Interim Report
Harlingen Upper Cretaceous Subsidence
September 22, 2010

VERMILION
ENERGY

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Introduction

This is an interim report on the progress of the study carried out by Golder Associates, the Norwegian Geotechnical Institute and SGS Horizon for Vermilion Oil & Gas Netherlands B.V.. The purpose of this report is to summarize the work and results to date of the investigation by Vermilion Oil and Gas Netherlands B.V. into the discrepancy between the forecast of subsidence above the Harlingen Upper Cretaceous Gas Reservoir and the actual subsidence measured over time. It is important to note that the conclusions to date are based only on the work that has been completed and that our understanding of the various factors involved and their interactions may lead us to different conclusions as the work progresses.

In the summer of 2008 it became apparent that the amount of subsidence over the Harlingen Chalk gas-field was more than the forecast by the subsidence model developed previously. It was therefore decided to shut in the gas production and investigate the cause of the additional subsidence. To that end several studies have been commissioned, namely:

1. A seismic re-interpretation of the field and surrounding areas for the purpose of a structural model;
2. A geological model concentrating on the porosity distribution of the Chalk reservoir;
3. A rock-mechanical laboratory study in three phases on samples from the Harlingen Chalk reservoir to determine its mechanical rock properties;
4. A dynamic reservoir model of the gas-production to provide updated pressure profiles; and,
5. A geomechanical study to establish a new subsidence model.

Items 1 and 2 have been completed by SGS Horizon in The Hague. Phases 1 and 2 of the rock mechanics study are finalized. Phase 1 was completed by Liege University (Belgium) and Phase 2 by the Norwegian Geotechnical Institute (NGI, Oslo). Phase 3 will also be done by NGI and is scheduled to be completed in fall 2010. A dynamic reservoir model was completed by Vermilion based on the reservoir pressure history before gas production was terminated in 2008. Recent static pressures taken in the reservoir after a shut in period of approximately 2 years indicate that the reservoir model needs to be fine-tuned to incorporate this latest data. This is expected to be completed in October.

A relatively simple 2.5D compaction / surface subsidence model will be developed for the geomechanical study first to test scenarios and scaling effects. The modeling for this phase will use the AESubs code developed by TNO. This will help determine input parameters for more detailed 3D Finite Element geomechanical modeling. The finite element (FE) modeling is subdivided in two parts: a part that will concentrate on the chalk gas-field only; and, a part that concentrates on the contribution of the nearby salt-mining. The FE modeling work is being done by Golder Associates in Turino, Italy. Subsidence data obtained by satellite imaging will be integrated in the geomechanical study. The satellite data has the potential to improve the model through denser and more frequent data coverage than leveling surveys alone. This part of the modeling will be finalized when the satellite data is made available. The FE modeling phase is waiting on additional lab tests from NGI due in October 2010 and the results of the 2.5D AESubs modeling.

Interim Results

1) Areas of greater subsidence correspond to areas of higher porosity and correspondingly greater pressure depletion in the gas reservoir;

2) Conventionally predicted rock compaction in the gas reservoir does not account for the subsidence that has occurred based on the available laboratory data and established methodologies. This remains the case even if it is taken into account that pore collapse* can occur in the highest porosity layers of the reservoir (with porosities between 35 and 40%);

3) The rate at which rock is loaded in the field compared to conventional laboratory test loading rates can have an effect on the pore collapse threshold and therefore needs to be properly accounted for in the laboratory testing protocol. If lowering the loading rate in laboratory testing causes the pore collapse threshold pressures to be reduced, then pore collapse in the field will occur at a lower porosity than was determined form earlier more conventional laboratory tests. Pore collapse in the field would then be more widespread then conventionally predicted. Laboratory tests currently in progress aim to determine how, and by how much, loading rate will affect pore collapse and pore collapse threshold pressures;

4) Creep** following pore collapse could explain some of the additional compaction and resulting subsidence, in particular continued subsidence after interruption of production;

5) Salt movement as a contributor to subsidence in the gas production area is still being investigated but will likely not produce a significant enough effect to explain the observed discrepancies. The planned detailed FE modeling will quantify this;

6) The impact of water saturation in the gas reservoir is probably not a factor. Tests currently underway will need to confirm that hypothesis;

7) The geology above and below the gas pool and in the vicinity of the salt producing reservoir near Harlingen is complex with varying thickness of salt layers and overburden. It is planned to correctly capture the thickness and rock properties of all of the layers above and below the gas reservoir in completing the finite element models; and,

8) Pressure support and water movement below the gas is believed to be small limiting pressure depletion to the gas filled rock. However recent pressure data needs to be incorporated to be conclusive.

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* a sudden significant increase in rock compressibility after a given amount of pressure depletion, see refs xx - xx.

** continued compaction at constant stress

Discussion

1. Seismic Interpretation

Eighty four seismic profiles (2D seismic lines) over an area of about 250km^2 were available to do the structural interpretation on the Harlingen – Franeker area. The data were of different vintages and were re-processed together to obtain a homogeneous database. Thirty five of the seismic profiles were acquired in high resolution mode to allow interpretation of both top and base of the reservoir. The seismic quality in the area is such that it was often possible to also do this on the other seismic profiles. A total of 17 wells were available in the area to tie the seismic horizons, of which 13 wells are on the gas-field that were used to calibrate the top (and occasionally the base) of the reservoir.

In addition to the top and base reservoir horizons, three levels above the reservoir have been interpreted and seven levels below the reservoir have also been interpreted. The purpose of interpreting more than just the top and base of the Chalk reservoir was to establish a structural model from surface down to the Base Zechstein Salt. The main conclusion of this study was that on a regional scale, thickness variations exist in the Tertiary and Mesozoic sequences and that the Zechstein Salt layer varies in thickness over the area. Figure 1 is a structural map at Top Chalk level resulting from this study with the outline of the gas-reservoir indicated. Figure 2 is a seismic line crossing the field showing the thickness variations of the different layers.

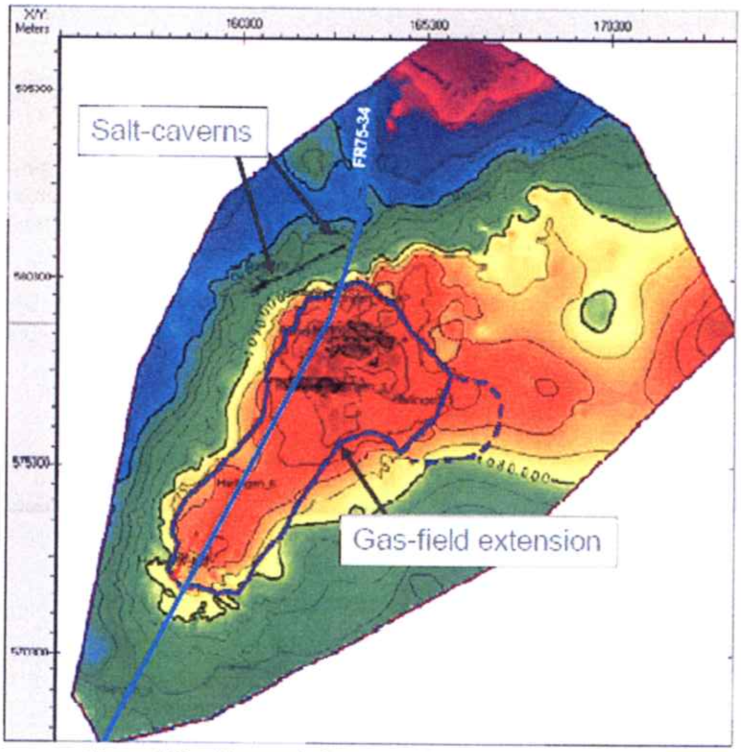


Figure 1 Top Reservoir Structural Map

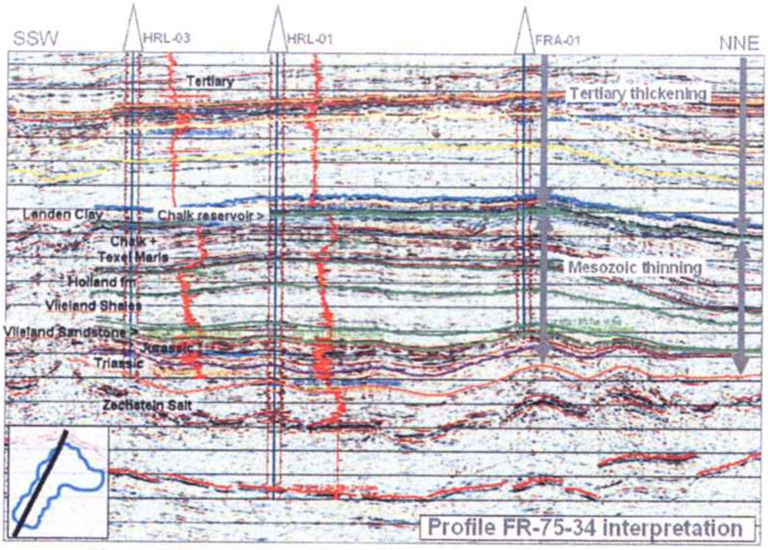


Figure 2 Seismic Line FR-75-34 (in blue on Figure 1)

In addition to the structuration of the layers, the petrophysical evaluation of the same layers was done for wells in the area in order to finalize the mechanical model. The logs used were the density log, the P-wave sonic log and wherever available, the S-wave sonic log. The resulting parameters were: density; bulk modulus; Young's modulus; and, Poisson's ratio. A correction had to be applied (refer to table 1 in the chapter on FE modeling) since these parameters are based on a dynamic investigation while static moduli are required.

2. Geology

A complete review of all the logs was performed with the purpose of establishing the layering (top and base) with corresponding lithology before the geological interpretation started. This was necessary for the chalk reservoir in particular to determine the porosity distribution and the water saturation profiles for each well. There were no wells where the minimum water saturation was calculated to be below 30%, Saturations below 30% may have consequences for the strength of the rock (see rock mechanics). Core plugs were taken from a number of wells and measurements of these samples were used to calibrate the logs.

Analyses of the reservoir chalk show a composition of the reservoir rock of 96-99% calcite, 1-4% quartz and 0-2% clay minerals. The chalk matrix is mainly composed of coccoliths. Good reservoir quality with the highest porosity is found in the upper few meters of the reservoir. Porosity ranges from more than 35% in the reservoir to less than 24% below the gas water contact (GWC). Good reservoir quality is due to early gas migration and the presence of the over-pressured gas preventing loss of porosity and permeability by diagenesis and compaction. This conclusion is supported by the high amount of intact coccoliths. Below the GWC a higher amount of calcite crystals can be observed. These may have been formed by recrystallization and could degrade the reservoir properties.

Average thickness of the reservoir is about 25m and all wells show that high porosities (ϕ>35%) occur only in the upper part of the Chalk in an interval of about 1.5m thickness. The highest porosities were found in the HRL-09 well, where porosities up to 40% were measured, albeit in a very thin layer. The remaining 22m of the reservoir has porosities between 28% and 35%. Porosities degrade continuously below the gas bearing reservoir, down to about 10% near the very base.

This information was used to develop the porosity model for input to the FE calculations. A statistical analysis was performed on the porosities calculated from the well logs. Sequential Gaussian Simulation was used to model the porosity distribution over the entire field based on the statistical analyses. Five layers were added for the porosity range above 35% because the very high porosities are averaged out by this statistical process. The maximum thickness for this layer is about 1.5m. A similar approach might be required for layers with porosities between 30 and 35% if the rock mechanical work indicates that these could also undergo pore collapse.

3. Rock Mechanical Studies

Gas production results in field pressure reduction and changes of the stress field in the reservoir and its surroundings. These stress field changes lead to deformation of the rock which is strongly dependent on porosity, particularly in the plastic deformation phase. The previous conventional subsidence models failed to properly describe the amount of subsidence. Therefore it was decided to perform additional lab tests in order to improve the rock mechanical model. The work is being carried out in three phases: phase 1 by the Liege University in Belgium; and phases 2; and 3, by the NGI in Oslo, Norway.

Pore collapse and creep occur following the elastic deformation phase and have a major impact on the cumulative deformation of the rock. The onset of pore collapse is dependent on porosity and the initial tests indicated that a threshold porosity of 35% exists below which pore collapse would not occur. However, further investigation into the literature has suggested that the onset of pore collapse may be loading rate dependent. Further lab tests designed to check for and quantify this effect have been initiated and are scheduled to be completed in October of 2010. The objective of these experiments is to test:

- whether the pore collapse threshold changes;
- by how much;
- when the deformation rate changes; and,
- the impact of creep following the pore collapse.

Water-saturation could be another important parameter affecting the amount of deformation. Tests by other labs have shown an incremental effect on deformation at increasing water-saturation with an upper limit of $S_w = 15\%$, above which no increase is observed. Since the minimum S_w in the Harlingen field is around 30%, no water saturation impact is expected. However this effect is still to be determined conclusively for the Harlingen gas field since threshold saturation has previously only been determined for oil-water boundaries.

The NGI core tests show that Biot's coefficient is close to 1.0. As a result the effect of the chalk grain compressibility can be ignored and all compaction will be the result of porosity reduction.

The results of all currently available measurements are presented in Figure 3 below. The experiments were carried out at loading rates of around 1 MPa/hour:

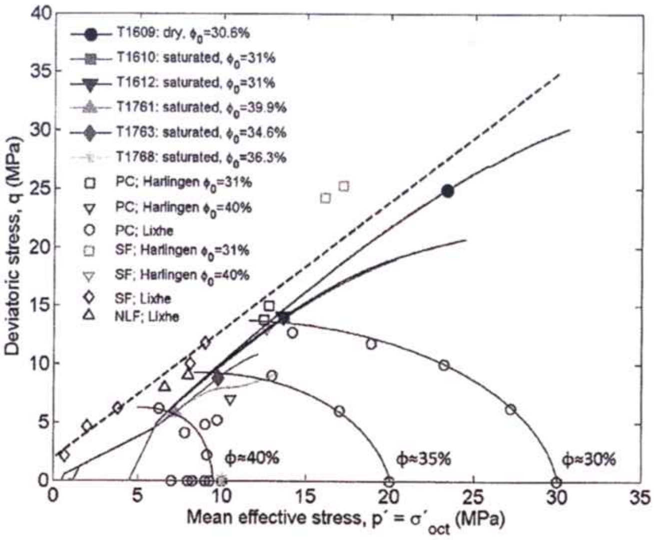


Figure 3 Pore Collapse Stress

Figure 3: Synthetic display of pore collapse stress levels and the indicative failure threshold for different porosities. Included here are stress levels and stress paths obtained by the two NGI studies (solid marks), and failure points from ULG's studies on Harlingen and Lixhe chalk (Schroeder, 2009). ULG data appear with empty markers. PC is short for pore collapse, SF denotes shear failure, and NLF mean non-localized failure. The dashed black annotation line marks the shear failure boundary, and is adapted to the Lixhe shear failure data by a linear fit.

4. Dynamical Modeling

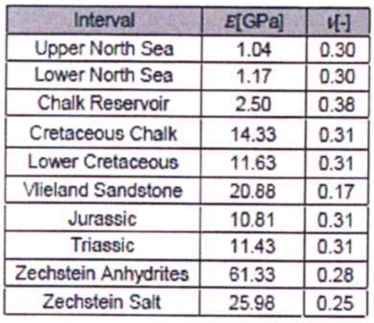
Stresses in the reservoir rock are dependent on the pressure changes due to gas-production. A dynamic reservoir model was history-matched to the well measurements taken up to the time production was stopped in mid 2008. Until recently it was believed that the history-matched dynamic model represented a good fit to actual pressure data. However, recent static pressure measurements of the wells taken approximately 2 years after the production was stopped show that the dynamic model needs to be fine tuned in order to match the post production build up history. A difficulty in history matching a reservoir like Harlingen is that it's generally low permeability implies that long static shut-ins are required to gain accurate information on reservoir pressure. The current plan is to fine tune the dynamic model to obtain a better fit. This is expected to be completed by October.

5. Finite Element Modeling

The geomechanical modeling is to be carried out in three phases:

- Data acquisition and geo-mechanical characterization;
- Two dimensional modeling to test sensitivity of the various parameters in combination with 2.5D AESubs modeling which will help determine the final inputs for the 3D modeling; and,
- Three dimensional FE modeling for final 3D subsidence calculations.

Phases 1 and 2 will be done with the 2.5D AESubs modeling code from TNO and are anticipated to be completed by October. Preparation of phase 3 is ongoing. Figure 4 shows the Young's modulus *E* and Poisson's ν per layer that have been used in the model.



Interval	*E*[GPa]	ν[-]
Upper North Sea	1.04	0.30
Lower North Sea	1.17	0.30
Chalk Reservoir	2.50	0.38
Cretaceous Chalk	14.33	0.31
Lower Cretaceous	11.63	0.31
Vlieland Sandstone	20.88	0.17
Jurassic	10.81	0.31
Triassic	11.43	0.31
Zechstein Anhydrites	61.33	0.28
Zechstein Salt	25.98	0.25

Figure 4 Elastic Moduli

These moduli have been derived from dynamic measurements and have been corrected for the difference between static and dynamic deformation processes.

Considerable attention was given to the visco-elastic response of the salt deformation. The main conclusion of this part of the study was that the mechanical properties of salt are not easily defined and most importantly need calibration against the surface subsidence measurements. This should be done in areas not affected by subsidence due to gas-production. Satellite imaging information is available through Delft University for this purpose. Calculations using the satellite data showed, amongst other things, coherency between leveling measurements and subsidence calculations based on satellite data. The 2D modeling showed that layering reflecting the actual regional thickness variations both vertically and laterally does affect the calculations. For the complete effect 3D FE calculations are necessary.

Initial modeling of subsidence due to gas-production showed that elastic deformation alone is not sufficient to explain the subsidence observed above the field. Taking pore collapse into account also does not lead to the observed subsidence levels. These calculations are currently based on a pore-collapse threshold of 35%. This may well change once the final lab measurements by the NGI are available. It has been demonstrated that loading rate and creep following pore-collapse, have an important impact on the deformation process and that they can contribute to a large amount of the overall subsidence. Whether this is sufficient to explain the measured subsidence still remains to be tested by the 2.5D AESubs model and ultimately by the 3D calculations based on the final lab deformation model.

6. References

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