Vs30 map of the Netherlands

Update of the proof-of-concept map of 2022

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Contents

1 Introduction

1.1 The update

This report is an update of the TNO 2022 R10324 report entitled *Ideation Challenge 2020: RHINOCEROS - Regional sHear-wave velocIty modelliNg fOr seismiC sitE RespOnSe - Final scientific report* (Stafleu et al., 2022a). This report accompanies a set of maps of the onshore part of the Netherlands showing the average shear wave velocity of the upper 30 m of the subsurface (Vs_{30}). The maps are based on the GeoTOP model of the shallow subsurface, version v1.4, combined with both Vs-measurements and modelling methods from Kruiver et al. (2017a, 2017b). Since 2022, three updates of GeoTOP have been published:

- GeoTOP v1.4.1: an improved lithological class distribution of the model area ‘Zuid-Holland’;
- GeoTOP v.1.5: model areas ‘Zeeland’ and ‘Goeree-Overflakkee’ have been replaced with an entirely new and combined model area ‘Zeeland and Goeree-Overflakkee’.
- GeoTOP v1.6: an extension of GeoTOP to include the new model area ‘Almere’ encompassing the south-western Flevopolder and parts of the surrounding waters.

GeoTOP now covers about 71% of the onshore part of Netherlands. In the eastern part of the Netherlands (a large part of Lake IJssel and the Flevopolders, Drenthe, Overijssel and parts of Gelderland), GeoTOP is still under construction. The same accounts for the southern part of Limburg.

It will take some years before the GeoTOP model reaches full national coverage. Following the recommendation in the original report, we used the NL3D model to complement the Vs_{30} map in areas where GeoTOP is not yet available. NL3D is a model very similar to GeoTOP, but with a lower resolution and a much simpler construction method (Van der Meulen et al., 2013). The model is less detailed and less accurate than GeoTOP, but still provides a sound basis for a Vs_{30} map on a national to regional scale. The update uses the latest version of NL3D (v2.0) which became available in 2024 (Stafleu & De Bruijn, 2024).

In summary, the update described in this report aims at creating new Vs_{30} maps using (a) the latest version of GeoTOP (v1.6), and (b) NL3D in those parts of the country where GeoTOP is not yet available. Methods and Vs-measurements are the same as in the original Ideation Challenge study.

1.2 The Ideation Challenge 2020

Earthquakes can cause damage to buildings and infrastructure. This holds for natural earthquakes as well as for human-induced earthquakes such as those in Groningen. For the Groningen earthquake area, a *Probabilistic Seismic Hazard and Risk Assessment* (PSHRA) is performed on a yearly basis. This PSHRA uses a Ground Motion Model that translates earthquake characteristics at the source into ground motions at the surface. Central to this translation is the shear-wave velocity structure of both the deep and shallow subsurface.

The energy transition calls for new uses of the subsurface, including CCUS, geothermal energy and energy storage. Such projects, which are being considered all throughout the Netherlands, may in some cases cause induced seismicity.

The TNO Ideation Challenge project aimed to make a first step into modelling the ground motions outside the Groningen area, by providing workflows to model the shear-velocity structure of both the shallow and deep subsurface. The original report as well as the current update describe the results of the project for the *shallow subsurface*.

The results of the Ideation Challenge, as well as the current update, such as the Vs_{30} map of the Netherlands, are a "proof of concept" only. Important caveats such as gathering representative Vs values for areas outside Groningen, as well as a proper way to take the uncertainties of the GeoTOP and NL3D models into account, have to be resolved before the results can be regarded as a full TNO product.

1.3 Shallow shear wave velocity modelling

The composition of the shallow subsurface plays a role in the extent of the damage caused by earthquakes, because 'weak soils' such as peat, clay and clayey sand/sandy clay can amplify the amplitude of seismic waves. One of the factors related to this 'site amplification' is the average shear wave velocity of the upper 30 m of the subsurface (Vs_{30}).

Kruiver et al. (2017a, 2017b) created a detailed Vs_{30} map for the Groningen gas field and a buffer zone of 5 km. This map is based on the GeoTOP area 'Oostelijke Wadden' v1.0, which is part of the 3D subsurface model GeoTOP v1.6. This model is publicly available at BROloket (www.broloket.nl/ondergrondmodellen). However, earthquakes have the potential to occur anywhere in the Netherlands, for example due to human use of the subsurface. That is why it is important to consider how earthquakes manifest as surface movements outside the Groningen area as well. To do so, we consider the shear-wave velocity of both the deep subsurface (up to ~5 km depth) as well as the top 30 meters in particular. Here we describe our work on the shallow (first 30 m) subsurface.

The subsurface model GeoTOP is available for ~71% of on-shore the Netherlands. In this report, Vs_{30} is calculated for the entire GeoTOP coverage area, complemented with NL3D for the remaining 29% of the country. The calculation is performed according to the method described in Kruiver et al. (2017a), and is based on the measurements of Vs therein. The method results in 100 different realizations of a raster map, for which each cell gets assigned a value of Vs_{30}. The 100 realizations represent the uncertainty in the field measurements of Vs.

Besides measurement uncertainty, we also want to account for model uncertainty in GeoTOP and NL3D. For Groningen, this is done by using the *geological homogenous zones* (Kruiver et al., 2017a, 2017b). Within these zones, the layering, structure and composition of the upper 30 m of the subsurface is considered to be mostly constant, allowing the assignment of Vs_{30} to the zone in term of an average and a standard deviation value (also for $\ln(Vs_{30})$).

Although we want to map geological homogenous zones for the entire country, we were not able to do so because this would require a significant effort and is therefore outside the scope of this research project.

2 Methods

2.1 Data and models used in this study

2.1.1 Subsurface model GeoTOP

GeoTOP is a 3D geological model of the shallow Dutch subsurface (down to a maximum of 50 m below Dutch Ordnance Datum (NAP)). It contains information on the geometry of geological layers as well as the lithological composition of those layers, structured in a regular 3D grid of connected voxels. These voxels are 100 x 100 m in map view and 0.5 m in thickness. Each voxel has a number of attributes, such as the lithostratigraphic unit (geological layer) the voxel belongs to, the lithological class (soil type) that is representative for the voxel, as well as a number of attributes describing the model uncertainty. GeoTOP also contains the detailed layer model and the interpreted borehole descriptions that were used to create the model. GeoTOP consists of model areas which roughly correspond to the Dutch provinces, but for which the borders are also determined based on the regional geology and other factors (Figure 2.1).

Figure 2.1: The eight model areas that constitute GeoTOP, version v1.6. 'Oost-Nederland' and 'Zuid-Limburg' are model areas under construction; in this report NL3D is used in these areas. The digital terrain model of the Netherlands is shown as a background map. Modified from Stafleu et al. (2023).

For the studies of the Groningen area for example, the modelling area 'GeoTOP Oostelijke Wadden' was used. This model area consists of roughly 43 million voxels, each with the following attributes:

- Geological unit;
- Most likely lithological class (soil type);
- Probability for each possible lithological class;
- Model uncertainty in the geological unit;
- Model uncertainty for the lithological class.

In this study, only the attributes *geological unit* and *most likely lithological class* are used. Figure 2.2 shows a selection of the different geological units in the model, Figure 2.3 shows the lithological classes. The Vs value of a voxel is largely determined through these two attributes. Typically 'weaker soils' (e.g. peat, clay, clayey sand & sandy clay) have lower Vs values than sand. The same lithological class may have a different Vs in different geological units due to a difference in depositional setting or burial history. Peat in the Basisveen Bed for example, is buried under a thick sequence of sand and clay and is therefore compacted into a thin, stiff layer of peat. Peat in the Hollandveen Member, however, is much looser and weaker.

'GeoTOP Oostelijke Wadden' is delineated by the Dutch-German border in the east, the North Sea to the North, 'GeoTOP Westelijke Wadden' to the west, and the Dutch National Grid y-coordinate 558,000 m to the south.

A detailed description about GeoTOP and its conception can be found in Stafleu et al. (2019, 2020; both in Dutch). Information on the updates of GeoTOP v1.4.1, v1.5 and v1.6 can be found in Stafleu (2022) and Stafleu et al. (2022b, 2023). All reports are publicly available at www.broloket.nl/ondergrondmodellen. A summary in English on the construction of 'GeoTOP Oostelijk Wadden' is given in Kruiver et al. (2017b).

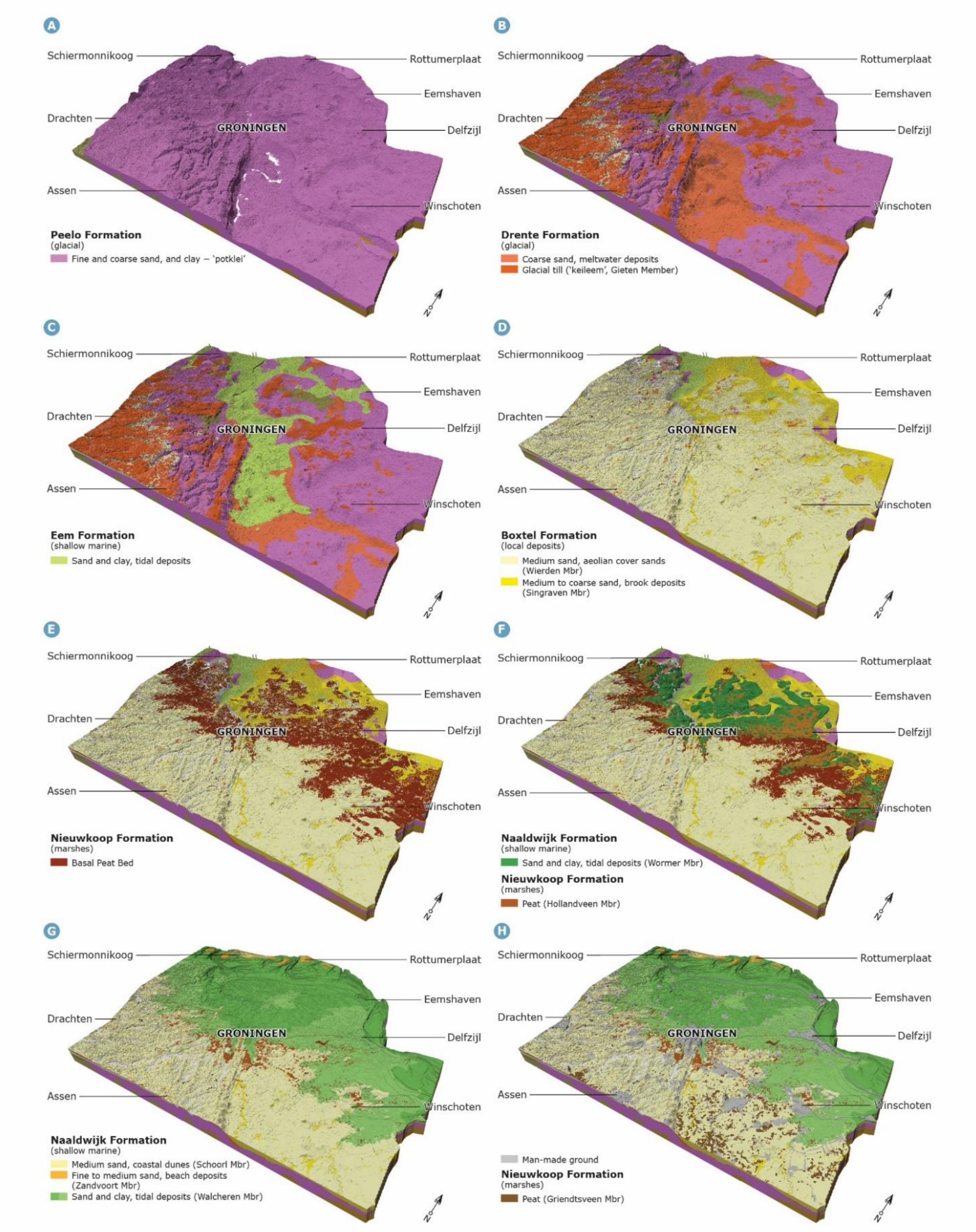

Figure 2.2: Geological units in GeoTOP Oostelijke Wadden. Several formations are composed of members and beds which are modelled as separate layers. For example, the Nieuwkoop Formation is modelled as three layers: (e) the Basal Peat Bed, (f) the Hollandveen Member, and (h) the Griendtsveen Member.

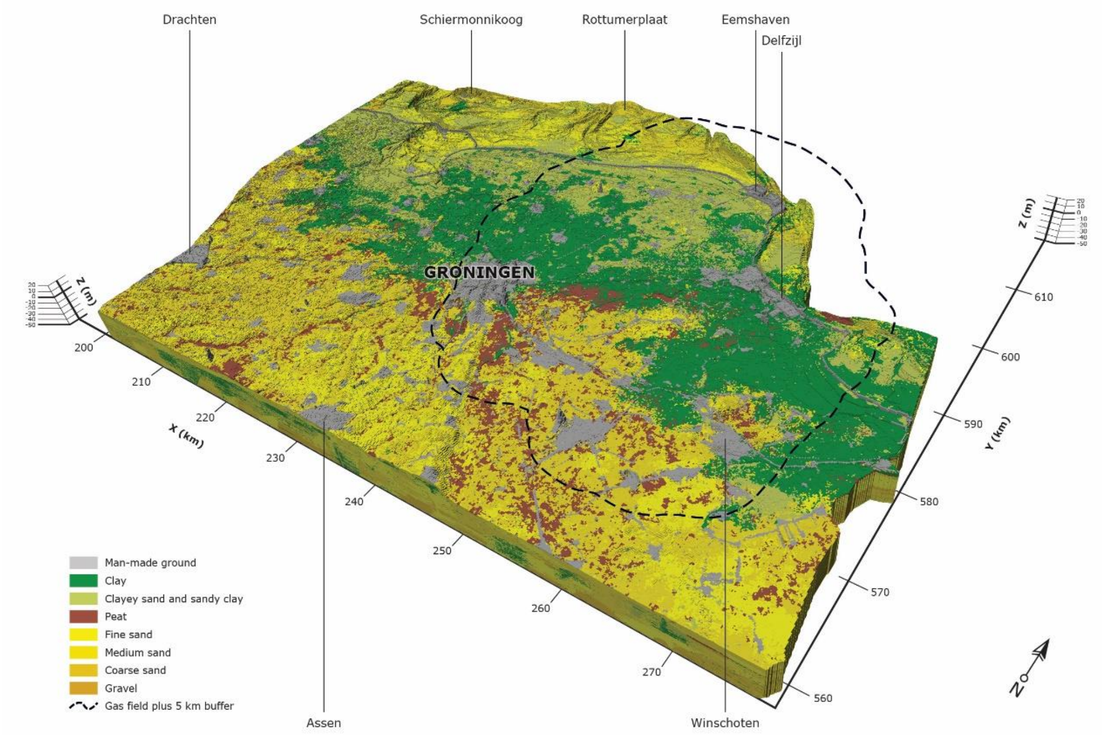

Figure 2.3: Lithological classes (soil types) in GeoTOP Oostelijke Wadden.

2.1.2 Subsurface model NL3D

To date, the GeoTOP model covers about 71% of the country (including inland waters such as the Wadden Sea). For the missing areas we have used the lower-resolution voxel model NL3D (version v2.0), which is available for the entire country (Van der Meulen et al., 2013; Stafleu et al., 2024). Like GeoTOP, NL3D models lithology and sand grain-size classes within geological units in a regular 3D grid of connected voxels. The voxels measure 250 x 250 m in map view and 1 m in thickness. The construction method of NL3D is much simpler than that of GeoTOP.

First, NL3D does not have a layer-based model of its own, but uses the surfaces of the DGM layer-based model to place each voxel within the correct lithostratigraphic unit. DGM is a layer-based model using a smaller dataset of some 26,500 manually interpreted borehole descriptions from the DINO database. Consequently, it is less refined than the layer-based model underpinning GeoTOP. For instance, DGM combines all Holocene formations in a single unit, whereas GeoTOP features some 35 different Holocene formations, members and facies units such as channel systems.

Second, the stratigraphical interpretation of the boreholes is done by intersecting each borehole with the top and base raster layers from the DGM model. The resulting stratigraphical interpretations are geometrically consistent with the DGM model, but not necessarily consistent with the borehole descriptions (e.g., a borehole interval describing ‘sand’ may erroneously fall within a unit that is characterized by clay deposits).

Figure 2.4 and Figure 2.5 show 3D views of NL3D, attributed with geological units and lithological classes, respectively.

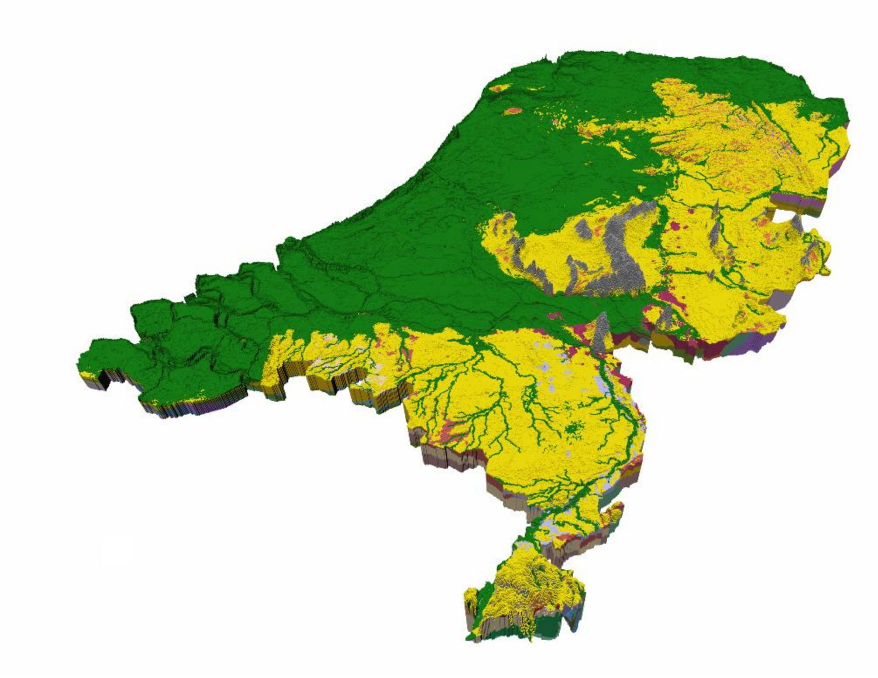

Figure 2.4: 3D view of NL3D, attributed with geological units. Vertical exaggeration 150x.

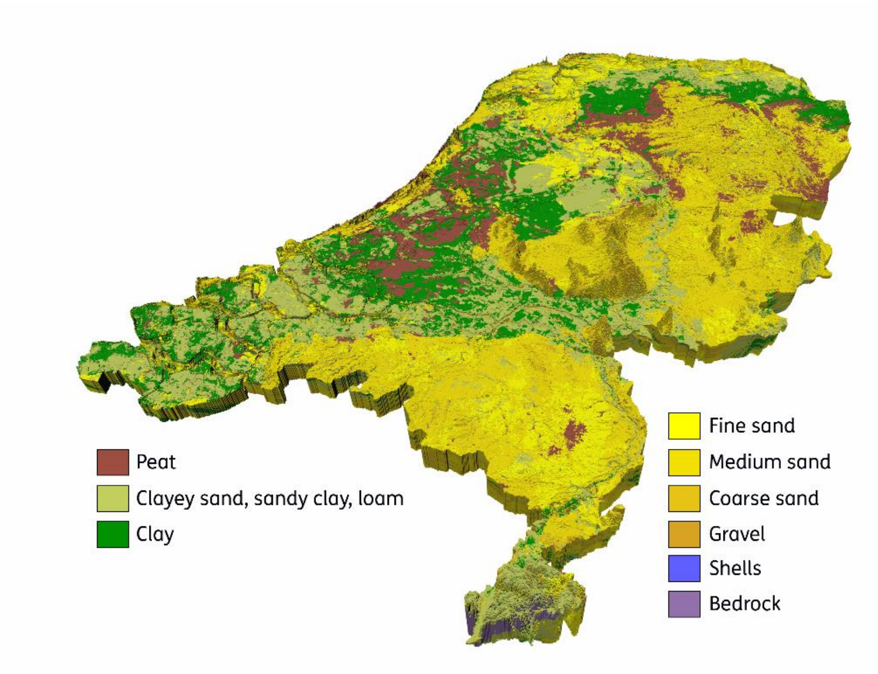

Figure 2.5: 3D view of NL3D, attributed with the most likely lithological class. Vertical exaggeration 150x.

2.1.3 Measured shear-wave velocities (Vs)

To develop a Vs-model in the area of the Groningen gas field (and a 5 km buffer area), seismic Cone Penetration Tests (CPTs) were used to determine shear wave velocities in 88 locations in the area (Kruiver et al., 2017a). Seismic CPTs measure the shear wave velocities, penetration resistance and sleeve friction in a vertical section of the shallow subsurface. The penetration resistance and sleeve friction can be related to the geological unit and lithological class. This allows the connection of the Vs measurements to the voxels in GeoTOP.

In general, Vs increases with confining stress. Kruiver et al. (2017a) used the following model for the Vs dependence on confining stress:

$$\ln(Vs) = \ln(Vs_1) + n \cdot \ln(\sigma'_0 / p_a),$$

where σ'_0 is the confining stress, p_a is the atmospheric pressure, $\ln(Vs_1)$ is a parameter that represents Vs at a confining stress equal to one atmosphere, and n is the slope that defines confining stress dependence (Sykora, 1987).

For some geological unit – lithological class combinations, a relation between Vs and confining stress (due to load of the overburden) could be determined from the seismic CPT measurements (Figure 2.6). For geological unit – lithological class combinations of this type, a depth-dependent Vs can be assigned in GeoTOP (see Table 1 in Kruiver et al., 2017a).

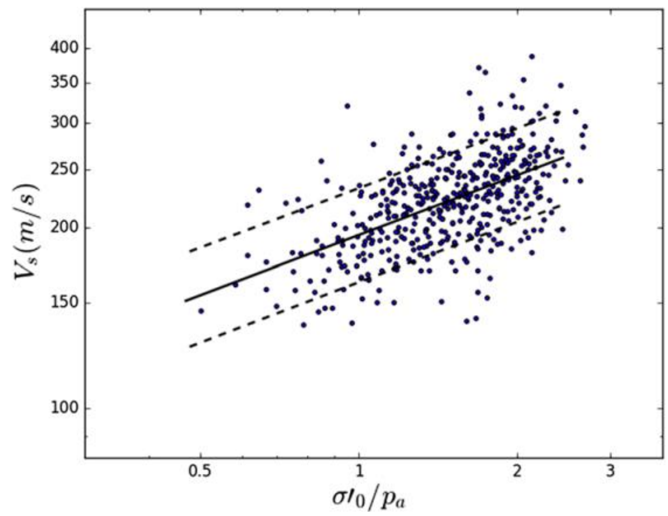

Figure 2.6: Example of Vs observations in the seismic CPT data set for clays in the Peelo Formation, plotted as a function of (σ'_0 / p_a). The solid line describes the regression while dotted lines indicate 95% confidence intervals. From Kruiver et al. (2017a).

For other geological unit – lithological class combinations, no trend was apparent, and a constant Vs is assigned (Table 2 in Kruiver et al., 2017a). For a third group of geological unit – lithological class combinations, no reliable Vs – depth relation could be extracted from the data and slope and intercept were taken from literature (Table 3 in Kruiver et al., 2017a). Finally, there is a fourth group of combinations of geological unit and lithological class for which no SCPT data was available. For this group, Vs parameters were based on comparable geological units and lithological classes within the Groningen area.

For the three tables, the parameters describing the probability distribution of Vs are listed in Table 2.1.

Table 2.1: Parameters for determining Vs and the standard deviation of Vs for each of the three types of combinations of geological unit and lthoclass as listed in Tables 1, 2 and 3 of Kruiver et al (2017a).

Type	Description	Vs	Standard deviation of Vs
1	Confining stress dependent Vs	⟩ Slope ⟩ Intercept Vs_1	⟩ Mean $\ln(\sigma'_0 / p_a)$ ⟩ Sum of squares of $\ln(\sigma'_0 / p_a)$ ⟩ Total variance of ln(Vs)
2	Constant Vs	⟩ Mean Vs	⟩ Standard deviation of Vs ⟩ Coefficient of variance of Vs
3	Confining stress dependent Vs from literature	⟩ Slope ⟩ Intercept Vs_1	⟩ Standard deviation of Vs

The Vs-parameters of the three tables and the fourth type were combined into a single look-up table summarizing the Vs-probability distribution for each combination of geological unit and lithological class that is present in the GeoTOP Oostelijke Wadden model.

2.1.4 Assigned shear wave velocities in this study

For the model area 'GeoTOP Oostelijke Wadden', to each combination of geological unit and lithological class Vs parameters were assigned based on the work described in Section 2.1.3. For other modelling areas in GeoTOP, the following workflow was followed:

- Geological units which are also present in GeoTOP Oostelijke Wadden, get assigned the Vs parameters as if they are situated in GeoTOP Oostelijke Wadden;
- Geological units which are not present in GeoTOP Oostelijke Wadden get assigned Vs parameters based on the most comparable units in GeoTOP Oostelijke Wadden.

Table 2.2 shows an overview of the geological units in GeoTOP. For each unit, it has been indicated whether that unit is also present in GeoTOP Oostelijke Wadden, and if this is not the case, which comparable unit has been used to assign Vs parameters to the voxels. Table 2.3 shows the same information for NL3D. In Zuid-Limburg, three formations which mainly consist of limestone are labeled 'bedrock'. Because of their different lithology, no comparable unit could be found in the GeoTOP Oostelijke Wadden area. Consequently, they are not assigned with a Vs-value.

Table 2.2: Geological units in GeoTOP v1.6. For each unit, it has been indicated whether that unit is also present in GeoTOP Oostelijke Wadden ('OW'), and if this is not the case, which comparable unit has been used to assign Vs parameters to the voxels. Fm = Formation, Mbr = Member. Units are according to the Dutch Stratigraphical Nomenclator of the shallow subsurface (TNO-GDN, 2024).

Unit Code	Unit Name	Present in OW?	Comparable unit
AAOP	Anthropogenic deposits, man-made ground	Yes	
AAES	Anthropogenic deposits, plaggen soil	No	NA
NIGR	Nieuwkoop Fm, Griendtsveen Mbr	Yes	
NASC	Naaldwijk Fm, Schoorl Mbr	Yes	
ONAWA	Naaldwijk Fm, Walcheren Mbr (upper unit)	No	NAWA
NAZA	Naaldwijk Fm, Zandvoort Mbr (upper unit)	Yes	
NINB	Nieuwkoop Fm, Nij Beets Mbr (informal unit)	Yes	
NAWAZU	Naaldwijk Fm, Walcheren Mbr, Zuiderzee Bed	No	NAWA

Unit Code	Unit Name	Present in OW?	Comparable unit
NAWAAL	Naaldwijk Fm, Walcheren Mbr, Almere Bed	No	NAWA
NAWA	Naaldwijk Fm, Walcheren Mbr (lower unit)	Yes	
OEC	Echteld Fm (above Hollandveen Mbr)	No	NA
NAWOBE	Naaldwijk Fm, Wormer Mbr, Bergen Bed	No	NA
KK1	Kreekrak Fm (upper unit)	No	NA
NIFL	Nieuwkoop Fm, Flevomeer Bed	No	NIHO
NIHO	Nieuwkoop Fm, Hollandveen Mbr (Holland Peat)	Yes	
NAZA2	Naaldwijk Fm, Zandvoort Mbr (lower unit)	Yes	
NAWO	Naaldwijk Fm, Wormer Mbr	Yes	
NAWOVE	Naaldwijk Fm, Wormer Mbr, Velsen Bed	No	NA
KK2	Kreekrak Fm (lower unit)	No	NA
NIBA	Nieuwkoop Fm, Basisveen Bed (Basal Peat)	Yes	
NA	Naaldwijk Fm	Yes	
EC	Echteld Fm (below Hollandveen Mbr)	No	NA
BXKO	Boxtel Fm, Kootwijk Mbr	Yes	
BXSI1	Boxtel Fm, Singraven Mbr (upper unit)	Yes	
BXSI2	Boxtel Fm, Singraven Mbr (lower unit)	Yes	
BXWI	Boxtel Fm, Wierden Mbr	Yes	
BXWIKO	Boxtel Fm, Wierden & Kootwijk Mbrs	No	BX
BXWISIKO	Boxtel Fm, Wierden, Singraven & Kootwijk Mbrs	No	BX
BXDEKO	Boxtel Fm, Delwijnen & Kootwijk Mbrs	No	BX
BXSC	Boxtel Fm, Schimmert Mbr	No	BX
BXLM	Boxtel Fm, Liempde Mbr	No	BX
BXBS	Boxtel Fm, Best Mbr	No	BX
BX	Boxtel Fm	Yes	
KRWY	Kreftenheye Fm, Wijchen Bed	No	URTY
KRBXDE	Kreftenheye Fm & Boxtel Fm, Delwijnen Mbr	No	URTY
BEOM	Beegden Fm, Oost-Maarland Mbr	No	BX
BEWY	Beegden Fm, Wijchen Bed	No	BX
BERO	Beegden Fm, Rosmalen Bed	No	BX
BE	Beegden Fm	No	BX
KW1	Koewacht Fm (clay-rich layer on top of the unit)	No	EE
KW	Koewacht Fm	No	EE
WB	Woudenberg Fm	No	BX
EE	Eem Fm	Yes	
DR	Drente Fm	Yes	
DRGI	Drente Fm, Gieten Mbr	Yes	

Unit Code	Unit Name	Present in OW?	Comparable unit
GE	Ice-pushed ridges (tectonic unit)	No	URTY
DN	Drachten Fm	Yes	
URTY	Urk Fm, Tijnje Mbr	Yes	
PE	Peelo Fm	Yes	
UR	Urk Fm	Yes	
ST	Sterksel Fm	No	URTY
AP	Appelscha Fm	Yes	
SY	Stramproy Fm	No	URTY
PZWA	Peize & Waalre Fms	No	URTY
MS	Maassluis Fm	No	URTY
KI	Kiezelooliet Fm	No	URTY
OO	Oosterhout Fm	No	URTY
IE	Inden Fm	No	URTY
BR	Breda Fm	No	URTY
RU	Rupel Fm	No	URTY
TO	Tongeren Fm	No	URTY
DO	Dongen Fm	No	URTY
AEC	unit EC, channelbelt generation A	No	NA
ABEOM	unit BEOM, channelbelt generation A	No	NA
ANAWA	unit NAWA, channelbelt generation A	No	NA
BEC	unit EC, channelbelt generation B	No	NA
BNAWA	unit NAWA, channelbelt generation B	No	NA
CEC	unit EC, channelbelt generation C	No	NA
DEC	unit EC, channelbelt generation D	No	NA
DNAWO	unit NAWO, channelbelt generation D	No	NA
EEC	unit EC, channelbelt generation E	No	NA
ENAWO	unit NAWO, channelbelt generation E	No	NA

Table 2.3: Geological units in NL3D v2.0. For each unit, it has been indicated whether that unit is also present in GeoTOP Oostelijke Wadden ("OW"), and if this is not the case, which comparable unit has been used to assign Vs parameters to the voxels. Fm = Formation. Units are according to the Dutch Stratigraphical Nomenclator of the shallow subsurface (TNO-GDN, 2024). Unit codes in lower case (hl, gs) are not formally defined in the Nomenclator.

Unit Code	Unit Name	Present in OW?	Comparable unit
hl	Holocene units	No	NA
BX	Boxtel Fm	Yes	
KR1	Kreftenheye Fm (upper unit)	No	UR1
BE	Beegden Fm	No	BX

Unit Code	Unit Name	Present in OW?	Comparable unit
KW	Koewacht Fm	No	EE
WB	Woudenberg Fm	No	BX
EE	Eem Fm	Yes	
KR2	Kreftenheye Fm (lower unit)	No	UR1
DR	Drente Fm	Yes	
gs	Ice-pushed ridges (tectonic unit)	No	UR1
DN	Drachten Fm	Yes	
UR1	Urk Fm (upper unit)	Yes	
PE	Peelo Fm	Yes	
UR2	Urk Fm (lower unit)	Yes	
ST	Sterksel Fm	No	UR1
AP	Appelscha Fm	Yes	
SY	Stramproy Fm	No	UR1
PZ-WA	Peize & Waalre Fms	No	UR1
MS	Maassluis Fm	No	UR1
KI	Kiezelooliet Fm	No	UR1
OO	Oosterhout Fm	No	UR1
IE	Inden Fm	No	UR1
BR-VI	Breda & Ville Fms	No	UR1
VE	Veldhoven Fm	No	UR1
RU	Rupel Fm	No	UR1
TO	Tongeren Fm	No	UR1
DO	Dongen Fm	No	UR1
LA	Landen Fm	No	UR1
HT	Heijenrath Fm	No	UR1
HM	Houthem Fm (Bedrock)	No	N/A
MA	Maastricht Fm (Bedrock)	No	N/A
GP	Gulpen Fm (Bedrock)	No	N/A
VA	Vaals Fm	No	UR1
AK	Aken Fm	No	UR1

2.2 Workflow

2.2.1 Calculation of Vs30

Below follows a summary of the Vs_{30} method of Kruiver et al. (2017a; their section 4.2). This method was applied to the GeoTOP and NL3D models resulting in a Vs_{30} map covering the onshore part of the Netherlands. A description of the general procedure is followed by details on the way in which uncertainty was taken into account.

2.2.2 General procedure

Using a so-called vertical voxel-stack analysis, the Vs values from section 2.1.3 and 2.1.4 were assigned to the GeoTOP and NL3D voxel models. In a vertical voxel stack analysis, all voxels at a specific x,y-location are processed from the uppermost voxel (at land surface) down to the lowermost one (at the bottom of the model). For each voxel in the stack, the corresponding Vs value was determined from the probability distributions described in sections 2.1.3 and 2.1.4 using the randomization procedure described in the next section (Figure 2.7). To do this, the depth of the voxel was converted to confining stress using the volumetric weight of the overlying voxels and assuming a constant phreatic groundwater level of 1 m below land surface.

After assigning a Vs value to all voxels in the stack, Vs_{30} was calculated as the harmonic mean of the 60 (GeoTOP) or 30 (NL3D) voxels that cover the upper 30 m. This results in a Vs_{30} value for the x,y-location of the voxel-stack. By repeating this procedure for all voxel-stacks in the model, a 2D raster map is created with cells measuring 100 x 100 m (GeoTOP) or 250 x 250 m (NL3D), attributed with Vs_{30}.

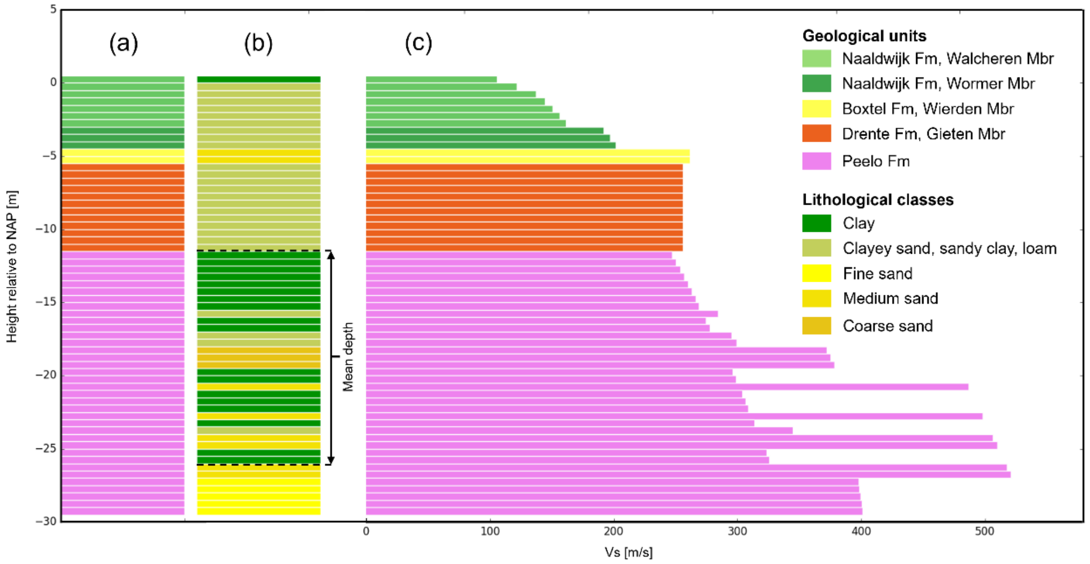

Figure 2.7: Example of GeoTOP voxel-stack processing. (a) vertical voxel-stack of 60 voxels attributed with geological units; (b) the same voxel-stack attributed with the most likely lithological classes. For the clays of the Peelo Formation, the mean depth of the combination of the unit and lithological class is shown; (c) bar graph of the sampled shear-wave velocity profile assigned to the voxels by applying the routine described in the text to the voxel-stacks. Modified after Kruiver et al. (2017a).

2.2.3 Randomization

In order to estimate the uncertainty of Vs in the Vs_{30} map, randomization was introduced to the voxel-stack analysis. Rather than calculating a single Vs_{30} value for each voxel stack using the mean Vs value from the Vs probability distribution, 100 different Vs_{30} values were calculated based on 100 random samples of Vs drawn from the Vs probability distributions. From these 100 Vs_{30} values, a mean Vs_{30} and a standard deviation for the vertical voxel-stack can be calculated.

For combinations of geological unit and lithological class for which no relationship between Vs and confining stress could be determined (Type 2 in Table 2.1), a random sample is drawn assuming a normal distribution of Vs described by the mean Vs and the standard deviation. An example is the Gieten Member, with the same Vs at each depth of occurrence (Figure 2.7).

For combinations for which a linear relationship between Vs and confining stress could be determined (Type 1 in Table 2.1), the procedure is more complicated and aims at randomizing the linear relationship. For these combinations, the standard deviation is related to the distance to the mean $\ln(\sigma'_0/p_a)$. In order to avoid sampling in the confining stress range either outside the range defined by the data, or always at the tails of the distribution which might results in relatively large standard deviation, the random sample $\ln(Vs_{sample})$ is taken at the mean depth of occurrence of the particular combination of geological unit and lithological class, assuming that this is comparable to the mean confining stress. The slope of the linear relationship is then used to calculate the Vs value for voxels above or below the voxel at the mean depth of occurrence. In effect, this means that only the intercept, and not the slope of the regression line is randomized. An example are the clays of the Peelo Formation, showing a linear increase of Vs with depth (Figure 2.7).

The following assumptions were made in the randomization procedure:

- Within one voxel-stack and within one combination of geological unit and lithological class a full correlation of Vs was assumed. This means that all layers of a given combination of geological unit and lithological class within one voxel-stack were based on one sample of Vs from the Vs probability distribution of this combination.
- Within one voxel-stack and between different combinations of geological unit and lithological class, a correlation coefficient of 0.5 was assumed. The correlated sampling ensures that the jumps in Vs between different combinations of geological unit and lithological class are not unrealistically large.
- In order to avoid Vs profiles that have extremely low or extremely high (and therefore unrealistic) Vs values, the distributions were truncated at two standard deviations.

A full description of the randomization procedure can be found in **Appendix A**.

2.2.4 Vs_{30} maps

The randomized voxel-stack analysis was repeated 100 times, resulting in 100 Vs_{30} raster maps. These maps were subsequently summarized in a mean Vs_{30} map and a map showing the standard deviation of Vs_{30}. In addition, maps of the natural logarithm of Vs_{30} were calculated.

2.2.5 Automation

The workflow described above is automated using Python-scripts (version 2.7.18). The scripts are included in the model development environment of GeoTOP and NL3D. This implies that the scripts can easily be rerun when updates of GeoTOP and NL3D become available in the future.

3 Results

3.1 Mean Vs_{30}

Figure 3.1 shows the mean Vs_{30} map of the on-shore part of the Netherlands. For the Groningen area, this map shows the same Vs_{30} distribution as the one published in Kruiver et al. (2017a), except for the upscaling to geological homogenous zones. Red colours indicate areas with a low Vs_{30} and hence a high probability of amplitude amplification of seismic waves.

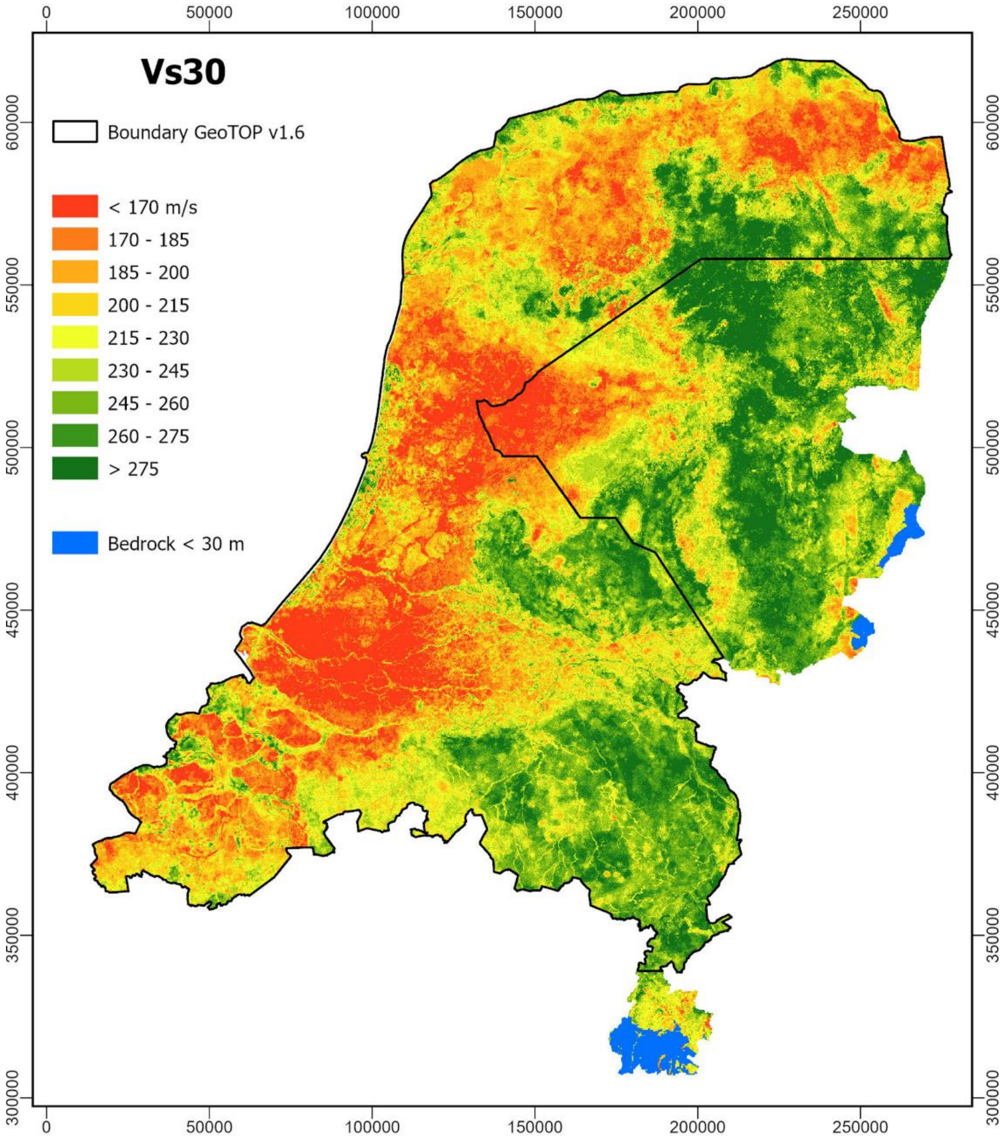

Figure 3.1: Mean Vs_{30} map of the on-shore part of the Netherlands. The black line indicates the area in which GeoTOP is available and used. Outside this area, the map is based on NL3D. Blue areas indicate parts of NL3D where bedrock is less than 30 m below land surface. See text for discussion.

The spatial distribution of Vs_{30} agrees well with the shallow geology of the Netherlands. The shallow subsurface of the coastal plains in the provinces of Zeeland, Noord-Holland, Zuid-Holland, Friesland and Groningen consists of soft, Holocene sediments (clay and peat) with low Vs_{30}-values. The coastal sand dunes however clearly show up as areas with relatively high Vs_{30}. The same applies for some of the areas with reclaimed land (for example south of Amsterdam), where peat layers have disappeared and layers with higher Vs-values are exposed.

The central part of the country is characterized by fluvial deposits of the rivers Rhine and Meuse. Clayey floodplain deposits with low Vs dominate in the downstream (western) part over the river system, whereas sandy channel belts prevail in the upstream (eastern) part. At a detailed level, individual sandy channel belts with high Vs_{30} may be followed as far as the North Sea coast.

Areas with predominantly high Vs_{30} include the sandy ice-pushed ridges of the Utrechtse Heuvelrug and the Veluwe area. The Gelderse Vallei area, a glacial valley in between these two ridges, shows patches of low Vs_{30} corresponding to peat areas (in the south of the area) and marine clays deposited in the former Zuiderzee (now Lake IJssel). The Pleistocene uplands in the south (Noord-Brabant, Limburg), north (Groningen and Friesland) and east (Overijssel, Gelderland) of the country generally have high Vs_{30} values as well. In contrast to the sandy channel belts of the rivers Rhine and Meuse, the infill of the small river valleys in Noord-Brabant consist of clay, peat and fine grained sand with lower Vs_{30} than the surrounding sandy deposits.

In some areas, the NL3D model reaches bedrock in less than 30 m (blue areas in Figure 3.1). In the eastern parts of Overijssel and Gelderland, these units are not modelled in NL3D. As a result, NL3D voxel-stacks are less than 30 m in thickness. In Zuid-Limburg, the Cretaceous limestones of the Houthem, Maastricht and Gulpen formations are part of NL3D, but we currently do not have an estimate of Vs of these units. In both cases, we have insufficient information to calculate a full 30 m profile of Vs30 in these areas.

3.2 Realizations

The map in Figure 3.1 was made by averaging the 100 different realizations of Vs_{30} produced by the randomized voxel-stack analysis. Two examples of these realizations are shown in Figure 3.2. The Figure zooms in on a small area south of Zandvoort aan Zee to show the differences in the realizations. The realizations look rather 'noisy' due to the fact that each voxel-stack is analysed independently from the surrounding voxel-stacks. This implies that within one realization, one voxel-stack may draw Vs values from the lower end of the probability distribution, whereas a neighbouring voxel-stack may draw from the higher end.

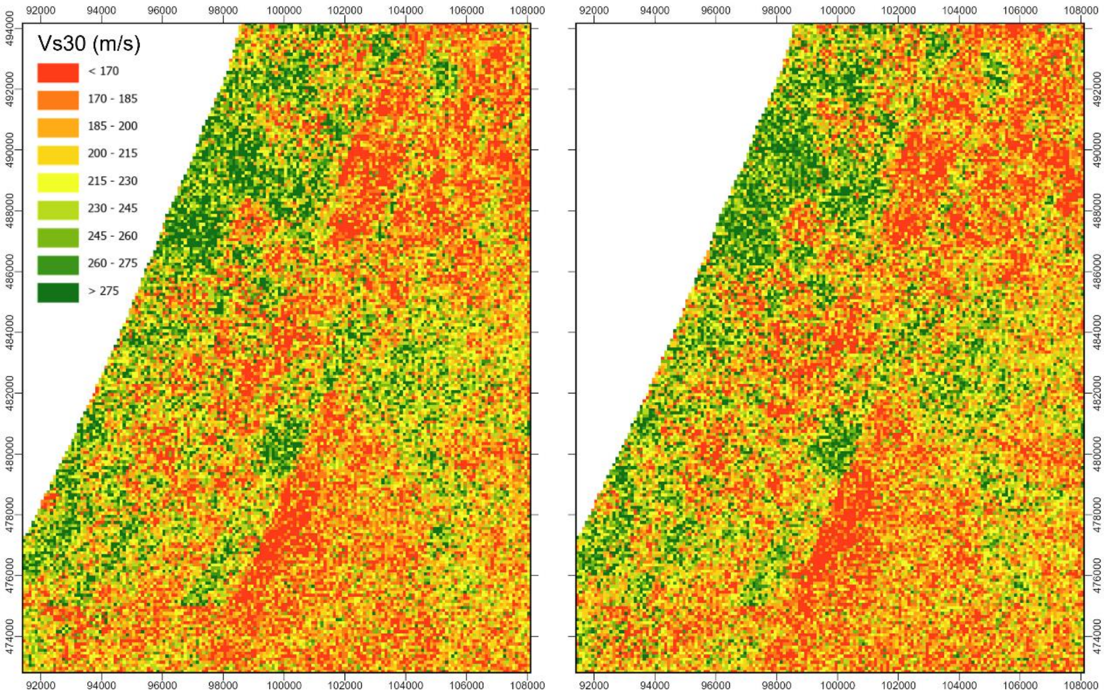

Figure 3.2: Two examples of the 100 realizations of Vs30 (left – realization #21; right – realization #77) zoomed in to a small area of GeoTOP to show the differences.

3.3 Standard deviation

The standard deviation derived from the 100 realizations ranges from 20 to 55 m/s with a few exceptions on the low and high ends (13.6 and 91.1 m/s, respectively) (Figure 3.3). Considering the relatively low Vs_{30} values, variation of Vs_{30} expressed by the standard deviation, can be rather significant. The degree of variation in Vs_{30} is not uniform across the country. In general, areas with higher Vs_{30} values show greater variations. A map of standard deviation expressed as a percentage of Vs_{30} would show less variation.

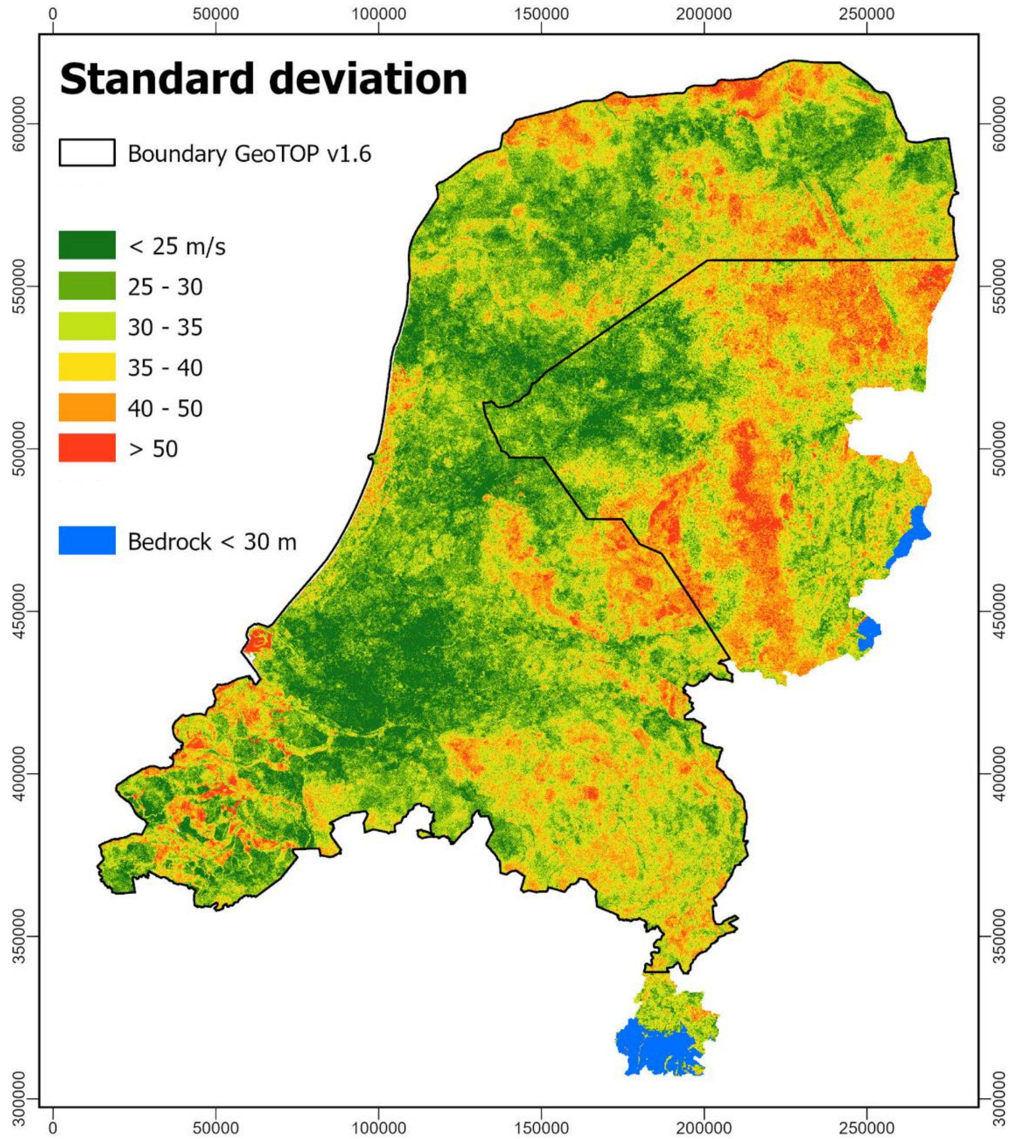

Figure 3.3: Map showing the standard deviation of the Vs_{30} map of the on-shore part of the Netherlands. The black line indicates the area in which GeoTOP is available and used. Outside this area, the map is based on NL3D. Blue areas indicate parts of NL3D where bedrock is less than 30 m below land surface. See text for discussion.

4 Concluding remarks

Using the methods and Vs-measurements of Kruiver et al. (2017a,b), we have successfully created a Vs_{30} map of the on-shore part of the Netherlands using the GeoTOP and NL3D voxel models of the shallow subsurface. The resulting map has unprecedented detail. Earlier work estimated Vs_{30} for relatively large, geological homogenous areas or focused on smaller areas.

However, the study has a number of important caveats. The first caveat concerns the Vs-values. All values were taken from the 88 seismic CPTs in the Groningen area and are therefore limited to geological units that occur in the shallow subsurface of that area. Though there are exceptions, e.g. for instance in Pleistocene geological units that have been covered and compressed by ice in the northern part of the country alone, one may assume that these values are representative for the same geological units occurring in other areas of the Netherlands (units indicated “Yes” in Table 2.1). However, the geological units that do not occur in the shallow subsurface of Groningen (units indicated “No in Table 2.2 and Table 2.3) clearly lack Vs-measurements. Assigning Vs-values of comparable geological units is at its best a first order approximation.

Secondly, the standard deviation map derived from the 100 realizations only represent the uncertainty in the field measurements of Vs. Besides measurement uncertainty, we should also account for the model uncertainty in GeoTOP. For Groningen, this was done by using the *geological homogenous zones* (Kruiver et al., 2017a, 2017b). Within these zones, the layering, structure and composition of the upper 30 m of soil is considered to be mostly constant, allowing the assignment of Vs_{30} to the zone in term of an average and a standard deviation value.

Thirdly, GeoTOP covers 71% of the on-shore the Netherlands, leaving 29% uncovered. In the current update, we have used NL3D to complement GeoTOP in the eastern part of the Netherlands and in Zuid-Limburg, However, NL3D has less detail than GeoTOP and is less accurate in estimating the lithological composition of the shallow subsurface.

Lastly, in some areas in Zuid-Limburg and in the east of Gelderland and Overijssel, bedrock is closer than 30 m to land surface. Since we lack Vs-measurements of these units, we were not able to estimate Vs_{30} in these areas.

Our recommendations are therefore to:

- Invest in acquiring Vs-measurements, especially for those geological units that do not occur in the shallow subsurface of the Groningen area. Alternatively, invest in research leading to the unlocking of the vast database of hundreds of thousands of conventional CPTs available in the Dutch National Key Registry of the Subsurface (BRO). These CPTs may serve as a proxy for Vs profiles. Kruiver at al. (2021) report promising shear-wave velocity correlations derived from CPT soundings.
- Seismic reflection data, as available in NLOG (https://www.nlog.nl/) for most parts of the Netherlands, especially those making use of a seismic vibrator, show surface waves. From these surface waves a local shear wave velocity profile down to about 30 m can be estimated. This is a rather standard method. Although it has a lower vertical resolution

than seismic CPTs, it may still be valuable to obtain Vs values for units that do not have a Vs assigned yet.

- Take the model uncertainty of GeoTOP and NL3D into account. This can be done by mapping *geological homogenous zones*. However, doing this for the whole of the on-shore part the Netherlands requires a significant effort.
- A recent (confidential) Vs_{30} study of the Groningen area investigated an alternative way to upscale Vs_{30} and its standard deviation to *administrative zones* with promising results. Examples of such administrative zones are municipalities and areas defined by the first four digits of the Dutch postal code system ('PC4'). Using predefined administrative zones is clearly much less time-consuming than mapping geological homogeneous zones. We therefore recommend to investigate if administrative zones are indeed useful for upscaling Vs_{30} and its standard deviation.

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Appendix A
Randomization

This appendix describes the randomization of Vs in the vertical voxel-stacks of GeoTOP and NL3D. The text is largely based on section 4.2 in Kruiver et al. (2017a). The randomization procedure is illustrated by the voxel-stack shown in Figure 2.7 and in the flowchart of Figure a.1 (next page).

Vs profiles are calculated for each vertical voxel-stack. For each combination of geological unit and lithological class in the voxel-stack (Figure 2.7), the corresponding Vs relationship is selected from the look-up table described in section 2.1.3. Within one voxel-stack and one combination of stratigraphy and lithological class we assume full correlation of Vs. This means that all layers of a given combination of geological unit and lithological class within one voxel-stack are based on one sample of Vs from the Vs probability distribution of this combination of geological unit and lithological class.

Within one voxel-stack and between different combinations of geological unit and lithological class, we assume a correlation coefficient ρ of 0.5. In order to avoid Vs profiles that have extremely low or extremely high (and therefore unrealistic) Vs values, the distributions were truncated at two standard deviations. To compensate for the truncation, the Vs values are sampled from a distribution with a standard deviation that is increased by 16%. This value corresponds to the value that would render a truncated distribution with the desired (target) standard deviation. The Vs probability distributions were standardised in order to be able to sample in a correlated way between combinations of geological unit and lithological class having different Vs distributions (different mean and standard deviation of ln(Vs)). Truncation was implemented as follows:

Step 1: Draw a random sample $\ln(Vs_{sample})$ from a normal distribution with

$$\mu = \ln(Vs_{mean}) \qquad \text{and} \qquad \sigma^* = 1.16 \cdot \sigma_{\ln(Vs)} \qquad \text{(Eq. 1)}$$

Step 2: Standardise to a distribution with $\mu = 0$ using

$$\ln(Vs_{sample\ standardised}) = (\ \ln(Vs_{sample\text{-}standardised}) - \mu\ ) / \sigma^* \qquad \text{(Eq. 2)}$$

Step 3: Repeat steps 1 and 2 until

$$|\ \ln(Vs_{sample\ standardised})\ | < 2.0 \qquad \text{(Eq. 3)}$$

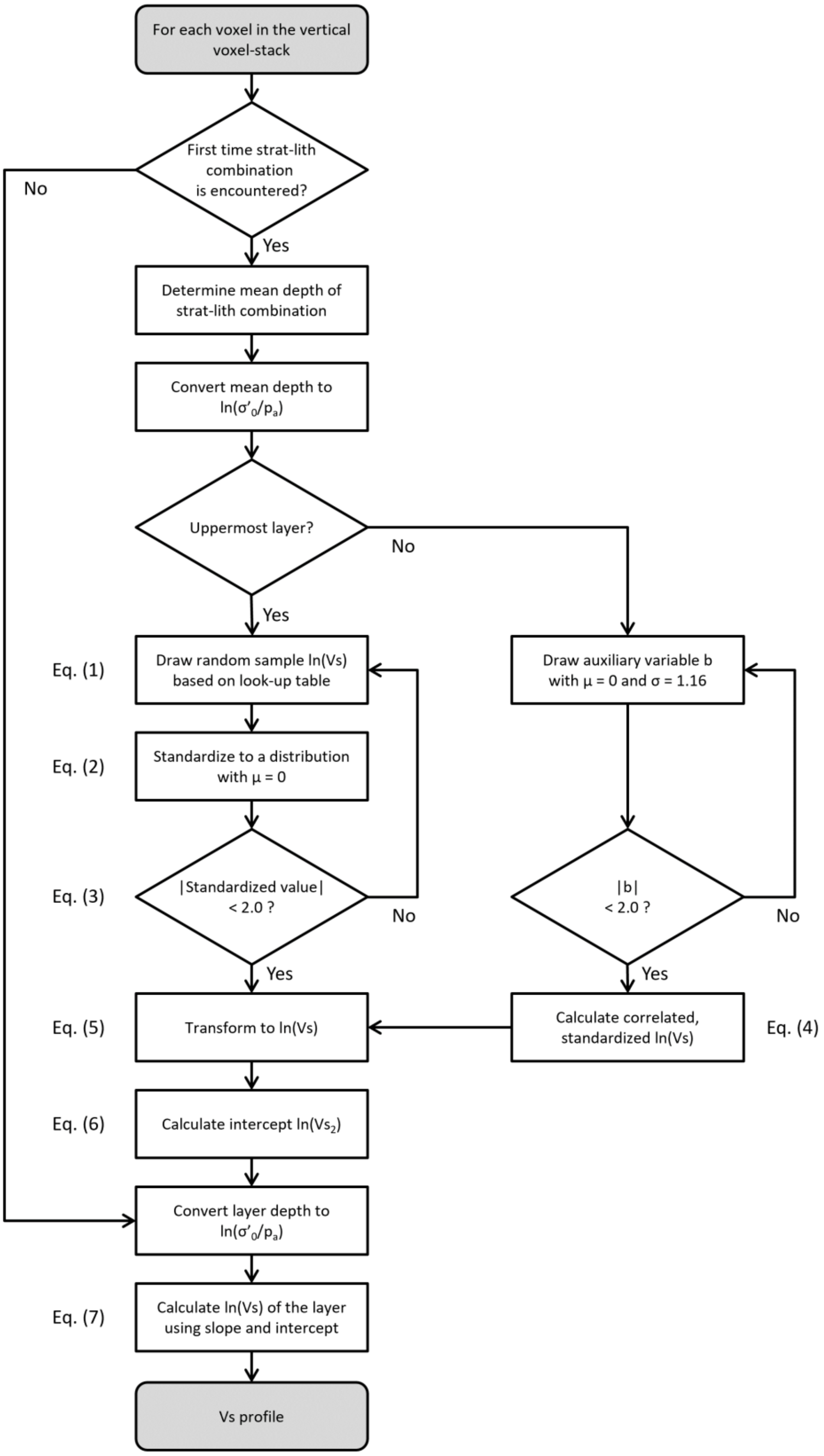

Figure A.1: Flowchart illustrating the randomization procedure of Vs. In this chart, 'strat-lith' is short for a combination of geological (stratigraphical) unit and lithological class. Modified after Kruiver et al. (2017a). Numbered equations refer to the text.

The random sample for each combination of geological unit and lithological class is taken at the mean depth of occurrence of this combination in the voxel-stack. For the confining stress-dependent Vs relations the standard deviation is related to the distance to the mean $\ln(\sigma'_0 / p_a)$. In order to avoid sampling in the confining stress range either outside the range defined by the data, or always at the tails of the distribution which might results in relatively large standard deviation, the random sample $\ln(Vs_{sample})$ is taken at the mean depth of occurrence of the particular combination of geological unit and lithological class, assuming that this is comparable to the average confining stress.

When moving to the next combination of geological unit and lithological class in the voxel-stack, correlated sampling is applied, again at the average depth of occurrence of the next combination. The correlated sampling is implemented as follows:

Step 1: Draw an auxiliary variable b (needed for a standardised and truncated distribution) from a normal distribution with $\mu = 0$ and $\sigma = 1.16$.

Step 2: Repeat step 1 until $|\, b\, | < 2.0$.

Step 3: Calculate $\ln(Vs_{sample\ standardised})$ correlated to the previous layer using the correlation coefficient ρ and auxiliary variable b using:

$$\ln(Vs_{sample\ standardised}) = \rho \cdot \ln(Vs_{previous\ layer\ standardised}) + b \cdot \sqrt{(1 - \rho^2)} \qquad \text{(Eq. 4)}$$

Step 4: Transform $\ln(Vs_{sample\ standardised})$ to $\ln(Vs_{sample})$ using:

$$\ln(Vs_{sample}) = \mu + \sigma^* \cdot \ln(Vs_{sample\ standardised}) \qquad \text{(Eq. 5)}$$

where μ is the mean Vs value at that depth.

Step 5: Use $\ln(Vs_{sample\ standardised})$ as $\ln(Vs_{previous\ layer\ standardised})$ in Eq. (4) in the calculation of the next combination of geological unit and lithological class.

Using the procedure described above, the truncated and correlated ln(Vs) is sampled for each combination of geological unit and lithological class at one depth per combination. In order to determine Vs at other depths of this combination in the voxel-stack, the updated intercept $\ln(Vs_2)$ is determined using the slope n of the corresponding distribution and $\ln(Vs_{sample})$ from Eq. 5 for this combination of geological unit and lithological class using:

$$\ln(Vs_2) = \ln(Vs_{sample}) - (n \cdot \ln(\sigma'_0 / p_a)_{at\ average\ depth}) \qquad \text{(Eq. 6)}$$

Finally, the $\ln(V_s)$ values at all other depths (and thus confining stresses) within this voxel-stack of this combination of geological unit and lithological class are calculated using:

$$\ln(V_s) = \ln(Vs_2) + n \cdot \ln(\sigma'_0 / p_a) \qquad \text{(Eq. 7)}$$

In effect this means that only ln(Vs) and not the slope n is randomized in Eq. 7.

An example of a randomized Vs profile is shown in Figure 2.7. For uniform geological units, the confining stress dependent increase in Vs is apparent (e.g. the clayey sand & sandy clay lithological class in the Walcheren Member of the Naaldwijk Formation). The correlated sampling ensures that the jumps in Vs between combinations of geological unit and lithological class are not unrealistically large. However, because of a correlation coefficient of 0.5, jumps from relatively high sampled Vs to relatively low sampled Vs between combinations of geological unit and lithological class are still possible.

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