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CREST - Chalk Structural and Depositional Evolution in the Vicinity of Salt Structures in the Dutch Subsurface: Geological and Geophysical Characterisation

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The CREST project aims at better understanding the Chalk Group in the vicinity of salt structures. It is essential to understand the structural and depositional evolution of the Chalk Group near those growing structure as they have played a crucial role in localising deformation and creating variable accommodation for the various Chalk sediments. To achieve this main goal of this project, we investigated the Late Cretaceous- Early Paleocene interval in the Dutch offshore by studying the Chalk Group in three case studies located in different parts of the offshore (Broad Fourteens Basin, Dutch Central Graben, Step Graben) and showing different styles of syn-depositional tectonics. Within these case study areas, multi-disciplinary approaches were conducted, including geological, and geophysical research techniques.

The Late Cretaceous and early Paleocene (Cenomanian - Danian) is characterised by a period of relatively high eustatic sea level that accommodated a large carbonate system over northwest Europe. The most common deposit associated with this carbonate system is chalk, which consists almost exclusively of biogenic coccolith skeletons. Chalk deposits usually contain high (micro)-porosities, but permeabilities are generally too low for Chalk to be considered a proper reservoir. However, in some places Chalk deposits contain better reservoir properties, as might for instance be the case for allochthonous Chalk, where Chalk particles have been reworked after deposition; either via bottom currents or via mass transport complexes (MTCs), such as slides and slumps. Additionally, siliciclastic deposits, related to periods of Late Cretaceous uplift and subsequent erosion, might be present locally within the Chalk Group.

Geophysical research techniques that were applied included various types of seismic data conditioning, including conventional seismic reprocessing techniques, such as denoising, as well as novel reprocessing techniques, including Non-Local Means (NLM), Sparse Spike Deconvolution (SSD) and Automatic Envelope Correction (AEC). In addition to these seismic data conditioning techniques, Joint Migration Inversion (JMI) was performed on several 2D lines. JMI is another relatively new seismic imaging technique that uses the full pre-stack seismic wavefield that combines velocity model building and seismic migration within a single inversion process to appraise subsurface model parameters with improved accuracy and resolution. An important goal of the CREST project was also to explore the use of these geophysical techniques in complex geological settings and investigate to what extent these techniques provide better seismic imaging for detailed tectonostratigraphic analysis and hence are being beneficial in achieving the main research goal: understanding the structural and depositional evolution of the Chalk Group in the Dutch offshore.

Geological research techniques that were applied in the CREST project include high resolution 3D seismic interpretation, seismic attribute mapping via stratal slicing, and well correlations. Within the case study areas, several intra-Chalk seismic horizons were interpreted based on 3D seismic data, aided by the geophysical data conditioning techniques described above. Based on the interpretation of these key seismic horizons, 3D geomodels were constructed by using PaleoScan software, which allowed to perform seismic attribute mapping via stratal slicing of a dense horizon stack. Well correlations were performed by making use of well log-, and biostratigraphic data. Biostratigraphic data was used both from legacy reports, as well as from several new analyses that were performed by PetroStrat for the northern Central Graben area, as part of the current project.

Based on these multi-disciplinary and data-rich techniques, various sedimentological, stratigraphical, structural, paleo topographical and palaeogeographical analyses could be performed. This led to the following main results as described in the next three sections.

1. Geophysics

a. Geophysical data conditioning by NLM denoising and AEC scaling enabled a better imaging of the Chalk interval on top of the salt structures. Additionally, both data conditioning techniques proved to enhance the seismic imaging of intra-Chalk complexities, leading to a more robust interpretation of intra-Chalk depositional features.
b. JMI modelling updates the velocity model and can therefore aid in clarifying whether relatively high velocity Chalk is present in structurally complex settings, leading to a better understanding of main structural boundaries such as the outline of salt structures and the trajectories of large-scale faults. The combination of JMI modelling, detailed 3D seismic interpretation and PaleoScan modelling, led to a better understanding of the structural evolution of a complex fault zone within the Broad Fourteens Basin.

2. Geology

a. Several depositional features, containing possibly improved reservoir potential, were recognised within the case study areas by performing 3D seismic interpretation and attribute analyses via stratal slicing. These depositional features include MTCs (such as slides and slumps) and large-scale bottom-current deposits.
b. In some areas, uplift associated with tectonic inversion pulses caused erosion of pre-Chalk strata, possibly leading to the accumulation of local zones of siliciclastic material within the Chalk, similar to the deposits described by Van Lochem (2018).
c. Salt Bodies are mechanically weak zones within the rock column and often underwent a complex and highly dynamic geological history in the northern Dutch offshore. During tectonic inversion pulses, salt structures often localised deformation, causing uplift in the area above the salt structures, which in turn triggered the activity of depositional features. On the other hand, during periods of tectonic quiescence, salt structures also formed areas of relatively low-, or minor topography.
d. The main period of activity for the depositional features approximately coincides with tectonic inversion pulses, which triggered (local) uplift and associated topographic differences, leading to basin confinement.

3. Tectonostratigraphic evolution

The main findings regarding the structural evolution of the Chalk Group in the Dutch offshore are listed below, note that some differences in timing occur for the different case studies:

a. The Cenomanian to Middle Santonian interval is largely characterised by laterally continuous reflectors throughout the case study areas, indicating relatively stable conditions where pelagic Chalk was deposited during a period of regional post thermal subsidence, following the Upper Jurassic-Lower Cretaceous rifting phases. Thickness differences do occur in this interval, but are generally characterised by gradual, smooth trends that appear to be the result of basin-scale differences in accommodation.

b. The Late Santonian to early Middle Campanian interval is characterised by an increase in the activity of various depositional features, including bottom current deposits and Mass Transport Complexes (MTCs). In the northern Dutch offshore, MTCs are for instance observed adjacent to salt structures and display a sediment transport direction away from these salt structures. The latter indicates that tectonic inversion was localised by salt structures, causing uplift, subsequent erosion and the shedding of material in supra salt areas that was redeposited into adjacent paleo lows. An unconformity associated with this phase of uplift is regionally recognised in the Broad Fourteens Basin and locally in the Step-, and northern Dutch Central Graben.
c. The late Middle Campanian to most of the Late Campanian is characterised by a period of relatively tectonic quiescence, as few depositional features are recognised and seismic reflectors are generally continuous. Onlaps are observed locally onto the Early Campanian Unconformity.
d. The latest Campanian to Early Maastrichtian is characterised by strong regional uplift of the northern part of the Dutch Central Graben, as well as parts of the Broad Fourteens Basin. Regional uplift caused basin confinement, leading to various types of bottom current deposits in the northern Dutch offshore, including deep moats, as well as broad sheeted-, and elongated drift deposits. The contemporaneous timing of various bottom current deposits within different North Sea areas, as well as the sheer size of some of the moats suggests that strong large scale bottom current systems where active during this time when sediments were likely transported of hundreds of kilometres, likely to the northern Atlantic and possibly driven by a thermohaline driving force. A significant unconformity associated with this phase of uplift is regionally recognised in the Step Graben and northern Dutch Central Graben, as well as the adjacent platform areas. Local unconformities related to this period are also recognised in the Broad Fourteens Basin and adjacent platform areas.
e. During the Late Maastrichtian to Danian, bottom currents remained active, but as topographic differences waned over time and the basin widened again, bottom current velocities decreased, allowing generally more aggradational pattern of (smaller scale) moats and levees to develop. Onlaps are regionally observed onto the Late Campanian-Early Maastrichtian Unconformity in several areas.
f. At the end of the Danian, a third phase of inversion tectonics caused regional uplift in some areas, including parts of the Step Graben and Dutch Central Graben areas. Uplift appears to have been most pronounced though in northern Broad fourteens Basin, where most sediments of Danian age have likely been eroded.

4. Implementation of the project

The results obtained in this study significantly increases the knowledge of structural and depositional evolution of the Chalk Group within parts of the Dutch offshore.

Additionally, the study provides insights in the importance of understanding to structural evolution of salt structures that act as mechanically weak zones, which may localise deformation and influence Chalk deposition by increasing the activity of various depositional features. Furthermore, the study showcases the advantages of various geophysical data conditioning techniques that can enhance seismic imaging.

The results of CREST are relevant for the E&P and Geothermal industry since the Chalk is often an interval crossed by new drilled and doublets and constitute a drilling risk due to its lithological heterogeneities, velocity field and local gas accumulation. By providing a new set of integrated techniques, including innovative seismic data reprocessing, seismic waveform imaging and neural network seismic modelling, the CREST research offer new avenue for geoenergy industry to further de-risk the subsurface. By being able to construct more robust velocity models thanks to these multidisciplinary techniques, the uncertainties in drilling deep gas or geothermal targets can be significantly decreased, especially in complex structural context as encountered in the Dutch sector where polycyclic fault and salt activity throughout the Meso-Cenozoic is frequently encountered.
Additionally, the results of CREST could be relevant for future subsurface activities, such as underground energy storage, CCS and geothermal exploration, that will possibly take place in similar geological settings either offshore or onshore.
Further development of Joint Migration Inversion (JMI) techniques is ongoing to incorporate 3D seismic. This will be tested in upcoming research projects at TNO and may provide additional tools for the Dutch geoenergy industry sector in the coming years.

A spin-off project focus on fault characterization involving the same team of researchers is planned in 2022. The results of this project will also be used in a collaborative effort by TNO and EBN to add new information specific to the Chalk Group within the GEODE Platform (https://www.geodeatlas.nl/).
No publications have yet been compiled beside the confidential report (198 pages) for this project, but some will be written in 2022 for peer-reviewed journals. Knowledge transfer towards other Dutch and international industry partners are also planned in the first quarter of 2022 to disseminate the research results to a wider audience.

The CREST project is a great example of successful collaboration between TNO geoscientists and the project's industry partners EBN, Wintershall, NAM, TGS. The kick-off meeting was held in Q4 2019 at TNO's location in Utrecht and where the project plan and various aspects of the project were presented and discussed. Project progress meetings were organized twice per year to share the status of different activities, discuss the findings and the planning of the coming period. Moreover, additional meetings covering newly acquired knowledge were organized with specific partners whenever needed throughout the project. These meetings were highly appreciated and assisted in fine tuning the ongoing research for maximum impact. The active participation of the partners and the fruitful discussions played an important role in the success of the project. Another important aspect in the project was the availability of relevant data and which were provided timely by Wintershall and by TGS.
As part of the project the TNO project team organized and taught a Salt Tectonics Course on the 22nd and 23rd September 2022. The course was held online during two-afternoons session and was attended by 30 participants from the industry (One-

Dyas, EBN, Wintershall, NAM), Utrecht University and TNO. This course together with the CREST research were very well received and cemented TNO's position as the main knowledge hub on salt tectonics-related research in the Netherlands.

5. Strengthening of the Dutch knowledge position

The innovative character of this project is in large part related to its multidisciplinary nature, with innovative geophysical and geological methods integrated to decipher the Chalk Group tectonostratigraphic evolution. The implementation of Full Wave Inversion, that has been used in this project, is a brand-new inversion technique that has so far not been used on 2D seismic data in the Netherlands. One of the implementations of forward wave inversion is Joint Migration Inversion (JMI), developed by Qu and Verschuur (2017) at TU Delft in the Delphi Consortium. In the CREST project, these new techniques were further tested and update using new code and optimization. Likewise, the use of novel seismic interpretation technique such as PaleoScan on the Chalk has never been done by a research group before in The Netherlands. Separately, some of the research activity involved in the CREST project has been tested in Denmark (Smit et al, 2018) and the Netherlands (Qu and Verschuur, 2017; Bouroullec et al., 2018). However, the combination of such techniques and the addition of biostratigraphic analysis is original and innovative.

This project provides valuable addition and will increase not only the Dutch knowledge base, but will also provide new results that can be applicable in other European countries where Chalk is considered as a geothermal and gas target. This project contributes fundamentally to our understanding of the Southern Permian Basin in a wider sense. In this broad perspective, projects such as CREST also develop the necessary knowledge base to support future activities in the North Sea area. Above that, the knowledge base developed through decades of gas exploration can also be expected to be a key success factor for geothermal energy to become an increasingly viable part of the energy mix.

The project also promotes cross-border communication and collaboration as it integrates stratigraphic concepts and nomenclature of the neighbouring countries, especially Denmark, Germany, Norway and the United Kingdom. Although, an apparent paradox, as competition between nations and companies is a given in the E&P sector, a buoyant in the E&P sector in North-Western Europe will be beneficial for the Dutch economy. For instance, the process of de-commissioning and conversion of the Dutch offshore infrastructure will need to be attuned to the activities in the bordering countries. Moreover, the expertise and knowledge of the subsurface that is developed in the CREST project will be highly relevant for future uses of the North Sea basin’s subsurface.

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