Rotliegend geology in the Southern Permian Basin: the development of synrift sediments and its relation to seismic imaging

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Abstract

In order to further examine the tectonosedimentary development of the Permian Rotliegend formation in the Southern Permian Basin area, existing well log data and literature were reviewed in light of influence of basal strata on overlying tectonosedimentary development. Moreover, 2D seismic data of the Dutch Offshore was reviewed in light of syntectonic sedimentation in the Rotliegend sediments. In the North Sea area, Rotliegend sediments were found to contain six transgressive-regressive cycles and a few narrow graben structures developed during the transtensional tectonics yielding the basin. In the Lower Saxony region, straddling the contact between harder Variscan orogenic basal strata and softer foreland Paleozoic sediments, a series of large N-S oriented graben structures occur in a concentrated area. In the Mid-Polish Trough, tectonic structures from the Variscan Orogeny seem to predetermine locations of faults in the Rotliegend, however this could have several other causes. 2D seismic interpretation yielded two main phenomena: the lithological boundaries of the Rotliegend reservoir units can be mapped purely based on their seismic character, and there are two scales of lithological variations (1) the variation on the basin-scale and (2) the variation of coarse-to-fine clastics on the individual fault-block scale.

Keywords: *stratigraphy, North Sea, petroleum geology, growth fault, Rotliegend, Permian, Variscan Orogeny*

1. Introduction

In the North Sea area, the rich natural gas play anchored around the Permian Rotliegend reservoir formation has been the target of hydrocarbon exploration ever since the discovery of the Dutch onshore 100 TCF Groningen gas field Netherlands in 1959 (*Grötsch* et al., 2011). This Rotliegend formation, consisting mainly of fluvial and aeolian sandstones and shales, has been studied extensively in the industry in attempts to predict fluid flow, connectivity and other reservoir properties within hydrocarbon traps (*i.e. SEPM Special Publication 98*). Because this formation lies relatively deep in the subsurface, sometimes over 5 kilometers below present-day sea level, reflection seismic data is limited in its precision. However, due to the copious amounts of wells drilled and reflection seismic data shot in this formation, a wealth of high-resolution data is publically available. This data allows us to investigate not only petroleum geology-related topics, but also answer other interesting questions. For instance, a major uncertainty in the depositional history of the Rotliegend formation is how syntectonic sedimentation occurred throughout the area. Currently, the Rotliegend in the subsurface shows a typical horst-and-graben structure, in which most of the normal faulting has been associated with later stages (post Rotliegend deposition) of extension. However, the Rotliegend intervals have in fact been interpreted as synrift sequences (*Duin* et al., 2006), which are by definition linked to the occurrence of 'growth' faults, normal faults which propagate up to the surface which are accompanied with syntectonic sedimentation. These growth faults can be identified by the sediment thickness variations across faults. In this research paper, existing seismic data, well logs and available literature will be reviewed in light of syntectonic sedimentation within the Rotliegend.

Preceding the deposition of Permian Rotliegend sediments in the Southern Permian Basin area, a major erosional event occurred throughout the area, yielding the Base Permian, or otherwise called Variscan, Unconformity. This unconformity often overprints several older unconformities. Due to the hiatus resulting from these unconformities, the Rotliegend sediments directly overlie the Carboniferous sediments of the Westphalian formations in most of the North Sea area and large parts of the Dutch and German onshore, and parts of the Variscan Orogeny in more southerly and southeasterly parts of the Southern Permian Basin (SPB), such as large parts of the Polish onshore. This distinct difference in rock properties which underlie the Rotliegend formations could in theory give rise to a different expression of tectonic features within the Rotliegend.

This difference in tectonic features within the Rotliegend due to the mechanical strength of underlying strata is also reviewed in this research. More specifically, the difference in tectonic styles, sequence stratigraphy and quantity of tectonic activity during the Late Permian will be investigated.

Another interesting aspect of the Rotliegend of the Netherlands specifically, is that it is so well-studied due to the high data density, that it is possible to link its character in seismic reflection (i.e. how it looks in seismic imaging) with the actual lithologies that exist in the formation. As the Rotliegend consists of shallow marine shales and evaporites and fluvial-aeolian sandstones which vary laterally, it is one of the major uncertainties in the hydrocarbon industry whether or not good reservoir sands (aeolian and fluvial) are present. If there is a way to predict lithology directly from the seismic character of the Rotliegend, perhaps hydrocarbon play prospectivity maps can be altered and improved. Here, I try to investigate whether or not the lateral lithology change in the Rotliegend is accompanied by a change in seismic character and how these two relate.

2. Geological context

Tectonic framework in the Southern Permian Basin

During the formation of supercontinent Pangea out of the final suture of Laurussia and Gondwana, a significant orogenic phase is recorded which is of interest in the formation of the Southern Permian Basin. A major dextral shear system tectonically linking the Appalachian mountain chain with the Ural mountains ran through the Variscan Orogeny, which resulted in the decrease of topography and allowed the erosion of the mountain chain. The erosional unroofing of the Variscan mountains accompanied with large-scale shearing was reacted to by a rising asthenosphere, further assisting the broad-scale uplift of the Variscan orogeny and the Southern Permian Basin area. This broad uplift yielded the Variscan Unconformity at the base of the Permian Rotliegend sediments. The Southern Permian Basin formed through a broad thermal sag accompanied with localized extensional tectonics which inheritably followed the thermal uplift. This thermal relaxation increased subsidence rates at the start of the Late Permian, causing relative sea levels to rise.

Pre-Rotliegend: Paleozoic rocks

In northwest Europe, a large package of Carboniferous strata can be found underlying the Permian Rotliegend deposits. In the Rotliegend petroleum system these Carboniferous sediments provide source rocks. These source rocks are mostly all gas-prone as they are continentally deposited source rocks (coal seams) which originate from a time when land plants were built up of less diverse types of carbon chains (i.e. ferns), which do not convert into petroleum oil when buried to depth. Throughout the North Sea area, most rocks of the Westphalian are fluviodeltaic, sandstones and shales with some shallow water facies, whereas the sediments from Namurian and Dinantian times are mostly deepwater shales and shelf carbonates. A more complete lithological description of these rocks can be found in *Doornebal & Stevenson* (2010).

The pre-Rotliegend rocks of the Paleozoic are mostly part of the foreland basin created by the lithospheric loading of the Variscan Orogeny during the formation of Pangea. This advancing orogenic wedge of the Variscan mountains caused the Rheno-Hercynian Shelf to subside with a high rate, allowing deposition of a thick package of deepwater sediments and orogen-derived clastics and deltaic deposits in Namurian times. This foredeep got deformed in a later phase of compressional tectonism, giving rise to the fold-and-thrust belt at the end of the Carboniferous. During the Permian, this fold-and-thrust belt was significantly lower in strength than the more axial parts of the Variscan Orogeny, and therefore the extension which lead to the formation of the Southern Permian Basin was concentrated mostly in this fold-and-thrust belt. However, in the Mid-Polish Trough developed in the Early Permian over the north-west-trending Teisseyre -Tornquist Zone, a very complex lithospheric boundary which has been the focus of many studies (see *Doornebal & Stevenson, 2010 pg 27 for an overview of authors).* The most significant feature of the Teisseyre-Tornquist Zone in light of this research is the fact that the rocks in this zone are of a much more metamorphic nature than the rocks subcropping the Rotliegend in other areas of the Southern Permian Basin. However, due to the complex nature of this boundary zone, the strength of the basal strata of the Southern Permian Basin in the Mid-Polish Trough is debatable and might therefore not cause any difference to be exhibited in structures developing in the overlying sediments.

Rotliegend geology

During nearly the entire Permian, aridity dominated the climate in northwest Europe. The Rotliegend sediments in the Southern Permian Basin range from coarse clastics (continental conglomerates) to fluvial and aeolian sandstones, shales and some evaporites. A schematic north-south cross section through the northern Netherlands (Groningen Field) is shown in figure 2. As most sediments originated from the south, there is a strong lateral variation from coarse clastics close to the massif, to very fine shales and evaporites in the more northern part of the basin. The

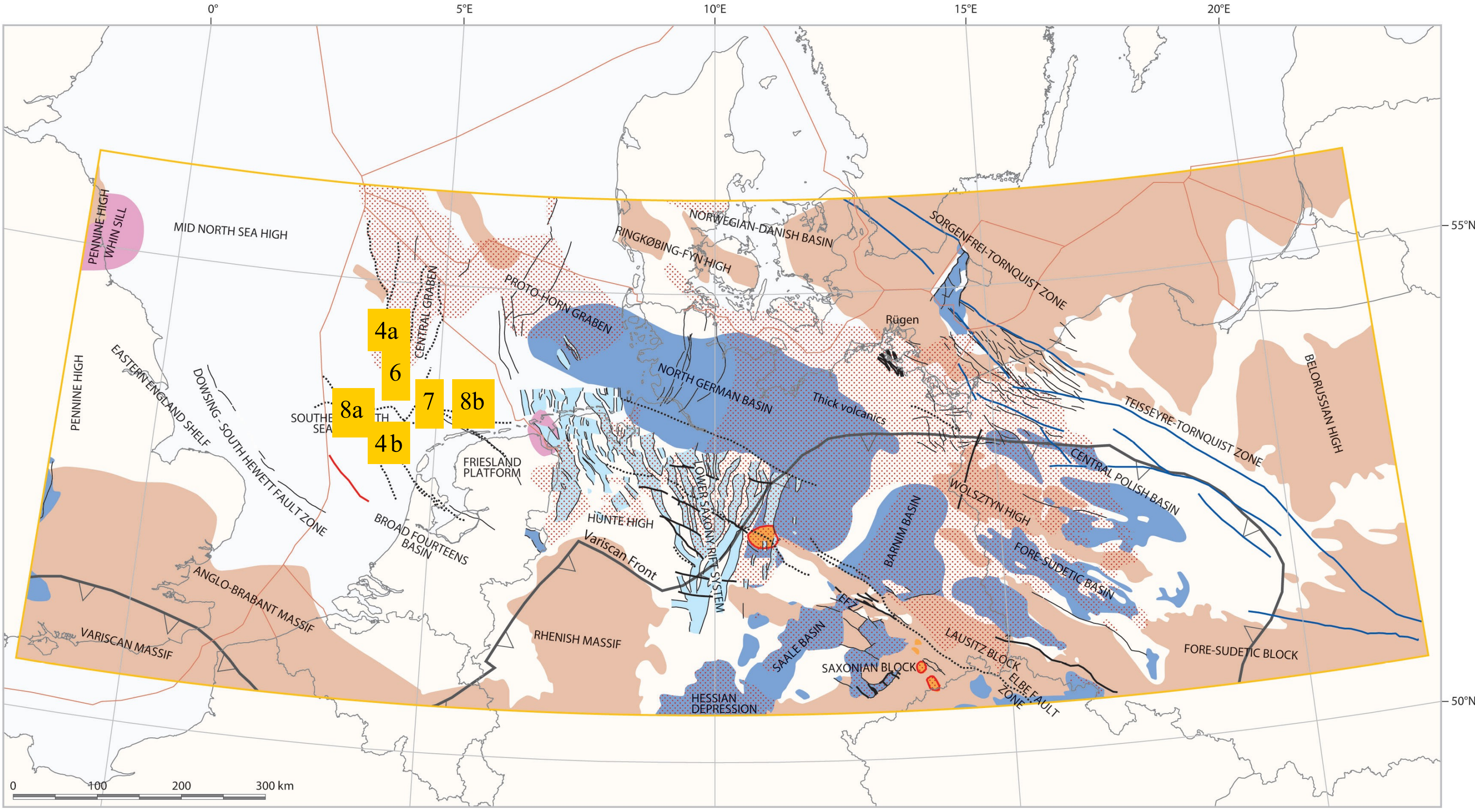

Figure 1. Early Permian (lower Rotliegend) tectonic evolution in the Southern Permian Basin area: Artinskian, 208 Ma. Structural template map. Locations from figures 4a, 4b, 6, 7, and 8 are shown. From *Doornebal & Stevenson (2010).*

depositional environment (also shown in figure 2) is a typical arid near-topography system, containing fluvial 'wadi' deposits, products of desert-environment dry river systems, and aeolian dunes in the more proximal parts of the basin and increasingly smaller grained materials in more distal sediments, such as shales. Further into the basin, some horizons of evaporites have been observed. In terms of stratigraphy, there is discussion on how the different lithological units originate in the Southern Permian Basin. For example, there is some debate on whether the small-scale cyclicity in Rotliegend sediments is orbitally forced under the influence of Milankovitch cycles (*Bailey, 2001*). Other authors have collected and interpreted high quality well data to determine tectonically controlled sedimentary sequences, showing as much as six transgression-regression cycles within the Dutch part of the Southern Permian Basin (*Van Ojik et al., 2011*).

Post-Rotliegend: Zechstein evaporites

Following a major transgressive event, a shallow restricted marine basin existed in the Southern Permian Basin throughout most of the Late Permian, allowing a massive evaporitic sequence to be deposited (locally up to several kilometers thick). This sequence, containing mainly thick halite packages, some anhydrite and shallow water carbonates, often yields the seal in the hydrocarbon system of the Rotliegend. At the base of this sequence, just overlying the major transgressive surface initiating the deposition of the Zechstein, there are widespread reefal carbonates which are generally about 30 meters thick.

3. Rotliegend structures

Evidence for structuration within the Rotliegend sediments of the Southern Permian Basin is most distinctively found in large-scale lateral variations (appendix 1). The Southern Permian Basin rift is characterized by a very broad (hundreds of kilometers) and shallow (tens to hundreds of meters) rift. The extension throughout the Southern Permian Basin is therefore most likely accommodated by sagging and a large number of very small-scaled normal faults, which size are below the resolution of seismic data. Even though the recorded thinning of the crust during Permian times was to 28 to 35 km, only in a very limited number of well-defined graben structures extensional tectonic features have been found (*Ziegler* et al., 2004). The majority of the Southern Permian Basin is believed to be formed under influence of thermal relaxation of the lithosphere. In fact, the preceding uplift and erosion yielding several unconformable surfaces (such as the Variscan Unconformity) are believed to be caused by the thermal uplift that is subsiding and relaxing in Permian times. However, by analyzing thickness variations observed in well logs drilled into the sequence, some indication can be found for these synrift features.

Structures overlying fold-and-thrustbelt sediments

In one of the few places there is observable tectonic activity within the older units of the Rotliegend, block faulting (without a clear preferred orientation) is observed in the Norwegian and Danish offshore at the northern rim of the Southern Permian Basin. This rifting is considered to be Stephanian or Early Rotliegend in age.

At the beginning of the Late Rotliegend, extension in the Lower Saxony basin formed an array of graben structures oriented roughly N-S (figure 1). As these graben structures also overlie the Variscan deformation front they will also be discussed in the next section.

In the Dutch offshore only a few NW-SE trending normal faults developed during the deposition of the Rotliegend. Authors investigating the tectonic development of the Southern Permian Basin have argued that extension was predominantly oriented in a NE-SW direction, consistent with the dominant fault direction within the North Sea area. However, as the elongated shape of the entire basin is in an E-W direction, some more complex and different directionalities of faults are also present, such as in the Lower Saxony basin described before.

Other faults in a more N-S orientation occur within the Central Graben and Proto-Horn Graben in the North Sea area (figure 1).

Structures overlying Variscan orogenic strata

As previously mentioned, the Lower Saxony basin graben structures formed on top of both the fold-and-thrustbelt sediments and the Variscan orogenic strata. In the areas where faulting propagates into Variscan orogenic material the grabens are somewhat broader, and less grabens actually formed. There are several possibilities for the absence of as many grabens within the sediments overlying Variscan basal strata. Firstly, the grabens existing in this area could have formed in a later stage of the development of the Lower Saxony basin, and have propagated from existing faults within the fold-and-thrustbelt sediments, forcing faults to be formed within the Variscan strata. Secondly, within the Variscan Orogenic belt there could have already been older faults in roughly the same orientation, which were reactivated when extension occurred in the Lower Saxony basin.

Thirdly, the rocks of the Variscan Orogeny could have undergone such a complex history of deforma-

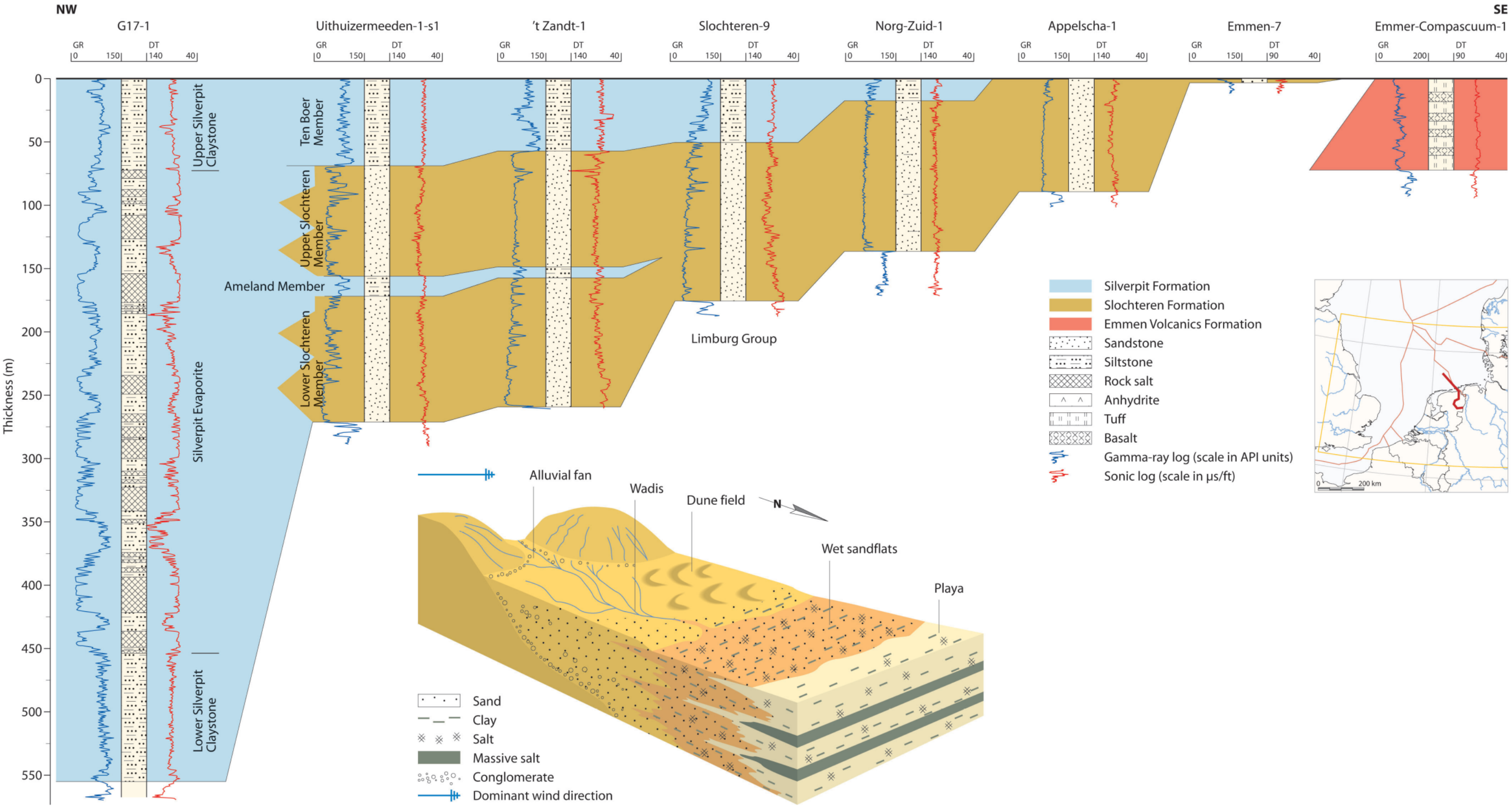

Figure 2 Schematic cross-section showing the lateral and vertical variations within the Rotliegend strata in the northeast of the Netherlands (across the Groningen Field). Modified from: Geluk, 2011.

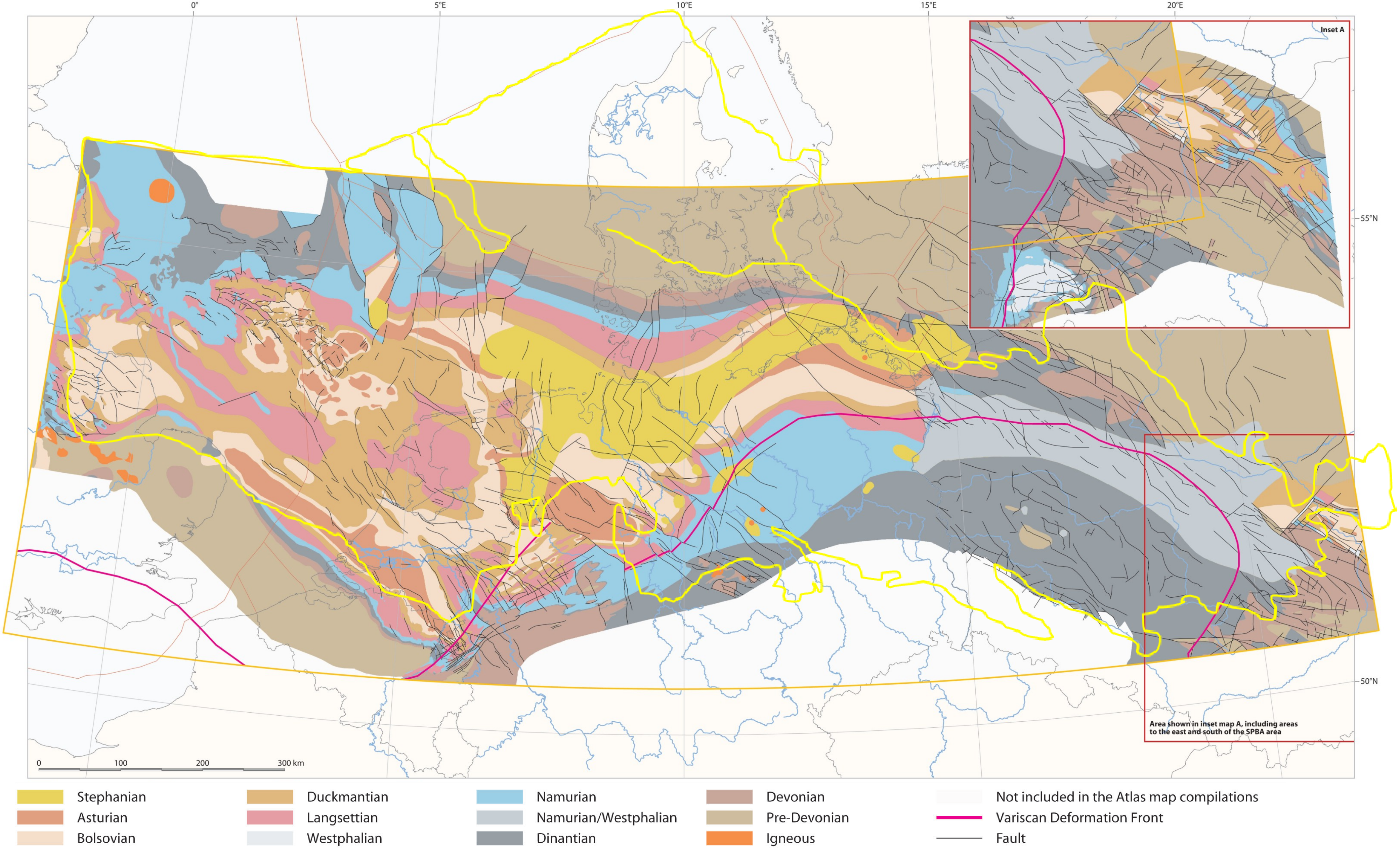

Figure 3. Permian Rotliegend Subcrop map of the Southern Permian Basin area showing basal strata throughout the depocenter for Rotliegend sediments. Note that rocks belonging to Westphalian through Stephanian (youngest six formations) are relatively soft, folded sediments, whereas Namurian and older stata form a harder substrate. The outline of Rotliegend deposits in the Southern Permian Basin is shown with the yellow line. Modified from Doornebal & Stevenson, 2010.

tion and metamorphism that the actual difference in mechanical behavior between the soft sediments of the fold-and-thrustbelt and the orogeny is very small. This would then allow the grabens to form without any preferred mechanical weak locations.

Within the Mid-Polish Trough, strong faulting occurred in the Rotliegend with strikes running roughly NW-SE, like in certain parts of the North Sea. The nature of faulting in this region is significantly different and more expressive than in other parts of the Southern Permian Basin, implying that this area is in fact a weaker zone than the material in the fold-and-thrustbelt thought to be most easily deformed. The occurrence of the Teisseyre-Tornquist zone poses a possible explanation, as this zone is so strongly deformed it is possibly significantly weakened.

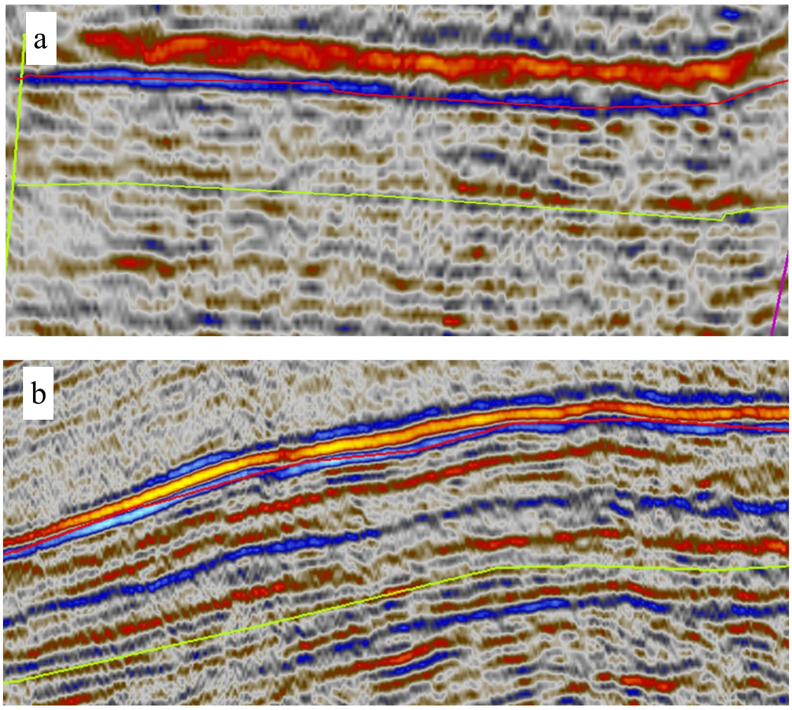

Figure 4. Two seismic lines containing the Rotliegend sedimentary sequence in the North Sea. a) A seismic cross-section from line 06A, a distal section of the Rotliegend containing Silverpit shales and anhydrites. b) A seismic cross-section from line 25G, a proximal section of the Rotliegedn containing more fluvial and aeolian sandstones. The Top Rotliegend marker is indicated with the red line, the Hercynian Unconformity is marked in yellow. Note the distinct difference in amplitude of the seismic reflectors, more sand-rich sediments show much stronger reflection than the shale-dominated lithologies. Locations shown in figure 1.

4. Rotliegend sequences

In the Netherlands, six transgressive-regressive sequences can be distinguished within the Upper Rotliegend (*Van Ojik et al, 2011*). Here, Lower Rotliegend is absent. Therefore, in light of the comparative nature of this research, the focus in sequence stratigraphy will be on the Upper Rotliegend throughout the entire Southern Permian Basin. In central German wells, as many as thirteen different members can be found, which correspond to about six notable transgressive-regressive sequences (*Doornebal & Stevenson, 2010)*. In the Polish part of the Southern Permian Basin, the same six sequences can be found within the Upper Rotliegend formations. It seems, therefore, likely that these sequences are not a local phenomenon related to small-scale fault activity, but much more likely related to basinwide subsidence rate variations determined by the underlying plate tectonic movements.

5. First-order Rotliegend seismic character variations in the Dutch Offshore

By analyzing the 2D seismic lines shot in the Dutch Offshore by TNO in 1983, combined with the knowledge already present in other publications, a clearer image of the Rotliegend sediments in this region is obtained. As it is very hard to locate the different sedimentary facies and the extent of sand-rich bodies within this sequence, it is of great value to be able to predict and map lithologies purely based on their seismic character. However, this has proven difficult as reflection seismics often yield the same image for different rock types, if their densities are similar. However, within set constraints, it proves possible to distinguish between one or two rock types based on the seismic image alone. In the Rotliegend of the Dutch offshore, two main rock types can be distinguished: shales and sandstones. The more shale-rich rocks are located in the north of the North Sea, and more southerly the coarser, more sand-rich sediments occur in these formations. For decades, the Slochteren sandstone formations, in which also the Groningen Field is located, have been targeted as the gas-bearing reservoir in the southern North Sea. As shown in figure 1, the sandstones belonging to these formations pinch out towards the north. In the hydrocarbon industry, it would be greatly beneficial to map out precisely where the outer limit of the sand extends to. In order to do so, the combination of well data (of which a copious amount exists) and, more interestingly and controversially, perhaps the seismic imaging could provide insight. In recent years, the extent of Lower and Up-

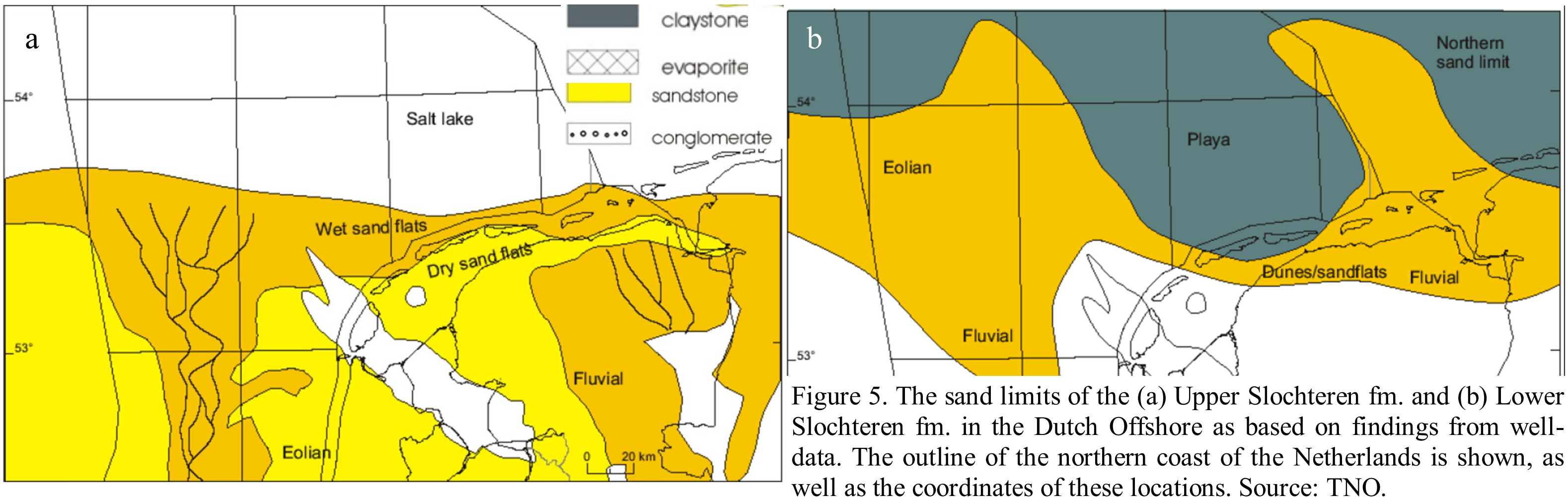

Figure 5. The sand limits of the (a) Upper Slochteren fm. and (b) Lower Slochteren fm. in the Dutch Offshore as based on findings from well-data. The outline of the northern coast of the Netherlands is shown, as well as the coordinates of these locations. Source: TNO.

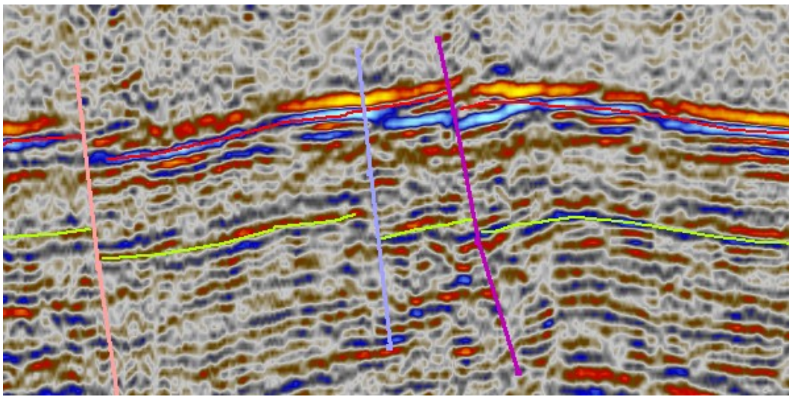

Figure 6. 2D seismic cross-section showing the Rotliegend as in figure 1. Note the strong reflectors at the base of the Rotliegend, and the growth over the middle fault (blue). The two other faults (pink and violet) in the image are interpreted post-depositional.

per Slochteren sandstone formations have been moved northwards several times, as more exploration wells found these sand-rich formations to occur more northerly than expected. Comparing the reflectivity of Rotliegend sediments throughout the Dutch Offshore, it is visible that in the north of the Dutch Offshore, where the Rotliegend consists of shales and anhydrites, the Rotliegend is much more transparent in the seismic image. Except for the top of the Rotliegend, which is regionally a very strong seismic reflector, the entire sequence is characterized by a low-amplitude set of reflections. A key example of this is shown in figure 4. This first-order variation in lithologies is quite well-documented by several authors (*Geluk, 2005, Doornebal & Stevenson, 2010, Van Ojik et al, 2011)* and several maps are available which show the currently assumed extent of the sand limits for both the Upper and Lower Slochteren formations (figures 5a and 5b, respectively). These maps are based primarily on the occurrence of the Upper and/or Lower Slochteren sands in the wellbores drilled in the region. However, experience shows that these maps often show an underestimation of the upper sand limits in the Rotliegend, as the extent has been shifted northwards for both of the formations over the last few years. Moreover, the sand limit might not be as clear-cut and continuous as currently assumed, as there seems to be a smaller-scale variation which takes place at the limit as well. This smaller-scale variation will be discussed in the next paragraph.

The large-scale lithological variation, from coarse sandstones and even basal conglomerates in the southern part of the North Sea to the shales and anhydrites in the northern part of the Dutch North Sea, can be distinguished well on seismic imaging, as shown in figure 4. Using well-data to constrain the seismic image coming from the different lithologies, one could start mapping the entire Dutch offshore with a combined approach: using both the well data as the seismic reflectivity to indicate whether or not there is sand present in the Rotliegend sequence at a certain location. For example, 2D seismic line number 12A from the 1987 TNO regional survey (figure 6) shows bright reflectors within the lowermost part of the Rotliegend, whereas it is located at a point where, according to the current maps, the sand has pinched out (location shown in figure 1). This would imply that there is in fact sand present where currently there is no sand interpreted. By comparing the amplitude of the seismic image at the base of the Rotliegend sediments at locations where sand has been drilled, to the seismic image at locations where there is no sand found in the Rotliegend reservoir units, it becomes clear that sand-rich Rotliegend rocks have higher amplitude seismic reflections than shale-rich Rotliegend rocks. This is actually counter-intuitive, as shales are denser and often show a much stronger reflection in seismic imaging. An explanation for the occurrence of these high amplitude reflections in the sand-rich Rotliegend reservoir rocks is found in looking at the lithologies more closely. Even the reservoir levels of the Rotliegend rocks which are considered "gross reservoir", in other words, the part of the sequence which is considered to contain significant sand content and porosity, actually consists of a sharp alternation between layers with very high sand content ("net"-reservoir) and shale beds. These shale beds are especially pronounced in the more distal parts of the extent of the reservoir units (figure 5). As reflection seismic im-

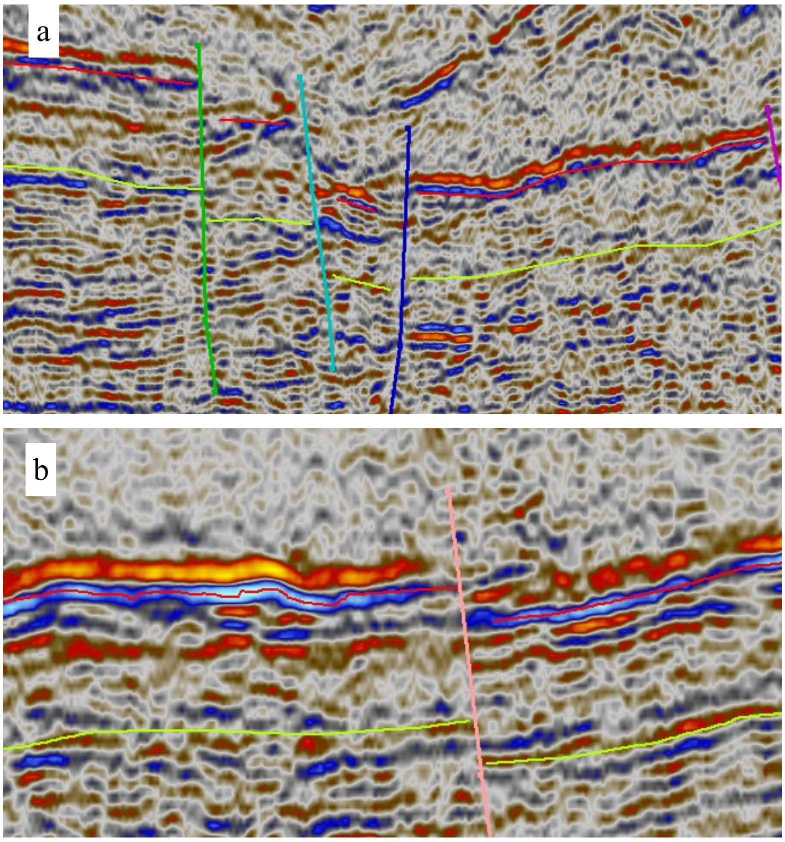

Figure 7. Two seismic cross-sections showing stronger reflectors within the Rotliegend in the hanging wall. In figure a) the graben structure shows significantly stronger reflectors, which is most likely caused by the higher sand content within this part of the Rotliegend compared to the tilted fault blocks and grabens surrounding it. Locations shown in figure 1. b) The downthrown block shows higher amplitude reflectors than the footwall.

aging shows the *change* in seismic velocities of rocks, this can explain why relatively low-velocity rocks show such high amplitude reflections. The strongly interbedded Rotliegend reservoir units therefore show high amplitude reflections, whereas the homogeneous Silverpit shales in the north of the North Sea (where the Rotliegend contains no sand) have little to no change in seismic velocity, and subsequently show low amplitude reflections.

6. Second-order seismic character variations in the Dutch offshore

Besides the larger-scale lithological variations in more proximal, sand-rich sediments in the south of the North Sea and the more distal shales and anhydrites in the northern North Sea, there is another smaller-scale variation which is visible on the seismic imaging. Whenever a syndepositional fault develops on the transition zone between sand-dominated and shale-dominated deposits, relief is created. At the scale of the fault block itself, in the order of tens to hundreds of meters, there will be a variation in lithology. Close to the fault in the hanging wall, coarser sediments will be deposited compared to the sediments in the footwall as a result of the created relief during deposition. In these ‘holes’, a more sand-rich and thicker package will be deposited. On the width of the fault block itself there will therefore be a small-scale transition between coarser sand-rich clastics near the normal fault, to finer clastics and shales at the other end of the block. Just like the way it is visible in the regional scale variations, this shaling-out towards the footwall-side of a tilted fault block (in other words, the higher sand content in the hanging wall) will be visible in its seismic reflectance. The higher the amplitude of the seismics, the more sand there is assumed to be present in that location. In figure 7, two examples of this phenomenon are shown.

Moreover, erosion on the crest of the footwall structure can also be indicative of synkinematic sedimentation. A key example of this phenomenon is shown in figure 8. As this section is quite distal, there is not much variation in seismic reflection amplitudes across the faults. The interpretation is in this case that both the hanging wall and footwall blocks contain only marine shales in this sequence, and the sand simply does not reach this location despite the accommodation space created by the growth faulting.

These smaller-scale variations in sand content can be quite significant, as can be seen in figure 7b. Due to the paleotopography during deposition of the Rotliegend, some thick sand bodies belonging to the Upper– or Lower Slochteren formations may actually exist beyond the extent of the northern sand limit as shown in figure 5a and b. On the other hand, the currently drawn maps of the extent of the sand may also include wells which happened to be drilled in such a smaller sand body, after which the entire surrounding area was interpreted to contain sand. Therefore, these maps must be revised in light of these second-order variations. The sharply drawn line of the sand extent

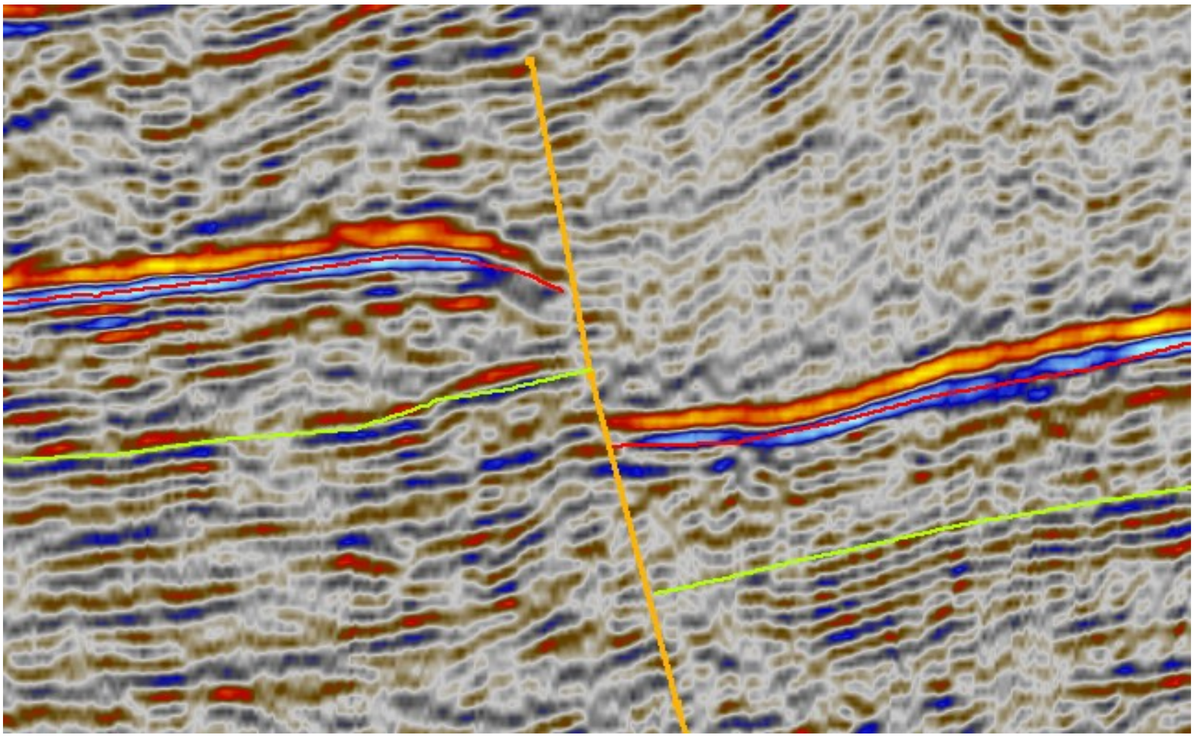

Figure 8. Seismic cross-section of the Rotliegend showing synkinematic sedimentation and significant erosion of the crest of the footwall. Location shown in figure 1.

is in any case unrealistic and must be considered a rough indicator rather than an accurate map. A evolutionary model showing the pre-Rotliegend structure and character of the Hercynian Unconformity is shown in figure 9a, the facies changes and synkinematic sediments of the Permian (Rotliegend and Zechstein groups) are shown in figure 9b and the post-Permian tectonic style is shown in figure 9c.

5. Discussion

Due to the current depth of the Rotliegend sediments, it is difficult to obtain high-resolution seismic images of these sequences. The occurrence of small variations across faults can therefore be very difficult to determine and even more difficult to quantify. This significantly reduces data availability, as it is presumably impossible to tell whether or not synkinematic sedimentation occurred, and therefore impossible to determine the age of the faulting. In sediments of Carboniferous age and older, this problem is even greater as these sequences are much less prolific in terms of hydrocarbon potential and well data is even much scarcer. Overall, data availability is an important quality limiting factor in the research of any study of the Southern Permian Basin.

Moreover, no studies have targeted pre-Rotliegend rocks of the Southern Permian Basin in light of their mechanical strength on a basin-scale, so all observations on interactions between basal strata and Rotliegend sediment deformation can be classified as merely speculative. However, observing the difference between tectonic styles across the same sedimentary basin in light of their substrate shows promise and possibly future studies could determine causes for this and support observations noted here. The occurrence of growth faulting within the Rotliegend of the Dutch Offshore is apparent. However, as only 2D seismic imaging is available on this regional scale, a lot of 3D features are possibly missing. Faults which are visible on these 2D lines may very well have larger offset in the third dimension, and faults could be missed altogether. Moreover, the seismic data is obtained and shot in a direction which is not entirely perpendicular to the sedimentary facies change, which results in possible errors as well. Nonetheless, synkinematic sedimentation is clearly visible throughout the area, and large– and small-scale lithological changes of both the first and second order can be determined purely from seismic data, which is a very valuable observation for the hydrocarbon industry.

6. Conclusions

Based on the observations in Rotliegend sequence stratigraphy throughout the Southern Permian Basin, no clear difference could be determined between stratigraphy which directly overlies Variscan orogenic materials and the Paleozoic rocks from the foreland fold-and-thrustbelt. Possible explanations for this is that relative sea levels have fluctuated dominantly on a regional scale due to the thermal subsidence fluctuating in rate, as opposed to relative sea levels being largely dependent on local tectonics.

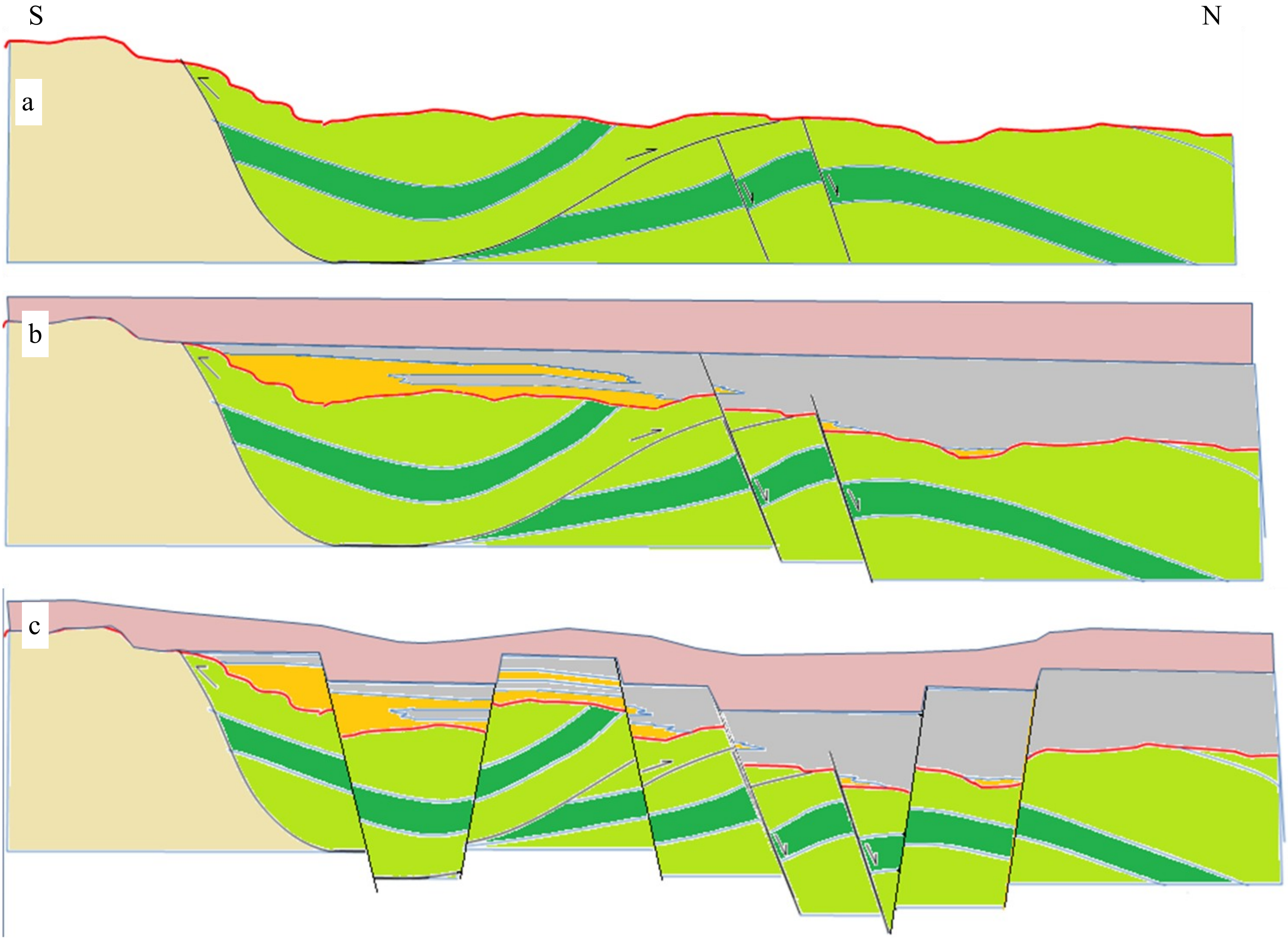

Figure 9. Schematic south-north cross section of the tectonosedimentary evolution in the Dutch Offshore. Rocks from the Variscan front (left) are shown in light brown, Carboniferous rocks from the fold-and-thrust belt are shown in green. Permian sand-rich rocks are shown in yellow, shales are shown in grey. Salt deposits are shown in pink. Figure a. shows the pre-Permian structure of the area, showing the Hercynian unconformity in red. Note the old tectonic features in these rocks. Figure b shows Rotliegend and Zechstein deposition, showing synkinematic faulting and reactivation of older Carboniferous faults, and the patchy nature of the sand extent northwards. Figure c shows the post-depositional faulting in the Rotliegend rocks, which is accomodated plastically within the overlying Zechstein Salt. Note that most faults are post-depositional, but the two faults which are also active in figure b are syndepositional.

Based on observations in light of character of faulting such as directionality and 3d geometry, there is some (although limited) indication that the underlying strata directly impact the faulting in the Rotliegend. When Rotliegend sediments are faulted above relatively strong rocks belonging to the Variscan orogeny, faults seem to occur in lower numbers but accommodate more extension per fault. Moreover, it seems that reactivation of older faults plays a much bigger role in these areas as opposed to in the areas where Rotliegend sediments cover fold-and-thrustbelt material. Possible future research should focus on providing a more reliable image of pre-Rotliegend strata and their mechanical properties to determine whether these relations can be considered justified.

In light of the seismic reflectivity analyses of the Rotliegend in the Dutch offshore, a clear relation can be shown between the seismic reflectance amplitude and lithology. The sand-rich reservoir formations belonging to the Upper and Lower Slochteren show high amplitude reflectors within the Rotliegend, whereas the Silverpit Shale formation shows low amplitudes. This variation has shown to occur on the large basin-wide scale as previously described by other authors (i.e. *Doornebal & Stevenson,* 2010*)*, but also at the boundary of the pinching out of these reservoir units, there is a smaller-scale variation caused by the synkinematic sedimentation. When a growth fault occurs in the area near the northern sand limits of the reservoir formations, there is a higher concentration and volume of sand within the downthrown block, near the normal fault. This could provide insight into why some wells have drilled sand within the Rotliegend, whereas it was not expected to occur at those latitudes, and possibly extend the sand limit further northwards. The currently available reservoir sand extent maps will have to be altered in light of these insights.

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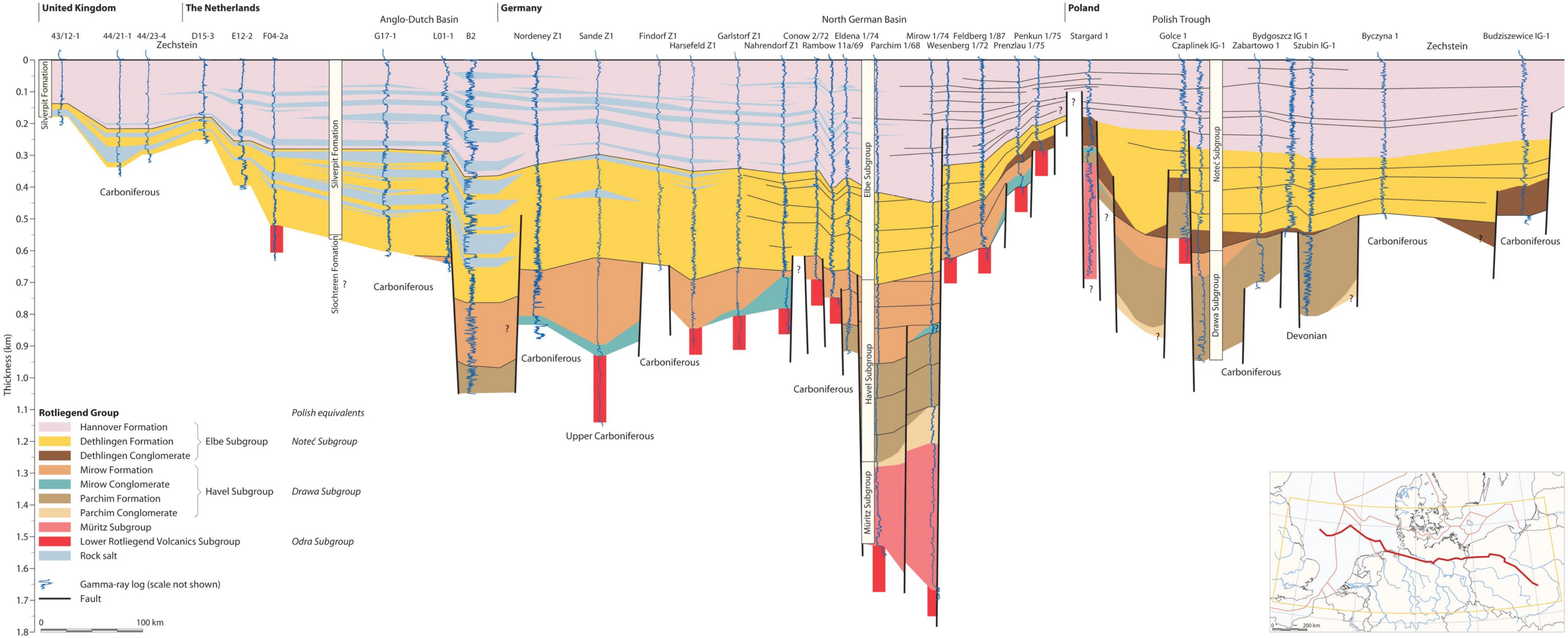

Appendix 1. Series of Rotliegend well correlations from the UK, Netherlands, Germany and Polish parts of the Southern Permian Basin. Note the significant lateral thickness variations. All these wells have been drilled at locations where the Rotliegend is deposited on relatively soft fold-and-thrustbelt materials belonging to Carboniferous strata.