British Geological Survey
Expert | Impartial | Innovative

MUSE GeoERA GEO-ENERGY
Managing Urban Shallow Geothermal Energy

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166

Geological and Hydrogeological Investigations in the Colchester Northern Gateway Boreholes: February 2020 survey

Open Report OR/20/011

BRITISH GEOLOGICAL SURVEY

EU GeoERA MUSE Project

OPEN RESEARCH REPORT: OR/20/011

Geological and Hydrogeological Investigations in the Colchester Northern Gateway Boreholes: February 2020 survey

Prepared by: D P Boon, A Butcher, B Townsend, M A Woods

Checked by: D A Gunn, C Abesser

Keywords

Report; borehole geophysics, chalk, colchester, essex, geothermal, tromino.

National Grid Reference

SW corner 600000,229000
NE corner 601000,230000

Map

Sheet 224/242, 1:50 000 scale, Colchester and Brightlingsea

Front cover

Photo montage of fieldwork being undertaken in Colchester in February 2020.

Bibliographical reference

BOON, D, P., BUTCHER, A., TOWNSEND, B., WOODS M A. 2020. Geological and Hydrogeological Investigations in the Colchester Northern Gateway Boreholes: February 2020 survey. *British Geological Survey Open Research Report,* OR/20/011. 48pp.

Keyworth, Nottingham British Geological Survey 2020

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of UK Research and Innovation.

British Geological Survey offices

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3100

BGS Central Enquiries Desk

Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales

Tel 0115 936 3241
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP

Tel 0131 667 1000
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Cardiff University, Main Building, Park Place, Cardiff CF10 3AT

Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB

Tel 01232 666595
www.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House, Swindon SN2 1FL

Tel 01793 444000
www.ukri.org

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Foreword

This report is the published product of a study by the British Geological Survey (BGS) and describes the results of borehole geophysical surveys done in geothermal wells at the Colchester Northern Gateway (CNG) development, Essex, UK in February 2020. The report includes results from groundwater temperature profiling, borehole geophysical logs, and passive seismic surveys (H/V). The work forms a deliverable of Work Package 4 'Investigations in pilot areas' of the EU GeoERA MUSE (Managing Urban Shallow Geothermal Energy) project (2018-2021).

Acknowledgements

The BGS extends its gratitude to Michael Woods of Colchester Amphora Energy (CAE) for allowing access to the boreholes and surrounding land. The authors also thank Dr David Birks of WSP consultants for his early technical input, and Rodney Chatters for assistance with site access. Dave Gunn, Milly Lewis and Corinna Abesser are thanked for their support, advice, and report peer-review. This project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 731166 (MUSE GeoERA) and BGS-UKRI National Capability funding.

Contents

FIGURES

TABLES

Summary

This research report describes borehole geophysical and passive seismic surveys done at the Colchester Northern Gateway (CNG) geothermal district heat network and housing development in Essex, UK, between 10-13 February 2020. The first part of the report introduces the project context, the second part describes survey methods, and the third presents the 'baseline survey' results and stratigraphic interpretation. The final section summarises the key learnings, relevance of the findings to future geothermal district heating schemes in the Chalk and London Basin, and makes some recommendations for follow-up monitoring research.

Five recently drilled production/injection boreholes at CNG were logged with Calliper, Temperature and Conductivity, Natural Gamma, Optical Televiewer (OPTV) tools. Some of the holes also had Resistivity and Impeller flow tools run but results were inconclusive. A site-wide *Tromino* H/V passive seismic survey was acquired to characterise the resonant frequency of the subsoils between the boreholes, to aid stratigraphic correlation, profile the concealed chalk 'rockhead' surface (i.e. depth of bedrock aquifer), and look for any evidence of the presence of faults/fracture zone, and characterise the thickness of karst and weathering profiles.

The main geological formation boundaries were identified based on a combination of interpretation of Natural Gamma logs and correlation of sedimentary features observed in the OPTV images. The eroded top of the Newhaven Chalk is around 72 m below ground level (-24 m OD) in all five boreholes (BH1-5). The high-resolution OPTV images provide rich visual information on the fracture state of the upper 'productive' part of the chalk aquifer. A notable feature in BH4 is an 18 m long NW-SE orientated open vertical fracture that persists through the Newhaven Chalk but terminates at the top of the Seaford Chalk. The OPTV data also aids identification of key litho-stratigraphic marker horizons, such as tabular flint bands, hard grounds and marls seams. The Natural Gamma aids identification of key marls, such as the Buckle Marl and Shoreham Marls and the top and base of the London Clay and top of Chalk. Marls and flint bands are useful litho-stratigraphic markers for site- to regional-scale correlation and structural analysis, and for developing hydrogeological and thermo-geological conceptual and observational geo-models to inform the set-up of numerical flow models (e.g. FeFLOW models).

The interpretation of the new survey data concluded that the near-surface geology at CNG comprises c.72 m of thin Superficial deposits and Palaeogene sediments resting on Cretaceous Chalk bedrock (White Chalk Sub-group). The two deepest (200 m) boreholes (BH2 and BH4) penetrate 4-5 m of superficial deposits (cover sand and gravels) resting on c.36 m of London Clay, c.8.5 m of Harwich Formation, c.10 m of Lambeth Group, c.12 m of Thanet Formation, c.23 m of slightly karstified and fractured basal Newhaven Chalk, c.59.4 m of Seaford Chalk and terminate within c.31 m of upper Lewis Nodular Chalk Formation.

Groundwater temperature profiling in February 2020 suggests a shallow geothermal gradient of around 2.4°C per 100 m in the top 200 m of the Chalk aquifer in the Colchester area. Under natural conditions (i.e. no influence from other subsurface users), groundwater source heat pump schemes can therefore expect seasonally stable ambient source temperatures of around 11.7°C and 14.3°C at 100 m and 200 m depths, respectively, with 130 m open loop schemes predicted to yield borehole inflow temperatures of around 12.5°C all year round (assuming no thermal interactions/breakthrough), making open loop ground source heat pump schemes a viable option for low carbon/no carbon heating systems, and larger district heating and cooling grids.

Pumping tests in the CNG wells (undertaken by the developer Amphora Energy Ltd in c.2018) yielded 2 to 10 l/s (Birks et al 2021). The highest yields were from BH4 & 5 located on the far western side of the CNG development site and were attributed to the switch to a reverse-circulation

drilling technique, however the presence of karstified open fractures (BH4) may also be a contributing factor.

Open loop GSHP heating capacities of between 60 and 300 kW thermal per 130m well-doublets (depending on local aquifer properties) are therefore probably feasible for similar schemes in the region, assuming a sustainable thermal productivity (ΔT_{gw}) of 7°C (i.e. abstraction at 12.5°C and injection at 5.5°C). Larger yields may be possible using larger diameter boreholes and in more fractured, weathered or karstified parts of the aquifer (i.e. fracture systems associated with the major NW-SE bedrock lineaments described by Woods and Chacksfield (2012)).

The passive seismic H/V data collected across the CNG site in 2020, prior to the new house construction, suggests chalk aquifer and seismic rockhead surface in-between the boreholes (BH1-5) is relatively level and planar at an elevation of around -24 m OD, although some karstification may have occurred in the upper 10-20m of the aquifer. This top chalk elevation is consistent with the old borehole records from the nearby Severalls Hospital. From interpretation of the closely-spaced H/V survey results there is no suggestion of a major fault/fracture system within the chalk at the CNG site, although there could be undetected fault systems at other locations in the region and potentially at depth in the area.

1 Introduction

1.1 BACKGROUND TO THE SURVEY

The UK government has committed to a 2050 net-zero CO_2 emissions target to speed up decarbonisation to limit the effects and impacts of global climate change. Domestic heating currently makes up around 40% of the UK's CO_2 emissions, and electrification of domestic and industrial heating using heat pumps is seen as a key technology for decarbonisation. Many new climate-conscious housing developments are developing '4th-' or '5th-generation' low-temperature district heat networks/grids that use open loop ground source heat pump systems, sited on major aquifers such as the Cretaceous Chalk, to provide 45°C - 65°C flow temperatures for space heating and hot water for buildings. The use of groundwater source heat pumps in the UK is currently very low but properly designed and installed systems are very clean and efficient with system efficiency (SPF-H4) of >4.5 proven (e.g. Boon et al., 2019). Geological and geophysical characterisation of five recently constructed water wells in north Colchester, Essex, provided a cost-effective way for BGS to collect new geological and geophysical data in the Colchester area, with the aim to support and inform emerging urban shallow geothermal energy schemes.

In 2018, Colchester Borough Council (CBC) embarked on constructing one of the largest open loop GSHP district heat network in the UK to supply heating to around 300 homes, offices and a planned health centre at Colchester's proposed new Northern Gateway development. The scheme, called Colchester Northern Gateway (CNG), received a £3.5 million grant from the first round of the UK Government/BEIS Heat Networks Investment Project in 2017 to develop a low-carbon heat network. Delivery and operation of the scheme is the responsibility of Colchester Amphora Energy Ltd (CAEL), owned by CBC. The scheme planned to utilise five new water wells to abstract/reinject up to 18 L/sec of groundwater from the Cretaceous Chalk aquifer. The boreholes were drilled by Drilcopp (BH1) and WJ Groundwater (BH2-5). The client's engineers were WSP. The scheme has a design peak heat capacity of 800 to 900 kW, supplying 80% of the heating load, with the remaining 20% peak loads planned to come from conventional gas boilers. The project will deliver approximately 5.5 GWh of low carbon heat per year when the Northern Gateway development is complete. The concept involves a centralised heat pump energy centre that will lift the temperature from ambient water source of ~13°C, up to 60-65°C for domestic space heating and domestic hot water (DHW). Five 300 mm diameter cased boreholes were drilled and pump tested by CAEL/WSP in 2018-19: two at the eastern end of the site for production (one 200 m and one 135 m deep well), and three approx. 550 m away at the western end of the site for cold water injection at 5°C (one 200m and two 135m deep wells) as shown in Figure 1. Borehole locations with 6-figure national grid references are given in Appendix 4.

In September 2019, the BGS was approached by Colchester Amphora Energy Ltd and offered access to their boreholes for use by the BGS-MUSE project to support urban shallow geothermal research in the area and with the idea to establish a long-term GSHP monitoring site at CNG. The project offered a rare opportunity for BGS to collect new downhole geophysical data in a currently data-poor part of the London Basin that hosts the Chalk, which is an important water supply source as well as a potential low-carbon heat source. The new field data collected will help improve the regional understanding of the regional chalk stratigraphy, structure, hydrogeology, shallow geothermal resource potential, and seismic ground response in the London Basin.

The geophysical survey work described herein was funded by the EU Managing Urban Shallow geothermal Energy (MUSE) project and BGS/UKRI National Capability funding.

1.1 SITE SETTING

The topography of the CNG study site is very flat and lies at an elevation of around +48 m OD. The site covers an area of approximately 700 m by 700 m and features several playing fields with a predominant land cover of short grass with a few mature trees. The sports fields are surrounded by roads and housing with some commercial units at the northern boundary. The northern site boundary is close to Junction 28 of the A12 road. The eastern fields were accessed via the Rugby club car park off Mill Road.

Figure 1. Google Earth colour image showing CNG site in June 2018 and location of boreholes 1-5. BH 1-3 are planned injection wells and BH4 and 5 are for water abstraction/ heat production. Well separation between abstraction (BH4-5) and injection zones (BH1-3) is c. 550 m. Map Data: Google Earth.

1.2 GEOLOGY

The site is located at the eastern end of the London Basin (Figure 2) on Thames Group sedimentary bedrock. The site geology is depicted on the 1:50 000 scale BGS map Sheet 224/242 'Colchester and Brightlingsea' (BGS, 2010).

The basement in the area is probably Silurian shales and slates (grey, sandy, hard) at around 350 m below surface (approximately -300 m aOD). There is an unconformity at the base of the (Lower Cretaceous) Gault Formation (grey mudstone, 6 to 23m thick), overlain unconformably by the Cretaceous Grey Chalk Subgroup (45m) and the White Chalk Subgroup, (about 225m), traditionally named the 'Upper Chalk'. The Grey Chalk is overlain by the Chalk Rock Member, Lewis Nodular Chalk Formation, Seaford Chalk Formation, Newhaven Chalk, which is unconformably overlain by Palaeogene overburden of the Thanet Formation and the Lambeth Group (previously Woolwich and Reading Beds, 15-30m combined thickness; Thanet is variable <1 – c.10 m), overlain unconformably by the Thames Group comprising the Harwich Formation (15-20 m) resting on the London Clay Formation (0-35m).

The surface geology (youngest to oldest) at the CNG site comprises a mantel of Quaternary Pleistocene-age 'cover loam' (2-5m) (variable pebbly sandy clay, locally silty and sandy upper part), and pre-Anglian age Kesgrave sands and gravels (<5m thick, restricted to the far eastern end of the site in the area of BH4 and 5).

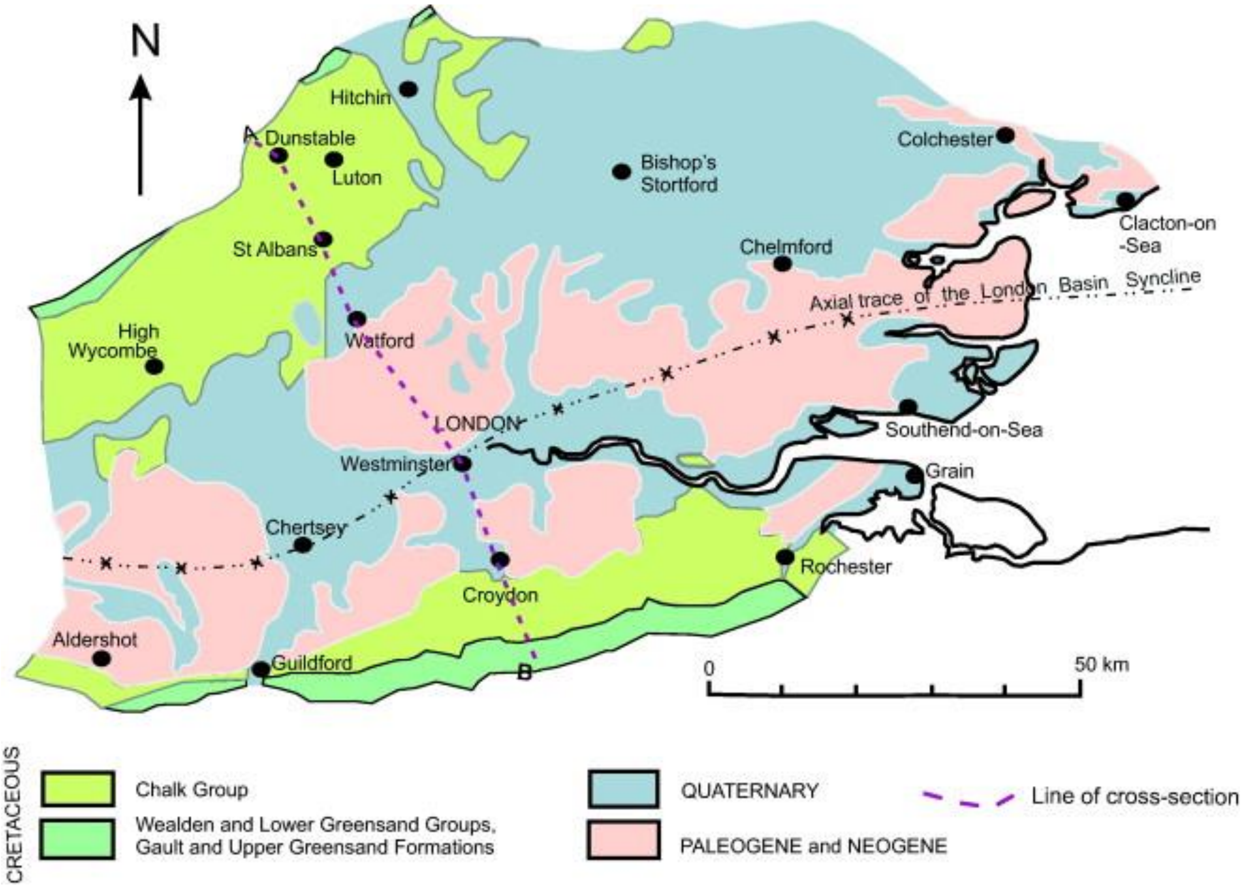


Figure 2. Simplified geology of the onshore London Basin showing the location of Colchester town on its northern limb (after Royse et al., 2012). Reproduced with permission from the Geologists Association.

1.2.1 White Chalk Subgroup

The White Chalk Subgroup is concealed beneath Paleogene deposits in the Colchester area and is within the "Transitional" Province of the English Chalk. The stratigraphy and structure of the chalk in the Colchester District is not well understood and correlation and structural models rely on evidence from only a handful of key boreholes with biostratigraphical or lithostratigraphical information (e.g. Pop' Bridge Pumping Station at Nayland, Bowdens Farm and Kelvadon boreholes). The BGS' desk study phase suggested the CNG water abstraction/heat production wells (BH1-5) likely penetrate the lower part of the Newhaven Chalk at rock head, extend through the Seaford Chalk, and terminate in the upper Lewis Nodular Chalk.

The Lewis Nodular Chalk Formation (LECH) is described in the BGS Lexicon as composed of hard to very hard nodular chalks and hardgrounds (which resist scratching by finger-nail) with interbedded soft to medium hard chalks (some grainy) and marls; some griotte chalks. The softer chalks become more abundant towards the top. Nodular chalks are typically lumpy and iron-stained (usually marking sponges). The overlying brash (derived top soils) is rough and flaggy or rubbly, and tends to be dirty. The formation is distinguishable by the regular seams of nodular flint, some large, that commence near the base of the formation and continue throughout. In the "Transitional" Province (includes Colchester-Ipswich area) the formation is condensed in response to the later inception of nodularity and hardground development, such that the lower boundary is diachronous here and placed below the "Chalk Rock Member" at the Reed Marl (the lateral equivalent of the Bridgewick Marls of the Southern Province). The upper boundary is conformable at the change from nodular flinty gritty chalks up into the base of the Shoreham Marl 2 (Seaford Chalk Formation), which is equivalent to the East Cliff Marl 2 in Kent and identified at the Anstey Quarry [TL 395 329] south of Royston, in the "Transitional" Province. In the field (and on geophysical logs), this is the most difficult boundary to place precisely because of the gradual upward transition in predominant lithology, with interbeds of hard chalk in soft chalk and vice versa. The most positive criterion is the incoming of abundant thick-shelled inoceramid debris (Platyceramus) in soft chalks, although this might not be applicable everywhere. The presence of a sequence containing carious flints within the low Seaford Chalk and high Lewes Chalk is a helpful field indicator of the general proximity of the boundary.

The Seaford Chalk (SECK) is described in the BGS Lexicon as 'Firm white chalk with conspicuous semi-continuous nodular and tabular flint seams (Hopson, 2005). Hardgrounds and thin marls are known from the lowest beds. Some flint nodules are large to very large. Mortimore (1986) recognises seven tabular flints; the most persistent and thickest flint band is the **Seven Sisters Flint Band** (SSFB), which crops out along the hard coastal cliffs between the River Cuckmere and Birling Gap in East Sussex (Mortimore, 1986). The SSFB flint band is in the order of 10-15 cm thick at Seaford Head and is laterally very persistent (and very hard and abrasive) making it a useful stratigraphic marker (it extends under the channel to France) and it likely extends under Colchester and as far east as Ipswich.

The Newhaven Chalk Formation (NCK) is distinctly less flinty than the Seaford Chalk with numerous marl seams. It is composed of soft to medium hard, smooth white chalks with numerous marl seams and flint bands, including abundant Zoophycos flints (notably at levels near the base). The formation is known to contain distinct phosphatic chalks of limited lateral extent. Equivalent beds, the Margate Chalk of north Kent, are marl-free and contain little flint. The lower boundary is conformable at the base of **Buckle Marl 1** in the Sussex succession (Mortimore, 1986). In typical sections (and boreholes), the lower boundary is the lower limit of chalk with numerous marl seams above several tens of metres of flinty chalk without marl seams (the Seaford Chalk Member). The incoming of common Zoophycos flints and the presence of the zonal Uintacrinus socialis crinoid at the base of the Newhaven Chalk Formation are useful indicators in the field/core. There is a basal unconformity at the base of the Palageogene recording a period of erosion.

1.2.2 Palaeogene

1.2.2.1 Thanet Formation

The Thanet Formation (TAB) is typically glauconite-coated, with a nodular flint layer at its base ('Bullhead Beds'), overlain by pale yellow-brown, fine-grained sand that can be clayey and glauconitic. It contains rare calcareous or siliceous sandstones.

The reference section in the Colchester area is the 1987 'Bradwell 217' borehole (TM00NW43) [NGR 601769 209156], Essex, located at Bradwell on Sea approximately 20 km south of CNG. The borehole cored dominantly argillaceous (clay grain size) lithologies of the Thanet Beds

(Jolley, 1992). Here, Thanet is interpreted from 60.2 m to about 82.3 m depth (22.1 m thick) by Jolley (1992, Fig 7). However, the Thanet Formation thins to 2m over the Ipswich-Felixstowe structural axis (Aldiss, 2012). At Nayland, around 6 km NW of the CNG study area, the Pop's Bridge Borehole records 0.6 m of 'Thanet' comprising grey sandstone - though its thickness here may be underestimated (in the authors opinion). 'Thanet' is recorded in several BGS boreholes drilled around 5 km north of CNG (e.g. Dedham Mill c.12 m thick, Flatford Lock c.12 m). At Wormingford Mere (TL93SW1; NGR 692670 232620), a borehole recorded 11.50 m of grey sands with beds of mottled glauconitic clay assigned to the Thanet Beds (Ellison, 1976). It therefore seems likely that the Thanet Formation is present at CNG and that it is between 10 and 20 m thick, and probably closer to 13 m (+/- 2m) comprising mainly fine sands with minor beds of clay.

The upper boundary is drawn at the unconformable boundary marked by an upward change from fine-grained sands of the Thanet Formation to glauconitic sand of the Woolwich and Reading Beds (Lambeth Group) and so the gamma signal though this transition may be subtle if not barely distinguishable.

1.2.2.2 Lambeth Group

The Lambeth Group (LMBE) (previously named Woolwich And Reading Beds) comprises lithologically vertically and laterally variable sequences mainly of clay, some silty or sandy, with some sands and gravels, minor limestones and lignites and occasional sandstone and conglomerate. The base of the Lambeth Group is taken at the base of the Upnor Formation. In the centre and east of the London Basin it overlies the Thanet Formation. The top of the Lambeth Group is marked by the eroded or interburrowed surface at the base of the overlying Thames Group. The Lambeth Group is overlain by sands, silts, clays or gravel beds of the Harwich Formation, depending on the local sequences, or gravelly sandy clays at the base of the London Clay Formation. The Lambeth Group extends throughout the London Basin, extending north into Suffolk (Aldiss, 2012) and is likely to extend under CNG.

1.2.3 Thames Group

1.2.3.1 Harwich Formation

The Harwich Formation (HWH) varies regionally. In East Anglia, the Harwich Formation comprises mainly bioturbated silty clays and sandy clayey silts with subordinate sandy silts and silty sands, some of which are glauconitic. There is a notable component of volcanic ash, both disseminated and in discrete beds (Knox and Ellison, 1979; Knox and Harland, 1979). Fossils include marine invertebrates, especially molluscs, with birds and mammals (Benton and Cook, 2006; Hooker, 1991, 1996, 2010). Previous names include Blackheath Beds, Hales Clay Member, London Clay Basement Bed, Oldhaven Beds.

The base of the Harwich Formation is an eroded unconformity surface on the underlying Lambeth Group (formerly Reading or Woolwich Formation). The base is sharply defined, being formed by a planar or slightly undulose discontinuity with a basal lag of very well-rounded flint gravel and fine to coarse quartz grains in a finer glauconitic matrix. Burrows commonly extend down into underlying beds.

The top of the Harwich Formation is a discontinuity marking the upwards change from sandy sediments to silty clays and clayey silts of the transgressive marine Walton Member (London Clay Formation). In distal areas there is commonly a thin bed of silty sand at the top of the Harwich Formation, overlain by sandy clay (Ellison et al., 1994). Its thickness is up to 24 m in East Anglia, locally up to 24 m in south-east London though more generally up to 10 m, but commonly less than 2 m. The Harwich Formation occurs almost throughout the London Basin, and in parts of East Anglia, and likely occurs below the London Clay at CNG.

1.2.3.2 London Clay Formation

The London Clay Formation (LC) mainly comprises bioturbated or poorly laminated, blue-grey or grey-brown, slightly calcareous, silty to very silty clay, clayey silt and sometimes silt, with some layers of sandy clay. It commonly contains thin courses of carbonate concretions ('cementstone nodules') and disseminated pyrite. It also includes a few thin beds of shells and fine sand partings or pockets of sand, which commonly increase towards the base and towards the top of the formation. At the base, and at some other levels, thin beds of black rounded flint gravel occurs in places. Glauconite is present in some of the sands and in some clay beds, and white mica occurs at some levels.

The base of the London Clay formation was redefined by Ellison et al. (1994) to correspond to the base of the Walton Member (Division A2) of King (1981). It is usually marked by a thin bed of well-rounded flint gravel or a glauconitic horizon, or both, typically resting on a sharply defined planar surface, although locally uneven. The London Clay Formation overlies the Harwich Formation or, where the Harwich Formation is absent, the Lambeth Group. Its thickness is up to 150 m in eastern part of the London Basin (Essex) but is more likely to be c.35m where it crops out in the north Colchester area.

2 Methods

Between 10-13 February 2020 the BGS undertook downhole geophysical surveys in all five water boreholes at CNG (Figure 3). Passive seismic micro-tremor soundings were made over each borehole and in-between the boreholes to measure horizontal to vertical spectral ratios (HVSR) of surface waves to further to characterise ground conditions, particularly to estimate depth to the chalk aquifer across the site and to identify any significant variability in rockhead surface and to screen for any major (hydraulically conductive) fault zones affecting the chalk.

2.1 BOREHOLE GEOPHYSICS

The boreholes at CNG had been drilled and pump tested several months prior to the BGS geophysical survey and it was assumed that water levels and downhole temperatures had settled back to ambient conditions. The main purpose of the survey was to measure the ambient temperature and fluid electrical conductivity profiles in each well to record pre-operation baseline conditions for comparison with future GSHP monitoring data. The second reason was for BGS to collect new /modern geophysical data to aid litho-stratigraphic correlations in the chalk across the region to support wider geoscientific research.

The well logging tools used were:

- Calliper (up direction, all 5 boreholes)
- Natural Gamma (up and down in BH1,2,3,4). Gamma tool broke on BH5.
- Optical Televiewer - OPTV (up and down, all 5 boreholes)
- Fluid/groundwater temperature and conductivity (up and down, all 5 boreholes)
- Point electrical resistivity (BH4)
- Impeller flow logger (BH2 and BH4).

Tool calibration: The temperature and conductivity sensors were calibrated in the BGS workshop after the field survey using ice bath and independent temperature measurement device at near room temperature. A guide to the sondes used by BGS is presented in Appendix 3.

2.2 PASSIVE SEISMIC

A *Tromino 3G* 3-component digital seismometer (Serial no. TE3-0325/02-17) was used to undertake Microtremor (HVSR) soundings at approximately 25 m spacing along linear survey lines between all CNG boreholes and a reference borehole (Pop's Bridge) at nearby Nayland. The locations of the soundings made at CNG are plotted on the map in Figure 3. The HVSR (or H/V) survey and modelling approach followed is described by Castellaro and Mulargia (2009).

Additional soundings were also made beyond the borehole locations to enable extension of the survey lines in the HVSR contour sections and to more provide context to the study site. The 25 m survey spacing was chosen for two reasons; firstly, because it was achievable to collect readings along lines at this spacing within the operator time available (2 person-days); secondly, from previous project experience it has been suggested that this spacing can resolve large lateral velocity impedance contrasts associated with changes in Paleogene overburden thickness and major faults affecting the Chalk, which would be relevant to the hydrogeology and thermogeology (David Morgan/Andy Farrant/Mike Raines pers. com. 2019).

The soundings were located on natural soil as close as possible (less than 2 m) to the CNG boreholes for sub-soil model calibration purposes. In total, 38 soundings were acquired at the CNG site between 10-13 February 2020, with two additional soundings done outside the area at Nayland on 10 February for comparison. Accurate locations of soundings at CNG and others performed nearby by the authors (e.g. Mersea Island) are listed in Appendix 5. The acquisition time duration was set to 12 minutes at 128 Hz sample frequency. The Tromino's long legs were used as the ground cover was short cut grass on a firm loam top-soil, negating the need to remove/replace turf before/after each sounding. The instrument was always orientated to the North using a declination-corrected Silva compass. Care was taken to minimise footsteps and noise during the acquisition period. Unwanted noise, such as that made by dog walkers or vehicles, was filtered out at the processing stage. A handheld Garmin GPS60 unit was used for location purposes (easting and northing). The Environment Agency LiDAR data (2016 version) digital elevation model (DEM) was sampled back in the office using a GIS to provide accurate ground level elevation values (z) because it is considered more accurate than using the hand-held GPS values. Environment Agency LiDAR data has a vertical accuracy of 5-15 cm +/- RMSE and a horizontal accuracy of 40 cm +/- RMSE, whereas hand held GSP units are circa 200 cm horizontal accuracy, at best. It was noted that ground levels at the CNG site have not changed significantly since 2016.

The depth to chalk rockhead value is proved by borehole drilling records, and this was confirmed by BGS' Natural Gamma logs. This information was used for 'calibration' when forward modelling Vs soil velocity profile in *Grilla*, which is the Tronimo's standard H/V curve modelling software routine.

2.2.1 H/V contour plots

Log10 H/V contouring files were generated in Surfer using files (asc.) generated from the H/V contouring analysis tools in *Grill*a software (Release 7.6, 2018) for passive/active surface waves analysis and modelling. *Grilla* is distributed by www.moho.world (Italy), who manufacture the *Tromino* instrument. Contouring using a 'Top Vs' value (Layer 1 shear wave velocity) of Vs=150m/s returned a good fit with the peak of the H/V curves collected next to the boreholes and so all profiles were processed using these values. This approach is justifiable given that the geology across the site is fairly uniform. The exponent value (*alpha* in Ibs V.S. Wholenberg, 1999) of 0.1 was used as this best represents empirical data of shear wave velocity increase with depth (effective stress) described at other sites (e.g. Heathrow Terminal 5) in the London Basin (Hight et al, 2003).

2.2.2 Nayland and Mersea Island H/V surveys

Two additional Tromino passive seismic (HVSR) soundings were acquired at the nearby village of Nayland for comparison of site response with CNG. Nayland is a low-lying site located in the bottom of the River Stour valley, 10 km to the north of the CNG site. The geology in the valley bottom is markedly different to CNG; the 1:50 000 scale BGS mapping indicates the London Clay Formation is absent, having been completely removed by glacial erosion and fluvial incision. The near-surface geology is recent river alluvium overlying glacial gravels resting directly on Lambeth Group, with (supposedly) thin Thanet Formation (<1 m) and weathered and non-weathered White Chalk bedrock. To explore the effect of this near-surface geology on ground resonance one 12 min Tromino HVSR sounding was acquired at [NGR 597060 233890], around 30 m northeast from Pop's Bridge Pumping Station borehole (TL93SE/7A). The borehole is used for calibration when performing the subsoil profile forward modelling routine. The ground level at the Pops Bridge borehole (and similar at the measurement Tromino site) is 12.68m above OD Newlyn, some 35m lower in elevation than CNG. A second Tromino sounding was acquired in the churchyard of St James's in Nayland village [NGR 597569 234249] for lateral comparison. The ground response in Nayland village is also of historic engineering seismology interest as two churches (St James and the Methodist church) and several brick buildings there suffered structural damage in the 22 April 1884 Colchester Earthquake, despite the village being located 20 km north of the epicentre in the Abberton-Wivenhoe area (Haining, 1976; Baptie, 2012).

Three soundings collected from Mersea Island previously by David Boon; the peak natural frequencies from raised river terrace deposit and tidal flat/foreshore sites on London Clay bedrock sites are included in the results in Appendix 2 for comparison.

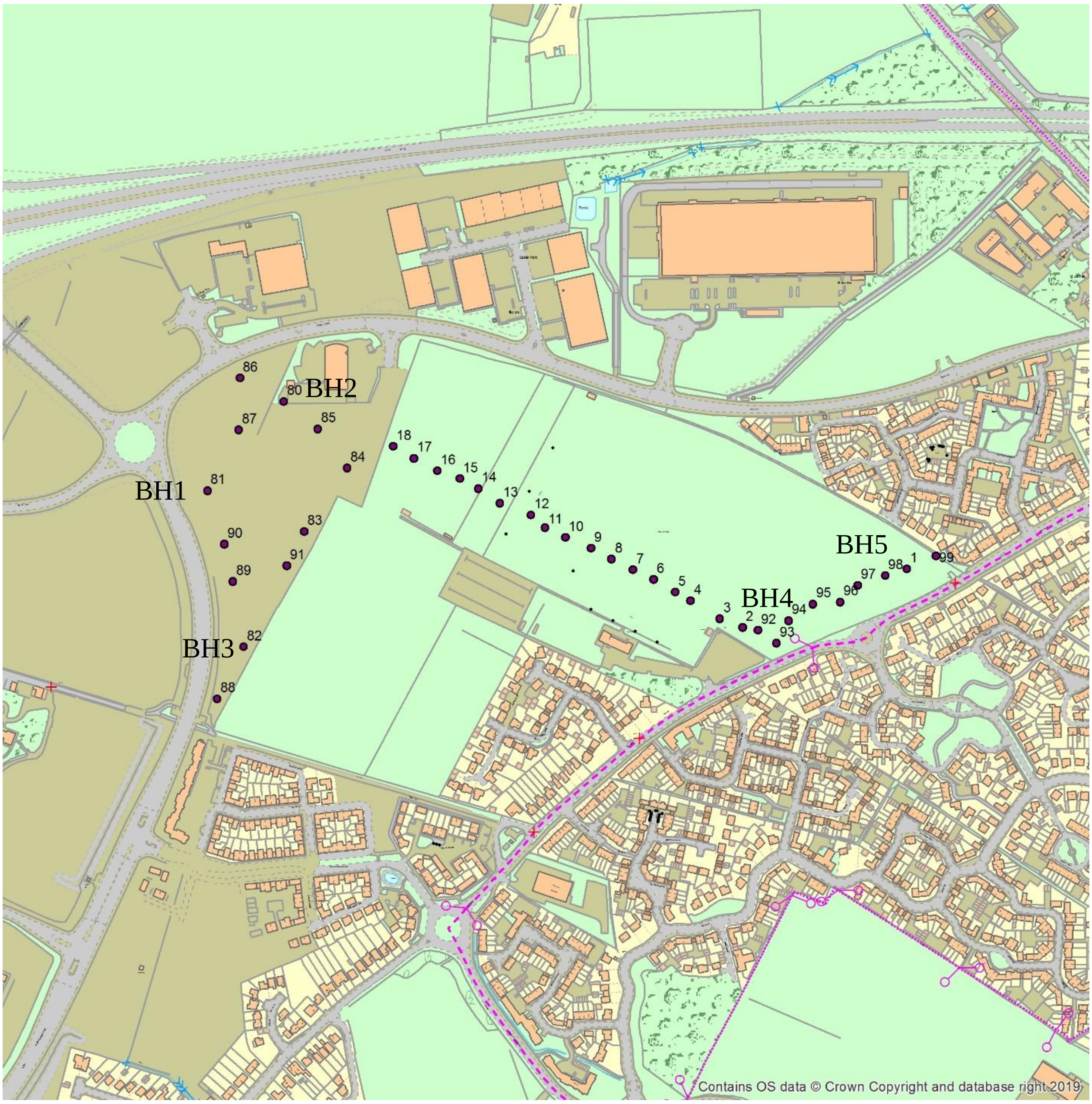


Figure 3. Location of CNG boreholes (BH1-5) and Tromino soundings (numbered 1-99). Tromino sounding ID number should be cross-referenced with the H/V curves, contour plots and data presented later in this report (Appendix 5). Contains Ordnance Survey data © Crown copyright and database rights 2020.

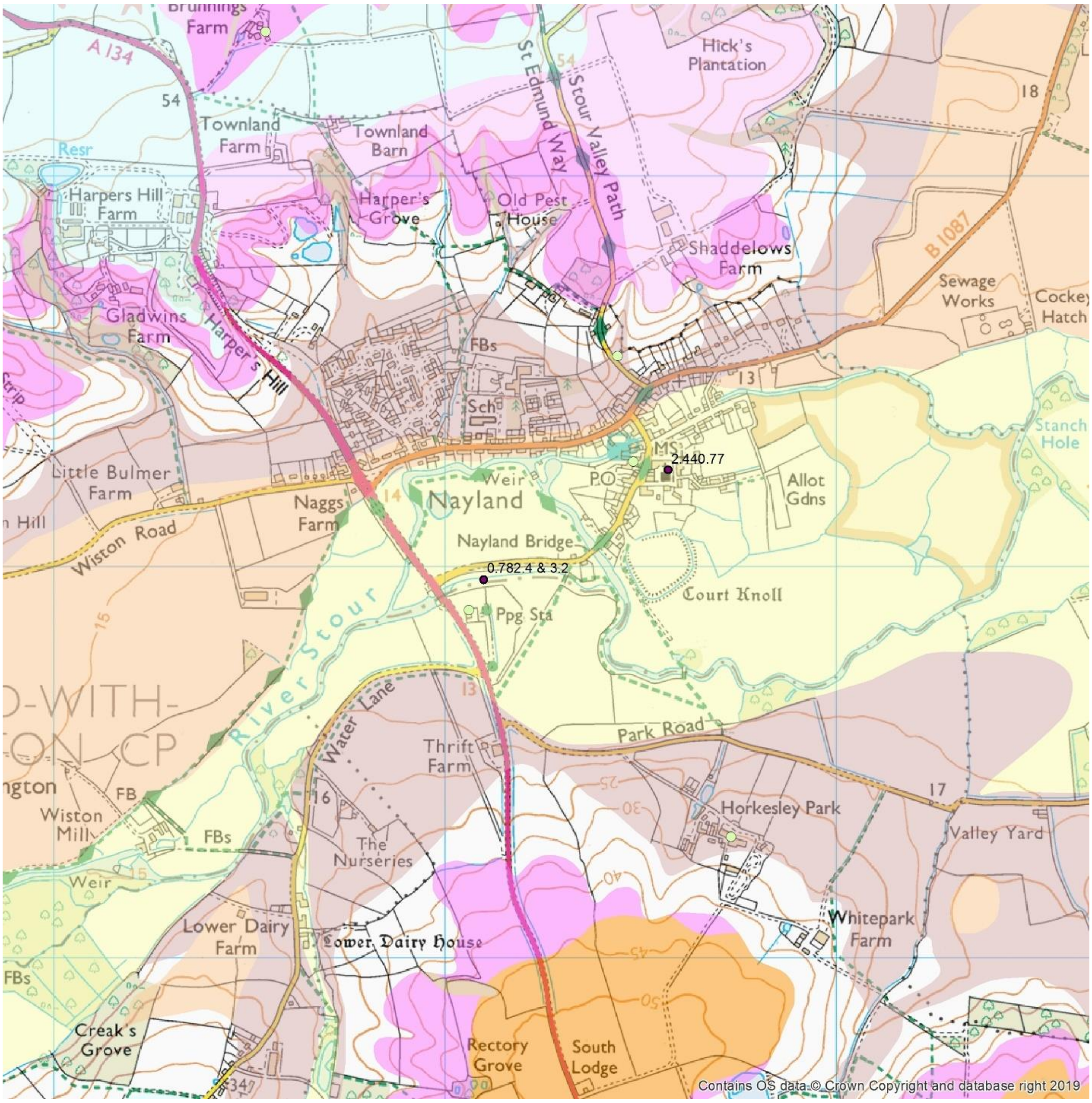


Figure 4. Locations of two Tromino HVSR soundings made at Nayland, Essex on 10 February 2020. 1:50 000 DigMap geology overlay – pale yellow is recent river alluvium. Label values indicate Peak (fundamental) and Secondary sub-soil resonant frequency (Hz), respectively (e.g. 0.78 peak, 2.4 & 3.2 secondary). Contains Ordnance Survey data © Crown copyright and database rights 2020.

3 Results

3.1 BOREHOLE GEOPHYSICS

3.1.1 Groundwater levels, temperatures and conductivity

The rest water level (RWL) in BH2 was 45.07 m below top of casing (44.4 m bgl) on 10 Feb 2020. The RWL in BH5 was 43.43 m below top of casing on 13 Feb 2020. It is suspected that the local (natural) groundwater flow direction in the Chalk aquifer is roughly from north west towards the south east (i.e. down-dip and towards the Essex coast).

The measured groundwater temperature and conductivity profiles from February 2020 are plotted in Figure 5 and Figure 6, respectively, and well log data summarised in Appendix 4. These temperature profiles indicate that the groundwater temperature in the confined White Chalk aquifer at the site increases with depth from around 10.5°C at the water table (c.45m below surface) to around 14.3°C at 200m below ground level. The measured groundwater temperatures in the two deepest wells (BH2 & BH4) were 13.0°C at 150 m and 14.1°C (+/- 0.1°C) at 190 m. In BH2, there are slight temperature 'kicks' (increases) at 158 m and 160 m depth (Figure 5). In general, the ambient temperature in the aquifer at CNG is around 11.5°C at 100 m depth and 14.2°C at 200m depth, equating to a shallow geothermal gradient of +2.4°C per 100 m.

3.2 DISCUSSION ON TEMPERATURE DATA

For comparison, the temperature gradient at CNG is higher than the 2.0°C per 100 m reported in the central London area (Headon et al 2009), and slightly below the UK average of 2.6 °C per 100 m (Busby et al 2009; Rollin et al 1987). These new data provide the first published undisturbed ground temperature profiles in the area.

Interestingly, some variation in aquifer temperature and fluid electrical conductivity was observed across the 550m wide survey area. For example, in BH1 and BH3 (the most westerly wells) the temperature 120m below ground surface was around 12.1°C, but in BH2 and BH4 (the two deepest wells) it was 12.3°C at 120m, and in BH5 (the eastern most production well) it was 12.4°C. The deep groundwater in BH4 and BH5 (in the planned geothermal heat abstraction zone) also have the highest specific electrical conductivity (SEC).

The reason for the groundwater in BH5 being consistently 0.3°C warmer and more conductive than the other wells is not clear, but this anomaly was also noted in the pumped temperatures measured during the pumping testing works done in 2019 by CNG. Possible explanations for this observation include that (1) the aquifer is progressively warming towards the town centre/built up area due to the effects of the subsurface urban heat island effect, (2) groundwater is older and has longer residence times (BH4 and 5 are further down-gradient than BH 1 & 3) or (3) it is an effect of the acidisation treatment undertaken when developing the wells (although the heat produced by this should have dissipated after a year?). It is also possible that nearby faulting is transmitting warmer fluid upwards from depth, but there are currently no reliable data to confirm this, though we know from regional gravity data that there are deep structural lineaments in the area which affect the thickness and nature of the chalk (Woods & Chacksfield, 2012). Another cause of temperature anomaly can be nearby geothermal schemes or leaking sewers, but to our current knowledge, there are no closed loop Domestic RHI GSHP scheme(s) nearby that could cause thermal interferences at these depths but there could be unregistered or non-domestic GSHP boreholes nearby. It would be interesting to map the subsurface temperature further up and down the groundwater flow direction (from chalk recharge area towards to the sea/blackwater estuary) to explore this feature further.

Initial groundwater source temperatures in a 200m open loop GSHP or free cooling production well might be expected to fall somewhere between this range. For example, between 12°C and 13°C where a submersible well pump is placed at 120 m depth, as water will be drawn in from a range of depths under pumped conditions and mixing will occur in the well before entering the BH pump inlet. Using BH4 and BH5 as production wells will access the highest temperatures available and will help maximise heat pump system efficiency with seasonal COP's of >4 likely to be achievable in well-designed open loop GSHP systems.

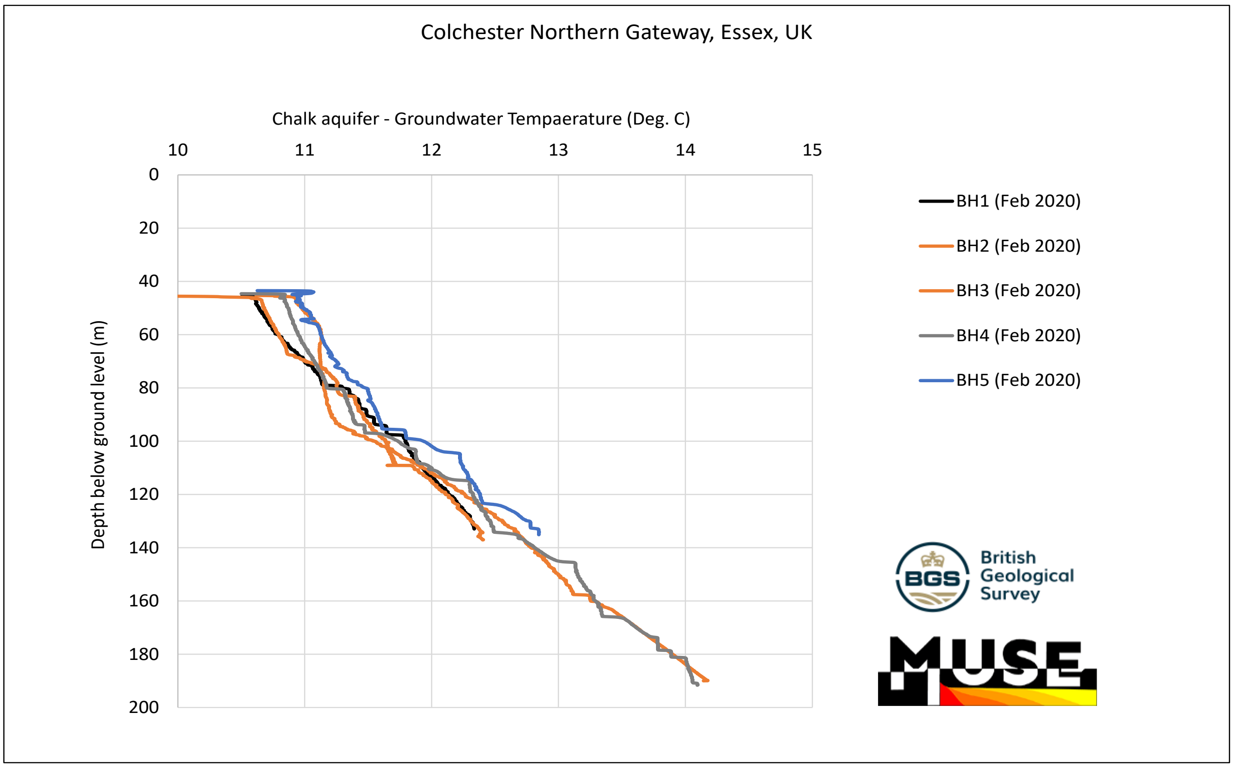


Figure 5. Groundwater (fluid) temperature profiles (February 2020)

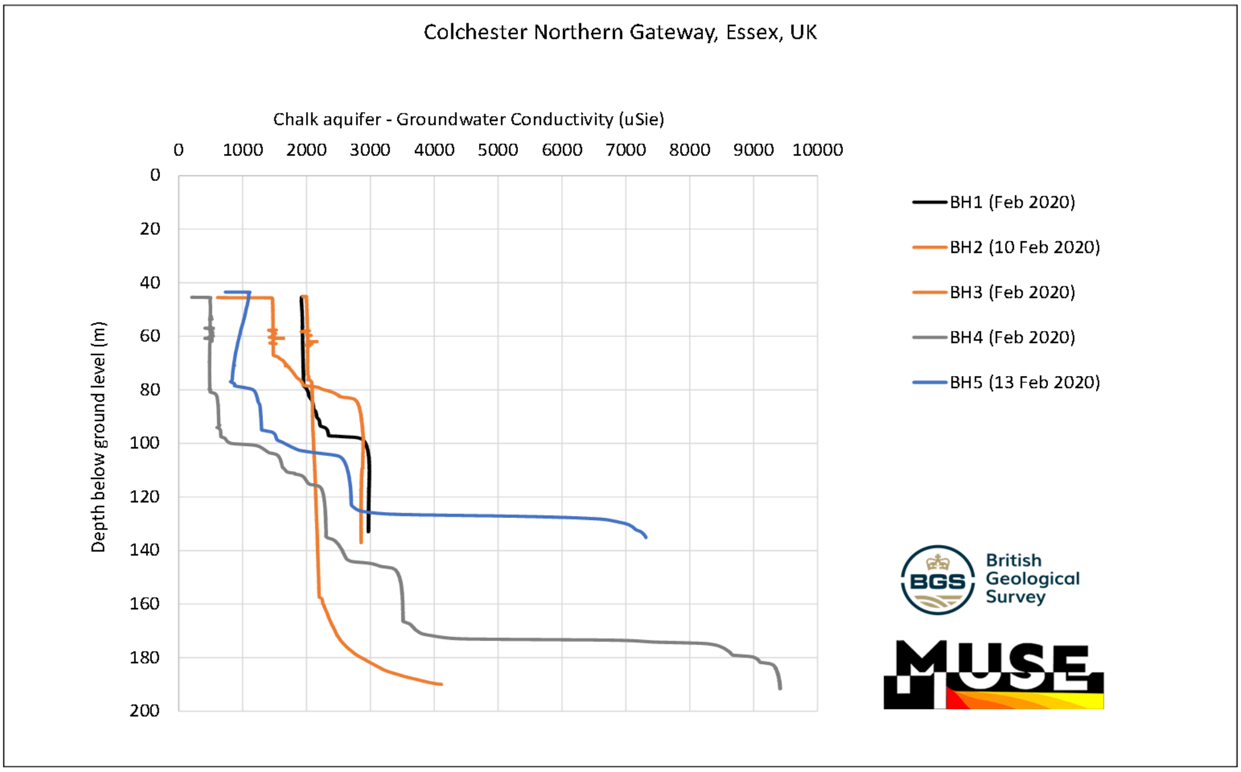


Figure 6. Groundwater electrical conductivity profiles. Top of White Chalk (Newhaven) and steel casing is around 74m bgl.

3.3 CORRELATION OF DOWNHOLE GEOPHYSICS AND GEOLOGY

See Appendix C for geophysical log compilations for each borehole at CNG.

3.3.1 Gamma ray logs

Figure 7 provides a correlation of gamma-ray signatures in the Lambeth Group and Thanet Formation in London (after Ellison et al 2004, Fig 10). This panel has been used as a rough guide to interpret the CNG downhole geophysical data. Figure 8 presents a correlation panel with all the CNG borehole data and with relevant stratigraphic boreholes from the area (Layer-de le Haye). We have picked tentative boundaries of the Palaeogene Formations (which are concealed behind permanent steel casing in the wells) based mainly on the natural gamma-ray response and expected thickness and lithology. The gamma-ray response behind the casing is muted. In all 4 boreholes with natural gamma-ray data (BH1,2,3,4) there is a near continuous gamma response (20 CPS) for around 10 m to 12 m above the top of the chalk. This feature is interpreted as fine-grained sand material corresponding to the Thanet Formation.

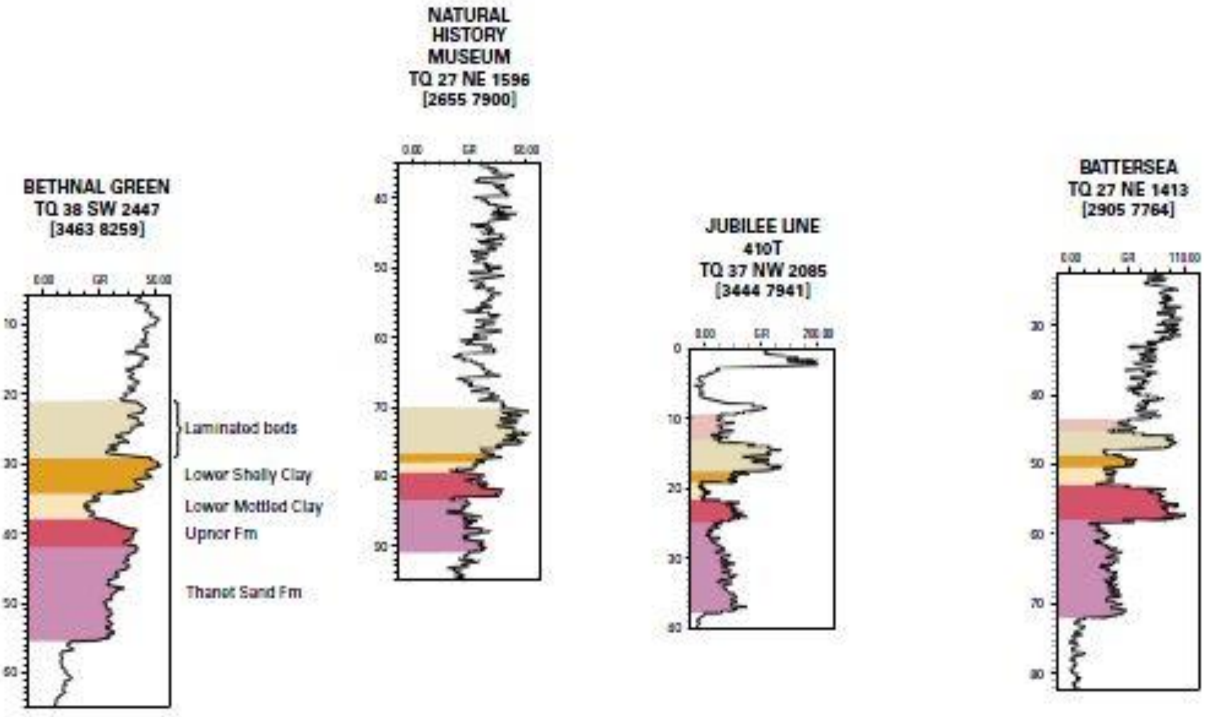


Figure 7. Correlation of gamma-ray signatures in the Lambeth Group and Thanet Formation in the London area (after Ellison et al 2004, Fig 10)

The presence of chalk is marked by a very low gamma response in the CNG boreholes (also seen as basal white interval in Figure 7), except a few peaks that correspond to marl bands. The top of the chalk aquifer is taken as the drop in Gamma from around 20 CPU (presumed Thanet) to around 5 CPU (chalk). The depth of this change in Gamma corresponds closely to the chalk described in CNG BH1-5 driller's logs (not yet lodged with BGS, but reviewed by the authors). The elevation of the top chalk surface (and thickness of Thanet) seems to vary in North Essex by some 10 m or so, as evidenced by contrasting reduced level of base Thanet Beds in a borehole at Layer de la Haye (Mortimore, 2014) and Bradwell 217 borehole (Jolley, 1992). This variation is depicted for regional context in Figure 8. However, the gamma data collected at CNG shows no evidence for much local undulation of the top chalk surface at the CNG site (see Tromino results). Two historic water supply boreholes (TL92NE123 and TL92NE254) at the former Severalls Hospital, located 1km to the west of CNG site, proved 51.8 m LC and 22.9 m WRB (LG) & TH (undifferentiated), with Upper Chalk from 74.7 m depth. The borehole start height at Severalls is 50.6 m, which is c.2m higher than ground level at CNG, suggesting the elevation of the top chalk surface there is very similar to CNG (i.e. approximately -24 m OD).

The natural gamma data from CNG suggests the steel casings penetrate at least the upper 5 m of chalk. Between 95 and 96 m depth in Figure 8 the OPTV data shows a hardground and conspicuous marl-filled burrows with a corresponding gamma peak below. These features correlate with similar features described in boreholes at Layer de la Haye (Mortimore, 2014) and Pop's Bridge, Nayland, and mark the top of the Seaford Chalk (at -48m aOD). Gamma spikes also mark the **Belle Tout Marls** and **Shoreham Marl 2**, with the later placing the top of the Lewis Nodular Chalk at around 155.4 m (-107.4 m aOD) in BH2 making the Newhaven Chalk c.23.0 m thick and the Seaford Chalk c.59.4 m thick at the CNG site. The **Severn Sisters Flint Band** is also tentatively identified at around 132 m in BH2.

The blue line visible in BH5 OPTV image between 120 m to 135 m depth (Appendix 2) was a blue plastic pipe probably dropped during the drilling/acidisation operation which has since been removed (Michael Woods pers. com, Feb 2021).

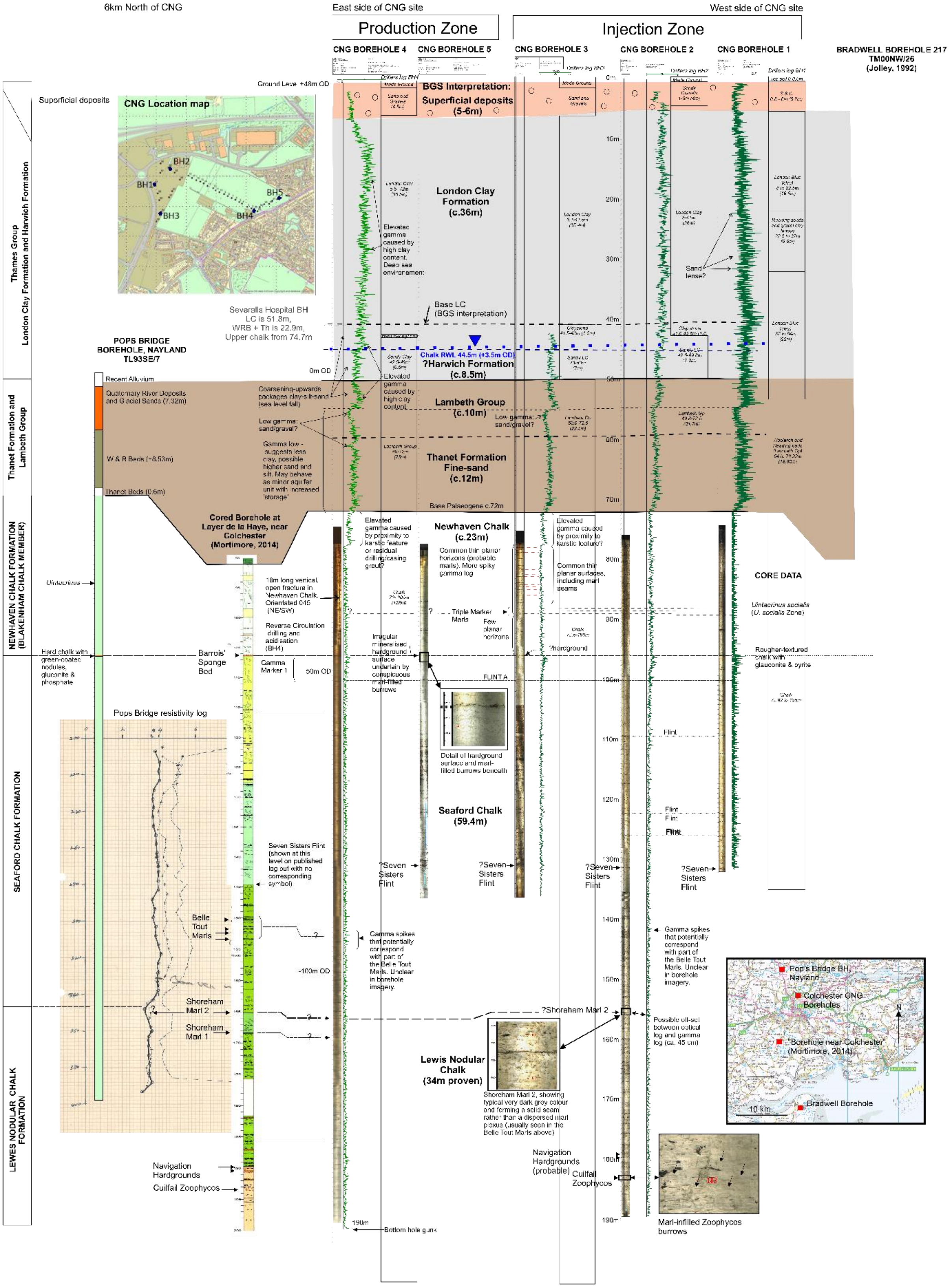


Figure 8. The stratigraphy of the Palaeogene and Chalk in the Colchester CNG boreholes (BH1-5), and regional correlation. Core log of the Layer-de-la-Haye Borehole from Mortimore (2014) and reproduced herein courtesy of Rory Mortimore and Whittles Publishing. Contains Ordnance Survey data © Crown copyright and database rights 2020.

3.4 H/V PASSIVE SEISMIC

The H/V curves from CNG site consistently have a ‘clear’ fundamental peak between 0.7 and 0.8 Hz with a secondary ‘shoulder’ peak at around 1.3 Hz, as shown in the H/V curve from BH2 in Figure 9. The exception is TR93, located close to BH4 at the far eastern end of the site adjacent to Mill Road, which only has one ‘clear’ peak at 1.2 Hz. This suggests there is possibly a change in the ground response not far from the injection zone (BH 4 and 5), potentially due to a change in the geology or structure (e.g. weathering or fault in chalk), though additional investigation is needed to examine and understand the relevance of this anomaly (one interpretation is that it could relate to a bedrock fault zone east of Mill Road).

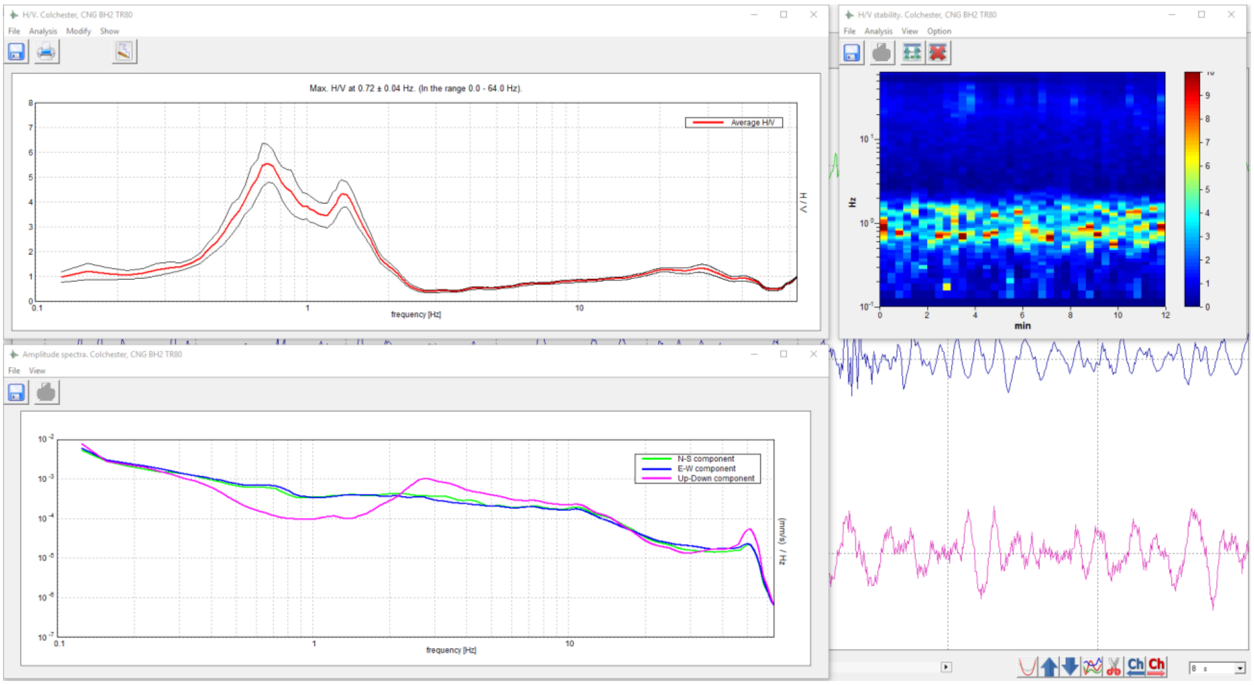


Figure 9. Tromino data from CNG BH2 (Colchester). H/V curve (top left), amplitude spectra (bottom left), frequency-time window (top right) [NGR 599885 228956, g.l .+48m aOD]. Geology is 72 m of ‘soft’ Palaeogene sedimentary deposits ‘engineering soils/lightly-overconsolidated very stiff clays / extremely weak claystone resting on relatively ‘hard’ or extremely weak to moderately strong Cretaceous chalk bedrock in BS5930 descriptive terms.

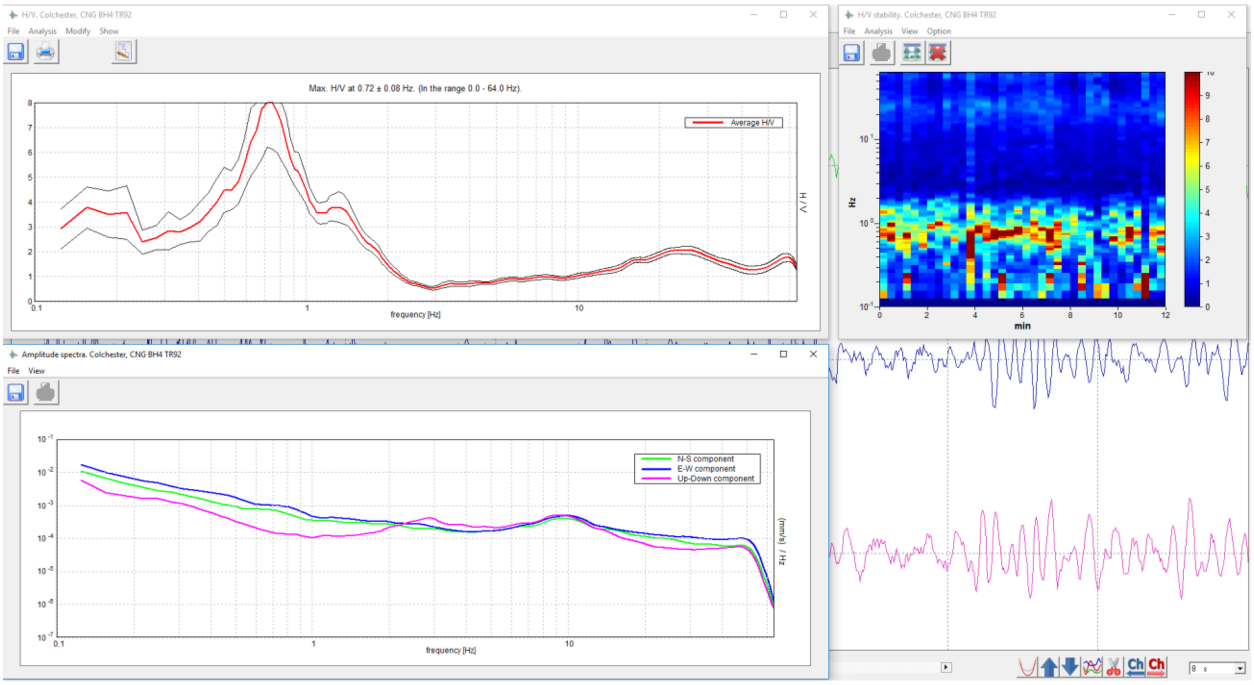


Figure 10. Tromino H/V curve from CNG BH4 [NGR 600370, 228722, g.l.+48m aOD]. Geology is 72 m of 'soft' Palaeogene marine 'engineering soils/lightly-overconsolidated clays / sediments resting on relatively 'hard' Cretaceous chalk bedrock.

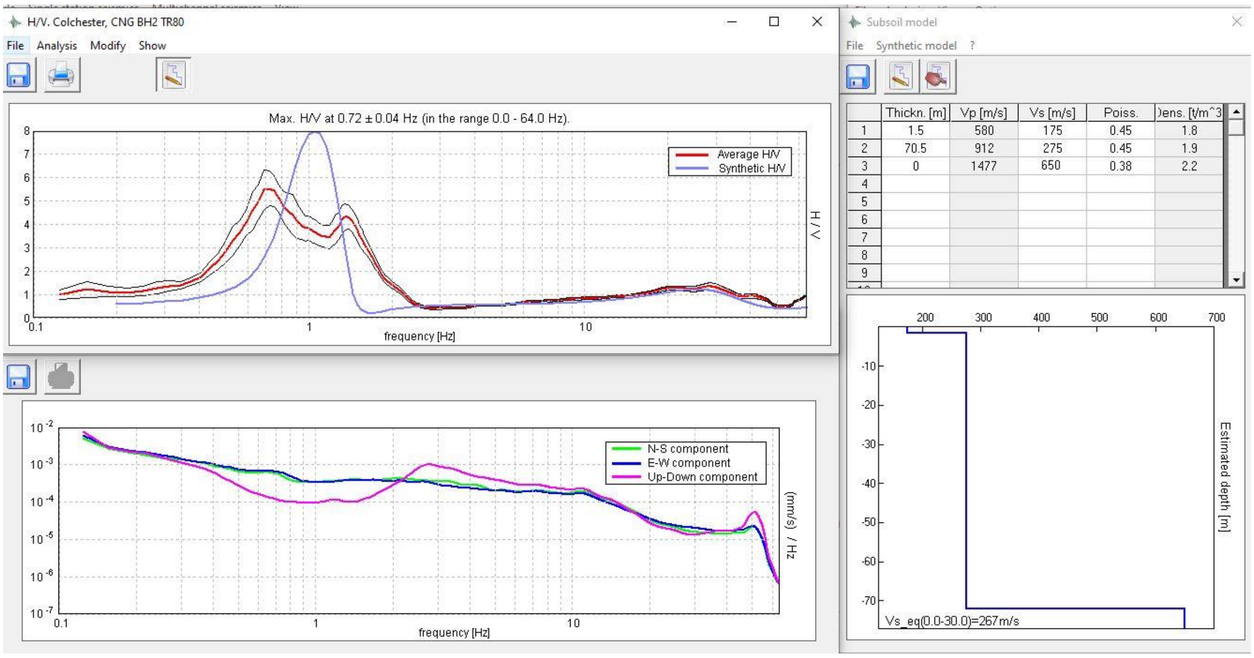


Figure 11. 3-Layer Vs subsoil model for CNG BH2 with Vs30 = 267m/s. Geology is 72 m of 'soft' Palaeogene sediments lightly-overconsolidated clays, silt and sands (London Clay, Lambeth Group, and Thanet Sand Formation) resting unconformably on Cretaceous White Chalk Group bedrock.

3.4.1 Stratigraphic interpretation of the CNG seismic noise data

The shape of the H/V curves from BH2 and BH4 are almost identical. In BH2 chalk rockhead was proven at c.72.0m bgl. and the chalk/Palaeogene aquifer water table is around 44.4 m bgl. Note the presence of a clear double peak feature between 1.5 Hz and 0.72 Hz on the H/V curve shown in Figure 9. Note also that the H/V ratio goes below 1 between around 2.5 Hz and 10 Hz, suggesting a possible velocity inversion or change in amplification magnitude within the Palaeogene overburden. The water table in the chalk is coincident with the top of the Lambeth Group and so the Harwich Formation and London Clay are in the 'unsaturated zone' at this level which might explain the velocity change (Dave Gunn pers comm).

In BH4, chalk is similarly encountered below 72.0 m and the OPTV and gamma log confirms that it is continuous to the base of the hole to TD at 190 m depth. The corresponding H/V curve, shown in Figure 10, shows a double peak, with a 'clear' main peak sitting at 0.72 Hz and a secondary 'shoulder' peak at around 1.4 Hz. The H/V ratio goes below 1 between 3 and 10 Hz suggesting a velocity inversion and is consistent with the H/V curves for the other CNG BHs. In BH4 there is also a low amplitude but clear peak at around 25 Hz which is interpreted as a near-surface impedance contrast probably associated with a thin (<1m) layer of softer Made Ground, or superficial deposits ('cover loam' or Kesgrave sands and gravels), resting on a stiffer layer of unsaturated London Clay Formation. This feature is also seen in the H/V curve from BH2. The very-low frequency peak at around 0.2 Hz in the curve from BH4 could either relate to the deep Gault/Silurian boundary, or seismic background noise produced by large ocean waves, but it is absent (or barely discernible) in the nearby BH2 curve. A longer recording (e.g. 2 hours, not 12 minutes) may provide more information about this low frequency feature.

Figure 11 shows the results of 'forward subsoil modelling' for CNG BH2 based on the Tromino data. The best-fit solution, with good borehole control, is a simple 3-layer model, treating the two main peaks as one peak at around 1Hz;

- Layer 1 is a 1.5m thick layer of soft Made Ground/Superficial Deposits with modelled Vs of 175m/s.
- Layer 2 is 70.5m thick and represents the Palaeogene 'overburden' (including some shallow superficial deposits, Thames Group, Lambeth Group and Thanet combined) with modelled Vs of 275m/s.
- Layer 3 represents 'Transitional Province' Newhaven Chalk bedrock with modelled Vs of 650m/s.

The average shear wave velocity (Vs) in the upper 30m (**V_s30)** is modelled as 267m/s.

Note the Vs of fresh Cretaceous Chalk reported in the literature is typically higher (e.g. 1100-1200 m/s) but using this higher velocity produces an erroneous model curve in *Grilla*. The shape of the H/V curve suggests the upper few meters of the chalk is weathered and softened (less stiff and seismically slower), which would be expected in this geological setting. Other sub-soil model solutions are possible, but this is the simplest solution and therefore our current favoured interpretation.

Figure 12 provides a 1:1 (h:v) scale summary of all the seismic noise measurements collected at CNG presented as contoured logH/V plots with control boreholes plotted alongside. The red-orange filled contours indicate a high impedance contrast associated with the change from relatively 'soft' Palaeogene sediments ('engineering soils') to relatively 'hard' chalk bedrock. The deep blue colour indicates negative logH/V values suggesting the velocity inversion situation is a consistent geophysical feature across the site. The position of colour transition (e.g. blue-green) does not directly represent a specific geological boundary, nor the water table, and should not be interpreted as such. The annotations describe key features, control boreholes, and interpretations.

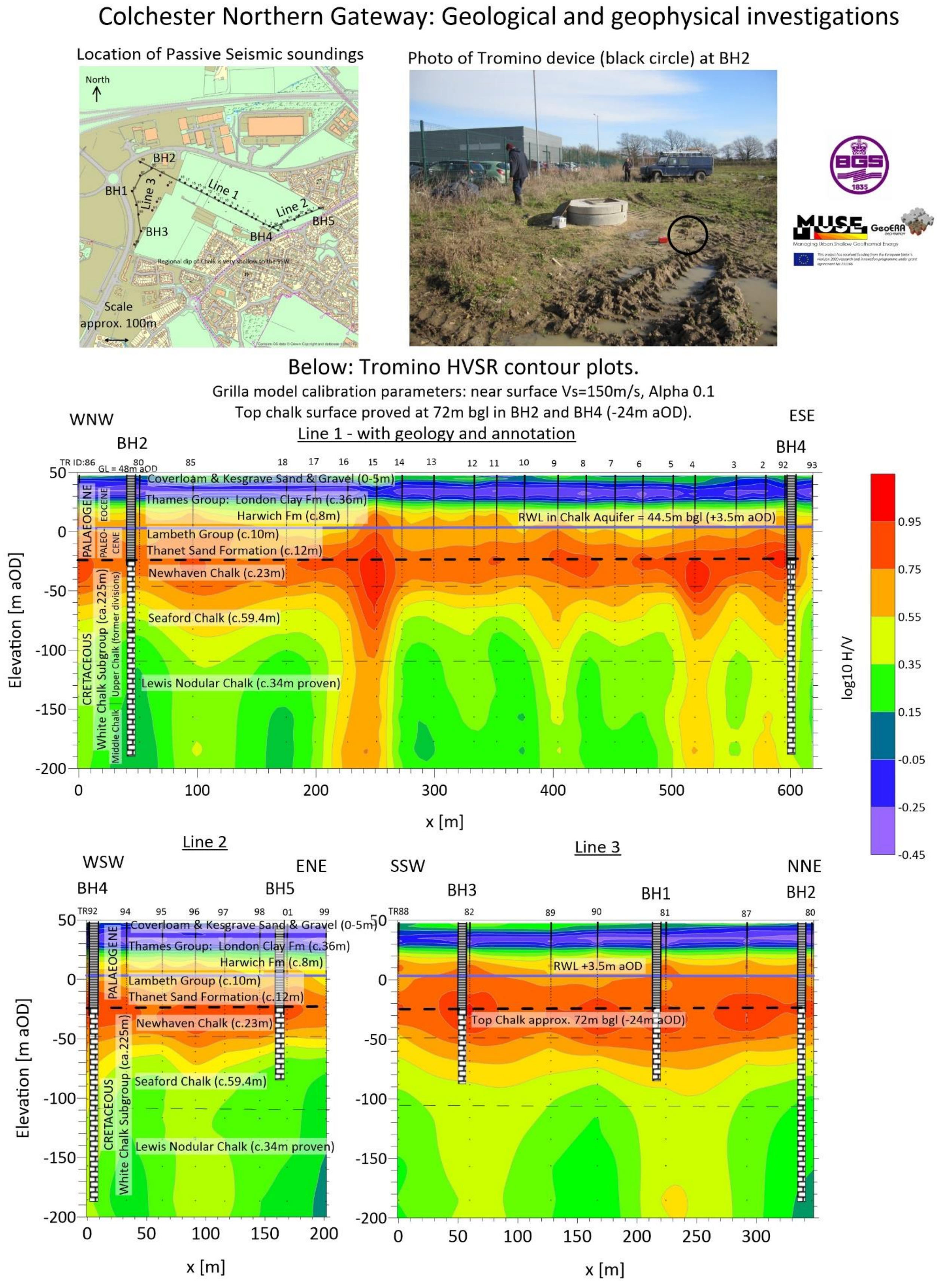


Figure 12. Results: log H/V contour plots annotated to show main geological unit boundaries (unit thicknesses) and CNG borehole control points. Line 1 is a profile between the planned production and injection zones. Line 2 is a profile between the two production wells BH4-5. Line 3 is a profile between all three injection wells at the western end of the site (BH1-3).

Contains Ordnance Survey data © Crown copyright and database rights 2020. Photo taken by D P Boon/BGS.

3.4.2 Stratigraphic interpretation of the Pop's Bridge (Nayland) H/V curves

The 1949 Pop's Bridge Nayland water supply borehole [TL93SE7] provides the key stratigraphic data for the region and was used to interpret and model the Nayland Tromino curves. This provides an independent 'sense check' for the interpretation of the CNG H/V curves, as well as a data point to aid regional stratigraphic correlation. The thickness of the units provided on the available drillers logs is reproduced in Table 1,**Error! Reference source not found.** and is summarised as: Layer 1: recent (Holocene) river alluvium and glacial sands (7.3 m); Layer 2: Lambeth Group silt, clay and sands (12.5 m); Layer 3 hard fine-grained glauconitic sandstone of the Thanet Formation (0.6m), Layer 4 soft chalk rock from 20.4 m bgl to the bottom of the borehole at 121.9 m.

Table 1 Geology profile in the Pop's Bridge (Nayland) borehole (TL93SE7)

Depth (m)	Thickness (m)	Lithology	Stratigraphy
0 to 0.91	0.91	Dark brown sandy gravel	River Deposits and Glacial sand and gravels
0.91 to 3.35	2.44	Ochreous flint gravel	
3.35 to 4.88	1.52	Clean sandy gravel	
4.88 to 7.32	2.44	Fine grained light brown sands with traces of silty material	
7.32 to 8.23	0.91	Dark reddish brown fine grained sand with silty material	Woolwich and Reading Beds (now Lambeth Group)
8.23 to 8.38	0.15	Variegated greyish green reddish brown sandy loam	
8.38 to 11.28	2.90	Light greenish grey silt	
11.28 to 19.81	8.53	Dark greenish grey silt with some argillaceous material	
19.81 to 20.42	0.61	Relatively hard fine-grained grey sandstone with much glauconite	?Thanet Sands (now Thanet Formation, TAB, part of Montrose Group)
20.42 to about 45.70	25.28	Chalk (soft, numerous marls)	lower Newhaven Chalk (strat. inferred by authors based on description)

About 45.70 to 121.92 (base not proven)	>76.22	Chalk (harder with flints)	Seaford Chalk (inferred by authors based on description)

Given the geological context (in river valley just south of the Anglian Glacial limit), it is highly probable the double peak between 2-4 Hz in the Pop's Bridge H/V curve, shown in Figure 13, is caused by a strong impedance contrast at the interface between the soft Palaeogene bedrock (engineering 'soils') and hard Cretaceous Chalk bedrock ('weak rock' in BS5930:2015 engineering geology terminology), with the deepest (low frequency) peak on the double peak being a response of harder or less weathered chalk. The geological log describes the upper 25 m of the chalk is 'soft', and this is a common feature in a river valley setting where enhanced groundwater flow leads to more intense weathering (Allen et al 1997). The depth of chalk weathering below the Tertiary sediments on the CNG site, located on an interfluve setting not in a valley, would be expected to be shallower and the hence impedance contrast weaker. The higher frequency peaks at 20 and 30Hz appear to be natural (based on the shape of the amplitude spectra up-down components relative to the horizontal components) and probably relate to shallow layers such as the near-surface gravels overlain by 1-2 m of soft recent river flood plain alluvium (unconsolidated and non-cemented clay, silt, sand and gravel). There is also a lower frequency peak at around 0.8Hz that resembles the main peaks seen in the CNG H/V curves. The low frequency peak at Pop's Bridge Nayland is interpreted to relate to a deeper structural feature – the unconformity between Gault Clay Formation resting on hard Palaeozoic (Silurian) mudstone basement rocks – rather than to the Paleogene/chalk unconformity seen at CNG. This situation is represented in the 5-layer model solution presented in Figure 14, which includes:

- Layer 1 of soft Holocene river alluvium (1.5m);
- Layer 2 of stiffer river gravels, Quaternary gravels, Lambeth Group and Thanet (20.5m)
- Layer 3 of weathered Newhaven Chalk (25m);
- Layer 4 of Seaford Chalk to base Chalk and Gault (190m);
- Layer 5 of hard/strong rock of Silurian basement?

This model implies that the H/V technique can sometimes distinguish marly Newhaven Chalk from the stiffer flinty Seaford Chalk below. The modelled Vs30 of the site is 327m/s, and though this is higher than the Vs30 at CNG site, the H/V curve of this valley alluvial site in-fact shows greater potential for frequency-dependant seismic ground motion effects on low rise buildings during earthquake.

However, the deep stratigraphic interpretations based on only rapid H/V curves come with uncertainty, because of a lack of deep borehole information for calibration of the HVSR soundings. It is recommended that longer-duration (e.g. 2hrs) HVSR surveys should be undertaken at key 'deep BGS borehole' (Golden Spike) sites such as the Weeley Borehole (TM12SW1) [NGR 614737 221833] to aid stratigraphic interpretations in data-sparse parts of the London Basin.

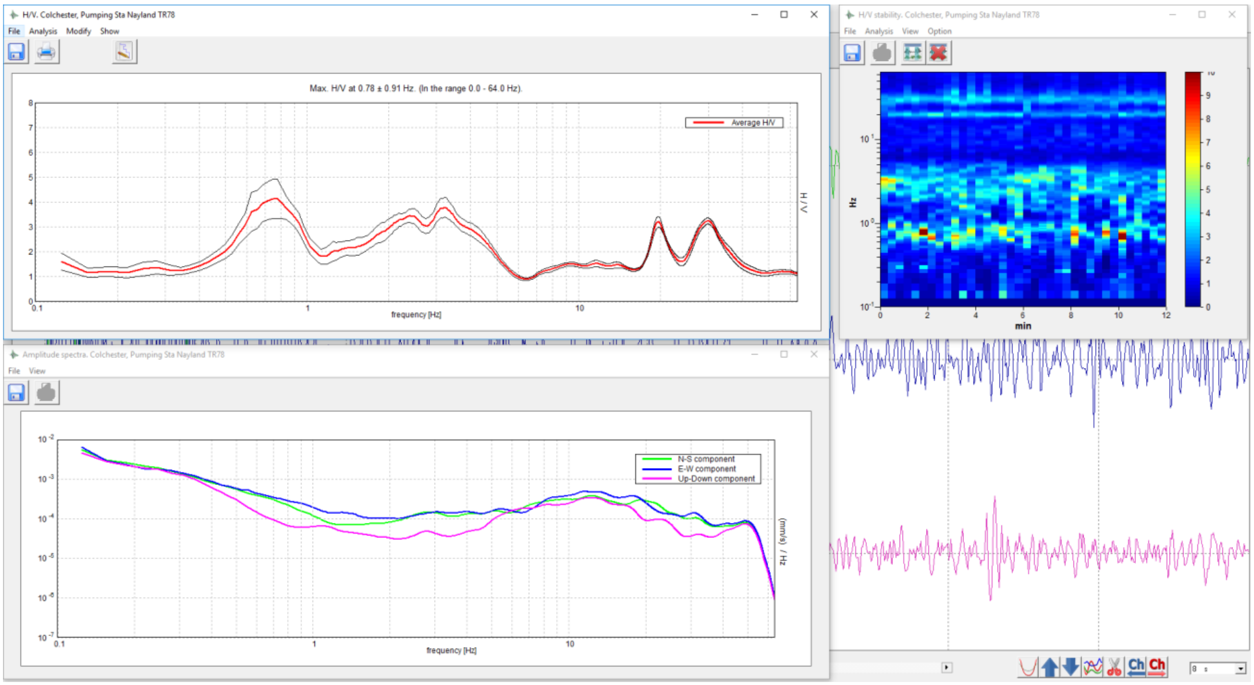


Figure 13. Tromino H/V curve (top left) close to Pop's Bridge Pumping Station borhole, Nayland, [Tromino location NGR 597098, 233969, ground level is 12 m above OD]. Data acquired 10 February 2020. Vertical and horizontal components (bottom left) shows two broad natural low-frequency main peak and two high-frequency natural secondary peaks. Raw time window data top right. There is no evidence of a strong pumping station-related anthropogenic peak(s).

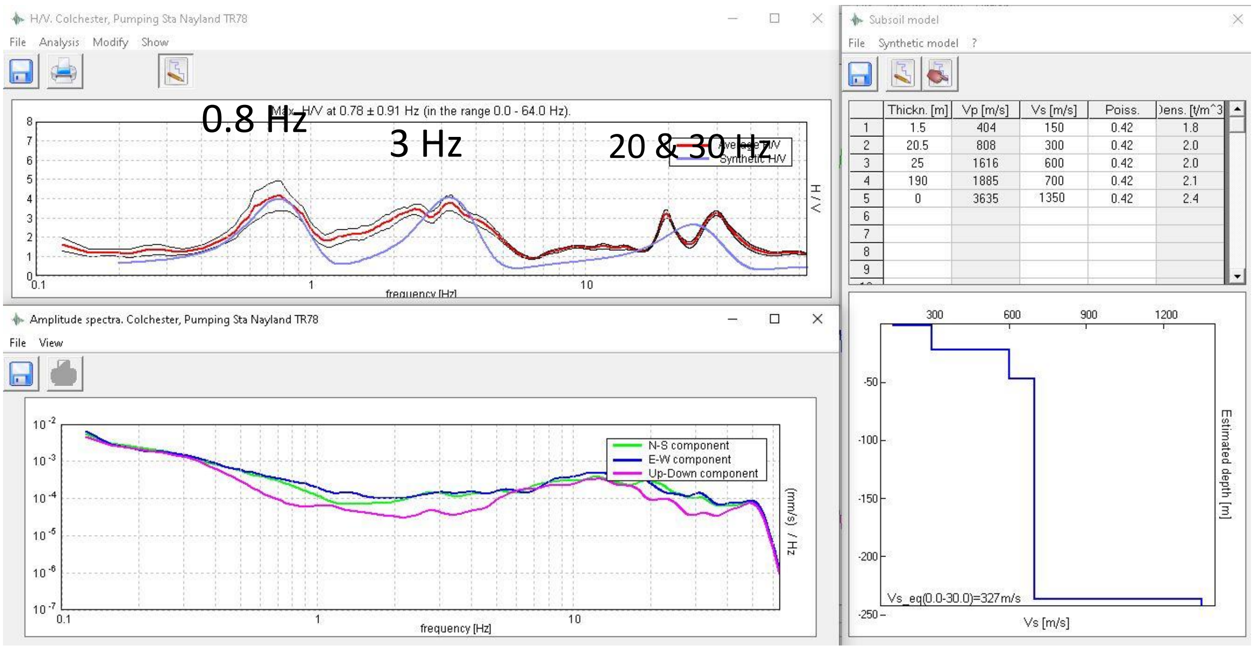


Figure 14. 5-Layer subsoil model for Pops Bridge Nayland site: Layer 1 soft Alluvium (1.5m); Layer 2 stiff Quaternary gravels, Lambeth Group and Thanet (20.5m); Layer 3 marly Newhaven Chalk (25m); Layer 4 hard flinty Seaford Chalk-base Chalk and Gault (c.190m); Layer 5 hard Silurian basement.

4 Conclusions

This study provides an independent example of the typical thermogeological and geophysical data that can be quickly, and relatively cheaply, acquired during at the early ground investigation stage and soon after drilling/construction of geothermal wells. The data brings significant value to the development of engineering ‘ground models’ as part of the de-risking and optimisation of the use of subsurface. The study demonstrates the acquisition and benefit of baseline borehole geophysics for characterising staring condition of shallow geothermal resources. The techniques are applicable to initial ground investigations for both open loop and closed loop ground source heat pump projects, as well as energy piles and tunnels, particularly where the depth to the top of the chalk aquifer across an area or route is of primary interest.

The local geothermal gradient in the top 200 m in north Colchester is around 2.4°C per 100 m, with groundwater source temperatures ranging from 11.5-11.9°C (mean 11.7°C) at 100m depth and around 14.3°C at 200 m depth.

The benefits of collecting geophysical and well log data as part of a large-scale shallow ground source heat pump projects include:

1. Potential for improvement to the conceptual ground model for the site/region; particularly the vertical and lateral heterogeneity of aquifers, geothermal resource estimation, characterisation of confining layers /overburden geology and drilling/ground conditions at planned geothermal wells.
2. Characterisation of fracture zones; the optical televiewer data provided a rich insight into the physical state and secondary permeability of the chalk aquifer rock mass, particularly presence and nature of fractures/joints and extent and degree of karstification, potential enhanced flow zones. For example, a previously unknown 18 m long open vertical fracture was identified in a production well (BH4) that probably enhances and focuses flow, but this sort of fracture-flow feature could also lead to thermal short-circuit if intersected by another injection well from this scheme (which does not appear to be the case presently) or another extraction/injection well from another nearby scheme.
3. High quality baseline data; acquisition of aquifer/ground temperature profiles prior to heat production/cold injection provides undisturbed aquifer condition reference data for future monitoring and modelling purposes, and provides the system designer and economic modellers with confidence in the expected source temperatures and heat pump efficiency (COP) and system thermal capacity.
4. Reduction in geological uncertainty; interpretation of the down hole imagery and well log data enabled confident identification of key lithostratigraphic marker horizons such as tabular flint bands (Severn Sisters Flint) and marl seams enabled correlation of the Chalk Formations and structure across site and the wider region. This information enables geologists and hydrogeologists to make more reliable prognoses of higher and lower yielding parts of the aquifer at the technical feasibility stage of a geothermal or groundwater management project. This information informs and de-risks decisions on where to site test wells to maximise yields, and aids considered siting and required depth of wells to ensure stable and sustainable low carbon heat supplies and minimise CAPEX cost (drilling costs).
5. Improved litho-stratigraphic interpretations and geological model; even though the Natural Gamma Ray logs were run down the inside of the steel casing in the Palaeogene strata, which attenuated the signal slightly, the data collected helped the geologists to interpret changes in lithologies and identify tentative formation boundaries and thicknesses. For example, it was possible to pick tentative boundaries for the Thanet Formation sands aquifer (c.14 m), Lambeth Group sand and clays (c.10 m), London Clay (c.36m), and Quaternary superficial deposits (c.5m). Although not targeted as the main productive aquifer/heat source, the high effective porosity Thanet and Lambeth Group sediments will

likely contribute additional water and heat storage capacity. This additional geological fidelity improved the early numerically-coupled groundwater-heat flow model for the site (Sezer et al 2021).

6. Reduced uncertainty in aquifer geometry; the non-intrusive Tromino H/V passive seismic survey provided added confidence that the top chalk surface the site is fairly level and planar between the planned production and injection well zones, and there was no obvious indication of large vertical off sets to suggest any normal or reverse faulting locally affecting the aquifer rock mass, depth of aquifer or thickness of overburden. This contextual information can improve the hydrogeological conceptual models of a site, which in turn enables more realistic and accurate numerical groundwater and heat flow modelling and sustainable geothermal system management.
7. Value for money; the typical cost of a downhole geophysical survey (in 2020, not including data interpretation) is equivalent to around 1.5% of the project's total drilling and pump testing budget (for example £25 000 for a £2M drilling budget). The cost of an H/V survey for a similar sized site, including data processing and interpretation, and reporting would be around £10 000. A full cost/benefit analysis of employing these ground investigation techniques is outside the scope of this report, but clearly the insights gained from the post-drill geophysical surveys and early ground-based geophysical surveys can provide the Developer, Designer and Principal Contractors with an increased level of confidence in the assumption made at the design stages, and an improved level of understanding and better management of key project risks.

Borehole geophysical surveys employing Caliper, OPTV, natural gamma, resistivity techniques, as demonstrated here, might be considered as additional 'best practice' in the context of CIBSE COP3: Open-loop groundwater source heat pumps: Code of Practice for the UK (2019). Commissioning and operational benefits of downhole geophysics include a high-quality baseline data set for comparison against future borehole condition inspections, and for planning maintenance and for monitoring and validation (M&V) purposes.

Geophysical surveys may not be financially viable for smaller or single GSHP schemes but should be considered where possible and where geological complexity and variability is anticipated to be high and could affect the aquifer resource or ground conditions.

Beyond geosciences, the visually rich data of the high resolution OPTV images can be an asset for creating impactful visual media for public outreach/education and stakeholder engagement and public perception of geothermal energy projects, and may even provide inspiration for artists, architects, teachers and pupils to foster a 'sense of place', connecting newly established eco-home communities through the natural capital they all benefit from.

4.1 RECOMMENDATIONS FOR CONTINUED RESEARCH AT CNG

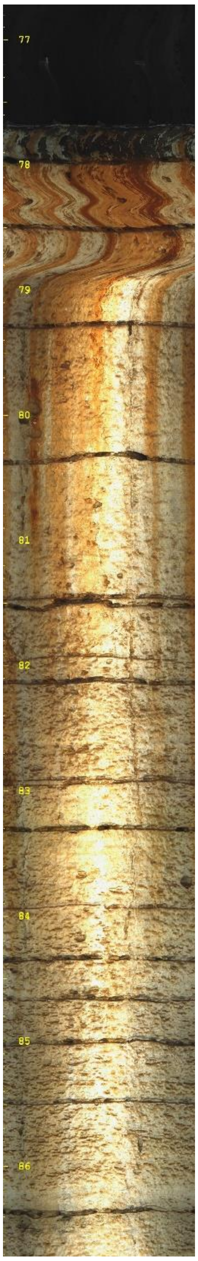
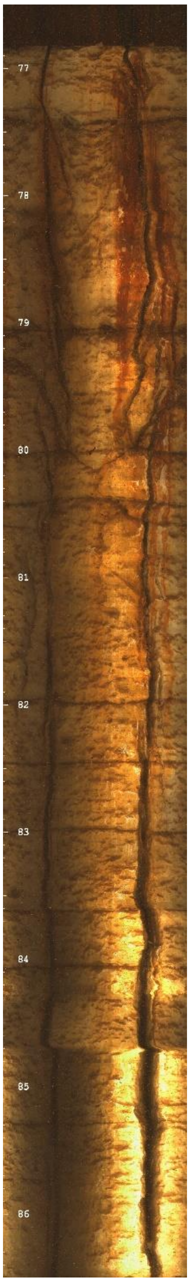
1. All five wells (BH1-5) should be instrumented with (distributed) temperature sensors to enable continuous long-term monitoring of the thermal evolution of the aquifer during the operational lifetime of the GWHP system. Water quality, temperature and flow rate sensors with digital loggers should also be installed on borehole inflow and outflow pipework and data/records should be saved and kept in maintenance records and made easily available to maintenance teams (as per CIBSE COP3). A copy of the data could also be lodged with the BGS and the Regulator.
2. If further boreholes are drilled at CNG one could be continuously cored from surface, with geophysical logs run. Core material could then be inspected and logged by a BGS geologist to accurately describe and classify the strata. Physical and thermal property testing could be performed. Any digital versions of borehole logs (AGS) and pumping test records should be lodged (by law) with the BGS NGDC / HR Wallingford for archiving.

3. Further *Tromino* HVSR surveys could be undertaken at the site and at key stratigraphic boreholes in the region, such as ‘Weeley Borehole’ (TM12SW1) [NGR 614737, 221833] and other deep boreholes in the region to aid interpretation of H/V curves and enable calibration of regional geophysical models. Survey transects could also be done across zones where major basement lineaments/ faults, fracture zones and variations in chalk aquifer thickness and stratigraphy are suspected (e.g. between Colchester and Ipswich).
4. Tracer tests could be performed to explore aquifer properties.
5. Further groundwater flow modelling could be undertaken, with models set up to incorporate the new geological understanding described in this report, to investigate the long-term (+20yr) impact of GWHP operation on the aquifer condition and monitoring of thermal plumes that will develop around the injection wells using geophysical techniques (e.g. ERT, Fibre-Optics DTS/DAS).

Appendix 1 Optical Televiewer Image Logs

Depth corrected optical televiewer image logs contrast sedimentary structures and spacing of marl seams in Newhaven Chalk and show an open vertical fracture in BH4. Black object at top of all images is bottom of permanent steel casing.

OPTV – BH1-5 (75M-86M) SHOWING TOP OF (MARLY) NEWHAVEN CHALK.

Injection zone (west)			Production zone (c.500m to east)	
BH1	BH2	BH3	BH4	BH5
GL 48m aOD	GL 48m aOD	GL 48m aOD	GL 48m aOD	GL48m aOD
			**NOTE 18M LONG OPEN VERTICAL DISCONTINUITY** 	

Appendix 2 Compiled Geophysical Logs

BH1 - COMPILED LOG

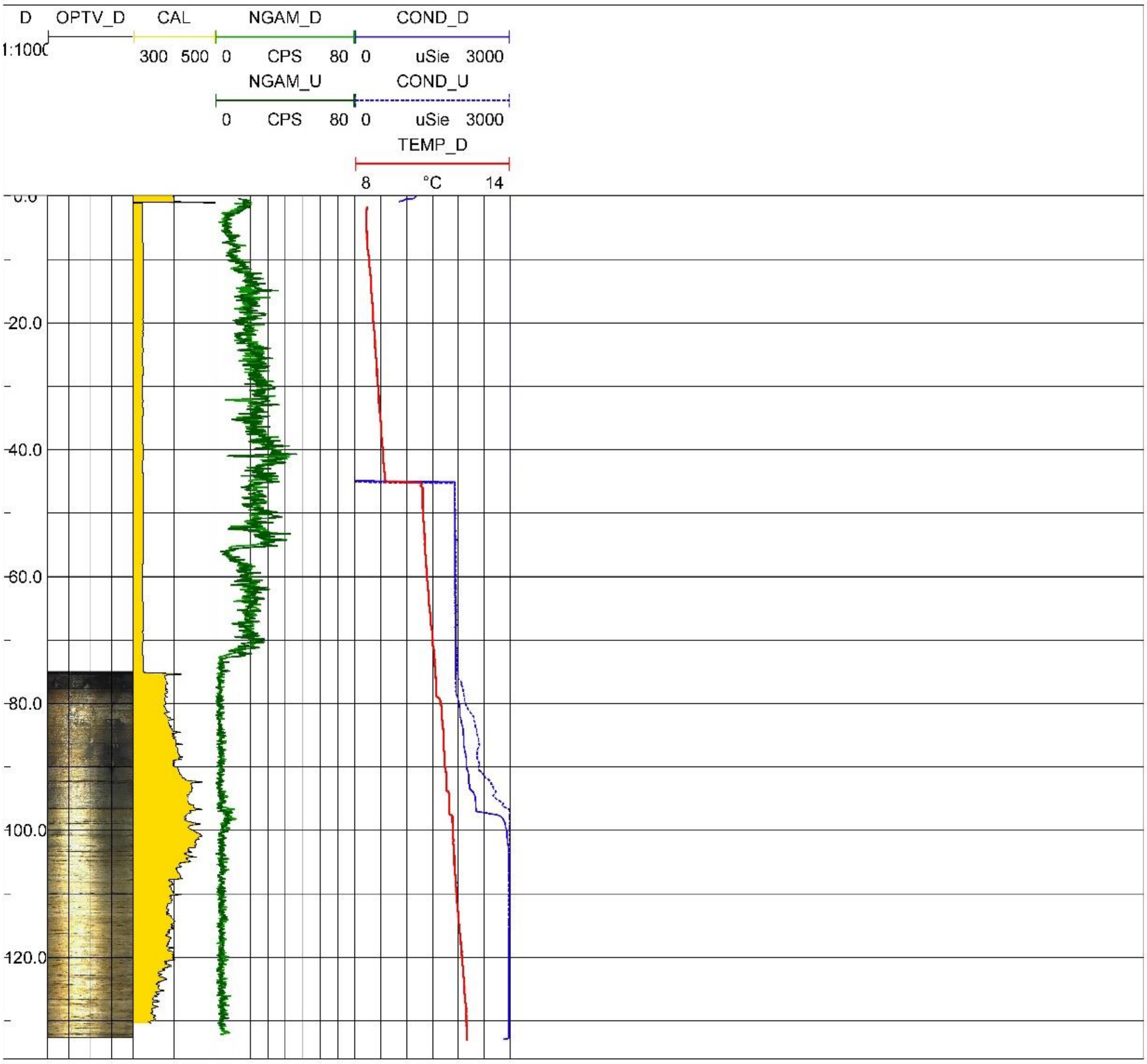
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

PROJECT	CNG
WELL	BH#1
LOCATION	Colchester NGR 599804 228859
ELEVATION	Temp Datum CT
LOGGER	ASB/BRT
DATE	02/20

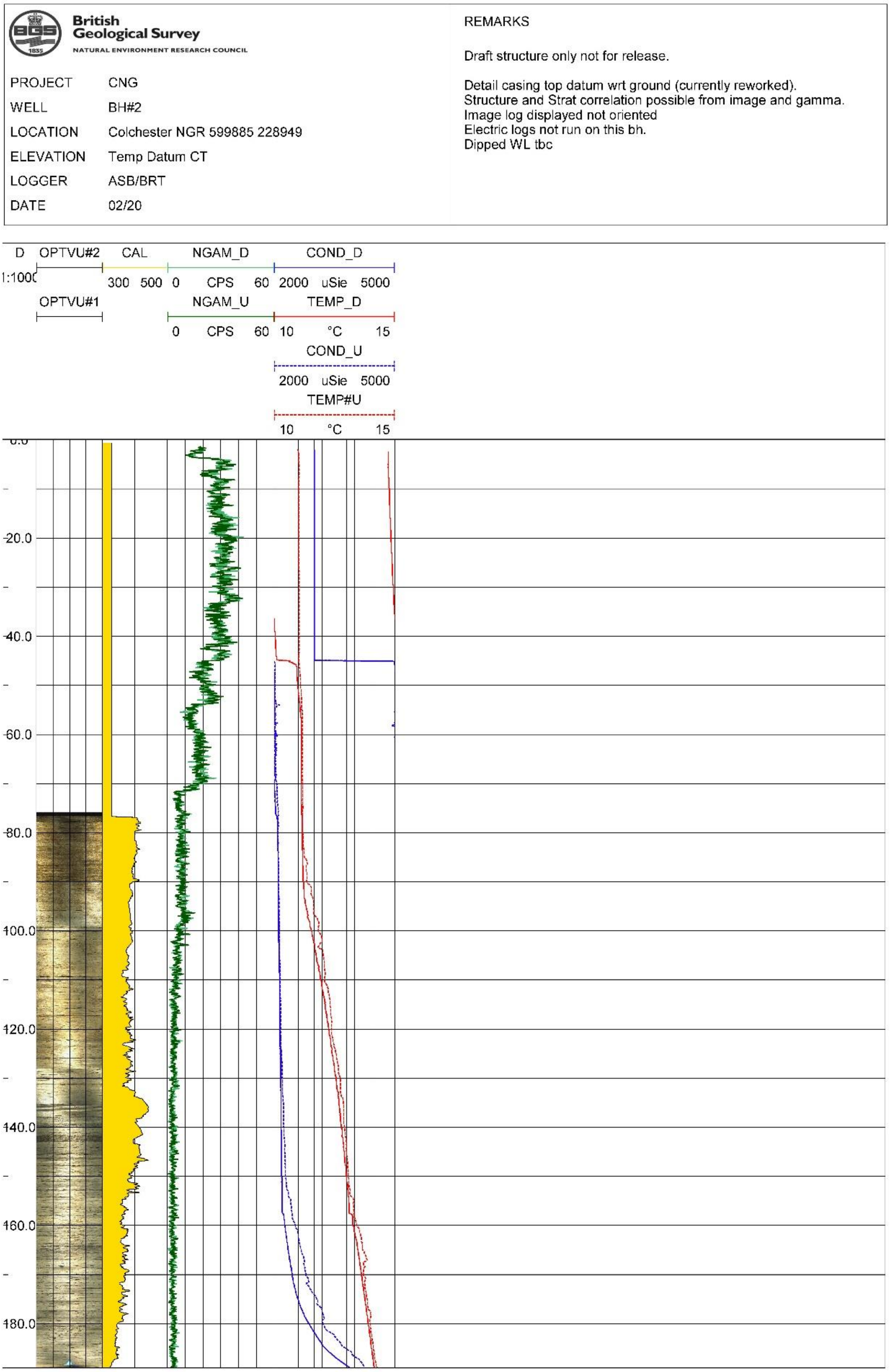
REMARKS

Draft structure only not for release.

Detail casing top datum wrt ground (currently reworked).
Structure and Strat correlation possible from image and gamma.
Image log displayed not oriented
Electric logs not run on this bh.
Dipped Water Level 45.1m bct



BH2 - COMPILED LOG



BH3 - COMPILED LOG

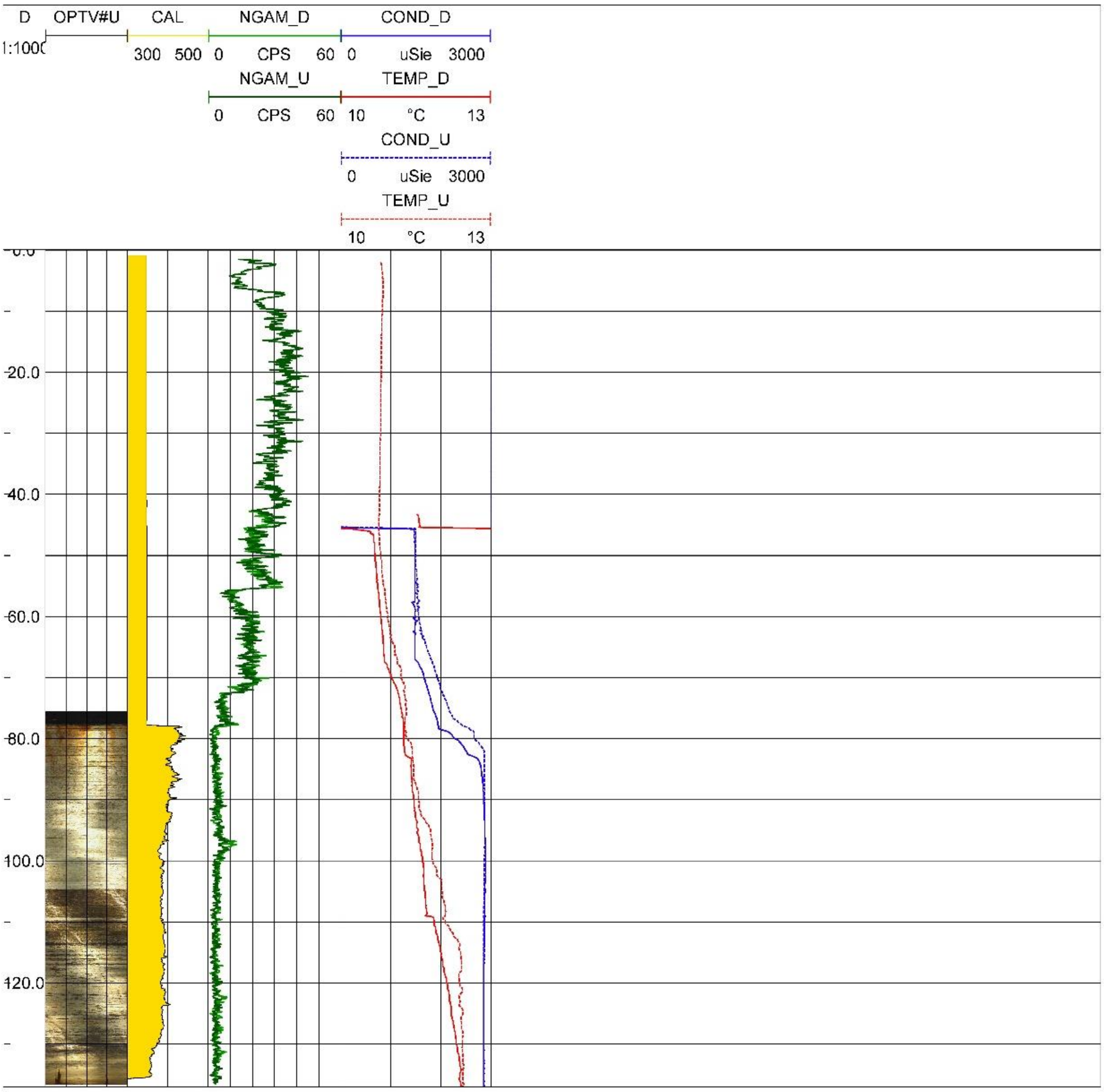
British
Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

PROJECT	CNG
WELL	BH#3
LOCATION	Colchester NGR 599840 228701
ELEVATION	Temp Datum CT
LOGGER	ASB/BRT
DATE	02/20

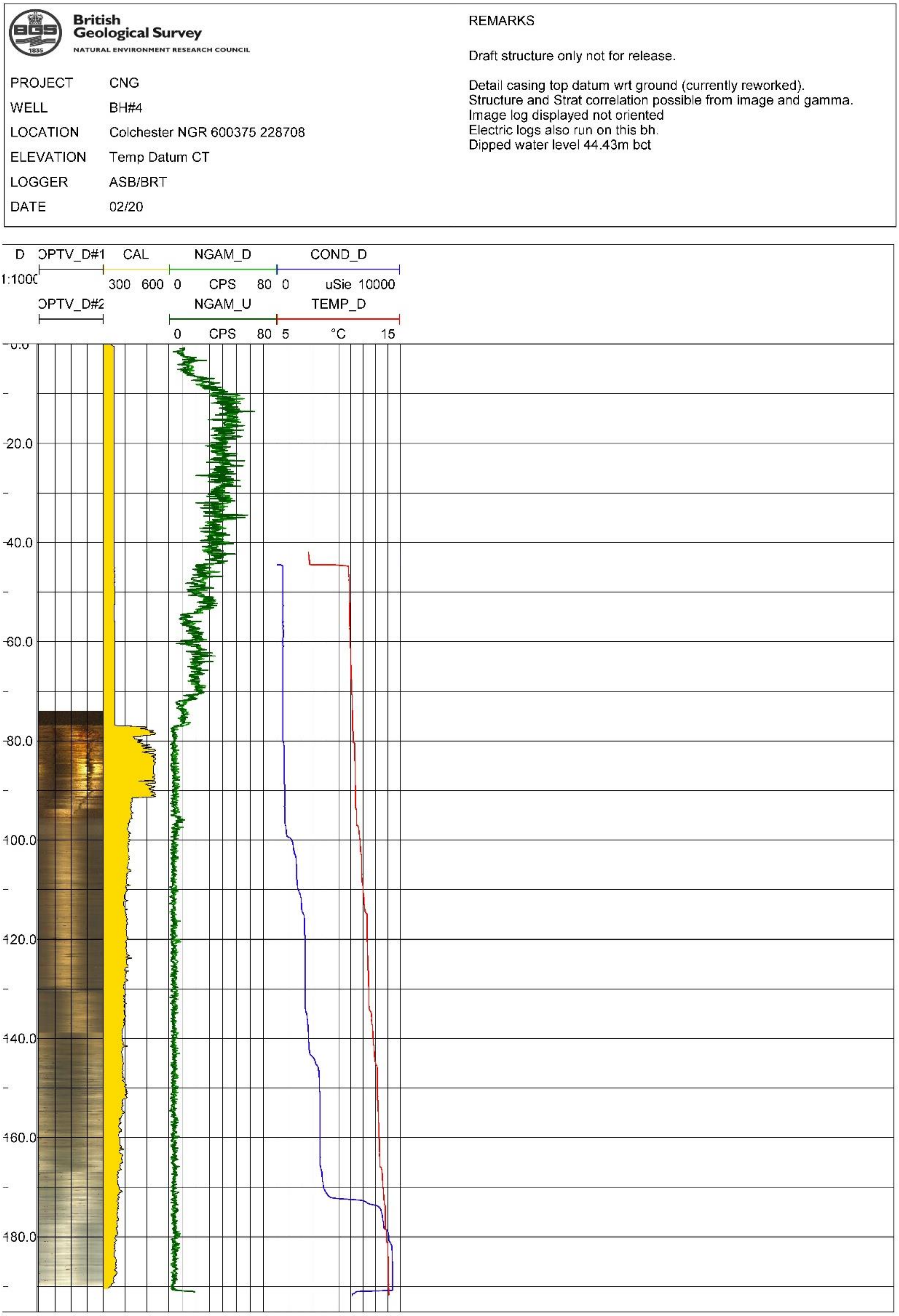
REMARKS

Draft structure only not for release.

Detail casing top datum wrt ground (currently reworked).
Structure and Strat correlation possible from image and gamma.
Image log displayed not oriented
Electric logs not run on this bh.
Dipped WL 45.46 mbct



BH4 - COMPILED LOG



BH5 - COMPILED LOG

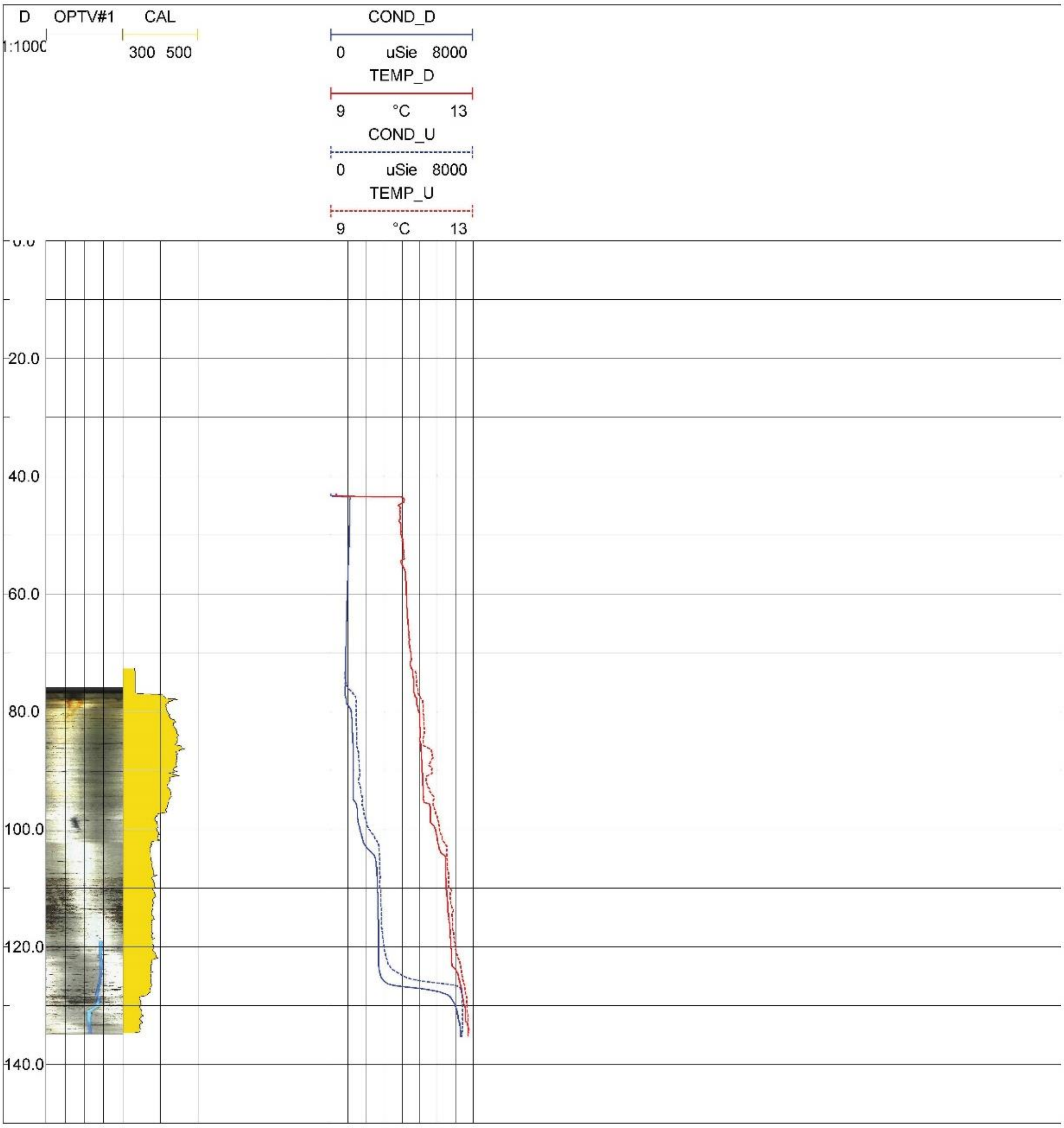
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

PROJECT	CNG
WELL	BH#5
LOCATION	Colchester NGR 600526 228779
ELEVATION	Temp Datum CT
LOGGER	ASB/BRT
DATE	02/20

REMARKS

Draft structure only not for release.

Detail casing top datum wrt ground (currently reworked).
Structure and Strat correlation possible from image and gamma.
Image log displayed not oriented
Electric logs not run on this bh.
Dipped Water Level 43.43m bct



Appendix 3 Guide to Sondes

CALIPER

The caliper probe provides a continuous record of the diameter of the borehole and its casing. It is lowered to the bottom of the hole closed, then opened remotely and the measurements are recorded on the run up to the surface. The caliper used was a Geovista Ltd two-arm caliper. Caliper probes may have two, three or four arms either linked or independent.

The diameter profile is interpreted to confirm length and diameter of casing installed, and to differentiate harder layers where the diameter is narrower from softer layers where the diameter is usually larger.

NATURAL GAMMA

The gamma ray measurements made were recorded with a natural gamma ray probe which records the total gamma ray activity within the borehole as a count rate in counts/second received by the detector. It has no radioactive source attached and is simply a crystal detector. Gamma rays are emitted by rocks containing natural radioactive minerals. The natural radioactive elements responsible are potassium (K40) uranium (U238), and thorium (Th232). In clastic sediments these elements preferentially adsorb to finer grained material and relatively high gamma activity is associated with clays. However, potassium, uranium, and thorium are present in the crystalline lattice of igneous deposits that may, therefore, be associated with very high gamma ray activity. The gamma ray log can be run in any borehole and provides a measurement of total gamma ray activity above and below fluid level, through steel or plastic casing.

INDUCTION RESISTIVITY

The resistivity measurements were made using an induction-resistivity probe having a transmitter coil and two receiving coils providing a deep and a shallow ground conductivity measurement. The units recorded are mS/m, and an induction resistivity curve is derived from the ground conductivity measurement to give a profile that resembles a conventional electrical resistivity curve. The electrical field created by the induction resistivity probe is smaller than that created by the focused electrical resistivity probe (FER) and does not require water to transmit it from the probe to the rock. The probe is, therefore, more suited to short steel lined boreholes where the steel would otherwise interfere with the electrical field of the FER and the unsaturated zone.

FLUID TEMPERATURE & FLUID ELECTRICAL CONDUCTIVITY

The fluid temperature and electrical conductivity measurements were made with a GEOVISTA TCME probe. It has a measuring section containing electrodes which measure fluid conductivity, a platinum resistance thermistor (sensitivity 0.03ºC) and a monitor electrode which warns if the probe is in dirty water or mud. The fluid conductivity values recorded at the ambient temperature are converted to specific conductivity (EC25) by normalisation to the value at 25ºC. The measurements are made on the run down and are recorded first before there is any disturbance of the fluid column. The probe is stopped just below the water table to allow it to equilibrate with the fluid temperature before continuing.

Groundwater as it circulates from recharge to discharge zones travels by different routes and has different circulation paths and residence times. This influences its Specific Electrical Conductivity (SEC) and fluid temperature. Generally deeper circulations are warmer and exhibit higher SEC than shallower (quicker) circulations because they have circulated deeper and have dissolved more rock material. Although in urban environments water near the surface is often heated by leakage from drains, pipes and sewers. Fluid temperature and conductivity may also be raised by contaminants.

By measuring these natural differences in the fluid column the water inflows penetrated by the borehole can be indicated. Where permeability of the rock strata permit, confirmation of the importance of inflows is usually done by repeating the measurements when the hole is pumped as this 'sharpens up' the profiles, and the productivity of a flowing horizon can be measured using a borehole flow-meter.

IMPELLER FLOWMETER

The Sondex flow-metre works by recording the revolutions of a multi-bladed ‘propeller’ in revolutions per minute (rpm), as it is raised or lowered through the water column. Water movement in the column, either pumped or unpumped is recorded as an increase or decrease in rpm from the background rpm induced by the upward or downward motion of the probe.

OPTICAL IMAGING

The Optical Televiewer provides continuous logs of oriented, high resolution unwrapped video images of borehole walls. Further processing allows for the computation and display of standard information on fractures and other geological features.

Unlike an Acoustic Televiewer, the Optical Televiewer can be run in both air filled and (clear) water filled holes.

Appendix 4 Summary wireline log [LOG] data

Borehole Name	CNG BH1		CNG BH2		CNG BH3		CNG BH4		CNG BH5	
Location (National Grid Reference & ground level) Horz. accuracy +/- 2m	E 599807 N 228865 GL 48m aOD		E 599885 N 228956 GL 48m aOD		E 599844 N 228705 GL 48m aOD		E 600370 N 228722 GL 48m aOD		E 600522 N 228785 GL 48m aOD	
Depth below ground level (m)	TEMP °C	COND uSie	TEMP °C	COND uSie	TEMP °C	COND uSie	TEMP °C	COND uSie	TEMP °C	COND uSie
50	10.64	1929	10.99	2003	10.68	1474	10.87	495	10.99	1053
60	10.79	1936	11.13	2014	10.80	1470	10.95	464	11.13	949
70	11.01	1946	11.12	2016	11.01	1661	11.08	483	11.25	864
80	11.30	2006	11.15	2088	11.25	2277	11.17	494	11.48	1164
90	11.49	2160	11.21	2095	11.46	2853	11.38	624	11.57	1285
100	11.79	2924	11.54	2114	11.64	2889	11.73	1222	11.93	1658
110	11.93	2984	11.92	2128	11.87	2867	12.00	1725	12.25	2641
120	12.13	2975	12.26	2147	12.11	2855	12.32	2277	12.38	2697
130	12.31	2967	12.56	2162	12.31	2856	12.46	2305	12.77	7002
140			12.79	2175			12.81	2579		
150			13.00	2187			13.15	3467		
160			13.25	2258			13.29	3510		
170			13.62	2446			13.61	3786		
180			13.90	2858			13.89	9074		
190			14.14	4114			14.06	9408		

Notes:

1. Rest water level approx. 45m below ground level (approx. +3 mOD) in all boreholes (10-13 Feb. 2020).

2. Higher resolution data and Gamma Ray log data is available from the BGS on request.

3. TEMP = fluid temperature; COND = fluid electrical conductivity

Appendix 5 Tromino HVSR (passive seismic) sounding locations and results

Site Name	NGR X [m]	NGR Y [m]	H/V Peak Frequency, f_0 [Hz]	H/V Secondary Frequency [Hz]
Colchester District				
No. 14 The Lane, West Mersea, Essex	600210	213114	0.75	2
Cudmore Grove cliff top, East Mersea, Essex	606701	214619	0.8	NULL
Cudmore Grove foreshore, East Mersea, Essex	606946	214722	0.8	2.5
Pumping Station, Nayland, Essex TR78	597098	233969	0.78	2.4 & 3.2
St James Churchyard, Nayland, Essex TR79	597569	234249	2.44	0.77
Colchester Northern Gateway site				
Colchester Northern Gateway TR80 **(BH2)**	599885	228956	0.72	1.37
Colchester Northern Gateway TR81 **(BH1)**	599807	228865	0.63	1.25
Colchester Northern Gateway TR82 **(BH3)**	599844	228705	0.72	1.22
Colchester Northern Gateway TR83	599906	228823	0.69	1.2
Colchester Northern Gateway TR84	599950	228888	0.72	1.4
Colchester Northern Gateway TR85	599920	228928	0.69	1.4
Colchester Northern Gateway TR86	599840	228980	0.7	1.25
Colchester Northern Gateway TR87	599839	228927	0.7	1.36
Colchester Northern Gateway TR88	599817	228652	0.72	1.25
Colchester Northern Gateway TR89	599833	228772	0.69	1.35
Colchester Northern Gateway TR90	599824	228810	0.63	1.32
Colchester Northern Gateway TR91	599888	228788	0.78	1.39
Colchester Northern Gateway TR92 **(BH4)**	600370	228722	0.72	1.3
Colchester Northern Gateway TR93	600389	228709	1.2	32
Colchester Northern Gateway TR94	600401	228732	0.75	1.2
Colchester Northern Gateway TR95	600426	228749	0.63	1.23
Colchester Northern Gateway TR96	600454	228751	0.69	1.3
Colchester Northern Gateway TR97	600472	228768	0.69	1.15
Colchester Northern Gateway TR98	600500	228778	0.72	1.3
Colchester Northern Gateway TR99	600552	228798	0.75	NULL

Colchester Northern Gateway TR01 **(BH5)**	600522	228785	0.72	1.2
Colchester Northern Gateway TR02	600354	228725	0.75	NULL
Colchester Northern Gateway TR03	600331	228734	0.78	1.35
Colchester Northern Gateway TR04	600301	228752	0.72	NULL
Colchester Northern Gateway TR05	600285	228761	0.72	NULL
Colchester Northern Gateway TR06	600263	228774	0.75	1.32
Colchester Northern Gateway TR07	600242	228784	0.75	1.39
Colchester Northern Gateway TR08	600220	228795	0.72	1.4
Colchester Northern Gateway TR09	600199	228806	0.72	NULL
Colchester Northern Gateway TR10	600173	228817	0.72	1.35
Colchester Northern Gateway TR11	600152	228827	0.72	1.25
Colchester Northern Gateway TR12	600138	228840	0.63	1.2
Colchester Northern Gateway TR13	600106	228852	0.69	1.25
Colchester Northern Gateway TR14	600084	228867	0.69	1.07
Colchester Northern Gateway TR15	600065	228877	0.59	NULL
Colchester Northern Gateway TR16	600042	228885	0.78	1.42
Colchester Northern Gateway TR17	600018	228898	0.72	1.38
Colchester Northern Gateway TR18	599997	228910	0.69	1.39

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

ALDISS, D. T. 2012. The stratigraphical framework for the Palaeogene successions of the London Basin, UK. British Geological Survey Open Report, OR/12/004. 94pp

ALLEN, D. J., BREWERTON, L. J., COLEBY, L. M., GIBBS, B. R., LEWIS, M. A., MACDONALD, A. M., Wagstaff, S. J., and Williams, A. T. 1997. The physical properties of major aquifers in England and Wales. British Geological Survey Technical Report WD/97/34. 312pp. Environment Agency R&D Publication 8.

BIRKS. D., ADAMSON, C. WOODS, M.G. AND HOLMES, G. 2021. Evaluation of measures to improve the performance of an open loop ground source heat pump system in the chalk aquifer: a case study. Quarterly Journal of Engineering Geology and Hydrogeology 55, qjegh2021-074, 30 September 2021, https://doi.org/10.1144/qjegh2021-074

BOON, D. P., FARR, G., ABESSER, A., PATTON, A. M., JAMES, D. R., SCHOFIELD, D. I., AND TUCKER, D. G. 2019. Groundwater heat pump feasibility in shallow urban aquifers: experience from Cardiff, UK. Science of the Total Environment, 697. https://www.sciencedirect.com/science/article/pii/S0048969719337957?via%3Dihub

Boon, D., Sargeant, S., Raines, M., Dashwood, B., Morgan, D, Gunn, D. 2015. Assessing the impact of local geology on ground motion amplification in south east England. SECED2015 conference: Earthquake Risk and Engineering towards a Resilient World 9-10 July 2015, Cambridge UK (peer reviewed) http://www.seced.org.uk/index.php/resources/seced-2015-proceedings/190-selma-ozkul

British Geological Survey. 2010. Colchester and Brightlingsea. England and Wales Sheet 244 and 242 Bedrock and Superficial Deposits. 1: 50 000. (Keyworth, Nottingham: British Geological Survey)

BSSC. 2003. NEHRP Recommended Provisions for seismic Regulations for New buildings and other Structures, Part1: Provisions, FEMA 368, Federal Emergency Management Agency, Washington, D.C.

Busby, J., Lewis, M., Reeves, H. & Lawley, R. 2009. Initial geological considerations before installing ground source heat pump systems. Quarterly Journal of Engineering Geology and Hydrogeology, 42, 295–306.

Castellaro, S., Mulargia. F., 2009. VS_{30} Estimates Using Constrained H/V Measurements. Bulletin of the Seismological Society of America, Vol. 99, No. 2A, pp. 761–773, April 2009, doi: 10.1785/0120080179

Ellison, R.A., 1976. Wormingford Borehole. In: IGS Boreholes 1975. Inst. Geol. Sci. Rep., 78/21, p. 21

Ellison, R A, Woods, M A, Allen, D J, Forster, A, Pharoah, T C, and King, C. 2004. Geology of London. Memoir of the British Geological Survey, Sheets 256 (North London), 257 (Romford), 270 (South London) and 271 (Dartford) (England and Wales).

Haining, Peter (1976), The Great English Earthquake, Robert Hale, ISBN 0-7091-5395-3.

Headon, J, Banks, D, Waters, A and Robinson, V K. 2009. Regional distribution of ground temperature in the Chalk aquifer of London, UK. Quarterly Journal of Engineering Geology and Hydrogeology, 42, 313-323. https://doi.org/10.1144/1470-9236/08-073

Hopson, P M. 2005. A stratigraphical framework for the Upper Cretaceous Chalk of England and Scotland, with statements on the Chalk of Northern Ireland and the UK Offshore Sector. British Geological Survey Research Report RR/05/01 102pp. ISBN 0 852725175

Ibs-von Seht, M., Wohlenberg, J. 1999. Microtremor Measurements Used to Map Thickness of Soft Sediments. Bulletin of the Seismological Society of America, Vol. 89, No. 1, pp. 250-259. https://pubs.geoscienceworld.org/ssa/bssa/article/89/1/250/120443/Microtremor-measurements-used-to-map-thickness-of

Mortimore, R N. 1986. Stratigraphy of the Upper Cretaceous White Chalk of Sussex. Proceedings of the Geologists' Association, Vol.97(2), 97-139.

Mortimore, R N. 2014. Logging the Chalk (Whittles Publishing: Caithness.)

Royse K, R.,De Freitas, M., Burgess, W. G., Cosgrove, J., Ghail,R.C., Gibbard, P., King, C., Lawrence, U., Mortimore, R.N., Owen, H., Skipper, J. 2012. Geology of London, UK,Proceedings of the Geologists' Association, Volume 123, Issue 1,2012,Pages 22-45. ISSN 0016-7878. https://doi.org/10.1016/j.pgeola.2011.07.005

Sezer, T., Sani, A. K., Singh, R. M., and Boon, D. P. 2021. Numerical Modelling of a District Scale Groundwater Heat Pump Operation: Case Study from Colchester, UK, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-603, https://doi.org/10.5194/egusphere-egu21-603

Woods, M.A., Chacksfield, B.C. 2012. Revealing deep structural influences on the Upper Cretaceous Chalk of East Anglia (UK) through inter-regional geophysical log correlations. Proceeding of Geologists Association Volume 123, Issue 3, June 2012, Pages 486-499 https://doi.org/10.1016/j.pgeola.2011.11.005