BGS Technical Report WE/98/52
Environment Agency R&D Technical Report P 201

Effects of old landfills on groundwater quality: Phase 2 —
Investigation of the Thriplow landfill 1996–1997

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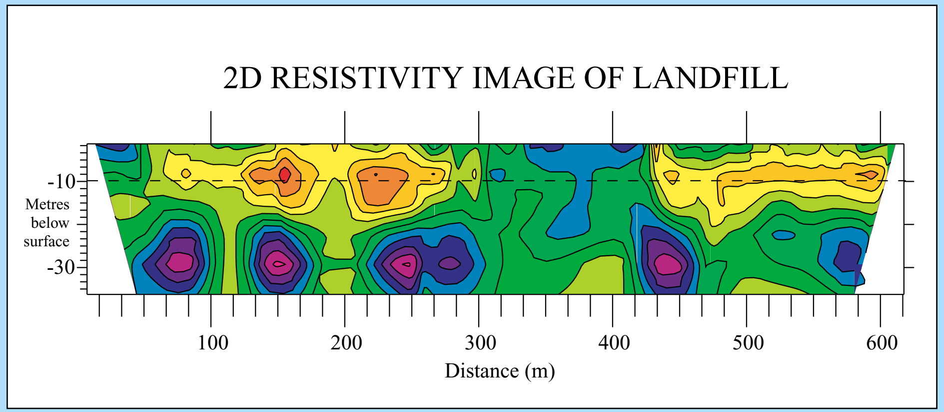
2D RESISTIVITY IMAGE OF LANDFILL

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Effects of old landfills on groundwater quality: Phase 2 — Investigation of the Thriplow landfill 1996–1997

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1 Environment Agency, Anglian Region, Peterborough

Cover illustration

2-D resistivity distribution over the landfill, used to identify the depth of the waste and migration of leachate.

Bibliographical reference

Williams, G M, Boland, M P, Higgo, J J W, Ogilvy, R D, Klinck, B A, Wealthall, G P, Noy, D J, Trick, J K, Davis, J A, Williams, L A, Leader, R U, and Hart, P. 2000. Effects of old landfills on groundwater quality: Phase 2 — Investigation of the Thriplow landfill 1996–1997. *British Geological Survey Technical Report*, WD/00/4. 00pp. Environment Agency R&D Technical Report P 201.

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Statement of use

This report provides information on the investigation of the Thriplow landfill which will help assess the impact of similar sites on groundwater quality.

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Foreword

This investigation forms part of an on-going joint investigation by the British Geological Survey (BGS) and the Environment Agency (EA) into the impact of old landfills on groundwater quality.

It has been carried out within the terms of the memorandum of understanding between the Environment Agency and the Natural Environment Research Council (British Geological Survey) which aligns research activities.

The work lies within the framework of fundamental research by the British Geological Survey into the properties of the UK Chalk aquifer and the migration of solutes within it. The Environment Agency's component is part of the research programme "Effect of old landfills on groundwater quality". Phase 1 of the latter was undertaken for the Environment Agency (then the National Rivers Authority), by Geraghty and Miller, and involved a review of a large number of landfills in England and Wales in order to identify those sites where groundwater pollution was known, or thought likely, to occur. The Thriplow landfill was identified and short-listed for further study, and this report forms Phase 2 of the Environment Agency's Programme to assess the site. Phase 3 of the work is currently underway and seeks to clarify aspects of the preliminary site investigation discussed in this report.

ACKNOWLEDGEMENTS

The authors are grateful in particular to Peter Ord (EA), and to Mike Martin and Tony Reynolds (Cambridgeshire CC), and to many BGS colleagues who have participated in this work. The work undertaken by Dr Chris Coggins (Luton University) and Dr Mike Sleat of Milton Treharne and Davies is also acknowledged as an important contribution to the landfill characterisation.

STEERING COMMITTEE

The steering committee for this phase of the work comprised, Bob Harris, Dr Jan Gronow, David Tester, Dr Paul Hart, Peter Ord, Paul Waldron, Ian Davey and Dick Flavin representing the EA. Tony Goryn represented Cambridgeshire CC.

Executive summary

Disused sand and gravel excavations overlying the major Chalk aquifer at Thriplow in Cambridgeshire have been filled with domestic waste in two phases. One area (Phase 1) was filled between 1957–77 with little compaction of the refuse and was left uncapped, while Phase 2 was deposited between 1981–87 and capped with clay. Aerial photography and surface resistivity surveys indicate that the site geometry is complex, with several phases of landfilling into excavations of differing depths. Drilling through the waste indicates that leachate production and waste stabilisation proceed at different rates in capped and uncapped landfills. Analysis of leachate obtained by centrifugation or squeezing appears to give more insight into the pollution potential than do leach tests with distilled water. The Biological Methane Potential (BMP) of the waste appears to be related to the quantity of decomposable material but the chemical oxygen demand (COD) values are distorted by the presence of reduced metals. Too few boreholes have been drilled to define the leachate source in terms of its spatial distribution and little is known of how its composition has changed with time. However, hydraulic conductivity measurements on the landfill caps suggest that it is sufficiently permeable for all rainfall to potentially infiltrate the waste.

Boreholes outside the landfill penetrate the Upper and Lower Chalk, and identify the Melbourn Rock and underlying Plenus Marls at the junction of the two formations about 20 m below ground level (bgl). Surface resistivity surveys using the BGS RESCAN system, confirm aerial photographs of the extent of the landfill and also suggest that leachate has migrated beyond the base of the landfill. Evidence of leachate migration in pre-existing screened boreholes completed above and below the Plenus Marls suggests that leachate is flowing above the Plenus Marls. Hydraulic head measurements whilst drilling a borehole to the base of the lower Chalk approx. 70 m bgl revealed the potential for upward groundwater flow through the Plenus Marls. Thus, previously-drilled boreholes penetrating the Plenus Marls are expected to recharge upwards into the shallow aquifer above the Plenus Marls diluting any leachate in the upper aquifer and distorting the flow regime. Several of these boreholes have subsequently been modified to stem the flow across the Plenus Marls.

One borehole down-gradient to the west of the site revealed a large thickness of drift composed of both sand and clay rich material. This suggests the existence of a buried channel, the hydrogeological significance of which has yet to be assessed.

Groundwater chemistry appears to be influenced by three major factors. (a) the landfill leachate (b) the composition of shallow groundwater in the top 10 m of the Chalk, and (c) the composition of water from the Lower Chalk. Limited groundwater monitoring data appear to display a cyclic variation in chloride concentration. The origin for this is not clear but it may correlate with cyclic variations in groundwater levels when the water table rises into the waste. Cyclic flushing of the landfill may release leachate into the aquifer giving rise to pulses of chloride. Alternatively changes in chloride may arise by the changing direction of groundwater flow which as yet has not been assessed.

A conceptual hydrogeological model in which flow is limited to above the Plenus Marls has been used to develop a more appropriate groundwater flow and solute transport model. However, the model lacks data on aquifer properties, on contaminant inputs concentrations, fluxes and spatial variations, and there is a paucity of monitoring data for calibration. Nonetheless preliminary transport modelling using an equivalent porous medium approach shows that an effective porosity of about 5% best fits the regional data. Since this is much less than the total porosity of about 40% for the Chalk, it would appear that only part of the Chalk is available for flow but that matrix diffusion could play an important role in leachate attenuation. Discrete fracture modelling using the FRACTRAN code has allowed some scoping to be made of the hydraulic properties of the aquifer by comparison with chloride hydrographs, but these again need to be better conditioned by in-situ measurement of fracture distributions and transmissivities.

A number of additional activities are required to improve the understanding of flow and contaminant transport at the site. These include better spatial definition of the waste distribution, improved data on the hydraulic properties of the Chalk aquifer, and the use of automatic monitoring to record temporal changes in groundwater chemistry and groundwater levels.

Part I — Review of existing data

1 INTRODUCTION

In 1994, the National Rivers Authority (now the Environment Agency) initiated a desk–based survey “to assess the extent of the groundwater and surface water pollution potentials of landfill sites containing domestic/ commercial/co-disposal wastes, particularly those overlying major aquifers, in order to assist with management decisions”.

This study, (NRA, 1995), identified a number of sites where groundwater contamination was likely, or was known to exist, and where additional investigations were recommended.

Amongst those sites identified for further study was the completed landfill at Thriplow, Cambridgeshire, where primarily domestic waste had been deposited in two distinct phases. Operated on the “dilute and disperse principle”, monitoring boreholes indicated groundwater in the underlying Chalk aquifer to be affected by landfill leachate.

A detailed investigation of the Thriplow Landfill is currently underway funded jointly by the Environment Agency (EA) and the British Geological Survey (BGS).

The overall objectives of this project are to:

- characterise the plumes emanating from the landfills
- identify controls on leachate migration and attenuation
- develop a well-constrained model to describe groundwater flow and reactive mass transport to describe the existing plume distribution and predict future plume extent
- provide facilities for long term monitoring to determine natural attenuation processes and confirm model predictions.

Part I of this report summarises the results of a desk study by Boland (1996a). Part II describes the first two phases of field investigation (Williams et al., 1997, Williams and Boland, 1997), re-appraises the conceptual models, and presents recommendations for the next phase of the project.

2 SITE LOCATION, RAINFALL AND DRAINAGE

2.1 Location

The Thriplow landfill (TL 446 447) is situated to the south of the A 505 in former excavations in the Taele Gravels (Figure 2.1). It lies in an area of relatively low relief (30 m above ordnance datum, AOD) below the Chalk escarpment to the south east which rises to 120 m AOD.

2.2 Rainfall

Weekly manual rain gauge data are held by the Environment Agency for Fowlmere public water supply, the record starts in 1966. A more complete meteorological record is held for Chesterford Park, 9 km south east of the landfill, where daily records of rainfall, temperature, sun hours, humidity and wind speed have been recorded since 1966. Effective rainfall data derived from the Meteorological Office Rainfall and Evaporation Calculation System (MORECS), were acquired for the area modelled in Part 1 of this study (Table 2.1). Recharge was estimated using these data in combination with calculated recharge values determined by Carey (1986) in his doctoral research on the hydrology of the Great Ouse catchment.

2.3 Drainage

The main drainage is provided by the River Cam 5 km to the east of the site and the River Rhee 6 km to the north. These two rivers converge just south of Cambridge. The rivers are fed by a number of tributary streams, many of which rise from ephemeral springs. The Environment Agency holds flow data for numerous stream gauging stations on the Rivers Cam and Rhee and for springflow sites on the brooks in the Thriplow area.

Figure 2.1 Location map for the Thriplow landfill site (NGR TL 446 447).

Table 2.1
MORECS rainfall data for the period 1964–1996 (mm).

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Year
46.8	33.6	0.5	2.3	0.8	0.9	0.6	0.9	1.7	2.3	6.4	40.2	137.2	1961
53.5	6.9	2.3	5.8	0.7	0	2.1	1.5	1.9	1.4	3	18.6	97.8	1962
16.8	9.8	21.6	9.5	2	0.9	2	2.9	1.7	2.2	30.8	8.5	108.6	1963
13.3	7.9	53.6	12.2	1	3.4	0.5	0.2	0.1	0.6	1.3	4	98.2	1964
14.5	4.5	25.1	2.3	1.4	1.5	1.8	1.5	5.5	2.4	22.4	74.2	157	1965
22.1	36.8	1.2	10.9	0.7	1.5	1.9	2.8	0.9	4	18.6	51	152.5	1966
24.1	21.1	4.8	8.1	4.9	1	1.4	0.8	1	7.8	29.8	38	142.7	1967
31.6	18.1	0.3	1.1	0.8	1.2	3.1	9.9	54.5	23.4	23.9	34.5	202.5	1968
48.9	32	36.5	0.9	4	0.9	2.2	1.4	0	0.1	3.7	26.6	157.2	1969
50.8	38	16.3	26.5	0.5	0.5	0.6	1.1	0.9	0.9	17.6	35.8	189.5	1970
59.2	8.3	14	1.7	1.2	4.4	0.9	1.2	0.7	5.3	25.1	11.9	133.9	1971
38.4	27	17.6	2.9	0.5	0.3	1.6	0.2	1.2	0.1	2	4.2	96.1	1972
2.3	2.5	2.2	0.7	2.7	2	1.5	0.4	2.3	2.5	2.1	6.8	28.1	1973
21.8	29.3	7.9	0.3	0.4	1.2	0.9	2.3	2.8	33	83.1	16.6	199.5	1974
38.1	18.3	56.2	31.2	2.6	0.6	0.2	0.3	2.5	0.2	3	2.2	155.5	1975
5.2	3.2	0.4	0.4	0.4	0.2	1	0.9	2.1	8.5	45	53.6	120.9	1976
53.6	55.5	11.6	1.2	2	1.2	0.1	7.4	0.5	0.6	3.6	36.9	174.1	1977
57.6	27.3	30.2	5.6	43.7	1.4	1.3	0.8	0.7	0.1	0.6	16	185.4	1978
48.9	41.8	53	11.4	2.5	1.2	0.3	1.6	0.3	2.1	3.6	54.6	221.3	1979
32.5	30	37.6	0.9	0.2	2.2	1.6	0.8	0.5	4.2	5.4	17.9	133.8	1980
16.4	9.2	64.1	22.4	9.9	0.3	1.8	1.4	2.7	15	12.3	38.7	194.2	1981
26.7	5.2	19.5	0.1	1.3	2	1.2	1.8	2.9	45.1	52.6	45.4	203.9	1982
15.7	31.8	13.9	42.2	30.8	0.3	1.2	0.3	1.9	0.9	5	17.7	161.6	1983
46.9	23.7	13.5	2	4.9	2	0.3	0.8	4.9	3.3	35.6	34.3	172.3	1984
38	6.3	7.6	5.8	1.7	5.9	1.3	0.6	0	0.4	2.6	30.8	101	1985
43.1	10	13.8	30.1	1.1	0.3	1.7	2.8	0.7	3.6	20.9	37.7	165.8	1986
15	14	19.8	23	1.2	4.6	3.3	9.1	1.2	74.4	38.5	14.7	218.8	1987
84.3	18.1	43.2	1.4	0.9	1.3	2.5	0.5	1.4	5.1	6.9	7.4	173	1988
17.4	16.9	24.4	23.6	0.1	0.8	1.4	0.8	0.4	0.8	1	13.6	101.3	1989
31.7	43.9	4.1	0.7	0.4	0.6	0.2	0.4	0.6	1.3	1.5	3.7	89.1	1990
5.7	10.3	13.2	1.4	0.7	1.7	0.9	0.4	1	0.6	2.1	1.9	39.9	1991
20.4	2.3	17.4	2.7	1.3	1.1	1.8	1.4	5.2	25.3	55.7	34	168.6	1992
34.8	2.6	1.7	14.4	1.2	1.2	1.2	1	4.8	34.6	35.8	64.7	198	1993
43.6	18.3	6.2	25.6	1.3	0.3	0.3	0.8	2.9	4.2	3.2	20	126.7	1994

3 PREVIOUS WORK AND DISPOSAL HISTORY

3.1 Previous work

In 1976 boreholes were drilled in the older landfilled area and into the Chalk to investigate leachate migration. This study (Tester and Harker, 1981) concluded that groundwater was affected by leachates from the landfill, but that the pollution plume was limited in extent of as a result of natural attenuation reactions. While the results concurred with those of the Department of Environment landfill research programme at that time (Department of Environment, 1978), the authors pointed out that the investigation lacked information on the dynamics of plume development and recommended that monitoring be continued to assess the long term effects of domestic refuse leachate on groundwater quality. They also recommended a study of the fate of pathogenic micro-organisms and of the possibility of biological clogging of the aquifer.

Additional information on the Thriplow landfill is recorded in six reports held by the Environment Agency. Apart from a report by Woodrow (1991) the reports have no authorship. Two of the six reports were commissioned following the proposal to develop the second landfilling phase, while the remaining reports date from the early 1990's and relate to four Environment Agency monitoring boreholes constructed in 1994. These reports provide general information on the geology, hydrogeology and monitoring of the site and also provide the main source of information on the nature of the waste. They are listed in the references section.

Eleven boreholes have been drilled around Thriplow (Figure 3.1). Thriplow landfill monitoring boreholes (TBH 1–3) were sunk in 1976, and TBH 4 was drilled in 1977. TBH 2 was sunk through 4 m of fill, which was cased off, and was completed at 21 m bgl in the Melbourn Rock. TBH 3 and 4 were both drilled to a depth of 50 m (Tester and Harker, 1981). TBH 5–7 were sunk in 1982. Four further boreholes, (A17, A30, B15 and B30) were drilled by the NRA in 1994. Over the years, large amounts of unpublished data on groundwater levels and groundwater chemistry have been collected by the NRA and the waste disposal authority.

In order to assess the impact of an extension of the disposal operations, Oakes (1986) modelled pollutant transport using a steady state, finite element model. This used an effective aquifer thickness of 20 m, a porosity of 0.35,

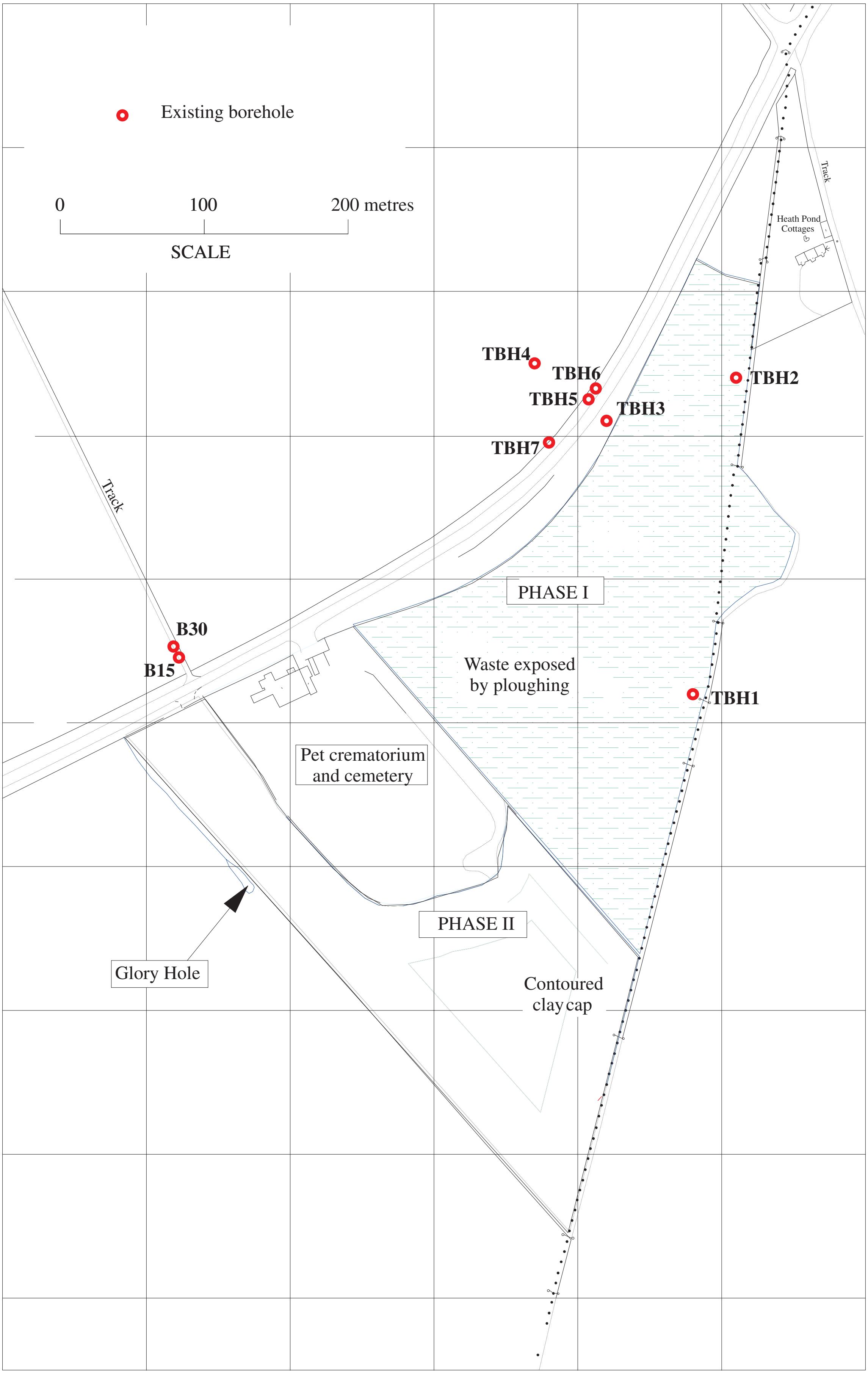


Figure 3.1 Thriplow site plan with landfill phases and positions of pre-project boreholes.

longitudinal and transverse dispersivities of 120 m and 60 m. Fowlmere public water supply (Figure 2.1) was considered to be pumping at its average rate for 1970. The landfill leachate was assumed to contain 1000 mg/l of a conservative species (such as chloride). Based on the leachate composition determined in the existing landfill, the model predicted that when Fowlmere public water supply was pumping at its maximum licensed abstraction rate, groundwater flow would be diverted towards it, and a maximum ammoniacal nitrogen level of 1–2 mg/l would be reached in 80 years. The model predicted that 50% of the maximum concentration would be reached in 25 years.

3.2 Disposal history

The history of the site has been inferred from the EA archives and from aerial photographs taken over a 35 year period. The following history has been built up from archives. The aerial photographs are analysed in detail in the next section.

Phase 1 This operated between 1957 and 1977. The site was operated by South Cambridgeshire Regional District Council until 1974, when the ownership was transferred to Cambridgeshire County Council. This site covered an area of 7.21 hectares, and was filled to a depth of between 3 m and 9 m below ground level giving a waste volume of 3×10^6 m^3. The site took household waste and some commercial and industrial wastes. Between 1970 and 1976 the waste was pulverised prior to filling. No records of annual volumes are held by either the Waste Regulation Authority or the County Council, but unpublished data collected during the Review of Waste Disposal Facilities in England and Wales (Gray et al., 1974) give the annual rate of fill as 14,800 tons of solid waste and 15,142 m^3 of liquid waste. This consisted of 11,000 tons of pulverised household and trade waste, 1,800 tons of domestic and trade wastes, 1,000 tons delivered trade waste and 100 tons construction and demolition waste. Tester and Harker (1981) later reported an input of 15,800 tons of solid waste and 1,800 m^3 of liquid waste. No waste was deposited at Thriplow between 1977 and 1981.

Phase 2 This operated between 1981 and June 1987 and covered an area of 3.98 hectares. It was excavated to a depth of between 1.8 and 9 m below ground level and had a volume of 1.4×10^6 m^3. The site was filled above the original ground level primarily with household, commercial and industrial waste. From August 1982 the site was licensed to take up to 3,120 m^3 per annum of sewage sludge cake from Sawston sewage treatment works but there is no evidence that this ever took place. The site was also licensed to take 984 m^3 per annum of biodegradable, low nitrogen, “non-special” liquid wastes such as septic tank/cesspool emptyings.

The planning permission for this phase of the site stipulated that the site would be restored with a minimum covering of 1 foot (0.3 m) of top soil to suitable contours. A report in January 1978 recommended that a 2 m layer of sand and gravel be left on the base of the site before landfilling above, but it is not known whether this was done.

3.3 Interpretation of aerial photographs

Six sets of aerial photographs were obtained over the period from 1946 to post-closure in 1988 and have been used to chronicle the stages of quarrying and landfilling.

1946 to 1948 (Figure 3.2) — The photographs show two chalk quarries (A and B) to be present. There is no substantial difference between the two sets of photographs indicating little activity. The northern-most quarry (A) has an area of made ground which may be old gravel workings or, more likely, a dump. Anecdotal evidence suggests that during the Second World War this area was used for waste disposal by the American Air Force base at Duxford.

1952 (Figure 3.3) — Limited quarrying activity is apparent in both areas A and B, but in area standing water suggests that the excavation had intercepted the water table.

1969 (Figure 3.4) — Extensive quarry workings are evident with the two older pits being reworked and extended, while a new quarry has been developed in the middle of the site between A and B. The quarrying to the north has extended into the area of made ground and ponds can be seen. Shallow gravel working is also evident on the opposite side of the road at Heath Farm (TL 439 445). At this time landfilling is taking place in the northernmost (A), and in the southern (B), quarries.

1974 (Figure 3.5) — An incinerator is now on site, and the workings at Heath Farm have been backfilled. The original three quarries are now backfilled. Recent waste deposition exists in the area to the south east and east of the incinerator, and in a small area on the north eastern side of the landfill. Active quarrying is taking place to the south of the incinerator in area C forming an ‘L’ shaped excavation which is later to become the Phase 2 landfill.

1977 (Figure 3.6) — Open tipping continues in the area to the east of the incinerator and there appears to be a chalk rubble cover. Baled waste appears at the northern tip of the site which has a recently emplaced soil cover with evidence of vehicle tracks. There is no change in the shape of newer working, C, to the south of the incinerator.

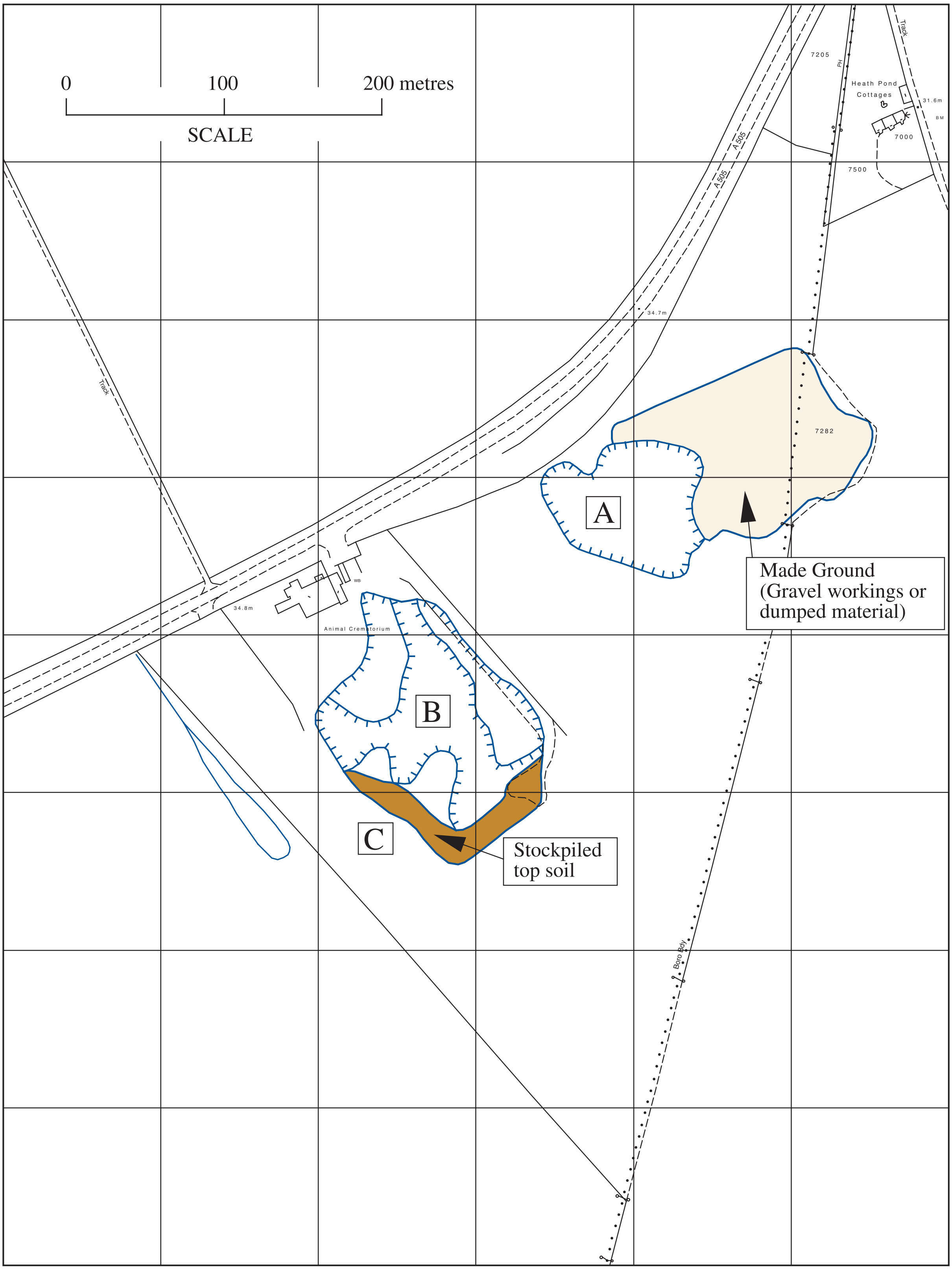


Figure 3.2 Interpretation of aerial photographs from Thriplow Landfill 1946–48.

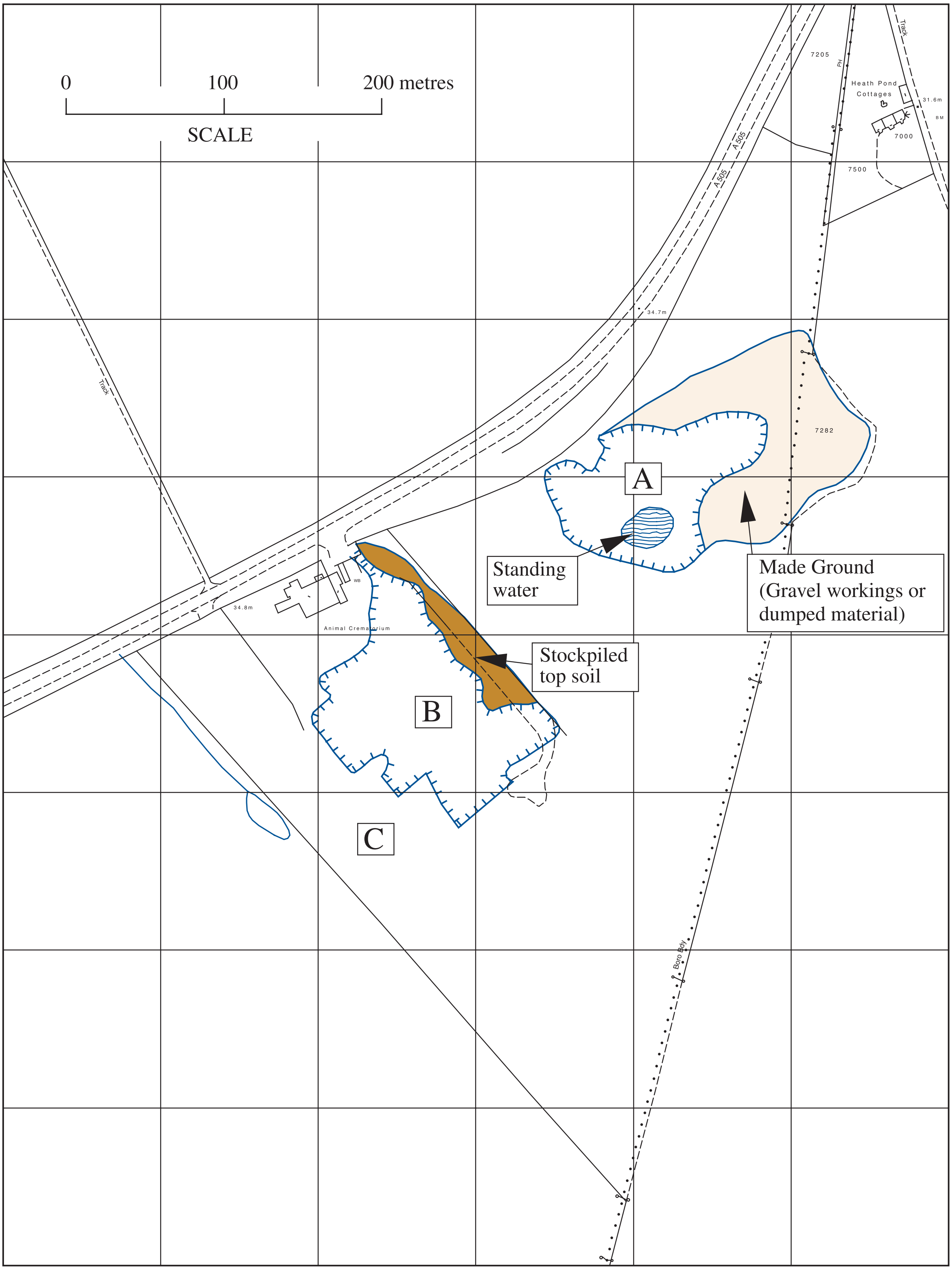


Figure 3.3 Interpretation of aerial photographs for Thriplow Landfill 1952.

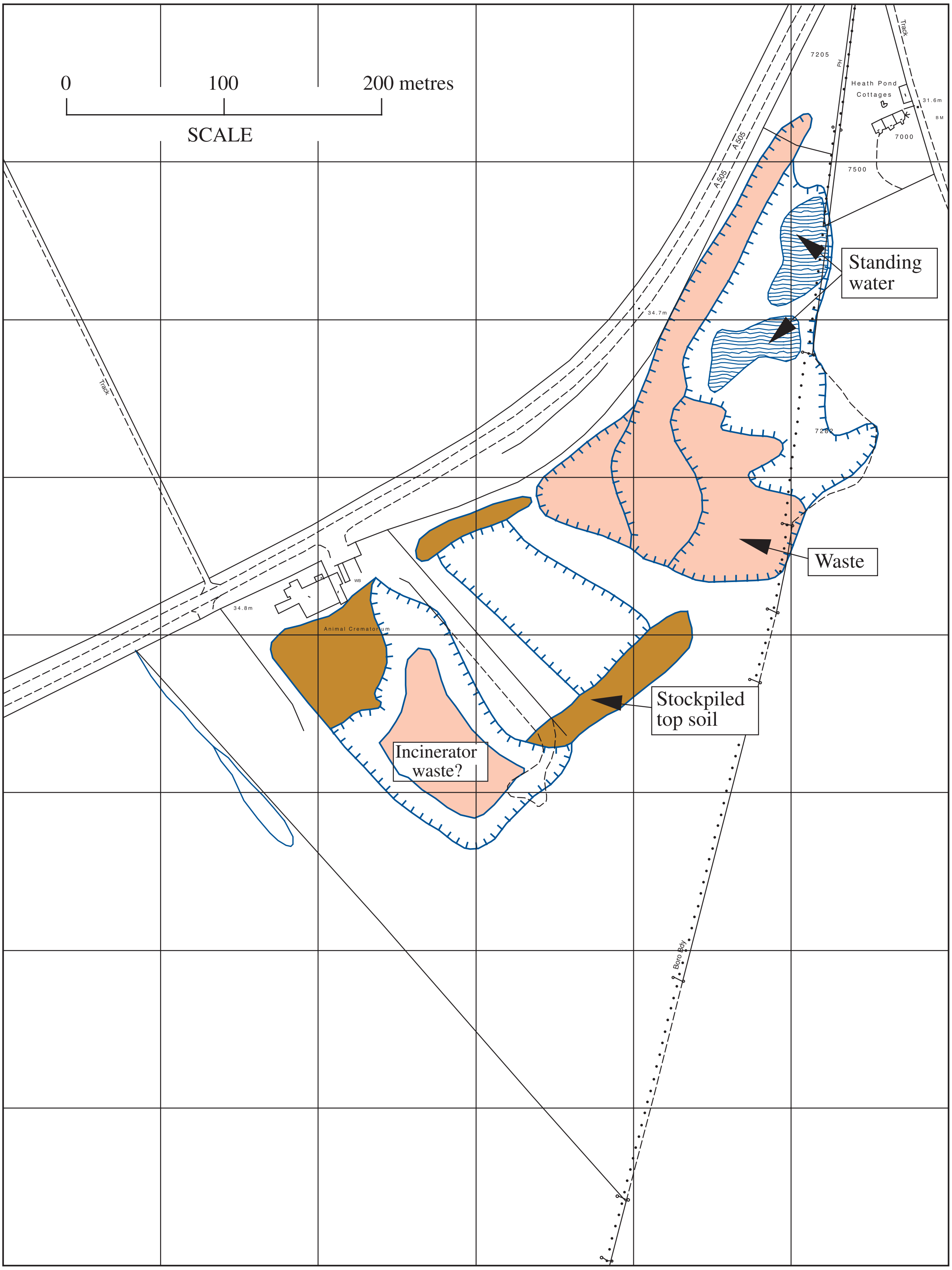


Figure 3.4 Interpretation of aerial photographs for Thriplow Landfill 1969.

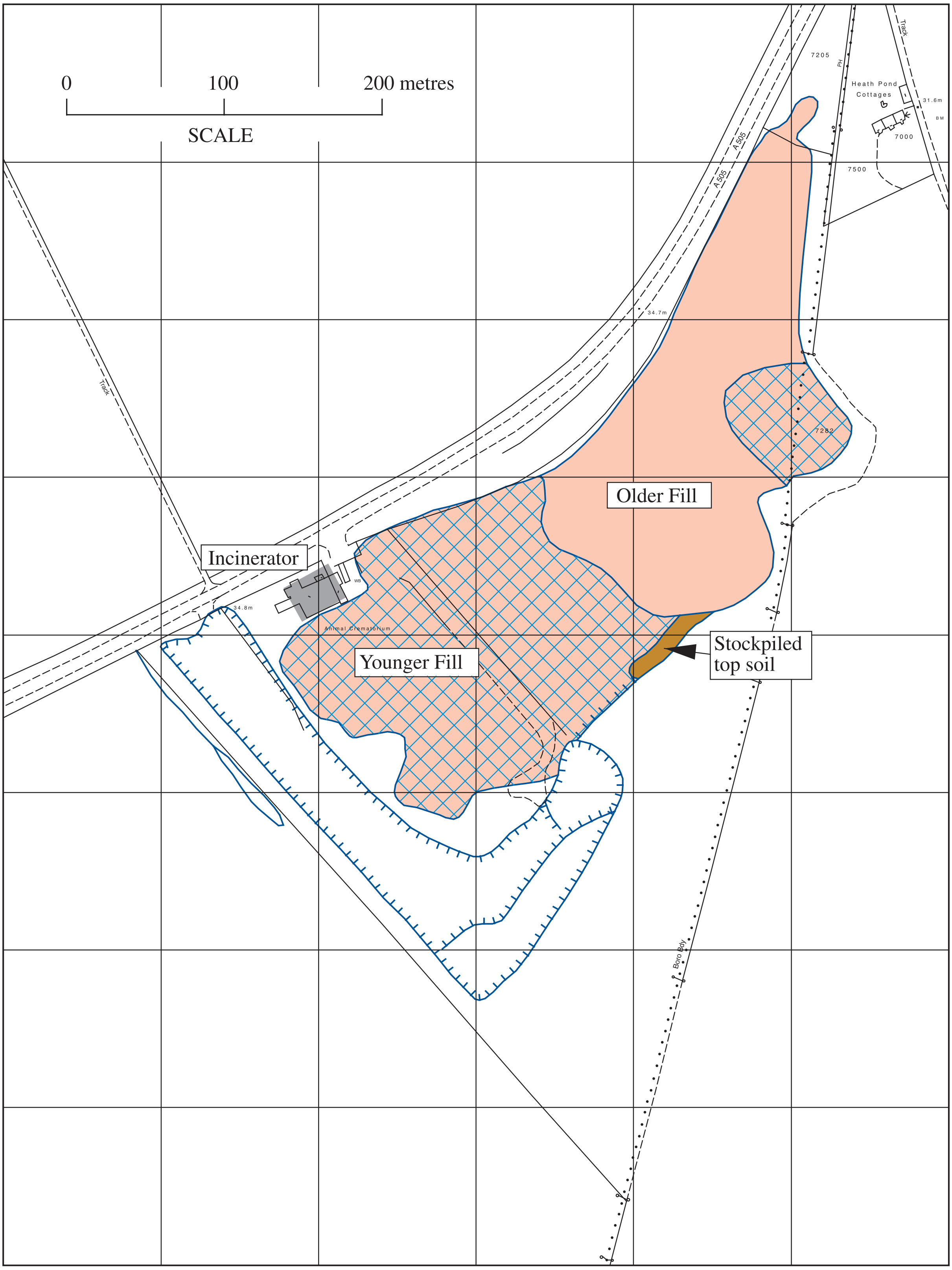


Figure 3.5 Interpretation of aerial photographs for Thriplow Landfill 1974.

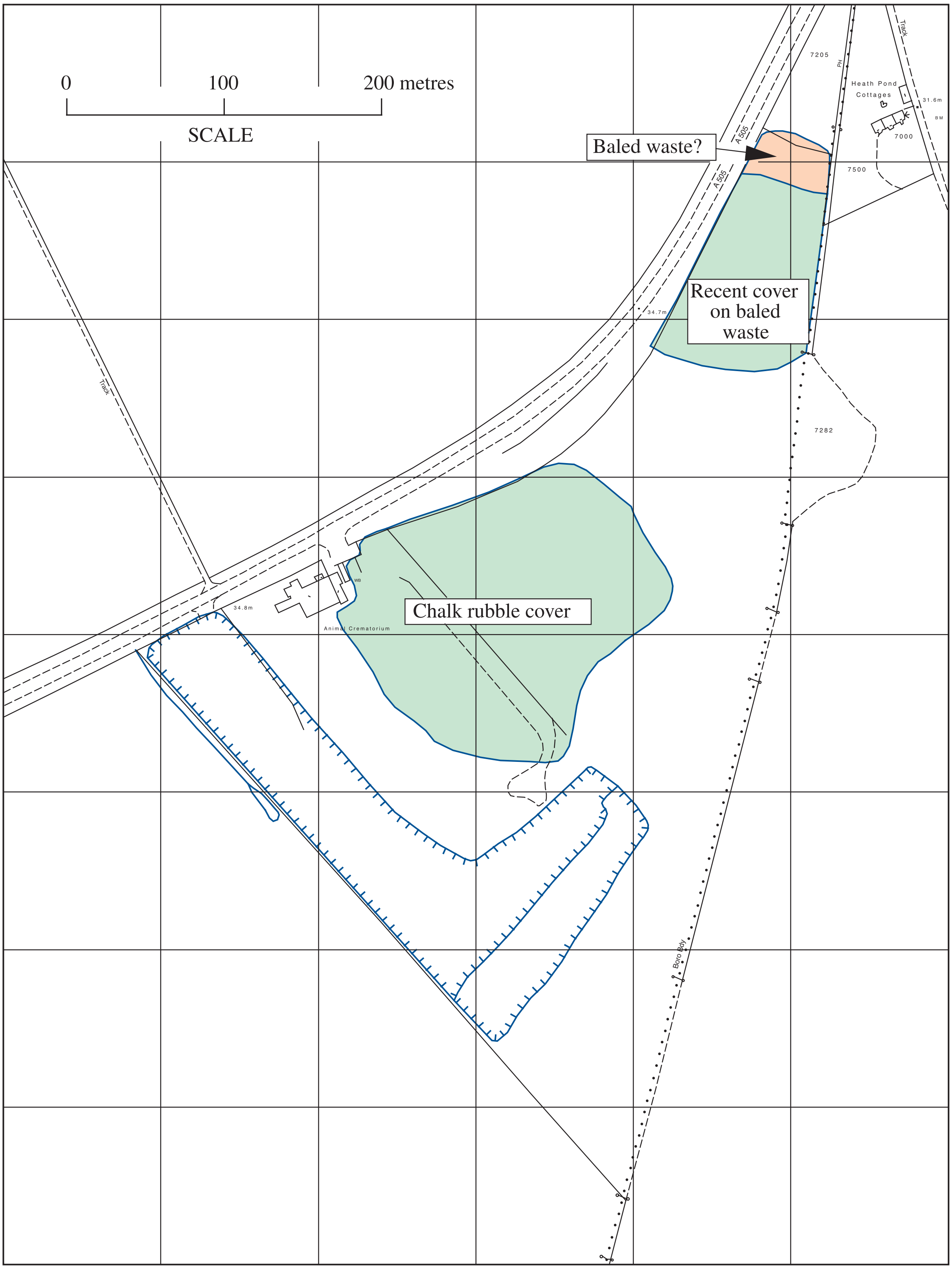


Figure 3.6 Interpretation of aerial photographs for Thriplow Landfill 1977.

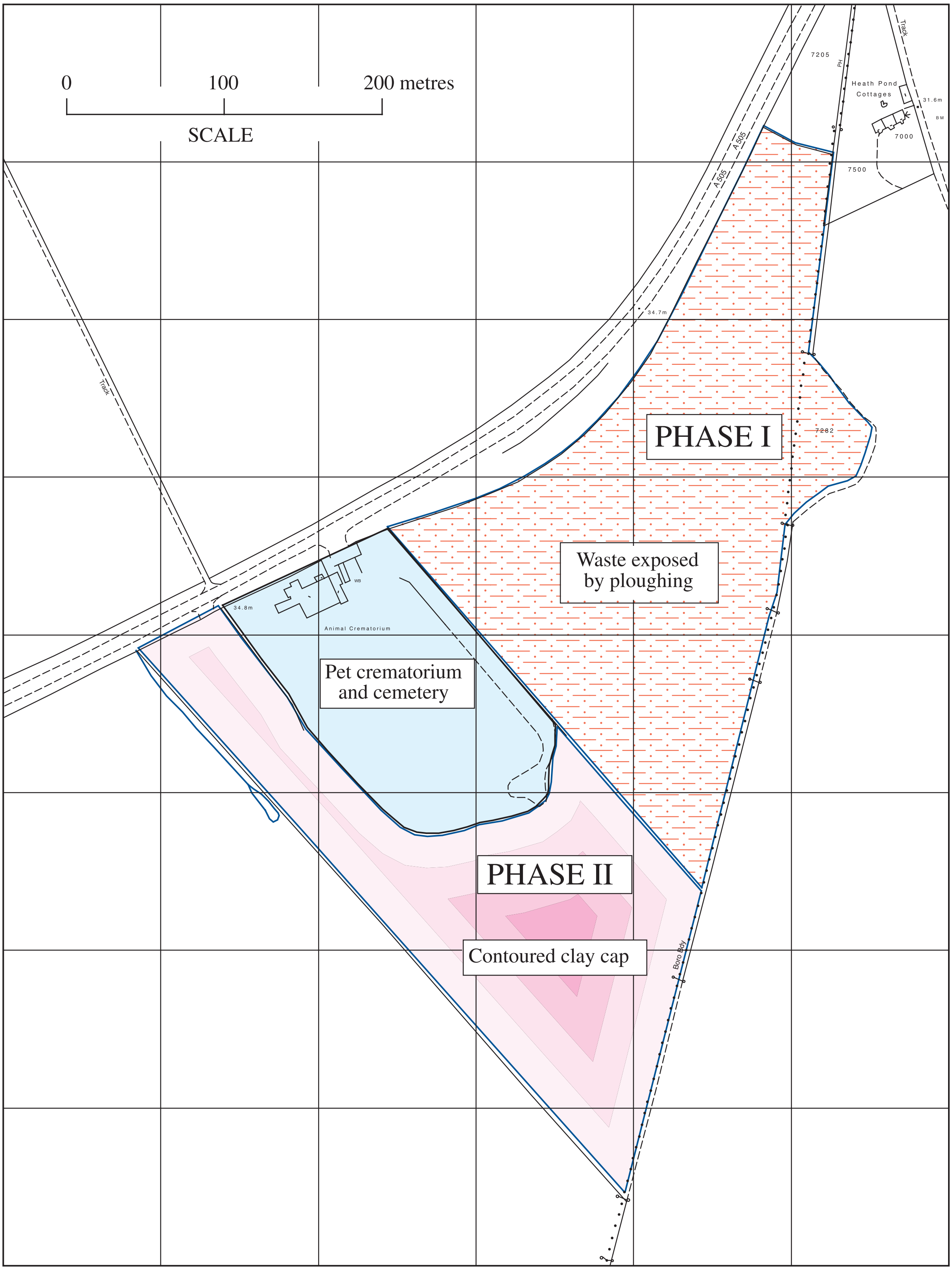


Figure 3.7 Interpretation of aerial photographs for Thriplow Landfill 1977.

1988 (Figure 3.7) — The site is now completely restored and the pet cemetery is landscaped. A small pit remains in the incinerator grounds which has been used for ash disposal. The area referred to as Phase 2 above has been contoured. The reinstatement continues up to the boundary fence, suggesting that between 1977 and 1988 excavation of the L-shaped quarry was extended to the site boundary.

Throughout the period, the elongate gravel pit (glory hole) along the south western boundary of the site appears on all photographs, but it progressively reduces in size from 1969 onwards suggesting that tipping was taking place. In 1988, it is much diminished in size, but has access to the main road. Local anecdotal evidence suggests that liquid wastes were discharged into the glory hole by tankers during this period. At the time of writing (1997) the glory hole is completely backfilled. There is also clear evidence in the field of recent trial pitting in its vicinity, thought to have been carried out prior to a land transaction.

4 GEOLOGY

The geology of the area is shown on BGS One inch sheet 205 (Saffron Walden), published in 1932 and described in an accompanying memoir. A more recent description of the Chalk stratigraphy and lithology is given in the memoir accompanying Sheet 221 (Hitchin), published in 1996 for the area immediately to the south-west of the Saffron Walden sheet. The generalised succession for Thriplow is given in Table 4.1.

The Thriplow landfill was developed in sand and gravel workings in the Taele Gravels. The gravels are reported to have had a maximum thickness of 9 m at the centre of the present landfill, thinning to 4 m at the quarry boundaries. The geological map shows the gravels extending 270 m north of the A505. Borehole logs from the Flint Cross Gravel quarry, 3 km to the south west of the Thriplow quarry, show the Taele Gravels to vary in thickness from 0.6 m to 3 m and to consist of an upper layer of clay with flint gravel and a lower layer of sand and gravel with Chalk fragments. Although no details of gravel working at Thriplow have been found, aerial photographs suggest that these deposits were completely removed, so the base of the landfill lies directly on Chalk.

The site lies on the Middle Chalk, the base of which is the Melbourn Rock. Locally the Melbourn Rock is recorded as being 5–8 m in thickness and is directly underlain by the Plenus Marls which is 1–2 m thick. The borehole log for the Environment Agency observation borehole 135 (TL 456 438) records the Totternhoe Stone as being 4 m thick lying 33 m below the base of the Plenus Marls, while the borehole log of Fowlmere public water supply No. 3 (TL 4265 4455) records a 5 m thickness of Totternhoe Stone occurring 22 m below the Melbourn Rock. Thus some uncertainty exists about the absolute thickness of these units in the area. At Fowlmere the Totternhoe Stone is underlain by 9 m of Chalk Marl which is in turn underlain by Gault Clay, the Upper Greensand being absent in the area. The whole sequence dips at about 5° towards the southeast.

Table 4.1 Stratigraphic sequence at Thriplow.

Division	Stratigraphic name	Thickness
Superficial deposits	Taele Gravels	4 - 9 m
Middle Chalk	Undifferentiated Chalk	Up to 10 m
	Melbourn rock	5 - 8 m
Lower Chalk	Plenus Marls	1 - 2 m
	Undifferentiated Chalk	12 -33 m
	Totternhoe Stone	4 - 5 m
	Chalk Marl	8 - 9 m
Gault	Clay	6.65 m penetrated

5 HYDROGEOLOGY

5.1 General properties of the Chalk

The hydraulic characteristics of the Chalk have been described by Price et al. (1993), and Lloyd (1993). Flow in the saturated zone is generally restricted to the upper 30–60 m of the aquifer, the so called “effective aquifer thickness”. However, significant flows may be found at greater depths due to increased fracturing associated with brittle layers such as the Chalk Rock, Melbourn Rock and Totternhoe Stone.

Matrix hydraulic conductivity is low and the bulk of the transmissivity relates to fissure flow. Enhancement of fissures by solution is prevalent within the zone of water table fluctuation. The fact that this process is unrelated to the depositional history of the Chalk means that the zones of enhanced hydraulic conductivity do not conform to stratigraphical boundaries and are thus difficult to map out. This process may be superimposed on any primary heterogeneity within the Chalk. Fissure flow decreases with depth due to the decrease in fissure density and the reduction in solution enhancement of fissures. Fissure spacing within the Chalk is reported as varying between 10 m and 500 m. Minor fissures may be sealed with calcite. The majority of boreholes around 50 m deep receive the bulk of their flow from one or two fissures near the water table.

The specific yield of the Chalk is low, being 0.01–0.02 at depths below the effective saturated thickness, 0.03–0.05 within the zone of effective flow and 0.001 beneath interfluves. These low specific yields lead to the large fluctuations in the water table following infiltration. However increased transmissivities as well as higher specific yields in the zone of effective flow can damp the normally large water level fluctuations. The matrix porosity varies from 40–50% for the Upper and Middle Chalk, to 20–30% for the Lower Chalk and 20% for the Melbourn Rock and Totternhoe Stone.

5.2 Locally derived aquifer properties

Values of transmissivity (T) and storativity (S) for the local area have been obtained from 20 boreholes near Thriplow included in the report of the physical properties of major aquifers in England and Wales (Allen et al., 1997). No data are available for any of the landfill monitoring wells.

For each aquifer test, the database may hold a range of values derived from different observation wells or by interpreting the data using different analytical methods. Thus for the Duxford public water supply, a Jacob analysis of drawdown in the pumped borehole yielded a transmissivity value of 1374 m^2/d while a Theis analysis of recovery in observation borehole 1 (OBH 1) yielded a value of 4920 m^2/d. A further complication is the fact that another Theis recovery value of 2300 m^2/d is also given for OBH 1.

The transmissivity values obtained from the database for wells in the area around Thriplow range from 12–7000 m^2/d, while the storativity values varied from 0.0002–0.3. Where possible values from Boulton or Theis late-drawdown interpretations were used as being most appropriate for the unconfined Chalk aquifer. An approximation of the variation in T and S values show changes in T from 500 m^2/d on the till covered Chalk plateau, increasing to 2000 m^2/d on the low lying Chalk around Thriplow and to 6000 m^2/d around the River Cam. This latter value may either reflect enhanced permeability due to increased flows adjacent to the river or some river-aquifer interaction during the pumping test. Values of S appear to vary gradationally from 10^{-4} beneath till covered Chalk to 10^{-2} around Thriplow and northwards. These averaged values correspond closely to the values obtained from a seven day constant-rate test carried out in 1979 at Fowlmere No. 3 borehole where seven different methods of analysis gave T ranging from 2300–2945 m^2/d and S between 1.92×10^{-3} and 4.35×10^{-2}.

The T and S values held in the data base of physical properties of major aquifers in England and Wales (Allen et al., 1997) relate mainly to pump tests carried out in open holes and thus reflect average values for the Chalk. Data for National Grid TL 44 contained only one value relating specifically to the Melbourn Rock and none to the Totternhoe Stone, while a search of all Chalk aquifer test data gave only seven values for the Melbourn Rock and two for the Totternhoe Stone. This lack of data on individual flow horizons within the Chalk increases the level of uncertainty associated with contaminant transport modelling.

5.3 Groundwater levels

The Environment Agency piezometric database provides monthly water level data from 84 observation wells from a radius of 10 km around Thriplow. The wells include data from the seven original Thriplow landfill monitoring boreholes. Data exist from 1963 to the present day, but many of the wells were not monitored continuously within this period. Of the Thriplow boreholes, only BH 4 has continuous monthly measurements since it was drilled in 1978. Gaps of up to 3 years exist in the data for the other Thriplow boreholes.

Piezometric maps of monthly data have been produced using the Surfer contouring package. The contours produced reflect the volume and density of data being contoured. Thus the contour pattern around the site may vary depending on whether only data from the seven monitoring boreholes are being contoured or if data is used from a larger area.

The piezometric maps at all scales show an overall flow direction towards the N-NW (Figure 5.1), a pattern which agrees with that shown on the BGS 1:100 000 scale "Hydrogeological map of the area between Cambridge and Maidenhead". The piezometric gradient changes northwards from 1:100 (20 m over 2 km) associated with the Chalk escarpment to 1:400 (10 m over 4 km) on the low lying ground around the site.

Figure 5.2 shows a hydrograph for TBH 4, which demonstrates an annual fluctuation in water level of 2 m to 5 m. The hydrograph also demonstrates a steady decline in groundwater elevation from 1978 to 1993. Figure 5.3

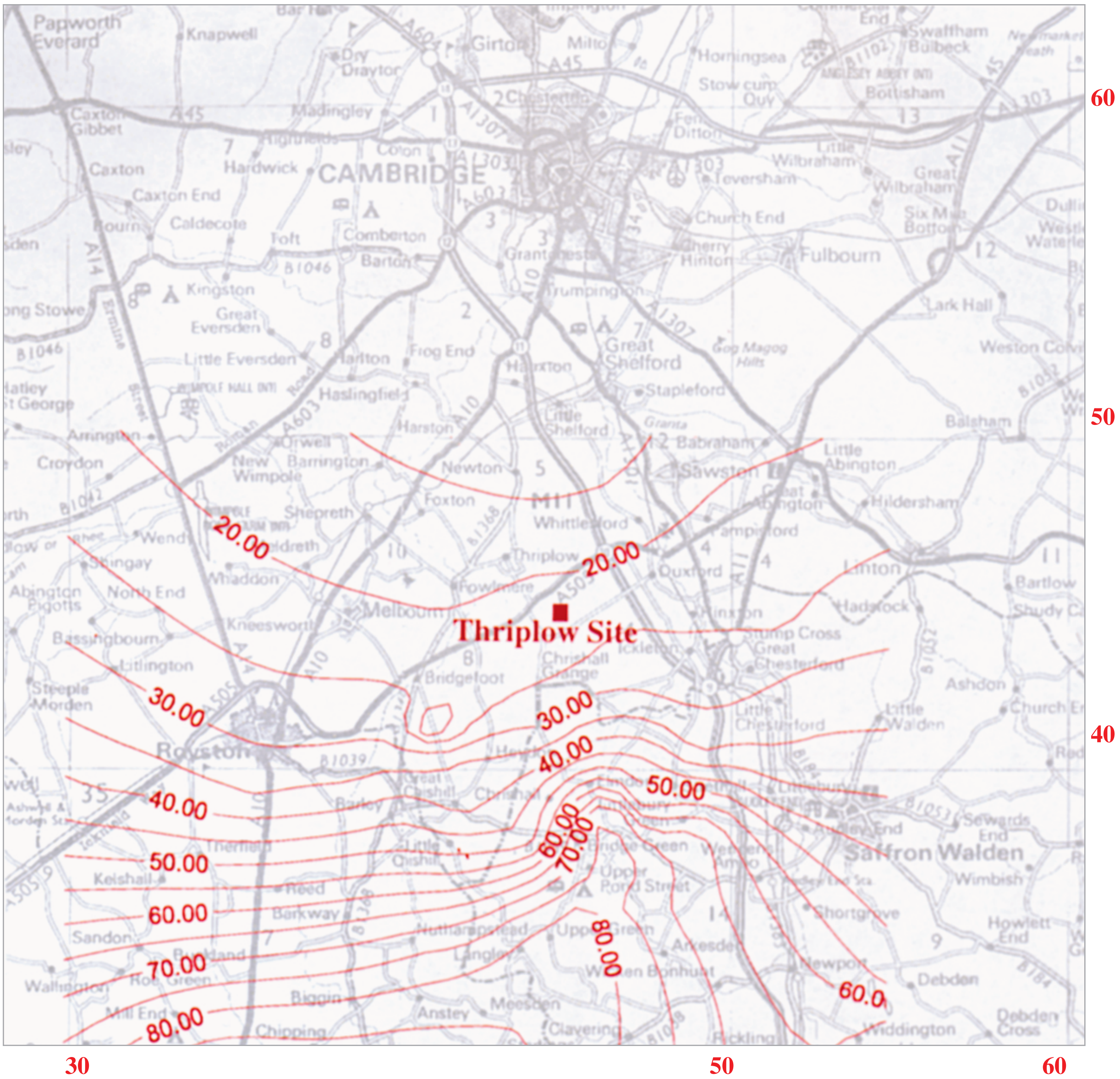


Figure 5.1 Peizometric map of water level data from April 1982.

shows hydrographs of Thriplow boreholes TBH 1 and TBH 7, which respectively lie up gradient and down gradient of the site. The hydrographs show that the water level in TBH 7 is occasionally higher than that in TBH 1 inferring at least a local reversal in the direction of groundwater flow.

5.4 Groundwater chemistry

The trends over time of a number of chemical parameters measured in the monitoring boreholes are shown in Figures 5.4 to 5.8. Figure 5.4 shows that chloride concentrations measured in TBH 3 have decreased from around 800 mg/l between 1977–1984 to about 600 mg/l today. This contrasts to the steady increase in TBH 4 from ~30 mg/l in 1978 to around 200 mg/l today. The chloride trends also show a “seasonal” variation of up to 300 mg/l, presumably related to the flux of precipitation through the site. This can be seen in Figure 5.5 where the water level hydrograph for TBH 3 matches the fluctuations in chloride concentration measured in the borehole.

A lag appears to occur between the peak chloride concentration in TBH 3 and those further away. This lag, may reflect the travel time of the chloride pulse away from the landfill, and is shown for the peak concentration of chloride in different boreholes in Figure 5.6, while the offset between peak water levels and peak chloride concentration in TBH 4 is shown in Figure 5.7.

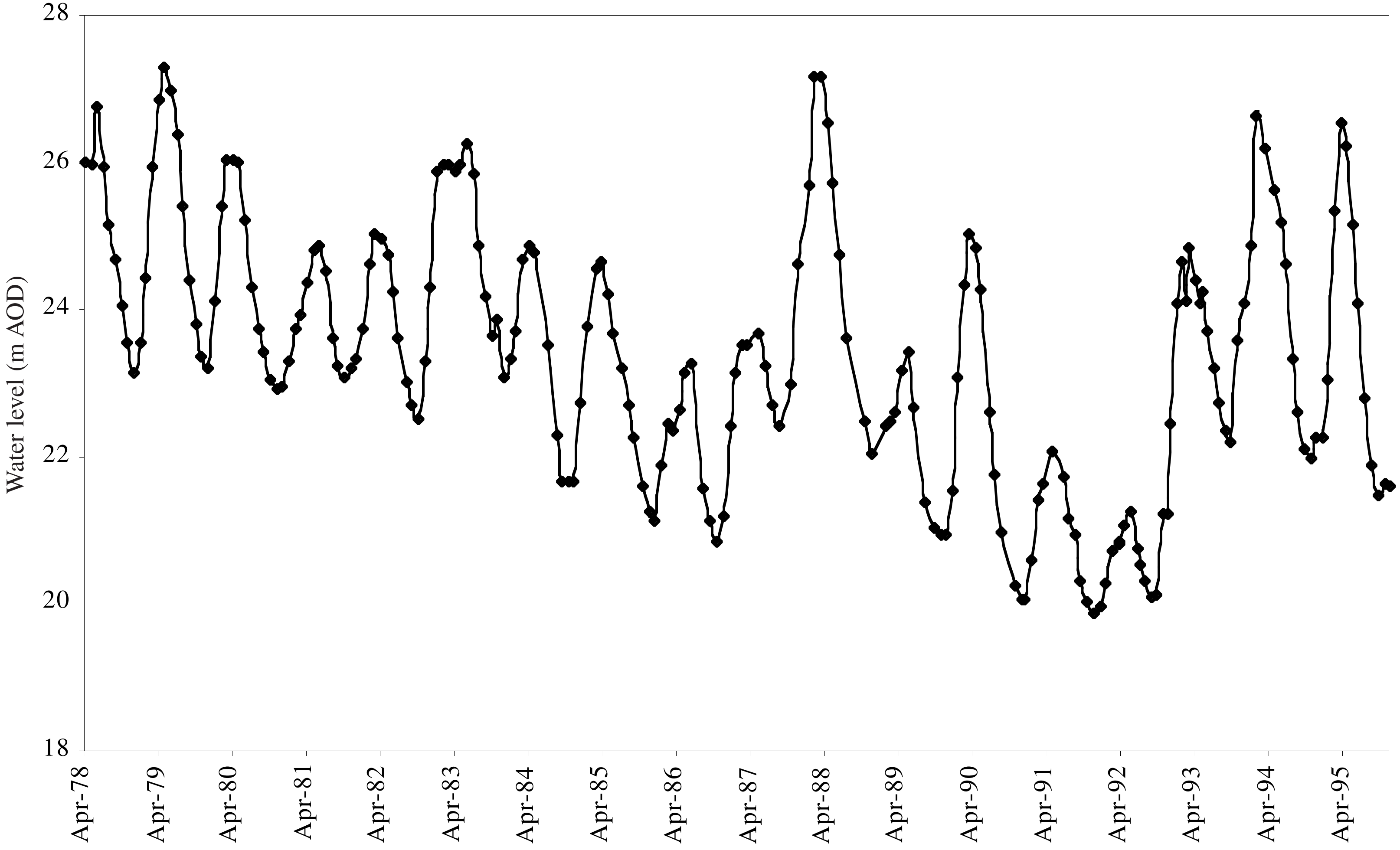


Figure 5.2 Hydrograph ofTBH 4 1978–1996.

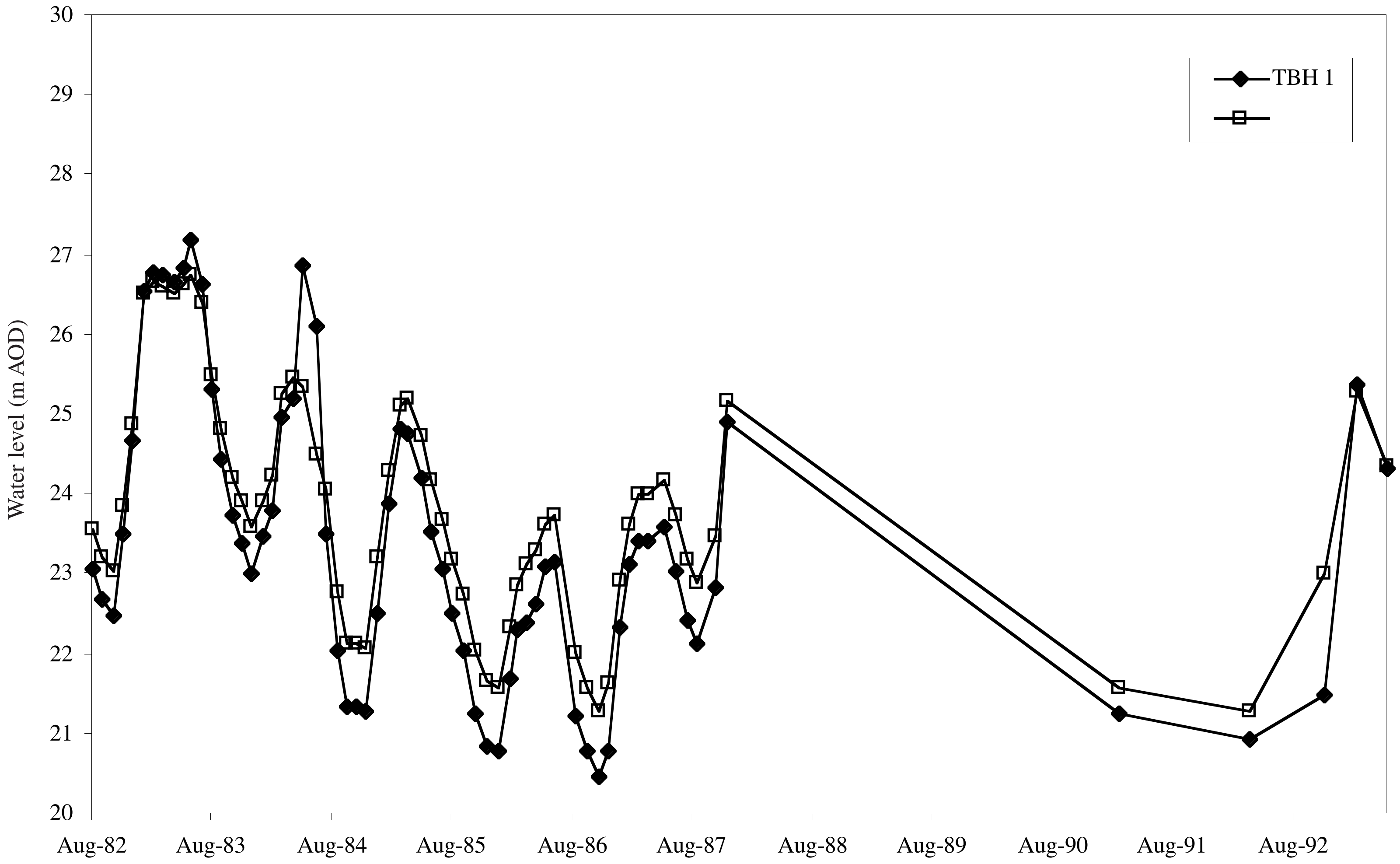


Figure 5.3 Hydrographs of TBH 1 and TBH 7.

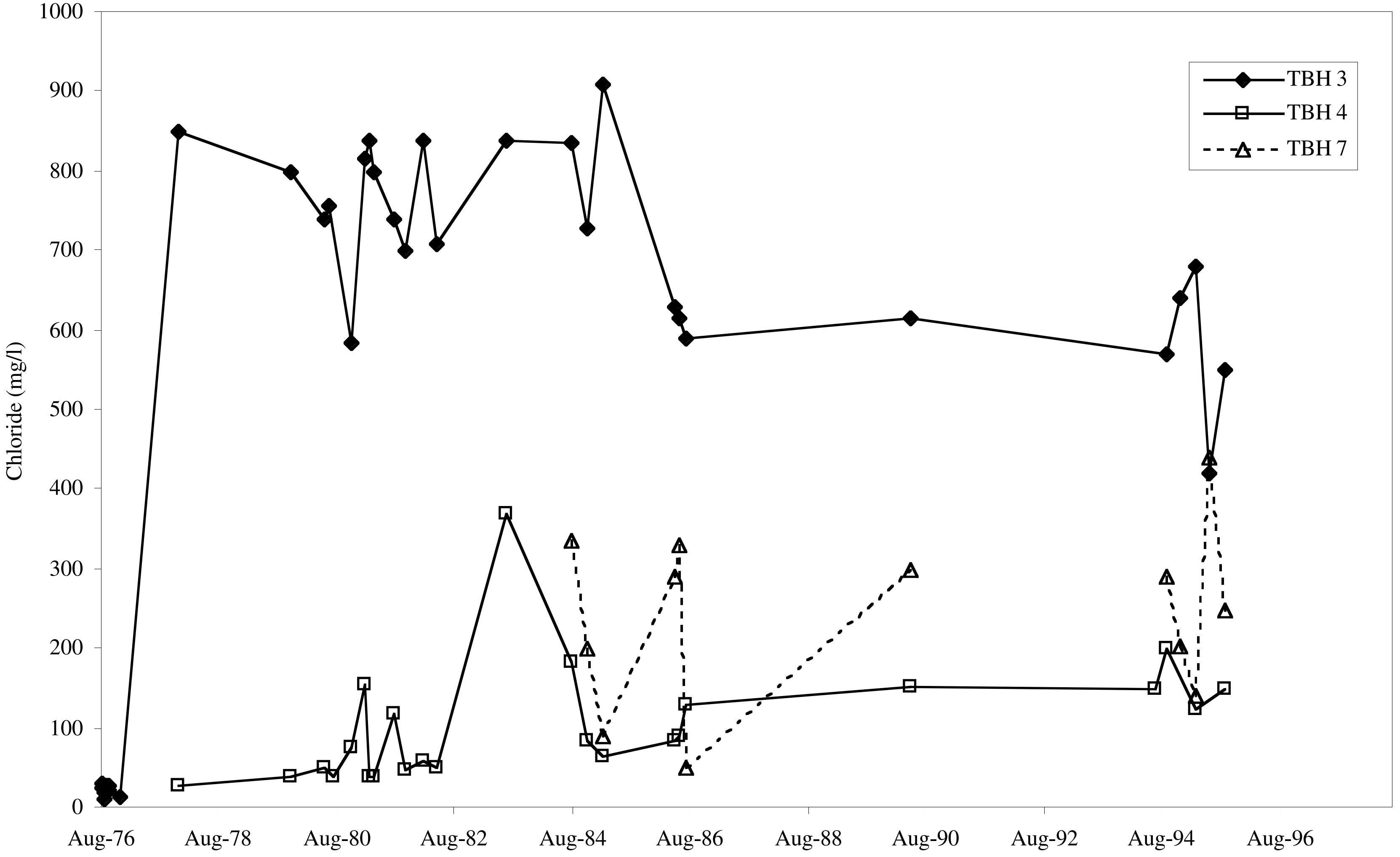


Figure 5.4 Chloride concentrations in TBH 3, 4, and 7 1976–1996.

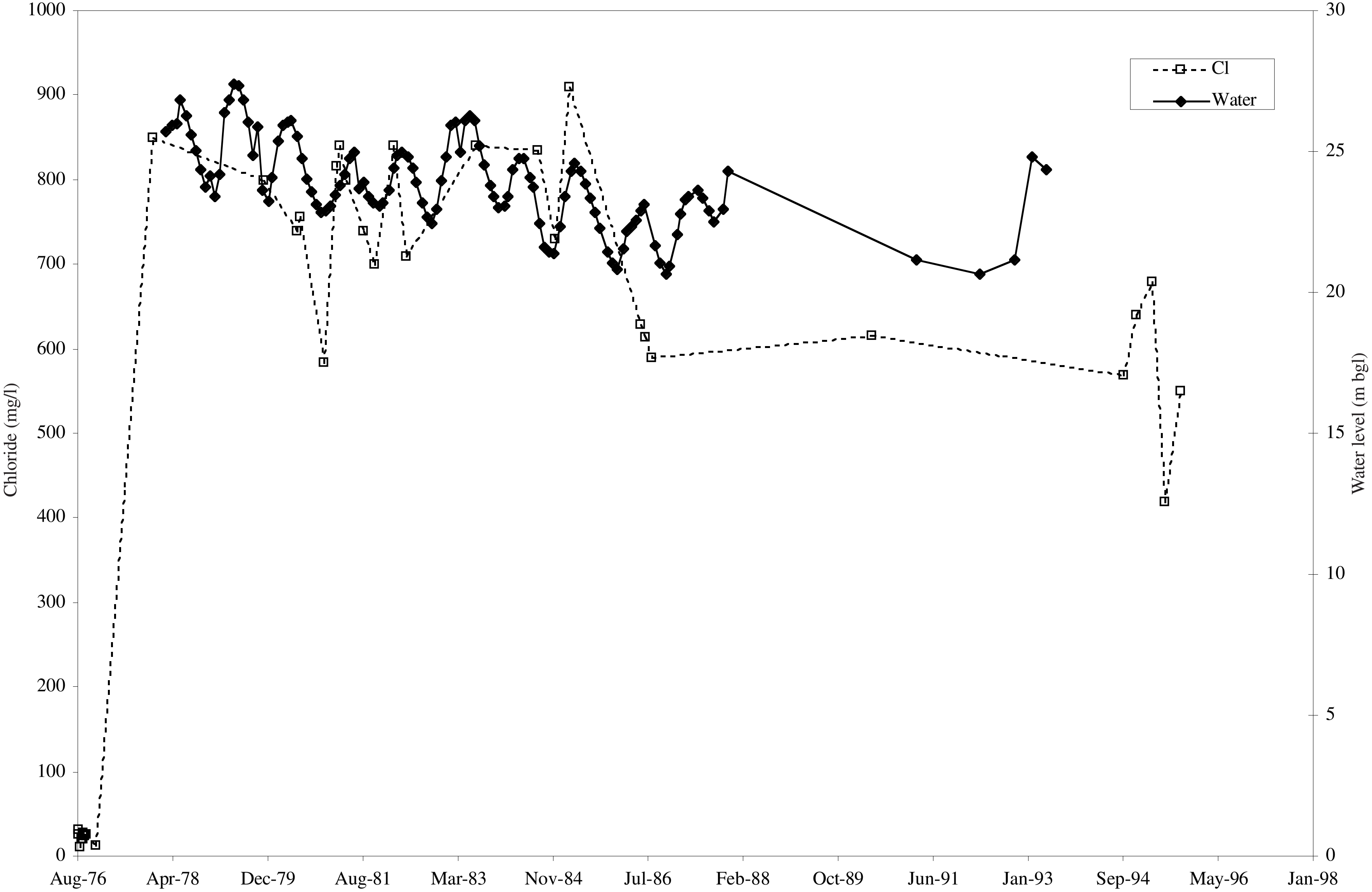


Figure 5.5 Plot of chloride concentration and water levels in TBH 3.

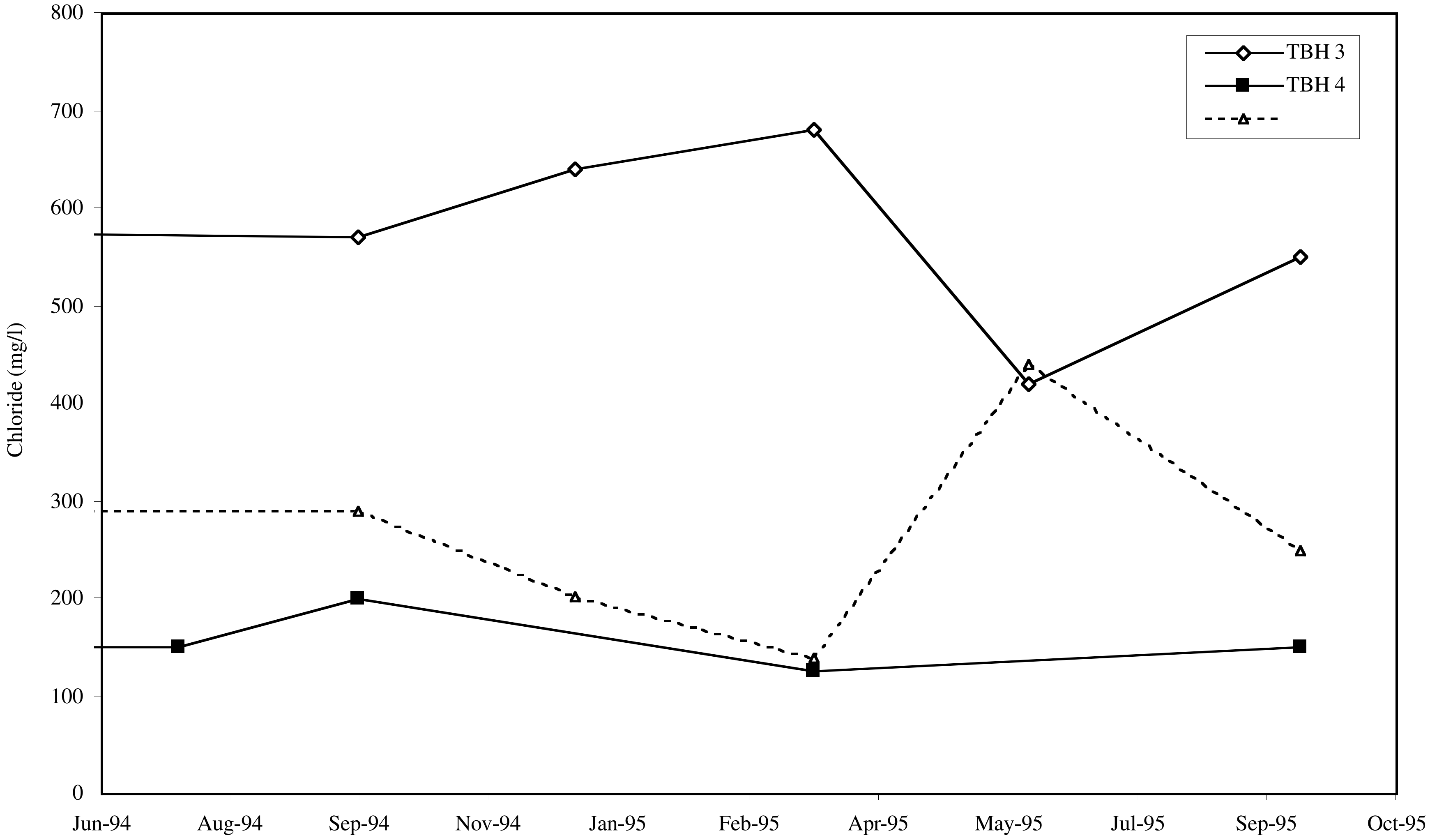


Figure 5.6 Chloride concentrations in TBH 3, 4 and 7 since 1994.

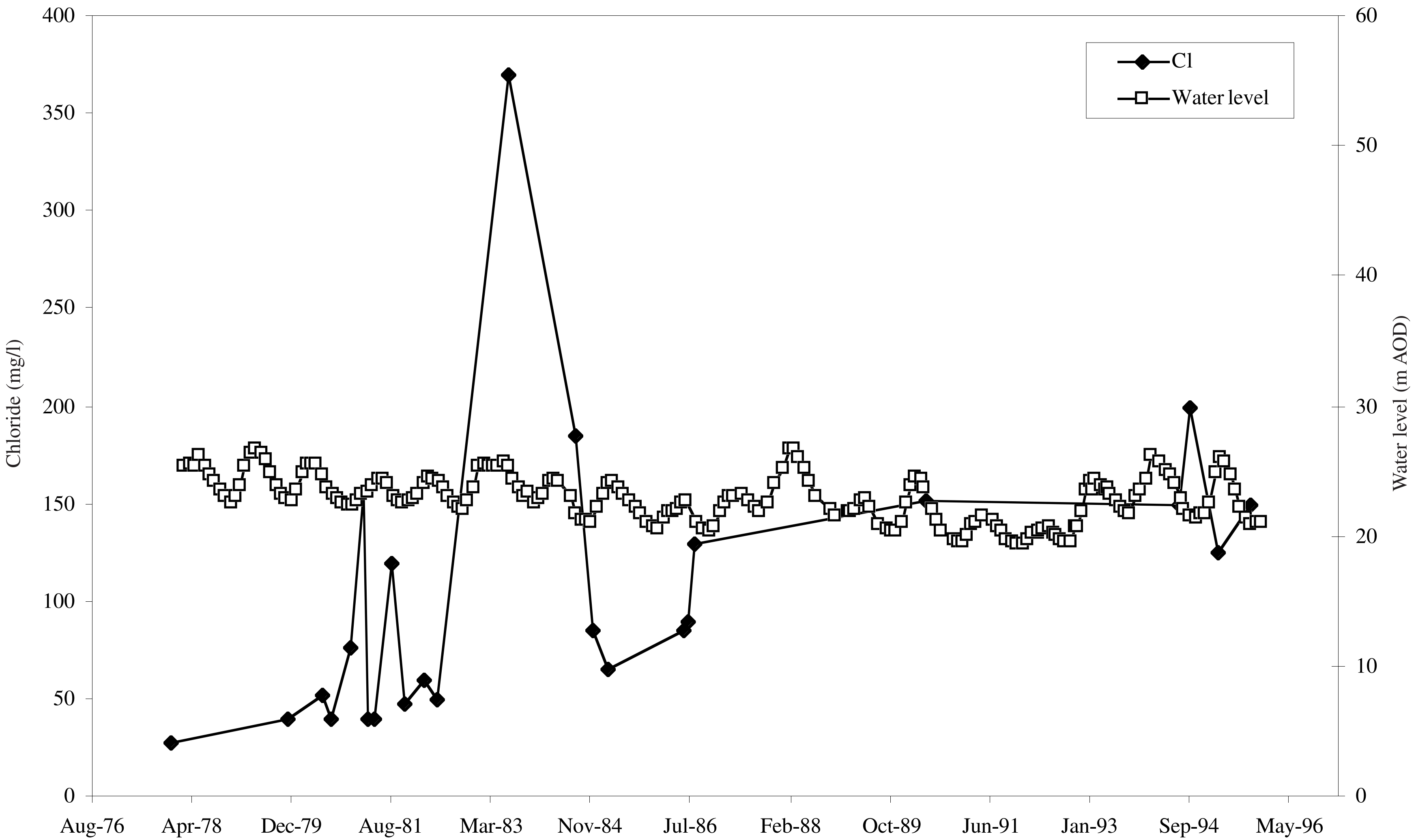


Figure 5.7 Chloride and water level in TBH 4.

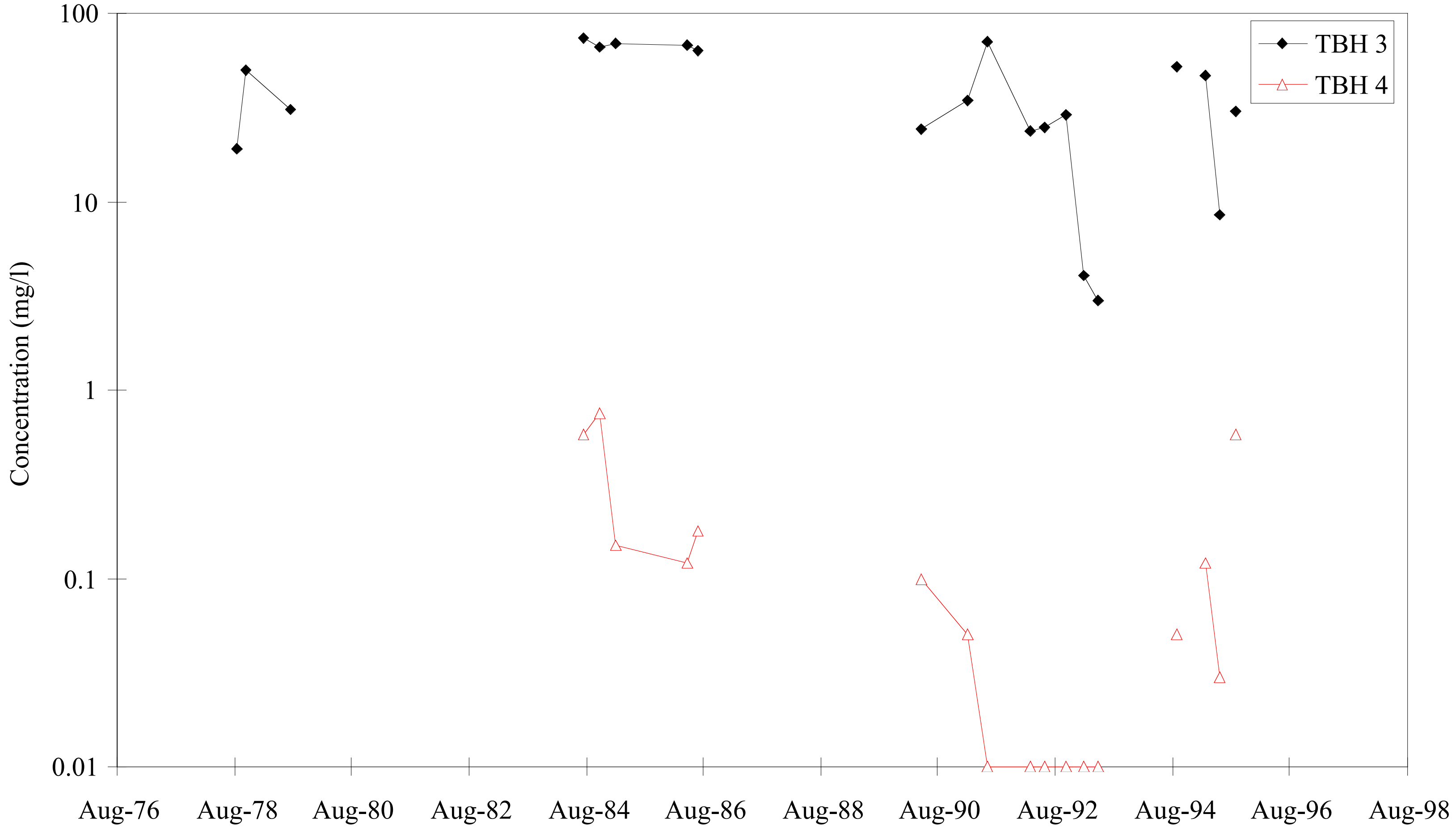


Figure 5.8 Trend in ammoniacal-N concentrations in TBH 3 and TBH 4.

Although the fact that the boreholes were only sampled quarterly means that the date of the maximum concentration in each borehole is not known exactly, the lag between maximum measured concentrations in each borehole gives a rough indication of groundwater flow velocities. Thus the 90 day lag between TBH 3 and TBH 4 which are sited ~85 m apart gives an average flow velocity of ~1 m/d. However, this cyclic pattern could also arise from a seasonal change in ground water flow direction, and the cause of the chloride fluctuation needs further study.

Ammonium concentrations in boreholes TBH 3 and TBH 4 appear to vary considerably but still maintain peak values of 90 mg/l and 1 mg/l respectively (Figure 5.8). However, ammonium concentrations in TBH 7 continue to increase to a peak of ~7 mg/l in 1990. The samples taken by BGS in TBH 3 and TBH 7 (discussed later) both show marked increases in ammonium concentrations from the previous samples taken in 1992, while ammonium was shown to still be effectively absent from TBH 4. It is unclear as to whether this change reflects a real increase in the mass of ammonium present or whether the micro-purge sampling technique has reduced the dilution effect in the borehole column.

Total Organic Carbon (TOC) shows a similar marked increase from concentrations of around 5 mg/l in boreholes 3 and 5 in 1991–1992, to values of 66 mg/l and 40 mg/l respectively in the BGS samples from 1996. Again whether this reflects reduced dilution in the samples is unclear. Analysis of the groundwater chemistry sampled in the Environment Agency boreholes B15 and B30 show negligible concentrations of ammonium and TOC, but elevated concentrations of chloride. Chloride concentrations of 500 mg/l are recorded in the borehole B15 sampling at 15 m depth, with the values dropping to 150 mg/l in the borehole B30 which is screened at 30 m. This pattern is repeated in boreholes A17 and A30, sited 1 km from the landfill, which record concentrations of 70 mg/l and 20 mg/l respectively above and below the Plenus Marls. This suggests, that in at least some places, the Plenus Marls restricts the downward migration of leachate.

The chloride concentrations recorded in B15 down gradient of the Phase 2 landfill, are consistently higher than those recorded in TBH 7 down gradient of the Phase 1 landfill, (Figure 5.9). The chloride concentrations in B15 and B30 also remain constant over a time period when the concentrations in TBH 3 and TBH 7 fluctuate by up to 300 mg/l. Discrepancies in the sampling may however, reflect the completion of the borehole and the fact that in the early boreholes water is drawn from a large screened length and mixing of clean and contaminated water reduces the contaminant concentrations.

6 PRELIMINARY SITE MODELLING

Following a review of several existing models of the regional aquifer, and the Phase 2 extension (Oakes, 1986), a preliminary groundwater flow and transport model has been developed for the landfill (Boland, 1996b).

This comprises a transient groundwater flow model for the 4 year period between 1984–1987 for a 660 km^2 area surrounding the landfill. Because data on aquifer transport properties are lacking, modelling is restricted to a one layer, unconfined aquifer whilst acknowledging that the Melbourn Rock, and probably the Totternhoe Stone, may constitute zones of relatively high transmissivity. Modelling over the period 1984–1987 was selected because this provides the best monitoring data for model calibration. Hydraulic conductivity values were increased northwards and towards the major rivers in line with existing data on aquifer properties. A good match of piezometric contours and selected water level changes near to the landfill site was achieved. Trends in the water level hydrographs were closely matched by the first run of the model, suggesting that estimates for the transient parameters, recharge and pumping rates, were appropriate. Modelled fluctuations in water levels were greater than those measured but these fluctuations were damped by assuming a specific yield of 0.03, a value typical of the effective aquifer. Sensitivity analysis showed that varying the hydraulic conductivity (or effective aquifer thickness) altered the flow direction about the landfill site; halving it producing a 10° swing clockwise while doubling it produced a 10° swing anti-clockwise.

Contaminant transport modelling using MT3D was limited by lack of control on input parameters and poor calibration data. Modelling the leachate flux from the landfill was best achieved by assigning a recharge concentration. The pulsed nature of the leachate input was achieved by using the recharge concentration multiplier. Neither of these parameters were derived from measured site data, rather they were varied within the model to obtain a best fit to the measured concentrations. Initial modelling, using a porosity of 40%, a matrix value typical of the Middle Chalk, produced little contaminant advection from the landfill, reflecting dilution of the leachate within the porewater volume of the cell containing the landfill. Reduction of the model porosity to 5% and 1%, values typical of fracture porosities, produced concentration fluctuations at the model observation nodes comparable to those measured in the monitoring boreholes. Modelled concentrations and concentration fluctuation from the 5% porosity model matched the observed data better than from the 1% porosity model, though this could be varied depending on the input concentrations.

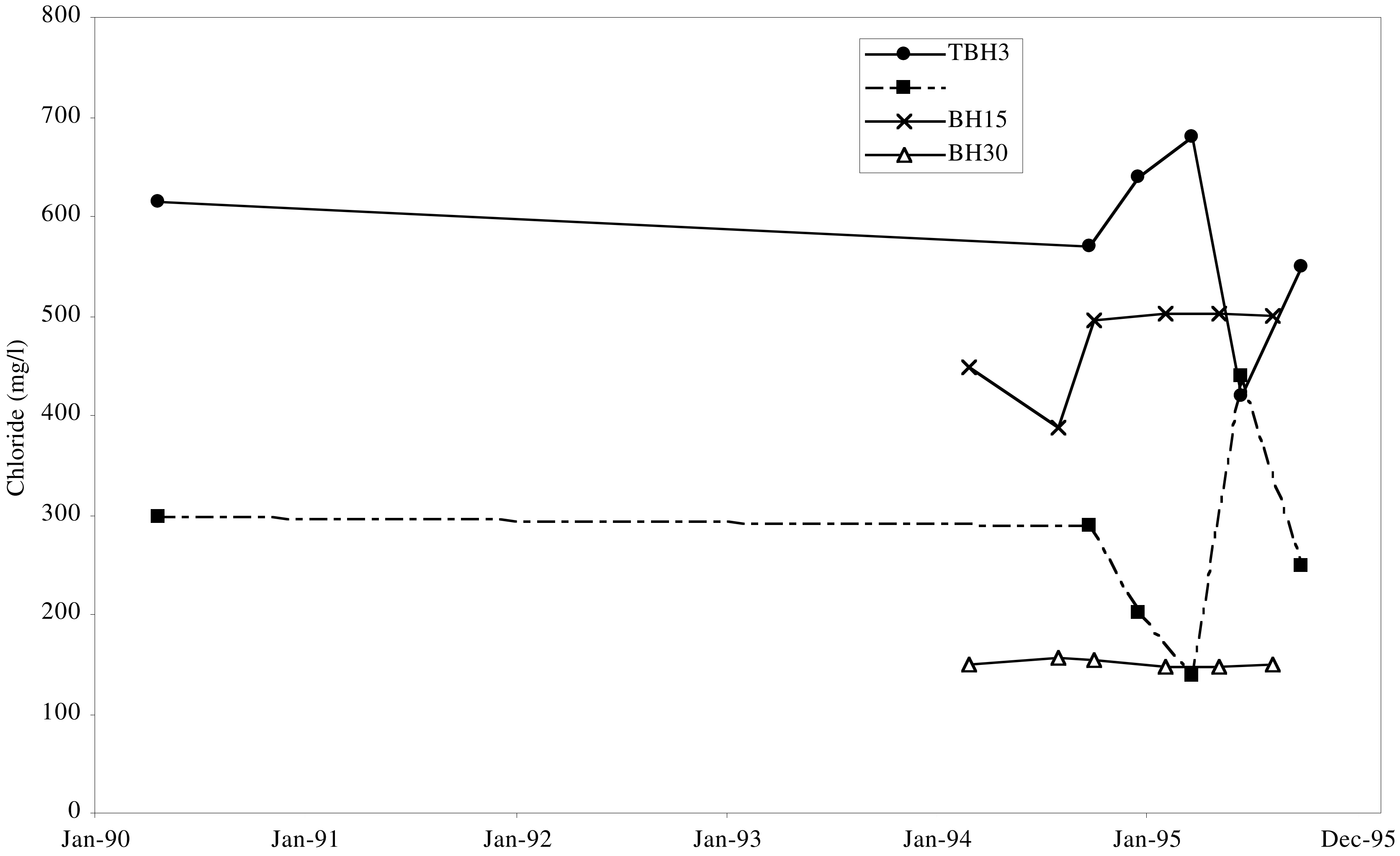


Figure 5.9 Chloride concentrationsin TBH 3, TBH 7 and EA monitoring boreholes BH15 and BH30.

Contoured maps of chloride concentration show the development of contaminant plumes down gradient of the landfill site for both the 5% and 1% models. Chloride concentrations of 50 mg/l were found 4.4 km down-gradient of the landfill at the end of the 4 year simulation run when the porosity was set to 1%. Average linear velocities calculated for the 1% model were in the range 0.2–4 m/d while those for the 5% model were 0.03–0.9 m/d. Again, the velocity predicted by the 5% fracture porosity model is in closest agreement with that based on the time lag between concentration peaks in monitoring boreholes.

Using a porosity of 5% intermediate between a matrix and fracture value, appears to give the most realistic results overall, and conforms to the model of the Chalk as a dual porosity system.

7 SUMMARY AND COMMENTS ON THE DESK STUDY

7.1 Summary

The desk study has identified the following:

- Waste was deposited in excavations into the Taele Gravel up to 9 m deep, overlying the Middle Chalk.
- The history of landfilling is complex and two phases of disposal have occurred. Phase 1 was landfilled between 1957–1977. Phase 2 was landfilled between 1981–1987.
- Aerial Photographs and well hydrographs indicate that leaching from the landfills may vary seasonally as the rising water table periodically saturates the base of the landfill.
- Phase 1 and Phase 2 landfills are adjacent and transverse to the groundwater flow direction. Thus two independent pollution plumes are likely to develop to the north west. Investigation and comparison of these two plumes may give valuable information on the effects of differing landfill practice on groundwater quality.
- Groundwater monitoring data indicate that groundwater quality is affected by both Phase 1 and Phase 2 landfills, but the existing boreholes have not detected extensive plumes.
- The propagation of periodic pulses in chloride concentrations in groundwater quality have been used to derive a groundwater flow velocity of about 1 m /day, but this needs to be confirmed.
- The aquifer is considered to be typical of the Chalk with dual porosity properties. In the absence of appropriate data on aquifer transport parameters it has been modelled as a 1-layered equivalent porous medium without matrix diffusion which must be regarded as preliminary only. It is necessary to assume a porosity of about 5% to match the observed chloride fluctuations in monitoring boreholes. This generated groundwater flow velocities of 0.3–0.9 m/d.
- The effective aquifer thickness is not known but it is possible that vertical flow is restricted by the Plenus Marls.

7.2 General comments on the desk study

The desk study whilst providing much useful information, underlines the need for much better or more appropriate information to produce a reasonable assessment of the impact of the landfill on groundwater quality. Although seven boreholes were drilled to investigate groundwater contamination from the site in the 1970's, subsequent monitoring has been sporadic and does not provide good data for model calibration.

The sampling interval varies from initially weekly, to several years when between 1986 and 1990 no samples were collected. The initial seven (TBH) boreholes were drilled open-hole below 9 m, and in most cases down to 50 m. In retrospect this completion may be inappropriate in the light of the fact that two, apparently isolated, flow systems exist below the site, one above and one below the Plenus Marls. Recharge through the boreholes puncturing the Plenus Marls may well compromise the spatial integrity of the samples which may have been further compounded by the sampling methodology. The more recently drilled boreholes, which have been sampled on a quarterly basis since they were drilled in 1994 are an exception, and may ultimately yield useful data.

Uncertainty exists about the nature of the waste deposited since few records could be found about the rate of disposal or the exact waste composition. This means that accurate source terms cannot be proposed when predicting the evolution of the site. Construction details are also lacking. How the site was operated, its depth and extent, or whether recommendations relating a 2 m blanket of sand and silt overlying the Chalk were adhered to, are not available.

As a general comment, the data which have been obtained were disseminated amongst several sources and, although help was forthcoming from both the National Rivers Authority and the Waste Disposal Authority, a significant effort was required to collate them.

Part II — Field investigation

8 OBJECTIVES

The first phase of field investigation, carried out in April and July 1996, was aimed at confirming and refining the conceptual model of the site developed from the initial desk study presented in Part I. The specific objectives of this phase of the study are as follows:

- To confirm the condition and construction of existing landfill monitoring boreholes.
- To sample available wells, boreholes and springs for water chemistry.
- To use surface resistivity to identify the extent of any plume and the geometry of the landfill.
- To drill boreholes into the landfill to obtain samples of the waste for further characterisation.
- To drill on any resistivity anomaly identified by surface geophysics to investigate the presence of a pollution plume, and obtain hydraulic data to support the groundwater flow model.
- To measure the hydraulic conductivity of the landfill caps in order to estimate infiltration potential.

9 CONDITION OF EXISTING LANDFILL MONITORING WELLS

The accessible boreholes in 1996 were investigated by CCTV and details are given in Table 9.1. Completion details of the eleven monitoring boreholes drilled between 1976 and 1993 are given in Table 9.2. The CCTV showed that some borehole depths were at variance with those recorded in the EA borehole records. The accessible boreholes were also logged for fluid temperature and electrical conductivity (Boland, 1996a).

10 GROUNDWATER CHEMISTRY FROM EXISTING WELLS

The seven landfill monitoring wells at Thriplow were sampled on 10–12 April 1996, using the micro-purge low-flow procedure outlined by Shanklin et al. (1995). This technique has the advantage over the usual method of purging three well volumes in that it minimises disturbance of any stratified contaminant plume in the aquifer. The samples obtained are thus level specific and do not suffer dilution effects resulting from mixing between clean and contaminated water. The groundwater chemistry is reported in Appendix A.

Sampling positions were selected based on the electrical conductivity logs and the CCTV data. Marked changes in electrical conductivity were taken to indicate potential flow horizons in the borehole and where possible, were cor-

Table 9.1 Completions as shown by CCTV for boreholes drilled between 1976 and 1993.

Borehole Name	Water level (m bgl)	Borehole diameter (mm)	Solid casing	Slotted casing	Borehole depth (m)
TBH 1	9.66	150	to 9.66 m	9.66 to 11.7 m	43.59
TBH 2	7.61	150	to 8.55 m broken from water table		28.87
TBH 3	9.17	100 inside original 150	to 9.86 m	100 mm pipe with 10 mm holes to base of hole	47.35
TBH 4		100 inside original 150		as above ?	
TBH 5	9.46	150	to 16.11 m		48.86
TBH 6	9.4	150	to 5.24 m	5.24 to 16.12 m	16.12
TBH 7	9.39	150	to 5.63 m	5.63 to 16.74 m	47.74

Table 9.2 Details of Thriplow monitoring boreholes.

BGS Borehole name	TL44 SW53	TL44 SW54	TL44 SW55	TL44 SW56	TL44 SW58	TL44 SW59	TL44 SW60	TL44 SW61	TL44 SW63	TL44 SW64	TL44 SW65
NRA Borehole name	TL44/43	TL44/44	TL44/45	TL44/46	TL44/311	TL44/312	TL44/313	TL44/413	TL44/415	TL44/416	TL44/414
Original name	TBH 1	TBH 2	TBH 3	TBH 4	TBH 6	TBH 5	TBH 7	A30	B30	B15	A17
Description	Rubbish tip off A505, Thriplow	Rubbish tip off A505, Thriplow	Rubbish tip off A505, Thriplow	near waste site off A505, Thriplow	Thriplow tip, A505 road Thriplow	Thriplow tip, A505 road Thriplow	Thriplow tip, A505 road Thriplow	Old Thriplow WDS BHA1, Farm track off A505	Old Thriplow WDS BHB1, Footpath opp. Pet Crem. off A505	Old Thriplow WDS BHB1, Footpath opp. Pet Crem. off A505	Old Thriplow WDS BHA2, Farm track off A505
Easting	446800	447100	446200	445700	446200	446100	445900	434100	443200	443200	434100
Northing	447200	449400	449100	449500	449300	449200	448900	446000	447500	447500	446000
Ground level (m AOD)	33.8	31.4	33.2	32.3	33.8	33.8	34.265	36.606	33.921	33.829	36.682
Depth recorded on EA borehole log (m)	31.91	31.16	50	52	17.2	50	52	30	30	15	17
Depth from CCTV	43.59	28.87	47.35		16.2	48.86	47.74				
Date drilled	31/8/1976	31/8/1976	31/8/1976	31/7/1977	30/4/1982	31/3/1982	30/4/1982	31/12/1993	31/12/1993	31/12/1993	31/12/1993

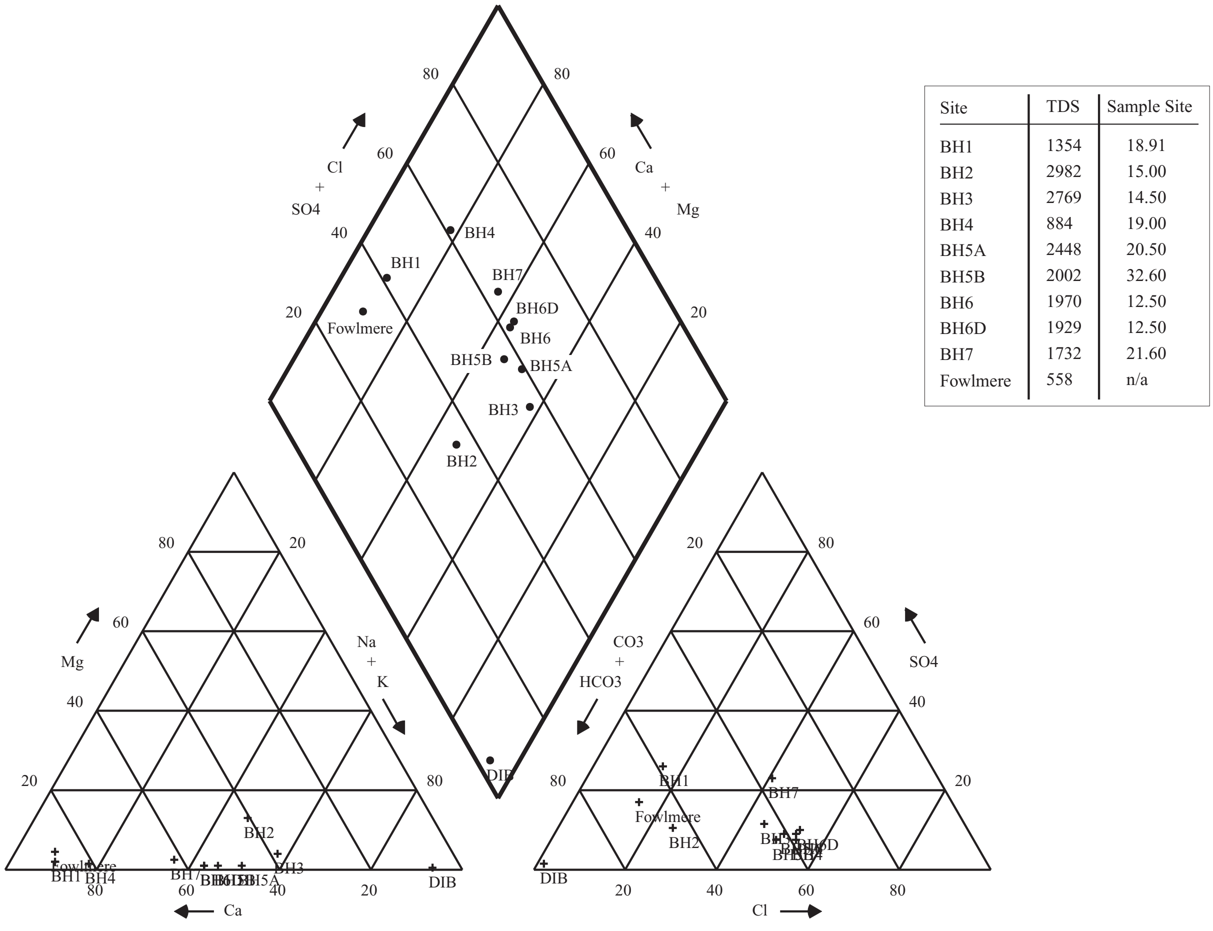
related with fissures identified on the CCTV. The upper flow horizon located was sampled in each borehole, with a second lower horizon being sampled in TBH 5 to indicate possible chemical stratification.

Water level readings were taken prior to, and after, emplacement of the pump at the level to be sampled. The pumping flow rate was set to produce insignificant drawdown in the borehole. This was achieved in all boreholes except TBH 2 from which a sample of possibly stagnant borehole water was obtained. The flow rates were adjusted to be below the recommended maximum rate of 1 l/min. The water quality was monitored for DO_2, pH, Eh, temperature and conductivity at 5 minute intervals. A sample was taken when these values had stabilised to within 5% over four consecutive readings. In addition to the monitoring boreholes, a sample was taken from a spring at the Fowlmere RSPB site (TL 4085 4533; Figure 3.2).

The groundwater chemistry is plotted on a Piper diagram (Figure 10.1) which shows the similarity between the groundwater sampled from TBH 1 and that from Fowlmere springs. TBH 4 shows elevated chloride concentrations which are intermediate between background and those in contaminated boreholes such as TBH 3 and TBH 5. TBH 2, which samples the landfill, has a high bicarbonate content of 1422 mg/l which may reflect high concentrations of CO_2 generated in the landfill.

Overall, the groundwater samples do not show evidence of significant chemical reduction. DO_2 concentrations in the monitoring boreholes range from 1–3 mg/l, but nitrate and ammonium exist together in several samples. The is no evidence of Mn, Fe or sulphate reduction.

Chloride concentrations are highest in boreholes TBH 3, TBH 5 and TBH 6 down gradient of the site, with the highest concentration of 624 mg/l being recorded in TBH 5. Chloride concentrations appear to reduce laterally into TBH 4 and TBH 7. Ammonium shows a similar pattern but with the concentration reducing more rapidly away from the site. No ammonium was present in TBH 4. Up-gradient of the site, TBH 1 shows a much lower concentration of ammonium relative to the down gradient boreholes. TOC concentration in TBH 3 is 66 mg/l, but



Site	TDS	Sample Site
BH1	1354	18.91
BH2	2982	15.00
BH3	2769	14.50
BH4	884	19.00
BH5A	2448	20.50
BH5B	2002	32.60
BH6	1970	12.50
BH6D	1929	12.50
BH7	1732	21.60
Fowlmere	558	n/a

Figure 10.1 Trilinear plots for pre-existing boreholes, April 1996.

decreases in TBH 5. As with ammonium the TOC concentration in TBH 4 is at background, while that in TBH 7 is much lower compared with TBH 3 and TBH 5.

Comparison of the samples at depths 20.5 m and 32.6 m from TBH 5, gives some indication of the vertical solute distribution. These can also be compared to the sample taken at 12.5 m in TBH 6, which lies a few metres from TBH 5. In TBH 5 chloride decreases from 624 mg/l at 20.5 m, to 494 mg/l at 32.5 m, while at 12.5 m depth in TBH 6 the concentration is 515 mg/l. Other indicators of landfill leachate such as ammonium and TOC similarly show higher concentrations at the shallower depth in TBH 5, but concentrations at both positions in TBH 5 are higher than those in TBH 6.

Although the number of samples taken is insufficient to define any geochemical zones within the groundwater, it should be noted that the more contaminated sample in TBH 5 corresponds to the position of the Melbourn Rock as interpreted from the gamma log. A more detailed programme of micro-purge low-flow depth sampling from the boreholes would help define how the concentration of individual species vary with depth and with time.

11 SURFACE GEOPHYSICS

Resistivity imaging was selected as potentially the most suitable non-invasive technique for detecting and mapping a leachate plume emanating from the landfill. Formations affected leachate can be expected to exhibit very low resistivity. Initially, a single continuous traverse was surveyed around the combined area of Phase I and Phase II landfills (Figure 11.1). Low resistivity anomalies which might be associated with leachate were traced away from the landfill perimeter by stepping out 20 m and running off-set traverses. Two traverses were also undertaken across the landfills to delineate the internal geometry and structure of the landfill.

11.1 Resistivity imaging

Resistivity imaging or resistive tomography is a new and rapidly evolving technology for the non-invasive mapping of subsurface geology. The emergence of this survey technique owes much to recent advances in high-density, computer-controlled data acquisition and mathematical inversion theory. The resistivity images obtained from this technique provide more accurate information on the shape, depth and geo-electric properties of subsurface features than in the case of traditional resistivity pseudo-sections.

The BGS-designed RESCAN system was programmed to collect pole-dipole resistivity data for a dipole spacing of 5 m. This configuration was considered adequate to achieve a depth of investigation of about 30 m from a single line scan. Each line was scanned in two directions to improve data density, quality and lateral resolution. Continuous coverage at a specified depth was obtained by moving the surface cable along the traverse in overlapping segments.

11.2 2.5-D numerical inversion

A 2.5-D finite element inversion program was used to automatically generate model resistivity cross-sections from observed measurements on each line. The Finite Element Method (FEM) is a well-established numerical approach for computing the electric potential response of a 2-D earth due to a 3-D source. This problem is termed 2.5-D (Hueber and Thornton 1988). In brief, the subsurface is divided into a mesh or individual elements and the electrical resistivity is calculated for the discrete number of transform variables at the nodes of the mesh. The adjoint equation approach has been incorporated into the FEM scheme in order to calculate the Jacobian matrix and minimise the difference between the observed data and the finite element model. Convergence between the theoretical and observed data is achieved by means of a non-linear least squares optimisation procedure and a smoothness constrained (Occam) formulation to improve the stability of the iterative process and the reconstructed image. A typical 2.5-D inversion took over 2 hours on a Silicon Graphics workstation. Details of the theoretical basis for this approach can be found in Constable et al. (1987), Sasaki (1994), and Ogilvy et al. (1995).

No a priori assumptions are made in the 2.5-D inversion scheme concerning the initial starting model, but it is implicit in the finite element algorithm that the earth is 2-D in the direction of the geological strike. Hence the interpreted model may have restricted reliability where the geologic features are 3-D in nature.

Although the Occam inversion algorithm has been found to be one of the most reliable methods for image reconstruction, the inversion is unconstrained and the method attempts to fit the simplest geological model to the observed data. Invariably, a range of theoretically equivalent models can be obtained and this equivalence will increase with depth. Such ambiguity is inherent in all geophysical survey methods. Work is in progress to permit the incorporation of known geological constraints (e.g. borehole control) into the inversion process to minimise this problem.

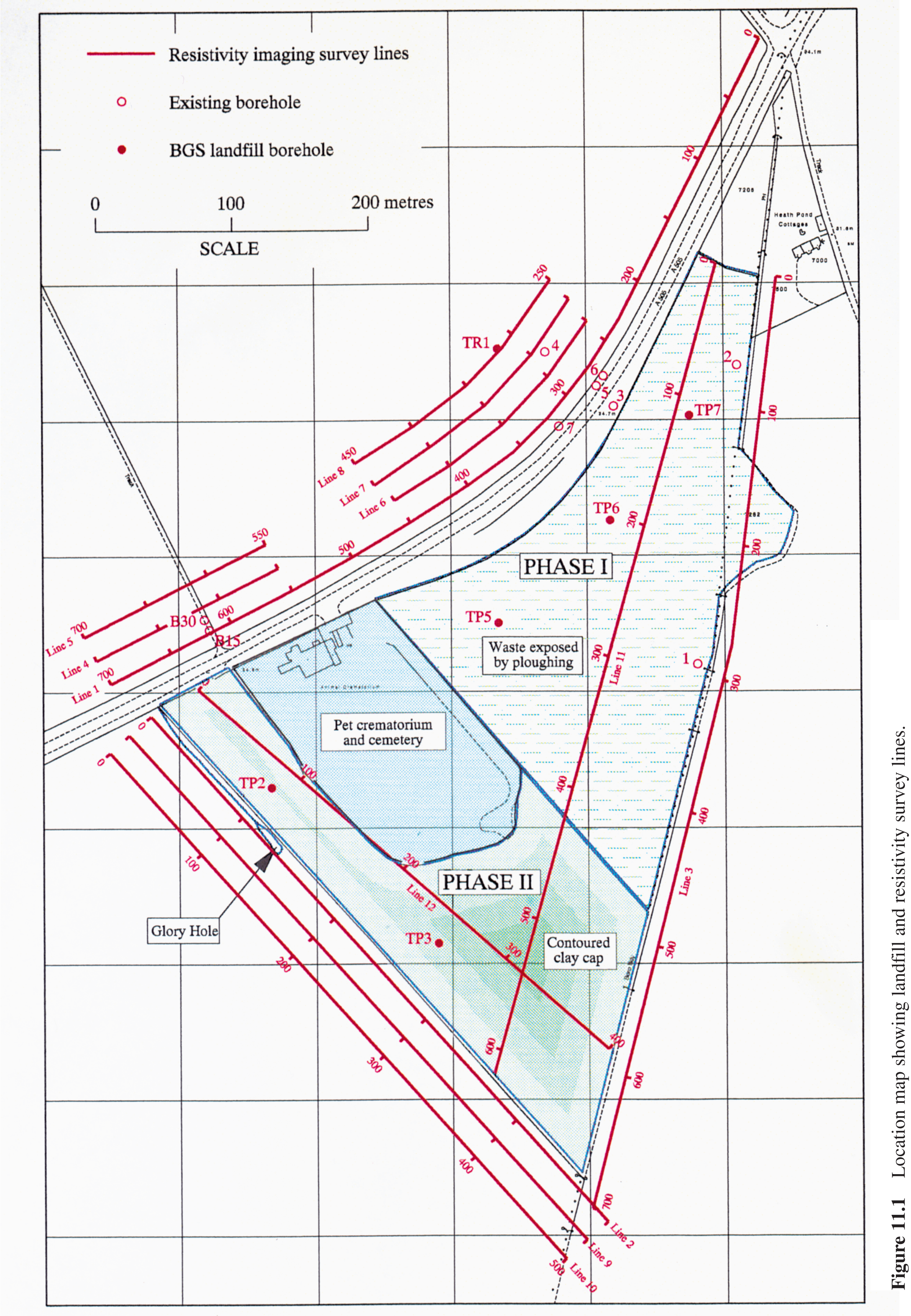


Figure 11.1 Location map showing landfill and resistivity survey lines.

11.3 Results

The results of the numerical inversions are presented as model 2-D cross-sections of the subsurface resistivity distribution. Based on representative resistivity values, (Ogilvy et al., 1996) the main lithologies and materials in these images can be identified as in Table 11.1. The ranges of resistivity for any formation are indicative only and significant overlap may occur between them depending on their relative composition, porosity, water-saturation and the degree of leachate contamination. Because leachate is highly conductive, it will reduce the resistivity of any formation.

Table 11.1 Range of formation resistivities.

Formation	Resistivity	Colour-code
Gravel beds:	6 - 300 ohm.m	blue - purple
Chalk:	25 - 65 ohm.m	yellow -green
Melbourn Rock:	65 - 250 ohm.m	blue - purple
Contaminated Chalk	<10 ohm.m	red
Waste:	<10 ohm.m	red

11.3.1 *Resistivity survey over the landfill*

Line 11

Prior to drilling, Line 11 was surveyed across both Phase I and Phase II of the landfill (Figure 11.2). The results indicated that the landfill did not occupy a single quarry, but was probably made up of several discrete pits, all of which were filled and subsequently covered by a thin layer of surficial waste. An area of apparently undisturbed ground is indicated between stations 300–420 m (shown in purple). The discrete waste pits are characterised by zones of low resistivity (shown in red).

Comparison with the photo-geological interpretations (section 3.2) showed that the resistivity images had clearly delineated the edges of the two pits traversed by Line 11. The apparent discrepancy at x = 550 m on Phase II suggests that after 1977 the quarry was extended and filled until completion in 1988. If so, the image indicates the SE edge of the waste pit to be at x = 610 m, as shown in Figure 11.2. This boundary almost coincides with the edge of the capping at x = 620 m. Subsequently, boreholes TP6 and TP7 confirmed the depth to the Chalk and permitted an interpolated cross-section to be overlaid on the image. Low resistivity values extend well below the known base of the pits (~10 m) associated with both Phase I and Phase II landfills and this result can be attributed to the infiltration of leachate into the underlying Chalk. Resistivity values in excess of 50 ohm.m are indicative of relatively uncontaminated chalk (shown in purple). Such zones are observed below a depth of about 20 m, although localised channels are evident below both pits. These channels may be associated with preferential leachate flow along fracture zones within the Chalk.

Line 12

Line 12 was surveyed NW-SE across Phase II of the landfill. Low resistivity values associated with waste infill are evident across the entire line (Figure 11.3). Photogeology from 1977 indicates a single pit extending from 0–320 m; the NW boundary of which correlates well with the resistivity interface at x = 10 m. Again, there is evidence that post-1977, the waste pit was extended to the SE. Assuming a similar landfill depth of about 10m for Phase II, the resistivity distribution suggests that leachate infiltration has penetrated to about 15 to 20 m into the Chalk. Borehole TP2, slightly off set from Line 12, indicated leachate at 14.92 m bgl, but little or no leachate at the bottom of the hole at 17.5 m bgl. This result is entirely consistent with the resistivity image, which suggests uncontaminated Chalk below 18 m (shown in purple). However, the most striking feature on this line is a broad channel of low resistivity values between 170–250 m. This is tentatively attributed to leachate saturated Chalk but would need to be tested by direct drilling.

11.3.2 *Landfill boundary resistivity survey*

Several low resistivity zones (<10 ohm.m) were identified around the perimeter of the Thriplow landfill. One of these was investigated by drilling borehole TR1, which was located on a persistent low resistivity feature below Line 8 in the depth interval 34–50 m bgl (Figure 11.4). The results of this borehole are discussed fully in Section 13, but despite being drilled on the geophysical anomaly did not encounter contamination at any level. The anomalous low resistivity values derived from numerical modelling were found to be largely a result of increased equivalence with depth. In the light of these results and the control from TR1, it is concluded that the resistivity technique has not identified a plume outside the site, but has provided insight on the structure and geometry of the landfill, and of the general stratigraphy surrounding the landfill.

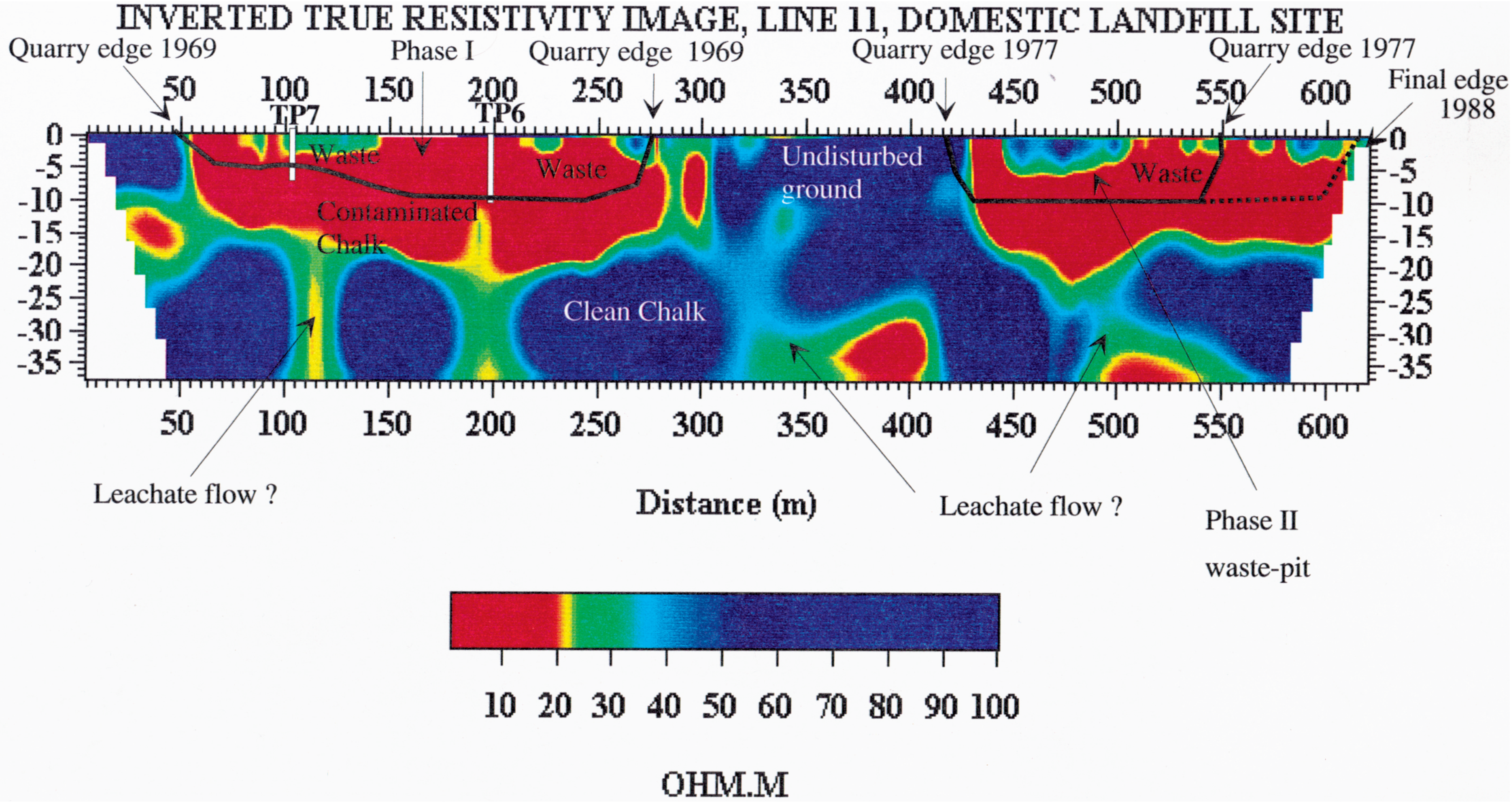


Figure 11.2 Inverted model resistivity image, Line 11, inside landfill.

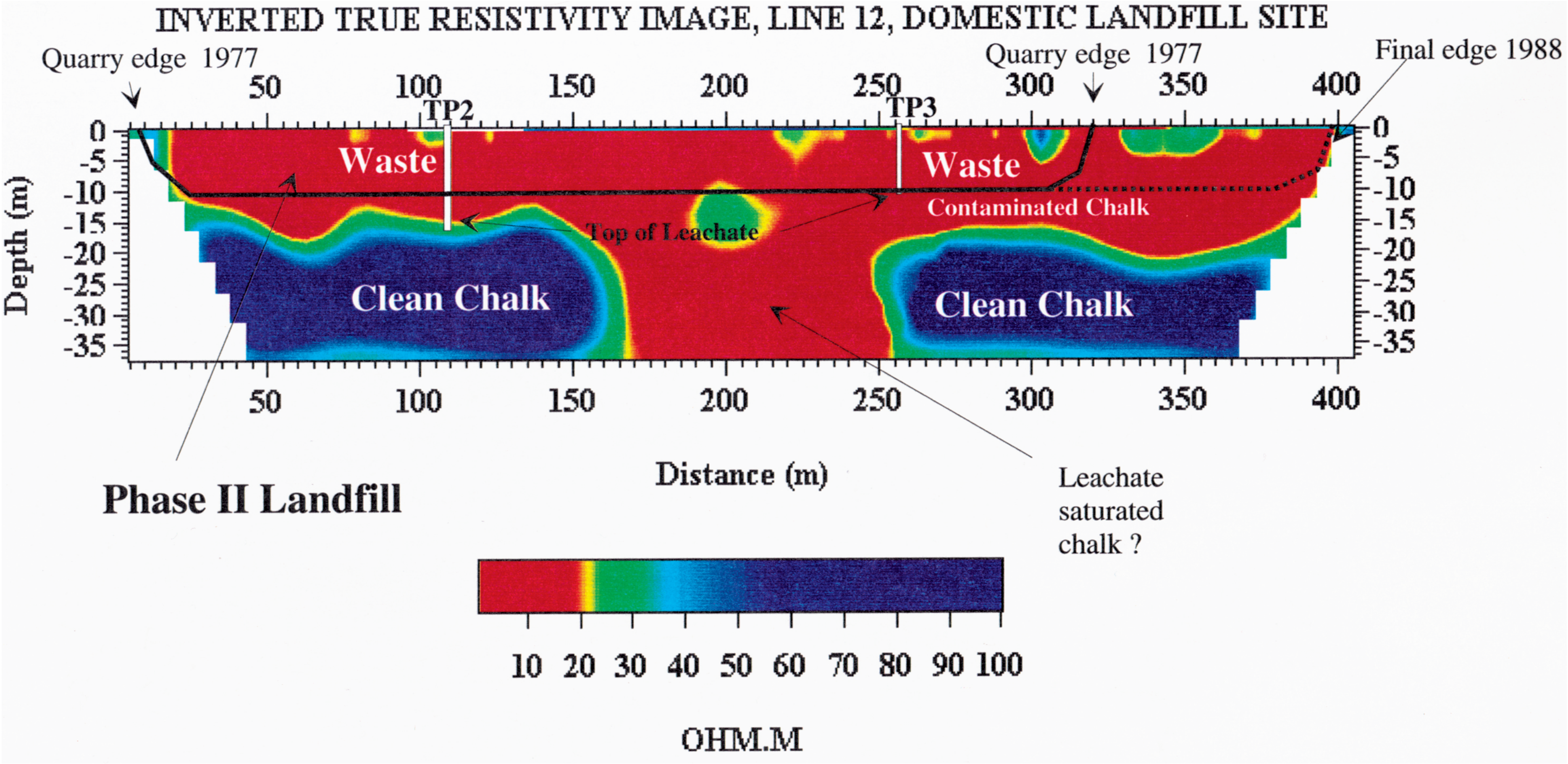


Figure 11.3 Inverted model resistivity image, Line 12, inside landfill.

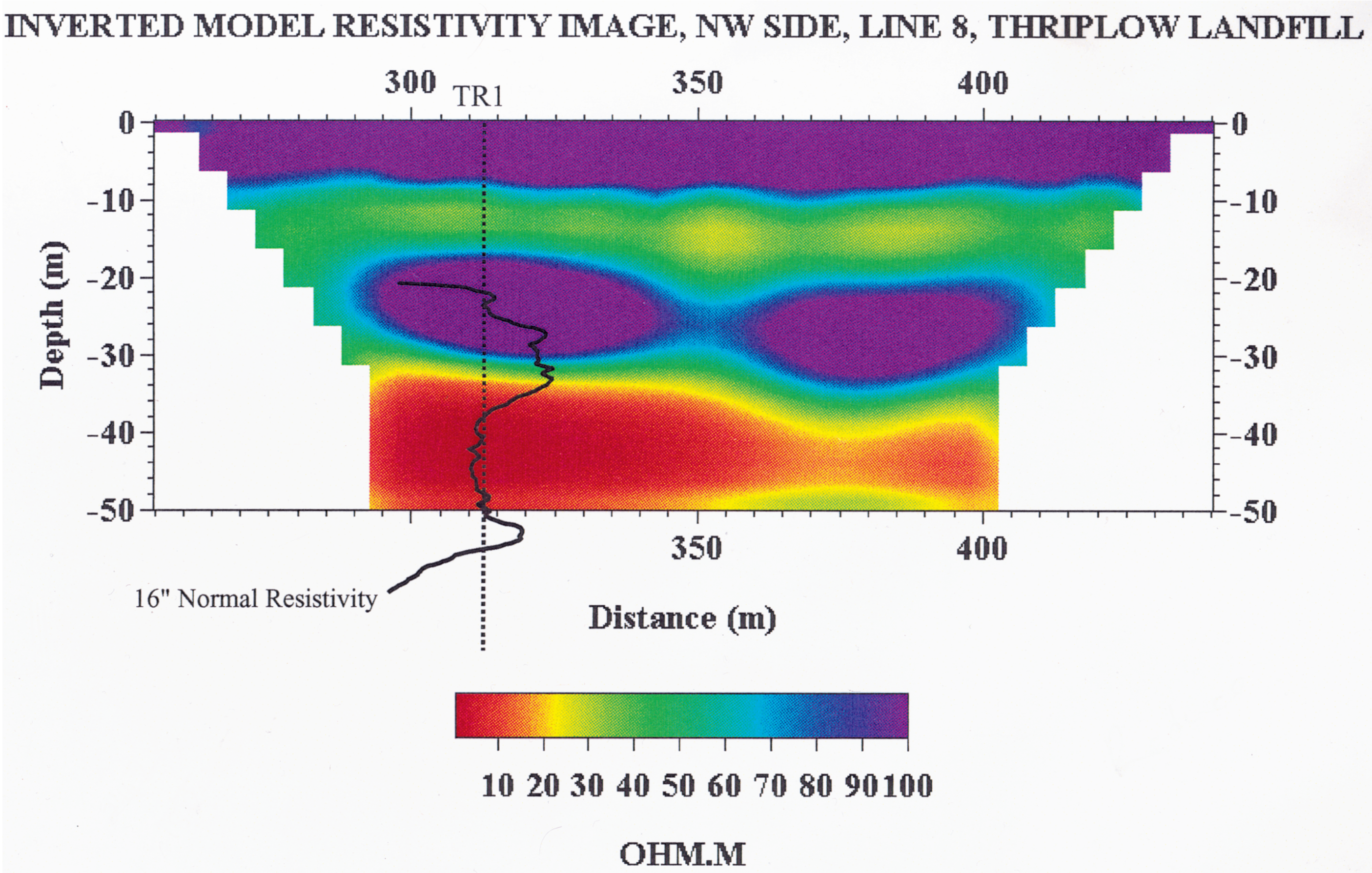


Figure 11.4 Comparison of inverted model resistivity image, Line 8, with 16” Nornal Resistivity log.

11.4 Re-processing of RESCAN resistivity data using improved 2-D inversion software

Line 1 of the RESCAN resistivity survey has been reprocessed to remove excessive noise and then re-modelled using more advanced 2-D inversion software (Figure 11.5). Line 1 is on the NW boundary of the landfill. Given the regional SE-NW hydraulic gradient, this side of the landfill was considered to be the most likely location for any leachate plume. Significantly better noise rejection has been achieved (RMS error down to 1.8%) compared to earlier modelling. However, despite this re-modelling, there is still no indication of a conductive plume at any location on Line 1. Broad stratigraphic correlations are evident. For example, the high resistivity zones (colour-coded blue) in the sections appear to correlate well with the spatial distribution of gravel deposits, but there does not appear to be a strong resistivity contrast at the Chalk interface. The inferred depths to bedrock based on resistivity values show some variance with borehole observations, which can only be explained by a transitional change in geo-electric properties with depth. The Chalk bedrock is characterised by quite low intrinsic resistivity levels of ~30 ohm.m (colour-coded red).

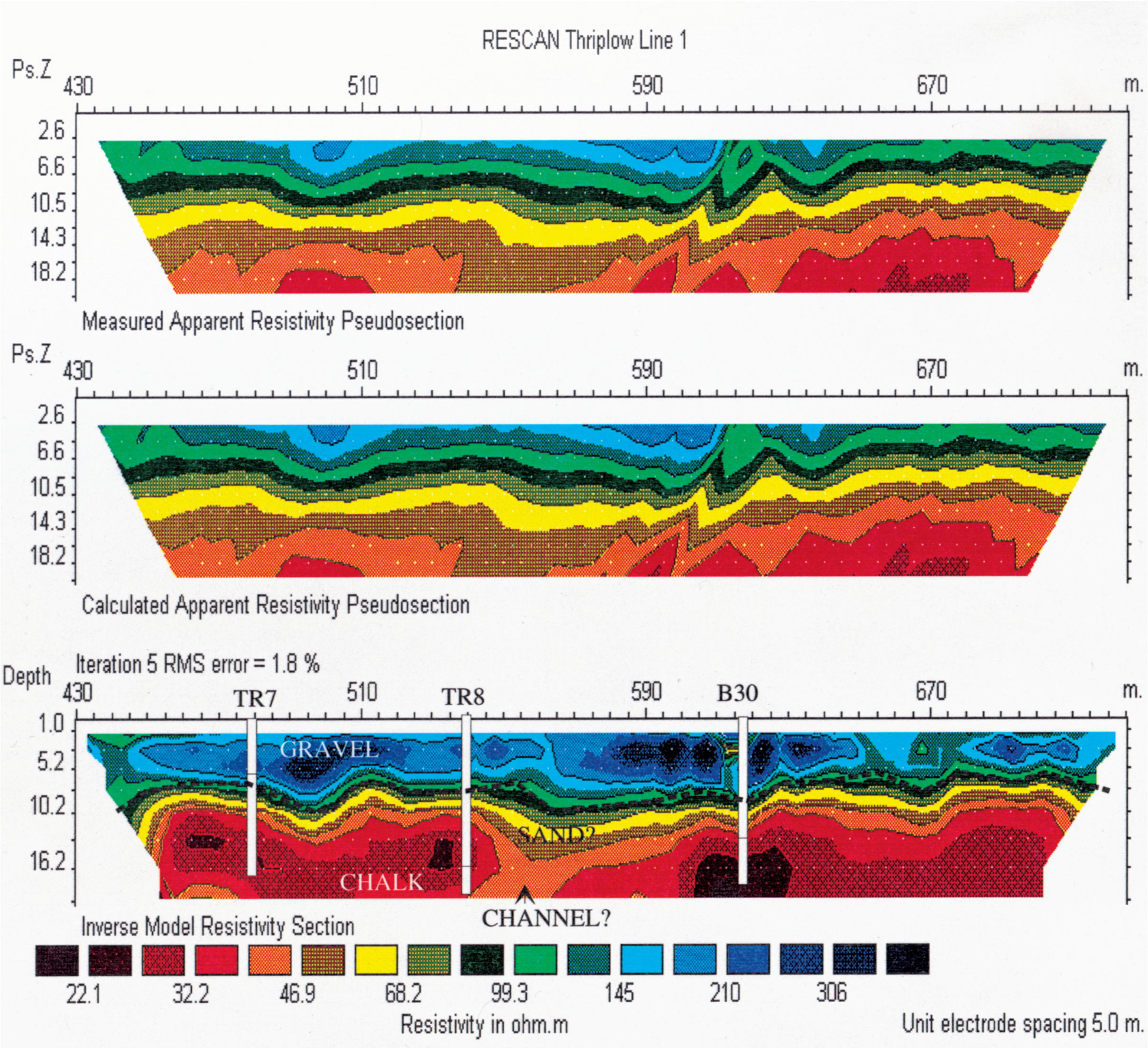


Figure 11.5 RESCAN resistivity image, Thriplow, Line 1 (from 430–725 m).

To illustrate the above, the inverse model resistivity section for stations 430 m–710 m is shown in Figure 11.4. It will be noted that the suspected buried palaeo-channel between boreholes TR7 and TR8 corresponds to a sub-vertical discontinuity in the resistivity model section at station x = 555 m but this feature is not well developed. Overall, it must be concluded that the resistivity imaging provides some insight on the stratigraphy but does not provide any evidence of a contaminant plume migrating down gradient to the north west.

12 CHARACTERISATION OF THE LANDFILL

12.1 Landfill drilling, on site sample preservation and testing

Using aerial photographs and the resistivity cross sections, five borehole locations were chosen to confirm the geometry of the landfill and the composition of waste and leachate (Figure 12.1).

Two boreholes, TP2 (16.2 m deep, 24 samples) and TP3 (10 m deep, 15 samples) were drilled in the newer, capped zone of the landfill (Phase 2). Three boreholes, TP5 (9 m deep, 16 samples), TP6 (11 m deep, 21 samples) and TP7 (7.5 m deep, 11 samples) were drilled in the older uncapped zone of the landfill (Phase 1). Judging by the aerial photographs (Section 3.2), the waste in which TP3 is situated was older than the waste sampled by TP2. Similarly waste intercepted by TP5 was younger than that sampled by TP6 and TP7.

All waste, removed from the drilling shell, was weighed so that the in-situ density could be estimated from the diameter and depth of the core run. The waste samples were then tightly sealed in high density polyethylene bags and stored in the dark at 4°C. Immediately after each drill run a packer was inserted just above the base of the borehole and O_2, CO_2 and CH_4 concentrations determined using an Analox 1200 gas analyser. The rest water level (RWL) was measured in each borehole and samples of leachate taken for complete analysis.

A double ring infiltrometer was used to determine the saturated hydraulic conductivity at 10 locations over the Phase 1 landfill and at 2 locations on Phase 2 area (Figure 12.1).

12.2 Sample characterisation

Twenty selected refuse samples were sent to MTD (Minton, Treherne and Davis) who homogenised the whole sample and then:

- Obtained leachate by squeezing in a large press. They then determined fatty acid concentrations in a portion of each leachate by gas chromatography (GC). The remaining portions of leachate were returned to BGS where they were analysed for cations, anions, NH_4, total organic carbon (TOC), total inorganic carbon (TIC) and tritium. Selected samples were sent to the Water Research Centre (WRC) for adsorbable organic halogen (AOX) determination. Cations were determined by Inductively Coupled Optical Emission Spectrometry (ICP-OES), anions by Ion Chromatography (Dionex). NH_4 was determined by flow-injection analysis and Fe(II) by colorimetry (2, 2 - bipyridyl). AOX was determined using a commercial organic halide analyser (Dressman and Stevens, 1983, Jekel and Roberts, 1980)
- Prepared samples for leach tests. The material was prepared without drying and with minimum grinding (only the oversize material was ground) to give a final particle size of 5 mm. The prepared material was returned to BGS, where the leach tests were carried out according to the NRA protocol (R&D Note 301). The procedure involved equilibrating 100 g of sample at natural moisture with 1000 ml distilled water for 24 hr. The liquid was then filtered through a 0.45 m filter and analysed.
- Prepared samples for biological methane potential (BMP) and chemical oxygen demand (COD). This involved drying and grinding to give final particle size of <1 mm. These measurements were carried out by MTD. The method used for BMP determinations has been described in detail by Biotal, (1992) and Croft and Campbell (1994). The technique involves incubation of small (0.5 g) samples of ground sample under controlled anaerobic conditions and measurement of methane production. For COD determinations, samples were oxidised by gently boiling with a solution of potassium dichromate, sulphuric acid and ortho-phosphoric acid. Excess dichromate was determined by titrating with ferrous sulphate solution. In addition to organic carbon, reduced inorganic species such as ferrous iron, sulphide, manganous manganese etc. are oxidised quantitatively under the test conditions.
- Determined the water content of the homogenised waste by drying.
- The remaining (approx. eighty) refuse samples were sent to the Centre for Waste Management (CWM), based at the University of Luton, for sorting and characterisation. Here the bags of waste were spread out on mesh tables (5 mm) and the material hand-sorted into 24 different categories). The <5 mm fraction and the unidentifiable "residue" usually formed the bulk of the waste, paper and plastics etc. were also well represented.

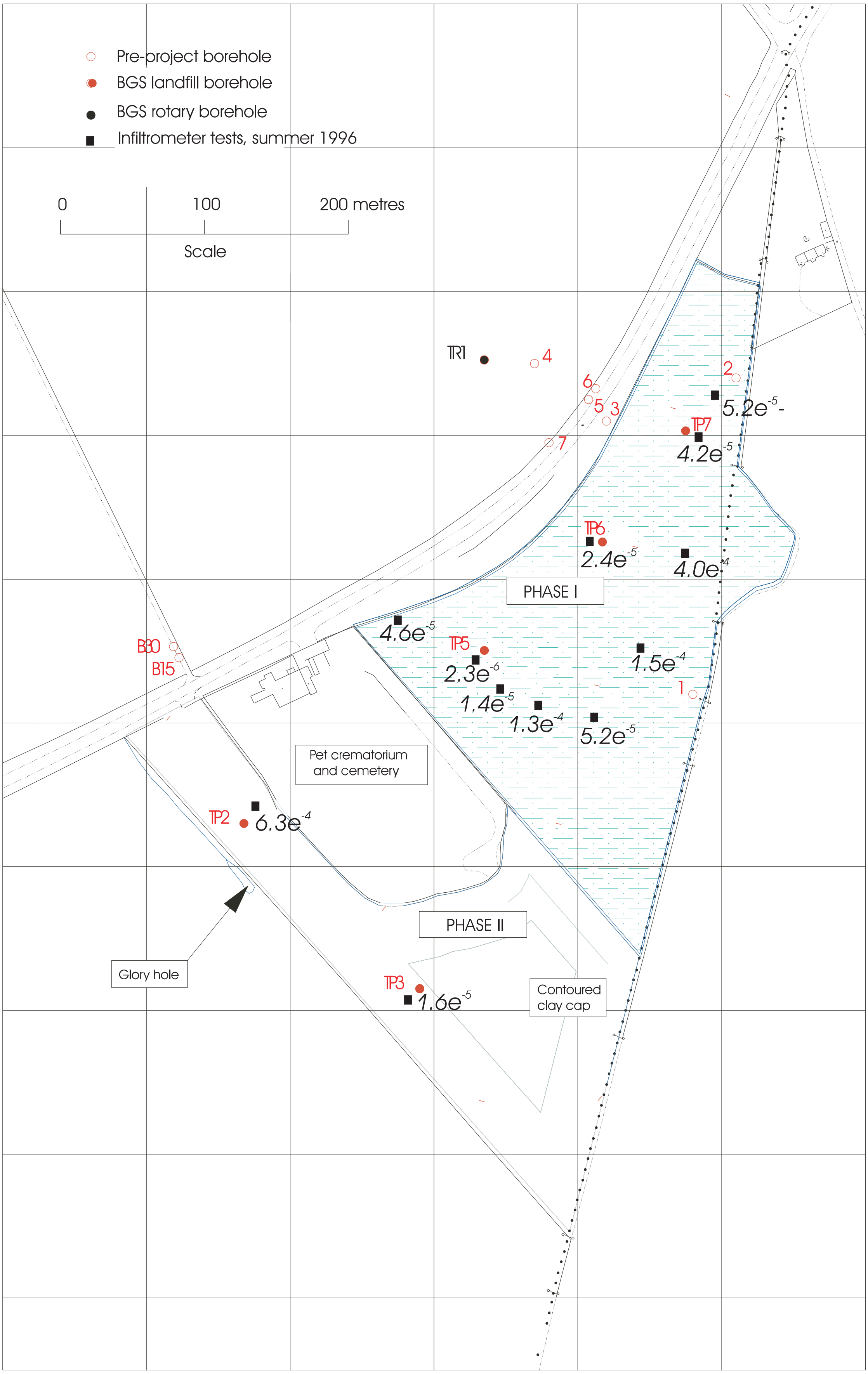


Figure 12.1 Location of boreholes constructed, infiltrometer tests, and values for saturated hydraulic conductivity of the landfill cap (m/s), undertaken in Summer 1996.

- The Chalk samples from the 5–6 m layer and the base of TP2 were retained at BGS. Porewater samples were obtained by centrifugation and analysed for cations, anions, NH_4, TIC and TOC.
- The leachate samples from the base of the boreholes were analysed for cations, anions, NH_4, TOC, TIC, AOX, Fatty Acids, VOC/VOX, COD, PAHs and tritium.

12.3 Results and discussion

During drilling it became clear that the landfill was very heterogeneous. No two samples were the same and there were no clear trends apart from the fact that the proportion of well-rotted material was higher at the base of the older uncapped landfill (TP5, TP6 and TP7). The capped landfill was drier and an intermediate layer of Chalk had been deposited at around 5 m bgl. The fatty acid content of the porewaters (Section 12.3.4) was highest at the top, just under the cap indicating active degradation. Lower down, material was often dry and many samples showed little or no sign of degradation.

12.3.1 *Density and gas composition*

Figures 12.2 and 12.3 show how the density of the material and the gas composition varied with depth. Density showed no clear trend but methane and carbon dioxide concentrations generally increased with depth. There was a methane peak above the base of the landfill in all boreholes and also immediately above the 5 m bgl intermediate layer of chalk rubble in TP2. There was some correlation between the methane concentration and the presence of rotting organic material, e.g. black mulch (Section 12.3.2) but no correlation with biological methane potential (BMP) of the solid phase.

As would be expected, plots of methane against carbon dioxide and oxygen (Figure 12.4) were linear with correlation coefficients of 0.89. Methane concentration was directly proportional to carbon dioxide and inversely proportional to oxygen concentration.

12.3.2 *Composition of waste*

The results of the careful sorting by CWM into 25 different categories are detailed in Appendix B. For the purpose of illustration the categories were combined into eight groups and their distributions with depth are shown in the Figures 12.5 and 12.6. The material is heterogeneous and the proportions of each category vary haphazardly. The chalk layer at 5.4 m bgl in the capped landfill is clearly visible. The proportions of combustibles and putrescibles decreases with age, thus the proportion in TP3 > TP2 >>TP5 and TP6. TP7 was not illustrated because there were insufficient data points but it appeared to show the same pattern. The waste at the base of the uncapped landfill was well rotted and odorous.

Where dated material was found e.g. old newspapers, they confirmed the dates deduced from the aerial photographs. The age of waste penetrated in the two phases is summarised in Table 12.1.

12.3.3 *Solid Phase: BMP and COD*

The results of the Biological Methane Potential (BMP) and the Chemical Oxygen Demand (COD) determinations are illustrated in Figures 12.7 and 12.8 and listed in Tables 12.2 (Phase 1) and 12.3 (Phase 2).

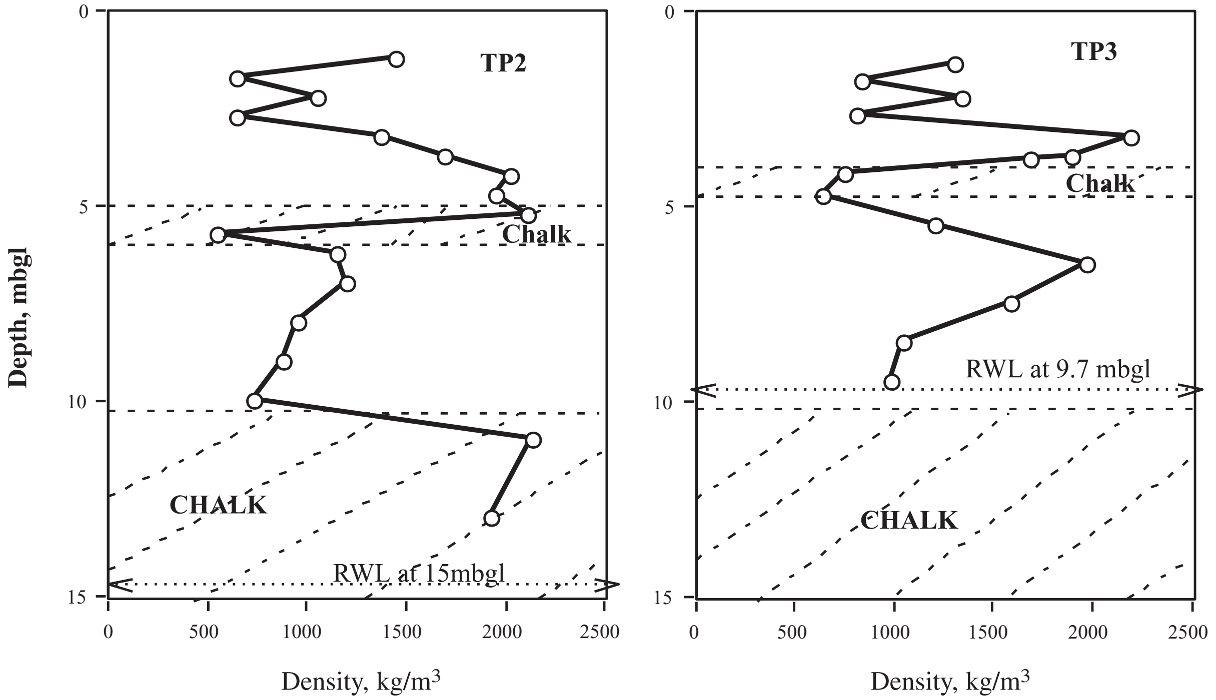
BMP values were high near the top of the capped landfill where active acetogenesis appears to be occurring (see Section 12.3.4). Elsewhere they are low and it appears that the old uncapped landfill has very little remaining potential for producing methane. There is some correlation with the proportion of combustibles in the uncapped landfill but the low BMP values in TP3 are surprising as this borehole contained the highest proportion of combustibles and putrescibles. The correlation between BMP and COD is poor (Figure 12.9). This is not surprising, even although the COD values are reported as “kg C / tonne dry wt” since, unlike soil samples for which the method is designed, the waste contained quantities of reduced inorganic species. If very low BMP values are ignored (Figure 12.9) then the correlation is better presumably because these samples contain a high proportion of biodegradable (organic) matter.

12.3.4 *Porewater composition*

Although 22 samples were sent to MTD, six were so dry that they produced no leachate when they were pressed. Three of these were from borehole TP2, so that in this borehole only the top two samples produced leachate. However, leachate was extracted by centrifugation from the Chalk at the base of this borehole. All porewaters/leachates were analysed for a wide range of cations, anions and fatty acids. The leachate recovered from the base of each well was also analysed for AOXs (adsorbable organic halides), VOXs (volatile organic halides) and PAHs (polyaromatic hydrocarbons).

Tables 12.4 and 12.5 show porewater analyses for the boreholes in the two phases of landfilling respectively. Also given are analytical data for groundwater sampled from the monitoring boreholes outside, but adjacent to, the landfill.

Phase 2: Capped Landfill



Phase 1: Uncapped Landfill

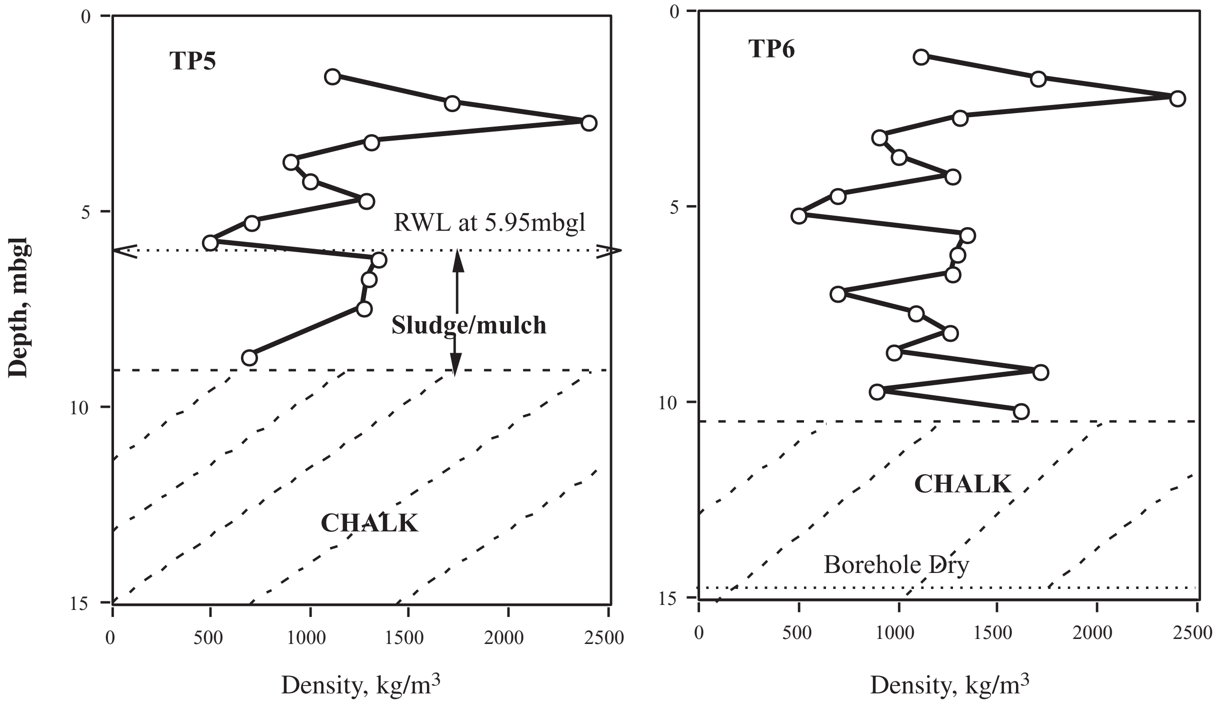


Figure 12.2 Density of landfill material.

These data reflect the heterogeneity of the landfill, and only a few trends or correlations are revealed in the correlation matrix given in Table 12.6, principally between fatty acids (VFAs) and ammonium, Zn, Cu and Al.

Concentrations of fatty acids (and hence TOC), ammonia, and metals (Fe, Mn, Ni, Cu, Zn, Cr) were high in the top three metres of TP2 (immediately under the cap) indicating active acetogenesis some ten years after capping. The

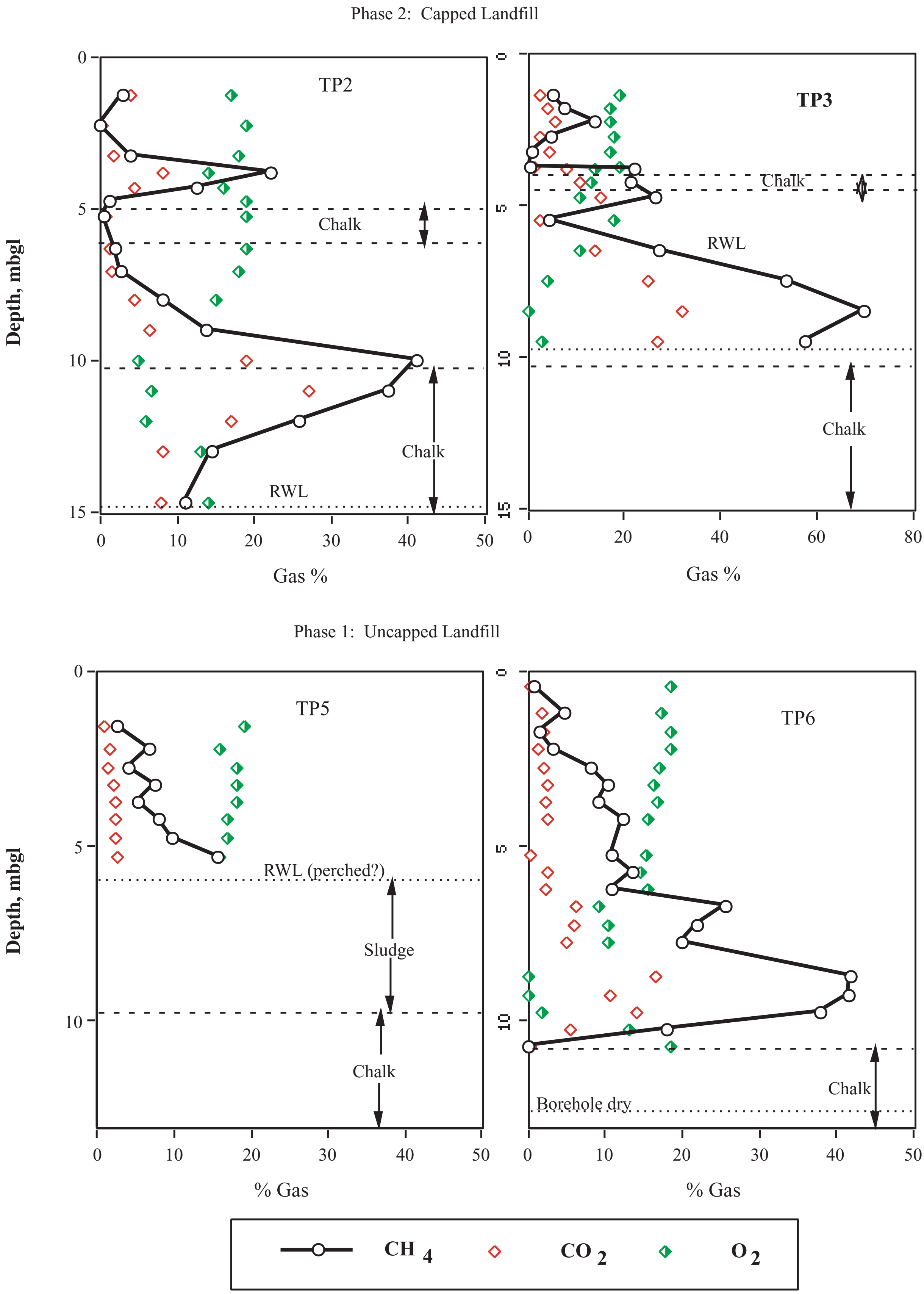


Figure 12.3 Gas composition in landfill boreholes.

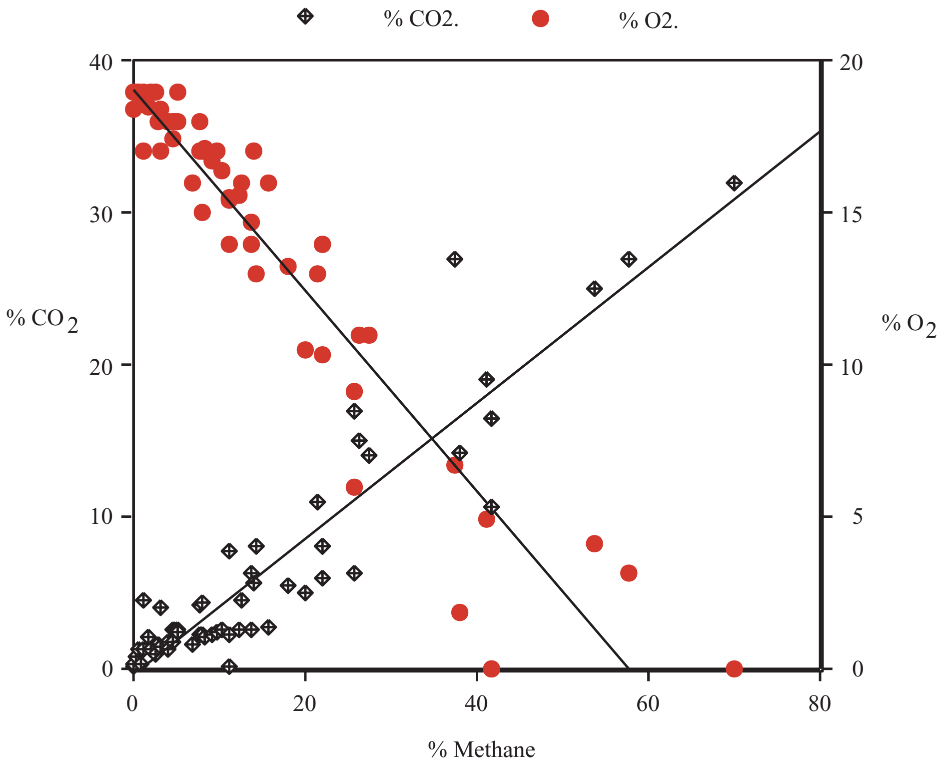


Figure 12.4
Correlation between $\%CH_4$, $\%CO_2$ and $\%O_2$ in landfill gases.

For CH_4 vs CO_2: $y = 0.455x - 0.334$ $r2 = 0.886$
For CH_4 vs O_2: $y = 0.331x + 19.084$ $r2 = 0.889$

next 3 m were so dry that water could not be extracted. However, the top of the Chalk layer at 11.0 m bgl contained high concentrations of calcium, TOC, ammonia and measurable Ni and Cu (fatty acids were not determined) and it is probable that acetogenesis was occurring throughout the top 10 m, possibly only in zones where there is sufficient moisture.

Lower concentrations of fatty acids are also present in TP3 porewaters. This is the newer section of the capped landfill and it may be that degradation is only just beginning.

Fatty acids were detected in only three samples from the Phase 1 boreholes and the concentrations were low. As this was uncapped and was completed some 20 years ago it is likely that the acetogenic phase is over and any degradation still occurring is methanogenic.

The high methane concentrations in the gases at the base of all the boreholes indicates that methanogenesis is still occurring at the bottom of both landfill phases and is probably related to the water content.

Calcium concentrations were high in the upper samples and then decreased steadily with depth in boreholes from both Phase 1 and Phase 2. Calcium in the base leachates is no higher than in the adjacent boreholes (BH15 and TBH 5).

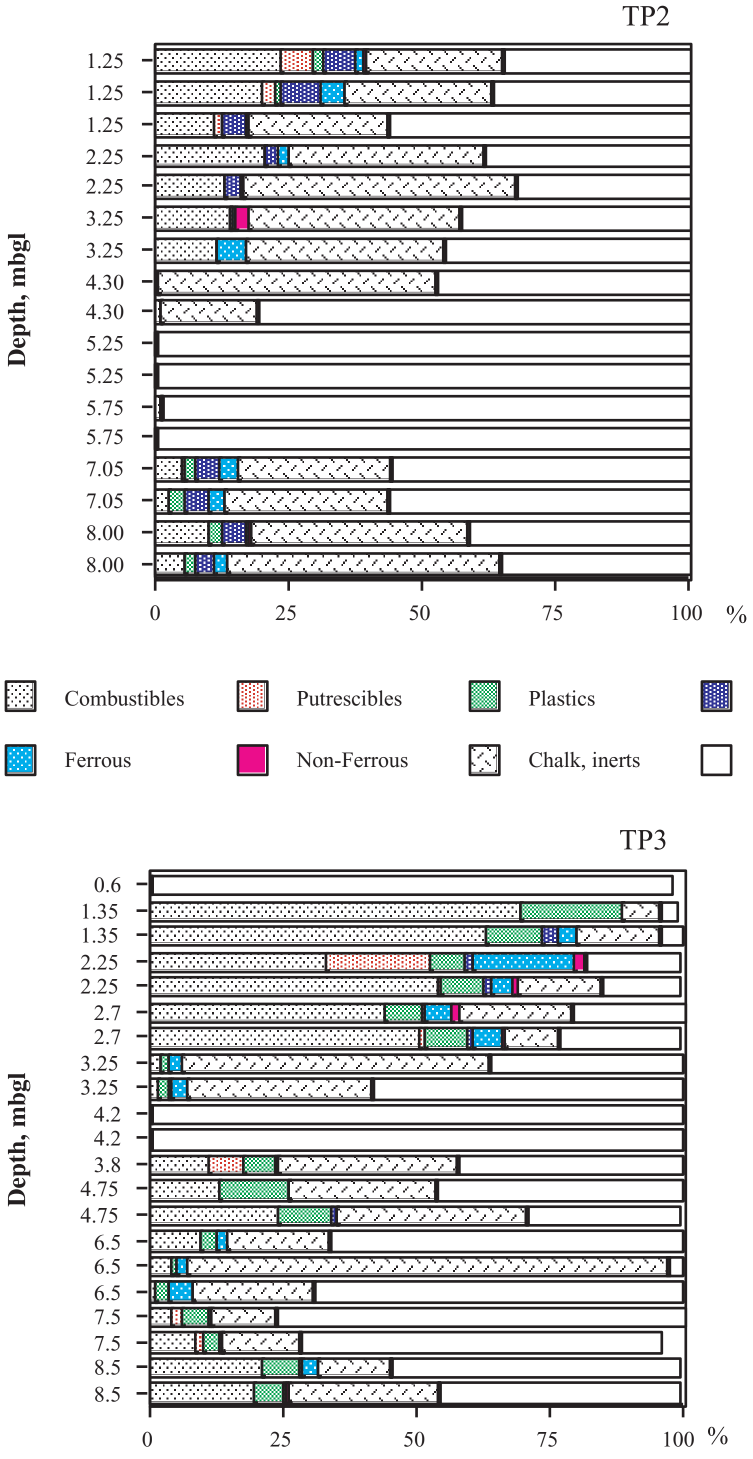
There is a strong correlation ($r > 0.9$) between the fatty acid concentration and the concentrations of calcium, aluminium and zinc. There is a significant correlation ($r > 0.7$) between the fatty acid concentration and the concentrations of ammonia and copper. Presumably the metals dissolved in the acid porewater, and ammonia was another degradation product.

Mg, Na, K, Mn and Si concentrations show no trends but there was some correlation between Na, K and Cl.

Sulphate concentrations were high (>1 g/l) in all porewater samples but were low in the base leachate and in the chalk layer at the base of TP2. There was good correlation between NO_3 and SO_4 ($r = 0.81$) but none with fatty acids or other analytes.

Chloride concentrations in the waste were variable, ranging from 200 mg/l to 4000 mg/l. There was little correlation between Cl and Br ($r = 0.56$) and none with the other anions.

Figure 12.5 Composition of the waste — Phase 1: Uncapped landfill.



Boron concentrations were highly variable. There is some correlation with magnesium, nitrate and sulphate. Boron is probably associated with cleaning materials (sodium borate) which are disposed of haphazardly.

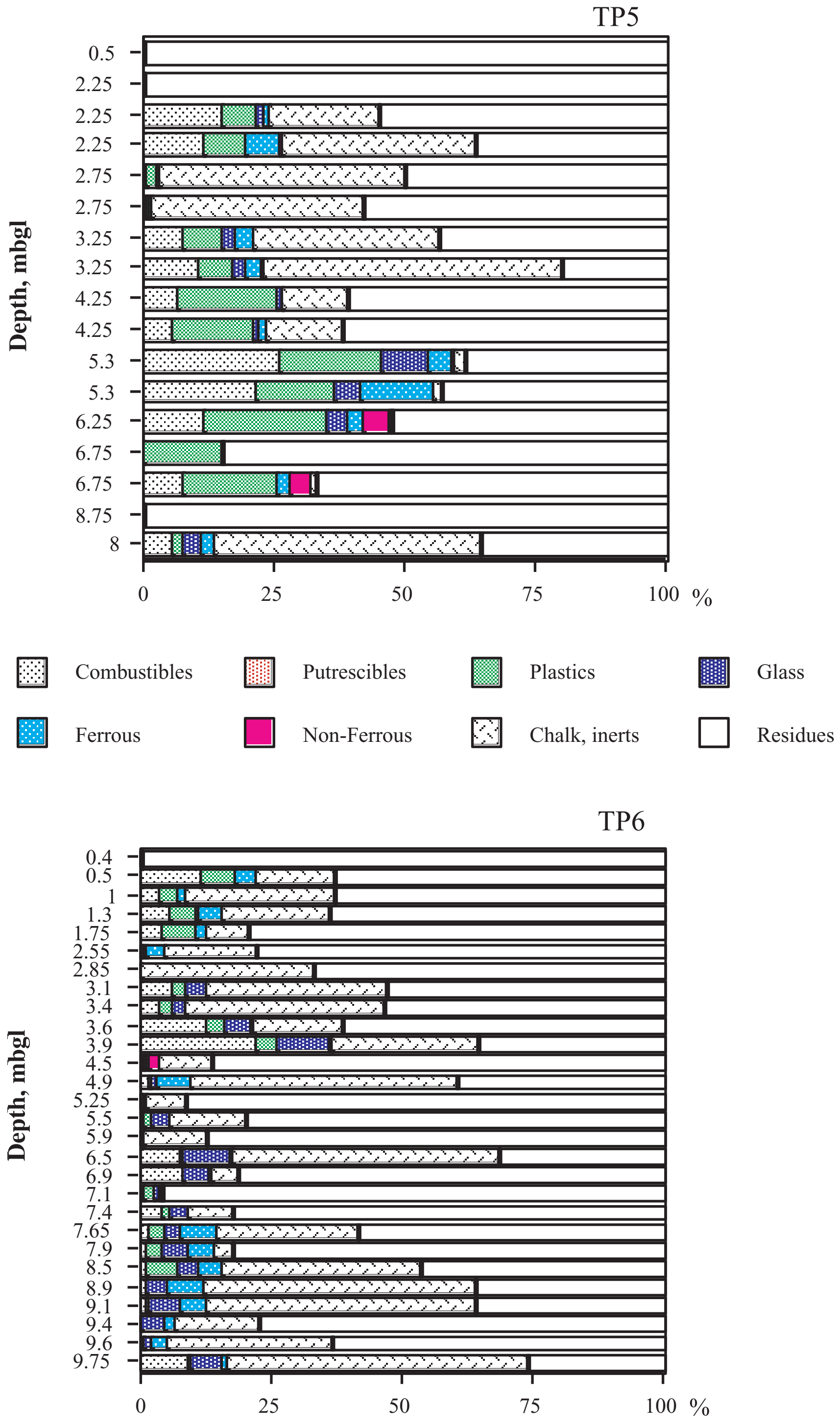
Tritium, AOX, VOX and PAH were determined in the monitoring well and the base leachates only.

Tritium was low in all except the base leachate from TP3 where the value was 4450 T.U. Its potential as an indicator of leachate from the landfill may be limited.

AOX values ranged from 285 to 2800 mg/l Cl. These values are higher than those reported by Robinson et al. (1986) and may reflect the presence of toxic non-volatile organic halogen compounds.

Neither PAHs nor VOXs were detected in any of the four samples.

Figure 12.6 Composition of the waste Phase 2: Capped landfill.



12.3.5 *Leachates obtained from the base of the landfill boreholes*

Tables 12.3 and 12.4 include the composition of the leachate taken from the base of the boreholes and from the monitoring well situated between TP2 and TP3. The monitoring well was heavily polluted. It contained 10 g/l TOC, high concentrations of ammonia, nitrite, and iron as well as some metals. The design of this well is not known and therefore it is impossible to say which parts of the landfill it samples. The fresh leachates from the boreholes, on the other hand, were relatively unpolluted. In fact they were only slightly more contaminated than the water from the monitoring wells on the edge of the landfill (cf. TP2 and 3 with BH15 and TP5, TP6 and TP7 with TBH 3, TBH 4, TBH 5 and TBH 7). These samples were taken soon after completing the boreholes and they may not be representative of the leachate that percolates through the undisturbed landfill. It is recommended that further leachate samples be taken in order to determine whether the composition changes with time.

Table 12.1 Dates attributed to exhumed material.

Phase	Cap	Boreholes	Age of waste
1	uncapped	TP6 and TP7	1967 to 1971
		TP5	1972 to 1975
2	capped	TP2:	1979 to 1984
		TP3	1983 to 1987

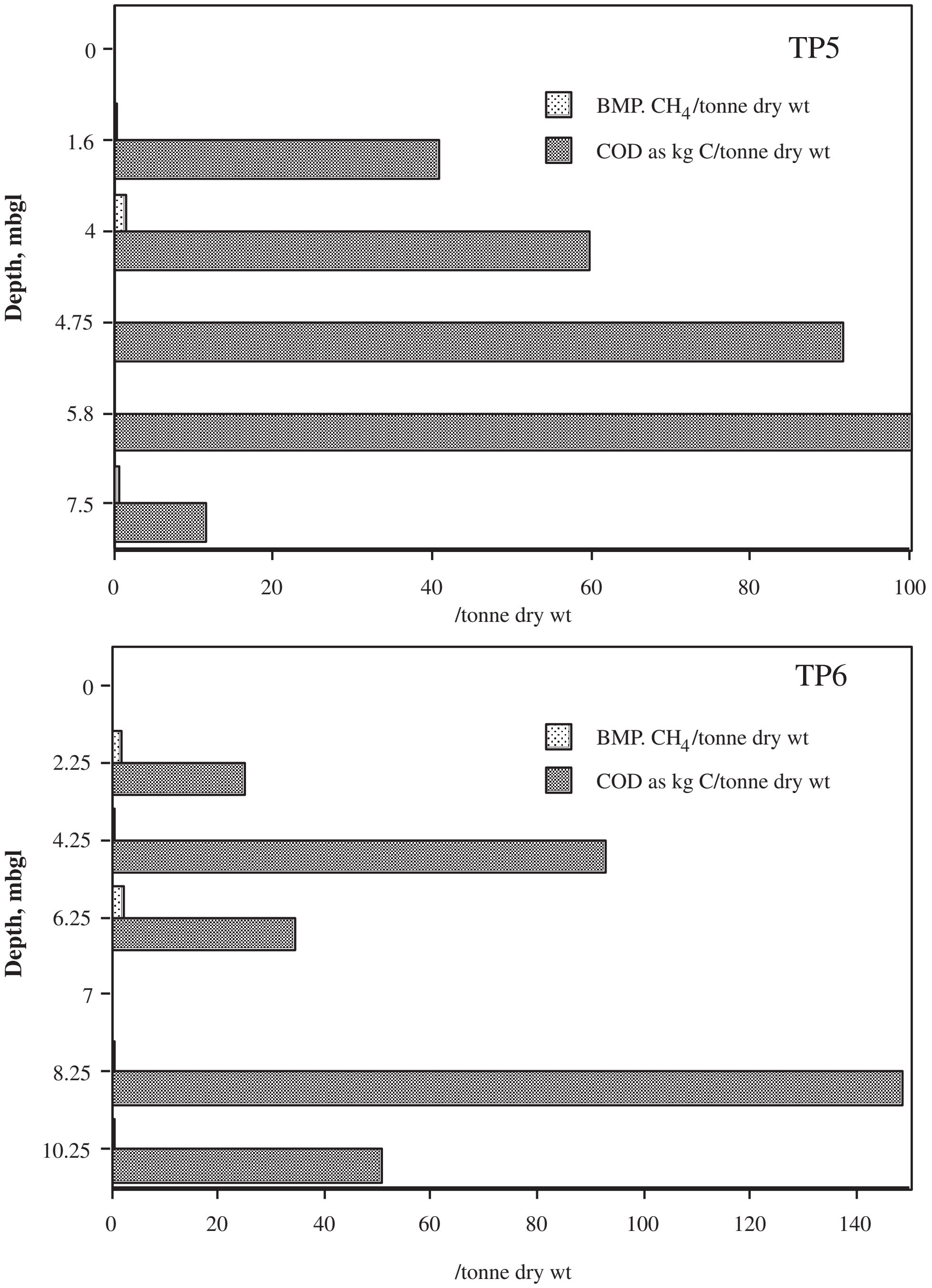


Figure 12.7 BMP and COD. Phase 1: Uncapped landfill.

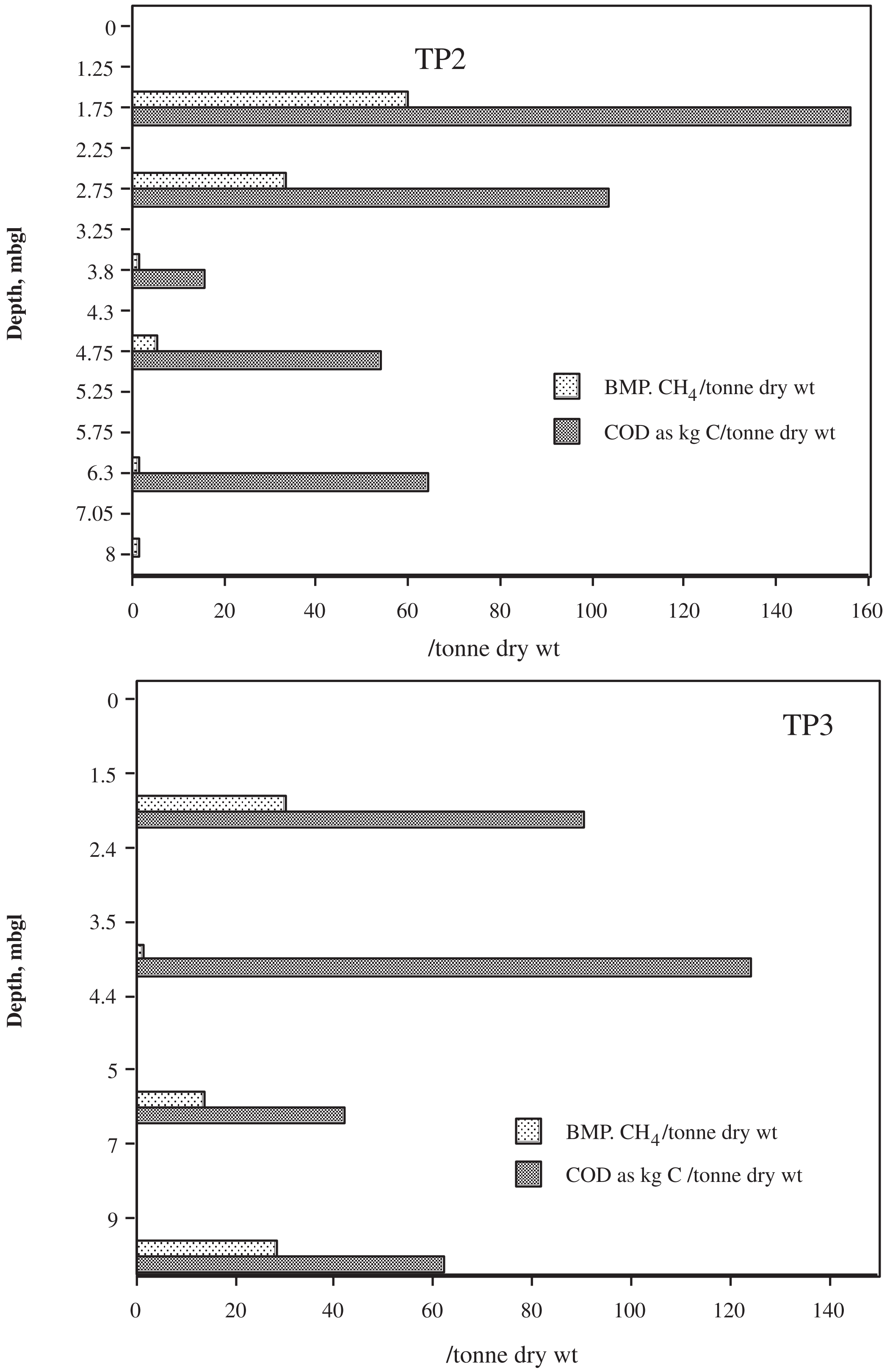


Figure 12.8 BMP and COD — Phase II: Capped landfill.

Table 12.2 Biological methane potential and chemical demand — Phase I: Uncapped landfill.

Borehole/ Sample no	Depth m bgl	BMP m^3 CH_4/ tonne dry wt	Water content % of wet weight	COD as kg C/tonne	Putrescibles	Combustibles	Total fatty acids mg/l
TP5/1	0.5				0	0	
TP5/2	1.6	0.06	19.71	40.7			<20
TP5/3	2.25				0.6	9	
TP5/4							
TP5/5					0.05	0.6	
TP5/6	2.75						
TP5/7	3.25				2.1	8.95	
TP5/8	4	1.41	30.42	59.6			<20
TP5/9	4.5				1.15	6.45	
TP5/10	4.75	0	51.38	91.3			102
TP5/11	5.3				7	24.15	
TP5/12	5.8	0	18	185.4			<20
TP5/13	6.25						
TP5/14	6.75				0.15	3.65	
TP5/15	7.5	0.47	18	11.4			
TP5/16	8.75				0	0	

Table 12.2 Continued.

Borehole/ sample no	Depth m bgl	BMP m^3 CH_4/ tonne dry wt	Water content % of wet weight	COD as kg C/tonne	Putrescibles	Combustibles	Total fatty acids mg/l
TP6/1	0.43				0	0	
TP6/2	1.18				0	7.35	
TP6/3	1.75				0	4.8	
TP6/4	2.25	1.43	21.23	24.7			51
TP6/5	2.75				0	0	
TP6/6	3.25				0	4.55	
TP6/7	3.75				0	17.2	
TP6/8	4.25	0.1	29.41	92.3			<20
TP6/9	4.75				0	1	
TP6/10	5.25				0	0.2	
TP6/11	5.75				0	0.35	
TP6/12	6.25	2.05	20.26	33.9			<20
TP6/13	6.75				0	7.7	
TP6/14	7.25				0	2.3	
TP6/15	7.75				0	1.2	
TP6/16	8.25	0	24	148.4			<20
TP6/17	8.75				0	0.85	
TP6/18	9.25				0	0.55	
TP6/19	9.75				0	4.9	
TP6/20	10.25	0	14.87	50.6			
TP6/21	10.75						

Table 12.2 Continued.

Borehole/ sample no	Depth m bgl	BMP m^3 CH$_4$/ tonne dry wt	Water content % of wet weight	COD as kg C/tonne	Putrescibles	Combustibles	Total fatty acids mg/l
TP7/1	0.18						
TP7/2	0.93						
TP7/3	1.75				0.3	2.8	
TP7/4	2.25	0	32.11	141.4			132
TP7/5	2.75				0	19.5	
TP7/6	3.25	5.44	37.67	18.05			<20
TP7/7	3.75				0	15.4	
TP7/8	4.25	0	30.31	63.2			22
TP7/9	5.00						
TP7/10	6.00						
TP7/11	7.00						

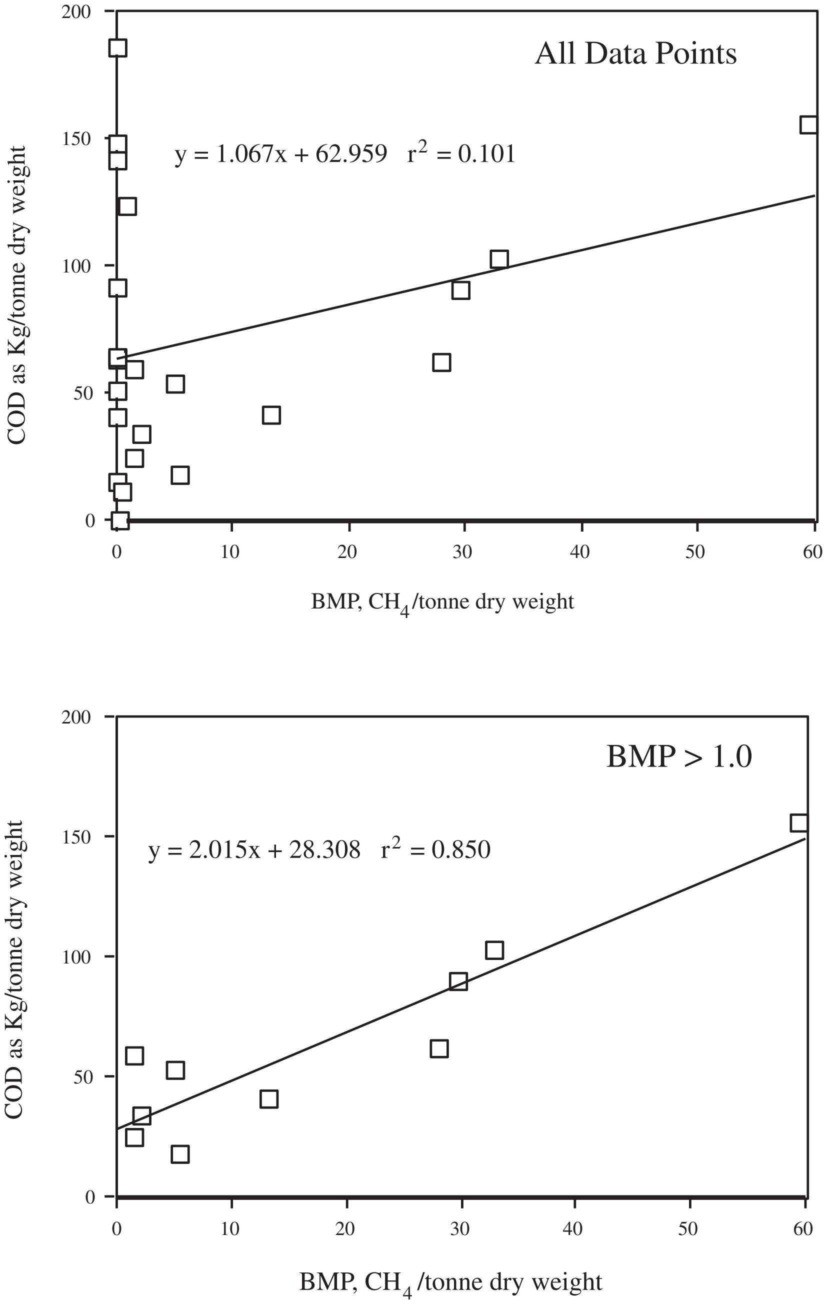
Table 12.3 Biological methane potential and chemical oxygen demand — Phase 2: Capped landfill.

Borehole/ sample no	Depth m bgl	BMP m^3 CH$_4$/ tonne dry wt	Water content % of wet weight	COD as kg C/tonne	Putrescibles	Combustibles	Total fatty acids mg/l
TP 2/4	1.25				3.3	18.3	
TP 2/5	1.75	59.40	37.08	155.90			53,107
TP 2/6	2.25				0	12.4	
TP2 /7	2.75	32.86	28.14	103.00			673
TP2/8	3.25				0	12.6	
TP2/9	3.80	0.00	14.33	15.20			
TP2/10	4.30				0	0	
TP2/11	4.75	4.90	14.93	53.40			
TP2/12	5.25						
TP2/13	5.75				0	0	
TP2/14	6.30	0.00	15.73	63.80			
TP2/15	7.05				0.2	3.9	
TP2/16	8.00					7.6	

Table 12.3 Continued.

Borehole/ sample no	Depth m bgl	BMP m^3 CH$_4$/ tonne dry wt	Water content % of wet weight	COD as kg C/tonne	Putrescibles	Combustibles	Total fatty acids mg/l
TP3/1	1.20				0	0	
TP3/2	1.50				0	66.5	
TP3/3	2.10	29.56	23.27	90.2			690
TP3/4	2.40				10	43.6	
TP3/5	3.00				0.4	47.5	
TP3/6	3.50				0	1.9	
TP3/7	4.00	0.85	14.91	123.8			
TP3/8	4.40				0	0.1	
TP3/9	4.10				6.4	11.1	
TP3/10	5.00				0	18.8	
TP3/11	6.00	13.14	35.82	41.4			263
TP3/12	7.00				0	5	
TP3/13	8.00				1.7	6.5	
TP3/14	9.00				0	20.6	
TP3/15	10.00	27.9	37.29	61.7			567

Figure 12.9
Relationship between BMP and COD.



12.3.6 *Leach tests*

The results of the leach tests are given in Table 12.7. Concentrations are expressed as mg/kg wet solid. If these values are compared with the concentrations in the porewaters obtained by squeezing, also expressed as mg/kg wet solid, it is clear that for many of the species simply diluting porewater from 1 kg of waste would give the same concentration as leaching. Thus, in most samples there is no significant difference between diluted porewater and eluent for Mg, Na, K, Fe, TOC, Br and Cl. However, Ca, SiO_2 and Al concentrations tended to be higher in leachates reflecting the high chalk and clay content of many of the samples. The concentrations of metals Cu, Zn and Ni were slightly higher in the leachates for most, but not all, of the samples. Boron concentrations also tended to be higher in the leachate. As boron is probably anthropogenic this must be a solubility effect.

Table 12.4 Porewater and groundwater composition — Phase 1: Uncapped landfill.

Sample Code	Moisture	Treatment	mid-point	Type	density	pH	DO2	Ca	Mg	Na	K	HCO3	Cl	SO4	NO3	Br	NO2
	%		mbgl		kg/m3		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
TP 5/2	19.71	Squeezed	1.6	refuse	1222			1250	89	124	106		225	1926	967	<1.5	66.7
TP 5/8	30.42	Squeezed	3.75	refuse	1589			872	217	425	595		367	4065	<5	3.51	<1
TP 5/10	34.48	Squeezed	4.75	refuse				722	242	620	616		572	4191	<5	5.18	<1
TP 5/12	51.38	Squeezed	5.8	refuse	1324			598	201	480	337		556	2732	<5	4.04	<1
TP5/15	18	Sq/No L.	7.5	refuse													
TP5				leachate		8.05		212	72	288	237	2432	296	<5	<5	2.09	<1
TP 6/4	21.23	Squeezed	2.25	refuse	2403			2620	209	796	289		778	2115	3915	24.6	1643
TP 6/8	29.41	Squeezed	4.25	refuse	1279			1450	371	1090	447		1164	2352	208	5.9	2174
TP 6/12	20.26	Squeezed	6.25	refuse	1296			799	206	929	469		1198	3297	84	10.6	191
TP 6/16	24	Squeezed	8.25	refuse	1263			489	499	1030	720		753	8302	<5	7.52	<1
TP 6/20	14.87	Sq/No L.	10.25	refuse													
TP7/4	32.11	Squeezed		refuse				1025	511	1510	1110		1425	6015	<5	14.2	2.39
TP 7/6	37.67	Squeezed		refuse				664	644	1720	1420		1916	8187	<5	18.4	10.6
TP 7/8	30.31	Squeezed		refuse				772	287	722	785		848	4678	<5	8.03	<1
TP7				leachate		8.08	4.5	159	83	298	266	2682	304	34	<1	3.133	0.28
TBH5A			20.5	GW		6.38	3.0	352	5	427	6	866	624	151	9	3.84	<0.2
TBH5B			32.6	GW		6.41	2.0	318	4	315	4	748	494	101	10	3.1	<0.2
TBH6			12.5	GW		6.52	2.0	345	4	302	2	642	515	117	38	0.57	<0.2
TBH2			15	GW		6.84	2.0	282	55	267	173	1500	338	188	172	1.56	<0.2
TBH3			14.5	GW		6.91	2.0	302	18	492	34	1040	614	211	49	6.56	0.32
TBH4			19	GW		6.85	2.0	220	2	55	1	279	223	41	57	1.64	<0.2
TBH1			18.91	GW		6.57	1.0	340	5	39	7	538	81	186	153	0.26	<0.2
Fowlmere Spr.				GW		7.11	7.0	130	4	12	5	259	32	51	59	<0.1	<0.2

Sq/No L.=squeezed no leachate produced

Sample Code	TOC	TIC	NH4	Al	Si	SiO2	Mn	Total Fe	Reduced Fe, mg/l	Ni	Cu	Zn	Cr	Mo	Cd	Pb	B
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
TP 5/2	124	19.9	22.7	0.57	1.33	2.85	2.6	<0.1		<1	<0.05	<0.05	<0.1		<0.05	<1	1.2
TP 5/8	651	39.9	364	<0.5	2.44	5.22	4.22	2.01		<1	<0.05	<0.05	<0.1		<0.05	<1	3.8
TP 5/10	233	74.3	442	<0.5	2.2	4.71	2.86	0.17		<1	<0.05	<0.05	<0.1		<0.05	<1	4.1
TP 5/12	297	56.4	431	<0.5	2.47	5.28	2.56	1.68		<1	<0.05	<0.05	<0.1		<0.05	<1	3.0
TP5/15																	
TP5	148	474	311		11.9		0.252	17.3	19.9	<0.02	<0.1	<0.1	<0.1	<0.1	<0.005	<0.1	
TP 6/4	1810	83.9	17.8	1.136	1.81	3.87	4.65	<0.1		<1	<0.05	<0.05	<0.1		<0.05	<1	1.9
TP 6/8	204	25.3	4.74	0.746	2.2	4.71	6.05	<0.1		<1	<0.1	0.335	<0.1		<0.05	<1	4.9
TP 6/12	359	42.2	270	<0.5	1.04	2.22	1.35	<0.1		<1	<0.05	<0.1	<0.1		<0.05	<1	3.6
TP 6/16	537	53.6	1695	<0.5	3.72	7.96	7.48	0.49		1.00	<0.05	6.367	<0.1		<0.05	<1	10.9
TP 6/20																	
TP7/4	1030	76.4	432	3.106	4.57	9.78	14.2	5.7		<1	0.158	3.69	<0.1		<0.05	<1	13.6
TP 7/6	597	66.4	1110	1.735	2.73	5.84	7.63	<0.1		<1	0.131	1.639	<0.1		<0.05	<1	11.3
TP 7/8	272	44.3	766	<0.5	1.07	2.29	2.58	<0.1		<1	<0.05	<0.1	<0.1		<0.05	<1	6.9
TP7	113.2	492.8	454		9.53		0.175	0.47	0.81	<0.1	0.025	-0.005	<0.02	<0.02	<0.005	<0.1	
TBH5A	39.9	174	7.92		8.06		0.79	0.04	0.04	0.05	0.04	0.204	<0.01		<0.005	<0.1	
TBH5B	29.7	151	4.83		7.72		0.06	0.04	0.01	0.03	0.014	0.09	<0.01	<0.02	<0.005	<0.1	
TBH6	12.2	127	0.05		5.29		0.02	0.01	<0.01	0.02	0.008	0.106	<0.01	<0.02	<0.005	<0.1	
TBH2	66	292	130		6.72		0.22	0.04		0.06	0.128	0.191	<0.01	<0.02	<0.005	<0.1	
TBH3	66	222	36		8.67		0.175	0.08	0.08	0.06	0.035	0.114	<0.01	<0.02	<0.005	<0.1	
TBH4	4.57	54.3	<0.05		5.16		0.002	<0.1	<0.01	<0.02	<0.005	0.023	<0.01	<0.02	<0.005	<0.1	
TBH1	<5	104	0.12		4.96		0.06	0.03	0.07	<0.02	0.014	0.124	<0.01	<0.02	<0.005	<0.1	
Fowlmere Spr.	6.78	51	<0.05		6.71		<0.001	<0.01		<0.02	<0.005	0.054	<0.01	<0.02	<0.005	<0.1	

Sample Code	acetic	propionic	isobutyric	butyric	isovaleric	valeric	caproic	ethanoic	TOTAL VFAs	AOX	Tritium	VOX	PAH
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	g/l Cl	TU*	mg/l	mg/l
TP 5/2	<20	<20	<20	<20	<20	<20	<20	<20	<20				
TP 5/8	22	<20	<20	<20	<20	<20	<20	<20	22				
TP 5/10	39	23	<20	<20	<20	<20	<20	<20	102				
TP 5/12	<20	<20	<20	<20	<20	<20	<20	<20	<20				
TP5/15													
TP5	<20	<20	<20	<20	<20	<20	<20	<20	<20	287	<1800	<1	<5
TP 6/4	51	<20	<20	<20	<20	<20	<20	<20	51				
TP 6/8	<20	<20	<20	<20	<20	<20	<20	<20	<20				
TP 6/12	<20	<20	<20	<20	<20	<20	<20	<20	<20				
TP 6/16	<20	<20	<20	<20	<20	<20	<20	<20	<20				
TP 6/20													
TP7/4	132	<20	<20	<20	<20	<20	<20	<20	<20				
TP 7/6	<20	<20	<20	<20	<20	<20	<20	<20	<20				
TP 7/8	22	<20	<20	<20	<20	<20	<20	<20	<20				
TP7	<20	<20	<20	<20	<20	<20	<20	<20	<20	285	72	<1	<5
TBH5A													
TBH5B													
TBH6													
TBH2													
TBH3													
TBH4													
TBH1													
Fowlmere Spr.													

*1TU = 1 Tritium Unit = 0.118 Bq/Kg water

Table 12.5 Porewater and groundwater composition Phase II: Capped landfill.

Borehole/	Moisture	Treatment	mid-point	Type	Density	pH	DO2	Ca	Mg	Na	K	HCO3	Alk	Cl	SO4	NO3	Br	NO2
Sample	%		mbgl		kg/m^3		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
TP 2/5	37.08	Squeezed	1.75	refuse	648			14,620	847	1,540	1,970			2,232	1,465	18.9	6.13	<10
TP2/7	28.14	Squeezed	2.75	refuse	648			2,460	441	1,250	676			4,236	2,133	<10	25.80	<2
TP2/9	28.14	Sq/No L	3.80															
TP2/11	14.33	Sq/No L	4.75															
TP2/14	14.93	Sq/No L	6.30															
TP2/19		Centrifuged	11.00	clay/chalk		7.77		1,180	72	251	158	4,010		271	<5	<5	1.67	3.22
TP2/20		Centrifuged	12.00	clay/chalk		8.09		106	2.2	41	5.8	126		109	74	<0.5	0.58	0.17
TP2/21		Centrifuged	13.00	clay/chalk	1,934	8.12		108	3.5	53	10.0	153		139	65	0.7	0.47	0.27
TP2/22		Centrifuged	14.00	clay/chalk		7.96		117	2.7	13	4.0	163		23	91	9.4	<0.15	0.56
TP2/23		Centrifuged	14.70	clay/chalk		8.22		120	2.8	17	6.3	184		27	107	12.5	<0.15	0.71
TP2/24		Centrifuged	15.45	clay/chalk		8.10		70	1.4	8	2.2	187		41	124	25.3	0.25	0.66
TP2				leachate		7.49	3.50	411	3.4	22	1.7	913		42	104	24	<0.60	1.50
B15	(20/6/95&13/9/95)					6.80		411	4.3	158	1.3	36	150	670	200			
B30	(20/6/95&13/9/95)					7.00		185	1.3	40	0.7	250	19	143	50			
TP3/3	23.27	Squeezed	1.80	refuse				741	146	1,040	1.7			1,817	2,049	<5	7.14	<1
TP3/7	14.91	Sq/No L	3.75															
TP3/11	35.82	Squeezed	5.50	refuse				953	323	1,750	1,130			2,845	5,609	<5	61	<1
TP 3/15	37.29	Squeezed	9.50	refuse	987			568	272	1,990	925			3,045	2,278	<5		2.04
TP3				leachate		8.31		137	253	1,745	985	8,869		2,390	61	<10	116	<2
TBH4						7.65		1,900	627	1,630	1,270	15,324	304	1,610	<50	<50	<15.00	11.50

Sq/No L = squeezed but no leachate

Borehole/	TOC	TIC	NH4	Al	Si	SiO2	Mn	Fe Total	Reduced	Ni	Cu	Zn	Cr	Mo	Cd	Pb	B
Sample	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	Fe, mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
TP 2/5	39,220	534	2,325	18.9	13.3	28.4	50.1	339.0		4.39	0.27	12.98	1.01		<0.05	<1	8.20
TP2/7	4,220	8.6	84	1.69	15.20	32.60	5.90	46.90		1.28	<0.05	<0.05	<0.10		<0.05	<1	3.88
TP2/9																	
TP2/11																	
TP2/14																	
TP2/19	2,340	20.2	116		1.81		2.40	<0.01		0.23	0.056	<0.01	<0.01		<0.005	<0.1	2.09
TP2/20	13.9	23.6	0.59		2.40		2.40	<0.01		<0.1	0.012	<0.01	<0.01		<0.005	<0.1	
TP2/21	13.7	27.6	0.20		2.65		0.07	<0.02		<0.2	<0.010	<0.01	<0.02		<0.01	<0.2	0.21
TP2/22	7.2	34.9	0.10		7.25		0.04	<0.02		<0.40	<0.020	<0.02	<0.04		<0.02	<0.4	<0.1
TP2/23	7.2	32.8	<0.05		6.51		0.02	<0.04		<0.40	<0.020	0.04	<0.04		<0.02	<0.04	<0.05
TP2/24	6.6	35.6	<0.05		3.38		0.02	<0.04		<0.2	<0.010	<0.01	<0.02		<0.01	<0.2	<0.05
TP2	12.0	196	0.73		9.92		0.07	<0.02	<0.01	<0.02	<0.005	0.050	<0.02	<0.02	<0.005	<0.1	
B15	4.5			5.93		<0.01	0.04			<5	<2	<1		<0.1	<1		
B30	6.5		7.50	5.32		<0.01	<0.03			23	<2			<0.1	<1	<0.1	
TP3/3	1,890	73.4	48.40		5.01	10.70	1.96	25.30		<1	0.239	0.607	<0.1		<0.05	<1	3.30
TP3/7																	
TP3/11	1,500	54.6	1,500		4.11	8.79	4.24	9.30		<1	<0.05	<0.05	<0.1		<0.05	<1	3.17
TP 3/15	834	222	140	<0.50	6.56	14.00	1.35	18.50		<1.00	<0.050	<0.050	<0.10		<0.05	<1	6.34
TP3	930	1,570	1,060		12.30	26.25	3.97	3.97	5.27	<0.2	<0.050	1.620	<0.20	<0.20	<0.05	<1	
TBH4	10,720	432	2,320		21.60	11.40		228.00	137.00	<0.20	<0.050	1.591	<0.20	<0.20	0.18	<1	

Borehole/	Acetic	propionic	isobutyric	butyric	isovaleric	valeric	caproic	ethanoic	Total VFAs	AOX	Tritium	VOX	PAH
Sample	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	g/l Cl	TU*	mg/l	mg/l
TP 2/5	15,922	6,842	699	15,270	1,347	5,776	7,123	128	53,107				
TP2/7	495	65	<20	64	<20	<20	49	<20	673				
TP2/9													
TP2/11													
TP2/14													
TP2/19													
TP2/20													
TP2/21													
TP2/22													
TP2/23													
TP2/24													
TP2	68	22	<20	33	<20	<20	<20	<20	<20	123	<60	<1	<5
B15													
B30													
TP3/3	452	44	<20	84	<20	39	71	<20	690				
TP3/7													
TP3/11	263	<20	<20	<20	<20	<20	<20	<20	263				
TP 3/15	394	51	<20	55	<20	22	45	<20	567				
TP3	48	27	<20	42	<20	<20	<20	<20	117	2,790	4,450	<1	<5
TBH4										1,210	<1800		

*1TU = 1 Tritium Unit = 0.118 Bq/Kg water

Table 12.6 Correlation coefficients between landfill porewaters.

	B	Cl	Br	Al	Si	TOC	NH_4	SO_4	Cu	Zn	VFAs	Ca	Mg	Na	K	Nitrate
B	1.00															
Cl	0.23	1.00														
Br	-0.01	0.56	1.00													
Al	0.27	0.34	-0.18	1.00												
Si	0.15	0.43	0.31	0.37	1.00											
TOC	0.19	0.30	-0.05	0.96	0.43	1.00										
NH_4	0.46	0.25	0.25	0.64	0.19	0.62	1.00									
SO_4	0.74	0.25	0.01	0.00	-0.55	-0.09	0.38	1.00								
Cu	0.10	0.92	0.41	0.89	0.20	0.64	0.45	0.32	1.00							
Zn	0.26	0.29	-0.25	0.99	0.43	0.84	0.66	0.12	0.61	1.00						
VFAs	0.27	0.14	-0.21	0.99	0.44	1.00	0.76	-0.23	0.72	0.96	1.00					
Ca	0.18	0.29	-0.08	0.98	0.38	0.97	0.51	-0.05	0.64	0.87	0.98	1.00				
Mg	0.75	0.46	0.85	0.68	0.38	0.23	0.41	0.05	0.69	0.10	0.16	0.18	1.00			
Na	0.44	0.74	0.62	0.34	0.06	0.28	0.40	0.44	0.78	0.28	0.23	0.24	0.56	1.00		
K	0.60	0.57	0.36	0.71	0.15	0.60	0.69	0.48	0.58	0.68	0.69	0.56	0.53	0.82	1.00	
Nitrate	0.78	0.01	-0.08	-0.14	-0.47	-0.14	0.27	0.81	0.10	0.04	-0.18	-0.11	0.10	0.32	0.36	1.00

12.3.7 *Hydraulic conductivity of the landfill cap*

The vertical saturated hydraulic conductivity of the Phase 1 cover varied between 2.3×10^{-6} and 4×10^{-4} m/s, with a geometric mean of 4.46×10^{-5} m/s (arithmetic mean 9.12×10^{-5}). Values for Phase 2 were 6.3×10^{-4} and 1.6×10^{-5} m/s with a geometric mean of 1×10^{-4} m/s (arithmetic mean of 3.23×10^{-4}), (see Figure 12.1).

These values of hydraulic conductivity of the landfill caps are high enough to ensure that all of the effective rainfall can potentially infiltrate into the landfill.

12.4 Conclusions

- These investigations show clearly how difficult it is to characterise an old landfill with its inherent heterogeneity. The investigation provides only a single snapshot in time, but because of the different ages of the waste layers they do provide information about ageing processes in both capped and uncapped landfills.
- Leachate production and the time taken for stabilisation clearly proceed at different rates in capped and uncapped landfills.
- Analysis of leachate obtained by centrifugation or squeezing appears to give slightly more insight into the pollution potential than do leach tests with water.
- BMP values do appear to be related to the quantity of decomposable material but the COD values are distorted by the presence of reduced metals.
- Too few AOX values were obtained for an assessment of their value. However, as some concentrations were high (> 1 mg/l) it would be worthwhile attempting to identify the individual organic halogens using GCMS.

The landfill was investigated in order to gain an understanding of the “source term” of the leachate plume. This aim was only partially achieved due to the heterogeneity of the landfill and the variability in geometry of the excavations. Identifying how the composition of the leachate varies with time and with location within the site, and where it drains to groundwater would require many more boreholes. It is recommended that boreholes be drilled into the zones where the RESCAN study indicates perched levels of leachate or zones of migration. Ideally a network of boreholes drilled into the Chalk beneath the landfill are required to determine where leachates enter groundwater.

13 CHARACTERISATION OF THE CHALK AQUIFER

13.1 Drilling objectives

Based on the apparent resistivity anomaly, (discussed in Section 11.3.2), the borehole TR1 was drilled to the north-west of the landfill (Figures 11.4 and 12.1). The objectives of this borehole were to:

Table 12.7 Leach test comparisons with porewater.

TOC Leach Test mg/kg wet solid	TIC Porewater mg/kg wet solid	TIC Leach Test mg/kg wet solid	NH4 Porewater mg/kg wet solid	NH4 Leach Test mg/kg wet solid	Si Porewater mg/kg wet solid	Si Leach Test mg/kg wet solid	Mn Porewater mg/kg wet solid	Mn Leach Test mg/kg wet solid	Fe Total Porew. mg/kg wet solid	Fe Total Leach Test mg/kg wet solid	Al Porewater mg/kg wet solid	Al Leach Test mg/kg wet solid	Ni Porewater mg/kg wet solid
10,208	198	1,110	862	1,606	4.9	29.1	18.58	26.65	125.70	87.18	7.01	3.42	1.63
763	2	764	24	1,462	4.3	35.5	1.66	5.81	13.20	4.10	0.48	0.84	0.36
227		227		837		20.0		0.28		<0.1		1.06	
438		438		2,129		19.7		3.65		<0.1		0.44	
77		250		<500		26.1		0.55		0.67		0.76	
695	17	695	11	142	1.2	16.1	0.46	7.83	5.89	7.83	<0.1	1.17	<0.2
218		218		134		10.5		1.05		1.06		0.52	
403	20	404	537	401	1.5	14.8	1.52	6.49	3.33	6.49	<0.1	2.08	<0.2
769	83	770	52	120	2.4	28.2	0.50	5.21	6.90	5.22	<0.1	0.96	<0.2
91	4	235	4	995	0.3	12.2	0.51	2.44		0.15	0.11	0.52	<0.2
196	12	365	111	<100	0.7	11.5	1.28	5.84	0.61	0.69	<0.1	0.73	<0.3
137	26	208	152	3	0.8	11.4	0.99	6.50	0.06	<0.1	<0.1	0.84	<0.3
152	29	340	221	119	1.3	10.4	1.32	7.71	0.86	0.17	<0.1	0.62	<0.5
64		149		964		3.0		0.09		<0.1		2.68	
149	18	242	4	146	0.4	12.8	0.99	2.92		0.33	0.24	0.68	<0.2
149	7	286	1	427	0.6	11.1	1.78	4.72		0.14	0.22	0.90	<0.3
65	9	284	55	<200	0.2	8.1	0.27	0.74		<0.1	<0.1	0.51	<0.3
227	13	314	407	2,834	0.9	19.7	1.80	23.11	0.12	0.68	<0.1	4.17	0.20
82		276		330		18.4		7.65		<0.1		0.78	
457	25	274	139	273	1.5	9.9		8.74	1.83	3.15	1.00		<0.3
203	25	324	418	585	1.0	7.7	2.87	9.41		0.21	0.66		<0.4
120	13	203	232	2	0.3	4.5	0.78	2.31		<0.1	<0.1		<0.3

Ni Leach Test mg/kg wet solid	Cu Porewater mg/kg wet solid	Cu Leach Test mg/kg wet solid	Zn Porewater mg/kg wet solid	Zn Leach Test mg/kg wet solid	Cr Porewater mg/kg wet solid	Cr Leach Test mg/kg solid	Cd Porewater mg/l	Cd Leach Test mg/kg wet solid	Pb Porewater mg/l	Pb Leach Test mg/kg wet	B Porewater mg/kg	B Leach Test mg/kg wet	TOTAL Porewater Fatty acids mg/l
1.29	0.10	0.30	4.81	0.45	0.37	<0.01	<0.05	<0.05	<1		3.04	5.37	53107
<1	<0.01	<0.05	<0.01	0.14	<0.03	<0.1	<0.05	<0.05	<1	<0.1	1.09	3.27	673
<1		<0.05		0.28		<0.1		<0.05	<1			2.02	
<1		0.38		0.30		<0.1		<0.05	<1			2.10	
<1		0.08		<0.05		<0.1		<0.05	<1	<0.1		1.15	
<1	0.06	0.09	0.14	1.80	<0.023	<0.1	<0.05	<0.05	<1	<0.1	0.77	2.52	690
<1		<0.05		<0.05		<0.1		<0.05	<1	<0.1		0.81	
<1	<0.02	0.13	<0.02	0.75	<0.036	<0.1	<0.05	<0.05	<1		1.14	2.94	263
<1	<0.02	<0.05	<0.02	0.16	<0.037	<0.1	<0.05	<0.05	<1	<0.1	2.37	5.42	567
<1	<0.02	<0.05	<0.01	0.32	<0.02	<0.1	<0.05	<0.05	<1		0.24	1.22	<20
<1	<0.02	0.12	<0.02	1.14	<0.03	<0.1	<0.05	<0.05	<1		1.17	4.12	22
0.45	<0.02	<0.05	<0.02	0.56	>0.03	<0.1	<0.05	<0.05	<1		1.42	4.16	102
1.69	<0.02	<0.05	<0.03	<0.05	<0.05	<0.1	<0.05	<0.05	<1		1.57	4.92	<20
<1		<0.05		<0.05		0.1	<0.05	<0.05	<1	<0.1		0.77	
<1	<0.01	<0.05	<0.01	0.29	<0.02	<0.01	<0.05	<0.05	<1	<0.1	0.41	2.01	51
<1	<0.01	0.11	0.10	0.52	<0.02	<0.1	<0.05	<0.05	<1	<0.1	1.45	4.39	<20
<1	<0.01	0.07	<0.02	0.38	<0.02	<0.1	<0.05	<0.05	<1		0.73	3.60	<20
1.69	<0.01	0.12	1.53	13.25	<0.02	<0.1	<0.05	<0.05	<1	<0.1	2.61	7.60	<20
<1		0.10		1.48								5.68	
0.42	<0.05	0.62	1.18	6.43	<0.02	<0.01	<0.05	<0.05	<1		4.37	10.29	<20
0.37	<0.05	0.16	0.62	1.70	<0.04	<0.1	<0.05	<0.05	<1		4.27	9.02	<20
<0.1	<0.02	0.09	<0.03	0.37	<0.03	<0.1	<0.05	<0.05	<1		2.08	5.91	<20

- Confirm that the resistivity anomaly correlated with a contaminant plume in the aquifer.
- Provide core material for accurate lithological description of the strata down to the underlying Gault Clay
- Provide core material for chemical analysis of the porewater
- Provide core material for laboratory measurement of hydraulic properties.
- Allow a profile of hydraulic head and hydraulic conductivity to be determined in order to define groundwater flow zones and help refine the contaminant transport model.
- Investigate groundwater chemistry in packered sections of the borehole
- Allow a suite of reference geophysical logs to be run to help correlate the succession in existing and future boreholes.

13.2 Drilling technique

The borehole was percussion drilled through the superficial deposits into the Chalk bedrock. Casing was run in to seal off the superficial deposits and the hole cored using a rotary technique with water flush provided from borehole TBH 4. The borehole was cored using a double tube core barrel, with a clear plastic core liner, which produced a core diameter of 90 mm and a nominal hole diameter of 120 mm. Previous experience of rotary core drilling in fractured Chalk suggested that core-barrel lengths in excess of 1.5 m were prone to blocking. Two barrel lengths were therefore made used: a 1.5 m barrel for fractured horizons, and a 3 m barrel for more competent, less-fractured zones. The core samples were capped and sealed with tape, prior to preservation in nitrogen-flushed pvc sample tubing. The core was kept at 4°C in a mobile refrigerator van prior to transport back to the laboratory.

At the end of each core run, an inflatable packer was run in to isolate the bottom core interval of the borehole. Water was pumped out of the packered interval using a submersible pump and a groundwater sample taken, if possible after removing at least 3 borehole volumes. Measurements of hydraulic head and transmissivity were also made in these packered intervals. This involved measuring the head, and undertaking a constant head abstraction test or, in the less transmissive test zones, a slug test.

13.3 Lithology and physical properties of the Chalk

The core material was logged lithologically and sub-samples taken for porosity-permeability determinations and for porewater chemistry. A full pictorial description of the core is given in Appendix C. Porosity and permeability are given in Tables 13.1 to 13.3.

Table 13.1 Summary of porosity and permeability tests carried out on Core from TRI.

H = horizontal
V = vertical
Y = done
N = not done
N/A = not applicable.

Sample Number	Sample Depth (m)	Sample Type	Sample Orientation	Porosity Test	Gas Permeability Test
TH1	7.4	Block	N/A	Y	N
TH2	7.7	Plug	H	Y	N
TH3	7.7	Block	N/A	Y	N
TH4	11.7	Plug	V	Y	Y
TH5	12.15	Plug	H	Y	Y
TH6	12.15	Plug	V	Y	Y
TH7	13.2	Block	N/A	Y	N
TH8	13.63	Plug	V	Y	Y
TH9	15	Block	N/A	Y	N
TH10	15.7	Plug	H	Y	Y
TH11	17.62	Plug	H	Y	Y
TH12	18.03	Plug	H	Y	Y
TH13	18.03	Plug	V	Y	Y
TH14	18.5	Block	N/A	Y	N
TH15	19.05	Block	N/A	Y	N
TH16	21.14	Block	N/A	Y	N
TH17	21.15	Plug	H	Y	Y
TH18	21.5	Plug	H	Y	Y
TH19	21.5	Plug	V	Y	Y
TH20	27.1	Plug	H	Y	N
TH21	27.3	Plug	V	Y	Y
TH22	27.5	Plug	V	Y	Y
TH23	33.2	Block	N/A	Y	N
TH24	33.83	Block	N/A	Y	N
TH25	40.5	Plug	H	Y	Y
TH26	40.57	Plug	V	Y	Y
TH27	40.62	Plug	H	Y	Y
TH28	40.7	Plug	V	Y	Y
TH29	40.92	Plug	H	Y	Y
TH30	48.23	Block	N/A	Y	N
TH31	48.38	Plug	H	Y	Y
TH32	50.3	Plug	V	Y	Y
TH33	52.77	Plug	V	Y	Y
TH34	53	Plug	V	Y	Y

Table 13.2 Hydraulic conductivity measurements on core from borehole TR1.

Sample number	Length (mm)	Diameter (mm)	Pressure (mB)	Flow rate (ml/min)	Atmos. pressure (mB)	Gas viscos. (cP)	Uncorr. perm. (mD)	Liq. eqiv. perm. (mD)	Hydraulic conductivity (m/d)
TH4	23.34	24.25	800	38.17	1000.2	0.0174	5.061	3.622	2.33E-03
TH5	22.26	24.09	800	30.85	1000.6	0.0174	3.954	2.788	1.79E-03
TH6	31.95	24.14	200	4.259	1000.1	0.0174	3.971	2.801	1.80E-03
TH8	31.52	24.34	200	3.54	1000.1	0.0174	3.203	2.23	1.43E-03
TH10	31.59	24	200	1.227	1000.1	0.0174	1.144	0.749	4.82E-04
TH11	31.3	23.77	400	1.379	1000.1	0.0174	0.595	0.375	2.41E-04
TH12	24.26	24.55	600	1.955	1000.6	0.0174	0.378	0.231	1.49E-04
TH13	26.14	23.95	600	1.525	1000.2	0.0174	0.333	0.203	1.30E-04
TH17	19.6	24.04	200	4.687	1000.2	0.0174	2.703	1.863	1.20E-03
TH18	25.95	24.05	200	3.998	1000.2	0.0174	3.05	2.118	1.36E-03
TH19	25.63	24.2	200	3.212	1000.2	0.0174	2.391	1.636	1.05E-03
TH21	32.03	23.95	200	3.26	1000.1	0.0174	3.096	2.151	1.38E-03
TH22	32.24	23.8	200	3.013	1000.2	0.0174	2.916	2.019	1.30E-03
TH25	26.66	24.12	200	1.675	1000.2	0.0174	1.305	0.861	5.54E-04
TH26	31.86	24.38	400	2.53	1000.1	0.0174	1.057	0.689	4.43E-04
TH27	29.9	24.25	400	3.442	1000.1	0.0174	1.364	0.902	5.80E-04
TH28	31.72	24.28	400	2.28	1000.1	0.0174	0.956	0.619	3.98E-04
TH29	30.45	24.27	400	1.528	1000.1	0.0174	0.616	0.388	2.50E-04
TH31	25.23	24.44	200	1.156	1000.2	0.0174	0.83	0.533	3.43E-04
TH32	31.85	24.25	400	1.212	1000.1	0.0174	0.512	0.319	2.05E-04
TH33	31.6	24.12	400	1.546	1000.1	0.0174	0.655	0.414	2.66E-04
TH34	31.48	24.14	400	0.883	1000.1	0.0174	0.372	0.228	1.46E-04

13.4 Hydraulic head and conductivity profile

The value of hydraulic head is reported as total hydraulic head [h] (relative to ordnance datum) and is equal to the sum of the elevation head [z] and the pressure head [h_p], (Fetter, 1994). The testing methodology provides a quasi-equilibrium value which is an estimate of the *in situ* hydraulic head, and one which may be influenced by longer term transients resulting from drilling induced recharge. The hydraulic head is also expressed as a differential head, relative to the open borehole, providing an indication of potential inflow and outflow zones in the open borehole system.

The hydraulic head depth profile (Figure 13.1) is characterised by the following:

- the shallowest head value is anomalous and probably represents drilling induced recharge in the unsaturated zone;
- there is an upward hydraulic gradient between c.22 m and 15 m depth, where the Plenus Marls appears to be confining water in the Lower Chalk;
- below 22 m depth, the head profile shows a slight decline in head with depth from c.21.9 m at 28 m depth to c. 1.7 m at 59 m depth. The low head zone (c.21.3 m) at 48.5 m depth is associated with a high transmissivity horizon, whilst the lowest head (c.21.2 m) occurs in the Gault at 61.5 m depth.

The differential head profile illustrates the potential for significant vertical flow in the open borehole. This indicates that there will not be any downward migration of landfill leachate through the Plenus Marls. It also indicates that any open borehole drilled through the Plenus Marls, close to the landfill site will generate an upward flow of groundwater which will dilute (or displace) any shallow pollution plume. This has implications for the existing boreholes around the Phase 1 landfill drilled through the Plenus Marls. With the exception of TBH 6 (depth 16.12 m bgl) the remaining TBH boreholes (1, 2, 3, 4, 5 and 7) are drilled through the Plenus Marls. All of these are potentially capable of allowing water to recharge upwards. These boreholes should therefore be sealed at the base of the Melbourn rock, but since they have been in existence for almost 20 years, their effect on the plume is probably well manifest and sealing them now could result in a significant change in plume distribution. These aspects could best be considered initially by modelling.

Transmissivity was determined using analytical solutions for single well tests in the software package AQTESOLV (Duffield, 1994). Storativity is not reported since it cannot be determined reliably using curve fitting routines on single-well test data.

Table 13.3 Porosity measurements on core from borehole TR1.

Sample number	Dry weight (g)	Sat^d.wt. (fluid) (g)	Sat^d.wt. (air) (g)	Fluid density (g/cm^3)	Dry Bulk density (g/cm^3)	Sat^d Bulk density (g/cm^3)	Grain density (g/cm^3)	Porosity (%)
TH1	48.579	34.361	57.564	0.79	1.654	2.041	2.699	38.7
TH2	16.163	11.438	19.123	0.79	1.662	2.047	2.702	38.5
TH3	38.093	26.853	45.246	0.79	1.636	2.025	2.677	38.9
TH4	17.283	12.242	20.526	0.79	1.648	2.04	2.709	39.1
TH5	17.412	12.338	20.239	0.79	1.741	2.099	2.711	35.8
TH6	24.292	17.26	28.707	0.79	1.676	2.062	2.729	38.6
TH7	53.251	37.654	61.937	0.79	1.732	2.09	2.697	35.8
TH8	25.151	17.825	29.292	0.79	1.733	2.094	2.712	36.1
TH9	44.43	31.442	48.346	0.79	2.076	2.308	2.702	23.2
TH10	27.698	19.631	30.755	0.79	1.967	2.242	2.712	27.5
TH11	28.252	20.027	31.013	0.79	2.032	2.283	2.714	25.1
TH12	22.602	16.017	24.907	0.79	2.009	2.268	2.712	25.9
TH13	23.846	16.894	26.26	0.79	2.011	2.269	2.71	25.8
TH14	31.731	22.454	35.401	0.79	1.936	2.22	2.702	28.3
TH15	60.778	43.032	67.183	0.79	1.988	2.253	2.706	26.5
TH16	44.63	31.591	53.647	0.79	1.599	2.007	2.704	40.9
TH17	15.328	10.859	17.847	0.79	1.733	2.093	2.71	36
TH18	19.815	14.038	23.217	0.79	1.705	2.076	2.71	37.1
TH19	19.775	14.007	23.261	0.79	1.688	2.065	2.708	37.7
TH20	14.169	10.029	17.424	0.79	1.514	1.954	2.704	44
TH21	22.327	15.817	27.301	0.79	1.536	1.969	2.709	43.3
TH22	22.522	15.955	27.332	0.79	1.564	1.987	2.709	42.3
TH23	50.705	35.916	60.539	0.79	1.627	2.026	2.709	39.9
TH24	25.542	18.105	31.47	0.79	1.51	1.953	2.713	44.4
TH25	21.668	15.327	24.974	0.79	1.774	2.117	2.7	34.3
TH26	26.426	18.69	30.228	0.79	1.809	2.139	2.699	33
TH27	24.551	17.362	27.975	0.79	1.828	2.15	2.698	32.3
TH28	26.776	18.936	30.509	0.79	1.828	2.15	2.698	32.3
TH29	25.496	18.01	29.037	0.79	1.827	2.148	2.691	32.1
TH30	27.172	19.239	31.127	0.79	1.806	2.138	2.706	33.3
TH31	21.032	14.892	23.908	0.79	1.843	2.162	2.706	31.9
TH32	25.673	18.168	29.722	0.79	1.755	2.106	2.702	35
TH33	25.587	18.113	29.334	0.79	1.801	2.135	2.705	33.4
TH34	25.9	18.331	29.604	0.79	1.815	2.144	2.703	32.9

The value of transmissivity ranges from 1×10^{-6} m^2/sec to in excess of 1×10^{-3} m^2/sec which, in a 3 m test interval, is equivalent to hydraulic conductivities of 3.33×10^{-7} m/sec and 3.33×10^{-4} m/sec respectively. However, for most of the profile the transmissivity exceeds 1×10^{-4} m^2/sec. These values fall within the range given by Price et al. (1993) who report hydraulic conductivity for fissured Chalk of 1×10^{-5} to 1×10^{-3} m/sec, and for the Chalk matrix 1×10^{-9} to 1×10^{-8} m/sec. A slug test conducted in TBH 3 which is drilled to 47 m bgl, yielded a transmissivity value of 1.45×10^{-3} m^2/sec for most of the Chalk present beneath the site.

13.5 Borehole geophysics

Two suites of down hole geophysical logs were run with the aim of characterising the lithological and hydrogeological properties of the Chalk. The electrical and formation logs (resistivity, gamma, porosity and calliper) provide continuous depth scale measurements which may be correlated with a detailed lithological and fracture log of the core (Figure 13.2). Fluid flow logging was also undertaken (Figure 13.3). The electrical resistivity and neutron porosity logs were used to generate a fracture index log.

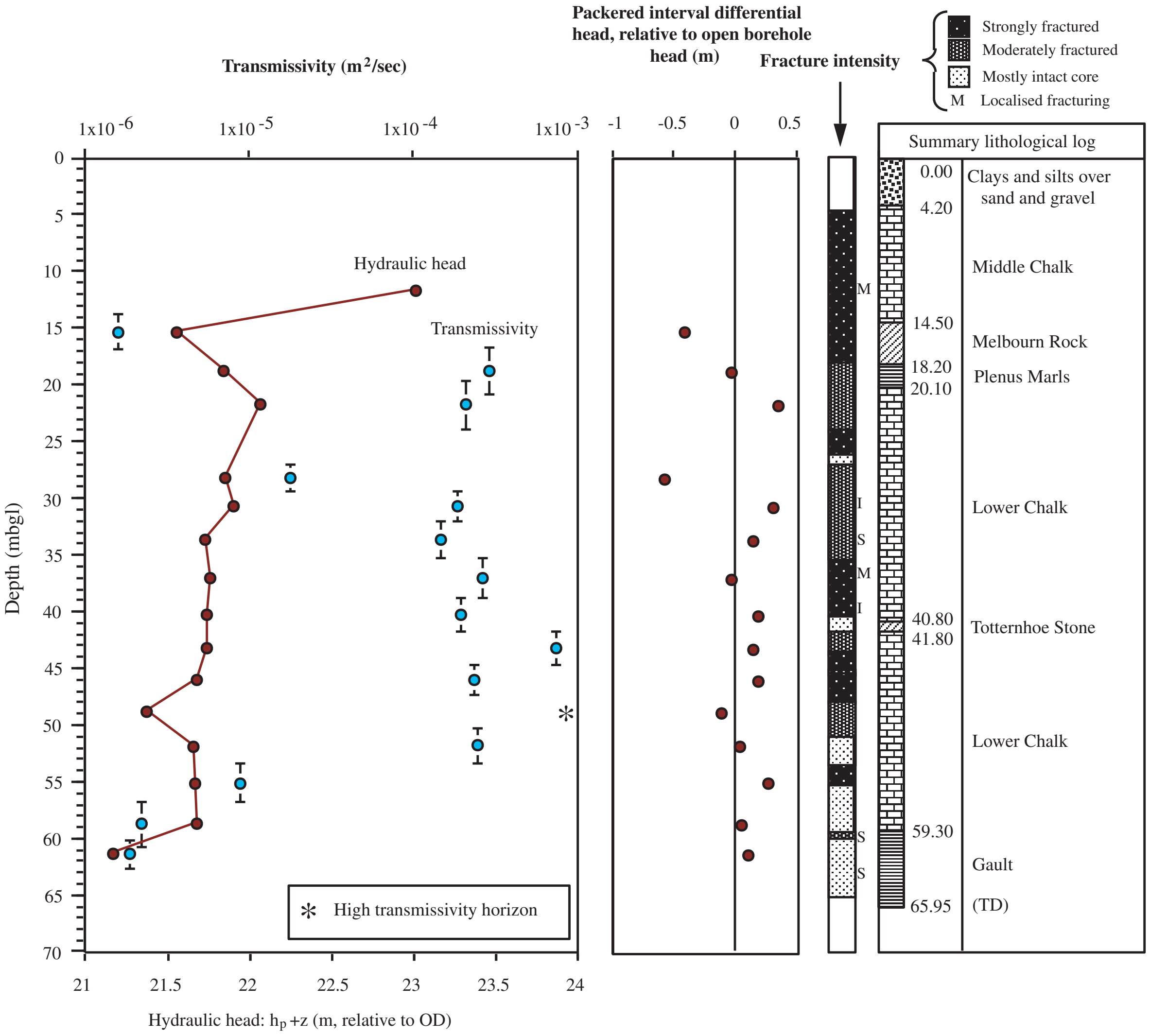


Figure 13.1 Thriplow borehole TR1: summary of hydraulic properties.

By combining the fluid logs (flow and electrical conductivity), with the fracture index log and fracture intensity log (derived from the core logging) it has been possible to interpret the fluid flow characteristics of the open borehole as shown in Table 13.4. The open borehole exhibits upward flowing groundwater. The Melbourn Rock and the Totternhoe Stone represent outflow horizons which, appear to exert considerable control on the groundwater flow.

13.6 Groundwater chemistry from borehole TR1

Analysis of groundwater from the Chalk was undertaken on two sets of samples: water removed from the packered interval during drilling and thus indicative of the fracture water chemistry; and porewater centrifuged from the Chalk matrix. Profiles are given in Appendix D which also gives as a reference, the chemistry of the water from borehole TBH 4 used as a drilling flush. The ammonium profile shows only two packer water samples and one porewater sample at levels above the analytical limit of detection. Analytical data is given in Appendix A, but provides no indication of contamination by landfill leachate.

Porewater and packer water concentrations are similar for Na, SO_4, NO_3, NO_2, Al, Cl and Br. Porewater concentrations exceed packer water for TOC where there is a constant discrepancy of at least 100%, and for boron. The boron profile shows two major peaks at 15 m bgl and at 40 m bgl. Boron in uncontaminated Chalk groundwater is normally associated with chloride as an indication of connate water. If the boron was derived from the landfill then its concentration in the packered water would perhaps be expected to exceed porewater concentrations. SiO_2 and K are also higher in porewater as opposed to packer water and may reflect the mineralogy and connate water chemistry. Ca, Mg and alkalinity are much higher in packer water than in the porewater. This is reflected on the trilinear plot (Figure 13.4) which displays three groundwater types:

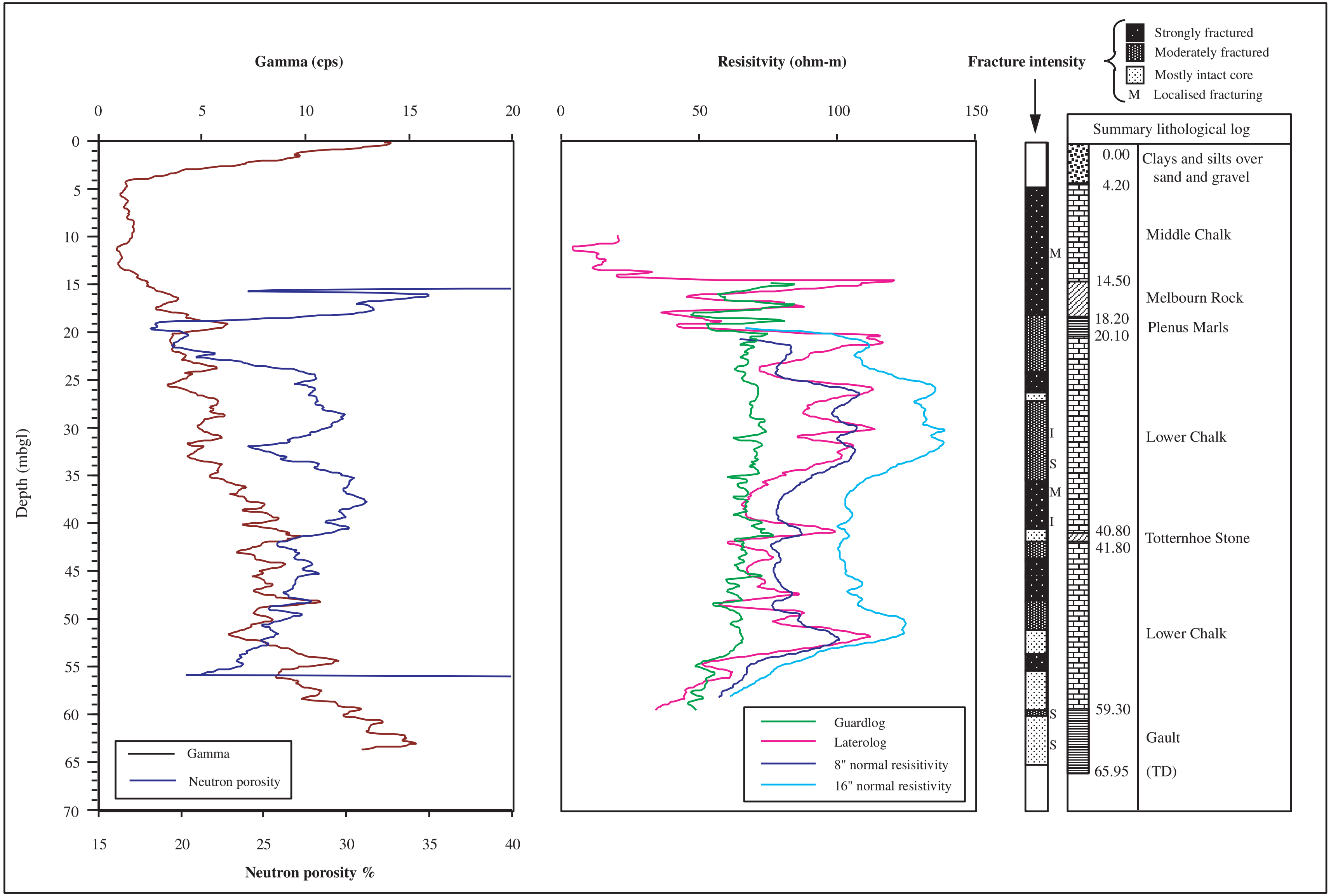


Figure 13.2 Thriplow borehole TR1: lithology, natural gamma and resistivity logs.

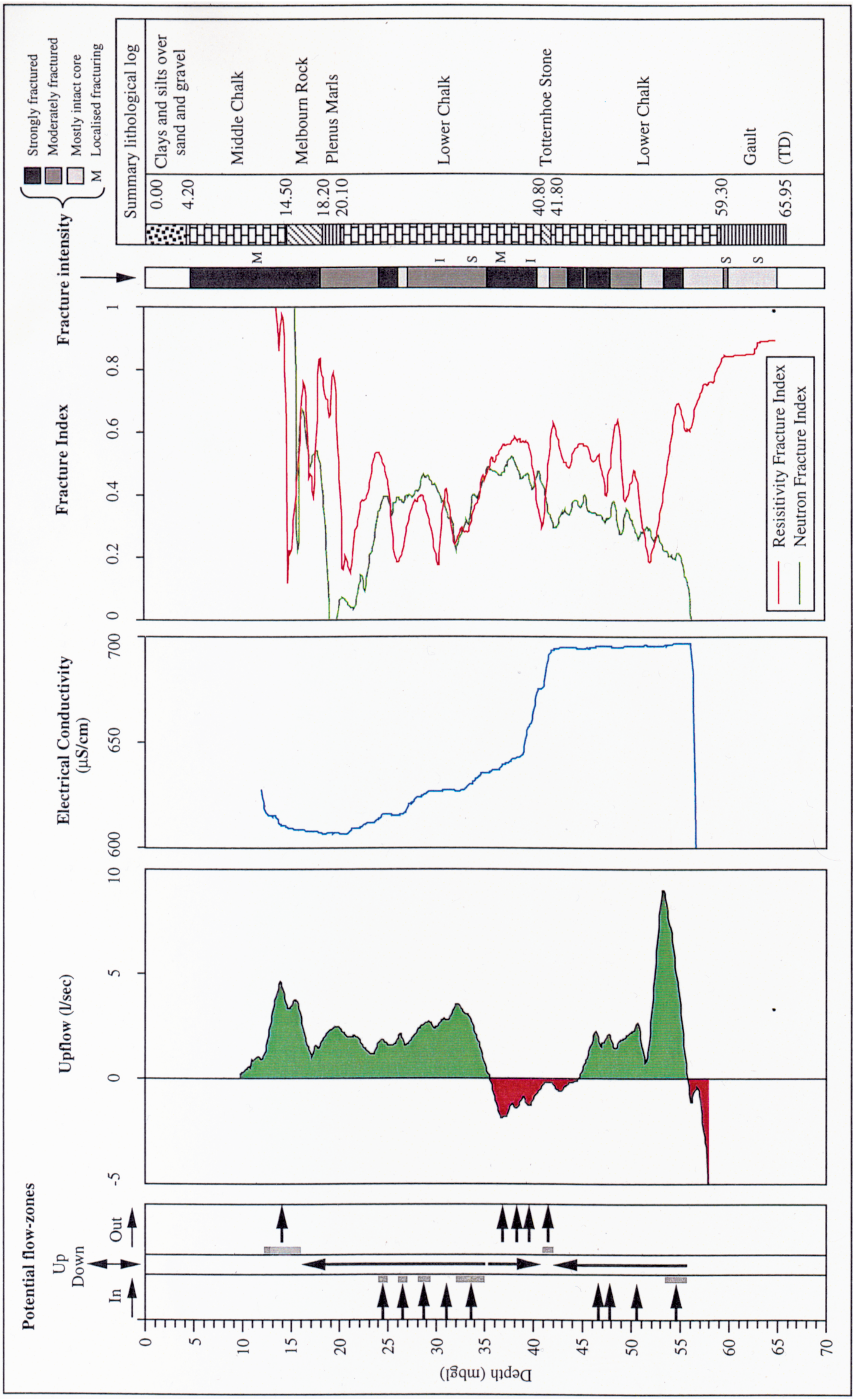


Figure 13.3 Thriplow borehole TR1: flow, fluid conductivity and fracture index log.

Table 13.4 Potential flow-zones in borehole TR1.

Top (m bgl)	Base (m bgl)	Potential flow zone characteristics
12.0	16.0	Zone IV (Outflow/Upflow) Outflow zone above the Plenus Marls.
16.0	35.0	Zone III (Inflow/Upflow) Major inflow zone at c.35 m and minor inflows above. Net upflow in open borehole.
35.0	42.0	Zone II (Outflow/Downflow) Major outflow zone associated with the Totternhoe Stone. Downflow from the flow-zone at c. 35 m.
42.0	55.0	Zone I (Inflow/Upflow) Major inflow towards base of Lower Chalk, although lower boundary difficult to define. Minor inflows above. Net upflow.

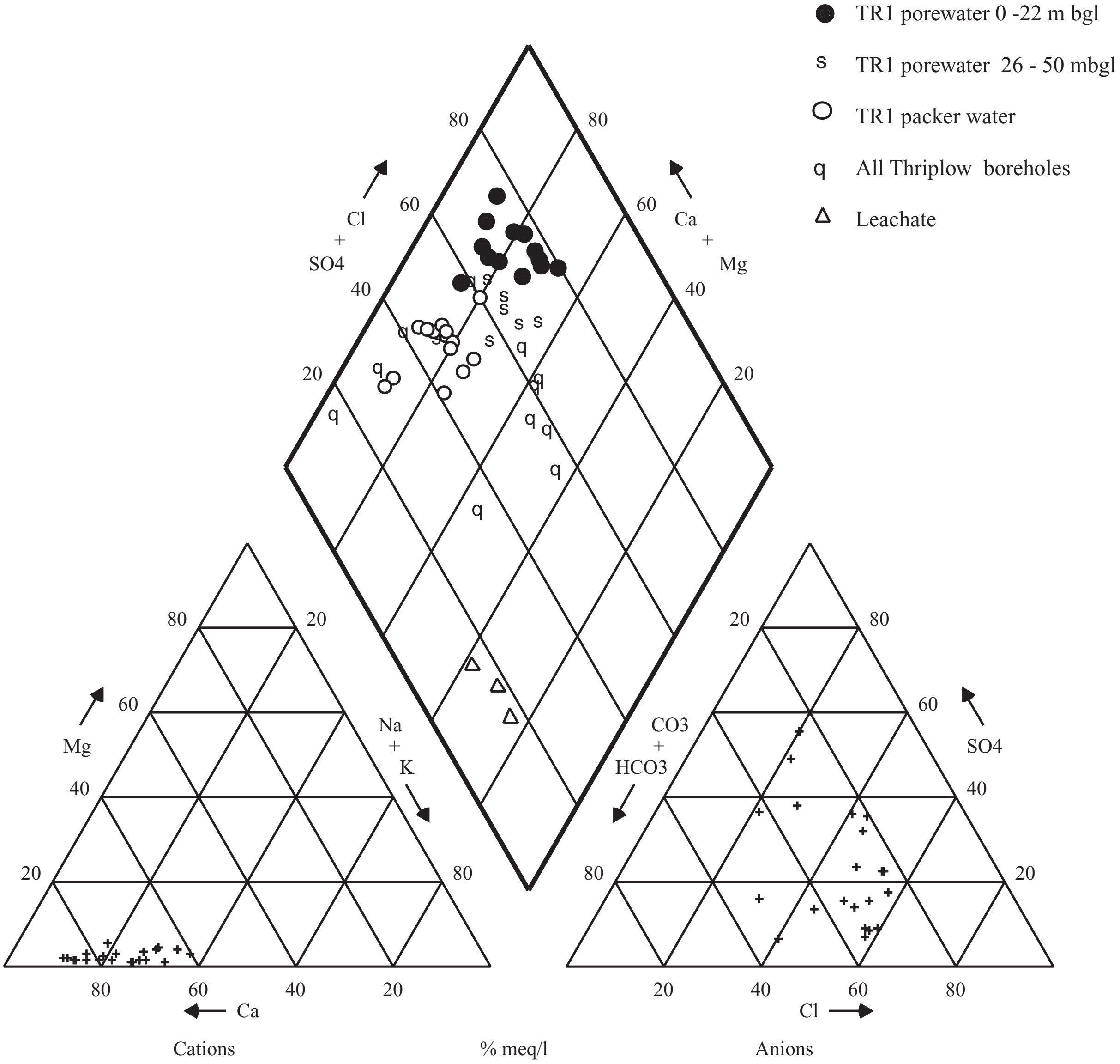


Figure 13.4 Trilinear plot of groundwater and porewater from all boreholes.

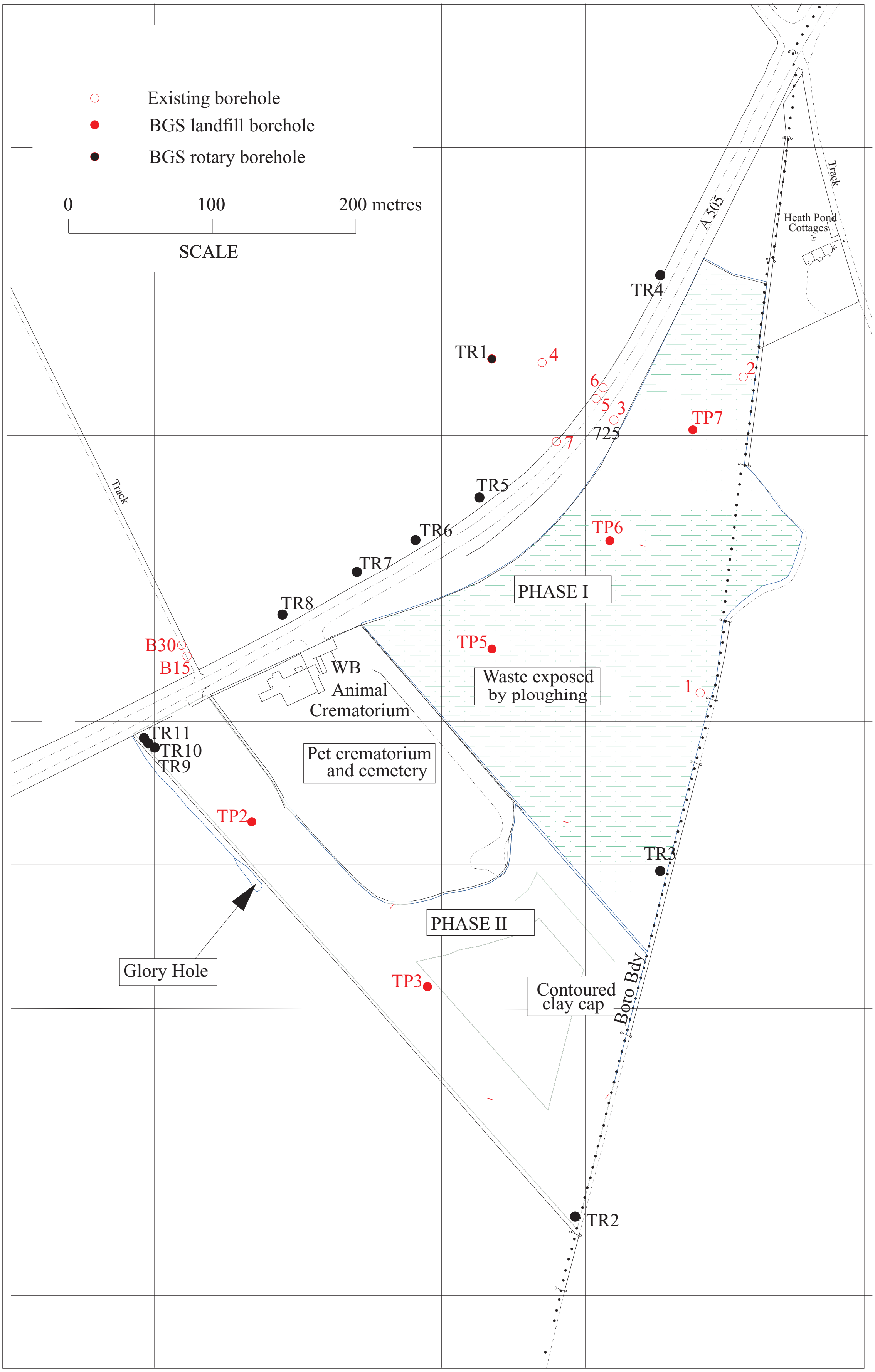


Figure 13.5 Position of boreholes TR2–TR11, drilled May–June 1997.

Table 13.5 Summary of in-situ hydraulic measurements undertaken in May/June 1997.

Test reference	Test interval m bgl	Solution –Drawdown data	Solution –Recovery data	Transmissivity m^2/s	Storativity	Hydraulic conductivity m/s
TR3_1	14.33 – 15.83	Theis unconfined (m)		1.78E-05	0.671	1.184E-05
		Theis unconfined (a)		1.78E-05	0.1	1.184E-05
		Cooper-Jacob unconfined (m)		2.46E-05	0.464	1.642E-05
		Cooper-Jacob unconfined (a)		2.46E-05	0.1	1.642E-05
			Theis confined (m)	1.99E-05		1.326E-05
			Theis confined (a)	3.18E-05		2.120E-05
TR3_2	15.83 – 18.22	Cooper-Jacob unconfined (m)		2.57E-05	0.0152	1.077 E-05
		Cooper-Jacob unconfined (a)		9.47E-05	0.0008	3.963 E-05
			Theis confined (m)	1.52E-04	0.158	6.339 E-05
			Theis confined (a)	5.72E-04	0.011	2.392 E-04
TR5_1	11.22 – 14.44		Cooper-Papadopolous	9.34E-06	0.00001	2.900 E-06
TR5_3	15.89 – 17.22	Theis unconfined		4.82E-06	0.02086	3.621 E-06
				1.87E-04	0.00001	1.406 E-04
TR5_4	17.22 – 18.46		Cooper-Papadopolous	1.95E-04	0.00001	1.575 E-04
TR7_2	15.43 – 18.00	Theis unconfined	Cooper-Papadopolous	1.09E-04	0.00042	4.257 E-05

A Leachate with a predominantly sodium bicarbonate composition.

B Porewaters from the Middle Chalk in TR1 (i.e. above 22 m bgl) with a predominantly calcium chloride/sulphate composition.

C Fowlmere spring is a calcium bicarbonate water which is similar to the composition of groundwater from the lowest horizons of the Chalk in TR1.

Mixing between these end members is suggested by water of intermediate compositions:

D Groundwater intermediate in composition between Type A and B comprising water from the existing investigation boreholes TBH 2, TBH 3, TBH 5A, TBH 5B, TBH 6 and TBH 7.

E Intermediate compositions between Type C and Type B porewaters, which are typified by groundwater from the packered interval, and borehole TBH 1.

13.7 Installation of the groundwater monitoring network

This work was based on the recommendations made in the interim report by Williams et al. (1997), and aimed to address the following:

- Pollution plume identification
- Measurement of aquifer transport parameters
- Facilities for long term monitoring.

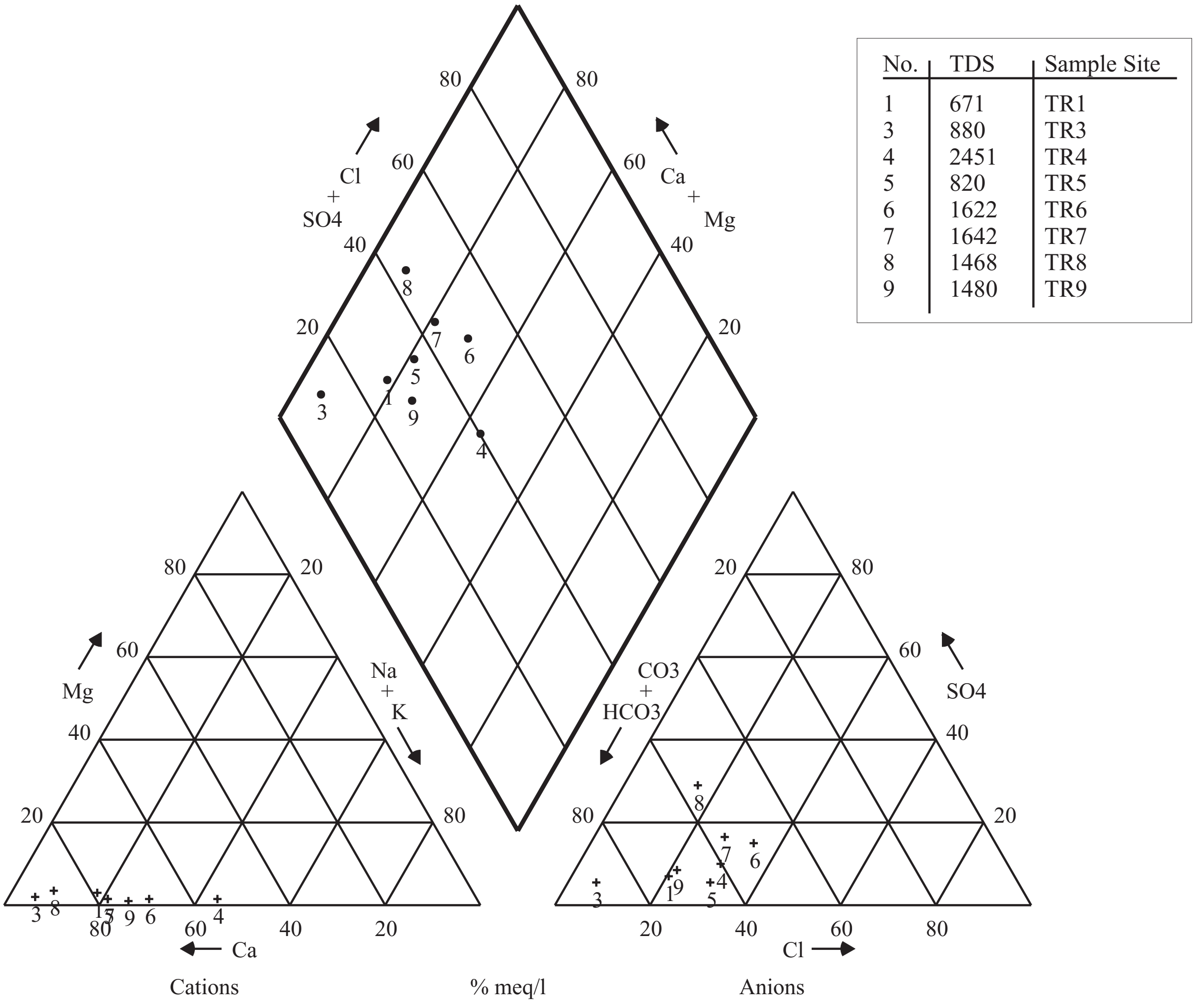
A series of boreholes, TR 2 to TR 11, were drilled in May and June 1997 in the locations shown on Figure 13.5. Some were drilled open-hole while others were cored and hydraulically tested during drilling. Details of the tests and completions are given in Table 13.5. Existing open boreholes TBH 1, TBH 2, TBH 5 and TBH 7 were also modified to ensure that they monitor groundwater in the discrete horizons above, and below, the Plenus Marls. The remaining open boreholes TR 1, TBH 3 and TBH 4 remain to be modified.

The drift thickness intercepted in boreholes TR 2 to TR 11 varies considerably. Borehole TR 8 intercepted 16.5 m of sand/gravel and silt, which may represent a buried channel in the surface of the Chalk. The Chalk aquifer also varies lithologically from a relatively pure Chalk up hydraulic gradient of the site (in borehole TR 3), to a "putty" Chalk with low hydraulic conductivity in the down gradient boreholes. Whether this is a natural lithological variation, or whether the "putty" Chalk is evidence of decalcification due to interaction with leachate is not clear. Groundwater samples taken during drilling were analysed for TOC and a full suite of inorganic species (Appendix A). The variations in groundwater chemistry as seen on the trilinear diagram (Figure 13.6) are very similar to those observed previously (Williams et al., 1997). The chemistry of groundwater in boreholes down gradient of the site (boreholes TR 5, TR 6, TR 7 and TR 8) have compositions consistent with mixing between natural Chalk groundwater and leachate, although they consist dominantly of natural groundwater.

14 ROUTINE MONITORING

14.1 Groundwater levels

Hourly monitoring of water levels in three boreholes around the site, TR2, TR4 and TR9, began in July 1997 using TUBER data monitors. The data from the loggers is presented in Figures 14.1 to 14.3. The three boreholes show the same overall trends though some difference in the degree and timing of water table fluctuation exists. The maximum water table fluctuation, of approximately 3 m, is seen in TR2 while a fluctuation of about 2.25 m is seen in TR4. The water table is at its deepest from late September to early December, while the peak water levels are seen in May. A small decline in water level is seen during March 1998 probably reflecting the dry February experienced that year. The water level fluctuations in TR2 are not only more extreme than those seen in the other two monitoring boreholes but also appear to occur more rapidly. This is demonstrated by the peak water level in TR2, which not only occurs earlier than in the other boreholes, but also changes from a rising to a falling water table much more rapidly.



No.	TDS	Sample Site
1	671	TR1
3	880	TR3
4	2451	TR4
5	820	TR5
6	1622	TR6
7	1642	TR7
8	1468	TR8
9	1480	TR9

Figure 13.6 Trilineat plots for boreholes TR1–9, September 1997.

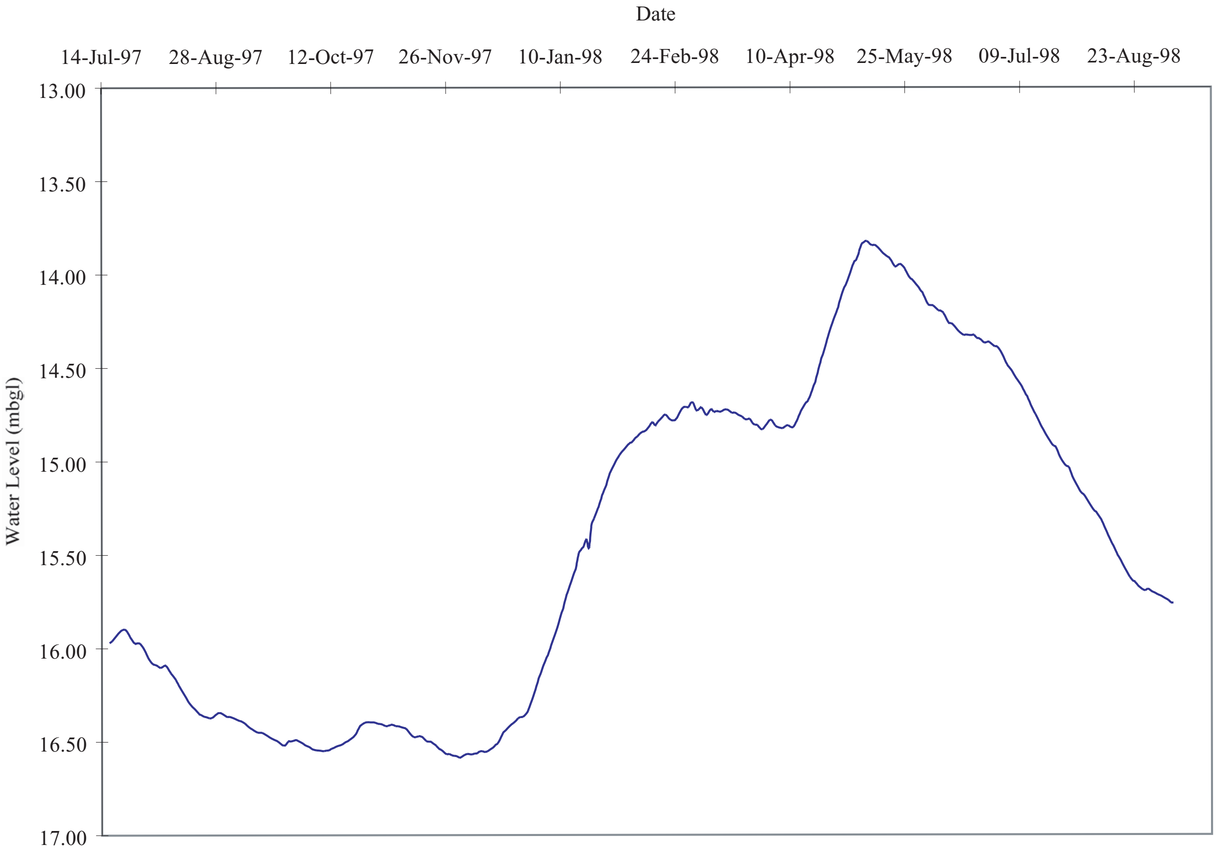


Figure 14.1 Water levels recorded in monitoring borehole TR2.

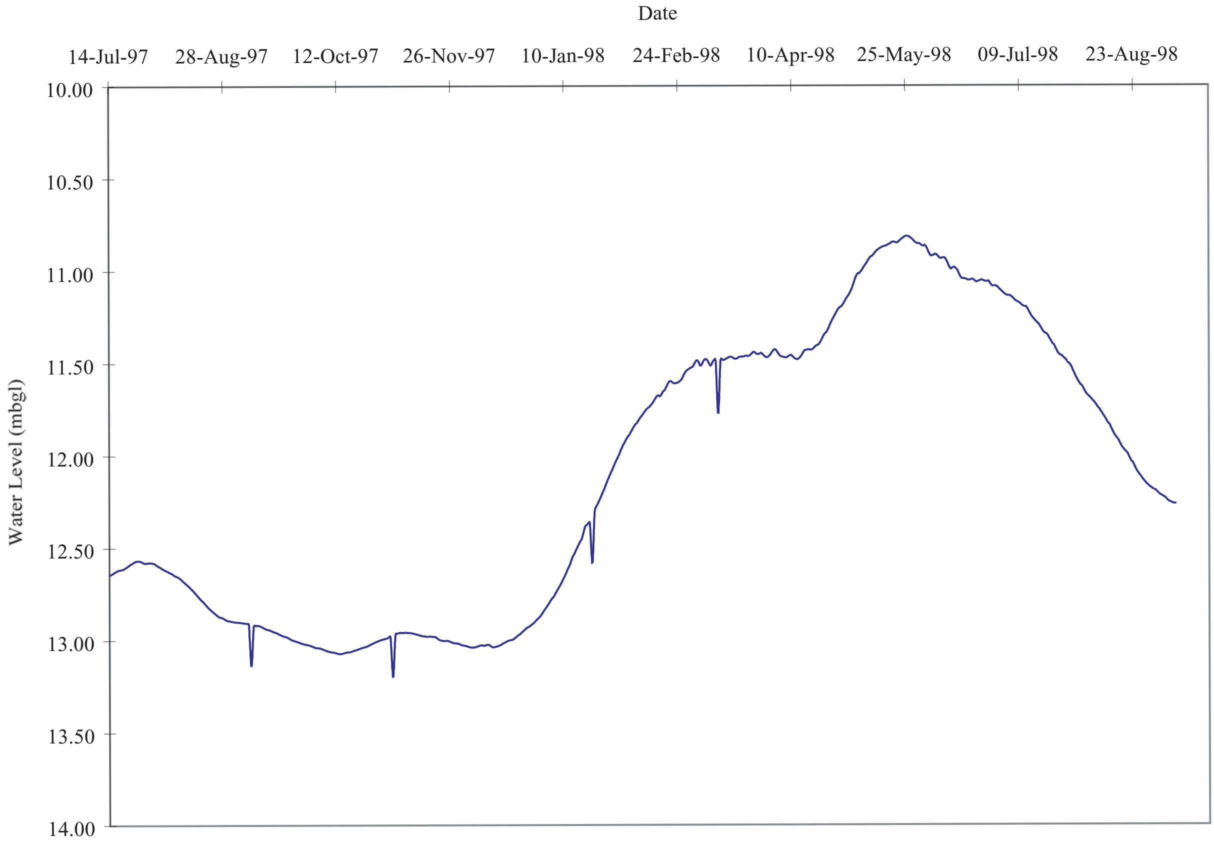


Figure 14.2 Water levels recorded in monitoring borehole TR4.

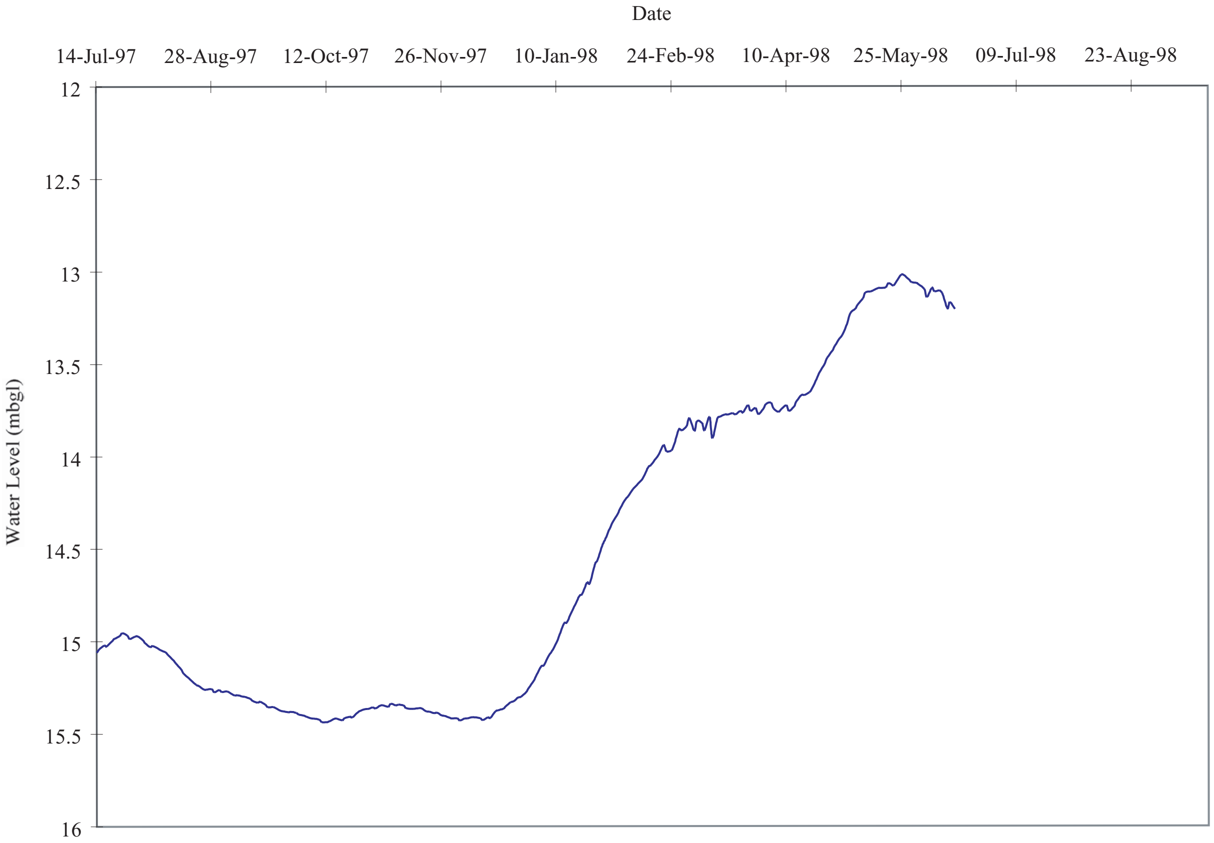


Figure 14.3 Water levels recorded in monitoring borehole TR9.

14.2 Groundwater sampling

After drilling additional monitoring boreholes at Thriplow site May–June 1997 it was decided to initiate a programme of bi-monthly groundwater sampling. To reduce costs samples were only analysed comprehensively on alternate sampling rounds. Between these only a limited number of boreholes were sampled and these were analysed for ammonium, TOC and chloride, in the laboratory, while DO_2, pH, electrical conductivity and total alkalinity were measured in the field.

A full sampling programme was carried out in September 1997, with a restricted round following in November. To date these are the only sampling rounds for which all the analytical results are available, although subsequent sampling was carried out in January, March and September of 1998. Thus only interpretation of data up to and including the November 1997 samples is presented in this report.

Figures 14.4 to 14.6 show the distribution of chloride, TOC and ammonium as measured in September 1997. The highest ammonium concentrations are seen in the boreholes completed within the landfill waste in the youngest parts of the landfill (1852 mg/l in TP3), and decreasing as the age of the waste gets older, 447 mg/l in TP5 and 74.5 mg/l in TP7. Ammonium is only present in boreholes TBH 3, TBH 5 and TBH 7 and in TR4, with the concentration decreasing with distance down-gradient of the landfill from 48.4 mg/l in TBH 3 to 4.29 mg/l in TBH 5. The same pattern in concentrations is shown by TOC. The highest concentration is recorded in TP3 (203 mg/l), and the only boreholes which show concentrations elevated above background, which is taken as the 5 mg/l recorded in TR3, are TBH 3, TBH 5, TR4 and B15. Again concentrations decrease with distance down-gradient of the landfill, with background levels being found in all the new monitoring boreholes except TR4.

The pattern of the conservative tracer chloride differs from that shown by ammonium and TOC, with all boreholes down gradient of the site showing elevated concentrations with respect to the background of 37 mg/l measured in TR3. Chloride concentrations of 345 mg/l and 296 mg/l are measured in TR6 and TR7 respectively, while TR1, the borehole furthest down-gradient of the site, has a concentration of 93 mg/l. Again the maximum concentration is measured in TP3 (2,262 mg/l) and decreases with the age of the waste. However unlike ammonium and TOC a higher chloride concentration is now measured in TBH 3 and TBH 5 down-gradient of the landfill, 725 mg/l and 512 mg/l respectively, than is measured in the nearest borehole within the landfill, 350 mg/l in TP7. Unlike the other determinands, chloride is present at concentrations above background.

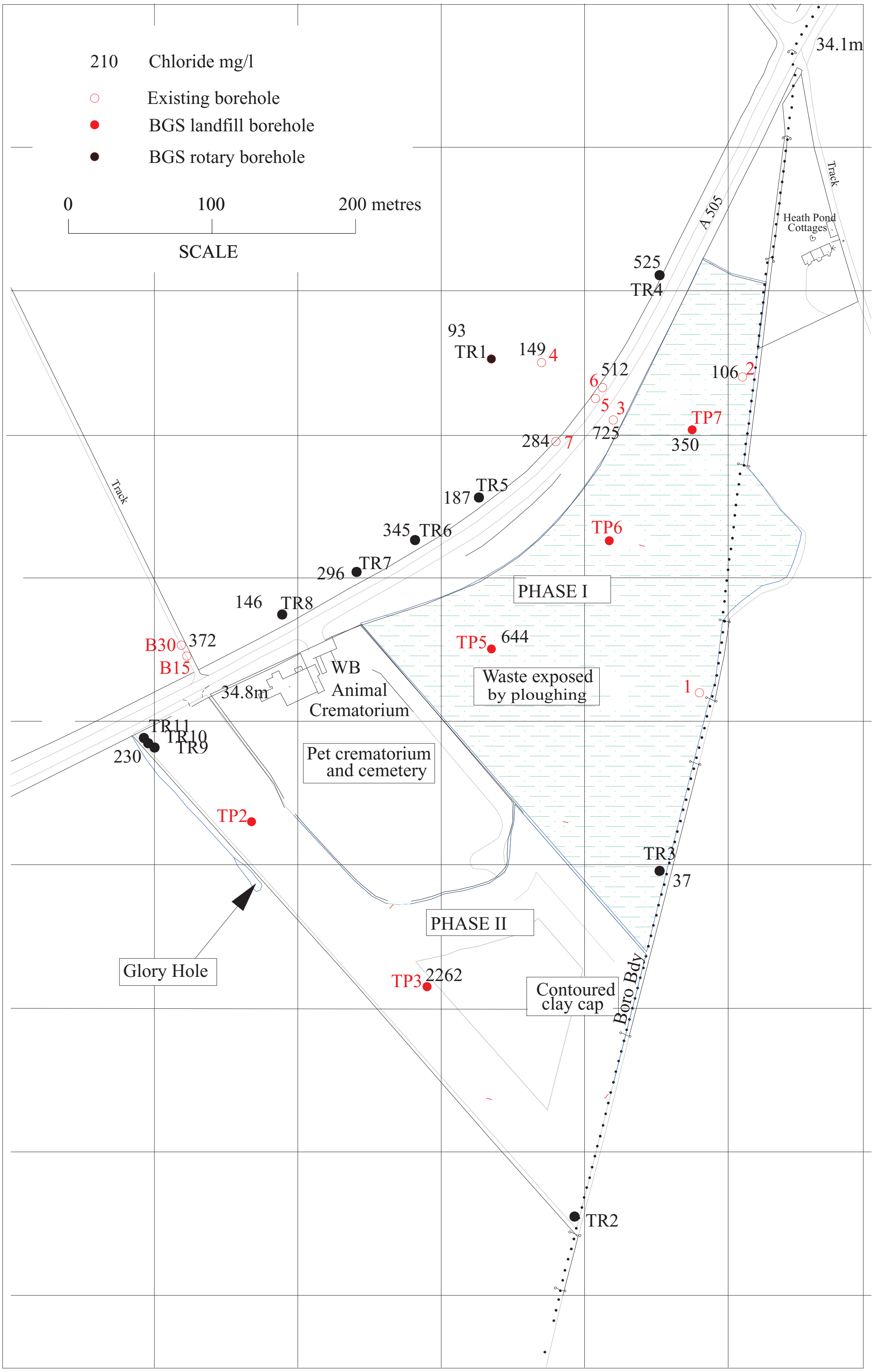


Figure 14.4 Chloride concentrations measured at Thriplow Landfill in September

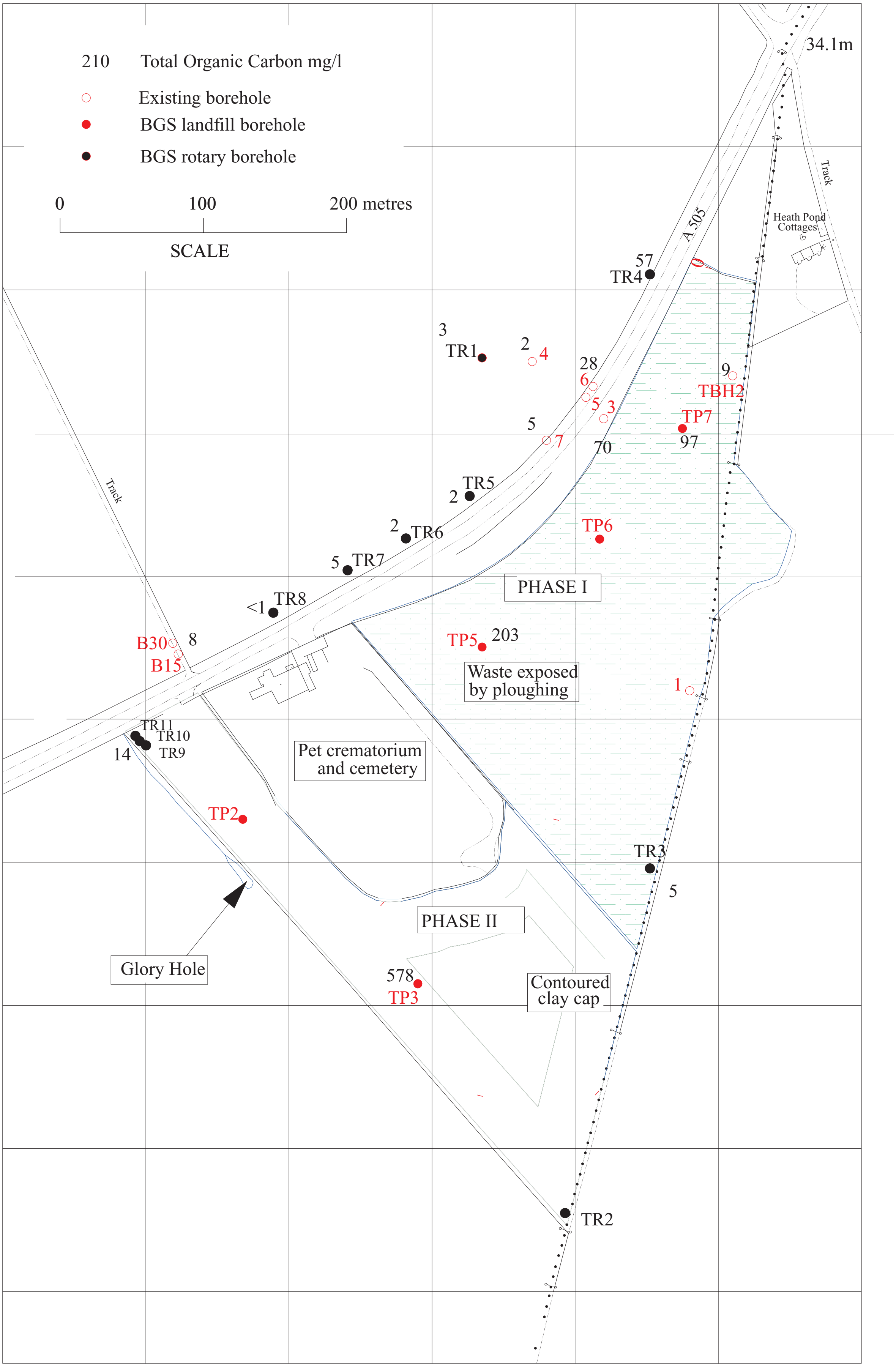


Figure 14.5 Total Organic Carbon measured at Thriplow landfill in September 1997.

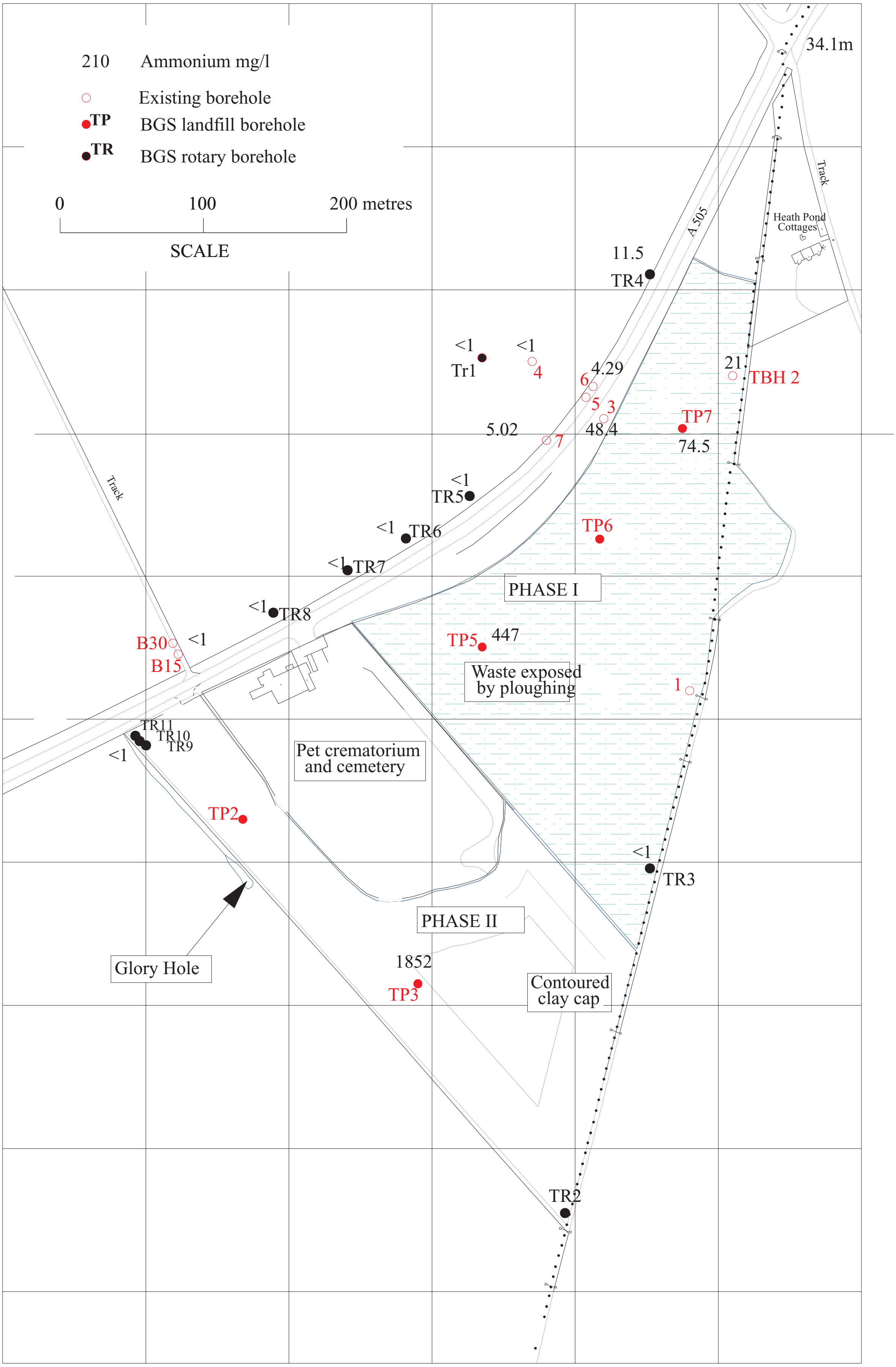


Figure 14.6 Ammonium concentrations measured at Thriplow landfill in September 1977.

As described in Section 13.7, borehole TBH 5 has been modified so that groundwater can be sampled from both above and below the Plenus Marls. Concentrations are consistently higher above the Plenus Marl. For instance chloride measured in September 1997 was 512 mg/l above the Plenus Marl and 257 mg/l below it. The same sampling round gave TOC values of 27.7 mg/l and 18.8 mg/l, and ammonium of 4.29 mg/l and 1.05 mg/l, in the shallow and deep completions respectively. The similarity in values recorded in the upper and lower completions in TR5 is due to the fact that these completions are in hydraulic connection, as shown by the water levels in the completions, and thus are not sampling different levels of the aquifer.

Contaminant concentrations show a steady decline in TBH 5 and TBH 4, from June to November. However in TBH 3 and TR4, which are both closer to the landfill, chloride concentrations show an increase over the same period. Ammonium and TOC show a steady decline in TR4, while the lowest TOC concentration which was recorded in TBH 3 in September corresponds to the time of the peak ammonium concentration in the same borehole. However, the significance of these small fluctuations in TOC and ammonium concentration seen in TBH 3 can only be judged in the context of the longer term monitoring. The overall pattern however does seem to be one of seasonal pulsing with increasing chloride being the first indicator of the next contaminant input into the groundwater system.

15 MODELLING FRACTURE SYSTEM EFFECTS ON PLUME DEVELOPMENT

15.1 Introduction

Initial phases of work on this project have involved reviewing existing data, carrying out preliminary field investigations, and performing some initial model calculations using an effective porous medium approach on a regional scale. These studies were reported in Williams et al. (1997).

The initial modelling was carried out at a regional scale using a porous medium representation of the Chalk aquifer system. Whilst this was adequate for developing a preliminary understanding of the site, the fractured nature of the Chalk necessitates a more complex representation of the system for studies of plume development in the vicinity of the landfill. However, a detailed representation of the fractured Chalk aquifer with all its fractures and matrix blocks explicitly represented over an area extending for 1 to 2 km from the site could necessitate the use of a model containing of the order of 1010 elements. This is at least 4 orders of magnitude larger than could be considered for use with currently available computing facilities and 5 or 6 orders larger than can comfortably be used for repeated simulations on a PC or small workstation. Clearly, such models are unlikely to be practicable in the near future. It is therefore necessary to look for ways in which the representation can be simplified and try to study the effects of such simplifications on the computed results. Following the preliminary studies of Williams et al. (1997) it was therefore considered that the next phase of modelling should have the following aims:

- To model the interaction between the contaminant plume and the Chalk fracture system.
- To include a detailed representation of the fracture system together with infilling matrix blocks.
- To examine the effects of fracture aperture variation and changes in source zone infiltration rates.
- To examine the use of simplified representations for making predictions of plume development on larger scales.

15.2 FRACTRAN modelling

In order to make the task computationally feasible it is necessary to adopt a highly simplified conceptual model incorporating the most essential features, and to make use of the most efficient numerical techniques. The code FRACTRAN (Sudicky and McLaren, 1992) was chosen because of the efficiency of the Laplace Transform Galerkin approach (Sudicky, 1989, 1990) that it uses for solving the solute transport equations. This makes it possible to use models with large numbers of fractures and matrix blocks without incurring excessive computational costs. There are, however, some limitations that arise from the use of this numerical method. These benefits and limitations are described in more detail in Noy (1998).

As indicated above, the current phase of modelling work is directed towards understanding how a fracture and matrix system of the type found at the Thriplow site can affect the movement of solutes. In order to isolate these effects as clearly as possible, it is appropriate to adopt a highly simplified representation of the geometry and boundary conditions, incorporating just the essential features of the nature of the site. The main features and boundary conditions used in these calculations are shown in Figure 15.1, and have been based largely on observations made in borehole TR1 as detailed in Williams et al. (1997). Model parameters have been chosen to be broadly representative of the rocks found at the site, but spatial variability has not been introduced since its complications would be likely to obscure the effects to be studied. In addition, site specific data are not yet available in sufficient detail to define the spatial variability of parameter values.

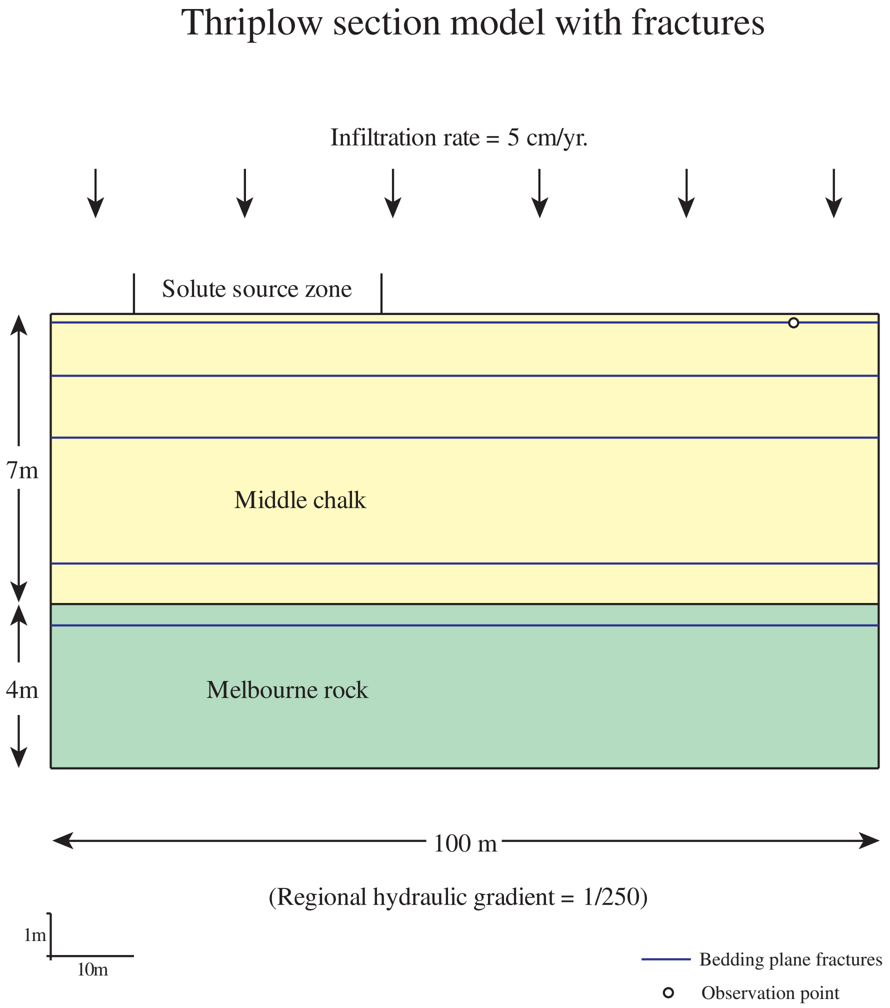


Figure 15.1 Schematic diagram showing conceptual model and boundary conditions used for discrete fracture network simulations of solute transport at the Thriplow landfill site. The chalk layers between the bedding plane fractures are filled with randomly generated, small aperture, vertical fractures with an average spacing of 67 cm.

The field investigations show the presence of a number of major bedding plane fractures and these have been included as explicit horizontal fracture elements in the model located at the elevations observed in borehole TR1. These fractures are assumed to be continuous across the whole section modelled in this work. Between these bedding plane fractures, a large number of smaller sub-vertical fractures are found. For the modelling, these were generated randomly between each pair of bedding planes with an average spacing over the section of 67 cm. These vertical fractures were given a transmissivity that was 5% of that of the bedding plane fractures. The plume development and movement were found to be very sensitive to the effective hydraulic apertures given to the main bedding plane fractures. Data from the site were not considered to be adequate to provide more than a qualitative indication of the appropriate value, so two particular examples have been used to illustrate the effect. The effective fracture apertures in the two cases differed by a factor of two.

The dense vertical fracturing generates very large computational grids so that it was necessary to restrict the length of the section to 100 m for most of the calculations. These grids comprised about 24,000 nodes and 32,000 fracture and matrix elements. A few additional calculations were run in which the length of the model was extended to 550 m, resulting in grids of over 130,000 nodes and 170,000 elements.

As boundary conditions for the groundwater flow, a head gradient of 1 m in 250 m was applied across the section. There is considerable uncertainty as to the appropriate level of surface infiltration at the site, so most of the calculations were done with an infiltration rate of 5cm per year into the top boundary, supplemented by additional calculations in which the rate was set to 25 cm per year and 2.5 cm per year. A no-flow boundary was set on the base of the section. Although there is evidence of an upwardly directed hydraulic gradient across the Plenus Marl, the hydraulic conductivity of that formation is thought to be low so that any upflow into the base of the modelled section should be small compared to the horizontal flow in the Middle Chalk due to the regional gradient. The solute transport boundary conditions comprise a source zone 30 m long on the top surface of the section, starting 10 m from the inlet end of the section, on which solute concentration is fixed at 1 for 6 years. All other boundaries use zero gradient conditions.

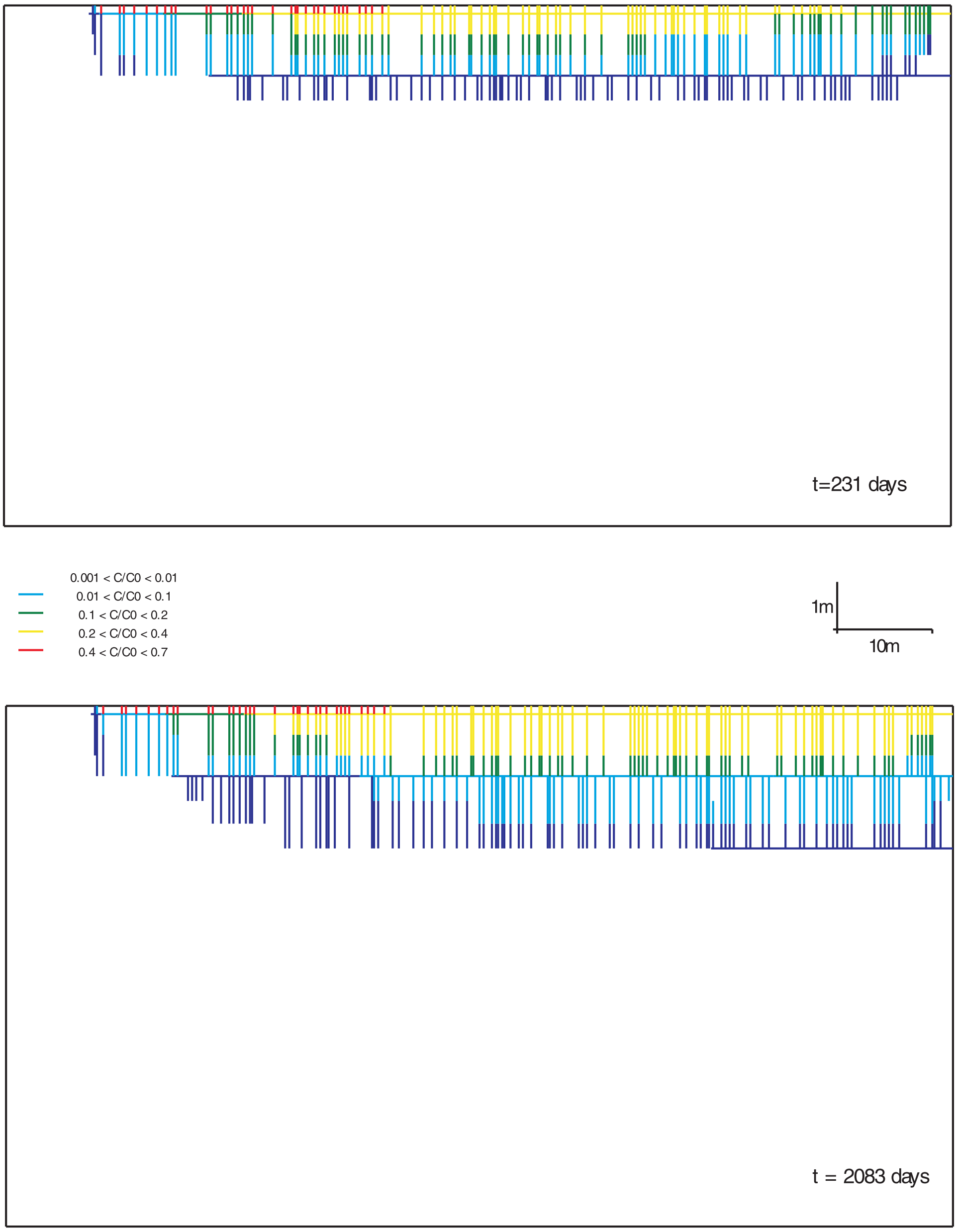
15.3 Conclusions

Due to the lack of detailed monitoring data it has not been possible to make direct comparisons between observations and model predictions, and the highly simplified nature of the representation of the site details would probably make any such comparison difficult to evaluate. However, some qualitative observations made in Williams et al. (1997) have helped to infer something about the general nature of the fracture sizes. The following conclusions may be drawn

Any solute plume developed from the site is likely to be restricted to the uppermost part of the saturated zone of the aquifer over distances of several hundred metres. Continuity of the bedding plane fractures is likely to be the main restriction on this behaviour. Figure 15.2 illustrates the development of a plume for the case of the larger fracture apertures.

Comparison between the model responses to changes in the source and qualitative observations at the site suggest that the main bedding plane fractures have effective hydraulic apertures more like the larger option used in this work (5.6×10^{-4} m). Figure 15.3 shows the sensitivity of the breakthrough time to the fracture apertures, with the difference between the two models being just a factor of two change in that parameter. It will be necessary to make use of detailed monitoring data to provide more accurate estimates of the values for parameters used in the models.

Figure 15.2 Fracture solute concentrations during plume formation for the large fracture aperatures model.



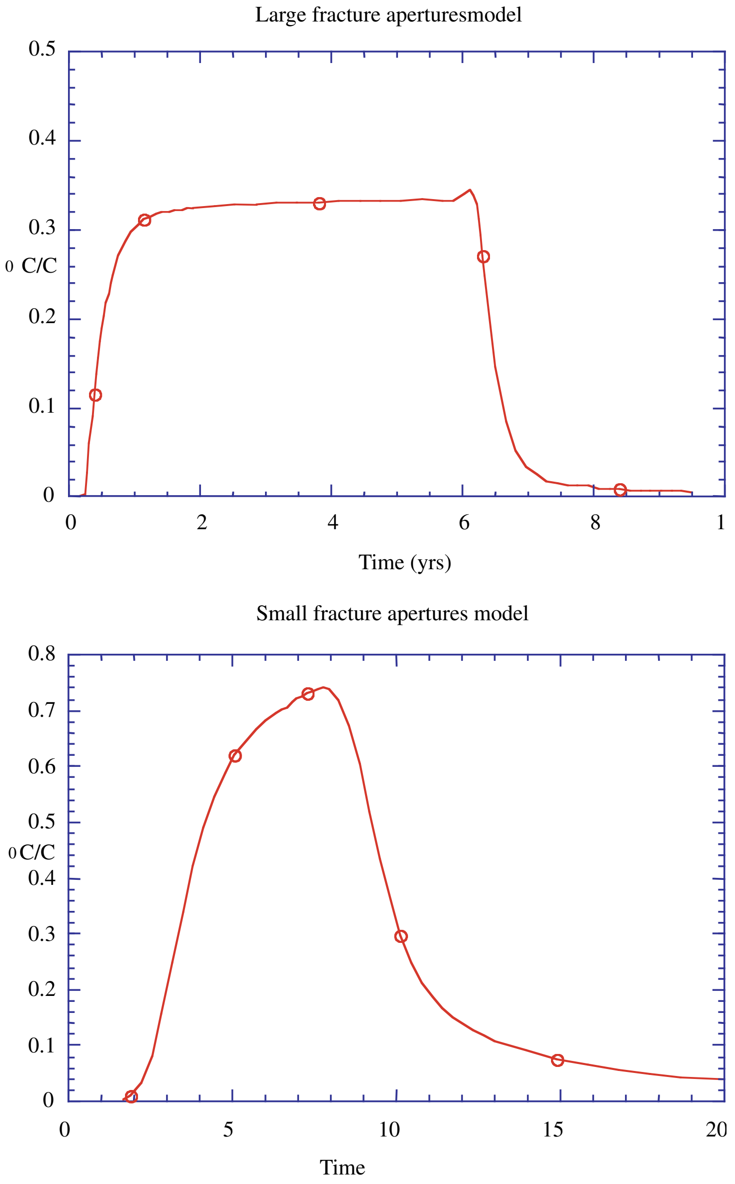


Figure 15.3 Breakthrough curves at the observation point marked on Figure 15.1.

Changes in surface infiltration rate can have significant effects on the peak solute concentrations observed in the plume. These effects are not simply linearly related to the infiltration rate, an observation which may be of importance for understanding transient responses of the system. Figure 15.4 shows a comparison of breakthrough curves obtained under different infiltration rates.

The use of a dual-porosity model as a simplification for regional scale modelling appears to give poor results. This is probably due to the presence of bedding plane fractures as continuous large scale features. Figure 15.5 shows comparisons of breakthrough curves for discrete fracture and dual-porosity models for the two fracture aperture sizes used in the current work.

A model which uses explicit bedding plane fractures separated by porous medium blocks that represent both chalk matrix and small vertical fractures appears to provide a useful simplification for regional scale modelling, although more work is needed to refine the choice of model parameters. Figure 15.6 compares the breakthrough curves obtained at 200 m and 500 m for the detailed and simplified models. Application to the field problem would require careful calibration and validation.

Clearly, the calculations presented in this report provide only an interim step towards the overall project objective of developing a well constrained model of the site. However, the identification of a class of simplifications that could greatly reduce the computational cost of a complete site specific model of flow and transport is an essential step towards making such a model feasible. The modelling done in this study has considered only steady state flow conditions, a limitation imposed by the use of the Laplace Transform Galerkin technique, a choice in turn

Figure 15.4 Comparison of the breakthrough curves at the observation point in Figure 15.1 for different values of the surface infiltration rate.

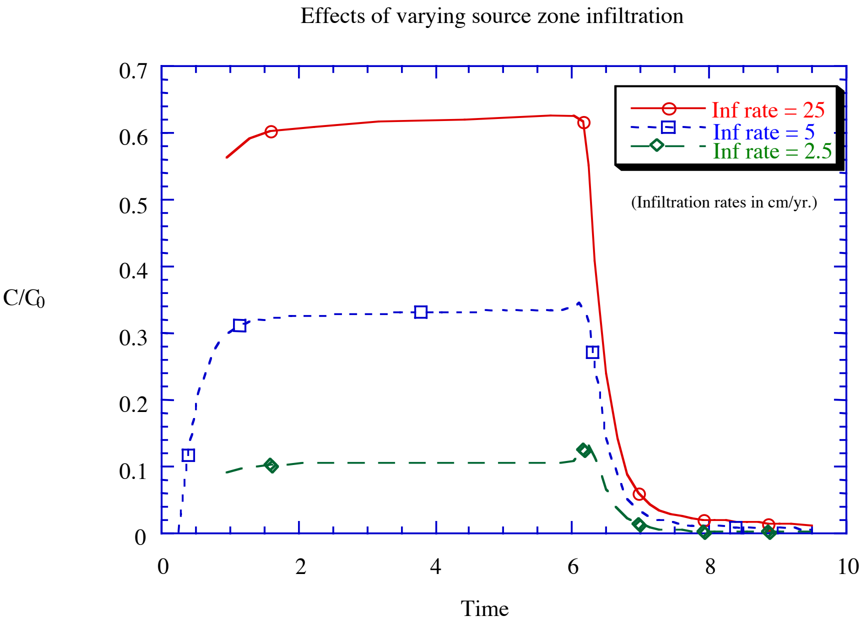


Figure 15.5 Comparison of breakthrough curves for full discrete fracture and simplified dual-porosity models.

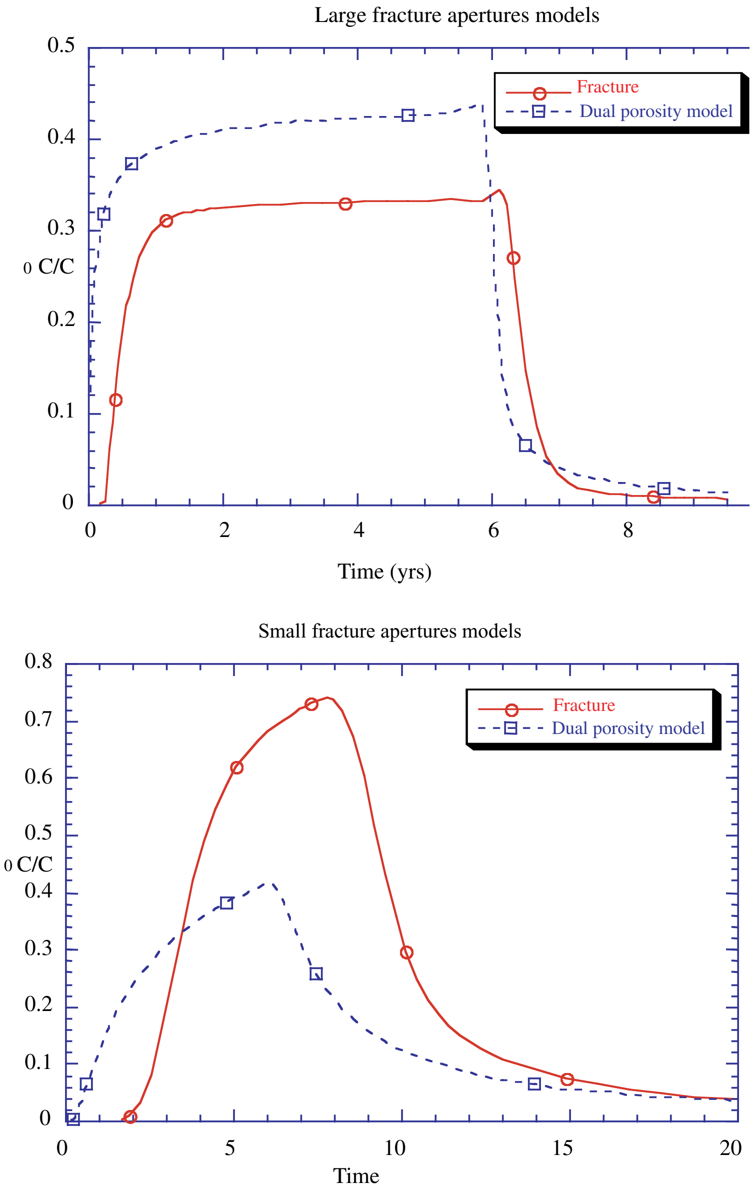
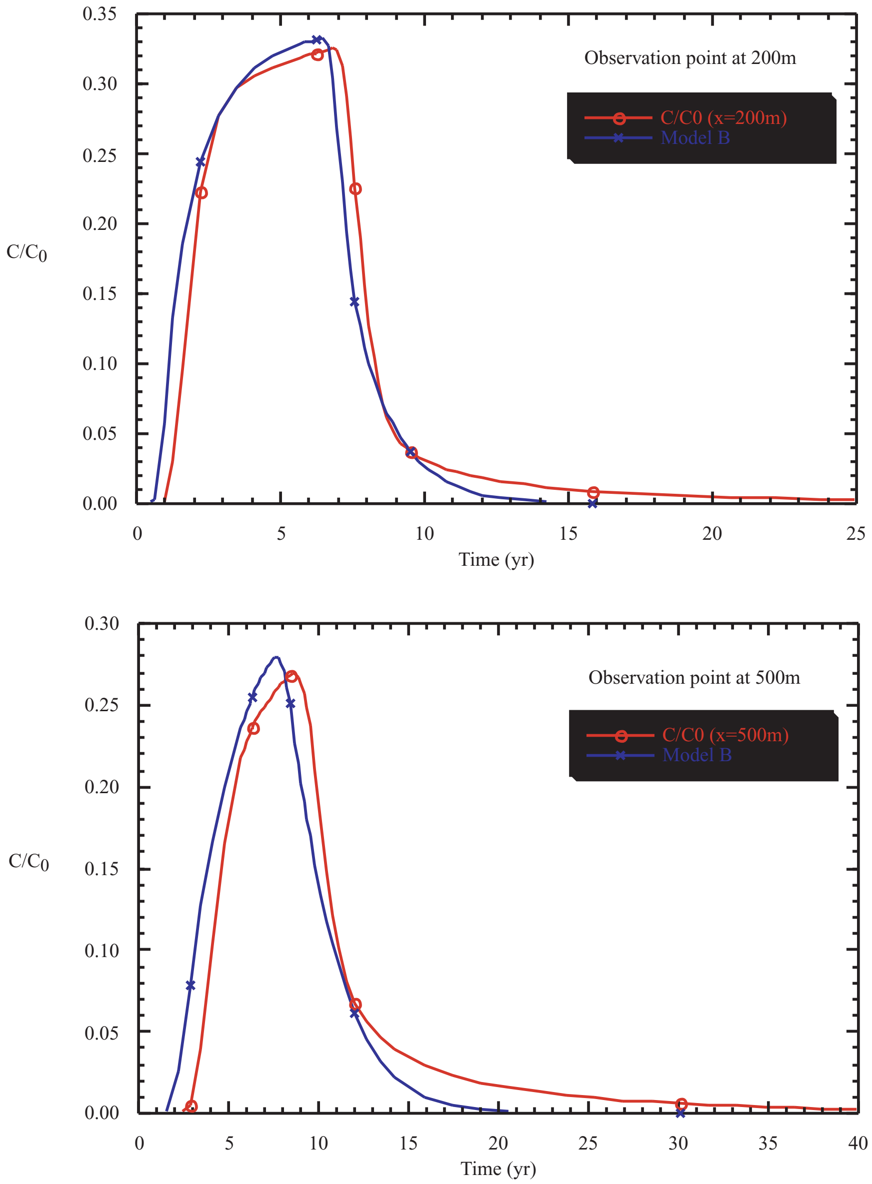


Figure 15.6 Comparison of breakthrough curves at two points for the full discrete fracture model and a simplified model.



dictated by the requirement to adopt a highly detailed representation of the fracture system in the chalk aquifer. The adoption of the simplified conceptual model with appropriately chosen parameters should make possible the inclusion of transient groundwater flow conditions, such as annual cycles of rainfall and source zone input. The response of the system could then be modelled for comparison with the detailed site monitoring data.

16 REFINEMENT OF THE CONCEPTUAL MODEL

The results of the field investigation have helped define the conceptual hydraulic model of the site. Most importantly the depth of leachate flow in the Chalk is restricted by the presence of the Melbourn Rock and the underlying Plenus Marls, beneath which upward flow is to be expected. The hydraulic gradient determined from water level measurements in the zone above the Plenus Marls indicated that flow is towards the NW (Figure 16.1). This accords with the flow direction deduced from the deep wells that are screened through the aquifers above and below the Plenus Marls. The degree of leakage upwards through the Plenus Marls has not been assessed. The head difference across it is 0.5 m in a vertical distance of 2 m but the vertical hydraulic conductivity of the Plenus Marls could not be determined from the core samples obtained. Thus, the contaminant transport model need only consider the Chalk above the Plenus Marls, i.e. to a depth of 20 m bgl but should investigate the sensitivity of the model to upward flow through the Plenus Marls.

Aquifer transport properties of the Chalk are not well constrained in this zone. Two packer tests in TR1 gave hydraulic conductivity values of 5.14×10^{-7} and 6.94×10^{-5} m/s at packer mid points of 15.29 m and 18.75 m bgl

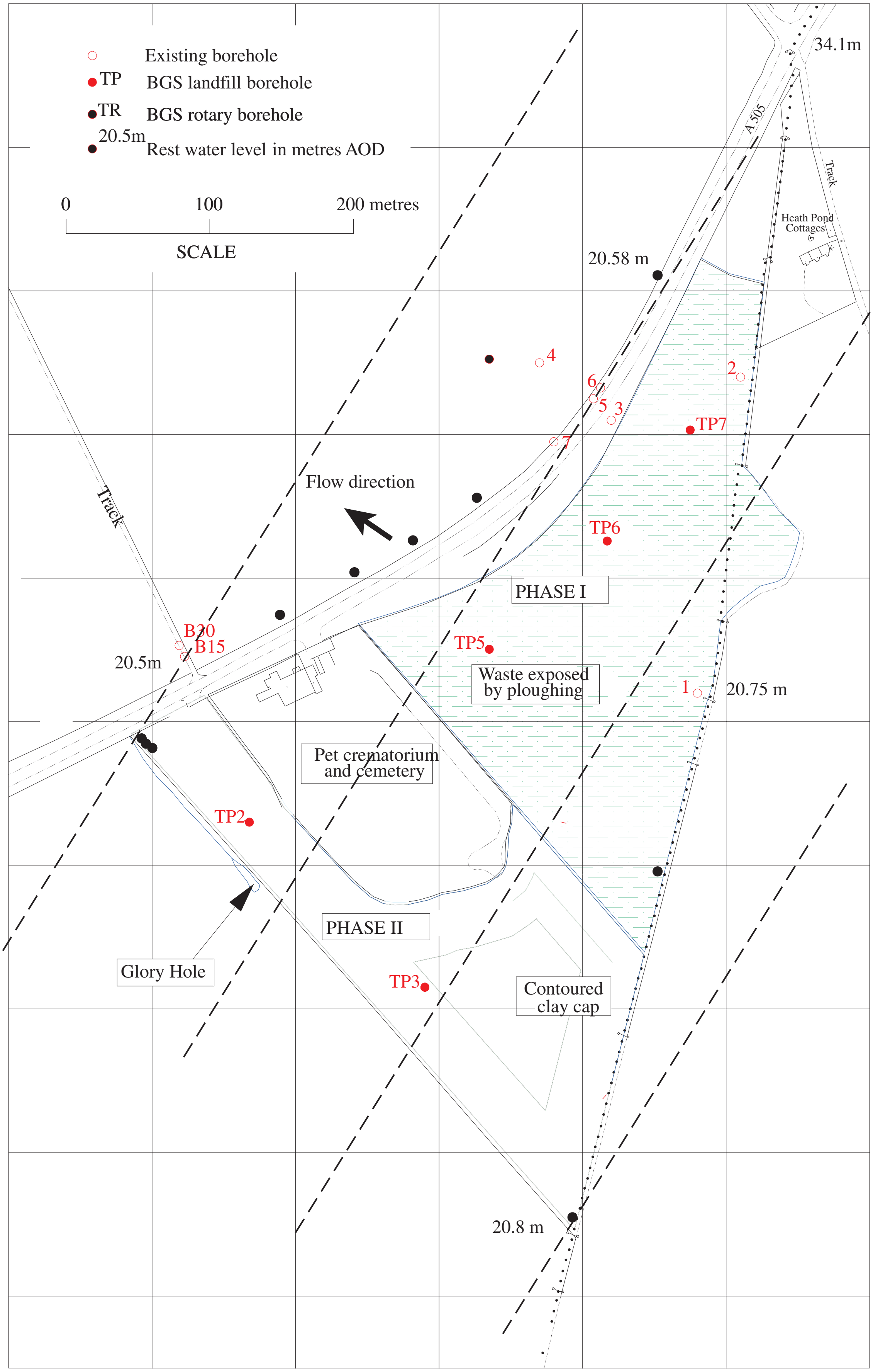


Figure 16.1 Groundwater levels measured in June 1997 and interpreted groundwater flow direction and gradient.

respectively. Groundwater flow rates are directly influenced by the fracture porosity of the Chalk as would be expected, and this is also poorly constrained. Matrix diffusion may be significant in attenuating the plume and this must be evaluated by measurement of fracture versus matrix porosity. However, there is a need for accurate measurements of flow velocities, fracture spacings and fracture porosity in the top 10 m of the saturated zone. The orientation of the fracture sets giving a hydraulic anisotropy may also need to be addressed.

The Chalk aquifer varies lithologically from a relatively pure Chalk up hydraulic gradient of the site (in borehole TR 3), to a "putty" Chalk with low hydraulic conductivity in the down gradient boreholes. Is this a natural lithological variation or is the "putty" Chalk evidence of decalcification due to interaction with leachate?

The drift thickness varies considerably (Figure 16.2). Borehole TR8 intercepted 16.5 m of sand/gravel and silt, which may represent a buried channel with a higher transmissivity than the surrounding Chalk. If so this may constitute a major control on groundwater flow and provide a fast or localised migration pathway for leachate. If the interaction of leachate with Chalk lowers its hydraulic conductivity then this has very important implications in transport modelling. "Self-sealing" as leachate reacts with the chalk along the flow path may cause leachate to back-up and move laterally increasing the apparent transverse spreading of the plume. It is possible that the contamination in TR4 is evidence of this.

The leaching behaviour of the waste is a major area of uncertainty. The leachate source term and the area through which infiltration occurs are not defined precisely. The significance of the deeper excavations in the quarry identified from the aerial photographs, in terms of the type of waste or their effect on infiltration, is not known.

The water levels measured at the time of drilling were significantly lower than those measured during the previous field campaign in September 1996. The solute concentrations in the down-gradient monitoring wells indicate relatively low impact from leachate. This may reflect a low rate of leaching from the landfill when the water table falls below the waste (and when infiltration is low)? If so, a pulse of leachate may be released when the water table rises again into the waste (and infiltration is higher), as suggested by Boland (1996a,b). Solute transport modelling using a dual porosity medium has shown that the fracture water concentrations in the aquifer decrease very rapidly after the source term is removed (Noy, 1998). This would support the idea that pulses of leachate could be observed in the aquifer following a change in the flow of leachate from the landfill.

17 SUMMARY OF RESULTS

17.1 History of landfilling

- The landfill consists of two distinct phases, the older part uncapped, and the newer phase capped.
- Aerial photography and surface resistivity surveys indicate that the site geometry is complex, with several phases of landfilling into excavations of differing depths.

17.2 Landfill

- The waste sampled is primarily domestic waste.
- Leachate production and the time taken for stabilisation proceed at different rates in capped and uncapped landfills.
- Analysis of leachate obtained by centrifugation or squeezing waste appears to give a better insight into the pollution potential than leach tests with distilled water.
- BMP values do appear to be related to the quantity of decomposable material but the COD values are distorted by the presence of reduced metals.
- Too few AOX values were obtained for an assessment of their value. However, as some concentrations in the landfill were high (2790 mg/l Cl) it would be worthwhile attempting to identify the individual organic halogens using GCMS.
- The landfill source term is not well defined at present in terms of its composition and spatial distribution. No direct information is available on the long term leaching behaviour of the site.
- The hydraulic conductivity of the landfill caps are sufficient to allow all rainfall to infiltrate.

17.3 Geophysics

- Surface geophysics using RESCAN appears to detect the solute front beneath the landfill and not necessarily the waste/Chalk interface.

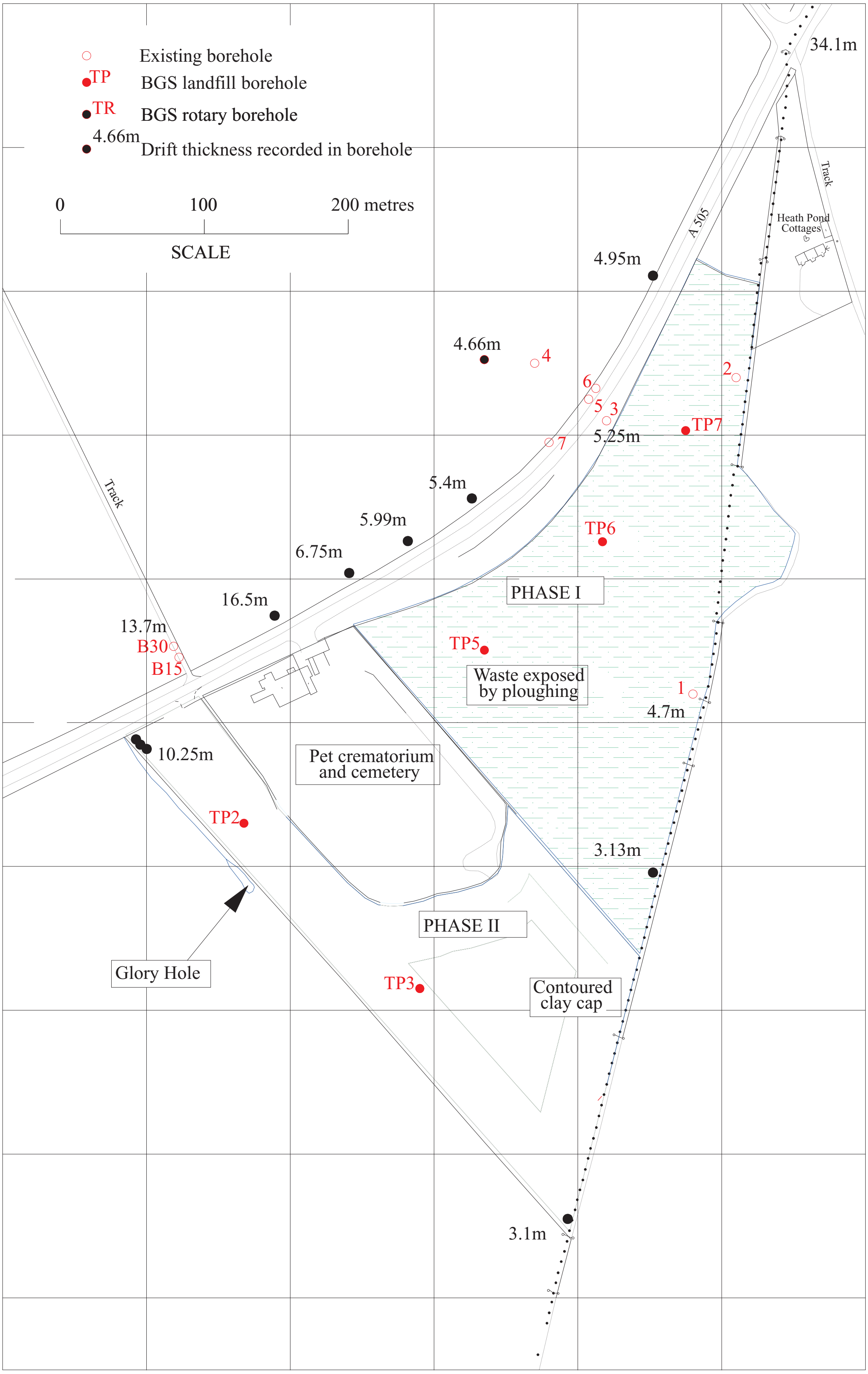


Figure 16.2 Drift thickness recorded in boreholes drilled at thriplow.

- Interpretation of the geophysical survey over the landfill is supported by evidence from aerial photos.
- Re-evaluation of the resistivity interpretation in the light of the borehole evidence indicates that the RESCAN system is insensitive to large variations in formation resistivity at depths beyond 30 m bgl although shallower data appear reliable.
- A constrained inversion is required which allows layers of known resistivity to be fixed during the inversion process. This will help re-interpret existing data.

17.4 Chalk groundwater

- There is evidence of leachate migration from groundwater sampled from pre-existing screened boreholes (B15 and B30) suggesting that leachate is flowing in the shallow part the aquifer above the Plenus Marls rather than in the deeper aquifer.
- The borehole TR1 drilled on an apparent resistivity anomaly at 40 m depth down gradient from the site, has not detected contamination.
- TR1 indicates that below the Plenus Marls water flow is upwards. This means that leachate from the landfill will be restricted to the zone above the Marls, i.e. within 20 m of the surface and within the top 10 m of the saturated zone.
- The existing borehole TBH 4 which penetrates the Plenus Marls may potentially allow recharge to occur from below into the shallow aquifer above the Plenus Marls. This will dilute any leachate in the upper aquifer and distort the flow regime.
- Groundwater chemistry appears to be influenced by three major factors; the landfill leachate, the composition of shallow groundwater in the top 10 m of the Chalk, and the composition of water from the Lower Chalk. The groundwater samples analysed reflect various mixtures of these end member compositions.

18 RECOMMENDATIONS FOR FUTURE WORK

18.1 Aims of future work

The preliminary site investigation has provided considerable information on the flow regime beneath the site which helps focus future investigations. In the light of new field evidence the conceptual model can now be refined to develop a more appropriate groundwater flow and solute transport model. Data on aquifer properties for the new model are scant and need to be measured directly. The model will also be limited by insufficient monitoring data for calibration. Better evaluation of leachate input is required. This may be approached using existing leachate generation models with site specific rainfall data if available. Assessment of the alternative landfilling methods also requires a good knowledge of their leaching behaviour spatially and with time. To fully appreciate the extent of leachate attenuation requires that the contaminant plume is adequately identified and characterised. The work required to address these aspects are discussed below.

18.2 Pollution plume identification

Further monitoring boreholes will be drilled through the landfill and along the axis of the plume to provide distance/(time) related data which can be used to calibrate an advection-dispersion model incorporating matrix diffusion to infer dispersivity and effective matrix diffusion. Biodegradation reactions may also be determined by parameter fitting degradation rates to achieve the observed distribution of biodegradable species. However, accurate determination of these parameters is dependent on a good appreciation of flow regime in the aquifer.

18.3 Aquifer transport parameters

The transport modelling has revealed that the extent and morphology of the plume is very sensitive to fracture and matrix porosities. These need to be constrained by better in situ measurement of aquifer properties, in addition to a better definition of any plume. Improved values for critical aquifer properties, fracture spacings, fracture porosity, transmissivities and permeability anisotropy need to be obtained for the top 10 m of the saturated zone.

Fracture spacing and aquifer anisotropy could be evaluated by two means. Azimuthal resistivity could be used from the surface to infer fracture orientations at depth. Alternatively, a direct study of the Chalk could be undertaken by excavating at the base of the old quarry to the North-West of the landfill (TL 445 453). This excavation would also provide data on fracture density. Borehole television and packer testing could be used to determine the density of horizontal bedding plane fractures in new boreholes. Point dilution measurements in open boreholes, packered-off as necessary, would help determine groundwater flow rates directly. Small scale tracer tests in an array of boreholes which is best constructed up gradient of the landfill could be used for radially convergent tracer experiments from which porosity could be characterised on a number of fracture planes. A natural gradient test could be considered down gradient from the site and would require a dense network of monitoring wells to detect tracer breakthrough. Initially, conservative tracers could be used to determine hydraulic transport parameters but later reactive species, such as degradable organics could be employed for more advanced investigations into chemical fate.

18.4 Leaching behaviour of the landfill

A better evaluation of the leaching behaviour of the landfill is required as a source term for the solute transport model. It is evident that the landfill is heterogeneous and the leaching behaviour cannot be modelled as a uniform input over the area of the site. Definition of the leaching behaviour ideally would involve a grid of boreholes drilled to the water table beneath the landfill. Spatial and temporal variations in contaminant concentrations in these built up from a future monitoring programme could be used directly to indicate the areas of leachate release and could be correlated with rainfall to produce an assessment of the leaching behaviour of the landfill. From the existing data the significance of the leachate plume beneath Phase 1 is uncertain. It is not clear whether it is now decaying following release of the highest concentrations of leachate. Information on the major areas of leachate release may be gained from the boreholes drilled along the west boundary outside the site. To identify exactly where leachate infiltration occurs will then require boreholes to be drilled through the site into the Chalk up-gradient of highest concentrations detected in the perimeter wells.

18.5 Bioactivity within the landfill

There is limited information on the degree of degradation in the waste and such measurements rely on drilling, sampling and a long term measurement of methane potential. An alternative approach is to measure methane fluxes on site. This could be done either passively measuring the flux of gas over a given area of cap, or by active pumping of a borehole in the waste. Techniques are now available for passive flux measurements over the landfill cap, in which up to 10 canopies (area .1 m^2) are laid out and monitored over a period of weeks. The magnitude of the flux can be related to the bio-activity of the waste below.

18.6 Long term monitoring

As new boreholes are constructed they should be incorporated into a monitoring scheme to build up seasonal and long term knowledge of groundwater and leachate plume dynamics. As outlined in the first part of this report, time series data are essential for calibrating the solute transport model and allowing it to be used to predict future contaminant distributions. Water level data should be collected but in boreholes constructed to monitor one hydrogeological unit. The remaining boreholes which penetrate the Plenus Marls and therefore form man made connections between otherwise hydraulically separate zones need modification.

18.7 Modelling

The overall aim of the project is to produce a well-constrained solute transport model for the landfill. Insight into the mechanisms affecting transport and fate requires constant iteration between field data and modelling results to assess the control of various site characteristics on leachate migration. Modelling using a dual porosity representation of the aquifer is now required and “matrix diffusion” type effects in numerical models of the site need to be considered in more detail.

The modelling undertaken so far has assumed a porous medium approach, which is appropriate as an initial step and would also be valid for more detailed modelling if the fracture density was such that fracture and matrix solute concentrations come to equilibrium over the scales of interest. In the current case, however, the preliminary modelling suggests that an effective porosity of about 5% best fits the data. Since this is much less than the total porosity of about 40%, it would appear that only part of the matrix is being accessed by solute.

There are two alternative ways that this solute transport problem may be addressed. Firstly, calculations may be carried out using a network of explicitly represented fractures embedded in matrix blocks. This is often considered the ideal approach because the model representation most closely approximates the physical nature of the system. The current version of the FRACTRAN code allows this approach to be taken. The main difficulty that arises is that the numbers of finite elements in a model may become prohibitively large as the fracture spacing reduces. Thus, on a site such as Thriplow where an area with sides up to a few kilometres need to be considered, it may not be possible to use fracture spacings much less than 50 to 100 m. Fracture spacings observed in chalk are generally of the order of 1 m or less, but it has yet to be established how many such fractures are in fact hydraulically active. It is suggested that some calculations of the type described here would be useful, if only as a point of comparison with other models.

The second approach is to use a dual-porosity formulation in which the fracture network and intervening matrix blocks are treated mathematically as overlapping continua, with a transfer function determining the way in which solute is distributed between them. The transfer function may be derived from consideration of matrix blocks with certain idealised shapes such as spheres and slabs, but the representation is generally more abstract than in the explicit model described above. The current version of FRACTRAN does not include a facility to use this dual-porosity approach. However, the Laplace Transform Galerkin formulation that this model uses means that a dual-porosity capability could be added much more easily than in a conventional solute transport model. It is therefore suggested that undertaking this modification would be most valuable to this project.

All the modelling options considered so far have been concerned primarily with the migration of unreactive leachate components. Understanding these processes is a necessary prerequisite to undertaking the modelling of reactive transport, which is also an important objective of the project.

18.8 Programme of work for Phase 3

The specific objectives for Phase 3 of the investigation are:

- to undertake further site investigation to improve the definition of the pollution plumes emanating from the two phases of landfilling.
- to develop conceptual models of the pollution plumes from the two landfills and set up flow and contaminant transport models.
- to obtain monitoring data over time to enable flow and transport models to be calibrated to predict the future contaminant distributions from the landfills.

The following activities have been identified to produce the outputs listed above:

18.8.1 *Sub-waste monitoring*

The spatial variability in leaching from the landfill is presently unclear. It is known that the base of the original quarry excavation was very irregular particularly beneath the Phase 1 landfill and this may control where leachates are entering groundwater. In order to evaluate the leaching behaviour of both landfills boreholes are needed to monitor the groundwater immediately beneath the waste and determine the influence of any unsaturated zone in transmitting or attenuating leachate. It is proposed that seven boreholes be drilled through the landfilled area to further characterise waste, to obtain samples of unsaturated zone and groundwater from the Chalk aquifer. These boreholes will be completed to sample groundwater in the Chalk and will be fitted with closely spaced resistivity electrodes to assess vertical variations in leachate distributions. Completions within the landfill will be made where a saturated zone is encountered within the waste.

These data will be used to define the source term for contaminant transport modelling through the Chalk aquifer and will help compare the leaching characteristics of the two phases of landfilling.

18.8.2 *Characterisation of core material*

Drilling to identify the pollution plume in the Chalk (Williams and Boland, 1997) revealed a zone of low permeability putty chalk down gradient from the landfill in contrast to the usual lithified Chalk up-gradient. There is also evidence of a buried channel in the surface of the chalk infilled with superficial deposits. It is proposed to carry out a mineralogical and porewater study of putty chalk from the recently drilled boreholes to determine whether it is natural (i.e. due to weathering associated with a buried channel) or due to leachate interaction. If leachate interaction gives rise to putty chalk and a reduction of hydraulic conductivity, this self-sealing effect could have profound implications on the development of pollution plumes in Chalk and is therefore an important area of study.

Chalk core material collected from drilling through the waste will be studied in the same way to determine the mineralogical interactions between chalk and leachate. These unsaturated zone profiles will indicate the extent of attenuation in the unsaturated zone and will be compared with material from the “buried channel”.

18.8.3 *Plume characterisation*

Delineation of a buried channel using RESCAN — In addition to the mineralogical study, there is a need to define the buried channel down gradient from the site. A perimeter borehole drilled in summer 1997 intercepted 18 m of drift overlying Chalk suggesting the existence of a buried channel to the west of the Phase 1 landfill. This could dominate groundwater flow and may be an important migration pathway for landfill leachate.

Borehole drilling — A number of boreholes have been drilled around the perimeter of the landfilled area to locate contaminant plumes. These boreholes are presently insufficient to characterise the plumes in detail. The existing borehole network needs to be upgraded and extended to provide a 2-D transect along the axis of each plume so that distance (time) related data can be used to infer attenuation parameters. These boreholes will also allow long term monitoring data to be collected to study plume dynamics and to calibrate the solute transport models. The initial aim will be to monitor leachate propagation through the aquifer following "winter leaching" of the waste. It is proposed to drill the following boreholes in spring 1999. The exact positions of these boreholes will be determined after the results of the RESCAN survey have been studied.

Phase 1 landfill Five boreholes will be drilled down gradient of the Phase 1 landfill to form a 2-D profile with distance and improve spatial discrimination of contaminant plume.

Phase II landfill Two boreholes will be drilled down gradient of the Phase 2 landfill to augment existing boreholes B15 and B30.

18.8.4 *Rehabilitation and upgrading of existing boreholes*

The Plenus Marls form a barrier to downward leachate migration in the Chalk. Some previously drilled boreholes penetrate, and are screened across, the Plenus Marls allowing groundwater to recharge upwards. Some of these boreholes have been successfully modified to discretely monitor above and below the Marls, but three boreholes still require sealing.

Because contaminant transmission is predominantly along fractures, there is a need to obtain depth specific samples from the Chalk aquifer above the Plenus Marls in the saturated zone between 10–20 m bgl. Depth sampling in fully screened boreholes in this zone provides vertically averaged groundwater compositions which are poorly reproducible and lack qualitative interpretation. Level specific sampling can be achieved by installing a sock type packer fitted with small diameter multi-level tubes for water sampling, and with electrodes for resistivity monitoring. These down hole electrodes will also facilitate tomographic imaging of resistivity data in conjunction with surface electrode arrays.

18.8.5 *Geochemical characterisation of the contaminant plumes*

Once the monitoring network is established, the distributions of inorganic and organic contaminants can be accurately determined. Inorganic redox sensitive species will be used to determine the redox zonation within the aquifer, which constitutes an important control on breakdown pathways and rates of organic degradation. Water samples will be analysed by HPLC, and GCMS in order to identify principal organic constituents and their potential breakdown products. Integrating the distribution of organic contaminants with the groundwater flow model will allow the field determination of degradation rates to be assessed. Providing sufficient organic material can be obtained consideration will be given to Compound Specific Isotope Analysis (CSIA) to identify systematic changes in stable carbon isotope ratios which can be indicative of microbially mediated degradation reactions. The techniques for this are being developed as part of a separate NERC research project (Environmental Diagnostics Programme).

1 8.8.6 *Systematic monitoring*

In fractured aquifers flow rates can be large and frequent or continuous monitoring may be required to measure contaminant propagation rates. The field data already collected suggests that contaminants may flush through the aquifer relatively rapidly following periods of winter recharge, saturation of the waste and pulsed release of leachate into groundwater. It is proposed that this cyclic pulse is confirmed by high resolution monitoring because it effectively constitutes a large scale tracer experiment from which information on the aquifer transport parameters including longitudinal and transverse dispersion, matrix diffusion, and leachate attenuation can be inferred. Direct water sampling at two month intervals; and continuous monitoring of water levels and electrical conductivity in a smaller number of boreholes will be employed. Direct water sampling will revolve around a full suite of inorganic determinations and TOC once a year with analysis of TOC, Cl and NH4 in the intervening sampling rounds. Continuous monitoring will help to define the appropriate sampling frequency should water samples be required for more detailed analysis.

18.8.7 *Modelling*

A Source term evaluation

Estimates of leachate production with time from the waste will be calculated using site specific data on rainfall and evaporation obtained from the meteorological office. These data will be used in the US-EPA HELP model to predict leaching behaviour and will be compared with the spatial variability in leaching behaviour to attempt to provide a better source term for subsequent groundwater flow and contaminant transport modelling.

B Contaminant transport modelling

Contaminant transport modelling using equivalent porous medium and a dual porosity aquifer approach will be undertaken using the data collected from groundwater monitoring for calibration. Estimates of reaction rates and matrix diffusion effects will be inferred by parameter fitting appropriate reaction types to describe the known distribution of contaminant species. Future scenarios will be considered in predictive modelling to estimate the long-term impact of each phase of landfilling on groundwater quality. These models will be considerably more complex than the reductionist approach used in LANDSIM and will form a useful benchmark to evaluate the effectiveness of LANDSIM and to improve parameterisation within it.

19 REFERENCES

ALLEN, D J, BREWERTON, L S, COLEBY, L M, GIBBS, B R, LEWIS, M A, MACDONALD, A M, WAGSTAFF, S J, and WILLIAMS, A T. 1997. The physical properties of Major Aquifers in England and Wales. *British Geological Survey Technical Report*, WD/97/34.

BIOTAL. 1992. Further assessment of landfill assessment methods: a potential gas yield and gas production rate test. *DOE Controlled Waste Management Paper*, CWM090/92.

BOLAND, M P. 1996a. Summary report on Phase 1 of the investigation into the effect on groundwater quality of the Thriplow Landfill Site. *British Geological Survey Technical Report*, WE/96/28/C.

BOLAND, M P. 1996b. Preliminary modelling of contaminant migration from the Thriplow landfill site, Cambridgeshire. *British Geological Survey Technical Report*, WE/96/27/C.

BRITISH GEOLOGICAL SURVEY. 1932. One inch sheet 205 (Saffron Walden). (HMSO.)

BRITISH GEOLOGICAL SURVEY. 1996. 1;50,000 Sheet 221 (Hitchin). (HMSO.)

CAREY, M A. 1985. Title unknown. PhD Thesis University of Birmingham.

CONSTABLE, S C, PARKER, R L, and CONSTABLE, C G. 1987. Occam’s inversion: A practical algorithm for generating smooth models from EM sounding data: Geophysics, 52, 289–300.

CROFT, B, and CAMPBELL, D J V. 1994. Assessment of a test for biological methane potential. *DOE Controlled Waste Management Paper*, CWM103/94.

DEPARTMENT OF THE ENVIRONMENT. 1978. Co-operative programme of research on the behaviour of hazardous wastes in landfill sites. Final report of the policy review committee (Chairman J Sumner). Her Majesty’s Stationery Office, London. 169 pp.

DRESSMAN, R C, and STEVENS, A A. 1983. “The analysis of organo-halides in water-an evaluation update.” *Journal AWWA 1983*, 431–434.

DUFFIELD, G M. 1994. AQTESOLV. Aquifer test solver, Version 2.0.Geraghty & Miller, Inc Modelling Group, 10700 Parkridge Boulevard, Suite 600, Reston, Virginia 22091.

FETTER, C W. 1994. Applied Groundwater Hydrology 3rd Edition. Macmillan College Publishing Company, Inc., 866, Third Avenue, New York 10022.

GRAY, D A, MATHER, J D, and HARRISON, I B. 1974. Review of groundwater pollution from waste disposal sites in England and Wales, with provisional guidelines for future site selection. *Quarterly Journal of Engineering Geology*, Vol. 7, No 2, 181–196.

HUEBER, K H, and THORTON, E A. 1988. The Finite Element Method for Engineers. (John Wiley: New York, 1982.)

JEKEL, M R, and Roberts, P V. 1980. “Total organic halogen as a parameter for the characterisation of reclaimed waters: Measurement, occurrence, formation and removal.” *Environmental Science and Technology*, 14(8), 970–975.

LITTLE, R, MULLER, E, and MACKAY, R. 1996. Modelling of contaminant migration in a chalk aquifer. *Journal of Hydrology*, 175, 473–509.

LLOYD, J W. 1993. The United Kingdom. In 220–249 The Hydrogeology of the Chalk of North-West Europe. DOWNING, R A, Price, M, and Jones, G P (editors). (Oxford Science Publications.)

MURRAY, K H. 1982. Correlation of electrical resistivity marker bands in the Chalk of the London Basin. *British Geological Survey Technical Report*, WD/82/1.

NATIONAL RIVERS AUTHORITY. 1995. The effects of old landfill sites on groundwater quality. *R&D Repor*t, 569/3/A.

NATIONAL RIVERS AUTHORITY. **YEAR**. Leaching tests for assessment of contaminated land: Interim NRA guidance. R&D Note 30.

NOY, D J. 1998. Fractured medium models for the Thriplow landfill site. *British Geological Survey Technical Report*, WE/98/36C.

OAKES, D B. 1986. Model simulations of pollutant transport in the chalk in the vicinity of the Thriplow landfill. *WRc report for Cambridge County Council.*

OGILVY, R D, JACKSON, P D, STRAUB, A, and SIDERIS, G N. 1995. Development of electrical imaging and inversion techniques for mineral exploration. *British Geological Survey Technical Report*, WN/95/21R.

OGILVY, R D, MELDRUM, P I, SHEDLOCK, S L, and CRIPPS, A C. 1996. 2-D resistivity Imaging of Leachate Plumes from the Thriplow Landfill, Cambridge. *British Geological Survey Technical Report*, WN/9/28C.

PRICE, M, DOWNING, R A, and EDMUNDS, W M. 1993. The Chalk as an aquifer. In 35–58 “The Hydrogeology of the Chalk of North-West Europe”. DOWNING, R A, PRICE, M, and JONES, G P (editors). (Oxford Science Publications.)

ROBINSON, H D. 1996. A review of the composition of leachates from domestic waste in landfill sites. Department of the Environment Report No CWM /072/95. Obtainable from AEA Technology, Culham, Oxfordshire.

SASAKI, Y. 1994. Resolution of resistivity tomography inferred from numerical simulation. *Geophysical Prospecting*, 40, 453–463.

SHANKLIN, D E, SIDLE, W C, and FERGUSON, M E. 1995. Micro-purge low-flow sampling of uranium-contaminated groundwater at the Fernald environmental management project. *Groundwater Monitoring Review*, 168–176.

SUDICKY, E A. 1989. The Laplace Transform Galerkin technique: A time-continuous finite element theory and application to mass transport in groundwater. *Water Resources Research*, 25, 1833–1846.

SUDICKY, E A. 1990. The Laplace Transform Galerkin technique for efficient time-continuous solution of solute transport in double-porosity media. *Geoderma*, 46, 209–232.

SUDICKY, E A, and MCLAREN, R G. 1992. User’s guide for FRACTRAN: an efficient simulator for two-dimensional, saturated groundwater flow and solute transport in porous or discretely-fractured porous formations. Waterloo Centre for Groundwater Research, University of Waterloo, Ontario, Canada.

TESTER, D J, and HARKER, R J. 1981. Groundwater pollution investigations in the Great Ouse basin — Solid waste Disposal. Water Pollution Control 1981.

WILLIAMS, G M, and BOLAND, M P. 1997. Effect of old landfills on groundwater quality: The Thriplow landfill: Preliminary assessment of field data — May/June 1997. *British Geological Survey, Technical Report*, WE/97/28C.

WILLIAMS, G M, BOLAND, M P, HIGGO, J J W, OGILVY, R D, KLINCK, B A, WEALTHALL, G P, DAVIES, J R, NOY, D J, and TRICK, J. 1997. Effect of old landfills on groundwater quality: The Thriplow Landfill: Field Investigations 1996. *British Geological Survey Technical Report*, WE/97/4C.

WOODROW, B. 1991. Investigation into Thriplow waste disposal site. Environment Agency Reference Number 591/00/86.

WRIGHT, C E. 1974. Combined use of surface and groundwater in the Ely, Ouse and Nar catchments. *Report of the Water Resources Board.*

Modelling Reports

Lodes and Granta Investigations — Main Report. 1988. A report for Anglian Water by the University of Birmingham.

Great Ouse Groundwater Development Scheme — River Rhee Catchment: — development and use of groundwater models. 1981. A report by the Anglian Water Authority.

Chalk groundwater to regulate the River Rhee, Cambridgeshire. 1975. A report by the Central Water Planning Unit.

Appendix A

Groundwater chemistry data for sampling carried out between April 1996 and November 1997

Thriplow groundwater composition, April 1996.

Location	Sample Depth	Field Temp	Field Eh	Field pH	Field HCO3	Field Conductivity	DO2	Conductivity	Lab pH	Ca	Mg	Na	K	HCO3	Cl
	m	°C	mV		mg/l	µS/cm	mg/l	µS/cm		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
BH1	18.91	17.7	401	6.57	527	1540	1.00	1580	7.01	340	4.58	38.7	7.06	538	81.30
BH2	15.00	18.8	451	6.84	1422	3650	2.00	3780	7.36	282	55.0	267	173	1500	338.00
BH3	14.50	14.2	382	6.91	975	3690	2.00	3830	6.91	302	18.3	492	33.7	1040	614.00
BH4	19.00	10.2	635	6.85	254	1200	3.00	1280	7.59	220	2.28	54.6	1.27	279	223.00
BH5A	20.50	15.1	519	6.38	829	2980	3.00	3310	7.02	352	4.80	427	5.96	866	624.00
BH5B	32.60	14.5	485	6.41	741	2540	2.00	2700	8.06	318	4.07	315	4.14	748	494.00
BH6	12.50	14.1	577	6.52	668	2470	2.00	2720	7.47	345	3.85	302	1.57	642	515.00
BH6 Duplicate	12.50	14.1	577	6.52	668	2471	2.00	2740	7.51	333	3.66	293	1.20	611	514.00
BH7	21.60	12.2	387	6.99	541	2280	1.50	2310	7.45	315	7.28	200	16.9	512	334.00
Fowlmere Spring	n/a	11.0	606	7.11	293	671	7.00	711	7.73	130	4.26	11.6	5.49	259	32.20

Location	SO4	NO3	Br	NO2	HPO4	F	TOC	TIC	Total P	Total S	Reduced S	NH4
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
BH1	186.00	153	0.26	<0.20	<0.05	0.22	<5.00	104	<0.10	56.6	<0.005	0.10
BH2	188.00	172	1.56	<0.20	<0.05	0.16	66.0	292	<0.10	n/d	<0.005	130
BH3	211.00	49.4	6.56	0.32	0.05	0.23	66.0	222	<0.10	66.5	0.005	36.0
BH4	41.20	57.3	1.64	<0.20	<0.05	0.16	4.57	54.3	<0.10	15.0	<0.005	<0.05
BH5A	151.00	8.81	3.84	<0.20	<0.05	0.19	39.9	174	<0.10	50.0	0.013	7.92
BH5B	101.00	10.3	3.10	<0.20	<0.05	0.16	29.7	151	<0.10	35.5	0.016	4.83
BH6	117.00	38.0	0.57	<0.20	<0.05	0.18	12.2	127	<0.10	38.7	<0.005	<0.05
BH6 Duplicate	130.00	38.0	0.58	<0.20	<0.05	0.18	10.5	120	<0.10	38.8	<0.005	0.20
BH7	254.00	85.9	1.30	<0.20	0.06	0.21	11.8	100	<0.10	76.5	<0.005	1.57
Fowlmere Spring	50.50	58.5	<0.10	<0.20	<0.25	0.28	6.78	51.0	<0.10	13.2	<0.005	<0.05

Thriplow groundwater composition, April 1996.

Location	SiO2	Ba	Sr	Mn	Total Fe	Reduced Fe	Al	Co	Ni	Cu	Zn	Cr	Mo	Cd	Pb	V	Li
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
BH1	10.62	0.170	0.415	0.060	0.03	0.07	<0.10	<0.02	<0.02	0.014	0.124	<0.01	<0.02	<0.005	<0.10	<0.01	0.011
BH2	14.38	0.239	0.907	0.221	0.04	n/s	0.13	<0.02	0.06	0.128	0.191	<0.01	<0.02	<0.005	<0.10	<0.01	0.238
BH3	18.55	0.163	0.414	0.175	0.08	0.08	0.11	0.02	0.06	0.035	0.114	<0.01	<0.02	<0.005	<0.10	<0.01	0.099
BH4	11.03	0.074	0.396	0.002	<0.01	<0.01	<0.10	<0.02	<0.02	<0.005	0.023	<0.01	<0.02	<0.005	<0.10	<0.01	0.010
BH5A	17.25	0.193	0.501	0.079	0.04	0.04	0.13	0.02	0.05	0.039	0.204	<0.01	<0.02	<0.005	<0.10	<0.01	0.055
BH5B	16.52	0.159	0.502	0.064	0.04	0.01	<0.10	0.02	0.03	0.014	0.088	<0.01	<0.02	<0.005	<0.10	<0.01	0.038
BH6	11.33	0.138	0.423	0.015	0.01	<0.01	<0.10	<0.02	<0.02	0.008	0.106	<0.01	<0.02	<0.005	<0.10	<0.01	0.007
BH6 Duplicate	11.32	0.092	0.412	0.016	0.02	<0.01	<0.10	<0.02	<0.02	0.007	0.098	<0.01	<0.02	<0.005	<0.10	<0.01	<0.005
BH7	13.96	0.156	0.440	0.034	0.02	0.01	0.10	<0.02	<0.02	0.006	0.079	<0.01	<0.02	<0.005	<0.10	<0.01	0.056
Fowlmere Spring	14.36	0.181	0.551	<0.001	<0.01	n/s	<0.10	<0.02	<0.02	<0.005	0.054	<0.01	<0.02	<0.005	<0.10	<0.01	<0.005

Thriplow groundwater composition, May 1996.

Location	Field	Field	Field	Field	Conductivity	DO2	pH	Ca	Mg	Na	K	HCO3	Cl	SO4	NO3	Br	NO2	TOC	TIC	Total	Total	Reduced	NH4
	Temp	Eh	pH	HCO3	µS/cm															P	S	S	
	°C	mV		mg/l		mg/l		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	mg/l
TBH1	15.8	454	6.72	410	1330	2	8.05	279	4.00	28.8	9.36	447	69.3	144	131	<0.30	<0.20	5.60	71.7	<0.15	48.7	23	0.37
TR2	13.2	402	7.39	356	793	6	7.98	174	1.50	12.7	5.11	326	37.0	71.5	62.3	<0.15	<0.10	4.35	59.5	<0.10	24.2	29	<0.25
TR3_1	13.3	422	7.06	439	668	6 to 8	8.14	138	1.90	11.2	45.1	266	81.1	26.0	79.8	<0.15	<0.10	2.91	47.0	<0.10	9.70	18	<0.25
TR3_2	11.8	336	7.36	276	681	5 to 6	8.02	136	2.00	11.3	0.97	274	29.3	21.0	85.0	<0.15	<0.10	2.21	50.7	<0.10	7.93	20	<0.25
TBH1 @30m	13.7	411	6.72	536	1227	5	7.73	274	4.00	29.0	7.23	443	65.6	145	132	<0.30	<0.20	5.59	72.2	<0.10	49.8	28	0.56
TR4	12.7	470	6.41	834	2880	4 to 5	8.03	385	6.20	330	8.26	861	499	228	6.17	3.75	<0.40	64.6	156	0.10	78.6	27	11.9
TR4 Repeat	13.7	469	6.38	1241	2970	2 to 3	6.97	388	7.33	359	12.5	872	501	226	3.90	3.87	<0.40	36.0	158	0.11	79.9	<3	12.50
Blank	13.2	573	6.81	27	26	6 to 8	5.49	0.14	0.02	0.08	4.87	<40	<0.10	<0.10	<0.10	<0.03	<0.02	0.86	2.15	<0.10	0.22	4	<0.05
TR5_3	16.3	346	7.17	558	841	2 to 3	8.21	156	1.26	25.0	0.84	238	112	19.7	61.0	0.56	<0.10	2.79	48.9	<0.10	7.66	13	<0.50
TR5_4	18.1	328	7.35	458	771	4 to 5	8.25	145	0.98	20.5	0.92	240	91.2	16.9	64.3	0.48	<0.10	2.15	46.1	<0.10	6.73	4	0.67
BH 30	14.6	180	7.05	344	1061	1 to 2	7.31	173	1.07	39.2	4.17	346	142	56.6	30.8	0.62	<0.10	4.62	54.9	<0.10	17.5	25	<0.50
BH 15	14.5	510	6.62	530	2350	1 to 2	7.17	439	4.05	136	1.60	526	419	213	104	0.63	<0.40	5.20	86.1	<0.10	73.1	12	0.74
TBH6	15.9	427	6.46	1536	2560	3 to 4	8.33	336	5.85	307	9.30	764	462	193	25.2	1.80	<0.40	20.6	150	<0.10	66.4	50	5.98
TR5 Upper	16.3	421	7.01	429	1332	10 to 12	8.32	204	6.45	77.3	5.00	325	182	92.7	60.3	0.82	<0.20	4.92	62.1	<0.10	32.3	22	<1.00
Blank	18.2	438	8.86	37	19	6 to 8	4.29	0.90	<0.00	0.01	<0.50	<20	<0.10	0.10	3.46	<0.03	<0.02	<1.00	3.77	<0.10	0.06	100	<0.50
TBH4 @14m	16.7	343	7.13	293	1062	5 to 6	8.38	180	3.88	46.6	5.42	296	151	42.7	53.3	0.94	<0.10	3.12	54.4	<0.10	15.6	57	<0.50
TR7	25.1	287	7.03	522	1195	5 to 6	8.47	200	3.91	54.3	2.25	322	169	62.9	54.8	0.87	0.23	5.52	64.4	<0.10	21.9	25	0.59
TR7 @ 15.43	12.9	476	6.74	1127	1913	5 to 6	8.09	367	4.06	121	0.96	489	286	213	64.3	0.56	<0.20	3.51	54.1	<0.10	71.7	23	<0.50
TR7_2	17.3	314	6.68	483	1834	6 to 8	7.75	345	3.38	104	0.63	408	299	168	65.3	0.41	<0.20	6.39	75.5	<0.10	56.2	142	<0.50
TBH7	16.4	384	6.43	483	1937	1 to 2	8.32	273	3.94	187	7.09	495	294	185	46.1	1.87	<0.20	11.4	74.8	<0.10	63.6	24	2.24
TBH5	16.5	324	6.40	778	2940	1 to 2	7.93	338	4.87	361	5.97	811	545	135	5.46	4.08	<0.40	51.0	192	<0.10	48.6	4	10
TR1	8.2	409	7.23	258	803	3 to 4	7.95	144	3.06	29.3	1.14	263	90.7	29.9	48.8	0.49	0.52	2.65	52.1	<0.10	11.0	24	<0.50
TBH3	17.7	313	6.39	1124	3990	0.8 to 1	7.41	342	9.74	597	23.4	1,164	719	254	<2.00	6.76	<0.40	81.1	240	<0.10	88.1	<3	43.20
TBH2	21.7	407	6.53	580	1587	1 to 2	7.42	297	11.8	55.4	32.0	599	108	156	111	0.34	<0.20	5.96	106	<0.10	52.7	<3	7.94
TR9_1	18.2	199	6.52	644	1418	0.8 to 1	6.99	293	3.69	58.6	0.67	638	90.8	114	9.40	0.41	<0.20	4.91	117	<0.10	38.9	23	<0.50
TR9_2	16.5	269	6.36	619	1735	0.8 to 1	7.15	344	2.54	109	0.93	624	235	124	14.0	1.35	0.36	12.7	108	<0.10	44.2	39	<0.50
BH4	14.9	93	6.93	8671	18800	n/d	7.28	>500	589	1545	1140	13,469	1,909	7.31	<5.00	10.2	<2.50	9,098	412	0.23	36.9	97	1,808
TP2	16.7	286	6.55	805	1484	4 to 5	7.38	362	3.80	38.5	10.7	822	85.4	91.4	<1.00	0.63	<0.20	<6.00	162	<0.10	34.7	101	1.37
TP3	15.9	130	7.41	7574	17800	>1	8.12	78.3	183	1300	781	8,596	2,284	158	<5.00	102	1.07	472	1,543	2.72	65.2	11	1,926
TP5	14.9	93	6.11	2282	4200	1.00	7.74	168	66.8	275	232	2,155	351	36.8	<2.00	2.38	<0.40	122	425	0.12	18.8	194	342
TP7	15.1	269	6.86	936	3550	2.00	7.97	329	98.8	264	206	1,014	277	678	302.7	2.28	20.8	51.5	194	0.14	220	282	54.8

Thriplow groundwater composition, May 1996.

Location	Si	SiO2	Ba	Sr	Mn	Total	Reduced	Al	Co	Ni	Cu	Zn	Cr	Mo	Cd	Pb	V	Li	B
						Fe	Fe												
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
TBH1	4.29	9.18	0.049	0.396	0.007	<0.01	0.01	0.09	<0.02	<0.10	<0.005	0.035	<0.01	<0.02	<0.005	<0.10	<0.01	0.008	0.16
TR2	3.60	7.70	0.031	0.255	0.003	0.02	0.03	0.07	<0.02	<0.10	<0.005	0.008	<0.01	<0.02	<0.005	<0.10	<0.01	<0.005	<0.05
TR3_1	4.27	9.13	0.030	0.291	0.007	0.03	0.04	0.05	<0.02	<0.10	<0.005	0.011	<0.01	<0.02	<0.005	<0.10	<0.01	<0.005	<0.05
TR3_2	4.39	9.39	0.031	0.298	0.013	0.15	0.19	<0.05	<0.02	<0.10	0.008	0.101	<0.01	<0.02	<0.005	<0.10	<0.01	<0.005	<0.05
TBH1 @30m	4.31	9.22	0.049	0.410	0.017	0.02	0.03	0.10	<0.02	<0.10	<0.005	0.057	<0.01	<0.02	<0.005	<0.10	<0.01	0.008	0.07
TR4	7.65	16.4	0.104	0.579	0.152	<0.01	0.03	0.10	<0.02	<0.10	0.020	0.033	<0.01	<0.02	<0.005	<0.10	<0.01	0.062	2.56
TR4 Repeat	7.92	16.9	0.106	0.563	0.181	<0.01	0.06	0.18	<0.02	<0.10	0.025	0.036	<0.01	<0.02	<0.005	<0.10	<0.01	0.079	2.67
Blank	<0.01	<0.02	0.001	<0.001	<0.001	<0.01	<0.01	<0.02	<0.02	<0.10	<0.005	0.014	<0.01	<0.02	<0.005	<0.10	<0.01	<0.005	<0.05
TR5_3	4.01	8.58	0.036	0.261	0.006	0.05	0.04	0.07	<0.02	<0.10	<0.005	0.117	<0.01	<0.02	<0.005	<0.10	<0.01	<0.005	0.14
TR5_4	3.84	8.21	0.034	0.229	0.008	0.04	0.04	0.07	<0.02	<0.10	<0.005	0.182	<0.01	<0.02	<0.005	<0.10	<0.01	<0.005	0.07
BH 30	3.92	8.39	0.038	0.240	0.009	0.01	<0.01	0.08	<0.02	<0.10	<0.005	0.052	<0.01	<0.02	<0.005	<0.10	<0.01	0.027	0.09
BH 15	6.11	13.1	0.095	0.548	0.011	0.02	0.07	0.22	<0.02	<0.10	<0.005	0.010	<0.01	<0.02	<0.005	<0.10	<0.01	0.006	0.07
TBH6	6.07	13.0	0.082	0.441	0.116	0.04	0.11	0.22	<0.02	<0.10	0.008	0.053	<0.01	<0.02	<0.005	<0.10	<0.01	0.040	2.07
TR5 Upper	5.02	10.7	0.087	0.440	0.200	<0.01	<0.01	0.10	<0.02	<0.10	<0.005	0.023	<0.01	<0.02	<0.005	<0.10	<0.01	0.010	0.40
Blank	<0.01	<0.02	<0.001	0.001	<0.001	<0.01	<0.01	<0.02	<0.02	<0.10	<0.005	0.015	<0.01	<0.02	<0.005	<0.10	<0.01	<0.005	<0.05
TBH4 @14m	5.31	11.4	0.047	0.563	0.004	<0.01	<0.01	0.07	<0.02	<0.10	<0.005	0.036	<0.01	<0.02	<0.005	<0.10	<0.01	0.010	0.49
TR7	5.29	11.3	0.039	0.533	0.232	1.03	1.21	0.09	<0.02	<0.10	<0.005	0.047	<0.01	<0.02	<0.005	<0.10	<0.01	0.017	0.45
TR7 @ 15.43	5.73	12.2	0.063	0.474	0.026	0.06	0.06	0.14	<0.02	<0.10	<0.005	0.068	<0.01	<0.02	<0.005	<0.10	<0.01	0.007	0.08
TR7_2	5.37	11.5	0.062	0.460	0.018	0.15	0.29	0.13	<0.02	<0.10	0.029	0.364	<0.01	<0.02	<0.005	<0.10	<0.01	0.007	0.09
TBH7	6.14	13.1	0.067	0.482	0.035	0.02	0.14	0.10	<0.02	<0.10	0.009	0.336	<0.01	<0.02	<0.005	<0.10	<0.01	0.053	2.11
TBH5	7.56	16.2	0.082	0.525	0.095	0.07	0.12	0.15	<0.02	<0.10	0.029	0.546	<0.01	<0.02	<0.005	<0.10	<0.01	0.059	4.09
TR1	4.39	9.39	0.038	0.452	0.010	<0.01	0.07	0.06	<0.02	<0.10	<0.005	0.082	<0.01	<0.02	<0.005	<0.10	<0.01	0.011	0.31
TBH3	8.82	18.9	0.097	0.497	0.172	0.77	1.16	0.15	<0.02	<0.10	<0.005	0.546	<0.01	<0.02	<0.005	<0.10	<0.01	0.128	5.46
TBH2	5.05	10.8	0.086	0.570	0.180	0.04	0.05	0.11	<0.02	<0.10	0.019	0.396	<0.01	<0.02	<0.005	<0.10	<0.01	0.027	0.35
TR9_1	10.6	22.7	0.052	0.405	0.316	38.2	46.7	0.10	<0.02	<0.10	<0.005	0.038	<0.01	<0.02	<0.005	<0.10	<0.01	0.012	0.28
TR9_2	7.09	15.2	0.064	0.445	0.049	2.13	2.62	0.14	<0.02	<0.10	0.008	0.326	<0.01	<0.02	<0.005	<0.10	<0.01	0.011	0.59
BH4	17.9	38.4	0.076	6.819	6.813	213	120	0.59	<0.02	0.12	0.098	<0.133	<0.10	<0.20	<0.050	<1.00	<0.10	1.552	7.59
TP2	9.33	20.0	0.078	0.601	0.244	7.13	7.67	0.09	<0.02	<0.10	<0.005	0.063	<0.01	<0.02	<0.005	<0.10	<0.01	0.007	0.16
TP3	8.91	19.1	0.219	1.017	0.071	1.23	2.45	0.12	<0.02	0.16	0.015	0.075	0.07	<0.02	<0.005	<0.10	0.02	0.568	2.72
TP5	11.6	24.8	0.308	1.146	0.125	23.4	25.1	0.10	<0.02	<0.10	<0.005	0.036	<0.01	<0.02	<0.005	<0.10	<0.01	0.207	1.750
TP7	8.53	18.2	0.118	1.474	0.401	0.33	0.25	0.18	<0.02	<0.10	0.012	0.115	<0.01	<0.02	<0.005	<0.10	<0.01	0.440	3.210

Thriplow groundwater composition, July 1996

Location	Field Temp °C	Field Eh mV	Field pH	Field HCO3 mg/l	Conductivity S/cm	DO2 mg/l	pH	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO3 mg/l	Cl mg/l	SO4 mg/l	NO3 mg/l
Drilling Fluid	19.6	346	7.14	249	1,265	5.00	7.95	207	2.82	64.4	2.37	306	173	86.9	66.8
DI Water Blank	n/d	#VALUE!	n/d	20	n/d	n/d	4.23	<0.05	<0.10	<0.02	<0.50	<20	<0.10	<0.10	<0.10
BH4	16.7	49	6.85	11583	34,200	n/d	7.65	1,900	627	1,630	1,270	15,324	1,610	<50.0	<50.0
TP5	15.2	114	7.12	2170	4,290	n/d	8.05	212	71.6	288	237	2,432	296	<5.00	<5.00
TP3	19.5	247	7.77	10558	17,750	n/d	8.31	137	253	1,745	985	8,869	2,390	61.2	<10.0
TR1/1	25.9	391	7.41	244	1,407	6.00	7.71	213	2.81	62.9	2.26	275	155	116	80.0
TR1/3	13.3	412	7.09	222	674	5.50	7.64	151	1.46	22.5	0.64	226	88.8	19.3	69.2
TR1/4	14.9	355	7.19	224	901	4.50	7.51	173	2.30	37.6	1.35	255	113	32.6	63.6
TR1/5/2	14.0	374	7.17	210	802	3.50	7.58	158	2.09	28.5	0.83	249	101	26.7	61.9
TR1/7	15.1	394	7.13	239	908	4.50	7.63	176	4.13	43.0	1.62	277	126	37.1	51.8
TR1/8	15.6	414	7.14	244	903	3.50	7.62	181	4.09	46.6	1.60	286	127	39.4	52.7
TR1/9	17.4	487	6.51	273	920	3.50	7.60	187	5.30	56.1	1.66	317	143	35.9	40.3
TR1/10	14.8	553	7.25	317	971	3.50	7.45	190	5.14	79.8	1.73	361	168	65.9	39.3
TR1/11	15.3	423	7.04	390	1,052	2.50	7.52	172	5.28	71.0	1.58	360	146	58.2	37.0
TR1/12	18.0	392	7.08	293	964	3.50	7.47	166	5.93	64.5	1.82	340	102	49.3	34.0
TR1/13	18.3	444	7.14	239	990	4.50	7.57	180	4.86	52.0	1.87	287	121	50.1	53.6
TR1/14	15.5	409	7.16	249	720	3.50	7.80	132	5.52	20.1	1.79	275	47.3	28.8	38.5
TR1/15	14.6	454	7.10	249	736	3.50	7.53	137	5.94	22.5	2.02	266	52.2	30.8	37.8
TR1/16	19.6	461	7.12	224	1,240	4.50	7.43	162	2.39	31.9	1.46	256	100	35.2	63.3
TP2	30.9	379	6.30	800	1,868	3.50	7.49	411	3.44	21.7	1.66	913	41.9	104	24.0
TP7	22.6	385	7.37	2487	4950	3.50	8.08	159	82.7	298	266	2,682	304	34.3	<1.00

Thriplow groundwater composition, July 1996.

Location	Br	NO2	TOC	TIC	Total	NH4	Si	Mn	Total	Reduced	Al
					S				Fe	Fe	
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Drilling Fluid	1.09	0.26	3.33	61.8	29.6	<0.10	5.97	<0.005	0.04	0.11	0.12
DI Water Blank	<0.03	<0.02	<1.00	<0.50	<0.20	<0.10	<0.02	<0.005	<0.02	<0.01	<0.02
BH4	<15.0	11.5	10,720	432	51.5	2,320	21.6	11.4	226	139	1.07
TP5	2.09	<1.00	148	474	6.12	311	11.9	0.252	17.3	19.9	0.13
TP3	116	<2.00	930	1,570	51.2	1,060	12.3	0.267	3.97	5.27	<0.20
TR1/1	1.12	0.25	6.96	55.8	39.2	<0.10	5.23	0.014	<0.02	0.02	0.10
TR1/3	0.62	0.15	2.24	44.3	7.72	0.20	4.75	0.032	<0.02	0.01	0.09
TR1/4	0.65	0.31	2.84	51.4	12.8	0.13	5.44	0.009	0.02	0.03	0.10
TR1/5/2	0.68	0.27	2.47	50.4	10.3	<0.10	5.12	0.020	0.02	0.06	0.07
TR1/7	0.89	0.28	3.11	57.4	14.2	<0.10	6.26	0.006	<0.02	0.02	0.07
TR1/8	0.92	0.27	1.69	58.4	15.0	<0.10	6.40	0.008	<0.02	0.03	0.07
TR1/9	0.76	0.26	3.80	63.7	13.8	<0.10	7.21	0.007	<0.02	<0.01	0.07
TR1/10	1.27	0.35	4.78	71.4	23.7	<0.10	7.07	0.007	<0.02	<0.01	0.08
TR1/11	1.06	<0.20	4.15	70.2	20.0	<0.10	7.32	0.008	0.01	0.01	0.09
TR1/12	0.66	0.31	3.57	67.9	18.3	<0.10	8.02	<0.005	<0.02	0.03	0.07
TR1/13	0.53	0.29	2.78	56.0	19.0	<0.10	6.73	0.011	<0.02	<0.01	0.08
TR1/14	0.27	<0.20	2.41	57.2	11.0	<0.10	7.23	0.005	<0.02	<0.01	0.06
TR1/15	0.25	0.26	2.44	55.0	12.1	<0.10	7.12	<0.005	<0.02	<0.01	0.56
TR1/16	0.48	<0.20	3.87	49.5	13.3	<0.10	5.00	0.063	<0.02	0.03	0.08
TP2	<0.60	1.50	12.0	196	35.3	0.73	9.92	0.072	<0.02	<0.01	0.14
TP7	3.13	0.28	113	493	15.7	454	9.53	0.175	0.47	0.81	0.11

Thriplow groundwater composition, July 1996.

Location	Co	Ni	Cu	Zn	Cr	Mo	Cd	Pb	V	Li	B
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Drilling Fluid	<0.02	<0.10	0.021	0.067	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	0.062
DI Water Blank	<0.02	<0.10	<0.005	<0.005	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	<0.005
BH4	<0.20	<1.00	<0.050	1.591	<0.20	<0.20	0.182	<1.00	<0.10	1.67	0.010
TP5	<0.02	<0.10	<0.005	0.015	<0.02	<0.02	<0.005	<0.10	<0.01	0.23	0.005
TP3	<0.20	<1.00	<0.050	1.620	<0.20	<0.20	<0.050	<1.00	<0.10	0.67	0.005
TR1/1	<0.02	<0.10	0.020	0.106	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	0.044
TR1/3	<0.02	<0.10	<0.005	0.038	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	<0.005
TR1/4	<0.02	<0.10	<0.005	0.059	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	<0.005
TR1/5/2	<0.02	<0.10	<0.005	0.049	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	0.017
TR1/7	<0.02	<0.10	<0.005	0.054	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	<0.005
TR1/8	<0.02	<0.10	<0.005	0.046	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	<0.005
TR1/9	<0.02	<0.10	<0.005	0.049	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	<0.005
TR1/10	<0.02	<0.10	<0.005	0.065	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	0.089
TR1/11	<0.02	<0.10	<0.005	0.069	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	0.080
TR1/12	<0.02	<0.10	<0.005	0.069	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	<0.005
TR1/13	<0.02	<0.10	<0.005	0.041	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	<0.005
TR1/14	<0.02	<0.10	<0.005	0.033	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	0.013
TR1/15	<0.02	<0.10	<0.005	0.102	<0.02	<0.02	<0.005	<0.10	<0.01	0.02	0.000
TR1/16	<0.02	<0.10	0.010	0.102	<0.02	<0.02	<0.005	<0.10	<0.01	0.01	0.021
TP2	<0.02	<0.10	<0.005	0.050	<0.02	<0.02	<0.005	<0.10	<0.01	<0.01	<0.005
TP7	<0.02	<0.10	0.025	<0.005	<0.02	<0.02	<0.005	<0.10	<0.01	0.36	<0.005

Thriplow groundwater composition, September 1997.

Location	Date	Field	Field	Field	Field	Conductivity	DO2	NH4	pH	Ca	Mg	Na	K	HCO3	Cl
	Collected	Temp	Eh	pH	HCO3										
		°C	mV		mg/l	µS/cm	mg/l	mg/l		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
TR5 (lower)	1/9/97	21.3	475	6.91	244	1129	2-3	0	7.90	183	1.91	37.3	33.4	292	160
TR5 (upper)	1/9/97	24.2	480	6.83	1804	1425	4-5	0	7.98	527	3.41	51.0	3.78	1,804	187
TR6	1/9/97	24.3	470	6.80	334	2200	3-4	0	8.07	327	3.87	91.9	119	434	345
B15	1/9/97	20.5	532	6.70	471	2340	3-4	0	8.14	432	3.93	124	4.92	562	372
TBH3	1/9/97	18.4	347	6.48	1073	4060	0.6-0.8	~50	7.87	324	9.22	606	52.6	1,149	725
TR9 (lower)	2/9/97	16.1	305	6.42	673	1749	0.8-1.0	0	7.86	322	2.60	125	5.74	641	230
TBH5 (upper)	2/9/97	17.3	427	6.82	780	2900	2-3	~2.5	7.69	353	5.66	344	16.7	814	512
TBH5 (lower)	2/9/97	14.6	434	7.04	551	1540	0.3-0.4	0	8.12	207	4.59	146	23.8	515	257
TBH7	2/9/97	16.9	435	6.91	580	2200	1-2	~2.5	8.10	266	4.60	241	36.1	555	284
TR8	2/9/97	16.2	405	7.20	507	1680	2-3	0	8.40	392	8.97	34.5	16.3	449	146
TBH4	8/9/97	18.9	476	7.31	305	1048	1-2	0	8.43	174	4.26	49.7	3.75	315	149
TR1	8/9/97	19.6	455	7.22	305	918	2-3	0	8.01	148	3.63	36.8	2.96	283	93.2
TR7 (lower)	8/9/97	21.4	570	6.66	532	2030	3-4	0	7.77	392	4.06	121	1.511	511	296
TR4	8/9/97	14.4	464	6.65	800	3230	0.8-1.0	~10	7.02	400	6.51	362	8.92	893	525
TBH2 (outer)	9/9/97	14.3	483	7.61	561	1431	1-2	~25	8.15	208	13.4	70.0	41.9	589	106
TBH2 (inner)	9/9/97	14.7	494	8.29	351	822	1-2	~10	8.31	130	6.42	31.5	19.7	352	44.2
TR3 (lower)	9/9/97	17.0	486	6.99	419	910	4-5	0	8.48	220	2.66	13.8	2.633	469	37.4
TP7	9/9/97	16.9	-38	7.08	1439	3600	1	~100	7.77	187	110	336	263	1,531	350
TP5	9/9/97	16.7	101	7.36	2624	5630	0.6-0.8	~400	7.85	128	68.9	513	328	2624	644
TP3	9/9/97	20.2	130	7.46	7754	17300	~1	~400	7.92	87.5	216	1678	900	7854	2,262
Monitoring well	9/9/97	18.0	40	7.39	n/d	13600	n/d	~200	7.77	380	403	1194	751	4805	1,622

Thriplow groundwater composition, September 1997.

Location	SO4	NO3	Br	NO2	TOC	TIC	Total	Total	Reduced	NH4
							P	S	S	
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	mg/l
TR5 (lower)	40.9	62.8	0.70	<0.10	1.46	56.4	<0.10	16.4	10.4	<1.00
TR5 (upper)	101	70.8	0.62	<0.10	1.77	69.7	0.68	37.5	18.5	<1.00
TR6	206	84.4	0.67	<0.10	2.31	90.8	<0.10	70.0	9.11	<1.00
B15	213	90.8	0.94	<0.40	7.98	113	<0.10	71.4	18.2	<1.00
TBH3	231	<2.00	7.33	<0.40	69.7	248	<0.10	83.9	158	48.4
TR9 (lower)	125	16.2	1.63	<0.20	14.1	131	0.19	44.2	23.1	<1.00
TBH5 (upper)	187	17.8	3.33	<0.40	27.7	174	<0.10	64.6	69.8	4.29
TBH5 (lower)	47.1	24.8	2.15	<0.40	18.8	106	<0.10	19.2	53.7	1.05
TBH7	296	89.5	1.75	<0.20	5.30	107	<0.10	98.9	17.5	5.02
TR8	379	30.6	0.51	<0.10	<1.00	89.9	<0.10	128	36.0	<1.00
TBH4	38.2	48.0	1.10	<0.10	2.38	62.7	<0.10	17.1	6.88	<1.00
TR1	44.1	48.2	0.70	<0.10	3.05	56.8	<0.10	18.8	10.5	<1.00
TR7 (lower)	244	59.9	0.71	<0.10	5.20	97.4	<0.10	86.2	15.4	<1.00
TR4	241	<2.00	5.00	<0.40	56.9	210	<0.10	86.4	64.7	11.5
TBH2 (outer)	118	83.0	0.53	<0.10	8.98	112	<0.10	40.7	18.5	21.0
TBH2 (inner)	34.3	74.9	0.26	<0.10	5.42	68.3	<0.10	12.7	6.84	7.41
TR3 (lower)	44.6	78.2	0.18	<0.10	4.63	93.6	0.20	16.9	11.3	<1.00
TP7	270	172	3.16	1.00	96.3	313	0.77	95.6	1981	74.6
TP5	<2.00	<2.00	5.39	<0.40	203	517	0.399	8.70	1116	447
TP3	84.5	<5.00	101	<1.00	578	1,546	4.237	53.4	36.3	1852
Monitoring well	<5.00	<5.00	11.9	<1.00	1,586	946	1.145	20.4	48.3	1220

Thriplow groundwater composition, September 1997.

Location	Si	Ba	Sr	Mn	Total	Reduced	Oxidised	Al	Co	Ni	Cu	Zn	Cr	Mo	Cd
					Fe	Fe	Fe								
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
TR5 (lower)	4.14	0.059	0.306	0.010	<0.01	0.02	<0.04	<0.10	<0.02	<0.02	<0.005	<0.005	<0.01	<0.02	<0.005
TR5 (upper)	9.18	0.094	0.772	0.393	3.66	<0.01	#VALUE!	2.40	<0.02	<0.02	<0.005	0.028	<0.01	<0.02	<0.005
TR6	4.97	0.081	0.454	0.067	<0.01	0.02	<0.00	0.11	<0.02	<0.02	<0.005	<0.005	<0.01	<0.02	<0.005
B15	5.66	0.089	0.537	0.014	0.04	0.06	<0.01	0.15	0.05	<0.02	<0.005	0.015	<0.01	<0.02	<0.005
TBH3	8.12	0.101	0.479	0.169	0.65	0.89	<0.00	<0.10	<0.02	0.06	<0.005	0.013	<0.01	<0.02	<0.005
TR9 (lower)	6.11	0.067	0.422	0.067	0.67	0.81	0.03	0.12	<0.02	0.02	<0.005	<0.005	<0.01	<0.02	<0.005
TBH5 (upper)	6.12	0.094	0.496	0.143	0.02	0.07	0.01	0.15	0.02	0.03	<0.005	0.019	<0.01	<0.02	<0.005
TBH5 (lower)	6.06	0.060	0.587	0.086	0.07	0.13	0.02	<0.10	<0.02	<0.02	<0.005	0.014	<0.01	<0.02	<0.005
TBH7	5.38	0.061	0.432	0.030	<0.01	0.03	0.01	<0.10	<0.02	<0.02	<0.005	0.010	<0.01	<0.02	<0.005
TR8	5.12	0.088	0.652	0.293	0.02	0.06	#VALUE!	<0.10	<0.02	<0.02	<0.005	0.006	<0.01	<0.02	<0.005
TBH4	5.29	0.049	0.608	0.001	<0.01	0.07		<0.10	<0.02	<0.02	<0.005	0.010	<0.01	<0.02	<0.005
TR1	4.70	0.040	0.516	0.013	0.03	0.03		<0.10	<0.02	<0.02	<0.005	0.019	<0.01	<0.02	<0.005
TR7 (lower)	5.61	0.072	0.485	0.009	<0.01	0.09		<0.10	<0.02	<0.02	<0.005	0.010	<0.01	<0.02	<0.005
TR4	7.66	0.100	0.574	0.171	0.01	0.05		0.149	<0.02	0.05	0.022	0.019	<0.01	<0.02	<0.005
TBH2 (outer)	4.31	0.073	0.477	0.115	<0.01	0.03		<0.10	<0.02	0.02	0.018	0.035	<0.01	<0.02	<0.005
TBH2 (inner)	3.91	0.055	0.326	0.044	<0.01	0.02		<0.10	<0.02	<0.02	<0.005	0.010	<0.01	<0.02	<0.005
TR3 (lower)	5.42	0.047	0.408	0.006	<0.01	0.01		<0.10	<0.02	<0.02	<0.005	<0.005	<0.01	<0.02	<0.005
TP7	8.57	0.126	1.137	0.235	0.38	2.95		<0.10	<0.02	0.02	<0.005	0.028	<0.01	<0.02	<0.005
TP5	11.5	0.329	0.997	0.146	20.2	22.1		<0.10	<0.02	0.04	0.014	0.215	0.038	<0.02	<0.005
TP3	11.2	0.256	1.150	0.065	2.30	4.30		0.12	<0.02	0.18	<0.005	<0.005	0.086	<0.02	<0.005
Monitoring well	15.4	0.065	2.817	0.721	50.7	83.8		0.14	<0.02	0.12	<0.005	<0.005	<0.01	<0.02	<0.005

Thriplow groundwater composition, September 1997.

Location	Pb	V	Li	B
	mg/l	mg/l	mg/l	mg/l
TR5 (lower)	<0.01	<0.01	<0.010	0.15
TR5 (upper)	<0.01	<0.01	0.012	0.15
TR6	<0.01	<0.01	<0.010	0.08
B15	<0.01	<0.01	<0.010	0.08
TBH3	<0.01	<0.01	0.132	5.43
TR9 (lower)	<0.01	<0.01	<0.010	0.73
TBH5 (upper)	<0.01	<0.01	0.045	2.58
TBH5 (lower)	<0.01	<0.01	0.023	1.70
TBH7	<0.01	<0.01	0.100	1.88
TR8	<0.01	<0.01	<0.010	0.14
TBH4	<0.01	<0.01	0.012	0.47
TR1	<0.01	<0.01	0.011	0.29
TR7 (lower)	<0.01	<0.01	<0.010	0.05
TR4	<0.01	<0.01	0.075	2.78
TBH2 (outer)	<0.01	<0.01	0.040	0.36
TBH2 (inner)	<0.01	<0.01	0.016	0.13
TR3 (lower)	<0.01	<0.01	<0.010	<0.05
TP7	<0.01	<0.01	0.564	3.42
TP5	<0.01	<0.01	0.273	2.06
TP3	<0.01	<0.01	0.704	3.34
Monitoring well	<0.01	0.01	1.095	5.91

Thriplow groundwater composition, November 1997.

Location	Temp	pH Field	DO_2 Field	Chloride	TOC	Ammonia
	°C		mg/l	mg/l	mg/l	mg/l
TBH2	n/d	6.84	n/d	109	8.35	20.8
TBH3	13.6	6.36	n/d	817	76.5	38.8
TBH4	10.6	7.55	n/d	132	2.17	0.03
TBH5 - Upper	13.2	6.25	n/d	511	14.4	2.31
TBH5 - Lower	12.4	7.52	n/d	138	3.21	0.03
TBH7	12.7	6.89	n/d	284	9.11	8.6
TR3 - Lower	n/d	6.71	n/d	36	1.73	0.04
TR4	11.2	6.4	0.7	563	36.4	4.82
TR5 - Upper	12	7.33	n/d	139	2.31	0.03
TR5 - Lower	12.4	7.52	n/d	138	3.21	0.03
TR6	n/d	n/d	n/d	266	4.18	0.03
TR7 - Lower	n/d	n/d	n/d	320	5.62	0.05
TR8	13.9	6.95	n/d	151	2.97	0.03
TR9 -Lower	14	6.98	n/d	249	4.8	0.13
n/d - not determined						

Appendix B

Waste characterisation
TP2, TP3, TP5, TP6 and TP7

TP2 waste characterisation (Phase 2: capped).

Reference	Depth Midpoint mbgl	Dated Material	Paper %	Card Board %	Plastic Film %	Plastic Bottles %	Dense Plastic %	Blown Plastic %	Textiles %	Brown Glass %	Green Glass %	Clear Glass %	Putrescible %	Non Ferrous Unidentifiable %	Non Ferrous Beverage Cans %	Foil Containers %	Non Ferrous Closures %
TP/02/04/A	1.25		14.8	6.3	5.0	~	2.0	~	~	~	~	1.1	5.9	0.5	~	~	~
TP/02/04/B	1.25	1984	9.3	9.0	5.2	~	0.8	~	0.3	1.0	1.0	0.2	2.5	~	~	~	~
TP/02/04/C	1.25	1984	8.5	1.2	4.0	~	~	~	~	~	~	0.5	1.5	~	~	~	~
TP/02/06/A	2.25		8.8	~	2.5	~	~	~	11.7	~	~	~	~	~	~	~	~
TP/02/06/B	2.25		2.9	~	2.7	~	0.4	~	8.3	~	~	~	~	~	~	~	~
TP/02/08/A	3.25		0.2	~	0.3	~	0.3	~	0.2	~	0.3	~	~	2.5	~	~	~
TP/02/08/B	3.25		0.3	0.2	~	~	0.2	~	2.0	~	0.2	~	~	~	~	~	~
TP/02/10/A	4.3		~	~	~	~	~	~	~	~	~	~	~	~	~	~	~
TP/02/10/B	4.3		0.6	~	~	~	~	~	~	~	~	~	~	~	~	~	~
TP/02/12/A	5.25		~	~	~	~	~	~	~	~	~	~	~	~	~	~	~
TP/02/12/B	5.25		~	~	~	~	~	~	~	~	~	~	~	~	~	~	~
TP/02/13/A	5.75		~	~	~	~	~	~	~	~	~	~	~	~	~	~	~
TP/02/13/B	5.75		~	~	~	~	~	~	~	~	~	~	~	~	~	~	~
TP/02/15/A	7.05	1979	3.1	0.8	2.8	~	2.0	~	0.4	0.3	~	1.3	0.4	~	~	~	~
TP/02/15/B	7.05		1.6	0.9	3.7	~	2.9	~	~	~	~	0.6	~	~	~	~	~
TP/02/16/A	8		6.7	1.0	3.8	~	2.9	~	~	~	~	0.4	~	0.2	~	~	~
TP/02/16/B	8		1.4	2.2	3.1	~	2.3	~	0.8	~	~	0.2	~	~	~	~	~

Reference	Ferrous Unidentifiable %	Ferrous Food Can %	Ferrous Closures %	Aerosols %	Wood %	Other Combustibles %	Other Non Combustibles %	Chalk /Cinder %	Fines (5mm) %	Residue %	Empty Bag %	Pre-sort Weight g
TP/02/04/A	~	1.6	~	~	1.4	0.9	~	5.3	20.0	33.9	0.6	16000
TP/02/04/B	4.5	~	~	~	0.8	0.8	~	6.0	21.7	35.5	0.8	15000
TP/02/04/C	0.5	~	~	~	1.5	~	0.5	0.5	25.0	52.8	1.5	5000
TP/02/06/A	1.9	~	~	~	0.2	~	~	1.0	35.4	37.5	0.8	12000
TP/02/06/B	0.6	~	~	~	1.6	~	~	15.8	35.4	30.9	1.0	12000
TP/02/08/A	0.3	~	~	~	12.5	0.9	1.1	5.6	32.8	41.9	0.9	16000
TP/02/08/B	5.2	~	~	~	8.8	~	0.2	3.9	32.8	45.4	0.8	16000
TP/02/10/A	~	~	~	~	0.3	~	0.1	9.7	42.3	46.8	0.5	19500
TP/02/10/B	0.3	~	~	~	0.6	~	~	1.4	16.3	80.1	0.8	20000
TP/02/12/A	~	~	~	~	~	~	~	~	~	99.4	0.5	24000
TP/02/12/B	~	~	~	~	~	~	~	~	~	99.2	0.8	18500
TP/02/13/A	0.4	~	~	~	0.8	~	~	~	~	97.9	0.8	13000
TP/02/13/B	~	~	~	~	~	~	~	~	~	98.6	1.1	14000
TP/02/15/A	3.3	~	~	~	0.4	0.5	~	7.5	21.3	55.5	0.5	20000
TP/02/15/B	3.2	~	~	~	~	0.1	~	8.2	22.1	55.3	0.7	17000
TP/02/16/A	0.8	~	~	~	2.1	~	1.7	3.3	35.4	40.0	1.0	12000
TP/02/16/B	2.5	~	~	~	0.2	0.8	3.1	8.8	39.1	34.4	0.9	16000

TP2 waste characterisation (Phase 2: capped).

Reference	Description of Sample	CO2	CH4	O2
		%	%	%
TP/02/04/A	Majority of sample paper and plastic with numerous pieces of organics.	9.40	0.02	8.50
TP/02/04/B	Paper and plastics (surface mould), low content of soil and clay. 1984 newspaper.	13.50	0.08	4.40
TP/02/04/C	Clay material, fragments of wood, newsprint and chalk. 1984 bank statement.	0.92	0.01	0.92
TP/02/06/A	Clay material with pieces of white plastic and film.	8.74	0.01	0.64
TP/02/06/B	Soil/chalk material with textiles and plastics.	8.10	0.01	10.60
TP/02/08/A	Large pieces of wood, with soil, clay and chalk pieces.	0.97	0.04	0.92
TP/02/08/B	Soil/builders rubble with pieces of plastic.	0.11	0.11	22.00
TP/02/10/A	Soil/clay with large pieces of brick rubble/ferrous metal fragments.	0.87	0.11	20.20
TP/02/10/B	Clay/chalk and brick rubble.	1.29	2.10	16.10
TP/02/12/A	Clay and chalk material.	3.00	0.04	21.90
TP/02/12/B	Chalk and fill material with pieces of clay.	0.02	0.01	21.60
TP/02/13/A	Mostly chalk/clay with fragments of plastic.	0.60	0.04	20.40
TP/02/13/B	Clay and soil material only.	0.49	0.09	20.80
TP/02/15/A	Clay, chalk pieces with surface mould on plastics. (Piece of paper found 1979).	6.95	0.02	13.70
TP/02/15/B	Clay and chalk with pieces of plastic.	1.36	0.06	20.00
TP/02/16/A	Clay material with chalk and plastic remains.	3.17	0.01	18.00
TP/02/16/B	Soil, clay and chalk material with plastics and ferrous pieces.	7.42	0.04	9.20

TP3 waste characterisation (Phase 2: capped).

Date	Reference	Dated Material	Depth. Midpoint	Paper	Card Board	Plastic Film	Plastic Bottles	Dense Plastic	Blown Plastic	Textiles	Brown Glass	Green Glass	Clear Glass	Putrescible	Non Ferrous Unidentifiable	Non Ferrous Beverage Cans
			mbgl	%	%	%	%	%	%	%	%	%	%	%	%	%
9/8/00	TP/03/01/G		0.6	~	~	~	~	~	~	~	~	~	~	~	~	~
9/8/00	TP/03/02/A	Dec-87	1.35	10.0	12.5	13.8	~	5.4	~	45.8	~	~	~	~	~	~
8/8/00	TP/03/02/B		1.35	18.8	13.8	8.8	0.3	1.3	~	28.1	1.3	1.4	0.3	~	~	~
8/8/00	TP/03/04/A	Apr-87	2.25	20.0	3.9	5.6	~	1.1	~	2.8	~	~	1.4	19.4	~	0.6
9/8/00	TP/03/04/B		2.25	15.9	25.0	4.7	~	3.4	~	10.3	~	~	1.3	0.6	0.9	~
9/8/00	TP/03/05/A	1980/81	2.7	16.0	7.3	3.8	0.3	2.8	~	19.5	~	~	0.8	~	~	1.3
9/8/00	TP/03/05/B	1985	2.7	18.3	15.8	5.4	0.8	2.1	~	8.3	~	~	0.8	0.8	~	0.2
8/8/00	TP/03/06/A	1986	3.25	1.0	0.3	1.2	~	0.2	~	0.4	~	~	0.2	~	~	~
9/8/00	TP/03/06/B		3.25	0.6	0.2	1.8	~	0.3	~	~	~	~	0.3	~	~	~
10/8/00	TP/03/08/A		4.2	~	~	~	~	~	~	~	~	~	~	~	~	~
9/8/00	TP/03/08/B		4.2	~	~	~	~	~	~	~	~	~	~	~	~	~
8/8/00	TP/03/09		3.8	1.4	~	1.1	~	5.0	~	0.2	~	~	0.5	6.4	~	~
10/8/00	TP/03/10/A		4.75	3.4	0.3	8.1	~	3.8	1.0	0.6	~	~	~	~	~	~
9/8/00	TP/03/10/B		4.75	9.1	5.3	9.4	~	0.3	0.3	2.5	~	0.3	0.6		~	~
8/8/00	TP/03/12/A		6.5	~	1.6	2.7	~	0.5	~	2.7	~	~	~	~	~	0.2
8/8/00	TP/03/12/B	1983	6.5	2.3	0.4	1.1	~	0.2	~	0.2	~	~	~	~	~	~
10/8/00	TP/03/12/C		6.5	~	1.4	1.3	~	1.1	~	~	~	~	~	~	~	~
8/8/00	TP/03/13/A		7.5	2.3		3.3	~	1.9	0.1	0.5	~	~	0.1	1.7	~	~
8/8/00	TP/03/13/B		7.5	3.6	2.0	2.5	~	0.5	~	0.9	~	~	0.1	1.7	~	~
9/8/00	TP/03/14/A	1983	8.5	6.7	2.7	4.7	~	2.2	~	0.2	~	~	0.7	~	~	0.2
8/8/00	TP/03/14/B		8.5	13.7	2.7	5.6	~	~	~	0.1	~	~	0.2	~	~	0.1

TP3 waste characterisation (Phase 2: capped).

Reference	Foil	Non Ferrous	Ferrous	Ferrous	Ferrous	Aerosols	Wood	Other	Other Non	Chalk /Cinder	Fines	Residue	Empty	Pre-sort
	Containers	Closures	Unidentifiable	Food Can	Closures			Combustibles	Combustibles		(5mm)		Bag	Weight
	%	%	%	%	%	%	%	%	%	%	%	%	%	g
TP/03/01/G	~	~	~	~	~	~	~	~	~	~	~	94.3	3.6	3500
TP/03/02/A	~	~	~	~	~	~	1.3	~	~	4.2	2.5	1.7	1.7	6000
TP/03/02/B	~	~	0.1	3.1	0.1	0.1	1.3	1.3	~	3.1	12.5	3.1	0.9	8000
TP/03/04/A	0.3	~	18.9	~	~	1.1	0.3	6.1	~	~	~	16.7	1.1	9000
TP/03/04/B	~	~	~	4.4	~	~	0.3	2.5	~	~	15.6	12.5	1.6	8000
TP/03/05/A	~	~	5.0	~	~	~	0.5	0.8	2.5	6.0	12.5	19.5	1.5	10000
TP/03/05/B	0.2	~	5.4	~	~	~	1.3	7.1	~	~	10.4	20.8	1.3	12000
TP/03/06/A	~	~	0.5	1.3	0.7	~	0.4	~	0.9	11.2	45.2	35.6	0.7	26000
TP/03/06/B	~	~	3.0	~	~	~	0.7	0.1	~	1.8	33.0	57.2	0.5	25000
TP/03/08/A	~	~	~	~	~	~	~	~	~	~	~	99.3	0.6	22000
TP/03/08/B	~	~	~	~	~	~	0.2	~	~	~	~	98.7	0.8	15000
TP/03/09	~	~	~	~	~	~	9.5	~	0.5	3.6	29.5	40.9	1.1	11000
TP/03/10/A	~	~	~	~	~	0.3	8.8	~	1.9	10.0	15.6	44.4	1.3	8000
TP/03/10/B	~	~	~	~	~	~	7.5	~	2.5	17.5	15.6	26.9	1.6	8000
TP/03/12/A	~	~	1.8	~	~	~	5.2	~	1.1	3.2	14.8	65.5	0.6	22000
TP/03/12/B	~	~	1.7	~	~	~	1.1	~	~	9.0	81.0	2.4	0.5	21000
TP/03/12/C	~	~	4.6	~	~	~	~	~	1.1	13.6	7.5	68.2	1.1	14000
TP/03/13/A	~	~	0.5	~	~	~	1.5	~	0.1	7.3	4.4	77.6	0.5	26000
TP/03/13/B	~	~	0.4	~	~	~	2.2	~	0.1	13.0	1.1	67.4	0.4	23000
TP/03/14/A	~	~	2.7	~	~	~	9.7	2.0	0.2	6.7	6.7	53.3	0.7	15000
TP/03/14/B	~	~	0.3	~	~	~	2.5	0.8	0.9	20.0	7.1	44.2	0.8	12000

TP3 waste characterisation (Phase 2: capped).

Reference	Description of Sample	CO2	CH4	O2
		%	%	%
TP/03/01/G	Soil/clay material.	0.62	0.01	21.60
TP/03/02/A	Mixed paper, plastic and textiles, very few fines or residue.	13.20	0.01	0.38
TP/03/02/B	Soil and clay material with fragments of plastics and organics.	15.80	0.10	2.90
TP/03/04/A	Waste not well degraded, odorous, plastics, newsprint April 1987, textiles and a nappy.	0.17	0.05	21.30
TP/03/04/B	Majority of sample paper, card and plastic, very little soil.	3.04	0.01	17.40
TP/03/05/A	Mixed sample, textiles, plastics, paper and a 1987 newspaper. Not well degraded (mould abundant).	2.64	0.07	18.00
TP/03/05/B	Mostly cardboard and paper, 1985 newspaper, waste not degraded (surface mould growth).	1.60	0.01	19.70
TP/03/06/A	Very granular sandy clay with pieces of tarmac, plastics and 1986 magazine.	1.50	0.01	19.80
TP/03/06/B	Very granular with pieces of chalk, very few other remains.	3.49	0.03	17.70
TP/03/08/A	Chalk and clay material only.	0.24	0.09	20.40
TP/03/08/B	Clay/chalk with fragments of paper.	0.98	0.03	20.50
TP/03/09	Clay material, numerous pieces of chalk, oil filter with paper fragments.	0.54	0.03	21.00
TP/03/10/A	Soil and chalk with mixed paper/ plastic and wood.	0.06	1.70	17.60
TP/03/10/B	Clay and builders rubble with large pieces of cardboard and plastic sheeting.	0.04	0.15	12.70
TP/03/12/A	Soil/clay residue with fragments of paper and plastic.	3.99	0.07	17.40
TP/03/12/B	Clay material, white plastic flakes, degraded fragments of newsprint (1983).	0.33	0.01	21.20
TP/03/12/C	Soil/clay material with white plastic flakes and degraded newsprint.	2.84	0.12	19.61
TP/03/13/A	Clay material, black organics highly degraded.	3.17	0.18	11.60
TP/03/13/B	Clay material with paper fragments, textiles, large chalk pieces.	0.25	0.01	21.30
TP/03/14/A	Clay and chalk material, numerous pieces of plastic, plus a 1983 newspaper.	4.02	0.02	17.60
TP/03/14/B	Well rotted organics, plastic film, ferrous fragments with a clay/chalk material.	10.60	0.26	8.40

TP5 waste characterisation (Phase 2: capped).

Date	Reference	Depth Midpoint mbgl	Dated Material	Paper %	Card Board %	Plastic Film %	Plastic Bottles %	Dense Plastic %	Blown Plastic %	Textiles %	Brown Glass %	Green Glass %	Clear Glass %	Putrescible %	Non Ferrous Unidentifiable %	Non Ferrous Beverage Cans %	Foil Containers %	Non Ferrous Closures %
10/8/00	TP/05/01	0.5		~	~	~	~	~	~	~	~	~	~	~	~	~	~	~
9/8/00	TP/05/03/A	2.25		~	~	~	~	~	~	~	~	~	~	~	~	~	~	~
9/8/00	TP/05/03/A	2.25		6.8	0.4	4.4	1.6	0.4	~	8.0	~	~	1.4	~	~	~	~	~
10/8/00	TP/05/03/B	2.25		5.0	~	5.7	~	2.0	~	6.1	~	~	0.4	~	0.4	~	~	~
9/8/00	TP/05/06/A	2.75		~	~	1.5	~	0.3	~	0.1	~	~	0.1	~	~	~	~	~
10/8/00	TP/05/06/B	2.75		~	~	0.2	~	0.2	~	0.4	~	~	~	~	~	~	~	~
8/8/00	TP/05/07/A	3.25	1972	4.5	0.6	5.3	~	2.2	~	0.3	0.3	0.2	1.9	0.2	~	0.3	~	~
10/8/00	TP/05/07/B	3.25	1975	3.3	3.8	5.0	~	1.5	~	3.5	~	~	2.3	~	~	0.3	~	~
10/8/00	TP/05/09/A	4.25		5.3	~	16.3	~	2.5	~	1.0	~	~	1.3	~	~	~	~	~
9/8/00	TP/05/09/B	4.25	1975	4.4	~	13.5	~	2.1	~	0.8	~	~	1.0	~	~	~	~	~
8/8/00	TP/05/11/A	5.3	1974	17.6	0.3	13.2	~	6.2	~	0.5	~	~	9.1	~	~	0.5	~	~
9/8/00	TP/05/11/B	5.3		12.0	~	12.0	~	3.2	~	0.8	~	~	4.9	~	~	0.2	~	~
10/8/00	TP/05/13/B	6.25		6.9	~	21.9	~	2.0	~	2.5	~	~	3.8	~	5.2	~	~	~
9/8/00	TP/05/14/A	6.75		~	~	14.9	~	~	~	~	~	~	~	~	~	~	~	~
10/8/00	TP/05/14/B	6.75		0.5	~	16.3	~	1.7	~	6.1	~	~	0.3	~	3.7	~	~	~
9/8/00	TP/05/16/A	8.75		~	~	~	~	~	~	~	~	~	~	~	~	~	~	~

Reference	Ferrous Unidentifiable %	Ferrous Food Can %	Ferrous Closures %	Aerosols %	Wood %	Other Combustibles %	Other Non Combustibles %	Chalk /Cinder %	Fines (5mm) %	Residue %	Empty Bag %	Pre-sort Weight g
TP/05/01	~	~	~	~	~	~	~	~	~	98.3	1.7	6000
TP/05/03/A	~	~	~	~	~	~	~	~	~	99.1	0.9	17000
TP/05/03/A	0.8	~	~	~	~	~	~	15.2	6.0	52.8	1.6	12500
TP/05/03/B	6.4	~	~	~	0.5	~	~	13.6	23.2	35.7	0.9	14000
TP/05/06/A	0.8	~	~	~	0.4	~	~	18.8	27.9	49.6	0.4	26000
TP/05/06/B	0.3	~	~	~	0.3	~	~	23.6	17.0	57.2	0.5	25000
TP/05/07/A	3.4	~	~	~	1.9	~	0.2	8.4	26.6	42.5	0.3	16000
TP/05/07/B	3.3	~	~	~	~	~	0.5	24.0	32.5	19.0	0.8	10000
TP/05/09/A	~	~	~	~	0.3	0.5	~	~	12.5	58.0	1.3	10000
TP/05/09/B	1.3	~	~	~	0.2	0.4	~	~	14.6	52.5	0.8	12000
TP/05/11/A	4.5	~	~	~	7.6	0.2	0.5	~	1.5	33.3	1.8	16500
TP/05/11/B	13.8	~	~	~	8.6	0.7	0.4	~	1.2	40.0	1.9	21000
TP/05/13/B	2.8	~	~	~	1.9	0.2	0.3	0.3	~	51.3	0.6	16000
TP/05/14/A	~	~	~	~	~	~	~	~	~	84.1	0.6	17000
TP/05/14/B	2.5	~	~	~	0.7	~	~	1.2	~	65.8	0.7	19000
TP/05/16/A	~	~	~	~	~	~	~	~	~	99.5	0.5	19000

TP5 waste characterisation (Phase 2: capped).

Reference	Description of Sample	CO2	CH4	O2
		%	%	%
TP/05/01	Chalk, paper and plastics.	0.78	0.15	20.10
TP/05/03/A	Black organics, black plastic sheeting with a strong odour.	2.01	0.82	17.80
TP/05/03/A	Wet clay material, organics, plastic and textiles.	2.11	0.01	16.80
TP/05/03/B	Chalk/clay material, plastics and wood fragments.	0.72	0.13	20.30
TP/05/06/A	Mostly clay/soil material with fragments of brick rubble.	0.63	0.02	21.00
TP/05/06/B	Soil/clay, house bricks.	0.90	0.22	21.00
TP/05/07/A	Clay material, very degraded newsprint (1972), wood fragments & plastics.	0.01	0.01	21.10
TP/05/07/B	Soil/clay, blocks of tar and plastics, possible newspaper dated (1975).	1.93	0.17	19.20
TP/05/09/A	Black organic remains, surface mould and pieces of plastic.	2.21	0.02	19.20
TP/05/09/B	Soil material, degraded newsprint (1975) and black plastic bags.	1.84	0.02	19.80
TP/05/11/A	Very degraded organic wastes, odorous, wet to touch with newsprint. (Bob Wilson still goalkeeper)	0.21	0.02	21.00
TP/05/11/B	Clay material, plastics, very odorous with degraded organics.	2.80	0.74	17.00
TP/05/13/B	Soil and chalk material. Wet odorous slime.	1.05	1.25	17.80
TP/05/14/A	Black organic matter, pieces of plastic, odorous remains.	2.51	0.30	15.70
TP/05/14/B	Black organic matter, pieces of plastic, odorous.	0.98	0.14	19.70
TP/05/16/A		0.01	0.09	21.30

TP6 waste characterisation (Phase 1: capped).

Date	Reference	Dated Material	Depth Midpoint	Paper	Card Board	Plastic Film	Plastic Bottles	Dense Plastic	Blown Plastic	Textiles	Brown Glass	Green Glass	Clear Glass	Putrescible	Non Ferrous Unidentifiable
			mbgl	%	%	%	%	%	%	%	%	%	%	%	%
9/8/00	TP/06/01/G		0.43	~	~	~	~	~	~	~	~	~	~	~	~
9/8/00	TP/06/02/A		0.43	0.2	~	3.4	~	3.0	~	0.9	~	~	0.3	~	~
10/8/00	TP/06/02/B		1.18	~	~	1.3	~	2.2	~	1.8	~	~	0.3	~	~
9/8/00	TP/06/03/A		1.18	~	~	4.0	~	0.8	~	0.5	~	~	0.4	~	~
9/8/00	TP/06/03/B		1.75	0.1	~	4.4	~	2.1	~	0.5	~	~	0.1	~	~
9/8/00	TP/06/05/A		2.75	~	~	0.4	~	~	~	~	~	~	0.6	~	~
8/8/00	TP/06/05/B		2.75	~	~	~	~	~	~	~	~	~	~	~	~
8/8/00	TP/06/06/A		3.25	2.3	~	2.3	~	~	0.2	3.5	~	~	4.0	~	~
9/8/00	TP/06/06/B		3.25	1.3	0.5	2.5	~	~	~	1.5	~	~	2.5	~	~
8/8/00	TP/06/07/A	1971	3.75	11.3	0.7	2.3	~	1.2	~	0.5	~	~	5.0	~	~
8/8/00	TP/06/07/B		3.75	20.0	1.1	1.9	~	2.2	~	0.8	4.4	~	5.6	~	~
9/8/00	TP/06/09/A		4.75	~	0.3	0.3	~	0.3	~	~	~	~	0.8	~	1.9
9/8/00	TP/06/09/B		4.75	1.7	~	0.4	~	~	~	~	~	~	0.8	~	~
9/8/00	TP/06/10/A&B		5.25	~	~	~	~	~	~	~	~	~	0.4	~	~
9/8/00	TP/06/11/A		5.75	~	~	~	~	1.5	~	0.7	~	~	3.5	~	~
10/8/00	TP/06/11/B		5.75	~	~	~	~	~	~	~	~	~	0.5	~	~
9/8/00	TP/06/13/A	1967	6.75	6.7	~	~	~	0.3	~	0.2	~	2.5	6.7	~	~
10/8/00	TP/06/13/B		6.75	6.3	~	~	~	0.2	~	~	~	~	5.0	~	~
9/8/00	TP/06/14/A		7.25	0.6	~	0.3	~	1.7	~	~	~	~	1.0	~	~
9/8/00	TP/06/14/B		7.25	~	~	1.7	~	~	~	~	~	0.6	2.5	~	~
10/8/00	TP/06/15/A		7.75	~	~	1.1	~	1.8	~	0.7	~	~	3.4	~	~
10/8/00	TP/06/15/B		7.75	~	~	1.9	~	1.3	~	0.6	~	~	5.0	~	~
9/8/00	TP/06/17/A		8.75	~	~	6.0	~	~	~	~	~	~	4.4	~	~
10/8/00	TP/06/17/B		8.75	~	~	~	~	~	~	~	~	~	3.9	~	~
10/8/00	TP/06/18/A		9.25	0.1	~	0.2	~	0.5	~	~	~	~	6.0	~	~
10/8/00	TP/06/18/B		9.25	~	~	~	~	0.1	~	~	~	~	4.5	~	~
8/8/00	TP/06/19/A		9.75	0.3	~	~	~	~	~	~	~	~	1.3	~	~
8/8/00	TP/06/19/B		9.75	9.2	~	~	~	0.3	~	~	0.7	~	5.2	~	~

TP6 waste characterisation (Phase 1: capped).

Reference	Non Ferrous	Foil	Non Ferrous	Ferrous	Ferrous	Ferrous	Aerosols	Wood	Other	Other Non	Chalk / Cinder	Fines	Residue	Empty	Pre-sort
	Beverage Cans	Containers	Closures	Unidentifiable	Food Can	Clousres			Combustibles	Combustibles		(5mm)		Bag	Weight
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	g
TP/06/01/G	~	~	~	~	~	~	~	~	~	~	~	~	98.3	1.7	6000
TP/06/02/A	~	~	~	4.1	~	~	~	10.3	~	0.3	0.6	14.1	60.0	0.9	16000
TP/06/02/B	~	~	~	1.4	~	~	~	1.5	~	~	10.6	18.1	61.1	1.0	18000
TP/06/03/A	~	~	~	4.5	~	~	~	1.5	3.6	0.1	14.5	6.3	63.0	0.6	20000
TP/06/03/B	~	~	~	1.8	~	~	~	1.6	1.8	0.8	0.9	6.3	77.5	0.6	20000
TP/06/05/A	~	~	~	3.3	~	~	~	~	~	0.1	5.0	12.5	75.0	0.6	18000
TP/06/05/B	~	~	~	~	~	~	~	1.0	~	~	26.0	7.0	63.3	0.8	15000
TP/06/06/A	~	~	~	0.2	~	~	~	~	~	0.4	7.1	27.1	52.1	0.8	12000
TP/06/06/B	~	~	~	0.3	~	~	~	~	~	0.4	5.0	32.5	51.0	1.0	10000
TP/06/07/A	~	~	~	0.3	~	~	~	~	~	0.3	2.0	15.0	60.0	0.7	15000
TP/06/07/B	~	~	~	0.3	~	~	~	~	~	1.7	1.7	25.0	32.2	1.4	9000
TP/06/09/A	~	~	~	~	~	~	~	~	~	~	10.0	~	84.4	1.1	9000
TP/06/09/B	~	~	~	6.7	~	~	~	~	~	~	21.7	29.2	36.7	1.7	6000
TP/06/10/A&B	~	~	~	0.6	~	~	~	0.2	1.0	~	7.5	~	87.5	1.0	12000
TP/06/11/A	~	~	~	~	~	~	~	~	~	~	1.3	13.0	78.2	0.7	17000
TP/06/11/B	~	~	~	~	~	~	~	~	~	~	11.9	~	86.3	0.6	16000
TP/06/13/A	~	~	~	0.3	~	~	~	0.7	~	0.3	6.0	45.0	30.0	0.7	15000
TP/06/13/B	~	~	~	0.3	~	~	~	1.5	~	1.0	0.8	3.3	80.0	0.7	15000
TP/06/14/A	~	~	~	0.6	~	~	~	~	~	~	~	~	93.3	1.1	9000
TP/06/14/B	~	~	~	~	~	~	~	4.0	~	0.4	~	8.3	68.9	1.1	8000
TP/06/15/A	~	~	~	6.6	~	~	~	0.7	~	3.4	3.2	20.5	57.3	0.9	11000
TP/06/15/B	~	~	~	4.8	~	~	~	~	0.4	0.8	2.9	~	80.8	1.2	13000
TP/06/17/A	~	~	~	4.4	~	~	~	~	0.8	2.3	0.4	35.4	44.2	1.0	12000
TP/06/17/B	~	~	~	7.3	~	~	~	~	0.9	1.8	2.5	47.7	33.2	1.8	11000
TP/06/18/A	~	~	~	4.8	~	~	~	0.1	0.8	2.0	5.6	43.8	35.0	0.6	20000
TP/06/18/B	~	~	~	2.0	~	~	~	0.1	~	3.3	1.8	10.7	76.2	0.5	21000
TP/06/19/A	~	~	~	3.3	~	~	~	~	0.3	2.0	7.0	22.5	60.0	1.3	10000
TP/06/19/B	~	~	~	1.3	~	~	~	~	~	6.2	8.7	42.5	24.0	0.8	10000

TP6 waste characterisation (Phase 1: capped).

Reference	Description of Sample	CO2%	CH4%	O2%
TP/06/01/G	Clay material, fragments of chalk and builders rubble.	2.01	0.78	15.00
TP/06/02/A	Clay/soil with fragments of plastic.	0.09	0.03	20.90
TP/06/02/B	Clay material, degraded organic remains and pieces of chalk.	2.11	0.07	19.00
TP/06/03/A	Clay material, chalk matter with plastics and organic remains.	0.37	0.03	21.10
TP/06/03/B	Clay material, very sloppy, plastics and rotten organics.	5.01	0.01	15.30
TP/06/05/A	Clay material, fragments of wood, newsprint and chalk.	2.24	0.03	18.90
TP/06/05/B	Large blocks of clay, pieces of hard-core/tarmac with fragments of timber.	0.09	0.01	21.00
TP/06/06/A	Soil/clay material, degraded newsprint, organic remains with clasts of chalk.	0.70	0.05	20.90
TP/06/06/B	Clay and soil material, very few other remains.	3.34	0.01	18.10
TP/06/07/A	Soil / clay material, pre 1971 newsprint, with well rotted organic remains.	2.15	0.04	19.60
TP/06/07/B	Soil /clay material, pair of jeans and newspaper (pre-decimal prices).	0.54	0.01	21.00
TP/06/09/A	Soil material with brick rubble.	2.62	0.41	21.70
TP/06/09/B	Mostly soil, with bits of rubble and ferrous pieces.	2.01	0.05	19.30
TP/06/10/A&B	Soil/clay material with chalk pieces.	2.53	0.02	17.50
TP/06/11/A	Clay, chalk with house bricks.	4.14	0.02	17.60
TP/06/11/B	Soil material, mixed paper, plastic with pieces of chalk.	2.62	0.04	19.60
TP/06/13/A	Soil material with fragments of chalk, brick rubble and a 1967 newpaper.	1.92	0.01	19.20
TP/06/13/B	Chalk and soil reside - pieces of glass, old newsprint.	2.84	0.12	19.61
TP/06/14/A	Clay and chalk with a tarry residue. Strong smell of tar.	1.12	0.30	19.80
TP/06/14/B	Mostly clay/soil material, wet to touch, no other remains.	17.30	0.09	19.40
TP/06/15/A	Black organic remains, soil/clay material, strong odour and visible oily sheen.	0.02	0.01	21.60
TP/06/15/B	Organic mulch, odorous, black plastic fragments, soil and clay material. Oily.	2.01	0.42	20.60
TP/06/17/A	Clay/soil with pieces of chalk.	2.10	0.04	18.90
TP/06/17/B	Clay/soil, pieces of chalk with glass and metal.	0.97	0.01	19.80
TP/06/18/A	Soil, cinder and glass.	0.68	0.02	20.70
TP/06/18/B	Soil with organics, glass and cinder fragments.	1.20	0.06	20.70
TP/06/19/A	Sandy clay material with sporadic fragments of plastic and paper.	1.02	0.03	19.90
TP/06/19/B	Soil and clay material with fragments of glass and plastics.	0.05	0.01	21.50

TP7 waste characterisation (Phase 1: capped).

Date	Reference	Depth to Midpoint	Dated Material	Paper	Card Board	Plastic Film	Plastic Bottles	Dense Plastic	Blown Plastic	Textiles	Brown Glass	Green Glass	Clear Glass	Putrescible	Non Ferrous Unidentifiables	Non Ferrous Beverage Cans	Foil Containers
		mbgl		%	%	%	%	%	%	%	%	%	%	%	%	%	%
7/8/96	TP/07/03/B	1.75		2.8	~	4.4	~	4.1	~	~	~	~	1.3	0.3	~	~	~
7/8/96	TP/07/05/A	2.75	1970s	17.0	~	6.5	~	0.5	~	0.5	~	~	7.0	~	~	~	~
7/8/96	TP/07/05/B	2.75		14.0	~	4.5	~	1.5	~	1.0	0.5	~	1.0	~	~	~	~
7/8/96	TP/07/07/A	3.75	1971	13.3	0.3	2.8	~	2.8	0.2	1.1	2.2	1.4	5.0	~	~	~	~
8/8/96	TP/07/07/B	3.75		12.3	0.3	6.7	1.7	2.0		1.7	~	1.3	2.7	~	~	~	~
7/8/96	TP/08/03/A			0.6	0.9	1.5	~	1.3	~	3.4	~	0.3	1.6	~	~	~	~

Reference	Non Ferrous Closures	Ferrous Unidentifiable	Ferrous Food Can	Ferrous Closures	Aerosols	Wood	Other Combustibles	Other Non Combustibles	Chalk / Cinder	Fines (5mm)	Residue	Empty Bag	Pre-sort Weight
	%	%	%	%	%	%	%	%	%	%	%	%	g
TP/07/03/B	~	1.9	~	~	~	~	~	~	1.9	53.1	28.1	1.3	8000
TP/07/05/A	~	~	~	~	~	2.0	3.5	0.5	1.0	45.0	14.0	2.4	5000
TP/07/05/B	~	2.5	~	~	1.0	1.0	~	~	6.5	45.0	17.0	2.0	5000
TP/07/07/A	~	2.2	~	~	~	0.3	1.1	1.1	1.9	25.0	37.8	1.4	9000
TP/07/07/B	~	6.0	~	~	~	~	0.3	~	1.3	36.7	30.0	1.3	7500
TP/08/03/A	~	5.6	~	~	~	2.2	0.3	0.6	15.0	28.1	35.6	1.6	8000

Reference	Description of Sample	CO2	CH4	2
		%	%	%
TP/07/03/B	Clay and soil material. Paper with pieces of plastic and glass.	6.11	0.02	14.60
TP/07/05/A	Clay material, early 1970s newsprint with brick rubble.	0.53	0.04	21.10
TP/07/05/B	Soil/clay material, degraded newsprint, organic remains with clasts of chalk.	0.33	0.03	21.30
TP/07/07/A	Clay material, 1971 newsprint with fragments of plastic and pottery.	0.82	0.05	21.00
TP/07/07/B	Soil/clay material, decomposed newsprint with very few pieces of plastic.	2.89	0.02	17.80
TP/08/03/A	Soil/clay material, fragments of decomposed textiles with pieces of chalk.	1.62	0.05	19.90

Appendix C

Lithological description of TR1

Borehole Log Record

Logged for: BGS

Borehole Name: THRIPLOW TRI

Borehole Code: NGRC TL44SW/66

Client Code:

Borehole Location: THRIPLOW LANDFILL SITE, CAMBRIDGESHIRE

Easting: 544535

Northing: 244949

Quarter Sheet: TL44SW

1:50K Sheet Name and Number: SHEET 205 SAFFRON WALDEN

Drilled from: ☐ OD ☐ KB ☐ RT

OD Level: 32.56m

Logging Date: 17/3/1997

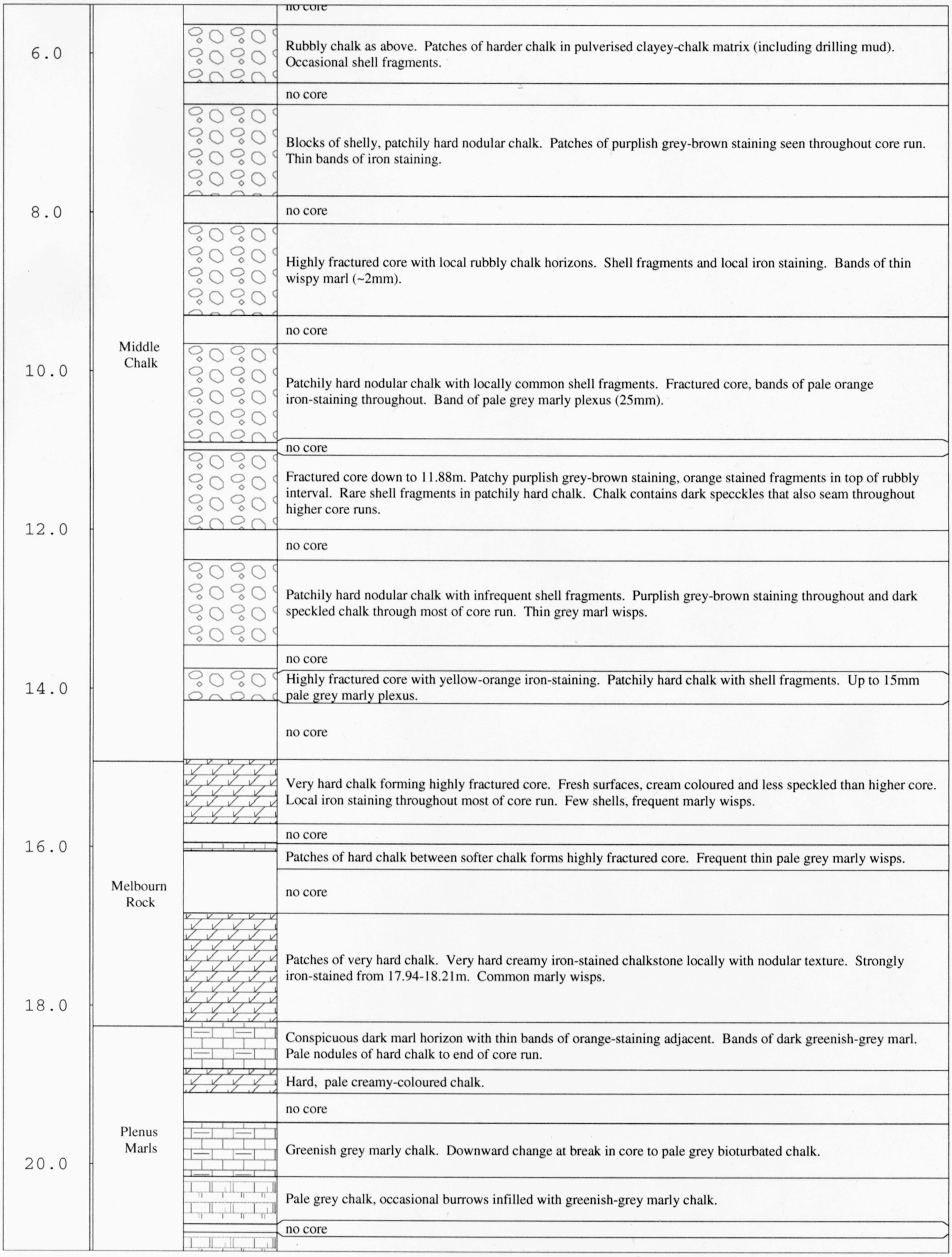
Drilling began:

Logged by: M A WOODS

Drilling ended:

Checked by:

0.0			
2.0	Silt and clay on sand and gravel		no core
4.0			
			Firm to hard rubbly chalk with occasional shell fragmnets. some weakly developed orange discolouration. Patches of purplish brown discolouration.



no core

Rubbly chalk as above. Patches of harder chalk in pulverised clayey-chalk matrix (including drilling mud). Occasional shell fragments.

no core

Blocks of shelly, patchily hard nodular chalk. Patches of purplish grey-brown staining seen throughout core run. Thin bands of iron staining.

no core

Highly fractured core with local rubbly chalk horizons. Shell fragments and local iron staining. Bands of thin wispy marl (~2mm).

no core

Patchily hard nodular chalk with locally common shell fragments. Fractured core, bands of pale orange iron-staining throughout. Band of pale grey marly plexus (25mm).

no core

Fractured core down to 11.88m. Patchy purplish grey-brown staining, orange stained fragments in top of rubbly interval. Rare shell fragments in patchily hard chalk. Chalk contains dark specckles that also seam throughout higher core runs.

no core

Patchily hard nodular chalk with infrequent shell fragments. Purplish grey-brown staining throughout and dark speckled chalk through most of core run. Thin grey marl wisps.

no core

Highly fractured core with yellow-orange iron-staining. Patchily hard chalk with shell fragments. Up to 15mm pale grey marly plexus.

no core

Very hard chalk forming highly fractured core. Fresh surfaces, cream coloured and less speckled than higher core. Local iron staining throughout most of core run. Few shells, frequent marly wisps.

no core

Patches of hard chalk between softer chalk forms highly fractured core. Frequent thin pale grey marly wisps.

no core

Patches of very hard chalk. Very hard creamy iron-stained chalkstone locally with nodular texture. Strongly iron-stained from 17.94-18.21m. Common marly wisps.

Conspicuous dark marl horizon with thin bands of orange-staining adjacent. Bands of dark greenish-grey marl. Pale nodules of hard chalk to end of core run.

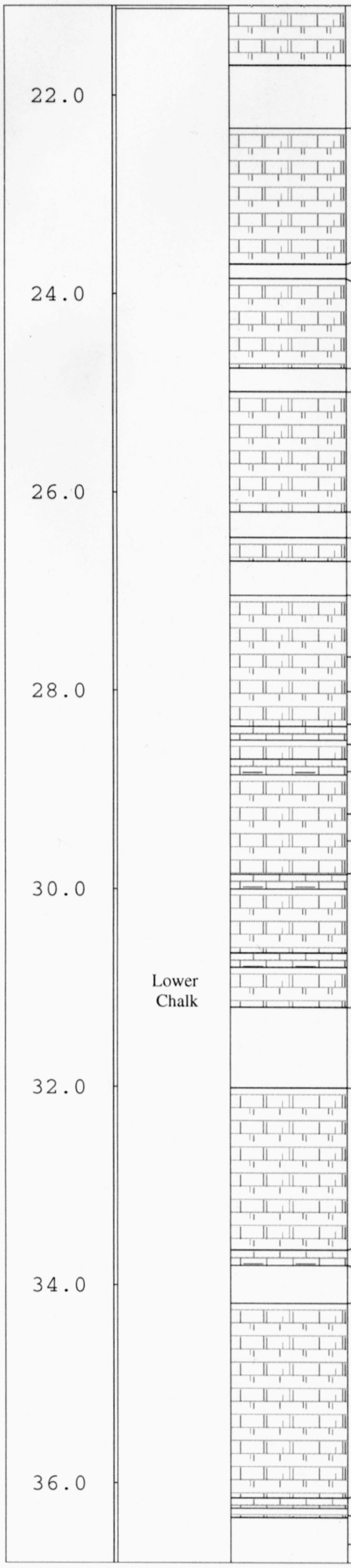
Hard, pale creamy-coloured chalk.

no core

Greenish grey marly chalk. Downward change at break in core to pale grey bioturbated chalk.

Pale grey chalk, occasional burrows infilled with greenish-grey marly chalk.

no core



Pale grey chalk, local shell fragments. Broken core at end of run with iron-staining.

no core

Pale grey chalk. Chrondites bioturbation picked out by paler chalk infill. Local shell fragments, burrows infilled with fish debris.

no core

Pale grey chalk, locally bioturbated. Highly fractured core could be due to shearing on thin marly horizons.

no core

Pale grey chalk, rare shell fragments. Conspicuous bioturbation to end of core run.

no core

Pale grey chalk with shell fragments and bioturbation picked out by darker marly chalk infill.

no core (core interval unaccounted for)

Pale grey bioturbated chalk.

Dark grey marly chalk.

Pale grey chalk with bands of orange-staining, burrows infilled with fish debris.

Dark grey marly chalk.

Pale grey bioturbated chalk.

Dark marly chalk.

Pale grey patchily bioturbated chalk.

Dark marly chalk.

Pale grey chalk with frequent dark marly wisps.

no core

Pale grey chalk locally bioturbated, with burrows infilled with darker marly chalk. Interval of locally strong iron-staining midway through core run.

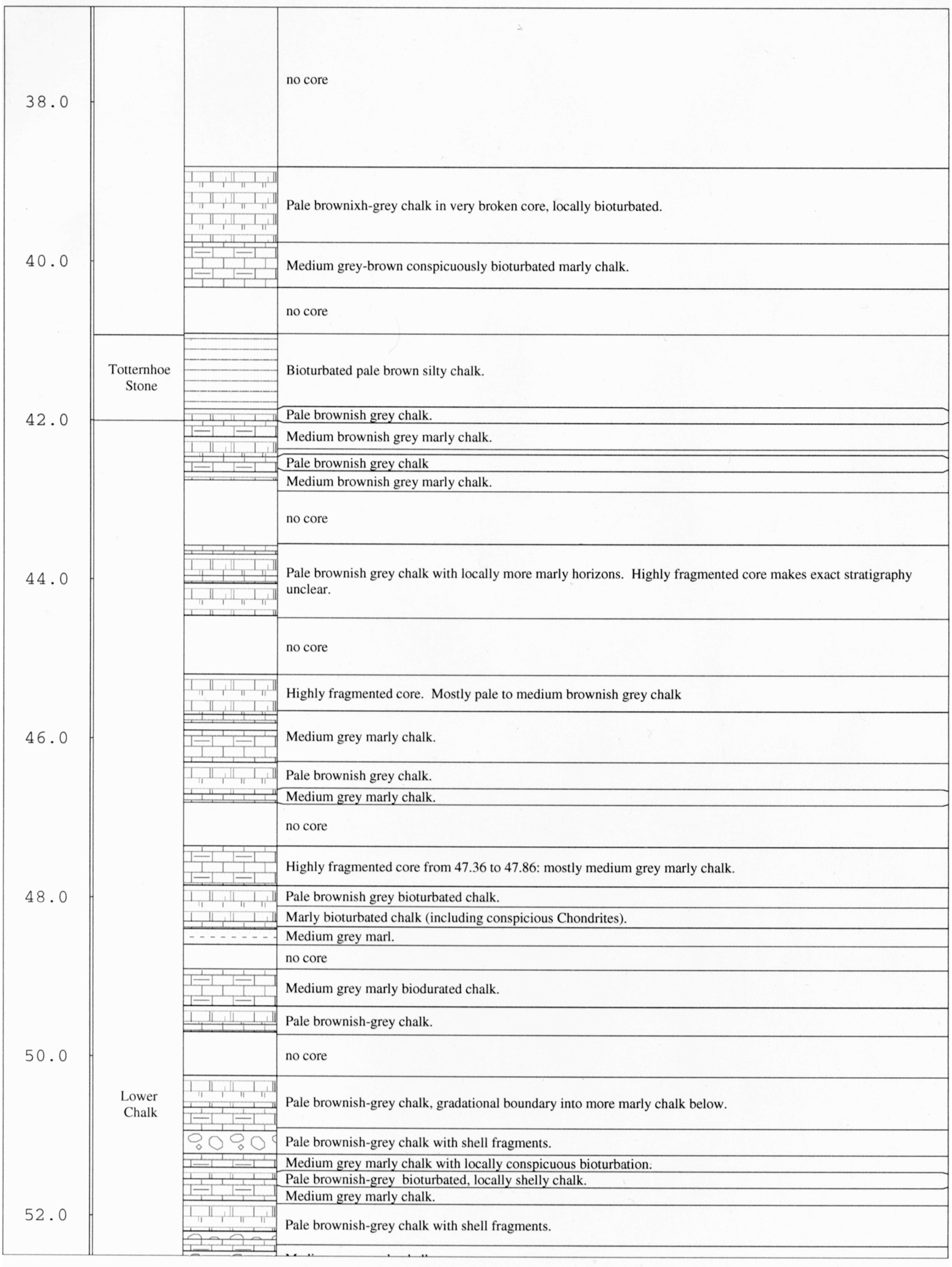
Darker grey marly chalk in fractured core below 33.65m.

no core

Pale grey chalk strongly bioturbated midway through core run. Downward change to pale brownish-grey chalk.

Darker marly chalk with bioturbation picked out by paler chalk.

Pale brownish-grey chalk.



no core

Pale brownixh-grey chalk in very broken core, locally bioturbated.

Medium grey-brown conspicuously bioturbated marly chalk.

no core

Bioturbated pale brown silty chalk.

Pale brownish grey chalk.

Medium brownish grey marly chalk.

Pale brownish grey chalk

Medium brownish grey marly chalk.

no core

Pale brownish grey chalk with locally more marly horizons. Highly fragmented core makes exact stratigraphy unclear.

no core

Highly fragmented core. Mostly pale to medium brownish grey chalk

Medium grey marly chalk.

Pale brownish grey chalk.

Medium grey marly chalk.

no core

Highly fragmented core from 47.36 to 47.86: mostly medium grey marly chalk.

Pale brownish grey bioturbated chalk.

Marly bioturbated chalk (including conspicious Chondrites).

Medium grey marl.

no core

Medium grey marly biodurated chalk.

Pale brownish-grey chalk.

no core

Pale brownish-grey chalk, gradational boundary into more marly chalk below.

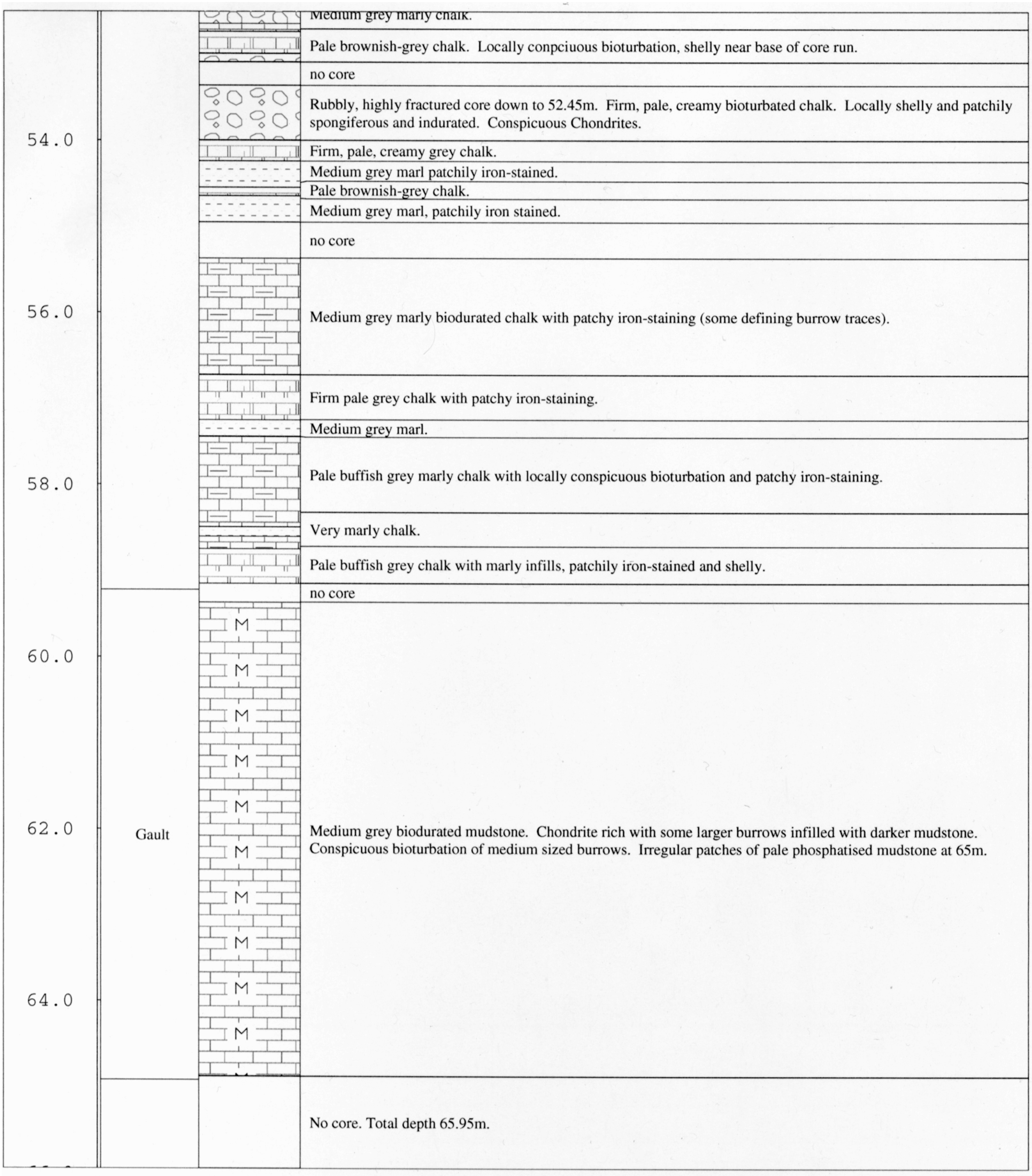
Pale brownish-grey chalk with shell fragments.

Medium grey marly chalk with locally conspicuous bioturbation.

Pale brownish-grey bioturbated, locally shelly chalk.

Medium grey marly chalk.

Pale brownish-grey chalk with shell fragments.



Medium grey marly chalk.

Pale brownish-grey chalk. Locally conpciuous bioturbation, shelly near base of core run.

no core

Rubbly, highly fractured core down to 52.45m. Firm, pale, creamy bioturbated chalk. Locally shelly and patchily spongiferous and indurated. Conspicuous Chondrites.

Firm, pale, creamy grey chalk.

Medium grey marl patchily iron-stained.

Pale brownish-grey chalk.

Medium grey marl, patchily iron stained.

no core

Medium grey marly biodurated chalk with patchy iron-staining (some defining burrow traces).

Firm pale grey chalk with patchy iron-staining.

Medium grey marl.

Pale buffish grey marly chalk with locally conspicuous bioturbation and patchy iron-staining.

Very marly chalk.

Pale buffish grey chalk with marly infills, patchily iron-stained and shelly.

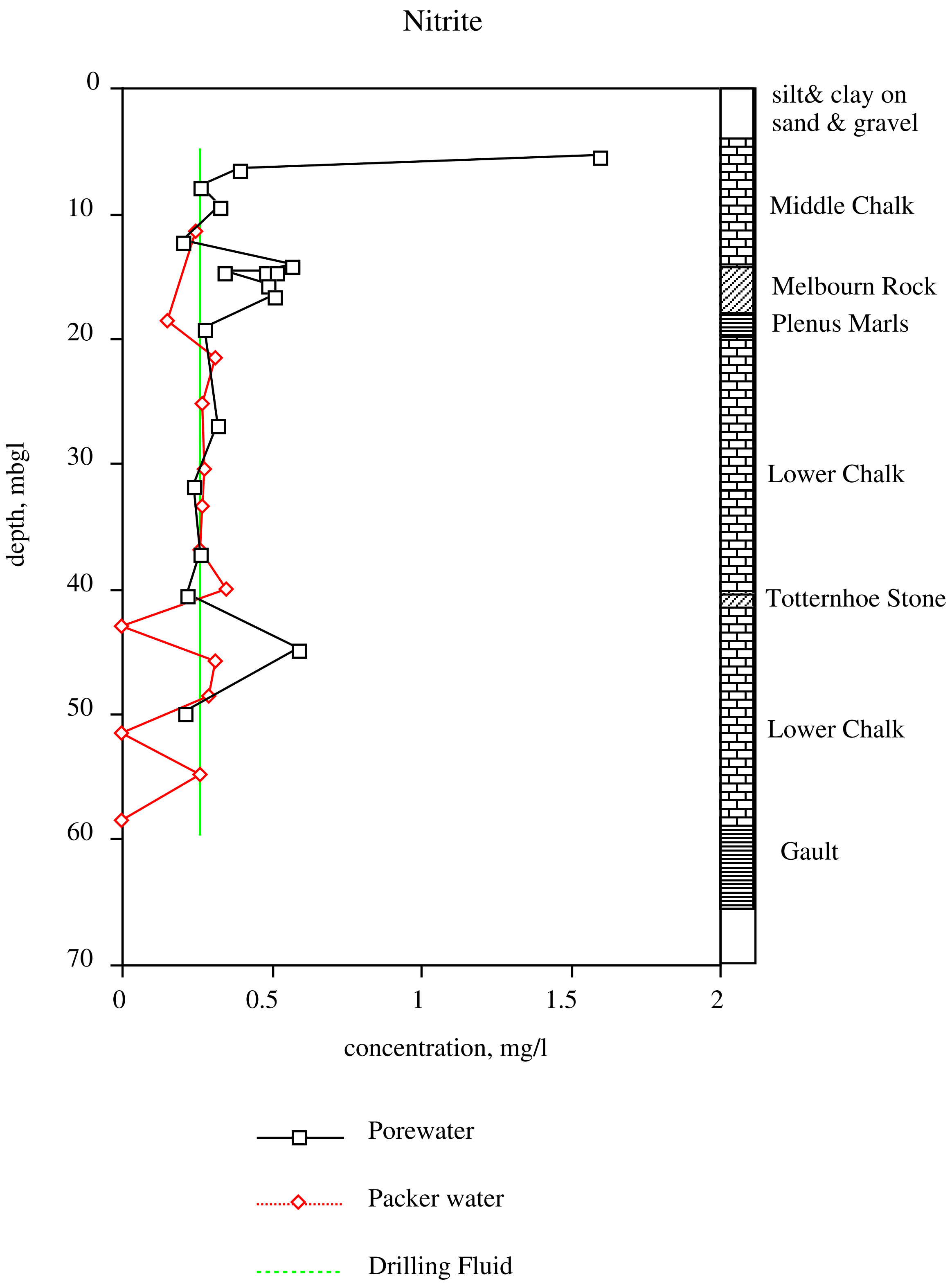
no core

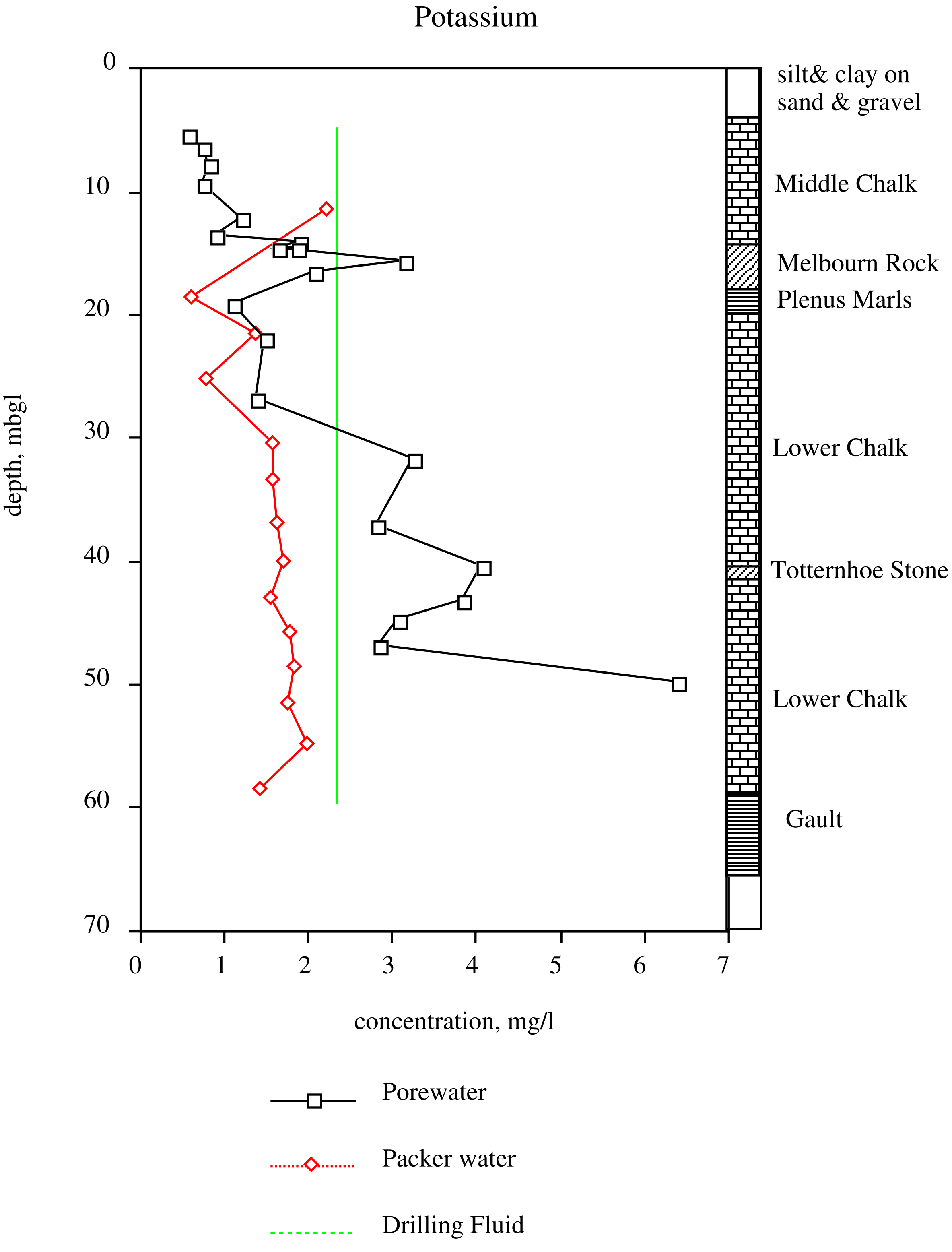
Medium grey biodurated mudstone. Chondrite rich with some larger burrows infilled with darker mudstone. Conspicuous bioturbation of medium sized burrows. Irregular patches of pale phosphatised mudstone at 65m.

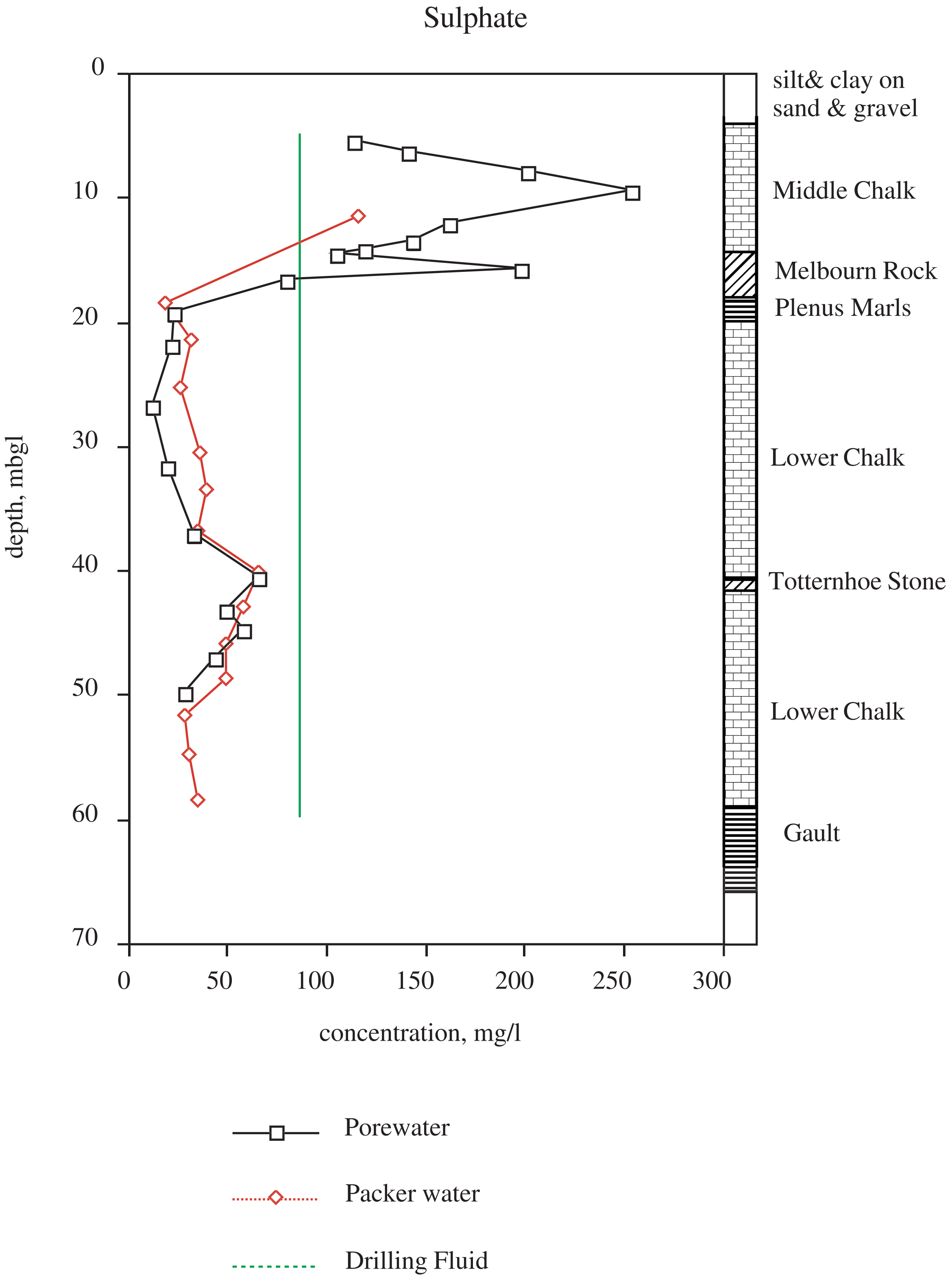
No core. Total depth 65.95m.

Appendix D

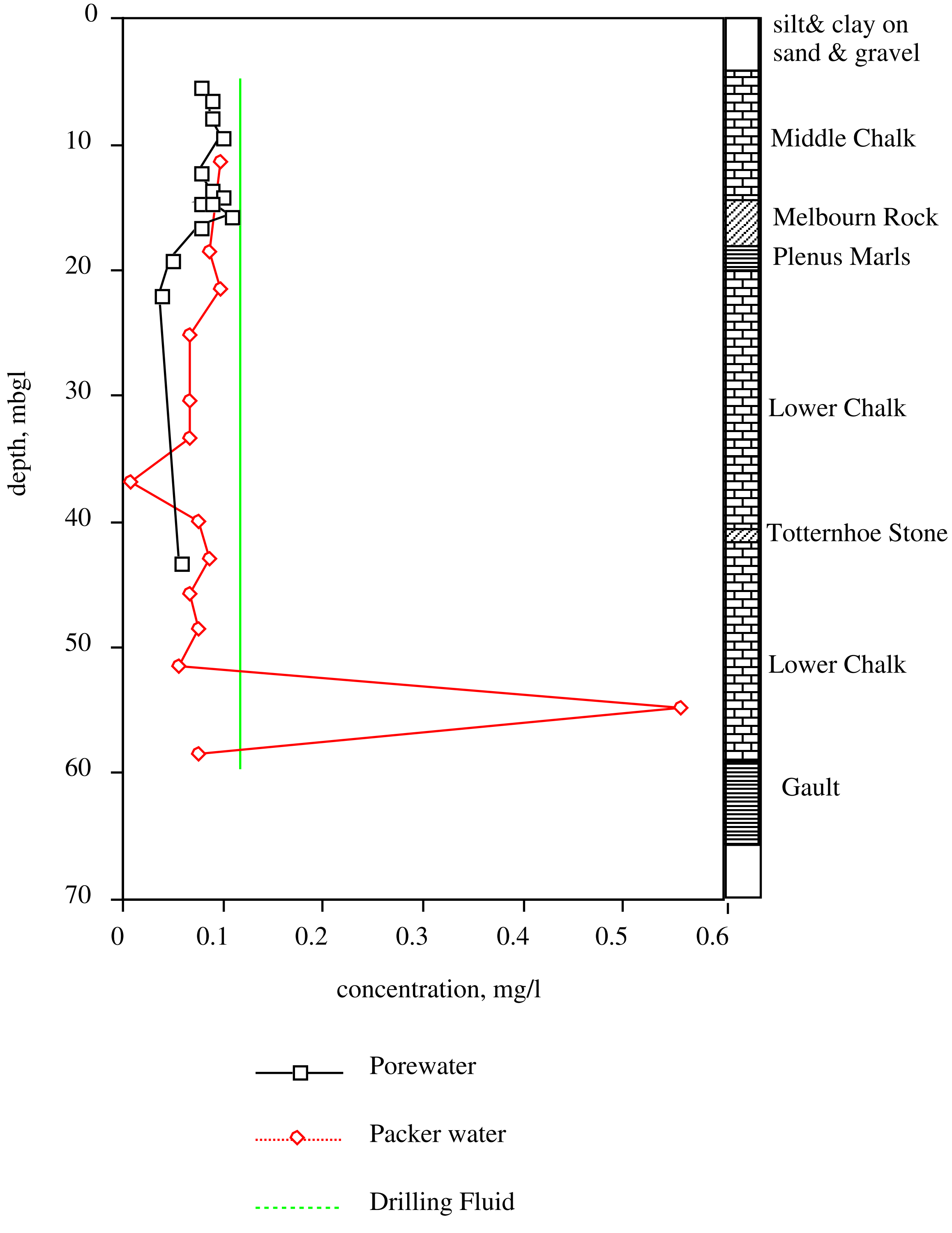
Porewater and packer water chemistry depth profiles in TR1

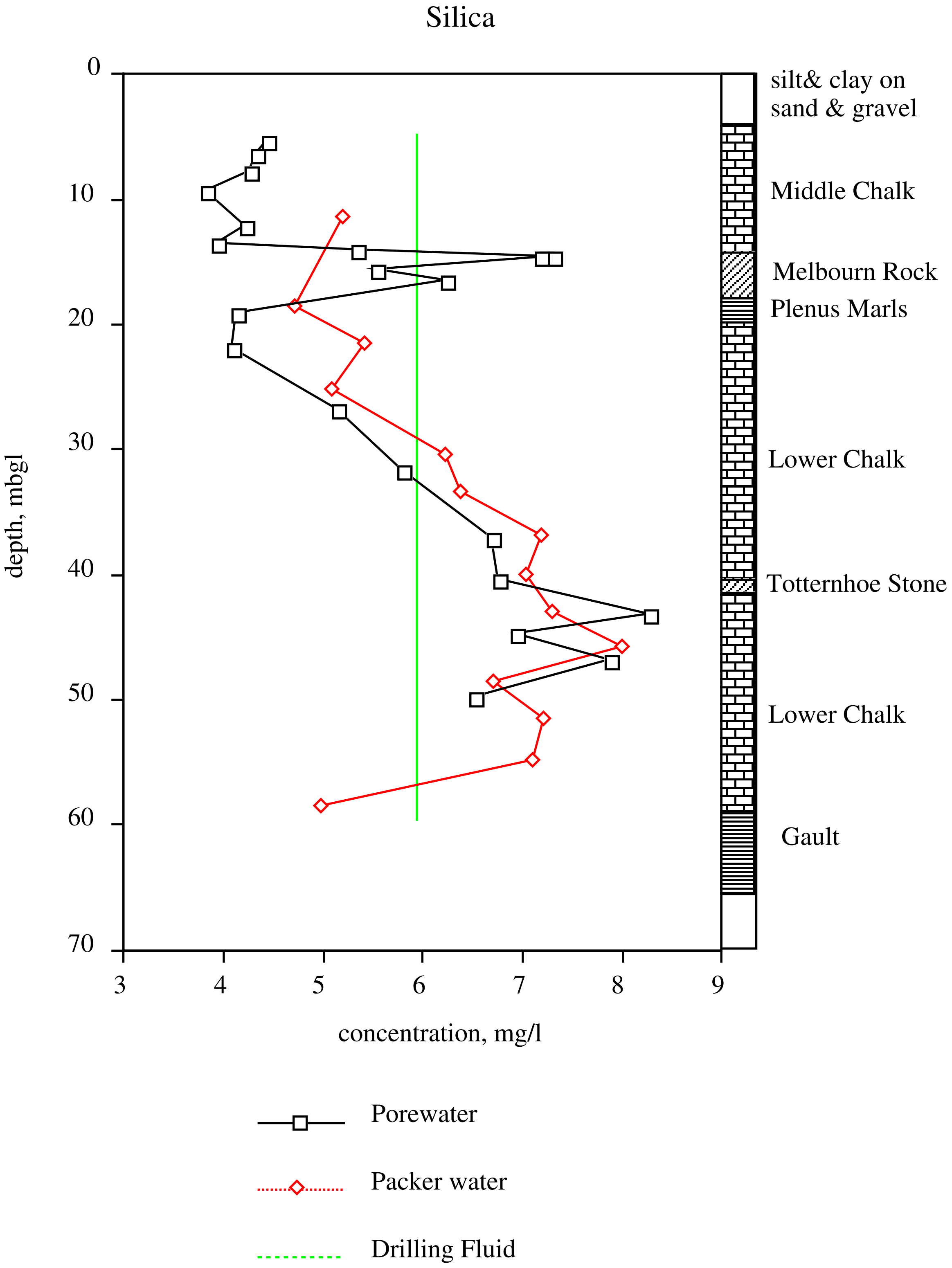

Nitrite
depth, mbgl
0
10
20
30
40
50
60
70
0
0.5
1
1.5
2
concentration, mg/l
silt& clay on
sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling Fluid

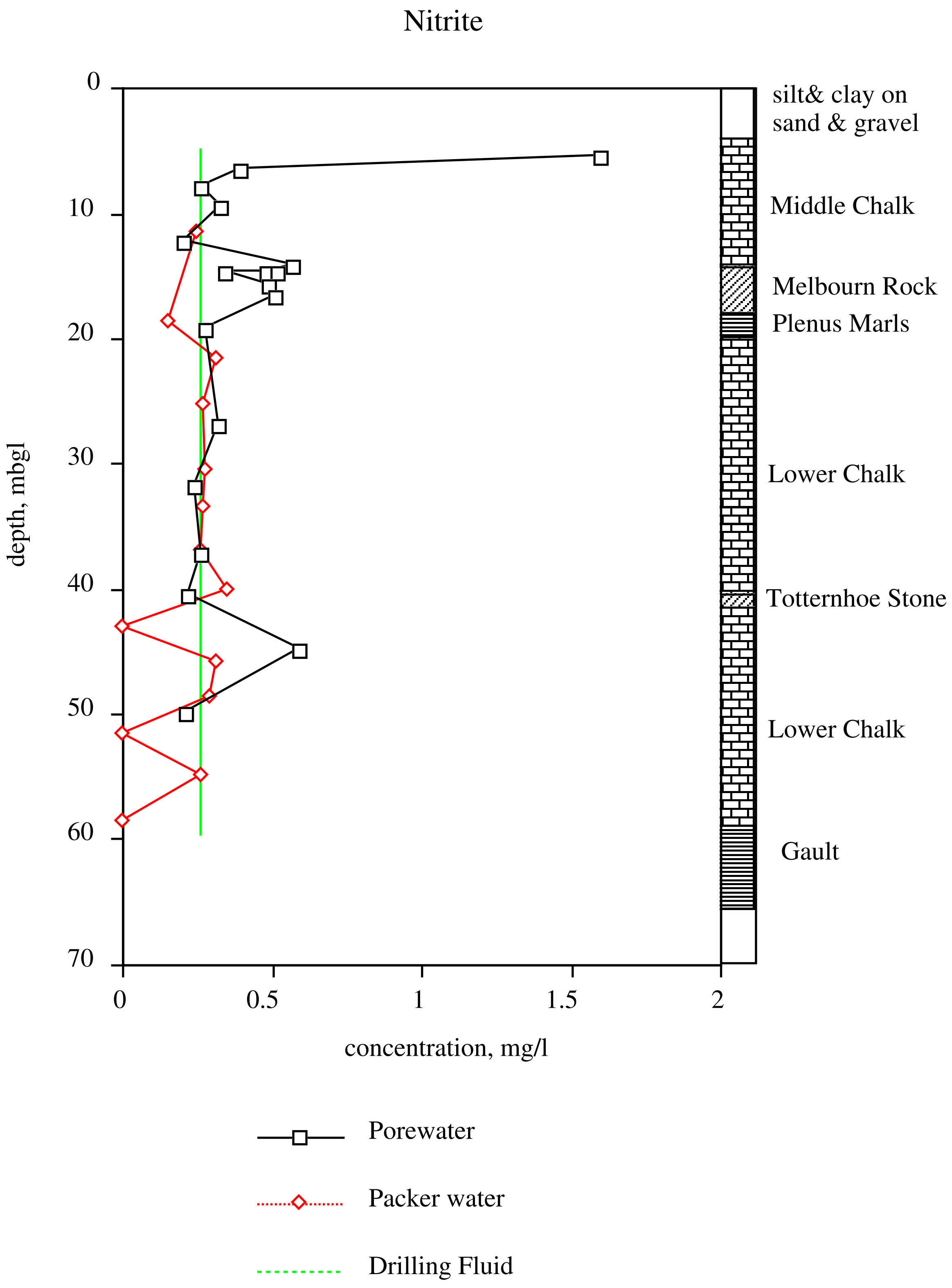

Potassium
depth, mbgl
0
10
20
30
40
50
60
70
0
1
2
3
4
5
6
7
concentration, mg/l
silt& clay on sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling Fluid

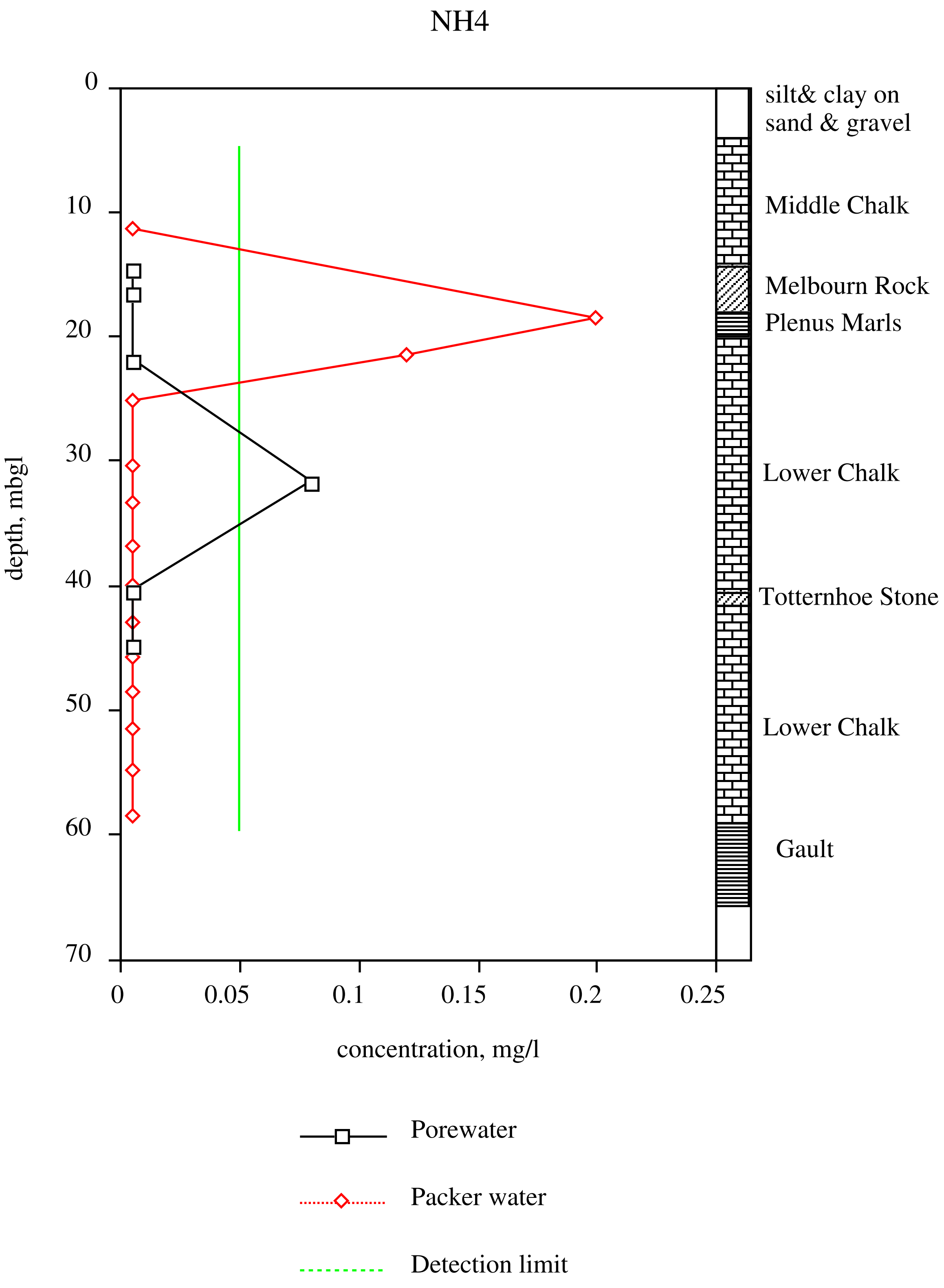

Sulphate
depth, mbgl
0
10
20
30
40
50
60
70
0
50
100
150
200
250
300
concentration, mg/l
silt& clay on
sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling Fluid

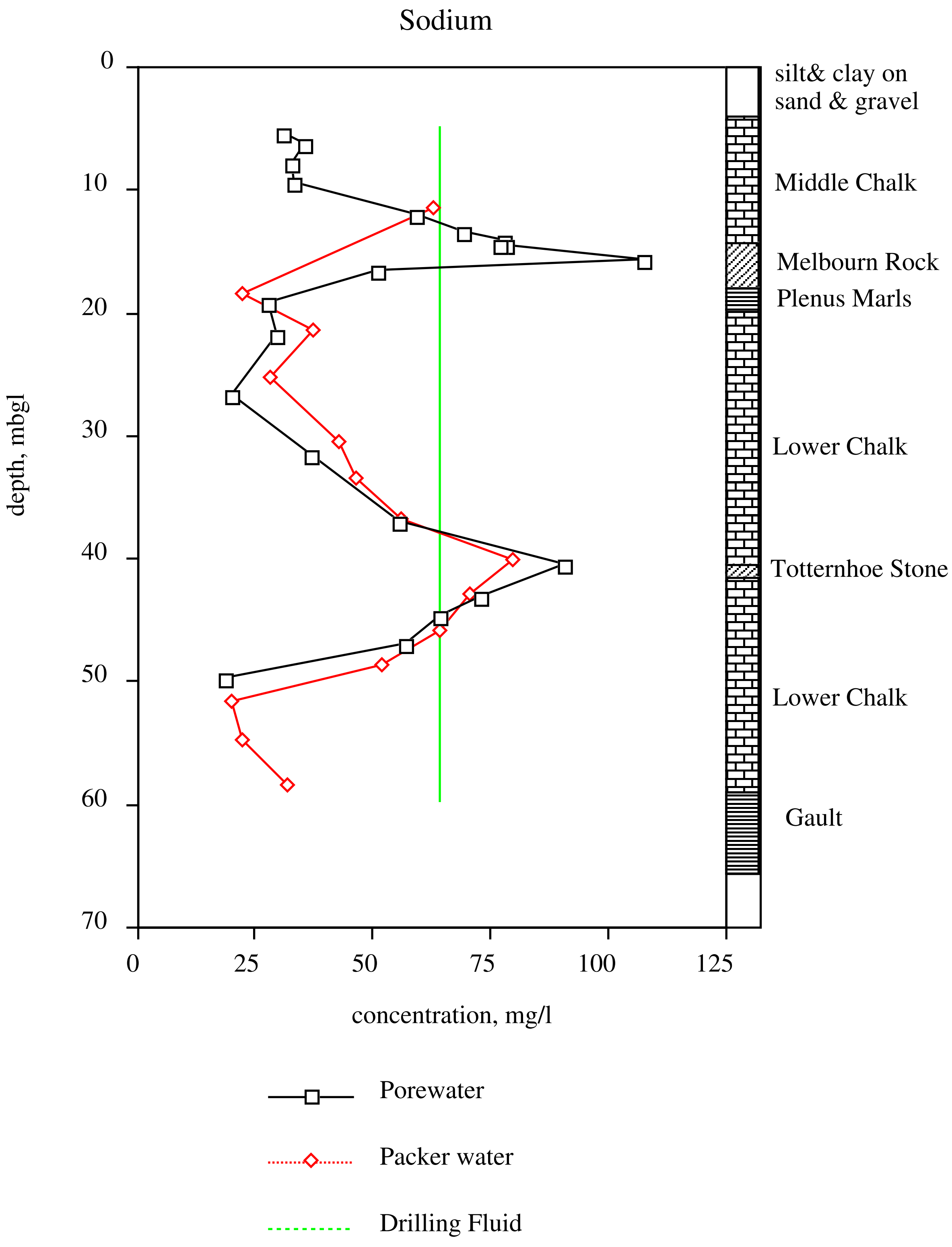
Aluminium

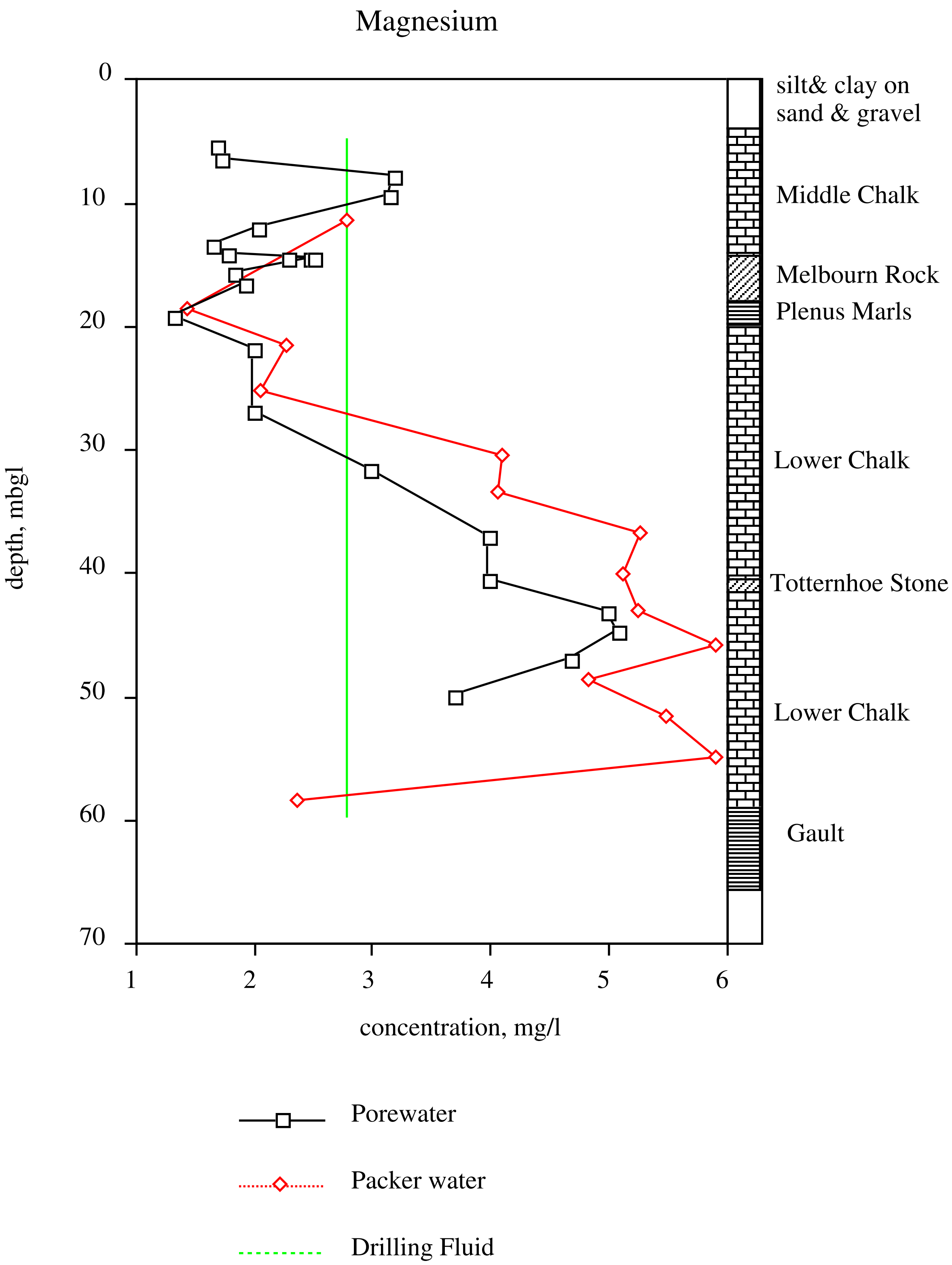

0
10
20
30
40
50
60
70
depth, mbgl
0
0.1
0.2
0.3
0.4
0.5
0.6
concentration, mg/l
silt& clay on
sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling Fluid

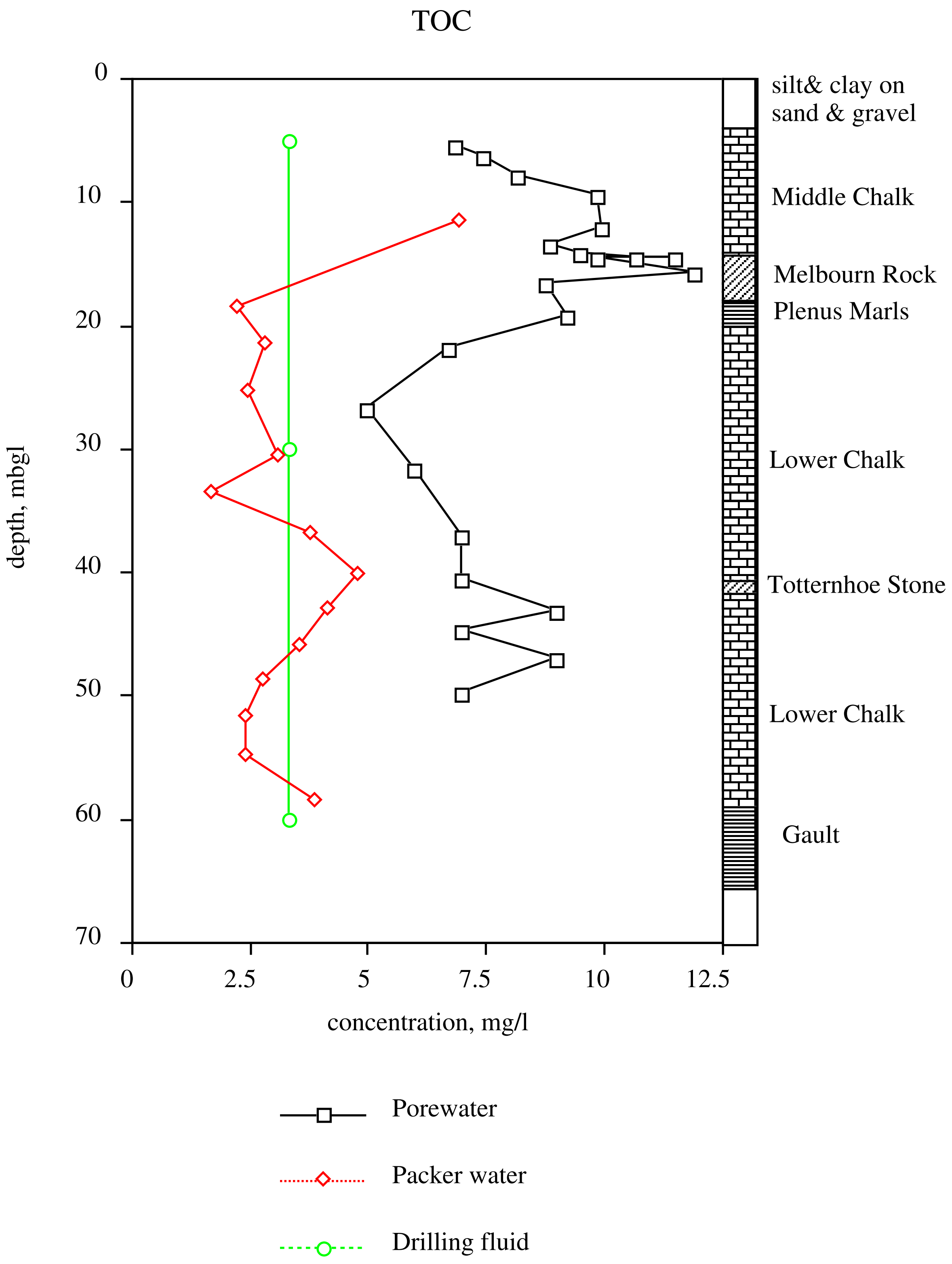

Silica
0
10
20
30
40
50
60
70
depth, mbgl
3
4
5
6
7
8
9
concentration, mg/l
silt& clay on sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling Fluid

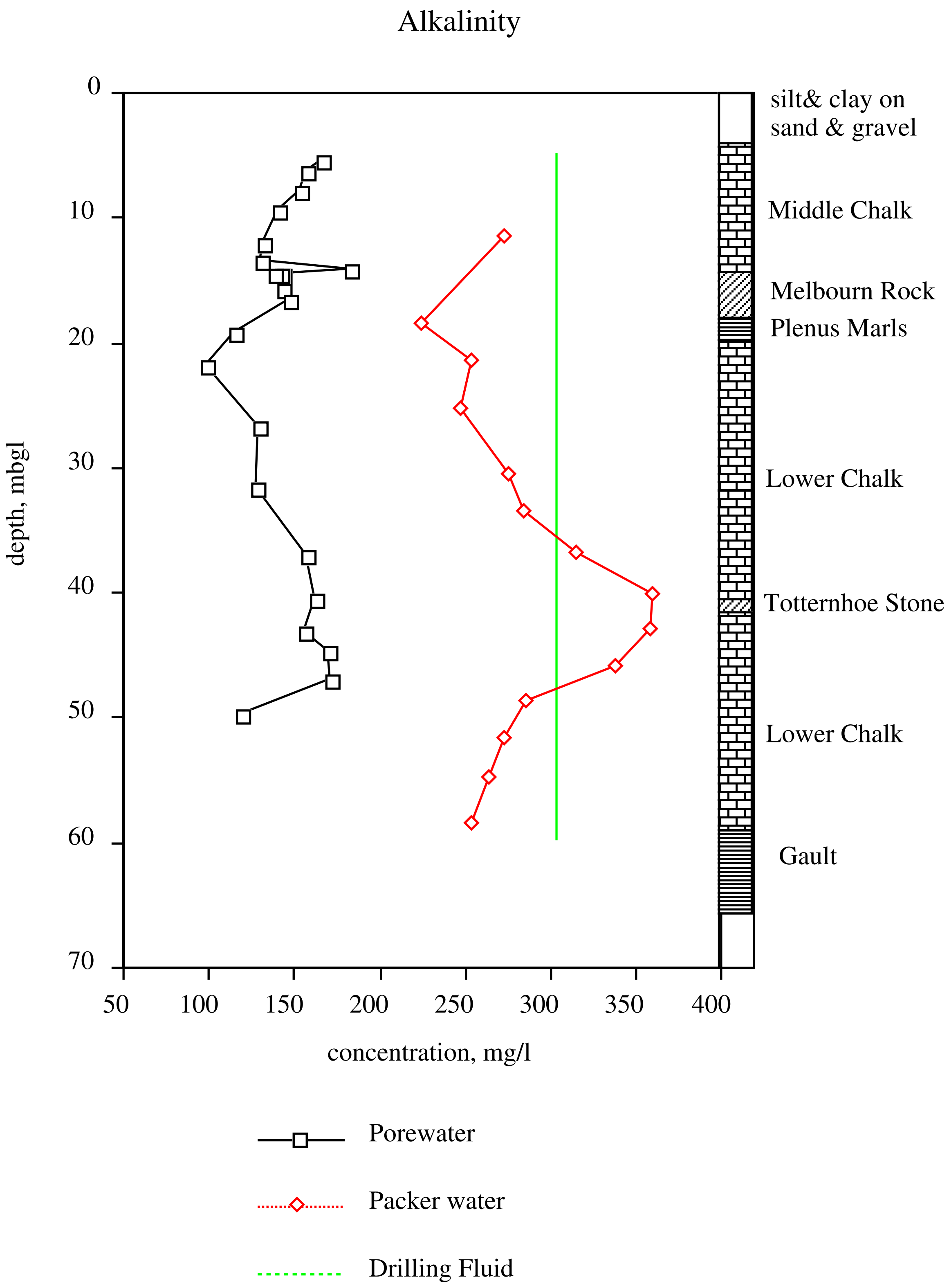

Nitrite
0
10
20
30
40
50
60
70
depth, mbgl
0
0.5
1
1.5
2
concentration, mg/l
silt& clay on
sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling Fluid

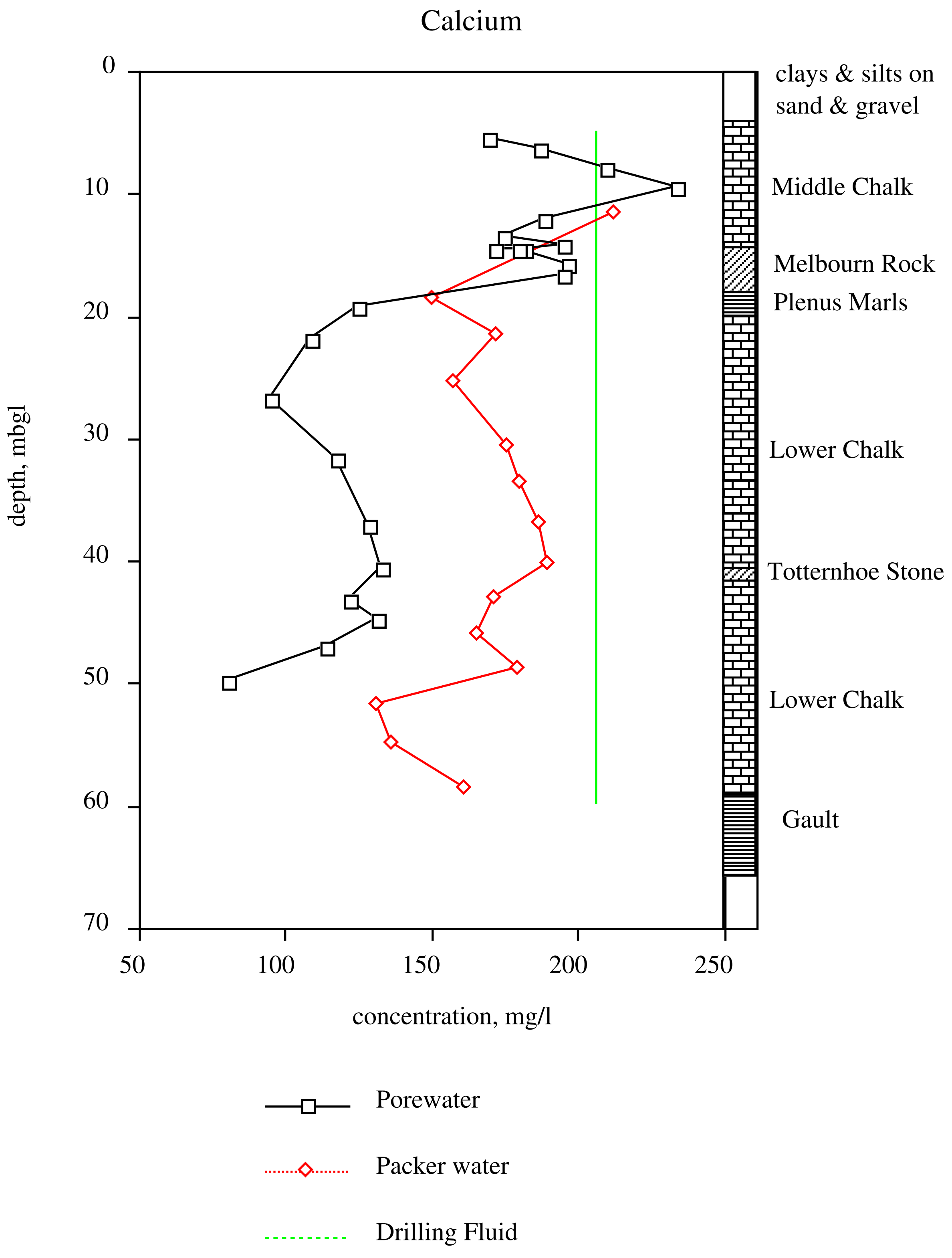

NH4
0
10
20
30
40
50
60
70
depth, mbgl
0
0.05
0.1
0.15
0.2
0.25
concentration, mg/l
silt& clay on sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Detection limit

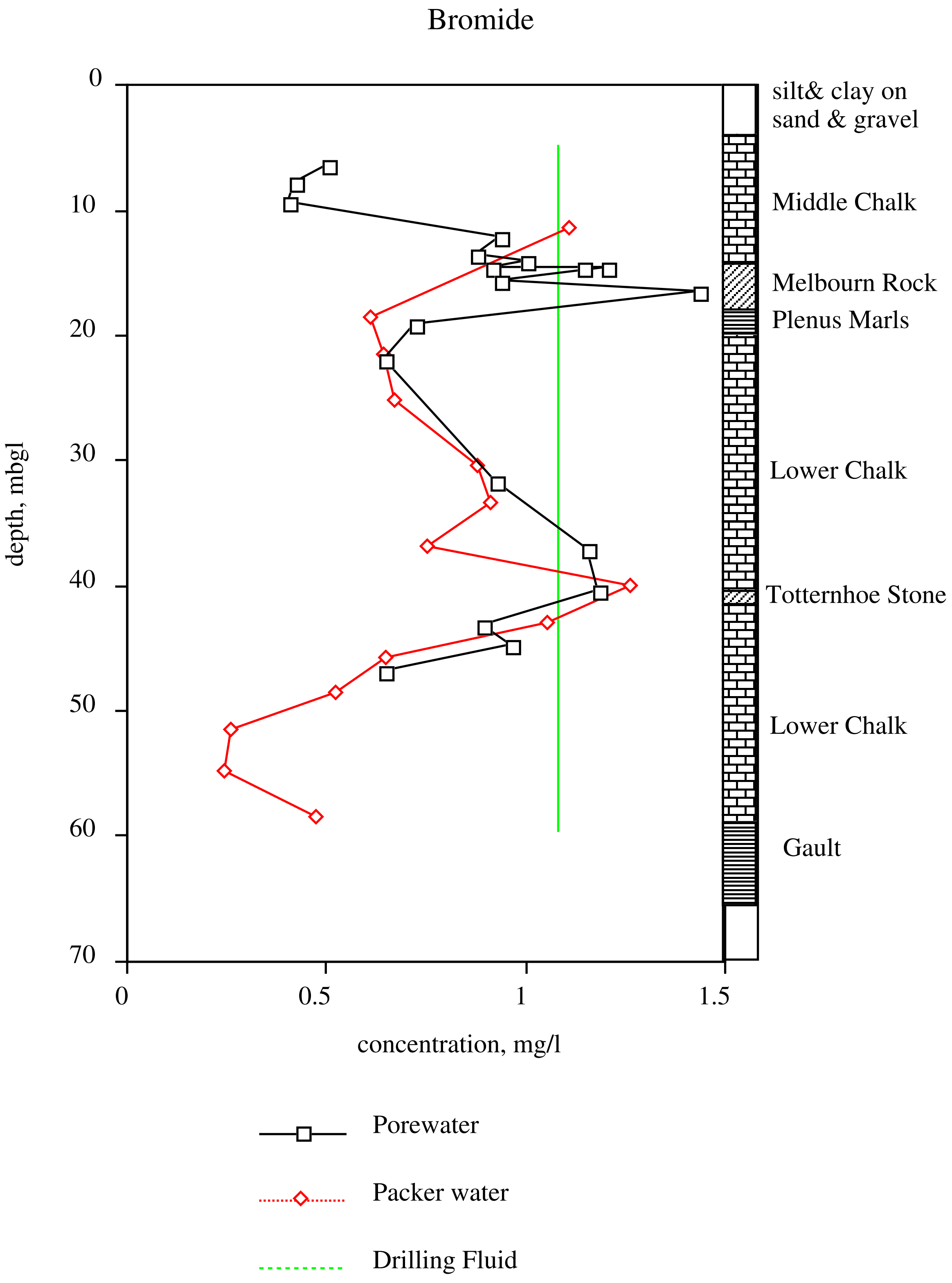

Sodium
depth, mbgl
0
10
20
30
40
50
60
70
0
25
50
75
100
125
concentration, mg/l
silt& clay on sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling Fluid

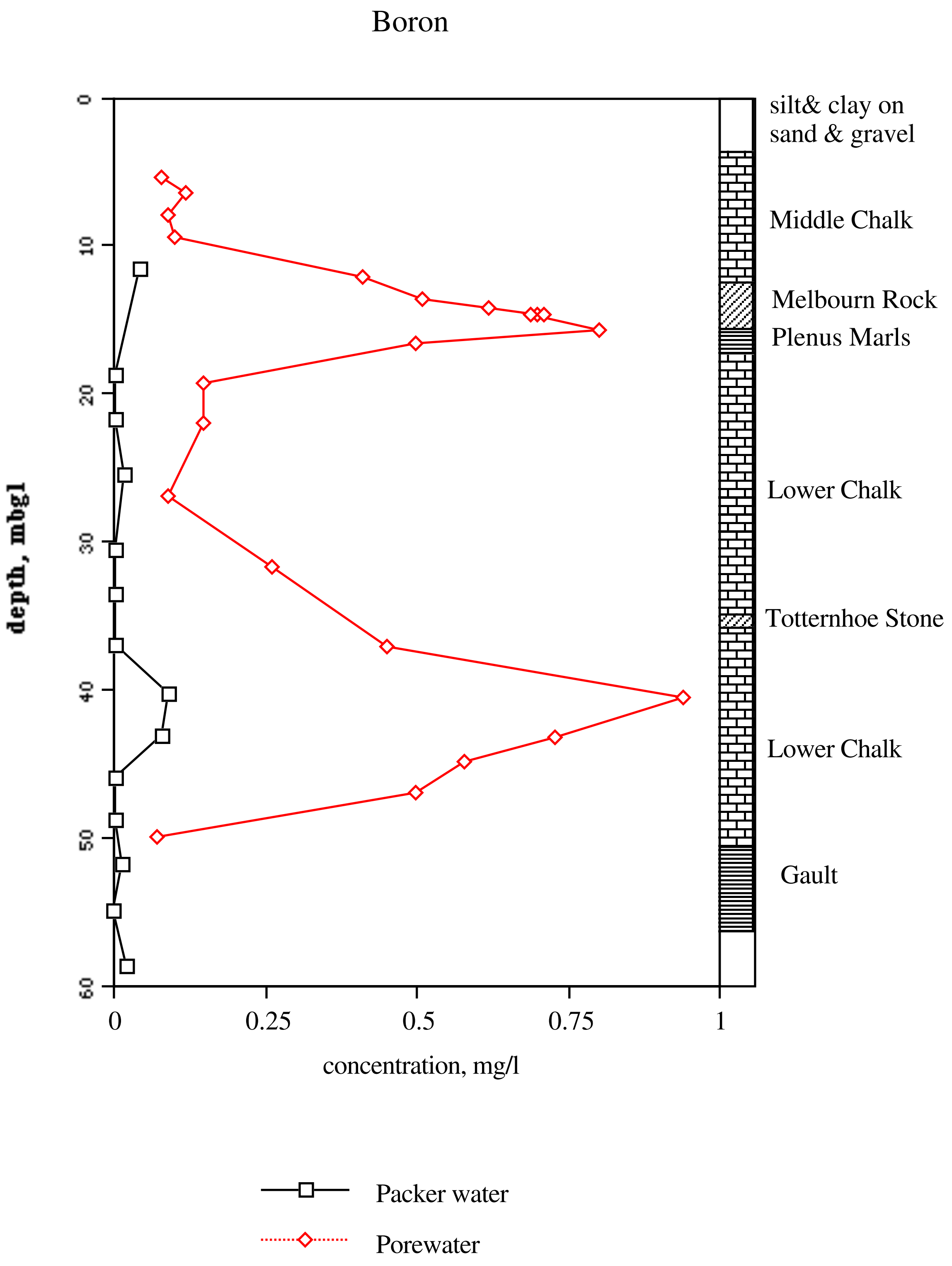

Magnesium
0
10
20
30
40
50
60
70
depth, mbgl
1
2
3
4
5
6
concentration, mg/l
silt& clay on sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling Fluid

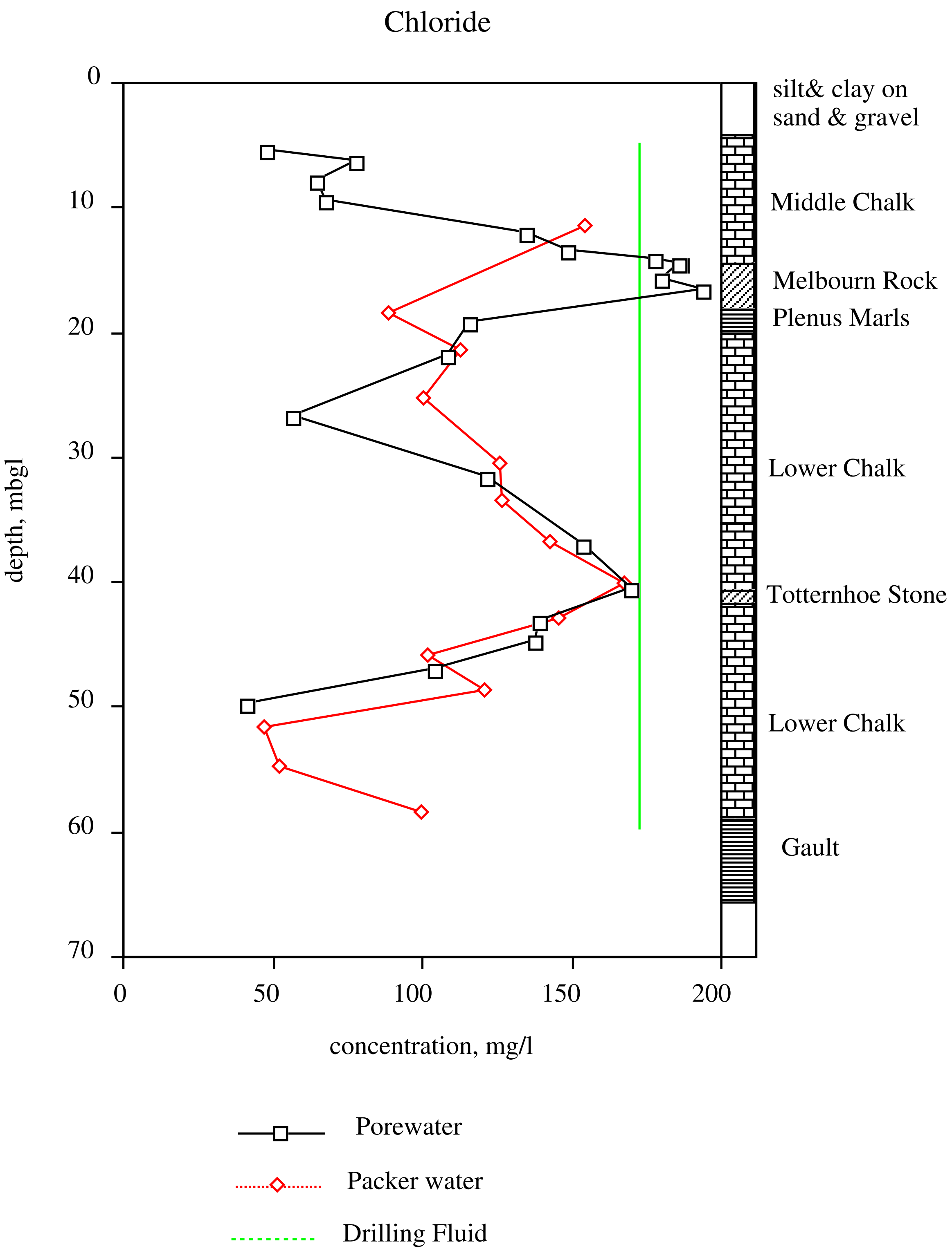

TOC
depth, mbgl
0
10
20
30
40
50
60
70
0
2.5
5
7.5
10
12.5
concentration, mg/l
silt& clay on sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling fluid


Alkalinity
0
10
20
30
40
50
60
70
depth, mbgl
50
100
150
200
250
300
350
400
concentration, mg/l
silt& clay on
sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling Fluid


Calcium
depth, mbgl
0
10
20
30
40
50
60
70
50
100
150
200
250
concentration, mg/l
clays & silts on
sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling Fluid


Bromide
0
10
20
30
40
50
60
70
depth, mbgl
0
0.5
1
1.5
concentration, mg/l
silt& clay on
sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling Fluid


Boron
depth, mbgl
0
10
20
30
40
50
60
0
0.25
0.5
0.75
1
concentration, mg/l
silt& clay on
sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Packer water
Porewater


Chloride
0
10
20
30
40
50
60
70
depth, mbgl
0
50
100
150
200
concentration, mg/l
silt& clay on sand & gravel
Middle Chalk
Melbourn Rock
Plenus Marls
Lower Chalk
Totternhoe Stone
Lower Chalk
Gault
Porewater
Packer water
Drilling Fluid