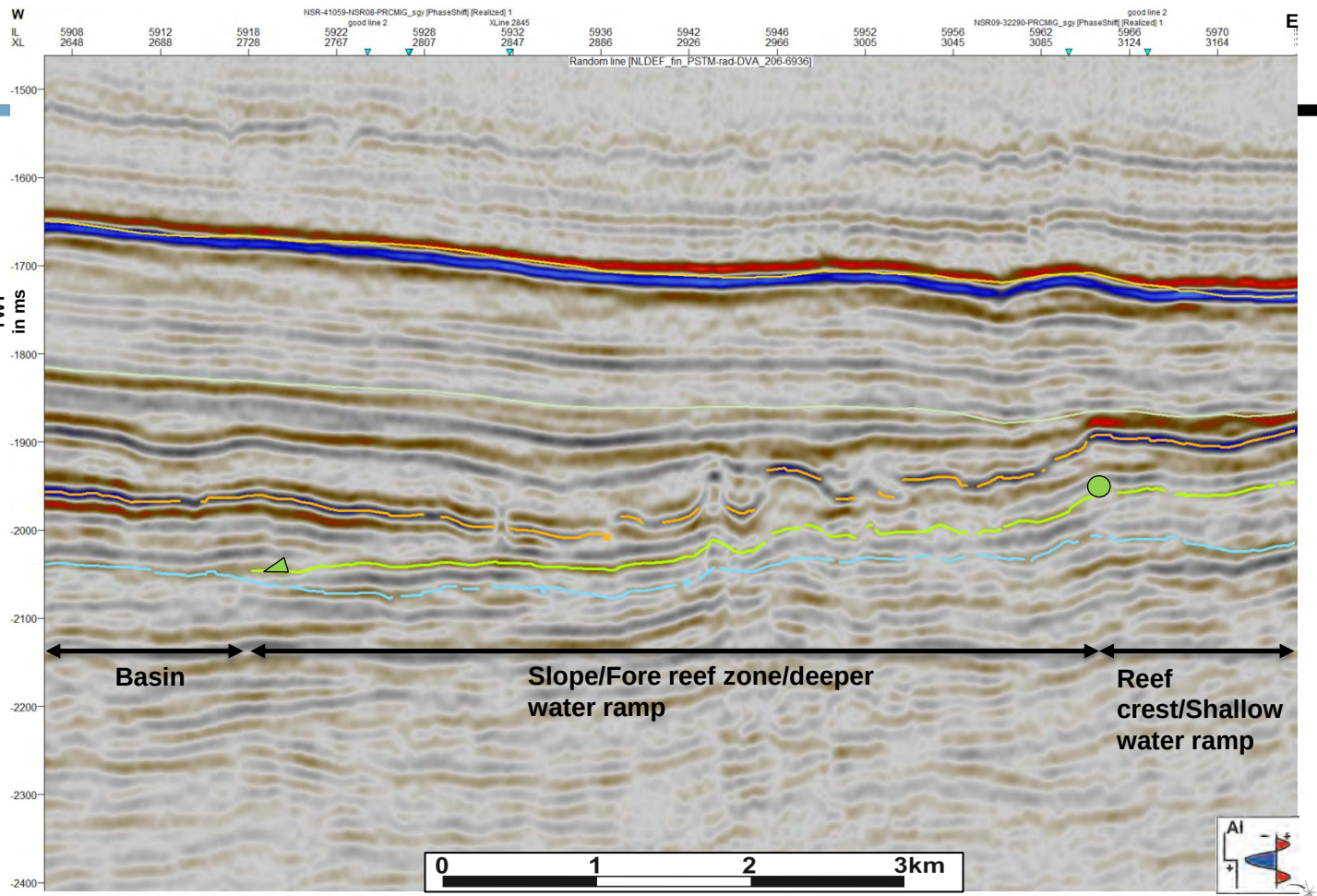




RESULTS – SEISMIC SOUTH OF ESH

- E02-02 build-up
- Platform facies likely more extensive than initially indicated by Tolsma (2014).
- Note configurations of inflection point and downlap

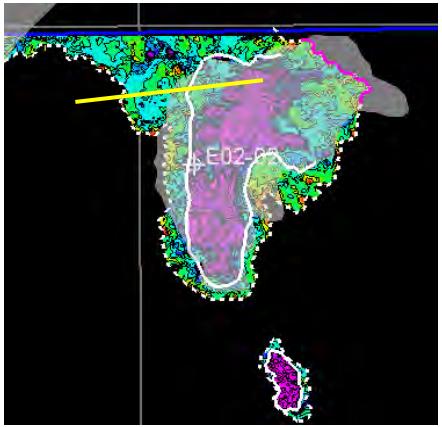


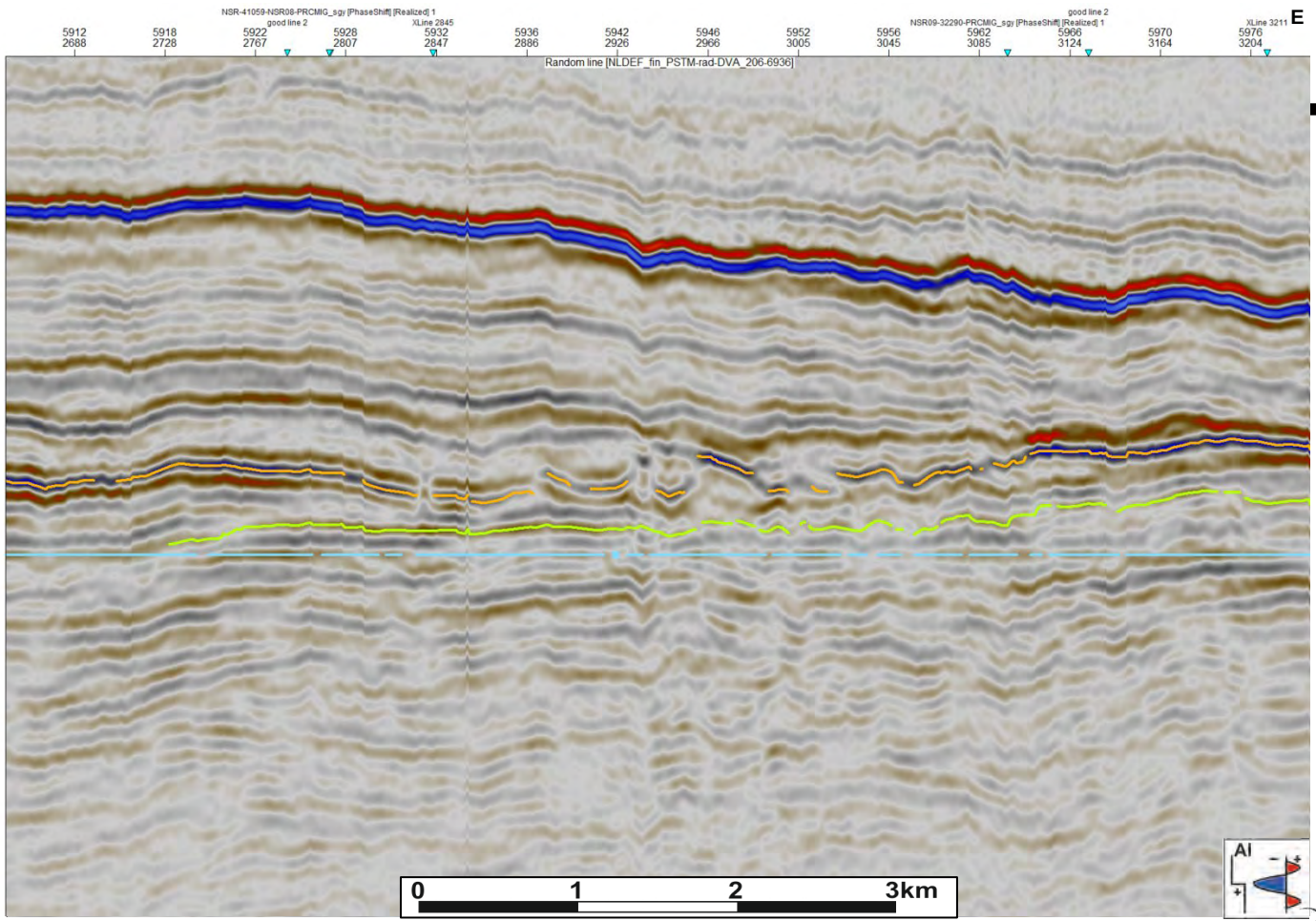


- Note downlap of sub ZEZ2C reflector (i.e. slope apron).

RESULTS – SEISMIC SOUTH OF ESH

- E02-02 build-up
- Flattened on base ZE

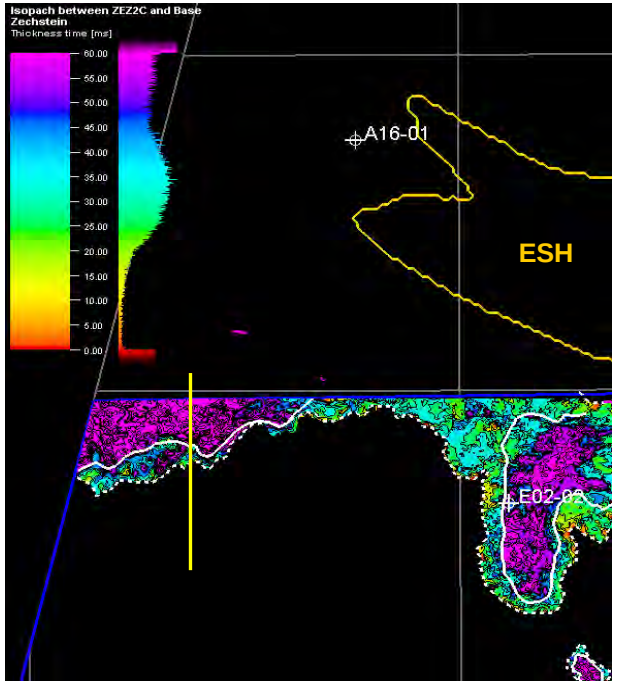


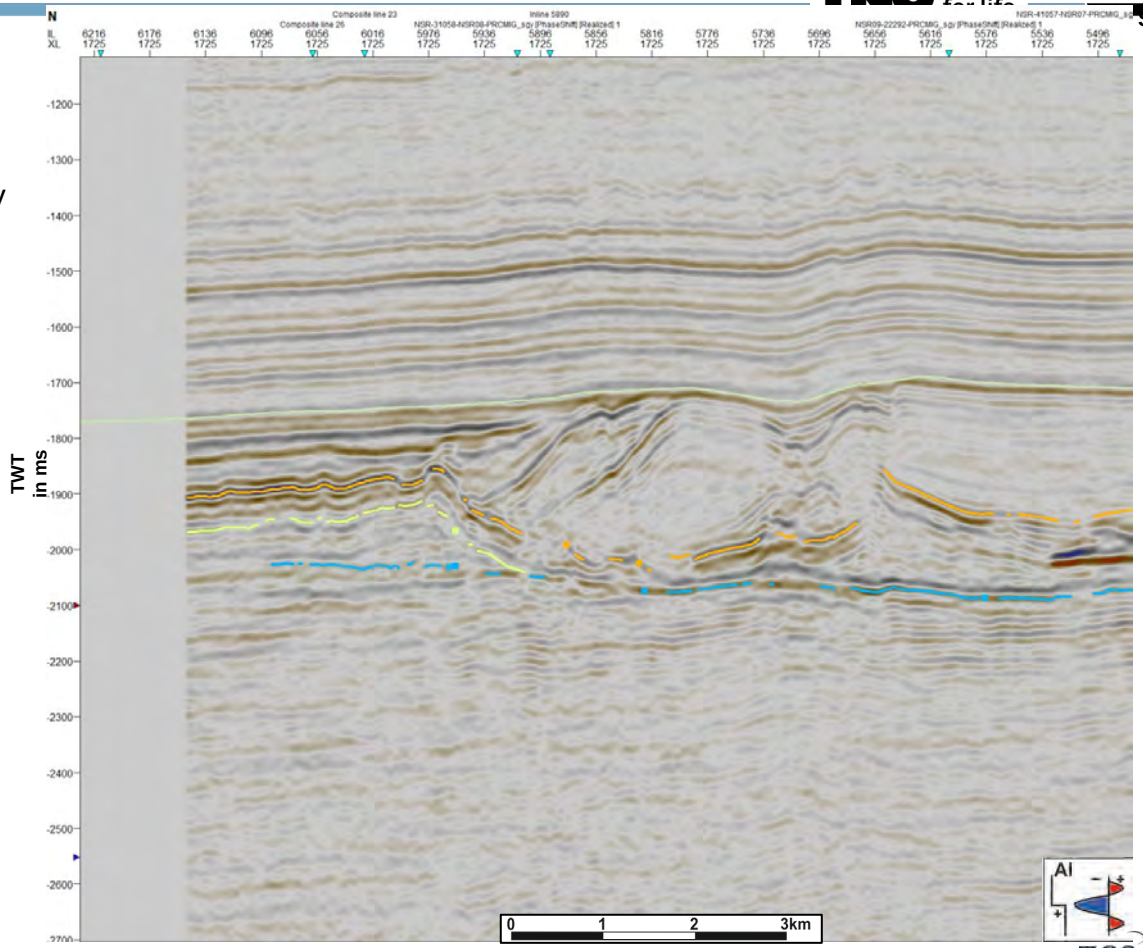


- Note downlap of sub ZEZ2C reflector (i.e. slope apron).
- Also note gradual decrease in thickness of sub ZEZ2C interval towards the W/SW; more gradual slope.

RESULTS – SEISMIC LINES SOUTH OF ESH

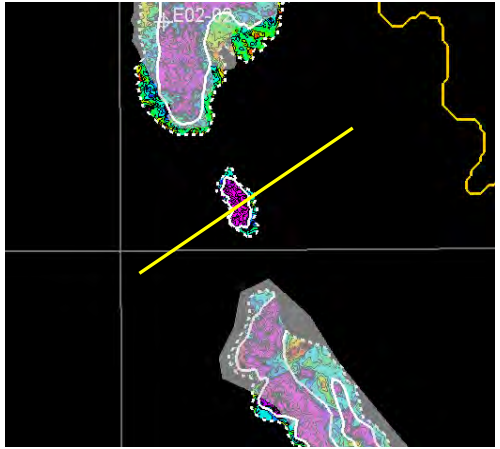
- Platform southwest of A16-01
- Note inflection point and downlap towards the basinal part
- Salt that was deposited slightly further south likely acted as decollement for Triassic raft systems

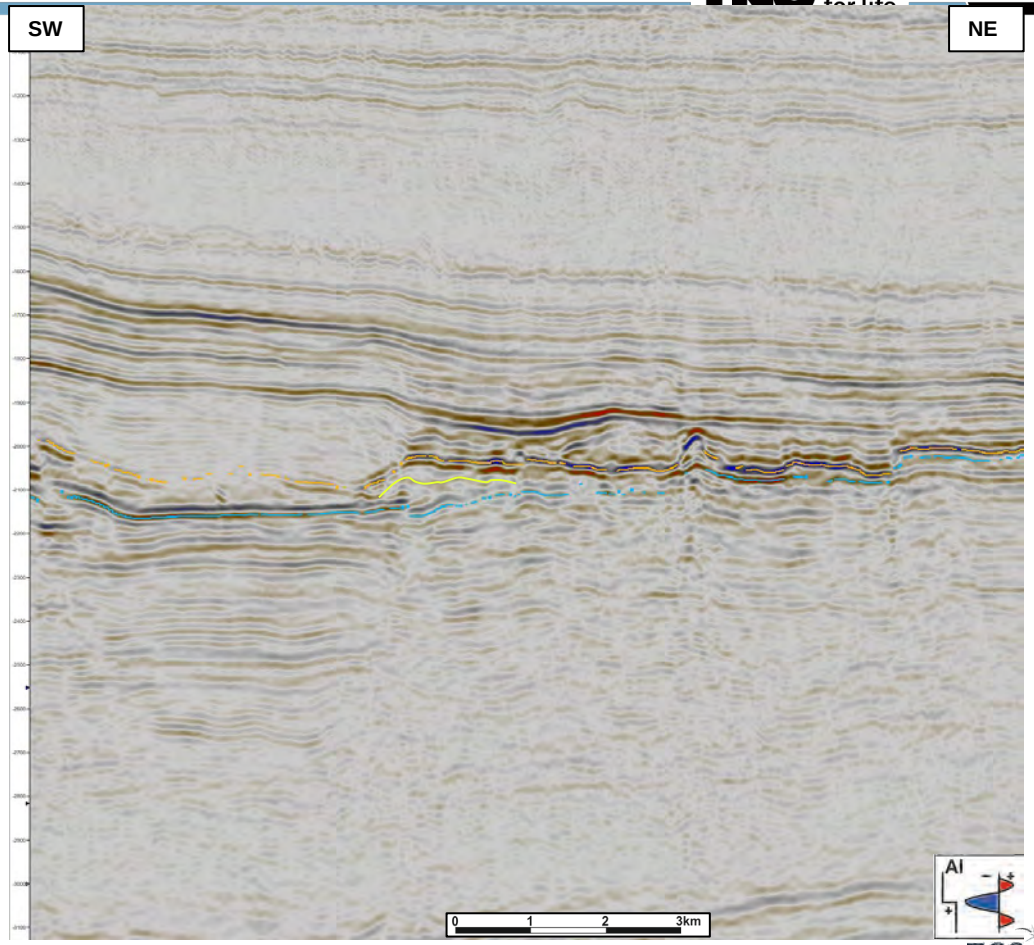




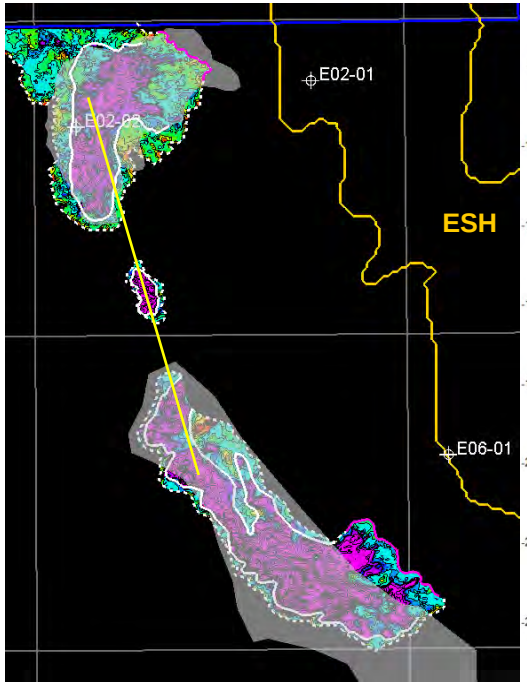
RESULTS – SEISMIC SOUTH OF ESH

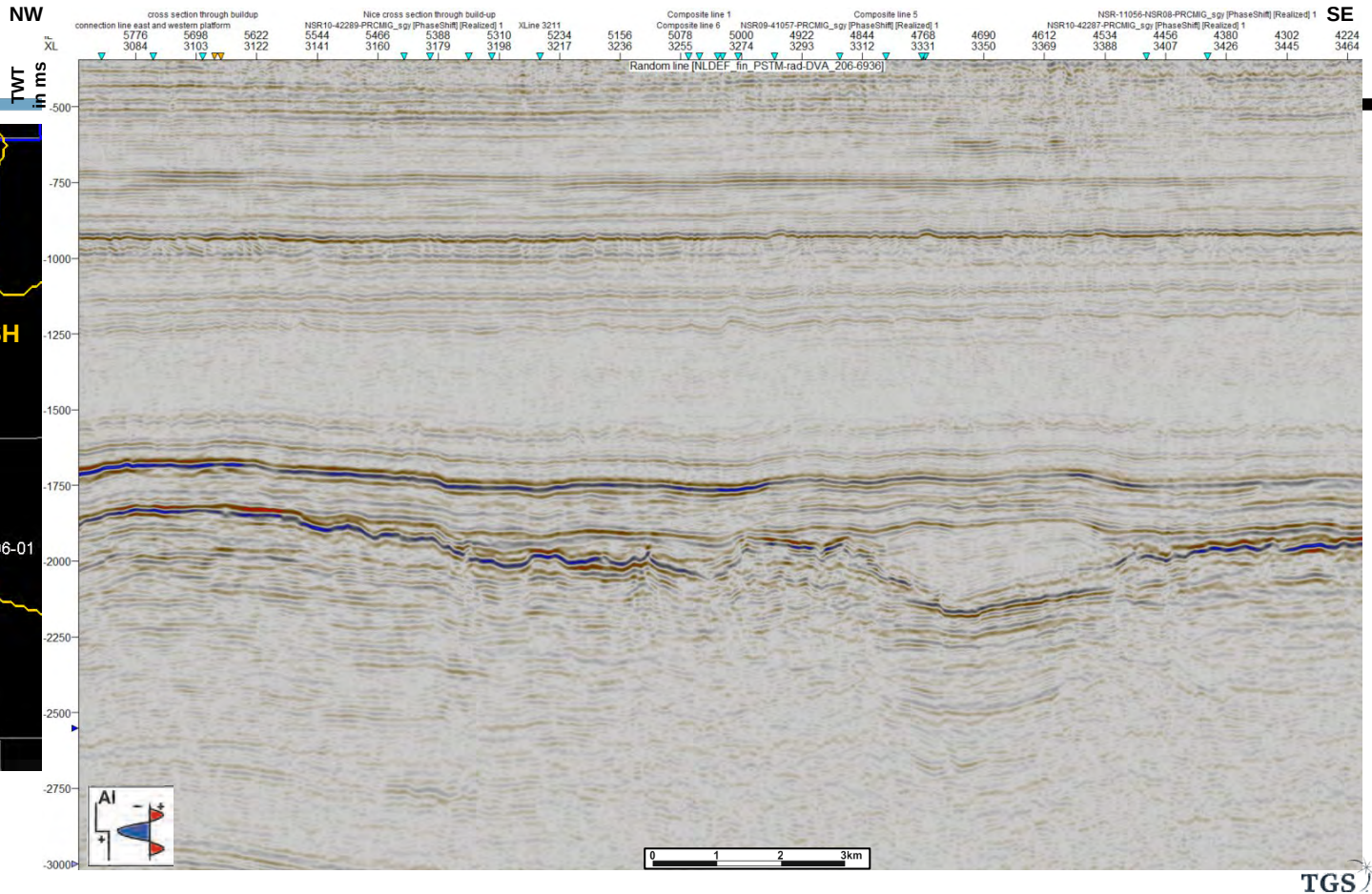
- Small build-up that was not mapped by Tolsma (2014)
- Thinner than build-ups towards the north and south, but inflection point and downlap are present





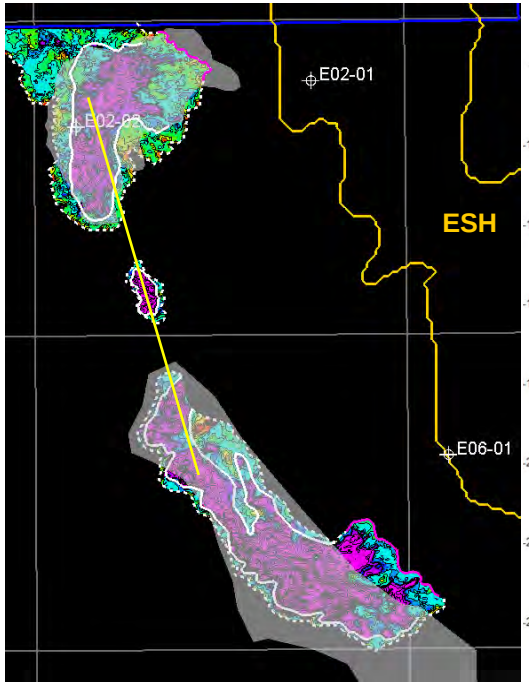
RESULTS – SEISMIC SOUTH OF ESH

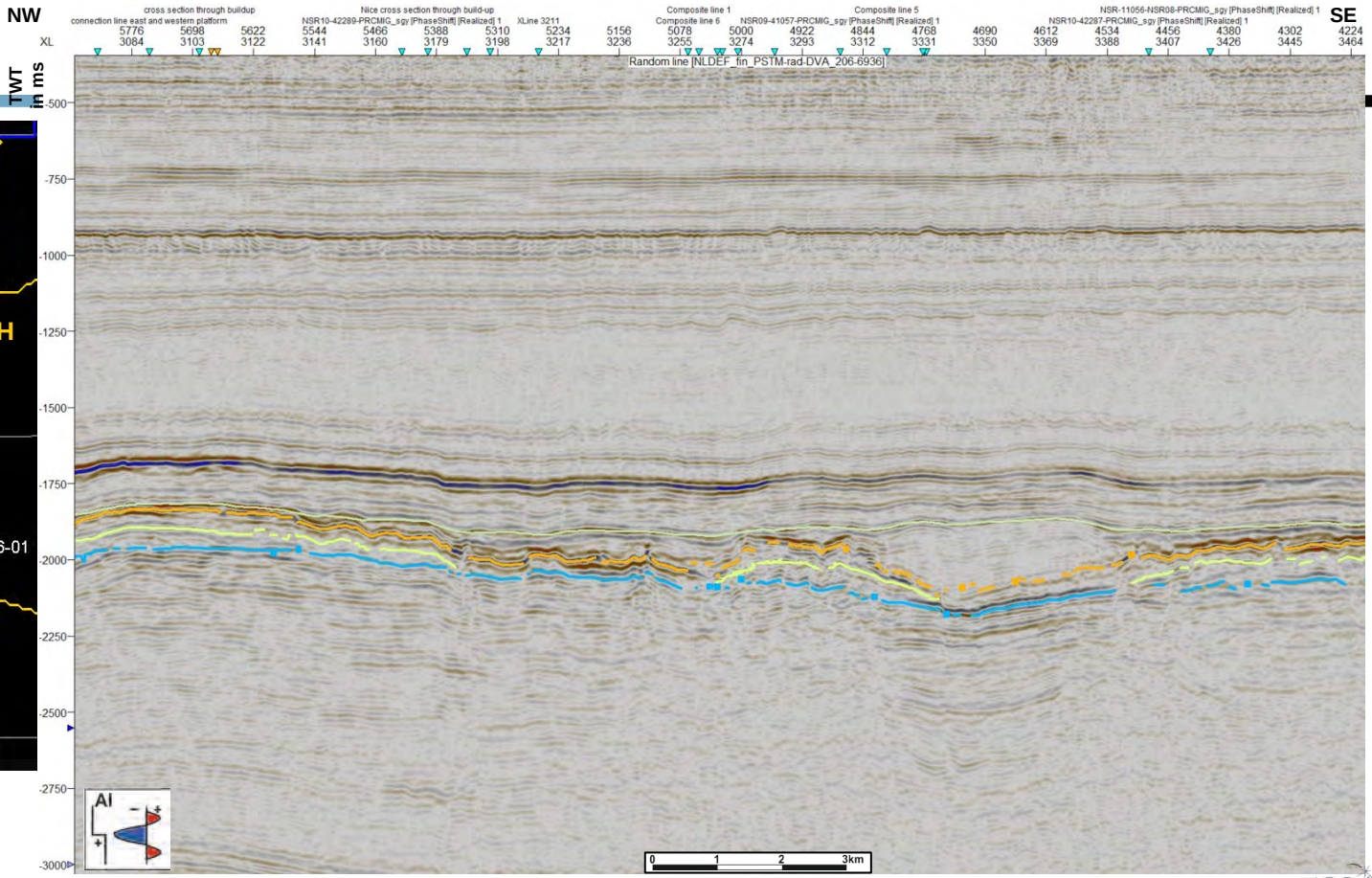




- Line showing 3 build-ups.

RESULTS – SEISMIC SOUTH OF ESH

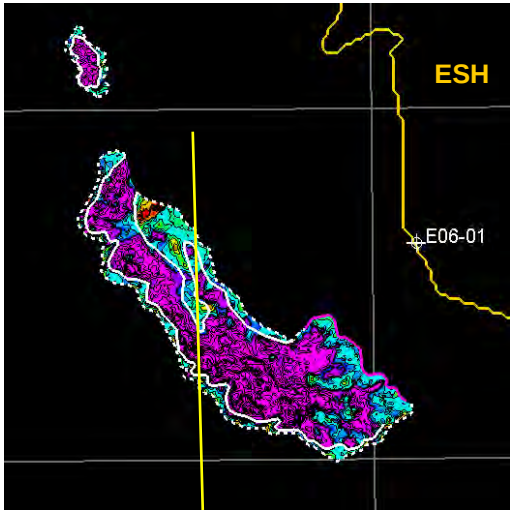


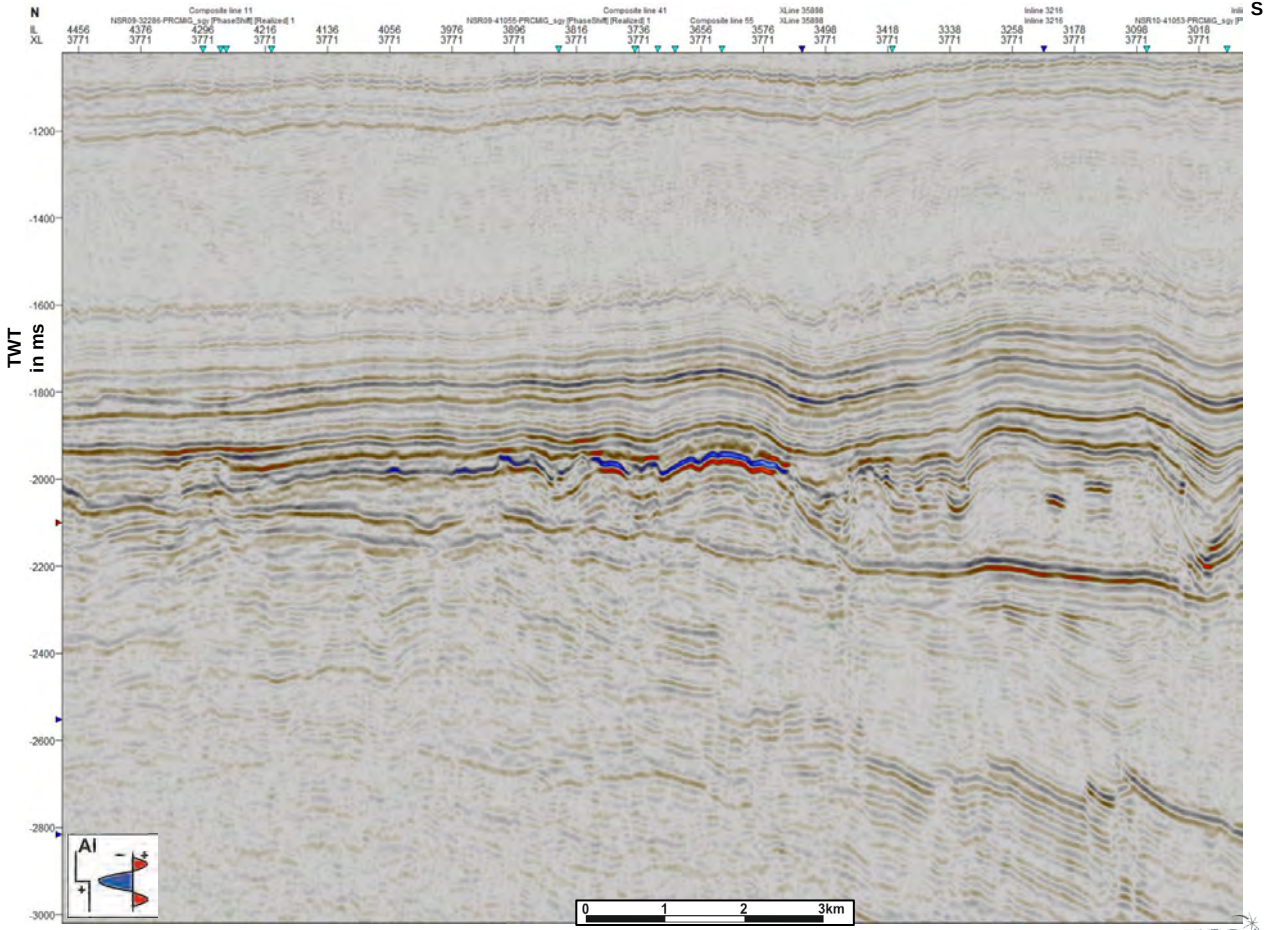


- Line showing 3 build-ups.
- Note that downlaps are observed between the individual reefs (individual build-ups don't appear to be fully connected)
- 2 build-ups south of E02-02 build-up aren't drilled. Hence less reliability because build-ups aren't connected and no seismic to well tie

RESULTS – SEISMIC SOUTH OF ESH

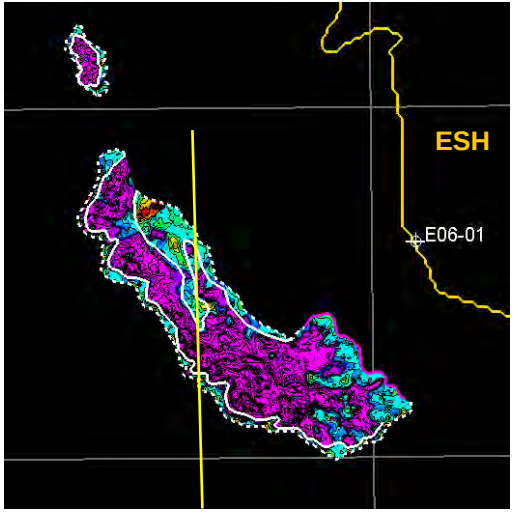
- Build-up southwest of E06-01

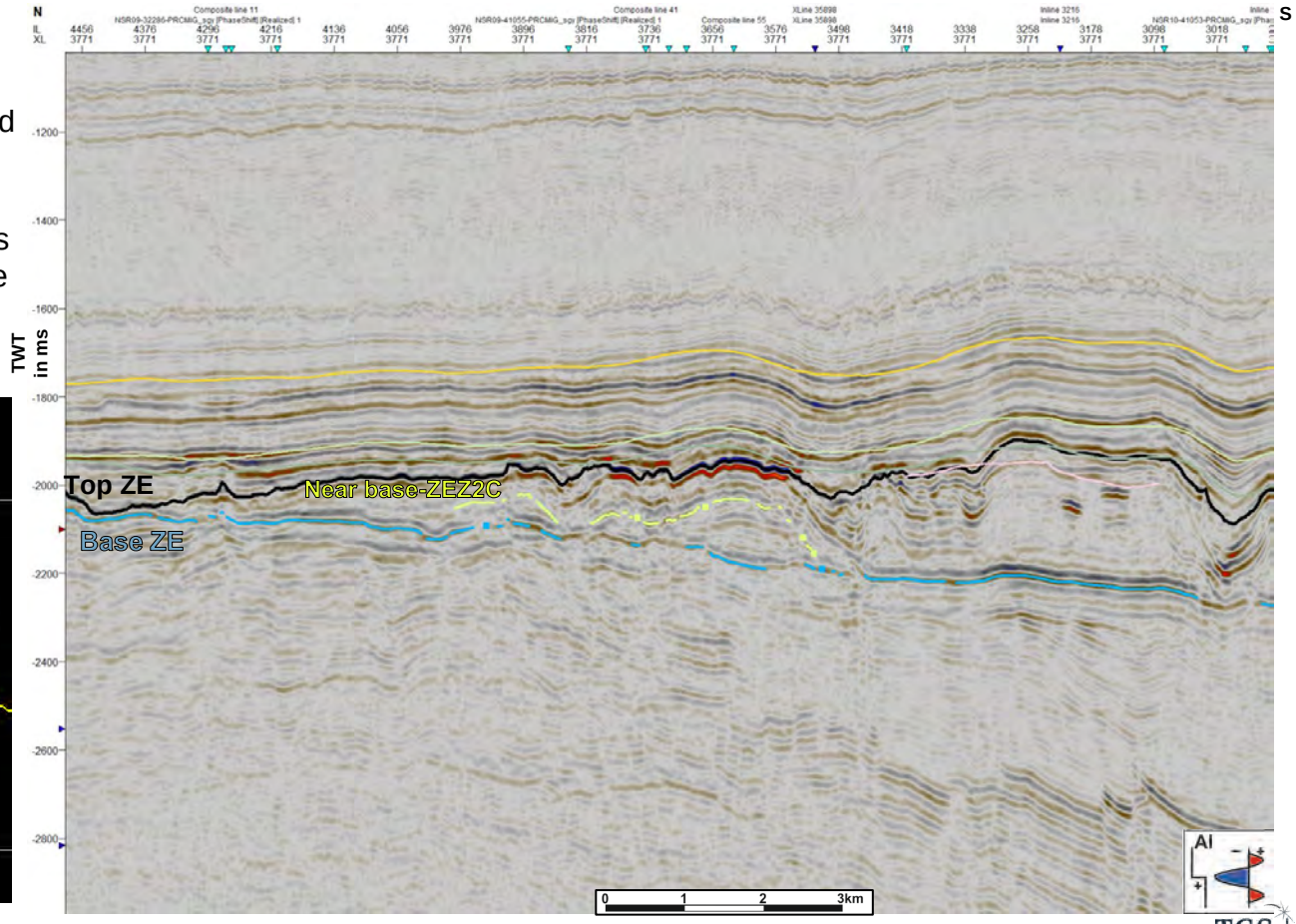




RESULTS – SEISMIC SOUTH OF ESH

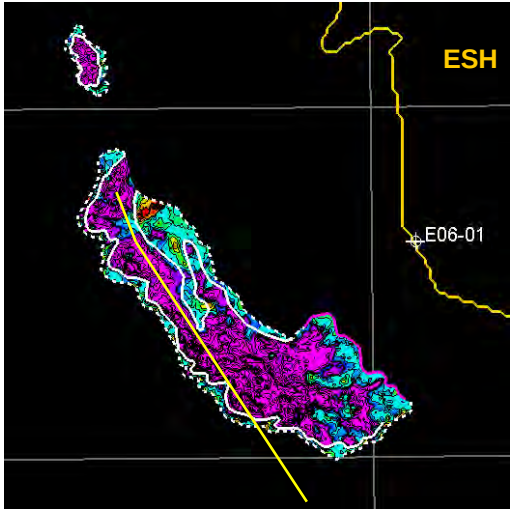
- Build-up southwest of E06-01
- note; build up consists of multiple core parts with alternating thicker and thinner ZEZ2C-Werra anhydrite intervals
- Also note thickness increase towards south (towards basin), likely because there was more accommodation

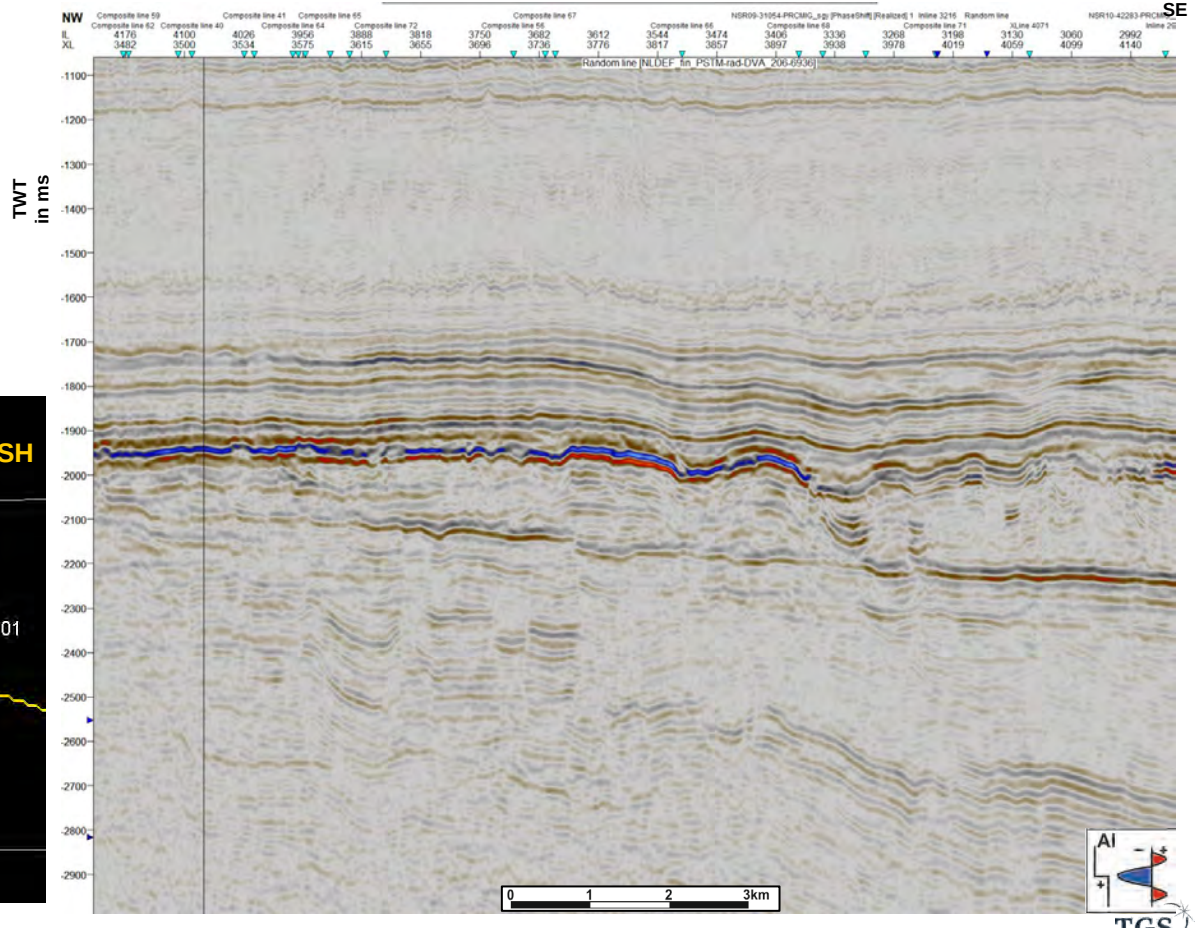




RESULTS – SEISMIC SOUTH OF ESH

- Random line through outer rim of build-up, displaying the thickest part of the build-up.





RESULTS – SEISMIC SOUTH OF ESH

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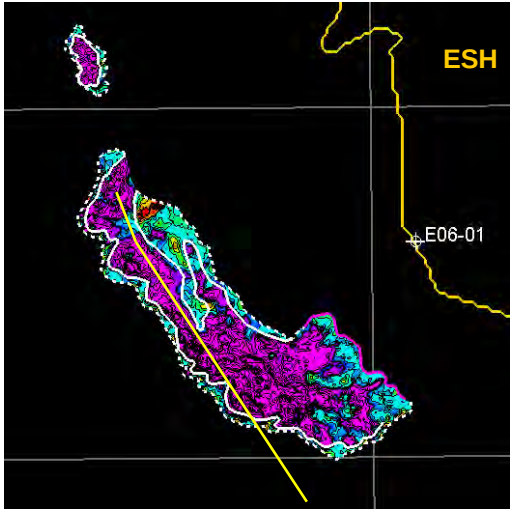
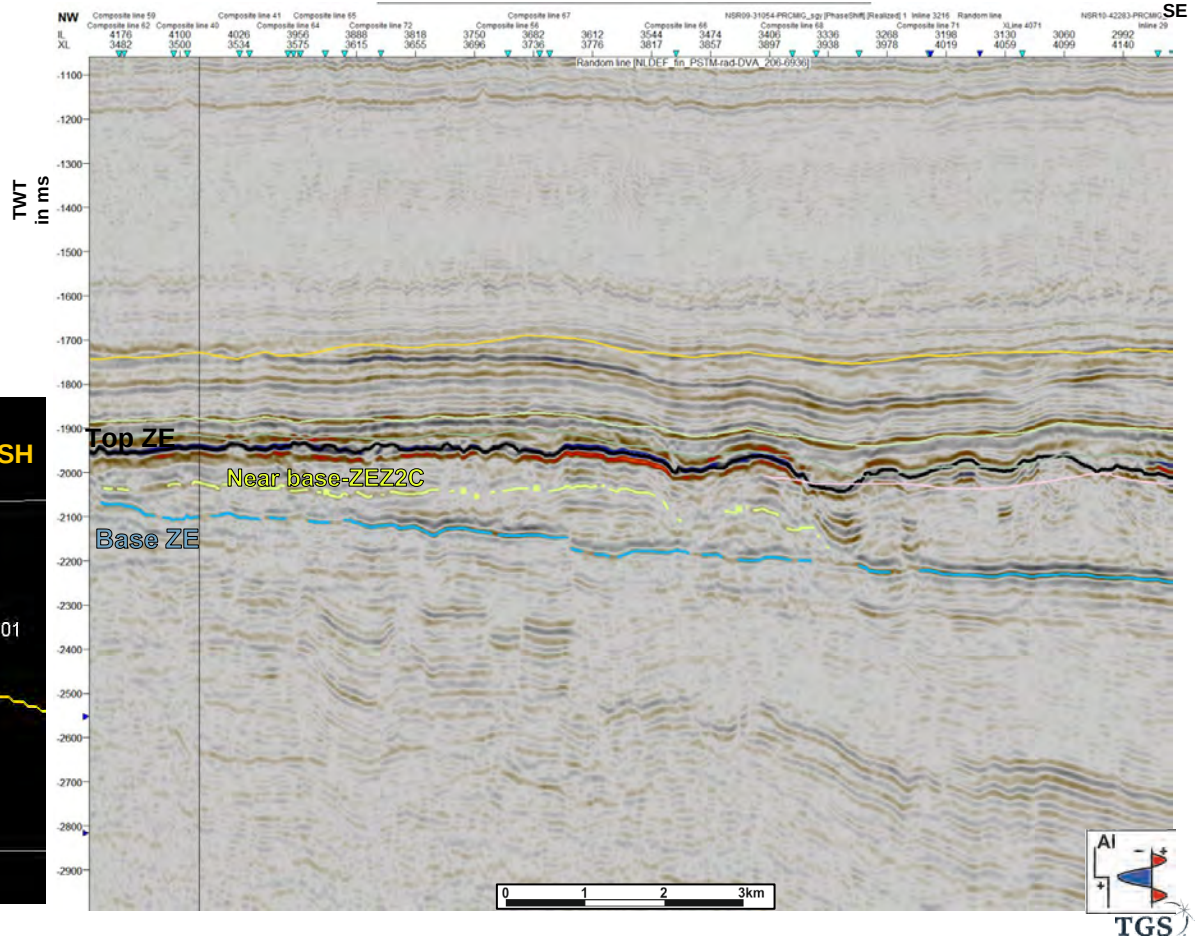
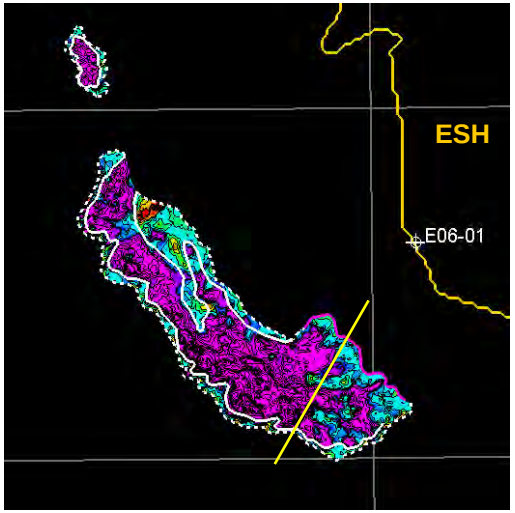
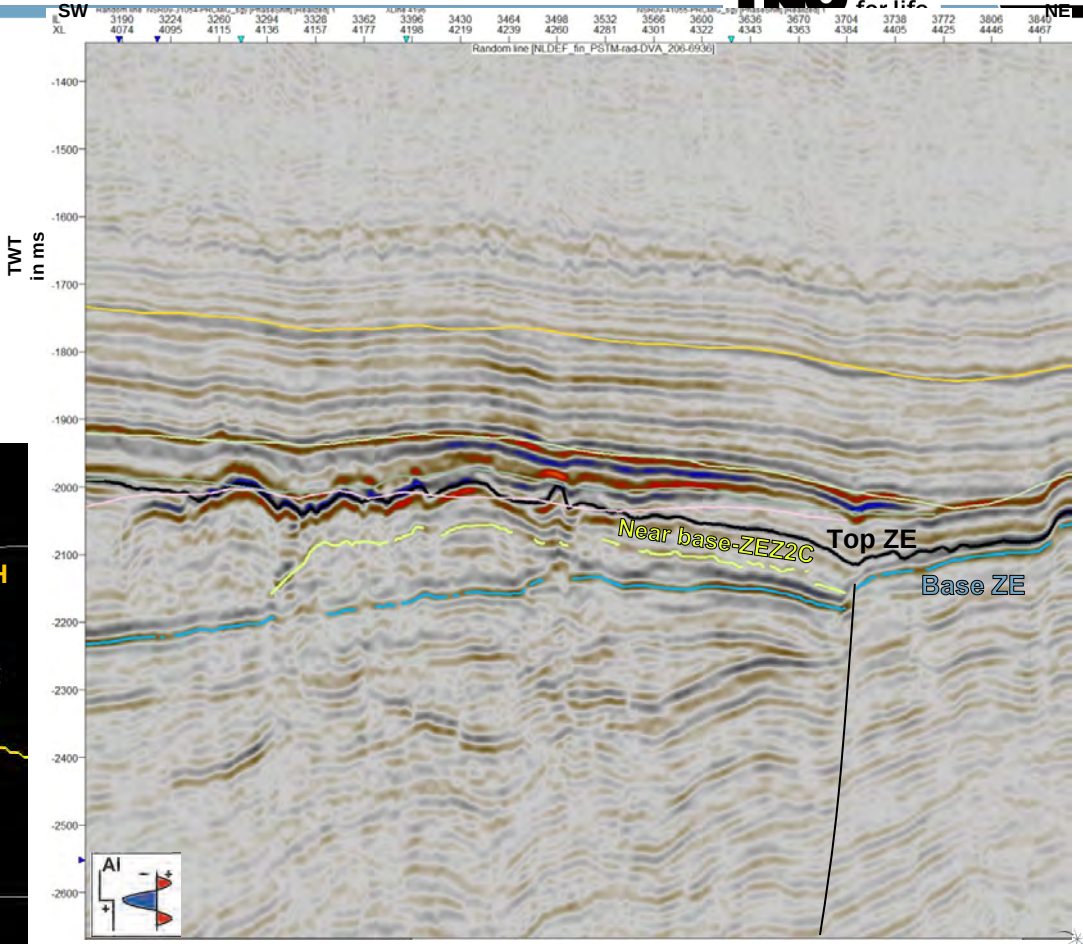




RESULTS – SEISMIC SOUTH OF ESH

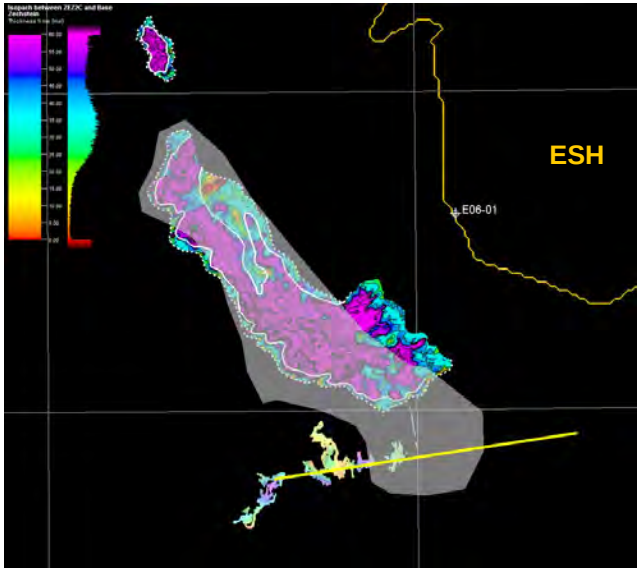
- Note onlap/thinning towards the ESH, also fault related in this case

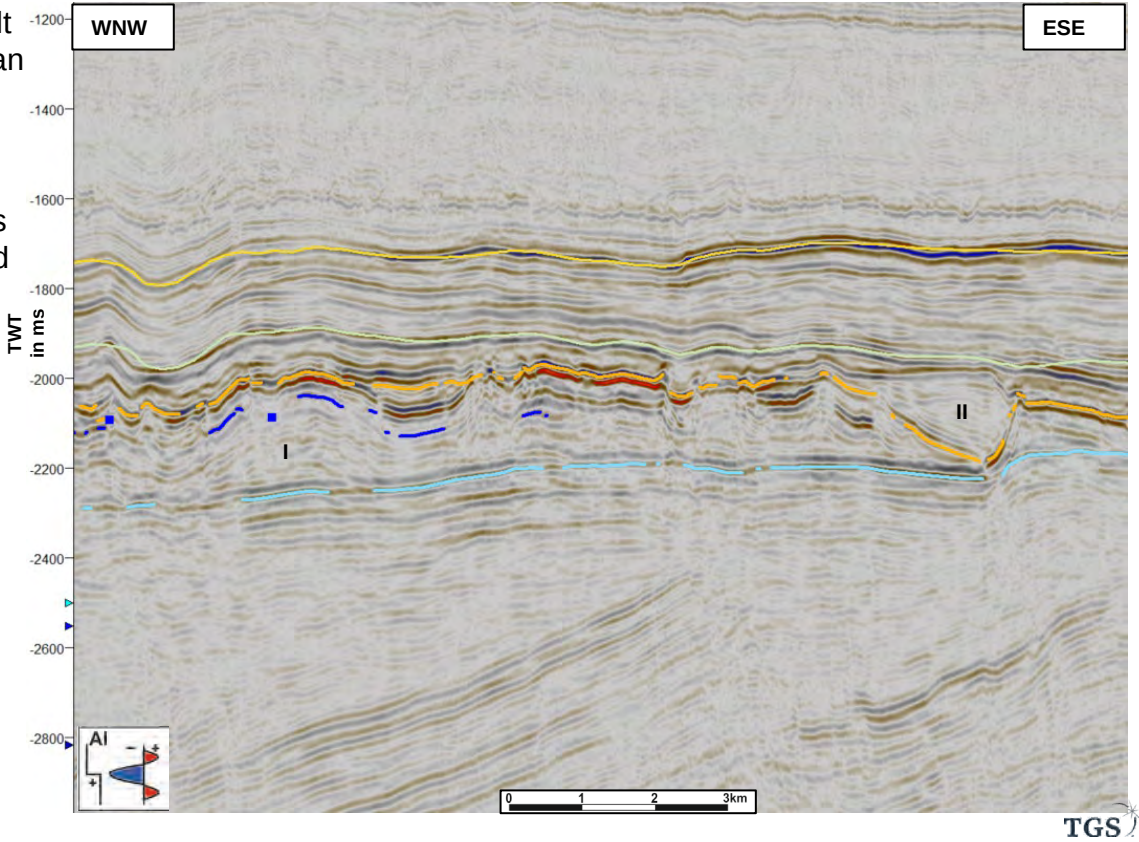




RESULTS – SEISMIC SOUTH OF ESH

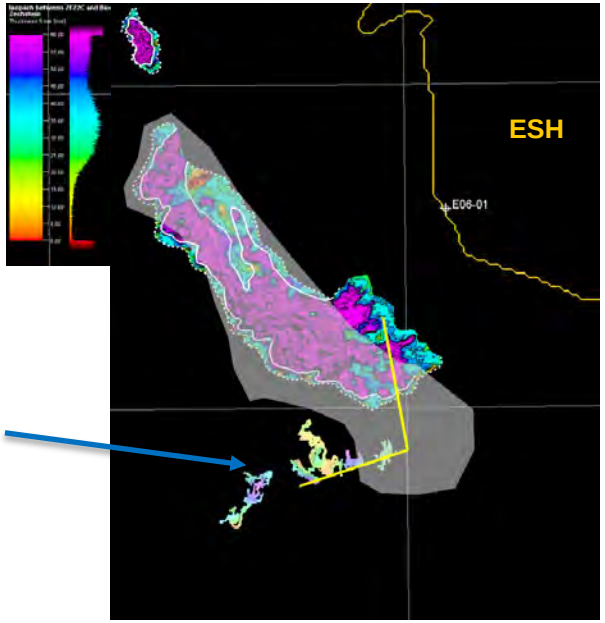
- Southern part is likely no build-up, but mainly salt that is yet too thin for real diapirism. Diapirism can be observed to the southwest (see I in section).
- Also Triassic rafts are indicative for presence of salt (see II in section)
- Blue is intra salt (likely ZEZ2H) reflector that was used to correlate to the position of the postulated ZEZ2C reflector



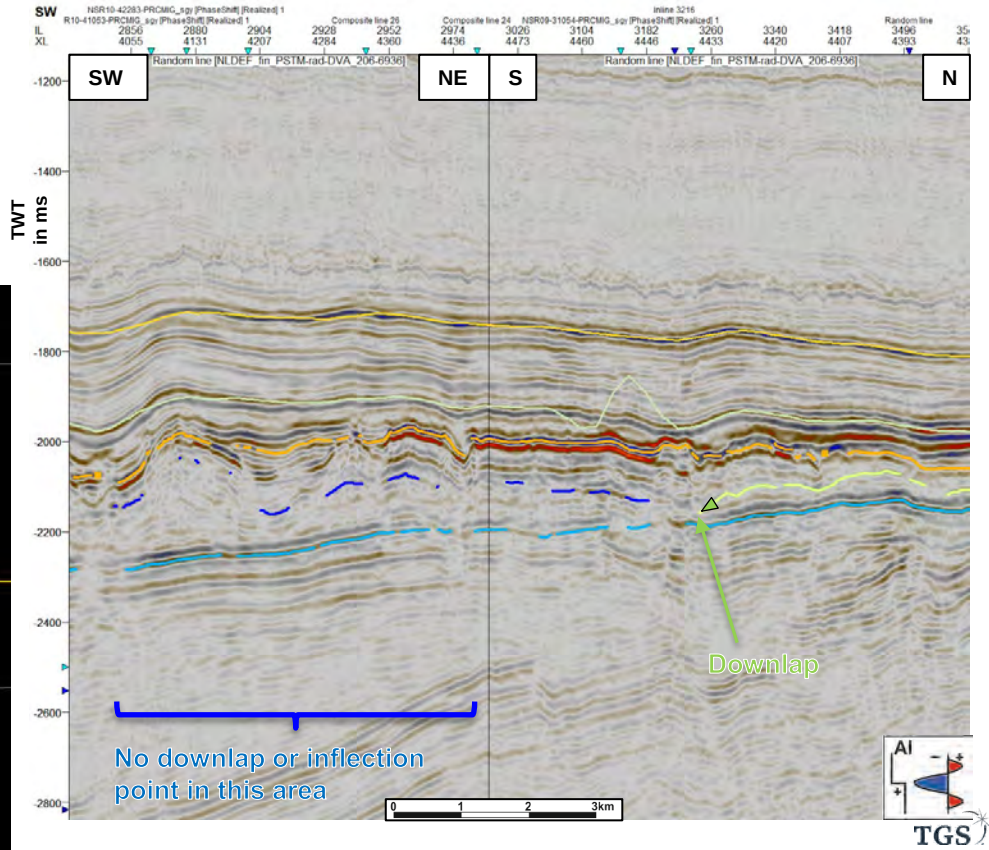


RESULTS – SEISMIC SOUTH OF ESH

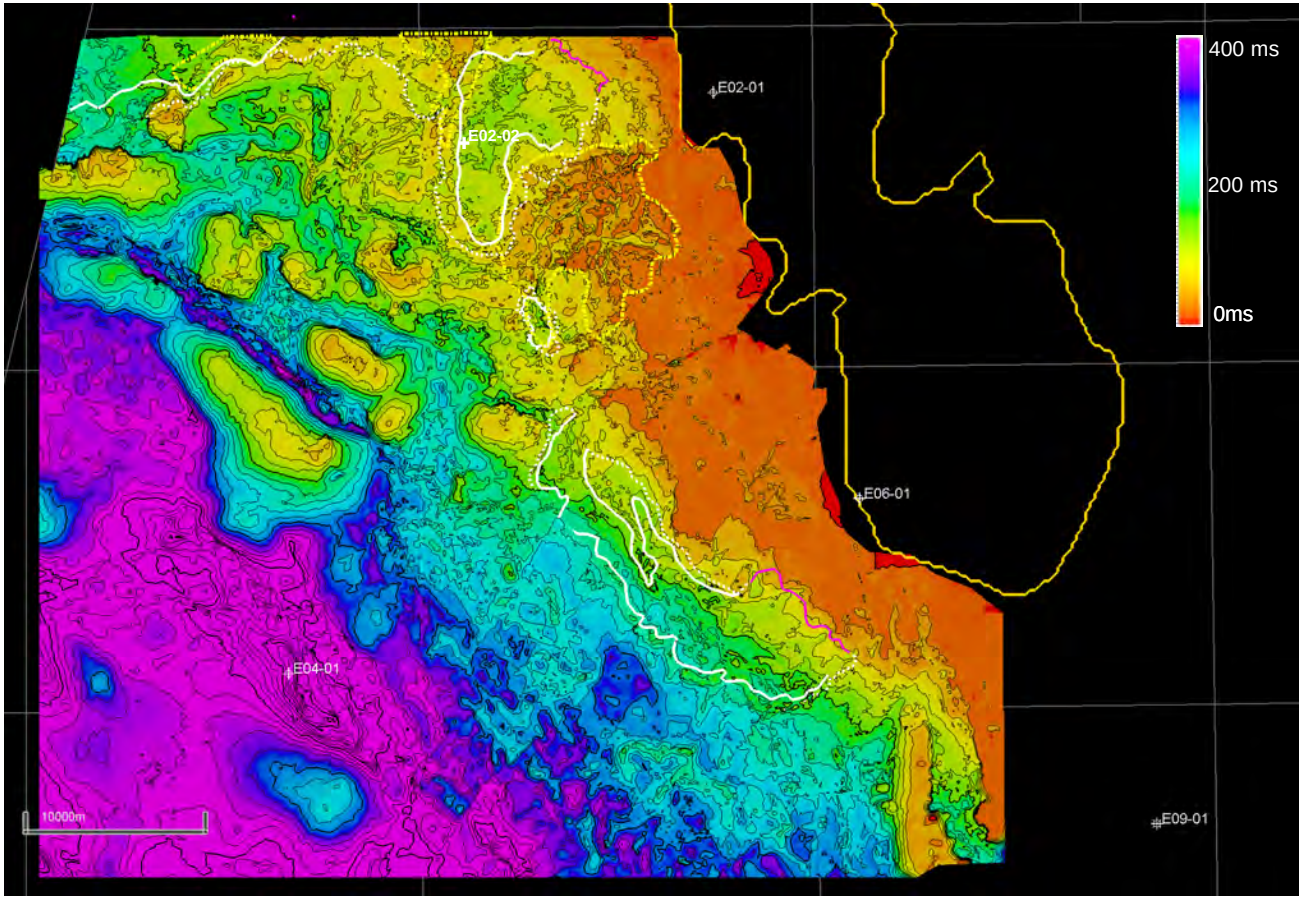
- Note that intra salt (likely ZEZ2H in blue) reflector doesn't match with the postulated ZEZ2C reflector
- No inflection point, nor downlap visible on intra salt blue reflector. Southern part of Build-up likely smaller than previously interpreted by Tolsma (2014)



Intra ZE halite reflector

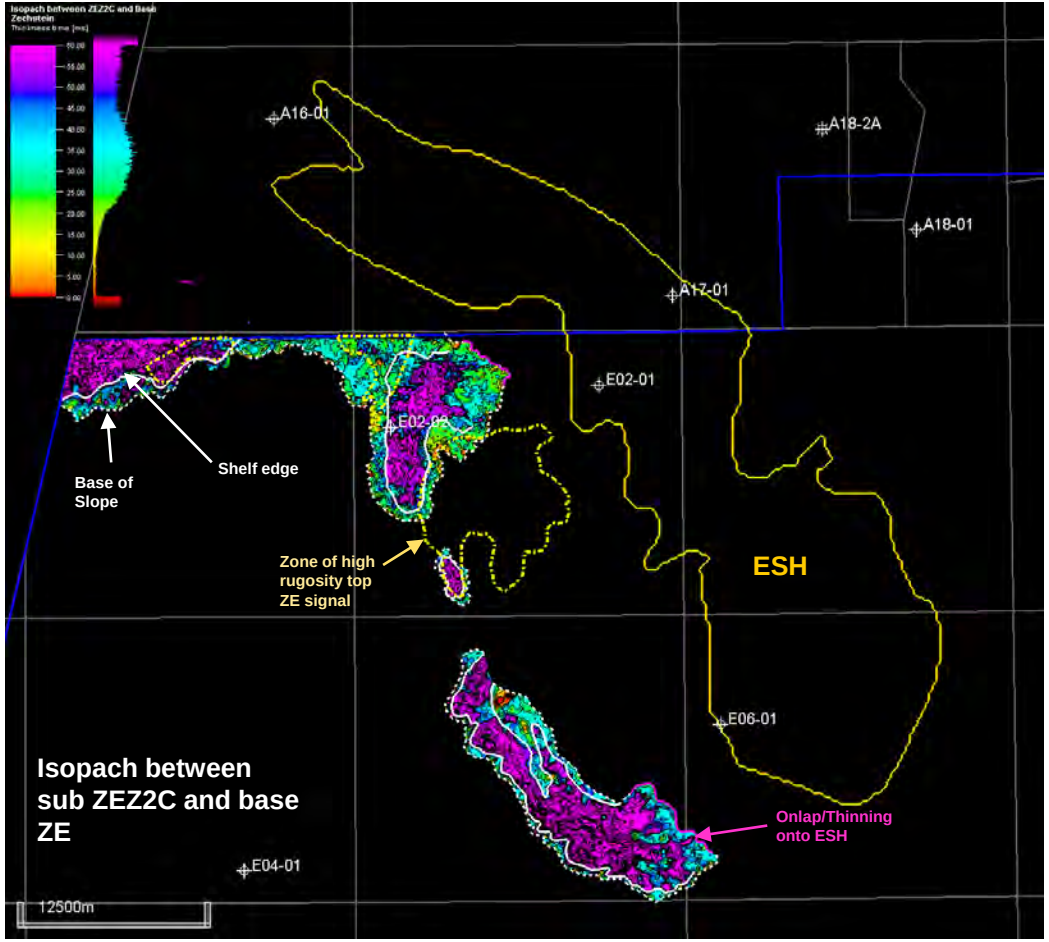


DISCUSSION – HIGH RUGOSITY ZONE SOUTH OF ESH

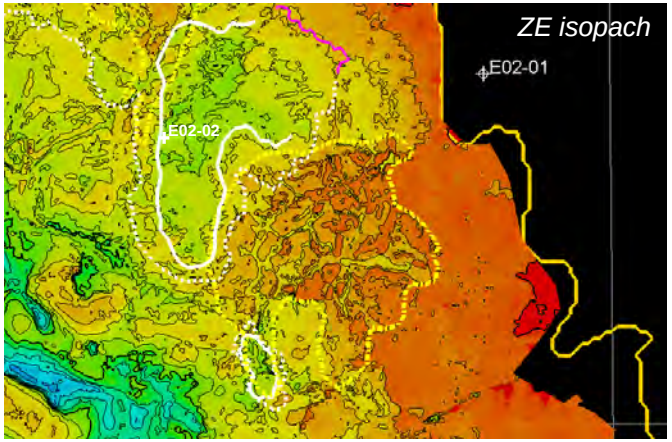


- Note complex zone east of the E02-02 platform (indicated within the white dashed circle). Top Zechstein displays high rugosity. Base Zechstein hard to map. Three hypothesis that could cause this seismic signal (more on this in discussion);
  - Karst due to dissolution
  - Isolated reef patches
  - Faulting and related pop-ups

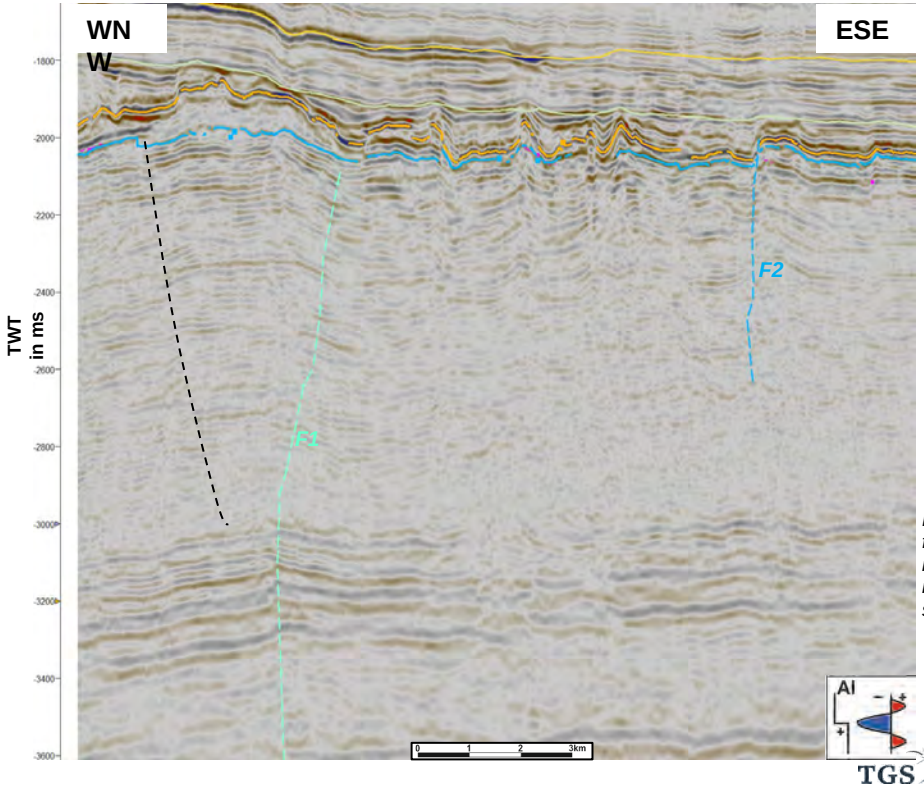
DISCUSSION – HIGH RUGOSITY ZONE SOUTH OF ESH



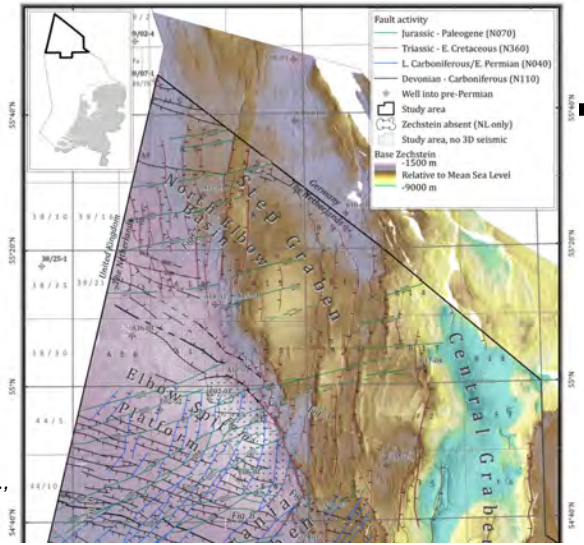
- Isopach of interval between sub ZEZ2C reflector and Base Zechstein
- White lines: ZEZ2C Shelf edge, represented by inflection point of reflector
- Dashed white lines: Base of slope represented by downlap of ZEZ2C reflector
- Dashed yellow lines: zones of high rugosity for sub ZEZ2C/Top Zechstein reflectors when compared to base of Zechstein (either Karst or pinnacle reefs in lagoonal zone)



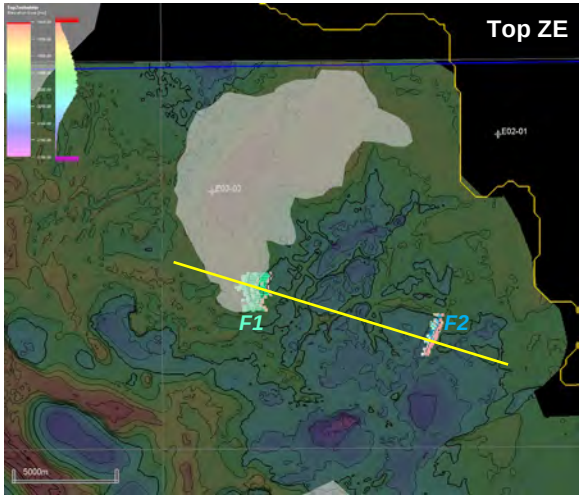
DISCUSSION – HIGH RUGOSITY ZONE SOUTH OF ESH



Note that not all faults have been interpreted on the map or the seismic section.

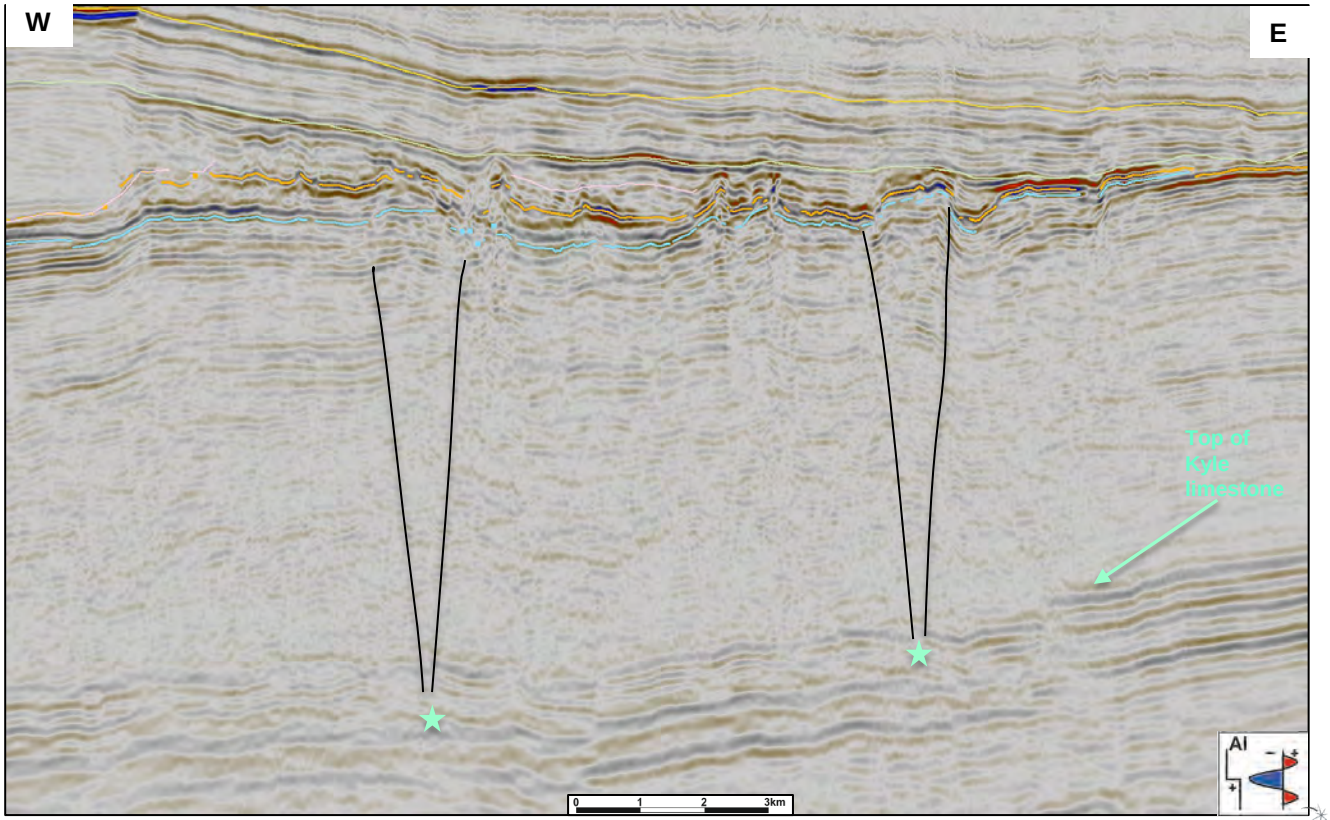


From Ter Borgh et al., (2018)

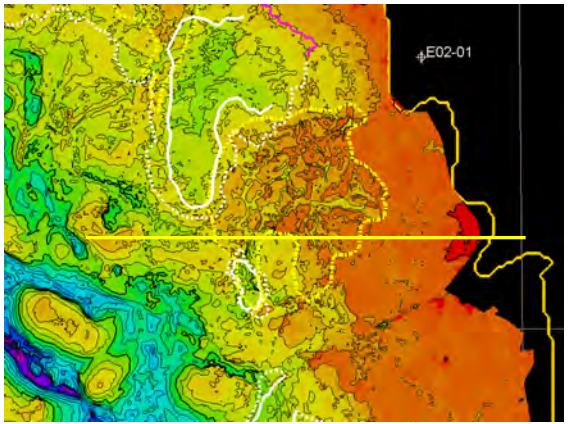


- Build-ups likely related to highs that were present prior to Late Permian. These highs often display a anticlinal or pop-up geometry that appears to correspond with Lower Carboniferous/Early Permian fault trend (~N040) recognized also by Ter Borgh et al., (2018).

DISCUSSION – HIGH RUGOSITY ZONE SOUTH OF ESH

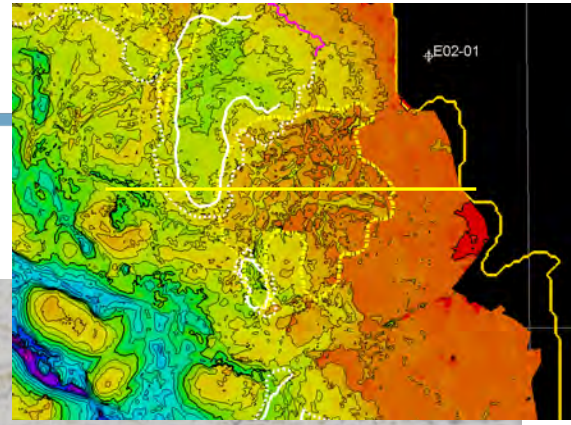


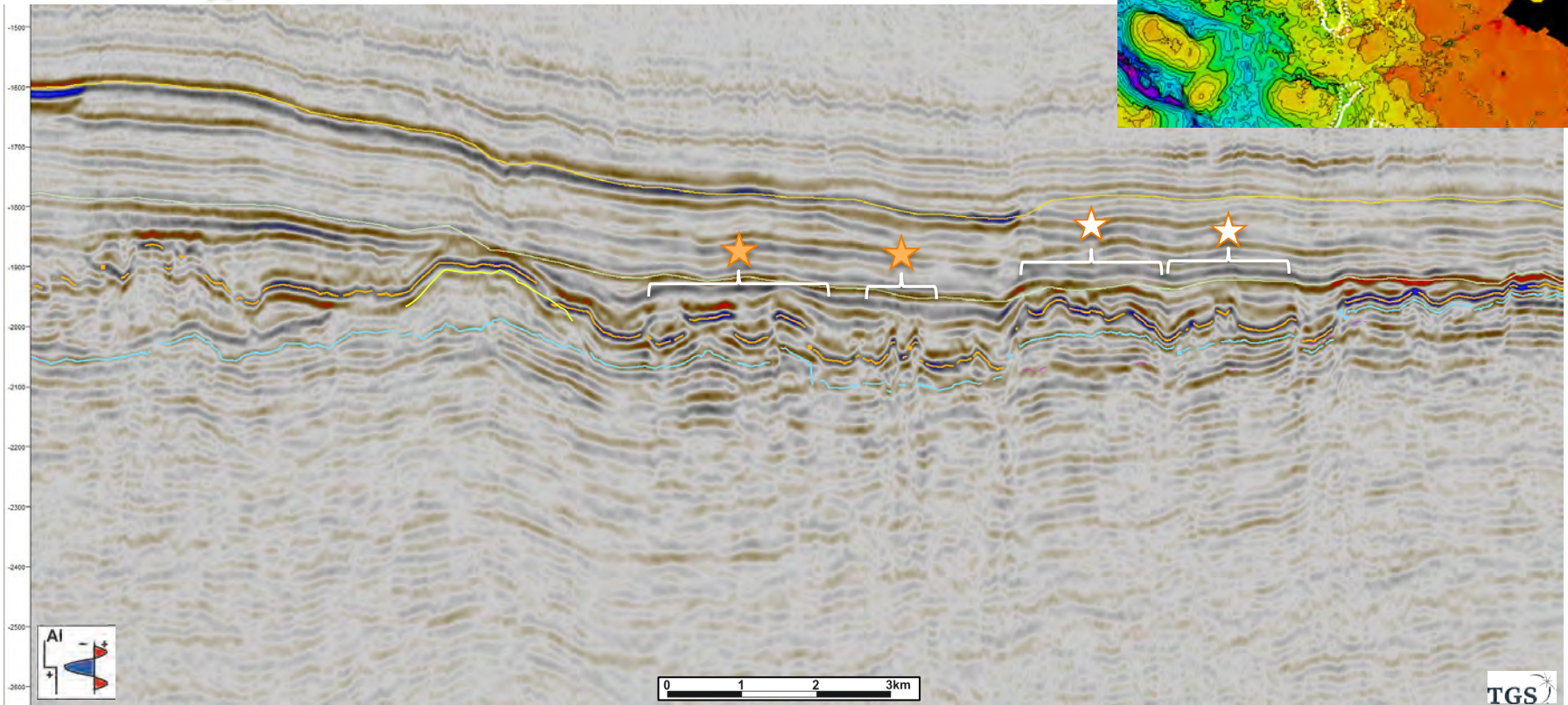
- Upward inclined strata of Kyle limestone and upward widening fault pattern indicate presence of local pop-up structures
- Note that both top and Base ZE are elevated on top of these pop-ups (pop-ups mainly display NNE-SSW (N040) orientation



DISCUSSION – HIGH RUGOSITY ZONE SOUTH OF ESH

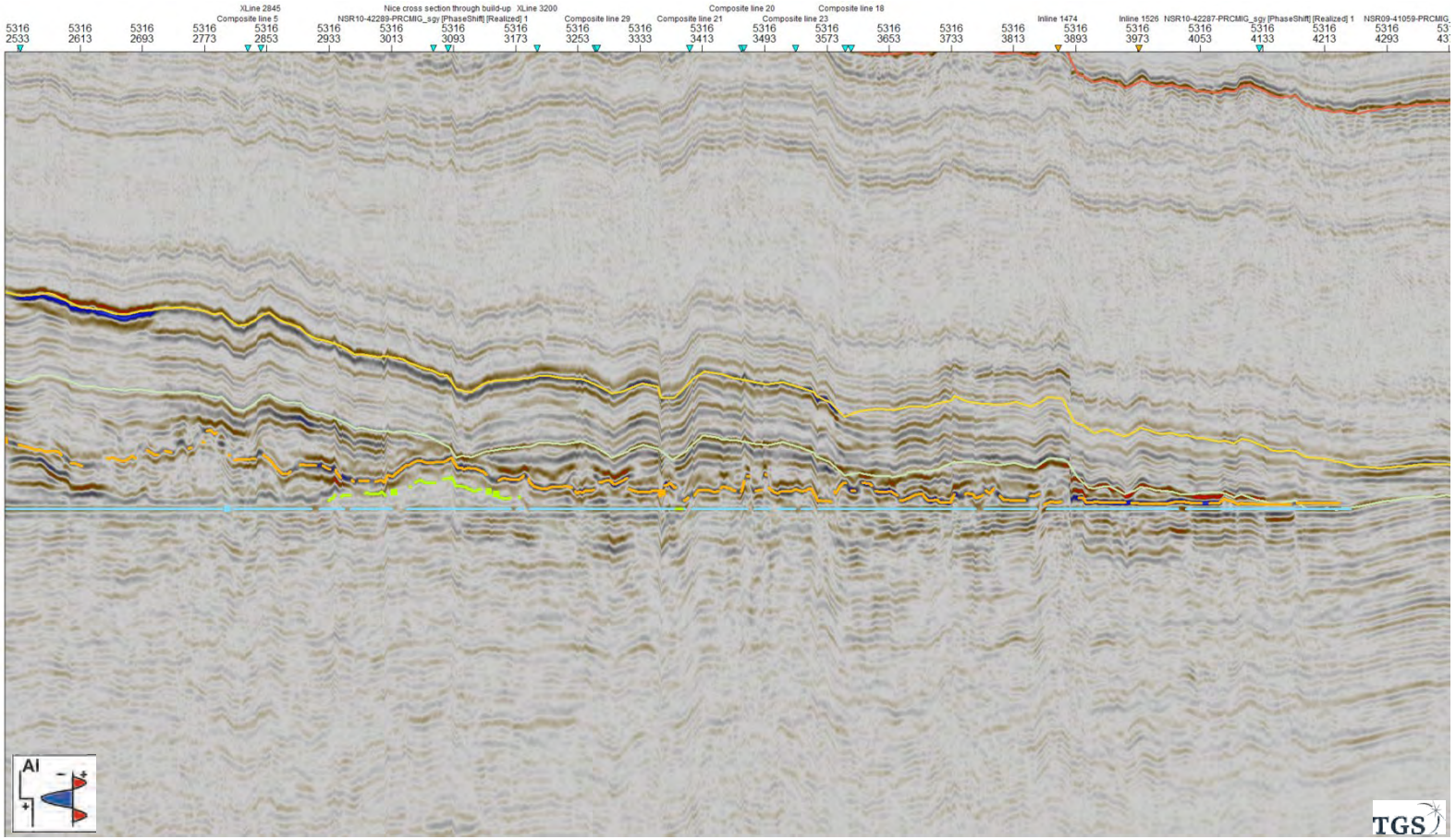
- However, not all of this rugosity at the top ZE can be explained, just by underlying pop-up structures, deep rooted faulting because base ZE is not as irregular as the top ZE in some places
- In other area's it remains a bit unclear, but at least part of the top ZE rugosity appears not to be related to faults.

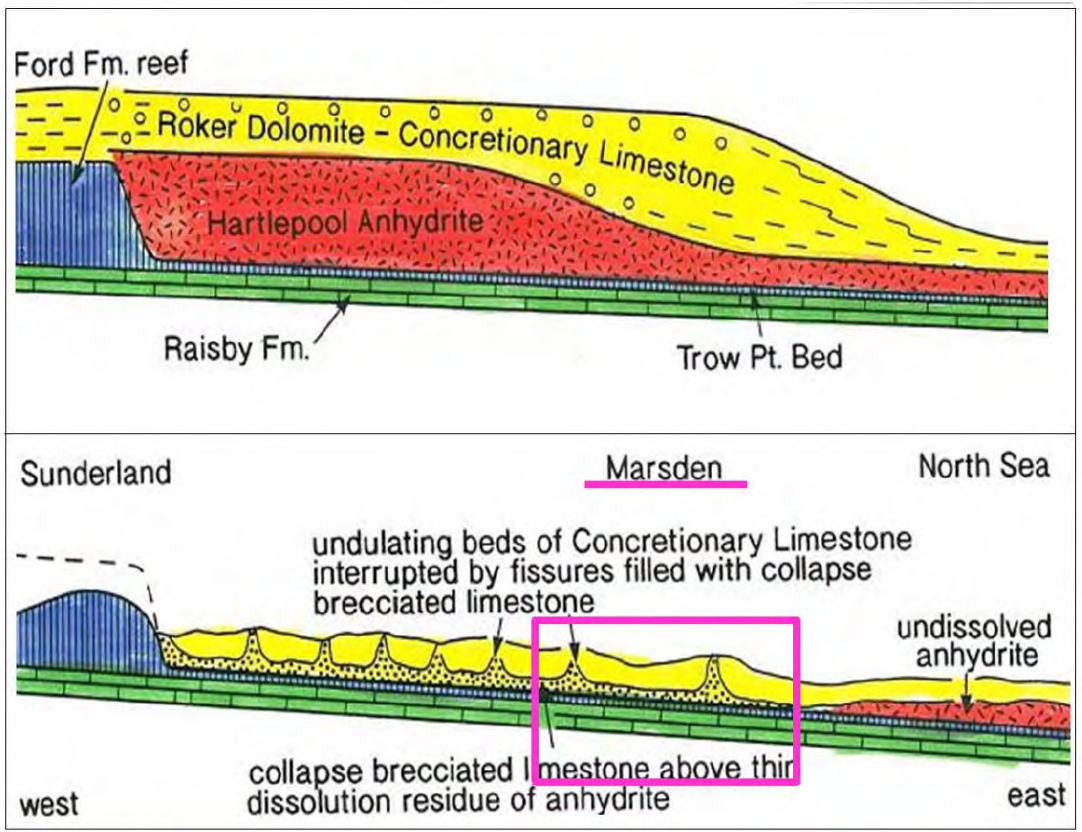




DISCUSSION – HIGH RUGOSITY ZONE SOUTH OF ESH

- Same line as previous slide; flattened at base ZE





Sketch of effect of evaporite dissolution at Marsden Bay *After Pettigrew, 1980*

- Hence, part of rugosity should likely be explained by:
  - Karst due to dissolution
  - Isolated reef patches
- Possible equivalent for karst features: Hartlepool Anhydrite in UK, visible in outcrops

Hartlepool Anhydrite = time equivalent to Werra Anhydrite (ZEZ1W)
Roker Dolomite = Time equivalent to Hauptdolomite (ZECA2)

Figure from Daniels et al., 2020 (After Pettigrew, 1980)

DISCUSSION - COLLAPSE ZE BRECCIAS NE UK

- Multiple types of Breccias with varying amounts of dissolution and collapse
- Collapse breccia pipes cross cut in-situ breccia pipes
- Timing of dissolution poorly constrained (could be end of Permian, but also during Tertiary Uplift)

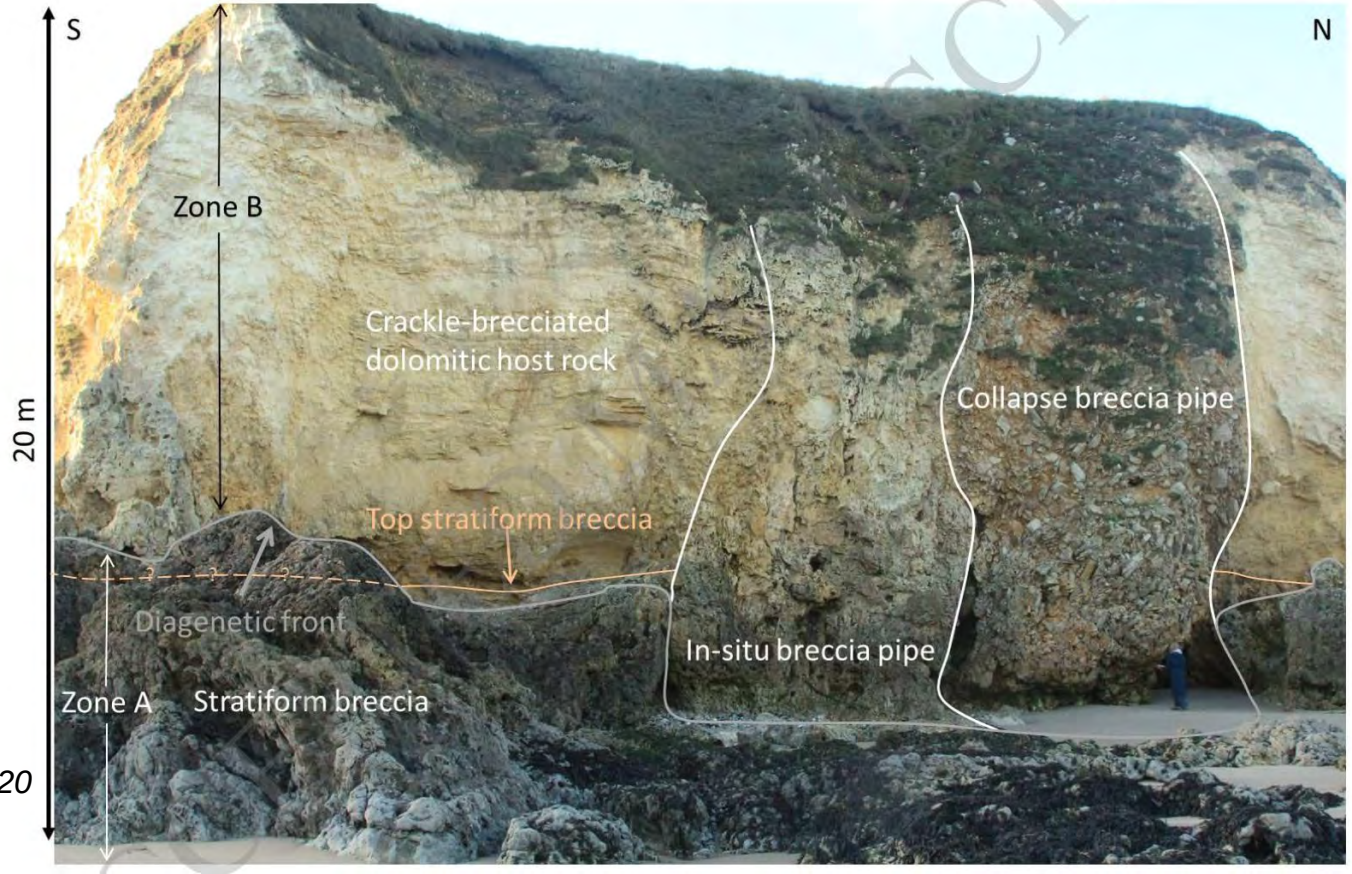
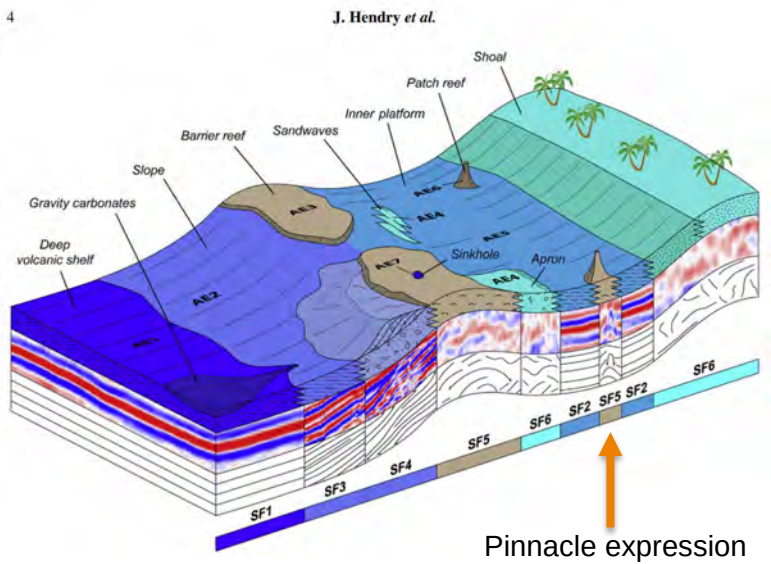


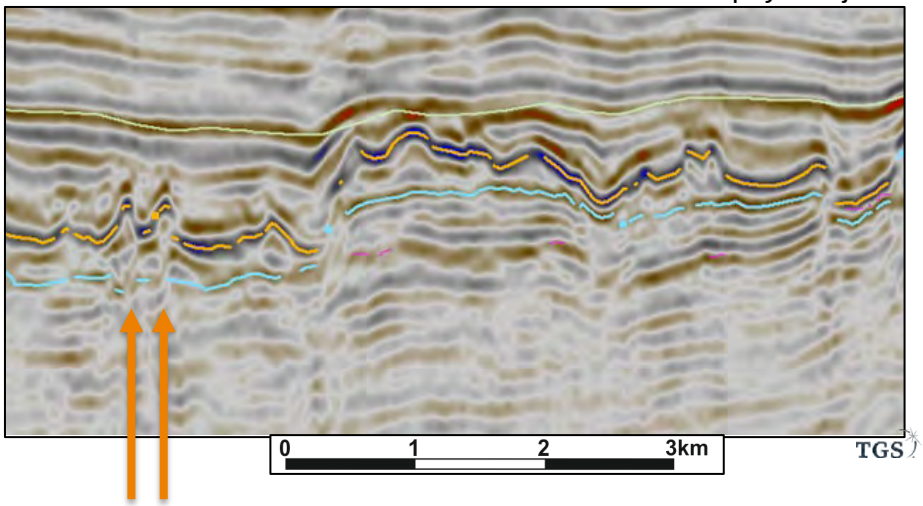
Figure from Daniels et al., 2020

- Besides karst and/or faulting, part of the top ZE rugosity could be explained by:
  - *Isolated reef patches/pinnacles behind the main barriers*



Hendry et al., 2021

Zephyr Project



Expressions that displays similarities with the pinnacle/patch reef expression from Hendry et al., 2021 (left figure)

DISCUSSION – PINNACLE REEFS

Example of seismic expression of Late Oligocene-Miocene pinnacle reefs formed offshore northwestern Australia in the Browse Basin. Seismic response shows similarities with some parts of the current study area (see figures D-F)

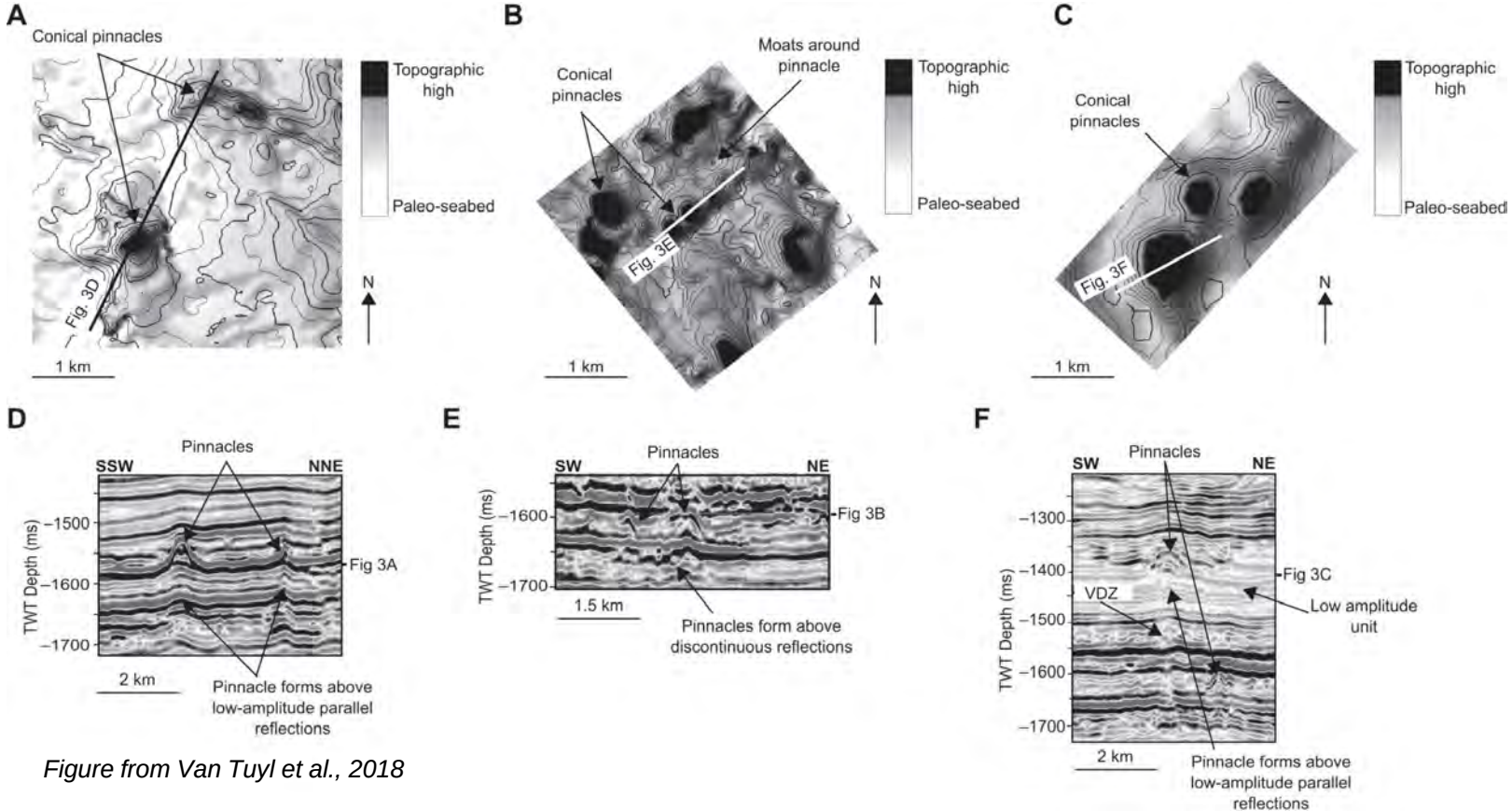
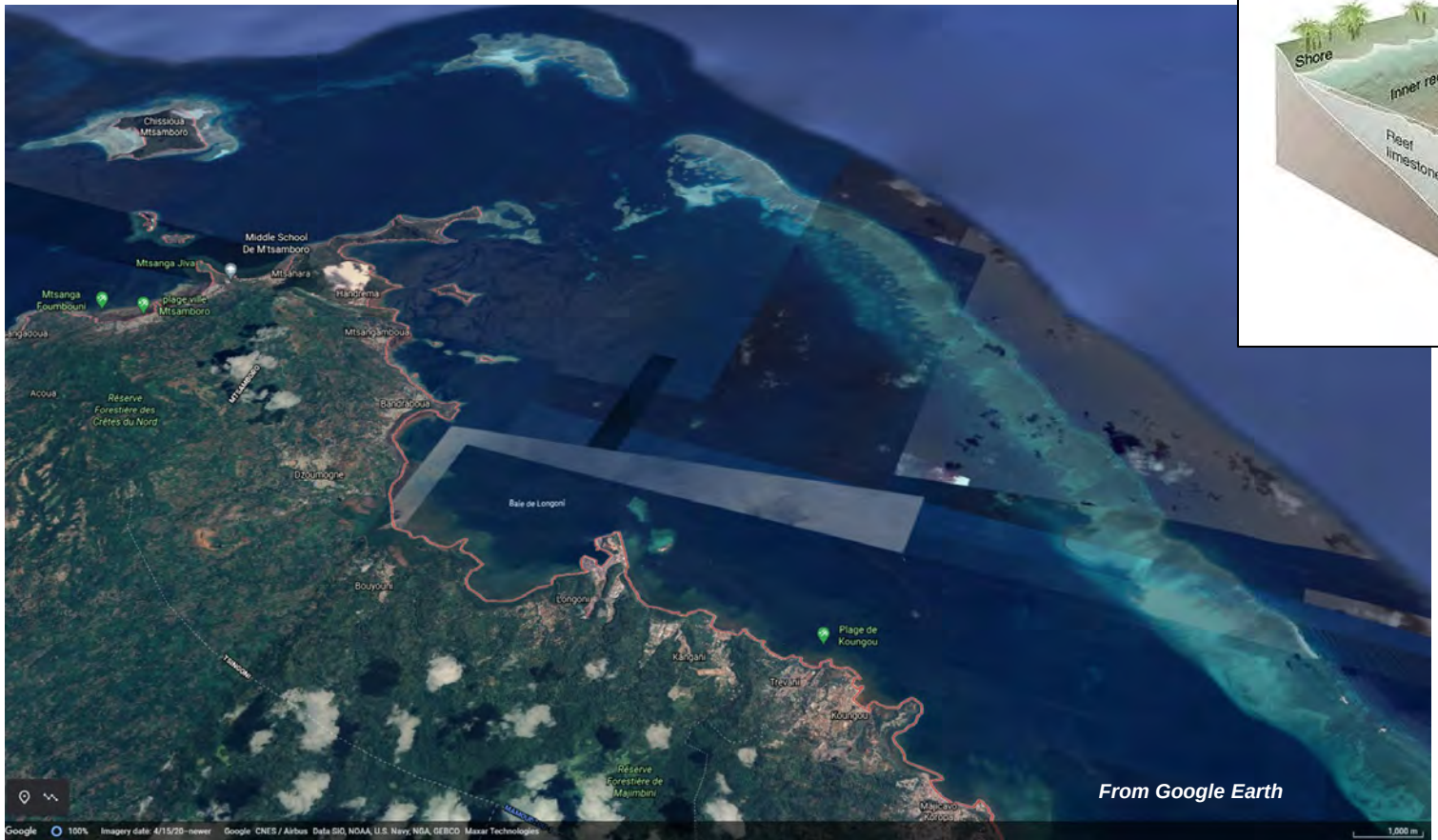


Figure from Van Tuyl et al., 2018

DISCUSSION – PINNACLE REEFS

- Example: Fringe reef offshore Mayotte (Indian Ocean)



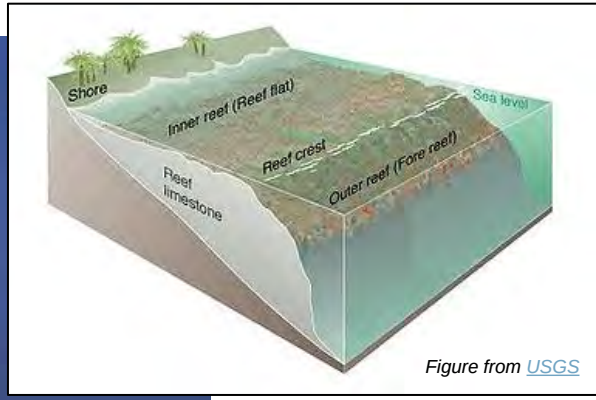
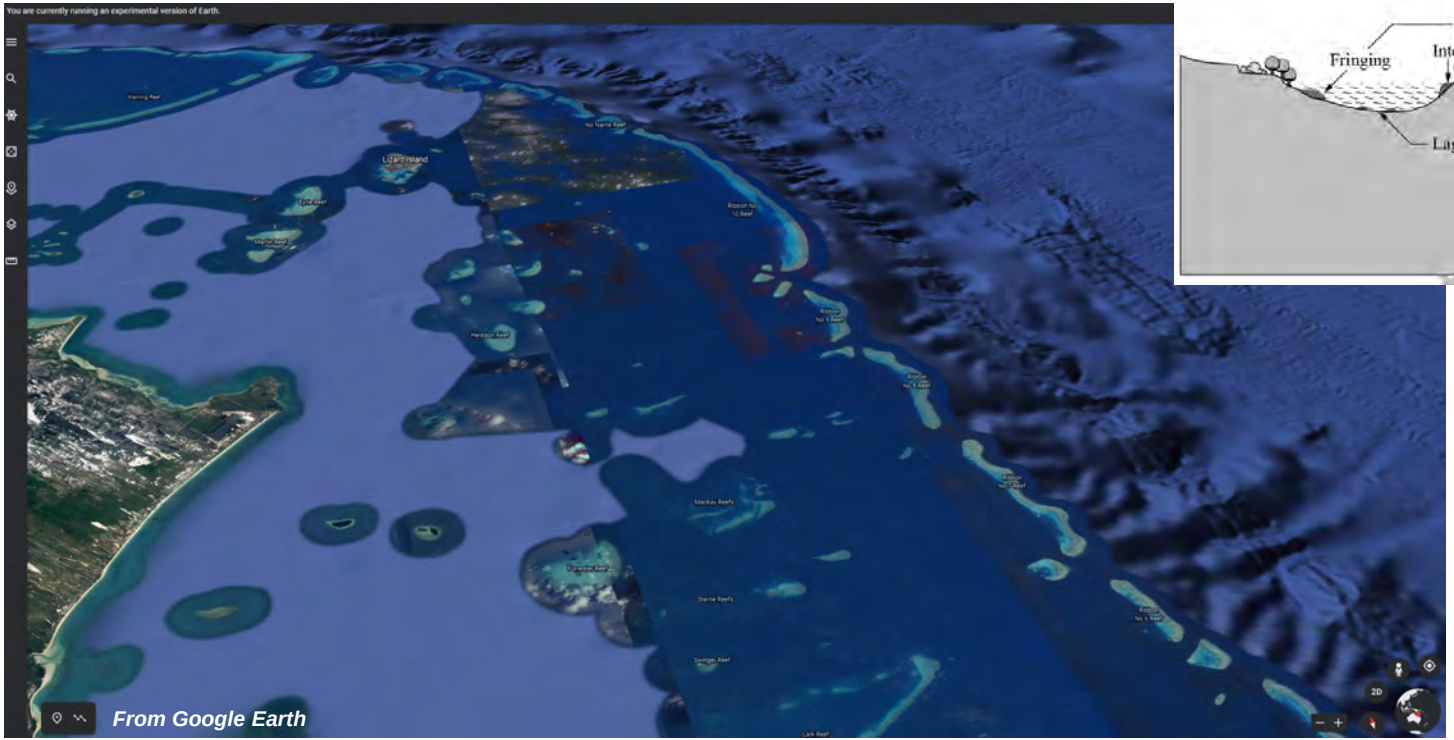


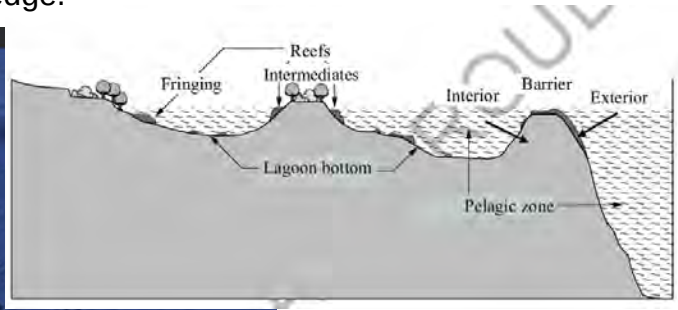
Figure from USGS

- Although not entirely comparable to the hot, saline fringe reefs that are present around the Permian ESH, this and the following slide illustrate that modern reef system can display a wide range of geometries. Some of them also contain isolated reef patches (pinnacles) behind the main barrier reef (see next slide)

DISCUSSION – PINNACLE REEFS

- Example: part of Australian Great Barrier Reef with several individual reefs present in the lagoonal zone behind de barrier reefs that are present directly at the shelf edge.

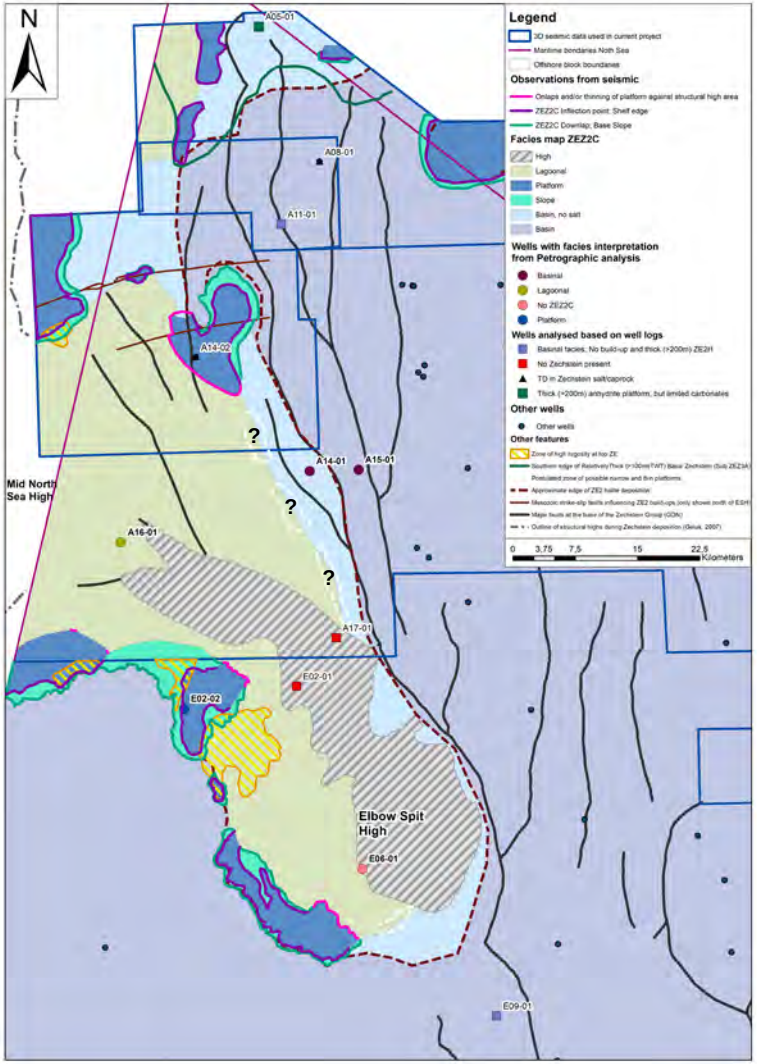


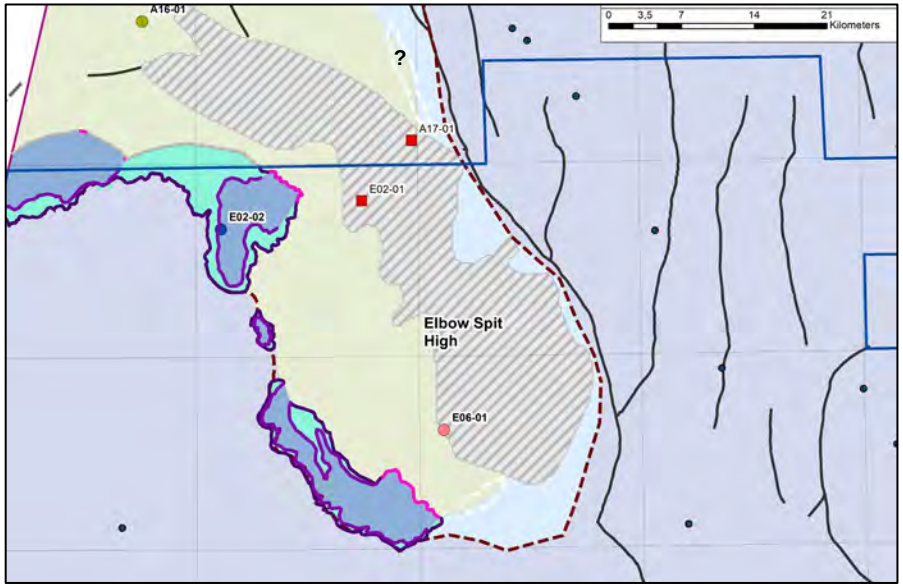


Schematic cross-section of barrier reef with build ups in lagoonal zone. Figure from Kulbicki et al., 2015

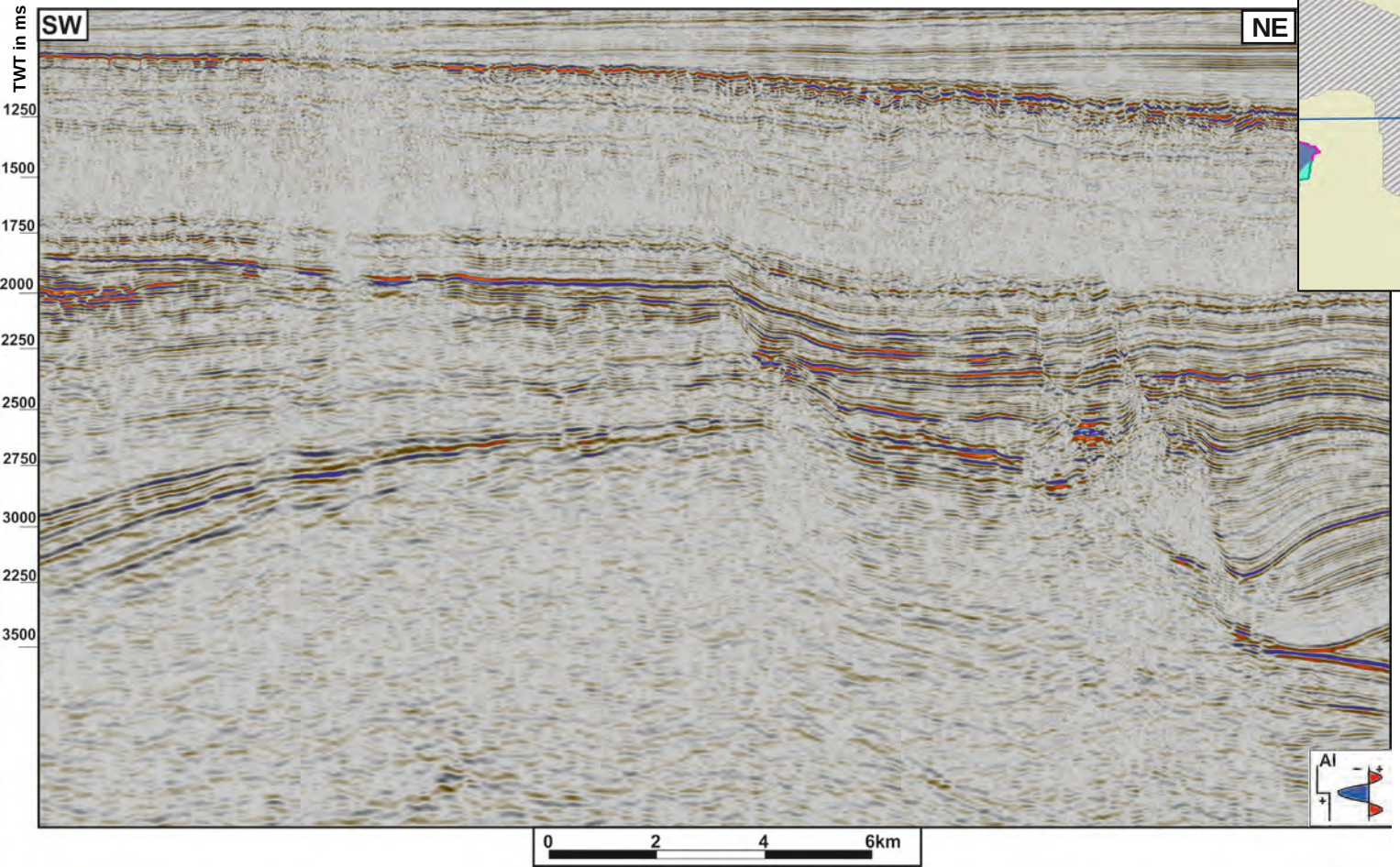
CONCLUSIONS SOUTH OF ESH – ZEZ2C FACIES MAP & INTRODUCTION TO NORTH OF ESH

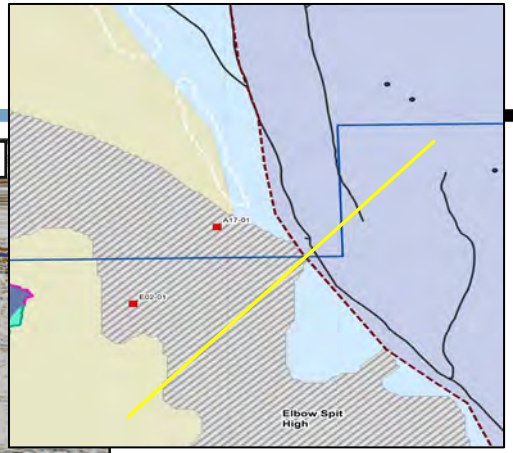
- South of ESH: Facies and detailed 3D seismic mapping was applied of Base-, and top ZE, as well as (postulated) sub ZEZ2C reflector.
- The northeastern boundary of the ESH is heavily faulted; likely rapid transition from high to basinal area during deposition of ZEZ1A and ZEZ2C, thereby likely limiting favorable conditions for platform growth. A small zone of (relatively thin/minor) build-ups could possibly be present here. These are not clearly confirmed on seismic, but it is noted that partly only 2D seismic data is available in this area.
- Further north/northwest of ESH: several build-ups are present; only inflection points and downlaps were mapped for these build-ups and there is no direct well control. Next slides will show seismic examples north of ESH



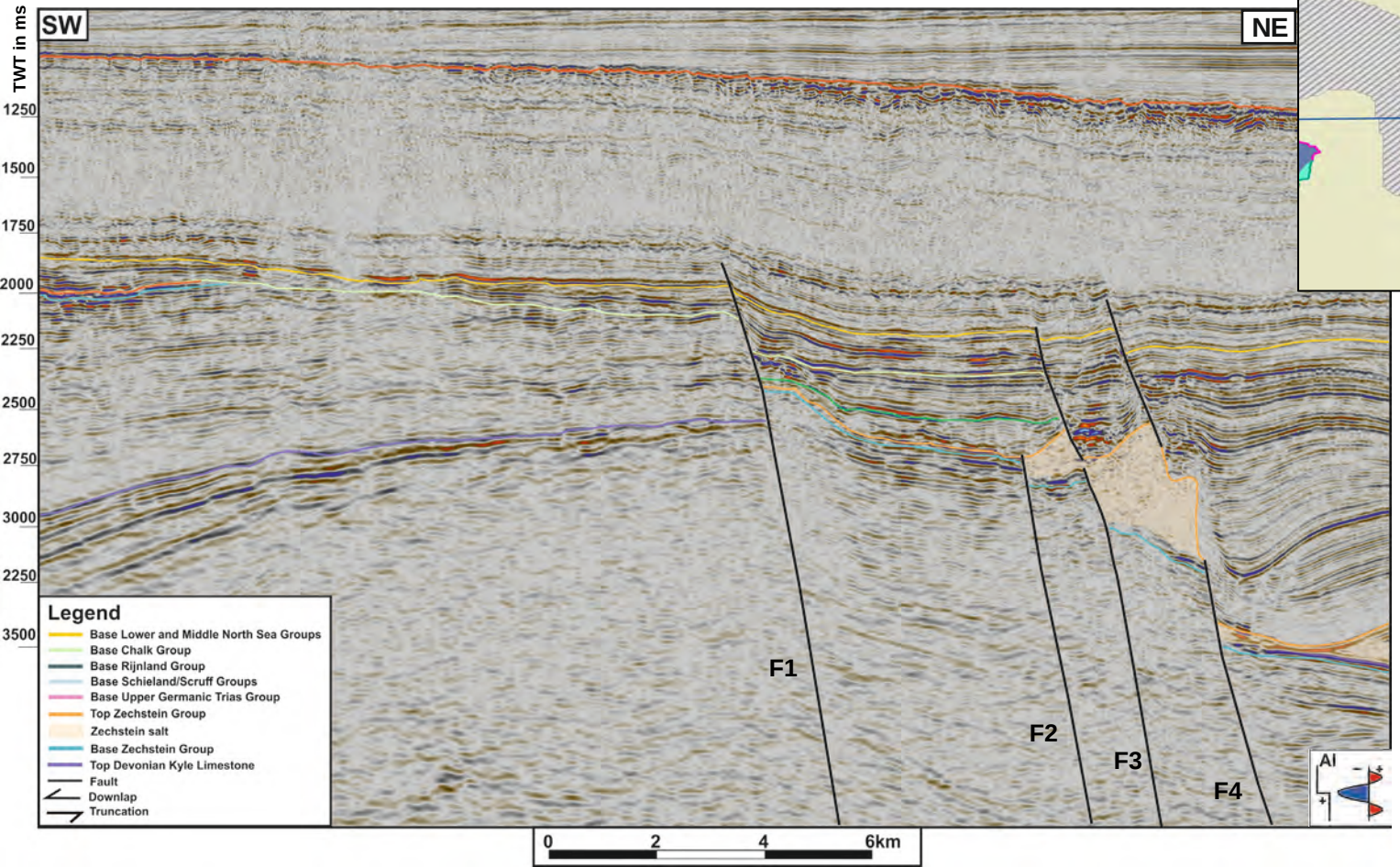


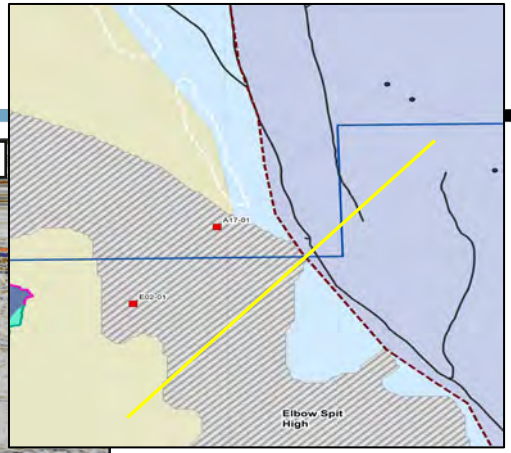
RESULTS – SEISMIC ACROSS ESH





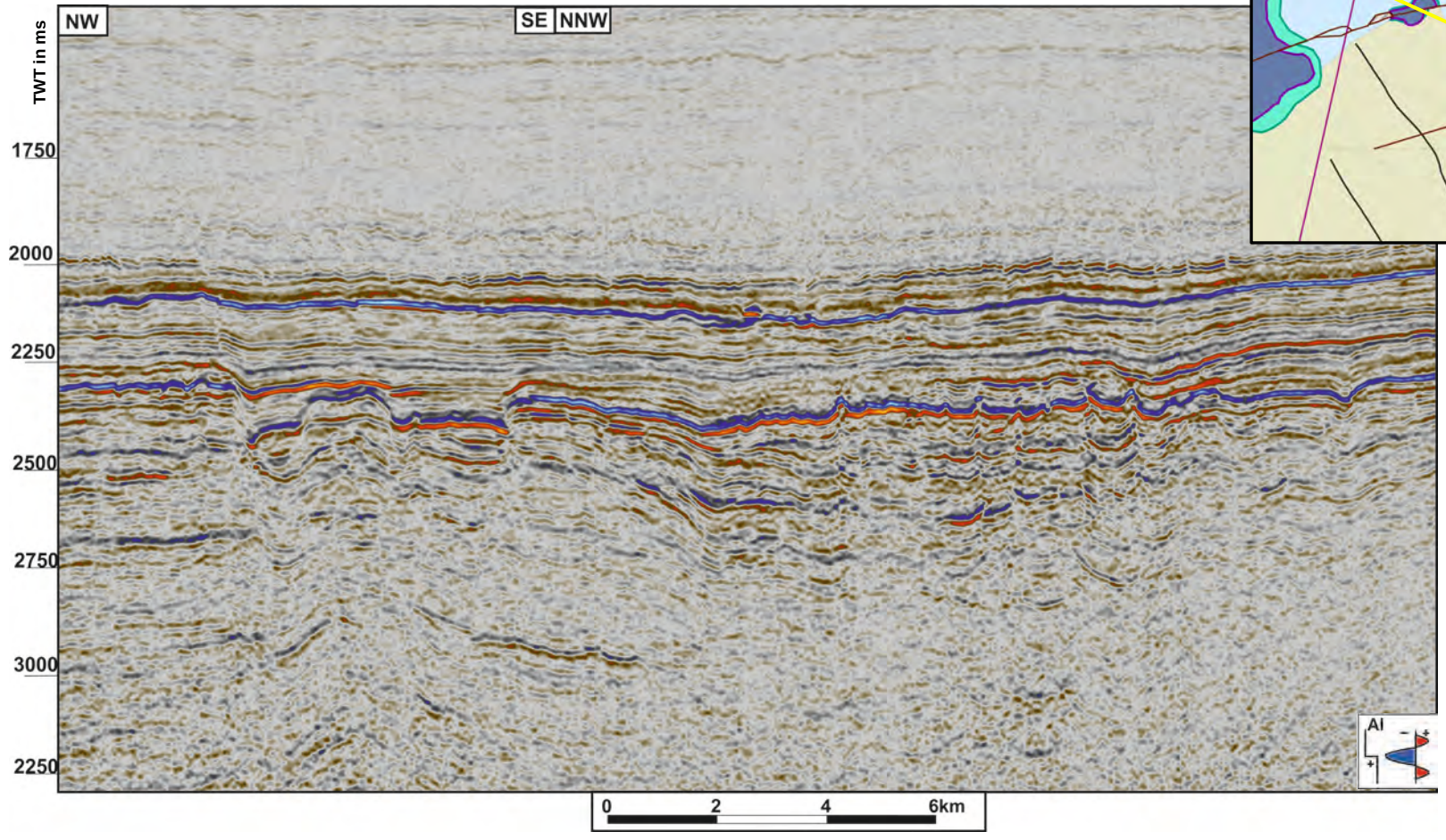
RESULTS – SEISMIC ACROSS ESH



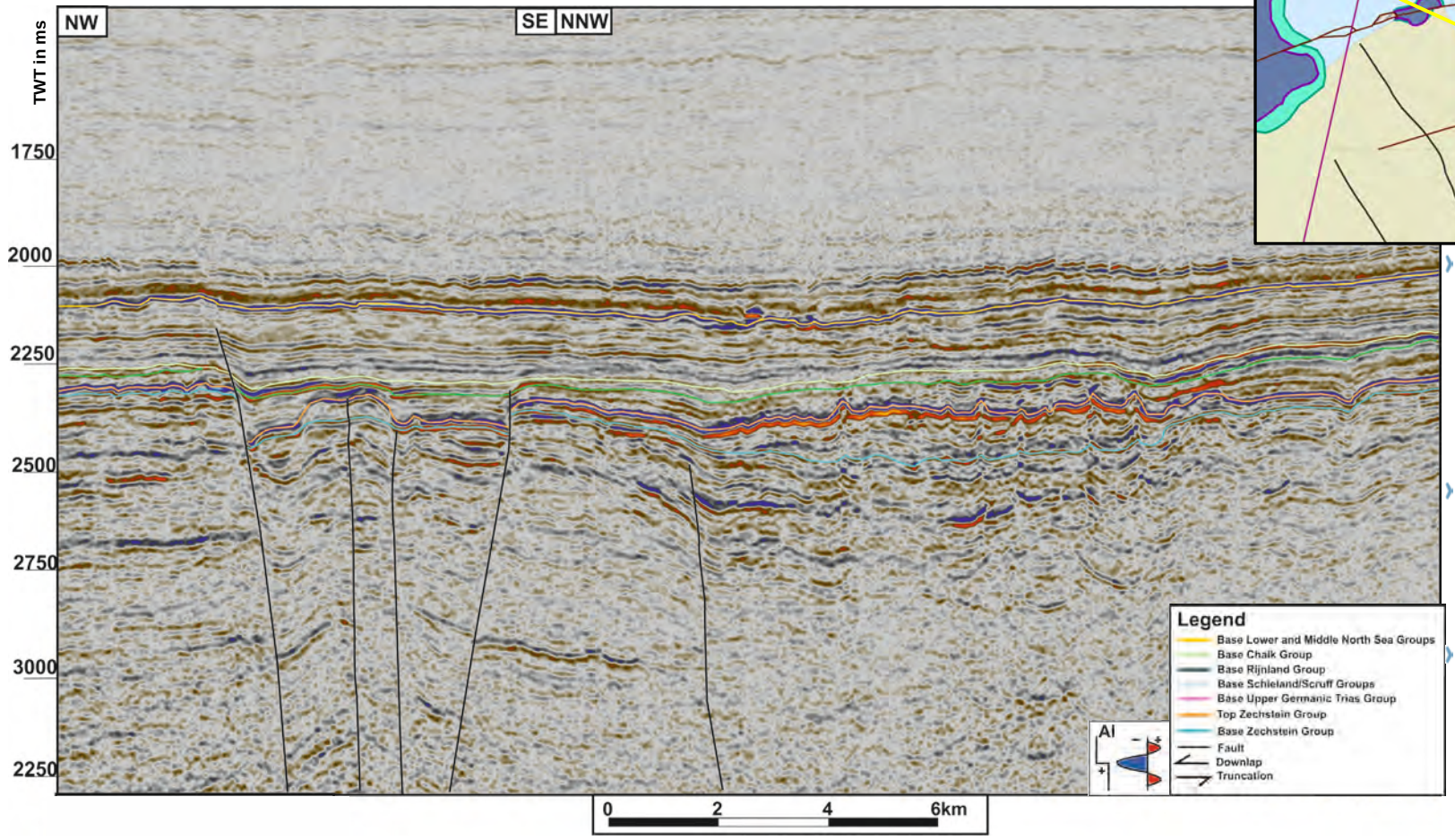


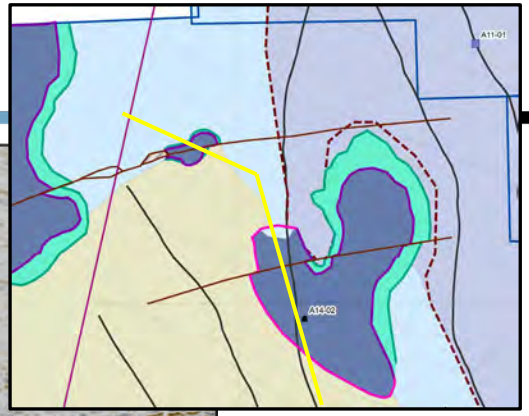
- Note heavily faulted NE boundary of ESH
- Rapid transition from basinal facies with salt (see petrographic analysis for wells A14-01 & A15-01) to no Zechstein
- Chalk is on top of Lower Carboniferous/ Devonian (Buchan Group – well A17-01) west of fault F1

RESULTS – SEISMIC NORTH OF ESH



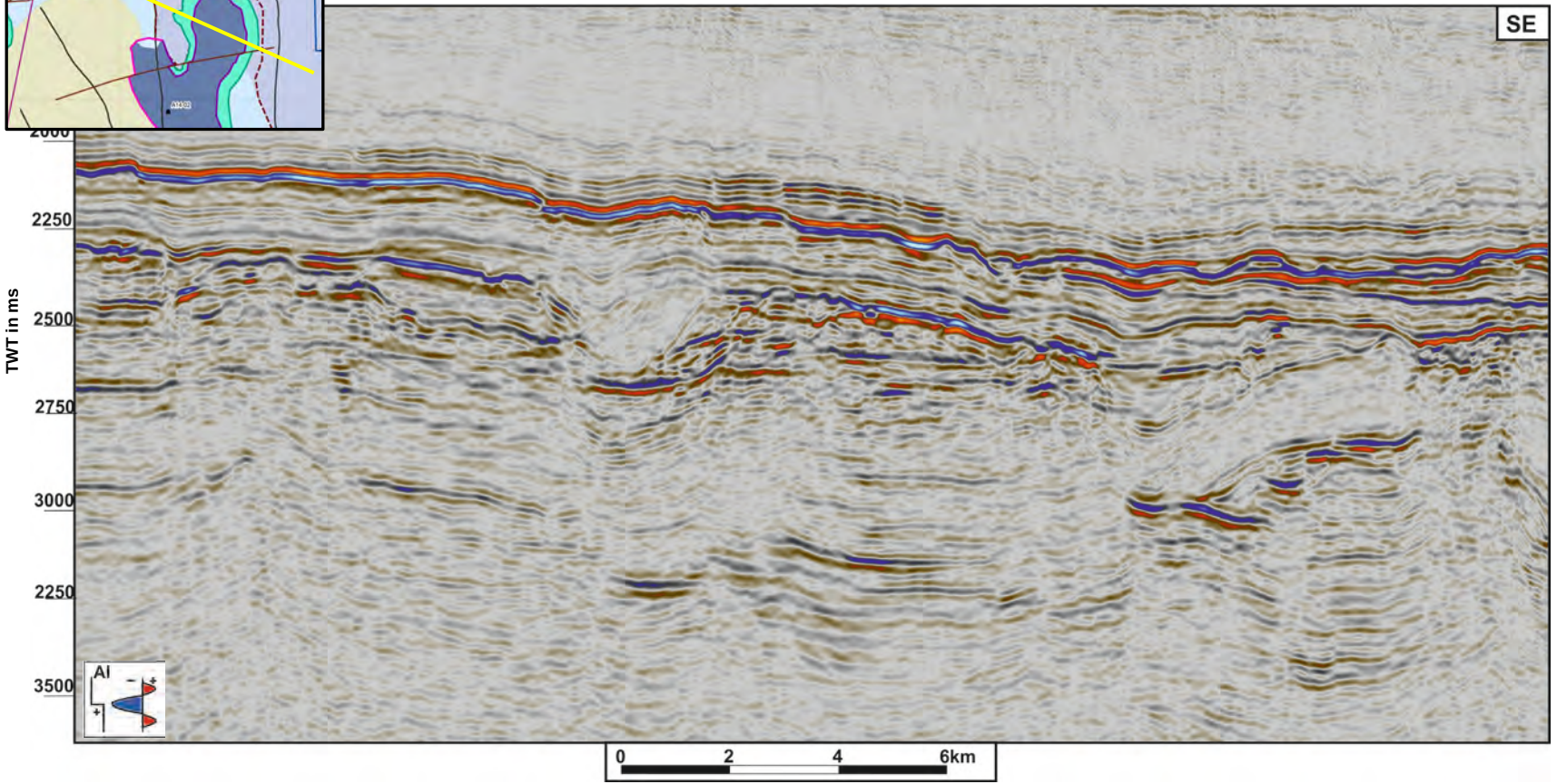
RESULTS – SEISMIC NORTH OF ESH



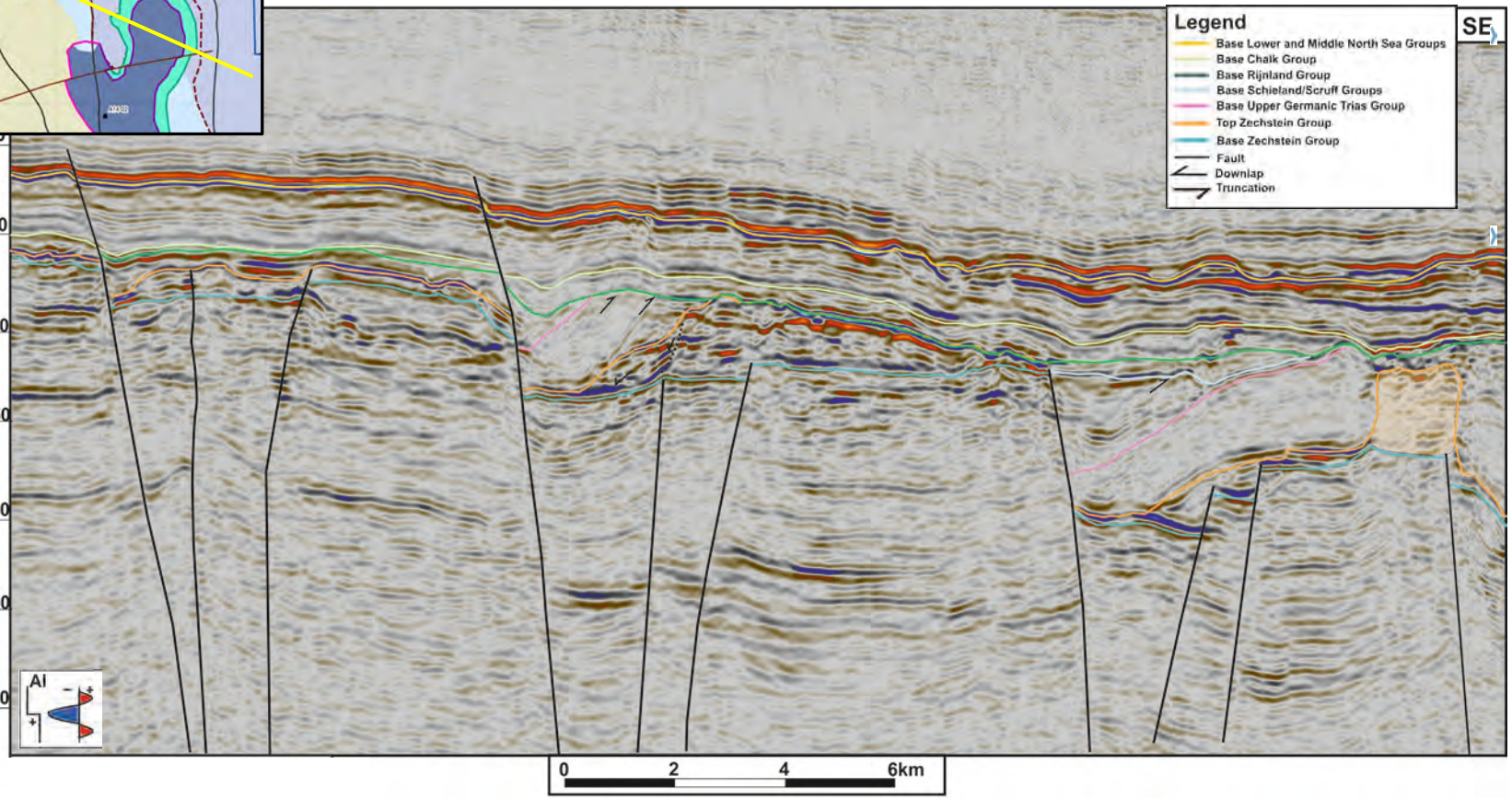


- Complex area with several (reactivated) faults trends. E.g. WSW-ENE trending strike-slip faults offset build-ups
- Transition though from lagoonal to basinal is more gradual than directly east of ESH
- However, inflection points and downlaps generally less clear than south of ESH

RESULTS – SEISMIC NORTH OF ESH



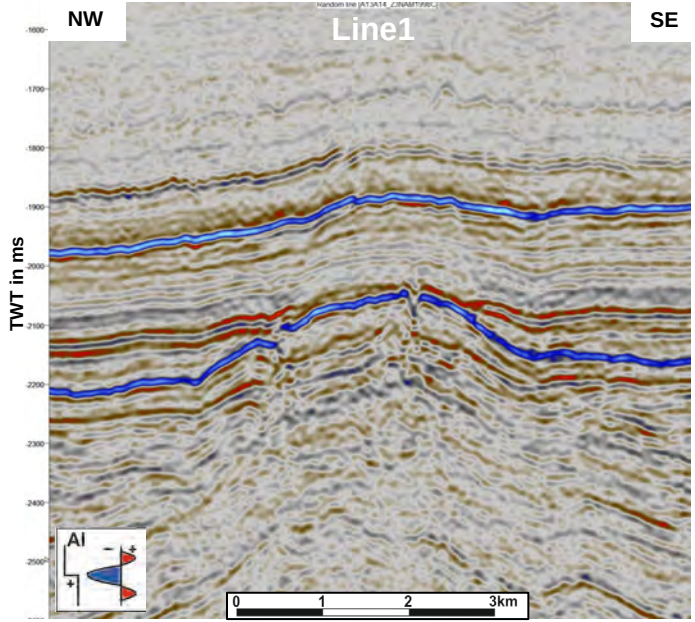
RESULTS – SEISMIC NORTH OF ESH

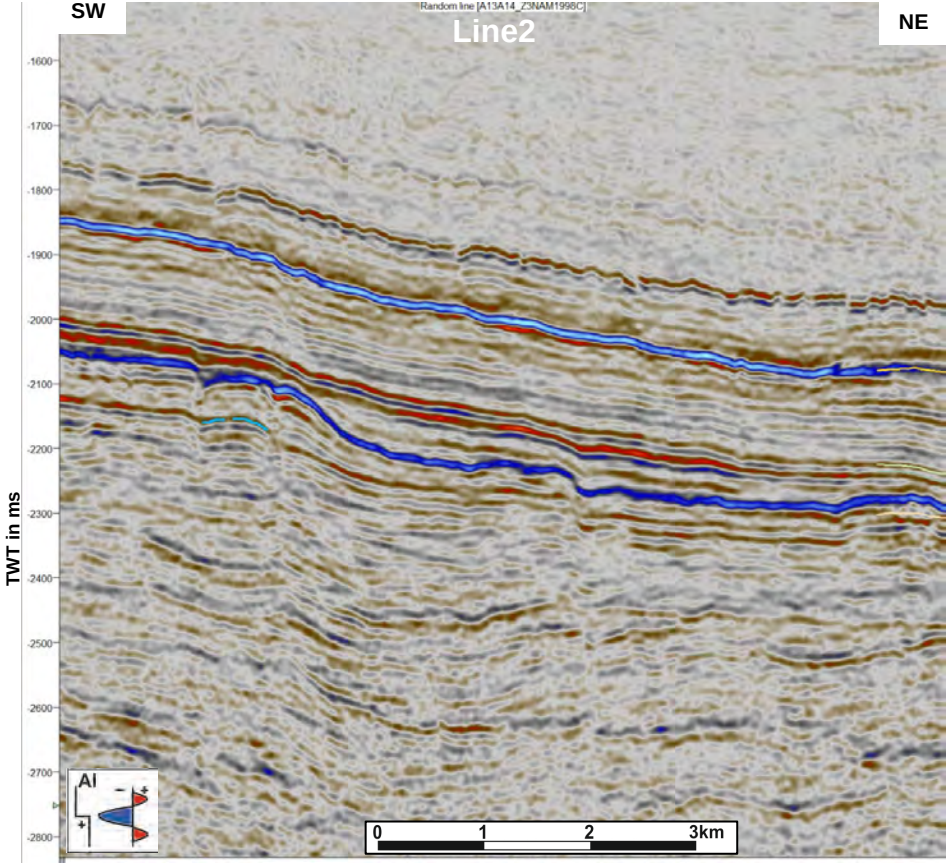


Note A14-02 build-up and smaller build-up towards NW on NSR-line

Salt on either side of build-up causes Triassic rafts

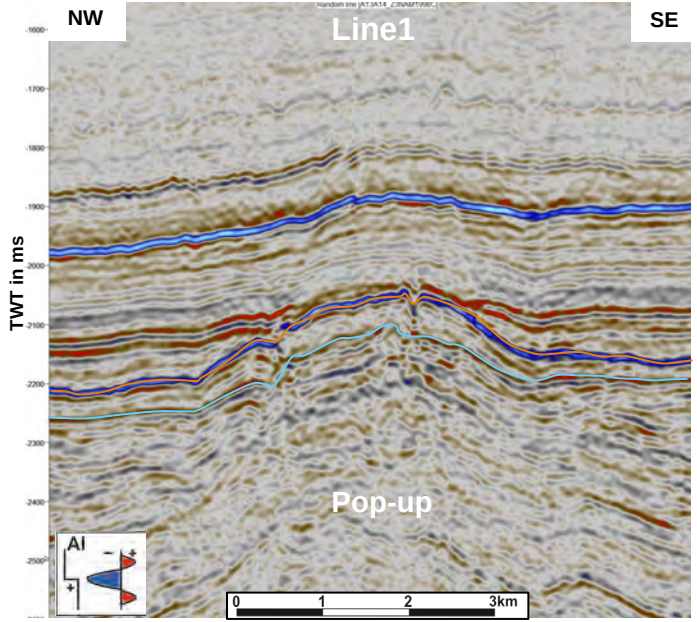
RESULTS – SEISMIC NORTH OF ESH



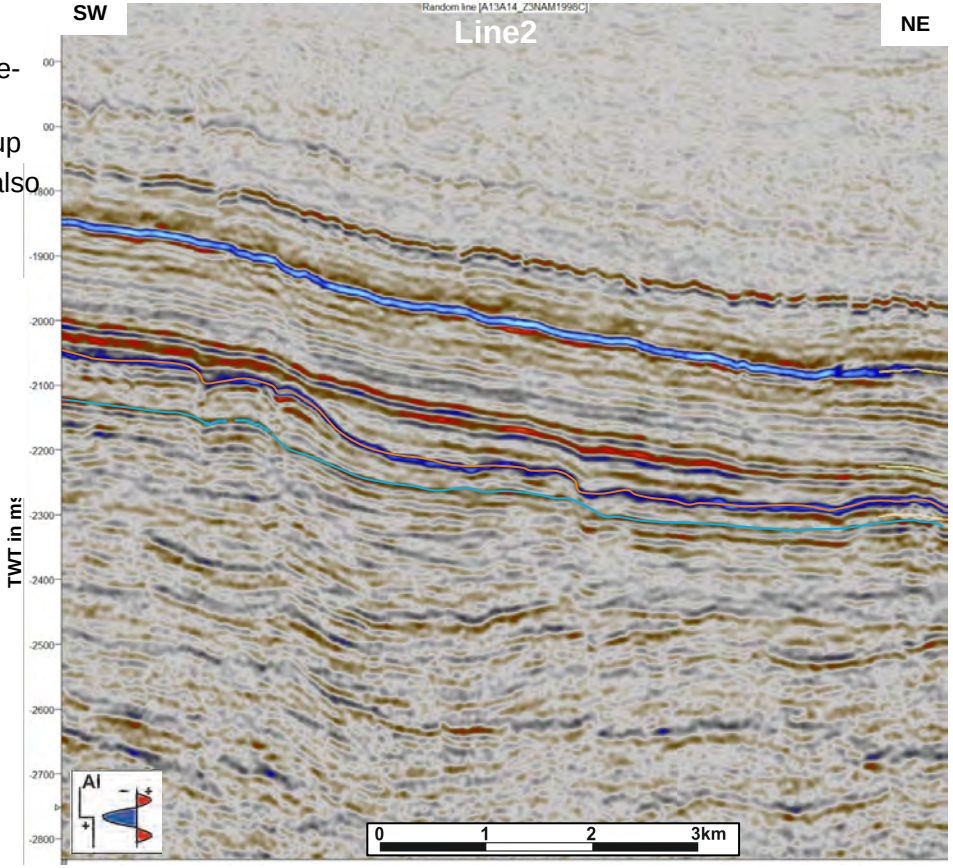


RESULTS – SEISMIC NORTH OF ESH

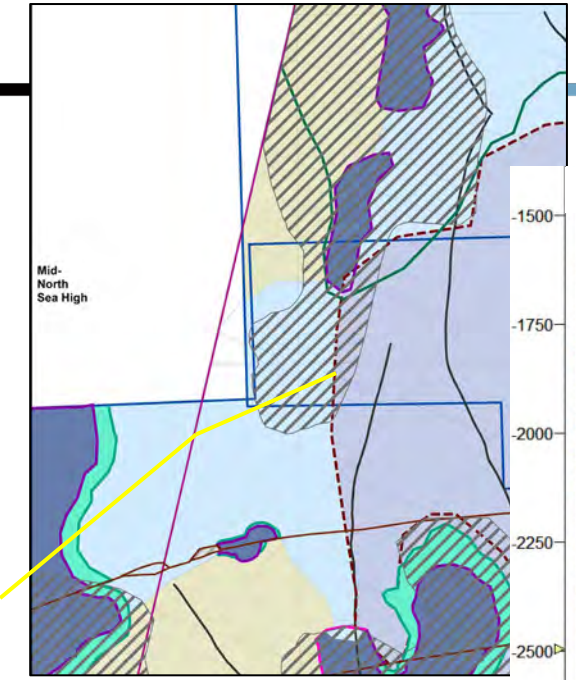
- Build-up structure on UK-side (east of MNSH)
- Line1: High angle sub-ZE reflectors indicate pop-up/faults likely active Pre-ZE.
- Note also ZE thinning on top of pop-up
- Thinning of post ZE strata indicates also post ZE activity

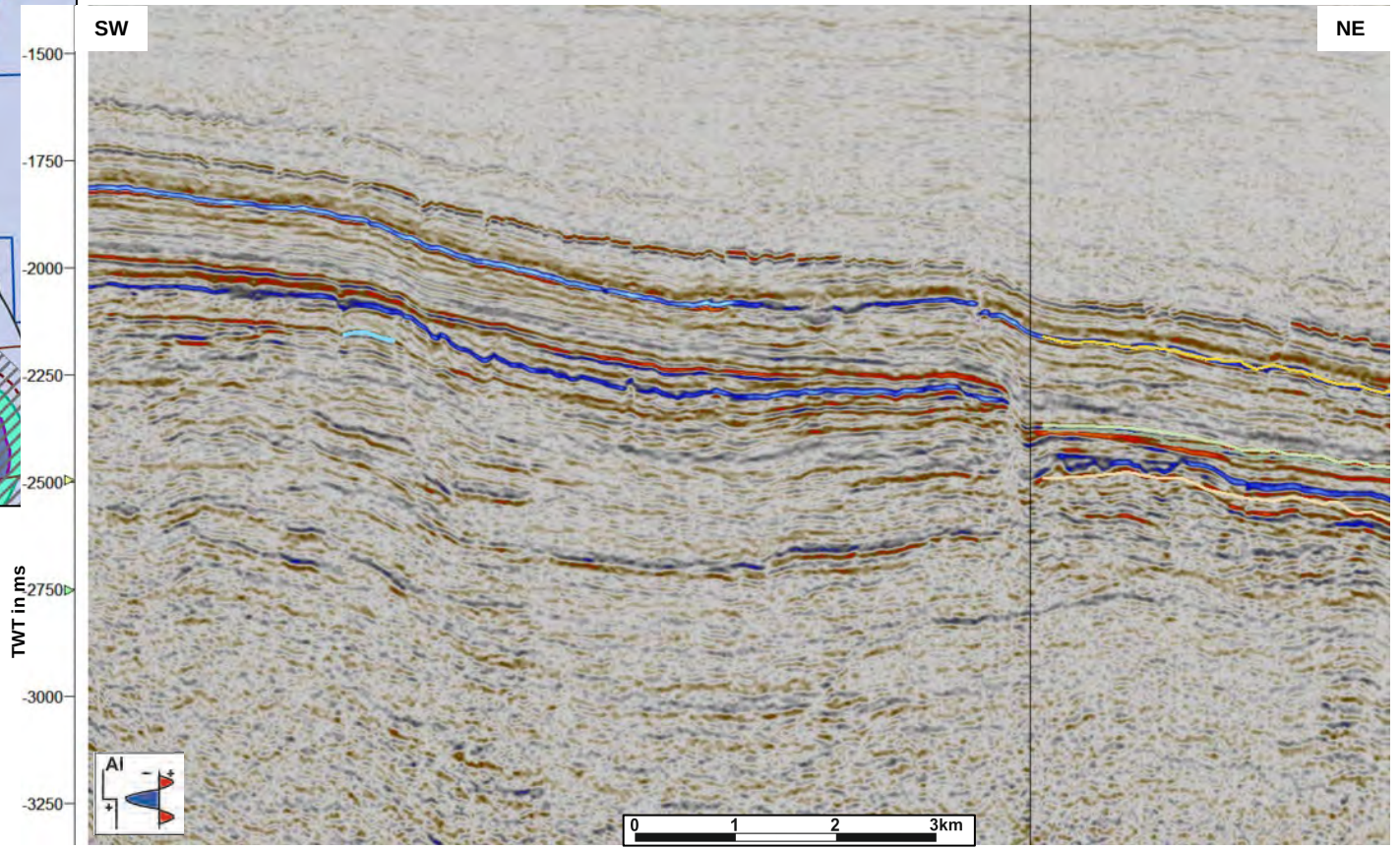


- Line 2: Note thinning of ZE towards Dutch sector into lower basinal part

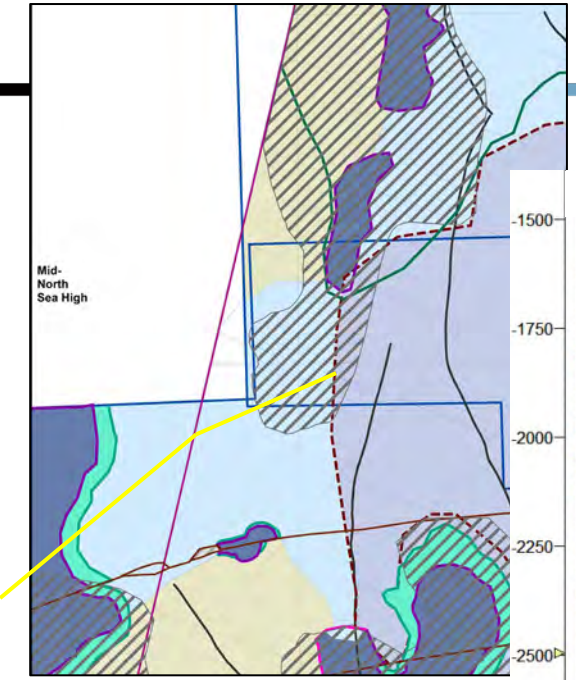


RESULTS – SEISMIC NORTH OF ESH

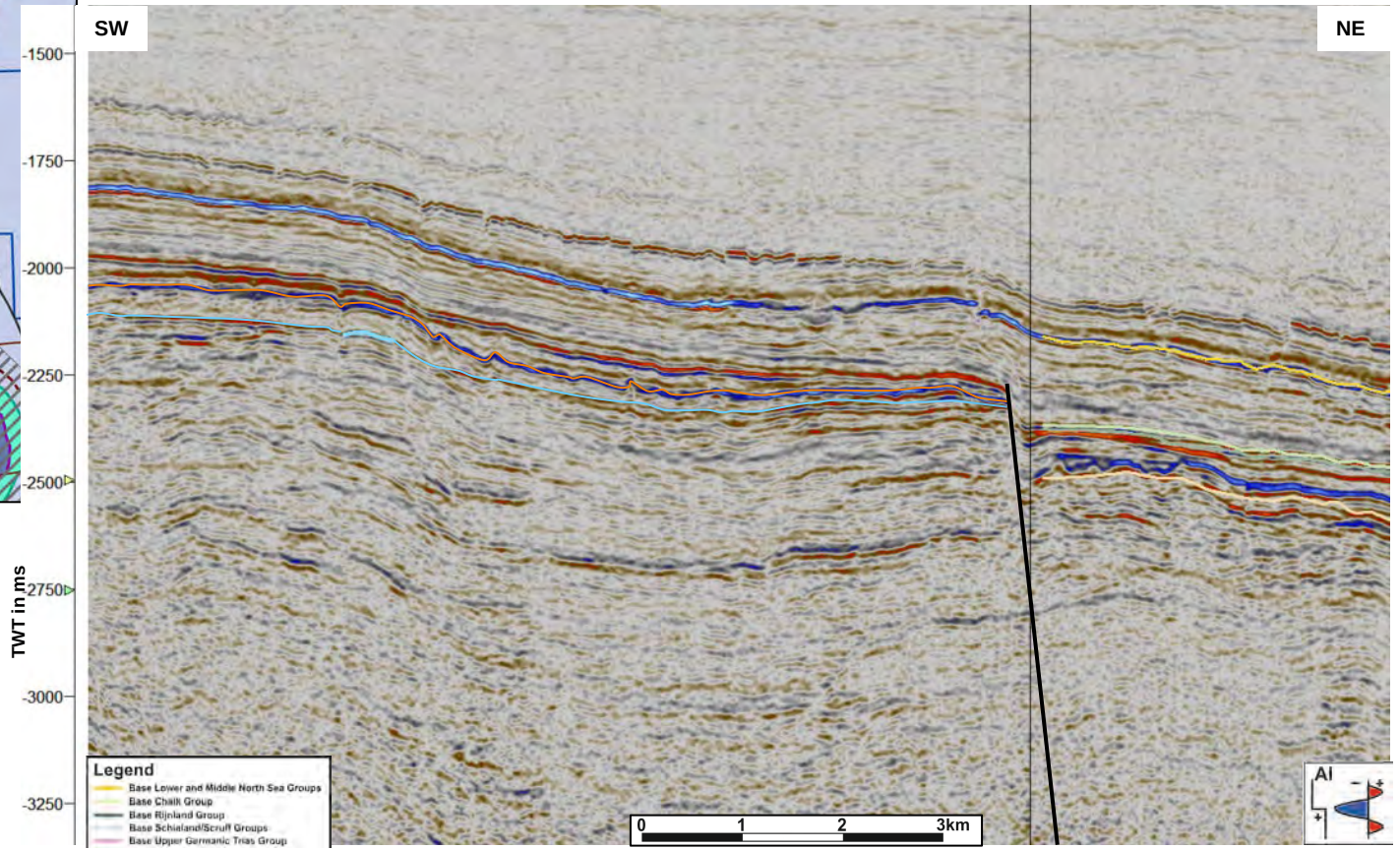


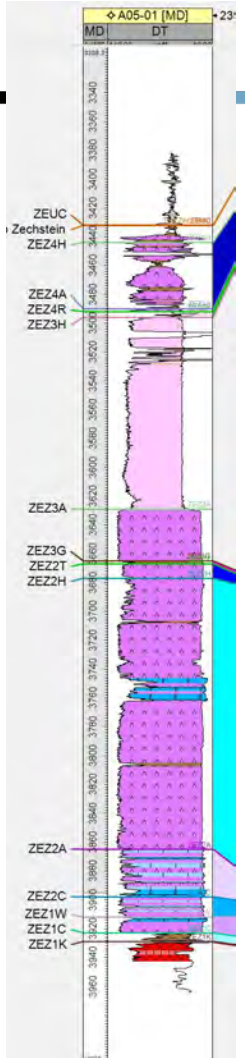


RESULTS – SEISMIC NORTH OF ESH



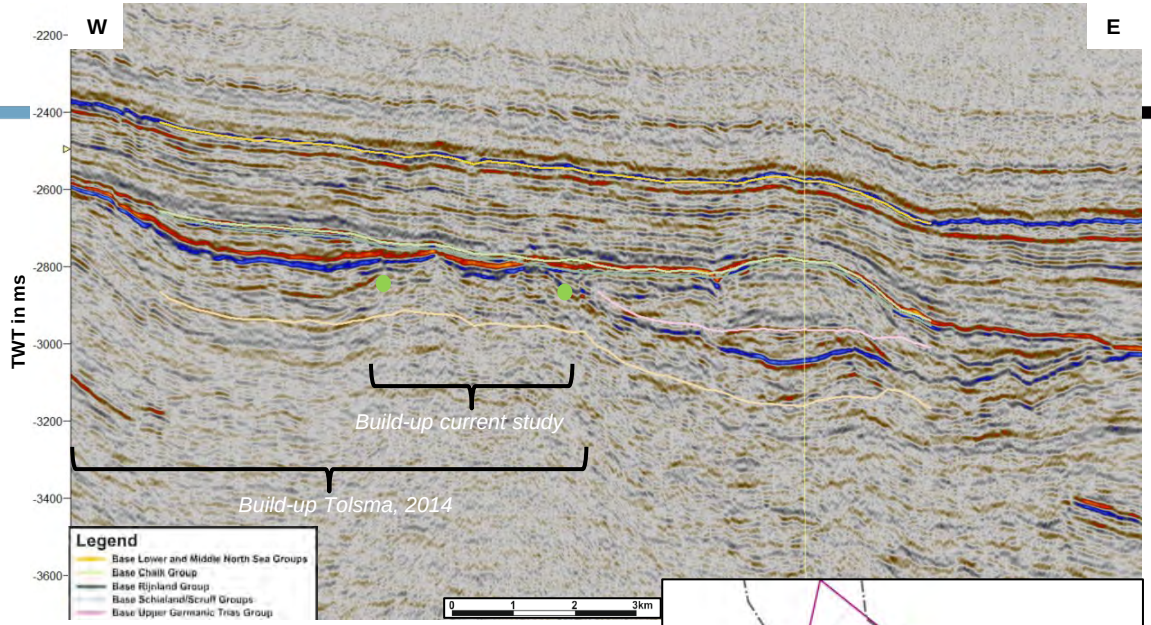
- Southern part of northern most platforms likely no build-ups; ZE too thin here; clear inflection point and downlap are all missing

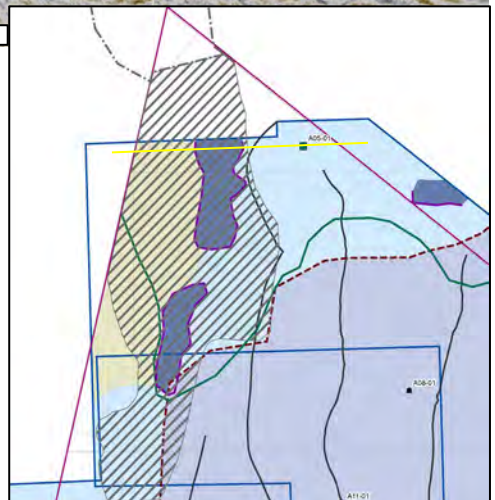




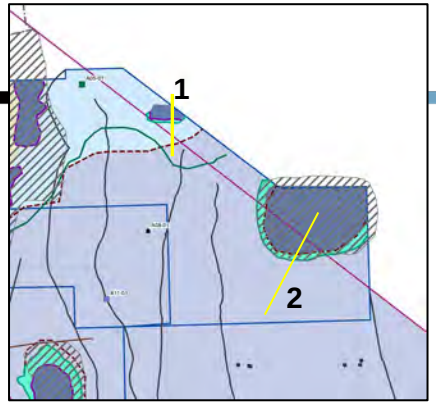
RESULTS – SEISMIC NORTH OF ESH

- Thick anhydrite package at A05-01 well (>250m)
- Only very thin carbonates. Thickness of interpreted ZEZ2C likely representative of basinal facies (like petrographically analysed A14-01 and A15-01 wells)



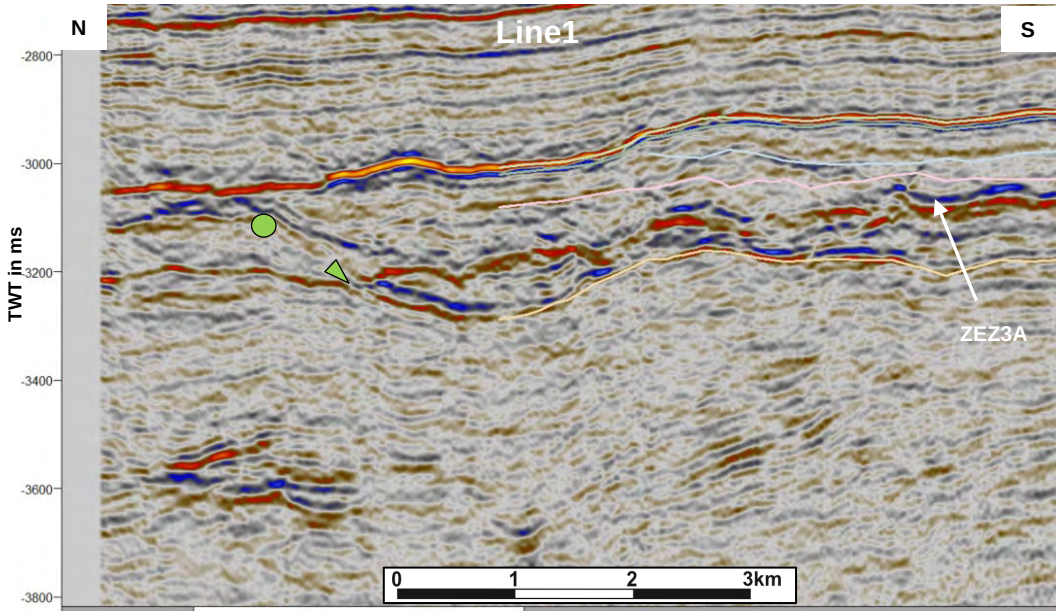


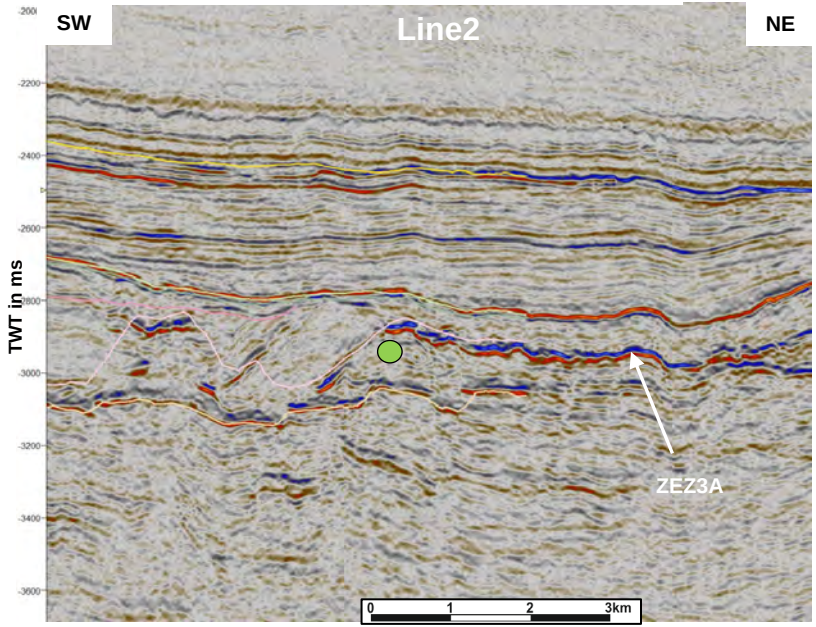
- Build-ups not clearly recognizable; i.e. downlaps hard to observe.
- Interpretation of build up west of A05-01 was picked between inflection points, thereby reducing interpretation when compared to Tolsma (2014).
- It is emphasized though that no clear downlaps where observed; hence exact build-up configuration here is unclear. Based on seismic and well data, a thick anhydrite package is present; but in contrast to the south, based on A05-01, no thick ZEZ2C platform facies is present on top of the anhydrites.
- More work needed in this area to gain better understanding of the system.



RESULTS – SEISMIC NORTH OF ESH

- Inflection point and possibly downlap indicate small zones were there is a higher chance of a build-up along the Dutch-German boundary. Build-ups here positioned at southern margin of Ringkøbing Fyn High
- Note also relatively thick basal ZE south of the build-up (line1), similar to the A05-01 well/area (outer extent of this line indicated by green line in map
- More work needed in this area to gain better understanding of the system.



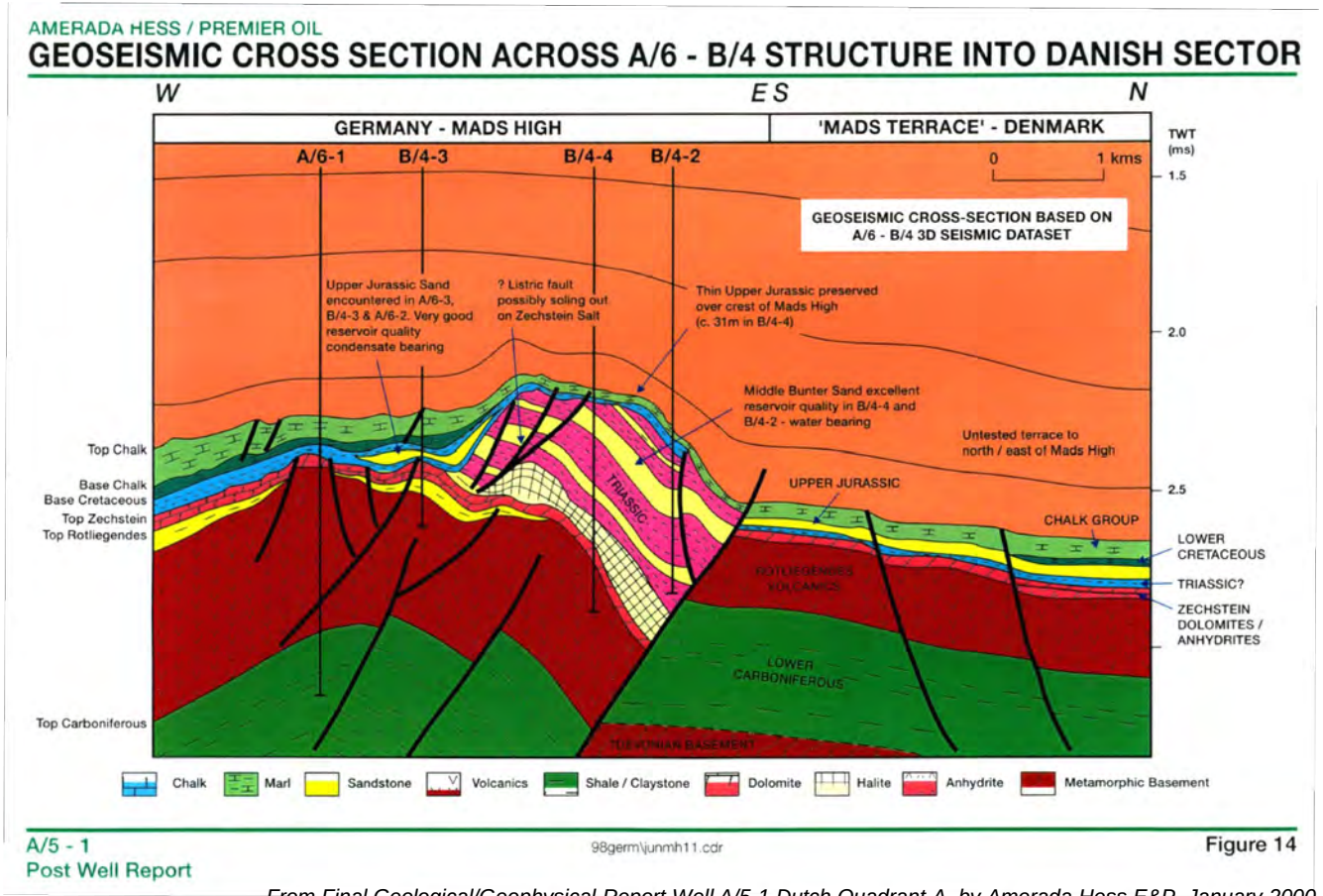


THE A05-01 AREA

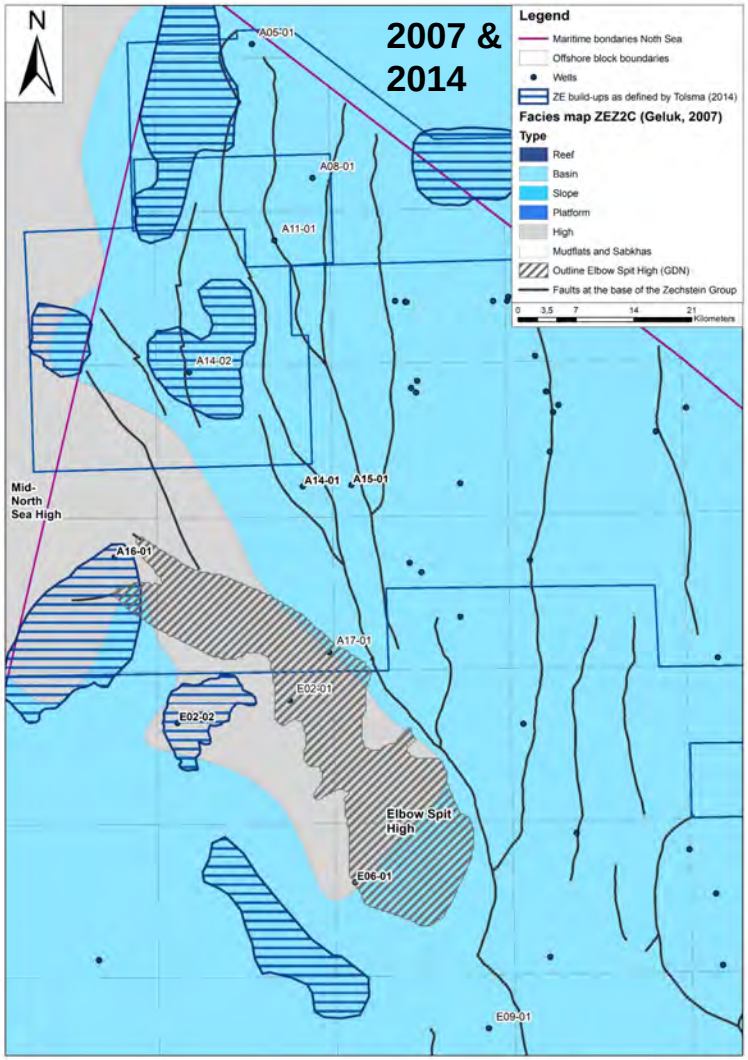
- Despite the uncertainties of the ZEZ2C carbonate distribution in the far north Dutch Offshore that were pointed out earlier, Amerada Hess (1999) was convinced of the Zechstein prospectivity in the area, mainly based on the A6/B4 wells in the adjacent A06 block

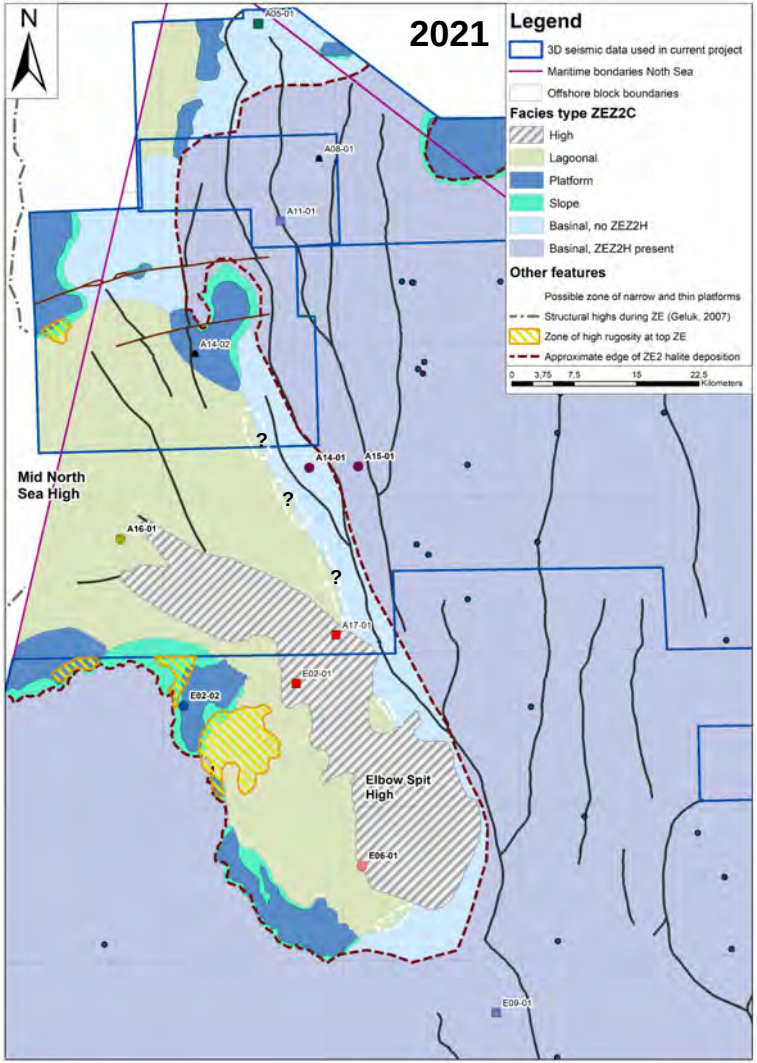
Zechstein carbonates are productive in the A/6-B/4 cluster to the east of the Licence area. The sedimentary facies represented are interbedded carbonates and anhydrites interpreted to be of basin margin origin. Gas was encountered in the carbonates and was tested in all the wells with flow rates up to 48MMscfd. Reservoir quality of the Zechstein carbonates depends strongly on the amount of leaching that may occur during subareal exposure in the Triassic. Top Zechstein was mapped across the area and the potential for stratigraphic prospectivity is suggested as this formation pinches out towards the Mid North Sea High.

From Final Geological/Geophysical Report Well A/5-1 Dutch Quadrant A, by Amerada Hess E&P, January 2000



From Final Geological/Geophysical Report Well A/5-1 Dutch Quadrant A, by Amerada Hess E&P, January 2000

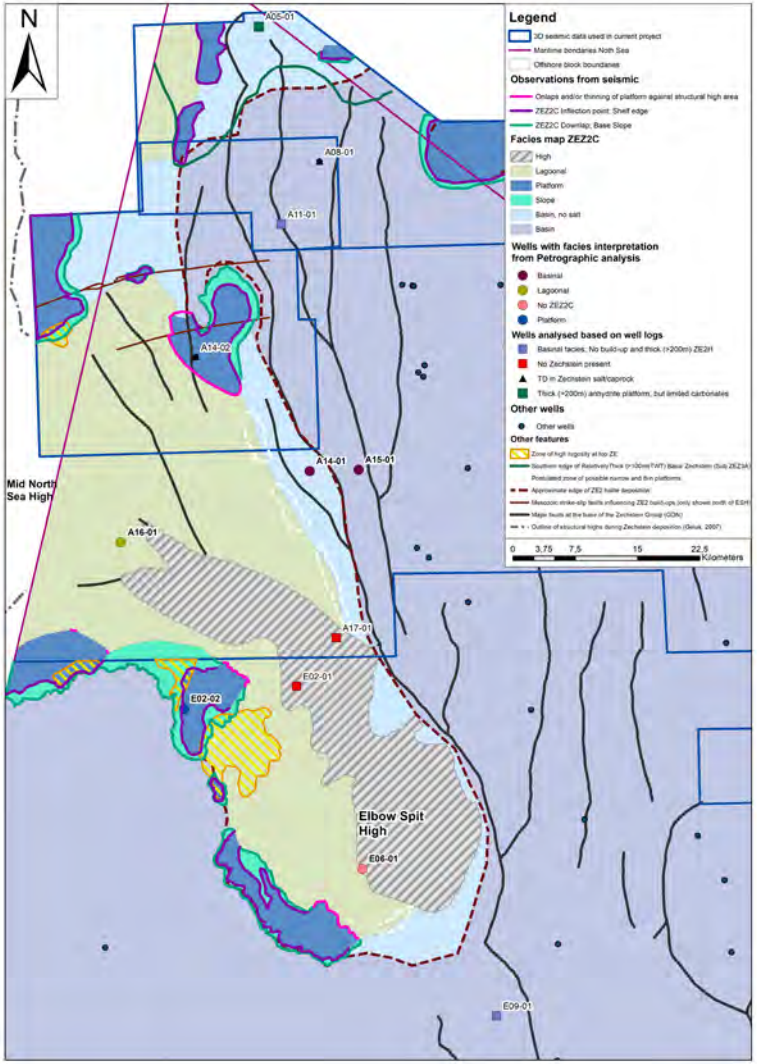




TNO innovation for life

CONCLUSIONS

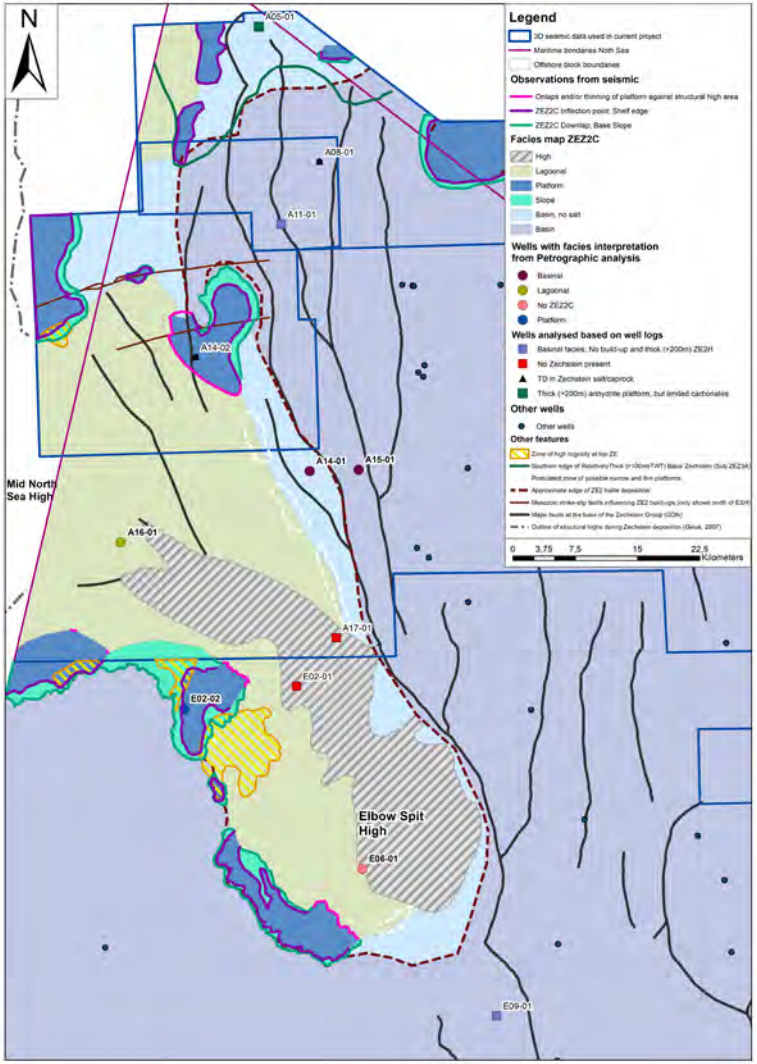
- Left map shows the facies interpretation for the ZEZ2C from Geluk (2007) and the interpreted build-ups from Tolsma (2014)
- Right map shows the result of the current ZEPHYR project



CONCLUSIONS

South of ESH

- Facies and (postulated) sub ZEZ2C reflector mapped in detail south of ESH by using DEF-survey
- Gradual transition from proximal to basinal facies separated by build-ups that developed primarily on pre-existing paleo topographic highs.
- Downlaps and inflection points can in general be recognized enabling to determine the location of build-ups
- Location of build-ups was updated with respect to work of Geluk (2007) and Tolsma (2014);
  - Especially A16-01 platform and platform south of ESH are considered to be smaller
- Build-ups are generally thickest towards the basinal side, likely because increased accommodation allowed higher grow rates here.
- Especially platform southwest of E06-01 displays complex intra build-up geometries, indicating this build-up is composed of individual thicker zones.
- Individual build-ups likely not fully connected but separated by zones of thin Werra and ZEZ2C or slope facies
- The exact position of the base Zechstein is of key importance in understanding the platform distribution, but it is difficult to map in some area's, especially southeast of the E02-02 platform, where it coincides with the area that is characterized by a high rugosity top Zechstein signal. A new Base Zechstein interpretation was conducted in this area, during this project. Better quality seismic data could increase the understanding of this area, which is possibly partly karstified and/or characterized by back barrier pinnacles. (See also recommendations).



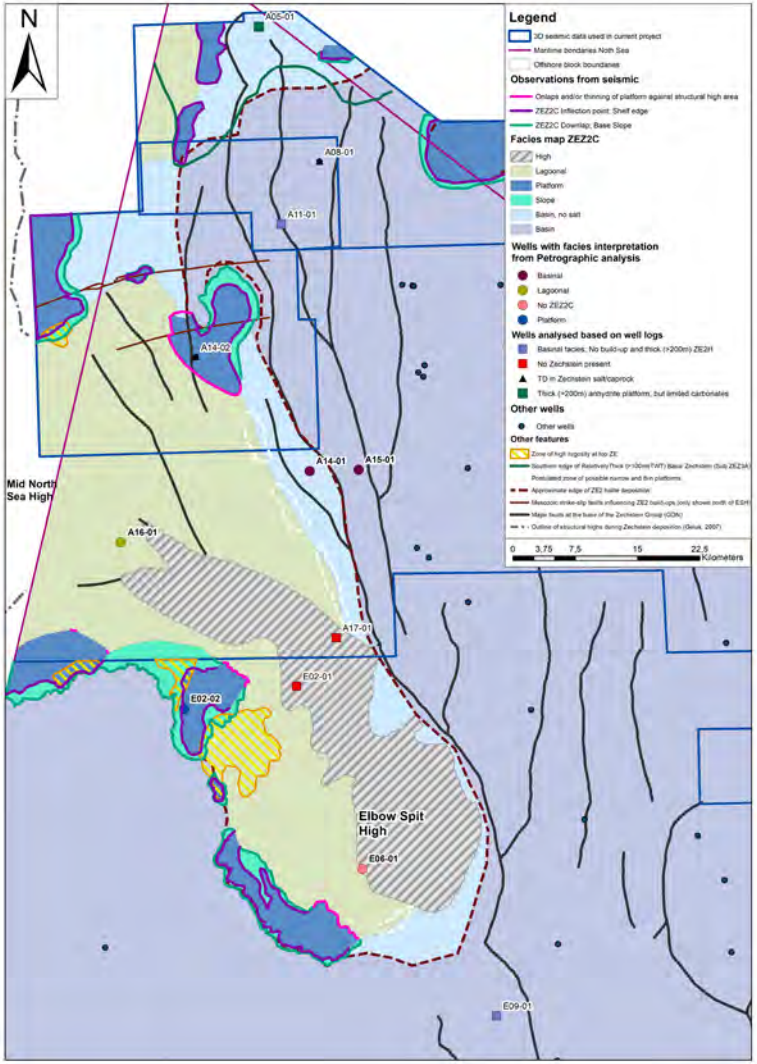
CONCLUSIONS

North of ESH

- Only inflection points and downlaps were mapped north of ESH (no direct well control within platforms)
- Rapid transition from high to basinal area during deposition of ZEZ2C at the northeastern margin of the ESH. A small zone of (relatively thin/minor) build-ups could possibly be present here. These are not clearly confirmed on seismic, but it is noted that partly only 2D seismic data is available in this area.
- Similar to southern rim; build-ups are present on NW side of ESH (A10-A14 blocks). ZE in this area is heavily faulted; faults are characterized by complex fault history
- Northern A-blocks display a thick (>200ms TWT) basal Zechstein on seismic; however; well A05-01 indicates only minor carbonates that are present. Presence of carbonate build-ups remains enigmatic in the northern A-blocks

Far North

- Northern A-blocks display a thick (>100ms TWT) basal Zechstein on seismic. However; well A05-01 indicates only minor carbonates that are present.
- Presence of carbonate build-ups is enigmatic in the northern A-blocks. Some inflection points were mapped (difficult, not very reliable), but clear downlaps are absent in this area.



RECOMMENDATIONS FOR FUTURE WORK

South of ESH

- Reprocessing/updating the velocity model of the DEF-survey would allow for a better interpretation of the base Zechstein.
- Full integration of the results of this project with well-, & seismic data from the UK side would allow for a better understanding of the differences and similarities between the two areas
- Integrate recent knowledge from Rotliegend mapping in the evaluation of the Zechstein depositional setting, including detailed subcrop mapping and fault mapping.

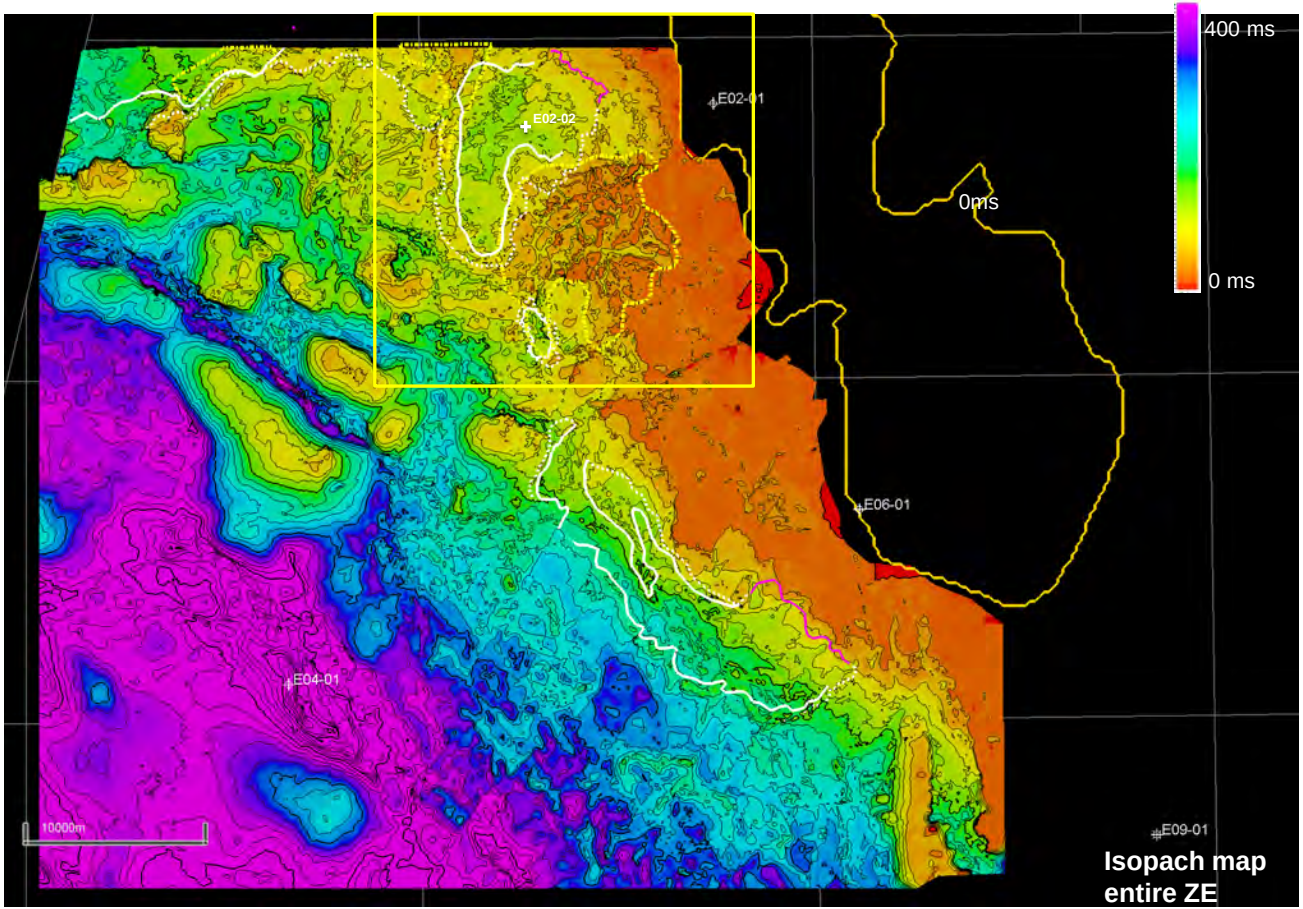
North of ESH

- More time could be spent on mapping the individual build-ups (lack of well control will make this difficult though)
- Reprocessing/updating velocity models of northern surveys would allow for a better interpretation of base & intra-Zechstein reflectors.
- Additional petrographic/isotope analysis of well A05-01 would shed more light on ages and depositional environment of this well
- Integrate recent and future knowledge from Carboniferous mapping in the evaluation of the Zechstein depositional setting, including detailed BPU subcrop mapping and fault mapping.
- Stratigraphic forward modeling (Dionisos) of platform growth in the area
- Source rock focused investigations

REFERENCES

- Daniels, S.E., Tucker, M.E., Mawson, M.J., Holdsworth, R.E., Long, J.J., Gluyas, J.G., Jones, R.R., 2020. Nature and origin of collapse breccias in the Zechstein of NE England: local observations with cross0border petroleum exploration and production significance, across the North Sea. In Cross-Border Themes in Petroleum Geology: The North Sea. Geological Society, London, Special Publications, 494.
- Geluk, M.C., 2007. Permian. In: Wong, Th.E., Batjes, D.A.J. & de Jager, J. (eds.): Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences, 63-83.
- Grant, R.J., Underhill, J.R., Hernandez-Casado, J., Barker, S.M., Jamieson, R.J., 2019. Upper Permian Zechstein Supergroup carbonate-evaporite platform palaeomorphology in the UK southern North Sea. Marine and Petroleum Geology; 100, 484-518.
- Hendry, J., Burgess, P., Hunt, D., Janson, X., Zampetti, V., 2021. Seismic characterization of carbonate platforms and reservoirs: an introduction and review. Geological Society, London, Special Publications, 509, 1-28, 8 June 2021
- Kulbicki, M., Adjeroud, M., Carassou, L., Chabanet, P., 2015. Biocomplexity of coral ecosystems: diversity in all its states. In book: Marine Ecosystems – Diversity and Functions (pp. 107-164)
- Patruno, S., Reid, W., Jackson, C.A-L, Davies, C., 2017. New insights into the unexploited reservoir potential of the Mid North Sea High (UKCS quadrants 35-38 and 41-43): a newly described intra-Zechstein sulphate-carbonate platform complex. *In Petroleum Geology of NW Europe: 50Years of Learning – Proceedings of the 8th Petroleum Geology Conference*. Geological Society, London, Special Publications.
- Pettigrew, T.H. 1980. Geology, in The Magnesian Limestone of Durham County (ed. T.C. Dunn), Durham County Conservation Trust. Durham, UK, 4-26.
- Ter Borgh, M.M., Jaarsma, B., Rosendaal, E.A., 2018. Structural development of the northern Dutch offshore: Paleozoic to present. *In Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, 471.
- Tolsma, S., 2014. Seismic Characterization of the Zechstein carbonates in the Dutch northern offshore. MSc. Thesis, Utrecht University and EBN.
- Van Tuyl, J., Alves, T.M., Cherns, L., 2018. Pinnacle features at the base of isolated carbonate buildups marking point sources of fluid offshore Northwest Australia. GSA Bulletin, 130 (9-10), 1596-1614.
- Wilson, J.L., 1975. Carbonate Facies in Geologic History, Springer-Verlag.

APPENDIX A
PALEOSCAN MODEL SOUTH OF ESH



Isopach map entire ZE

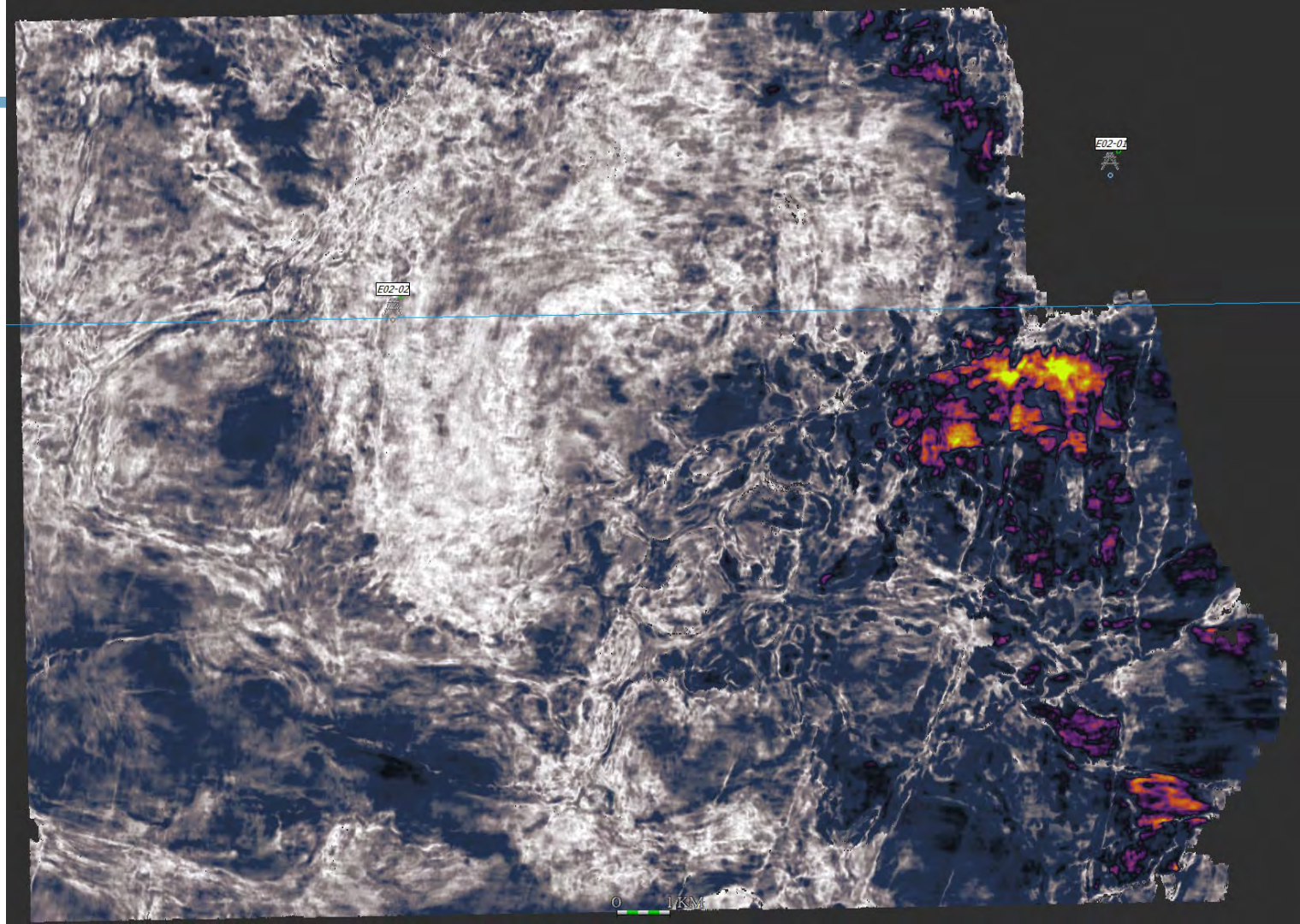
PALEOSCAN MODEL

Isopach ZE,
two PaleoScan models;
Model1; Around E02-02 platform (indicated by orange square)
Model2: Larger area in the E01-E06 blocks covering the extend of the ZE isopach map shown here.

APPENDIX – PALEOSCAN MODEL

RMS amplitude map hz. 113 (approx. ZE2ZC)

- Circular features southeast of E02-02 build-ups; possibly Breccia pipes or pinnacles. See discussion chapter south of ESH



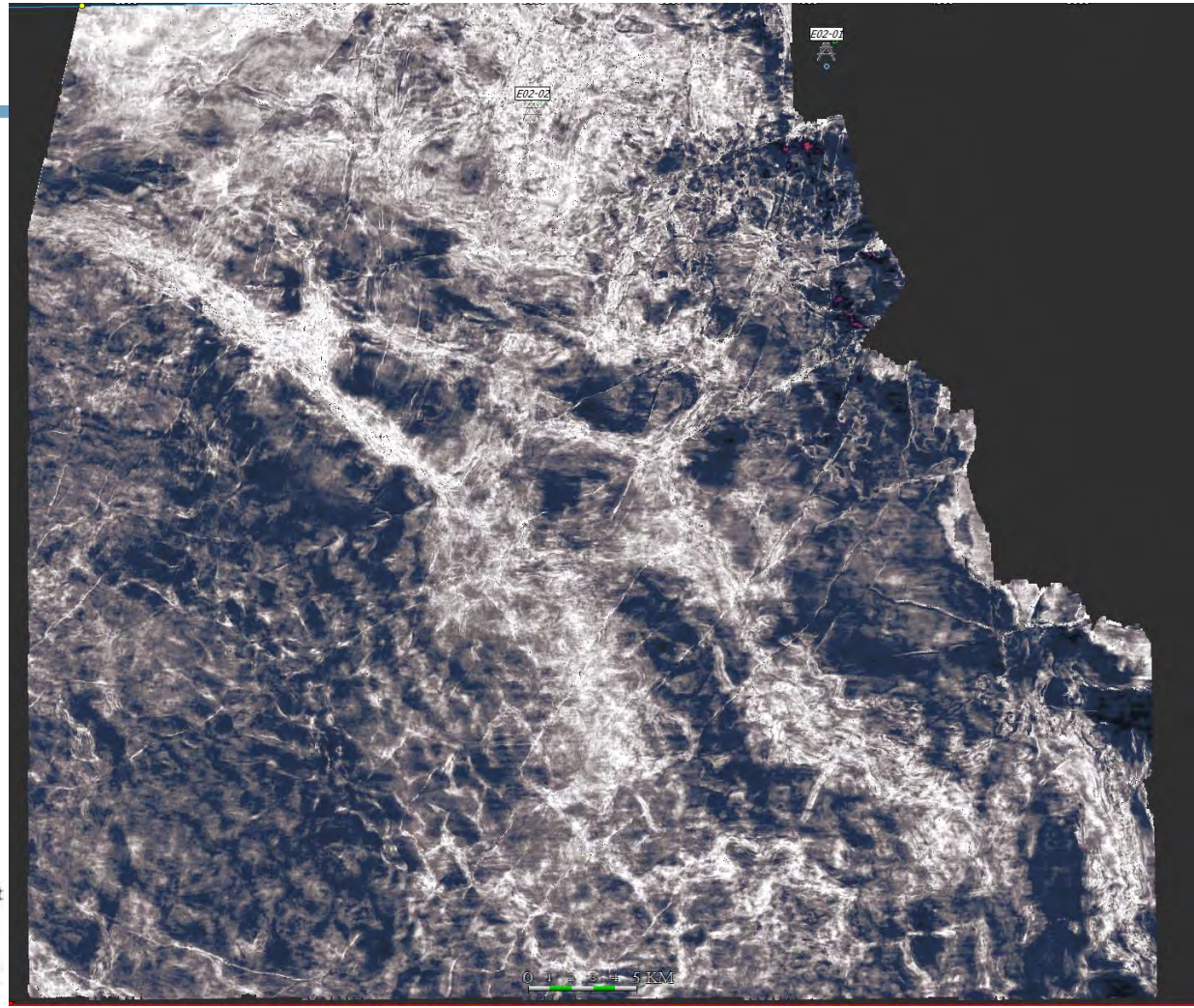
RMS amplitude

High amplitude contrast

Low amplitude contrast

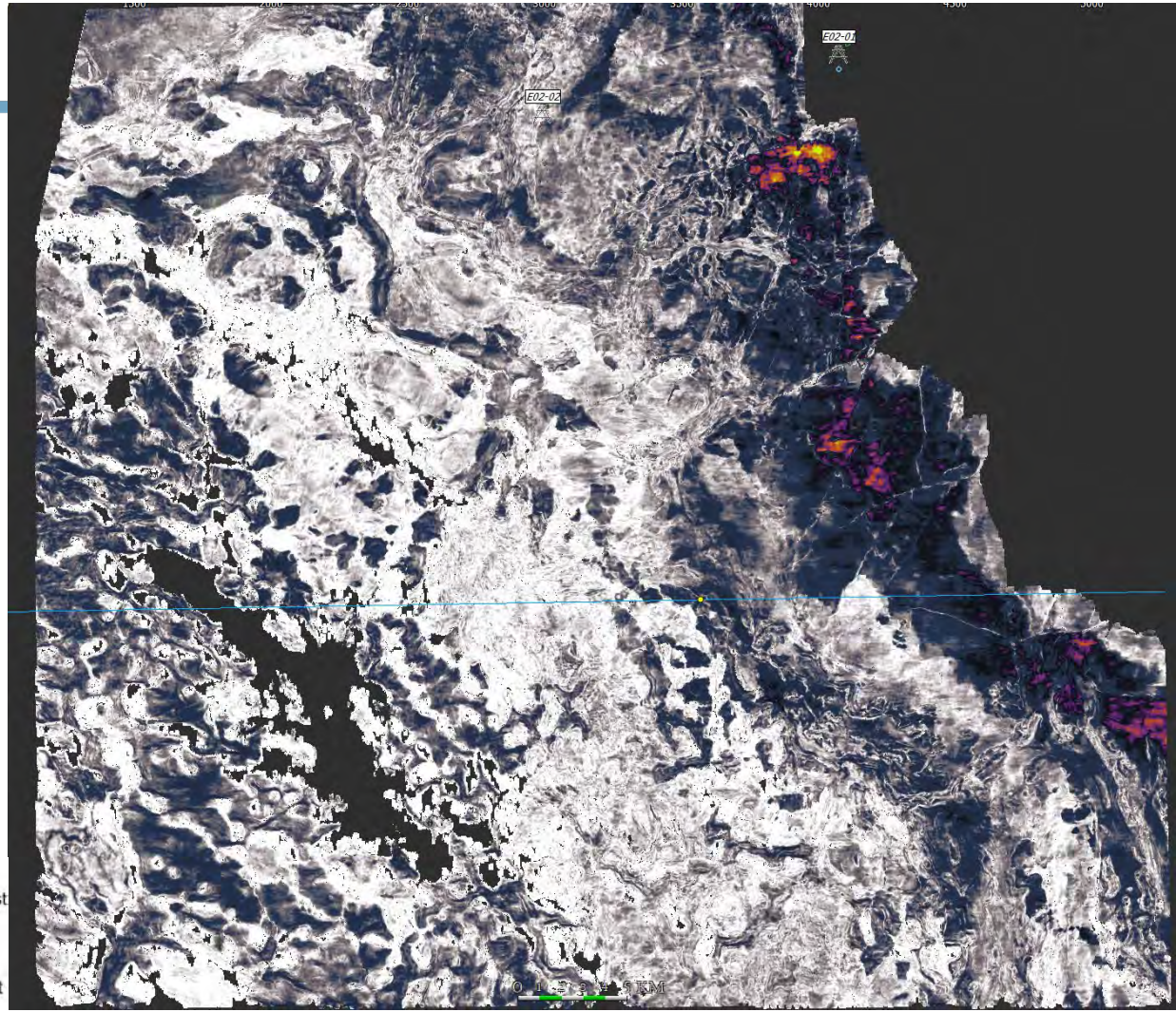
APPENDIX – PALEOSCAN MODEL

RMS amplitude map Base Zechstein



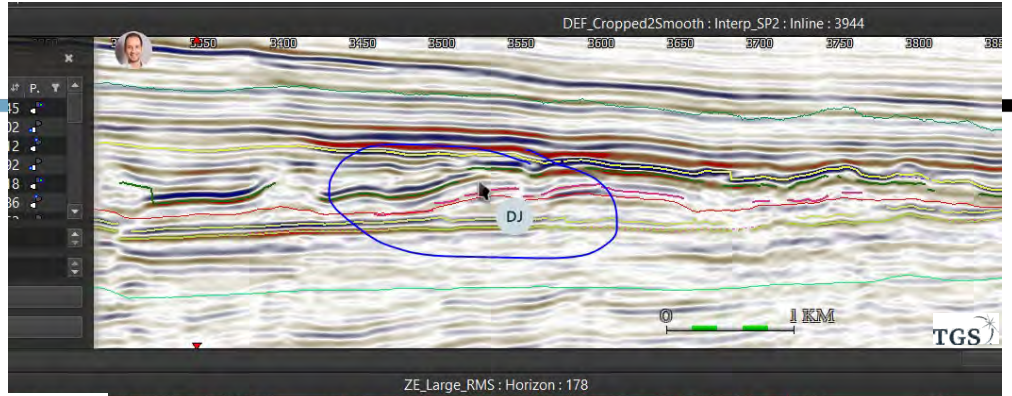
APPENDIX – PALEOSCAN MODEL

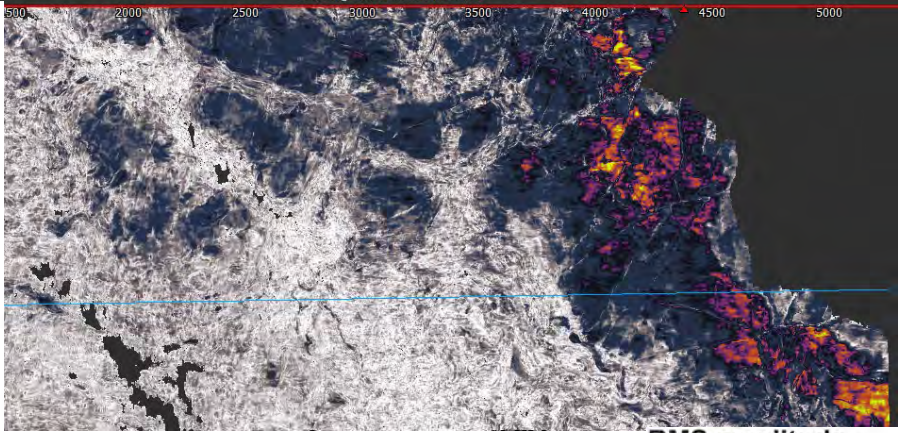
- RMS map at approx. ZE3A (hauptanhydrite, plattendolomite) level. Note floaters that are present within the salt in the western part of the study area. In the east, this event represents (by approximation) the top of the Zechstein.

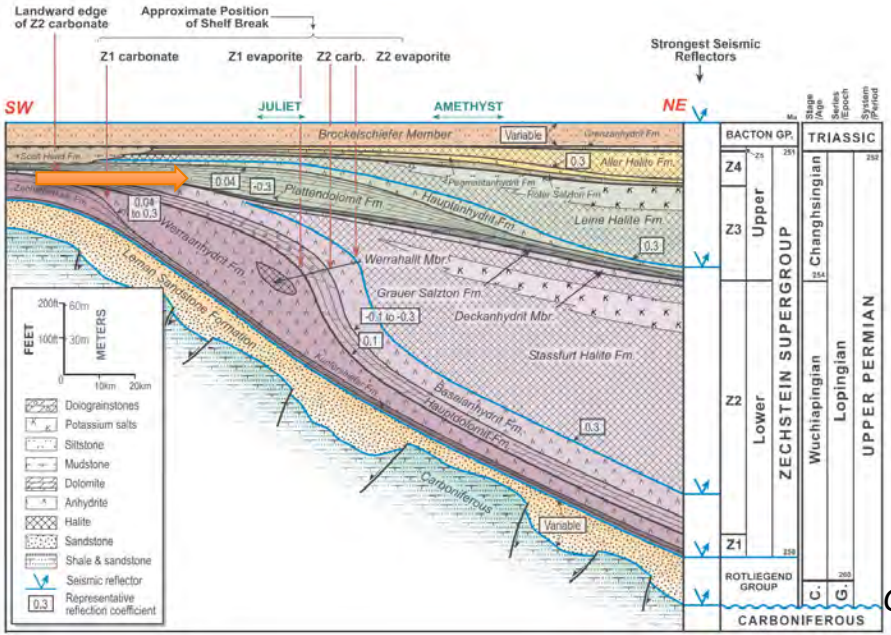


APPENDIX – PALEOSCAN MODEL

- ZE3 carbonate possibly present on platform south of E02-02 platform. Note clinoform like geometry and the more gentle angle of the platform slope. Geometry would be in accordance with Grant et al., (2019)







Grant et al., 2019