Jersey Deep Groundwater Investigation

BGS Groundwater Management Programme

BGS Commissioned Report CR/06/221C

BRITISH GEOLOGICAL SURVEY AND ENTEC UK LIMITED

BGS GROUNDWATER MANAGEMENT PROGRAMME

BGS COMMISSIONED REPORT CR/06/221C

Jersey Deep Groundwater Investigation

CS Cheney, J Davies and WG Darling (British Geological Survey)
N Rukin and B Moon (Entec UK Limited)

Keywords

Jersey, gruondwater resources, underground streams, isotopes, hydrochemistry,fractures.

Front cover

Drilling operations at St Catherine

Bibliographical reference

CHENEY CS, DAVIES J, DARLING WG, RUKIN N AND MOON B. 2006. Jersey Deep Groundwater Investigation. *British Geological Survey BGS Commissioned Report*, CR/06/221C. 151pp.

Keyworth, Nottingham British Geological Survey 2006

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desks at Nottingham, Edinburgh and London; 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.

The Survey publishes an annual catalogue of its maps and other publications; this catalogue is available from any of the BGS Sales Desks.

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 its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development and other agencies.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

Keyworth, Nottingham NG12 5GG
☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.geologyshop.com

Murchison House, West Mains Road, Edinburgh EH9 3LA
☎ 0131-667 1000 Fax 0131-668 2683
e-mail: scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE
☎ 020-7589 4090 Fax 020-7584 8270
☎ 020-7942 5344/45 email: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU
☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF
☎ 028-9038 8462 Fax 028-9066 2835
e-mail: gsni@detini.gov.uk

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491-838800 Fax 01491-692345
e-mail: hydro@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais Cardiff, CF15 7NE
☎ 029–2052 1962 Fax 029–2052 1963

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Acknowledgements

A large number of individuals in both the UK and Jersey have contributed to the project. This assistance has been received at all stages of the study.

The authors would like to thank Mr George Langlois and Mr Lewis de la Haye for their time and effort put into the careful identification of the two investigation borehole sites and particularly Mr Langlois for being on site to ensure that the drilling rig was set up precisely at the required locations. Mr Alan Bree, landowner at La Rocque and Mr. Bunny de la Mare, landowner at St Catherine are also to be thanked for allowing access to and use of their land for the construction and hydraulic testing of the boreholes. The assistance provided by Green Street Renovations Co. Ltd in providing access to the La Rocque site was also very much appreciated.

Thanks are also due to Dr John Renouf and Dr Ralph Nichols for sharing their extensive local geological knowledge and providing helpful advice regarding the geological logging of the drilling rock chip cuttings.

The authors also wish to thank the members of the Deep Groundwater Advisory Group (DGAG) who visited the sites, whilst drilling and borehole construction were taking place, for their interest and for taking the opportunity to directly observe field activities.

The willing and enthusiastic involvement of the management and staff of the drilling contractors Amplus and their contribution in overcoming the often-unanticipated difficulties inherent in this (for Jersey) unusually complex hydrogeological study, has been much appreciated, as has their completion of all works according to the original or revised specifications.

The timely manner in which inorganic analyses and age dating analyses were provided respectively by the Official Analyst Laboratory, States of Jersey and Dr Darren Goody (British Geological Survey) is hereby acknowledged.

Particular thanks are due to Dr Tim du Feu for his highly effective organisational skills that were used most efficiently to arrange the complex logistics required to carry out all aspects of the field activities, without which the study could not have proceeded in such a smooth and timely manner. His unstinting assistance and support both during the field activities and subsequent phases of the study have also been very much appreciated.

Finally, the authors would like to thank Dr Stuart Sutton of Entec and Dr Denis Peach of the British Geological Survey for reviewing and approving this joint report.

Contents

FIGURES

PLATES

TABLES

Summary

This report provides a record of all activities of the deep groundwater investigation carried out to assess the magnitude, sustainability and origin of 'deep' groundwater resources that may be present beneath the Island of Jersey, Channel Islands. The work has been undertaken with inputs and overview from both the British Geological Survey (BGS) and Entec UK Ltd (Entec).

The report first provides a brief background to the investigation and then gives a detailed account of the drilling and construction of the two investigation boreholes. The sites of the boreholes were identified by local water diviner Mr George Langlois and well driller Mr Lewis de la Haye at La Rocque in the south-east of the Island and at St Catherine, in the north-east of the Island. Mr Langlois and Mr de la Haye sited the boreholes at locations where they believed 'underground streams' were present at depth. Mr Langlois predicted that the depths at which the 'streams' would be encountered as 150 ft (45.7 m) at La Rocque and 250 ft (76.2 m) below ground level at St Catherine.

Full details of the geology penetrated and construction details of the two boreholes are provided, as are records of the groundwater inflows encountered, the air flush yields measured, and the samples collected for analysis. The borehole drilling and construction was supervised by BGS staff.

The lower open section of each completed borehole was hydraulically tested through a step test, constant rate test and measurement of recovery. These tests were designed to evaluate the yield and hydraulic properties of the strata at depth and the hydraulic connection of the deeper strata with water in existing nearby shallower boreholes. Further samples were collected during this hydraulic testing. The hydraulic testing was supervised by Entec UK Limited staff.

Separate chapters are provided on the evaluation of the inorganic, isotope and age dating analyses performed on the samples collected. Entec have provided the detailed evaluation of the inorganic chemical analyses provided by the Official Analyst Laboratory, States of Jersey and BGS staff have undertaken and evaluated the isotope and age dating analysis.

All data obtained from the field activities (borehole drilling, construction and hydraulic testing) and from water sample analyses (inorganic chemistry, isotope and age dating analyses) have been jointly reviewed and interpreted by both BGS and Entec UK Limited.

In summary, the principal conclusions of this investigation into the potential 'deep' groundwater resources of Jersey are as follows;

- Two investigation boreholes were constructed to completely seal out all shallow groundwater inflows, permitting valid samples to be obtained from depth and for the 'deep' strata to be hydraulically tested.
- There is **no** evidence that single large 'underground streams' were penetrated by either borehole but that total groundwater inflows in both boreholes increased incrementally with depth as additional fractures were encountered. Not insignificant, for Jersey, groundwater flows and yields (~3.0-3.5 l/sec) were measured at depth (down to –50 mOD[1]) at La Rocque, although inflows and yields were less than those

[1] OD; Ordnance Datum: (elevations OD as used in this report should regarded as synonymous with the Jersey datum - Mean Sea Level)

(~7.0-8.0 l/sec) encountered at a shallower depth. At St Catherine, only minor inflows and yields (~0.2-0.3 l/sec) were recorded.

- Isotopic 'signatures' obtained from the 'shallow' and 'deep' sections of each of the two boreholes are indistinguishable and are also consistent with the range of isotope signatures for Jersey groundwaters.
- There is **no** evidence to suggest that either the shallow or deep groundwater beneath Jersey has a source that is located outside of the Island.
- The test yield obtained for the La Rocque borehole was above average but not exceptional, whilst that obtained at St Catherine was very low and the water quality was poor and not potable.
- The information available from the two boreholes indicates that the groundwater at depth is hydraulically connected to shallower groundwater via a network of interconnected fractures and **does not** represent a separate major groundwater resource that would be capable of significant future development.

1 Introduction

Since the mid 1930s, a number of detailed studies into the hydrogeological characteristics of groundwater resources of the Island of Jersey have been carried out and reported upon (BGS 1992, Robins and Rose 2005). These studies provided a characterisation of the aquifer beneath Jersey, which consists of ancient basement rocks (principally shales, granites, volcanic rocks and conglomerates, ranging from Precambrian to Ordovician age). The studies concluded that the bulk of groundwater abstraction was met from resources that occur in the relatively shallow fractured and weathered section of the bedrock aquifer and that this resource was sustained by recharge from local rainfall.

The Jersey bedrock aquifer consists of hard fractured rocks, which possess minimal primary (intergranular) porosity or permeability. Groundwater flow and storage occurs almost entirely within the fractures and borehole yields are dependent on the number, size and degree of lateral and vertical interconnection between the fractures. Under such conditions, failure to penetrate an adequate number of productive fractures will result in a low yielding or sometimes effectively dry borehole. In common with similar aquifers elsewhere, fractures are generally most common, larger and better interconnected at relatively shallow depths, generally becoming fewer, less dilated and less well interconnected with increasing depth. Total yields commonly increase cumulatively with depth, as a borehole penetrates an increasing number of productive fractures. Higher yields are normally obtained from the zone that occurs a few tens of metres below the water table. Usable and high yields can however sometimes be obtained at depth from occasional more productive fractures. BGS has previously concluded that the available information suggested that the deep groundwater beneath Jersey represents a relatively limited resource, with small potential for significant development (Robins and Smedley 1998).

There is, however, a long-held traditional local belief that groundwater is also derived from a source in mainland France. The Pyrenees (Jersey Evening Post (JEP), 27 July 2004) have been suggested as a possible source but more recently ‘Petite Suisse’ located to the south of Caen (Vibert Scrutiny Panel 2004; JEP, 13 October 2005), has been cited as the probable source. It has been asserted that this groundwater flows in streams beneath the sea to sustain the ‘deep aquifer’ beneath the Island. It has also been stated that the deep aquifer represents a major groundwater resource capable of significant future development.

1.1 BACKGROUND TO THIS INVESTIGATION

The Deep Groundwater Advisory Group (DGAG) was established in October 2005 by the Environment and Public Services Committee to provide advice to the Committee, taking an evidence based approach, on the magnitude, sustainability and origin of ‘deep’ groundwater resources that is present beneath the Island of Jersey.

Some members of DGAG proposed that, in addition to the known relatively shallow groundwater resources that provide supplies to the majority of boreholes and wells on the Island, a further groundwater resource of significant size exists at depth that has its origin outside the Island. Subsequently, at a meeting of DGAG held on 7 December 2005, it was agreed that an investigation of the origin and the potential for exploitation of groundwater, reported to occur at depth beneath Jersey, should be undertaken as soon as feasible.

It was acknowledged by the members of DGAG that the main overall consideration of importance to the Island was whether the deep groundwater beneath Jersey represented a distinct, predictable and large resource, which could be exploited in a sustainable manner, rather than the question of whether the groundwater originates from outside the Island.

A series of proposals for investigations aimed at resolving the origin and resource potential of 'deep' groundwater beneath the Island of Jersey were subsequently submitted to DGAG by BGS and Entec UK Limited. The proposals included the drilling and construction of new boreholes that would be used to test the deep aquifer resource potential, as well as chemical, isotopic and age dating of groundwaters obtained from the boreholes to better define the age, extent and origin of the deep water.

To achieve these objectives, it was important that the DGAG members:

- identify the location of the source area of the deep groundwater;
- define the approximate number of years such groundwater would take to travel from that source area to the Island and account for the driving force behind such transport; and
- agree the proposed methodology and, more importantly, the potential findings of the investigation.

The initial draft of the agreement stated that *'the definitive test of the origin of the water samples will be by comparison of the isotopic signature of the sample from the test borehole with that of water in the <u>Petit Suisse region</u>'* After consideration by DGAG, it was felt that this limited the investigation to a specific region and a revised agreement was drawn up and agreed by the DGAG members. This agreement stated the following;

> "*Water samples will be obtained from two specially constructed boreholes to be drilled at locations chosen and divined by the well drillers and diviners as being the most likely to yield water that had its origins in mainland Europe. Exact construction details of the two boreholes will be agreed with technical advisers of BGS and Entec, but in essence boreholes will be drilled to whatever depth the drillers and diviners believe is necessary, up to a maximum depth of 750 feet, and fully lined and grouted throughout the depth to avoid cross-contamination with locally sourced water.*
>
> *The definitive test will compare the isotopic signature of the water samples from the two test bores with that from the surface aquifer.*
>
> *If the joint consultants BGS and Entec show that there <u>is</u> a significant difference in the isotopic signature then all parties accept that the sampled water has a different source to that of water from the surface aquifer.*
>
> *If the joint consultants BGS and Entec show that there <u>is not</u> a significant difference in the isotopic signature between the sampled water and the water from the surface aquifer then all parties will drop all claims of an underground water connection between Jersey and the European mainland.*
>
> *A positive test would lead to further work to quantify the usable flow of water from outside the island."*

A copy of the signed DGAG Agreement is provided in Appendix 1.

The British Geological Survey (BGS) and Entec UK Limited, organisations that have in the recent past both contributed significant hydrogeological expertise to the Water Resources Scrutiny Panel of the States of Jersey, were appointed by DGAG to jointly undertake the agreed investigations.

1.2 METHODOLOGY

The DGAG Agreement indicated that groundwater isotopic signatures would provide the definitive test to determine if groundwater found at the depth at which the underground streams was predicted was the same as that of shallow groundwater, or if the source could be external to the Island. In order to provide a valid comparison between isotope signatures for the shallow and deep samples obtained from each borehole, it was essential that cross contamination between shallow and deep samples be prevented.

In consequence, it was necessary to specify a design for both investigation boreholes that would permit water samples to be obtained from the shallow productive horizons whilst drilling and then seal out those horizons before drilling deeper to obtain uncontaminated water samples from the greater depths where the 'underground streams' were predicted. This involved drilling to a depth a few metres above that which the 'underground stream' was predicted by the water diviners and well drillers, installing casing and filling the borehole with impermeable grout to provide a seal that would prevent any groundwater originating from the shallow productive fractures from entering the borehole. Once the grout had set, the borehole was to be redrilled back through the casing and into the underlying rock to the required depth. Thus it would be possible to obtain groundwater samples at selected depths throughout the drilling process whilst preventing cross contamination between shallow and deep productive horizons. Details regarding the predicted depths of the 'underground streams' are provided in Section 3.1.1. A summary of the drilling and construction specifications for each of the two boreholes is provided in Section 2 below, whilst the detailed specification is provided in Appendix 2.

Although not specifically required by the Agreement, it was desirable that the boreholes be completed at a diameter that would permit the borehole to be test pumped at an adequate rate to allow an assessment of the groundwater resource potential.

Field activities (drilling supervision and hydraulic testing), isotopic and age dating analyses, data analysis and subsequent reporting were undertaken co-operatively by BGS and Entec. Specific tasks (for example water sampling, drilling supervision or hydraulic test supervision) were carried out and reported by one or other of the organisations, as appropriate in terms of staff availability and expertise, and to methodologies prior-agreed between the two organisations. The review and interpretation of data have been carried out jointly by the two organisations, with this report being issued as a jointly produced document.

1.3 FIELD OPERATIONS

1.3.1 Borehole Site Identification

To ascertain the origin of the deep groundwater and to investigate the resource potential of the deep strata, it was agreed by DGAG that two investigation boreholes would be drilled at locations identified by the water diviners and well drillers as being the optimal sites in Jersey where underground streams were considered to flow from outside the Island.

Mr Langlois and Mr de la Haye subsequently specified two sites located in the east of the Island, 1) La Rocque [570633 5447190] in the south-east of the Island and 2) Pine Walk, St Catherine [570827 5451960] to the south of St Catherine in the north-east of the Island. The two sites were considered to be located directly above 'underground streams'. Mr Langlois and Mr de la Haye predicted the depths below ground level (bgl) at which the 'streams' would be encountered at 150 ft (45.7 m) at La Rocque and 250 ft (76.2 m) at St Catherine.

1.3.2 Method statements and Risk Assessment

Method statements for the supervision of all drilling activities and hydraulic testing of the boreholes, together with associated Risk Assessments, were drawn up jointly by BGS and Entec. These documents were utilised as the basis of all subsequent field activities. Copies of these documents are provided in Appendix 2.

1.3.3 Schedule of Field Activities

Drilling operations began at the La Rocque site on 12 September 2006 and were completed to a final depth of 55.5 meters below ground level (m bgl) on 16 September 2006. The drilling rig was then mobilised to the St Catherine borehole site where drilling commenced on 19 September 2006 and the borehole was completed at a total depth of 79.5m bgl on 25 September 2006.

Suitable pumping equipment (based on the air flush yields obtained whilst drilling[2]) for each of the two boreholes was then procured and after installation in the boreholes, hydraulic testing was undertaken between 30 October 2006 and 5 November 2006.

1.4 SURVEYING

The locations and ground elevations at both boreholes were accurately surveyed after completion. The grid references and elevations for the two investigation boreholes and the unused domestic borehole at La Rocque, later used as an observation borehole during hydraulic testing, are provided in Table 1.

Table 1 Surveyed borehole locations and elevations

LOCATION	**EASTING**	**NORTHING**	**ELEVATION OF CASING TOP** (m aOD)*
La Rocque			
Investigation BH	570633	5447190	6.34
Observation BH	570654	5447190	6.08
St Catherine			
Investigation BH	570827	5451960	22.69

* metres above Ordnance Datum (in this report used as being synonymous with the Jersey datum of Mean Sea Level)

[2] Air flush uses an air compressor to pump air down a pipe into the water column in the borehole, which creates air bubbles that lift the water up the borehole to discharge from the borehole casing at surface.

2 Borehole Drilling and Construction

2.1 GENERAL

The two boreholes were drilled using a track mounted rotary down-hole hammer (DHH) air flush drilling rig operated by Amplus Ltd. Detailed specifications were drawn up for the two boreholes to be completed in a similar manner but the depths to which plain casing was to be inserted/grouted and total drilled depths differed. The water diviner, Mr Langlois was on site before drilling commenced, to ensure that the rig was positioned to drill exactly at the identified sites (Plate 1 and 2).

The common specified completion of the two boreholes is shown diagrammatically in **Figure 1**. The specified depths to which drilling at a diameter of 200 mm (8 inch), installation/grouting of 152 mm (6 inch) ID, and planned final total depth of the two boreholes are also indicated diagrammatically on **Figure 1**.

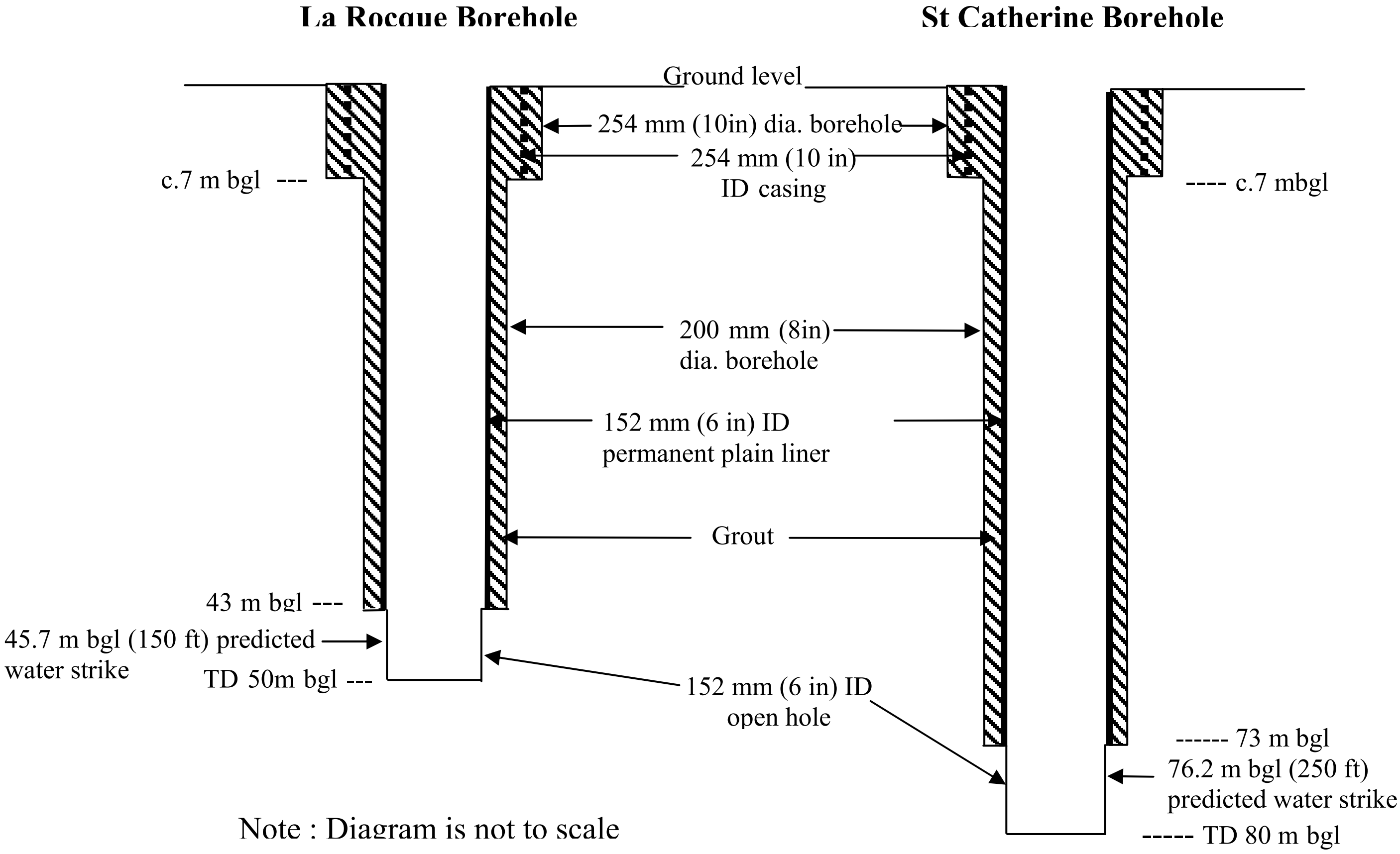


Figure 1 'Deep' investigation borehole constructions (as originally specified).

The original specification for the La Rocque borehole was designed to assess the hydrogeology of the strata within the 43 to 50 m bgl interval. To halt ingress of any water mt between the ground surface and 43 m bgl, that section of the borehole was to be cased and grouted, with the section below 43 m bgl being completed 'open hole'.

The St Catherine borehole specification was designed to assess the hydrogeology of the strata within the 73 and 79 m bgl interval. To halt ingress of any water met between the ground surface and 73 m bgl, the borehole was to be cased and grouted across that interval and the succeeding section below 73m bgl completed 'open hole'.

Plate 1 and Plate 2 Accurate positioning of the drilling rig.

2.2 METHODOLOGY

2.2.1 Borehole Drilling and Construction

The planned sequence of activities undertaken at each of the two borehole sites was as follows:

- Move rig and equipment to site and set up at the precise location specified. Erect temporary fencing around the drilling site and install drainage ditches (if required).
- Drill @ 254 mm (10 inch) diameter to below the base of unconsolidated/ weathered materials (c. 7m bgl) and install 254 mm OD plain steel drill casing.
- Drill @ 200 mm (8 inch) diameter to the required depth (43 m at La Rocque and 73 m bgl at St Catherine).
- Insert permanent 152 mm (6 inch) ID casing to the full depth of the borehole.
- Insert cement grout into the borehole from total depth to ground surface using a tremmie pipe (withdrawing the tremmie pipe as the inside of the casing and annulus fills).
- Grout should be left to harden for a minimum of 24 hours.
- Drill (at a diameter of c.152 mm (6 inch)) back through the casing to the total grouted depth.
- Drill open hole at a diameter of 152 mm to final total depth (50 m bgl at La Rocque and 80 m bgl at St Catherine).

- Clean hole of rock chips (cuttings) and develop by flushing until water produced is clean
- Install surface completion.
- Make good, dismantle and move to next site/demobilise.

2.2.2 Drilling Supervision

The site supervision was carried out by Mr Davies (British Geological Survey) and Dr du Feu (Environment Division, States of Jersey). During the drilling of the two boreholes, supervision activities carried out included:

- Maintaining a site diary recording items such as site visitors, drilling progress, geological logs, water strikes etc.
- Maintaining a photographic record of events during borehole drilling and construction.
- Recording drilling cuttings, including the photographing of samples of cuttings laid in sequence along lengths of half pipe as pseudo-cores (Plate 3).
- Recording drilling penetration rates (Plate 4).
- Recording depths of water strikes.
- Measurement and recording of water flush yields following water strikes and at regular depth intervals (Plate 5).
- sampling air flush water for inorganic and isotopic analysis (Plate 6).
- measurement of rest water levels below ground level after cessation of drilling (e.g. before start of drilling each morning, after lunch or other breaks longer than 1 hour).
- plumbing the borehole depth after the drilling tools were removed from the borehole.
- monitoring of the grouting procedure, in particular ensuring that the volume of grout pumped into the borehole was sufficient to fill the annulus and inside of the casing from total depth to ground level.

Plate 3 Rock chip samples.

During borehole drilling at both sites, rock chip samples of the superficial deposits and solid rocks penetrated were obtained at 0.5 m depth intervals. Drilling was halted at the end of each 0.5 m section for the borehole to be cleared of drill cuttings before the next 0.5m section was drilled. This ensured the collection of a representative sample of cuttings for the 0.5m section drilled and ensured that the verticality of the drilled borehole was maintained. Portions of each sample were bagged and placed in sequence along a marked half-section drainpipe the latter forming a pseudo-core of the borehole. The pseudo-core sections were photographed and the sample lithologies described and logged. The locations of fracture zones were identified, using specific physical characteristics discussed below, and recorded.

Plate 4 Monitoring penetration rates.

Drill penetration rates, related to specific hammer and bit assemblies, were measured at 0.5 m intervals, as marked with red paint on the drill rod, using a stop watch and recorded.

Plate 5 Measurement of air flush water yield.

During drilling, air flush water discharge rates were measured at 3 m depth intervals within the upper section to be grouted and at 0.5 m intervals in the lower open hole section. Discharge rates were determined by capturing the air flush water from the borehole within a bund around the top of the borehole, the water flowing through an outlet pipe to a 14 litre capacity bucket. The time taken for the bucket to fill was measured with a stopwatch.

Plate 6 Groundwater sampling.

Hydrochemical parameters including temperature, pH and specific electrical conductance were determined on site for discharge waters, at similar intervals as discharge measurements, and samples obtained for major ion and isotope determinations.

The descriptions of the lithological characteristics of the rock chip samples were discussed in detail with DGAG members Dr Renouf and Dr Nichols. During drilling all measurement and sampling procedures were undertaken with the wholehearted co-operation of the members of the drill crew from Amplus Ltd. The various members of the States of Jersey who were present during the drilling exercises showed keen interest in all aspects of the borehole drilling and sampling procedures. Every effort was made by the supervisory team to keep them fully informed of the results of the exercise as data became available. Mr Langlois was present on site for most of the drilling and construction exercises, during which he was constantly kept informed of all results.

2.3 LA ROCQUE BOREHOLE

2.3.1 General

Drilling operations began at the La Rocque site on 12 September 2006 after Mr Langlois had confirmed the accurate positioning of the drilling rig upon the exact mark that he had identified. The site is located about 26 m west of a borehole belonging to Mr Bree, the landowner. The rest water level in that borehole was approximately 2.0 m bgl on 13 September 2006. Drilling of the La Rocque borehole was completed to a final depth of 55.5 m bgl on 16 September 2006.

2.3.2 Geology, fractures and penetration rates.

The upper section of the La Rocque borehole, from 0 to10 m bgl, was drilled through unstable superficial loessic silts and fluvial silty gravels into weathered granite. The lower loess deposits were damp. Drill penetration was rapid through the superficial deposits but slowed considerably on entering compact granite below 9 m bgl. Between 10 and 43 m bgl, granitic rocks were penetrated. Fracture zones were identified by the presence of discoloured yellow or orange granite, as recorded in Appendix 3 and summarized on Figure 2. Drilling penetration rates increased between 19 and 26 m bgl in weathered granite but decreased in a more solid granite section between 26 and 34 m bgl and increased again in softer broken (probably weathered) granite from 35 to 42 m bgl (Figure 2). The penetration rates recorded for the granitic rocks penetrated between 43 and 55.5 m bgl (total borehole depth) were slower, indicating this section was harder than the sections above, with less fracturing being present (Figure 2).

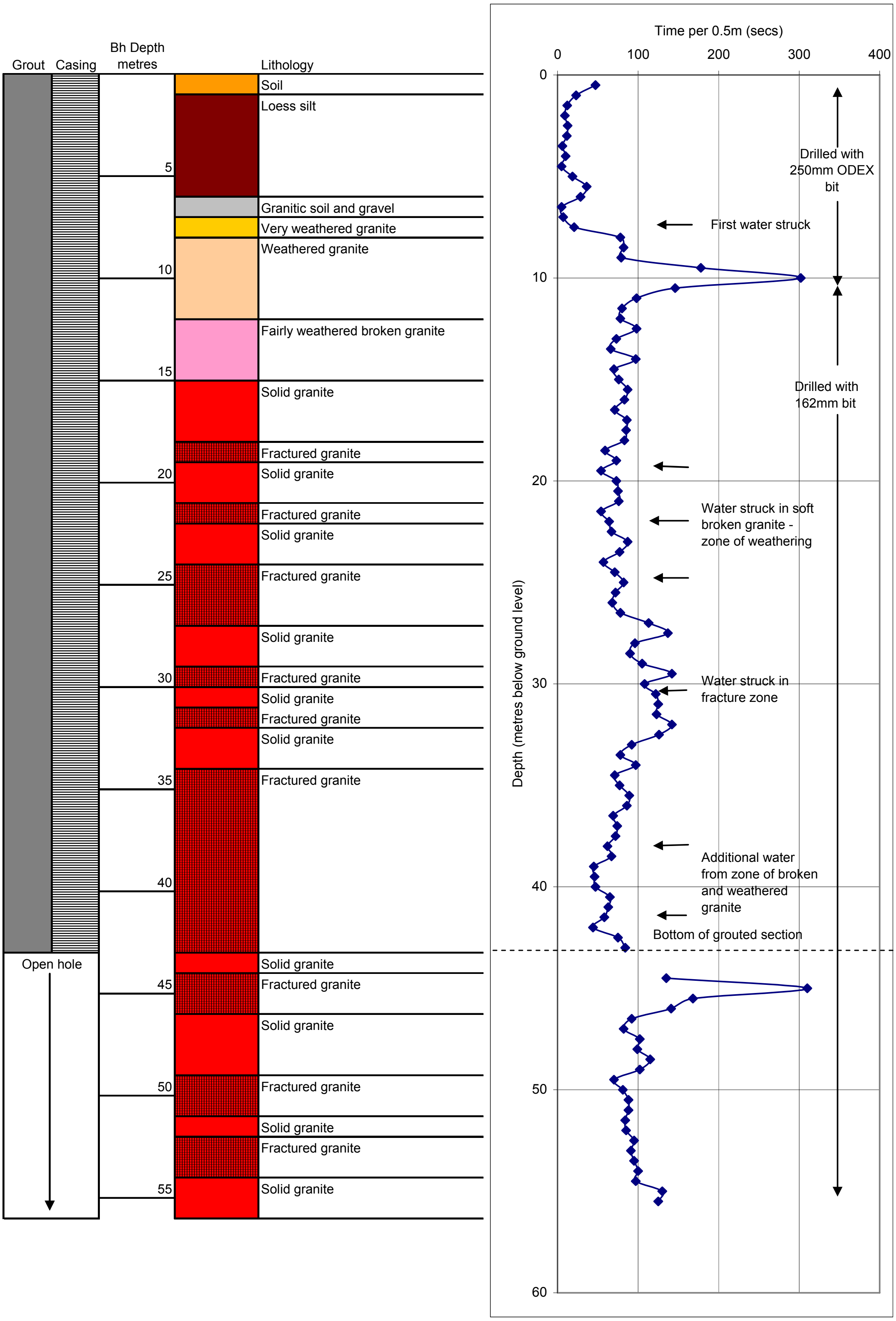


Figure 2 La Rocque borehole – construction, geological log and penetration rate.

2.3.3 Cumulative Yield with Depth and Wellhead Hydrochemistry

An air flush water yield of 0.9 litre per second (l/sec)(78 m^3/d) was obtained from the jointed weathered granite by 10 m bgl. During the drilling of the 10 to 43 m bgl section, air flush water discharge rates were measured at 3 m depth intervals (Figure 3). Hydrochemical parameters (temperature, pH and specific electrical conductance) were determined on site for the discharge waters (Plate 6) and samples collected for major ion and isotope analysis. Between 10 and 43 m bgl, pH values remained fairly constant in the range of 8.1 to 8.3, water conductivity (EC) varied between 1500 and 1620 µS/cm and water temperature varied between 13.1 and 13.8°C (Appendix 5). The rate of water discharge was seen to increase incrementally with depth from 0.6 l/sec (52 m^3/d) at 16.5 m bgl, to 2.5 l/sec (216 m^3/d)at 25.5 m bgl, 4 l/sec (346 m^3/d) at 34.5 m bgl and 7 l/sec (607 m^3/d) at 43 m bgl. The increases in water inflow correlated with the occurrence of recognisable weathered and fracture zones; no single inflow zone or "stream" was encountered during the drilling of the borehole. The rest water level in the 43 m deep borehole, before casing was installed, was 2.41 m bgl.

Following the drilling out of the grout to 43 m bgl, no water was detected within the borehole, indicating that an effective seal of shallow water ingress had been achieved. Whilst drilling between 43 and 45.5 m bgl, small quantities of water were encountered and the discharge rate increased gradually from 0.6 l/sec (52 m^3/d) at 43.5 m bgl to 0.7 l/sec (60 m^3/d) at 45.5 m bgl.

Between 46.5 and 55 m bgl, pH values remained fairly constant in the range of 8.3 to 8.7, conductivity varied between 1530 and 1670 µS/cm and water temperature varied between 12.9 and 13.5°C (Appendix 5). The rate of water discharge was observed to increase incrementally with depth but at a much slower rate than in the section above. No single inflow zone or "stream" was detected at (or near) the depth interval predicted by Mr Langlois or at any depth within the open hole section. The rate of discharge was seen to increase gradually from 0.7 l/sec (60 m^3/d) at 45.5 m bgl to 1.4 l/sec (121 m^3/d) at 50 m bgl and to 1.75 l/sec (152 m^3/d) at 55 m bgl, water inflow being from thin fracture zones in the granite.

Plate 7 Water being air flushed from the La Rocque borehole at the rate of 7 l/sec (607 m^3/d) from 43 m bgl, prior to the setting of casing and grout to that depth.

Plate 8 Water being air flushed from the La Rocque borehole at the rate of 1.7 l/sec (14 m^3/d) from 55 m bgl.

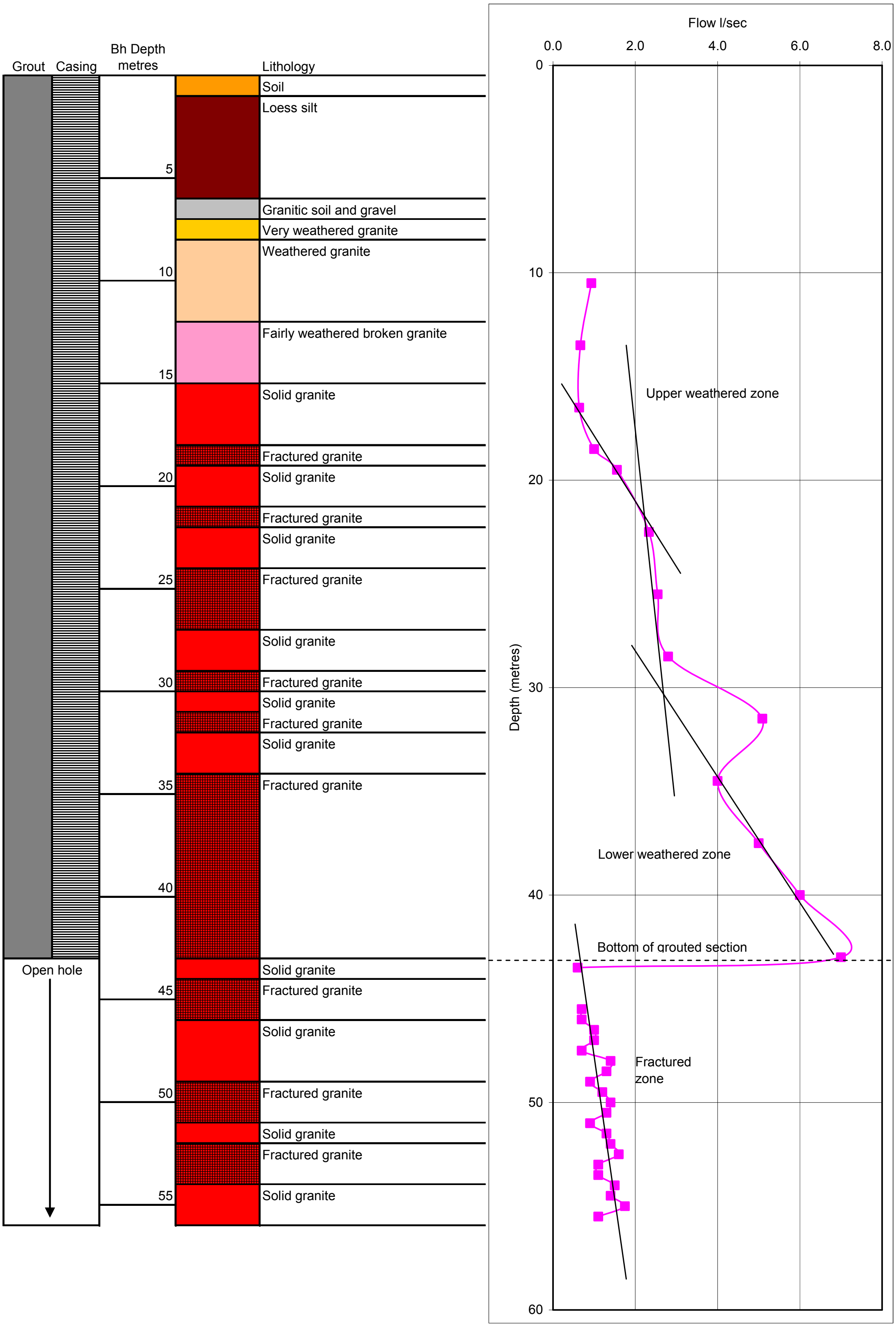


Figure 3 La Rocque borehole – construction, geological log and air flush yield.

2.3.4 Borehole construction

The borehole was drilled at 250mm diameter to a depth of 10 metres, using an ODEX system down hole air hammer and bit assembly, and cased with 250mm ID steel casing. From 10 to 43 m bgl, the borehole was drilled using a 6 inch down hole air hammer and 203 mm bit assembly. The borehole was then cased with 165 mm ID plastic casing (eight 6 m lengths of plastic casing) to a depth of 43 metres.

The casing assembly was suspended about 0.5 metres off the bottom of the borehole, a tremmie pipe was installed to the borehole base and cement grout (mixed at the rate of 100 litres of water with 5 x 25 kg bags of cement powder) was pumped into the borehole within the casing. Once the casing was filled to the top, additional cement grout was pumped down the annulus (the space between the outside of the casing and the drilled borehole wall) until both sections of the borehole were completely filled with grout. The cement grout was then allowed to harden for a 43 hour period; almost twice the minimum specified duration.

An unsuccessful attempt was made to drill out the hardened cement grout from the inside of the plastic pipe using the 6 inch air hammer fitted with a 162 mm diameter bit. Unfortunately this resulted in the rupturing of the plastic liner pipe close to the ground surface. Drilling was halted at a depth of 7 m, (whilst still inside the larger diameter steel pipe). The 6 inch hammer with 162 mm bit was replaced with a 4 inch hammer with a 89 mm (3.5 inch) diameter bit. This smaller assembly was used to drill a pilot hole through the hardened cement grout to a depth of 42.5 m. This showed that the grout within the plastic casing had set hard and that the plastic lined borehole was dry. A 127 mm (5 inch) diameter bit was then fitted to the 4 inch hammer and this assembly used to ream the borehole out to 43 m bgl. This had the effect of removing much of the cement grout from within the plastic casing while avoiding further damage to the plastic liner. The borehole remained dry after reaming to 43 m bgl had been completed. The 127 mm diameter bit assembly was then used to drill beyond the bottom of the grouted section to a depth of 45.5 m.

Unfortunately, a 156 mm drilling bit (to be used to drill out the grout and continue to drill the borehole below the grouted section) failed to arrive from the UK. It was, therefore, necessary to use the 6 inch hammer with 162 mm bit assembly. After damaging the plastic liner to a depth of 13 m bgl, the 162 mm bit assembly successfully ran into the plastic liner, which it followed to the bottom of the grouted section without apparent further damage to the plastic liner. Reaming out the open hole from 43 to 45.5 m bgl took much longer than anticipated. This was due to the presence of plastic debris mixed with rock cuttings infilling the lower section of the 127 mm (5 inch) diameter borehole. Once these cuttings had been cleared, drilling below 45.5 m bgl proceeded quickly. At the request of Mr Langlois, drilling proceeded beyond the original specified total borehole depth of 50 m bgl to a total depth of 52.5 m bgl. By that depth, no significant increase in discharge had been observed. At the request of the Minister for Planning and Environment, Senator Cohen, drilling then continued a further 3 metres to a final depth of 55.5 m bgl, but again there was no significant increase in water discharge (Figure 3). Drilling was, therefore, halted at that depth.

2.4 ST CATHERINE BOREHOLE

2.4.1 General

Drilling operations at St Catherine, at a site marked by a cross in a circle by Mr Langlois and Mr de la Haye, commenced on 19 September 2006. The site is located about 100 m south west of a borehole belonging to Mrs Jones at La Vielle Chapelle. The rest water level in Mrs Jones borehole was about 20.0 m bgl. Drilling of the St Catherine borehole was completed to a final depth of 79.5 m on 23 September 2006. Mr Langlois was on site to confirm the accurate positioning of the drilling rig upon the precise site that he had selected (Plate 1).

2.4.2 Geology, fractures and penetration rates

The initial 1.5 metres of this borehole was drilled through a very thin soil cover into broken and weathered rhyolite and tuff. Broken rhyolites and tuffs (presumable weathered) were encountered between 1.5 and 7 m bgl, with mainly hard rhyolites, fractured in parts from 7 to 36 m bgl. Drill penetration was rapid through the weathered tuff and rhyolite deposits but slowed considerably on entering compact rhyolite below 7 mbgl. In the section between 7 and 16 m bgl hard rock bands alternated with soft bands, but below 18 m bgl the rhyolite layers become progressively harder although much fracturing was evident. The fracture zones were identified by the presence of white vein quartz. During the drilling of the dry section between surface and 36 m bgl, much dust was produced, making sampling conditions difficult (Plate 9). At 36 m bgl a damp fractured rhyolite horizon was penetrated that halted dust production.

Plate 9 Excessive quantities of rock dust blown from the St Catherine borehole during drilling at 33 m bgl.

Between 36 and 58 m bgl, a succession of hard rhyolitic tuffs and rhyolites was penetrated. The rhyolitic tuffs between 36 and 45 m bgl were fractured, particularly between 39 and 42 m bgl. Compact non-fractured rhyolites and rhyolitic tuffs were found between 45 and 58 m bgl. From 58 to 79.5 m bgl, a sequence of mainly rhyolites with subordinate ashes, pyroclastics and tuffs were penetrated. Major fracturing was noted within rhyolites between 72 and 74 m bgl. The rate of drill penetration was fairly constant and rapid from 58 to 79.5 m bgl (Figure 4). A detailed geological log is provided in Appendix 4.

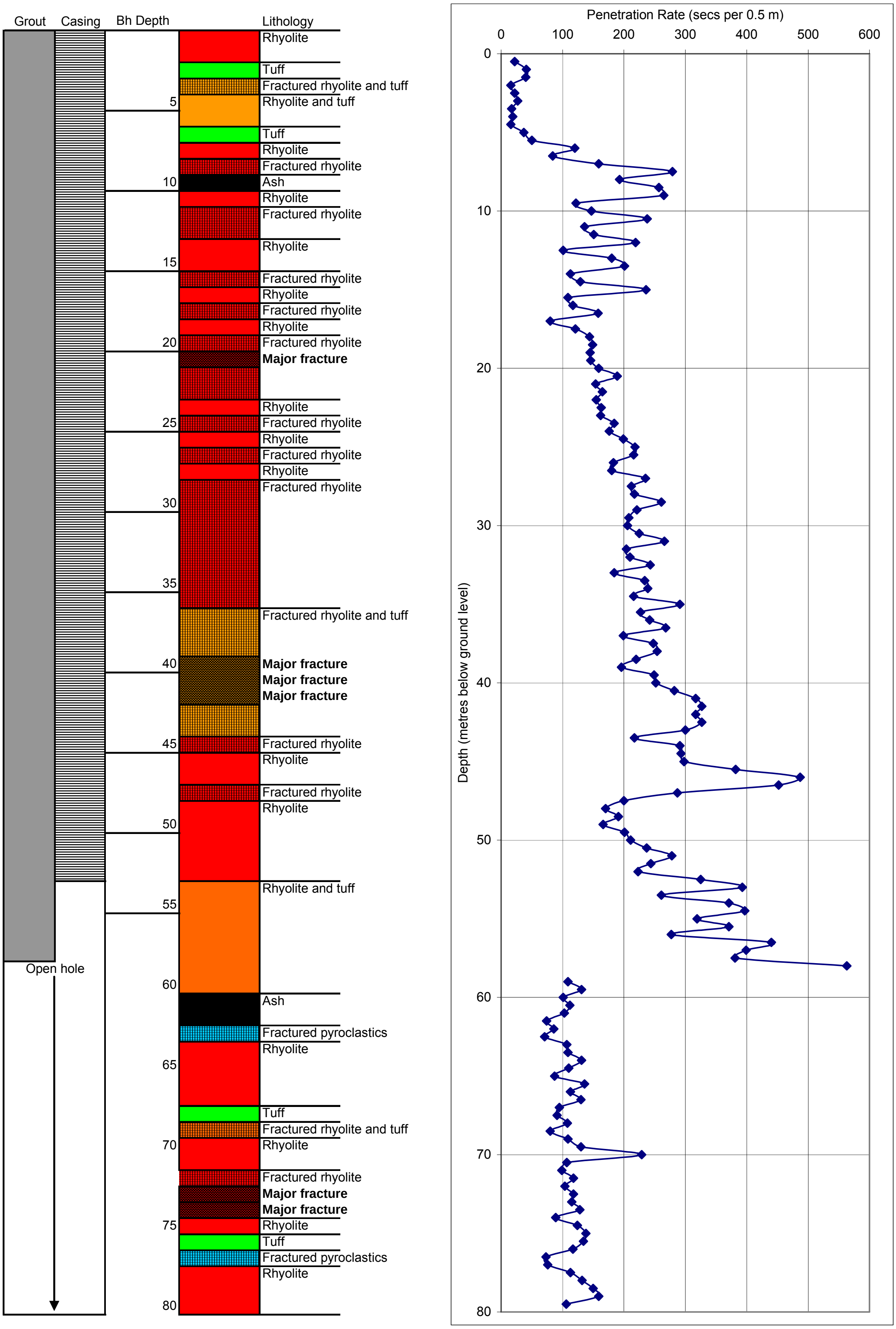


Figure 4 St Catherine borehole – construction, geological log and penetration rate.

2.4.3 Cumulative Yield with Depth and hydrochemistry

During drilling, the upper 36 m section of the St Catherine borehole proved to be completely dry. At 36 m there was sufficient dampness to suppress dust production during drilling. When left over-night at that depth, water accumulated in the borehole to a level of 23.19 m below the top of the casing. Seepage from the fractured rhyolitic tuff between 36 and 41 m bgl produced sufficient water inflow for a thick mud to be produced during borehole cleaning. Further inflows of water from a fracture zone between 39 and 42 m bgl and minor fractures below to a depth of 45 m bgl, were sufficient to produce a watery mud during borehole cleaning but inflow was still insufficient for the measurement of an air flush discharge rate.

There was little additional inflow between 45 and 58 m bgl. At 56.5 m bgl, an attempt to clean the borehole was unsuccessful, only a small discharge of muddy water being obtained after 15 minutes of flushing. Insufficient water was produced for a discharge measurement to be undertaken. However the pH, temperature and electrical conductance of samples of muddy water were determined and samples were obtained for isotope analysis. pH values remained fairly constant in the range of 7.5 to 8.0, between 38.5 and 50.0 m bgl, the conductivity varied between 570 and 650 µS/cm but from 50.5 to 58.0 m bgl steadily increased from 650 to 950 µS/cm (Appendix 5). Water temperature varied between 13.2 and 14.2°C between 38.5 and 58.0 m bgl with occasional peaks of 14.8°C. It proved impractical to obtain water samples for the determination of major ion chemical contents due to the low flow and high mud content. The rest water level was at 20.47 m bgl, when the borehole depth was 53.76 m bgl, before casing and grouting.

After drilling through the cement grout to 58 m bgl, further drilling produced some dampness from an ash band between 60 and 62 m bgl and a small water flow from a fractured pyroclastic layer at 63.5 m bgl. Air flush water discharge rates increased from 0.15 l/sec (13 m^3/d) at 65 m bgl to 0.34 l/sec (29 m^3/d)at 68.5 mbgl, below which discharge varied between 0.23 and 0.26 l/sec (20 and 22 m^3/d) to the total borehole depth at 79.5 m bgl. Minor water inflows were associated with zones of fracturing, as indicated by the presence of bands of white vein quartz but it is probable that many of the fractures are completely filled with quartz. Although several such fracture bands were encountered no large groundwater inflows were recorded. and the limited discharge obtained was very muddy (Plate 10), there being insufficient water to provide a clean flow after the cessation of drilling. The pH, temperature and electrical conductance of samples of muddy water obtained between 58 and 79.5 m bgl were determined and further samples obtained for isotope analysis. pH values declined from 12.9 to 11.6 between 65.0 and 79.5 m bgl, as the impact of the cement grout was reduced with the flushing of the borehole. The water conductivity declined from a high of 11,370 µS/cm at 65.0 m bgl to 6220 µS/cm at 70.0 m bgl but from 70.5 to 79.5 m bgl varied between 3000 and 2500 µS/cm. Water temperature varied between 14.1 and 15.6°C between 65.0 and 79.5 m bgl (Appendix 5).

Plate 10 Muddy water discharging from St Catherine borehole at about 0.27 l/sec (23 m3/d) from 75 m bgl.

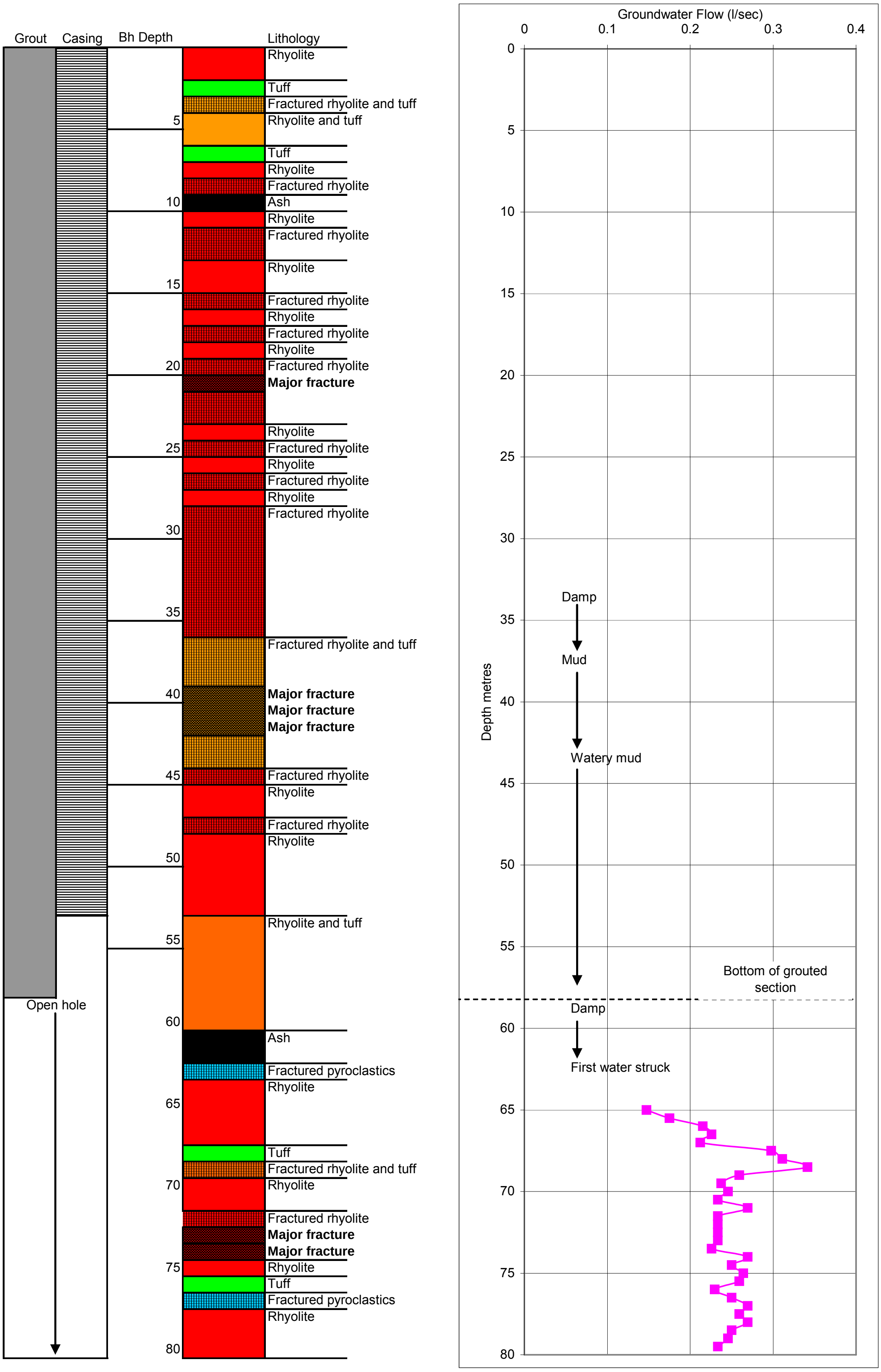


Figure 5 St Catherine borehole – construction, geological log and air flush water yield record.

2.4.4 Borehole construction

In light of experience gained during the drilling of the La Rocque borehole, Mr Langlois requested that the base of the cased and grouted section of the planned St Catherine borehole be raised from 73 m bgl to 58 m bgl in case the 'stream' was shallower than had been originally predicted. All parties also agreed that the design of the St Catherine borehole could also be amended to incorporate the use of 203 mm steel pipe instead of the 152 mm plastic casing as used in the construction of the La Rocque borehole.

The uppermost 1.5 metre section of the borehole was drilled using a 350 mm ODEX system hammer and bit assembly. A 2m length of flush joint 350 mm temporary steel drive pipe with a drive shoe was installed in the borehole to a depth of 1.5 m bgl. The 350 mm ODEX system hammer bit was exchanged for a 6 inch hammer with a 300mm diameter bit and the borehole was then drilled from 1.5m to the revised depth of 58 m at 300 mm diameter. Possible formation collapse from above the hammer was noted at that depth. After extraction of the drill rods and hammer, the depth of the borehole was plumbed at 53.5 m deep from top of casing, the lower part of borehole having backfilled with collapse material. A bund with pipe outflow was constructed around the top of the borehole and the borehole was flushed clean with air. Only a very small discharge of muddy water was noted.

The borehole was cased with nine 6 metre lengths of 198 mm ID spiral welded steel casing to a depth of 53 m, (with 1m above ground level). The casing lengths were joined by butt welding the lengths together.

The cement grouting tremmie pipe was installed to the base of the borehole at 58 m bgl. Cement grout was mixed at the rate of 100 litres of water with 5 bags of cement powder and was pumped into the borehole both inside and outside of the casing. The borehole was filled with grout to 27 m bgl, considerably above the highest occurrence of water whilst drilling. The steel casing was then lowered 0.5m further down into the borehole and the upper 0.55 m of steel pipe cut off to allow the temporary 305 mm diameter casing to be withdrawn. Additional cement grout was pumped into the annulus to bring the grout level to the ground surface at the top of borehole. The cement grout was then allowed to set hard for 48 hours.

The 6 inch hammer with a 162 mm diameter bit were run in to the borehole and used to drill out the hardened grout from inside the steel casing to 52.5 m bgl. The borehole at this point remained dry. Drilling was then continued through the grouted section below the steel casing to 58 m, (the drilled depth before casing and grouting), the borehole again remaining dry. Below 58 m bgl the formation proved to be sufficiently damp to prevent the formation of dust during drilling and drilling proceeded to the planned depth of 79.5 m. The borehole was completed 'open hole' between 58 and 79.5 m bgl.

2.5 DRILLING DATA INTERPRETATION

2.5.1 La Rocque

The shallow water bearing zone between ground level and 43 m bgl was completely sealed off so that the hydrogeological characteristics of the upper shallow and lower deep horizons could be defined and differentiated.

The upper shallow horizon comprised two zones of softer weathered granite separated by a harder jointed granite. These correlate with increasing rates of water inflow and rates of drill penetration as determined during drilling.

The lower deep horizon comprises harder jointed granite, with rates of groundwater inflow and drill penetration similar to those determined for the harder zone between the weathered zones above.

The use of a plastic casing within the upper borehole section caused some problems. Although the casing was damaged within the upper 13 m of the borehole, the integrity of the cement grout in sealing out shallow water bearing horizons was not compromised and the borehole remained dry after the grout had been removed from within the cased section of the borehole (see Box 2). The total discharge of 7 l/sec measured for the shallow upper zone was successfully closed out and only 1.5 l/sec was obtained from the lower deep zone.

No single major flow of water, (such as may be anticipated had an 'underground stream' or single large fracture been penetrated), was encountered during the drilling of the borehole, (either at the depth predicted by Mr Langlois, or within the basal 'open' section of the borehole between 43 and 55.5 m bgl), there being a gradual increase in water inflow with depth as increased numbers of water bearing fracture/joint zones were intercepted with depth.

2.5.2 St Catherine

This borehole was drilled though a sequence of interbedded rhyolites and rhyolitic tuffs with thin occasional bands of ash and pyroclastic materials. These formations showed distinct bands of fracturing.

The little water inflow that did occur during drilling was contributed from specific pyroclastic rock bands, as well as some of the fracture zones. Unlike the La Rocque borehole, there was no significant incremental increase in water inflow with depth contributed from regular fracture/joint zones.

No major inflow of water was encountered whilst drilling the borehole, which produced a yield that was significantly lower than may commonly be obtained from similar rocks elsewhere in Jersey. No major water strike occurred at the depth predicted, or at any depth within the basal 'open' section of the borehole between 58 and 79.5 m bgl.

3 Hydraulic Testing

3.1 INTRODUCTION

This section documents the results of pumping tests conducted on the boreholes at La Rocque and St Catherine between 30 October and 8 November 2006.

The tests were undertaken as part of the Jersey deep groundwater investigations and were intended to:

- Evaluate potential sustainable yield at each source.
- Investigate the hydraulic connection between the shallow and deep strata.
- Evaluate hydraulic parameters (transmissivity and storage) in the deeper strata.
- Investigate the resource potential of the deeper strata.

3.2 TEST DESCRIPTION

3.2.1 General Methodology

Pumping tests were conducted on the boreholes at La Rocque and St Catherine's between 30 October and 8 November 2006. Pumps were installed in each borehole by Amplus Ltd prior to testing in the week beginning 23 October 2006. Pumping tests were performed and supervised by Mr Moon (Entec) and Dr du Feu (Water Resources Section). All pumping tests were performed in accordance with British Standard 6316:1992 (Test Pumping of Water Wells).

Step, constant rate and recovery tests were performed on each borehole. Pumps and rising main works were installed at both sites, as illustrated in Figure 6 below, in the week beginning 23 October 2006.

At each site water levels were monitored and logged in the abstraction borehole (and at one observation borehole at La Rocque) using Mini-Diver® pressure transducers and loggers ('divers'). Prior to tests, pumps were tested and calibrated for one to two hours in order to determine their maximum achievable outputs and establish the gate valve settings to enable the pre-determined range of flow rates. Approximate discharge measurements using a stopwatch and containers of known volume were also taken at both sites to ensure flow meters were functioning properly prior to testing.

Boreholes were allowed to rest overnight and dipped prior to tests to ensure full recovery of rest water levels. Manual dips and flow rates were recorded according to the schedule given in BS6316 throughout the duration of the step tests and over the first two hours of each constant rate and recovery test. Divers were left installed in each borehole for up to three to four days beyond the end of constant rate testing (i.e. until 8 November 2006) to allow for any additional influences on ground water levels (e.g. tidal fluctuations) to be monitored.

Water quality was additionally monitored throughout the pumping tests. Electrical conductivity, pH, temperature and dissolved oxygen content of the pumped water were monitored using field meters at five minute intervals throughout step tests and at regular intervals during the constant rate tests. Water quality samples were taken 1 hour into step tests and at the beginning of each day during constant rate testing. Samples for carbon isotope dating were taken at the beginning and end of constant rate tests. Water quality and isotope analysis results are presented separately in Sections 4 and 5.

The large data set that has resulted from measurements taken during hydraulic testing is too large to include as part of this report but is available in digital format as a public record.

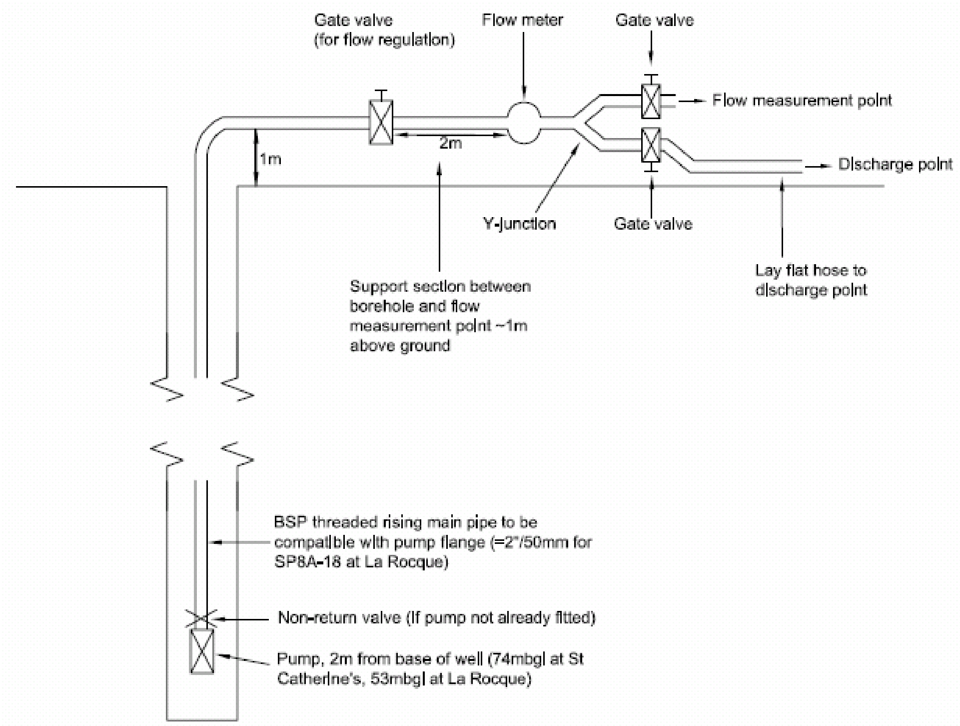


Figure 6 Pump and pipe-work installation (not to scale).

Specific arrangements for each site are detailed below.

3.2.2 La Rocque

A Grundfos SP8A-18 pump was installed with the pump inlet at 52 m bgl (3.5m above the base of the borehole). Hose was laid to discharge water into a coastal outfall drainage channel at a point approximately 40 m from the abstraction, with a gate valve and outlet close to the borehole to allow water quality sampling.

The water level diver was installed in the new borehole at approximately 48 m bgl on 30 October 2006, together with a barometric diver (for compensation of water level measurements to effects of variations in atmospheric pressure) suspended 1 m bgl in air in the same borehole.

An inactive domestic borehole is situated 21.8m from the new borehole (at grid reference: 570654 544719). This borehole is approximately 32m deep with steel casing (not grouted) and reported to be present from surface to 15 m bgl. This borehole was used as an observation borehole throughout the tests, with a water level diver installed at approximately 28 m bgl. It should be noted, however, that as this borehole does not penetrate to the depth of the open section of the abstraction borehole, it is not an ideal observation borehole and subsequent interpretation of the data for deriving hydraulic parameters is for guidance only.

A step drawdown test was conducted on the La Rocque borehole on 31 October 2006. Calibration pumping on 30 October 2006 determined a maximum pump output of 3.5 l/sec (302 m^3/day). Consequently four 90 minute steps were proposed at target pumping rates of 0.875, 1.75, 2.625 and 3.5 l/sec (76, 151, 226.8 and 302 m^3/day), with rates controlled by adjusting the gate valve fitted on the rising main on the surface. In practice pumping rates of 1.25, 1.91, 2.73 and 3.25 l/sec (108, 164, 236 and 281 m^3/day) were achieved, with variation from the target rates owing to the fine sensitivity of adjustments to the gate valve and the maximum discharge being slightly reduced when the sampling valve was closed and water was pumped further to the discharge point. The step test commenced at 08:58 on 31 October 2006. The pump was switched off at 14:58 the same day and left until the morning of 1 November 2006 to allow for recovery.

Following recovery, a constant rate test commenced at 09:19 on 1 November 2006. The pump was set to run at the maximum rate (gate valve fully open) of 3.25 l/sec (281 m^3/d) for three days (in accordance with BS6316, which recommends a minimum one day duration for constant rate tests on abstractions of less than 500 m^3/day. A short interruption to the test occurred on the morning of 2 November 2006 due to the generator running out of diesel in the early morning. As the duration of the interruption was determined to be less than one hour, the generator was restarted and constant rate testing continued, as in accordance with guidance in BS6316. The pump was switched off at 09:19 on 4 November 2006 and recovery monitored until rest water levels were restored. The average pumping rate achieved in practice over the duration of the constant rate test was 3.20 l/sec (276 m^3/d).

3.2.3 St Catherine

A Grundfos SQE 1-65 pump was installed with the pump inlet at 74 m bgl (5m above the base of the borehole). Hose was laid to discharge water at a point downhill along the track leading to the borehole, approximately 30m from the abstraction. A gate valve and outlet were installed close to the borehole to allow water quality sampling.

The water level diver was installed in the new borehole at approximately 70 m bgl on 31 October 2006. The barometric diver installed at La Rocque was considered also suitable for compensation of water level readings at St Catherine, with an elevation difference of only approximately 16m between the two sites.

A step drawdown test was conducted on the St Catherine borehole on 1 November 2006. Calibration pumping on 31 October 2006 determined a maximum pump output of 0.5 l/sec. Consequently four 90 minute steps were proposed at target pumping rates of 0.125, 0.25, 0.375 and 0.5 l/sec (10.8, 21.6, 32.4 and 43.2 m^3/day), with rates controlled by adjusting the gate valve fitted on the rising main on the surface. In practice pumping rates of 0.127, 0.255, 0.340 and 0.395 l/sec (11.0, 22.0, 29.4 and 34.1 m^3/day) were achieved, with variation from the target rates owing to the fine sensitivity of adjustments to the gate valve and the maximum discharge being slightly reduced when the sampling valve was closed and water was pumped further to the discharge point. The step test commenced at 11:03 on 1 November 2006. The pump was switched off at 17:03 the same day and left until the morning of 2 November 2006 to allow for recovery.

Following recovery, a constant rate test was commenced at 12:11 on 2 November 2006. As step test results suggested that the maximum 0.395 l/sec (34.1 m^3/day) discharge may not be sustainable over a full three days (and drying out of the borehole would be likely to result in damaging the pump), the pump was set to run at a reduced rate of approximately 0.21 l/sec (18.2 m^3/day) for three days (in accordance with BS6316, which recommends a minimum one day duration for constant rate tests on abstractions of less than 500 m^3/day). The pump was switched off at 12:17 on 5 November 2006 and recovery monitored until rest water levels were restored.

3.3 TEST RESULTS AND ANALYSIS

Water levels measured in abstraction and observation boreholes and pump flow data for the entire durations of the tests at La Rocque and St Catherine are shown in Figure 7 and Figure 8 respectively. All water levels were measured as depths below datum (ground level) but converted to depths relative to Ordnance Datum (OD) for plotting the hydraulic test graphs (Figure 7, Figure 8, Figure 9 and Figure 16).

Step tests have been analysed by the Hantush-Bierschenk method (Kruseman and de Ridder 1990) to derive coefficients of aquifer loss (B) and well loss (C) according to the relation:

$$s_{w(n)} = BQ_n + CQ^2 \qquad \text{or,} \qquad \frac{s_{w(n)}}{Q_n} = CQ + B$$

where: $s_{w(n)}$ = Drawdown (m) during the n-th step

Q_n = Constant discharge (m^3/day) during the n-th step

$s_{w(n)}/Q_n$ = Specific drawdown (days/m^2)

B = Aquifer loss coefficient (days/m^2)

C = Well loss coefficient ($days^2/m^5$)

Constant rate tests have been interpreted using Jacob's straight line method (Kruseman and de Ridder 1990) with semi-log time-drawdown plots to derive values of Transmissivity (T) and Storativity (S) from the relation:

$$s = \frac{2.30Q}{4\pi KD}\log\frac{2.25KDt}{r^2S}$$

where: s = Drawdown (m)

Q = Constant well discharge (m^3/day)

KD = Transmissivity (T) (m^2/day)

T = Time since pumping started (days)

R = Distance from the pumping well (m)

S = Storativity (dimensionless)

Recovery tests have been interpreted using Theis's recovery method (Kruseman and de Ridder 1990) to derive values of T according to the relation:

$$s' = \frac{2.30Q}{4\pi KD}\log\frac{t}{t'}$$

where: s' = Residual drawdown (m)

t' = Time since pumping ended (days)

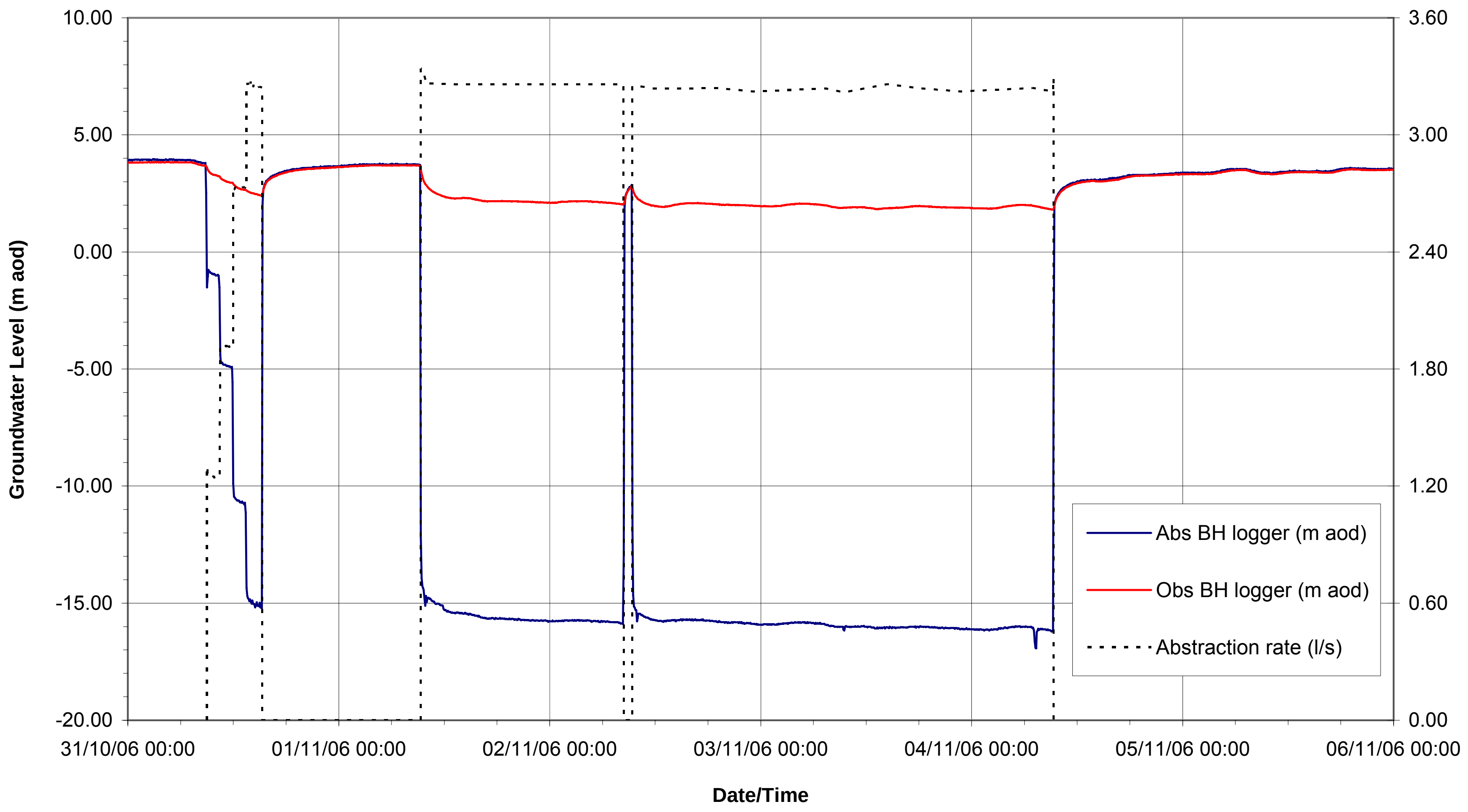


Figure 7 La Rocque Pumping Tests, 31 October to 6 November 2006.

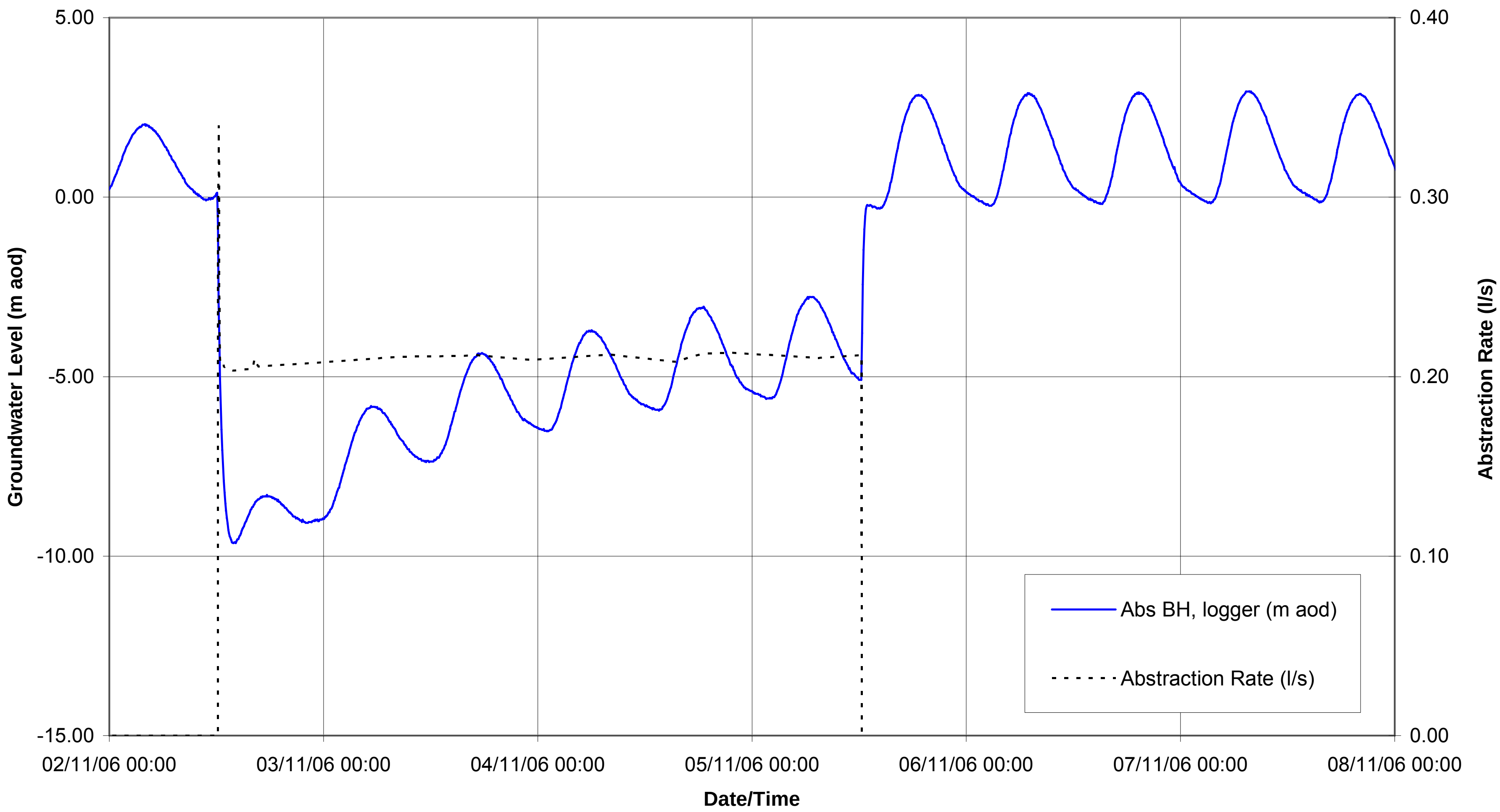


Figure 8 St Catherine Pumping Tests, 2 to 8 November 2006.

3.3.1 La Rocque

STEP TEST

All 4 planned steps of the test were completed. Pumping rates varied only marginally within each step. Pumping rates and water levels during the step test are shown in Figure 9. The drawdown, pumping rate and specific drawdown at the end of each step are shown in Table 2.

Table 2 Step Test Results, La Rocque.

Step	Final Water Level (mAOD)	Drawdown, S_w (m)	Pumping Rate, Q (m^3/d)	Specific Drawdown, S_w/Q (m per m^3/d)	Specific Capacity, Q/ S_w (m^3/d per m)
Rest	3.73	0	0		
1	-1.08	4.81	108.0	0.045	22.5
2	-4.97	8.70	164.2	0.053	18.9
3	-10.82	14.55	235.9	0.062	16.2
4	-15.09	18.82	280.8	0.067	14.9

The Hantush-Bierschenk plot for the La Rocque step test is shown in Figure 10. Pumping rates do not appear to have exceeded the capacity of the borehole. Assuming the capacity of the borehole would be exceeded at discharges above the range tested (i.e. the maximum achievable rate of 3.25 l/sec with the Grundfos SP8A-18 pump approaches the maximum capacity of the well), the data suggest a sustainable specific capacity of around 15 m^3/d/m at discharges not substantially greater than 3.25 l/sec (280 m^3/day).

The derived parameters for the La Rocque borehole are:

Aquifer loss coefficient (B) = 3.1×10^{-2} d/m^2

Well loss coefficient (C) = 1.3×10^{-4} d^2/m^5.

Rest water levels prior to the step test are observed to be approximately equal in the abstraction and observation boreholes (3.73 and 3.69 metres above Ordnance Datum (m aOD) respectively). Drawdowns in the observation borehole were observed to be 0.44 m, 0.72 m, 1.03 m and 1.24 m for steps one to four respectively.

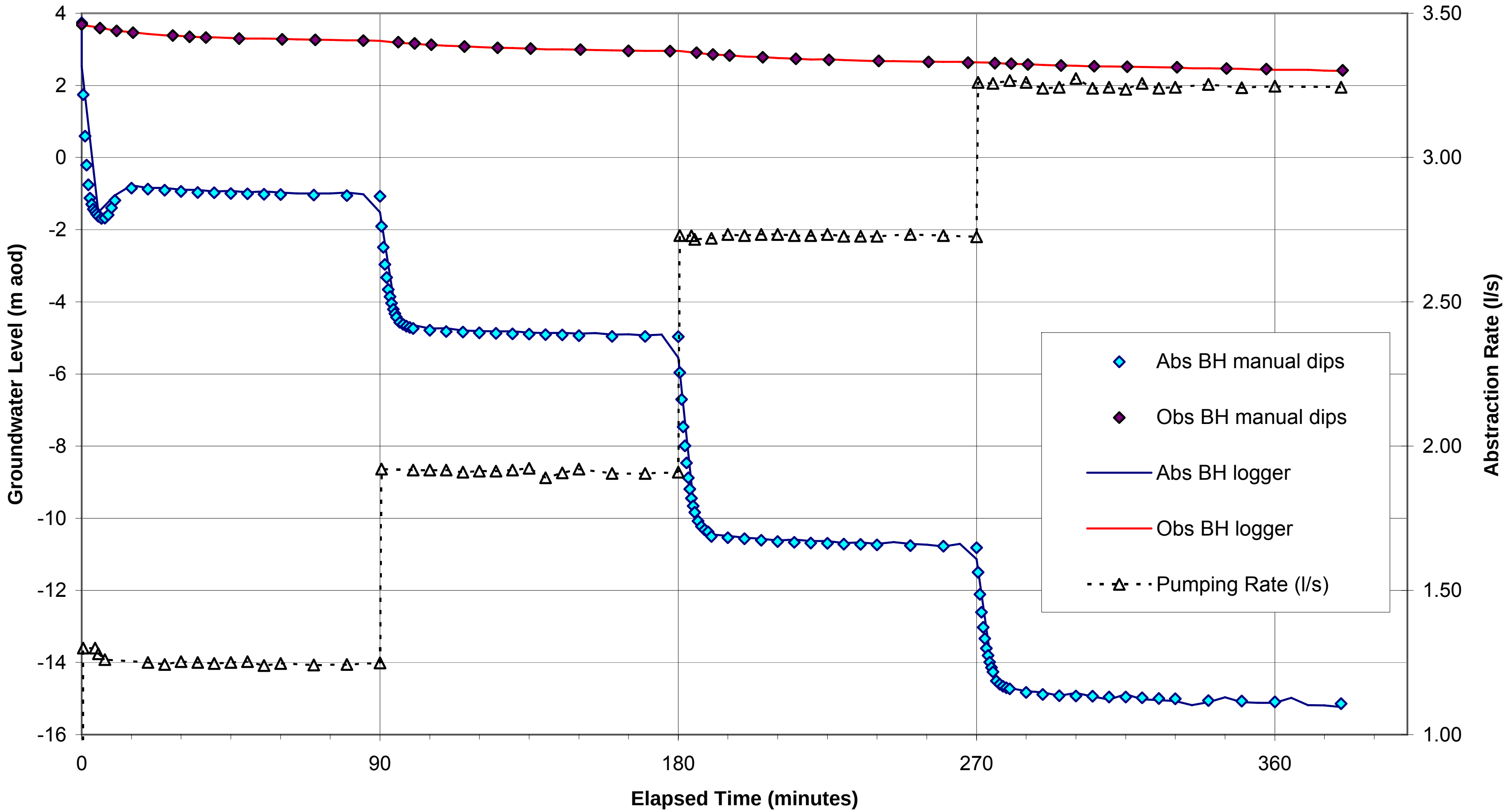


Figure 9 La Rocque Step Test, 31 October 2006.

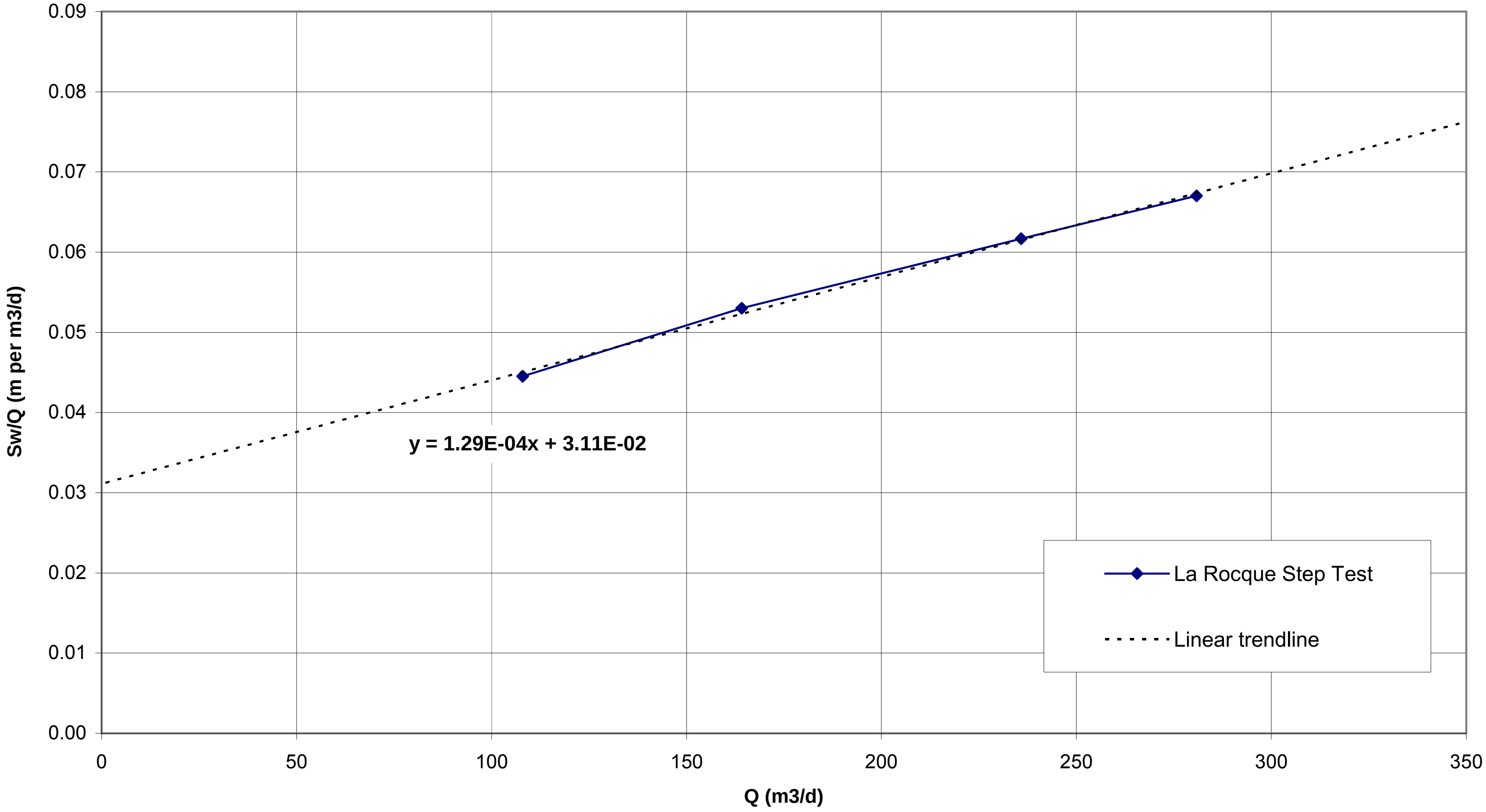


Figure 10 La Rocque Step Test: Hantush Bierschenk Plot.

No major changes in field quality parameters were observed during the duration of the step tests at La Rocque. Quality measurements during the step tests are summarised in Table 3 below.

Table 3 Summary of field water quality measurements during Step Test, La Rocque.

	pH	EC (□S/cm)	Dissolved Oxygen (%)	Temp °C
Start	7.28	1678	2.0 [1]	14.0
End	7.23	1666	0.0	13.2
Min	7.22	1666	0.0	13.1
Max	7.32	1678	2.0	14.0

[1]DO drops away to 0.0 by the beginning of Step 2

CONSTANT RATE TEST

Linear, semi-log and log-log plots of the drawdowns in the La Rocque abstraction and observation boreholes are shown in Figure 11, Figure 12 and Figure 13 respectively.

A line fitting exercise was carried out using the Jacob method, as shown in Figure 12. Drawdown at early times is prone to influence from well storage and non-horizontal flow effects. Well losses calculated from the step test suggest approximately the first 10 m (=CQ^2) of drawdown may be attributed to such losses at a discharge of 280 m^3/day, and hence have been neglected in the analysis. Measurements over the period of interruption in pumping are also ignored. The transmissivity and storativity values for La Rocque assessed by this method at the abstraction and observation boreholes are shown in Table 4 below.

It is not possible to determine a storativity value from single-hole observation of the abstraction borehole. Storativity has been estimated from the observation borehole, although it should be noted that due to the shallow penetration of the observation borehole relative to the abstraction borehole, values of hydraulic parameters may not be precise.

Table 4 Summary of Constant Rate Test Analysis, La Rocque.

Test Position	T (m^2/d)	S
La Rocque abstraction borehole	83	-
La Rocque observation borehole	88	1.3×10^{-5} [1]

[1] Estimation of S from partially penetrating observation borehole

Rest water levels prior to the test are observed to be approximately equal in the abstraction and observation boreholes (3.72 and 3.70 m aOD respectively). Maximum drawdown in the observation borehole is observed to be 1.8 m compared to 20.0 m in abstraction borehole over the duration of the constant rate test. Estimates of Transmissivity derived from the abstraction and observation boreholes are very similar.

No major changes in field quality parameters were observed during the duration of the constant rate tests at La Rocque. Quality measurements during the constant rate test are summarised in Table 5 below.

Table 5 Summary of Field Water Quality Measurements during Constant Rate Test, La Rocque.

	pH	EC (□S/cm)	Dissolved Oxygen (%)	Temp °C
Start	7.23	1666	0.0	13.2
End	7.33	1641	0.0	13.0
Min	7.23	1641	0.0	12.8
Max	7.36	1666	0.0	13.4

RECOVERY TEST

Recovery test data were analysed by the Theis recovery method. Recovery data are plotted in Figure 14. The Theis recovery plot for the La Rocque test is shown in Figure 15.

Transmissivity values for La Rocque assessed by this method are 84 m^2/d and 86 m^2/d at the abstraction and observation boreholes respectively.

Rest water levels following recovery are observed to be approximately equal in the abstraction and observation boreholes (3.62 and 3.58 m aOD respectively), with both boreholes recovering to rest water levels in the same amount of time. Estimates of transmissivity values derived from the recovery analysis of the abstraction and observation boreholes are very similar.

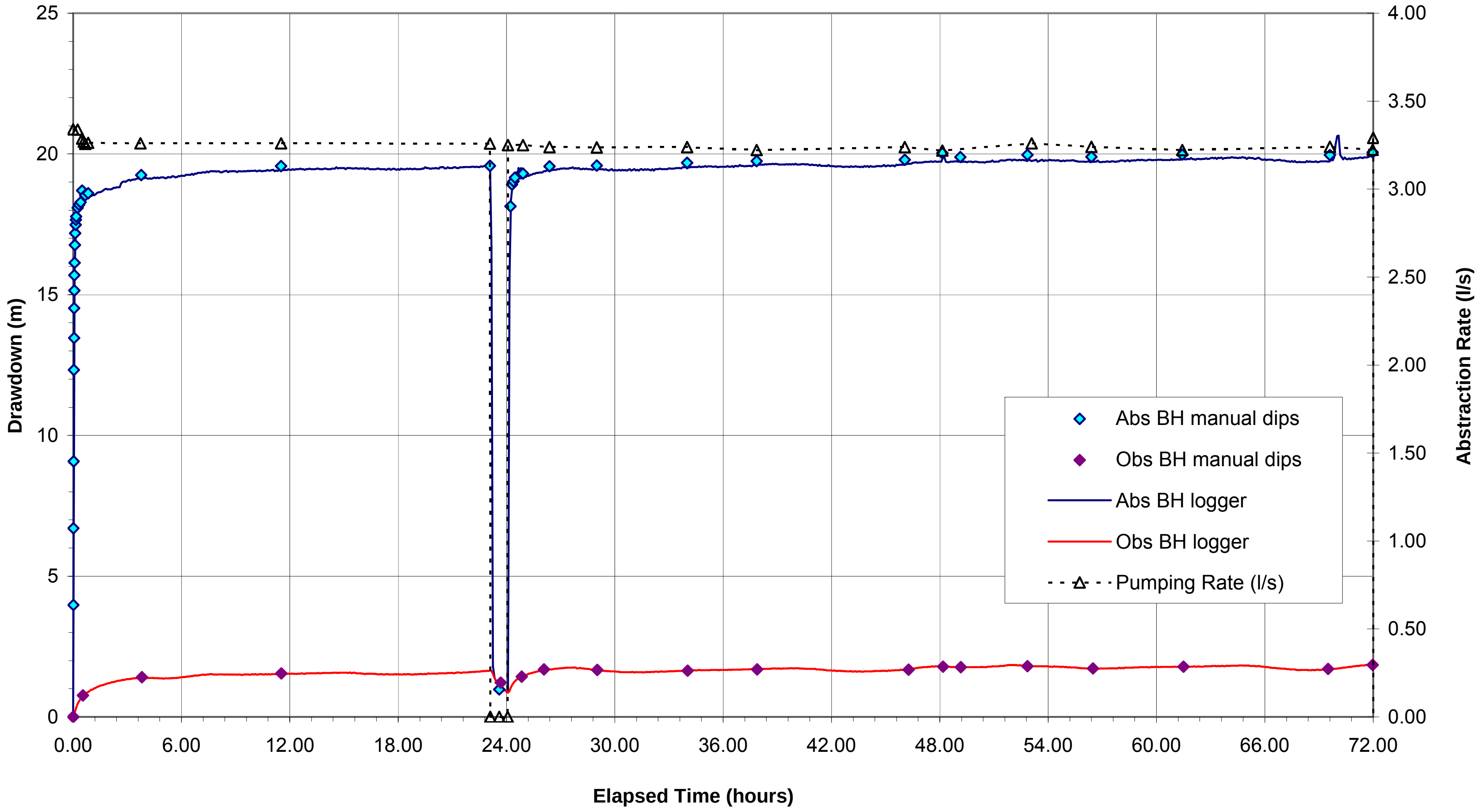


Figure 11 La Rocque Constant Rate Test: Linear Plot.

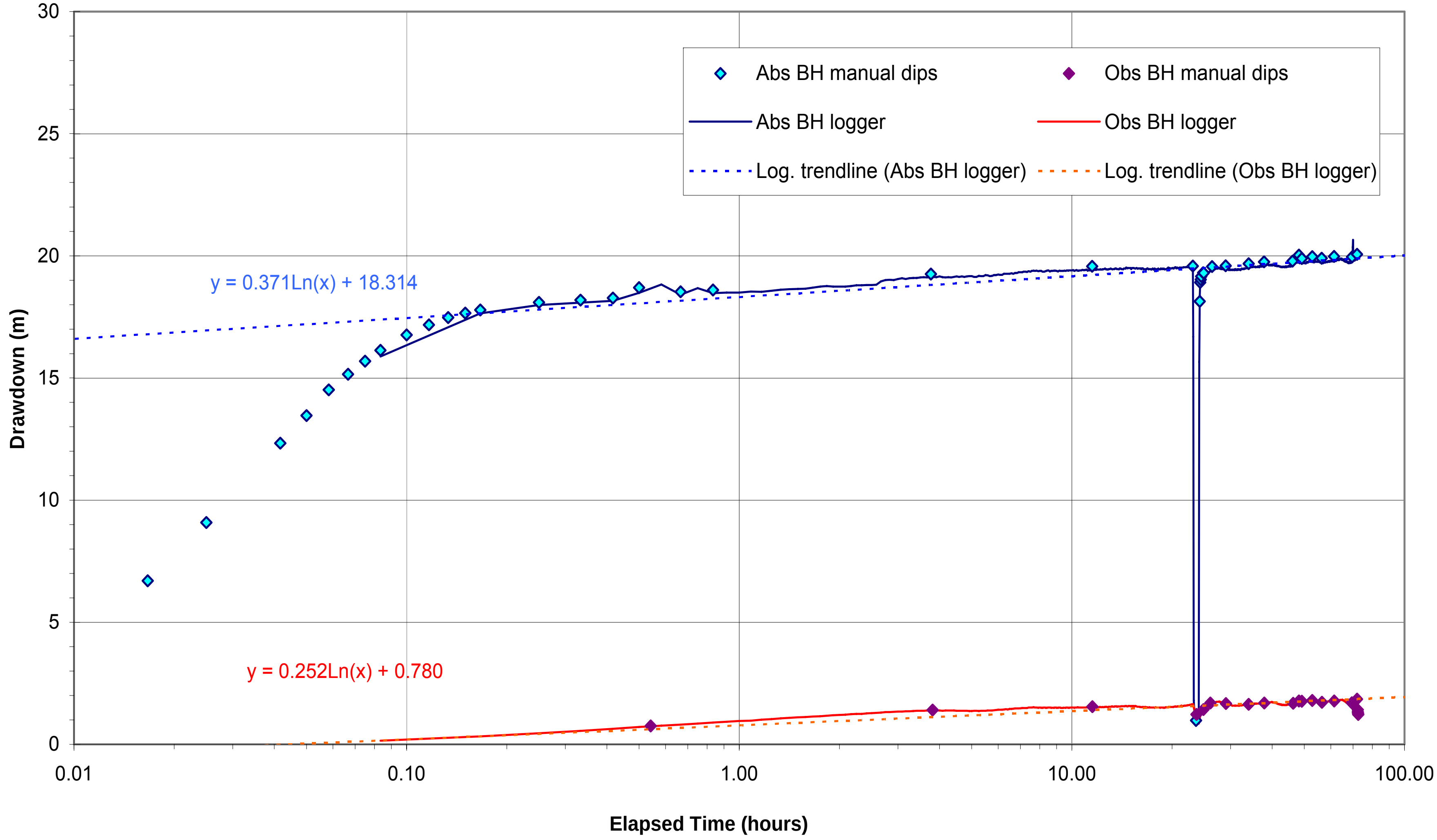


Figure 12 La Rocque Constant Rate Test: Semi-log Plot.

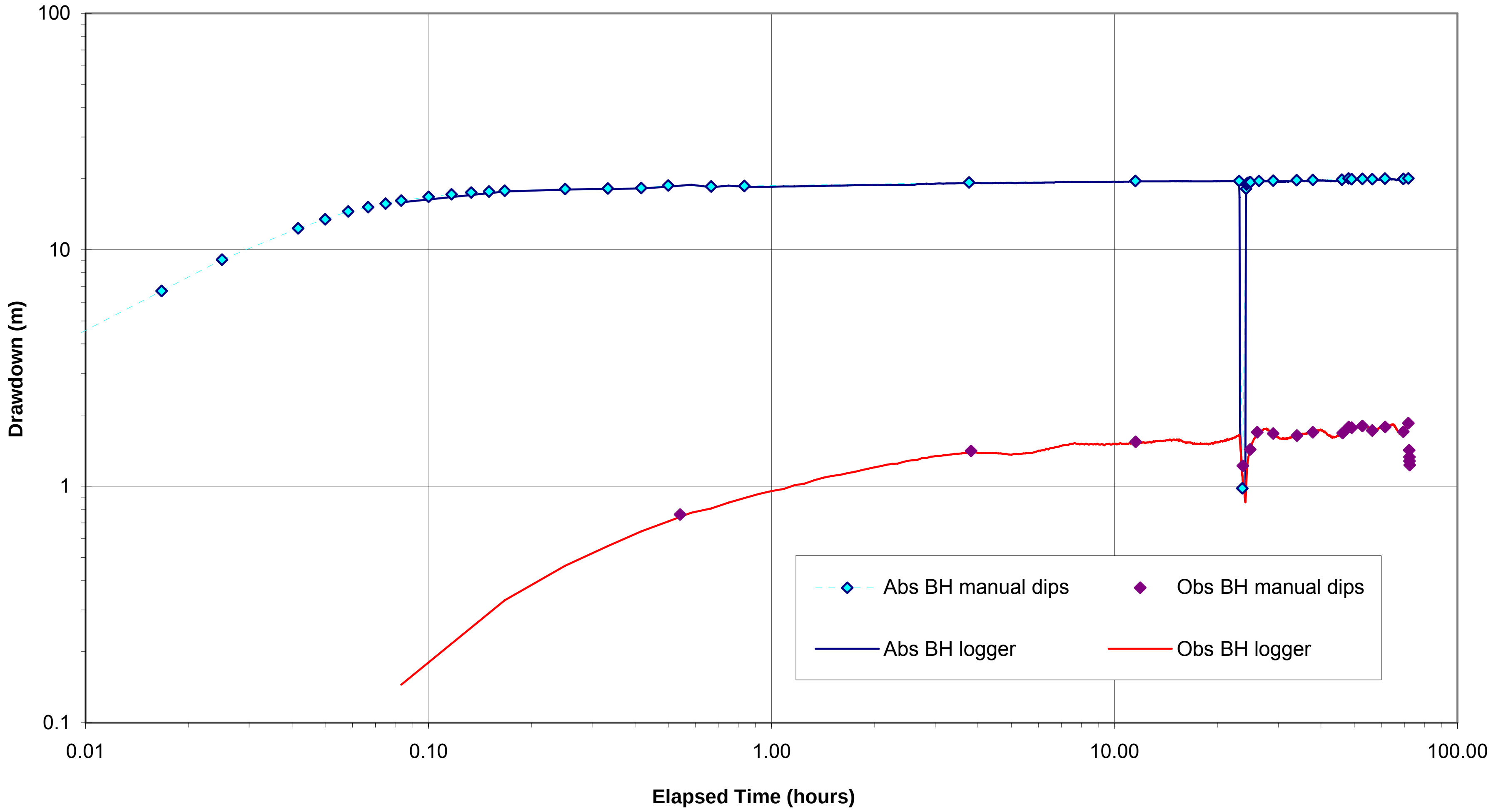


Figure 13 La Rocque Constant Rate Test: Log-log Plot.

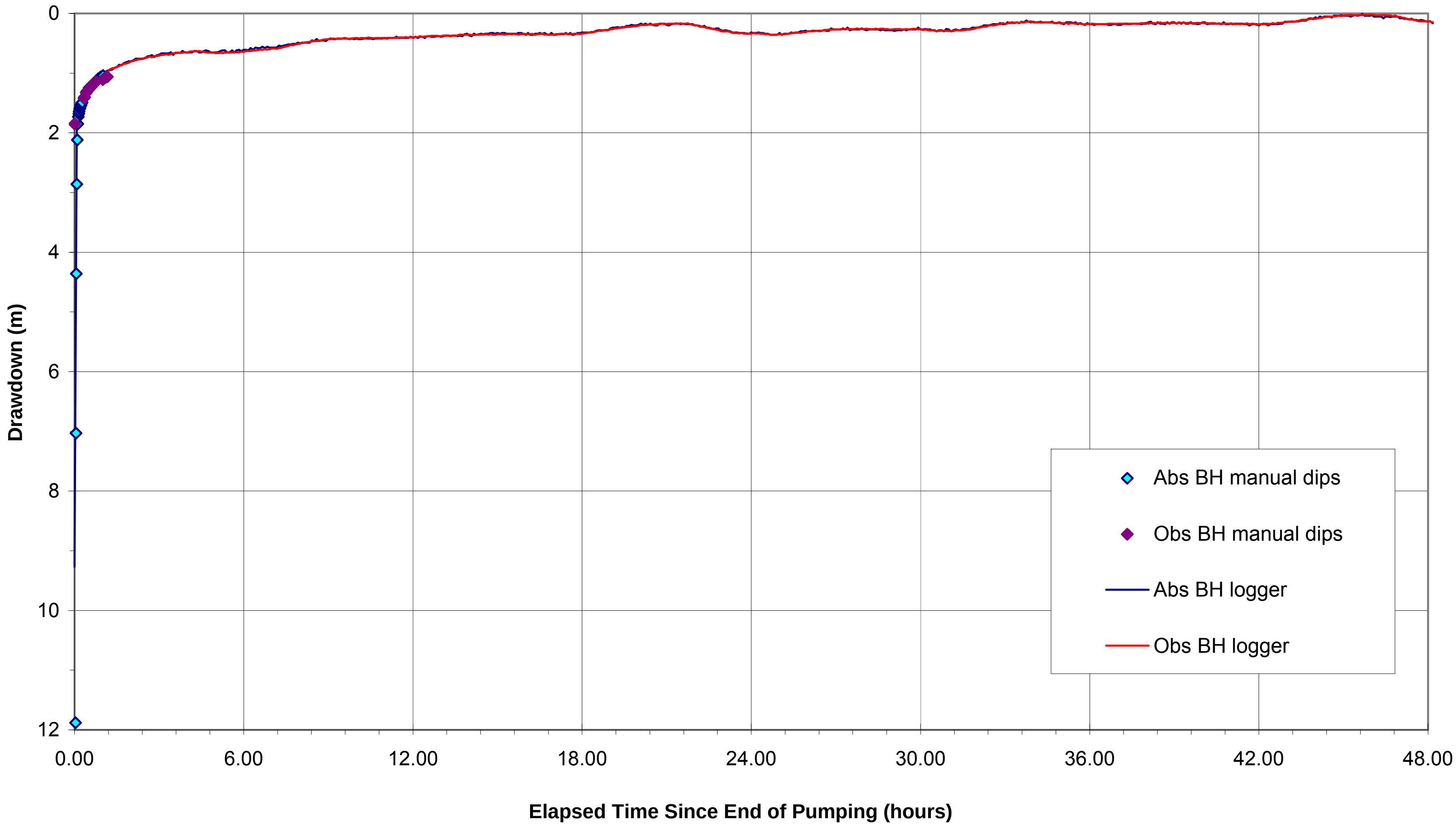


Figure 14 La Rocque Recovery Test: Linear Plot.

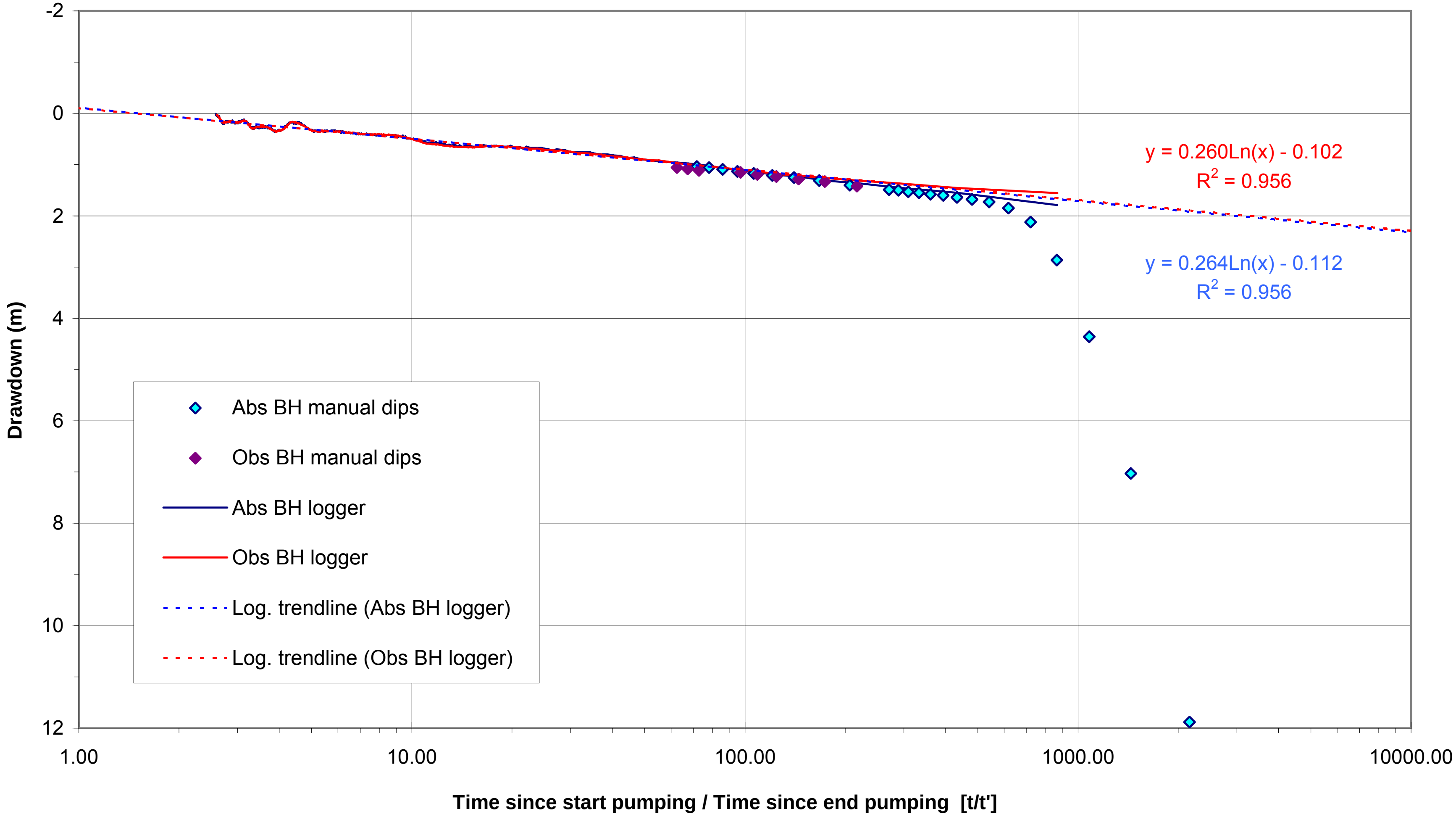


Figure 15 La Rocque Recovery Test: Theis Plot.

3.3.2 St Catherine

STEP TEST

All 4 planned steps of the test were completed. Pumping rates varied only marginally within each step. Pumping rates and water levels during the step test are shown in Figure 16. The drawdown, pumping rate and specific drawdown at the end of each step are shown in Table 6.

Table 6 Step Test Results, St Catherine.

Step	Final Water Level (mAOD)	Drawdown, S_w (m)	Pumping Rate, Q (m^3/d)	Specific Drawdown, S_w/Q (m per m^3/d)	Specific Capacity, Q/S_w (m^3/d per m)
Rest	0.28	0	0		
1	-3.77	4.05	10.97	0.369	2.71
2	-11.42	11.70	22.03	0.531	1.88
3	-20.74	21.02	29.38	0.716	1.40
4	-28.95	29.23	34.13	0.856	1.17

The Hantush-Bierschenk plot for the St Catherine step test is shown in Figure 12. Well losses appear to increase with increasing discharge. The rate at which specific drawdown increases (or conversely specific capacity decreases) appears to increase with increasing discharge. This suggests a low maximum obtainable yield for this borehole. A sustainable specific capacity of around 2 $m^3/d/m$ at discharges not substantially greater than 0.23 l/sec (20 m^3/day) is estimated.

The derived parameters for the St Catherine borehole are:

Aquifer loss coefficient (B) = 1.1×10^{-1} d/m^2

Well loss coefficient (C) = 2.1×10^{-2} d^2/m^5.

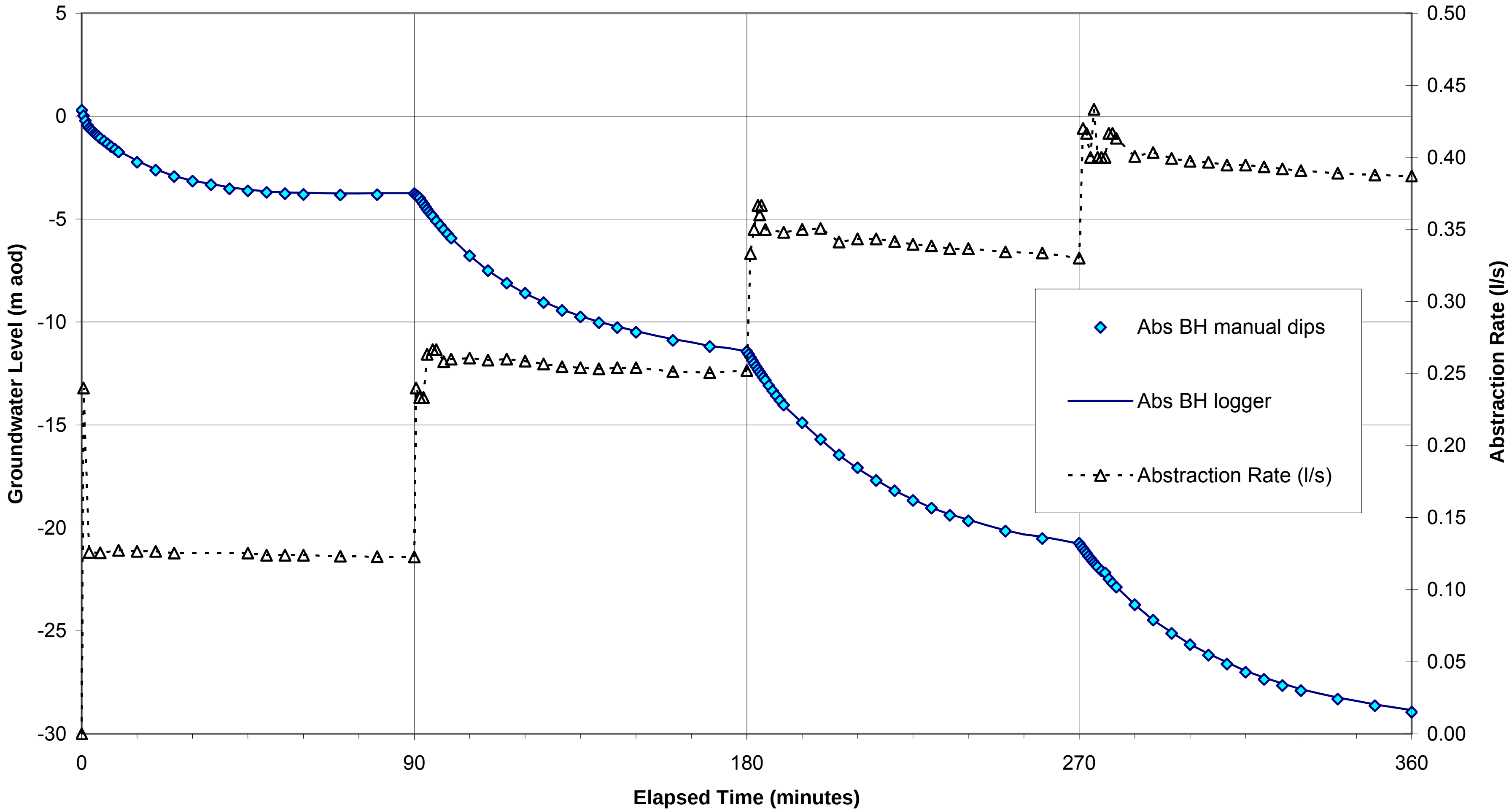


Figure 16 St Catherine Step Test, 1 November 2006.

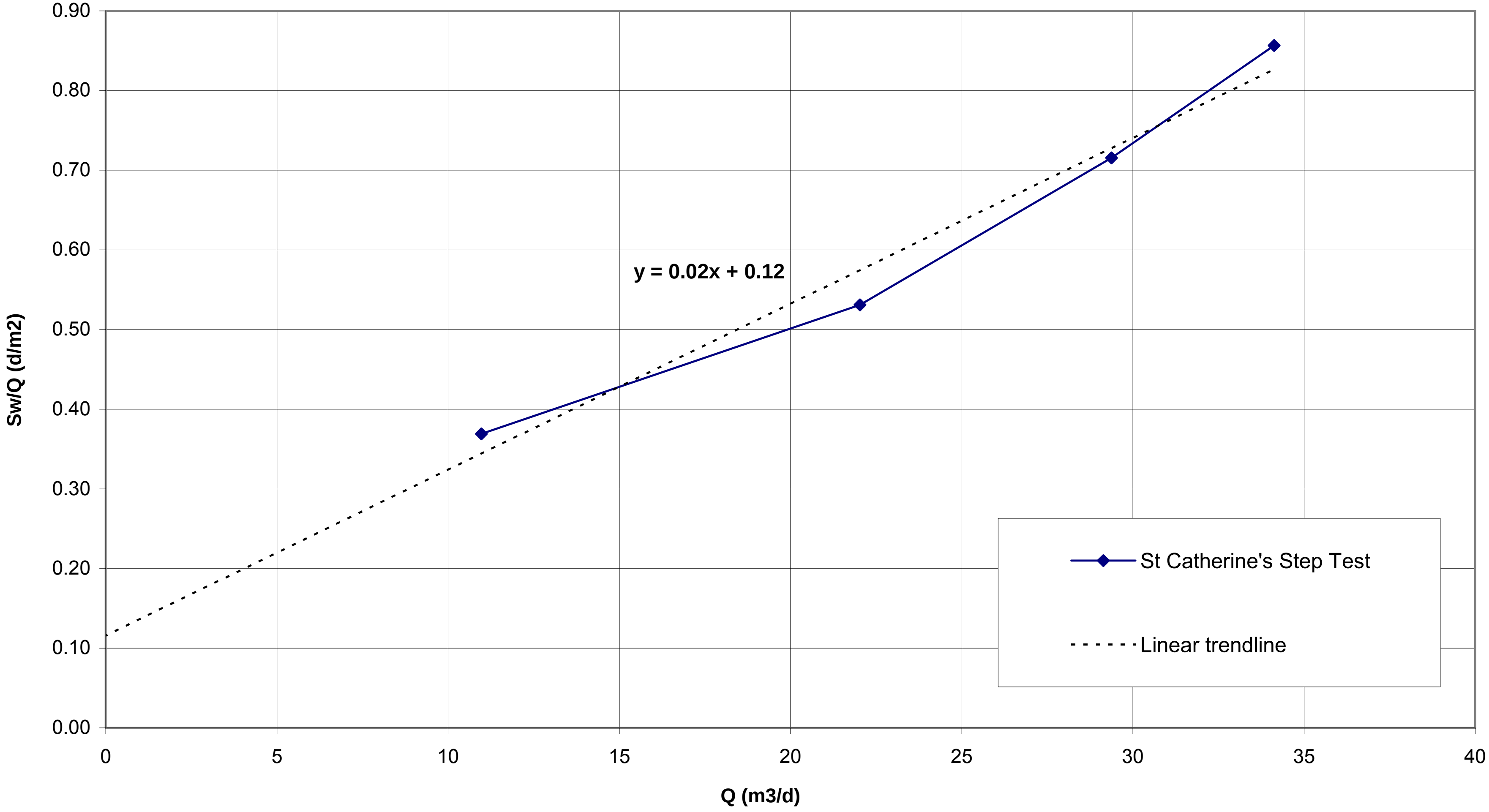


Figure 17 St Catherine: Hantush Bierschenk Plot.

Monitoring of field quality parameters at St Catherine showed some fluctuation in pH and electrical conductivity over the duration of the step test. Variations in observed pH and electrical conductivity in the abstracted water throughout the duration of the step test are shown in Figure 18. Variations in observed dissolved oxygen content and temperature of the abstracted water throughout the duration of the step test are shown in Figure 19.

Initial high conductivity of 6690 μS/cm quickly dropped to 2900 μS/cm within 25 minutes of pumping in the first step. An initial sharp drop followed by a steady increase in conductivity was observed in all steps, with measurements ranging between 2680 and 3510 μS/cm and a general upwards trend over the duration of the step test. pH was observed to rise from an initial 9.17 to 11.23 within the first 25 minutes of pumping in the first step, before dropping steadily to 9.61 by the end of the first step. An initial rise followed by a steady decrease in pH was observed in each steps. pH decreased more considerably over the fourth step to a final value of 7.47.

The initial variation in these parameters over the first half hour or so of pumping are considered to be due to purging of the borehole of standing water which has been in contact with the well casing and grout. Subsequent fluctuation in conductivity and steady decline of pH is considered likely to reflect an increasing influence of saline intrusion, as more saline water is drawn towards the abstracting borehole.

Quality measurements during the step tests are summarised in Table 7 below.

Table 7 Summary of Field Water Quality Measurements during Step Test, St Catherine.

	pH	**EC (□S/cm)**	**Dissolved Oxygen (%)**	**Temp °C**
Start	9.17	6690	23.4	12.5
End	7.47	3480	17.6	13.0
Min	7.47	2260	14.8	12.4
Max	11.22	6690	23.4	13.5

CONSTANT RATE TEST

A linear plot of the drawdowns in the St Catherine abstraction and observation boreholes is shown in Figure 20. A distinct pattern of regular semi-diurnal fluctuation in the water levels, together with a gradual increase in the average water level (i.e. drawdown decreasing), can be observed over the duration of the test. Comparison with tidal charts show the fluctuations in groundwater level to correspond with tidal variations at St Catherine. The gradual increase in water levels throughout the test corresponds with steadily increasing height of high water during the period of testing.

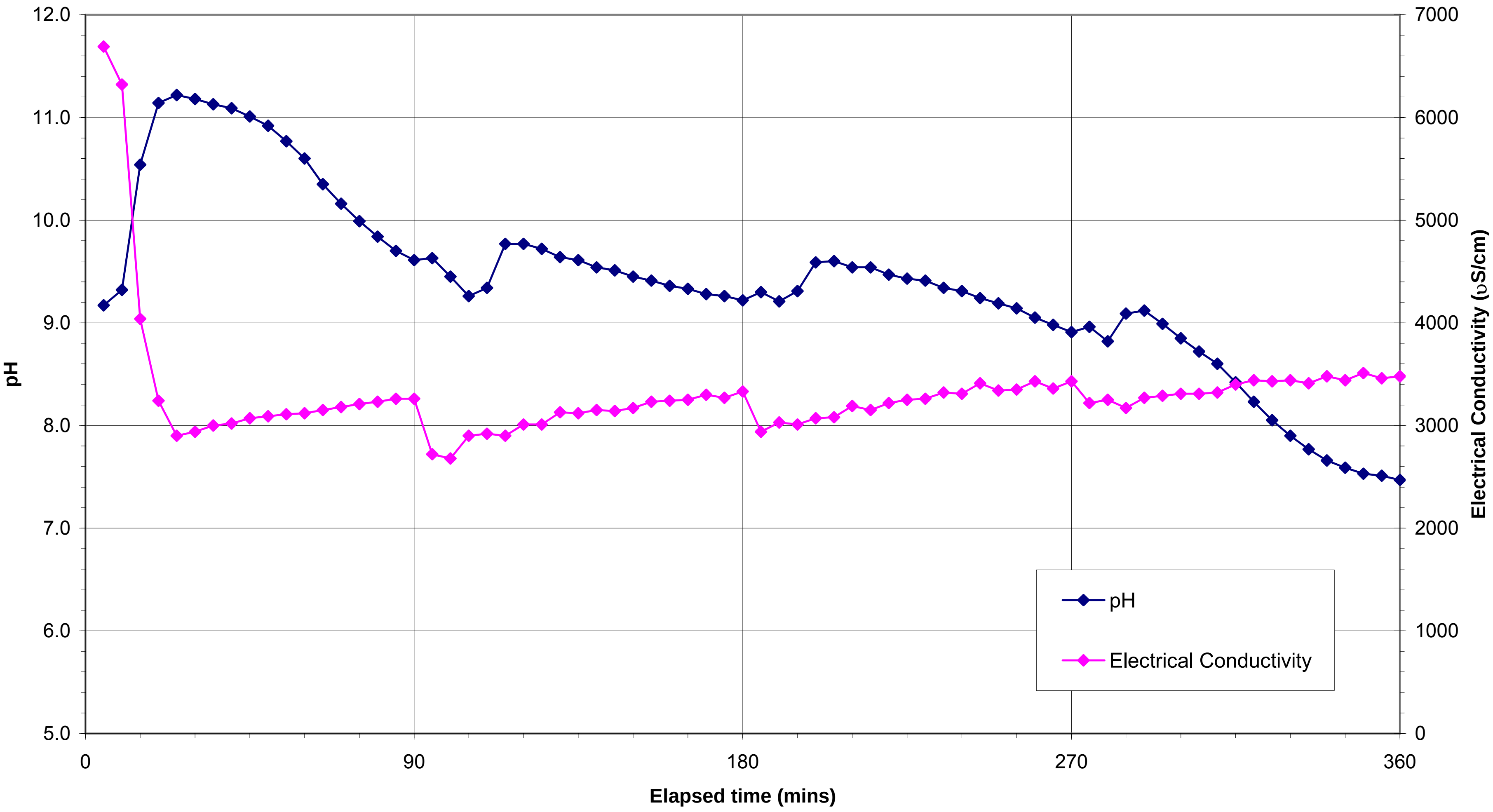


Figure 18 St Catherine Step Test: Variation of pH and EC.

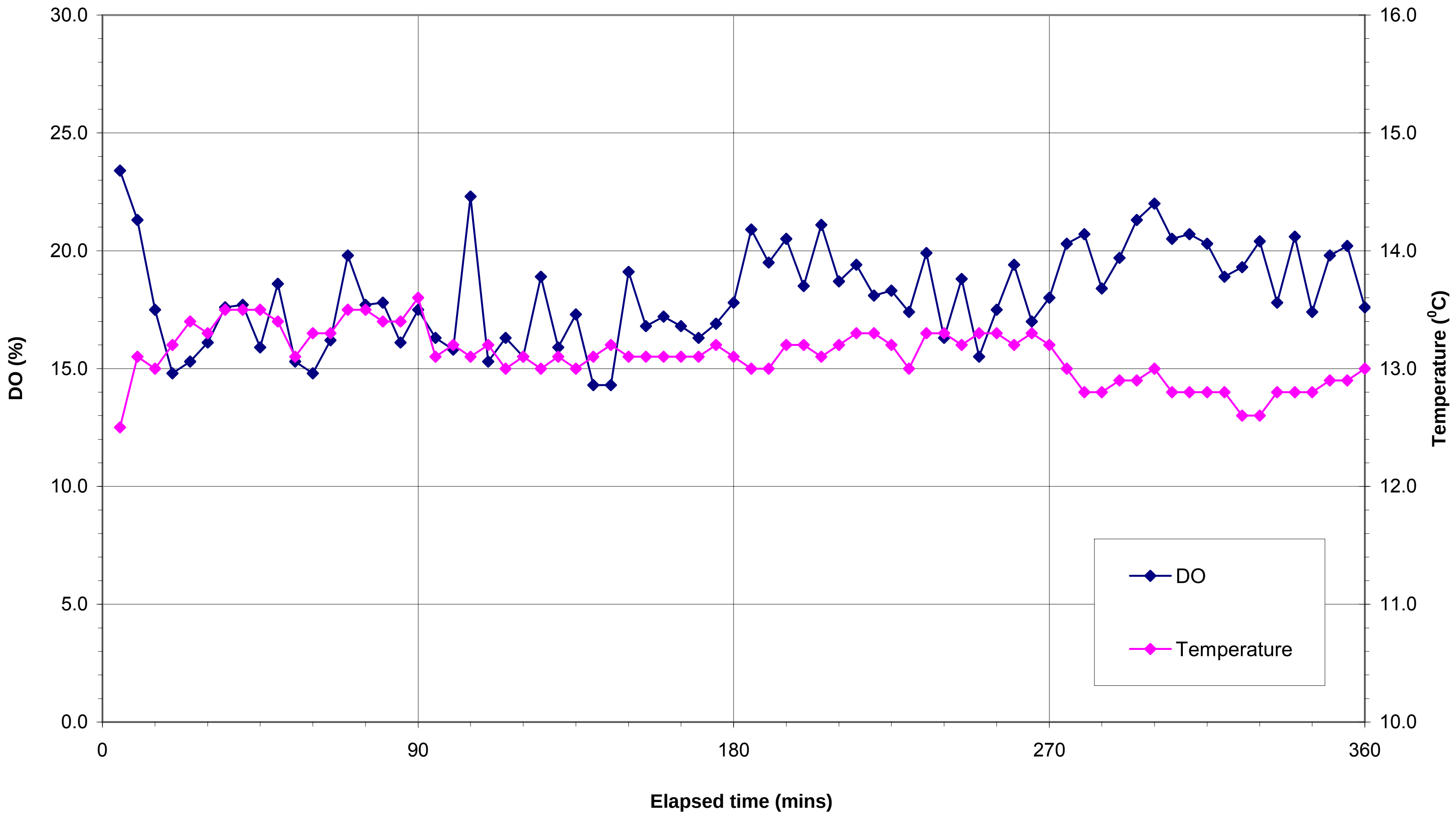


Figure 19 St Catherine Step Test: Variation of Dissolved Oxygen and Temperature.

The water level response to tidal fluctuation and low yield in the St Catherine borehole means it is not possible to analyse the data for hydraulic parameters. In order to derive a rough estimate of Transmissivity from the results of the step test, Logan's approximation (T=1.22/B, where B is the Aquifer Loss Coefficient) can be applied to give an estimated guide value of transmissivity of $10m^2/d$ for the St Catherine borehole.

Monitoring of field quality parameters at St Catherine showed some fluctuation in pH and electrical conductivity over the duration of the constant rate test. Variations in observed pH and electrical conductivity in the abstracted water throughout the duration of the constant rate test are shown in Figure 21. Variations in observed dissolved oxygen content and temperature of the abstracted water throughout the duration of the constant rate test are shown in Figure 22.

As in the step test, an initial high conductivity of 6810 μS/cm quickly dropped to 3220 μS/cm within 30 minutes of pumping. Conductivity was observed to gradually increase at a steady rate over the remainder of the test to reach 4870 μS/cm after three days of constant pumping. pH was observed to initially rise slightly from 7.23 to 7.80 over the first hour of pumping, before generally gradually reducing slightly over the test period to an end value of 6.94 after three days of constant pumping.

As with the step test the initial increases in pH and conductivity over the first 0 to 60 minutes of pumping are considered to be due to purging of the borehole of standing water which has been in contact with the well casing and grout. Subsequent gradual increase in conductivity and steady decline of pH is considered likely to owe to an increasing influence of saline intrusion, as more saline water from the sea is drawn towards the abstracting borehole.

Quality measurements during the constant rate test are summarised in Table 8 below.

Table 8 Summary of Field Water Quality Measurements during Constant Rate Test, St Catherine.

	pH	**EC (μS/cm)**	**Dissolved Oxygen (%)**	**Temp °C**
Start	7.23	6810	21.3	13.2
End	6.94	4870	10.7	13.4
Min	6.94	3220	10.1	13.0
Max	7.80	6810	24.8	13.6

RECOVERY TEST

Recovery data are plotted in Figure 23. Recovery of drawdown in the borehole is subject to the same influence of tidal variations as identified in the constant rate test. As such, no direct estimation of transmissivity can be made from the recovery data.

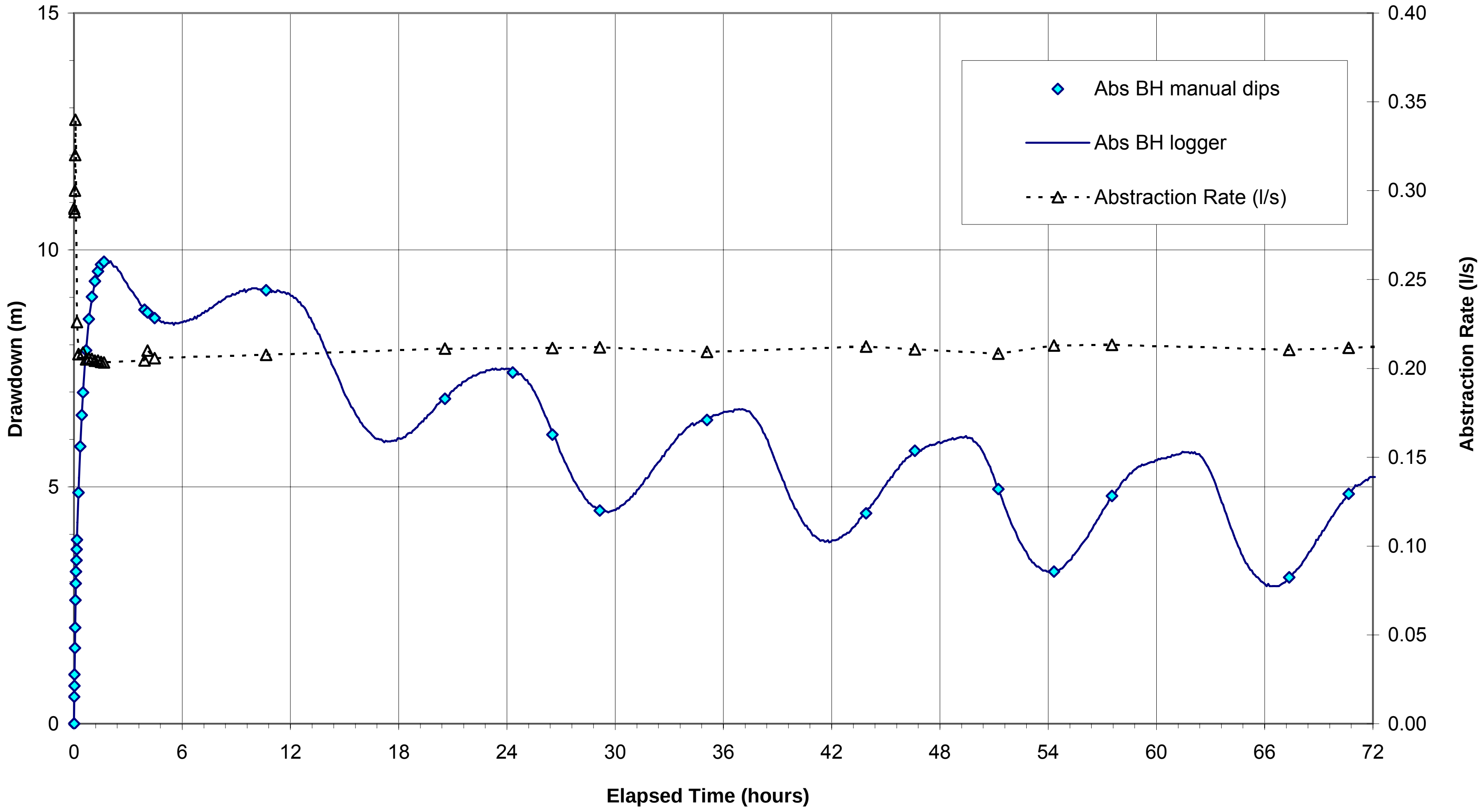


Figure 20 St Catherine Constant Rate Test: Linear Plot.

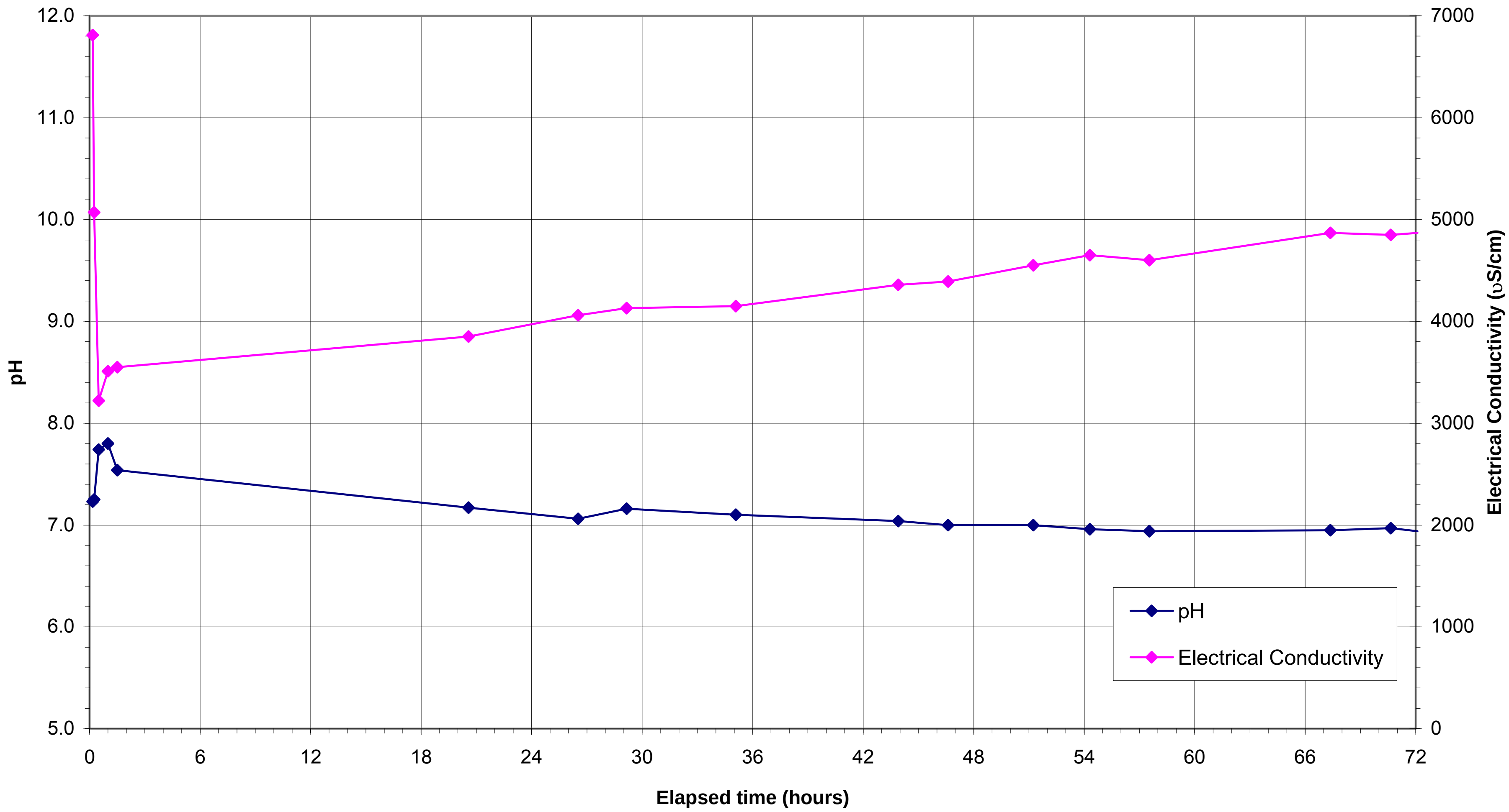


Figure 21 St Catherine Constant Rate Test: Variation of pH and EC.

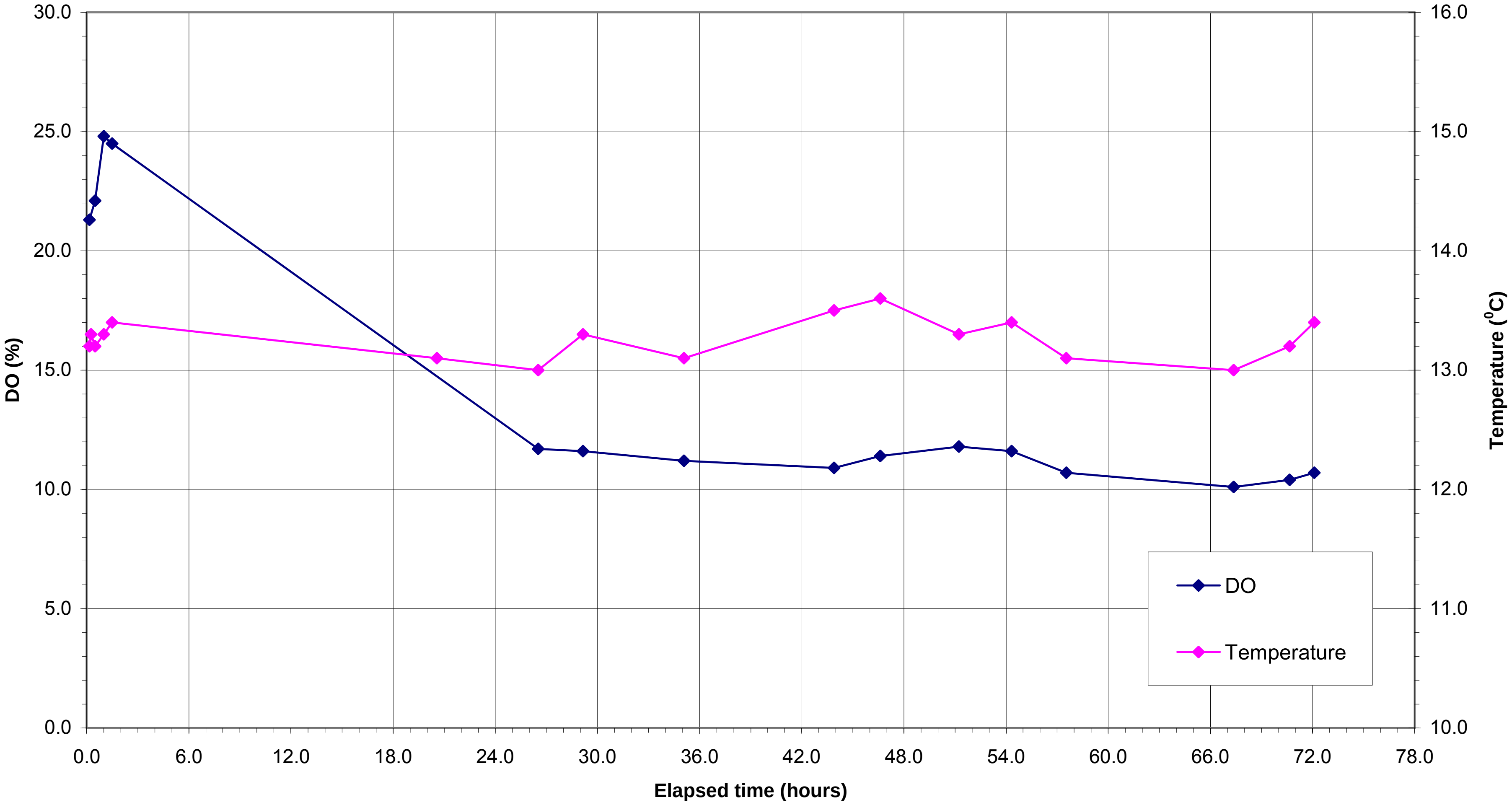


Figure 22 St Catherine Constant Rate Test: Variation of Dissolved Oxygen and Temperature.

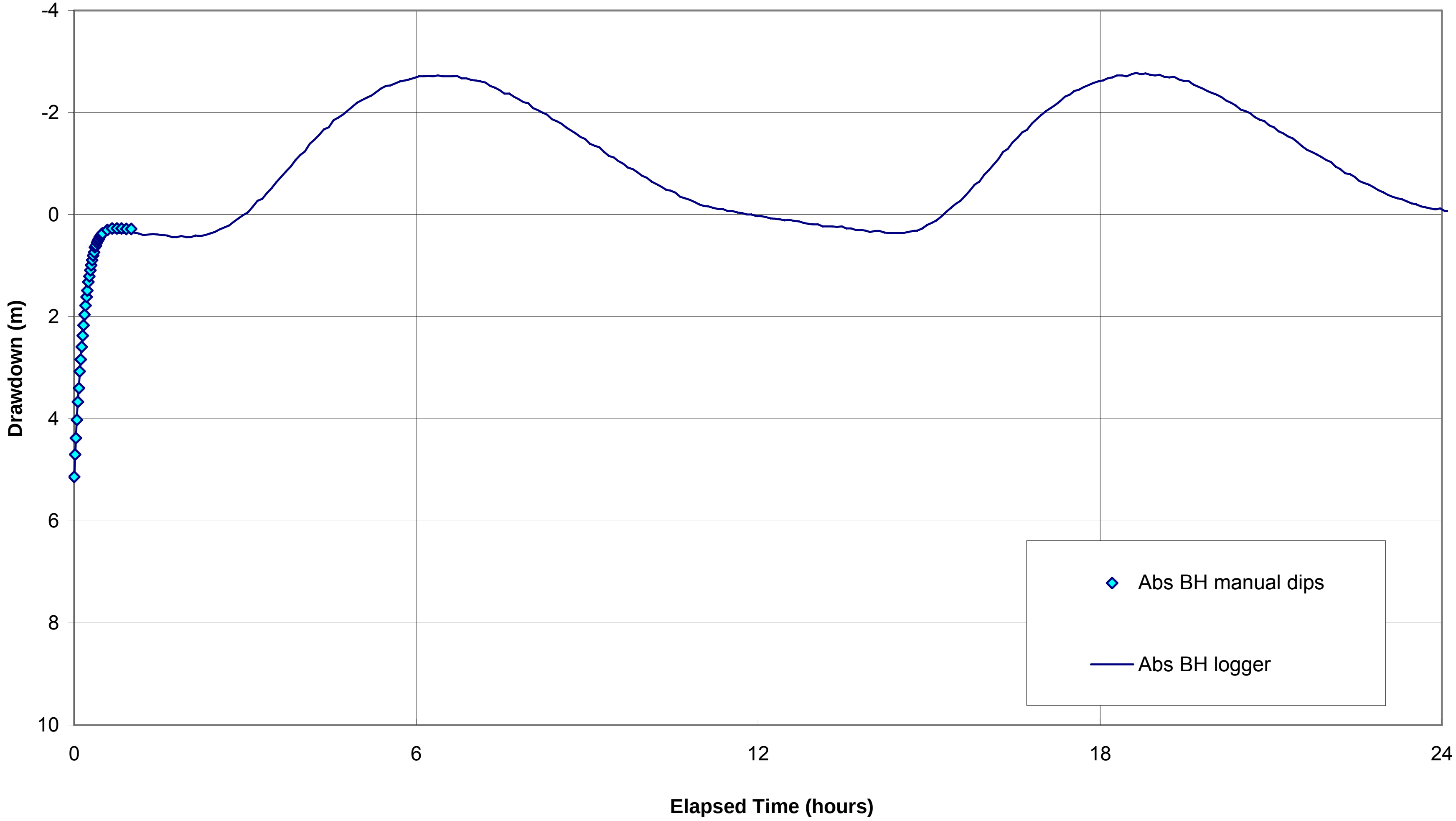


Figure 23 St Catherine Recovery: Linear Plot.

3.4 SUMMARY OF RESULTS

3.4.1 La Rocque

- Analysis of step test results derives an aquifer loss coefficient (B) of 3.1 x 10^{-2} d/m^2 and a well loss coefficient (C) of 1.3 x 10^{-4} d^2/m^5.
- Step tests suggest a sustainable specific capacity of around 15 m^3/d per m of drawdown at discharges not substantially greater than 3.25 l/sec (280 m^3/day).
- Analysis of constant rate tests derives transmissivity values of 83 m^2/d and 88m^2/d at the abstraction and observation boreholes respectively.
- Analysis of constant rate tests in the partially penetrating observation borehole suggests local storativity to be in the order of 1.3 x 10^{-5}.
- Analysis of recovery derives transmissivity values of 84 m^2/d and 86m^2/d at the abstraction and observation boreholes respectively.
- The close proximity of the transmissivity values derived from different boreholes and methods suggests approximately 80 to 90 m^2/d is a reasonably accurate evaluation of local Transmissivity.
- The closeness of rest water levels, recovery and derived transmissivity values in the two boreholes suggest both the deep abstraction and shallow observation borehole are intercepting the same aquifer and that the deep and shallow fracture systems are closely linked.
- No significant variation in basic field chemical parameters in the abstracted water was observed over the duration of the step and constant rate tests.

3.4.2 St Catherine

- Analysis of step test results derives an aquifer loss coefficient (B) of 1.1 x 10^{-1} d/m^2 and a well loss coefficient (C) of 2.1 x 10^{-2} d^2/m^5.
- Step tests suggest a sustainable specific capacity of around 2 m^3/d per metre of drawdown at discharges not substantially greater than 0.23 l/sec (20m^3/day).
- Constant rate and recovery tests are observed to be strongly influenced by tidal cycles. As it is not easy to remove the effect of these influences from the measurements, no detailed analysis of hydraulic properties at St Catherine has been possible. However, an approximate transmissivity of 10 m^2/d has been estimated from the step test results.
- High conductivity measurements show abstracted water to be brackish.
- Field water quality parameters of pH and conductivity were observed to increase steadily during the test, suggesting an increasing influence of seawater with continuous pumping.

4 Inorganic Chemical Analyses

4.1 SAMPLING

Water samples were collected from both new wells during drilling/construction and during the pumping tests as discussed in Sections 2.3.3/2.3.4 and 3.2.1 respectively. In addition water samples were collected from existing private boreholes in the vicinity of La Rocque and St Catherine.

During collection of each sample, field measurements of pH, (specific) electrical conductivity (EC) and temperature were undertaken. Dissolved oxygen and alkalinity were also determined during the pumping tests. Samples for dissolved metal analysis were filtered with a 0.2 µm filter to prevent the influence of suspended matter on the dissolved concentrations.

Samples were kept in a cool box on collection and despatched to the laboratory that day for analysis.

4.2 LABORATORY ANALYSIS

Laboratory analysis was undertaken by the Official Analyst's Laboratory, States of Jersey.

4.3 RESULTS AND VALIDATION

4.3.1 Reporting of Data

The field measurements and analytical data for each sample collected during the investigation are provided in Appendix 7.

4.3.2 Calculation of Ionic Balances and Alkalinity

Ionic balances have been calculated for each of the samples collected. As alkalinity was only determined for a few of the samples collected during the pumping tests, those samples with no alkalinity measurement show unsurprisingly a deficit of negative ions (anions). Where alkalinity was measured, the ionic balances are within ±10% indicating the major ion data are of good quality. Where alkalinity was not measured, concentrations have been calculated from the deficit of anions.

4.3.3 Effect of Air Flush on Water Quality during Drilling / Construction

The samples collected during drilling /construction of the boreholes were brought to the surface using airlift flushing. This technique is likely to mix air in with the water and in so doing can increase dissolved oxygen concentrations and reduce dissolved carbon dioxide concentrations.

An increase in dissolved oxygen can lead to the oxidation of dissolved trace metals in a reduced form, especially iron. A reduction in dissolved carbon dioxide will increase the pH of the water, which if previously saturated with respect to the common carbonate mineral calcite could reduce both calcium and alkalinity (dissolved carbonate) as calcite precipitates out of the water.

The La Rocque samples collected during drilling have lower iron, calcium and alkalinity and higher pH than the samples collected during the pumping test. This suggests that the samples collected during drilling/construction are affected to some extent by the airlift sampling. It is noted that this airlift sampling method will not affect the concentrations of Cl, SO_4, NO_3 (not when they are reported below detection) Br, and are unlikely to affect Mg, Na, K, PO_4, F and Sr.

4.3.4 Effect of Grout on Some Samples

The water quality from nine samples (B68 to B79.5 and BS01) from the St Catherine borehole were strongly affected by reaction of the borehole water with the cement grout. These samples have unnaturally high pHs and potassium concentrations and the high pHs have most likely affected calcium, magnesium and alkalinity concentrations. Whilst chloride, sulphate, and bromide concentrations are unlikely to be affected by reaction of water with grout, the other measurements, including electrical conductivity, for these samples are unreliable as data for natural groundwater quality at these locations and depths. The dominance of the grout signature on the water quality at St Catherine may be a reflection of the limited amounts of water encountered during drilling.

4.3.5 Representativeness of Pumped Samples

Samples collected from the discharge of the submersible pump during the pumping tests are likely to best represent the groundwater entering the borehole. Only the volume of water already in the borehole prior to pumping is likely to be aerated and degassed compared to the surrounding groundwater. This means that the pHs and concentrations of Ca, alkalinity, and Fe collected during the pumping tests will be more representative of the groundwater than the airlift samples collected during drilling and construction.

On pumping, water will enter the uncased section via fissures / fractures in the adjacent strata. As pumping continues, the groundwater in the strata immediately adjacent to the borehole will be replenished by groundwater moving laterally or leaking vertically from elsewhere.

4.4 INTERPRETATION OF DEPTH DATA FOR LA ROCQUE

4.4.1 General Variability in Water Quality with Depth

In general terms, the water quality sampled at the different depths throughout the La Rocque borehole is very consistent (<±20%) especially when compared to other boreholes in the La Rocque area. This is illustrated on Figure 24, which shows the concentrations of the major ions expressed in units of milliequivalent per litre (meq/l).

Note: Concentrations of meq/l are calculated by multiplying the mg/l by the charge of the ion (e.g. 2 for Ca^{2+}) and then dividing by the atomic weight of that ion (e.g. 40.08 for Ca^{2+}).

Importantly, there are no large differences in the water quality sampled in the upper (above 43 m bgl) and lower sections.

Despite the general water quality sampled during drilling and construction of the La Rocque being very consistent, there are some minor variations and these are discussed below.

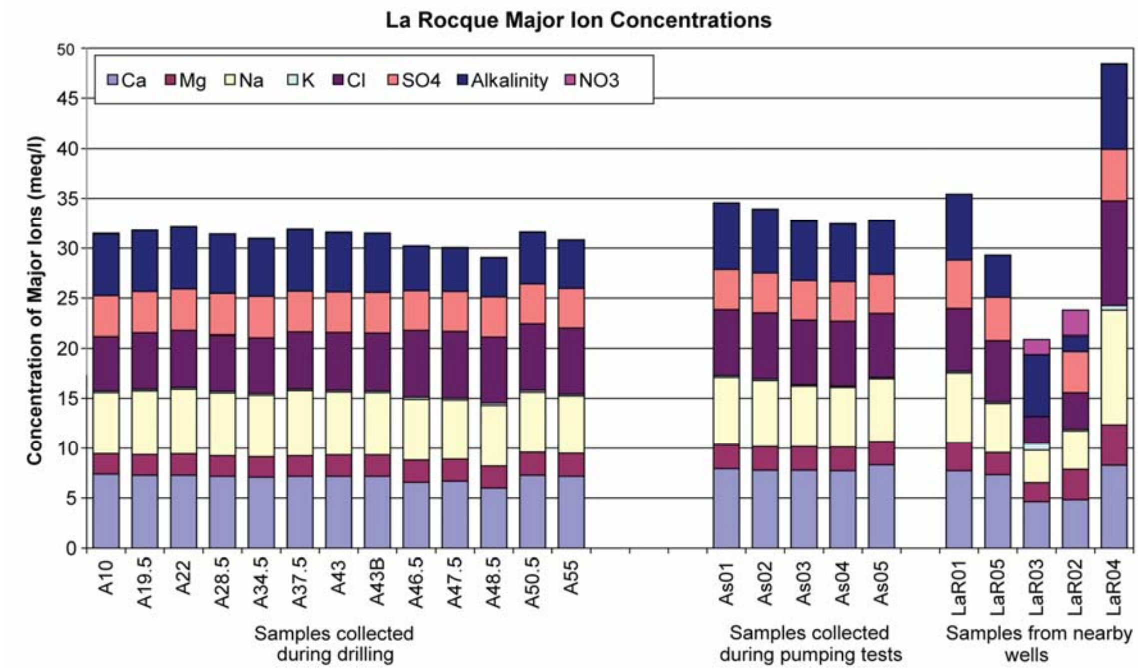


Figure 24 Major ion composition of La Rocque groundwaters.

4.4.2 Depth Variations in Air Flush Yields

To assist interpretation of the water quality data, the air flush yield data have been plotted against the geological log as the change in the air flush yield from one measurement to the next (see Figure 25). Air flush yields were recorded at 3 m depth intervals above 43 m bgl and at 0.5 m intervals below this depth. For ease of comparison with the upper section, the change in air flush yields over the 0.5 m intervals have also been presented as their average over a 3 m interval.

Note: The calculated change in air flush yields assume that any change is due to the increased depth penetration and the encountering of new water strikes rather than development of fissures higher in the uncased section.

4.4.3 Validity of Samples as Measures of Water Quality Changes with Depth

It is important to note that as water could enter the borehole over the whole uncased section(s), water samples collected at increasing depths reflect the average quality of water over that uncased depth range. This average quality reflects the main inflows over that uncased section to that depth i.e. the data are unlikely to reflect the water quality at that specific depth. The exceptions are:

(a) the first sample collected at 10 m depth,

(b) probably the sample collected at the water strike at 19.5 m bgl,

(c) probably the sample collected at 34.5 m bgl – the first after the large fracture zone inflow, and

(d) the first sample collected below the cased out section not affected by grout at 46.5 m depth.

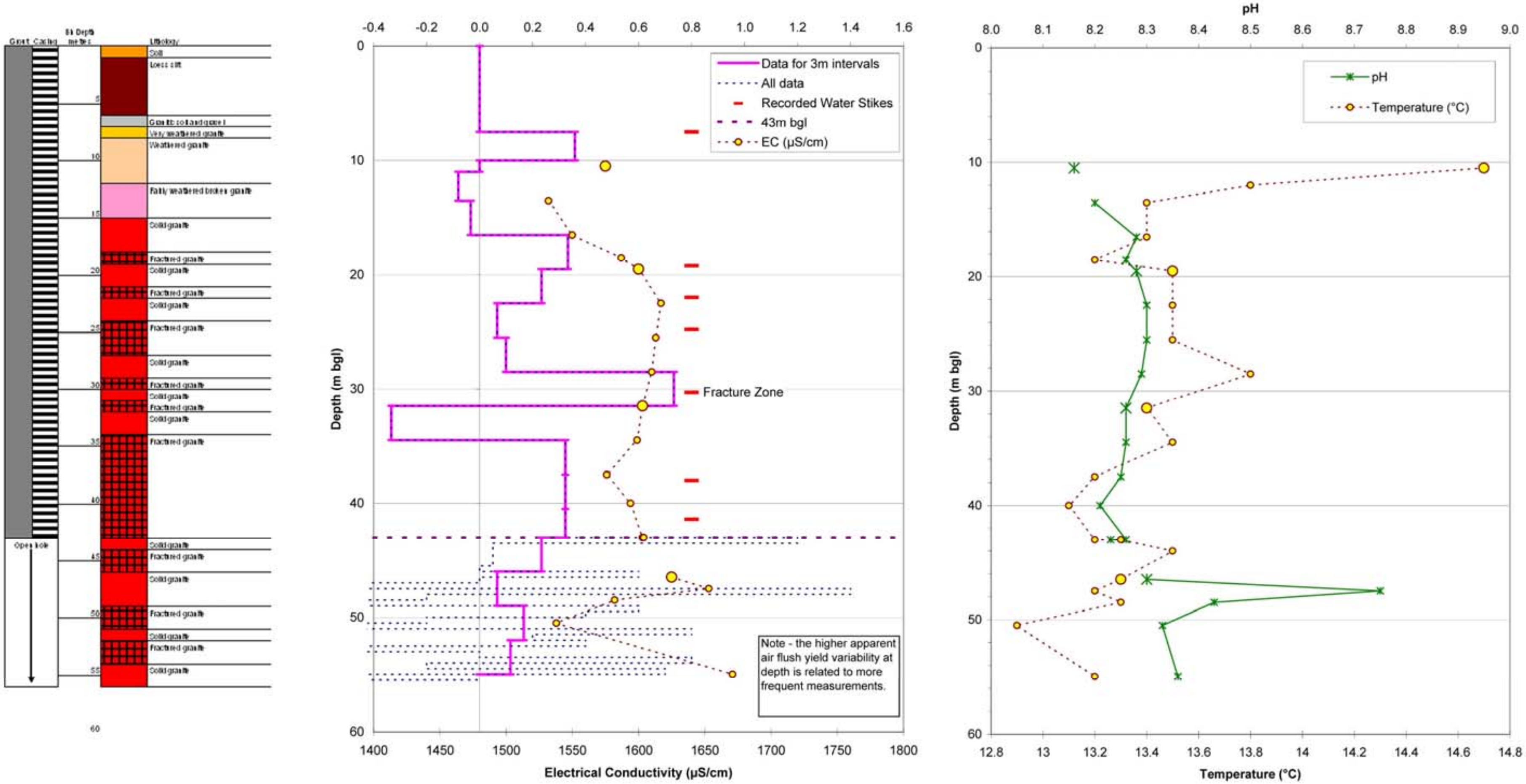


Figure 25 Change in air flush yields and variation of EC, pH and temperature during drilling of the La Rocque. borehole

4.4.4 Subtle Changes in Water Quality with Depth

Variations in field measurements (EC, pH and temperature) recorded during drilling of the La Rocque borehole are illustrated against the geological log in Appendix 5. Changes in concentrations of a number of parameters with the depth at which they were collected are illustrated on Figure 25 to Figure 28. Figure 26 also shows the change in air flush yields with depth, as discussed in Section 4.4.2.

Relying more on the samples identified above, the following depth variations are noted in the field measurements and sampled water quality for the La Rocque borehole:

- Electrical conductivity appeared to be lower (1575 µS/cm) at shallow depth (10 m bgl), higher (~1600 µS/cm) in the mid section between 19.5 and 34.5 m bgl and then more variable at depth (1538-1671 µS/cm).
- A nitrate concentration of 6 mg/l as NO_3 was measured in the uppermost sample (at 10 m bgl) within the weathered granite. Nitrate concentrations were below detection (<2 mg/l) in the next sample collected at 19.5 m bgl and in all the remaining samples.
- Chloride, bromide, potassium and magnesium concentrations all appear to show (10-30%) higher concentrations in the deeper section. Each of these ions is found in relatively high concentrations in seawater and this change in composition is therefore consistent with a slight increase in the amount of seawater from the deeper zone. A chloride concentration of 235 mg/l represents about 1% seawater. Br/Cl ratios are similar to those of seawater.
- Sodium and sulphate concentrations appear slightly lower in the deeper section, but the differences are small (<10%). Sodium to chloride ratios exceed that for seawater and so a second source of sodium is likely, possibly related to weathering of feldspars in the granite. Sulphate to chloride ratios also far exceed that for seawater. One possible source of sulphate is from the weathering of sulphide minerals from mineralization of fractures in the granite.
- Calcium, alkalinity, strontium and manganese each show a sharp decrease in concentration at 48 m bgl most likely related to a peak in pH. Samples may be affected by airlifting. Alkalinity and manganese concentrations remain lower in the deeper section.
- Phosphate concentrations are higher in the deeper section. Phosphate may be derived from the mineral apatite, often present in the granite.

Overall, the subtle changes with depth appear to show that water in the deeper zone is of a slightly different character to that in the granite above. The differences are possibly related to more weathering and flushing in the upper section than in the lower section. This is consistent with the geological description of the borehole with the granite being more weathered in the upper section.

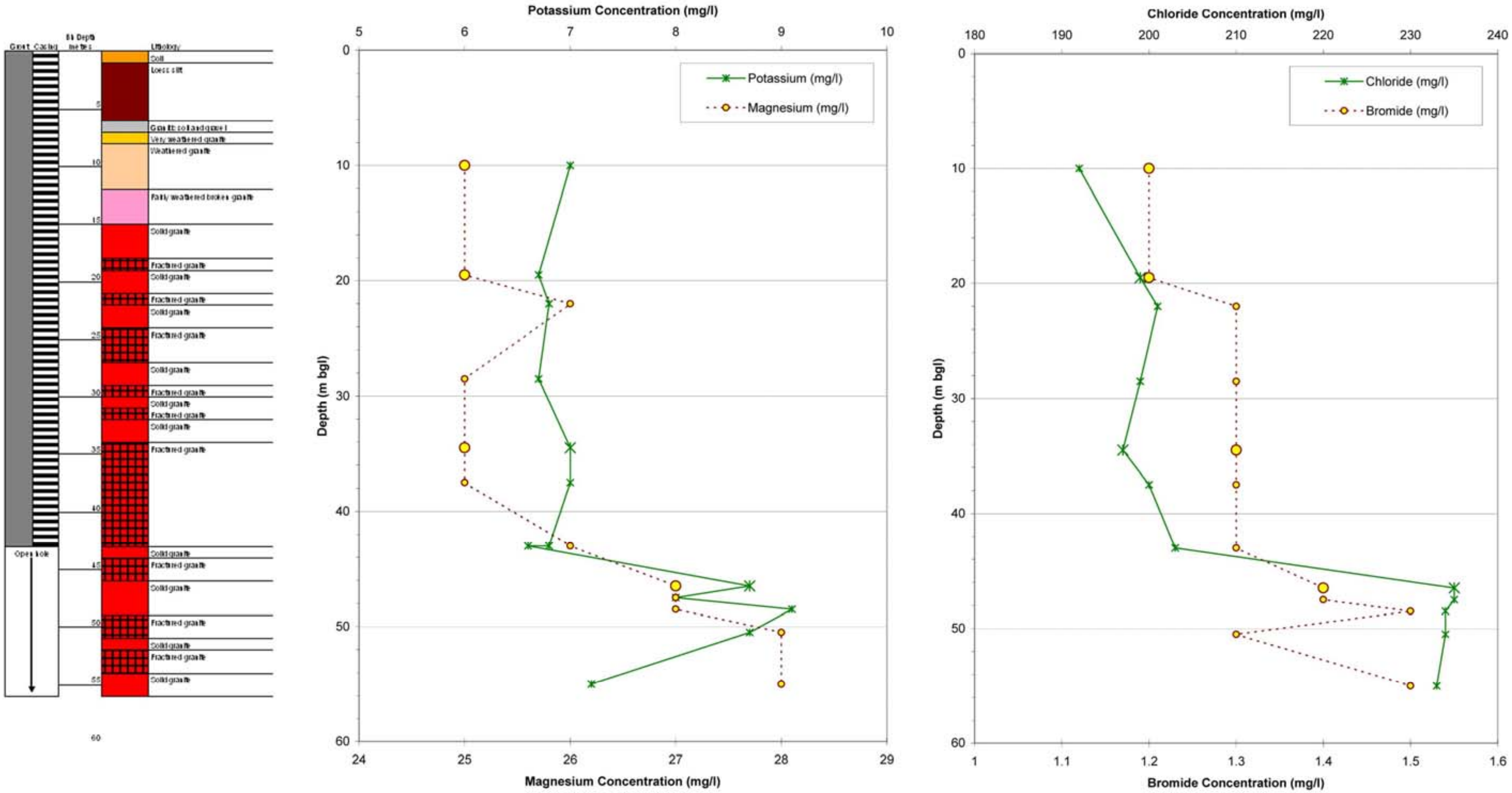


Figure 26 Variation in potassium, magnesium, chloride and bromide concentrations during drilling of the La Rocque borehole.

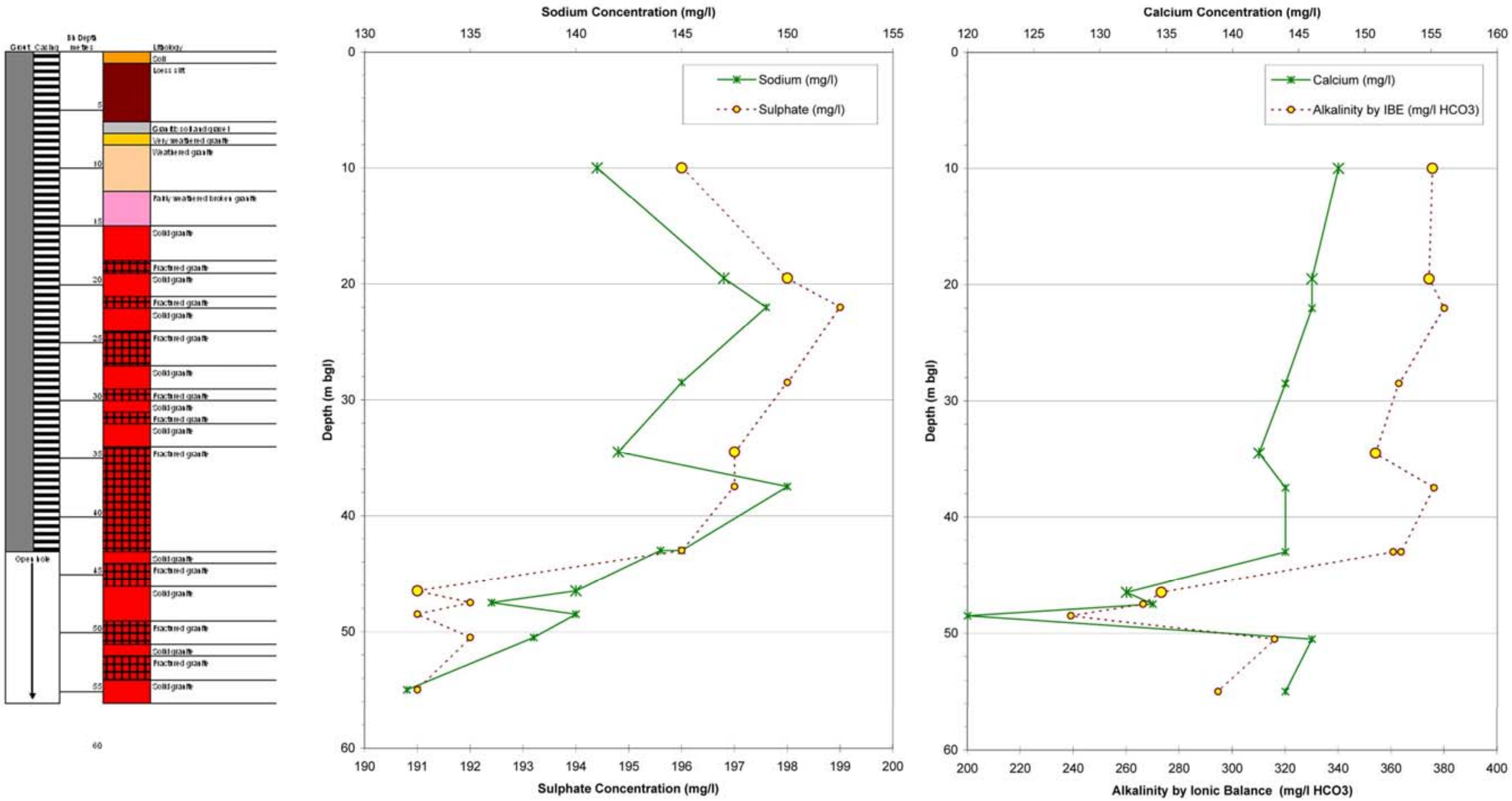


Figure 27 Variation in sodium, sulphate, calcium and alkalinity during drilling of the La Rocque borehole.

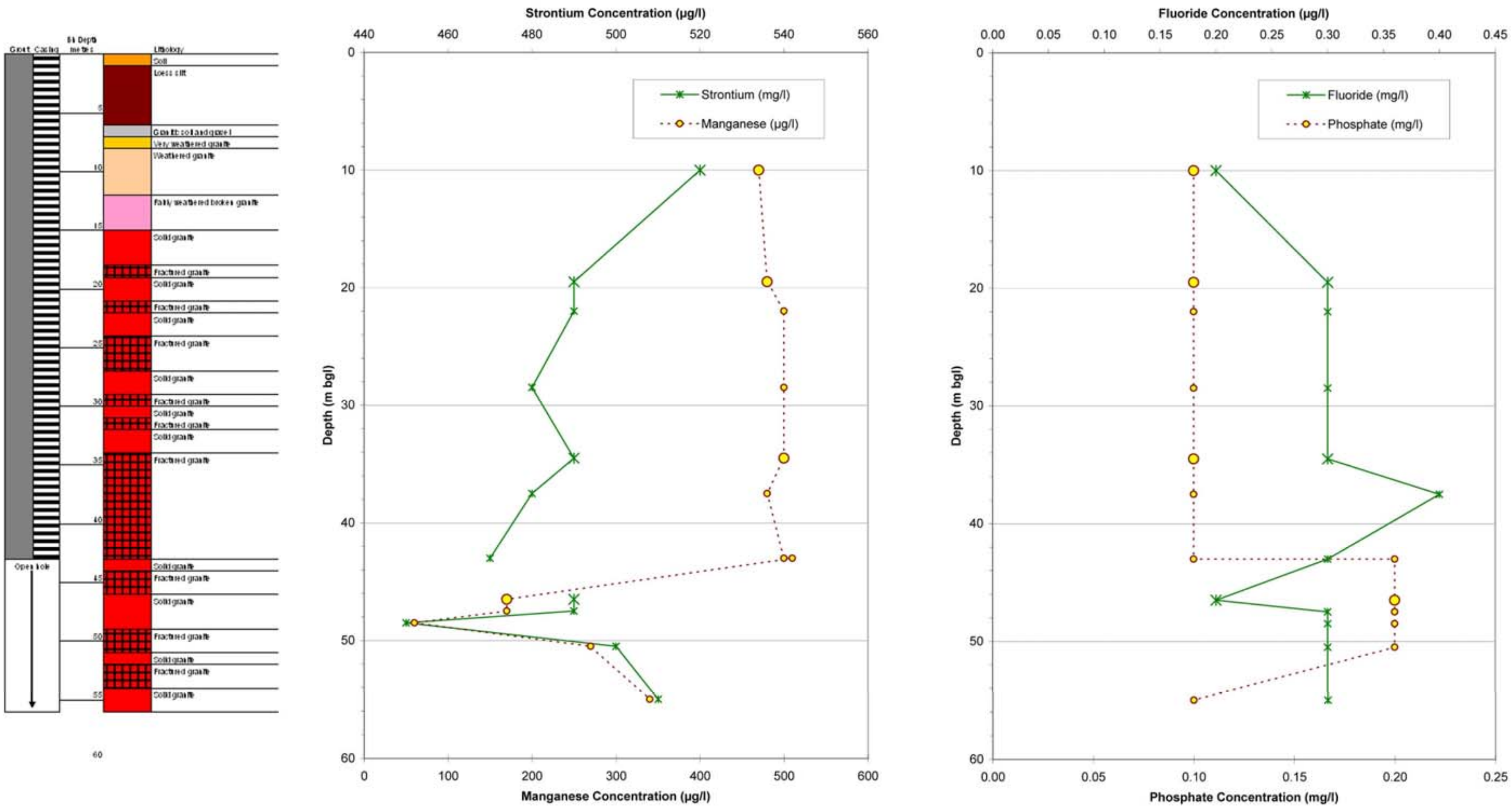


Figure 28 Variation in strontium, manganese, fluoride and phosphate during drilling of the La Rocque borehole.

4.5 INTERPRETATION OF PUMPING TEST CHEMICAL DATA FOR LA ROCQUE

4.5.1 Overview of Pumped Water Quality

The major ion composition of the pumped water was very similar in character to that sampled during drilling and construction of the borehole (see Figure 24). The calcium and alkalinity was slightly higher in the pumped samples due to the effect of airlifting on the samples collected during drilling / construction.

In terms of those parameters (Cl, SO_4, Br) for which the depth samples are unlikely to be affected by airlifting or grout, the pumped water was most like the depth samples collected from the lower section of the borehole.

Dissolved oxygen saturations were measured at 0% and nitrate concentrations remained below detection at <2 mg/l NO_3. Detectable iron concentrations of 10 and 50 µg/l in the later stages of the pumping test also indicate reducing conditions, as do the dissolved manganese concentrations. Fresh recharge would be expected to be oxygen saturated. Given the likely absence of organic material in the granites, the absence of dissolved oxygen, together with the measured sulphate concentrations suggests the oxygen may have been consumed by sulphide mineral weathering.

For the parameters analysed, the pumped water quality meets UK drinking water standards with the exception of an elevated manganese concentration (550 µg/l compared to the 50µS/cm required at the consumer's tap).

4.5.2 Subtle Changes in Water Quality During Pumping

During the pumping test, there were minor changes in the sampled water quality. Again, in terms of those parameters (Cl, SO_4, Br) for which the depth samples are unlikely to be affected by airlifting or grout, the composition moves slightly from that of the lower section towards that from the upper section. This is consistent with water from the upper section replenishing the water pumped from the lower section.

Figure 29 shows the change in concentration of chloride (for which there was the greatest concentration change) during the pumping test and translates this into proportions of 'shallow' and 'deep' waters. This suggests that at the end of the constant rate test, there was approximately a ~25% contribution of water from the upper section (above 43 m bgl). Conversely, it also means that after pumping 49.34 m^3 during the step test and 829.44 m^3 during the constant rate test, water characteristic of the lower section was still providing approximately ~75% of the inflows to the well.

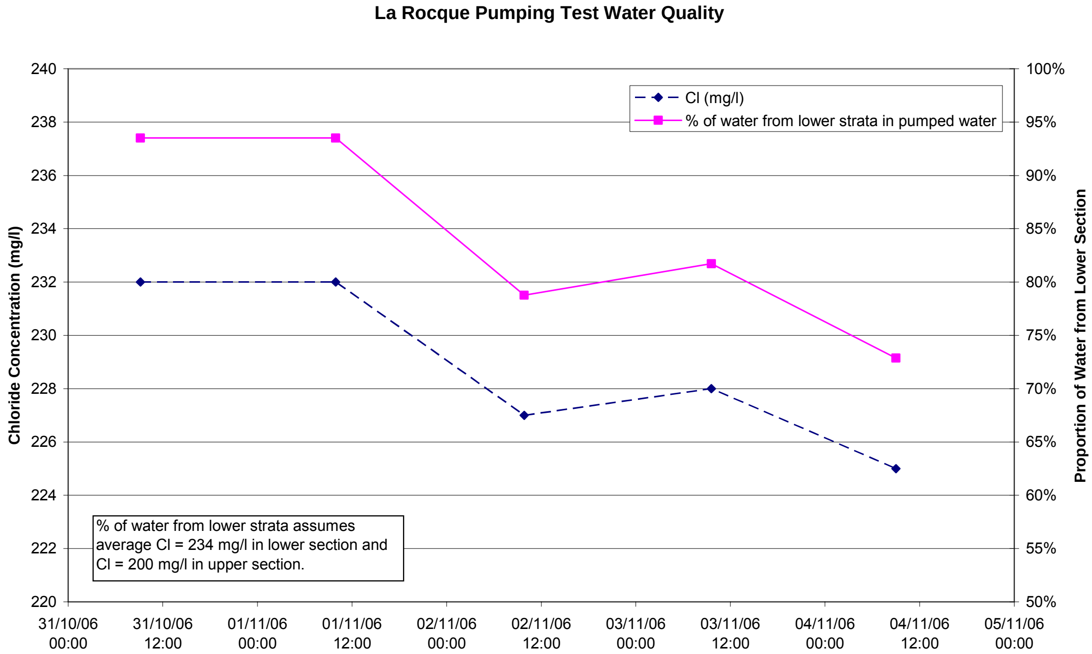


Figure 29 Change in chloride concentration and calculated proportion of water from lower section during pumping at La Rocque.

4.6 COMPARISON OF LA ROCQUE PUMPED WATER WITH ADJACENT BOREHOLES

The major ion composition of the water at La Rocque is compared to that for nearby boreholes in Figure 24. This shows that the water from the La Rocque borehole is very similar in character to that sampled from the 30.5 m deep borehole near the Chapel at Rue du Puits Mahaut (sample SC01 La Rocque B, ~270 m away) and the 32 m deep La Rocque observation borehole (sample SC05, La Rocque A ~26 m away). In terms of chloride concentration the water at these two nearby boreholes (~220 mg/l) falls mid way between that sampled at shallow depths (~200 mg/l) and deeper (~235 mg/l) in the La Rocque investigation borehole.

The water sampled at Le Bourg (SC04) is of a similar character, but concentrations of major ions, especially sodium and chloride, are higher.

The waters sampled from Rue au Long, St Clement (sample SC03, Fauvic B) and La Grande Route de St Clement (sample SC02, Fauvic A) are different, with very high nitrate concentrations and in the case of Fauvic B, an absence of sulphate.

4.7 INTERPRETATION OF DEPTH DATA FOR ST CATHERINE

4.7.1 General Variability in Water Quality with Depth

Due to the grout contamination of all but the shallowest samples from the St Catherine borehole and the effect this contamination has on concentrations of a number of major ions, comparison of the major ion composition with depth is not worthwhile.

The major ion composition of the shallowest sample, from very minor inflows encountered by 58 m bgl is shown on Figure 30.

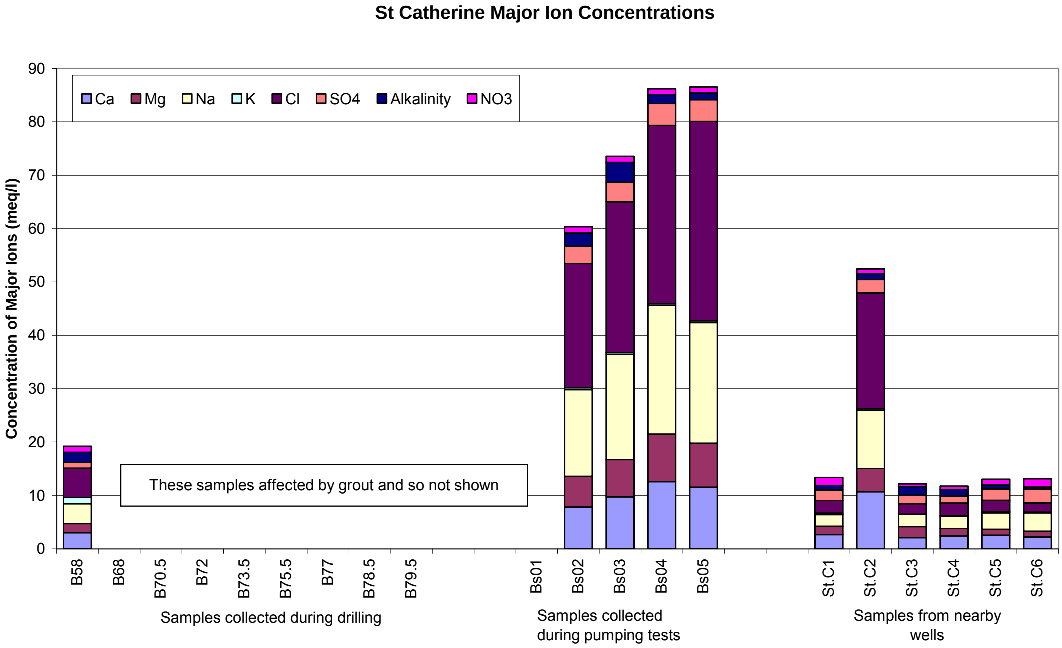


Figure 30 Major ion composition of St Catherine groundwaters.

4.7.2 Depth Variations in Air Flush Yields

Compared to La Rocque, air flush yields were low at St Catherine. The upper section was all but dry and the maximum cumulative yield achieved was 0.27 l/sec. As for the La Rocque borehole, the change in air flush yield at St Catherine is shown together with variations in selected chemical parameters in Figure 31.

4.7.3 Depth Variations in Rest Water Levels

To further assist the interpretation of the changes in water quality with depth, it is noted that the rest water levels recorded during drilling and construction changed as follows:

- 20 September 2006 (after being left to rest over night), borehole depth at 36 m bgl (pre-casing and grouting), 23.19 m below the top of the 8 inch casing;
- 21 September 2006 (after being left to rest over night), borehole depth at 53.79 m bgl (pre-casing and grouting), 20.47 m below the top of the 8 inch casing;

However, as the inflows to the boreholes were very minor, uncertainty remains as to whether these water levels are meaningful.

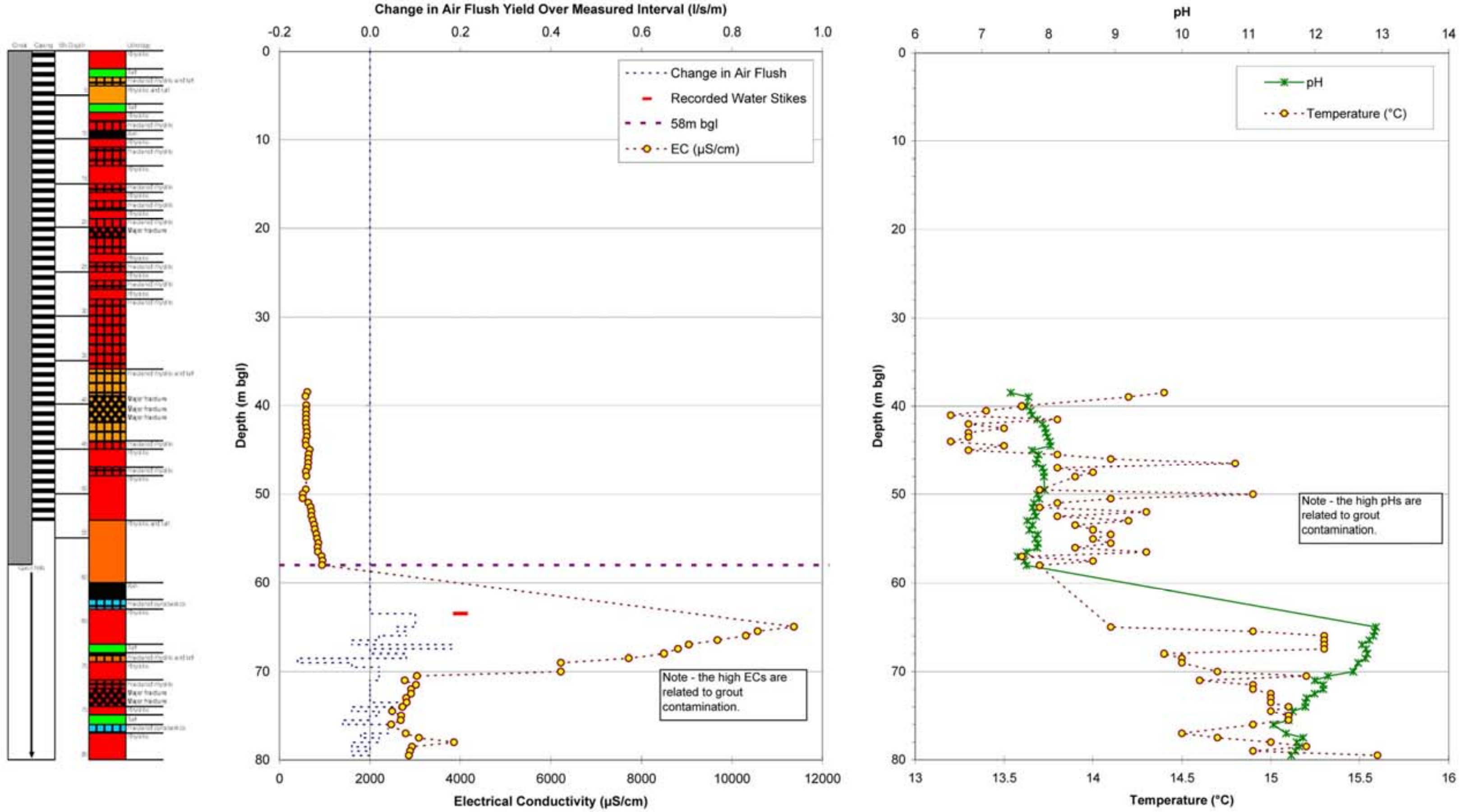


Figure 31 Change in air flush yields and variation of EC, pH and temperature during drilling of the St Catherine borehole.

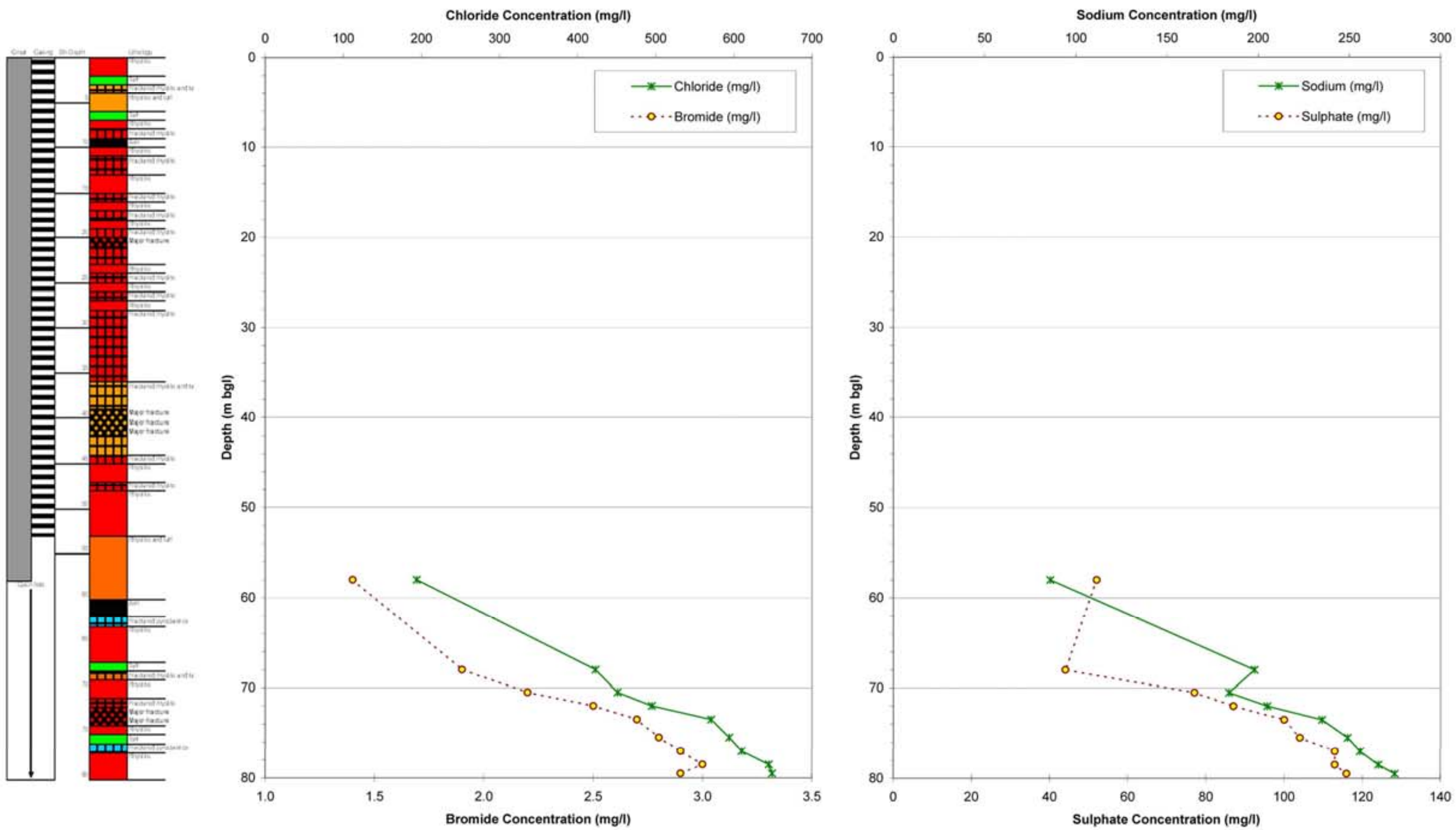


Figure 32 Variation in chloride, bromide, sodium and sulphate during drilling of the St Catherine borehole.

4.7.4 General Variability in Water Quality with Depth

The major ion composition of the shallowest sample, from very minor inflows encountered by 58 m bgl is shown on Figure 32.

As noted in Section 4.3.4, grout contamination will affect pH, EC and concentrations of calcium, magnesium, potassium, alkalinity and possibly strontium, iron and manganese. Figure 31 illustrates the effect of grout contamination on EC and pH.

Chloride, bromide, sodium and sulphate should not be overly affected by grout contamination and the concentrations of these ions with depth is shown in Figure 33. These figures show that each of these ions increases relatively uniformly with depth and Figure 4.11 shows that the concentrations increase at ratios similar to those in seawater.

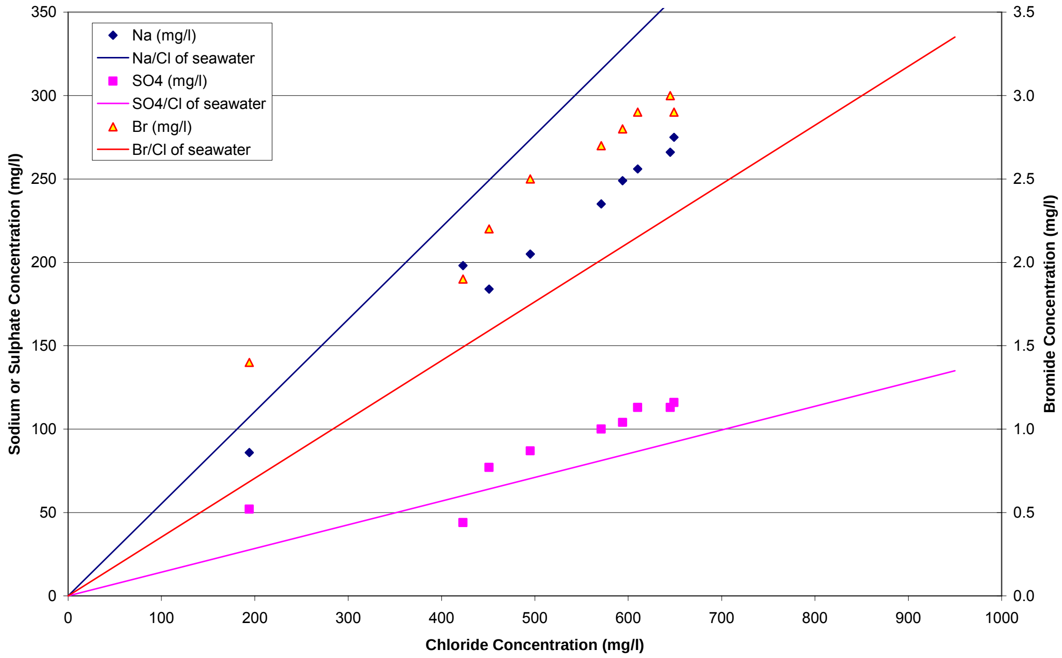


Figure 33 Comparison of chemical ratios in groundwater with seawater at St Catherine.

The lowest concentration of chloride is 194 mg/l and the highest is 649 mg/l. If all this chloride was derived from modern seawater (average chloride concentration 19,000 mg/l) then these concentrations translate into ~1% and 3.4% seawater.

Nitrate concentrations were 75±3 mg/l in all samples collected with little obvious variation in depth.

4.8 INTERPRETATION OF PUMPING TEST CHEMICAL DATA FOR ST CATHERINE

The major ion composition of the pumped water is different to the water sampled at 58 m bgl prior to grouting (see Figure 30). An increase in sodium and chloride concentrations during the pumping test is also apparent, consistent with an increase in the proportion of seawater from the ~3% level (Cl = 635 mg/l) measured in the deepest sample collected during borehole construction at the start of the tests to ~7% (Cl = 1324 mg/l). The total amount of water pumped was 9.03 m^3 during the step test and 54.6 m^3 during the three day constant rate test.

Nitrate concentrations decreased slightly from 75 to 68±1 mg/l NO_3 at the end of the pumping test. Some dissolved oxygen (11-25% saturation) was detected.

Of the parameters measured, the water sampled at St Catherine does not meet drinking water standards due to the high EC and high concentrations of magnesium, sodium, potassium, chloride and nitrate.

Overall the composition of the water pumped from the St Catherine borehole is consistent with a mixing of shallow nitrate contaminated recharge water with seawater.

4.9 COMPARISON OF ST CATHERINE PUMPED WATER WITH ADJACENT BOREHOLES

The major ion composition of the water at St Catherine is compared to that for nearby wells in Figure 30. This shows that the sample collected at 58 m bgl (pre-casing and grouting) from the St Catherine borehole is similar in composition to five out of six of the nearby (<30 m deep) wells. The sample from the 61 m deep borehole at Rue des Vivier, St Catherine (sample St.C2, Pine Walk) was similar in composition, if not more dilute, than the samples collected at the start of the pumping test.

5 Isotopic and Age Indicator Analyses

5.1 BACKGROUND

Modern groundwater investigations rely on combining the results of physical observations (rest water levels, drawdown during pumping, etc) with chemical measurements. While inorganic chemistry is still one of the most useful components of the latter (see previous section), in complex investigations such as the present study any additional evidence may be useful. The two techniques considered in this section – stable isotopes and trace gases – can be bracketed together as examples of *environmental tracers* – that is, characteristics that are automatically imparted to groundwaters, either naturally (stable isotopes) or anthropogenically (trace gases). Stable isotopes are basically used as indicators of groundwater provenance, while trace gases are mainly used as residence time indicators, but both can also be used to shed more light on processes like groundwater mixing.

5.2 SAMPLING

Samples for stable isotope analysis were obtained from the air flush water as drilling proceeded. A total of nine samples were taken and submitted for isotopic analysis from the La Rocque borehole and five from the St Catherine borehole. These samples were taken at depths where water strikes were recorded to have occurred or where a significant change in air flush yield was observed. The borehole depths at which the samples were obtained and the reason for sampling at that depth are indicated in Table 9. Further samples were obtained from abstraction boreholes in the vicinity of both test sites as detailed in Table 10. All samples were stored unfiltered in 28-ml McCartney glass bottles.

During the test pumping of the boreholes, the opportunity was taken to collect samples for CFC and SF_6 dating. This was carried out by staff of the Environment Division using the bottle-in-can technique devised by Oster (1994) to prevent contamination by the atmosphere.

Table 9 Isotope samples obtained from the investigation boreholes.

La Rocque Borehole	
Depth (m bgl)	**Comments**
10.0	First strike – yield c. 1.0 l/sec
19.5	Yield increased to 1.6 l/sec
22.0	Yield increased to 2.3 l/sec
34.5	Yield increased to 4.0 l/sec
37.5	Yield increased to 5.0 l/sec
43.0	Yield increased to a maximum of 7.0 l/sec
	Borehole cased & grouted to 43.0 m bgl
46.5	Yield 1.0 l/sec
50.5	Yield increased to 1.4 l/sec (just below the predicted water strike depth)
55.0	Yield increased to 1.7 l/sec – total borehole depth 55.5 m bgl.
St Catherine Borehole	
58.0	Base of upper section of borehole before casing & grouting.
	Borehole cased & grouted to 58.0 m bgl
68.0	Maximum measured yield 0.3 l/sec
75.5	Yield 0.26 l/sec
77.0	Yield 0.25 l/sec (just below predicted water strike depth
79.5	Yield increased to 0.23 l/sec – total borehole depth 55.5mbgl.

Note: Yield values are total yield and represent the sum of all water strikes above the specified depth in the pre-grouted and open sections of the borehole

Table 10 Samples from other boreholes in the vicinity of the two investigation sites.

La Rocque			
Sample No.	**Location**	**Grid Reference**	**BH Depth (m bgl)**
LaR1	La Rocque B, Rue du Puit Mahaut	570327 5447134	30.5
LaR2	Fauvic A, La Grande Route de St Clement	569632 5447576	42.7
LaR3	Fauvic B, Rue au Long	570115 5447535	39.6
LaR4	Le Bourg, La Grande Route de la Cote	569856 5446779	39.6
LaR5	La Rocque A, La Grande Route des Sablons (Observation borehole)	570654 544719	31.4
St Catherine			
St.C1	Bel Val Cove, St Catherine	570774 5452751	150.0
St.C2	Pine Walk A, Rue des Vivier	570804 5451982	61.0
St.C3	Pine Walk B, Rue du Champs du Rey	570674 5452131	18.3
St.C4	Pine Walk C, Rue du Champs du Rey	570723 5452040	28.0
St.C5	Mont des Landes, St Catherine	570830 5451682	28.3
St.C6	La Solitude, Rue de la Solitude	570545 5452023	Not known

5.3 ANALYTICAL METHODS

All measurements were carried out at BGS Wallingford. Stable isotopes were analysed by mass spectrometry following standard preparation methods, i.e. CO_2 equilibration for $\delta^{18}O$ and reduction with zinc shot for $\delta^{2}H$. The CFCs and SF_6 were determined by gas chromatography after pre-concentration by cryogenic methods (Bullister & Weiss, 1988). All results are presented in Appendix 7.

5.4 DATA INTERPRETATION

5.4.1 Stable isotopes

Stable isotope data are conventionally expressed in ‰ (permil) with respect to Vienna Standard Mean Ocean Water (VSMOW) on the delta scale:

$$\delta = [(R_{sample}/R_{standard})-1] \times 10^3$$

where R_{sample} is the $^{18}O/^{16}O$ or $^{2}H/^{1}H$ ratio of the samples, and $R_{standard}$ the corresponding ratio in VSMOW.

In temperate climates, the stable isotope values of rainfall and resulting groundwater normally plot on or near the World Meteoric Line (WML) of Craig (1961). The gradient of this line, defined using the equation $\delta^{2}H = 8\ \delta^{18}O + 10$, is actually an approximation of the average of observations from many rainfall stations, but serves as a convenient baseline to judge whether or not waters have been significantly affected by processes such as evaporation or saline intrusion. Figure 34 shows the WML together with the results of a basic groundwater survey carried out across Jersey in late May (see Appendix 7). This shows that Jersey groundwaters are overwhelmingly derived from rainfall.

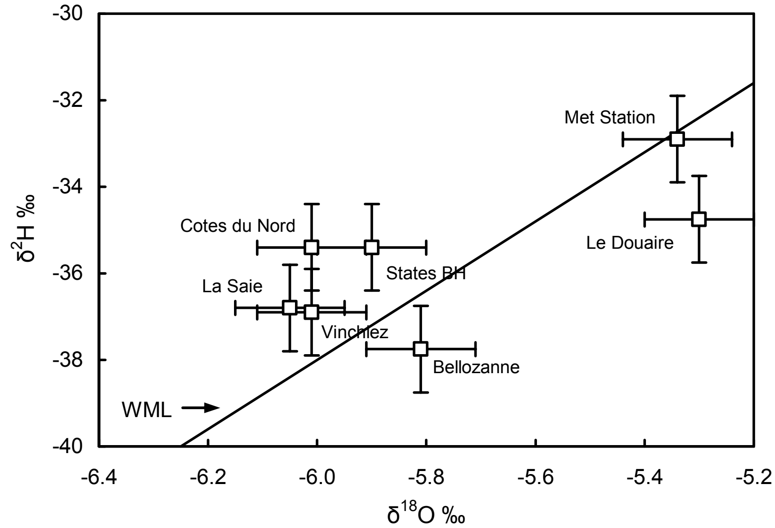


Figure 34 Cross-plot of the results of a survey of isotope values across Jersey, showing the scale of variation. Bars show the measurement precision. Also shown for reference is the World Meteoric Line (WML).

The use of O and H stable isotopes as indicators of groundwater provenance relies on the fact that isotope ratios in the rainfall recharging groundwater are very consistent from year-to-year for a particular geographical area. Basically this is a function of Mean Annual Air Temperature (MAAT), which itself is governed over land masses by distance from the sea and altitude of the recharge area. This results in the preferential rain-out of the 'heavy' isotopes ^{18}O and ^{2}H, leading to 'depleted' (i.e. more negative) d-values roughly from SW to NE in the case of Britain (Figure 35).

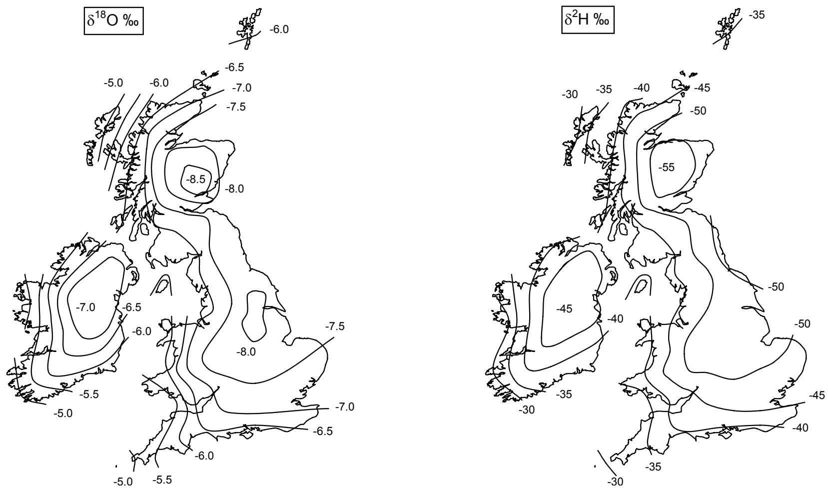


Figure 35 Stable isotope contours for groundwaters in the British Isles, showing the tendency for groundwater to become more negative inland as a result of the preferential rain-out of the heavy isotopes ^{18}O and ^{2}H. From Darling et al (2003).

However, since isotope ratios are closely linked to MAAT, changes in climate will inevitably affect them. In practical terms, this means that groundwaters recharged during the cold climate of the late Pleistocene (>10,000 years ago) will be more depleted (negative) than their modern counterparts. Although the regional differentials are likely to be maintained (Darling et al, 1997; Darling et al, 2003), it does mean that water age must be established beyond reasonable doubt where provenance is an issue, such as the present case.

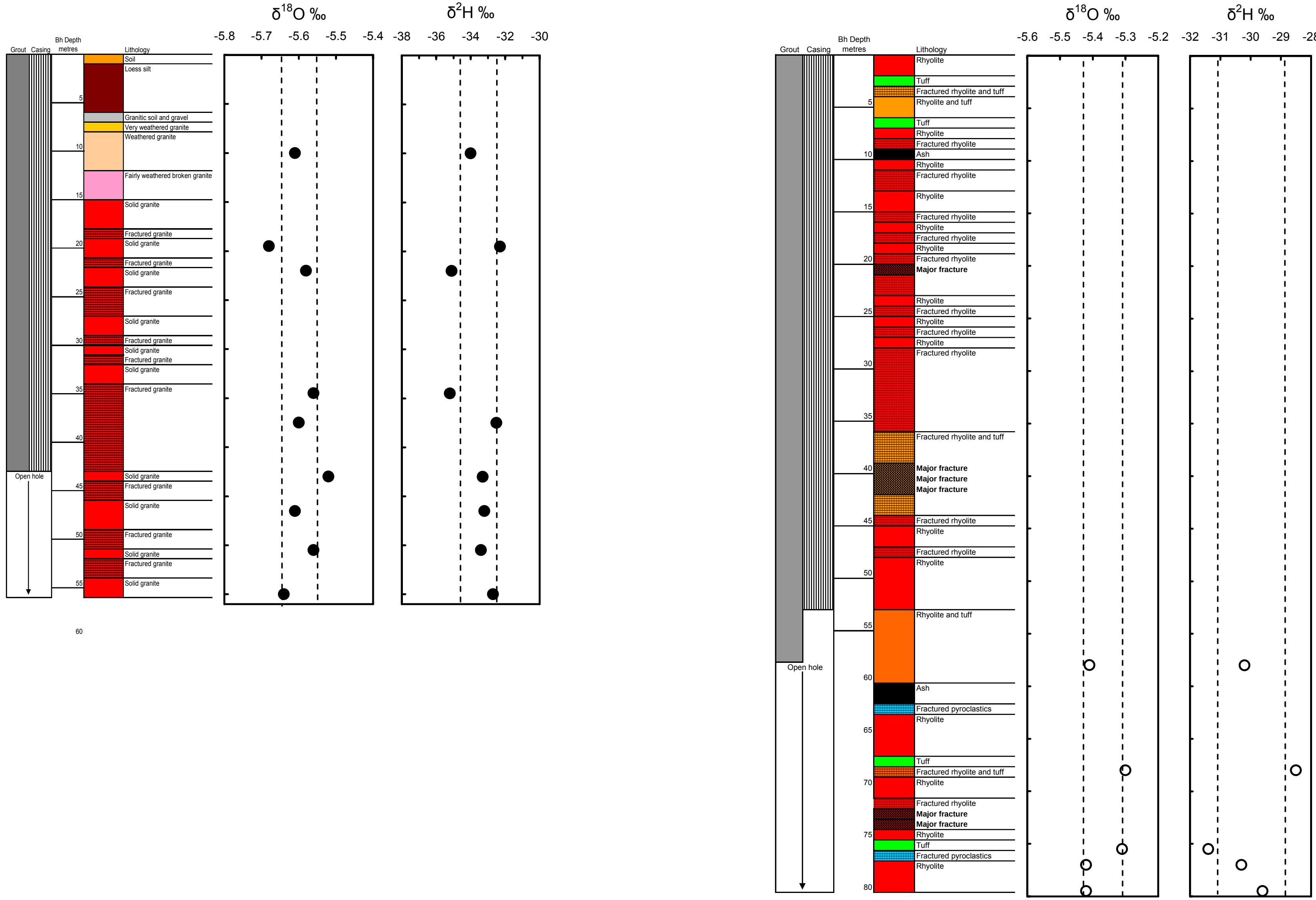


Figure 36 Profiles of δ18O and δ2H with depth for the La Rocque and St Catherine boreholes. Also shown is the standard deviation about the mean for each (dashed lines).

The two test boreholes produced the stable isotope depth profiles shown in Figure 36 (see 5.2 above for sampling rationale). It is clear that the variation in each borehole is not significantly outside the standard deviation of the mean, which in three out of four instances is less than the quoted isotope measurement precision (±0.1‰for $\delta^{18}O$, ±1‰ for $\delta^{2}H$). Therefore, there is no indication of any consistent depth-related change. In particular, there was no recorded significant change for either $\delta^{18}O$ and $\delta^{2}H$ isotope values samples from La Rocque borehole between the upper pre-cased/sealed section and those samples from the lower section (where the 'underground stream' was thought to exist)[3]. There is however a minor difference in the average compositions between the boreholes, which will be examined further below.

Local borehole compositions are shown on the following $\delta^{18}O$–$\delta^{2}H$ cross-plot (Figure 37):

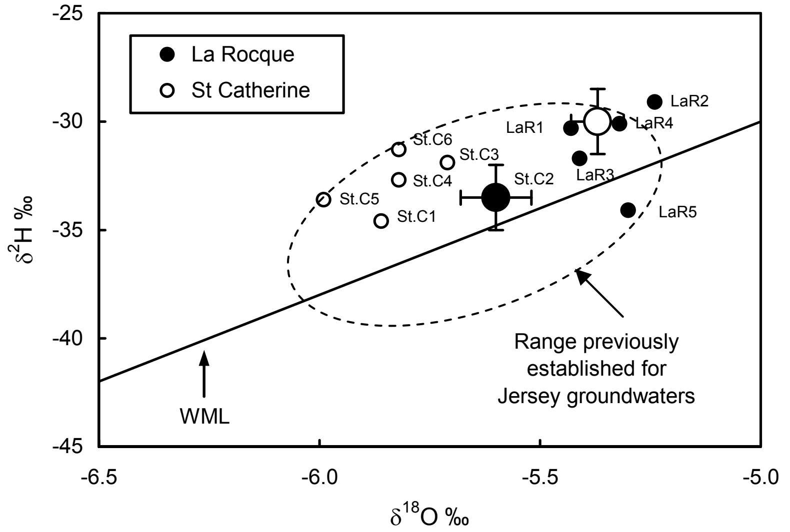


Figure 37 $\delta^{18}O$-$\delta^{2}H$ cross-plot of the average value from the La Rocque and St Catherine boreholes (bars show the variation within each borehole), plus the composition of pumped samples from boreholes in the vicinity of the test sites.

Neighbouring boreholes are slightly isotopically enriched compared to the La Rocque test borehole. Since there is no evidence from chloride contents for saline intrusion in these boreholes (see previous section), it probably indicates that the test borehole is on a flowline receiving recharge from a slightly greater altitude, i.e. inland on the Island. In contrast, the St Catherine test borehole is isotopically enriched compared to most of its local boreholes. Chloride measurements in this borehole suggest a ~5% modern seawater component, which would have the effect of adding ~0.3‰ in $\delta^{18}O$ and ~2‰ in $\delta^{2}H$ to the original composition (sea water has a chloride concentration of ~19000 mg/l and an isotopic composition close to 0‰ for both $\delta^{18}O$ and $\delta^{2}H$). If these values were subtracted from the measured values, the corrected isotopic composition for the St Catherine test borehole would be similar to those determined for the neighbouring boreholes.

[3] Student t-test for normal distribution with equal variance. P=0.75 for $\delta^{18}O$ and p= 0.43 for $\delta^{2}H$, df=7

Additional groundwater samples were obtained whilst pump testing the two boreholes (Table 11).

Table 11 Groundwater Samples obtained during hydraulic testing.

Sample No.	Description	Time	Date	Isotopes	CFC	SF_6	C_{14}
La Rocque Borehole							
AS01	Start of step test		31/10/2006	X			
AS02	Start of constant rate	0955	01/11/2006	X	x	x	x
AS03	first day constant rate	0950	02/11/2006	X			
AS04	second day constant rate	0935	03/11/2006	X			
AS05	End of constant rate	0705	04/11/2006	X	x	x	x
St CatherineBorehole							
BS01	Start of step test		01/11/2006	X			
BS02	Start of constant rate	1240	02/11/2006	X	x	x	x
BS03	first day constant rate	0850	03/11/2006	X			
BS04	second day constant rate	1045	04/11/2006	X			
BS05	End of constant rate	1100	05/11/2006	X	x	x	x

Samples taken during the pump testing of the La Rocque and St Catherine boreholes are shown on the $\delta^{18}O$-$\delta^{2}H$ cross-plot (Figure 38).

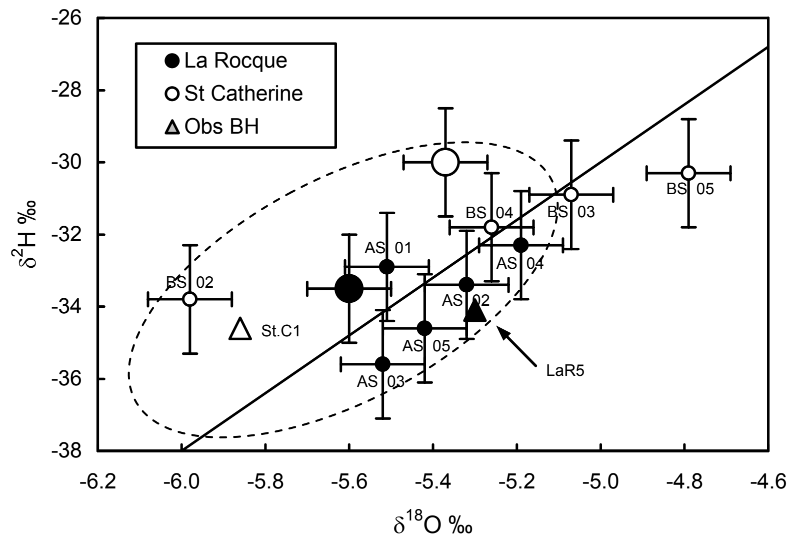


Figure 38 δ18O-δ2H cross-plot of samples obtained during the pump-testing of the La Rocque and St Catherine test boreholes. Large symbols represent drilling-phase average compositions. Jersey groundwater range shown for reference (dashed ellipse).

The small variation of isotopic results obtained for the La Rocque borehole is not significant in the context of the analytical measurement precision. The results are close to the average composition found during drilling and there is no obvious trend in isotope composition as the pumping tests progressed. The isotope values fall within the range of isotope values for Jersey groundwaters (Figure 34).

Compared to la Rocque, the St Catherine results show much more variation between start and finish, and appear to follow a trend, although bearing in mind the measurement precision this may not be very different in slope from the MWL. It is probably related to increasing amounts of seawater (see previous section), which would explain why the final sample (BS05) falls outside the previously established range for Jersey groundwaters. The most striking aspect, however, is the scale of variation in the pumping test waters compared to the average during drilling. The sample from the start of the constant rate test, BS02, is similar to the result from the observation borehole St.C1, i.e. the type of isotopic composition to be expected in the northeastern part of Jersey when saline intrusion is not an issue.

5.4.2 CFC and SF_6

The atmospheric trace gases CCl_3F (CFC-11), CCl_2F_2 (CFC-12) and SF_6 (sulphur hexafluoride) are increasingly being used as tracers of residence time age (Plummer and Busenberg, 1999).

Large-scale production of CFC-12 began in the early 1940s, followed in the 1950s by CFC-11. These gases were used for refrigeration and air-conditioning, but inevitably leaked into the environment, with atmospheric concentrations rising until the 1990s, when production was cut back to protect the ozone layer, (Figure 39**a**). SF_6, another industry-derived gas, has been detectable in the atmosphere since the early 1960s and is still rising steadily in concentration (Figure 39**a**). Unlike tritium, all three of these trace gases are well-mixed in the atmosphere and their input functions are better characterised. When their atmospheric mixing ratios are converted into dissolved concentrations (Figure 39**b**), using Henry's Law and known solubilities (Plummer and Busenberg, 1999), these can be compared with concentrations measured in groundwater samples and, assuming no contamination or degradation, the year of recharge can be inferred.

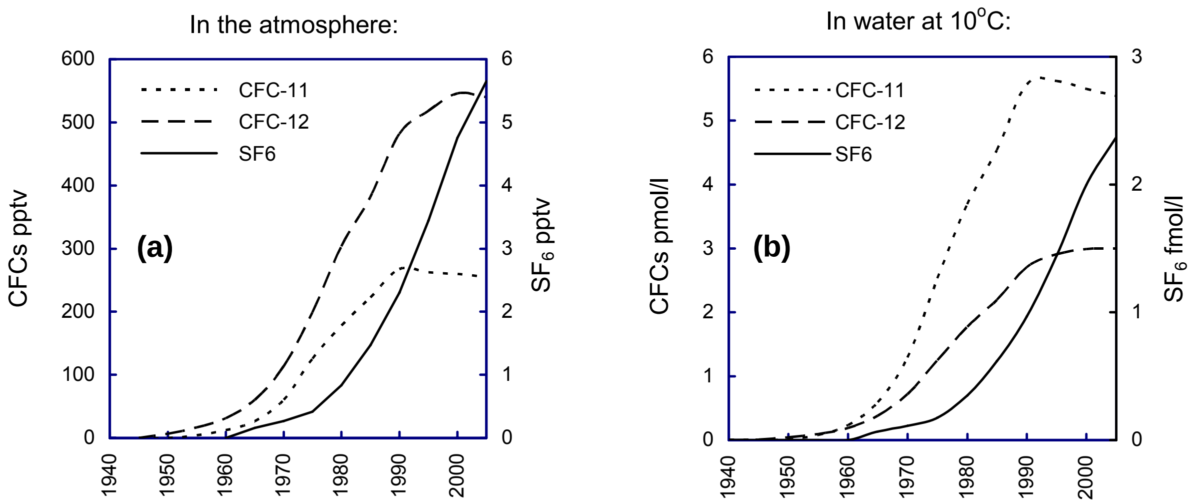


Figure 39 (a) Atmospheric inputs of the CFCs and SF_6 over the past 65 years, (b) concentrations expected for water equilibrated with air at a MAAT of 10°C.

Due to a requirement for specialist sampling techniques and the strong potential influence of air flush techniques on dissolved trace gas concentrations, samples for CFC and SF_6 analysis were collected only at the beginning and end of the constant-rate testing. Results are given in Table 12.

Table 12 CFC (chlorofluorocarbon) and SF_6 (sulphur hexafluoride) measurements from the pump-testing of the La Rocque and St Catherine boreholes.

Sample	CFC-11 pmol/l	CFC-12 pmol/l	SF_6 fmol/l
AS02	1.27	0.98	1.04
AS05	3.92	0.99	0.80
BS02	1.28	0.33	11.1
BS05	1.61	0.62	14.6

Note : Results are in picomoles (10^{-12} moles) per litre for the CFCs and femtomoles (10^{-15} moles) per litre for SF_6. The SF_6 results have been corrected for excess air.

Being a highly insoluble gas, SF_6 is subject to enhancement during the infiltration of rainwater by so-called ‘excess air’, i.e. the forced solution of air bubbles during percolation. This excess component has to be corrected for to arrive back at the equilibrium-derived atmospheric (i.e. datable) component. There is as yet rather little information on excess air in crystalline rocks, but the available British data show relative consistence and in consequence a correction factor of 0.75, based on the average value found so far in UK groundwaters (~4 cc/l at 10°C), has been applied.

Northern hemisphere atmospheric mixing ratios for CFC-11, CFC-12 and SF_6 at the beginning of 2006 would have resulted in equilibrium dissolved concentrations (at 10°C) of 5.27 pmol/l, 2.97 pmol/l and 2.57 fmol/l respectively. It is clear that while all the CFC results are below the present-day equilibrium value, the SF_6 results from St Catherine are considerably above this. They are unlikely to be attributable to excess air – even a correction using the highest recorded amount of excess air (50 cc/l – Wilson and McNeill, 1997) would barely bring them down to current equilibrium levels – so, therefore, cannot be used for dating purposes. The origin of these high concentrations is not clear; similarly high values have sometimes been found in crystalline rocks, but La Rocque shows no excess. High values of SF_6 would otherwise usually be attributed to pollution: for example they are sometimes encountered in boreholes near landfills, or in urban areas. In such circumstances, however, CFC contamination would also be expected. A third possibility is that they are in some way linked to the saline intrusion in the borehole.

However, enough ‘good’ data remain to investigate the age of the water. The optimal approach is to use a CFC–SF_6 plot, which can be done for La Rocque (Figure 40). This shows (i) no significant change over the period of the test, and (ii) that the samples fall on or close to the mixing line between modern and pre-1950 water. The second observation is typical of aquifers that rely on fracture porosity; only porous aquifers tend to exhibit unmixed ‘piston’ flow. Therefore while Figure 40 suggests that the borehole is tapping a water with a one-third modern component, it cannot be used to derive the age of the old component. A radiocarbon (^{14}C) measurement would be required for this purpose (currently in hand).

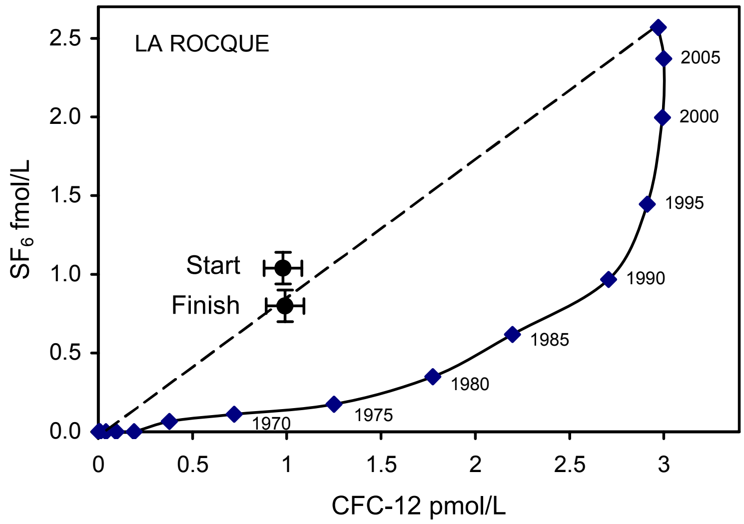


Figure 40 Cross-plot of CFC-12 vs SF_6 for samples from the La Rocque constant-rate pumping test. Also shown is the piston-flow curve based on atmospherically equilibrated water over the past 50 years, and the mixing trend (dashed line) between modern and pre-1950 water.

The chemistry results for the La Rocque pumping test show that the water is mildly reducing (see previous section). CFCs can suffer microbial degradation, but only under methanogenic (i.e. strongly reducing) conditions, and even then CFC-11 is consumed much more rapidly than CFC-12 (Oster et al, 1996). Methane in the AS05 sample was <1.5 mg/l and therefore insignificant; also the fact that CFC-11 was above the CFC-12 concentration both at the start and finish of the constant rate test indicates that degradation is unlikely to have affected the CFCs, and that, therefore, the mixing interpretation of Figure 40 should stand.

In contrast to the data in Figure 40, the CFC-11 result for La Rocque shows a rise of more than double over the course of the test. In view of the consistency of CFC-12 and SF_6, it is unlikely to be due to a change in age. It may be reflecting an increasing input from a waste water or landfill source; since a little artificial CFC-11 can cause very large excesses in groundwater, this result does not necessarily conflict with the CFC-12 and SF_6 data.

For the St Catherine test, because of the SF_6 excess, reliance has to be placed on the CFCs. Figure 41 shows the data superimposed on a CFC-12 vs CFC-11 cross-plot. Reference to Figure 39 shows that the CFCs have a relatively similar atmospheric history, and that therefore it is much less easy to distinguish mixing from piston-flow processes. In addition, the St Catherine data fall close to the area where the piston-flow and mixing lines cross over. If it is assumed that mixing is occurring, as at La Rocque, then a modern component of ~20% is suggested. The main difference from La Rocque is that more modern water appears to be present at the end of the test (up from ~15% to ~25%). The rise in SF_6 (Table 12) coincidentally or not supports this order of increase.

Although it is not currently possible to put an absolute age on the groundwater samples from either borehole, it may be concluded that a componant of modern water (post c.2000) is present in each borehole,(about 30% at La Rocque and 15 to 25% at St Catherine), with the balance consisting of pre-1950 water. The age of this older water can only be estimated by radiocarbon dating (currently in hand).

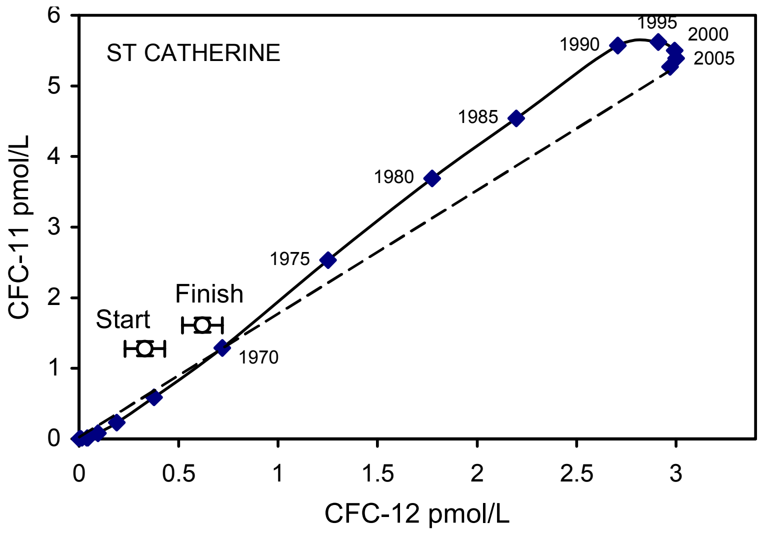


Figure 41 Cross-plot of CFC-12 vs CFC-11 for samples from the St Catherine constant-rate pumping test. Also shown is the piston-flow curve based on atmospherically equilibrated water over the past 50 years, and the mixing trend (dashed line) between modern and pre-1950 water.

6 Summary and Interpretation of Results

6.1 GENERAL

This section of the report provides an integrated interpretation of the multiple lines of evidence obtained from the different components of the investigation.

The interpretation will consider each of the two investigation boreholes individually, as in many ways the results obtained are very different. It is understood that the water diviners and well drillers sited the two boreholes at locations that they deemed most suitable for proving the presence of 'underground streams', in which significant quantities of fresh water from a source located on mainland Europe would flow at depth beneath the Island. They also provided the depths at which the predicted underground streams would occur

6.2 LA ROCQUE BOREHOLE

6.2.1 Borehole Drilling and Construction

This borehole was drilled and completed according to the original specification (Appendix 2).

- The borehole was initially drilled to a depth of 43 m bgl.
- The first water strike was at 10 m bgl, with the air flush yield increasing cumulatively with depth to reach a maximum of about 7 l/sec (147 m^3/d) at 43 m bgl.
- 150 mm ID plastic casing was inserted at that depth and the borehole was completely filled using cement grout, which not only filled the inside of the casing and annulus outside the casing but would also penetrate the adjacent water bearing fractures encountered during drilling.
- After the grout had completely hardened, the borehole was redrilled to the former depth of 43 m bgl. The borehole was completely dry until after that depth was passed, indicating that the upper water bearing sections of the borehole had been successfully sealed out; (this subject is discussed in more detail in Box 2 below).
- Drilling continued to the planned total depth of 50 m bgl, with the cumulative air flush yield increasing gradually to a maximum of 1.7 l/sec (147 m^3/d) as successively deeper productive fractures were penetrated.
- At the request of Senator Cohen drilling continued to a final depth of 55 m bgl, without obtaining any significant additional water yield.
- Water samples for inorganic and isotopic analysis were obtained from various depths as drilling progressed, as per the original specification; details of these samples are provided in Sections 4.1 and 5.3.1.

Box 2: Effectiveness of the La Rocque Borehole Grout Seal

Since the La Rocque borehole was constructed, some doubts have been expressed by members of the DGAG regarding the effectiveness of the grout seal that was installed in the upper 43 m depth of the borehole, following the damage that occurred to the uppermost 13 m of plastic casing whilst redrilling the borehole through the hardened grout.

The drilling contractor has wide experience using cement grout. A grout mix consisting of 100 litres of water to 5 bags of cement powder was used, as this would be sufficiently fluid to penetrate into fractures adjacent to the borehole but would also harden within the specified 24 hour period. Sand was not included in the grout mix as it has it settles to the base of the borehole and was likely to have resulted in a less fluid consistency that would have inhibited penetration and complete sealing of the fractures.

As indicated above the borehole was completely filled with grout and this was topped up to ground level to ensure maximum lateral penetration of the adjacent fractures penetrated by the borehole. At the time of grouting the base of the borehole was in an unfractured zone of the granite, which would have prevented downward migration of grout. The original specification required that the grout be left to set for a minimum of 24 hours after insertion but the grout was in fact left to harden for a total of over 43 hours before any drilling recommenced and 48 hours before drilling reached the former depth of 43 m bgl. The drill cuttings whilst redrilling the borehole consisted of dry hard chips of cement, indicating that the grout hardened sufficiently to be drilled out. The damage to the uppermost section of the plastic casing occurred during the early stages of redrilling and if this had breached the grout seal, water would have entered the redrilled borehole before it reached the original depth of 45 m bgl. No water was, however, observed until after the base of the grout had been penetrated and drilling had continued into the granite.

In addition to the above, an inflow of water would have been observed during hydraulic testing if the grout seal was not intact. The water level during hydraulic testing was drawn down to a maximum of 20 m, from a rest level of 2.36 m bgl. The upper section of the borehole where casing damage occurred (to c. 13 m bgl) would therefore have been substantially above the pumping water level. Water in this borehole was first encountered at about 10 m bgl, at which depth the air flush yield was about 1 l/sec. The yield gradually increased to about 2 l/sec by a depth of 22 m bgl (the approximate depth of the pumping water level during hydraulic testing). If leakage had occurred over the upper section of the borehole, the water would have cascaded down the borehole from the point of entry to the pumping water level. The cascading of water down a borehole in this manner is commonly audible even with the pump running and highly noticeable immediately after the pump stops. In addition, the use of a manual electrical water level dipper becomes difficult, if not impossible, when water is cascading down a borehole as the equipment gives an intermittent signal at about the level of inflow and it is not possible to measure the actual water level. In fact there were no difficulties in obtaining manually dipped water levels at any time during testing and the data thus obtained correlated closely with that obtained from the automated 'dipper' pressure transducer equipment. In addition no noise was noted from the borehole either whilst pumping or after pumping ceased (Dr du Feu and Mr Moon, pers. com.); the sound of cascading water would have been very noticeable as manual water level measurements were being taken at one minute intervals immediately after pumping stopped. The evidence shows that the effectiveness of the borehole grout seal had not been compromised when the plastic casing was damaged and that it was effective in sealing out all groundwater inflows from fractures penetrated whilst drilling between 10 and 43 m bgl.

6.2.2 Hydraulic Characteristics

Hydraulic testing at La Rocque provided remarkably consistent transmissivity values of between 80 and 90 m^2/d for both the investigation borehole and the nearby unused borehole that was used as an observation borehole during testing. Step testing indicated that the yield obtainable from the open section of the investigation borehole was no more than 3.25 l/sec. The data obtained from the observation borehole provided a storativity value of 1.3×10^{-5}.

The storativity value is indicative of confined conditions and this is confirmed by the fact that the first water strike was at 10 m bgl but the water rose to a rest level of 2.36 m bgl. The confining layer is likely to consist of the silty and clayey loess, present to a depth of 5.5 m bgl and underlying heavily weathered granites, in which any fractures are likely be filled with relatively impermeable material.

The confined conditions are indicative of recharge having occurred inland from the site through a part of the granite fracture system that is located at a slightly higher elevation than the site. Confinement of groundwater within an extensive linked fracture system is common in crystalline bedrock aquifers (such as granite). The presence of confined conditions also explains the rapid response to pumping of water levels in the observation borehole. The absence of tidal fluctuations in water levels recorded during hydraulic testing is also consistent with confined conditions, indicating that local connectivity between the sea and groundwater in the granite is limited. Tidal responses do not, therefore, transmit well hydraulically and the area may be less vulnerable to saline intrusion as long as hydraulic heads are maintained above mean sea level. In addition, the granite is not compressible and so loading effects related to the weight of the sea on confined compressible strata are not seen.

The base of the adjacent observation borehole (at 31.4 m bgl) is considerably above the base of the grout sealed section of the investigation borehole (at 43 m bgl) and it was possible that the open sections of the two boreholes could have been against completely separate shallow and deep water bearing fracture zones. However, the similarity of the rest water levels, together with the rapidity of water level response in the adjacent observation borehole to pumping, are indicative of a high degree of lateral and vertical interconnection of productive fractures in the vicinity of the two boreholes. Thus, although the geological logs (Appendix 2) indicate that some sections of the granite are relatively unfractured, the hydraulic testing shows that the two different depth boreholes have penetrated an interconnected set of fractures.

Specific capacity values derived from the La Rocque pumping test are compared with previously derived values for the shallow aquifer in the granite in Table 13. This shows that the values obtained from testing the deeper part of the system are significantly lower than those from the shallow aquifer, and reflect the difference in production potential between the shallow aquifer and the deeper fracture zones.

Table 13 Comparison of specific capacity values obtained previously for the shallow aquifer in Jersey (from Robins and Smedley 1998) with the values from the deeper horizons at La Rocque (Granite) and St Catherine (Volcanic group).

Formation	**Zone**	**Specific capacity ($m^3/d/m$) and [sample population]**
Granite (diorite)	Shallow aquifer	69 [11]
	La Rocque borehole - deep	15 [1]
Volcanic Group	Shallow aquifer	103 [15]
	St Catherine borehole – deep	2 [1]

6.2.3 Resource Potential

The test yield obtained from the deep open section of the investigation borehole (3.25 l/sec) is somewhat above average for Jersey, particularly for granite boreholes, although La Rocque is recognised as an area where larger yields are commonly obtainable from the granite. This yield, although good in comparison with other boreholes in Jersey, is by no means exceptional and larger yields have previously been obtained elsewhere on the Island. It should however be noted that a much larger cumulative air flush yield (about 7 l/s) was obtained from the shallower section of the borehole (above 43 m bgl) during drilling but was subsequently sealed out.

It should be stressed that the yields obtained from both the shallow and deep sections of the borehole were cumulative, and increased incrementally with increasing borehole depth as additional productive fracture horizons were penetrated. The total yield at any given depth, therefore, includes inflow contributions from all of the productive fracture horizons that were penetrated above that depth. It is also notable that no single major inflow of groundwater occurred at any depth, in particular the depth at which an ‘underground stream’ was predicted to occur (150 ft or 45.7 m bgl), whilst drilling the La Rocque borehole.

It is concluded from the drilling and hydraulic testing of the La Rocque borehole that;

- A fractured granite aquifer exists in the La Rocque area, which appears capable of providing significant, for Jersey, borehole yields. The most productive horizons are shallow rather than in the deeper granite and are related to a number of fractures rather than any one single large fracture or ‘underground stream’.
- There is a single fractured granite aquifer connected hydraulically at depth to the shallower granite ‘tapped’ by existing nearby boreholes. The pumping test clearly showed that if water were abstracted from the deeper granite there would be an effect on shallower wells. This means that although the deeper granite can provide a reasonable yield, it does not follow that it is a separate sustainable resource.

6.2.4 Inorganic Chemistry, Isotopic Signatures and the Source of the Groundwater

Overall the inorganic chemistry and isotope signatures for water samples obtained whilst drilling and testing the borehole show only small variations.

For the inorganic chemical parameters measured, the water is potable except for elevated manganese concentrations. Nitrate is absent in all but the uppermost sample and together with the absence of dissolved oxygen and the presence of dissolved manganese suggests reducing rather than oxygenated conditions. These conditions are consistent with the confined interpretation of the pumping test results.

There are subtle changes with depth in the inorganic chemistry consistent with a greater degree of weathering and groundwater flow in the shallower granite than at depth. This is consistent with both the evidence of weathering from the geological logs and the greater yields, from more frequent or more permeable fractures, in the upper granite. Slight changes in water quality during pumping suggest that although the water was supplied from the deeper strata initially, after three days about 25% of the water was probably being derived from the shallower granite, consistent with the hydraulic response and inference of leakage from the pumping test.

The isotopic signatures obtained for both the depth samples and those obtained during hydraulic testing are consistent with the range of isotope signatures for Jersey groundwaters, strongly suggesting a local source of aquifer recharge. The CFC and SF_6 results indicate that the pumped water samples consist of a mixture of about two thirds older water and one third of younger water. The absence of nitrate except at very shallow depth may be indicative of older water uncontaminated by relatively recent agricultural inputs or possibly that denitrification is occurring at depth. It is probable that these groundwaters are naturally stratified within the water bearing strata with the younger water at shallow depths and the older water at greater depths. The mixing of the two waters is likely to have occurred as a result of pumping, drawing down the near surface waters via interconnected fractures as testing proceeds.

In conclusion the inorganic chemistry, isotopic analyses and age indicator results strongly suggest that the source of both the shallow and deep groundwaters is within the Island of Jersey.

6.3 ST CATHERINE BOREHOLE

6.3.1 Borehole Drilling and Construction

In the case of this borehole there were a number of agreed amendments to the original specification (Appendix 2), made in the light of experience gained whilst drilling the La Rocque borehole. It was agreed that the base of the cased and grouted upper section of the borehole would be raised from the planned 73 m bgl to 58 m bgl, with a final borehole depth of 79.5 m bgl. This amendment to the original specification increased the open length of borehole from the specified 6.5 m to 21.5 m. It was also agreed to drill the upper section of the borehole at the larger diameter of 300 mm diameter to allow the use of 203 mm permanent steel casing rather than the 205 mm plastic casing used in the La Rocque borehole

- The borehole was initially drilled to a depth of 58 m bgl.
- The first 'water strike' was at about 36 m bgl, but despite other very small water strikes at greater depth, insufficient water was being flushed from the borehole when it reached a depth of 58 m bgl to allow a yield measurement to be made.
- 203 mm ID steel casing was inserted to a depth of 53 m bgl, with the borehole being filled with cement grout from the total depth of 58 m bgl. As in the La Rocque borehole, the borehole was completely filled using cement grout, which not only filled the inside of the casing and annulus but also penetrated into the adjacent water bearing fractures penetrated during drilling.
- The grout was left to completely harden for 48 hours, before the borehole was redrilled to the former depth of 58 m bgl. The borehole was completely dry until dampness was encountered below 60 m bgl (some 2 m below the base of the sealed section), indicating that the small amount of water in the upper sections of the borehole had been successfully sealed out.
- Drilling continued to the planned total depth of 79.5 m bgl, with the cumulative air flush yield increasing gradually to a 0.26 l/sec at total depth, as successively deeper 'productive' fractures were penetrated.
- Water samples for inorganic and isotopic analysis were obtained from various depths as drilling progressed, as per the original specification; details of these samples are provided in Sections 4.1 and 5.3.1.

6.3.2 Hydraulic Characteristics

The step test of the St Catherine borehole indicated that the yield obtainable from the open section of the investigation borehole was only 0.2 l/sec (17 m^3/d). The subsequent constant rate test at that pumping rate produced a maximum water level drawdown of almost 10m. A semi-diurnal water fluctuation was observed during the test due to a pronounced tidal influence. A low transmissivity value of 10 m^2/d was estimated. As no observation borehole was available it was not possible to estimate a storativity value.

The first water (dampness) was observed between 36 and 41 m bgl, with the first measurable water inflow below 65 m bgl. As the rest water level was at about 22.7 m bgl, the groundwater encountered at depth in this borehole is confined. The confined conditions are indicative of recharge having occurred some distance inland from the site through a part of the fracture system that is at probably located at a higher elevation than the site.

The geological log indicates the presence of a considerable number of fracture horizons that occur below the rest water level in the shallow section of the borehole but the logs also record the presence of white vein quartz as being associated with these zones of fracturing. It is probable that the fractures are in fact filled/sealed with vein quarts and are not therefore water bearing. In the absence of water bearing fractures, these impermeable volcanic strata will act as the confining horizon above the underlying weakly water bearing strata.

Specific capacity values derived from the St Catherine pumping test are compared with previously derived values for the shallow aquifer in the Volcanic Group in Table 13. This shows that the values obtained from testing the deeper part of the system are significantly lower than those from the shallow aquifer, and reflect the difference in production potential between the shallow aquifer and the deeper fracture zones

6.3.3 Resource Potential

The sustainable test yield obtained from the deep open section of the investigation borehole of 0.2 l/sec (17 m^3/d) is low compared to yields obtained from the majority of boreholes in Jersey. The yield is particularly poor when compared to yields commonly obtainable from similar volcanic strata elsewhere in the Island. This yield is, in fact, barely large enough to provide a sustainable supply for a single household. The hydraulic connection found between deep and shallow rock strata means that abstraction of groundwater at depth will directly affect the yield, and may cause the drying of neighbouring boreholes.

It should be stressed that the yields obtained from both the deep sections of the borehole were cumulative, and increased incrementally with increasing borehole depth as additional productive fracture horizons were penetrated. It is also notable that no single major inflow of groundwater occurred at any depth, including the depth at which the 'underground stream' was predicted to occur, whilst drilling this borehole.

It is concluded that the evidence obtained from drilling and testing the St Catherine borehole shows that;

- No 'underground stream' is present at any depth beneath the site, in particular at the depth predicted by divining.
- The hydraulic characteristics of the fractured volcanic strata at depth are very poor and in consequence it cannot be considered that any deep groundwater resource, capable of significant development in the future, is present.

6.3.4 Inorganic Chemistry, Isotopic Signatures and the Source of the Groundwater

Groundwater quality is poor, not potable and would not be suitable for domestic use. During pumping, the conductivity of the water increased steadily to a maximum of 4870 µS/cm.

The concentrations of various ions (including sodium, chloride, bromide and sulphate) increase with depth in this borehole. The concentrations increase at ratios that are similar to that of seawater and are indicative of the presence of an increasing component of seawater with depth. In addition, water conductivity and concentrations of sodium and chloride increased during the pumping test suggesting that pumping was increasing saline intrusion in the vicinity of the borehole.

Nitrate concentrations are relatively high (about 75 mg/l) but do not vary significantly with depth.

The isotopic signatures obtained for both the depth samples and those obtained during hydraulic testing are generally consistent with the range of isotope signatures for Jersey groundwaters and strongly suggesting a local source of aquifer recharge. The isotopic signatures are however enriched by the presence of a minor component of seawater. A trend of further isotopic enrichment was observed over the pumping period suggesting the present of an increasing component of seawater. This is consistent with the trend observed for inorganic analyses discussed above.

In conclusion the inorganic chemistry, isotopic analyses and age indicator results strongly suggest:

- That the source of the fresh component of the groundwaters is within the Island of Jersey.
- The groundwater contains an increasing component of seawater with depth.
- Groundwater abstraction induces an increase in water salinity with time.

7 Conclusions

7.1 THE INVESTIGATION

The deep groundwater investigation described in this report has generated valuable data to help understand the potential for a deep groundwater resource on Jersey. The investigation has followed up recommendations on borehole locations and depths provided by the Island's water diviners, with carefully designed, drilled and constructed, pump tested and sampled boreholes. This has allowed the States of Jersey to investigate the presence or absence of deep 'underground streams' beneath sites as defined by the water diviners.

The available data and its interpretation have been presented in considerable detail in this report, to allow, where desired, scrutiny of the findings by all parties interested in the future management of the Island's water resources.

The conclusions on the deep groundwater investigation at the two locations are set out below.

7.2 LA ROCQUE

- A fractured granite aquifer exists in the La Rocque area, which appears capable of providing significant borehole yields. Yields are better at shallow depth than in the deeper granite and are cumulative with increasing depth, being related to the number and productivity of the fractures penetrated, rather than the yield obtained from any one single large fracture or 'underground stream'.
- The fractured granite aquifer at depth (proven to –50 mOD) is connected hydraulically to the shallower granite 'tapped' by existing nearby boreholes. The pumping test clearly showed that if water were abstracted from the deeper granite there would be an effect on, and perhaps endangering of, yields from shallower wells. This means that although the deeper granite can provide reasonable yields, it does not follow that it provides a separate sustainable resource.
- The stable isotope signatures do not vary significantly with depth and are entirely consistent with a Jersey origin.
- There is evidence to suggest that at least some of the groundwater present at La Rocque is older than 1950.

7.3 ST CATHERINE

- Borehole yields were low at St Catherine both during drilling and on pumping, most likely due to fractures in the volcanic strata being infilled with quartz rather than being open for water movement. There was no evidence of a single large unfilled and productive fracture or 'underground stream' at any depth.
- The lower permeability of these strata is also consistent with poor, non-potable water quality affected by poor water movement. Pumping of the borehole lead to a deterioration in water quality, so the small yields are also not sustainable in water quality terms.

7.4 OVERVIEW

- **No evidence of a sustainable high yielding deep water resource (or 'underground stream') has been found during this investigation.**
  - Whilst there are usable quantities of groundwater within fractures at depth at La Rocque this is intimately connected to shallower productive fracture horizons and does not represent an additional resource.
  - No usable groundwater resource was found at St Catherine.
- **Groundwater isotopic signatures do not vary significantly with depth in either of the two investigation boreholes.**
  - A local groundwater source is strongly indicated by the isotopic signatures obtained for groundwaters from both boreholes.
  - A local groundwater source is also strongly supported by various aspects of the inorganic chemistry observed in the two boreholes.
- **There is no evidence to suggest the existence of a source of groundwater that is located outside the Island.**

8 References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

BGS 1992. Hydrogeological map of Jersey, 1:25,000 scale. British Geological Survey for the States of Jersey (Public Services Department). British Geological Survey, Keyworth, UK.

BRGM 2006. Aqifères and eaux souterraines en France. Ed. Jean-Claude Roux, Pub. BRGM, Orléans, France.

BULLISTER, J.L. and WEISS, R.F. 1988. Determination of $CC1_3F$ and $CC1_2F_2$ in seawater and air. Deep Sea Res., 35, 839–853.

BUNDESANSTALT FUR GEOWISSENSCHAFTEN UND RHOTOFFR (BGR) and UNESCO 1976. International Hydrogeological Map of Europe Sheet 4 London, Scale 1: 1,500,000.

DARLING W G, EDMUNDS W M and SMEDLEY P L (1997) Isotopic evidence for palaeowaters in the British Isles. Applied Geochemistry 12, 813-829.

DARLING, W.G., BATH, A.H. and TALBOT, J.C. 2003. The O & H stable isotopic composition of fresh waters in the British Isles. 2. Surface waters and groundwater. Hydrology & Earth System Sciences 7, 183-195.

KRUSEMAN GP AND DE RIDDER NA 1990. Analysis and evaluation of pumping test data (Second Edition). ILRI Publication 47, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

OSTER, H. 1994. Datierung von Grundwasser mittels FCKW: Voraussetzungen, Möglichkeiten und Grenzen. Dissertation, Universität Heidelberg.

OSTER, H., SONNTAG, C., MUENNICH, K. O. 1996. Groundwater age dating with chlorofluorocarbons. Water Resources Research 32, 2989-3001.

PLUMMER, L.N. AND BUSENBERG, E. 1999. Chlorofluorocarbons. In: P.G. Cook and A.L. Herczeg (eds) Environmental tracers in subsurface hydrology. pp 441–478, Kluwer, Dordrecht.

ROBINS N.S. AND SMEDLEY P.L. 1998. The Jersey groundwater study. British Geological Survey Research Report RR/98/5.

ROBINS N.S. AND ROSE EPF 2005. Hydrogeological investigations in the Channel Islands: the important role of German military geologists during World War II. Quarterly Journal of Engineering Geology and Hydrogeoogy, 38, 4, 351-362.

VIBERT SCRUTINY PANEL. 2004. Draft Water Resources (Jersey) Law 200- Transcript of Evidence, provided to the Vibert Scrutiny Panel by George Langlois, Water Diviner, Lewis de la Haye, Well Driller. Public Hearing Session on 26th July 2004. Sect. 25.

WILSON, G. B. AND MCNEILL, G. W. (1997). Noble gas recharge temperatures and the excess air component. Applied Geochemistry 12, 747–762.

9 Glossary

Aquifer: A rock formation that is sufficiently porous and permeable to yield a significant quantity of water to a borehole, well or spring. The aquifer may be unconfined beneath a standing water table, or confined by an impermeable or weakly permeable horizon.

Confined Aquifer: An aquifer whose upper and lower boundaries are low permeability layers which confine the groundwater under greater than atmospheric pressure. These aquifers are sometimes called artesian aquifers, the term first being used where the pressure surface was above ground level resulting in overflow under artesian pressure.

Drawdown: the reduction of the pressure head in an aquifer as the result of withdrawal of free water

Fracture: The term fracture is used to refer to a parting in a rock. The term does not imply any particular orientation or origin, except that of brittle failure. Thus joints and faults are fractures, but a fracture is only referred to as a joint or fault if the relevant mode of formation is known. The term fissure is commonly used by hydrogeologists but its meaning is imprecise and is not used in the report. Where fractures are thought to have been enlarged by solution they are described as such.

Fracture flow: The preferential flow of groundwater through dilated cracks, joints, bedding planes or other features of secondary porosity within an aquifer. It does not include preferential groundwater flow through a thin high-permeability horizon of an aquifer.

Ghyben-Herzberg Principle: A principle that accounts for the existence of a body of fresh water floating on sea water within an aquifer because of the different densities. Generally speaking, fresh water extends to a depth about forty times the height that the fresh water table is found above sea level.

Groundwater Recharge [mm/d, mm/a]: Inflow of water to a groundwater body from the surface. Infiltration of precipitation and its movement to the water table is one form of natural recharge.

Hydraulic conductivity, k [m/d]: For an isotropic porous medium and homogenous fluid, the volume of water that moves in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Commonly, though imprecisely taken to be synonymous with permeability.

Hydraulic gradient: Slope of the water table or potentiometric surface. The change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Hydraulic head [m]: The height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a ground water system. For a well, the hydraulic head is equal to the distance between the water level in the well and the datum plane.

Karst: a type of topography that is formed over limestone, dolomite or gypsum by the enlargement of fractures by dissolving or solution of the rock. Karst is characterised by a dry, often barren surface and underground drainage via channels with closed depressions, swallow holes, sinkholes, caves and large springs.

Lithostratigraphy: Stratigraphy based only on the physical and petrographic features of rocks; the delineation and classification of strata as three-dimensional, lithologically unified bodies.

Meteoric: Pertaining to water of recent atmospheric origin.

Permeability: the term, used in a general sense, refers to the capacity of a rock to transmit water. Such water may move through the rock matrix (*intergranular or primary permeability*) or through fractures, joints, faults, cleavage or other partings (*fracture or secondary permeability*).

Porosity: The ratio of the volume of the interstices to the total volume of rock expressed as a fraction. Effective porosity includes only the interconnected pore spaces available for groundwater transmission; measurements of porosity in the laboratory usually exclude any void spaces caused by cracks or joints (secondary porosity).

Pumping test: A field testing procedure to quantify aquifer properties at a site involving pumping water out of (or less commonly injecting water into) an aquifer and measuring the effect on water levels in that aquifer and sometimes in adjacent strata. There are several different procedures employed depending on the physical properties to be quantified. A constant-rate pumping test is conducted at a steady rate of discharge or injection; a step-test increases the discharge in stages to a maximum value; a bailing test is conducted during the drilling process, using the bailer drilling tool as a water withdrawal method.

Recharge: the process involved in the absorption and addition of water to an aquifer, usually from the surface. Recharge mar be derived directly from precipitation or come from surface water in the form of river or lake bed leakage.

Saline intrusion: The entry of sea water into a coastal aquifer. It may be caused by over pumping fresh water from the aquifer or insufficient natural head on the fresh water aquifer. Sea water is more dense than fresh water and it may form a wedge beneath the fresh water adjacent to the coast.

Specific Capacity Q/s [l/s/m, m^2/d, $m^3/d/m$]: The rate of discharge of water from the well divided by the resulting drawdown on the water level within the well.

Storativity (Coefficient of Storage) S [dimensionless]: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Transmissivity T [m^2/d]: the product of hydraulic conductivity and aquifer thickness, with values usually quoted as m^2/d. It relates to the ability of an aquifer to transmit water through its entire thickness.

Water table: The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere. The static water level in a well in an unconfined aquifer.

Yield Q [l/s, m^3/d]: The volume of water pumped or discharged from a borehole, well or spring.

Appendix 1 Deep Groundwater Advisory Group Statement of Agreement

Deep Groundwater Advisory Group **7 June2006**

Statement of Agreement on resolving the 'Water from France ' Issue

At the meeting of the Deep Groundwater Advisory Group held on 12 April 2006 all members agreed in principle a way in which the question of a flowing freshwater connection with mainland Europe would be dealt with once and for all.

The agreement

Water samples will be obtained from two specially constructed boreholes to be drilled at two locations chosen and divined by the well drillers and diviners as being the most likely to yield water that had its origins in mainland Europe. Exact construction details of the two boreholes will be agreed with technical advisors of BGS and ENTEC, but in essence boreholes will be drilled to whatever depth the drillers and diviners believe is necessary, up to a maximum depth of 750 feet, and fully lined and grouted throughout the depth to avoid cross-contamination with locally sourced water.

The definitive test will compare the isotopic signature of the water sampled from the two test boreholes with that of water from the surface aquifer.

If the joint consultants BGS and ENTEC show that there is a significant difference in the isotopic signature then all parties accept that the sampled water has a different source to that of water from the surface aquifer.

If the joint consultants BGS and ENTEC show that there is not a significant difference in the isotopic signature between the sampled water and water from the surface aquifer then all parties will drop all claims of an underground water connection between Jersey and the European mainland.

A positive test would lead to further work to quantify the useable inflow of water from outside the island.

Acceptance of this agreement in principle

	Signature	Date
Dr Ralph Nichols		13.06.06
Dr John Renouf		13.06.06
Deputy Sarah Ferguson		13.6.06.
Deputy Rob Duhamel		
Mr George Langlois		13.06.06
Mr Lewis de la Haye		13.06.06
Mr Neville George		15-06-06.
pp Mr Howard Snowden	Jonathan Howard.	13 June 06
Mr Chris Newton		13 June 06

Please sign under your name and return to Tim du Feu, Environment Department, Howard Davis Farm, La Route de la Trinite, Trinity, JE3 5JP before 12 June 2006

Deep Groundwater Advisory Group **7 June2006**

Statement of Agreement on resolving the 'Water from France ' Issue

At the meeting of the Deep Groundwater Advisory Group held on 12 April 2006 all members agreed in principle a way in which the question of a flowing freshwater connection with mainland Europe would be dealt with once and for all.

The agreement

Water samples will be obtained from two specially constructed boreholes to be drilled at two locations chosen and divined by the well drillers and diviners as being the most likely to yield water that had its origins in mainland Europe. Exact construction details of the two boreholes will be agreed with technical advisors of BGS and ENTEC, but in essence boreholes will be drilled to whatever depth the drillers and diviners believe is necessary, up to a maximum depth of 750 feet, and fully lined and grouted throughout the depth to avoid cross-contamination with locally sourced water.

The definitive test will compare the isotopic signature of the water sampled from the two test boreholes with that of water from the surface aquifer.

If the joint consultants BGS and ENTEC show that there is a significant difference in the isotopic signature then all parties accept that the sampled water has a different source to that of water from the surface aquifer.

If the joint consultants BGS and ENTEC show that there is not a significant difference in the isotopic signature between the sampled water and water from the surface aquifer then all parties will drop all claims of an underground water connection between Jersey and the European mainland.

A positive test would lead to further work to quantify the useable inflow of water from outside the island.

ENVIRONMENT
20 JUN 2006
H.D.F. TRINITY

Acceptance of this agreement in principle

	Signature	Date
Dr Ralph Nichols		
Dr John Renouf		
Deputy Sarah Ferguson		
Deputy Rob Duhamel	Rob Duhamel	15th June 2006
Mr George Langlois		
Mr Lewis de la Haye		
Mr Neville George		
Mr Howard Snowden		
Mr Chris Newton		

Please sign under your name and return to Tim du Feu, Environment Department, Howard Davis Farm, La Route de la Trinite, Trinity, JE3 5JP before 12 June 2006

Appendix 2 Work Method Statement and Risk Assessment

JOB METHOD STATEMENT

JERSEY 'DEEP' INVESTIGATION BOREHOLES

SUPERVISION OF THE DRILLING AND CONSTRUCTION OF BOREHOLES (INCLUDING "WELLHEAD ACTIVITIES")

1. BACKGROUND

Considerable characterisation has previously been carried out on the shallow aquifer beneath Jersey and it is clear that it is sustained by recharge from local rainfall. Groundwater at depth beneath the Island has also been discussed to a more limited extent and findings in the scientific literature suggest that the deep groundwater represents a limited resource with a relatively small potential for development. However, it has been asserted (principally by local water diviners) that the deep aquifer represents a relatively undeveloped resource of significant size, sustained by groundwater that travels from a source located outside of the Island; (specifically via underground streams that originate in mainland Europe).

In order to ascertain the origin of the deep groundwater and investigate the resource potential of the deep aquifer, two boreholes will be drilled in the east of the Island (at La Rocque and at Pine Walk, St Catherine), at locations identified by Mr George Langlois (a local water diviner) as being positioned directly above 'underground streams' that he has located. Mr Langlois has also provided prediction of depths at which the 'streams' will be encountered (150 ft (45.7m) at La Rocque and 250 ft (76.2 m) bgl at Pine Walk).

The construction of these boreholes will be such that all shallow aquifer horizons are cased out and only groundwater encountered at depth will enter the boreholes. Groundwater encountered at depth will be sampled for inorganic and isotopic analysis to define the age and potential origin of the deep water, whilst subsequent aquifer testing (assuming that sufficient groundwater is obtained) will assist in the assessment of the resource potential of the deep groundwater resource.

2. INTRODUCTION

The work will consist of the drilling of two boreholes by rotary down-hole hammer (DHH) air flush methods. Both boreholes will be drilled and completed in a similar manner but the depths to which plain casing is inserted/grouted and total depths will differ, as detailed below. The exploratory boreholes will be drilled and constructed at locations identified by the Island's water diviners. The boreholes will be located at La Rocque [^{5}7066 ^{54}4720] in the south-east of the Island and adjacent to Pine Walk [^{5}7080 ^{54}5198], to the south of St Catherine in the north-east of the island. It is essential that the two boreholes be positioned at exactly the positions indicated by the diviner. The two borehole locations are presently marked by stakes but it is considered essential that the diviner is on site as operations commence at each site, to ensure that the rig is correctly positioned so as to drill exactly on the required locations.

It is anticipated that the geology underlying the La Rocque site will consist of a relatively thin soil horizon overlying granite, which is likely to be heavily weathered near surface but progressively less weathered with depth. At the Pine Walk site, it is anticipated that the geology beneath the soil horizon will consist of the Bouley Bay Rhyolite Formation, which again is likely to be most heavily weathered near surface but progressively less so with depth. A north-east/south-west trending fault zone is present to the south-east of the Pine Walk site and, in consequence, the rocks beneath the site may be more fractured that than would be normal for this formation. Little is known regarding hydrogeological conditions beneath either site but in both cases the water table is likely to occur at an elevation that is within a few metres of sea level, and may vary in response to tidal fluctuations. No information is available regarding potential piezometric heads for potential 'deep' productive horizons at either site. It is however possible that confined groundwater may be encountered at depth (possibly below sea level), which may rise to a higher level in the borehole and possibly overflow at the ground surface if sufficient head is present.

The common completion of the two boreholes is shown in Figure 1. The depths to which drilling at a diameter of 200 mm (8 inch), installation/grouting of 152 mm ID, and final total depth of the two boreholes are also indicated on Figure 1.

Figure 1 'DEEP' INVESTIGATION BOREHOLE CONSTRUCTION

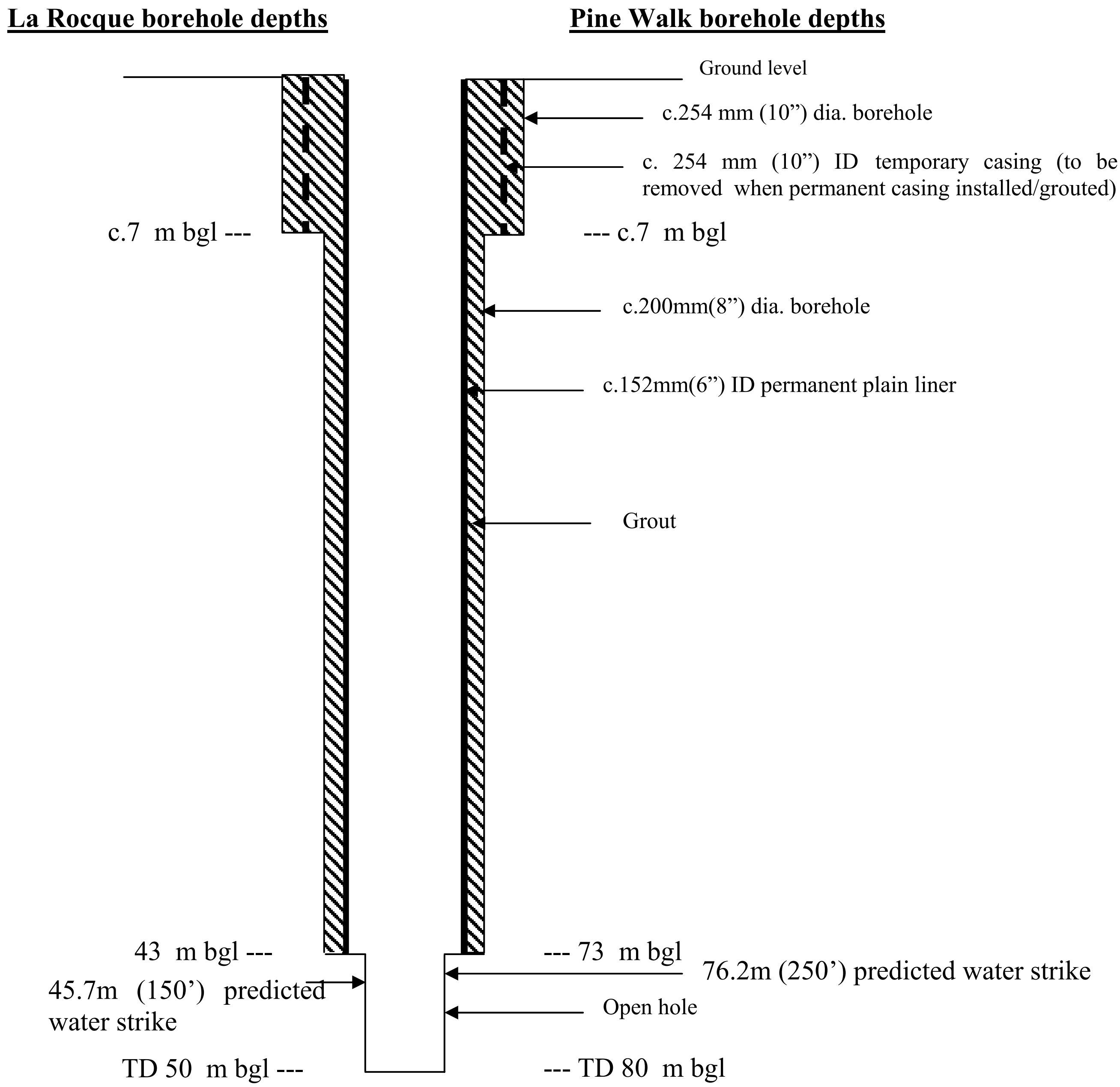
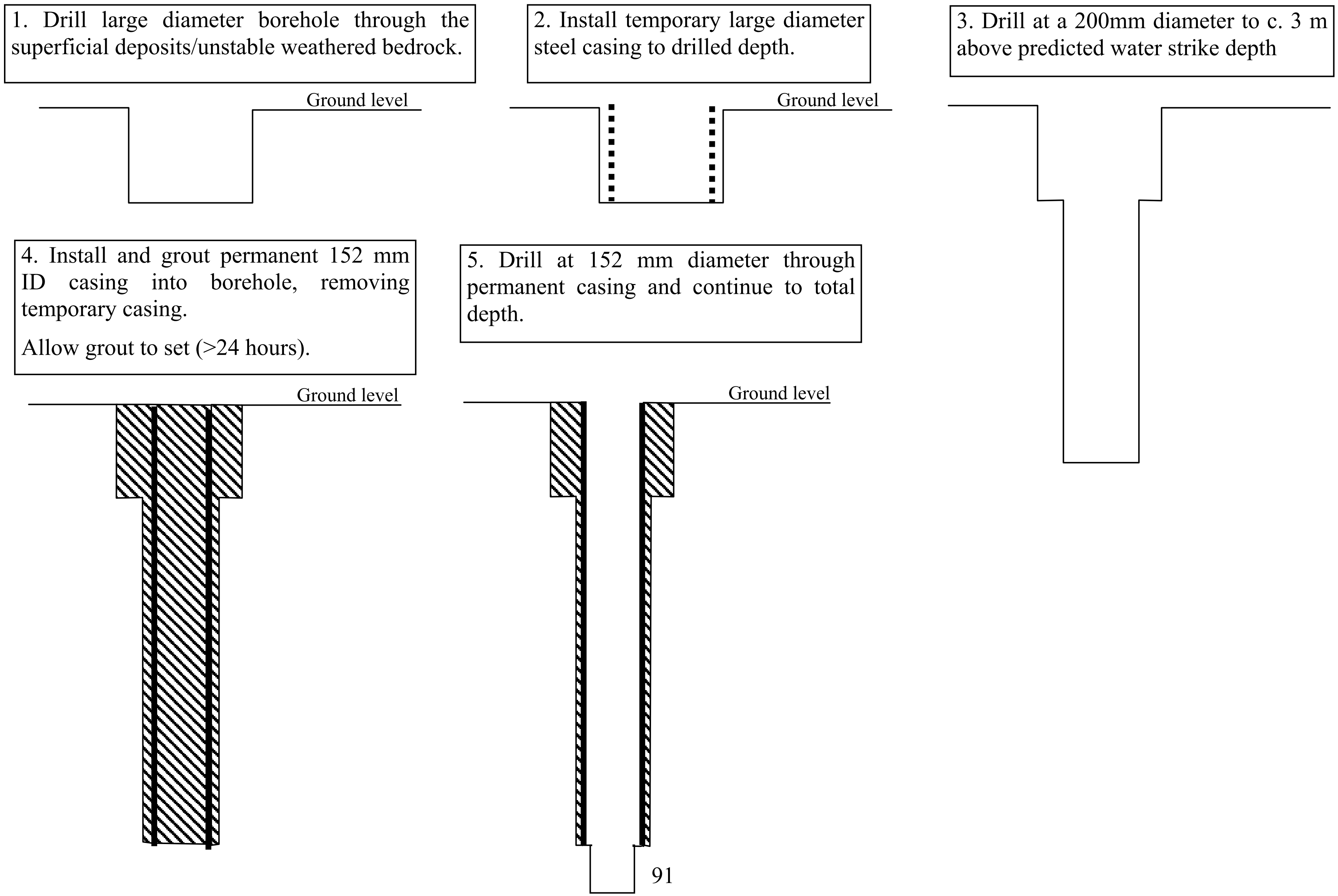


Figure 2 JERSEY ‘DEEP’ INVESTIGATION BOREHOLES : BASIC DRILLING AND CONSTRUCTION PROCESS



3. BOREHOLE DRILLING AND CONSTRUCTION

The sequence of events that will occur at each of the two borehole sites will be as follows:

- move to site and set up at the precise location specified (including, if required, the erection of temporary fencing to define the drilling site).
- drill @ 254 mm (10 inch) diameter to below the base of unconsolidated/weathered materials (c. 7 m bgl) and install 254 mm OD plain steel drill casing.
- drill @ 200mm (8 inch) diameter to the required depth (43m at La Rocque and 73 m bgl at Pine Walk).
- insert permanent 152 mm (6 inch) ID casing to the full depth of the borehole.
- insert cement grout under pressure into the borehole from total depth to ground surface using a tremmie pipe (withdrawing the tremmie pipe as the casing and annulus fills).
- grout should be left to harden for a minimum of 24 hours.
- drill (at a diameter of c.152 mm (6 inch)) back through the casing to the original total depth.
- drill open hole at a diameter of 152 mm to final total depth (50m at La Rocque and 80 m bgl at Pine Walk).
- clean hole of cuttings and develop by flushing until water produced is clean
- install surface completion.
- make good, dismantle and move to next site/demobilise.

The proposed basic stages for drilling and constructing the two boreholes are shown diagrammatically in Figure 2.

4. JOB METHOD STATEMENT

The supervision of drilling contractors involves:

- close liaison with the workforce involved in the drilling of the borehole.
- ensuring the borehole is correctly and safely drilled to the correct required depth at the correct locality and with the correct downhole completion.
- ensuring and supervising all ancillary work connected with these tasks are correctly completed, including site clearing and restoration after site works.
- ensuring that all current Heath and Safety aspects are complied with.
- recording all events and measurements in the site diary and geological logging.

It is the responsibility of the Site Supervisor in any drilling operation to ensure that Personal Protective Equipment (PPE) is worn at all times. The amount and nature of PPE worn by contractors will vary according to the H&S policy of the contracting company on site but as a **minimum** a hard hat and steel toe capped boots must be worn to comply with legal requirements. Other basic PPE such as ear defenders, safety glasses, overalls, suitable gloves etc. should also be considered. The supervisor is also responsible for the enforcement of BGS H&S rules, as determined by the activity in hand and by reference to the Risk Assessments (RA's) in force at the time.

Extreme caution should be exercised when moving around the drilling sites due to the presence of operating heavy plant and the general uneven nature of ground surfaces. Close proximity to moving/operating equipment should be avoided as far as possible.

A fully charged mobile telephone should be carried at all times for use in case of an emergency.

The location for the drilling of the borehole should be checked well before any rig or ancillary equipment movements and setting up are commenced. The site should be checked for accessibility and potential logistical problems (including for the presence of underground services by contacting the local utility companies, undertaking a CAT scan and, where necessary, hand digging a trial pit) BEFORE DRILLING COMMENCES. It is essential that the two boreholes be drilled at exactly the positions indicated by the water diviner. The two borehole locations have been marked by stakes but it is possible that the stakes could have been moved since they were originally positioned. It is therefore considered essential that Mr Langlois is on site when the rig is set up at each site, to ensure that the rig is correctly positioned, so as to drill exactly at the location specified by him.

There are a number of "wellhead activities" which should be carried out either by the Site Supervisor or the drilling rig operators as listed below. It is however the responsibility of the Site Supervisor to ensure that all of these activities are in fact carried out;

- maintenance of a site diary, (recording all events, site visitors, drilling progress, geological logs, water strikes etc.)
- maintaining a photographic record of significant events whist drilling/constructing the two boreholes.
- maintaining a log of drilling penetration rates.
- the logging of drilling cuttings, including the photographing of representative samples of cuttings laid in sequence along lengths of half pipe as pseudo-cores.
- recording of the depths of all apparent water strikes.
- measurement and recording of water flush yield following all apparent water strikes.
- the sampling of flush water following each water strike for inorganic analysis.
- measurement of rest water level below ground level after each significant cessation of drilling (eg before drilling commenced in the morning, after lunch or other cessation that exceeds c.1 hour)
- plumbing of borehole depth on any occasion that the drilling tools are removed from the borehole.
- careful monitoring of the grouting procedure, in particular that the volume of grout introduced into the borehole is sufficient to completely fill the annulus and inside of the casing from total depth to ground level.

a. Site diary

A daily record of all events that occur during the drilling and construction of the two exploratory boreholes will be maintained by the Site Supervisor(s). Where appropriate the time at which events occur (eg. the delivery of materials, the arrival/departure of staff and visitors (including names and who they represent) etc. should be recorded in the Site Diary, as should all aspects of the drilling operation, including drilling progress, geological log information, water strike depths and yields, water samples etc.

The drilling contractor should also provide a daily log, to include information on drilling progress, diameters/methods used, stoppages, casings installed/removed, materials used etc. for approval by the Site Supervisor. Digital photographs should be taken at the various stages of the drilling and borehole construction process, from pre-setup to completion.

b. Logging of drilling penetration rate

One method of knowing the nature of the material being drilled is to record the rate (speed) of drilling. Softer, loose, friable materials will generally be penetrated more rapidly than hard material. A log of penetration rates will give a comparative indication of the variation of materials drilled.

The logging of penetration rates can be done by a variety of methods. A suggested method follows:

> Immediately before breaking surface at each borehole, the driller will mark at convenient points on the rig drill string, a series of marks to enable a rate of progress of drilling to be determined. Marks at suitable (0.5m) intervals shall be used. When drilling commences, record accurate timings of the movement of these marks, relative to a convenient datum. In addition, the depth and time at which any noticeable change in rate of penetration occurred should also be recorded. Continue this process throughout the total drilling depth of the borehole; an accurate depth/time record and hence penetration rate log will thus be produced.
>
> Also note, by communication with the driller, the weight being applied to the drill bit if it becomes necessary to use any alternative drilling method (such as a tricone bit with air flush). Record as bit pressure if known. If such pressures are not known, the state shall be recorded as "positive pressure", "gravity drilling" or "drilling being held back" (by the application of rig brakes). Details from these logs should be recorded on suitable log sheets such as the core logging sheets or similar.

c. Logging of drill cuttings

Samples of the drill cuttings returned to the surface in the air flush will be taken in order to assist in logging the subsurface material and for possible future analysis. Samples will be taken at 0.5m intervals, as the borehole is drilled, placed in heavy duty plastic bags and labeled. Additional samples may be taken where a significant colour or lithological change occurs at a depth between the normal sampling intervals. An indelible marker pen will be used to record the borehole identification and sample depth on each plastic bag.

CAREFULLY log drill return cuttings (by visual inspection) at the time of collection to determine the exact nature of the sub-surface materials, noting the depths of any changes of geology and the nature (colour, lithology, moisture, resistance to penetration by a rattling/bouncing drill string etc.) of the material. Materials should be described in the style recommended in BS 5930 as far as is possible. Information is to be recorded on a suitable log sheet and an abbreviated version recorded in the site diary.

d. Water Strikes

The depths at which any water strike occurs should be accurately recorded and the flush yield should be measured, preferably using a settling tank with a 'v' notch weir at the outlet or similar suitable equipment. All measurements should be recorded in the site diary.

In addition, any water encountered during drilling, for example from a perched water table or productive horizons that occur at depth, should be collected for inorganic chemical analysis. It is usual practice for any "first strike" water samples to be taken as a matter of course during any drilling operation that encounters the water table but additional samples will be collected if additional water strikes occur at greater depth whilst drilling the two exploratory boreholes. Each sample will be obtained after flushing the borehole until the water is reasonably clean and will consist of two 100 ml filtered water samples in bottles that will be provided by the Water Resources Section. In addition the alkalinity, conductivity, temperature, dissolved oxygen concentration and pH of each water sample will be determined on site and recorded in the site diary.

e. Rest water levels and borehole depth

Rest water levels below ground level should be measured using a water level dipper after each significant cessation of drilling (e.g. before drilling commences each morning, after a lunch break or other significant cessation of drilling). Such measurements should be recorded together with the date, time and record of the period since drilling/flushing ceased in the site diary.

The borehole depth should be plumbed whenever access to the borehole is available (i.e. if the drilling tools are removed for any reason). Again, such measurements should be recorded together with the date and time in the site diary

f. Borehole drilling and construction

It is crucial that the Site Supervisor closely monitors and ensures that the two boreholes are drilled and constructed according to specifications. The borehole drilling and construction procedures are described in Section 1 and shown diagrammatically in Figures 1 and 2. It is particularly important that drilling at 200mm diameter ceases at the specified depths in each borehole (43m at La Rocque and 73 m bgl at Pine Walk) and that the permanent plain casing be installed and grouted in place at that depth. The volume of grout emplaced under pressure by tremmie pipe in the borehole should also be closely monitored to ensure that the volume is sufficient to completely fill both the casing volume and that of the annulus, from the drilled depth of the borehole to the ground surface

The depths to which casing is to be installed and grouted in place in each borehole are approximately three metres above the predicted water strike depths provided by Mr Langlois. The plain casing and grout will ensure that all shallower water bearing horizons are sealed and that only groundwater originating from the deepest water strike will be able to enter the borehole. Once grouting is complete, the borehole should be regularly checked to ensure that the backfill level remains at ground surface (grout may migrate into fractures penetrated by the borehole) and should be topped up as necessary. The grouted borehole should be left in a secure condition until the grout has completely hardened. It is anticipated that the grout will require between 24 and 36 hours to harden adequately before drilling can recommence. Drilling at 152 mm diameter through the grout filled casing should then continue until the original depth is regained. Careful note should be taken of any indication that water is entering this section of the borehole and the depth at which this occurs, as this would indicate that the seal is incomplete or has been breached. Ideally, no water should be encountered until all of the grout has been drilled out of the plain casing. Drilling at the same diameter should continue to the total specified depth (50m at La Rocque and 80 m bgl at Pine Walk).

Once all drilling has been completed it will be necessary to install a surface or wellhead construction, as specified in the contractor's tender submission. Each site should be made good at the surface before moving the rig to the next site unless it is planned to reinstate the sites "en-bloc" after drilling operations are complete, such as in times of excessive disturbance during wet ground conditions, where it may be advantageous to wait until ground dries out before reinstatement.

5. H&S RISK ASSESSMENT

A specific H&S Risk Assessment has been produced for this Job Method Statement (JMS), based on similar activities during previous periods of work on earlier drilling projects. The Risk Assessment should be regarded as subject to constant review, as necessary in the light of specific local site conditions and occurrences. **Attention is drawn to this associated document.**

It should also be noted that any work associated with this JMS will require a minimum of Personal Protective Equipment (PPE) to be worn whilst working on drilling site. MINIMUM PPE will consist of eye protection, hard hat, steel toe capped boots, ear defenders and gloves but in addition thermal clothing and/or wet weather clothing may also be required during periods of inclement weather.

The ‘working’ area around the rig and ancillary equipment should be defined using posts and flagging tape. All staff entering the working zone will wear minimum PPE and other optional items as required by prevailing conditions. The Site Supervisor will ensure that no visitors to the site be permitted to enter this zone. Visitors should only enter the general site area by prior arrangement with Water Resources Section (WRS) and be accompanied by a member of WRS staff. Unexpected visitors should be referred to WRS to arrange a suitable time to be accompanied onto the site. Even visitors that are wearing the minimum required PPE should not be permitted to enter the working area zone around the rig and ancillary equipment. If visitors insist on entering this delineated area, all drilling operations should be suspended until such time as it is considered safe to resume operations.

RISK ASSESSMENT FORM BRITISH GEOLOGICAL SURVEY

ACTIVITY: SUPERVISION OF THE DRILLING AND CONSTRUCTION OF BOREHOLES IN JERSEY (INCLUDING "WELLHEAD ACTIVITIES")					
Hazard	**Hazard effect**	**Risk** **(P = degree of possibility)** **(E = probable effect)**	**Risk factor** **(from matrix in Appendix)**	**Minimise risk by:**	**Residual risk**
1. Driving on official duty under "normal" circumstances					
i) Accident/ or other incident while driving on public roads	Physical injury	(P) Possible (E) Fatality/Major injury	2 – 10	Drive carefully and adhere to current NERC driving guidelines	Low – moderate
ii) Unfamiliarity with local roads/routes	Potential physical injury due to accident	(P) Possible (E) Fatality/Major injury	2 - 10	Drive carefully, keep to Jersey speed limits (max. 40 mph). WRS officer to accompany Supervisor to each drill site on first visit.	Low

ACTIVITY: SUPERVISION OF THE DRILLING AND CONSTRUCTION OF BOREHOLES IN JERSEY (INCLUDING "WELLHEAD ACTIVITIES")

Hazard	Hazard effect	Risk (P = degree of possibility) (E = probable effect)	Risk factor (from matrix in Appendix)	Minimise risk by:	Residual risk
2. Entry into and working within drilling site				**General Note** Carry (or maintain access to) a mobile phone at all times to summon assistance as required.	
i). Potential contact with any hazardous materials including noxious fumes (from engines etc.)	Damage to health by skin contact and/or inhalation.	(P) Possible (E) Long term illness	2 – 10	**1.** Conform to SI guidelines for working on drill sites **2.** Wear protective overalls or other suitable PPE as required **3.** No smoking/eating/drinking within defined drill site area.	Low
ii) Uneven surface of working site.	Personal injury via slips, trips and falls	(P) Possible (E) Injury requiring medical attention	4	General due care and attention when moving around site	Very low
iii.) Working on, near or next to the public or other highway .	Risk of injury from road traffic of all kinds	(P) Possible (E) Major injury	12	Sites are within fields, away from roads. Ensure vigilance at all times when leaving site and entering adjacent roads. Keep off public highway wherever possible – including parking off-road.	Low

ACTIVITY: SUPERVISION OF THE DRILLING AND CONSTRUCTION OF BOREHOLES IN JERSEY (INCLUDING "WELLHEAD ACTIVITIES")					
Hazard	**Hazard effect**	**Risk** **(P = degree of possibility)** **(E = probable effect)**	**Risk factor** **(from matrix in Appendix)**	**Minimise risk by:**	**Residual risk**
3. Drilling rig and all other associated equipment				**COMMENTS FOR ALL HAZARDS IN THIS SECTION**	
i) Presence of machinery and heavy equipment	Physical injury and/or noise	(P) Likely (E) Major injury	3 - 12	**1**. Wear protective clothing: Hard hat and steel toe capped boots AS A MINIMUM with ear defenders, eye protection (safety glasses), overalls, dust mask and protective gloves as required	Low
ii) Rotating parts	Personal entanglement (body and/or clothing)	(P) Possible (E) Major injury	2 - 8	**2.** No smoking/eating/ drinking **3.** Avoid close proximity to drilling and ancillary equipment as far as possible	
iii) Flammable materials	Fire	(P) Remote possibility (E) Fatal injury	1 – 5	**4**. Be aware and vigilant	
iv) Exposure to dust	Inhallation of dust leading to respiratory injury	(P) Possible (E) Serious injury	6	**5**. Ensure machinery guards are in place wherever possible. **6.** Flammable liquids/materials to be stores in suitable fire proof containers.	

ACTIVITY: SUPERVISION OF THE DRILLING AND CONSTRUCTION OF BOREHOLES IN JERSEY (INCLUDING "WELLHEAD ACTIVITIES")					
Hazard	**Hazard effect**	**Risk** (P = degree of possibility) (E = probable effect)	**Risk factor** (from matrix in Appendix)	**Minimise risk by:**	**Residual risk**
4. Air compressor and/or water/grout pumps.					
i) Possible exposure to high pressure air/water/grout flow	Physical damage to parts of or all of the body	(P) Possible (E) Serious injury	8	Keep as far away from compressor/pump and associated pipes as practically possible. Be aware and vigilant around compressor/pump whilst working.	Low
ii) Bursting and/or disconnection of pipes etc.	Physical injury caused by flailing loose pipes	(P) Possible (E) Serious injury	8	Ensure hose restraint cables are used to prevent flailing hoses.	Low
iii) Possible violent breakdown of compressor and/or pump(s) (mechanical failure)	Physical injury caused by violent explosion and/or flying components	(P) Possible (E) Serious injury	8	Keep as far away from compressor/pump and associated pipes as practically possible.	Low

ACTIVITY: SUPERVISION OF THE DRILLING AND CONSTRUCTION OF BOREHOLES IN JERSEY (INCLUDING "WELLHEAD ACTIVITIES")					
Hazard	**Hazard effect**	**Risk** **(P = degree of possibility)** **(E = probable effect)**	**Risk factor** **(from matrix in Appendix)**	**Minimise risk by:**	**Residual risk**
5. Logging of drill cuttings at wellhead, measuring water levels & water sampling					
i) Working in proximity to drilling rig	See 2 to 4 above	See 2 to 4 above	See 2 to 4 above	See 2 to 4 above	Low
iii) Working with abrasive materials (drill cuttings)	Possibility of injury or illness via abrasion (sand) and/or inhalation (dust)	(P) Possible (E) Serious illness (by inhalation of dust)	2	Wear protective gloves and dust mask as required	Low

ACTIVITY: SUPERVISION OF THE DRILLING AND CONSTRUCTION OF BOREHOLES IN JERSEY (INCLUDING "WELLHEAD ACTIVITIES")					
Hazard	**Hazard effect**	**Risk** **(P = degree of possibility)** **(E = probable effect)**	**Risk factor** **(from matrix in Appendix)**	**Minimise risk by:**	**Residual risk**
6. Working on well completions (downhole and surface)					
i) Working in proximity to drilling rig	See 2 to 4 above	See 2 to 4 above	See 2 to 4 above	See 2 to 4 above	Low
ii) Working with abrasive and cementitious materials (sand, cement and/or bentonite) materials	Possibility of injury/illness via abrasion (sand) and/or inhalation (cementitious materials)	(P) Possible (E) Serious illness (by inhalation of cementitious materials)	6	Wear gloves and dust masks if working with materials in question	Very low
Final assessment: Residual risk is low				**Overall risk: Low**	
Assessor: CS Cheney		**Date:** 24 August 2006	**Review:**		

RISK ASSESSMENT GUIDANCE NOTES AND MATRIX

Carrying out risk assessments

Appendix 3

1. Identifying the hazards

a. Take a logical approach (based on experience), set up headings such as those listed in b. below, or use one of the approaches set out in the *Guidance note: safety auditing* (issued in February 1992; copies available from your local safety adviser or the NERC safety adviser).

b. Examples of the types of heading to use are given below:

i fire - build-up of rubbish, blocked exits, procedures not known to or understood by staff.
ii. environmental - lighting, ventilation, fieldwork in adverse conditions.
iii. physical - noise, radiation.
iv. biological - genetically modified micro-organisms, allergens, animal-borne diseases.
v. electrical - wrongly-wired plugs, overloaded sockets, overloaded wiring.
vi. machinery and equipment - using power tools, moving parts of machinery.
vii. activity related - repetitive strain, manual handling.

These examples are not intended to be exhaustive.

2. Evaluating the risks

a. There are many ways of evaluating risks, varying from complex statistical analyses used by insurance companies and chemical works to simple "Is it acceptable? Yes/no" systems for minor risks. We suggest the following matrix for setting priorities, combining measures of probability (across) and severity (down):

	remote possibility	possible	likely	highly probable	virtual certainty
minor injury or illness	1	2	3	4	5
injury/illness requiring medical attention	2	4	6	8	10
injury/illness involving more than 3 days off work	3	6	9	12	15
major injury or long term illness	4	8	12	16	20
fatal injury/illness, permanent disability	5	10	15	20	25

b. Once you have determined the risk factor, use the second matrix (below) to inform your decision on further action:

rating	risk	action
1-2	negligible	no further action
3-5	low	further action as resources allow
6-9	high	requires action; set timetable for improvements
10-15	very high	priority action, control as soon as possible
16-25	unacceptable	stop activity until risk reduced

c. While the judgements used in reaching these decisions are subjective, they do help to concentrate attention on the most serious risks.

d. Controls can take many forms. All are intended to reduce risk. Some of the most important are:

i. substitution - changing the way a job is done, or equipment/material used, to remove the hazard or replace it with a less serious one.
ii. designing or engineering the hazard out of the process.
iii. providing proper information, instruction, training and supervision.
iv. personal protective equipment.

e. There is no need to "re-invent the wheel". Many excellent control stategies already exist in NERC or local guidance. It is quite legitimate to make use of them if they provide the necessary protection for staff. Once the controls have been put in place, check that they have actually reduced the residual risk.

4. Monitor

Risk assessments should not be simply filed away and forgotten. Line managers should check compliance with agreed procedures, to ensure that control procedures and precautions are working as intended. If they are not, change them.

5. Review

There should be a regular review of risk assessments to ensure that they are still up to date and adequate. Check them whenever there are any significant changes in work procedures, materials or any other factor. This need not be time-consuming, but should normally be done annually.

References

1. Management of Health & Safety at Work Regulations 1992 Approved Code of Practice L21 ISBN 07176 04128.*+
2. Successful Health and Safety Management HS(G)65 1991 ISBN 07176 0716X. * +
3. Upper Limb Disorders: Assessing the risks IND(G)171(L) ISBN 07176 07518. +
4. Risk: Analysis, perception and management. The Royal Society 1992 ISBN 0 85403 4676.
5. 5 steps to risk assessment; IND (G) 136L. * +
6. VDU work station checklist for risk assessment. * +
7. NERC guidance note: use of VDUs; HS3/93. *
*Copy held by each local safety adviser. + Published by HSE Books.

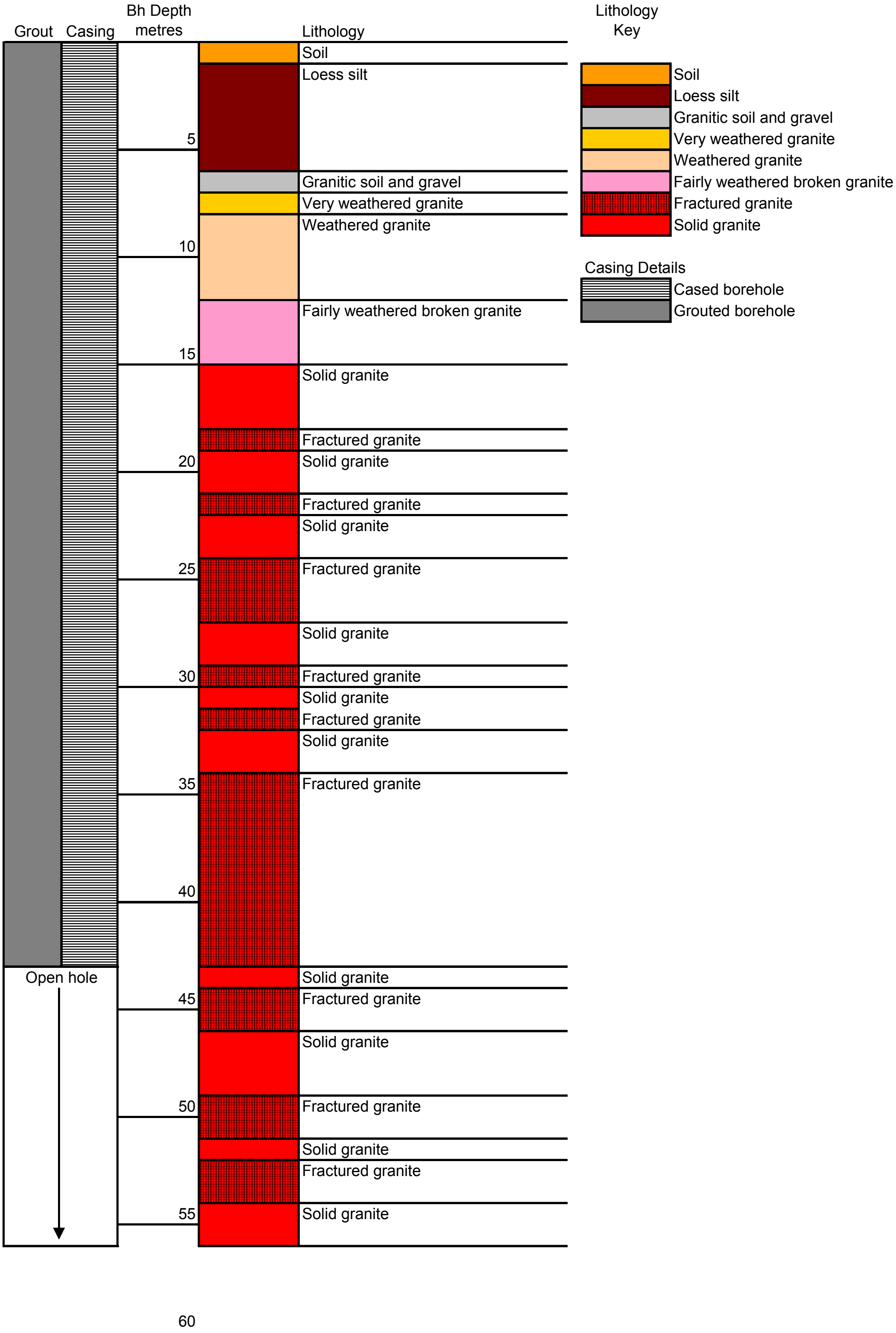
Appendix 3 Lithological Log for the La Rocque Borehole

Borehole geological log

Location La Rocque, south east Jersey

Date started 12/9/2006

Date completed 16/9/2006



Depth (metres)	Lithology
0.0 – 0.5	7.5YR4/2 brown loamy silt top soil
0.5 – 1.0	7.5YR5/1 damp grey clayey silt
1.0 – 1.5	7.5YR6/1 grey and7.5YR6/8 strong brown soft silt
1.5 – 2.0	7.5YR5/6 strong brown damp silt
2.0 – 2.5	7.5YR4/3 brown silt with mica and black brown peaty fragments damp
2.5 – 3.0	10YR5/1 grey and 10YR5/6 yellowish brown damp silt
3.0 – 3.5	10YR5/1 grey and 10YR4/6 dark yellowish brown damp silt
3.5 – 4.0	10YR4/1 dark grey damp silt some mica
4.0 – 4.5	10YR4/2 dark greyish brown silt, very wet
4.5 – 5.0	10YR4/2 dark greyish brown silt, very wet
5.0 – 5.5	Gley 1 3/n very dark grey silt with 10YR4/1 dark grey silt damp
5.5 – 6.0	5Y6/6 olive yellow and 5Y4/1 dark grey slightly clayey silt and fine sand
6.0 – 6.5	Rounded gravel of orange pink granite fragments
6.5 – 7.0	Light grey soft sand and gravel of very weathered orange pink granite
7.0 – 7.5	Grey sand of weathered orange pink granite with large broken fragments and much milky white quartz
7.5 – 8.0	Grey sandy weathered pink granite with large 25mm black grey and pink fragments with some white quartz
8.0 – 8.5	Greyish dirty weathered pink granite with large fragments
8.5 – 9.0	Weathered fragmented pink granite with odd large fragments
9.0 – 9.5	Orange and grey weathered pink granite
9.5 – 10.0	Orange and white grey weathered pink granite
10.0 – 10.5	Orange , grey and black weathered pink granite with some white vein quartz. Some water, took sample A10. 8" steel casing emplaced to 10.5 metres behind Odex type drilling bit. New Bull rock hammer and bit used to drill hole for emplacement of 6" ID plastic pipe is 2.37m long below drill pipe. Drill pipe in 3m lengths.
10.5 – 11.0	Orange grey fine grained weathered pink granite with some large quartz fragments. **Flow rate 0.9 l/sec**
11.0 – 11.5	Orange, milky white and black coarse sand grain-sized fragments of weathered granite
11.5 – 12.0	Orange, milky white and black gravel sized fragments of broken granite
12.0 – 12.5	Orange pink feldspars, milky white quartz and black hornblende coarse sand sized fragments of granite
12.5 – 13.0	Orange pink feldspars, milky white quartz and black hornblende of gravel sized fragments of granite
13.0 – 13.5	Light orange grey medium to coarse sand-grain sized hard fine grained granite of orange feldspar, milky white quartz and black hornblende. **Flow rate 0.7 l/sec**
13.5 – 14.0	Light grey and orange fine grained granite of orange feldspar, milky white quartz and black hornblende.
14.0 – 14.5	Coarse grained and fractured orange and milky white granite of orange feldspar, milky white quartz and black hornblende.
14.5 – 15.0	Medium grained broken granite with bright orange feldspar, milky white quartz and black hornblende.
15.0 – 15.5	Fine grained granite with bright orange and pink feldspar, milky white quartz and black hornblende.

15.5 – 16.0	Broken medium granite with pink and orange feldspars, milky white quartz and black hornblende
16.0 – 16.5	Medium grained granite with bright orange feldspars, milky quartz and black hornblende. **Flow rate 0.6 l/sec**
16.5 – 17.0	Medium grained granite of pink feldspars, milky quartz and black hornblende.
17.0 – 17.5	Medium to coarse-grained granite with pink to red feldspars, milky quartz and black hornblende.
17.5 – 18.0	Blocky fragments of medium to coarse-grained granite with pink to red feldspars, milky quartz and black hornblende.
18.0 – 18.5	25 mm blocky fragments of coarse-grained granite with red feldspars, milky quartz and black hornblende, some feldspars rotten red in places with yellow staining and blocky fractures. **FRACTURED**
18.5 – 19.0	Coarse grained granite with pink feldspars, milky quartz and some black hornblende, smaller fragments little to no yellow staining.
19.0 – 19.5	Medium to coarse-grained granite with pink feldspars, milky quartz and black hornblende. **Flow rate 1.6 l/sec**
19.5 – 20.0	Medium to coarse-grained granite with pink feldspars, white quartz and reduced black hornblende, small fragments.
20.0 – 20.5	Medium-grained granite mainly white quartz and pink feldspars with little black hornblende.
20.5 – 21.0	Greyish pink fine-grained granite with much white quartz, some red feldspars and black hornblende.
21.0 – 21.5	Pinkish grey fine-grained granite with much white quartz and pink feldspar, some black hornblende. Odd large fragment with yellow staining. **FRACTURED**
21.5 – 22.0	Reddish grey medium to fine-grained granite, small medium to coarse sand-grain sized fragments with red pink feldspars, white quartz and black hornblende.
22.0 – 22.5	Pinkish grey medium-grained granite with pink feldspars, white quartz and much black hornblende. Gravel sized fragments. **Flow rate 2.3 l/sec**
22.5 – 23.0	Pinkish grey medium-grained granite with pink feldspars, white quartz and some black hornblende. Coarse-grained sand to gravel size fragments
23.0 – 23.5	Greyish pink medium-grained granite with pink to reddish pink feldspars, white quartz and much black hornblende, some yellow staining. **FRACTURED**.
23.5 – 24.0	Greyish pink medium-grained granite with pink to reddish pink feldspars, white quartz and some black hornblende, with odd yellow staining. **FRACTURED.**
24.0 – 24.5	Pinkish grey medium to coarse-grained granite with pink to red feldspars, milky white quartz and some black hornblende, some large 20mm fragments with yellow staining. **FRACTURED**.
24.5 – 25.0	Pinkish grey medium-grained granite with pink feldspars, white quartz and black hornblende.
25.0 – 25.5	Pinkish grey medium to coarse-grained granite with pink to red feldspars, white quartz and much black hornblende, some yellow stained fragments. **FRACTURED**. **Flow rate 2.5 l/sec**
25.5 – 26.0	Pinkish grey medium-grained granite with pink feldspars, white quartz

	and some black hornblende, with fine grained purple fragments of vein material.
26.0 – 26.5	Pinkish grey medium-grained granite with pink feldspars, milky white quartz and some black hornblende, with fine grained purple vein material and some yellow staining. **FRACTURED**.
26.5 – 27.0	Greyish pink fine to medium-grained granite with pink feldspars, white to grey quartz and some black hornblende, some light green white staining. Water discoloured red. **FRACTURED**
27.0 – 27.5	Pinkish grey fine to medium-grained granite with much grey to white quartz and some pink feldspars, little black hornblende.
27.5 – 28.0	Greyish pink medium-grained granite with light pink feldspars, white quartz and some black hornblende.
28.0 – 28.5	Greyish pink medium-grained granite with light pink feldspars, white quartz and black hornblende. **Flow rate 2.8 l/sec**
28.5 – 29.0	Greyish pink medium-grained granite with white to light grey quartz, pink to orange feldspars and some black hornblende
29.0 – 29.5	Greyish pink medium-grained granite with milky white quartz, pink feldspars and some black hornblende.
29.5 – 30.0	Greyish pink medium-grained granite with milky white to light purple quartz, pink feldspars and black hornblende, some yellow white staining. **FRACTURED**
30.0 – 30.5	Pinkish grey medium to fine-grained granite with milky white quartz, light pink feldspars and some black hornblende
30.5 – 31.0	Pinkish grey fine to medium-grained granite with milky white quartz, light pink feldspars and some black hornblende
31.0 – 31.5	Pinkish grey fine-grained granite with milky white to white quartz, very pale pink feldspars and some black hornblende, with odd large 20mm fragment with yellow staining. **Flow rate 5 l/sec. FRACTURED**
31.5 – 32.0	Pinkish grey medium-grained granite with milky white quartz, pale pink to red feldspars and black hornblende sometimes in veins with some green staining.
32.0 – 32.5	Greyish pink medium-grained granite with milky white quartz, pale pink feldspars and black hornblende
32.5 – 33.0	Greyish pink fine to medium-grained granite with milky white quartz, pale pink feldspars and much black hornblende
33.0 – 33.5	Greyish pink fine to medium-grained granite with milky white quartz, pale pink feldspars and some black hornblende
33.5 – 34.0	Greyish pink medium-grained granite with milky white quartz, pink to orange feldspars and black hornblende, some yellow staining. **FRACTURED**
34.0 – 34.5	Greyish pink fine to medium-grained granite with milky white quartz, pink to orange feldspars and some black hornblende. **Flow rate 4 l/sec**
34.5 – 35.0	Greyish pink medium to coarse-grained granite with milky white quartz, pink to red feldspars and increased black hornblende, gravel sized fragments with yellow staining. **FRACTURED**
35.0 – 35.5	Greyish pink medium-grained granite with milky white to light grey quartz, pink orange and red feldspars and much black hornblende, gravel sized fragments with yellow staining. **FRACTURED**
35.5 – 36.0	Greyish pink to red medium-grained granite with milky white quartz, pink to dark red feldspars and black hornblende
36.0 – 36.5	Greyish red to pink medium-grained granite with milky white quartz,

	pink to orange And red feldspars and some black hornblende with yellow staining. **FRACTURED**
36.5 – 37.0	Greyish pink medium to fine-grained granite with milky white quartz, pink to orange and red feldspars and some black hornblende, with a little yellow staining. **FRACTURED**
37.0 – 37.5	Greyish pink medium to fine-grained granite with milky white quartz, orange pink and red feldspars and black hornblende with increased yellow staining. **FRACTURED**. Hammer stuck. **Too much water caused bund to collapse**
37.5 – 38.0	Greyish red and black medium-grained granite with milky white quartz, pink red and orange feldspars and much black hornblende, in gravel sized fragments.
38.0 – 38.5	Pinkish dark grey fine to medium-grained granite with milky white to grey quartz, pink to red feldspars and much black hornblende with some yellow staining. **FRACTURED**.
38.5 – 39.0	Pinkish dark grey fine to medium-grained granite with milky white quartz, pink to red feldspars and much black hornblende, increased yellow staining. **FRACTURED**
39.0 – 39.5	Greyish pink medium-grained granite with milky white quartz, pink feldspars and some black hornblende with much yellow staining. **FRACTURED**. Water discoloured yellow
39.5 – 40.0	Greyish pink medium-grained granite with milky white quartz, pink feldspars and some black hornblende with much yellow staining. **FRACTURED**. Water discoloured yellow
40.0 – 40.5	Yellowish grey and pink fine-grained granite with milky white quartz, pale pink feldspars and some black hornblende with much yellow staining. **FRACTURED. Too much water caused bund to collapse**
40.5 – 41.0	Grey and red medium to coarse-grained granite with milky white to grey quartz, pink to dark red and orange feldspars and much black hornblende with yellow and green staining. **FRACTURED**
41.0 – 41.5	Pinkish grey medium-grained granite with milky white quartz, pink orange and dark red feldspars and much black hornblende.
41.5 – 42.0	Greyish dark pink medium-grained granite with milky white to white quartz, pink to orange feldspars and some black hornblende with much yellow staining and rotten feldspars. **FRACTURED**
42.0 – 42.5	Dark pinkish grey medium-grained granite with milky white quartz, dark pink feldspars and much black hornblende with some yellow staining and yellow rotten feldspar. **FRACTURED**
42.5 – 43.0	Dark pinkish grey medium-grained granite with milky white quartz, pink to red feldspars and much black hornblende with 20mm fragments with yellow staining and soft rotten light green feldspar. **FRACTURED. Flow rate 6.5 - 7 l/sec**
43.0 – 43.5	Hard reddish pink and grey coarse-grained granite with red to orange and pink feldspar, grey white quartz and black hornblende. **Flow rate 0.6 l/sec**
43.5 – 44.0	Orange white coarse-grained granite with pink and orange white feldspars, white quartz and some black hornblende with some fragments up to 15mm
44.0 – 44.5	Reddish grey coarse-grained granite with red and orange feldspars with grey white quartz and some black hornblende

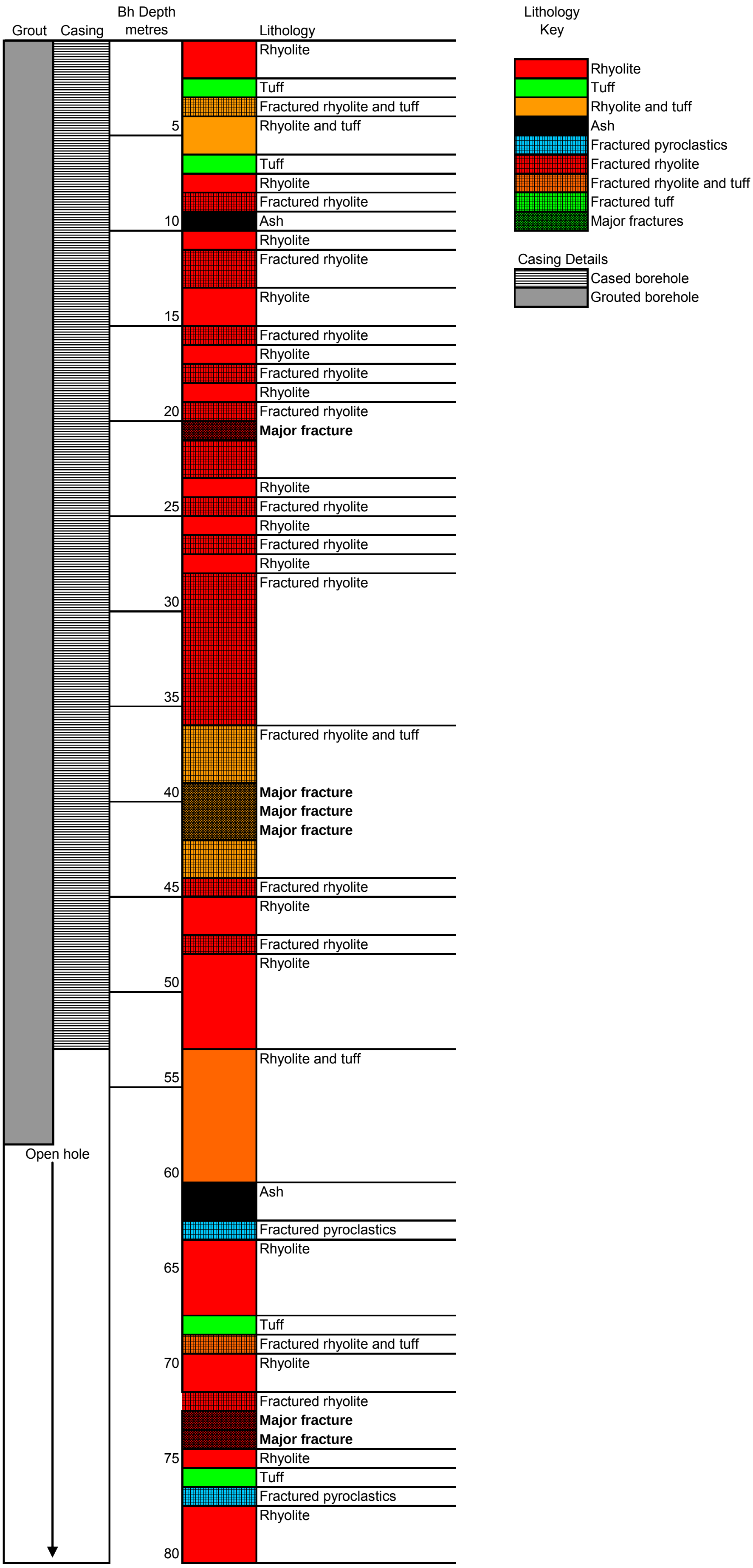
44.5 – 45.0	Greyish red medium-grained granite with medium to coarse sand-grain sized fragments of red and orange feldspars, white grey quartz and some black hornblende, with some yellow and light green staining. FRACTURED.
45.0 – 45.5	Greyish red medium to fine-grained granite with orange and pink feldspars, white grey quartz and some black hornblende, with little yellow staining. FRACTURED. **Flow rate 0.7 l/sec**
45.5 – 46.0	Greyish pink medium-grained granite with pink feldspars, white grey quartz and some black hornblende, with little yellow staining. FRACTURED. **Flow rate 0.7 l/sec**
46.0 – 46.5	Pinkish grey fine-grained granite with much clear grey quartz pink feldspars and little black hornblende. **Flow rate 1.0 l/sec**
46.5 – 47.0	Greyish pink medium to coarse-grained granite pale pink feldspars, clear grey quartz and black hornblende. **Flow rate 1.0 l/sec**
47.0 – 47.5	Greyish pink coarse-grained granite in gravel sized fragments of pale pink feldspars, white to grey quartz and black hornblende. **Flow rate 0.7 l/sec**
47.5 – 48.0	Reddish grey coarse-grained granite with pale pink to red feldspars, clear grey and greenish grey quartz and black hornblende. **Flow rate 1.4 l/sec**
48.0 – 48.5	Black, pink and white coarse-grained granite with much pale pink feldspar, with black hornblende and grey to clear quartz, some light green staining and some dark purple fine grained vein material. FRACTURED. **Flow rate 1.3 l/sec**
48.5 – 49.0	Greyish pink coarse-grained granite with mainly pale pink feldspars, some white grey quartz and little black hornblende. **Flow rate 0.9 l/sec**
49.0 – 49.5	Dark pinkish grey medium-grained granite with dark grey quartz pale pink feldspars, white grey quartz and some black hornblende, with much yellow rotten feldspar. FRACTURED. **Flow rate 1.2 l/sec**
49.5 – 50.0	Reddish grey medium-grained granite with red, orange and pink feldspars, grey quartz and much black hornblende, with some yellow white stained rotten feldspar. FRACTURED. **Flow rate 1.4 l/sec**
50.0 – 50.5	Pinkish grey red medium to coarse-grained granite with much grey to dark grey quartz, some pink and orange feldspars, and some black hornblende, with some yellow and light green staining. FRACTURED. **Flow rate 1.3 l/sec**
50.5 – 51.0	Reddish grey coarse-grained granite with much grey, dark grey and white quartz, orange and pink feldspars, and much black hornblende, with some white vein quartz. FRACTURED. **Flow rate 0.9 l/sec**
51.0 – 51.5	Greyish pink medium to coarse-grained granite with mainly pink to orange feldspars, grey to white quartz with little black hornblende. **Flow rate 1.3 l/sec**
51.5 – 52.0	Greyish pink coarse-grained granite with mainly pink feldspars, with grey and white quartz and some black hornblende. **Flow rate 1.4 l/sec**
52.0 – 52.5	Pinkish grey medium to coarse-grained granite with pink feldspars, some grey and white quartz, some black hornblende, with odd yellow and light green stained rotten feldspar. FRACTURED. **Flow rate 1.6 l/sec**
52.5 – 53.0	Pinkish grey medium-grained granite with pink feldspars, grey quartz and black hornblende, with some white vein quartz and yellow and

	light green stained rotten feldspar. FRACTURED. **Flow rate 1.1 l/sec**
53.0 – 53.5	Pinkish grey coarse to medium-grained granite with pink feldspars, grey white quartz and black hornblende, with some yellow staining. FRACTURED. **Flow rate 1.1 l/sec**
53.5 – 54.0	Pinkish grey coarse to medium-grained granite with much grey quartz, some pink feldspar and black hornblende, with little yellow staining. FRACTURED. **Flow rate 1.5 l/sec**
54.0 – 54.5	Greyish pink medium to coarse-grained granite with pink feldspar, some grey quartz and black hornblende. **Flow rate 1.4 l/sec**
54.5 – 55.0	Greyish pink medium to coarse-grained granite with black hornblende veins, pink feldspars, grey quartz and much black hornblende. **Flow rate 1.75 l/sec**
55.0 – 55.5	Greyish pink very coarse-grained granite with pink to orange feldspars, some grey quartz and some black hornblende, with some thin hornblende veins. **Flow rate 1.1 l/sec**

Appendix 4 Lithological Log for the St Catherine's Borehole

Borehole geological log

Location	St Catherine's, St Catherine's, north east Jersey
Date started	19/9/2006


Grout
Casing
Bh Depth metres
Lithology
Rhyolite
Tuff
Fractured rhyolite and tuff
5
Rhyolite and tuff
Tuff
Rhyolite
Fractured rhyolite
10
Ash
Rhyolite
Fractured rhyolite
Rhyolite
15
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
20
Fractured rhyolite
Major fracture
Rhyolite
25
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
30
35
Fractured rhyolite and tuff
40
Major fracture
Major fracture
Major fracture
45
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
50
Rhyolite and tuff
55
Open hole
60
Ash
Fractured pyroclastics
Rhyolite
65
Tuff
Fractured rhyolite and tuff
70
Rhyolite
Fractured rhyolite
Major fracture
Major fracture
75
Rhyolite
Tuff
Fractured pyroclastics
Rhyolite
80
Lithology Key
Rhyolite
Tuff
Rhyolite and tuff
Ash
Fractured pyroclastics
Fractured rhyolite
Fractured rhyolite and tuff
Fractured tuff
Major fractures
Casing Details
Cased borehole
Grouted borehole

Depth (metres)	Lithology
0.0 – 0.5	10YR4/3 brown silty loamy soil above soft weathered pink brown rhyolite
0.5 – 1.0	Red brown fine grained rhyolite, broken and blocky
1.0 – 1.5	Orange fine grained granular rhyolite, weathered but quite hard
1.5 – 2.0	Dark red granular medium-grained sand sized blocky tuff rubble (agglomerate?)
2.0 – 2.5	Angular limps of light brown fine grained rhyolitic and granular tuff, blocky rubble (agglomerate)
2.5 – 3.0	Reddish grey fine grained rhyolite and granular tuff, fragmented blocks (agglomeritic)
3.0 – 3.5	Red granular rhyolites with calcite filled spherical vesicles and clear vein quartz. FRACTURE
3.5 – 4.0	Very soft friable pink grey granular rhyolitic tuff
4.0 – 4.5	Pinkish grey medium to coarse grained sand of soft friable weathered brownish red granular rhyolitic tuff
4.5 – 5.0	Pinkish grey medium to coarse grained sand of soft friable weathered brownish red granular rhyolitic tuff
5.0 – 5.5	Pinkish grey medium to coarse grained sand of soft friable weathered brownish red granular rhyolitic tuff and rounded coarse gravel of rhyolite
5.5 – 6.0	Greyish purple granular rhyolitic tuff weathered with orange and white stained partings
6.0 – 6.5	Red to pink red granular tuffs with red and black speckled rhyolite some white quartz veining and grey and green stained partings, some weathered orange and white calcite filled vesicles
6.5 – 7.0	Dark red granular tuff and pink red weathered rhyolite with black manganiferous partings, very weathered
7.0 – 7.5	Red with black spots and partings weathered broken rhyolite
7.5 – 8.0	Pinkish red to red with black partings fine grained rhyolite with some orange stained veins and white calcite filled vesicles, weathered.
8.0 – 8.5	Dark reddish purple fine grained rhyolite with light brown ashy partings, some light green and orange thin layers or veins, weathered.
8.5 – 9.0	Reddish purple fine grained to granular weathered rhyolite with odd calcite filled vesicle and white vein quartz. FRACTURE
9.0 – 9.5	Dark red and dark purple soft friable band of fine grained ash with orange stained joints, weathered.
9.5 – 10.0	Dark red weathered fine grained rhyolite, uneven fracture, with some light green and orange stained vein deposits
10.0 – 10.5	Dark red to dark pinkish red fine grained rhyolite, uneven fracture, orange stained vein deposits with light green and orange stained calcite vesicle infill
10.5 – 11.0	Dark red fine grained rhyolite with uneven fracture, some orange stained weathered partings and odd calcite in-filled vesicle
11.0 – 11.5	Dark red angular fragments of hard siliceous rhyolite, some mineralization on weathered surfaces and odd quartz filled vesicle.
11.5 – 12.0	Dark red fine grained rhyolite, small fragments with some white calcite veining. FRACTURE
12.0 – 12.5	Dark red fine grained rhyolite, small fragments, with some orange and light green stained quartz partings.

12.5 – 13.0	Dark red fine grained rhyolite with some white and orange stained vein quartz. FRACTURE
13.0 – 13.5	Dark red and blackish fine grained rhyolite with small dendritic cracks in-filled with apple green deposits and green and orange stained veins deposits with odd white calcite filled vesicle.
13.5 – 14.0	Dark red fine grained rhyolite with odd yellowish white calcite in-filled vesicle, and white quartz on partings
14.0 – 14.5	Dark purple red fine grained rhyolite with fine dendritic cracks in-filled with green material, odd white calcite in-filled vesicle and white calcite vein deposits.
14.5 – 15.0	Dark red fine grained rhyolite with some orange stained white vein quartz and odd vesicle in-filled with white calcite
15.0 – 15.5	Dark red fine grained rhyolite with uneven fracture and white vein calcite. FRACTURE
15.5 – 16.0	Dark blackish red hard fine grained rhyolite.
16.0 – 16.5	Dark brownish red fine-grained rhyolite.
16.5 – 17.0	Dark purple red to orange red fine grained rhyolite with orange staining and white calcite in-filled vesicles.
17.0 – 17.5	Dark red to brownish red fine grained rhyolite with orange stained partings.
17.5 – 18.0	Dark reddish brown and dark red fine grained granular rhyolite with uneven fracture, some white calcite vein deposits. FRACTURE
18.0 – 18.5	Dark brown granular rhyolite with some red and white stained and banded rhyolite with odd black inclusion and banded apple green ash layers.
18.5 – 19.0	Dark reddish brown fine grained granular rhyolite.
19.0 – 19.5	Dark reddish brown fine grained granular rhyolite with some white vein quartz and orange staining. FRACTURE
19.5 – 20.0	Dark reddish brown fine grained granular rhyolite with odd fragment of white vein quartz. FRACTURE
20.0 – 20.5	Dark reddish brown fine grained granular rhyolite with much white vein quartz and some light green staining. FRACTURE
20.5 – 21.0	Dark greyish brown fine grained granular rhyolite and dark brown fine grained siliceous rhyolite with much white vein quartz. FRACTURE
21.0 – 21.5	Dark reddish brown fine grained rhyolite with white vein quartz. FRACTURE
21.5 – 22.0	Dark red fine grained siliceous rhyolite with dark red brown fine grained granular rhyolite with some white vein quartz. FRACTURE
22.0 – 22.5	Dark brown fine grained granular rhyolite with light brown coarser bands with white quartz veins. FRACTURE
22.5 – 23.0	Dark brown fine grained granular rhyolite to dark red and black weathered fine grained rhyolite with some white vein quartz. FRACTURE
23.0 – 23.5	Brecciated dark brown fine grained granular and dark red fine grained cherty rhyolite.
23.5 – 24.0	Dark brown granular and dark red fine grained brecciated and welded rhyolite.
24.0 – 24.5	Dark brown granular and dark red cherty fine grained rhyolite with odd fragment of white vein quartz. FRACTURE
24.5 – 25.0	Dark brown granular and dark red cherty fine grained rhyolite.

25.0 – 25.5	Dark red brown fine grained rhyolite with some light green vein deposits.
25.5 – 26.0	Dark reddish brown fine grained rhyolite with light green inclusions.
26.0 – 26.5	Reddish brown fine grained cherty rhyolite with thin light green ashy deposits and white vein quartz. FRACTURE
26.5 – 27.0	Dark red and dark reddish brown fine grained cherty rhyolite.
27.0 – 27.5	Dark reddish brown fine-grained rhyolite, very small chips with some black manganese stained partings.
27.5 – 28.0	Dark reddish brown fine grained ashy rhyolite cherty fragments.
28.0 – 28.5	Dark reddish brown fine-grained granular and cherty rhyolite.
28.5 – 29.0	Dark red brown and black cherty fine-grained rhyolite.
29.0 – 29.5	Dark red brown to dark purple fine-grained cherty rhyolite with white vein quartz. FRACTURE
29.5 – 30.0	Dark red brown to dark purple fine-grained cherty rhyolite with white vein quartz. FRACTURE
30.0 – 30.5	Dark red brown to dark purple fine-grained cherty rhyolite with white vein quartz. FRACTURE
30.5 – 31.0	Dark red brown to dark purple fine-grained cherty to granular rhyolite, small fragments.
31.0 – 31.5	Dark red brown to dark purple fine-grained cherty rhyolite with white vein quartz. FRACTURE
31.5 – 32.0	Dark red brown to dark purple fine-grained cherty rhyolite.
32.0 – 32.5	Dark red brown to dark purple fine-grained cherty rhyolite.
32.5 – 33.0	Dark red brown to dark purple fine-grained cherty rhyolite with white vein quartz. FRACTURE
33.0 – 33.5	Dark red brown to dark purple fine-grained cherty rhyolite with white vein quartz. FRACTURE
33.5 – 34.0	Dark red brown to dark purple fine-grained cherty rhyolite with odd fragment of white vein quartz and dark green chlorite stained quartz. FRACTURE
34.0 – 34.5	Dark red brown to dark purple fine-grained cherty rhyolite with odd fragment of white vein quartz and dark green chlorite stained quartz. FRACTURE. **Damp.**
34.5 – 35.0	Dark red brown to dark purple fine-grained cherty rhyolite with white vein quartz. FRACTURE. **Damp.**
35.0 – 35.5	Dark red brown to dark purple fine-grained cherty to granular rhyolite with white vein quartz band and odd dark green chlorite stained fragment. FRACTURE. **Damp.**
35.5 – 36.0	Very small fragments of dark red brown and purple fine grained cherty and granular rhyolite. **Damp.**
36.0 – 36.5	Very small fragments of dark red brown and purple fine grained cherty and granular rhyolite with fragments of white vein quartz and dark green chloritic material. FRACTURE. **Damp.**
36.5 – 37.0	Dark red brown and purple fine grained cherty rhyolite with large fragments of orange red coarsely granular rhyolitic tuff with some white vein quartz. FRACTURE. **Very small water flow**
37.0 – 37.5	Dark red brown and purple fine grained cherty rhyolite with large fragments of orange red coarsely granular rhyolitic tuff with some white vein quartz. FRACTURE. **Very small water flow**
37.5 – 38.0	Dark red brown and purple fine grained cherty rhyolite with large

	fragments of orange red coarsely granular rhyolitic tuff with some white vein quartz and much light green ash and dark green cherty vein material. FRACTURE. **Very small water flow**
38.0 – 38.5	Dark red brown and dark grey fine-grained cherty rhyolite with some white vein quartz and light green inclusions, with some granular orange red rhyolitic tuff. FRACTURE. **Very small water flow**
38.5 – 39.0	Dark red brown and black fine-grained cherty rhyolite with much interbedded light green ash, some orange staining, and some orange granular rhyolitic tuff fragments.
39.0 – 39.5	Dark red brown and black fine-grained cherty rhyolite with much interbedded light green ash, much white vein quartz, some orange staining, and some orange granular rhyolitic tuff fragments. FRACTURE
39.5 – 40.0	Dark red brown and black fine-grained cherty rhyolite with much interbedded light green and light brown ash, much white vein quartz, some orange staining, and some orange granular rhyolitic tuff fragments. FRACTURE
40.0 – 40.5	Dark red brown and black fine-grained cherty rhyolite with much interbedded light green and light brown ash, much white vein quartz, some orange staining, and some orange granular rhyolitic tuff fragments. FRACTURE. **Very small water flow**
40.5 – 41.0	Dark red brown and black fine-grained cherty rhyolite with interbedded light brown ash bands, much white vein quartz, some dark green chlorite staining, and some orange granular rhyolitic tuff fragments. FRACTURE
41.0 – 41.5	Dark red brown and black fine-grained cherty rhyolite with interbedded light brown ash bands, much white vein quartz, and some orange granular rhyolitic tuff fragments. FRACTURE
41.5 – 42.0	Dark red brown and black fine-grained cherty rhyolite with some interbedded light green ash, white vein quartz, some dark green chlorite staining, and some orange granular rhyolitic tuff fragments. FRACTURE
42.0 – 42.5	Dark red brown and black fine-grained cherty rhyolite with some interbedded light brown ash, white vein quartz, and some orange granular rhyolitic tuff fragments. FRACTURE
42.5 – 43.0	Dark red brown and black fine-grained cherty rhyolite with some interbedded light brown ash, white vein quartz, and some orange granular rhyolitic tuff fragments. FRACTURE
43.0 – 43.5	Dark red brown and black fine-grained cherty rhyolite with some interbedded light brown ash, white vein quartz, and some orange granular rhyolitic tuff fragments. FRACTURE. **Very small water flow**
43.5 – 44.0	Interbedded banded orange red, dark red brown, light green and light greyish brown rhyolites, cherty fragments with some dark green chloritic staining.
44.0 – 44.5	Interbedded dark red brown cherty fine grained rhyolite with light green and granular orange red fine grained rhyolite, with odd fragments of white vein quartz. FRACTURE
44.5 – 45.0	Interbedded dark red brown cherty and red, light brown and light green granular fine grained rhyolites.
45.0 – 45.5	Interbedded dark red brown cherty and red, light brown and much light

	green granular fine grained rhyolites.
45.5 – 46.0	Interbedded dark red brown cherty and orange red, light brown and light green granular fine grained rhyolites.
46.0 – 46.5	Orange red and red brown fine grained rhyolites and some light brown and light green interbedded ashes..
46.5 – 47.0	Orange red to red brown cherty to granular fine grained rhyolite with some light green ash bands with some black inclusions.
47.0 – 47.5	Orange red to red brown cherty to granular fine grained rhyolite with light green ash bands with some black inclusions.
47.5 – 48.0	Red brown and red fine grained rhyolite with light greenish white inclusions, with some white vein quartz – possible fine grained agglomerate. FRACTURE
48.0 – 48.5	Welded tuff of dark red and orange red fine grained rhyolite and light green stained quartz inclusions – auto-breccia?
48.5 – 49.0	Welded tuff of dark red and orange red fine grained rhyolite and light green stained quartz inclusions – auto-breccia?
49.0 – 49.5	Welded tuff of dark red and orange red fine grained rhyolite, orange red coarse granular rhyolitic tuff fragments and light green stained quartz inclusions – auto-breccia?
49.5 – 50.0	Dark red brown fine grained cherty rhyolite with whitish green and black inclusions – possible porphorytic rhyolite.
50.0 – 50.5	Dark red brown fine grained granular rhyolite with green inclusions, and light brown granular ashy bands.
50.5 – 51.0	Dark red and orange red fine grained cherty rhyolite with light green inclusions.
51.0 – 51.5	Dark red and orange red fine grained cherty rhyolite with some light green inclusions. **Increased flow – still small and muddy**
51.5 – 52.0	Dark red and orange red fine grained cherty rhyolite with some light green inclusions.
52.0 – 52.5	Dark red and orange red fine grained granular rhyolite with some light green inclusions.
52.5 – 53.0	Dark red brown and dark pink grey fine grained cherty to granular rhyolite with some light green inclusions and orange staining, and some orange red and pink red granular tuff – coarse agglomerate.
53.0 – 53.5	Dark red cherty fine grained rhyolite with dark red granular tuff, some light yellow ash bands and light brown to brown tuff fragments – coarse agglomerate.
53.5 – 54.0	Dark red cherty fine grained rhyolite with dark red granular tuff, some light brown to brown tuff fragments – coarse agglomerate.
54.0 – 54.5	Dark red cherty fine grained rhyolite with large fragments of dark red and orange red granular tuff, some light brown to brown tuff fragments – coarse agglomerate.
54.5 – 55.0	Dark red cherty fine grained rhyolite with large fragments of dark red and orange red granular tuff, some light brown to brown tuff fragments – coarse agglomerate.
55.0 – 55.5	Very mixed clasts mainly of coarse granular red grey and light brown tuff with some dark red rhyolite – agglomerate. **Less water.**
55.5 – 56.0	Mixed clasts mainly of coarse granular red grey and light brown tuff and dark red rhyolite – agglomerate
56.0 – 56.5	Large (10-20 mm) clasts of coarse granular red grey and light brown

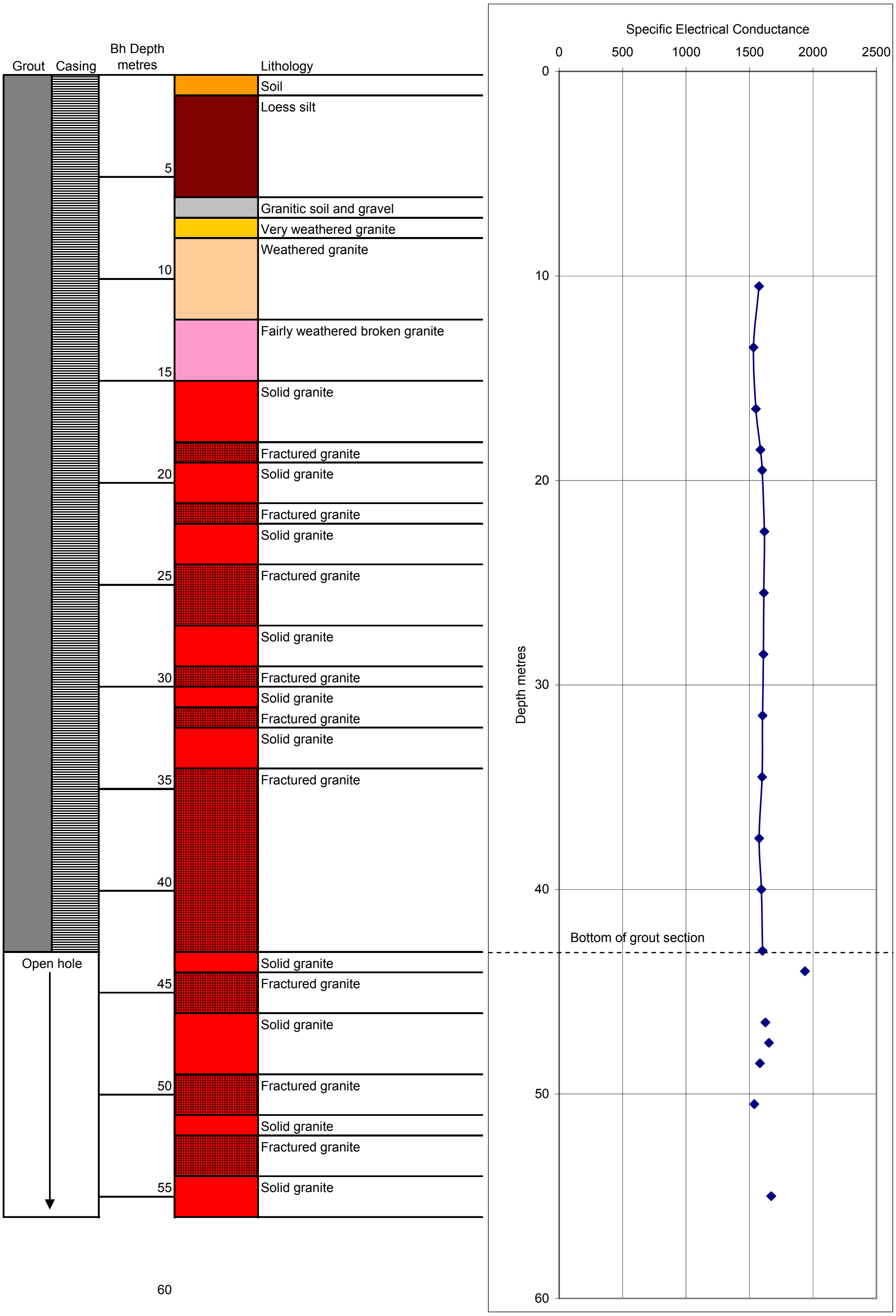
	tuff with some dark red rhyolite – agglomerate
56.5 – 57.0	Large (10-20 mm) clasts of coarse granular red grey and light brown tuff with some dark red rhyolite, with some dark green chlorite staining – agglomerate
57.0 – 57.5	Large (10-20 mm) clasts of coarse granular pink red and orange tuff with smaller fragments of dark red rhyolite and some white vein quartz – agglomerate.
57.5 – 58.0	Large (10-20 mm) clasts of coarse granular pink red and orange tuff with smaller fragments of dark red rhyolite and some dark green chlorite staining – agglomerate.
58.0 – 58.5	No sample. **Damp**
58.5 – 59.0	Dark red brown very fine rhyolite with some orange red and grey green fragments of granular tuff.
59.0 – 59.5	Dark red to grey and brown granular tuff
59.5 – 60.0	Grey ashy pyroclastic ignimbrite with some red rhyolite and granular tuff.
60.0 – 60.5	Grey fine grained cherty ash and pyroclastic deposits.
60.5 – 61.0	Grey fine grained cherty ash and dark red rhyolite.
61.0 – 61.5	Grey fine grained cherty ash with some red bands, odd band of coarser grained pyroclastic material.
61.5 – 62.0	Grey and red fine grained ash with pyroclastic deposits, some green stained quartz.
62.0 – 62.5	Grey and red fine grained ash with coarser pyroclastic deposits, some green stained quartz. SOFT
62.5 – 63.0	Transition from grey ash/pyroclastic deposits above coarser red granular tuff with some white vein quartz. FRACTURE
63.0 – 63.5	Transition from red granular tuff above red to pinkish red fine grained rhyolite lava. SOFT BANDS – **water strike**
63.5 – 64.0	Dark red fine grained granular to cherty rhyolite.
64.0 – 64.5	Dark greyish red granular to cherty banded fine-grained rhyolite with odd green fragment.
64.5 – 65.0	Dark reddish brown cherty and granular fine grained rhyolite. **Flow rate 0.15 l/sec.**
65.0 – 65.5	Dark reddish brown fine grained cherty and granular rhyolite with coarse grained red brown tuff, with black inclusions. **Flow rate 0.18 l/sec.**
65.5 – 66.0	Dark orange red and red brown cherty rhyolite with quartz inclusions. **Flow rate 0.22 l/sec.**
66.0 – 66.5	Dark red brown fine grained granular rhyolite with dark brown coarse grained tuff. **Flow rate 0.23 l/sec.**
66.5 – 67.0	Dark greyish red fine grained granular rhyolite. **Flow rate 0.21 l/sec.**
67.0 – 67.5	Dark reddish brown fine to medium grained tuff. **Flow rate 0.30 l/sec.**
67.5 – 68.0	Dark reddish brown fine-grained granular rhyolite and dark reddish. brown granular tuff, some white vein quartz. FRACTURE. **Flow rate 0.31 l/sec.**
68.0 – 68.5	Dark reddish brown fine-grained granular rhyolite and dark reddish brown granular tuff, some white vein quartz. FRACTURE. **Flow rate 0.34 l/sec.**
68.5 – 69.0	Dark reddish brown to dark grey granular tuff with white vein quartz with some dark green chloritic staining. FRACTURE. **Flow rate 0.26 l/sec.**

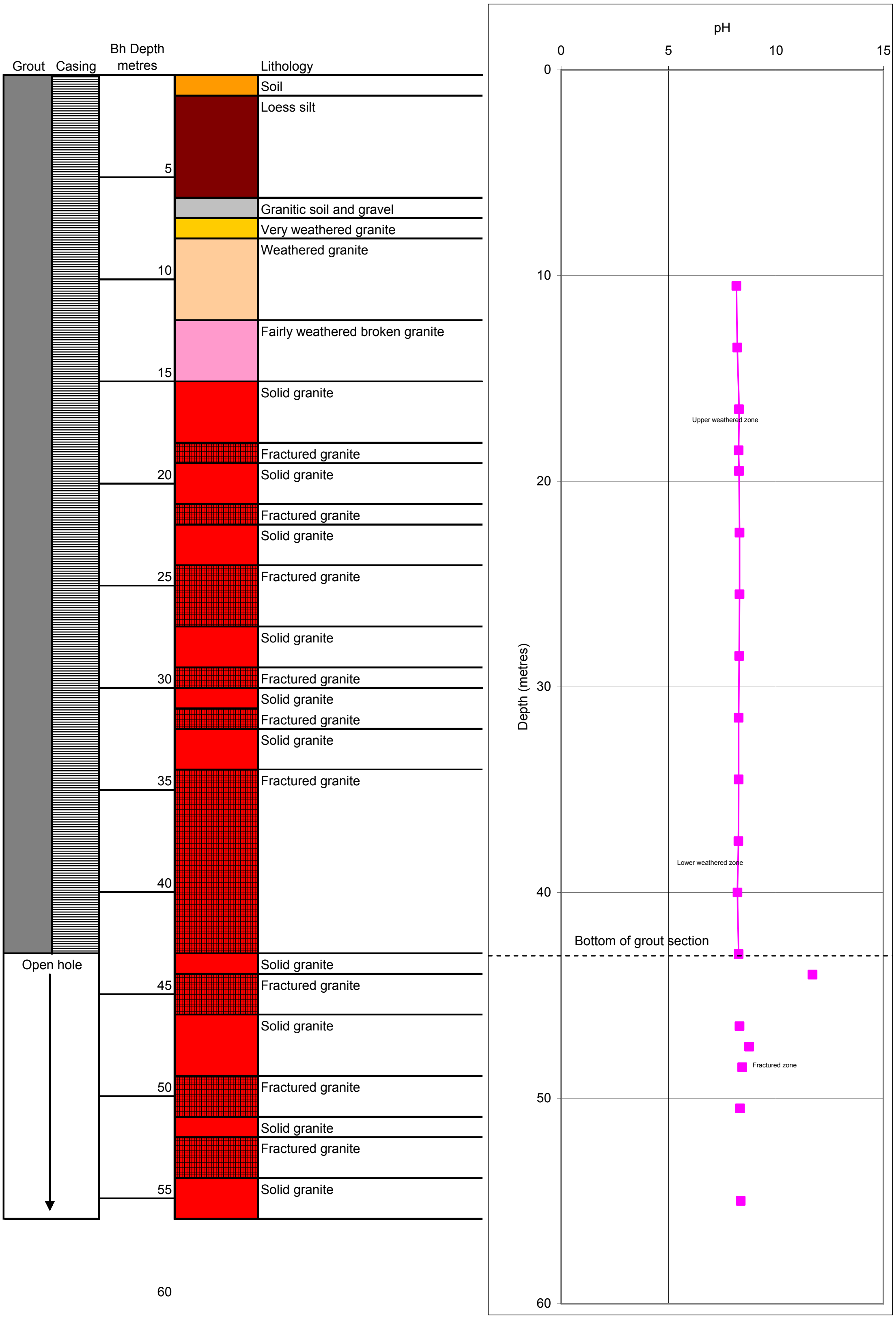
69.0 – 69.5	Dark red brown cherty to granular rhyolite with odd white vein quartz. FRACTURE. **Flow rate 0.24 l/sec.**
69.5 – 70.0	Dark red brown fine grained mainly cherty some granular rhyolite. **Flow rate 0.25 l/sec.**
70.0 – 70.5	Orange red slightly granular rhyolite with calcite filled white vesicles. **Flow rate 0.23 l/sec.**
70.5 – 71.0	Banded orange red slightly granular fine grained rhyolite. **Flow rate 0.27 l/sec.**
71.0 – 71.5	Dark blackish red brown fine grained granular rhyolite with thin brecciated surface. **Flow rate 0.23 l/sec.**
71.5 – 72.0	Dark greyish red to dark grey fine grained granular ashy rhyolite. **Flow rate 0.23 l/sec.**
72.0 – 72.5	Dark blackish red brown fine grained cherty rhyolite, some white vein quartz. FRACTURE. **Flow rate 0.23 l/sec.**
72.5 – 73.0	Dark reddish brown fine grained granular rhyolite with much white vein quartz, some orange and green chloritic staining. FRACTURE. **Flow rate 0.23 l/sec.**
73.0 – 73.5	Dark reddish brown fine grained granular rhyolite, fractured with white vein quartz, some orange and chloritic green staining. FRACTURE. **Flow rate 0.23 l/sec.**
73.5 – 74.0	Dark reddish brown fine grained granular rhyolite with much vein quartz, some fracturing with orange and chloritic green staining. FRACTURE. **Flow rate 0.27 l/sec.**
74.0 – 74.5	Dark reddish brown fine grained granular rhyolite, some tuff, much white vein quartz, some coarse granules cemented with white calcite. FRACTURE. **Flow rate 0.25 l/sec.**
74.5 – 75.0	Dark red brown and in parts speckled orange coarse grained tuff, some orange stained partings. **Flow rate 0.26 l/sec.**
75.0 – 75.5	Dark red brown increasingly granular tuff with included granular grey clasts, coarse pyroclastic material, some orange brown partings. **Flow rate 0.26 l/sec.**
75.5 – 76.0	Dark greyish red to dark grey welded pyroclastic tuff composed of large clasts of rhyolite and tuff, with calcite impregnated fragments. **Flow rate 0.23 l/sec.**
76.0 – 76.5	Reddish grey fine grained granular pyroclastic deposits with clasts of rhyolite lavas with white vein quartz and odd calcite filled vesicles. FRACTURE. **Flow rate 0.25 l/sec.**
76.5 – 77.0	Dark reddish grey to grey fine grained granular in part pyroclastic deposit with white vein quartz. FRACTURE. **Flow rate 0.27 l/sec.**
77.0 – 77.5	Dark grey to red brown with speckled orange tuff and pyroclastic material. **Flow rate 0.26 l/sec.**
77.5 – 78.0	Dark red brown granular to cherty fine grained rhyolite porphyitic lava with white impregnated calcite margins. **Flow rate 0.27 l/sec.**
78.0 – 78.5	Dark red brown fine grained cherty to granular porphyritic rhyolite. **Flow rate 0.25 l/sec.**
78.5 – 79.0	Dark red brown fine grained cherty to granular porphyritic rhyolite. **Flow rate 0.25 l/sec.**
79.0 – 79.5	Dark red brown fine grained granular porphyritic rhyolite lava with calcite cemented granular base. **Flow rate 0.23 l/sec.**

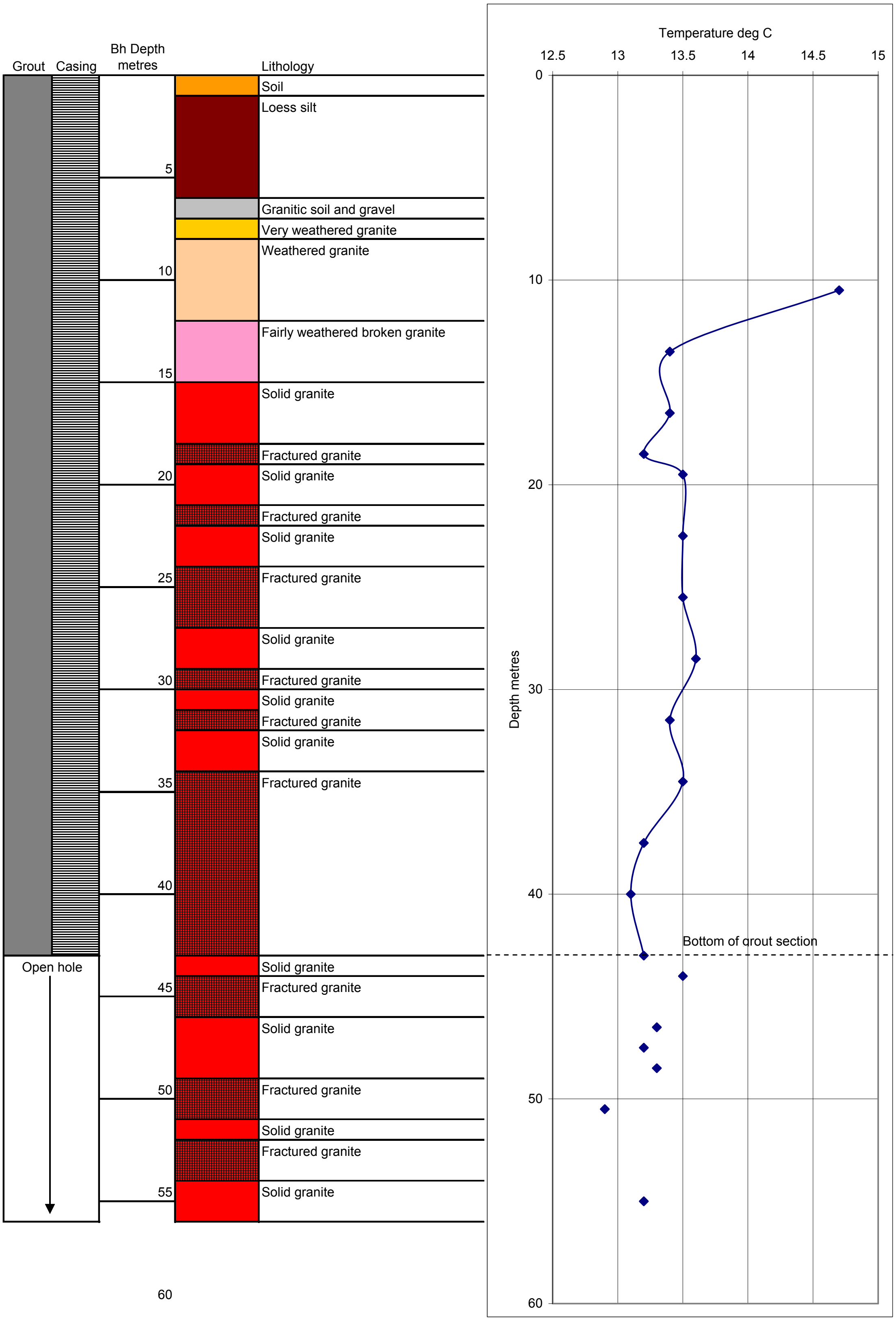
Appendix 5 Tabulation of Conductivity, Temperature and pH data collected whilst Drilling the La Rocque and St Catherine's Boreholes

La Rocque

Depth (m)	Cond	pH	Temp deg C	Isotope/Sample
10.5	1575	8.16	14.7	A10
12	1353	9.18	13.8	A12B
13.5	1532	8.20	13.4	
16.5	1550	8.28	13.4	
18.5	1587	8.26	13.2	
19.5	1600	8.28	13.5	A19.5
22.5	1617	8.30	13.5	A22
25.5	1613	8.3	13.5	
28.5	1610	8.29	13.8	A28.5
31.5	1603	8.26	13.4	
34.5	1599	8.26	13.5	A34.5
37.5	1576	8.25	13.2	A37.5
40.0	1594	8.21	13.1	
43.0	1603	8.26	13.2	A43
43	1604	8.23	13.3	A43B
44	1937	11.7	13.5	A44
46.5	1625	8.30	13.3	A46.5
47.5	1653	8.75	13.2	A47.5
48.5	1582	8.43	13.3	A48.5
50.5	1538	8.33	12.9	A50.5
55	1671	8.36	13.2	A55


Grout
Casing
Bh Depth metres
Lithology
Soil
Loess silt
Granitic soil and gravel
Very weathered granite
Weathered granite
Fairly weathered broken granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Open hole
5
10
15
20
25
30
35
40
45
50
55
60
Specific Electrical Conductance
0
500
1000
1500
2000
2500
Depth metres
0
10
20
30
40
50
60
Bottom of grout section

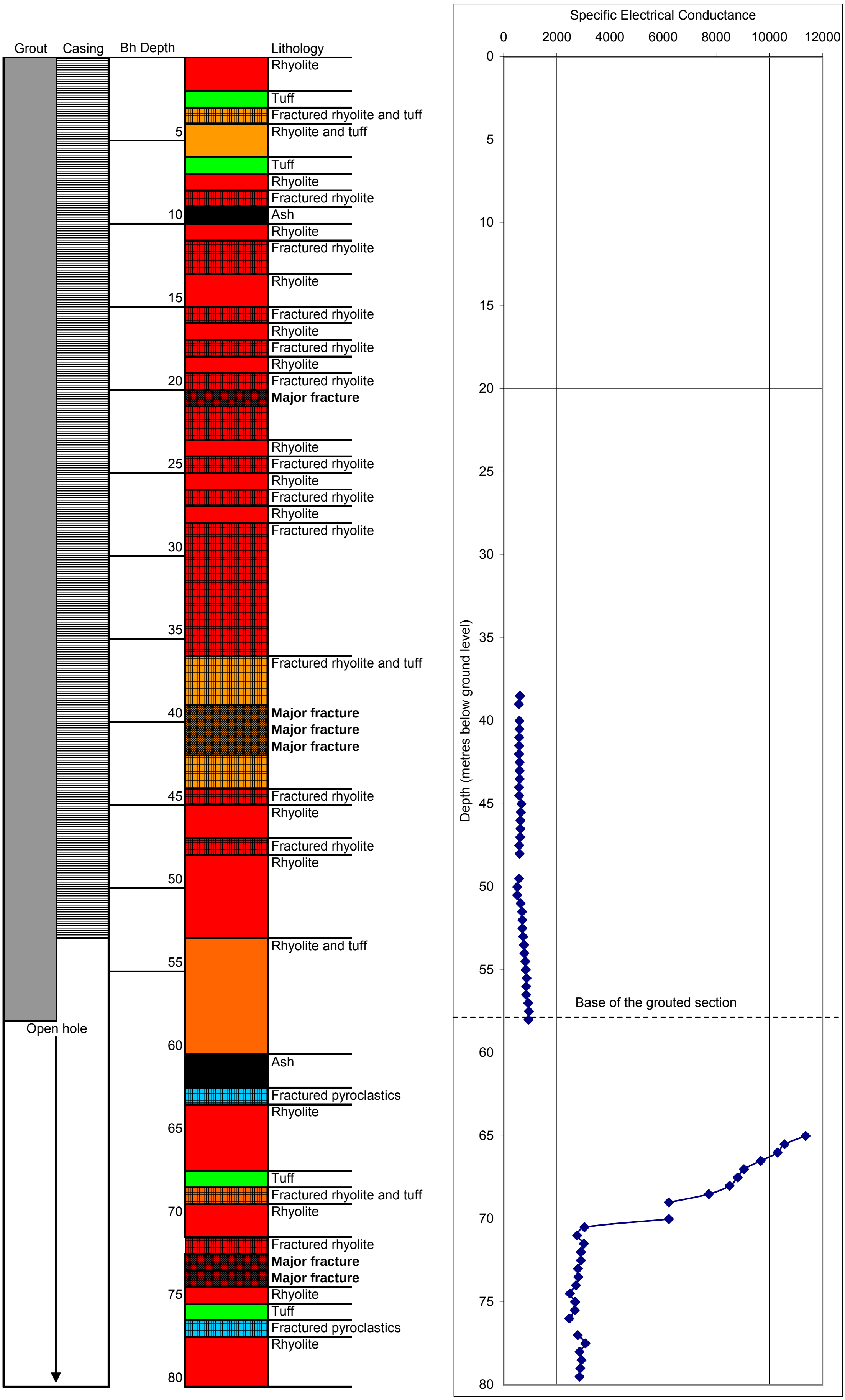

Grout
Casing
Bh Depth metres
Lithology
Soil
Loess silt
Granitic soil and gravel
Very weathered granite
Weathered granite
Fairly weathered broken granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Open hole
5
10
15
20
25
30
35
40
45
50
55
60
pH
0
5
10
15
Depth (metres)
0
10
20
30
40
50
60
Upper weathered zone
Lower weathered zone
Bottom of grout section
Fractured zone

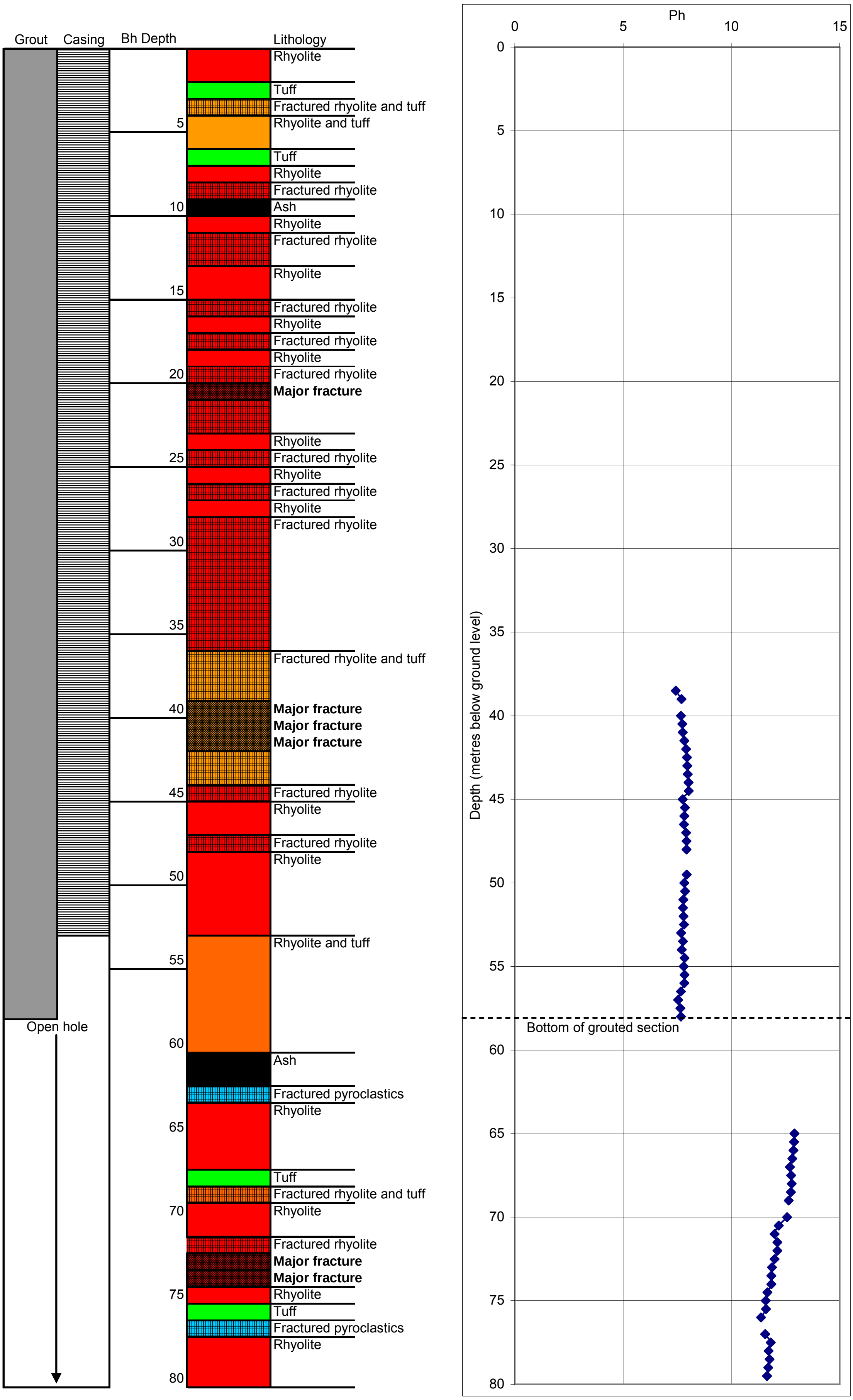

Grout
Casing
Bh Depth metres
Lithology
Soil
Loess silt
Granitic soil and gravel
Very weathered granite
Weathered granite
Fairly weathered broken granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Fractured granite
Solid granite
Open hole
5
10
15
20
25
30
35
40
45
50
55
60
Temperature deg C
12.5
13
13.5
14
14.5
15
Depth metres
0
10
20
30
40
50
60
Bottom of grout section

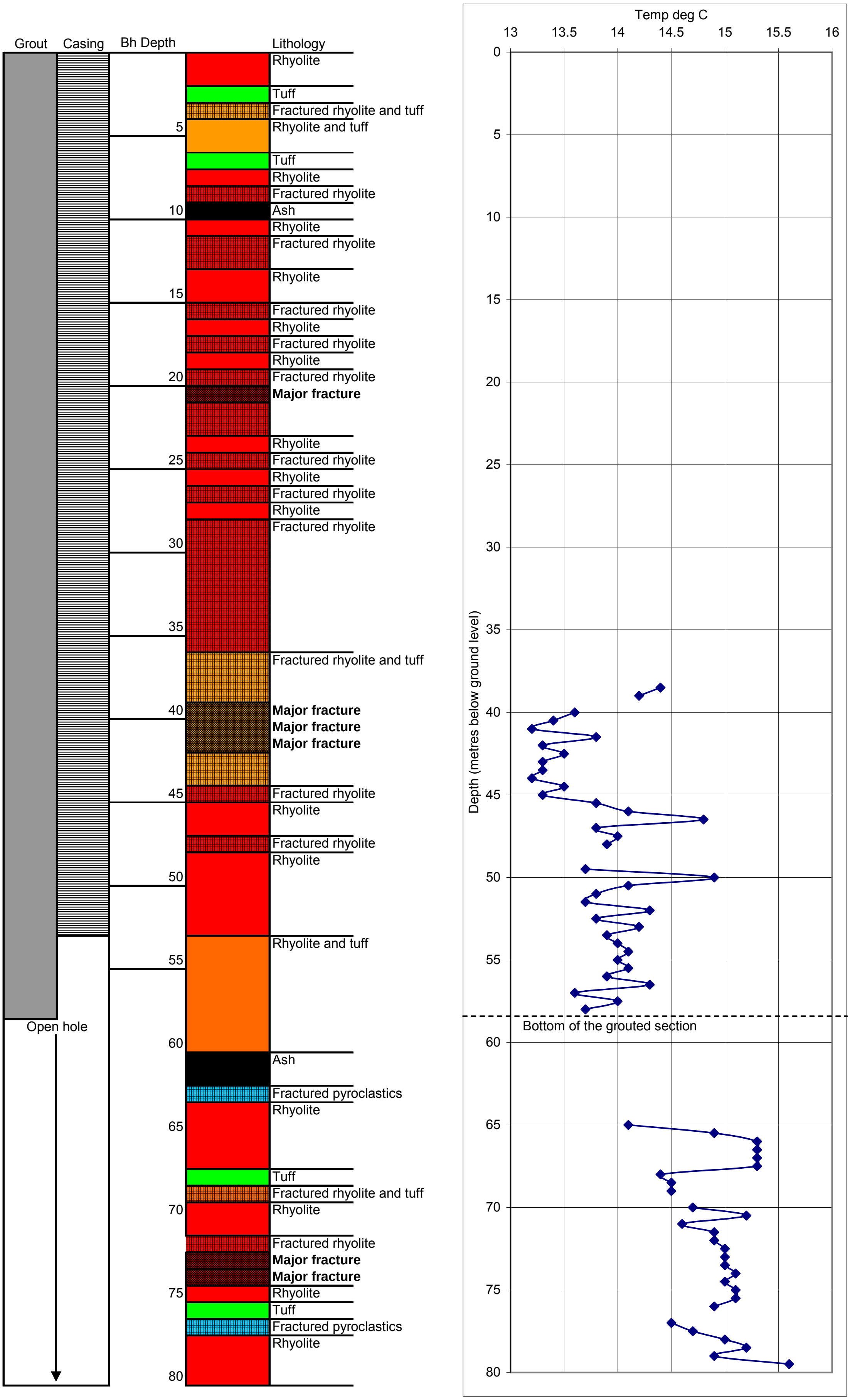
St Catherine's

Depth (m)	Cond	pH	Temp deg C	Isotope/Sample
38.5	614	7.43	14.4	
39.0	576	7.70	14.2	
40.0	594	7.67	13.6	
40.5	592	7.73	13.4	
41.0	589	7.75	13.2	
41.5	591	7.83	13.8	
42.0	582	7.91	13.3	
42.5	599	7.95	13.5	
43.0	605	7.96	13.3	
43.5	604	7.98	13.3	
44.0	579	8.02	13.2	
44.5	588	8.03	13.5	
45.0	668	7.75	13.3	
45.5	646	7.85	13.8	Is
46.0	636	7.83	14.1	
46.5	636	7.81	14.8	
47.0	625	7.91	13.8	
47.5	585	7.93	14.0	
48.0	599	7.93	13.9	
49.5	583	7.94	13.7	
50.0	516	7.83	14.9	
50.5	514	7.86	14.1	
51.0	638	7.78	13.8	
51.5	689	7.76	13.7	Is
52.0	707	7.79	14.3	
52.5	705	7.81	13.8	
53.0	734	7.68	14.2	
53.5	767	7.76	13.9	Is
54.0	782	7.71	14.0	
54.5	816	7.84	14.1	Is
55.0	832	7.80	14.0	
55.5	860	7.84	14.1	
56.0	845	7.83	13.9	
56.5	850	7.67	14.3	Is
57.0	932	7.54	13.6	
57.5	951	7.64	14.0	
58.0	940	7.67	13.7	Is

Depth (m)	Cond	pH	Temp deg C	Isotope/Sample
65.0	11370	12.91	14.1	
65.5	10570	12.89	14.9	
66.0	10310	12.87	15.3	
66.5	9680	12.81	15.3	
67.0	9050	12.70	15.3	
67.5	8810	12.76	15.3	
68.0	8500	12.78	14.4	
68.5	7720	12.75	14.5	
69.0	6220	12.64	14.5	
70.0	6220	12.57	14.7	
70.5	3040	12.19	15.2	
71.0	2770	11.99	14.6	
71.5	3020	12.12	14.9	
72.0	2910	12.12	14.9	B72
72.5	2910	11.99	15.0	
73.0	2800	11.87	15.0	
73.5	2810	11.85	15.0	B73.5
74.0	2720	11.85	15.1	
74.5	2490	11.66	15.0	
75.0	2690	11.59	15.1	
75.5	2680	11.60	15.1	B75.5
76.0	2470	11.37	14.9	
77.0	2790	11.56	14.5	B77
77.5	3080	11.82	14.7	
78.0	3860	11.72	15.0	
78.5	2930	11.76	15.2	B78.5
79.0	2890	11.7	14.9	
79.5	2860	11.64	15.6	B79.5


Grout
Casing
Bh Depth
Lithology
Rhyolite
Tuff
Fractured rhyolite and tuff
Rhyolite and tuff
Tuff
Rhyolite
Fractured rhyolite
Ash
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Major fracture
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Fractured rhyolite and tuff
Major fracture
Major fracture
Major fracture
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Rhyolite and tuff
Ash
Fractured pyroclastics
Rhyolite
Tuff
Fractured rhyolite and tuff
Rhyolite
Fractured rhyolite
Major fracture
Major fracture
Rhyolite
Tuff
Fractured pyroclastics
Rhyolite
Open hole
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
Specific Electrical Conductance
0
2000
4000
6000
8000
10000
12000
Depth (metres below ground level)
Base of the grouted section


Grout
Casing
Bh Depth
Lithology
Rhyolite
Tuff
Fractured rhyolite and tuff
Rhyolite and tuff
Tuff
Rhyolite
Fractured rhyolite
Ash
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Major fracture
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Fractured rhyolite and tuff
Major fracture
Major fracture
Major fracture
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Rhyolite and tuff
Open hole
Ash
Fractured pyroclastics
Rhyolite
Tuff
Fractured rhyolite and tuff
Rhyolite
Fractured rhyolite
Major fracture
Major fracture
Rhyolite
Tuff
Fractured pyroclastics
Rhyolite
Ph
Depth (metres below ground level)
Bottom of grouted section
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80


Grout
Casing
Bh Depth
Lithology
Open hole
Rhyolite
Tuff
Fractured rhyolite and tuff
Rhyolite and tuff
Tuff
Rhyolite
Fractured rhyolite
Ash
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Major fracture
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Fractured rhyolite
Fractured rhyolite and tuff
Major fracture
Major fracture
Major fracture
Fractured rhyolite
Rhyolite
Fractured rhyolite
Rhyolite
Rhyolite and tuff
Ash
Fractured pyroclastics
Rhyolite
Tuff
Fractured rhyolite and tuff
Rhyolite
Fractured rhyolite
Major fracture
Major fracture
Rhyolite
Tuff
Fractured pyroclastics
Rhyolite
Temp deg C
13
13.5
14
14.5
15
15.5
16
Depth (metres below ground level)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
Bottom of the grouted section

Appendix 6 Inorganic Chemistry Data

Sample ID	Sample Detail	Depth	Date (& Time)	pH	EC @20°C	DO	Temp	Ca	Mg	Na	K	Cl	SO4	Alkalinity (mg/l HCO_3)		NO_3	NO_2	PO4	Br	F	Fe
		m bgl			µS/cm	%	°C	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l		by IBE	mg/l NO_3	mg/l NO_3	mg/l P	mg/l	mg/l	µg/l
	La Rocque																				
	Borehole construction																				
A10	Prior to emplacement of 8" steel casing.	10.0	12/09/2006 11:05	8.20	1532		13.4	148	25	141	7.0	192	196		376	6	<0.015	<0.1	1.2	0.2	<10
A19.5		19.5	12/09/2006 13:25	8.28	1600		13.5	146	25	147	6.7	199	198		374	<2	<0.015	<0.1	1.2	0.3	<10
A22		22.0	12/09/2006 13:35	8.30	1617		13.5	146	26	149	6.8	201	199		380	<2	<0.015	<0.1	1.3	0.3	<10
A28.5		28.5	12/09/2006 14:15	8.20	1610		13.6	144	25	145	6.7	199	198		363	<2	<0.015	<0.1	1.3	0.3	<10
A34.5		34.5	12/09/2006 15:25	8.26	1599		13.5	142	25	142	7.0	197	197		354	<2	<0.015	<0.1	1.3	0.3	<10
A37.5		37.5	12/09/2006 17:00	8.25	1576		13.2	144	25	150	7.0	200	197		376	<2	<0.015	<0.1	1.3	0.4	<10
A43	End of first day	43.0	12/09/2006 17:15	8.26	1603		13.2	144	26	145	6.8	203	196		364	<2	<0.015	<0.1	1.3	0.3	<10
A43B	Start of second day,grout	43.0	13/09/2006 09:10	8.23	1604		13.3	144	26	144	6.6	203	196		361	<2	<0.015	0.2	1.3	0.3	<10
A46.5		46.5	16/09/2006 12:30	8.30	1625		13.3	132	27	140	8.7	235	191		273	<2		0.2	1.4	0.2	<10
A47.5		47.5	16/09/2006 12:45	8.75	1653		13.2	134	27	136	8.0	235	192		266	<2		0.2	1.4	0.3	<10
A48.5		48.5	16/09/2006 13:00	8.43	1582		13.3	120	27	140	9.1	234	191		239	<2		0.2	1.5	0.3	<10
A50.5		50.5	16/09/2006 13:30	8.33	1538		12.9	146	28	138	8.7	234	192		316	<2		0.2	1.3	0.3	<10
A55		55.0	16/09/2006 14:00	8.36	1671		13.2	144	28	132	7.2	233	191		295	<2		<0.1	1.5	0.3	<10
A12B	Second pass, through grout	12.0		9.18	1353		13.8	65	24	140	13.2	230	180		84	<2		<0.1	1.3	0.3	<10
A44	Into grout	44.0		11.70	1937		13.5	124	<1	142	21.8	234	183		156	<2		0.4	1.3	0.4	<10
	Pump testing																				
As01	First day Step test		31/10/2006 09:10	7.28	1680		14.0	159	29	156	7.0	232	194		407	<2		<0.1	1.5	0.2	<10
As02	First day constant rate test		01/11/2006 09:55	7.25	1661	0.0	12.8	156	29	152	6.8	232	193		388	<2		<0.1	1.4	0.3	<10
As03	Second day constant rate test		02/11/2006 09:50	7.27	1655	0.0	13.1	156	29	139	6.3	227	191		364	<2		<0.1	1.4	0.2	<10
As04	Third day constant rate test		03/11/2006 09:35	7.30	1648		13.1	155	29	137	6.3	228	191		354	<2		<0.1	1.4	0.3	10
As05	Shut down constant rate test		04/11/2006 09:00	7.33	1641	0.0	13.2	167	28	145	6.1	225	189	327		<2		<0.1	1.3	0.2	50
	Surrounding boreholes																				
Sc01	Near Chapel, Rue du Puits	30.5	02/11/2006 10:10	7.50	1748		13.1	155	34	161	7.2	221	233		402	<2		0.5	1.4	0.2	<10
Sc05	La Rocque observation borehole	32.0	31/01/2006 10:00	7.01	1604		12.6	147	27	113	7	217	207	*35*	256	<1					855
Sc03	Homegrown, Rue au Long, St Clement	42.0	02/11/2006 09:45	6.63	1051		15.1	93	23	75	25.7	96	0.2		380	94	<0.015	127	<1	0.1	<10
Sc02	Homefield farm, La Grande Route de St Clement	43.0	02/11/2006 10:30	6.48	1257		12.2	97	37	88	7.1	130	198		95	158		<0.1	1.1	0.2	<10
Sc04	Peacehaven, Le Bourg	37.0	02/11/2006 10:50	7.15	2550		13.4	166	49	264	16.8	373	249		517	2		<0.1	2.3	0.2	<10
Drinking WS	UK Water Supply (Water Quality) Regulations 2000			6.5-10	2500			250	50	200	12	250	250			50	0.1	2.2		1.5	200
Seawater	Data published in Hem, 1989 (p7)							410	1350	10500	390	19000	2700	142		0.67		0.09	67	1.3	3

Notes:
meq/l = milliequivalents per litre
Total cations = sum of the (meq/l) concentrations of Na+K+Ca+Mg
Total anions = sum of the (meq/l) concentrations of Cl+SO4+NO3+Alkalinity. Note Alkalinity not determined in a number of samples.
IBE = Ion balance error = (Total cations - Total anions)/(Total cations + Total anions) expressed as a %.

St Catherine

	Borehole construction																				
B58	Before casing/grouting	58.0	20/09/2006 14:45	7.67	940		13.7	60	21	86	45.0	194	52		116	72		0.2	1.4	0.4	<10
B68	After bh redrilled through hardened grout	68.0	23/09/2006 11:30	12.78	8500		14.4	590	<1	198	108.0	423	44		1637	75		0.2	1.9	0.3	10
B70.5		70.5	23/09/2006 12:00	12.19	3040		15.2	230	<1	184	47.3	451	77		316	78		0.2	2.2	0.3	20
B72		72.0	23/09/2006 12:20	12.12	2910		14.9	219	<1	205	45.1	495	87		247	78		0.2	2.5	0.3	10
B73.5		73.5	23/09/2006 12:30	11.85	2810		15.0	205	<1	235	52.7	571	100		149	77		0.2	2.7	0.4	<10
B75.5		75.5	23/09/2006 12:50	11.60	2680		15.1	188	<1	249	42.5	594	104		74	77		0.2	2.8	0.6	<10
B77		77.0	23/09/2006 13:00	11.56	2790		14.5	198	2	256	30.0	610	113		69	77		0.2	2.9	0.5	10
B78.5		78.5	23/09/2006 13:20	11.76	2930		15.2	210	<1	266	36.1	645	113		78	76		0.2	3.0	0.3	<10
B79.5		79.5	23/09/2006 13:30	11.64	2860		15.6	215	<1	275	39.0	649	116		111	76		0.2	2.9	0.5	<10
	Pump testing																				
Bs01	First day Step test		01/11/2006 12:40	9.45	2680	16	13.2	133	42	319	22.1	635	113		186	75		<0.1	2.9	0.1	<10
Bs02	First day constant rate test		02/11/2006 13:40	7.54	3550	25	13.4	157	70	373	14.3	826	153		154	72		<0.1	3.5	0.2	<10
Bs03	Second day constant rate test		03/11/2006 08:45	7.17	3850		13.1	195	85	454	12.3	1002	176		224	73		<0.1	4.2	0.2	<10
Bs04	Third day constant rate test		04/11/2006 10:37	7.00	4390	11	13.6	252	108	556	13.0	1183	196	102		67		<0.1	4.8	<0.1	<10
Bs05	Shut down constant rate test		05/11/2006 12:12	6.94	4870	11	13.4	231	100	521	12.2	1324	197	77		69		<0.1	4.2	<0.1	<10
	Surrounding boreholes																				
St.C1	Bel Val, St Catherine		14/02/2006 09:30	6.25	755		12.2	53	19	50	11.9	84	95		52	92					<10
St.C2	La Vielle Chapel, Rue des Vivier, St Catherine	65.0	21/09/2006 15:00					214	53	250	12.0	770	122		65	55		0.3	3.3	0.1	<10
St.C3	Le Petit Clos du Rey, Rue du Champs du Rey, St Catherine	20.0	21/09/2006 15:30	7.13	649		16.9	42	25	52	2.5	70	76	100		30	<0.015	<0.1	<1	0.2	<10
St.C4	L'Oasis, Rue du Champs du Rey, St Catherine	31.0	21/09/2006 15:50	7.37	657		19.9	48	17	53	2.6	85	63	73		40	<0.019	<0.1	<1	0.2	<10
St.C5	Anneville Lodge, Mont des Landes, St Catherine	30.0	21/09/2006 16:40	6.22	728		15.2	51	13	72	7.6	76	102	46		65	<0.015	<0.1	<1	0.1	<10
St.C6	La Solitude, Rue de la Solitude, St Catherine	?	21/09/2006 16:15	5.97	738		18.5	44	13	80	4.4	61	124	24		97	<0.015	<0.1	<1	<0.1	<10
Drinking WS	UK Water Supply (Water Quality) Regulations 2000			6.5-10	2500			250	50	200	12	250	250			50	0.1	2.2		1.5	200
Seawater	Data published in Hem, 1989 (p7)							410	1350	10500	390	19000	2700	142		0.67		0.09	67	1.3	3

Notes:
meq/l = milliequivalents per litre
Total cations = sum of the (meq/l) concentrations of Na+K+Ca+Mg
Total anions = sum of the (meq/l) concentrations of Cl+SO4+NO3+Alkalinity. Note Alkalinity not determined in a number of samples.
IBE = Ion balance error = (Total cations - Total anions)/(Total cations + Total anions) expressed as a %.

Appendix 7 Isotopic Data

Sample No	BGS lab ref	Grid ref	Location	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰
Jersey 1	S06-00881	-2.062* 49.237*	Bellozane	-5.81	-37.8
Jersey 2	S06-00882	570774 545275	Bel Val	-5.86	-34.6
Jersey 3	S06-00883	-2.224* 49.177*	Cotes du Nord	-6.01	-35.4
Jersey 4	S06-00884	570654 544719	La Rocque	-5.30	-34.1
Jersey 5	S06-00885	-2.029* 49.221*	La Saie	-6.05	-36.8
Jersey 6	S06-00886	-2.122 49.201*	Le Douaire	-5.30	-34.8
Jersey 7	S06-00887	-2.056* 49.238*	Met Station	-5.34	-32.9
Jersey 8	S06-00888	-2.095* 49.233*	States BH	-5.90	-35.4
Jersey 9	S06-00889	-2.211* 49.245*	Vinchlez	-6.01	-36.9
A10	S06-01254	570633 544719	La Rocque test BH - 10.0 m	-5.61	-34.0
A19.5	S06-01255	570633 544719	La Rocque test BH - 19.5 m	-5.68	-32.3
A22	S06-01256	570633 544719	La Rocque test BH - 22.0 m	-5.58	-35.1
A34.5	S06-01257	570633 544719	La Rocque test BH - 34.5 m	-5.56	-35.2
A37.5	S06-01258	570633 544719	La Rocque test BH - 37.5 m	-5.60	-32.5
A43	S06-01259	570633 544719	La Rocque test BH - 43.0 m	-5.52	-33.3
A46.5	S06-01260	570633 544719	La Rocque test BH - 46.5 m	-5.61	-33.2
A50.5	S06-01261	570633 544719	La Rocque test BH - 50.5 m	-5.56	-33.4
A55	S06-01262	570633 544719	La Rocque test BH - 55.0 m	-5.64	-32.7
C1	S06-01263	569856 544678	Peacehaven, Le Bourg, St Clement	-5.32	-30.1
C2	S06-01264	569632 544758	Homefield Farm, La Grande Route de St Clement	-5.24	-29.1
C3	S06-01265	570327 544713	Near Chapel, Rue du Puit Mahaut	-5.43	-30.3
C4	S06-01266	570115 544754	Homegrown, Rue au Long, St Clement	-5.41	-31.7
B58	S06-01267	570827 545196	St Catherine test BH - 58.0 m	-5.41	-30.2
B68	S06-01268	570827 545196	St Catherine test BH - 68.0 m	-5.30	-28.5
B75.5	S06-01269	570827 545196	St Catherine test BH - 75.5 m	-5.31	-31.4
B77	S06-01270	570827 545196	St Catherine test BH - 77.0 m	-5.42	-30.3
B79.5	S06-01271	570827 545196	St Catherine test BH - 79.5 m	-5.42	-29.6
D1	S06-01272	570804 545198	Pine Walk A, La Vielle Chapel, Rue des Vivier, St C.	-5.59	-33.3
D2	S06-01273	570674 545213	Pine Walk B, Rue du Champs du Rey, St C.	-5.71	-31.9
D3	S06-01274	570723 545204	Pine Walk C, Rue du Champs du Rey, St C.	-5.82	-32.7
D4	S06-01275	570830 545168	Archirondel, Mont des Landes, St C.	-5.99	-33.6
D5	S06-01276	570545 545202	La Solitude, Rue de la Solitude, St C.	-5.82	-31.3
AS01	S06-01277	570633 544719	La Rocque test BH - step test start	-5.51	-32.9
AS02	S06-01278	570633 544719	La Rocque test BH - CRT start	-5.32	-33.4
AS03	S06-01279	570633 544719	La Rocque test BH - CRT day 2	-5.52	-35.6
AS04	S06-01280	570633 544719	La Rocque test BH - CRT day 3	-5.19	-32.3
AS05	S06-01281	570633 544719	La Rocque test BH - CRT finish	-5.42	-34.6
BS02	S06-01282	570827 545196	St Catherine test BH - CRT start	-5.98	-33.8
BS03	S06-01283	570827 545196	St Catherine test BH - CRT day 2	-5.07	-30.9
BS04	S06-01284	570827 545196	St Catherine test BH - CRT day 3	-5.26	-31.8
BS05	S06-01285	570827 545196	St Catherine test BH - CRT finish	-4.79	-30.3

* Lat./Long.