Modifications of the Geological model for Site response at the Groningen Field

Deltares

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Editors Jan van Elk & Dirk Doornhof

General Introduction

The accelerations experienced at surface as a result of earthquakes induced by the production of gas from the Groningen field are locally dependent on the shallow geological and soil conditions. This is called the site response effect. NAM has therefore asked Deltares to build a detailed model of the shallow subsurface below Groningen.

A report describing the quaternary geology of the Groningen area was prepared by Deltares in June 2015 (Ref. 1 to 3). In preparing this model of the shallow subsurface below Groningen, Deltares has made use of the beta-version of the GEOTOP database of TNO Geologische Dienst Nederland (GDN) supplemented by more recent data. Additional data collected over the years in support of foundation design and other construction activities was sourced from Fugro and Wiertsema. These are mainly CPT measurements (cone penetrations tests). Additionally, geological data measured in the shallow geophone wells was used. This report documents modifications to the study published in June 2015 (Ref. 1 to 3) relating to the minimum size of geological zones, surface water, the increase in the depth of the reference base rock horizon and is aligned with the release of the official version of the GeoTOP 3D geological voxel model of the region.

Following the geological study, Deltares has performed site response measurements near the geophone and accelerometer stations of the extended geophone network (Ref. 4). Measurements with the flexible geophone network will be used in further development of the model for the shallow subsurface.

As an introduction to the quaternary geology of the Groningen area, Erik Meijles of the Rijksuniversiteit Groningen has written a report titled: "De ondergrond van Groningen: een geologische geschiedenis" (Ref. 5).

References:

1 Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part I, Deltares, Pauline Kruiver and Ger de Lange, June 2015.

2 Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part II, Deltares, Pauline Kruiver and Ger de Lange, June 2015.

3 Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part III, Deltares, Pauline Kruiver and Ger de Lange, June 2015.

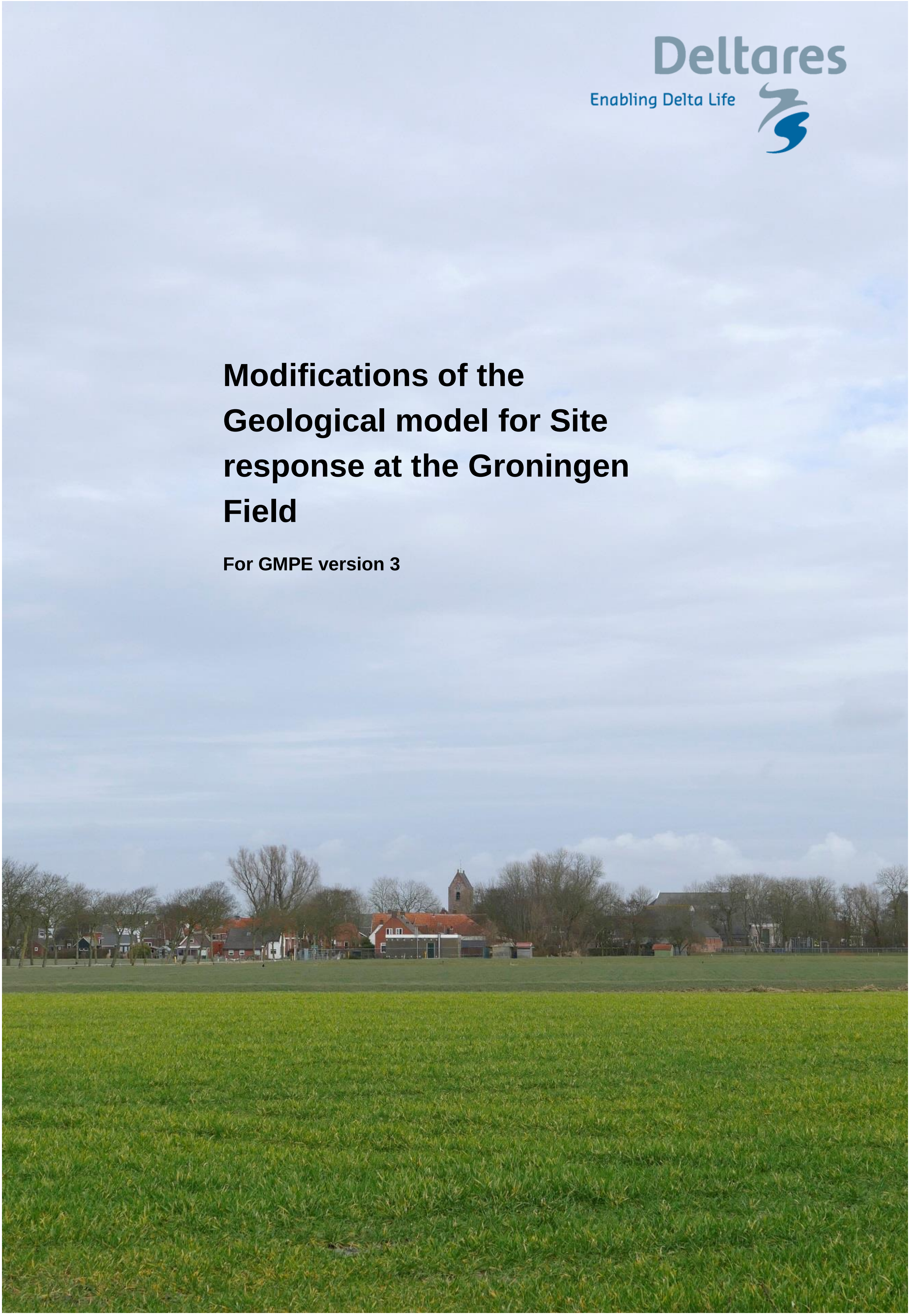
4 Geophysical Measurements of shear wave velocity at KNMI accelerograph stations in the Groningen field area, Deltares, Marco de Kleine, Rik Noorlandt, Ger de Lange, Marios Karaoulis and Pauline Kruiver, July 2016.

5 De ondergrond van Groningen: een Geologische Geschiedenis, Erik Meijles, April 2015.

These reports are also available at the study reports page of the website www.namplatform.nl.

NAM

Title	**Modifications of the Geological model for Site response at the Groningen Field**	**Date**	June 2016
		Initiator	NAM
Autor(s)	Pauline Kruiver, Ane Wiersma	**Editors**	Jan van Elk Dirk Doornhof
Organisation	Deltares	**Organisation**	NAM
Place in the Study and Data Acquisition Plan	Study Theme Comment: The accelerations experienced at surface as a result of the earthquakes induced by the production of gas from the Groningen field are locally dependent on the shallow geological and soil conditions. This is called the site response effect. NAM has therefore asked Deltares to build a detailed model of the shallow subsurface below Groningen.		
Directly linked research	Introductory text: "De ondergrond van Groningen: een geologische geschiedenis" by Erik Meijles of the Rijksuniversiteit Groningen Site-Response measurements near the geophone / accelerometer stations of the extended monitoring network.		
Used data	Official version of the GeoTOP 3D geological voxel model of the region and CPT data sourced through Fugro and Wiertsema.		
Associated organisations	Department of geography of the natural environment of the Rijksuniversiteit Groningen TNO Geologische Dienst Nederland (GDN)		
Assurance	The work by Deltares has been reviewed by a team of independent experts in quaternary geology; Adriaan Janszen (Exxonmobil), Eric Meijles (Rijskuniversiteit Groningen) and Joep Storms (TU Delft).		



Modifications of the Geological model for Site response at the Groningen Field

For GMPE version 3

Photo cover: Hans Sas Fotografie

Deltares

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Title
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Client	Project	Reference	Pages
Nederlandse Aardolie Maatschappij B.V.	1209862-005	1209862-005-GEO-0009	19

Keywords
Shallow geology, heterogeneity, earthquakes, subsurface model, site response, Groningen Province

Summary
The **G**eological model for the **S**ite response at the **G**roningen Field (GSG-model) was constructed to serve as one of the inputs for the site response calculations in the Ground Motion Prediction Equation (GMPE) for Groningen. Version 1 of the GSG model was described in Kruiver et al. (2015). For the GMPE version 3, several modifications to the original GSG model are documented in this report. The modifications are related to the minimum size of geological zones, surface water, the increase in the depth of the reference baserock horizon, the release of the official version of the GeoTOP 3D geological voxel model of the region and the amplification behaviour in GMPE version 2 (Bommer et al., 2015) and GMPE version 3 (Bommer et al., 2016).

Reference
Contract UI46802 “Studies on the soil in Groningen”

Version	Date	Author	Initials	Review	Initials	Approval	Initials
2	24 June 2016	Pauline Kruiver		Bert van der Valk		Bob Hoogendoorn	
		Ane Wiersma					

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Contents

1 Introduction

The NAM performs a seismic hazard and risk analysis for the Groningen gas field for the updated “Winningsplan”, to be submitted in 2016. Part of the seismic hazard and risk analysis is formed by the Ground Motion Prediction Equation (GMPE). As input for the site response within the GMPE, Deltares has constructed the **G**eological model for the **S**ite response at the **G**roningen Field (GSG-model). The first version of this model is extensively reviewed by an external committee of experts. This version is described in the Deltares report “Geological schematisation of the shallow subsurface of Groningen - For site response to earthquakes for the Groningen gas field” (report nr. 1209862-005_GEO-004-v5, 16 March 2105, referred to as Kruiver et al., 2015).

Recent developments, such as the requirements for GMPE version 2 (Bommer et al., 2015) and the release of the official GeoTOP model for the Groningen region by TNO Geological Survey of the Netherlands, induced the modification of the GSG model version 1. This document describes the modifications to the GSG model.

Chapter 2 gives a summary of the GSG model version 1. Chapter 3 describes the modifications of the GSG model version 1 for the application in the GMPE version 2. Chapter 4 describes the results of the quick-scan that was performed to assess the changes between the beta version of GeoTOP (used in GMPE version 2) and the official release of GeoTOP at the end of December 2015 (used in GMPE version 3). It also includes the current latest version of the GSG model (version 3). Other modifications are described in chapter 5. Recommendations are given in chapter 6.

The modified GSG model is used in the GMPE version 3 (June 2016, Bommer et al., 2016).

2 Summary GSG model version 1

The Geological model for the Site response at the Groningen Field (GSG-model) has been constructed between September 2014 and March 2015 and was based on the then available information. It has been reported as Kruiver et al. (2015) and is summarised in this chapter.

Data sources consisted of the borehole records from the DINO database, cone penetration tests (CPT) from the DINO database and from two contractors (Fugro and Wiertsema en Partners), seismic CPTs, the beta version of GeoTOP Oostelijke Wadden (September 2014), Digital Geological Model (DGM version v2.2, 2014), Regional Geohydrological Information System II (REGIS II, version v2.1, 2008), digital terrain model (AHN), borehole logs, palaeogeographic maps, fault maps and salt dome maps. The GeoTOP model is a 3D geological model of voxels of 100 m x 100 m in horizontal direction, and 0.5 m thickness with a maximum depth of 50 m below Dutch Ordnance Datum (NAP) (Stafleu et al, 2012).

The region of the Groningen gas field, including a 5 km buffer, was divided into zones with similar geological build-up. Within each zone a similar site response is expected, due to the similar composition and soil properties. Due to the maximum depth range of GeoTOP of NAP-50 m, the GSG model version 1 consists of two depth ranges:

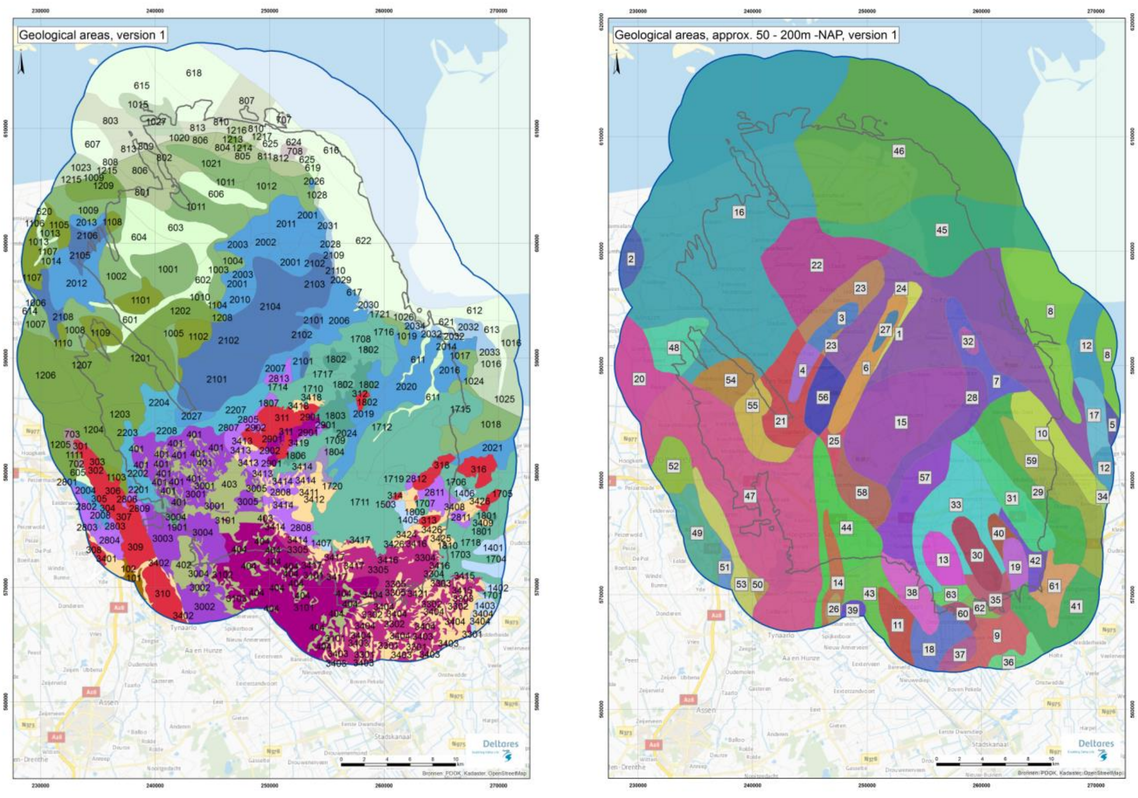

Figure 2.1 Left: geological zonation of the GSG model (version 1, Kruiver et al., 2015) for the surface to NAP-50m depth range (left). Similar colours indicate similar characteristic succession (profile type, see legend in Figure 3.2). Right: geological zonation of the GSG model in the NAP-50 m to NAP-200 m depth range. Colours are arbitrary for this depth range.

1. From surface to NAP-50 m. The zonation is shown in Figure 2.1 (left panel). The voxels contain the lithostratigraphy and lithoclass from GeoTOP.
2. From NAP-50 m to NAP-200 m, or to the base of the Peelo formation (max 235 m) when that is deeper. The zonation is shown in Figure 2.1 (right panel). The layering and infill consist of scenarios of probable successions, accompanied by the probability of occurrence of the scenarios.

The soil columns that form the input for the site response calculations are a combination of the GeoTOP voxel stack at one x-y coordinate, appended with a layering model between 50 m and 200 m taking into account the zonation of Figure 2.1 (right panel) and probabilities of the scenarios.

3 Modifications of the GSG model for GMPE version 2

In order to use the GSG model version 1 towards the GMPE version 2, several modifications were made. The first modification was done before the site response calculations were performed. Three other modifications were done based on the site response results. The modifications are listed below.

The modification that was required before the site response calculations could be performed was related to the maximum depth of the model:

1. The original GSG model version 1 had a maximum depth extent of 200 m to 235 m. The reference baserock horizon for GMPE version 2, however, was placed at the base of the Upper North Sea Group (NU_B). This level corresponds to the base of the Formation of Breda and is present at ~340 m on average in the area of interest. To accommodate this increase in depth, the scenarios were extended using DGM v2.2 (2014) and REGIS II (version v2.1, 2008). In effect, two geological model units were added to the scenarios, the Formation of Oosterhout and the Formation of Breda.

The other three modifications were made after the site calculations were performed. The three modifications were (Bommer et al., 2015):

2. Merging of very small zones (< 50 voxel stacks) with one of its neighbouring zones. The selection of the zone to be merged with was based on geology (profile type) and similar characteristics in the amplification function (AF).
3. Merging of patchy zones in the southern part of the region (see Figure 2.1, left). AF results for the patchy zones and the zones in which the patches are embedded did not differ significantly. Therefore, the zones were merged into larger zones with more regular outlines.
4. Excluding zones situated in the Wadden Sea (northern and north-eastern part of the area of interest).

The resulting modified geological zonation map for GMPE version 2 is shown in Figure 3.1 and is referred to as GSG model version 2. The deep zonation (Figure 2.1, right panel) was not modified.

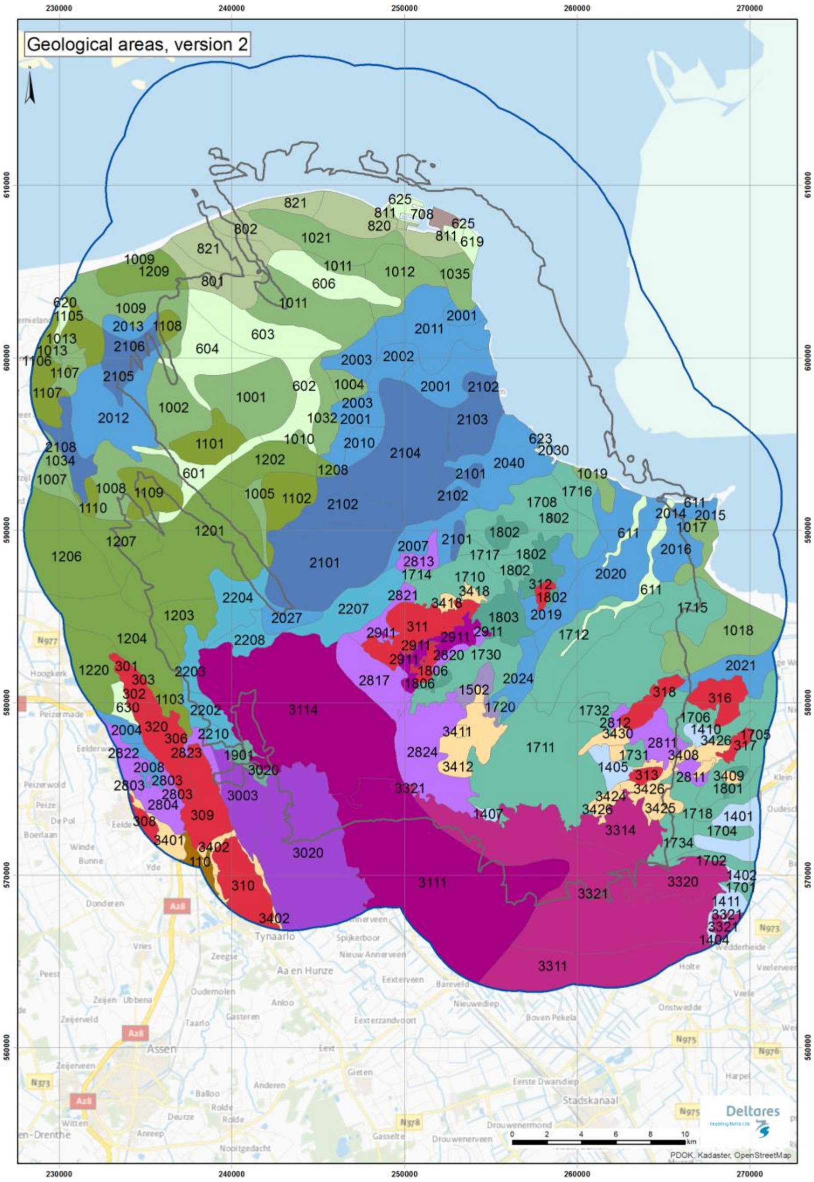

Figure 3.1 Modified map (version 2) of geological zones for the surface to NAP-50 m depth range for the Groningen gas field and 5 km buffer, used for GMPE version 2. Identical colours indicate similar geological build-up. The first 1-2 digits denote the profile type (for legend, see Figure 3.2), the last 2 digits represents a serial number.

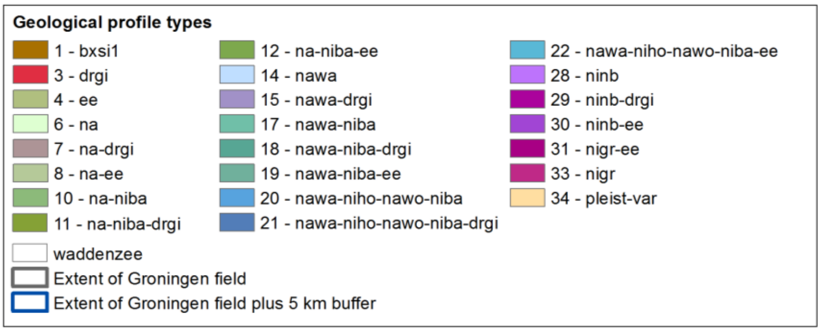

Figure 3.2 Legend to the map of geological areas for the surface to NAP-50 m depth range for the Groningen gas field and 5 km buffer.

4 Summary of GeoTOP official release

4.1 Introduction

The GSG model version 1 was based on the then available beta version of the GeoTOP Eastern Wadden (Oostelijke Wadden, v0.9). During the course of the NAM project, the GeoTOP model was improved and quality checked by TNO Geological Survey of the Netherlands. During the derivation of GMPE version 2 (released in October 2015, Bommer et al., 2015), this beta version was used.

At the end of 2015, TNO released the official version of GeoTOP Eastern Wadden (v1.3) which is available to the public via www.dinoloket.nl. The GMPE version 3 uses the official version of GeoTOP (version 1.3).

Relevant improvements from the beta version to the official version are the following:

1. Changes in potential lateral extent of model units.
2. Changes in interpretations of borehole data, partly based on changes in potential lateral extent.
3. Optimization of the modelling method of the top and base of several model units.
4. Modifications in the modelling method of thin model units, leading to thinner and less continuous layers.
5. Changes in the modelling approach for the lithoclass model of the Peelo model unit.

A combination of the changes mentioned above causes differences in the geometry of model units and thus in the actual extent of the model units. Within these model units, the subsequent lithoclass infill (e.g. clay, sand, peat) has also changed.

The zonation of GSG model version 1, however, was not solely based on the beta version of GeoTOP. Therefore, changes in potential lateral extents of model units could not be applied to the new GSG model directly and careful consideration was required. In order to be able to use the new GeoTOP model in the GMPE version 3 (with its own planning and deadlines), we performed a quick-scan to assess the impact of the differences between the beta and the official version of GeoTOP (§4.2 to §4.4). As a result, we made adjustments to a limited number of geological zones, resulting in a new geological zonation map (§4.5).

4.2 Potential lateral extent of model units and borehole interpretations

The potential lateral extents of several model units were modified between the beta and the official version of GeoTOP. These changes are based on:

1. Changes in the conceptual geological model;
2. Improved insight in the geological architecture of the Eastern Wadden area;
3. Changes in model set-up to better represent the composition of the subsurface within the lithoclass model.

The changes in potential lateral extent were effectuated in conjunction with changes in borehole data interpretation as an iterative process. The potential lateral extents of the following model units have been changed:

- Nieuwkoop Formation, Hollandveen Member (NIHO). The main changes are in the eastern part of the GSG model area (Figure 4.1, left panels).
- Nieuwkoop Formation, Basal Peat Bed (NIBA). The main changes are in the eastern part of the GSG model area (Figure 4.1, right panels).
- Naaldwijk Formation, Walcheren Member (NAWA). The main changes are in the eastern part of the GSG model area (Figure 4.2, left panels).
- Naaldwijk Formation, Wormer Member (NAWO). Large changes are present in the entire GSG model area (Figure 4.2, right panels). The lower clayey unit (Hefswal Bed) was previously incorporated in the undifferentiated Naaldwijk Formation (NA), but is now incorporated into the NAWO model unit to more accurately represent this unit in the lithoclass model.
- Naaldwijk Formation, undifferentiated (NA). There are limited changes in the eastern part of the GSG model area (Figure 4.3). The incorporation of the Hefswal Bed in the NAWO model unit has had limited or no effect on the potential lateral extent of the NA model unit as it is nearly always overlain by it.
- Drente Formation, Gieten Member (DRGI), only small changes in several areas.

Several other model units have had minor improvements and are not individually mentioned as they have limited effects on the GSG model or their impact in the lithoclass calculation is not significant.

4.3 Optimized modelling method geometry of model units and model results

In the official version, a modification of the modelling method determining the thickness and continuity of model units has been implemented. This modification is implemented for several relatively thin model units: from the Nieuwkoop model units these were the Hollandveen Mb. (NIHO), Basal Peat Bed (NIBA), Griendtsveen Mb. (NIGR) and Nijbeets Mb. (NINB). Additionally, the Boxtel Formation Singraven1 Mb. model unit (BXSI1) was also modified. This modification was implemented to reduce the overrepresentation of these model units. The result is that the modelled model units better match the interpreted boreholes and the units are usually thinner. As these model units are primarily composed of peat, this change resulted in a lower contribution of peat in the lithoclass model.

The potential lateral extent and the interpreted boreholes are used to interpolate the individual model units, resulting in an actual lateral extent based on the modelled geometry with a top, base and resulting thickness of each model unit. The actual extent differs from the potential extent: a model unit can for instance be eroded by the unit above and therefore be absent in the actual extent. Since both the potential lateral extent and the modelling and labelling have been modified, the actual extent of the model units in the official version 1.3 will also differ from the beta version 0.9 of GeoTOP. The lower panels of Figure 4.1 to Figure 4.3 show the difference in modelled thickness between the Beta (v0.9) and official version (v1.3). The difference is calculated only for locations where the model unit is present in both model versions.

The geometries of the model units are converted to a voxel model and subsequently used as boundary conditions for the lithoclass model. Changes in the geometries therefore directly influence the lithoclass model. For example, the Basal Peat Bed (NIBA) is thinner in large areas in the eastern part of the GSG area. As it is nearly completely composed of peat, the presence of peat in the lithoclass model is also less.

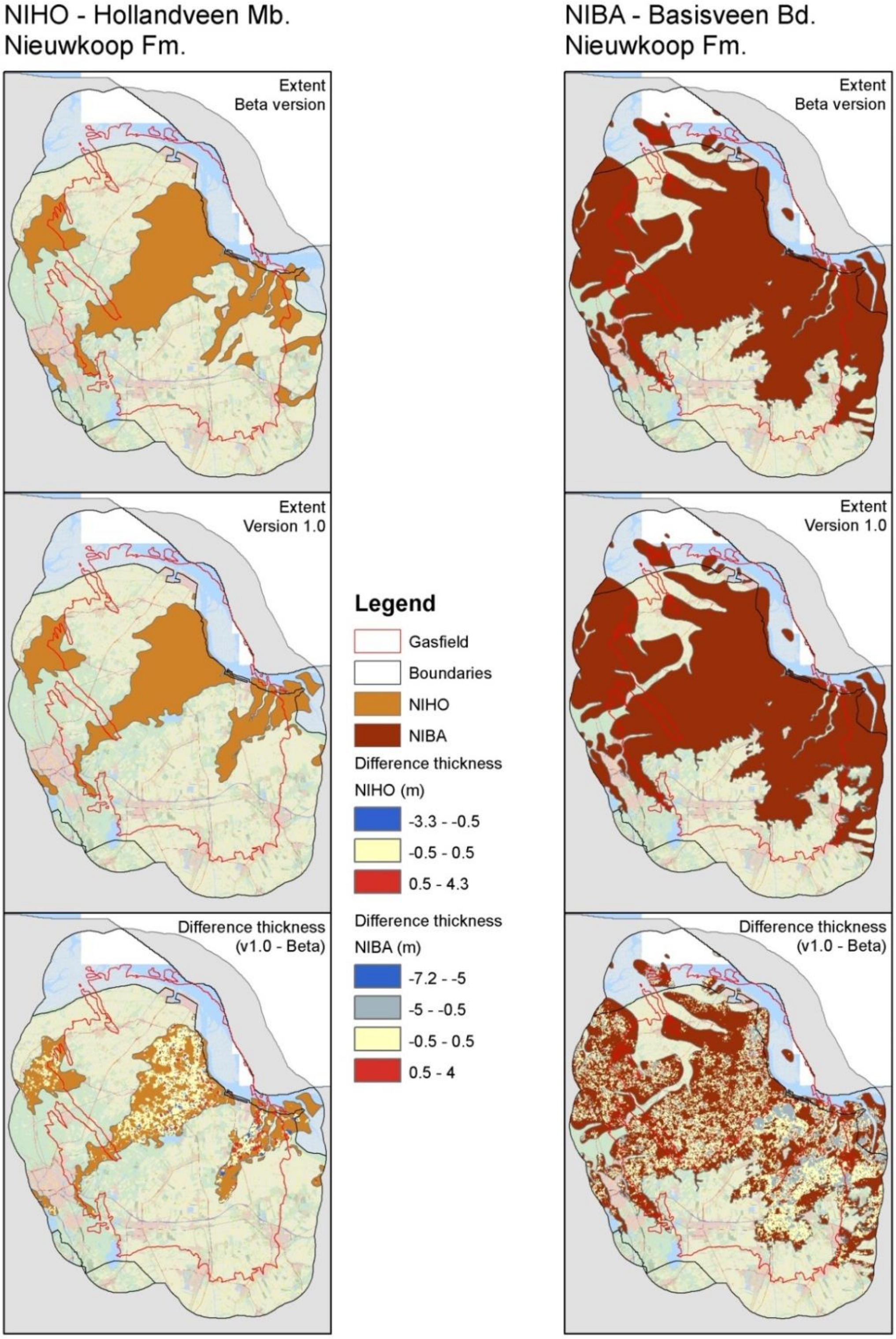

Figure 4.1 Modifications in the potential lateral extent of the Holland Peat Mb. (left) and Basal Peat Bed (right). Upper panels show the Beta (v0.9) version, centre panels show the released (v1.3) version. The lower panels show the calculated difference in thickness between both model versions for locations with modelled thickness in both model versions (colour scale of blue, yellow and red), plotted on top of the v1.3 extent (two shades of brown for NIHO and NIBA).

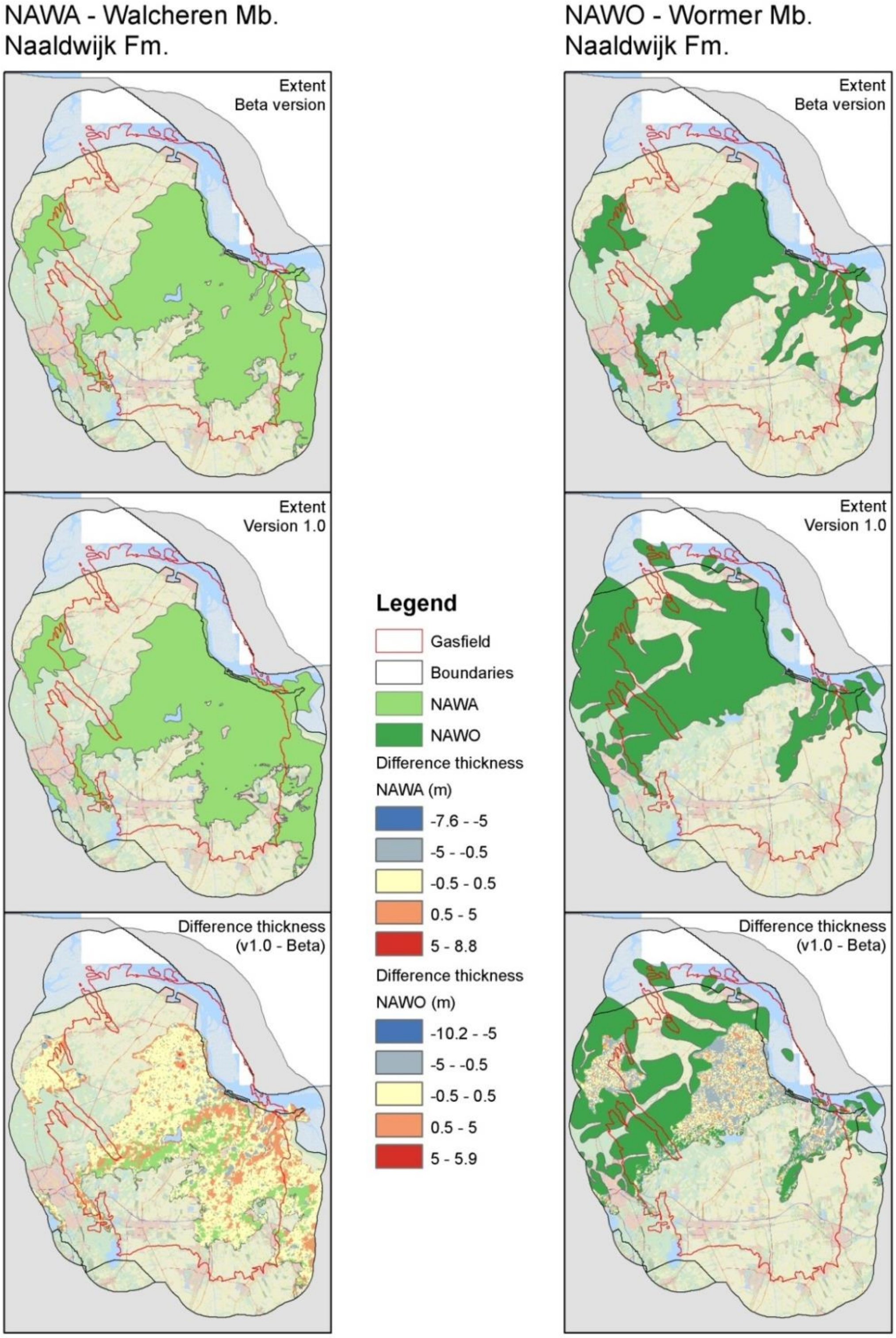

Figure 4.2. Modifications in the potential lateral extent of the Walcheren Mb. (NAWA, left) and Wormer Mb. (NAWO, right). Upper panels show the Beta (v0.9) version, centre panels show the released (v1.3) version. The lower panels show the calculated difference in thickness between both model versions for locations with modelled thickness in both model versions (colour scale of blue, yellow, orange and red), plotted on top of the v1.3 extent (two shades of green for NAWA and NAWO).

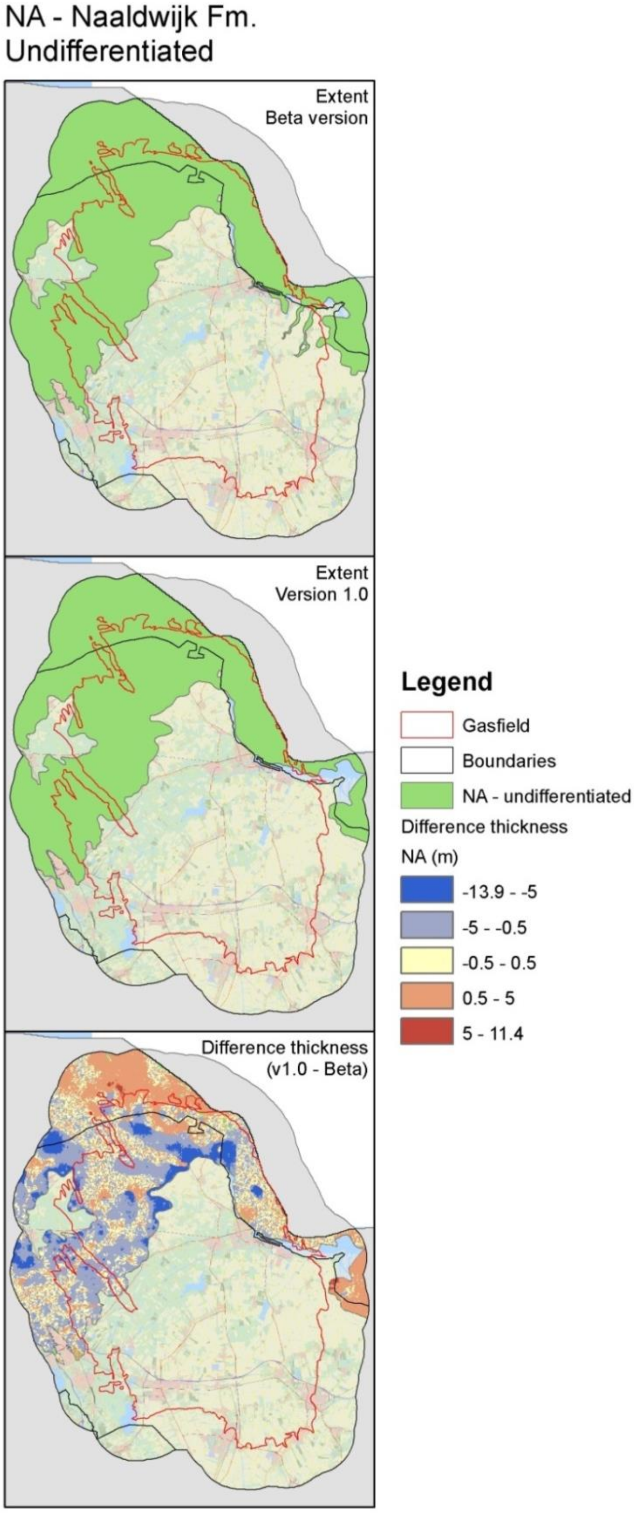

Figure 4.3. Modifications in the potential lateral extent of the Naaldwijk Fm. Undifferentiated. Upper panel shows the Beta (v0.9) version, centre panel shows the released (v1.3) version. The lower panels show the calculated difference in thickness between both model versions for locations with modelled thickness in both model versions (colour scale of blue, yellow orange and red), plotted on top of the v1.3 extent.

4.4 Improved modelling approach for lithoclass model of Peelo Formation

The Peelo Formation model unit is known for its thick intervals composed of hard clay, occasionally with some sandy beds, embedded in a clean sandy matrix. Due to low data densities in the deeper part of the GeoTOP Eastern Wadden model, the characteristic of two lithological end-members with a strong spatial component was not accurately represented in v0.9. The top panel of Figure 4.4 shows that large volumes of the Peelo Formation model unit had an unrealistic infill with an unnatural random distribution between sand and clay.

To resolve this issue, a novel modelling method was implemented in v1.3. Based on the newly updated geometry of the hydrogeological model REGIS II v2.2, the top and base of regionally mappable clayey units within the Peelo Formation (REGIS units PE-k-1 and PE-k-2) were used to guide the lithoclass infill. Clay and sandy clay were preferably present within these clayey REGIS units, whereas the sandy lithoclasses preferably occurred outside these units. The result was a strong reduction in the random infill in v1.3 (lower panel of Figure 4.4).

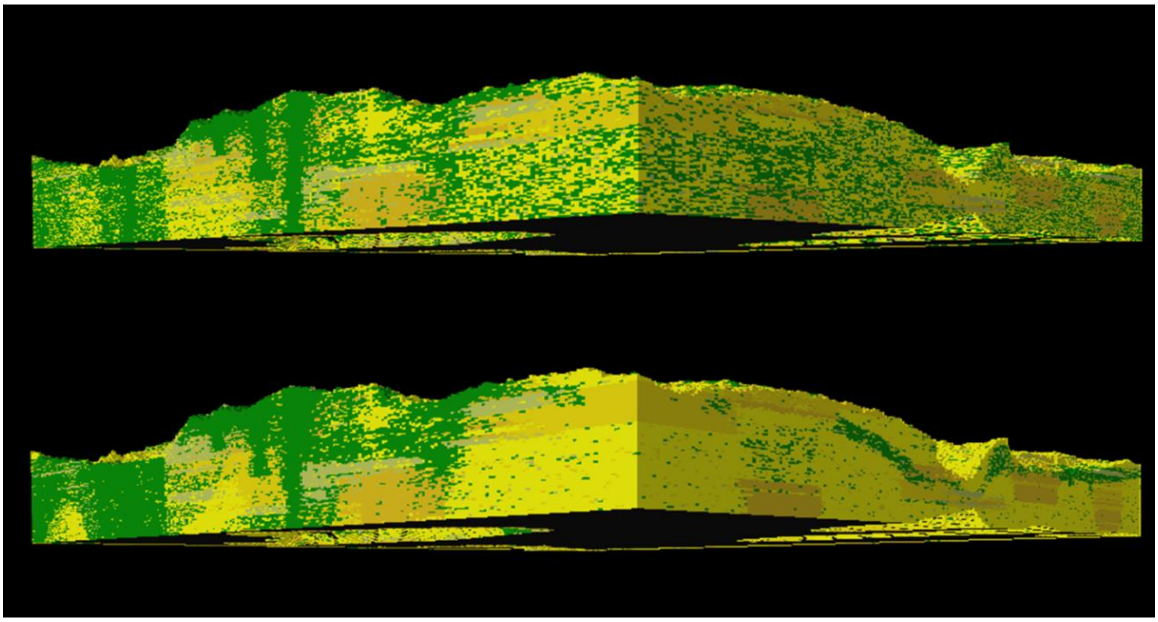

Figure 4.4 Effect of the modification in the Peelo Formation, indicated by a comparison of the lithoclass infill for an arbitrary location in the Groningen field (yellow and orange = sand, green = clay). Top panel: GeoTOP Beta version 0.9. Bottom panel: GeoTOP official release version 1.3. The lithoclass infill in the beta version is much more random than in the official release.

4.5 Modifications of geological zones in GSG model

Due to the changes between the beta version and the official release, described in §4.2 to §4.4, several geological zones were modified as they did not represent a characteristic geological sequence anymore. Modifications were made, because of changes in extents of Formations, the new presence or absence of typical layers. As a result, new boundaries were located in the middle of an old zone, and thus zones were merged or split. Approximately 16 zones were redefined. The resulting new geological zonation for the surface to NAP-50m depth range is shown in Figure 4.5. This zonation was the starting point for GMPE version 3 (GSG version 3A). Five further modifications were made to the zonation as a result of distinct and consistent patterns over various oscillator periods in amplification factor results, (Bommer et al., 2016). The final zonation for GMPE 3 (GSG version 3C) is shown in Figure 4.6.

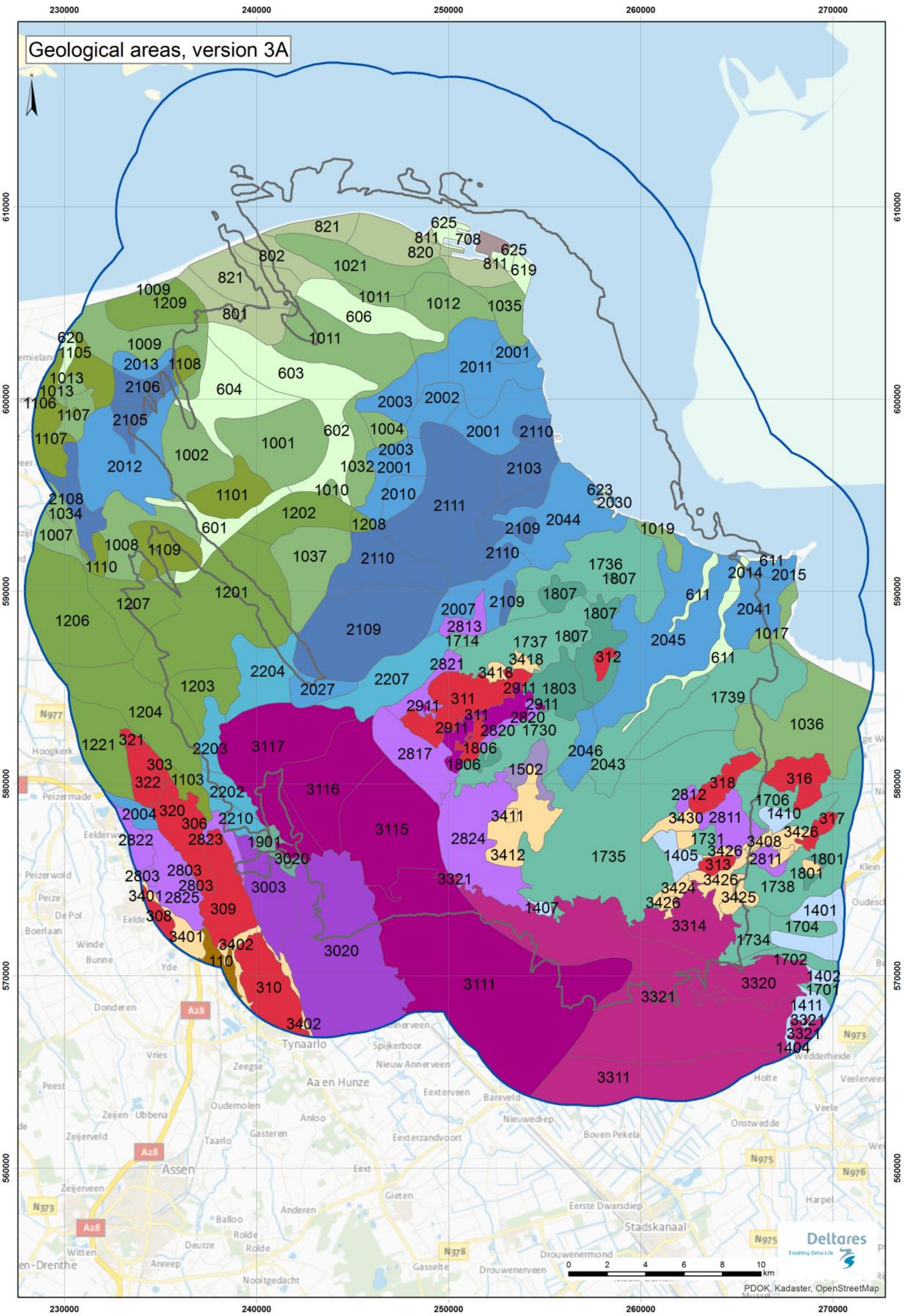

Figure 4.5 Modified map (version 3A) of geological zones for the surface to NAP-50 m depth range for the Groningen gas field and 5 km buffer, used as a starting point for the zonation in GMPE version 3. Identical colours indicate similar geological build-up. The first 1-2 digits denote the profile type (for legend, see Figure 3.2), the last 2 digits represents a serial number.

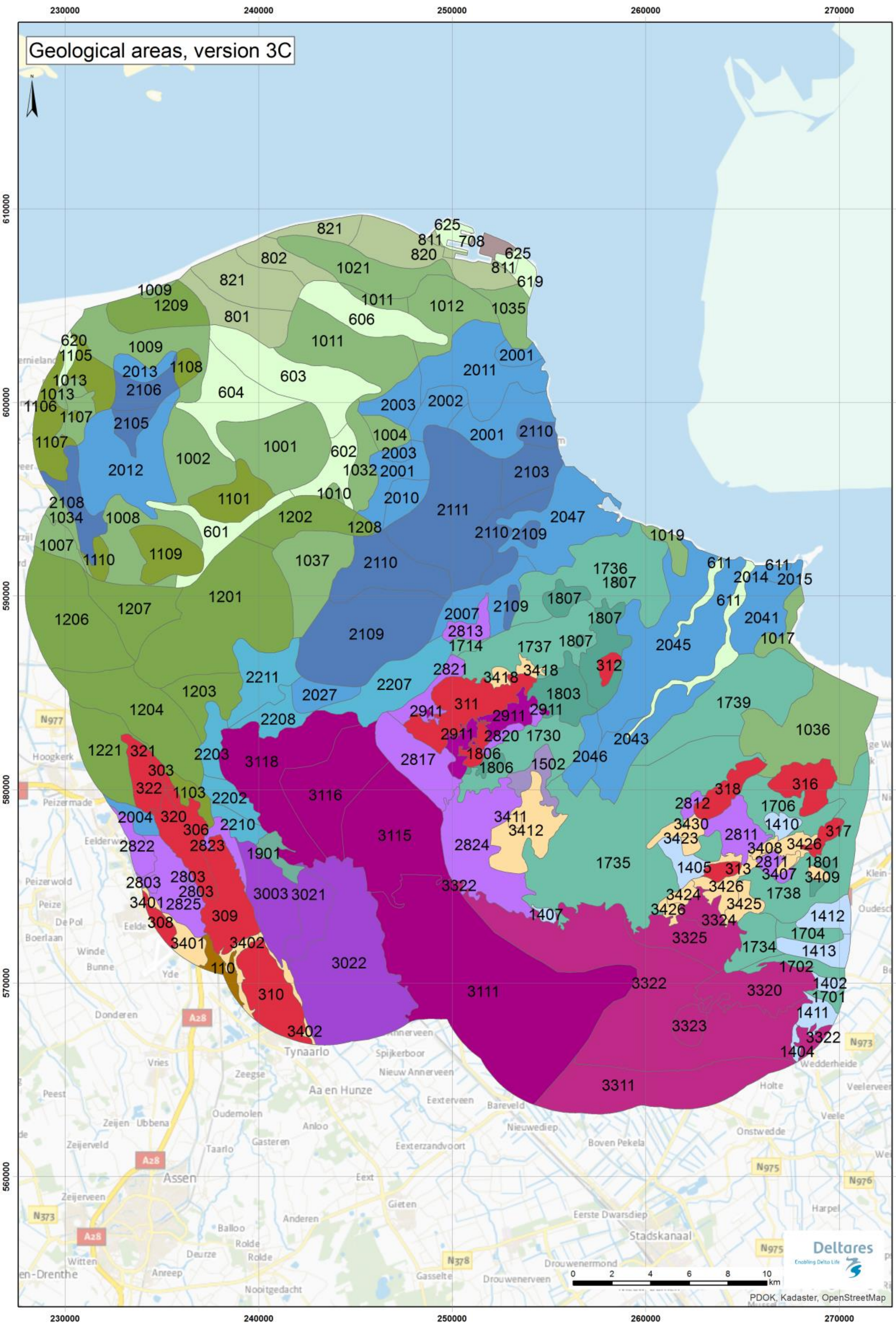

Figure 4.6 Final zonation for GMPE version 3 (Bommer et al., 2016). Identical colours indicate similar geological build-up. The first 1-2 digits denote the profile type (for legend, see Figure 3.2), the last 2 digits represents a serial number.

5 Other modifications of the GSG model for GMPE version 3

5.1 Reference baserock horizon

The reference baserock horizon in GMPE version 2 was located at the base of the Upper North Sea Group, NU_B. However, there is no impedance contrast present at that level. For GMPE version 3, therefore, the reference baserock horizon was lowered to the base of the Lower North Sea Group (NS_B), at ~ 800 m depth (Figure 5.1). At that level, there is a large impedance contrast due to the transition from the Lower North Sea Group to the Chalk Group. There is relatively little geological information available for the Lower North Sea Group.

For the Lower North Sea Group, linear soil behaviour is assumed because of the small strains and large confining stresses at these depths (pers. comm. Adrian Rodriguez-Marek). Therefore, the Lower North Sea Group will be regarded as one layer with homogeneous properties in terms of unit weight and damping. The only parameter that varies with depth and location is V_S. Information on V_S comes from the NAM model based on the sonic logs in Groningen.

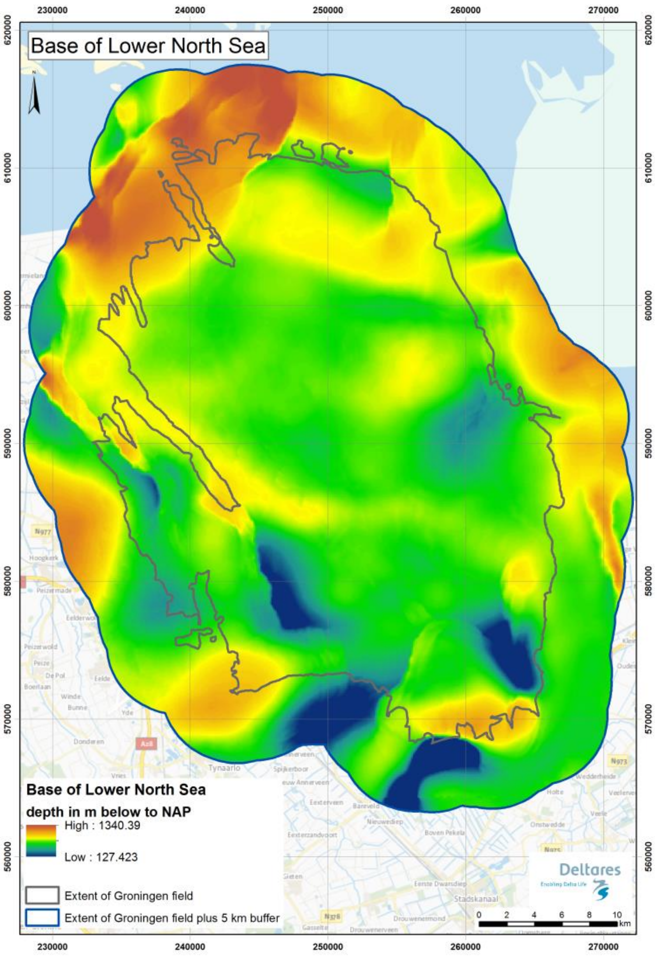

Figure 5.1 Depth of the reference baserock horizon NS_B (Base of the Lower North Sea Group). Source: NAM.

5.2 Merging between GeoTOP and scenario depth ranges

In order to construct the input files for the site response calculations, vertical stacks of layers through the model are required. For this, the layer models from the two depth ranges are merged. On the transition between the models, geological inconsistencies can occur.

We checked the merged layer files for logical geological successions. The only inconsistency found is the succession of Formation of Appelscha forming the base of the GeoTOP depth range that is followed by the Peelo Formation forming the top of the deeper scenario depth range. This order of Formations is incorrect, since the Peelo Formation is younger than the Formation of Appelscha. This order originated from the differences in the approach in the construction of the models for the different depth ranges and the limited amount of scenarios in the deeper depth range.

This inconsistency was solved by replacing lithofacies representing the Peelo Formation in the deeper scenario by the unit below it (Figure 5.2). This modification was done for ~ 7% of the voxel stacks. A limitation of this method is that the replacement might be incorrect and the Peelo Formation is actually present. The implications are estimated to be minor, because the composition and corresponding parameters for the Formation that replace the Peelo Formation are similar. In addition, the limited amount of scenarios for the deeper subsurface will result in larger uncertainties.

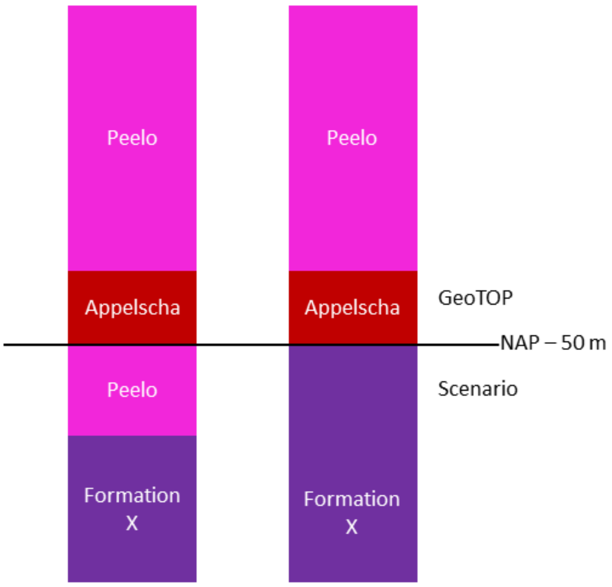

Figure 5.2 Correction of inconsistency during the merging of GeoTOP and scenario depth range. Left: original merge; right: corrected merge.

6 Recommendations

GSG model versions 1, 2 and 3 are all based on two separate depth ranges that are merged before the site response calculations can be performed. Because of the separate models, inconsistencies can occur at the transition of the models, as described in §5.2. Additionally, there is a difference in uncertainty between the models. The GeoTOP model is a full geostatistical model, whereas the layering and composition below NAP-50 m is much less known. This is reflected by the scenarios: in one deep zone, more than one scenario can be defined with associated probability of occurrence. The GSG model can be improved by building an integrated 3D geological model over the full depth range of interest. We recommend to closely follow the current developments of TNO Geological Survey of the Netherlands of improving their Digital Geological Model (DGM) including the extension to much deeper geology. Additionally, an inventory of existing public and Shell/NAM shallow seismics can shed light in the feasibility to reprocess these data in order to better pinpoint the location and depth of relevant geological structures, primarily the erosional tunnel valleys belonging to the Peelo Formation. Additionally, new deep boreholes of sufficient quality and with proper lithological description spanning the gap between the shallow (<100m) and real deep (>1000m) subsurface will increase our understanding of the intermediate subsurface and the quality of the models representing this.

The Rijksuniversiteit Groningen (RUG) recently performed a study for NAM on dwelling mounds in the Groningen region (Meijles et al., 2016). This information was not used in GMPE version 3. Therefore, we recommend extending this study and including the information on dwelling mounds in a next version of the GSG model and GMPE. This includes not only information on the location, thickness, composition and degree of heterogeneity, but also on the properties, such as shear wave velocity (V_S) and geomechanical properties.

A References

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