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Nederlandse Aardolie Maatschappij

Geology description of Twente Gas Fields: Tubbergen, Tubbergen-Mander and Rossum-Weerselo

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Nederlandse Publiekssamenvatting

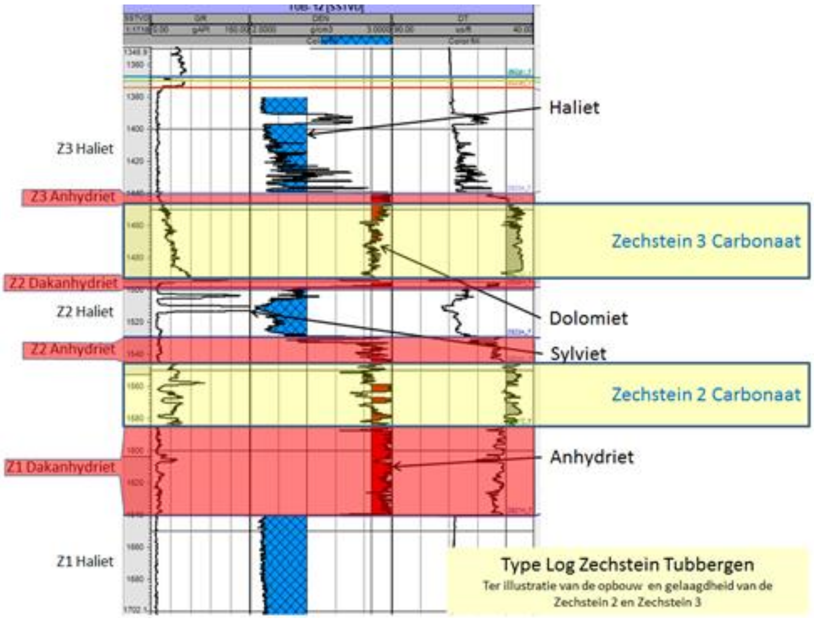
In dit rapport wordt de geologie van de oude (leeggeproduceerde) gasvelden van Tubbergen en Rossum-Weerselo beschreven. Deze lege gasvelden worden op dit moment gebruikt door NAM voor het in de diepe ondergrond injecteren van het productiewater afkomstig uit het Schoonebeek olieveld.

In de MER is uitvoerig aandacht besteed aan het mogelijk oplossen van de afdekkende steenzoutlaag indien deze laag in aanraking zou komen met het injectiewater. De MER concludeert dat deze zoutlagen niet of nauwelijks zullen oplossen in het injectiewater, echter om hierover aanvullende inzichten te verkrijgen is op verzoek van Staatstoezicht op de Mijnen besloten uitgebreide modelleringen uit te voeren.

Op basis van deze uitgebreide modelleringen is aangetoond dat de conclusie uit de MER juist is. Wel is het zo dat, mocht injectiewater langs de buitenzijde van de stalen verbuizing van de waterinjectieput kunnen stromen, het theoretisch niet uitgesloten kan worden dat de zoutlaag dan plaatselijk aangetast wordt.

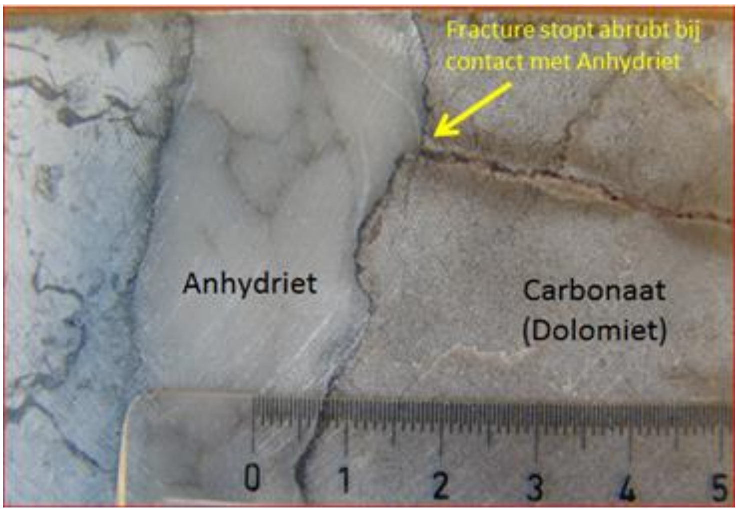
Op basis van vele boorputgegevens kan worden aangetoond dat het lege gas reservoir zowel aan de boven- als onderzijde gescheiden wordt van het steenzout door een onoplosbare anhydrietlaag. Deze anhydrietlaag vormt een perfecte afsluiting die er ook gedurende vele miljoenen jaren voor gezorgd heeft dat het gas in deze reservoirs opgesloten is gebleven. Alleen in de buurt van breuken is een situatie denkbaar waarbij het injectiewater in contact zou kunnen komen met het steenzout. Echter de boorputgegevens laten zien dat natuurlijke scheurtjes in het gesteente op die plekken al volledig met zout zijn opgevuld. Dit houdt in dat het water op deze plekken slechts heel langzaam kan stromen en dat oplossing dus in ernstige mate bemoeilijkt wordt.

In de Twentse gasvelden Rossum-Weerselo, Tubbergen en Tubbergen-Mander, vormen onder meer carbonaatlagen uit de Zechstein Periode de gasreservoirs (zandsteenlagen, behorende tot het Carboon zijn hier buiten beschouwing gelaten). In de Zechstein Periode (ongeveer 250 miljoen jaar geleden) heerste er in Europa een tropisch klimaat en werd het land bedekt door een grote ondiepe binnenzee die zich uitstrekte van Engeland tot Rusland en die bij tijd en wijle droog viel. In Nederland hebben in deze binnenzee 4 tot 5 indampingscycli plaatsgevonden. Deze cycli hadden tot gevolg dat bij een toenemende mate van indamping en droogvallen een opeenvolging van gesteentelagen kon vormen die begint met klei, gevolgd door kalksteen (Carbonaat), anhydriet en aan het eind van de cyclus zouten. Door de uitgestrektheid van de Zechsteinzee en de uniforme indamping zijn deze lagen regionaal in de ondergrond (met behulp van putgegevens en seismiek) over grote afstanden te volgen en zodoende is de opeenvolging van deze lagen nauwkeurig bekend. Ook de Zechsteinlagen in de Twentse gasvelden beantwoorden geheel aan de regionaal geologische kennis. Op basis van de gedetailleerde informatie die uit de boorputten in Twente verkregen is, is er een gedegen geologische kennis van de gasreservoirs en onder en bovenliggende lagen. De opbouw van het Zechstein in Twente is hieronder samengevat.



De oorspronkelijk gasvoerende lagen zijn bekend als de "Zechstein 2, en Zechstein. 3 Carbonaat". Deze carbonaatlagen zijn zowel aan de onder als bovenkant begrensd door anhydriet lagen, die ook weer in de verre regio te correleren zijn. Het zijn de anhydrietlagen, die voor de primaire afdichting van de gasreservoirs verantwoordelijk zijn en een direct contact tussen de carbonaat en steenzoutlagen (aangeduid als Haliet) verhinderen.

De reden dat de carbonaten van de Zechstein 2 en 3 gasvoerend en doorlaatbaar voor gas zijn, ligt aan de matrix van het gesteente, die in zekere mate porositeit (voor gasopslag) en permeabiliteit (doorlaatbaarheid voor gas) heeft. Vervolgens wordt de doorlaatbaarheid voor gas nog eens versterkt door de aanwezigheid van een (natuurlijk) netwerk van scheurtjes in deze ondergrondse formatie. De aanwezigheid van deze natuurlijke *fractures* is een functie van de plasticiteit van het gesteente (hoe plastischer het gesteente, hoe minder fractures). Aangezien anhydriet vele malen plastischer is dan het gasvoerende carbonaat, zijn hier dan ook geen *fractures* aanwezig. De foto hieronder illustreert hoe, op het grensvlak tussen Anhydriet (lichtblauw/grijs) en Carbonaat (grijsbruin) een typische fracture abrupt stopt. Dit maak anhydriet als goed afdichtend en niet oplosbaar materiaal een perfecte, natuurlijke barriere tussen de injectie reservoirs en het steenzout.



Alleen in de buurt van breuken, waar lagen ten opzichte van elkaar verzet zijn, zou een situatie voor kunnen komen waarbij het injectie reservoir in direct contact staat met steenzout. Boorputgegevens laten echter ook zien dat de natuurlijke 'fractures' in het carbonaat gesteente op die plekken volledig met zout zijn opgevuld, Dit houdt in dat het injectie water slechts heel langzaam kan stromen waardoor zoutoplossing in ernstige mate bemoeilijkt wordt.

Samenvattend kan gezegd worden dat de geologische omstandigheden zodanig zijn dat de kans dat het injectiewater al stromend in direct contact kan komen met het steenzout uiterst klein is. De overal aanwezige laag van het onoplosbare en goed afdichtende anhydriet vormt een natuurlijke barrière die het injectie-reservoir zowel aan de boven- als onderzijde scheidt van het steenzout. Alleen in de buurt van breuken is een situatie denkbaar waarbij het injectiewater in contact zou kunnen komen met steenzout maar door de slechte doorlaatbaarheid ter plekke wordt het oplossen in ernstige mate bemoeilijkt.

1. Summary

This report describes the geology of the depleted gas fields Tubbergen and Rossum-Weerselo. These fields are currently being used by NAM to re-inject low saline production water from the Schoonebeek Oilfield. The injection reservoirs in these fields are carbonate sequences sealed by a Halite cap rock which could be subject to local dissolution when in direct contact with the low saline injection water.

In the original Environmental Impact Assessment, a lot of attention was dedicated to the risk of degrading cap rock integrity through salt dissolution. The EIA concluded that this risk is very low. Nevertheless, the Dutch regulator (State Supervision of Mines) requested to do a further and more detailed study into the risk and possible effect of the injection of this low saline water on the cap rock integrity.

The probability and potential impact of Halite dissolution depends on the extent to which low saline injection water could connect to and flow past the Halite cap rock. To make an assessment of this potential risk a good understanding of the injection reservoir and associated cap rock geology is essential.

This report shows that in un-faulted areas, the injected water cannot contact directly the Halite cap- and base rock. Laterally continuous and non-soluble anhydrite layers directly above and below the Carbonate injection reservoir form a perfect barrier and prevent the injection fluids in the reservoir to get in contact with the under- and overlying halite sections. In faulted areas, Halite could be exposed to the Carbonate injection reservoir in case the fault offset is bigger than the anhydrite layer thickness.

Fluid flow within the Carbonate reservoir occurs predominantly via a laterally extensive network of natural fractures. The vertical communication between these fractured carbonate layers is however severely hampered by the existence of interlayered anhydrite banks. Because of this, the k_v/k_h ratio in the injection reservoirs is expected to be very low (i.e.10^{-4} to $5*10^{-3}$) for un-faulted areas and even lower near faults where fractures are seen to be plugged with salt.

Based on the above, it can be concluded that injected low saline water could laterally flow towards exposed Halite sections in faulted areas but that significant dissolution is not expected because the salt saturated water cannot vertically flow away from these areas due to a very low vertical communication within the injection reservoir.

The geological assessment of the Twente Carbonate reservoirs fully supports the conclusion from the original EIA in that the risk for significant halite dissolution is expected to be very low because of the presence of continuous anhydrite layers above and below the reservoirs as well as the low vertical permeability in the reservoirs.

2. Geological setting

2.1 General geological setting

There are three old gas fields, Tubbergen, Rossum-Weerselo and Tubbergen-Mander situated in the Twente area in the East Netherlands (fig. 1). All the three fields have been producing gas from the Zechstein -2 and -3 carbonates (Tubbergen and Rossum-Weerselo had also, in addition, gas production from the underlying Carboniferous clastic Westfal C/D reservoirs) (ref.1,2, 3). In general, both the Z2 and Z3 carbonates are deposited in the so called platform facies and hence in relatively shallow water (ref.1, 2). Although in the shallow waters there is a chance for deposition of carbonates with high primary porosities and general reservoir quality, the area of the three described fields was in a relative landward position and the predominant sediments are lagonal lime muds interspersed with gypsum, which later became anhydrite (ref. 4).

2.2 Tubbergen field

The Zechstein in the Tubbergen field consists of 4 evaporitic cycles which are encountered regionally. From the bottom up, each cycle comprises a sequence of Clay-Carbonates-Anhydrites-Salts and Halites/Anhydrites (fig.8). The 4th cycle may not be developed fully, and generally only shows a development of a halite sequence. Typical for the East Twente area, also the Z1 Halite is developed, which is absent in the remainder of the Dutch sub-surface (ref. 1). In fact, in Tubbergen (and also in Rossum-Weerselo) the Z1 Halite dictates the structural shape of the Z2 and Z3 carbonate reservoirs (figs. 2, 3). The Tubbergen Zechstein reservoirs are a fairly simple domal structure, intersected by a few faults. The Z2 and Z3 reservoirs are, in general, fairly conformal and separated by uniformly thick halite and anhydrite layers. All wells encountered Z3/4 Halites/Anhydrites on top of the Z3 Carbonate reservoir.

2.3 Rossum-Weerselo field

The Rossum-Weerselo field is located to the south of the Tubbergen Field. In geological terms, the Zechstein sequence and the lithostratigraphic sub-division in the Rossum Weerselo Field is very similar that in the Tubbergen Field (figs. 4, 5). The dome shape of the Rossum-Weerselo Zechstein structure is more elongated, with the main axis in a NW-SE orientation..

2.4 Tubbergen-Mander field

This field is located to the west of the Tubbergen Field, and separated from the latter by the Gronau Fault zone, a NW-SE trending fault zone which in part forms the south east boundary (figs. 6, 7). Like Rossum-Weerselo, the field is a NW-SE oriented domal structure between the above mentioned Gronau Fault in the NE and an faulted zone to the SW of the field. In contrast to the other two fields, Halites are virtually absent in the Tubbergen-Mander structure (apart from a Shale/Halite mixture on top of the Z3 Carbonate, fig. 9). Reason for the absence of halites in this field is most likely the more intense tectonic activity, causing the salts being “squeezed” out over geological time scales. The structure of the field is also points to a more complex tectonic history and has characteristics of a so called “pop-up” structure.

3. Lithostatic sub-division and reservoir characterization

As discussed, from a lithostratigraphic point of view the Tubbergen and Rossum-Weerselo fields are very similar whilst Tubbergen-Mander differs because of the almost complete absence of salts. Figures 8 and 10 detail the Z2 and Z3 cycles of the fields and describe a more general sub-division of the carbonate reservoirs and their adjacent layers. More detail is provided in selected core material.

From the base to top (Tubbergen and Rossum-Weerselo), there is first a section of Z1 Halite with variable thickness (giving the shape to the overlying Carbonate reservoirs). The end of the Z1 Cycle is marked by the development of the Z1 Roof Anhydrite, a regionally developed layer, at least some 30 m in thickness.

Above the Z1 Roof Anhydrite, the Zechstein 2 carbonate is deposited. This is the lower Zechstein reservoir and consists in general of carbonate (Dolomite) layers, some 4-5 m thick, interspersed by Anhydrite layers, of similar thickness. On top of the Zechstein 2 Carbonate reservoir, the regionally present Zechstein 2 Anhydrite is deposited, followed by the Zechstein 2 Halite. The Zechstein 2 Cycle, just as the Zechstein 1 Cycle, is completed with the development of a roof anhydrite, albeit that the Zechstein 2 roof Anhydrite is much thinner developed (2-5 m).

The deposition of the Grey Salt Clay (2-4 m) marks the onset of the Zechstein 3 Cycle. On top of this clay/salt layer, the Zechstein 3 Carbonate is deposited and forms the shallower Zechstein reservoir. The Zechstein 3 Carbonate is, in general, characterized by dolomitic layers (10-50 cm thick), interspersed by Anhydrites, ranging in thickness from centimetres to decimetres. The top of the Zechstein 3 Carbonate is marked by a laterally continuous and regionally present Anhydrite (Zechstein 3 Anhydrite) layer of 5 to15 m thickness. Above this Anhydrite follow salts and halites of the Zechstein 3-4 Cycle.

The carbonate reservoirs of the Tubbergen-Mander field are very similar to those of Tubbergen and Rossum-Weerselo, albeit that the halite layers (apart from the Zechstein 3-4 Halite) are missing. In all cases however, also here the carbonate reservoirs are bounded to the base and top by laterally continuous anhydrite layers.

In both the Z2 and Z3 Carbonate reservoirs, the main permeability is provided by the presence of open fractures (figs. 10-12). Inspection of the available core material clearly shows that the fractures occur in the clean carbonates (Dolomites) and are absent in the anhydrite layers. Also fractures in the carbonates are seen to abut against the anhydrite layers (see Figures 11 and 12). According to core plug measurements, the porosity of the matrix is around 3% (range 1-6 %) and the permeability is around 0.1 mD. Hence, although the matrix is capable to store fluids, the fluid flow is largely, if not exclusively, governed by open, highly permeable fractures. Based on the behaviour of the reservoir during the gas production phase, it is concluded that these fractures and fracture networks can have a large horizontal extent. The vertical extent however is very limited and governed by the intercalation of anhydrite layers in the reservoirs.

In thicker carbonate banks, fractures show often a vertical “en-echelon” geometry, resulting in finite vertical fracture extension, even in the absence of lithology changes. Observed fracture heights are generally not exceeding approximately 30 cm.

As the thickness of the individual carbonate layers in the Zechstein 2 reservoir is some 4-6 m, the vertical fracture extent is similar; each carbonate layers can be seen as an individual flow unit, separated by anhydrite “seals” of similar thickness. Given the different Carbonate/Anhydrite distribution in the Z3 Carbonate, the average fracture height is expected to be in the order of 30 cm. In view of the limited thickness of the anhydritic layers in the Z3 Carbonate (compared to the Z2 carbonate), the lateral extent of these anhydritic layers can be expected to be more limited (in the order of tens of meters, for an anhydrite of, say 10 cm), which means that the anhydrite layers are expected to constitute baffles for vertical flow rather than seals and that a certain degree of vertical fracture communication might still be possible in the Z3 reservoirs..

4. Permeability distribution in the Z2 and Z3 Carbonates

As the matrix properties of the Z2 and Z3 carbonates have been measured to be low (average matrix permeability from core plug measurements is around 0.1 mD) and the bulk fluid-flow is expected to be governed by the fracture distribution, the horizontal and vertical fracture distribution are expected to have by far the most influence of the K_v/K_h ratios on a reservoir scale. Hence, it will not suffice to define K and K_v/K_h from core plug measurements as these represent the wrong scale. A different approach has to be chosen in order to define reasonable K_v/K_h ratio's for fluid flow modelling.

The chosen approximation is based on well test derived permeabilities. Such a well test derived permeability is in the order of 1D (1000 mD) for a well like ROW-5, a well which is expected to be situated in a more densely fractured area (fractures associated with normal faulting). Another test derived permeability, is from the well ROW-9 and is estimated to be in the order of 10-20 mD only. This is in line with the observation that this well is relatively far away from seismic mapped faults and hence should be in an area relatively free of fault associated fractures.

The well test permeability is an approximation for the horizontal permeability. As discussed before, the vertical extent of the fractures is limited and governed by the Anhydrite distribution in the Carbonates. In order to still provide a value for vertical permeability, even when it can be expected that there is no vertical fracture connection, the average matrix permeability of 0.1 mD is suggested. Hence K_v/K_h, on a reservoir scale, in un-faulted reservoir is estimated to range from 0.0001-0.005 (i.e K_v/K_h, 10^{-4} to $5*10^{-3}$)

Near faults, where Halite can be juxtaposed against Carbonate layers, the fracture density in the fault damage zones is expected to be higher. Core data however show that due to salt creep these fractures are preferentially sealed and filled with salt (Figure 15). This means that both the horizontal and vertical effective permeability in the fault damage zones is likely even lower than in the un-faulted reservoir sections.

5. Faulting and juxtaposition

In order to assess the degree of cross-fault juxtaposition between the injection horizons and halite sections, vertical distances between the different layers in the Zechstein of the Tubbergen and Rossum-Weerselo Fields were measured. As Tubbergen-Mander is virtually free of salt, this analysis is nor relevant for this field.

The general well-log correlation panels (fig. 9) show slight thickness variations between Tubbergen and Rossum-Weerselo, meaning that similar fault offsets can result in (slight) juxtaposition differences in the two fields. When assessing juxtapositions, the thicknesses derived from stratigraphic tops and bases are not representative. As discussed, there are thicker, intra-reservoir Anhydrite layers, especially in the Z2 Carbonate reservoir that do not contribute to lateral flow. Hence the analysis needs to focus on the juxtaposition of clean carbonate layers (the actual flow units) against halite.

Figure 16 summarises the vertical separation between tops and bases of the flow units in the Z2 and Z3 carbonate reservoirs and also the distances between the flow units and halite sections. Using these separations, “juxtaposition diagrams” can be constructed for the Tubbergen and Rossum Weerselo fields, as shown in figures 17 & 18. These diagrams show in the bottom part the layers with which the Z2 carbonate is juxtaposed, considering the vertical offset as shown on the X-axis. In the top part it shows the relationship for the Z3 carbonate and Z3 halite scenario.

Using these diagrams, together with the fault offset analysis (example shown in figure 20), different (and for the fields realistic) modelling scenarios were developed. These scenarios were used as input for a reservoir simulation study (Ref 5). To arrive at a realistic spread of modelling scenarios not only the juxtaposition across faults, but also the distance between injection points and faults is required. The least distances between wells and seismically mapped faults were measured and summarized as shown in figure 19.

6. Conclusions

- Fractures are the dominant fluid conduits in the Zechstein 2 and -3 Carbonates of the Twente Gas Fields. Matrix porosity and permeability are low to very low.

- Fractures occur in the more brittle Carbonate (dolomite) layers, and abut against Anhydrites or Carbonates with increased Anhydrite content.

- The Zechstein 2 Carbonate is composed of dolomitic banks, inter-layered with anhydritic banks (both approx. 4-6 m in thickness), hence, the fractured zones within the Zechstein 2 Carbonates are not more than 4-6 m high, with sealing layers of similar thickness (un-fractured Anhydrites) above and below.

- The Zechstein 3 Carbonate is composed of dolomitic layers (10-50 cm in thickness) inter-layered by centimetre to decimetre thick anhydritic layers. Hence the individual fracture heights are significantly smaller than in the Zechstein 2 Carbonates.

- In thicker carbonate banks, fractures show often a vertical “en-echelon” geometry, resulting in finite vertical fracture extension, even in the absence of lithology changes. Observed fracture heights are generally not exceeding approximately 30 cm.

- From well logs and regional correlation, it can be established that both the Zechstein 2 and -3 Carbonates are stratigraphically (and hence physically) separated from Halites by regionally/basin wide developed Anhydrite layers.

- Given the good correlation of fractured zones in the Zechstein Carbonates across and within the Twente gas fields, rules can be set-up to predict juxtaposition (Carbonate/Halite, Carbonate/Anhydrite, Carbonate/Carbonate), depending of fault throws. Realistic modelling scenarios have been developed, using these rules.

- Based on well test data and reservoir matrix properties derived from core/plug data, the K_v/K_h, on a reservoir scale in un-faulted reservoir is estimated to range from 10^{-4} to $5*10^{-3}$

- Near faults, where Halite is juxtaposed against Carbonate layers, an overall further reduction in horizontal and vertical permeability is expected. This is due to salt creep which causes fractures near the fault to be filled with salt.

7. References

1 Geology of the Netherlands, Eds. Th. Wong, D.A.J. Batjes, J. De Jager, 2007

2 Petroleum Geological Atlas of the Southern Permian Basin, Eds. H. Doornenbal, A. Stevenson. 2010

3 Stratigraphical Nomenclature of the Netherlands, Mededelingen Rijks Geologische Dienst. Compiled by H.A. Adrichem Bogaert, W.F.P. Kouwe. 1993

4 Zechstein-Anhydrite, Fazies und Genese, G.Richter-Bernburg, Geologisches Jahrbuch 85, 1985

5. Halite dissolution modelling of water injection into Carbonate gas reservoirs with a Halite seal, Report: EP201310203080

8. Figures

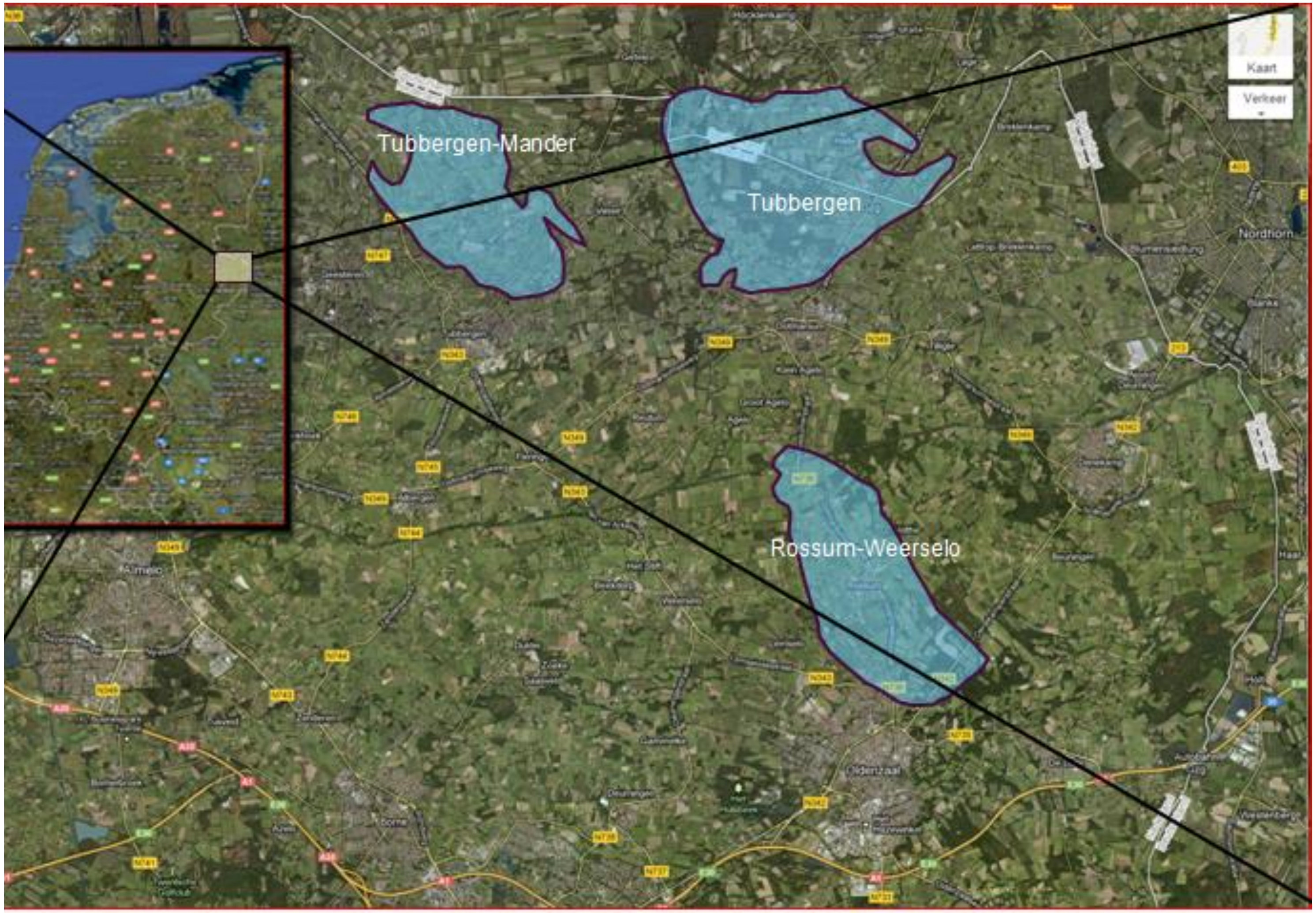


Figure 1, Geographical overview of the Twente Gas Fields

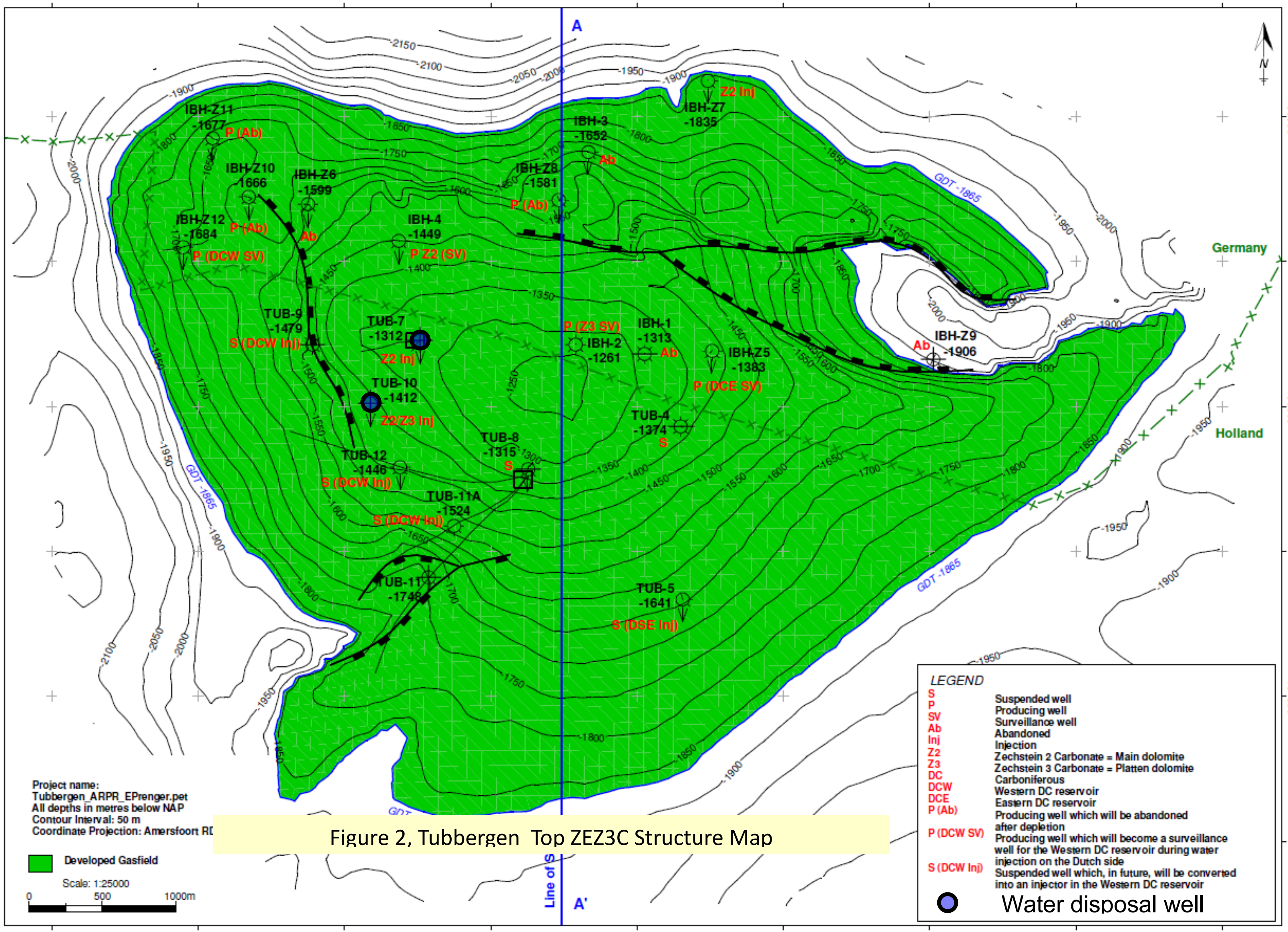


Figure 2, Tubbergen Top ZEZ3C Structure Map

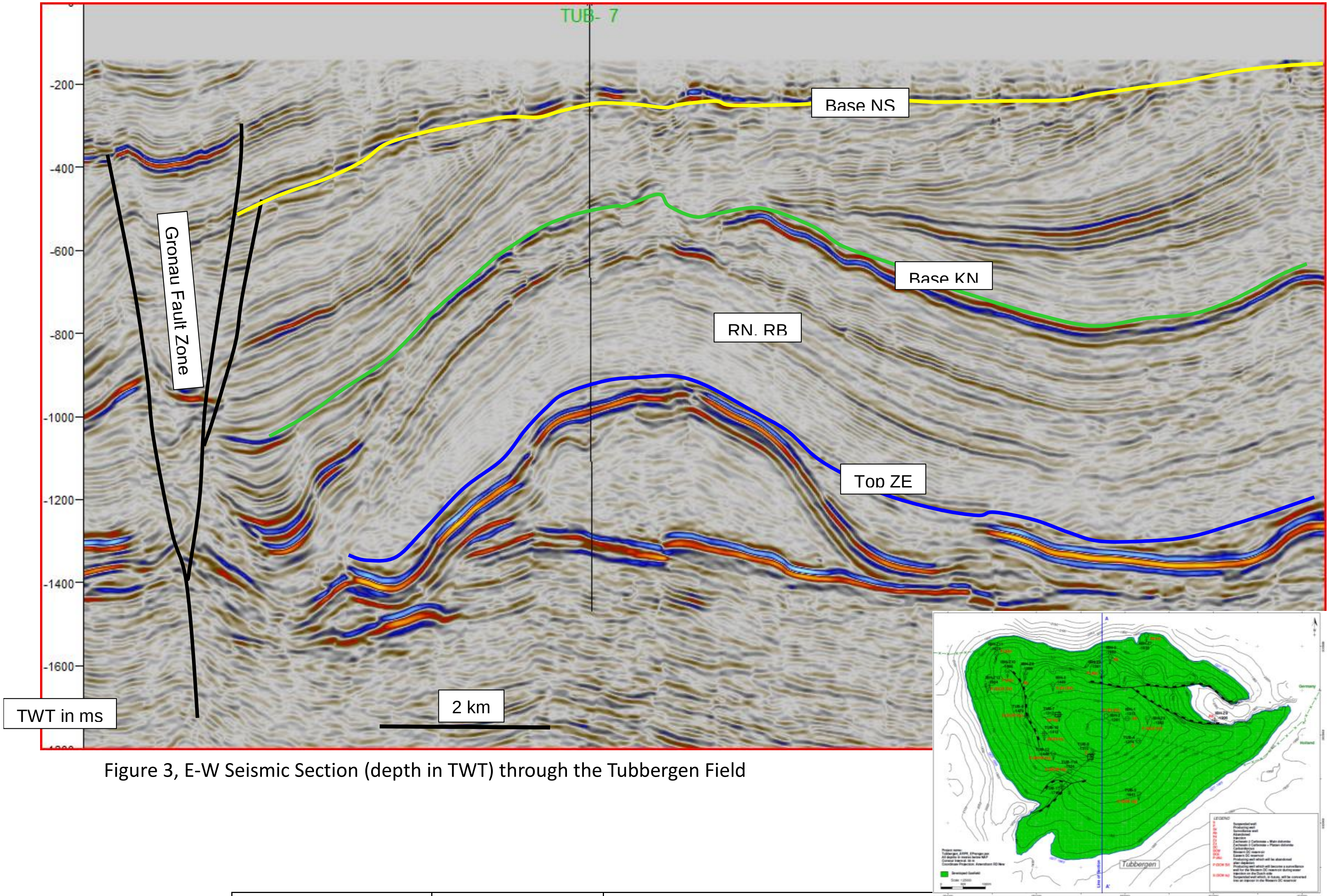


Figure 3, E-W Seismic Section (depth in TWT) through the Tubbergen Field

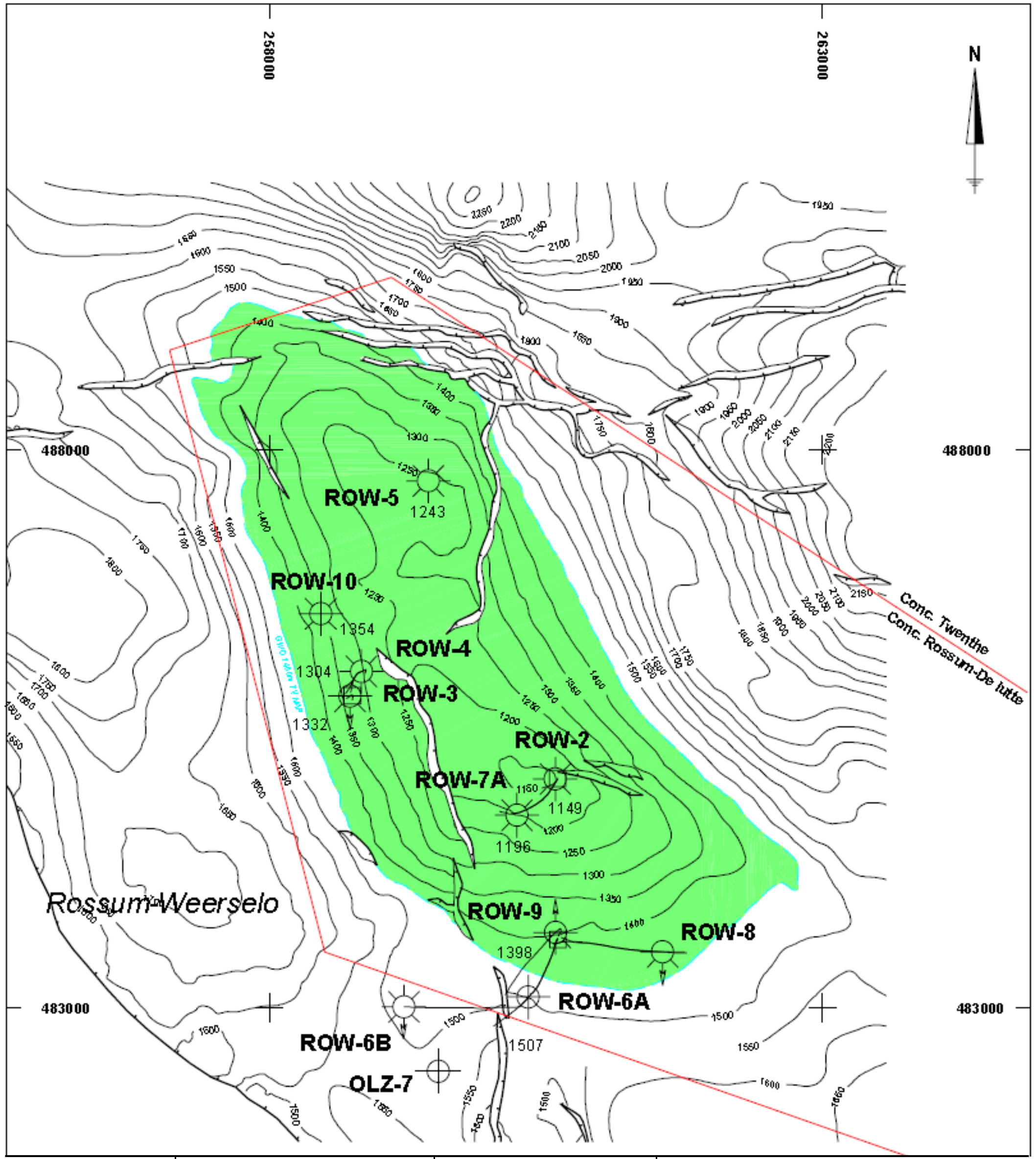


Figure 4, Rossum Weerselo

● Water disposal well

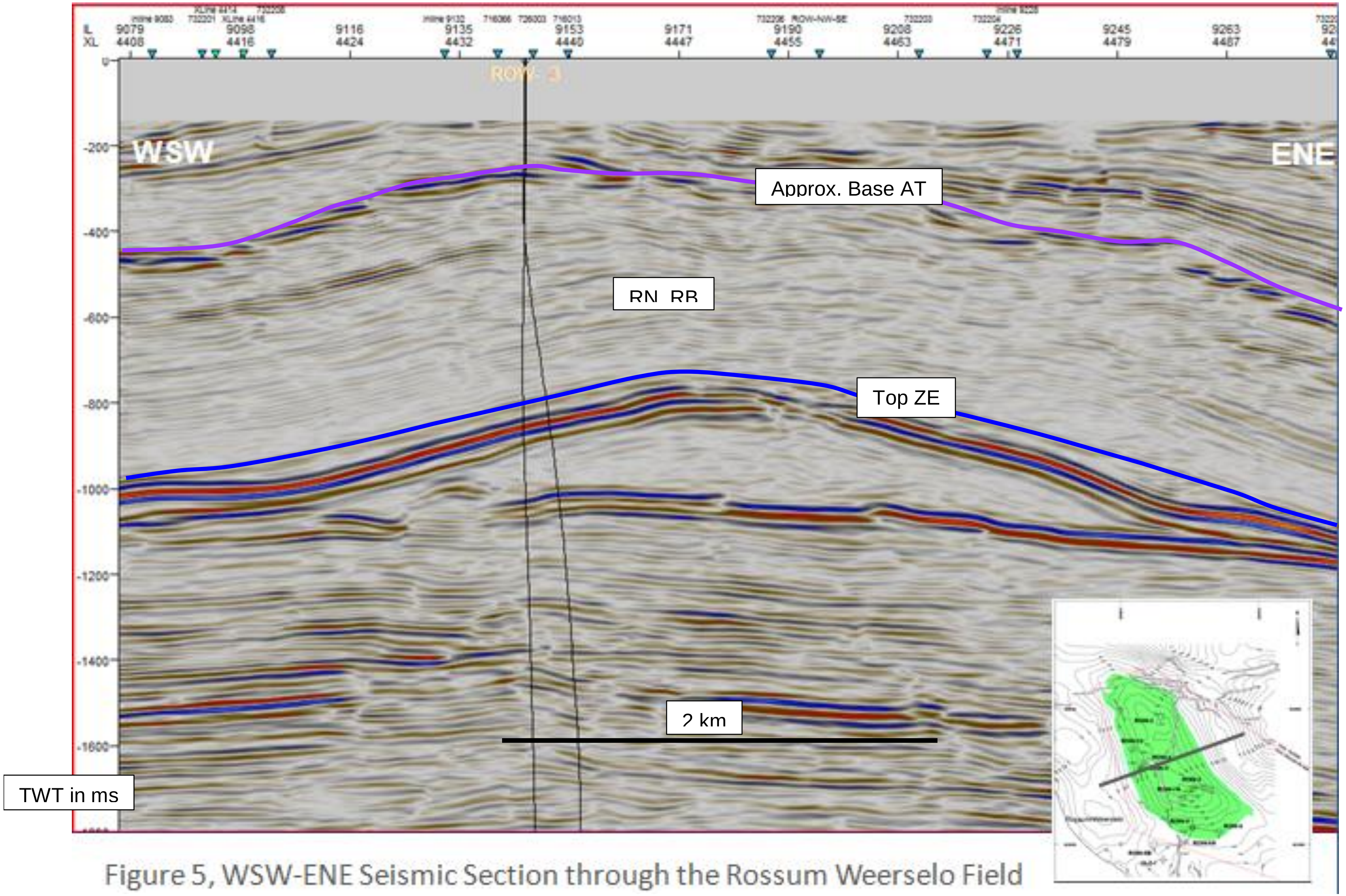


Figure 5, WSW-ENE Seismic Section through the Rossum Weerselo Field

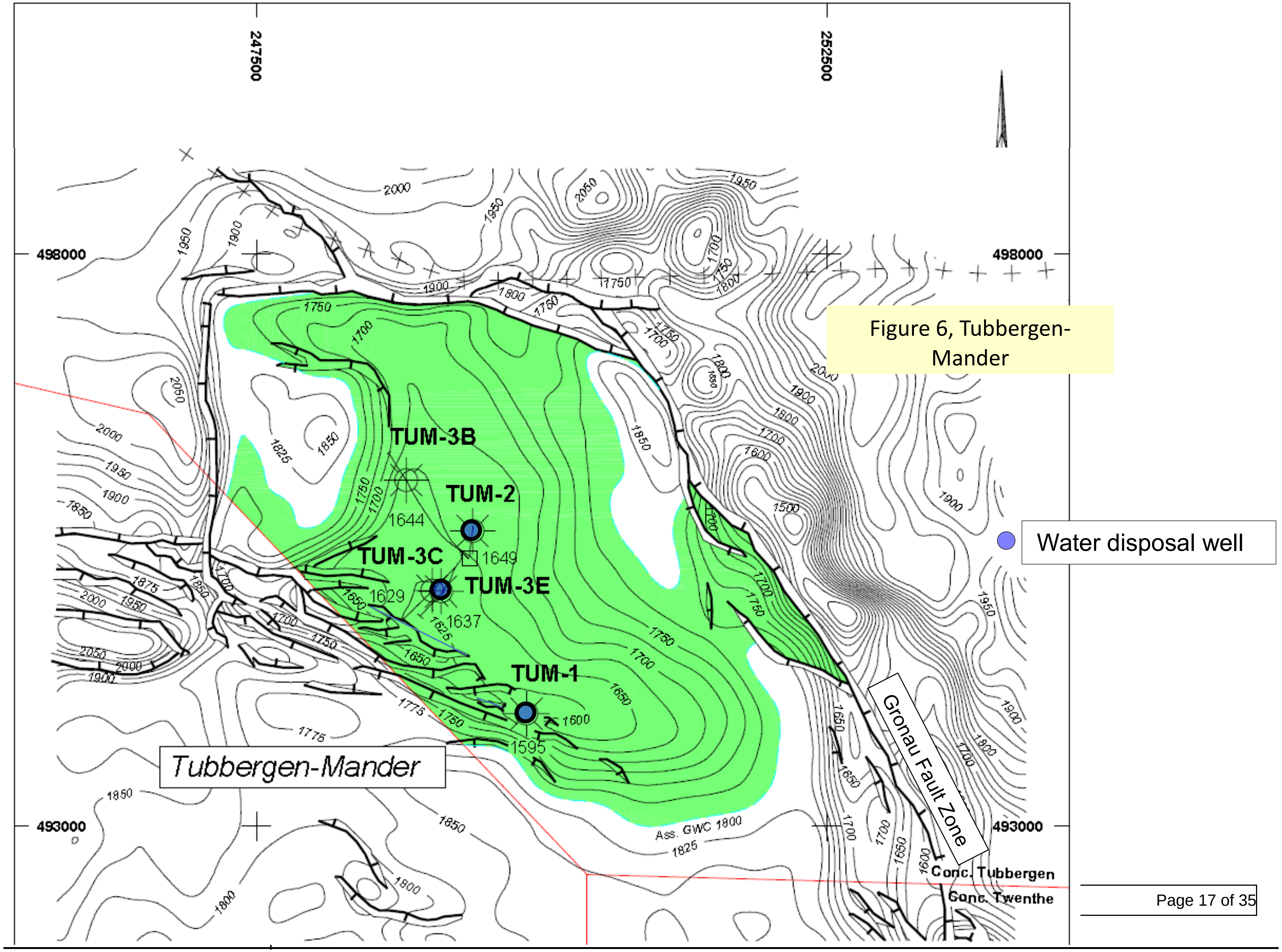


Figure 6, Tubbergen-Mander

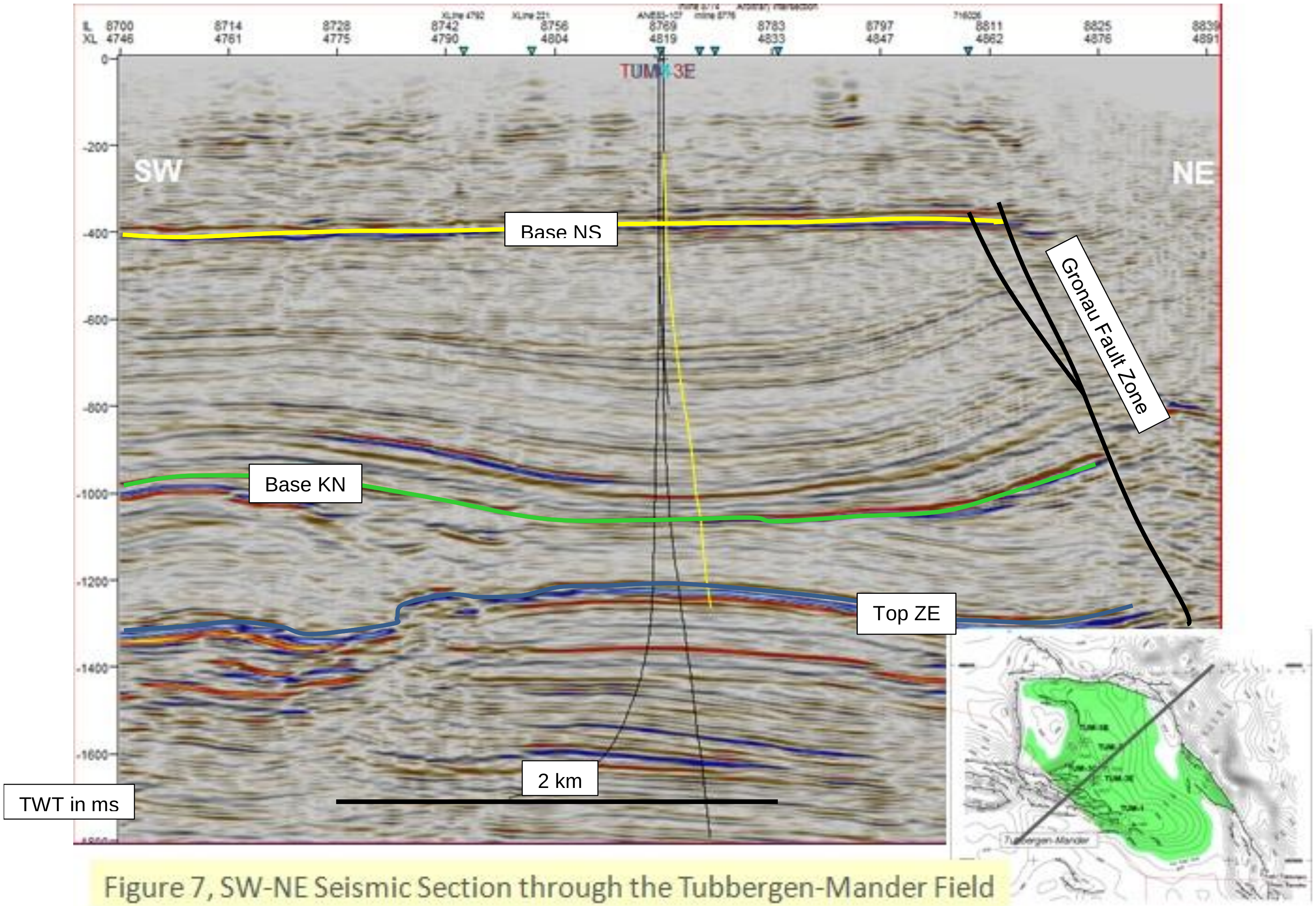
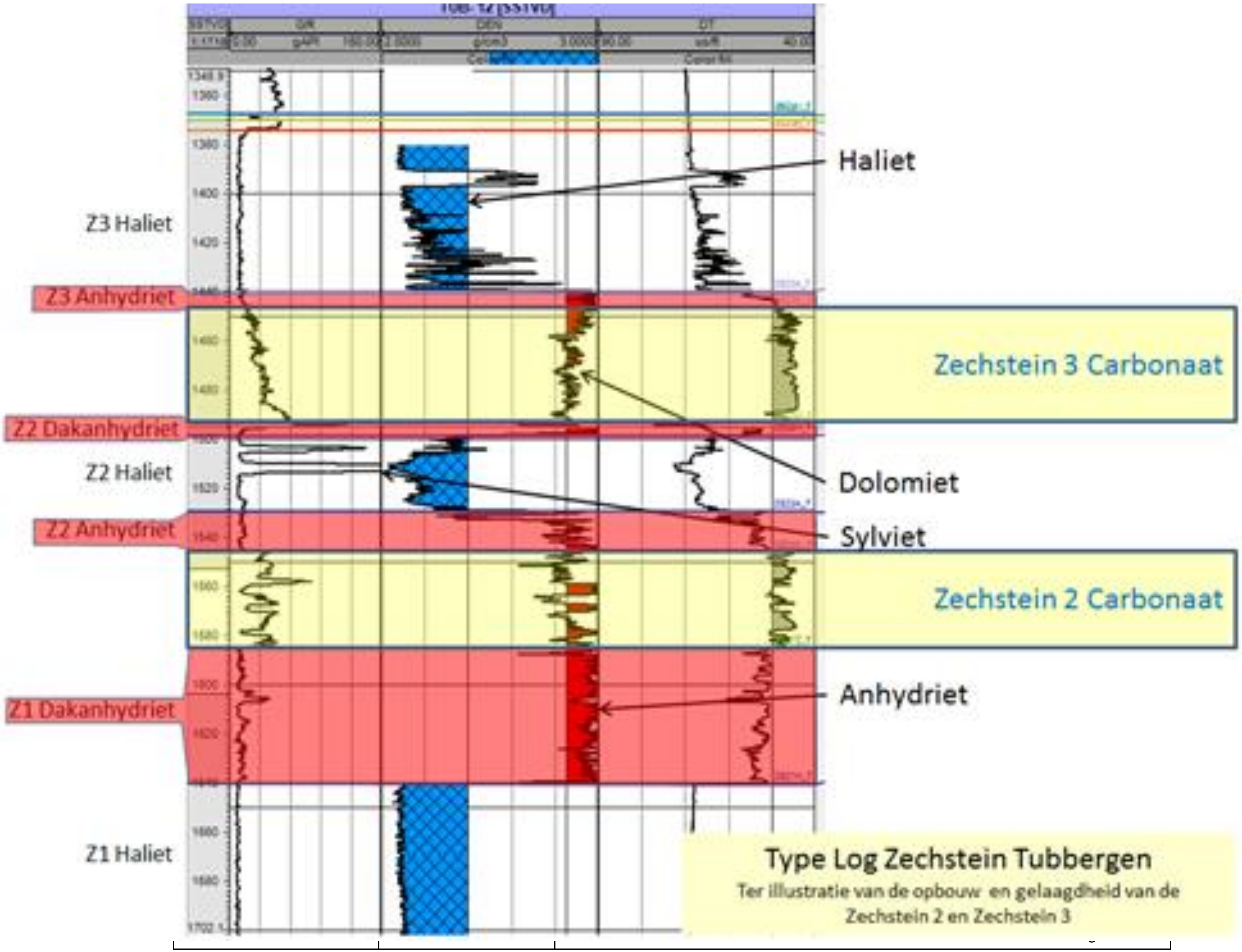


Figure 7, SW-NE Seismic Section through the Tubbergen-Mander Field



Type Log Zechstein Tubbergen

Ter illustratie van de opbouw en gelaagdheid van de Zechstein 2 en Zechstein 3

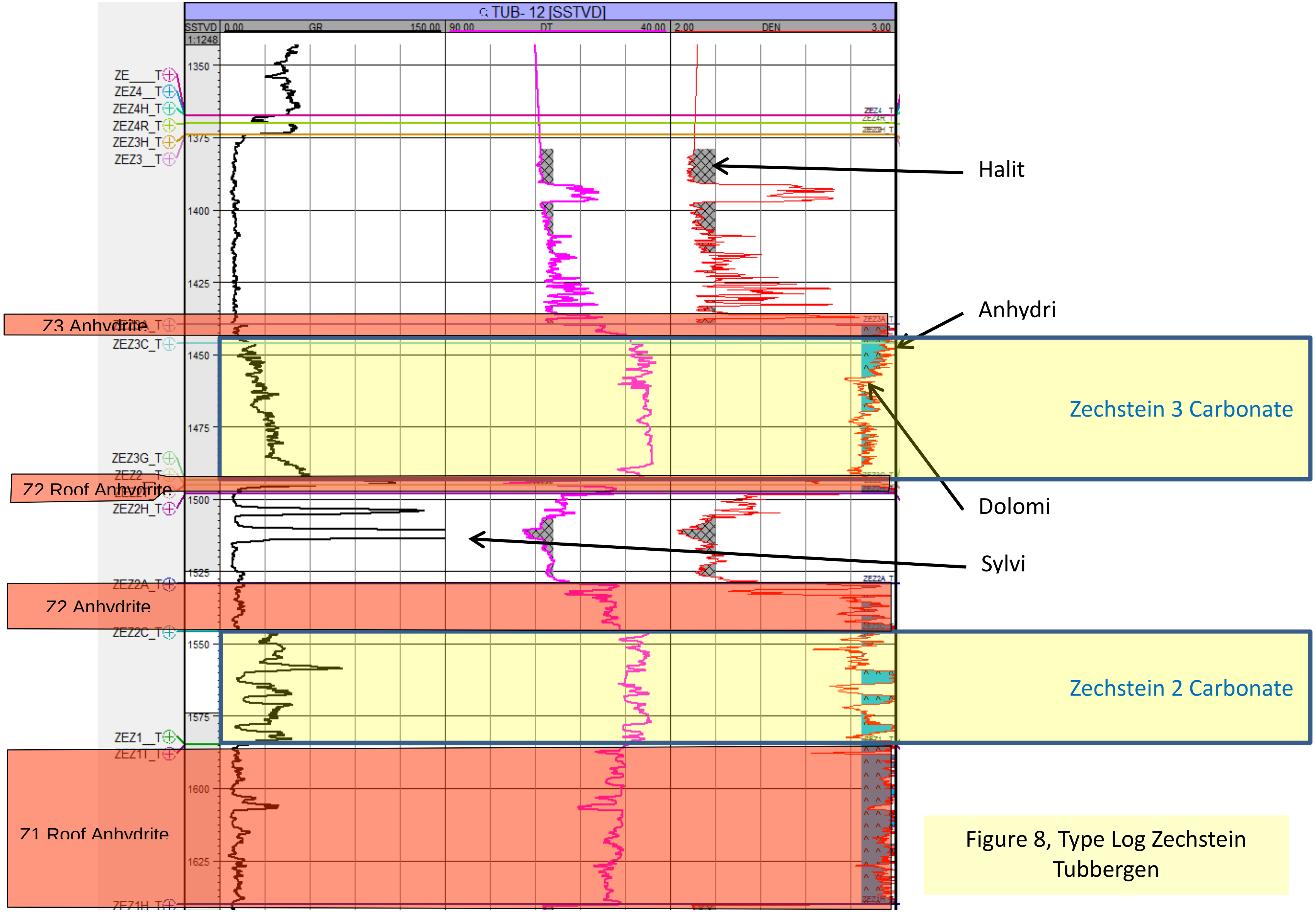


Figure 8, Type Log Zechstein Tubbergen

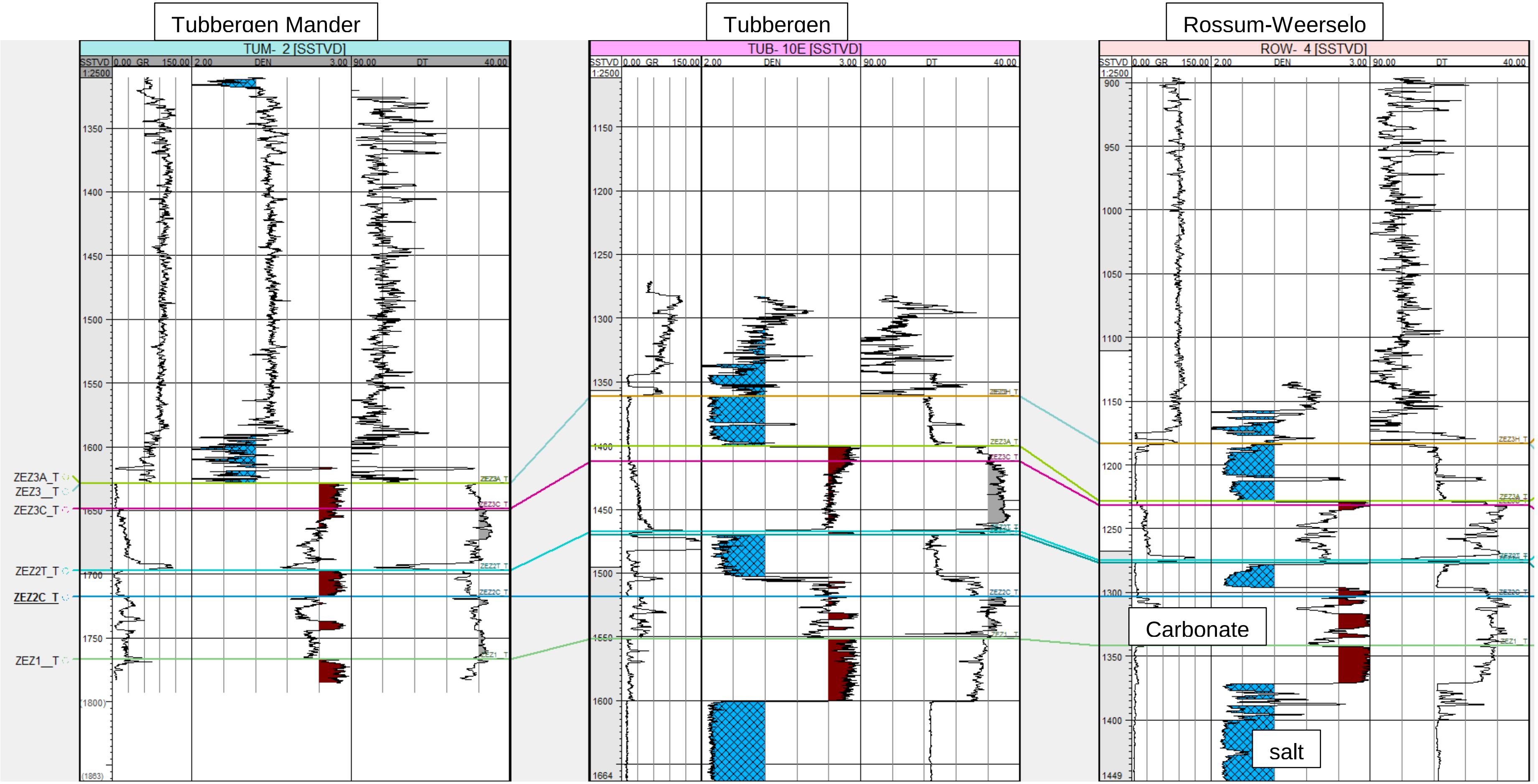
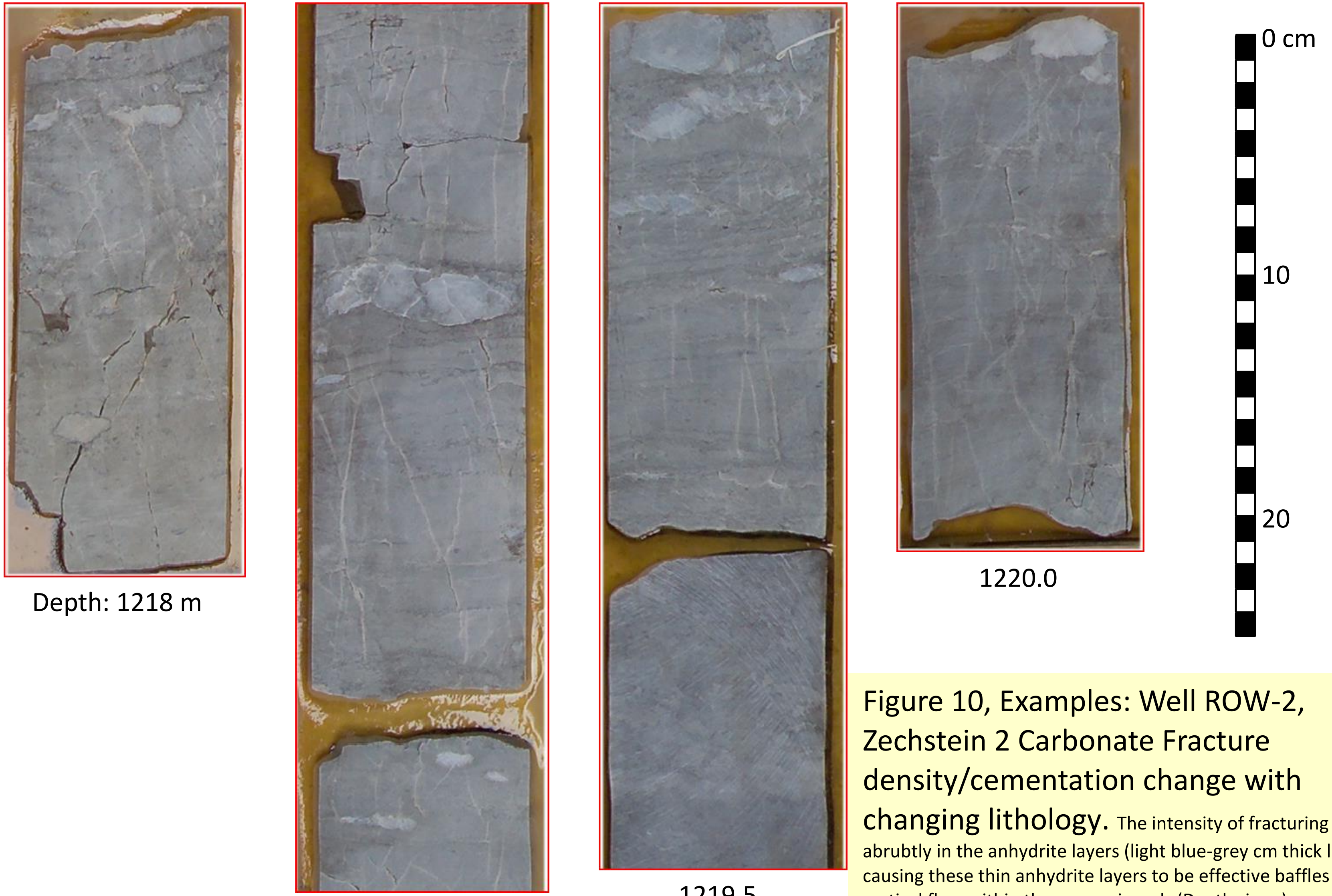


Figure 9, Thickness relationships of Carbonates and Salts between Tubbergen-Mander, Tubbergen and Rossum-Weerselo



Depth: 1218 m

1219.0

1219.5

1220.0

Figure 10, Examples: Well ROW-2, Zechstein 2 Carbonate Fracture density/cementation change with changing lithology. The intensity of fracturing changes abruptly in the anhydrite layers (light blue-grey cm thick layers), causing these thin anhydrite layers to be effective baffles to vertical flow within the reservoir rock (Depths in m)

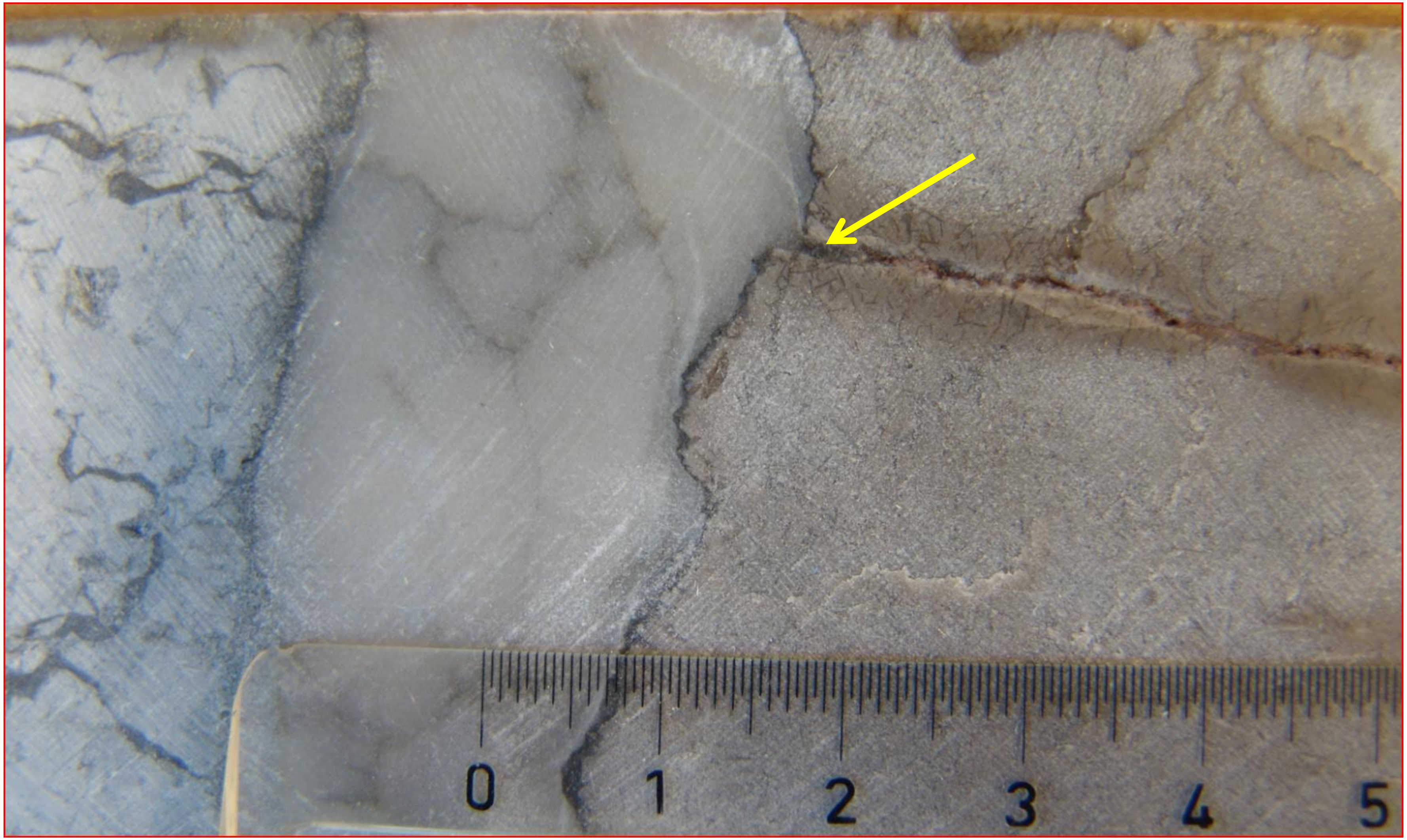


Figure 11, Rossum Weerselo-5 1195.8 ZEZ3C. Partly open fracture (+/- 1mm wide) in Dolomite abutting at lithology change to Anhydrite (arrow).

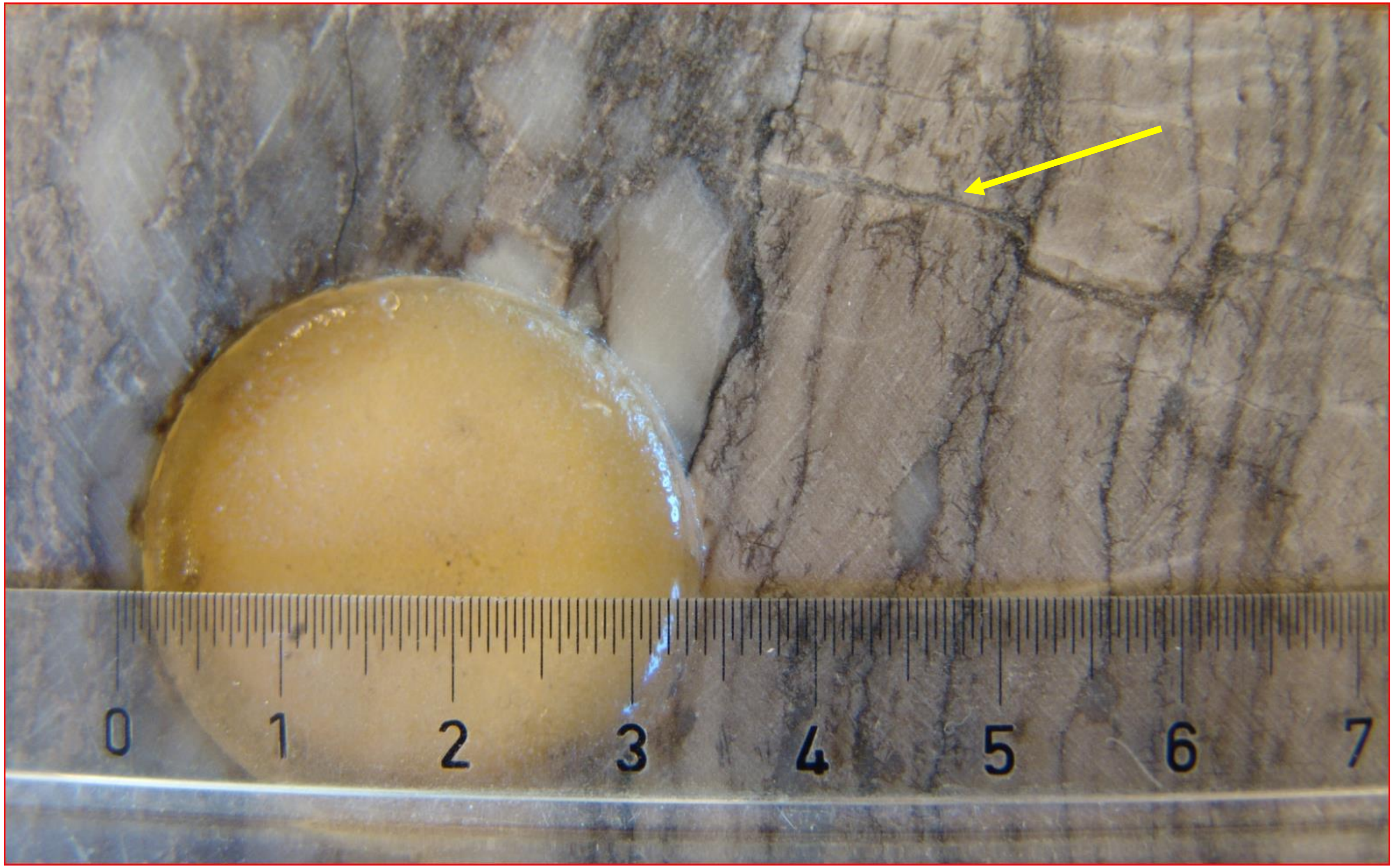


Figure 12, Rossum Weerselo-5 1194.9 ZEZ3C. Cemented fracture (+/- 0.8 mm wide) in Dolomite abutting at lithology change to Anhydrite (arrow). Plug: 0.6% Porosity, Permeability not measurable.

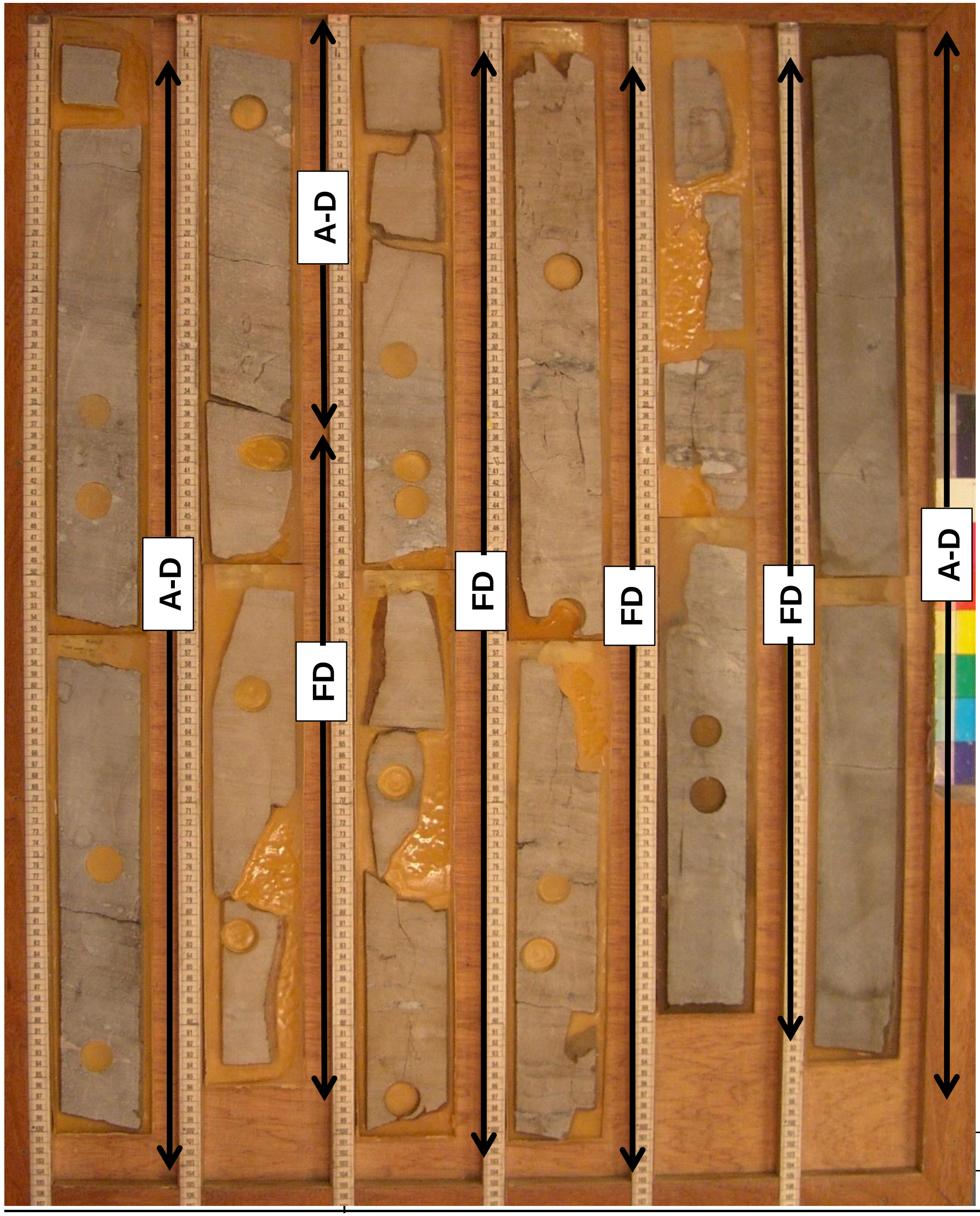
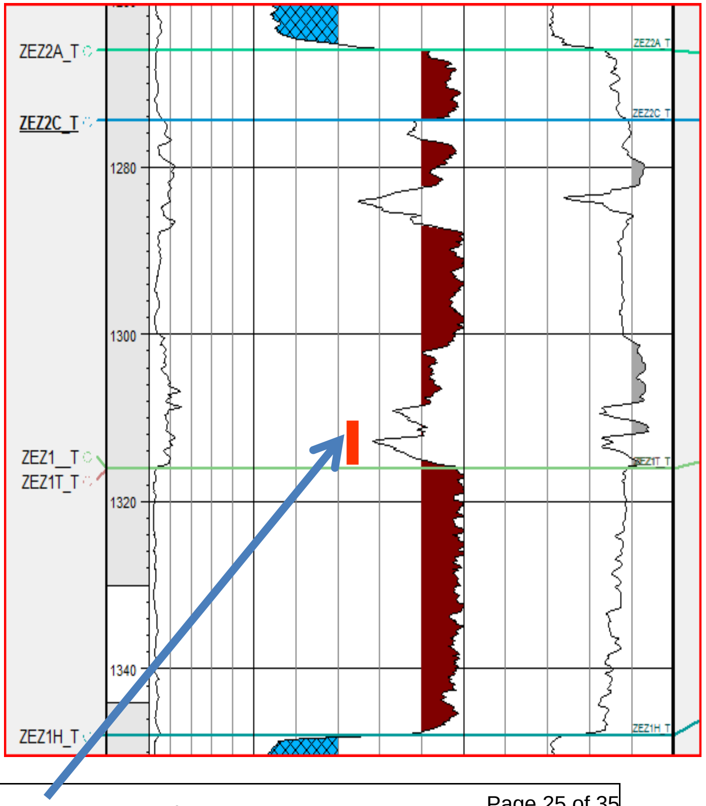


Figure 13, ROW-5 ZEZ2C
Interval 1309-1315m

Fractured Dolomitic layer (+/- 4m, indicated as “FD”) in between unfractured/cemented anhydritic dolomite sections (indicated as “A-D”)



Approx. shown

Figure 14, ROW-2 ZEZ3C
Interval 1142.9-1148.7m

Laminated Dolomite, interlayered by thin (nodular) Anhydrite, causing vertical fracture abutting.

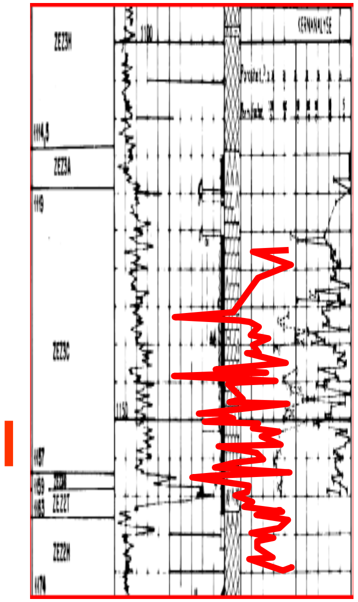
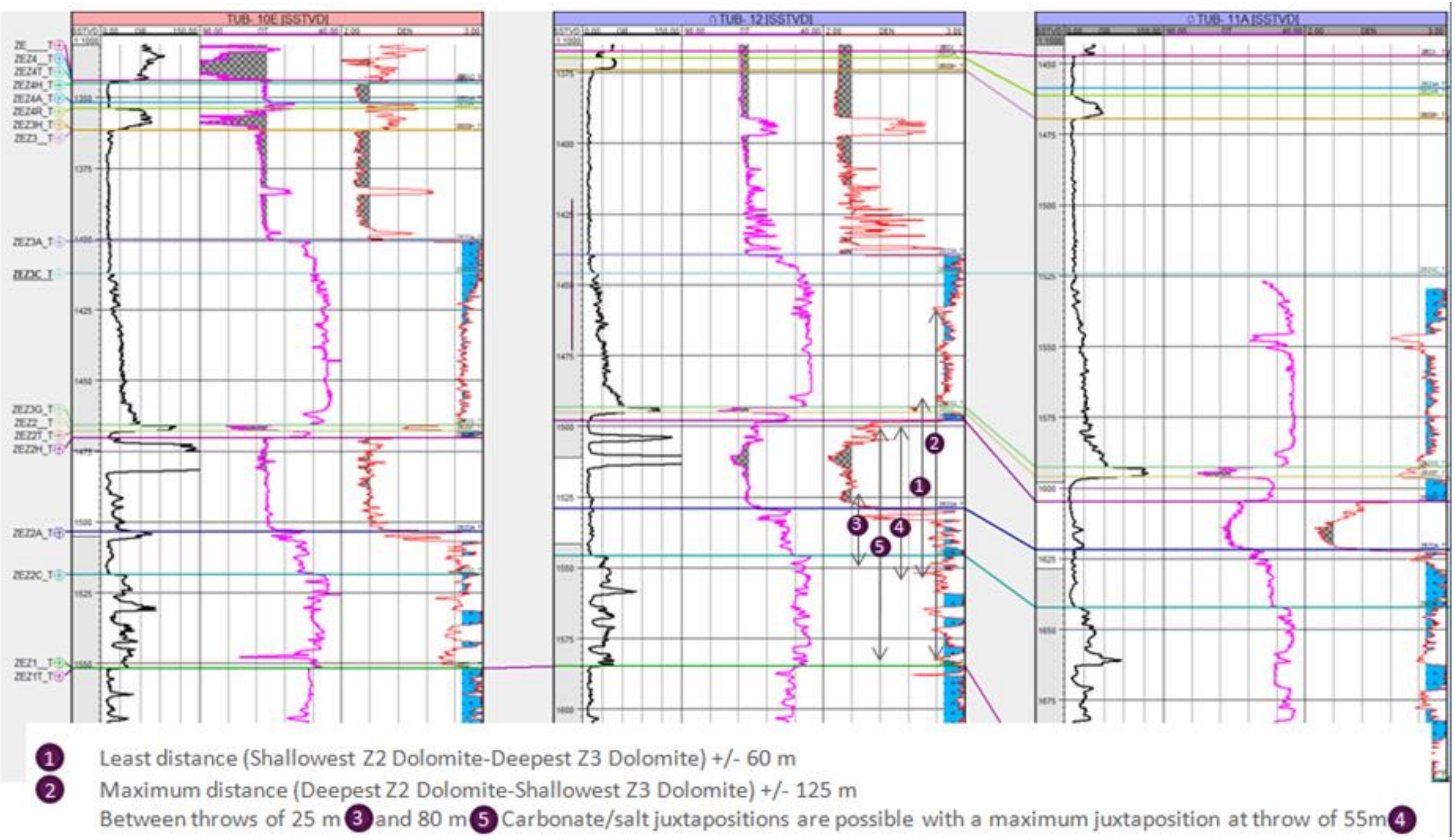


Figure 15. Tubbergen-7, 1490.8m AH, ZEZ2A. Halite filled fracture (arrow) in Anhydrite.

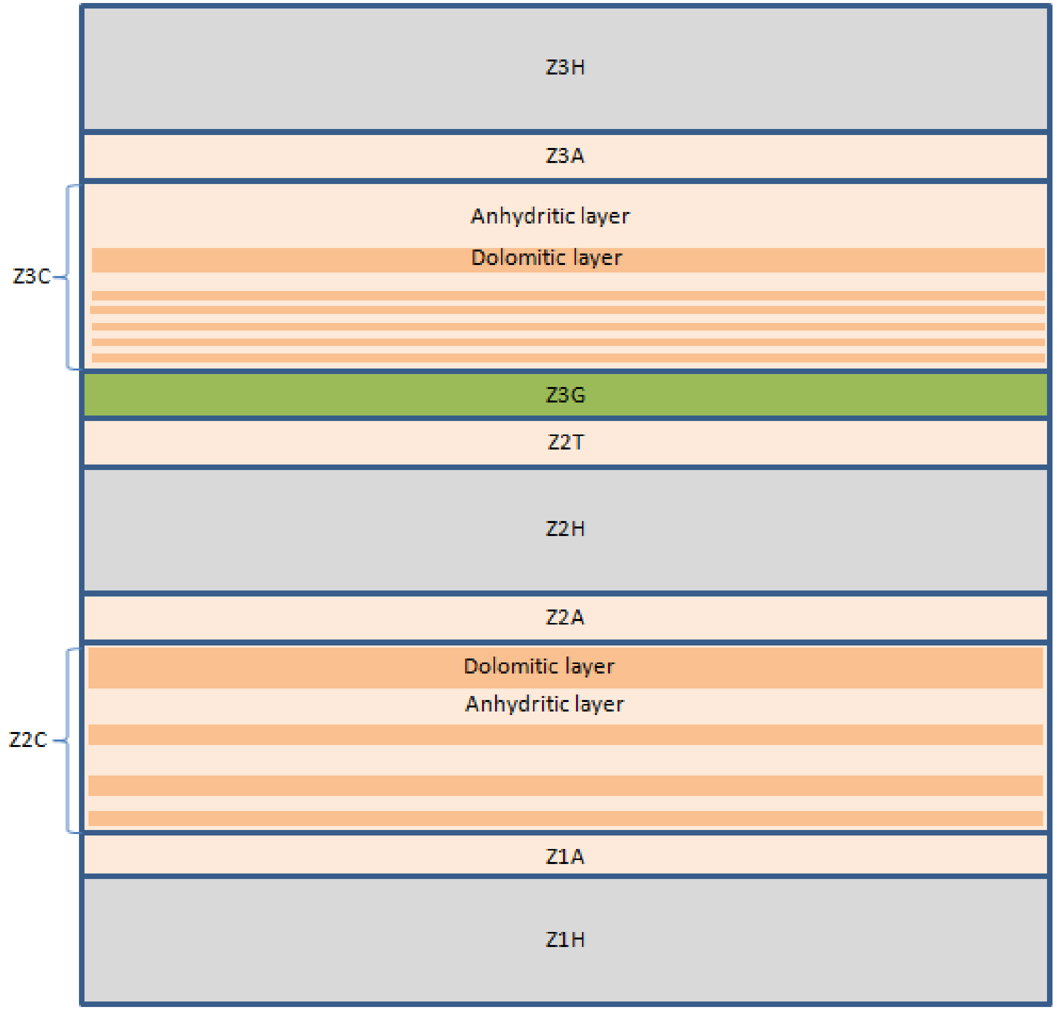


① Least distance (Shallowest Z2 Dolomite-Deepest Z3 Dolomite) +/- 60 m

② Maximum distance (Deepest Z2 Dolomite-Shallowest Z3 Dolomite) +/- 125 m

Between throws of 25 m ③ and 80 m ⑤ Carbonate/salt juxtapositions are possible with a maximum juxtaposition at throw of 55m ④

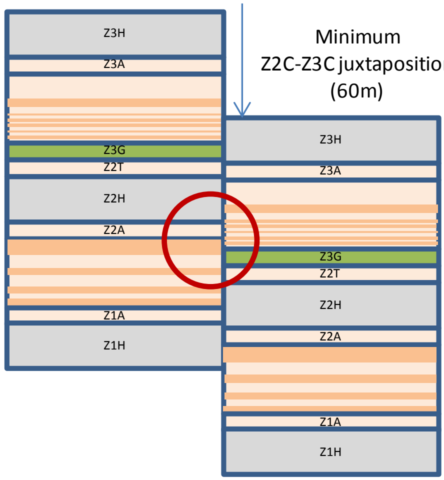
Figure 16, Geometrical aspects of the Zechstein 2 & 3 Cycle (example from Tubbergen)



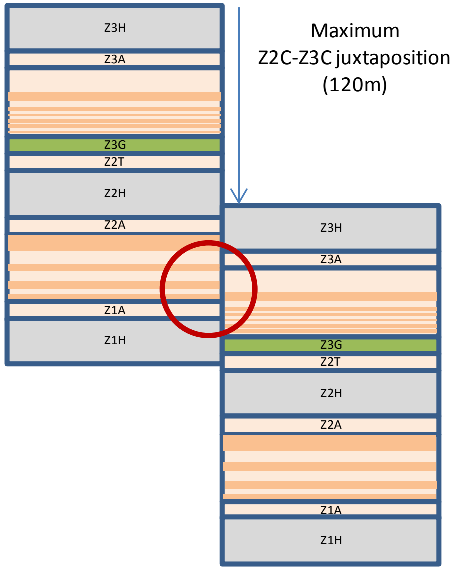
Z3H = Z3 Halite
Z3A = Z3 Anhydrite
Z3C = Z3 Carbonate
Z3G = Grey Salte clay
Z2T = Z2 roof anhydrite
Z2H = Z2 Halite
Z2A = Z2 Anhydrite
Z2C = Z2 Carbonate
Z1A = Z1 Anhydrite
Z1H = Z1 Halite

Figure 17, Schematic representation of TUB12 geology

Z2C-Z3C juxtaposition

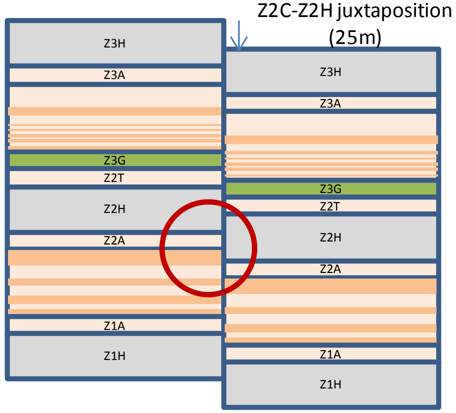


Minimum
Z2C-Z3C juxtaposition
(60m)

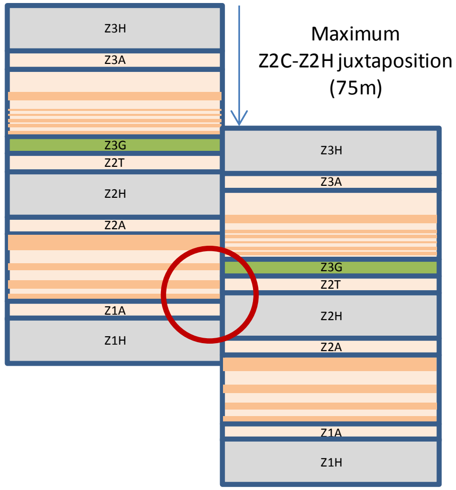


Maximum
Z2C-Z3C juxtaposition
(120m)

Z2C-Z2H juxtaposition

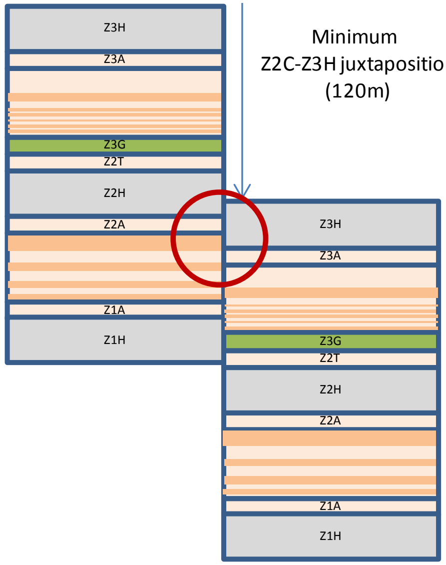


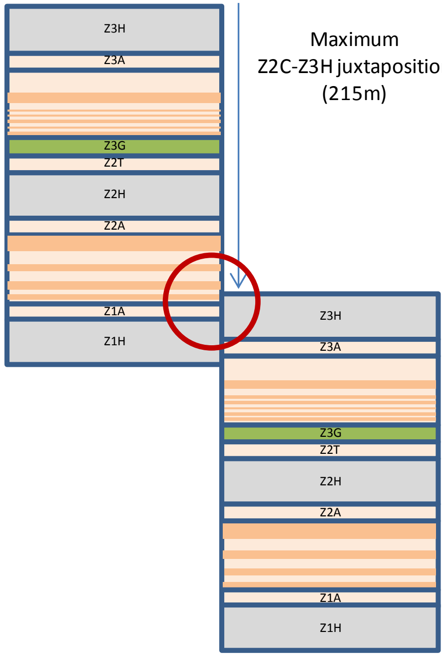
Minimum
Z2C-Z2H juxtaposition
(25m)



Maximum
Z2C-Z2H juxtaposition
(75m)

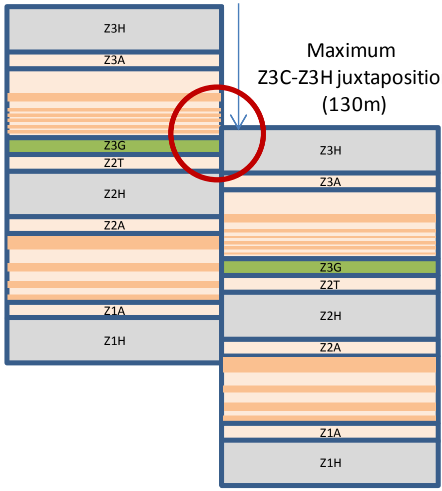
Z2C-Z3H juxtaposition

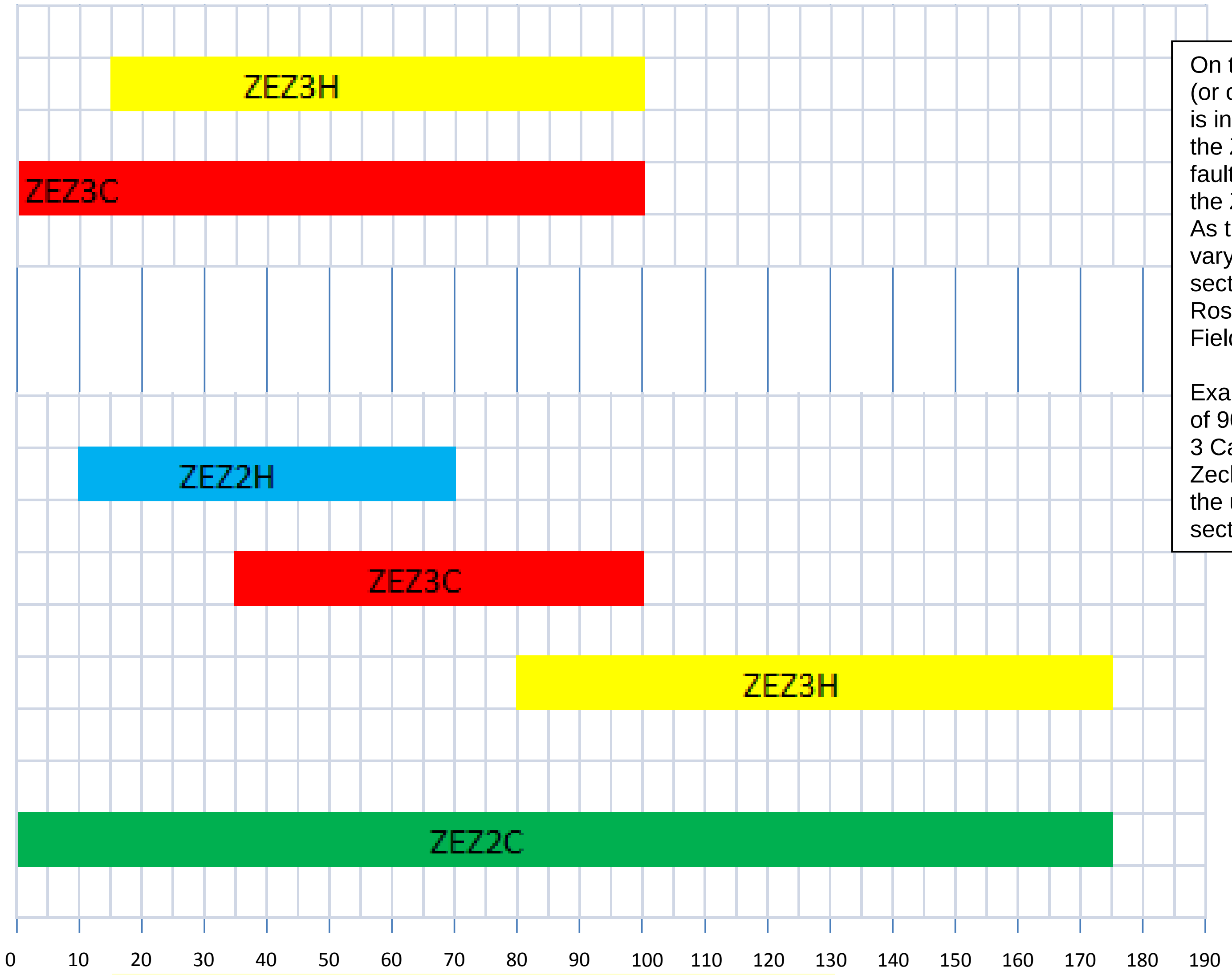

Minimum
Z2C-Z3H juxtaposition
(120m)


Maximum
Z2C-Z3H juxtaposition
(215m)

Z3C-Z3H juxtaposition


Minimum
Z3C-Z3H juxtaposition
(30m)


Maximum
Z3C-Z3H juxtaposition
(130m)



On the X-axis, a range of possible fault throws (or offsets) is shown. On the upper diagram, it is indicated which layers are juxtaposed against the Zechstein 3 Carbonate at the respective fault throw. On the lower diagram the same for the Zechstein 2 Carbonate.
As the thicknesses of the Zechstein layers may vary from field to field (especially the salt sections), a separate diagram was made for the Rossum-Weerselo Field and for the Tubbergen Field (Figure 18)

Example (on low diagram): for a fault with throw of 90m, the Zechstein 3 Halite or the Zechstein 3 Carbonate can be juxtaposed against the Zechstein 2 Carbonate. The overlap indicates the uncertainty as the thicknesses of the Halite sections vary in view of salt plasticity.

Figure 17, Juxtaposition diagram for ZEZ2C/3C in Rossum-Weerselo

For explanation, see Figure 17

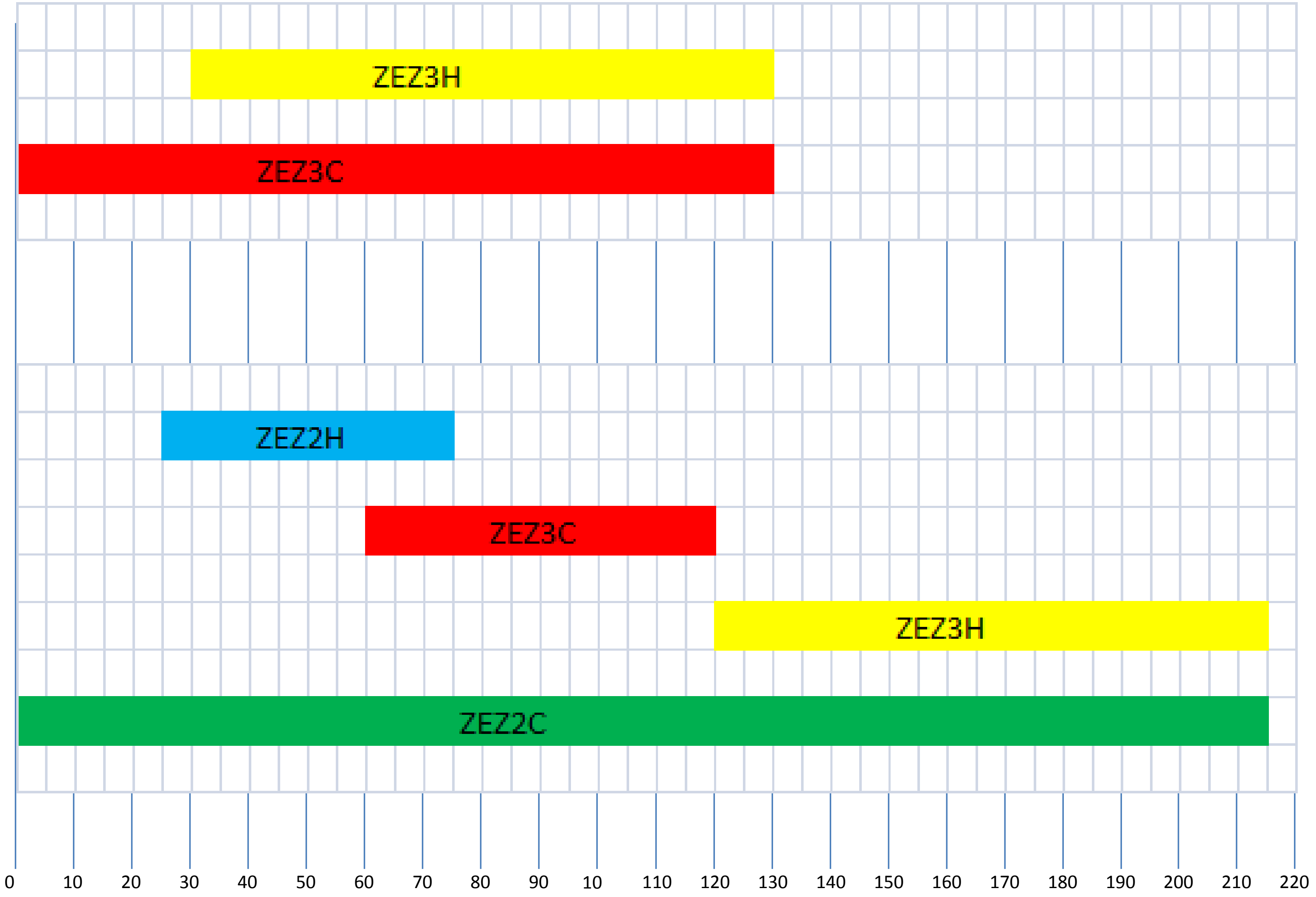


Figure 18, Juxtaposition diagram for ZEZ2C/3C in Tubbergen

Well	Distance to Fault	Azimuth	Azimuth Fault Strike	Fault Length (m)	Max Fault Offset (m)	Remarks
ROW-2	< 100 m	15°	100°	765	15	Shortest distance is to fault tip. Maximum throw of this fault is 15 m
ROW-4	230 m	45°	330°	2200	20	Shortest distance is to fault tip. Maximum throw of this fault is 15-20 m
ROW-5	600 m	90°	0-10°	2100	25	This is distance to mapped fault. Very minor fault visible on seismic, next to the well
ROW-5	50m	180°	70-110°?	50-75	5	This fault is only clearly visible on one line, hence orientation and length are approximate
ROW-7	500 m	240°	330°	2200	20	Same fault as ROW-4
ROW-9	750 m	260°	330°	780	40	Maximum throw of fault is 30 -40 m
TUB-7	700 m	270°	330°	2000	80	Fault has 80 m throw at TUB-7 position
TUB-10	150 m	270°	330°	2000	80	Fault has 25 m throw at TUB-10 position, same fault as in TUB-7
TUM-1	100 m	300°	300°	250	20	Well in en-echelon fault system. Quoted distance is to a fault tip. Max fault throw appears to be some20 m
TUM-2	1000 m	225°	300°	950	20	Well in a "quiet" area, core suggest minor fractures/low fracture frequency. Same fault as for TUM-3E
TUM-3E	200 m	225°	300°	950	20	Well expected to be perpendicular to expected associated fractures to en-echelon fault

1

2

3

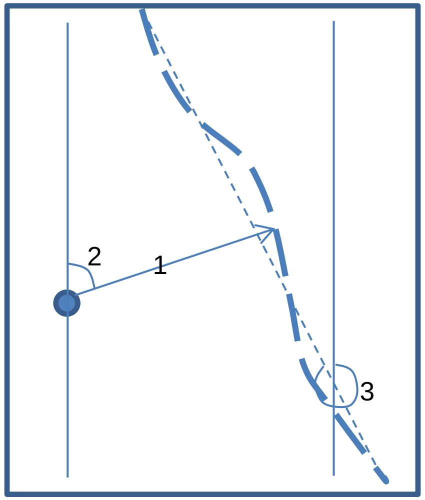


Figure 19, Distance of injectors to faults and fault details (Zechstein Carbonates level)

Fault throw (or Fault offset) analysis was done by measuring the vertical separation of the reflectors, representing the Zechstein 2 and 3 Anhydrite on regular distances along the mapped faults. At each point, where a measurement was done, the resulting offset is marked on the map. The values can be used, in conjunction with the scenarios depicted in figs. 17 and 18, to get an idea about the juxtaposition of the individual layers within the Zechstein

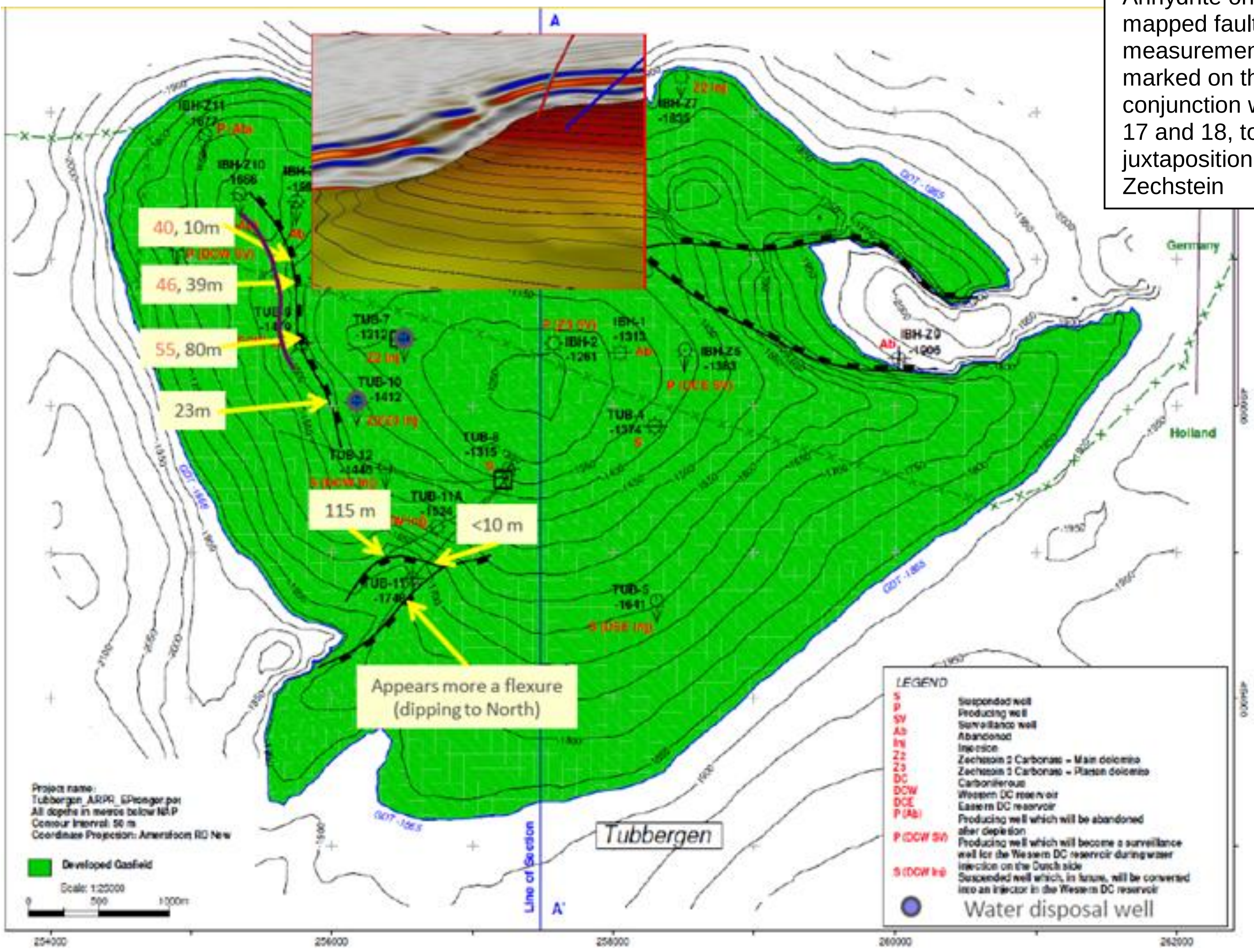


Figure 20, Example of fault throw analysis in the Tubbergen field