Notitie

Authors
L.B. Hunfeld, J.P.T. Foeken and B.M.M. van Kempen

Princetonlaan 6
3584 CB Utrecht
Postbus 80015
3508 TA Utrecht

www.tno.nl

T +31 88 866 42 56
F +31 88 866 44 75

Geomechanical parameters derived from compressional and shear sonic logs for main geothermal targets in The Netherlands

Datum
20 december 2021

E-mail
bart.vankempen@tno.nl

Summary

This document describes the methods used to derive a set of geomechanical parameters (Young's Modulus, Bulk Modulus, Shear Modulus, Poisson's Ratio) from compressional and shear sonic logs obtained in 41 wells that were drilled through key geothermal targets in the Netherlands.
The data (sonic logs, composite log files, density logs, lithostratigraphy and deviation surveys) were obtained from www.nlog.nl, and analysed using Interactive Petrophysics software. The results in terms of average parameter value per lithostratigraphic interval are summarized in Appendix B. Examples of basic interpretation of the data are included, such as basic trends in geomechanical parameters with lithology type and depth.

1. Data selection

The NLOG database was used to select 41 wells containing compressional and shear sonic logs, distributed over the onshore Netherlands (Fig. 1 & Appendix A). The main selection criteria was the availability of compressional (DTCO, DTC, DT4C or DT) and shear (DTSM, DTS or DT4S) sonic logs for intervals that contain main geothermal targets in the Netherlands. These include formations in the Cretaceous/Jurassic (e.g. De Lier, IJsselmonde, Delft Sandstone and Alblasserdam Members), Triassic (e.g. Solling, Röt, Hardegsen, Detfurth and Volpriehausen Formations) and the Rotliegend (Slochteren formation). Additional intervals that were covered by compressional and shear sonic logs within these wells were also included in the analysis.
For most wells, multiple compressional and shear sonic logs are available from NLOG (under the Logs/LIS/LAS data tab). For each of the selected wells, all the LAS, LIS or DLIS files having “sonic” annotation in the information (“Groep”) were downloaded and checked. Bulk density logs were also downloaded, as these are required for the calculations of some relevant geomechanical properties. Where possible, other associated composite log files were selected. In addition, lithostratigraphy and deviation surveys for the selected wells were also obtained from NLOG.

Datum
20 december 2021

Blad
2/7

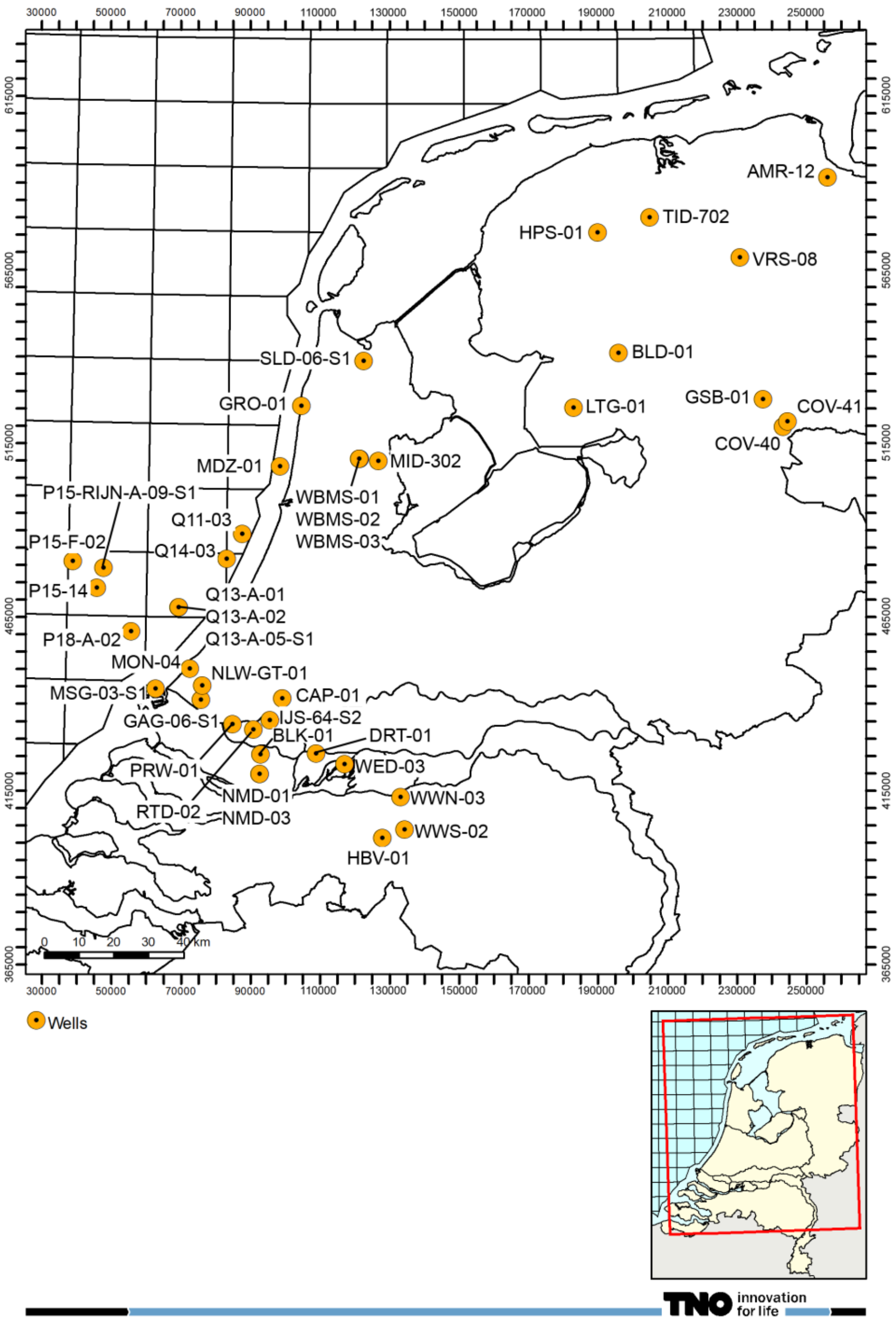

Figure 1A: Location of the 41 selected wells.

2. Methods

Interactive Petrophysics software (hereafter referred to as IP) was used to analyse the sonic logs (plus associated composite log files and density logs) for the wells selected, and calculate key geomechanical properties. A detailed workflow is described below.

2.1 Log import

The available logs for each well were imported into IP. A detailed import log was maintained during importing and loading of the logs. In the case of composite log files, only those containing DTCO and DTSM logs were loaded; logs without DT or DTCO were ignored. From each sonic file the compressional sonic logs (often as DTCO, sometimes as DT, DTC or DT4C) and shear sonic logs (often DTSM, sometimes as DTS or DT4S) were imported. Most of the logs also contained Poisson's ratio (PR) and VpVs ratio (VpVs) curves. For a few wells, also the Young's modulus, Bulk modulus and Shear modulus logs were available and imported.

When a sonic log file contained a gamma ray (GR) log, this curve was loaded to be able to determine if a depth shift was required (see section 2.2.1 below).

Density logs are required to calculate the elastic moduli (Young's modulus, Bulk modulus and Shear modulus) from the sonic logs. In many cases, density (RHOB) logs were available from the composite log files. In cases where no composite log file was available, the density log was downloaded from NLOG and imported separately.

For most wells, multiple compressional and shear sonic log files were available. Sometimes the logs in the different files are similar, but often slight differences existed between the various sonic logs for a well. To determine if such differences have an overall effect on the averaged interval values (after cut-off and summation, see section 2.3.3 below), each file was loaded into a separate set, and the geomechanical parameters were calculated for each set.

2.2 Log editing

In most cases, the imported logs required some degree of editing prior to calculating and subsequent averaging of the geomechanical parameters. The most common editing steps are briefly described below.

2.2.1 Depth shift

Each imported log file was checked to see if a depth shift was required. Initially, the GR of the composite log file (when available) was compared to the lithostratigraphical formation tops from NLOG. The GR of each imported sonic log was subsequently compared to the composite log file. When needed, a manual depth shift was made by adjusting the formation well tops to the GR in the composite and/or sonic log. For example in well BLD-01 (Fig. 2), a ~5m offset was observed between the lithostratigraphic formation tops derived from NLOG and the composite log file (GR, RHOB, DT & NPHI) and sonic log (DTCO & DTSM) – see red boxes in Figure 2A. When not corrected for, this will impact the averaged formation interval properties.

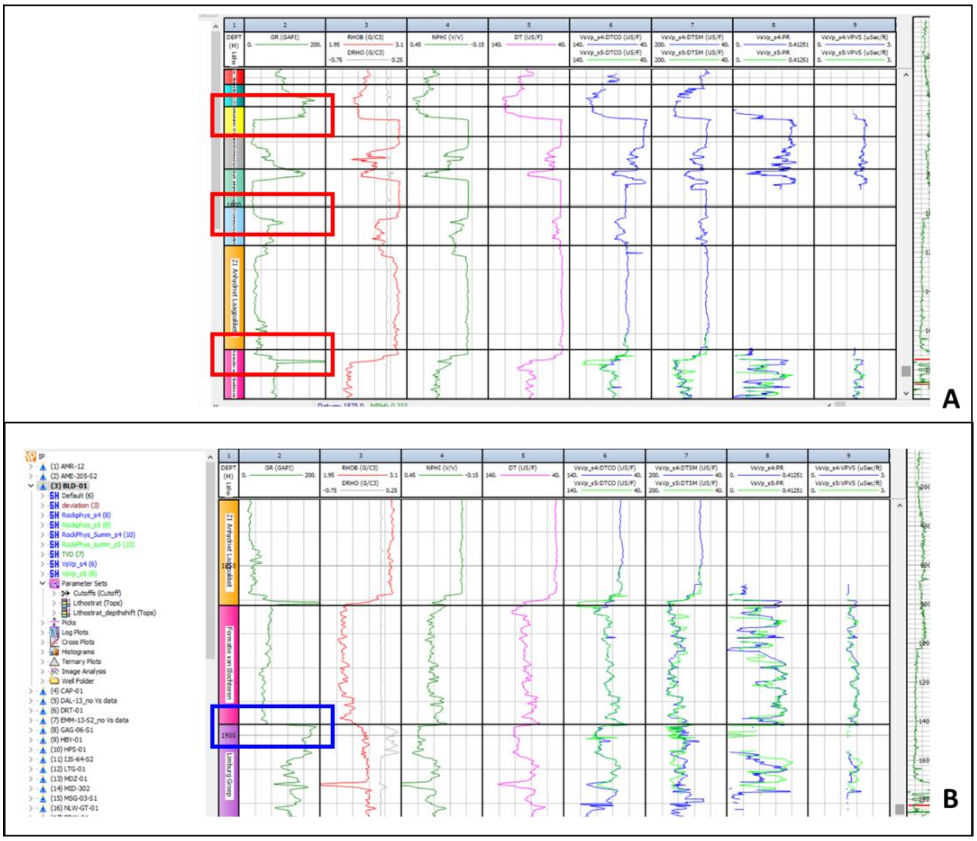

Figure 2: Example of a depth shift in formation tops with respect to the GR curve (well BLD-01, log data imported and displayed in Interactive Petrophysics software). A. Lithostratigraphy from NLOG compared to GR curve shows that the GR response does not coincide with the formation top depths (red boxes as example). B. Manually adjusted formation tops to coincide with the GR peaks (blue box). The corrected formation tops are used when averaging formation interval parameters.

2.2.2 Erratic log data elimination

Most loaded DTCO & DTSM logs required some log data elimination at the top and base of the curve, often easily recognised as a “flat line” (Fig. 3). The depth transition between “flat line” and regular curve was determined on the DTSM curve, and curve data was subsequently eliminated below or above that interval in both the DTSM & DTCO logs (set as “null” in IP).

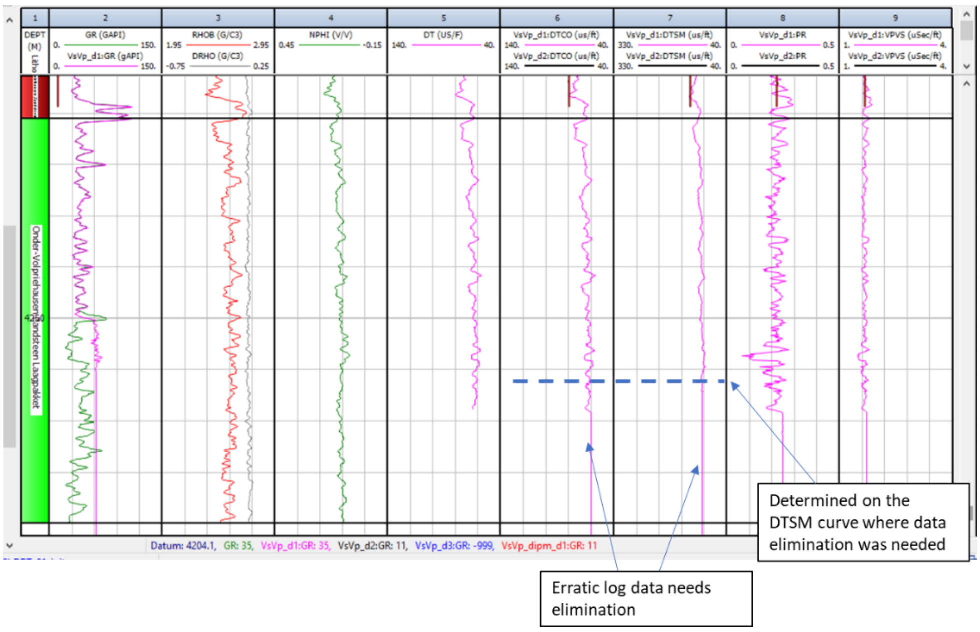

Figure 3: Example of a log interval with a “flat line” at the base, which was eliminated prior to the calculation of the geomechanical properties.

2.3 Data processing

2.3.1 Calculated geomechanical parameters

The following geomechanical parameters were calculated in IP (the standard equations for calculating the elastic moduli are given, where ρ is density in kg/m^3, and V_p and V_s the compressional and shear wave velocities in km/s):

- Young’s Modulus (E) $E = 2G(1+\nu)$
- Bulk Modulus (KB or K) $K = E/3(1-2\nu)$
- Shear Modulus (Mu or G) $G = \rho V_s^2$
- Poisson’s Ratio (PR or ν) $\nu = V_p^2 - 2V_s^2/2\left(V_p^2 - V_s^2\right)$

2.3.3 Cut-off & Summation

Average geomechanical properties are calculated for each interval using “the cut-off and summation” option in IP. Formation intervals (thicknesses as TVDSS) were defined based on the lithostratigraphy obtained from NLOG (or depth-corrected lithostratigraphy created in IP).
In some cases, the composite log files or sonic logs are not continuous (i.e. some data gaps exist), which leads to spikes or erratic low/high values for the calculated geomechanical parameters. To minimize the influence of these artefacts on the calculated average values, cut-offs were applied to PR, KB and Mu, removing the spikes and erratic low/high values.
In cases where there is no density log available over a specific interval or part of a formation, only the PR is calculated for this interval (along with Vp, Vs & VpVs).

2.3.4 Results Summary file

The calculated average geomechanical parameters per interval are summarized in an Excel sheet (Appendix B), organized per wellbore (Fig. 4).

Well	Zone name / Formation	Lithostratigraphic Group	Subgroup / Formation	Lithology type	Top (MD)	TVCSS Top (m)	Bottom (MD)	TVDSS Bottom (m)	% log data over interval for E, KB, Mu	Young's Modulus E (GPa)	Bulk Modulus KB (GPa)	Shear Modulus Mu (GPa)	% log data over interval for PR, Vp, Vs, VpVs (only listed if different from column J)	Poison Ratio PR	Vp (ft/sec)	Vs (ft/sec)	VpVs Ratio	File name logs
AMR-12	Laagpakket van Ten Boer	Boven-Rotliegend Groep	Silverpit Formatie	Kleisteen	3083	2734,68	3143	2789,37	53,0%	30,3	19,7	12,2		0,24	12.341	7.195	1,717	AMR-12_AMSWEER_
AMR-12	Formatie van Slochteren	Boven-Rotliegend Groep	Formatie van Slochteren	Zandsteen	3143	2789,37	3325,5	2955,36	99,3%	28,6	15,0	12,2		0,18	11.891	7.419	1,605	AMR-12_AMSWEER_
AMR-12	Caumer Subgroep	Limburg Groep	Caumer Subgroep	Kleisteen / Siltsteen	3325,5	2955,36	3348	2974,87	49,0%	45,3	25,5	18,8		0,20	14.301	8.726	1,639	AMR-12_AMSWEER_
BLD-01	Basale Dongen Tuffiet Laagpakket	Onder-Noordzee Groep	Formatie van Dongen	Klei / Silt	981,27	975,99	1004,27	999					88,9%	0,22	17.752	10.442	1,72	bld01_EBN05093.s
BLD-01	Landen Klei Laagpakket	Onder-Noordzee Groep	Formatie van Landen	Klei	1004,27	999	1030,27	1024,91					100,0%	0,29	18.332	9.819	1,878	bld01_EBN05093.s
BLD-01	Formatie van Ommelanden	Krijtkalk Groep	Formatie van Ommelanden	Kalksteen	1030,27	1024,91	1643,77	1638,28	17,1%	41,6	35,5	16,0	89,5%	0,30	15.478	8.213	1,884	bld01_EBN05093.s
BLD-01	Formatie van Texel	Krijtkalk Groep	Formatie van Texel	Kalksteen	1643,77	1638,28	1710,77	1705,31	98,9%	37,5	34,8	14,2	98,9%	0,32	14.886	7.647	1,948	bld01_EBN05093.s
BLD-01	Vlieland Kleisteen Formatie	Rijnland Groep	Vlieland Subgroep	Kleisteen	1758,17	1752,68	1766,67	1761,06	39,1%	35,3	20,1	15,1	39,1%	0,15	12.187	7.724	1,551	bld01_EBN05093.s
BLD-01	Z3 Hoofdanhydriet Laagpakket	Zechstein Groep	Z3 (Leine) Formatie	Anhydriet	1766,67	1761,06	1778,47	1772,94	100,0%	82,5	67,1	31,9	100,0%	0,29	19.907	10.747	1,851	bld01_EBN05093.s
BLD-01	Z3 Anhydriet/Carbonaat Laagpakket	Zechstein Groep	Z3 (Leine) Formatie	Anhydriet / Carbonaat	1778,47	1772,94	1790,5	1784,67	100,0%	47,6	33,0	19,1	100,0%	0,24	15.383	8.826	1,74	bld01_EBN05093.s
BLD-01	Formatie van Slochteren	Boven-Rotliegend Groep	Formatie van Slochteren	Zandsteen	1861,67	1856,11	1896,8	1891,14	97,0%	26,0	16,2	10,7	97,0%	0,22	11.883	7.054	1,689	bld01_EBN05093.s

Figure 4: Screenshot of the summary data excel sheet (Appendix B).

Averages are calculated over the true vertical thickness of each interval, but depths in MD for the respective interval are also given. Column J lists the percentage of the interval (TVD) for which the average parameter values are calculated. For those instances where separate output files are calculated for PR, Vp, Vs and VpVs (due to the lack of density data, see above), the TVD percentage of the interval included in the calculation is listed in column N instead (with no corresponding entry in column J). For wells for which multiple sonic logs exists, the output data is given per sonic log file name. Column N provides the name of the log files used.

2.4 Quality control

An internal quality control procedure was carried out to the resulting curves and interval averages of the calculated geomechanical parameters. The focus of the quality control was mainly on log quality (casing and washout effects, spikes, etc.) and the representativeness of the interval averages (percentage and character of calculated section w.r.t. the entire interval). Data regarded as unreliable has been removed.

2.5 Basic trends and interpretation

A first-order interpretation of the data was made by identifying the lithology type for each stratigraphic interval, based on the composite well logs (where available) from NLOG and information from www.dinoloket.nl. The following lithology types were encountered (see column E in the summary data excel file):

- Claystone
- Sandstone
- Siltstone
- Shale
- Limestone (Carbonates)
- Dolomite
- Anhydrite
- Rocksalt
- Marl

Unconsolidated sands and clays were also present in some cases, notably in the Middle- and Lower North Sea Groups. When the composite well logs indicate an alteration between two or more lithology types within a single formation, without a single dominant type, it is marked as type1 / type2 (e.g.: sandstone/claystone).

Fig. 5 shows a compilation of the data, plotting Young's Modulus (*E*) versus depth for different lithology types. Overall, the data show a general trend of increasing *E* with depth, but different lithology types show distinct clusters/trends. Sandstones, claystones (plus shale, siltstone) and carbonates show the clearest correlation with depth. Anhydrite and rocksalt on the other hand, show little systematic depth dependence. The highest *E* values at a given depth are typically found in anhydrite and carbonates.
The depth-dependence of *E* seen in the sandstones, claystones and carbonates may point to an inverse porosity-dependence, since porosity typically decreases with maximum burial depth for sedimentary rocks (e.g. Van Kempen et al., 2018).

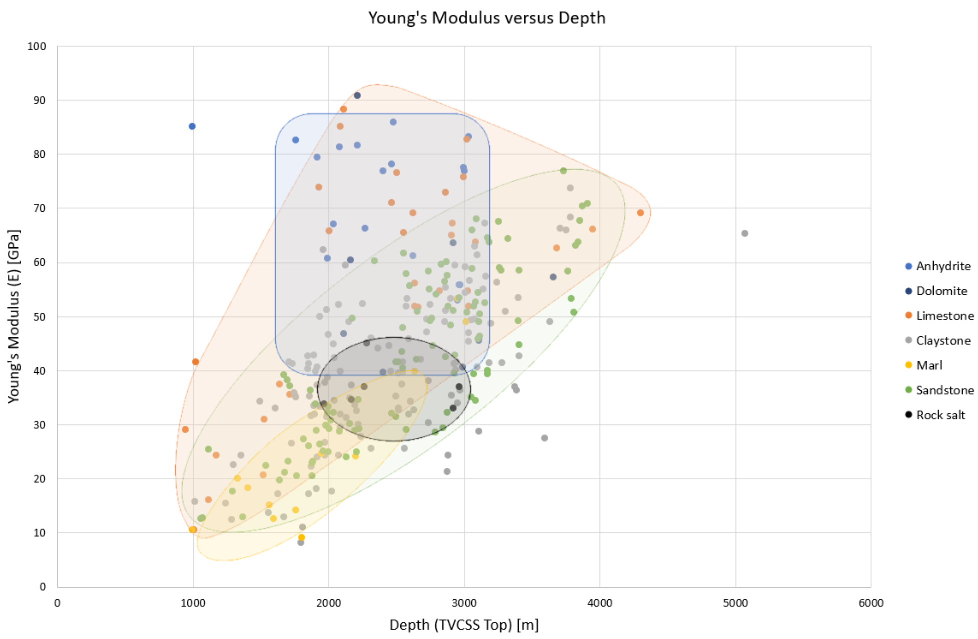

Figure 5: Young's Modulus (E) versus depth (TVDSS) for 7 lithology types selected from the Summary Excel file. Note that 'Claystones' includes the data for claystones, shales and siltstones in this graph. The overall trends are highlighted with shaded polygons. Sandstone and claystone data overlap to a large extent, and therefore only a polygon (green) for sandstones is drawn.

References

Van Kempen, B. M. M., Mijnlieff, H. F., & Van Der Molen, J. (2018). Data mining in the Dutch Oil and Gas Portal: a case study on the reservoir properties of the Volpriehausen Sandstone interval. *Geological Society, London, Special Publications*, *469*(1), 253-267

Appendices

A. List of wells with associated data that was used (Excel file). The filename of each loaded LAS, LIS or DLIS file is provided plus an overview of targeted formations
B. Summary data sheet (Excel file) listing the wells, stratigraphic formations and geomechanical parameters derived from the sonic log files.