

INVESTIGATION OF A SITE AT
TYTHEGSTON, GLAMORGAN

WLR Technical Note No 29

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Summary

Site

The Tythegston landfill (NGR SS 852 789) is situated to the north of the Porthcawl road at Tythegston, some 3.7 km north-east of Porthcawl and 5.5 km south-west of Bridgend, Mid-Glamorgan. The landfill covers an area of some 0.09 km² and occupies a disused quarry excavated in the Carboniferous Limestone. The quarry is some 200 m wide and 450 m long being elongated about an east-west axis. The limestone was worked in a series of rock benches to a maximum depth of 38 m in the central area of the quarry. Standing water, up to 13 m deep was encountered during the excavation of the central deeper area. Water levels in this depression were known to fluctuate but never rose above a certain level which was assumed to represent a natural overflow via fissure systems in the limestone.

Geology

The site lies within an inlier of the Carboniferous Limestone Series surrounded by younger Triassic and Jurassic strata forming the northern limb of an east-west trending anticline. Triassic deposits overlie the Carboniferous Limestone outcrop to the north-east and south-west of Tythegston. Extensive excavation of the limestone for crushed stone has created a number of large quarries within the inlier. Tythegston quarry is excavated in the Main Limestone of the Carboniferous Limestone Series, which may be of the order of 1 000 m thick in the area. The Main Limestone is a hard, massive, crystalline limestone, separated by bedding planes 0.5 to 3 m apart, some of which are marked by thin (less than 0.25 m) shaly partings. The general dip of the beds is about 5° northwards but cross-folding in the Tythegston area has steepened the dip to between 35° and 55° northwards. Structural mapping has shown that the limestone is cut by a conjugate set of essentially vertical fissures. One set strikes 003° to 183° (relative to Grid north) and

is characterised by infilling with fine-grained red and green argillaceous material derived from the overlying Triassic sediments. Solution widening of these joints has been observed. The second set run in the direction 112° to 292° and appear to be tension joints, typically infilled with secondary calcite. Both sets of joints are wider at the surface, decreasing in width below the quarry rim. The dominant set at Tythegston quarry is the 003° to 183° system.

High resistivity values and low gamma counts recorded from the geophysical logging of the investigatory boreholes are consistent with hard, massive limestones. The borehole walls were generally smooth with no evidence of large-scale fissuring. Examination of rock cores showed the presence of essentially vertical or oblique fissures in the limestone, most of which were infilled with red argillaceous material and calcite. Calcite veining in the limestone was found to be common, occurring as bands up to 10 mm thick.

Hydrogeology

Natural groundwater discharges from the Carboniferous Limestone occur in the Merthyr Mawr Warren area in the Cwm y Gaer (NGR SS 854 775) and at Burrows Well (NGR SS 857 773) some 1.3 and 1.6 km respectively, to the south of the landfill site. Groundwater movement from the landfill site, in a southerly direction, is probably controlled by the dominant 003° to 183° joint system. Natural discharge also takes place to the Ogmore River, which is in hydraulic continuity with the Carboniferous Limestone aquifer, some 3 km to the south-east of Tythegston. Springs at Schwyll (NGR SS 8882 7708 and 8879 7705) 4 km south-east of the landfill, which provide an average annual yield of $7.6 \times 10^6 \text{ m}^3$, are the nearest public supply source. The

Spring sources are separated from the Tythegston aquifer block by the Ogmere River and are unlikely to be affected by movement of leachate from the Tythegston landfill.

Intergranular permeability and porosity in the limestone is effectively zero. Groundwater storage and movement is expected to be via the secondary permeability developed by the fissure system. The effective permeability of the limestone, controlled by the degree of fissuring is likely to be low, many of the fissures being infilled with Triassic material.

Detailed observations of water levels in the quarry area were made during the recharge of the aquifer. Increases in water levels of between 30 and 45 m (indicative of a fissure storage system) have taken place since the start of recharge between the end of September 1976 and March 1977. At the end of September 1976 the water table in the limestone was some 10 m below the base of the landfill in the central depression, with a steep hydraulic gradient of 0.009 to the south west. At this time the saturated level within the landfill was 8.5 m above the base of the fill material in the central depression. By the end of October 1976 the water table in the limestone beneath the central quarry area had risen by some 20 m to form a common surface with the saturated level within the landfill. The hydraulic gradient from this central area was 0.05 to the south-west. By March 1977 a constant water table had been established in the quarry area with a hydraulic gradient of 0.02 to the south-west beyond the quarry limits. At this time the water table was just above the landfill surface and an extensive lagoon had developed in the central area of the quarry.

Continuous water level recorders were installed in boreholes B1 to B5 inclusive on 9 March 1977. Regular fluctuations of groundwater levels of up to 20 mm have been observed in three of the five boreholes. The cyclic form of the changes in water level is thought to be due to the responses of fissure systems to earth tides.

The long-term (1916-1950) mean annual rainfall for the Bridgend area is 1,765 mm, of which about 1,100 mm are estimated to percolate through the landfill, producing approximately $10^5 \text{ m}^3/\text{a}$ of leachate. High dilution of landfill leachate is expected to occur by lateral movement of groundwater during recharge, the water table in the limestone rising to the landfill surface.

History of Waste Disposals

The site, originally leased to Penybont R.D.C. which was succeeded by Ogwr Borough Council, received planning permission for the disposal of inert wastes in 1968. Disposal commenced in December 1968 and comprised domestic and paper mill pulp wastes deposited initially into the water-filled depression in the centre of the quarry. Planning permission was later amended to include the disposal of reject tyres and some two million tyres were subsequently disposed of in the waterlogged part of the quarry. In 1971 it was discovered that approximately $1,000 \text{ m}^3$ of potentially hazardous wastes had been deposited at the site in 45-gallon drums. Wastes contained within the drums included solvents such as xylene, styrene, methylene chloride, various partially polymerised resins such as phenolic, amine, acrylic resins, chemical residues such as peroxides, acrylic acid, used soluble oils, metal finishing effluent sludges and organic sulphides. As many of the drums as possible were recovered and removed from the site at the insistence of the Water Authority. In April 1972 a large number of tyres caught fire causing extensive burning within the landfill. Domestic and trade waste and paper mill wastes were being deposited at the site at the time of investigations, the landfill being some 10 to 15 m beneath the quarry rim. The depth of fill material was some 22 m in the central depression and 4 to 6 m on the rock benches at the edge of the quarry. Completion of infilling is expected in 1985.

Quality monitoring at Burrows Well 1.6 km to the south of the landfill site was carried out from the discovery of potentially hazardous substances in the landfill in 1971. Increases in the zinc content of leachates within the quarry from 11.1 mg/l to 129 mg/l following the fire in 1972 was detected at Burrows Well some 20 months later.

Site Investigation

A programme of drilling and sampling was carried out between July and October 1976. One type 'A' borehole was drilled to the base of the landfill in the central, deeper part of the quarry. Samples of the waste material and landfill liquids were recovered for detailed analysis. On completion of drilling and sampling, permanent slotted lining was installed in the borehole to allow long-term monitoring of the landfill liquids.

A total of six type 'B' boreholes were drilled during the investigation to approximately 20 m below the water table in the limestone. Most of the boreholes were completed at a time when water levels were particularly low. Five boreholes were drilled at Tythegston, four on rock benches within the quarry and one at a distance of 150 m to the south of the quarry. Additionally, one borehole was drilled within Cornelly Quarry (NGR SS 835 805) 2 km north-west of the Tythegston landfill. Samples of water encountered during the drilling were recovered for detailed analysis. All six boreholes were left open to enable the long-term monitoring of groundwater levels and quality changes.

Wastes from the Landfill

In the samples of solids from the landfill the concentration of cyanide varied from 0.02 to 0.9 mg/kg; halogenated solvents (mainly trichloroethylene) from 0.03 to 1.2 mg/kg and phenols from 3 to 37 mg/kg. The highest concentrations of solvents and phenols were found in the topmost sample taken, at a depth of 3 - 3.5 m.

The pH of the liquids was 6.0 - 6.9. The concentration of TOC ranged from 3,200 to 5,760 mg/l between 17.5 m and 20 m but fell to 930 - 1,170 mg/l at the base of the landfill at 21 - 22 m. The short chain fatty acids were distributed in a similar manner with concentrations declining from 5,000 - 9,400 mg/l to 1,680 - 2,180 mg/l at the base of the landfill. Phenols were present at concentrations of 6 - 25 mg/l. The concentrations of cadmium, copper, chromium and vanadium did not exceed 0.05 mg/l while those of nickel and zinc lay within the ranges 0.2 - 1.2 mg/l and 0.2 - 3.6 mg/l respectively.

Groundwater Quality

The distribution of landfill-derived contaminants in water samples from the limestone suggested that the dominant movement was along the 003 to 123° set of joints in a southerly direction.

The highest concentrations of TOC were found in water samples from boreholes B1 (80 - 130 mg/l) and B4 (100 - 430 mg/l). The concentrations in boreholes B2 and B3, at the western end of the quarry were 40 - 73 mg/l and 20 - 21 mg/l respectively. Concentrations in borehole B5 to the south of the quarry were 2 - 6 mg/l, similar to those from the control borehole, B6, in Cornelly Quarry.

Significant concentrations of carboxylic acids were present in boreholes B1 and B4, at concentrations up to 460 mg/l in B4. In the remaining type 'B' boreholes, carboxylic acids were present at concentrations of less than 10 mg/l. Phenols were detectable (1.1 to 1.6 mg/l) only in borehole B4.

Nickel and zinc were the only heavy metals detected in any of the type 'B' boreholes. The mean concentrations of nickel and zinc in any borehole did not exceed 0.1 mg/l and 0.3 mg/l respectively.

Evidence for the movement of leachate beyond the quarry perimeter was provided only by the distribution of chloride, the concentrations of which in B5 ranged between 90 and 200 mg/l, which compare with concentrations of 700 - 900 mg/l in B4, 200 - 300 mg/l in B3.

The analyses were carried out on water samples recovered during the drilling, when the water table was some 10 m below the base of the landfill. Geophysical logging was carried out in November 1976 when the water table was within the upper levels of the landfill. Liquid conductivity logs run in all the boreholes recorded conductivities of up to 2,660 mhos/cm within the quarry area whereas in B5 the conductivity was the order of 200 mhos/cm. The highest conductivities were recorded in boreholes B2 and B3 at the western end of the quarry and these values suggest that overspill had occurred from this area of the landfill with mixing of leachate and groundwater.

Further Studies

The existing array of observation boreholes is insufficient to define adequately the groundwater flow regime and it is proposed that further boreholes should be drilled in the eastern part of the quarry, to define the extent and influence of the transient recharge mound. Pumping and tracer tests should be conducted in order to measure local values of transmissivity, storage and, especially, dispersivity.

Monitoring of groundwater levels and quality parameters should be continued in order to clarify the relationships between the groundwater regime and pollutant flow paths during the changing conditions of the natural recharge/discharge cycle.

It is suggested that monitoring the carbonate hardness of local springs at times of peak and minimum flows may be used to determine the relative importance of conduit and diffuse groundwater flows contributing to their catchments. This technique may provide a simple, convenient method of assessing the pollution potential of groundwater sources in fissured limestone terrains.

INTRODUCTION

1.1 Background and Objectives

The landfill at Tythegston (Figure 1) is situated to the north of the A 4106 road, 3.7 km north-east of Porthcawl and 5.5 km south-west of Bridgend, Glamorgan (National Grid Reference, SS 852 789). The landfill lies within the outcrop of northwards dipping Carboniferous Limestone, in a region with a long term mean annual rainfall of about 1,750 mm. The wastes occupy a disused quarry in the limestones, of some 0.09 km² in area. The disposal of domestic and paper mill pulp wastes at the site commenced late in 1968 and continues to the present day. During the period 1970/72 industrial wastes, comprising reject motor tyres and drummed chemical and manufacturing industry wastes were co-deposited with the domestic wastes.

The investigation of this landfill was carried out by the Water Research Centre as part of the Department of the Environment's Programme of Research into the Behaviour of Hazardous Wastes in Landfills. The objectives of the investigation were (i) to ascertain the types and, if possible, the quantities of wastes deposited and remaining with the landfill, (ii) to determine the distribution, both laterally and vertically, of potential pollutants present in the leachate in the landfill, (iii) to determine the extent of pollution, if any, on the groundwater in the vicinity of the site and (iv) to interpret the results in terms of transport and attenuation mechanisms within the landfill and the underlying, massive, fissured strata.

1.2 History of waste disposal at Tythegston landfill

Planning permission for the disposal of inert domestic and industrial wastes was received by the leasees, the former Penybont Rural District Council, in 1968. An annual total of about 86 000 tonnes of predominantly solid, inert wastes has been deposited at the site, slightly less than half of which is composed of untreated domestic waste (Table 1) from a variety of local sources

(Table 2). Waste disposals commenced in December 1968 into a water filled depression, up to 15 metres deep, in the western and central parts of the quarry. Planning permission included the disposal of reject motor tyres.

Table 1 Composition of Waste Disposals

Category	Annual disposal, tonnes
Untreated domestic and trade wastes	40 000
Industrial waste - general factory rubbish	31 000
Industrial waste - inert process sludge	15 000
Total	86 000

Table 2 Sources of Waste Arisings

Domestic and trade wastes	Penybont Rural District Council 1968-74)	
	Bridgend " " " " ")	Ogwr
	Porthcawl Urban District Council " ")	Borough
		Council
		since
		1/4/74
Industrial wastes	Bridgend Paper Mills	
	Avon Rubber Company	
	Purle Waste Disposal Company - Discontinued 1972	

By 1971, when waste disposals had substantially infilled the deeper western and central portions of the quarry, it was discovered that approximately 1 000 m³ of potentially hazardous wastes had been deposited at the site in 0.2 m³ (45 gallon) drums. Wastes contained within the drums included solvents (xylenol, styrene, methylene chloride), partly reacted resins (phenolic, amine, acrylic, alkid, polyester and vinyl acetate), chemical residues (peroxides, acrylic acid), exhausted soluble oils, metal finishing effluent sludges and organic sulphides. Subsequently, at the insistence of Glamorgan River Authority (since 1 April 1974 Glamorgan Rivers Division, Welsh National Water Development Authority) all recoverable drums were removed from the landfill.

An estimated 2 000 000 motor tyres had been incorporated in the landfill by early 1972. On 9 April 1972 an extensive fire broke out within the landfill and the disposal of tyres at the site was subsequently discontinued. Combustion appears to have been confined to the surface layers of the landfill and increases in the concentrations of potential organic products of the pyrolysis of tyres were not apparent from a comparison of analyses of leachate samples taken from surface ponds within the landfill made before and after the fire (Table 3). A significant increase in the zinc content of the leachate was found, which may have been due to the release of zinc compounds present in the synthetic rubber and as galvanising on steel wound tyres, as a result of the effects of the fire.

Table 3 Comparison of Typical Analyses of Surface Leachate Samples taken within the Quarry before and after the Fire on 9 April 1972

Determinand	Date	
	28 September 1971	18 April 1972
pH	6.2	6.2
BOD mg/l	1000	not determined
Ammonia (as N)	23.8	47.5
Formaldehyde	0.6	2.0
Chloride	140.0	not determined
P.V.	138.0	not determined
Total Dissolved solids	710.0	not determined
Phenols	1.3	1.6
Sulphide (as S)	2.9	not determined
Zinc	11.1	129.0
Total chromium	0.07	not detectable
Iron	180.0	150.0
Copper	0.2	0.2
Nickel	not detectable	not detectable
Cadmium	not detectable	not detectable
Lead	not detectable	0.1
Manganese	not determined	11.1
Oil	22.0	not determined
Cyanide	not detectable	not detectable

Details of analyses provided by Glamorgan Rivers Division, WNWDA

Current waste disposals at the site are confined generally to untreated domestic and trade wastes, and paper mill pulp wastes, at the rate of about 8.4×10^4 tonnes per year. By late 1977 infilling had proceeded to within 15 metres of the rim of the quarry, completion of the site being anticipated in the mid 1980's, to be followed by reinstatement as agricultural land.

2.1 Geology

2.1.1 Geological succession

Tythegeston is situated on the southern limb of the complex, east-west trending, major synclinal structure that defines the South Wales Coalfield. The area studied is composed of a thick sequence of bio-clastic and chemically precipitated carbonate sedimentary rocks of Lower Carboniferous age dipping generally northwards towards the core of the main syncline and overlain, on the plane of a marked angular unconformity by an arenaceous, argillaceous and carbonate sedimentary sequence of Lower Mesozoic age. The unconformity records a period of subaerial erosion following the Hercynian orogeny (George 1970), during which solution widening of joints in the Carboniferous Limestone (karstification) allowed Lower Mesozoic continental sediments (Triassic age) to penetrate to depths of up to 54 m (Thomas, 1968) as neptunian dykes into the limestone bedrock.

Pleistocene and Recent deposits crop out as discontinuous patches in river valleys, capping high land and along the shores of the Bristol Channel. The succession of rocks cropping out in the area is given in Table 4 and their areal distribution shown on Figure 2.

2.1.2 Structure

The area lies on the southern limb of the South Wales Coalfield syncline, giving the Carboniferous beds a regional dip northwards of about 10 to 15 degrees. To the south east of Tythegeston, the Liassic beds, which overlie unconformably the Carboniferous Limestone, dip generally south or south eastwards at about 3 degrees.

The flanks of the main synclinal structure in South Wales are corrugated by sub-parallel, en echelon fold systems. George (1933) has shown that the series of folds known as the Cowbridge-Cardiff anticline extends westwards into the Tythegeston area as the Candleston anticline, running east-west 1.5 km

TABLE 4 Stratigraphic Succession of Rocks Cropping out in the Tythegston Area
(after George 1933, 1951; Owen and Rhodes 1969 and Thomas, 1968)

Era	Period	Series/Stage	Lithologies	Thickness
Quaternary	Recent	Recent	Alluvium	Probably exceeds 15 m locally
	----- Erosional Boundary -----			
	Recent/ Pleistocene		Blown sand, peats and sands	Probably exceeds 15 m locally
	----- Erosional Boundary -----			
Mesozoic	Pleistocene		Glacial sand, gravels and boulder clays	Variable
	----- Major Erosional Boundary (Unconformity) -----			
	Jurassic	Lower Lias	Alternating, fossiliferous blue-grey marine limestones and mudstones	c 70 m
			Blue-grey to brown, nodular limestones, occasionally conglomeratic with thin shale bands (Southerndown Beds), passing vertically and laterally into underlying pale coloured conglomeratic limestone (Sutton Stone)	0 - 30 m
				0 - 18 m
	Upper Triassic	Rhaetic *		
		Keuper	Red, calcareous conglomerates and red and green mottled siltstones and sandstones	0 - 50 m
	----- Major Erosional Boundary (Unconformity) -----			
	Palaeozoic	Upper Limestone Shale (D ₃)	Impure, fossiliferous, dark, muddy limestones with black shale partings	>7.5 m
		Dibunophyllum Zone (D ¹ and D ² ?)	Massive, fossiliferous limestone containing beds of sedimentary breccia	>180 m
		Seminula Zone (S ₂)	Oolites and pisolites with dark, massive, crystalline limestone and carbonaceous shaley partings	c 245 m
		(Carboniferous Limestone) Upper Caninia Zone (C ₂ S ₁)	Locally fossiliferous limestone with occasional oolites	110 - 140 m
		Caninia Oolite (Upper C ₁)	Pure, massive oolites with occasional crinoidal lenses Partial dolomitization	36 - 45 m
		Lower Caninia Zone (C ₁)	Fossiliferous limestone with dark, shaley partings. Local dolomitization in upper part	150 - 180 m
		Zaphrentis Zone (Z)	Crinoidal limestone and dolomite with cherts	>24 m

* Table 4

- * Rhaetic beds here form the transition between the continental deposits of Triassic age and the marine Jurassic beds, and are formally classified as being the uppermost stage of the Triassic (Ager, 1970).
-

south of Tythegstone Quarry, and its complimentary synclines (Figure 2). Structural mapping of the limestone outcrop northeast of Porthcawl (Holland, 1977) confirmed the presence of an east-west regional fold axis, plunging gently at about 5 degrees to the west (Figure 3). As a result of the subsidiary folding, undulations in the dip and reversals of dip are common in the area defined by Tythegston quarry and adjacent quarries (Figure 4).

A series of sub-parallel, north-south trending faults occur, the chief of which passes through Ogmere Down, 4 km southeast of Tythegston quarry (Rhiw fault), down-throwing the Carboniferous beds to the east by about 55 metres but not affecting adjacent Mesozoic beds, and thus of pre Triassic age (George 1933). The minor fault at Candleston Castle (SS 871 779) is of the same age and down throws about 24 metres westwards. The small fault immediately south of Tythegston quarry appears to be pre-Triassic, down-throwing westwards. In contrast, the Ty Coch fault, which runs northwards into Whitecross Down, 2 km west of Tythegston quarry, cuts both Carboniferous and Triassic beds and is, hence, of post-Triassic age, has displaced the beds by horizontal movement only (tear fault). The Newton fault, which north-west to south-east 1.75 km south of Tythegston quarry, was active in both pre and post-Triassic times. The westwards down throw of the fault, in Carboniferous rocks, reaches 450 metres in the vicinity of Black Rocks (SS 855 770), decreasing to between 60 and 90 metres towards the northwest. By comparison, the down throw affecting the Triassic beds, also westwards, is only of the order of 5 to 10 metres. Minor, normal faulting, with down-throws of 1 metre or less usually to the east, may be observed in many exposures (Holland, 1977).

The Carboniferous rocks of the area were found to be affected by a conjugate set of sub-vertical joints (Holland, 1977) at approximately 010° - 190° .

(Magnetic north) and $115^{\circ} - 295^{\circ}$ (Magnetic north) respectively (Figure 6). The $010^{\circ} - 190^{\circ}$ set were dominant, forming distinct features in all quarry exposures. The majority of this set of joints ranged between 10 and 50 mm in width, decreasing with depth below the original land surface, but occasional, solution enlarged joints, up to 4.0 metres width, were noted. The measured frequency in quarry exposures varied between one per 200 mm to one per 2 metres horizontal distance. This set were found to be infilled with red and green mottled silty Triassic sediments, the edges of the joints being occasionally lined with dog-tooth calcite crystals. The joints were not purely planar features, but undulated both vertically and along the strike, giving rise to the spread of measurements shown in Figure 6. The $115^{\circ} - 295^{\circ}$ jointing appeared to be the result of extensive calcite veining of the rock, possibly arising from recrystallisation in tension cracks. The joints were vertically discontinuous, often terminating in bedding planes with secondary calcite infills. The frequency of these joints ranged from 200 mm to 4 metres. Infrequent, solution enlarged joints of the $115^{\circ} - 295^{\circ}$ series, infilled with Triassic sediments were noted at Cornelly quarry (SS 835 800) by Holland (1977) whilst Thomas (1968) recorded Triassic infills of solution enlarged joints of both series, some up to 4.5 m in width and extending to depths in excess of 41 metres, at a number of localities.

2.2 Hydrogeology

Hydrogeological data referring to the Carboniferous Limestone aquifer around Tythegston are limited. Large groundwater sources have been developed locally by constructing sumps at the sites of natural springs and, consequently, few boreholes have been drilled for water supply (Table 5), although a number of site investigation boreholes sunk at the industrial estate to the east of Bridgend provide useful information on the physical properties of the limestone.

Table 5 Licensed Groundwater Abstractions in Tythegston/Bridgend Area

Name	NGR	Type of source	Licensed quantity $\text{m}^3/\text{a} \times 10^6$
Schwyl1	SS 8879 7705	Spring	7.956
Methyr-mawr Warren	SS 8450 7720	Spring?	0.220
Ffynnon-fawr	SS 8230 7797	Borehole	0.055
Bridgend Industrial Estate	SS 9225 7868	Borehole	1.182

Note: Location of sources shown on Figure 6

The limestone aquifer unit in which Tythegston quarry is situated (Figure 6) is bounded to the south and west by the coast from the mouth of the Ogmore River to Kenfig Burrows, to the east by the deeply incised valley of the Ogmore running north eastwards and north through Bridgend and to the north by a major east-west fault, bringing Triassic and Liassic beds overlying the Carboniferous Limestone into juxtaposition with the Coal Measures, which defines the southern face of Kenfig Hill. Topographically the Carboniferous Limestone and overlying Mesozoic beds form a rounded hill mass, rising to a maximum height of 109 metres o.d. at Stormy Down, 1.5 km north of Tythegston quarry. The western, southern and eastern flanks of the area are marked by dry valleys, or valleys containing ephemeral streams, whilst to the north of Stormy Down the surface slopes towards the Liassic floored valley of the Nant Ffornwg before rising steeply on the south face of Kenfig Hill.

The aquifer block thus defined covers an area of about 55 km^2 , of which 22 km^2 are underlain directly by Carboniferous Limestone, the remainder being covered by a veneer of variable thickness of Mesozoic rocks overlying the limestone.

Major natural groundwater discharges occur at, or close to, sea level as springs associated with faults at Porthcawl harbour (SS 823 765), Merthyr-mawr Warren (SS 845 720 and SS 857 773) and at Schwyll (SS 888 771) immediately east of the Ogmore River (Knox, 1933). Other discharges, not apparently associated with faults have been recorded (Knox, 1933) at Sker Point (SS 790 795) and St John's Well (SS 838 775). George (1933) has suggested that the Rhiw fault, which gives rise to the major discharges at Schwyll springs, may extend north-north-eastwards along the line of the Ogmore River, passing through the zone of swallow holes at Merthyr-Mawr House (SS 887 779) and giving rise to a series of small springs between Merthyr Mawr and Pwll Clement (SS 899 794) at Bridgend. Small springs draining northwards to the Nant Ffornwg at SS 870 816, SS 885 819, SS 886 813 and SS 890 810 are associated with small faults and represent drainage from sub-aquifers developed within the layered limestone-mudstone Lower Lias beds and, possibly, upwards leakage from the underlying Carboniferous Limestone. Springs discharging from the southern face of Kenfig Hill are controlled by the major east-west fault and are derived principally from storage in the Millstone Grit aquifer. Groundwater level fluctuations at sources close to sea level are small, a maximum difference of 0.48 metres (4.95 m.o.d. to 4.47 m.o.d.) having been recorded between 1928 and 1933 at Schwyll Spring. Small, regular water level fluctuations noted during a pumping test at Schwyll have been attributed to tidal effects, as have similar movements observed at St John's Well, where a 3 hour lag occurs (Knox, 1933). By contrast, descriptions of the water levels encountered during quarrying in the upland region indicated annual water level fluctuations of at least 20 metres in that zone, with minimum levels at Tythegston being generally below 50 metres o.d. (base of the quarry). George (1933)

noted that perennial flows in the Afon Alun, a tributary of the Ewenny River crossing the Carboniferous Limestone outcrop to the east of the Tythegston block, did not extend above Pontalun (SS 899 767, c. 15 m.o.d.) indicating a possible annual groundwater level fluctuation of 15 metres above that point). It is concluded, therefore, that the regional groundwater flow pattern within the Tythegston block is essentially radial (Figure 6), with natural discharge principally at the coast to the west and south and to the Ogmere River in the east, but with minor discharges to the north via upwards leakage.

The long term (1916-1950) average annual rainfall measured at Bridgend amounts to 1765 mm, whilst the average annual potential evaporation at Mumbles Head, Swansea, 20 km northwestwards, is 650 mm (Meteorological Office, 1973), indicating a mean effective rainfall, available for infiltration, of about 1100 mm/year. Infiltration at this rate over 22 km² of limestone outcrop would yield an annual recharge rate of 24.2 million cubic metres (6.6×10^4 m³/day). However, Fox and Rushton (1976) have shown that the recharge to fissured limestone aquifers may be under-estimated by allowance not being made for runoff from, and peripheral recharge around, low permeability beds overlying the limestones. Therefore, the mean annual recharge to the Tythegston limestone block is estimated to lie in the range 30 to 42 million cubic metres (8.2 to 11.6×10^4 m³/day). The suggestion by Knox (1933) that a dry weather flow of 1.6×10^4 m³/day (6.0×10^6 m³/year) at Schwyll Spring, measured after a period of drought in 1921 indicates that groundwater in the limestones is derived principally from recharge to the northern outcrop of the Carboniferous Limestone, some 40 km distant, and passes beneath the coalfield syncline before emerging as spring discharges along the Bristol Channel coast, cannot be substantiated.

The limestone outcrop around St Brides Major, which supports the Schwyll Springs, has an area of about 10 km^2 , providing an estimated minimum recharge of $3.0 \times 10^4 \text{ m}^3/\text{day}$ ($11.0 \times 10^6 \text{ m}^3/\text{year}$), sufficient to support the springs. Investigations at the Llanharry haematite mine (ST 006 804, Edworthy, Naylor, and Brown, 1976) 20 km east-north-east of Tythegston, provided no evidence of groundwater derived from the northern outcrop of Carboniferous Limestone, to depths in excess of 300 metres (240 metres below O.D.).

The Carboniferous Limestone is massive and partially recrystallised, with minimal intergranular porosity and permeability. A primary (intergranular) porosity of 0.2 per cent has been reported for Carboniferous Limestone from the Mendip Hills (Drew 1968), whilst a bulk storage coefficient (effective primary plus fissure porosity) of about 1 per cent has been measured by Atkinson (1977) from the same area. The latter value compares with porosity determination in the range 1 to 2 per cent made on cores from boreholes drilled during 1947 in the area of the Bridgend industrial estate (SS 920 790). Bulk density measurements of the same core samples fell in the range 2.7 to 2.8, comparable with the density of pure calcite (calcium carbonate, 2.71). Groundwater movements through such rocks is restricted essentially to fissures and bedding plane partings.

White (1969) divided groundwater movement through massive limestone aquifers into diffuse flow, via the plexus of fine, intersecting fissures and conduit flow ('rapid flow' of Fox and Rushton, 1976), through solution enlarged channels. The development of preferential, solution enlarged subsurface channels may be a continuous process, leading ultimately to complete karstification of the outcrop, which is then characterised by reduced or absent surface drainage, sinking streams (swallow holes) and the presence of major resurgent streams (valclusion springs) carrying a high proportion of the groundwater discharge.

Karstification of the Carboniferous Limestone of the Tythegston area, and of the Gower Peninsula 30 km to the north west and the Mendip Hills 60 km south east, has taken place during two separate periods. The first phase occurred during the Triassic period, as evidenced by the presence of red coloured triassic sediment infills of solution enlarged joints and caves (George 1970, Thomas 1968). In the Tythegston block it has been shown (Holland, 1977) that the development of enlarged joints and subsequent infilling took place principally along the north-south joint and fault direction. Subsequently, further karstic development occurred in late Pliocene or early Pleistocene times (Ford and Stanton, 1968) giving rise to the modern distribution of swallow holes, caves and resurgent springs. The association of the main springs in the Tythegston area with north-south trending faults suggests that karstification again favoured that joint direction, possibly re-activating the original Triassic karstic channel network (Figure 7a). A similar dominant north-south orientation of modern solution conduits is also present on the Gower Peninsula (Ede, 1975). The presence of parallel, preferential flow paths within an aquifer may generate significant anisotropy (Brereton and Wilkinson, 1978) with non-orthogonal intersections of groundwater flow lines with lines of equal hydraulic head (groundwater contours). Under such conditions, the direction of groundwater movement is dominated by the orientation of the preferential channels and may be oblique to the direction deduced from isolated groundwater level measurements (Figure 7b).

Groundwaters derived from limestone terrains characteristically possess a high total hardness, of which the greater part is attributable to bicarbonate, and are neutral or slightly alkaline. Prior to the investigation of the Tythegston landfill, groundwater analyses were restricted to three sites within the area (Table 6).

Table 6 Analyses of Groundwater from the Carboniferous Limestone,
Tythegston-Bridgend Area

Site	Burrows Well (SS 857 773)	Borehole at (SS 922 787)	Schwyll Spring (SS 888 771)
Date of sampling	Oct.74 - Feb.76	16 July 1942	1933
Total hardness (as CaCO_3) mg/l	not determined	310	274
Bicarbonate hardness (As CaCO_3) mg/l	not determined	285	not determined
Chloride "	27 - 33	15	" "
Nitrate (as N) "	7.2 - 8.8	nil	" "
Ammonia (as N) "	0.03 - <0.01	not determined	" "
Lead (as Pb) "	not determined	nil	" "
Iron (as Fe) "	" "	nil	" "
Zinc (as Zn) "	0.1 - 0.01	nil	" "
Copper (as Cu) "	0.004 - 0.012	not determined	" "
Electrical conductivity micro-mohs	603 - 711	" "	" "
Permanganate value mg/l	not determined	0.1	" "
ph	7.1 - 7.5	7.2	" "

Few estimates of the hydraulic properties of the Carboniferous Limestone aquifer have been reported. Primary (intergranular) porosity of 0.2 per cent and storage coefficient of 1 to 2 per cent have been noted above. Ede (1975) has estimated that between 26 and 64 per cent of the dry weather discharges of resurgent springs on the Gower are derived from diffuse recharge via small fissures, the remainder taking place through solution enlarged pathways. Estimates of the sources of recharge to the Mendip Hills by Atkinson (1977) suggest 50 per cent diffuse flow and 50 per cent conduit flow, who also suggested that although diffuse storage in the saturated zone exceeded that in conduits by a factor of 30 times, between 60 and 80 per cent of groundwater flows takes place via the conduits. Detailed analyses of groundwater recession curves provided an estimate of transmissivity for the diffuse flow through the aquifer of about $2\,700\text{ m}^2/\text{day}$ and a hydraulic conductivity of about 90 m/day . Analysis of limited data on a 21 day pumping test, carried

out in September 1928, at Schwyll pumping station (Knox, 1933) indicates a transmissivity of about $8\,000\text{ m}^2/\text{day}$. The maximum drawdown measured was less than 0.4 metres and it is concluded that the greater part of the water pumped during the test was derived from within the local conduit system (Figure 8a), confirming the efficiency of such channels as flow paths.

No results of field determinations of the dispersivity of the Carboniferous Limestone aquifer have been published, but Claasen and Cordes (1975) report values of 15 m and 38 m from fractured carbonate aquifers in Nevada and New Mexico respectively.

3.1 Synopsis of the Investigation

A programme of preliminary drilling and sampling using power auger techniques, similar to that employed at other sites investigated (Stiff, Young, Naylor and Brown, 1976, Young, Barber, Naylor and Maris 1978, Stiff, Young, Barber and Naylor 1977 and Barber, Young, Naylor and Blakey 1978), was not carried out because of the hard, compact nature of the Carboniferous Limestone. Instead, a structural survey of the surrounding area was carried out between 5 and 7 April 1976 (Holland 1977). The results of the survey have been discussed in section 2.1.2. Detailed investigations comprised the drilling of seven boreholes by Messrs Wimpey Laboratories Ltd., under contract to the Water Research Centre, between July and October 1976, using percussion and air flush rotary techniques as described by Barber, Naylor and Maris (1978). Because of the essentially impermeable nature of the limestone, core samples were taken only at 4 metre intervals, for the purposes of lithological description, but liquid samples were obtained from borehole fluids for chemical analysis. Continuous 'U 100' driven core samples were taken during drilling within the landfill, supplemented by disturbed, bulk samples where drive coring proved unsuccessful. Following completion of the boreholes, geophysical logging (gamma, resistivity, neutron, gamma-gamma, caliper, temperature and fluid conductivity) was carried out in the six boreholes outside the landfill, during November 1976, (Fleet 1977). Continuous water level recorders were installed on the five boreholes surrounding the Tythegston landfill on 9 March 1977 and on the borehole within the landfill on 13 April 1977. As a result of vandalism, all recorders were removed in October 1977 and a programme of regular water level measurements instigated, with the assistance of Glamorgan Rivers Division, Welsh National Water Development Authority. Monitoring of the quality of water in the observation boreholes at 3 monthly intervals commenced in March 1977.

3.2 Drilling and Sampling Programme

3.2.1 Boreholes within the landfill

One borehole (TA1, Figure 8) was sunk within the landfill, reaching the base of

the wastes at 22 metres below surface (Table 7). 150 mm internal diameter, permanent steel lining tubes were installed, the lower 9.80 metres of which were slotted and surrounded by a sand pack to allow sampling of landfill fluids. The upper 12.20 metres of plain casing were grouted into position using a sand/cement mix and finished at the surface with a 1.5 metre square, 150 mm thick concrete platform. The borehole has been maintained as a groundwater/leachate monitoring point.

3.2.2 Boreholes outside the main landfill

Six boreholes were drilled to depths of between 4.5 and 70.0 metres. Four holes (TB1-4 inclusive, Figure 8 and Table 7) were located within the quarry walls and passed through a thin veneer of wastes before entering the Carboniferous Limestone. A fifth borehole (TB5, Figure 8 and Table 7) was completed to a depth of 65.0 metres, in agricultural land 150 m to the south of the landfill. The sixth borehole (TB6, Figure 4 and Table 7) was drilled to 58.0 metres in the base of Cornelly Quarry (SS 835 799), 2 km north-west of the Tythegston landfill, for the purpose of obtaining fresh samples of rock and groundwater from the same aquifer unit, but remote from possible influences of the Tythegston landfill fluids. All six boreholes were completed with 150 mm internal diameter plain steel lining tubes, grouted to depths of between 6.0 and 16.20 metres below ground level and have been maintained as groundwater monitoring points. Borehole TB5 was found to have become blocked with red, marly material at a depth of about 15 metres in March 1977. The blockage was cleared to a depth of 30 metres on 18 April 1977, but further blockages of red silt took place, reducing the borehole depth to 18.5 metres by 20 April. In October 1977 the borehole was again cleared out and 24 metres of 125 mm internal diameter uPVC linings, the lower 16 metres of which had been slotted, were installed within the original 150 mm steel lining tube.

TABLE 7 Constructional details of boreholes in and around
Tythegston Landfill

General location	Tythegston						Cornelly Quarry
	Within landfill	Within quarry rim				Outside quarry rim	
Borehole No	TA 1	TB 1	TB 2	TB 3	TB 4	TB 5	TB 6
Datum level m.a.o.d.	76.43*	77.79*	78.72*	80.24*	76.33*	78.88	60.74
Ground level m.a.o.d.	71.39*	73.96*	75.15*	76.74*	71.98*	78.64	60.08
Depth of landfill m	21.80	5.00	5.60	5.00	4.20	0.0	0.0
Base of landfill m.a.o.d.	49.59	68.96	69.55	71.74	67.78	-	-
Depth of borehole m	22.00	62.50	70.00	70.00	45.50	65.00	58.00
Base of borehole m.a.o.d.	49.39	11.46	5.15	6.74	26.48	13.64	2.08
Length of lining b.g.l. m.	22.00	12.50	16.20	12.50	10.00	6.20	6.00
Base of lining m.a.o.d.	49.39	61.46	58.95	64.24	61.98	72.40	54.08
Length of plain lining m	12.20	12.50	16.20	12.50	10.00	6.20	6.00
Length of slotted lining m	9.80	0.0	0.0	0.0	0.0	0.0	0.0
Base of plain lining m.a.o.d.	59.19	61.46	58.95	64.24	61.98	72.40	54.08
Base of slotted lining m.a.o.d.	49.39	-	-	-	-	-	-
Dates of construction from	28.7.76.	13.9.76	11.9.76	19.8.76	5.8.76.	6.10.76.	19.10.76
to	4.8.76.	5.10.76.	17.9.76.	22.9.76.	19.8.76.	18.10.76.	2.11.76.

- * Ground level datums correct at time of drilling, flange levels at 8.10.76. Because of the high rate of waste disposal ground level rises necessitate the addition, from time to time, of further casing lengths to the top of these holes.

3.3 Sample Collection and Processing

3.3.1 Within the landfill (Borehole TA1)

Solid samples were recovered at approximately 1 metre intervals to a depth of 22 metres. They were double-wrapped and sealed in polythene and stored on site in a deep freeze prior to transportation to the laboratory for analysis. Where possible, 0.5 metre 'U100' core samples were taken; where this was not possible a bulk sample was recovered from the drill shell.

Liquid samples, approximately 2 litres in volume, were also taken at 1 metre intervals downwards from 12 metres depth, where standing water was first encountered. The liquids were filtered through Whatman GF/A filters, their pH values were measured and 500 ml portions were then acidified with 20 ml 'Aristar' hydrochloric acid in preparation for trace metal and organic carbon determinations. The acidified sample and the remainder of the filtered unacidified sample were then transferred to acid-washed glass bottles and stored in a refrigerator on site before transportation to the laboratory. Where direct filtration proved impracticable owing to the high content of particulate matter, the samples were allowed to settle during storage in the refrigerator and the supernatant liquid was decanted and filtered.

All samples were transported from site in cold boxes under melting ice. At the laboratory, solids were stored in a deep-freeze (-18°C) and liquids in a cold room (4°C) prior to analysis.

3.3.2 On the perimeter of and outside the landfill (Boreholes TB1 to TB6)

Boreholes TB1 - TB4 were drilled on the rock benches on the walls of the quarry; TB5 was drilled approximately 130 m to the south of the quarry; and TB6 was drilled at Cornelly Quarry, approximately 3 km to the northwest of Tythegston quarry (see Figure 4).

No solid samples were recovered for chemical analysis from these boreholes, but liquid samples were taken at 3 metre intervals using a Cassella sampler, when standing water was encountered in the boreholes. These samples were prepared for analysis as described in section 3.3.1.

3.4 Analysis of Samples

Samples of borehole standing water were analysed for the following:

- (i) Chloride
- (ii) Sulphate
- (iii) Phenol (colorimetric 4-aminoantipyrine method)
- (iv) Phosphorus (inorganic and organic totals)
- (v) Chemical Oxygen Demand (COD)
- (vi) Total Organic Carbon (TOC)
- (vii) Total Nitrogen (Kjeldahl)
- (viii) Ammoniacal Nitrogen
- (ix) Short Chain Carboxylic acids
- (x) Metals (Tables 12 to 17 inclusive)

In addition, selected samples of solid material from borehole TA1 were analysed for:

- (i) Moisture Content (105°C)
- (ii) Ash Content (500°C)
- (iii) Cyanide
- (iv) Halogenated solvents
- (v) Phenols (G.L.C.)

Routine groundwater quality samples have been analysed for a selection of the above determinands, chosen on the basis of their detection in samples taken during the drilling programme.

4.1 Geology

4.1.1 Landfill

Drilling at Tythegston quarry confirmed the presence of a central depression, approximately 16 metres deep, bordered to the north, west and south by a horizontal rock ledge varying in width from 10 to 40 metres (Figure 8). Domestic wastes mixed with recognisable motor tyres, steel drums, timber and paper pulp wastes were encountered in all boreholes penetrating the landfill, whilst admixed limestone rubble, probably derived from the quarry walls, was noted in boreholes TB1 to TB4 inclusive.

4.1.2 Rock strata

Cores recovered during the investigation at Tythegston quarry were composed predominantly of dark grey, dense limestone, with abundant crinoid fragments and occasional oolites. Chert bands were not encountered nor was extensive dolomite noted. Occasional bands of grey or brown silty shales were present in the sequence, which corresponded closely to George's (1933) descriptions of the Upper Caninia zone ($C_2 S_1$) and the underlying Caninia Oolite (Upper C_1). Cores from Cornelly Quarry (TB6; lithological summary of all boreholes Figures 9 to 15 inclusive) showed grey oolitic limestones with crinoid bands and thin, shaley partings, of the standard limestone division of the Main Seminula Zone (S_2).

Red silty and shaly fissure infilling was recorded in all boreholes penetrating the Carboniferous Limestone. A major Triassic infilling was penetrated at depths of between 10.90 and 13.90 metres below surface at borehole TB5. Red silts were found at depths of up to 38.0 metres below ground level at Tythegston quarry (TB4, Figure 13) and 51.50 metres below ground at Cornelly quarry (TB6, Figure 15). At both sites Triassic beds cap the Carboniferous Limestone close to the quarries' rims, and Triassic karstification of the limestone to depths below original ground level of at least 80 metres are indicated (c.f. Thomas, 1968).

4.1.3 Structure

Structural mapping at Tythegston quarry (Holland, 1977) showed undulating, isoclinal dips, ranging from 55 degrees at the southern end of the quarry to 20 degrees at the northern (Figure 4), with an azimuth direction of between 000 and 020 degrees True North. Enlarged joints, traceable across the width of the quarry, showing some evidence of water movement, are present in the 010 - 090 degrees (True North) direction, but similar enlargements were not noted in the 115-295 degree set in the eastern and western walls of the quarry. A shallow anticline/syncline system, with an east-west axis, was measured at Cornelly Quarry and an anticline plunging at 60 degrees in a direction of 026 degrees. Slickensided lineations were noted on calcite infills of bedding plane fractures at Cornelly quarry, indicating a second phase of movement subsequent to the tension cracking and fluid infill phase.

Vertical slickensides were noted on tubular sheets of calcite lining fissures in some core samples from Tythegston quarry whilst well developed calcite crystals, of 'nail head' habit, were observed lining an open, vertical fracture in cores from 48 metres depth at Tythegston (TB1, Figure 10).

Although continuous coring was not specified during drilling, between 40 and 57 per cent of the total depth drilled was recovered. Evidence of vertical and horizontal fractures not attributable to the drilling process was found in between 30 and 46 per cent of the cores examined, the highest density being recorded from Cornelly quarry. No significant decrease in the frequency of fractures was found to depths of 70 metres.

4.2 Hydrogeology

4.2.1 Groundwater levels

Investigation of the site took place during the late summer of 1976, at the end of a drought period of unprecedented severity. Groundwater levels in the limestone were found to be some 25 metres below the base of the landfill. A

perched water/leachate table was found to be developed in the landfill at about 56 m.o.d. (Figure 16). The drought in South Wales was broken on 10 September 1976 by 19.00 mm of rainfall, followed by 28.3 mm over 20/21 September. Although soil moisture deficits, for composite land use, had been estimated to be in excess of 100 mm in August and above 25 mm at the end of September of that year (Central Water Planning Unit, 1976), rises in groundwater levels were measured in borehole TB2 and TB3 between 14 and 17 September and 22 September and 1 October respectively. Less than 80 mm of rainfall had occurred before 17 September and it considered probable that rapid drainage through suncracked soils and via open fractures in the limestone occurred, bypassing the demands of the soil deficit. Groundwater levels rose rapidly during October 1976, forming a common surface with the perched table in the landfill in the latter part of the month. By late December 1976, groundwater levels had risen to above the level of the quarry floor and standing water persisted until April 1977. Groundwater recession commenced in all boreholes in late March or early April, falling to levels close to, or a few metres above, those recorded in the previous year by the end of September. The rapid response of groundwater levels to variations in drainage is characteristic of aquifers with low storage coefficients but relatively high permeabilities.

The effects of the relative importance of rapid recharge via large, open fissures and slower recharge via small fractures in the vicinity of individual boreholes was seen clearly during March 1977 (Figure 17). Marked, rapid responses in the water table were recorded in borehole TB2 on 19-20 March following a total of 17.5 mm of rainfall over 17-19 March, and more strikingly on 27 March following 18.8 mm rain on 26 March. The response at other boreholes was more subdued over the same period but the regular diurnal fluctuations of about 20 mm attributed to the effects of earth tides acting on a fissured mass were clearly recorded (TB4 Figure 17).

4.2.2 Estimation of landfill and aquifer hydraulic parameters

Measurements of the initial moisture volume content of domestic wastes in the United States (Fenn, Hanley and De Geare, 1975) gave values in the range 10 to 20 per cent, whilst the field capacities of the same wastes varied between 20 and 25 per cent. Domestic wastes used in pilot-scale leaching experiments in the United Kingdom (Newton, 1976) had an initial moisture volume content of 12.5 per cent, with a field capacity increasing from 21 per cent, for fresh refuse, to 30 per cent for aged material.

The increased retention of liquids in aged wastes, such as those in the lower parts of Tythegston landfill, may arise from the closing of voids by decomposition products and progressive compaction, thus inhibiting drainage under gravity. Because continuous free drainage can occur only at moisture contents above field capacity, the effective storage capacity (total porosity minus field capacity) of landfills composed predominantly of domestic refuse may be relatively small.

It has been noted (section 4.2.1) that groundwater levels in the aquifer began to rise in the aquifer between 14 and 17 September. By assuming that levels in the landfill (TA1, Figure 16) began to rise at the same time, it is estimated that an increase in level of 10.4 metres took place during the 44 days from 14 September to 29 October 1976. A total of just over 300 mm of rainfall was recorded at Bridgend during the same period, indicating an effective storage capacity of about 3 per cent. Similar estimates for the interim periods 14 to 21 and 14 to 19 October gave values of 2 per cent. After the end of October 1976 the water tables in the landfill and the aquifer were coincident and estimates of storage were modified by lateral flow between the landfill and the aquifer, leading to values of about 5 per cent.

The persistence of a perched water table within the landfill at the conclusion of a prolonged drought period, during which the water table in the limestone aquifer fell to at least 20 metres below the base of the landfill, suggests the presence of a layer of low permeability at the base of the fill. Measurements of the permeability of domestic wastes fall normally within the range 1 to 10^{-2} cm/s (10^3 to 10 m/day) (Stiff et al, 1977, Ministry of Housing and Local Government, 1961). Under the relative hydraulic heads in the landfill and the aquifer measured in August and September 1976, and again in October 1977 (Figure 16), such permeabilities would allow complete, rapid drainage of the perched water within the landfill. Solution of the Darcy equation:

$$Q = k \times i \times a \quad \text{where}$$

$$Q = \text{rate of flow (m}^3\text{/day)}$$

$$k = \text{permeability (m/day)}$$

$$i = \text{hydraulic gradient, and}$$

$$a = \text{cross-sectional area of flow (m}^2\text{)}$$

for a one metre square column of the landfill during the 42 day period of drought from 3 August to 14 September 1976 (Figure 16), assuming a one metre thick layer of reduced permeability at the base of the landfill, gives:

$$8 \times 0.02/42 \quad (\text{initial thickness of saturated fill} \times \text{effective storage/days of drainage}) = k \times 4 \quad (\text{average hydraulic gradient over the 42 days}) \times 1.$$

The permeability of the base of the fill is then estimated to be about 10^{-6} cm/sec (10^{-3} m/day), the low values being attributed to compaction of the basal wastes.

Estimates of the storage coefficient of the limestones, based on successive rises in groundwater levels between September 1976 and March 1977 and rainfall during the same periods, are shown graphically in Figure 18. Effective porosities (essentially synonymous with storage coefficient) of between 1 and 2 per cent are characteristic of the limestone below about 60 metres o.d., but increased storage in the range 6 to 8 per cent appears to be present in the

upper 5 to 10 metres of limestone, reflecting the occurrence of open fractures at this level noted by Holland (1977). A summary of the estimated hydraulic properties of the landfill and aquifer are given in Table 8.

Table 8 Estimated ranges of hydraulic parameters, Tythegston landfill

	Effective porosity (storage)	Permeability (m/day)
Landfill, bulk of wastes	0.02 - 0.05	$10^1 - 10^3$
Landfill, basal layer	not determined	c. 10^{-3}
Limestone, conduits)	0.01 - 0.08 (bulk value)	$10^3 - 10^4$ (1)
Limestone, diffuse flow)		$10^{-1} - 1.0$ (2)

Notes: (1) see section 2.2 (2) see section 5

4.2.3. Groundwater flow patterns

The effects of leakage from the perched water table in the landfill on water levels in the aquifer were recorded during times when the groundwater levels in the aquifer fell below the base of the landfill, in the form of a recharge mound beneath the landfill and increased TOC and chloride concentrations in the B type boreholes during periods of low groundwater levels. However, the siting of boreholes, drilled during the investigation, at the western end of the quarry was dictated by the requirements to avoid the areas of active landfilling at the eastern end. As a result, complete definition of the full extent and effects of the recharge mound has not yet been possible. The high groundwater gradients in a westerly direction, generated by the recharge mound at times of low permeability for the east-west fissure system, consistent with the observations of calcite infilling of this set of fractures made by Holland (1977). Rises in the water levels in the aquifer, due to natural recharge suppress the effects of leakage from the landfill (Figure 19b), and the dominant north to south groundwater flow pattern controlled by the 010 - 190° joint system becomes established within the quarry area after the formation

of a common water table between the landfill and aquifer (Figure 19c), although the greater storage of the wastes maintained a slight groundwater mound within the landfill area.

Limited dispersion of the leachate eastwards, normal to the main groundwater flow direction, and northwards, down the local dip of the limestones, counter to the flow direction, has arisen from the presence of the leakage mound sustained by the landfill. Combined lithological and geophysical logs of the boreholes drilled around the Tythegston landfill (Figures 10 to 14 inclusive), assembled as synoptic sections parallel (Figures 20 and 21) and normal (Figure 22) to the main groundwater flow direction, show that notwithstanding the northerly dip of the limestone, the main groundwater and leachate flow paths were southwest or southwards, controlled by the $010-190^{\circ}$ joint set, at the time of geophysical logging in November 1976. Isotherms record the dispersion of leachate derived from the warm interior of the landfill into the groundwater flow system. It should be noted that at the time of drilling and sampling, many of the zones which recorded high fluid conductivities during geophysical logging were above the contemporary water table.

4.3 Analytical Chemistry of borehole sample

4.3.1 Borehole TA1 (see table 9)

(a) Liquids Chloride concentrations ranged between 546 and 684 mg/l except at 12 m depth where a perched water table was encountered. Here the chloride concentration was 1210 mg/l. Concentration of sulphate varied between 285 and 503 mg/l, the highest concentration, again, being found at 12 m. A maximum concentration at the water table was also found for nitrogen (380 mg/l and mainly as ammonia), organic and inorganic phosphorus (1.23 mg/l and 0.71 mg/l respectively) and the metals potassium (300 mg/l), sodium (800 mg/l), magnesium (138 mg/l)

and molybdenum (0.18 mg/l).

The variations in concentration of most determinands probably reflect the general heterogeneity of the landfill.

The total fatty acid content of the borehole samples accounted for an average of 47% of the organic carbon; acetic and propionic acids being the major constituents (51% and 16% by weight respectively).

In all samples analysed, the ratios of the fatty acids, one to another, were similar. The total fatty acid concentrations varied by a factor of 10 within TA1. (see table 10).

No overall trends were apparent for the metals determined in the borehole liquids. The range of concentrations found for copper (0.02 - 0.05 mg/l) and zinc (0.24 - 3.6 mg/l) were not greater than the maximum permissible for drinking waters (1.5 and 15 mg/l respectively World Health Organisation, 1971); for chromium and vanadium the concentrations were 0.01 and 0.1 mg/l respectively. Calcium was found at high concentrations (400 to 1200 mg/l) but this is to be expected in a Carboniferous Limestone area where pH values of the borehole liquids lie between 6 and 7. Of the heavy metals determined, manganese was present at the highest concentrations (3.3 to 16.7 mg/l), the highest value being found at approximately 18 m depth.

(b) Solids Ten solid samples from TA1 were selected for analysis; results are given in Table 9.

Concentrations of cyanide ranged from 0.13 ug/g to 0.85 ug/g, this latter value being found in a sample of paper waste from 15 m depth.

Table 9 (a) ANALYSES OF BOREHOLE SAMPLES OF WATER COLLECTED DURING DRILLINGJULY - OCTOBER 1976

BOREHOLE NO. TA1

						13.5SW		12.5SW			
Sampling Depth (m)		12.0	17.5	18.0	18.5	(18.5)	19.0	20.0	(20.5)	21.0	22.0
Treatment of Sample		f*	c**	c**	c**	f	c	c	f	c	c
pH		6.9	-	-	6.2	6.1	6.0	6.0	-	6.4	6.5
Cl (mg Cl/l)		1210	627	654	546	684	617	654	610	560	599
SO ₄ (mg SO ₄ /l)		503	444	358	358	308	378	358	384	328	285
NH ₄ /N (mg N/l)		359	21	-	-	24	78	23	152	-	131
Kjeldahl N (mg N/l)		380	160	180	75	150	66	150	280	190	130
Metals (mg/l)	Ba	0.6	2.3	2.3	2.4	2.4	2.6	2.9	1.2	1.0	0.7
	Ca	430	1200	1100	970	1200	1100	900	630	550	400
	Cd	0.02	0.02	0.03	0.02	0.03	0.03	0.03	0.02	0.03	0.02
	Cr	0.04	0.04	0.04	0.04	0.03	0.05	0.04	0.02	0.05	0.02
	Cu	<0.01									
	Fe	13.8	266	-	-	-	121	18	58	-	40
	K	300	220	180	78	120	78	130	200	160	180
	Mn	4.4	16.7	16.7	15.3	15.7	15.5	12.0	3.3	5.6	4.3
	Mo	0.18	<0.03	0.03	<0.03	0.05	<0.05	<0.05	0.05	<0.1	0.05
	Na	800	480	400	340	400	330	450	520	460	430
	Ni	0.25	0.80	1.08	0.74	1.18	0.78	0.55	0.28	0.38	0.32
	Mg	138	128	117	93	110	110	110	108	100	97
	V	~0.05	~0.05	~0.05	~0.05	~0.05	~0.05	~0.05	~0.05	<0.1	~0.05
	Zn	1.45	3.60	2.50	1.10	0.56	0.75	0.69	0.24	1.02	0.38
COD		3200	18200	13800	16800	15000	11100	9700	2150	3700	2820
TOC		900	5490	4980	5760	4650	3860	3200	630	1140	920
Phenol		4.3	22.5	25.0	14.3	4.5	18.0	17.5	14.5	9.5	12.5
Organic P.		1.23	0.18	ND	0.14	0.20	0.12	0.12	0.36	0.13	0.11
Inorganic P.		0.71	0.15	0.30	0.08	0.20	0.06	0.06	0.08	ND	ND
H CHO		1.96	113	-	-	102	75	50	5.5	-	13.2
Short Chain Carboxylic Acids (mg/l)	A	700	4151	4822	2843	3586	3092	2506	518	1043	877
	P	257	1209	1411	881	1147	973	741	163	306	269
	iB	36	154	186	181	175	206	182	25	53	60
	nB	151	1288	1473	884	1107	984	764	126	260	220
	iV	170	476	563	344	416	364	299	43	153	104
	nV	76	477	523	321	402	328	252	50	106	88
	iC	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	nC	84	444	446	263	347	232	204	ND	71	57
Total		1474	8199	9424	5717	7180	6179	4948	920	1992	1675

P = Propionic Acid (C₃)iB, nB = iso-, normal-butyric acids (C₄)iV, nV = iso-, normal-valeric acids (C₅)iC, nC = iso-, normal-caproic acids (C₆)

c = centrifuge

f = filtered

* = filtered through 25 um GF/A

** = centrifuged at room temperature at 8000 rpm (20 minutes)

- no analysis available

ND not detected

SW standing water sample

Table 9 (b)

BOREHOLE NO. TA1: RESULTS OF ANALYSES OF SOLID SAMPLES (STANDING WATER AT 12 m)
JULY - OCTOBER 1976

Sampling Depth (m)	3.0-3.5	5.0	8.0	10.0	10.5-11.0	12.0	15.0	16.5-17.0	19.0	21.0
Sampling Type	U100	Bulk	Bulk	Bulk	U100	Bulk	Bulk	U100	Bulk	Bulk
Appearance	General Refuse	General Refuse	General Refuse	Oily/day. Mat.	Oily/Day. Mat.	Liquid Slurry	Paper Waste	Blue Paper Waste	Line-stone chips.	Clayey blue paper waste
Moisture Content (%)	36.4	36.3	22.3	43.9	28.9	70.5	69.7	69.5	20.0	77.8
Combustible Content (%)	27.6	35.8	16.2	34.6	17.5	14.9	25.8	26.3	4.8	18.7
Non-combustible Content (%)	36.0	27.9	61.5	21.5	53.6	14.6	4.5	4.2	75.2	3.5
Cyanide (ug/g)	0.24	0.04	0.13	-	0.08	0.17	0.85	-	<0.02	0.17
*** w.w.b.										
Halogenated Solvents	Total (ug/g)	1.23	1.33	0.13	0.13	0.14	0.20	0.07	0.03	0.12
	Major Constituent(s)	*p-e	*p-e	*T-e	*T-e	*T-e	*T-e	*t-c	*t-c	*T-e
	Phenol	5.78	0.64	1.16	0.90	0.89	0.68	1.65	2.30	1.53
	O-Cresol	8.67	1.91	0.48	0.50	0.71	0.64	0.87	0.39	1.53
	M-Cresol	ND	ND	ND	ND	ND	ND	2.18	0.30	1.40
	p-Cresol	22.9	5.86	0.53	3.69	0.27	1.66	1.16	4.51	0.95
Phenols (ug/g)	2:4 3:5 Xylenols	ND	ND	1.01	0.95	1.06	0.89	ND	ND	ND
*** ww	2:6 Xylenol Catechol	ND	ND	ND	ND	0.09	0.43	ND	ND	ND
	Total Phenols	37.4	8.4	3.2	6.0	3.0	4.3	5.9	7.5	5.4

*** calculated on wet weight basis

ND not detected

- no analysis available

*p-e perchloro-ethylene

*T-e Trichloro-ethylene

*t-c trichloroethylene chloroform

Table 10

BOREHOLE TA1: PERCENT OF INDIVIDUAL SHORT CHAIN FATTY ACIDS IN TOTAL
OF DETERMINED FATTY ACIDS

Sampling Depth (m)	Acetic	Propionic	i-Butyric	n-Butyric	i-Valeric	n-Valeric	i-caproic	n-caproic
12.0	47.5	17.4	2.4	10.2	11.5	5.2	ND	5.7
17.5	50.6	14.7	1.9	15.7	5.8	5.8	ND	5.4
18.0	51.1	15.0	2.0	15.6	6.0	5.5	ND	4.7
18.5	49.7	15.4	3.2	15.5	6.0	5.6	ND	4.6
13.5(18.5)SW	49.9	16.0	2.4	15.4	5.8	5.6	ND	4.8
19.0	50.0	15.7	3.3	15.9	5.9	5.3	ND	3.6
20.0	50.6	15.0	3.7	15.4	6.0	5.1	ND	4.1
12.5(20.5)SW	55.8	17.7	2.7	13.7	4.7	5.4	ND	-
21.0(C)	52.4	15.4	2.7	13.1	7.7	5.3	ND	3.6
21.0(F)	53.4	15.7	2.8	13.2	6.5	5.1	ND	3.4
22.0	52.4	16.1	3.6	13.1	6.2	5.3	ND	3.4
Average	51.2%	15.8%	2.8%	14.3%	6.6%	5.4%	-	4.4%
as carbon	20.5%	7.7%	1.5%	7.8%	3.9%	3.2%	-	2.7%

Average total fatty acid carbon 47.3%

Table 11 MEAN CONCENTRATIONS OF SELECTED DETERMINANDS IN SAMPLES OF BOREHOLE
WATER COLLECTED DURING DRILLING

concs mg/l	TB1	TB2	TB3	TB4	TB5	Background TB6	TA1	c TB5/cTB6
							Range	Enrichment
Chloride	454	452	245	740	145	38	546-1210	3.8
Sulphate	15	109	121	61	36	35	285-503	1.0
Ammonia	73	31	35	219	<0.4	<0.4	21-359	1.0
Total Nitrogen	71	35	38	219	<2.0	<2.0	66-380	1.0
C.O.D.	317	159	76	528	11.6	<5	2150-18200	~2
T.O.C.	114	42	21	180	3.7	3.3	630-5760	3.1
S.C.C.A.	120	<20	<10	121	<10	<10	920-9424	1.0
Calcium	105	4	6	26	146	46	400-1200	3.2
Potassium	110	93	79	18	12	3	78-300	4.0
Sodium	348	314	450	56	34	15	330-800	2.3
Magnesium	57	2	3	54	2	3	93-138	0.7
Barium	0.6	0.1	0.2	0.3	0.1	<0.1	0.6-2.9	1.0
Manganese	0.30	0.03	0.40	0.04	0.01	0.01	3 - 17	1.0
Zinc	0.28	0.11	0.11	0.10	0.05	0.13	0.24-3.6	0.4

Concentrations of halogenated solvents varied from 0.07 ug/g to 1.33 ug/g the highest concentrations being found in samples from the top 5 m of the borehole, and the major constituent being perchloroethylene. Phenols also occurred at their highest concentrations in the top 5 m; the highest concentration, 37.4 ug/g, was found in a sample taken at 3 - 3.5 m depth. The major constituents were phenol, O- and p-cresol, with m-cresol apparently confined to depths of greater than 12 m.

4.3.2 'Type B' Boreholes (Table 11)

Boreholes TB1 and TB4 were drilled to the north and south respectively, of TA1, and TB2 and TB3 to the east, TB5 was drilled 130 m to the south of the quarry and borehole TB6 approximately 2 km northwestwards of TA1 in Cornelly quarry (see Figure 4).

Borehole TB6 (see Table 12)

This borehole was sufficiently distant from the landfill and Tythegston Quarry to be unaffected by any movement of leachate from the latter. It was therefore considered to be a 'background' borehole. The average levels of parameters measured in samples of water from borehole TB6 are given in Table 11.

Borehole TB1 (see Table 13)

Liquid samples were collected during drilling, between depths of 27 and 59 m.

Chloride concentrations varied from 134 to 627 mg/l; the highest concentration, recorded at 56 m, was of the same order as chloride concentrations found in TA1.

Table 12 ANALYSES OF SAMPLES OF WATER COLLECTED DURING DRILLING

JULY - OCTOBER 1976

BOREHOLE NO. TB6

Sampling Depth (m)	28.9	30.7	36.6	40.2	44.2	48.3	51.3	54.3	57.2	58.0	9.2SW
Treatment of Sample	f	f	f	f	f	f	f	f	f	f	f
pH	7.9	7.9	7.8	8.1	7.6	7.5	8.3	7.3	7.6	7.6	7.7
Cl (mg Cl/l)	37	40	38	58	36	39	48	30	24	25	27
SO ₄ (mg SO ₄ /l)	27	30	22	20	25	49	47	40	41	51	47
NH ₄ /N (mg N/l)	<0.4										
Kjeldahl N (mg N/l)	<2.0										
Metals (mg/l)	Ba	<0.1									
	Ca	51	47	56	35	47	40	25	49	64	50
	Cd	<0.01									
	Cr	<0.03				0.08	<0.03				
	Cu	<0.01	<0.01	<0.01	<0.01	<0.01	<0.04	0.02	<0.01	<0.01	0.08 <0.01
	Fe	-	-	-	-	-	-	-	-	-	-
	K	1.8	2.1	1.5	5.0	3.0	2.9	8.8	2.0	1.8	1.7 3.9
	Mn	0.03	0.02	<0.01							
	Mo	<0.05									
	Na	14	14	12	20	13	16	22	16	16	13 17
	Ni	<0.03									
	Mg	2.1	2.1	2.1	4	2.9	4.3	2.2	4.3	2.1	2.3 2.5
	V	<0.05									
	Zn	0.01	<0.01	<0.01	0.02	<0.01	0.54	0.10	0.05	0.06	0.44 0.60
COD		<4	4	4	<4	14	<4	6	4	<4	<4 4
TOC		2.1	2.2	3.4	3.1	4.3	2.8	5.0	3.4	3.8	2.5 3.4
Phenol		<2					ND				
Organic P.		ND	0.06	<0.01	0.01	0.02	ND	0.02	0.04	ND	ND ND
Inorganic P.		ND	0.02	ND	ND	0.01	ND	0.01	0.01	ND	ND ND
H CHO		ND						0.30	ND		
Short Chain Carboxylic Acids (mg/l)	A	7	4	7	6	5	9	8	7	7	7
	P	ND									
	iB	ND									
	nB	ND									
	iV	ND									
	nV	ND									
	iC	ND									
	nC	ND									
Total		7	4	7	6	5	9	8	7	7	7

P = Propionic Acid (C₃)iB, nB = iso-, normal-butyric acids (C₄)iV, nV = iso-, normal-valeric acids (C₅)iC, nC = iso-, normal-caproic acids (C₆)

f = filtered

ND not detected

- no analysis available

SW standing water sample

Table 13

ANALYSES OF SAMPLES OF WATER COLLECTED DURING DRILLINGJULY - OCTOBER 1976

BOREHOLE NO. TB1

Sampling Depth (m)		27.0	31.0	53.0	56.0	59.0
Treatment of Sample		filtered	filtered	filtered	filtered	filtered
pH		7.2	6.8	7.5	6.9	-
Cl (mg Cl/l)		134	-	558	627	496
SO ₄ (mg SO ₄ /l)		ND	-	16.9	40.6	ND
NH ₄ /N (mg N/l)		26	-	81	87	98
Kjeldahl N (mg N/l)		26	-	76	83	98
Metals (mg/l)	Ba	0.8	0.5	0.2	0.2	1.1
	Ca	105	70	60	65	225
	Cd	<0.01				
	Cr	<0.03				
	Cu	0.02	0.01	<0.01	0.05	0.04
	Fe					
	K	103	113	108	113	113
	Mn	0.12	0.04	0.04	0.04	1.25
	Mo	<0.1	0.1	0.2	<0.1	0.1
	Na	330	350	350	380	330
	Ni	0.10	0.15	0.08	0.05	0.13
	Mg	54	59	49	56	67
	V	<0.25				
	Zn	0.51	0.15	0.12	0.26	0.38
COD		94	-	380	395	400
TOC		106	80	132	120	132
Phenol		<2	-	<2	<2	<2
Organic P.		0.02	-	0.48	0.13	0.08
Inorganic P.		0.03	-	0.44	0.04	ND
H CHO		0.74	0.50	-	0.58	0.37
Short Chain Carboxylic Acids (mg/l)	A	25	-	106	103	122
	P	ND	-	22	22	28
	iB	ND	-	4	3	4
	nB	ND	-	9	8	10
	iV	ND	-	4	3	5
	nV	ND	-	ND	ND	ND
	iC	ND	-	ND	ND	ND
	nC	ND	-	ND	ND	ND
	Total	25	-	145	139	169

P = Propionic Acid (C₃)iB, nB = iso-, normal-butyric acids (C₄)iV, nV = iso-, normal-valeric acids (C₅)iC, nC = iso-, normal-caproic acids (C₆)

ND not detected

- no analysis available

Table 14 ANALYSES OF SAMPLES OF WATER COLLECTED DURING DRILLING

JULY - OCTOBER 1976

BOREHOLE NO. TB2

Sampling Depth (m)	50.0	51.0	58.0	60.0	63.0	66.0	70.0	70mSW (30/9)	70mSW (7/10)	
Treatment of Sample	f	c	c	f	f	f	f	f	f	
pH	7.7			7.7	8.3	8.9	8.7	7.6		
Cl (mg Cl/l)	342	429	501	423	504	513	452	307	315	
SO ₄ (mg SO ₄ /l)	141	228	186	62	46	54	49	120	96	
NH ₄ /N (mg N/l)	30	17	13	39	42	39	38	36	38	
Kjeldahl N (mg N/l)	32	21	16	44	51	42	39	34	35	
Metals (mg/l)	Ba	0.2	-	-	<0.1	<0.1	<0.1	<0.1	0.6	0.8
	Ca	5.1	-	-	7.1	2.0	1.8	1.7	188	200
	Cd	<0.03	-	-	<0.03				<0.01	<0.01
	Cr	<0.03	-	-	<0.03					
	Cu	0.03	-	-	0.03				0.01	0.03
	Fe	-	-	-	-					
	K	110	-	-	93	90	95	75	160	128
	Mn	0.03	-	-	0.06	<0.02	<0.02	<0.02	3.4	3.8
	Mo	<0.1	-	-	0.1					
	Na	250	-	-	310	340	350	320	250	250
	Ni	0.08	-	-	0.10	0.10	0.10	0.08	0.10	0.05
	Mg	2.55	-	-	3.45	1.45	1.20	1.95	42	45
	V	<0.10	-	-	<0.10	0.20	<0.10	<0.10	<0.25	<0.25
	Zn	0.11	-	-	0.12	0.15	0.10	0.07	0.08	0.16
COD	144	-	-	136	144	144	136	186	220	
TOC	46	-	-	40	40	44	42	60	73	
Phenol	ND									
Organic P.	0.25	0.19	0.11	0.01	ND	0.02	0.02	ND	0.03	
Inorganic P.	0.11	0.08	0.19	0.10	0.08	0.04	0.08	0.04	ND	
H CHO	0.43	-	-	0.56	0.58	0.30	0.50	0.24	0.25	
Short Chain Carboxylic Acids (mg/l)	A	<5	<20	10	<5	<5	<5	<10	25	74
	P	5	ND	ND	<5	<5	<5	<5	6	10
	iB	ND								
	nB	ND								
	iV	ND								
	nV	ND								
	iC	ND								
	nC	ND								
Total	<10	<20	10	<10	<10	<10	<15	31	84	

P = Propionic Acid (C₃)iB, nB = iso-, normal-butyric acids (C₄)iV, nV = iso-, normal-valeric acids (C₅)iC, nC = iso-, normal-caproic acids (C₆)

N D not detected

- no analysis available

SW standing water sample

Table 15

ANALYSES OF SAMPLES OF WATER COLLECTED DURING DRILLINGJULY - OCTOBER 1976

BOREHOLE NO. TB3

Sampling Depth (m)	50.0	61.0	64.0	67.0	70.0	70mSW
Treatment of Sample	filtered	filtered	filtered	filtered	filtered	filtered
pH	8.5	7.5	7.5	8.2	8.2	7.3
Cl (mg Cl/l)	255	227	221	226	298	203
SO ₄ (mg SO ₄ /l)	120	85	80	225	93	241
NH ₄ /N (mg N/l)	16	41	41	39	36	43
Kjeldahl N (mg N/l)	18	41	44	40	39	43
Metals (mg/l)	Ba	<0.1	0.2	0.2	<0.1	<0.1
	Ca	1.0	9.2	8.6	1.3	1.2
	Cd	<0.03				
	Cr	<0.03				
	Cu	0.02	0.04	0.02	0.01	0.02
	Fe	-	-	-	-	-
	K	65	85	80	85	80
	Mn	<0.02	0.10	0.10	<0.02	1.74
	Mo	<0.1				
	Na	460	450	440	450	450
	Ni	0.08	0.10	0.08	0.08	0.05
	Mg	0.55	3.60	3.50	2.60	3.95
	V	<0.10				
	Zn	0.07	0.19	0.11	0.09	0.08
						0.05
COD	78	76	68	80	70	82
TOC	21	20	20	21	21	20
Phenol	ND					
Organic P.	ND	ND	ND	2.3	0.8	ND
Inorganic P.	ND	0.6	ND	0.3	0.08	0.04
H CHO	-	ND	ND	0.24	0.12	ND
Short Chain Carboxylic Acids (mg/l)	A	<5				
	P	<5				
	iB	ND				
	nB	ND				
	iV	ND				
	nV	ND				
	iC	ND				
	nC	ND				
Total		<10				

P = Propionic Acid (C₃)iB, nB = iso-, normal-butyric acids (C₄)iV, nV = iso-, normal-valeric acids (C₅)iC, nC = iso-, normal-caproic acids (C₆)

ND not detected

- no analysis available

SW standing water sample

Table 16

ANALYSES OF SAMPLES OF WATER COLLECTED DURING DRILLINGJULY - OCTOBER 1976

BOREHOLE NO. TB4

Sampling Depth (m)	21.0	29.0	31.5	41.0	42.0	43.0	44.0	45.0
Treatment of Sample	f	f	f	f	f	f	f	f
pH		8.0		8.1	8.3	8.0	8.3	8.5
Cl (mg Cl/l)	734	734	904	742	633	740	728	703
SO ₄ (mg SO ₄ /l)	173	47	36	74	91	16	30	20
NH ₄ /N (mg N/l)	284	187	255	230	188	204	228	172
Kjeldahl N (mg N/l)	279	229	244	210	193	205	226	166
Metals (mg/l)	Ba	0.3	0.5	0.3	0.3	<0.3	<0.3	<0.3
	Ca	68	78	20	14	8.5	5.5	4.5
	Cd	<0.01 →						
	Cr							
	Cu	0.04	0.02	0.05	0.02	<0.01	0.02	0.02
	Fe							
	K	18.8	16.8	21.3	18.0	18.5	17.0	17.3
	Mn	0.05	0.08	<0.03	0.03	<0.03	0.03	<0.03
	Mo	<0.1 →						
	Na	56	54	65	55	54	54	52
	Ni	0.15	0.15	0.18	0.15	0.03	0.10	0.08
	Mg	85	77	46	40	54	43	60
	V	<0.10 →						
	Zn	0.14	0.12	0.09	0.08	0.10	0.07	0.08
COD		1250	390	980	395	262	280	325
TOC		430	129	355	137	87	98	100
Phenol		1.2	1.6	1.2	1.6	<2.0	1.1	1.1
Organic P.		0.24	0.40	0.24	0.40	0.12	0.18	0.17
Inorganic P.		0.02	0.04	0.02	0.02	0.02	ND	ND
H CHO		1.08	1.05	1.11	1.54	-	1.35	1.29
Short Chain Carboxylic Acids (mg/l)	A	180	20	138	<10	-	3	4
	P	90	5	69	ND	-	ND	→
	iB	10	ND	7	ND	-	ND	→
	nB	150	10	98	ND	-	ND	→
	iV	27	ND	ND	ND	-	ND	→
	nV	ND	ND	19	ND	-	ND	→
	iC	2	ND	ND	ND	-	ND	→
	nC	ND	ND	ND	ND	-	ND	→
Total		459	35	331	<10	-	3	4

P = Propionic Acid (C₃)iB, nB = iso-, normal-butyric acids (C₄)iV, nV = iso-, normal-valeric acids (C₅)iC, nC = iso-, normal-caproic acids (C₆)

f = filtered

ND not detected

- no analysis available

Table 17

ANALYSES OF SAMPLES OF WATER COLLECTED DURING DRILLINGJULY - OCTOBER 1976

BOREHOLE NO. TB5

Sampling Depth (m)		38.7	51.0	51.0	62.5	65.0
Treatment of Sample		filtered	filtered	centrifuged	filtered	filtered
pH					8.4	(11.0?)
Cl (mg Cl/l)		197	92	90	161	185
SO ₄ (mg SO ₄ /l)		30	ND	ND	46	104
NH ₄ /N (mg N/l)		<0.4	0.5	<0.4	<0.4	<0.4
Kjeldahl N (mg N/l)		<2.0	1.0	<1.0	<2.0	<2.0
Metals (mg/l)	Ba	<0.1	0.2	0.2	<0.1	<0.1
	Ca	43	260	345	24	58
	Cd	<0.01				
	Cr	<0.03	0.05	0.05	<0.03	<0.03
	Cu	<0.01	0.02	0.02	<0.01	<0.01
	Fe					
	K	5.8	24	25	3.1	2.1
	Mn	<0.01	0.01	<0.01	<0.01	<0.01
	Mo	<0.05	0.10	<0.10	<0.05	<0.05
	Na	29	38	37	34	31
	Ni	<0.03	0.03	0.05	<0.03	<0.03
	Mg	5.8	0.3	<0.05	5.9	0.2
	V	<0.05	<0.25	<0.25	<0.05	<0.05
	Zn	0.04	0.12	0.05	0.02	0.04
COD		10	24	14	6	4
TOC		1.7	5.6	4.8	2.8	3.7
Phenol		<2				
Organic P.		ND	0.05	0.05	0.03	ND
Inorganic P.		0.26	0.04	0.03	0.07	0.19
H CHO		-	-	-	0.22	-
Short Chain Carboxylic Acids (mg/l)	A	12	11	11	11	7
	P	ND				
	iB	ND				
	nB	ND				
	iV	ND				
	nV	ND				
	iC	ND				
	nC	ND				
Total		12	11	11	11	7

P = Propionic Acid (C₃)iB, nB = iso-, normal-butyric acids (C₄)iV, nV = iso-, normal-valeric acids (C₅)iC, nC = iso-, normal-caproic acids (C₆)

ND not detected

- no analysis available

Sulphate concentrations were variable. The highest value of 40.6 mg/l, recorded at 56 m is an order of magnitude lower than the average value found in TA1.

Concentrations of ammonia (accounting almost entirely for the total nitrogen) range from 26 mg/l at 27 m to 98 mg/l at 59 m.

C.O.D. values increase downwards - 94 mg O₂/l at 27 m to 400 mg O₂/l at 59 m. Fatty acid concentrations, which never account for more than 60% of the organic carbon concentrations, increase down the borehole from 25 mg/l (27 m) to 169 mg/l (59 m), the major component being acetic acid.

Concentrations of formaldehyde ranged from only 0.74 mg/l at 27 m to 0.37 mg/l at 59 m, which is an order of magnitude lower than in borehole TA1.

Of the trace metals, only manganese (with a maximum value of 1.25 mg/l at 59 m) exceeds the maximum of 0.5 mg/l permitted for drinking waters (World Health Organisation 1971).

Borehole TB2 (see Table 14)

Liquid samples were collected at depths between 50 and 70 m. Chloride concentrations ranged between 342 and 513 mg/l, the highest concentration being recorded at 66 m. Sulphate varied in concentration between 46 and 228 mg/l - tending to decrease with increasing depth in the borehole.

Concentrations of organic carbon varied from 40 to 46 mg/l. No more than 25% of the carbon is accounted for by fatty acids.

No metal concentrations exceed the levels permitted for drinking waters (World Health Organisation 1971) - except manganese (3.4 and 3.8 mg/l) determined in standing waters at 70 m taken one and two weeks after drilling.

Borehole TB3 (see Table 15)

Liquid samples were collected at depths between 50 and 70 m. Chloride concentrations varied between 221 and 198 mg/l; these were the lowest concentrations of chloride found in TB1 to TB4. Concentrations of organic carbon

showed little variation with depth in the borehole (20-21 mg/l) and only 28% of the organic carbon concentration was accounted for by fatty acids.

Borehole TB4 (see Table 16)

Liquid samples were collected between 21 and 45 m. The highest concentrations of chloride recorded in any of the 'B type' boreholes were found in TB4, the range being from 703 to 904 mg/l. Maximum values compared with the other 'B' boreholes were also found for concentrations of ammonia in TB4 (172 to 284 mg/l).

Organic carbon concentrations were relatively high (87 - 430 mg/l), the highest values being found at the top 10 m of water in the borehole. The average concentration of organic carbon, 180 mg/l was, again, the highest recorded in the 'Type B' boreholes. 50% of the organic carbon concentration was accounted for by fatty acids.

Borehole TB5 (see Table 17)

Liquid samples were collected between 39 and 65 m. No significantly high values of any parameters were evident, and for most determinands, the average concentration found was much less than that recorded in boreholes TB1 - TB4 but greater than that found in the 'background' borehole (TB6). This might be expected in a borehole outside the boundary of a landfill where leachate is effectively being confined.

4.4 Long Term Quality Monitoring

Analytical data from the monitoring programme until November 1977 are presented in Tables 18A and 18B. Due to continued tipping at the landfill since drilling, it has been necessary to add sections of casing to some of the boreholes during the period of monitoring. Sampling depths are therefore given in metres above Ordnance Datum (m.A.O.D.) in Tables 18A and 18B.

Table 18A

LONG TERM MONITORING - ANALYTICAL RESULTS (CONCNS µg/l)

Sampling Date	Water Level		Sampling Depth (metres below *maod surface)	Temp D.O. (°C) (% Satn)	pH	Cl ⁻	SO ₄ ⁻	M E T A L S														
	metres	*maod						Ba	Ca	Cd	Cr	Cu	Fe	K	Mn	Mo	Na	Ni	Mg	Pb	V	Zn
BOREHOLE TA1																						
19.4.77.	4.50	71.93	71.43	-	-	747	203	-	800	-	-	-	-	400	-	-	770	-	300	-	-	0.08
13.7.77.	-	-	71.43	-	-	82	-	-	152	-	-	-	-	380	-	-	800	-	168	-	-	0.26
4.11.77.	22.50	53.93	53.43	-	7.3	1110	25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BOREHOLE TB1																						
28.3.77.	5.72	72.07	70.79	18.5	13	7.5	150	24	94	ND	ND	0.2	29	15	0.3	0.1	107	0.06	18	ND	ND	0.25
13.4.77.	6.04	71.75	62.79	17.0	ND	7.0	166	12	135	ND	ND	ND	38	15	0.7	ND	113	0.03	19	ND	ND	0.07
			42.79	13.5	ND	6.6	235	19	193	ND	ND	ND	36	33	5.6	ND	175	0.03	37	ND	ND	0.09
13.7.77	14.33	63.46	57.79	14.5	27	6.7	615	-	290	-	-	-	-	200	-	-	440	-	122	-	-	0.30
			27.79	11.5	25	6.7	635	-	280	-	-	-	-	220	-	-	460	-	132	-	-	0.22
4.11.77	28.25	49.54	47.79	-	-	6.9	560	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			12.79	-	-	6.7	610	33	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BOREHOLE TB2																						
28.3.77	6.98	71.74	58.72	15.5	33	7.3	154	273	430	ND	ND	ND	155	52	1.5	ND1	142	0.07	27	ND	ND	0.16
			18.72	12.0	26	7.3	204	291	420	ND	ND	ND	130	59	1.1	ND	147	0.07	27	0.2	ND	0.30
13.7.77	23.77	54.95	53.72	12.5	6	7.1	350	-	280	-	-	-	-	97	-	-	270	-	62	-	-	0.27
			18.72	10.5	22	6.7	365	-	430	-	-	-	-	94	-	-	290	-	65	-	-	0.50
4.11.77. No borehole standing water																						

* maod = metres above Ordnance Datum

Table 18A continued

LONG TERM MONITORING - ANALYTICAL RESULTS (CONCNS mg/L)

Water Level		M E T A L S																				
Sampling Date	metres below surface	Sampling Depth (maod)	Temp (°C)	D.O. (% Satn)	pH	Cl ⁻	SO ₄ ⁻	Ba	Ca	Cd	Cr	Cu	Fe	K	Mn	Mo	Na	Ni	Mg	Pb	V	Zn
<u>BOREHOLE TB3</u>																						
28.3.77.	9.75	70.49	60.24	16.0	21	7.6	70	106	ND	ND	ND	ND	34	51	1.1	ND	340	0.07	18	ND	ND	0.07
			20.24	13.0	14	7.6	115	116	ND	ND	ND	ND	6.7	69	1.2	ND	480	0.02	24	0.5	ND	0.11
13.7.77	29.50	50.74	49.24	12.0	19	6.7	382	-	165	-	-	-	-	125	-	-	400	-	90	-	-	0.11
			20.24	11.0	20	6.8	383	-	141	-	-	-	-	122	-	-	380	-	86	-	-	0.12
4.11.77.	43.31	38.53	36.84	-	-	7.0	290	34	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			19.84	-	-	6.7	285	36	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<u>BOREHOLE TB4</u>																						
13.4.77.	5.06	71.27	61.33	19.5	1	7.0	105	20	1.0	101	ND	ND	55	28	0.5	ND	66	0.05	16	ND	ND	0.11
			41.33	15.5	4	6.8	157	26	3.0	135	ND	ND	31	38	0.6	ND	107	0.06	25	ND	ND	0.24
13.7.77	12.73	63.60	62.33	17.5	8	7.6	90	-	-	36	-	-	-	21	-	-	47	-	11	-	-	0.09
			41.33	13.5	10	6.7	563	-	-	175	-	-	-	165	-	-	400	-	105	-	-	0.22
4.11.77.	31.63	46.23	44.86	-	-	6.6	270	16	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			26.86	-	-	6.8	610	18	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<u>BOREHOLE TB6 (Cornelly)</u>																						
28.3.77.	8.86	51.88	40.74	11.0	86	8.3	17	32	ND	78	ND	ND	0.6	ND	ND	ND	9	ND	2	0.1	ND	0.03
			10.74	11.0	85	8.4	16	33	ND	73	ND	ND	1.8	ND	ND	ND	9	0.02	2	0.1	ND	0.03
13.7.77.	14.34	46.40	40.74	10.2	72	7.5	37	-	-	59	-	-	-	ND	-	-	15	-	2	-	-	0.05
			10.74	10.2	67	7.2	47	18	-	55	-	-	-	ND	-	-	11	-	1	-	-	0.10
4.11.77.	11.06	49.68	40.74	-	-	7.2	45	18	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			10.74	-	-	7.0	15	22	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* maod = metres above Ordnance Datum

Table 18B

LONG TERM MONITORING - ANALYTICAL RESULTS (CONCNS mg/l)

Water Level		Sampling Date	metres below surface	°maod	Sampling Depth °(maod)	NH ₄ -N	KJN	COD	TOC	Chlorin- ated Solvents	PCB	Organic P	Total P	Total Phenol	Fatty Acids
BOREHOLE TA1															
19.4.77	4.50		71.93		71.43	300	320	10800	2600	0.06	-	0.2	0.3	4.9	5497
13.7.77	-		-		71.43	450	5	605	174	-					
4.11.77	22.50		53.93		53.43	542	561	1660	519	-					
BOREHOLE TB1															
28.3.77	5.72		72.07		70.79	13	14.2	40	15.0	-	-	ND	ND	-	ND
13.4.77	6.04		71.75		62.79	14.6	14.5	52	5.0	-	-	0.5	0.5	-	ND
					42.79	27.4	30.6	102	29.0	-	-	ND	ND	-	ND
13.7.77	14.33		63.46		57.79	202.0	208	335	89	-	-	-	-	-	10.0
					27.79	202.0	205	330	89	-	-	-	-	-	3.6
4.11.77	28.25		49.54		47.79	114	115	118	68	-	-	-	-	-	-
					12.79	185	210	296	101	-	-	-	-	-	-
BOREHOLE TB2															
28.3.77	6.98		71.74		58.72	15.5	19.4	120	31	-	-	ND	0.1	-	ND
					18.72	15.8	17.9	82	26	-	-	0.1	0.1	-	ND
13.7.77	23.77		54.95		53.72	60.0	60.0	345	114	-	-	-	-	-	98
					18.72	60.0	67.0	1600	570	-	-	-	-	-	877
4.11.77	No borehole standing water														
BOREHOLE TB3															
28.3.77	9.75		70.49		60.24	11.5	13.1	18.0	13.0	-	-	0.2	0.2	0.05	ND
					20.24	27	30.8	62	23.0	-	-	0.2	0.3	0.75	ND
13.7.77	29.50		50.74		49.24	74	75	190	54	-	-	-	-	0.23	19
					20.24	85	87	175	53	-	-	-	-	0.53	3.2
4.11.77	43.31		38.53		36.84	76.5	73.5	106	33	-	-	-	-	0.03	-
					19.84	69	88	100	33	-	-	-	-	ND	-
BOREHOLE TB4															
13.4.77	5.06		71.27		61.33	18.8	25.9	36	11.0	-	0.07	ND	ND	0.20	ND
					41.33	41.4	45.2	58	16.0	-	-	0.2	0.2	0.33	ND
13.7.77	12.73		63.60		62.33	12.0	12.0	32	9.7	-	-	-	-	ND	ND
					41.33	171	182	270	72	-	-	-	-	0.53	ND
4.11.77	31.63		46.23		44.86	91.5	94	112	35	-	-	-	-	0.04	-
					26.86	231	251	2544	84	-	-	-	-	ND	-
BOREHOLE TB6 (Cornelly)															
28.3.77	8.86		51.88		40.7	ND	0.6	ND	1.2	-	-	ND	ND	0.05	ND
					10.74	ND	0.5	ND	-	-	-	ND	ND	0.10	ND
13.7.77	14.34		46.40		40.74	ND	ND	ND	1.9	-	-	-	-	ND	ND
					10.74	ND	ND	ND	1.0	-	-	-	-	ND	ND
4.11.77	11.06		49.68		40.74	ND	ND	6.0	5.4	-	-	-	-	ND	-
					10.74	ND	ND	18.0	5.8	-	-	-	-	ND	-

° maod = metres above Ordnance Datum

Table 19 ENRICHMENT OF CHLORIDE AND ORGANIC CARBON RELATIVE TO BOREHOLE TB6 (BACKGROUND)

CHLORIDE (mg/l)

Monitoring	Average Concentration in TB6	Borehole TB1		Borehole TB2		Borehole TB3		Borehole TB4	
		Sample Depth (maod)	TB1/TB6	Sample Depth (maod)	TB2/TB6	Sample Depth (maod)	TB3/TB6	Sample Depth (maod)	TB4/TB6
Mar-April 1977	16	70.79	9.4	58.72	9.6	60.24	4.4	61.33	6.6
		62.79	10.4	18.72	12.8	20.24	7.2	41.33	9.8
		42.79	14.7	-	-	-	-	-	-
July 1977	42	57.79	14.6	53.72	8.3	49.24	9.1	62.33	2.1
		27.79	15.1	18.72	8.7	20.24	9.1	41.33	13.4
Nov 1977	30	47.79	18.7	No sampling		36.84	9.7	44.86	9.0
		12.79	20.3		19.84	9.5	26.86	20.3	
ORGANIC CARBON (mg/L)									
Mar-April 1977	1.2	70.79	12.5	58.72	25.8	60.24	10.8	61.33	9.2
		62.79	4.2	18.72	21.7	20.24	19.2	41.33	13.3
		42.79	24.2	-	-	-	-	-	-
July 1977	1.5	57.79	59.3	53.72	76.0	49.24	36	62.33	6.5
		27.79	59.3	18.72	380	20.24	35.3	41.33	48
Nov 1977	5.6	47.79	12.1	No sampling		36.84	5.9	44.86	6.3
		12.79	18.0		19.84	5.9	26.86	15	

Schematic sections of the landfill showing the boreholes and indicating the sampling depths during monitoring with respect to the Ordnance Datum are shown in Figures 23 and 24. Concentrations of chloride and organic carbon which are indicative of contamination of groundwater by leachate are also given on the figures at the sampled depths.

The concentrations of chloride and organic carbon were related to the overall groundwater level beneath the landfill, concentrations being high at periods of low recharge and comparatively low during periods of high recharge. This was presumably due to dilution of leachate by groundwater when the water table in the aquifer was above the base of the landfill.

Levels of chloride and organic carbon were highest in standing water from borehole TA1 within the main body of the landfill. Enrichment of chloride and organic carbon relative to concentrations found in borehole TB6 (see table 19) increased with depth below the landfill or remained constant in most cases, indicating movement of leachate vertically from the base of the landfill. This effect was more pronounced when monitoring at periods of high recharge.

The highest enrichment of chloride was found in boreholes TB1 and TB4 as was the case during the drilling programme. This suggests the importance of a north-south fissure network in the vicinity of the landfill as a pathway for leachate movement. The highest enrichments of organic carbon were found in borehole TB2 during July 1977 providing evidence for the existence of restricted fissure connections between the landfill and limestone strata to the west. The enrichment decreases further to the west of the landfill in borehole TB3 suggesting that this horizontal movement of leachate is confined to areas within close proximity of the landfill.

Sulphate concentrations in borehole TA1 were significantly lower during monitoring than those found during drilling and this may be because of sulphide production within the landfill by reduction of sulphate by micro-organisms. Certainly, dissolved oxygen determinations on standing waters from boreholes around the landfill would suggest the onset of anoxic conditions, the highest value being 33% saturation as compared with values as high as 86% saturation in the background borehole TB6. Borehole water temperatures were up to 8°C higher than those found in borehole TB6 during monitoring (see for example borehole TB4 analytical results) and this would appear to confirm microbiological action.

Ammonia concentrations had increased significantly in borehole TA1 during the period of monitoring and this was reflected by similar increases in all 'type B' boreholes within the landfill boundary apart from TB4 (where concentrations had remained approximately constant). Domestic waste normally produces a leachate which is high in ammonia.

DISCUSSION

The drilling, sampling and geophysical logging of boreholes in and around the Tythegston landfill, and the subsequent monitoring of groundwater level fluctuations have revealed the presence of an anisotropic, fissured aquifer system in which the regional, joint controlled, southerly directed groundwater flow pattern is seasonally modified by the development of a recharge mound beneath a perched leachate body within the landfill. The postulated cyclic changes in the groundwater regime are shown diagrammatically in Figure 25. At low groundwater levels, lateral and vertical dispersion of leachate into the underlying groundwater is controlled by the recharge mound (Figure 25a). However, prolonged drought would lead to the ultimate decay of the mound, as drainage from the perched leachate body decreases and, consequently, lateral dispersion effects would also lessen. During periods of active recharge (Figure 25b), the effects of the recharge mound would be expected initially to increase, leading to more extensive lateral dispersion of leachate. At the same time, direct recharge of uncontaminated rainfall in the direction of groundwater flow would modify the concentrations in the upper part of the pollution plume. The level at which preferential flow paths are developed may be expected to change as groundwater levels rise to a maximum (Figure 25c), into the upper, more permeable and porous section of the aquifer (Figure 18, Section 4.2.2). The recharge mound no longer exists and groundwater flows are essentially unidirectional, except as modified by the fracture permeability. The expected reduction in the concentrations of leachate components by dilution in the increased groundwater flows through both the landfill and aquifer was confirmed by the result of long term monitoring (section 4.4) and flushing of leachate from low level flow paths may have also occurred. During the recession period (Figure 25d), a new recharge mound develops beneath the perched leachate body, initiating a new phase of lateral dispersion of leachate, whilst leachate flows may revert to lower level preferential flow paths. In the presentation in

Figure 25 it has been assumed that the aquifer is essentially isotropic in the horizontal plane (see below, discussion of flows at Burrows Well). If, however, significant anisotropy is present, the form in the pollution plume would be expected to consist of elongated zones of contamination, possibly separated by essentially uncontaminated water, in both the vertical and horizontal planes.

Unequivocal evidence of the movement of leachate away from the vicinity of the landfill, other than that collected during the 1976 investigation and subsequent monitoring programme, is not available. However, the following the fire within the landfill (section 1), as a result of which the zinc concentration of the surface leachate in the quarry rose from 11 to 129 mg/l, monitoring of the water quality at Burrows Well, 1.5 km south of the landfill, showed an increase in the zinc concentrations and the electrical conductivity of the water between March and October 1974, followed by a decrease in March 1975 (Figure 26). If the increased zinc concentrations are attributable to the fire in April 1972, a lapse time of between 730 and 880 days occurred before the emergence of the diluted leachate, indicating a bulk permeability of c. 0.8 m/day for the intervening limestones. This value for permeability is considered low for a fissured aquifer when compared with 90 m/day reported by Atkinson (1977) as the bulk permeability of the Carboniferous Limestone of the Mendip Hills. The estimate suggests that groundwater movement along the flow paths between the quarry and Burrows Well is exclusively via small intersecting fissures, partially blocked by Triassic infills (diffuse flow), and thus approximates to an isotropic flow system. If the water sampled at Burrows Well in 1974/75 represented diluted leachate generated by the 1972 fire, a dilution factor of between 1:400 and 1:750 is indicated, assuming the absence of other mechanisms attenuating the zinc concentrations. However, at the pH values typical of the groundwaters of the region (Table 6), it is probable that some attenuation of zinc concentrations due to precipitation

would occur and the dilution factors are regarded as maximum values.

In contrast, the groundwater discharge at Schwyll (Figure 7a), and possibly also that at Porthcawl harbour (section 2.2), represents the resurgence point of a well developed conduit flow system (karstic). Rapid movement of leachate would be expected under such flow systems, with dilution being limited by the volume of uncontaminated groundwater present in the conduit system. Ede (1975) has shown that it is possible to estimate the proportion of conduit and diffuse flow contributing to the discharge of springs in fissured limestone terrains by measuring the variations in total carbonate hardness between peak winter flows and low summer flows. Maximum contrasts have been reported from springs fed by dominantly diffuse flow systems as a result of the greater contact area between the rock and recharge water encouraging the dissolution of carbonates during the summer months. Maximum contrasts have been reported from springs fed dominantly fissure flow systems as a result of the greater contact area between the rock and recharge water encouraging the dissolution of carbonates during the summer months. In view of the potentially greater pollution risk associated with conduit flow systems, it is suggested that Ede's technique provides a convenient method of distinguishing the groundwater flow regimes contributing to water supply sources in fissured limestone aquifers.

The landfill at Tythegston, composed mainly of domestic wastes mixed with limited quantities of industrial wastes, generates a leachate which contains significantly higher concentrations of chloride, sulphate, ammonia, organic carbon (including fatty acids, phenols and formaldehyde) and the metals potassium, sodium, magnesium, manganese, barium and zinc than groundwater in the vicinity of the site (compare tables 13 - 18 with Tables 9 and 12). Evidence was found of the presence of at least some of these components in groundwater beneath and in close proximity to the landfill itself.

The highest concentrations of chloride, sulphate and ammonia were found in borehole TA1 within the deepest part of the quarry. Boreholes TB1 - TB3 and particularly TB4, all within the confines of the quarry, also contained high concentrations relative to those in the 'background' borehole TB6. These concentrations showed only slight decreases with increasing depth beneath the landfill, which suggest that fissures intercepted by each borehole may be filled with leachate.

The concentrations of chloride in borehole TB5, drilled approximately 130 m to the south of the landfill, are lower than were found in TB1 - TB4 but still higher than in the 'background' borehole (enrichment factor 3.8) with respect to TB6 (See Table 11), possibly indicating lateral movement of leachate. However, ammonia would also be expected to be found in detectable concentrations in samples from TB5, if the chloride derives from the landfill, presuming ammonia had moved at the same rate as the chloride. The absence of detectable concentrations of ammonia in samples from TB5 at the time of drilling may be due to attenuation relative to chloride during movement through the limestone from the landfill to borehole TB5 or to derivation of the chloride from a source other than the landfill. Certainly chloride shows the most significant enrichment above background levels in borehole TB5, of all the parameters examined, while sulphate and ammonia show no significant enrichment (see Table 11).

The highest concentrations of organic carbon were found in borehole TA1 (maximum concentration 5760 mg C/l). Of the 'B' type boreholes within the confines of the landfill, TB4 (with a maximum concentration of 430 mg/l) and to a lesser degree TB1 (maximum concentration 132 mg/l) show the highest concentrations of organic carbon. There is little decrease in concentration with increasing depth in these boreholes suggesting vertical movement of organic components of the leachate beneath the landfill.

The concentrations of organic carbon found in borehole TB5 are much lower than were found in boreholes TB1 - TB4, the maximum concentration being 5.6 mg C/l. Comparison of concentrates found in TB5 with the 'background' borehole TB6 show that only slight enrichment exists in TB5 suggesting that movement of the organic components away from the landfill is insignificant or that considerable attenuation of those compounds takes place in a relatively short distance.

The Chemical Oxygen Demand bore a constant relationship to total organic carbon in liquid samples taken at the time of drilling from borehole TA1 and boreholes TB1 - TB4 (Figures 27 and 28).

Borehole TA1: COD = 3.08 TOC

Boreholes TB1 - TB4: COD = 2.91 TOC

Although phenols were found in borehole TA1 at a maximum concentration of 25 mg/l in the liquid samples and 37.4 mg/kg in the solid samples, they were either non-detectable or at the limit of detection in all samples from the Type 'B' boreholes.

Fatty acids constitute up to 60 per cent of the organic carbon in liquid samples from the boreholes. There is an approximately linear relationship between fatty acid content and total organic carbon (see Figures 29 and 30). The maximum concentrations were found in borehole TA1, whilst of the 'B' type boreholes, TB4 and TB1 contained the highest concentrations (both approximately 120 mg/l). They were barely detectable in borehole TB5 and in the background borehole TB6.

Sodium potassium and magnesium, possibly associated with chloride and sulphate, were present in highest concentrations within the confines of the landfill; however calcium was at its highest average concentration (146 mg/l) in borehole TB5. The 'background' level of calcium found in borehole TB6

(46 mg/l) average) was higher than in all but two of the other type 'B' boreholes suggesting that calcium concentration in the groundwater is controlled by the mineralogy of the limestones rather than any effect produced by the landfill. For sodium, magnesium and potassium, the concentrations recorded in borehole TB5 were similar to the background concentrations. Magnesium concentrations in TB5 are depleted with respect to TB6.

Sodium and potassium concentrations were highest in TB1 - TB3, comparable to the range found in borehole TA1, while levels in TB4 were similar to those found in borehole TB5. Magnesium concentrations, however, were about 25 times higher in TB1 and TB4 than in the other 'B' type boreholes. The small decrease in concentrations with depth provide evidence to support vertical movement of sodium, potassium and magnesium in leachate, from the landfill into the underlying groundwater.

The highest concentrations of barium were found in borehole TA1, borehole TB1 particularly, but also TB2 and TB3 contained concentrations above background levels, whilst TB5, outside the boundaries of the landfill, showed no enrichment with respect to background levels. Lateral movement of barium is restricted to the confines of the landfill but some vertical movement through fissures is suggested.

The highest concentrations of manganese were found in borehole TA1 within the deepest part of the quarry; the maximum concentrations in boreholes TB1 - TB3 were all in excess of 1 mg/l which contrasts with borehole TB5 and the background borehole TB6 where the concentrations were less than 0.1 mg/l.

The results suggest at least some vertical movement of manganese in the groundwater beneath the landfill, through the fissure system in the limestone.

An anomalous situation occurs with borehole TB2. Whereas the concentration of manganese in the groundwater during drilling did not exceed 0.06 mg/l, samples of standing water collected from the borehole one week and two weeks after drilling contained manganese of concentration 3.4 and 3.8 mg/l respectively. Concentrations of barium, calcium, potassium, magnesium and organic carbon had increased in these standing waters similarly and this may indicate restricted fissure connections between the landfill and borehole TB2.

Outside the landfill boundary, in borehole TB5, the manganese concentration is not enriched with respect to borehole TB6 and therefore any detectable lateral movement of the metal appears to be restricted to within the confines of the quarry.

The highest concentrations of zinc were recorded in borehole TA1 within the deepest part of the quarry. Of all the 'B' type boreholes considered, the maximum concentration during the period of drilling occurred in standing water from the 'background' borehole TB6 (0.6 mg Zn/l). This high value was not repeated in samples taken during the monitoring period to November 1977 (Table 18A), concentrations falling in the range 0.03 to 0.10 mg Zn/l. However, during the same period of time, samples from boreholes closely surrounding the landfill gave values in the range 0.07 to 0.50 mg Zn/l, indicating some migrations of zinc ions in leachate away from the landfill.

CONCLUSIONS

- 6.1 The aquifer at Tythegston is composed of massive Carboniferous Limestone in which groundwater flows are predominantly controlled by a north-south fissure pattern. Partial infilling of the north-south fractures by Triassic materials has been noted. A conjugate fissure set, running east-west, provide low secondary permeability along that axis, imposing strong anisotropy on the aquifer system.
- 6.2 Storage within the aquifer is small (0.02 - 0.08). Zones of high permeability ($10^3 - 10^4$ m/day) are associated with solution enlarged fractures (conduit flow), whilst the bulk permeability of the interconnected, fine fracture systems may be low ($10^{-1} - 1.0$ m/day).
- 6.3 A perched water table develops seasonally within the landfill, giving rise to a recharge mound by leakage and modifying groundwater flow patterns in the vicinity of the landfill.
- 6.4 Groundwater levels within the aquifer fluctuate rapidly in response to recharge, with a delay time of about 1 or 2 days.
- 6.5 The highest concentrations of potential pollutants were found within the lower portion of the landfill (TA1).
- 6.6 The highest concentrations of pollutants in boreholes sunk outside the main landfill were found to the north (TB1) and south (TB4) confirming the importance of the north-south fissure system in controlling groundwater movement.
- 6.7 Lateral dispersion of leachate into the groundwater flows, in the direction of the tight east-west fissures, was confirmed by high concentrations of manganese and total organic carbon measured in water samples from borehole TB2, to the north east of the landfill.

- 6.8 The presence of high concentrations of total organic carbon, chloride and ammonia to depths of up to 70 metres below the landfill surface vertical flows induced by the large groundwater level fluctuations, within the fissure systems.
- 6.9 The highest concentrations of pollutants in groundwater in boreholes immediately surrounding the landfill were measured at periods of minimum groundwater levels, whilst minimum concentrations occurred at the time of maximum groundwater levels and, hence, following recharge.
- 6.10 Unequivocal evidence of leachate migration beyond the immediate periphery of the landfill was limited to chloride enrichment (c. 4 times background levels), in borehole TB5, 150 m south of the landfill.
- 6.11 The present distribution of observation boreholes is insufficient to define completely the local groundwater flow pattern or pollutant transport paths. It is recommended that further boreholes be drilled in the eastern parts of the quarry in order to define the extent of the transient recharge mound.
- 6.12 The aquifer properties are incompletely estimated. It is recommended that pumping tests be carried out in order to measure local values of transmissivity, storage coefficient and dispersivity.
- 6.13 The monitoring of groundwater levels and quality should be continued so that the understanding of the dynamic relationships between groundwater levels, pollutant movement paths and the recharge/discharge cycle can be refined. The carbonate hardness of local springs should be monitored at peak and minimum flow periods to determine the relative importance of conduit and diffuse flows contributing to their catchments.

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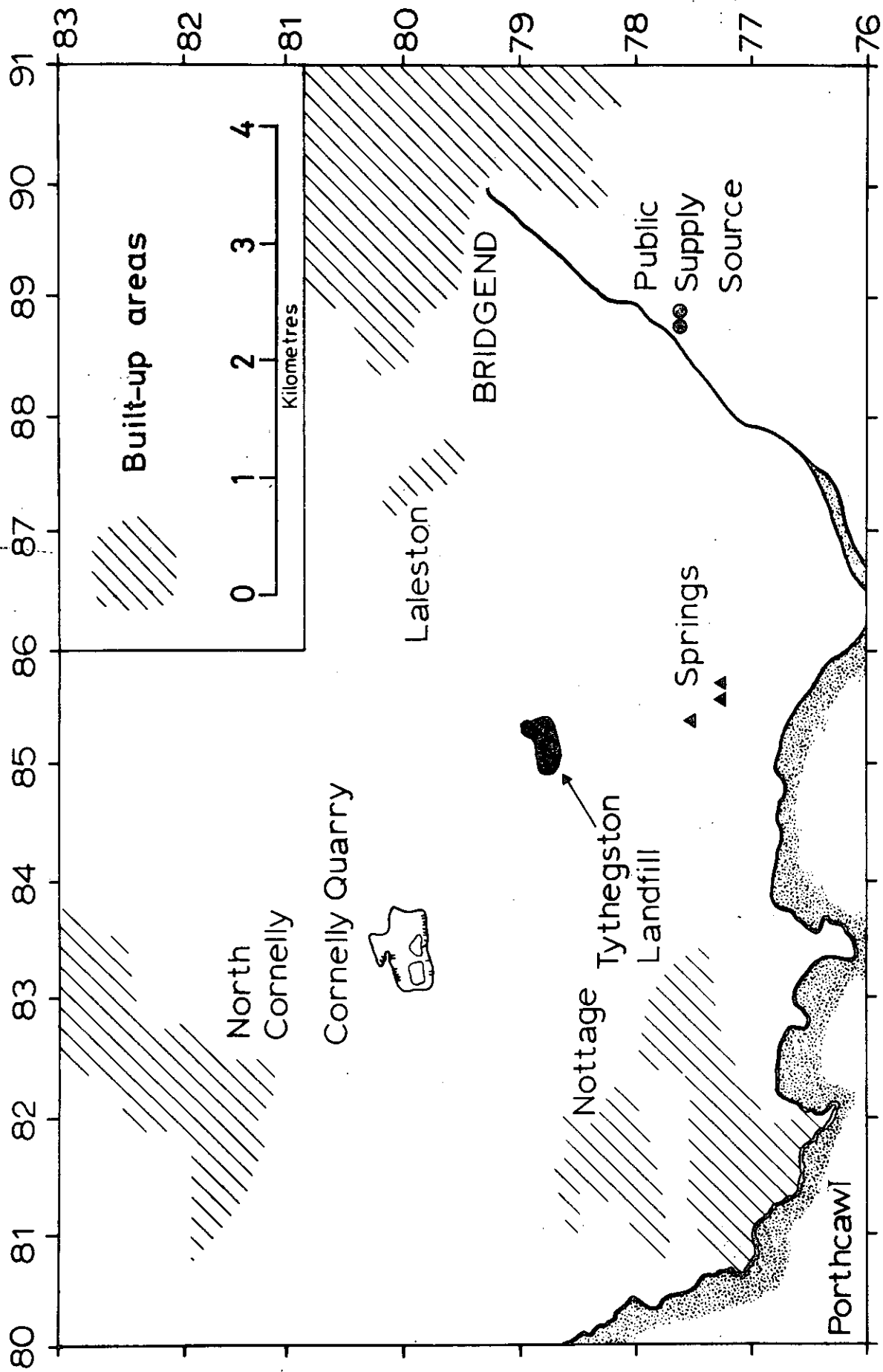


Figure 1. General location map.

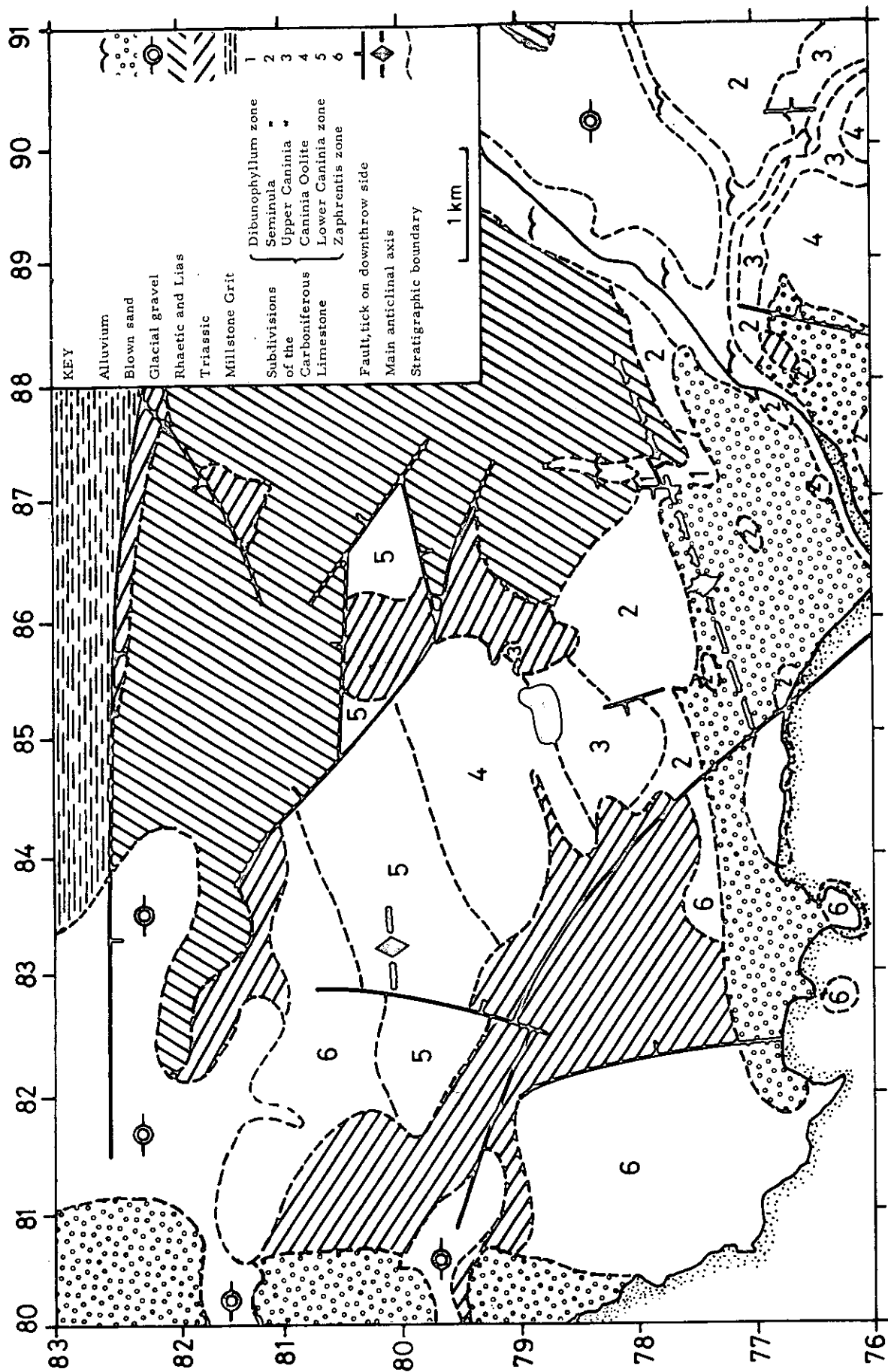


Figure 2. Stratigraphy and structural elements of the Tythegston area.
(After George, 1933).

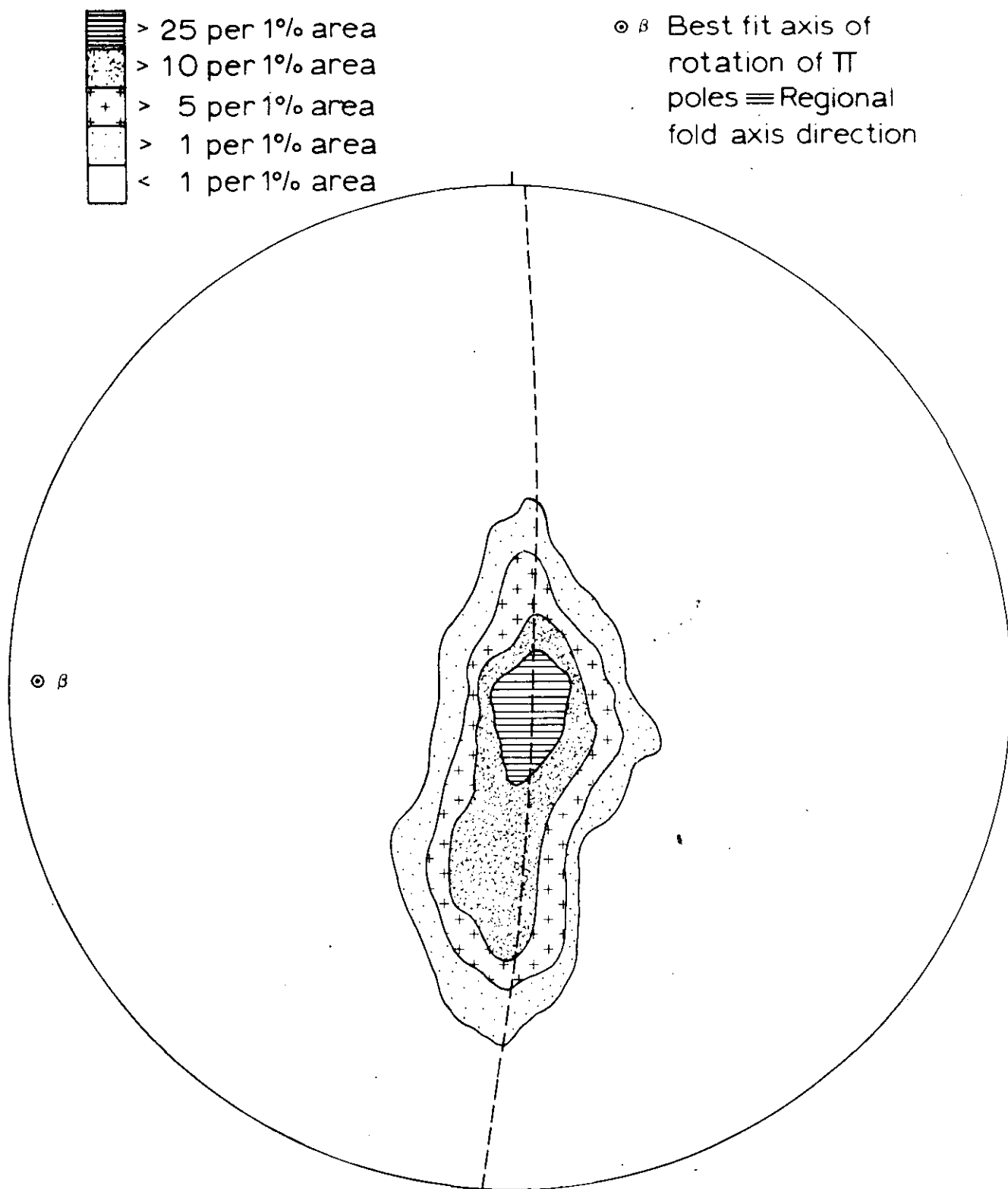


Figure 3. Stereographic plot of poles to bedding planes (91 readings), Tythegston area. (After Holland 1977).

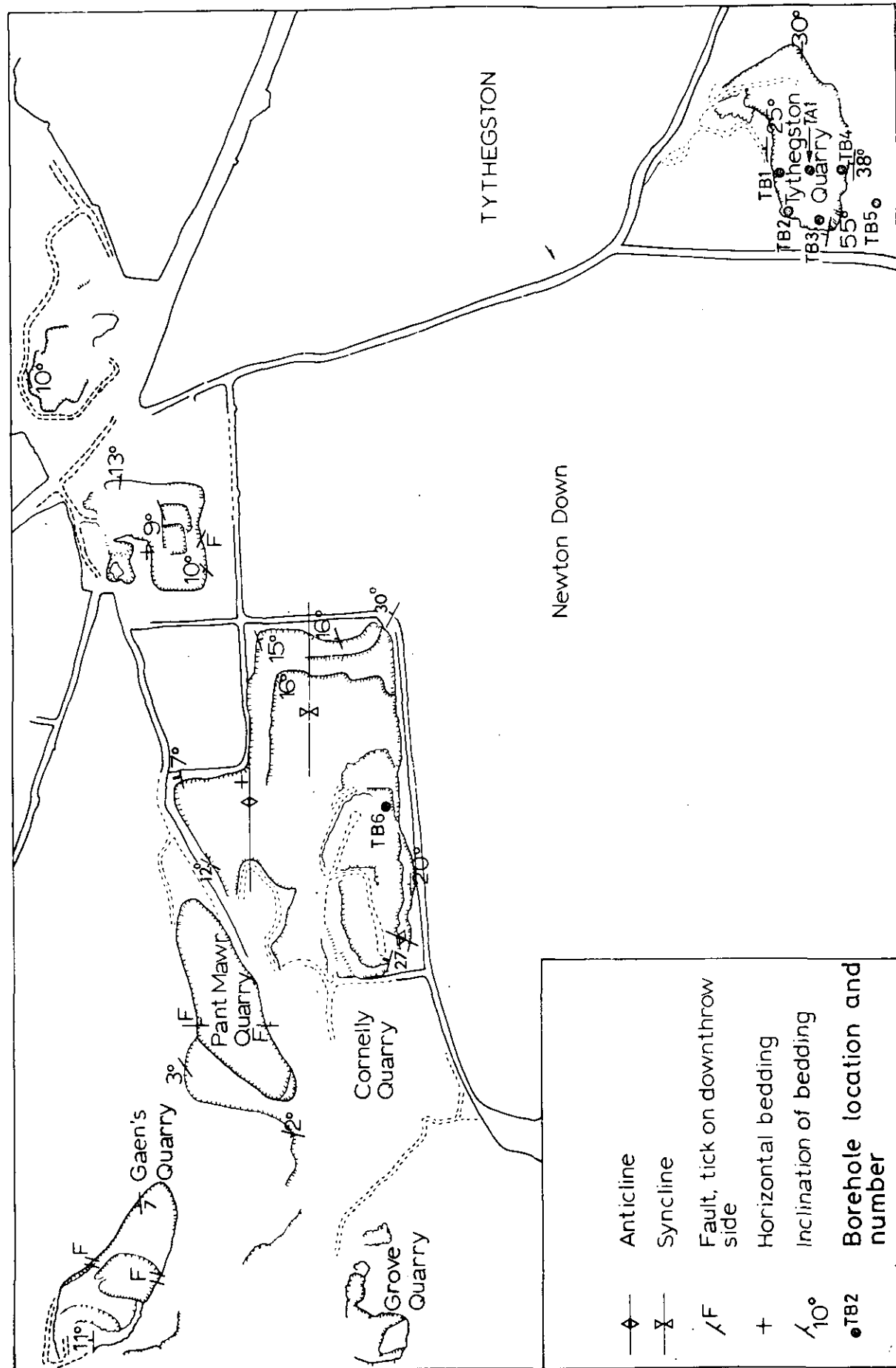


Figure 4. Detailed structural elements of the Tythegston area. (Modified from Holland 1977).

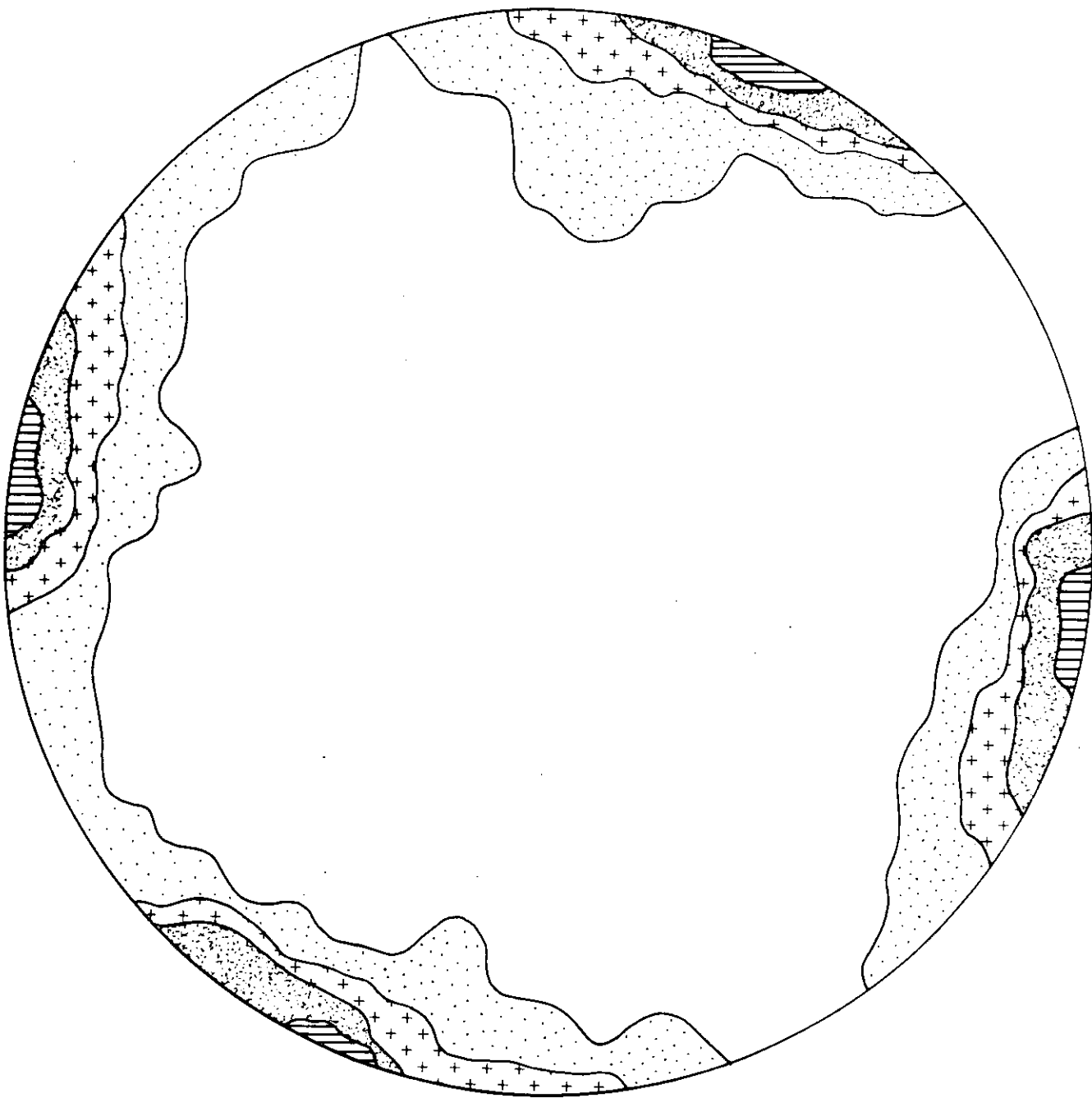
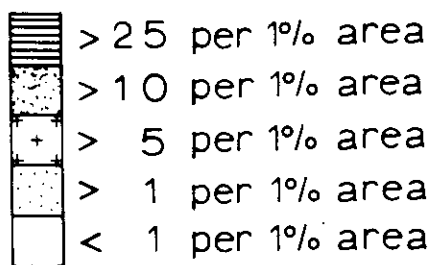


Figure 5. Stereographic plot of poles (149 readings) to joint surfaces Tythegston area (after Holland, 1977).

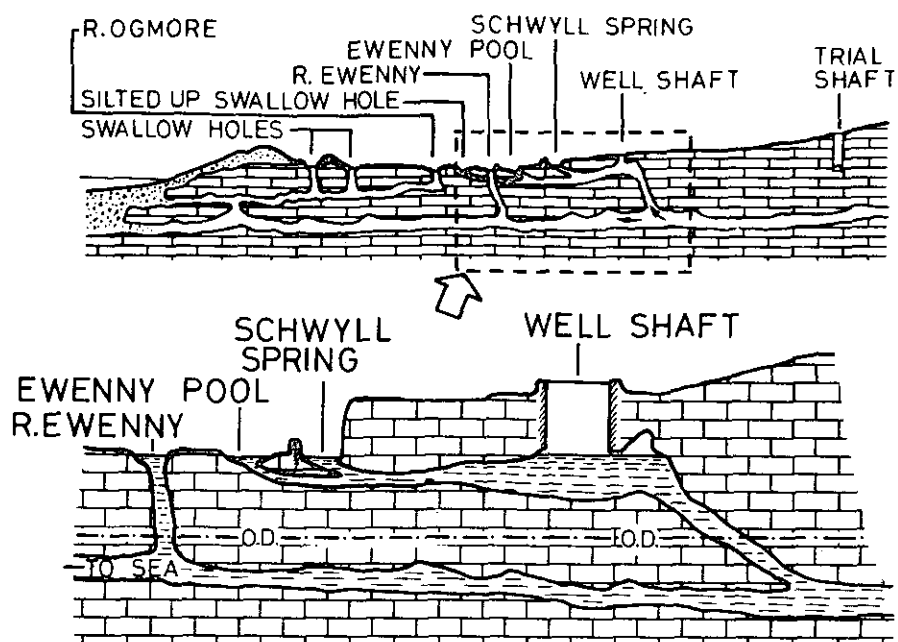


Figure 7. A. Section at Schwyll pumping station, showing karstic development (after Knox, 1933).

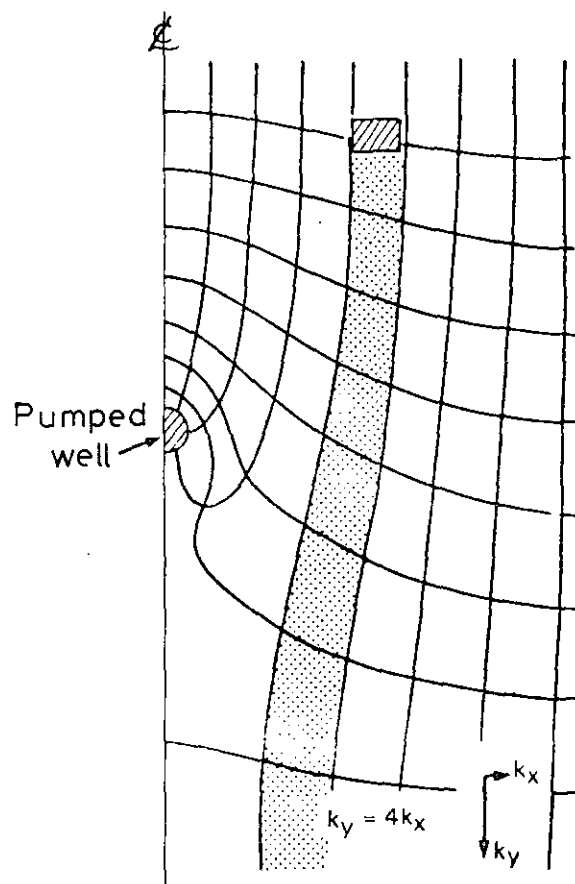


Figure 7. B. Flow lines in an anisotropic aquifer. (After Brereton and Wilkinson, 1978.)

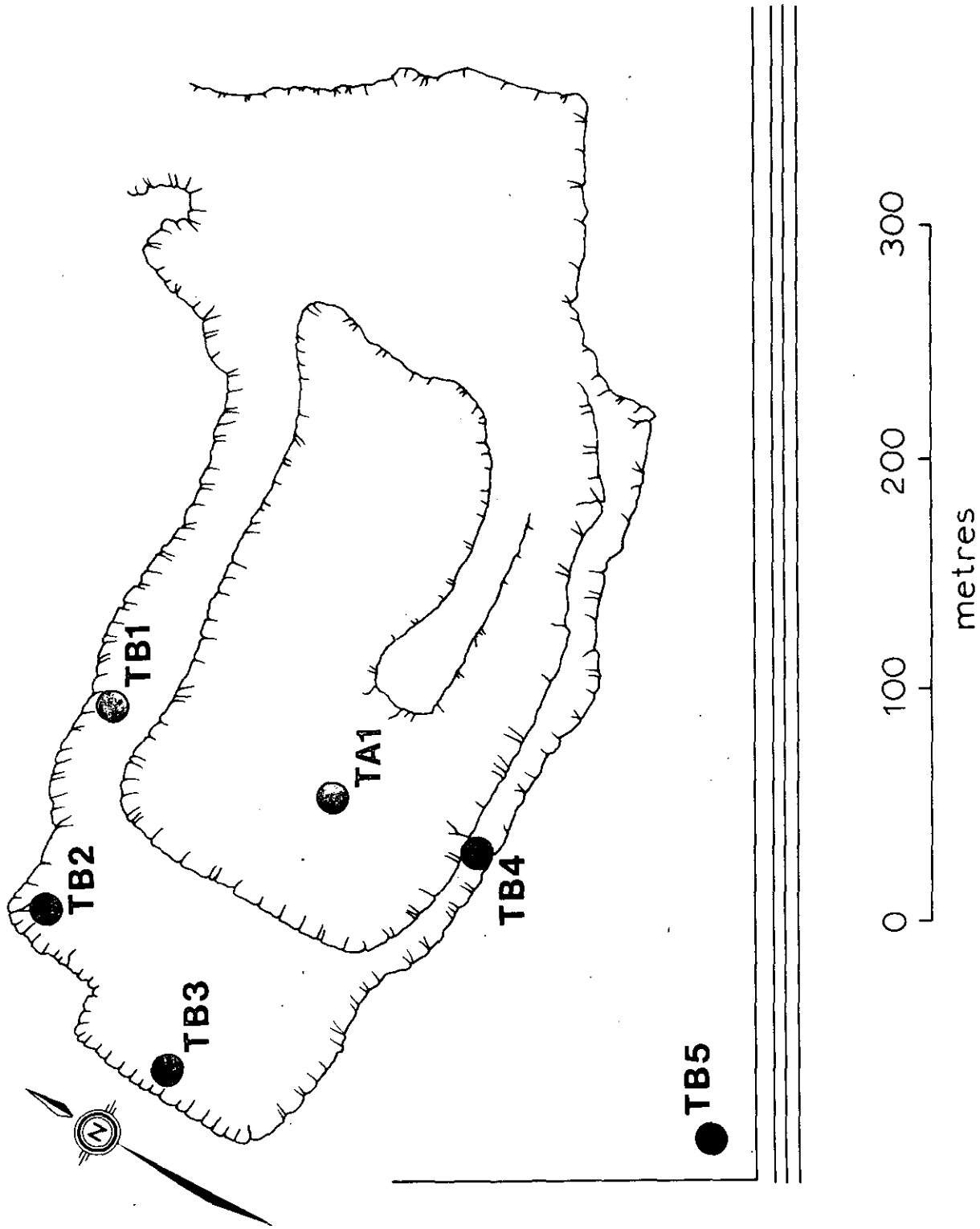


Figure 8. Location of boreholes at Tythegston Quarry.

Level metres above O.D.	Visual log.	Description	Fractures Core log.	Caliper log.	Differential temperature	Formation water con- ductivity	Formation resistivity	Gamma
90								
80								
70		Domestic wastes with occasional limestone boulders	NO GEOPHYSICAL LOGS					
60	 	Motor tyres Domestic wastes and tyres						
		Motor tyres						
		Paper pulp						
50		Domestic wastes with steel drums, and tyres						
		Limestone						
40								
30								
20								
10								

Figure 9. Summarised lithological and geophysical logs, borehole TA1.

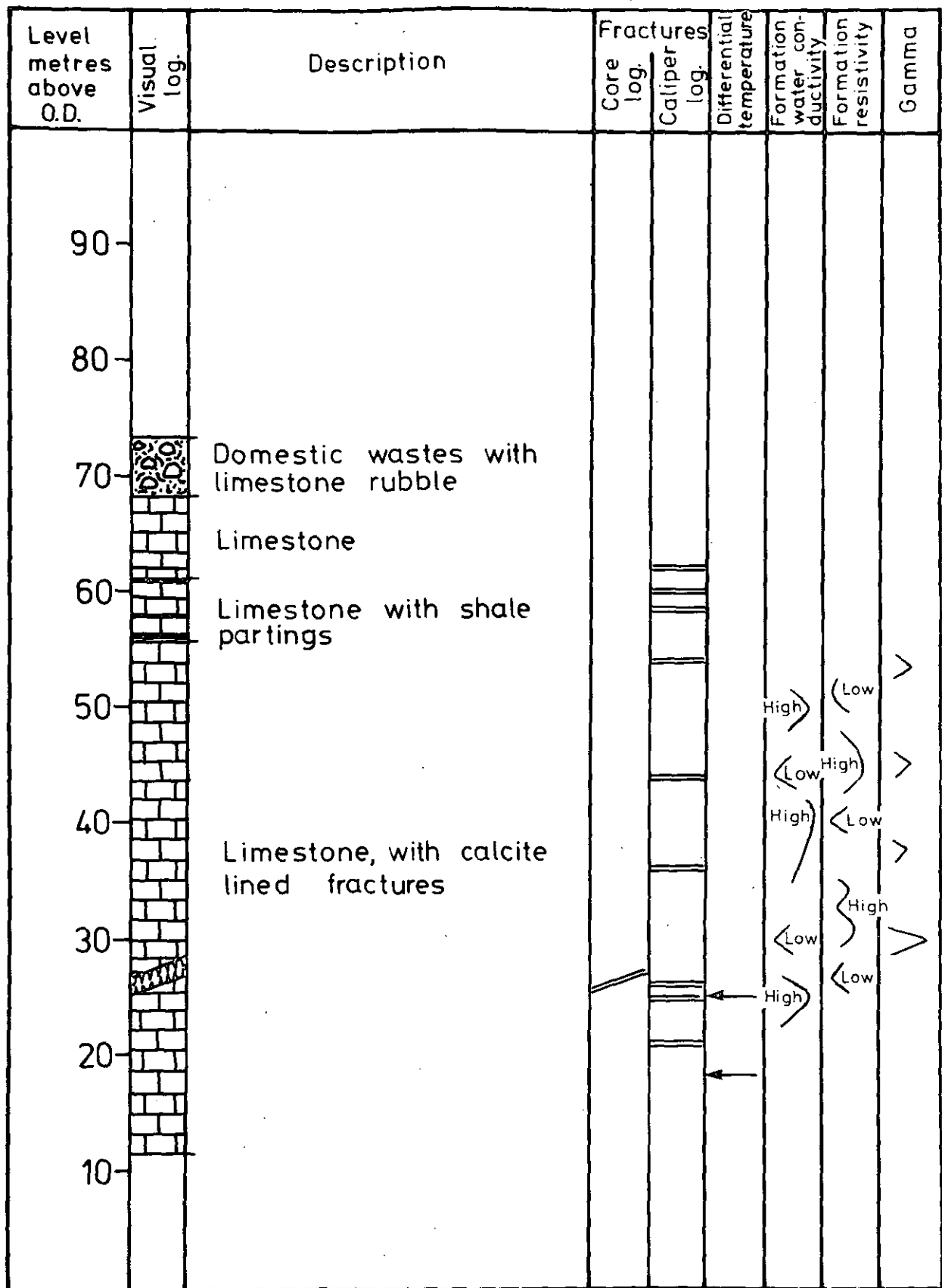


Figure 10. Summarised lithological and geophysical logs, borehole TB 1.

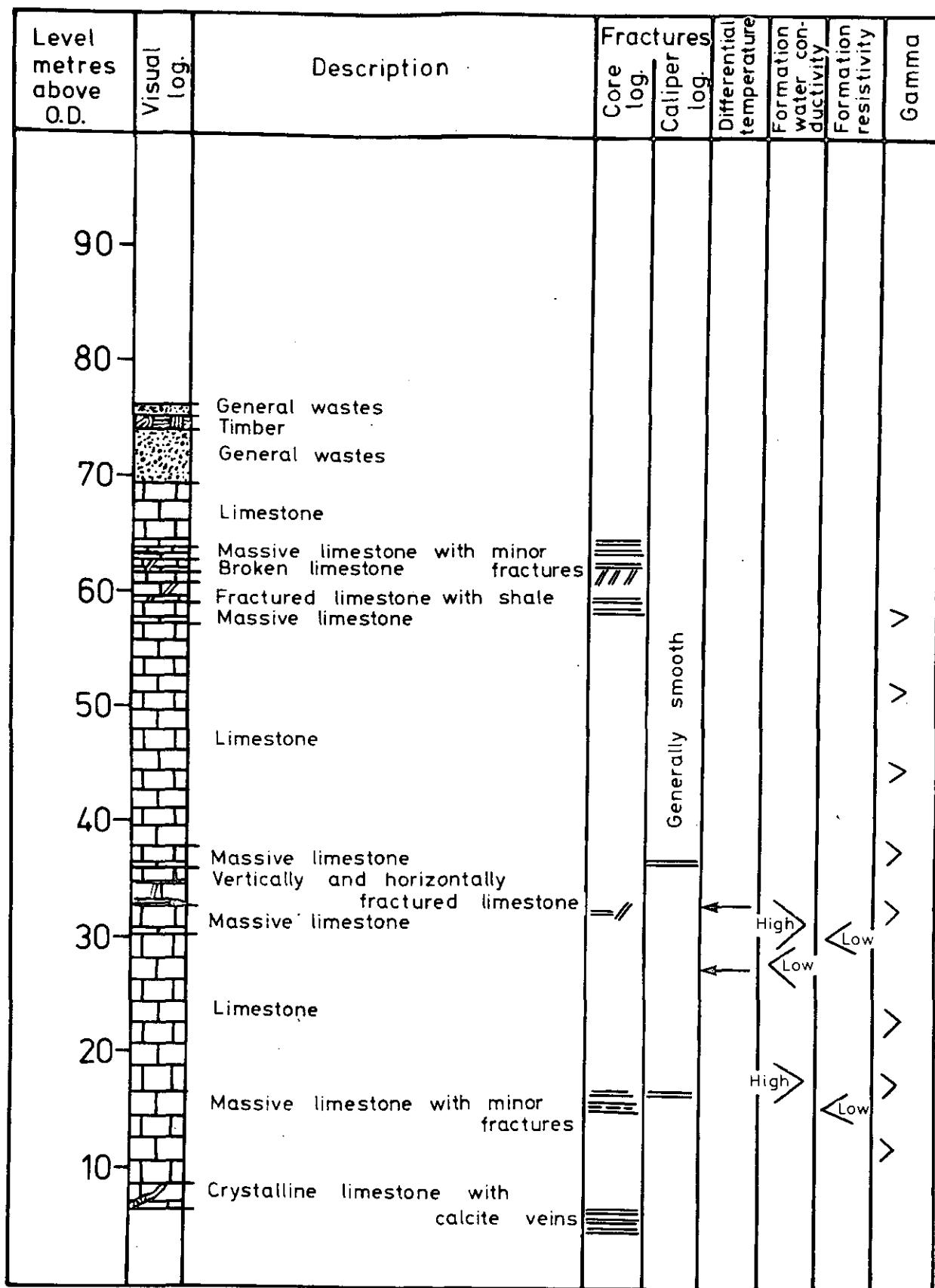


Figure 11. Summarised lithological and geophysical logs, borehole TB2.

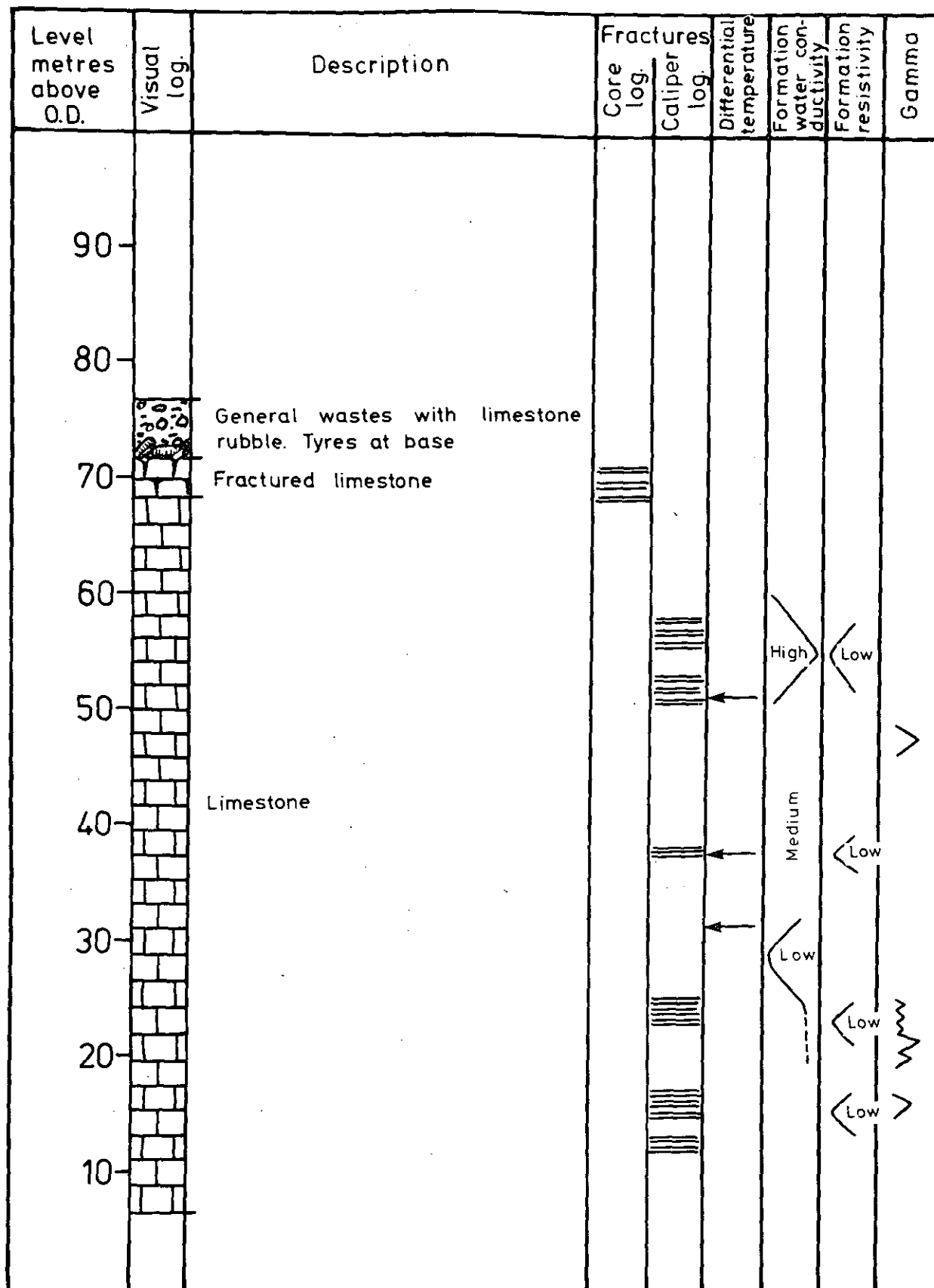


Figure 12. Summarised lithological and geophysical logs, borehole TB3.

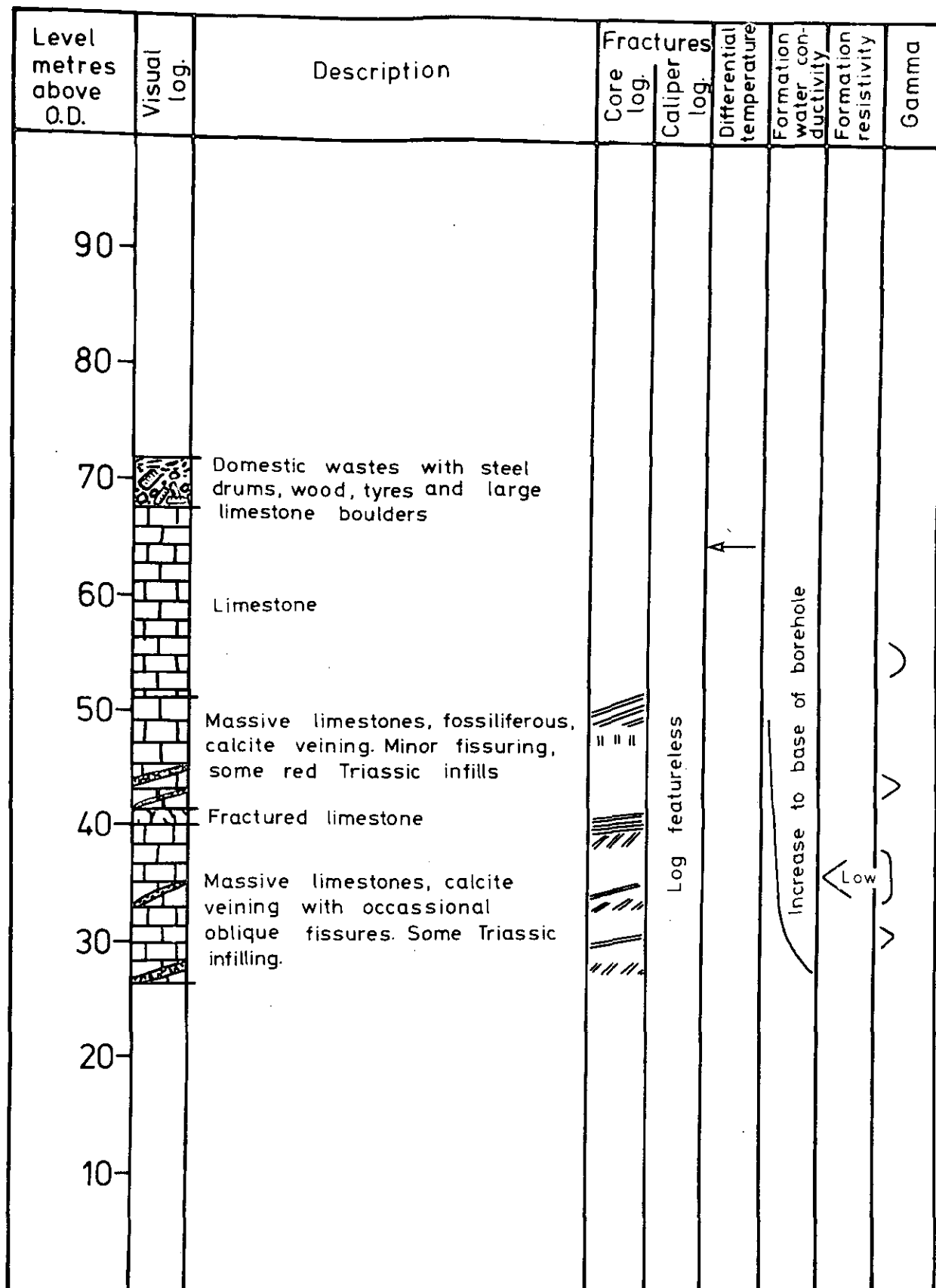


Figure 13. Summarised lithological and geophysical logs, borehole TB4.

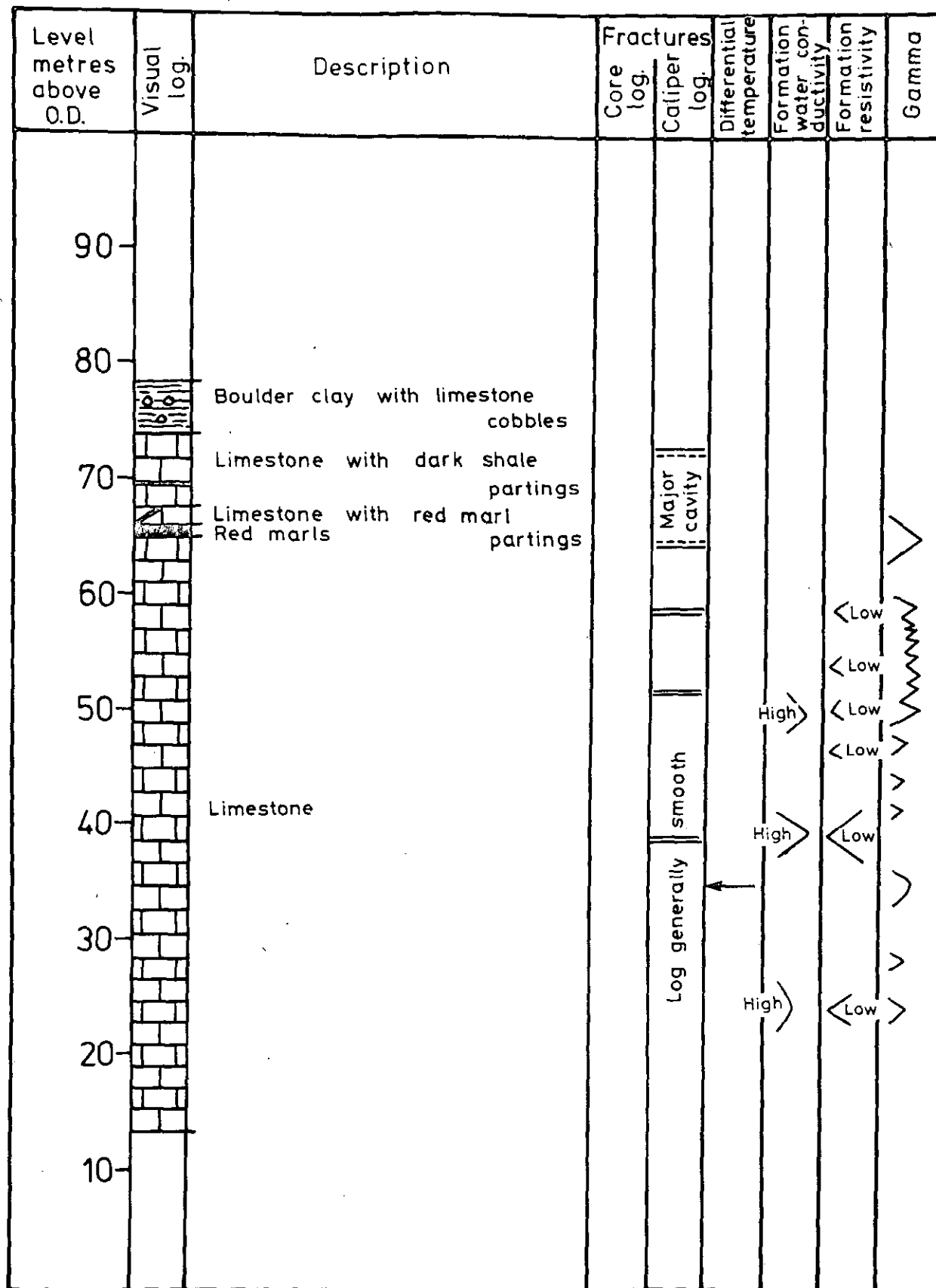


Figure 14. Summarised lithological and geophysical logs, borehole TB 5.

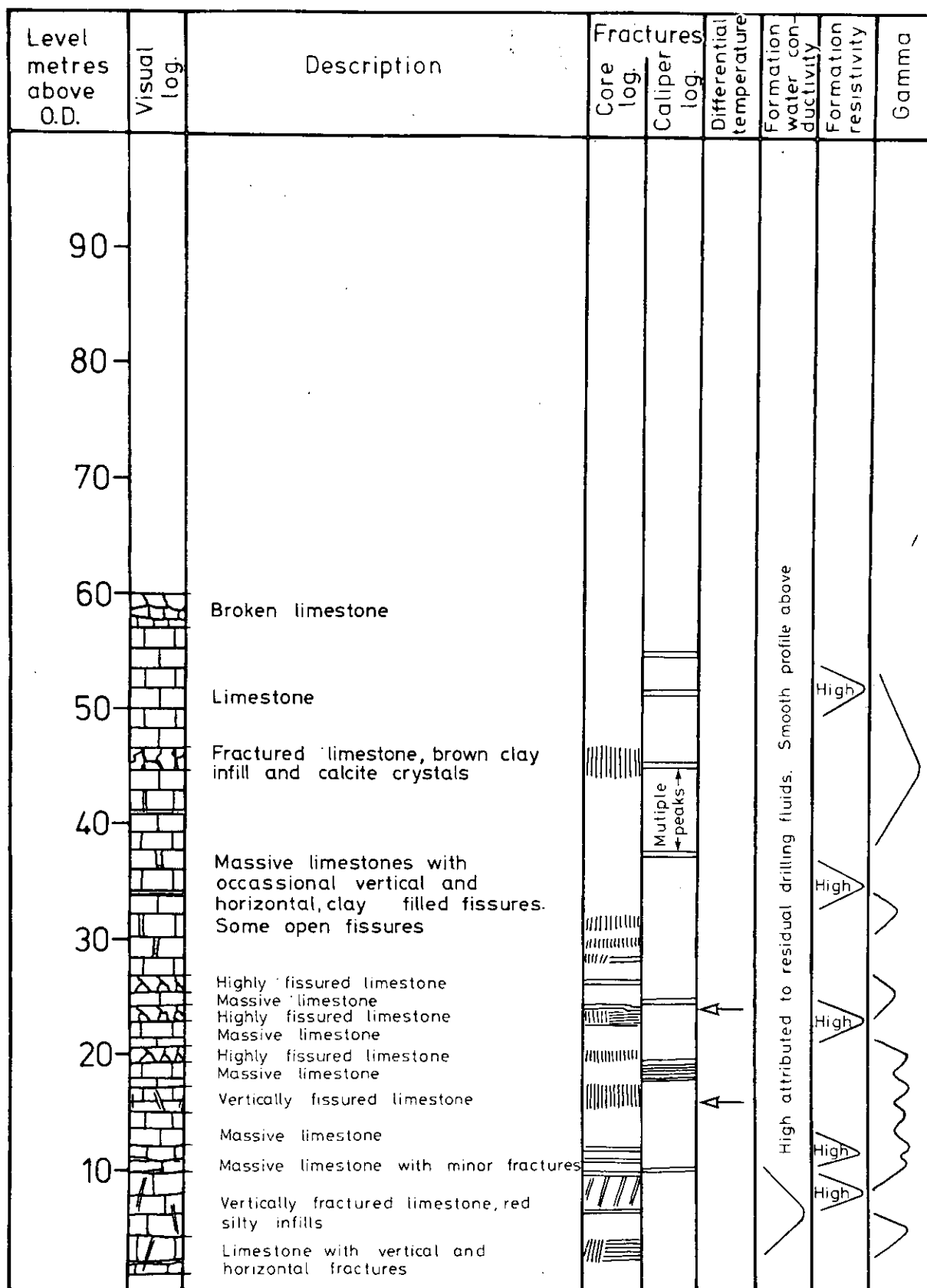


Figure 15. Summarised lithological and geophysical logs, borehole TB6.

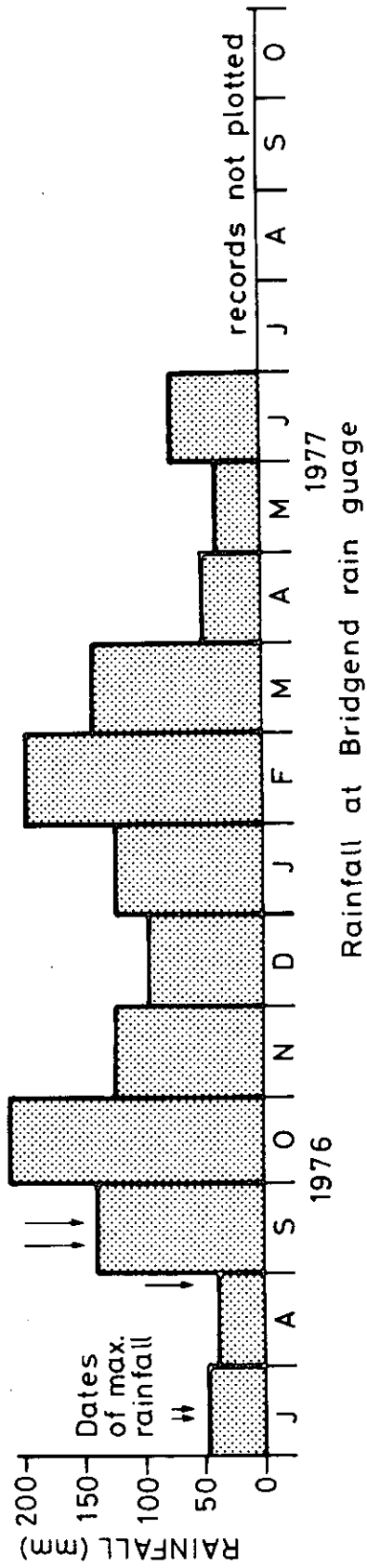
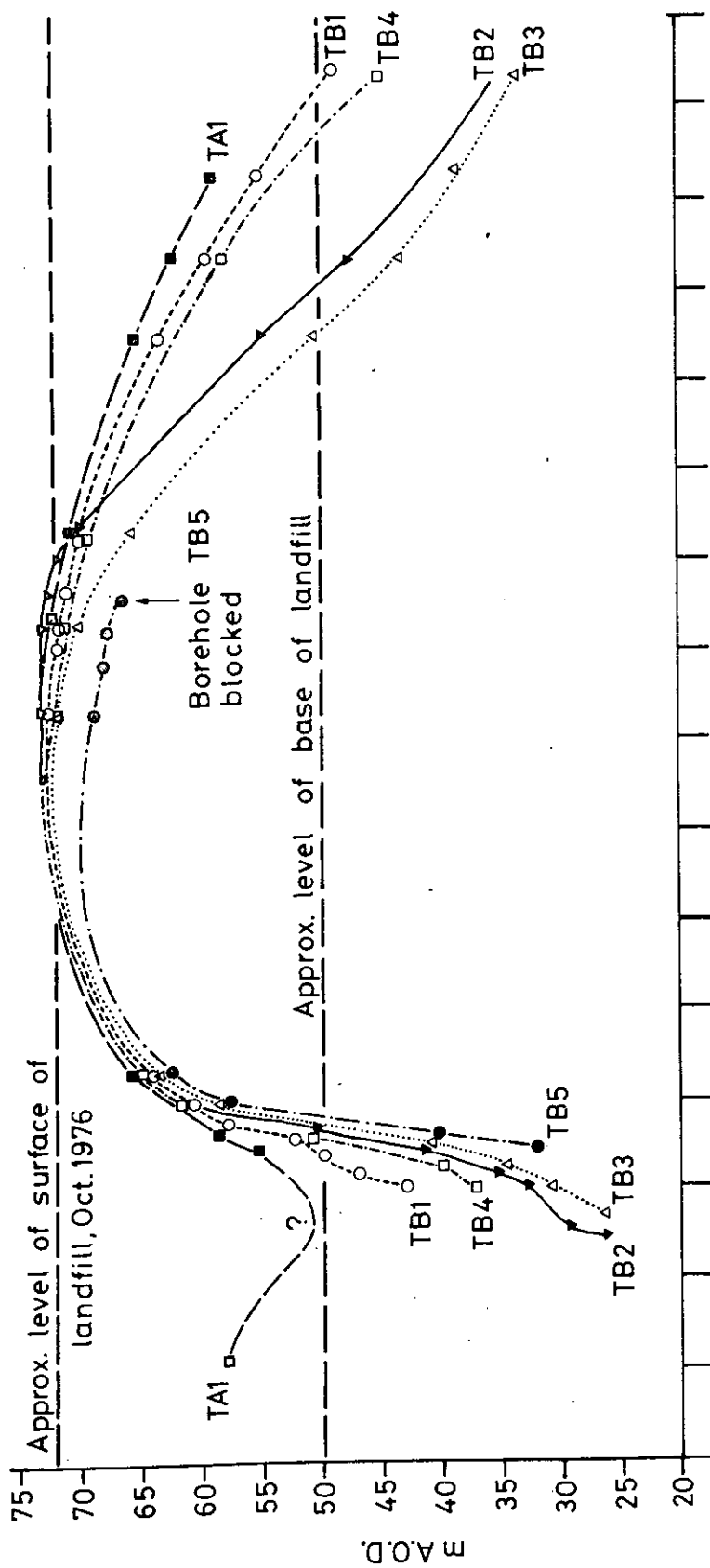


Figure 16. Groundwater level fluctuations.

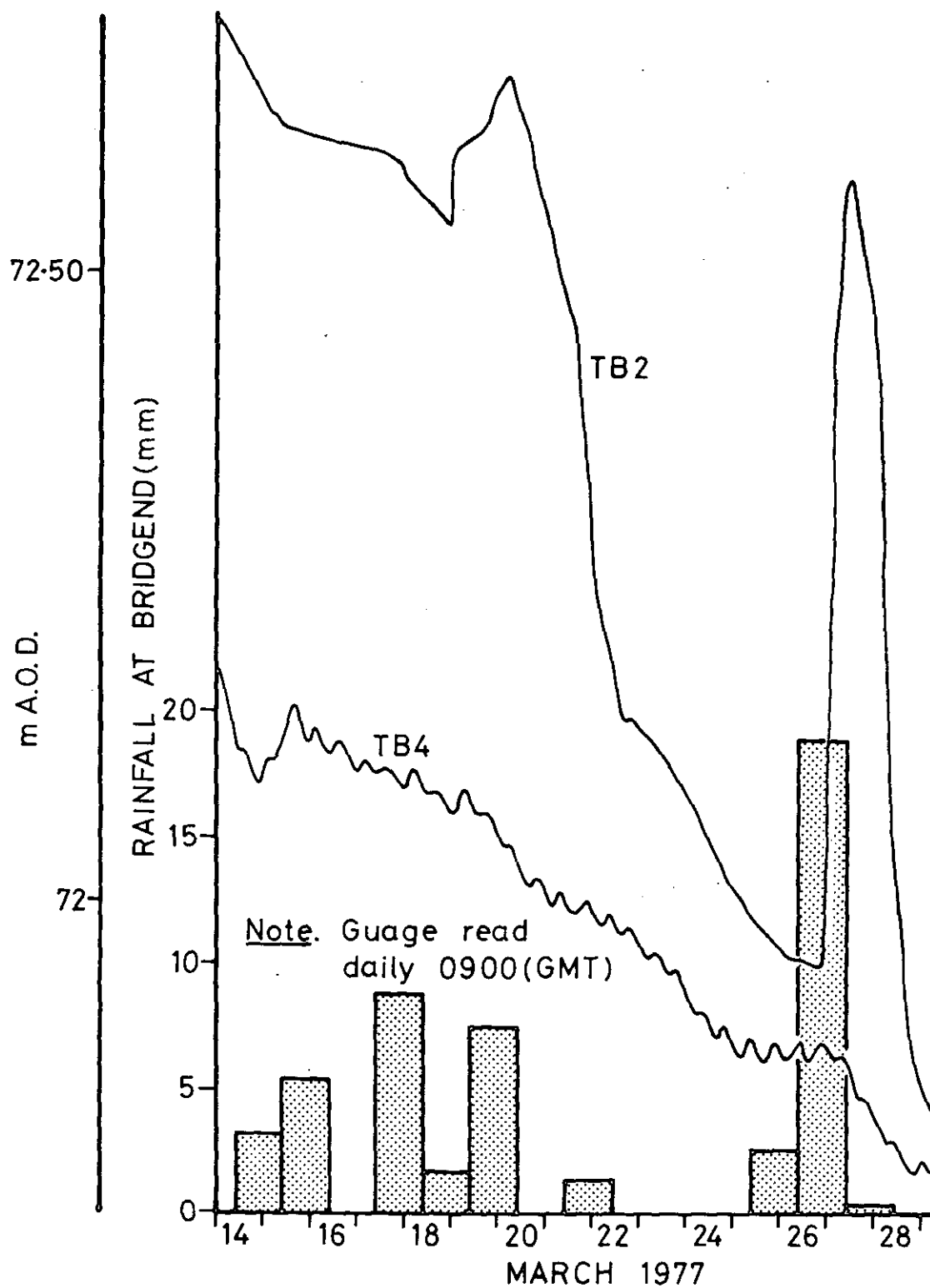


Figure 17. Response of groundwater levels to rainfall.

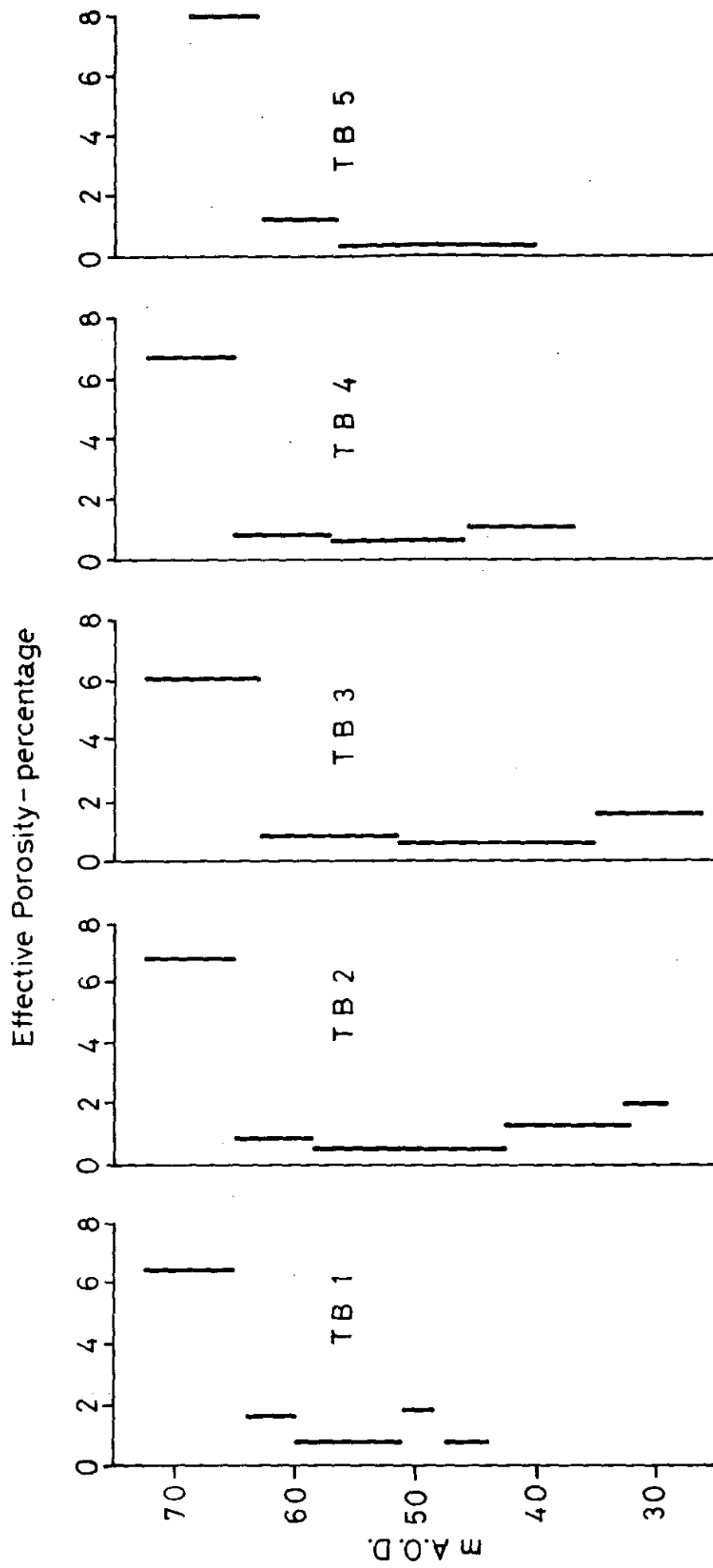
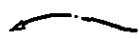
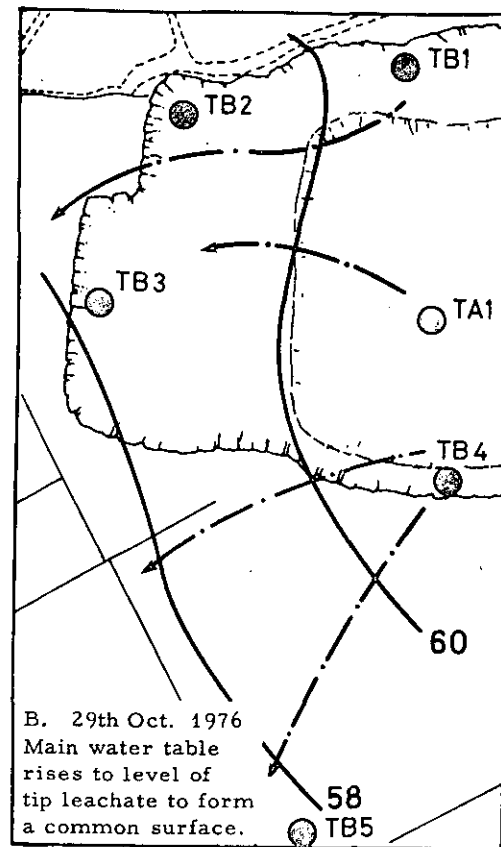
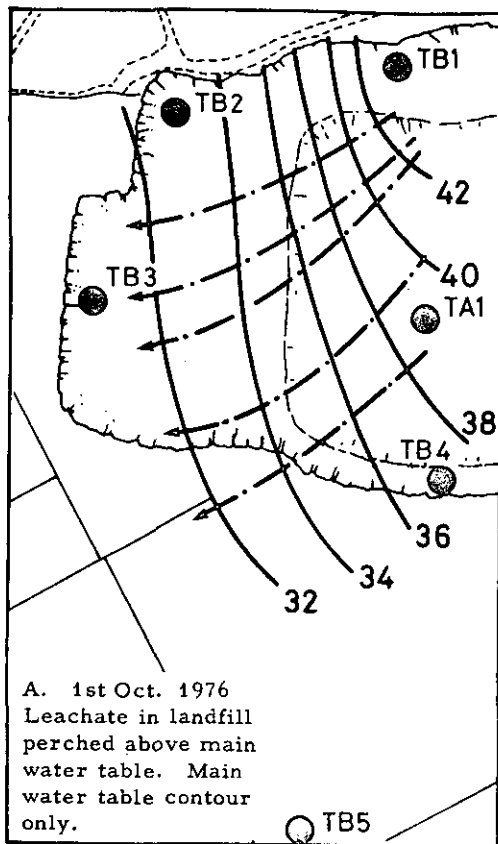


Figure 18. Variations in the effective porosity of the Carboniferous Limestone with depth.



Postulated flow lines

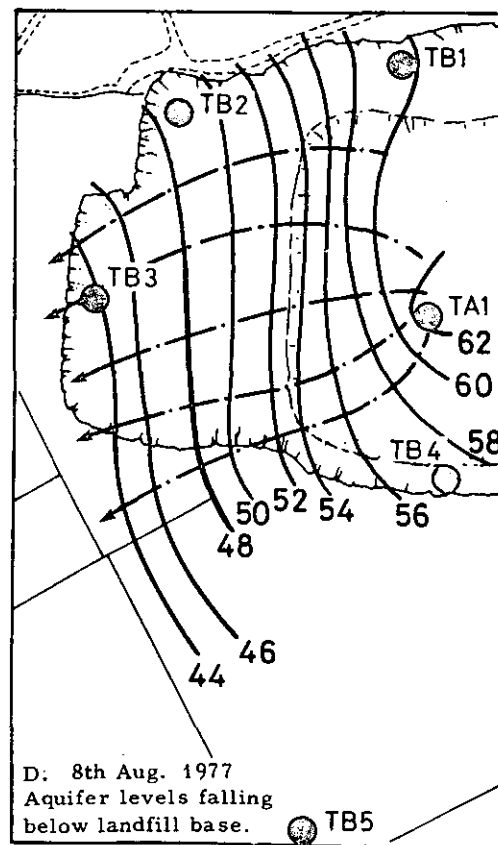
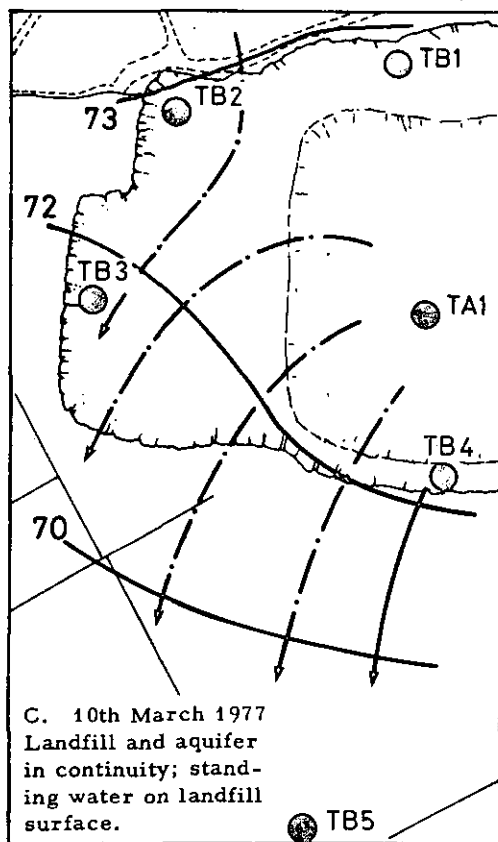


Figure 19. Groundwater level contours (metres O.D.) October 1976 to August 1977.

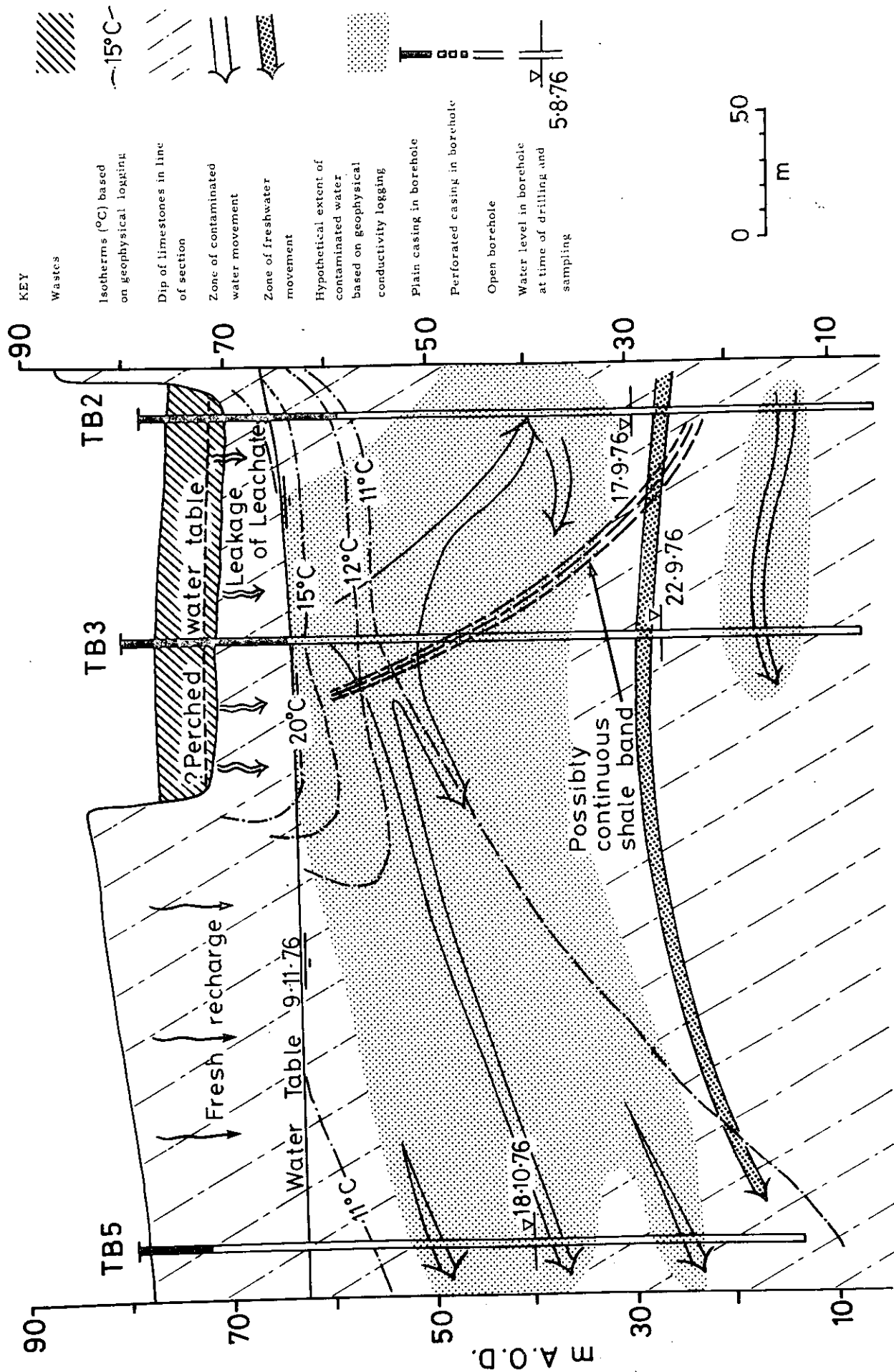


Figure 20. Section 1 through landfill parallel to groundwater flow. (Based on geophysical logging, Nov. 1976).

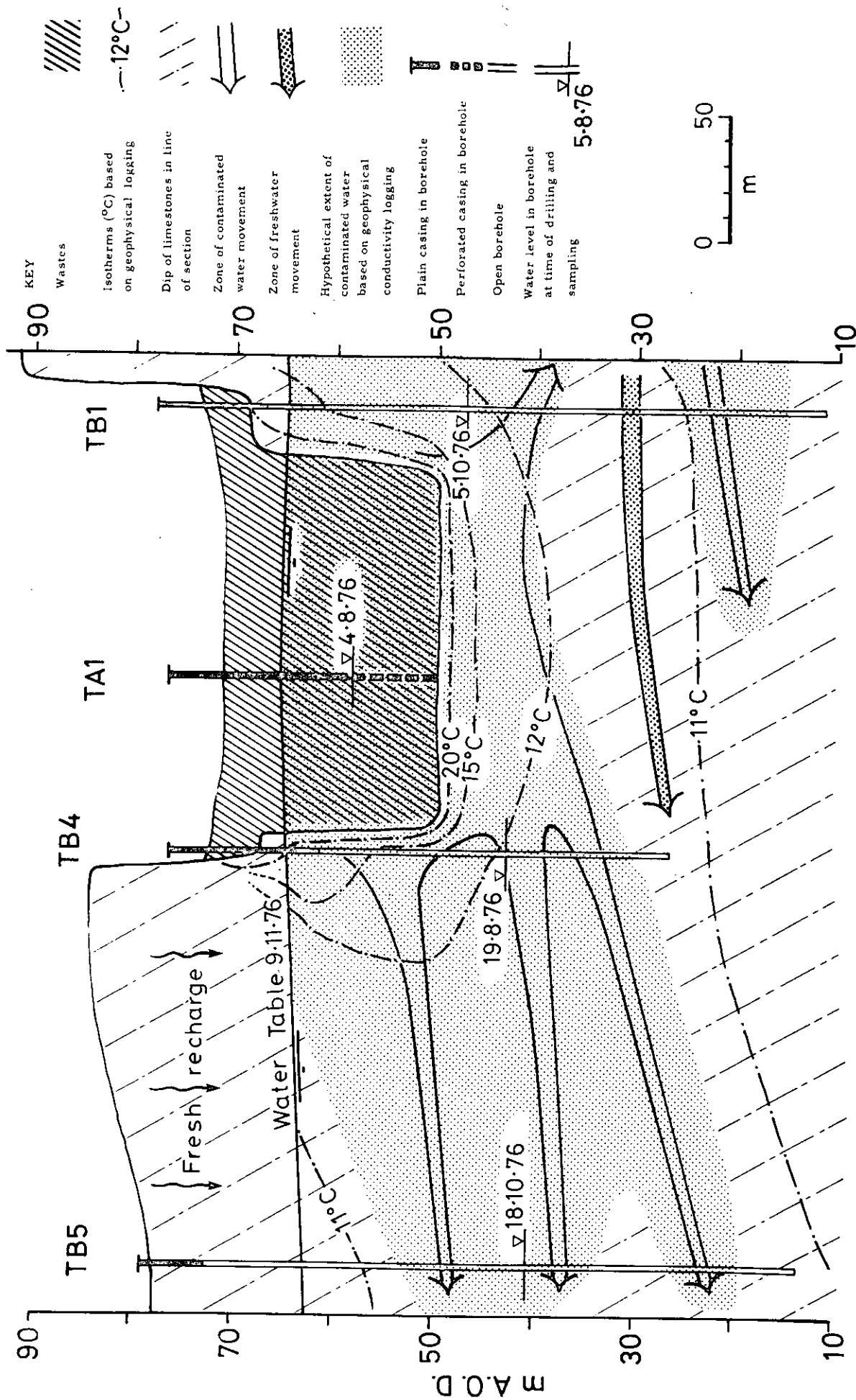


Figure 21. Section 2, through landfill parallel to groundwater flow. (Based on geophysical logging Nov. 1976)

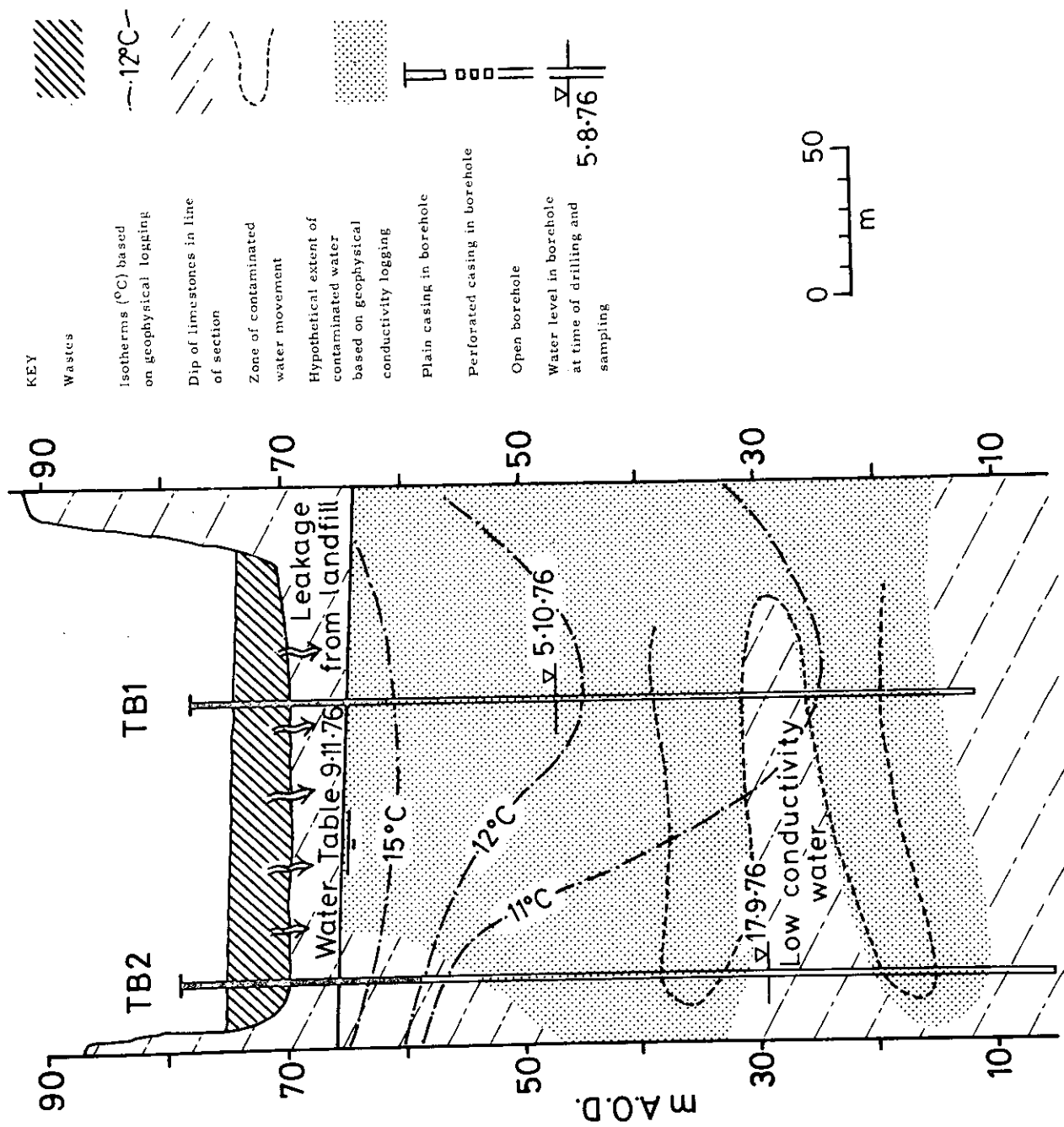


Figure 22. Section through landfill normal to groundwater flow. (Based on geophysical logging, Nov. 1976).

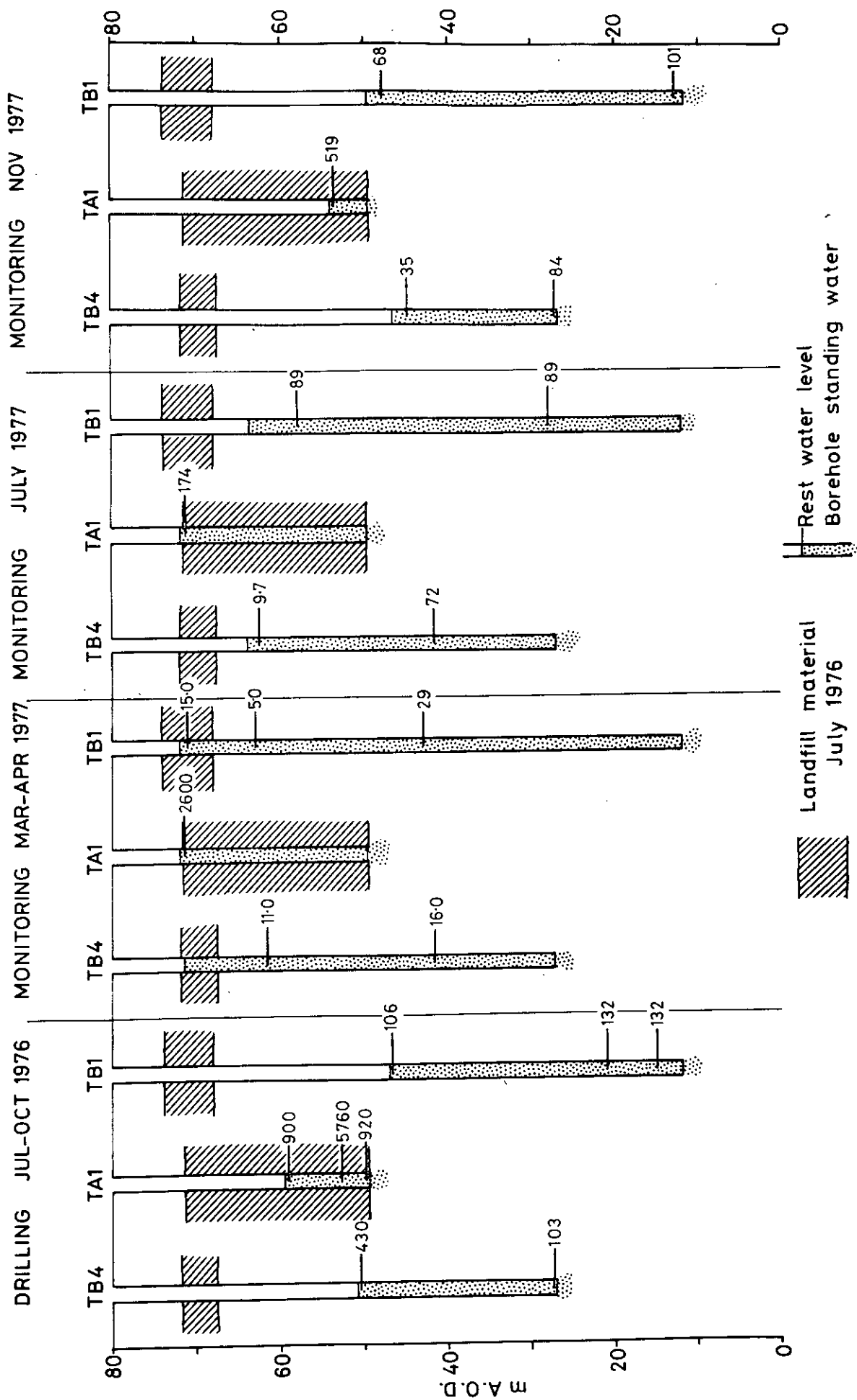


Figure 23. A. Borehole sampling at Tythegston 1976-1977. Variations in organic carbon concentrations (mg/l) with depth. North-South section.

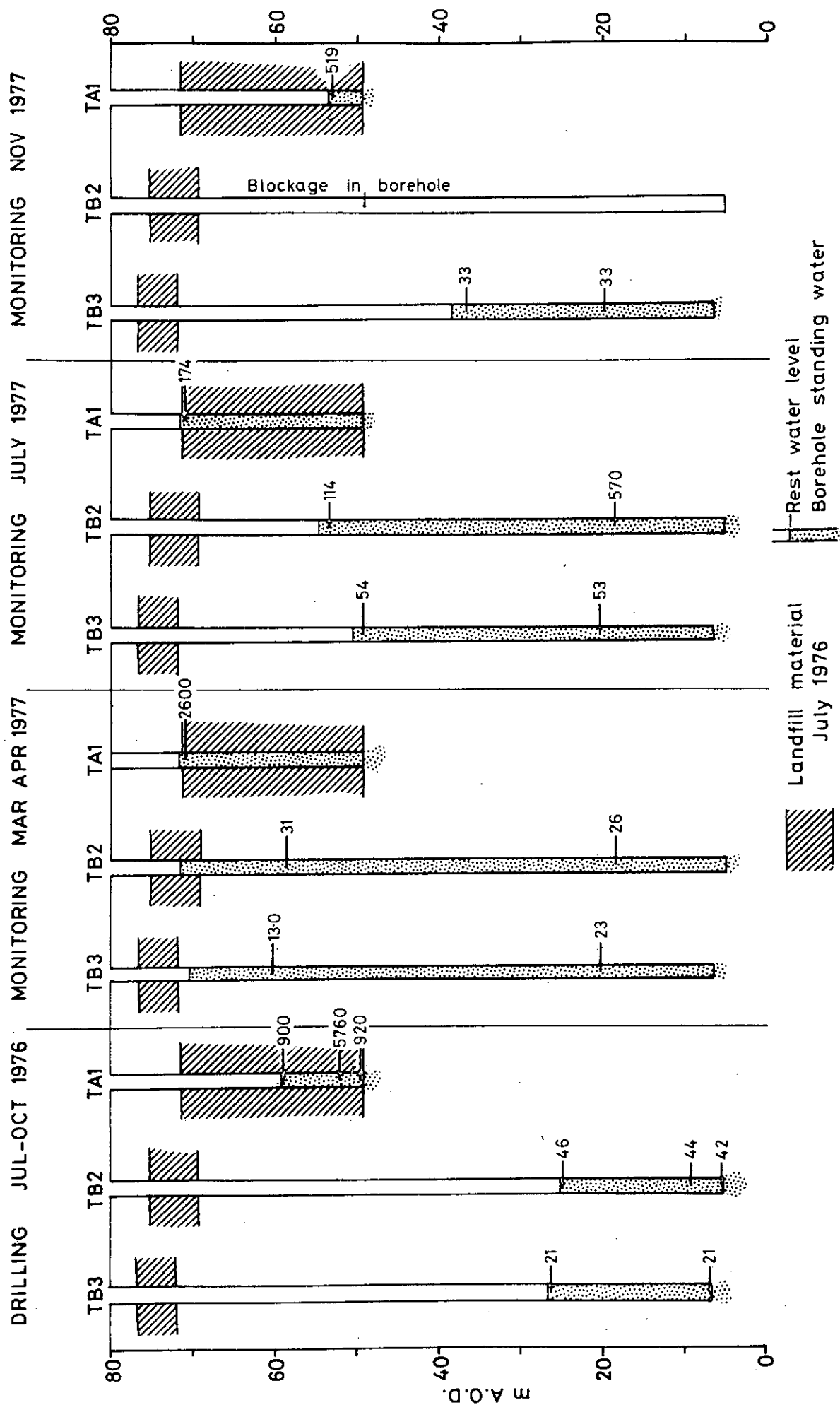


Figure 23. B. Borehole sampling at Tythegston 1976-77. Variations in organic carbon concentrations (mg/l) with depth. East-West section.

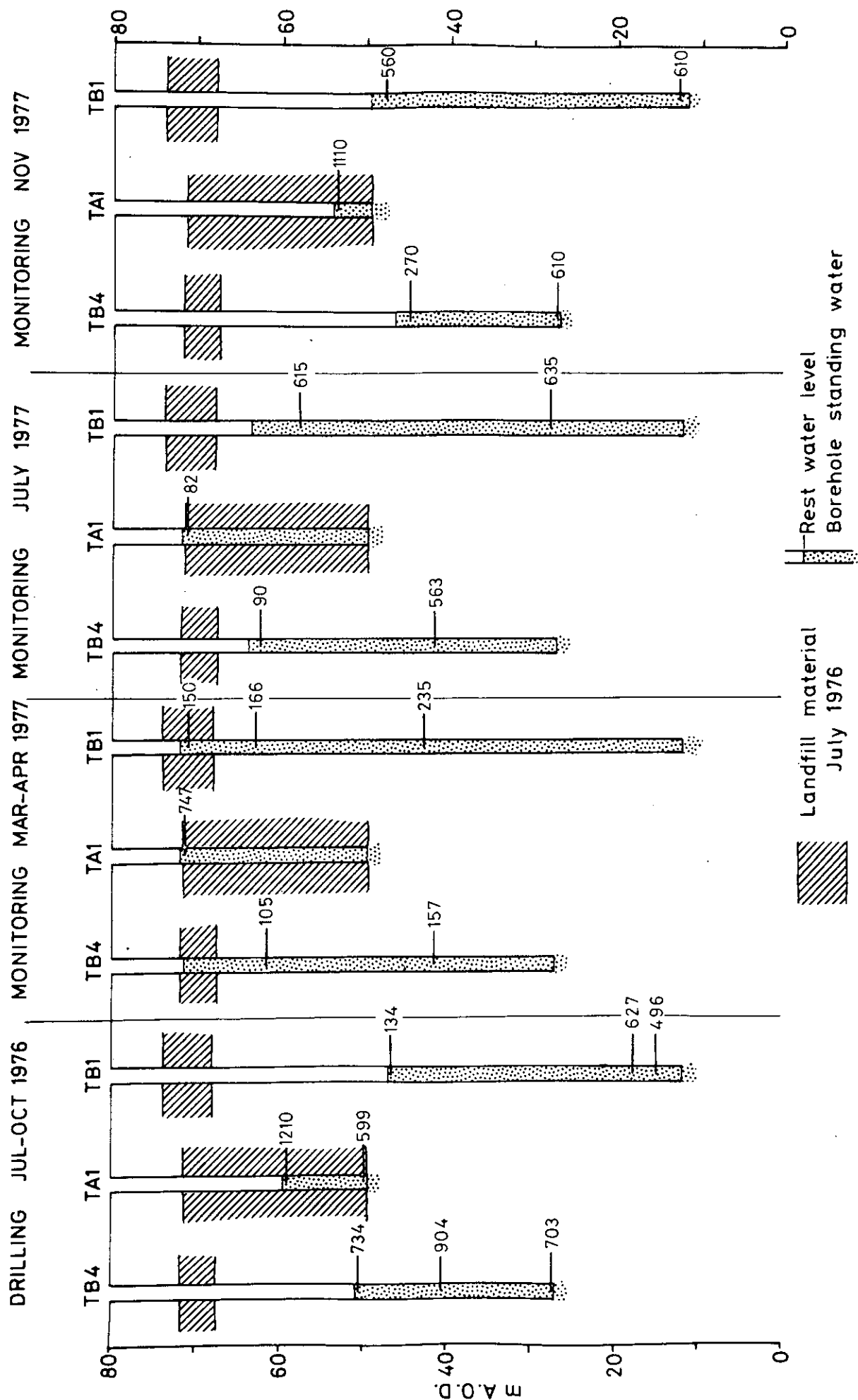


Figure 24.A. Borehole sampling at Tythegston 1976-77. Variations in chloride concentrations (mg/l) with depth. North-South section.

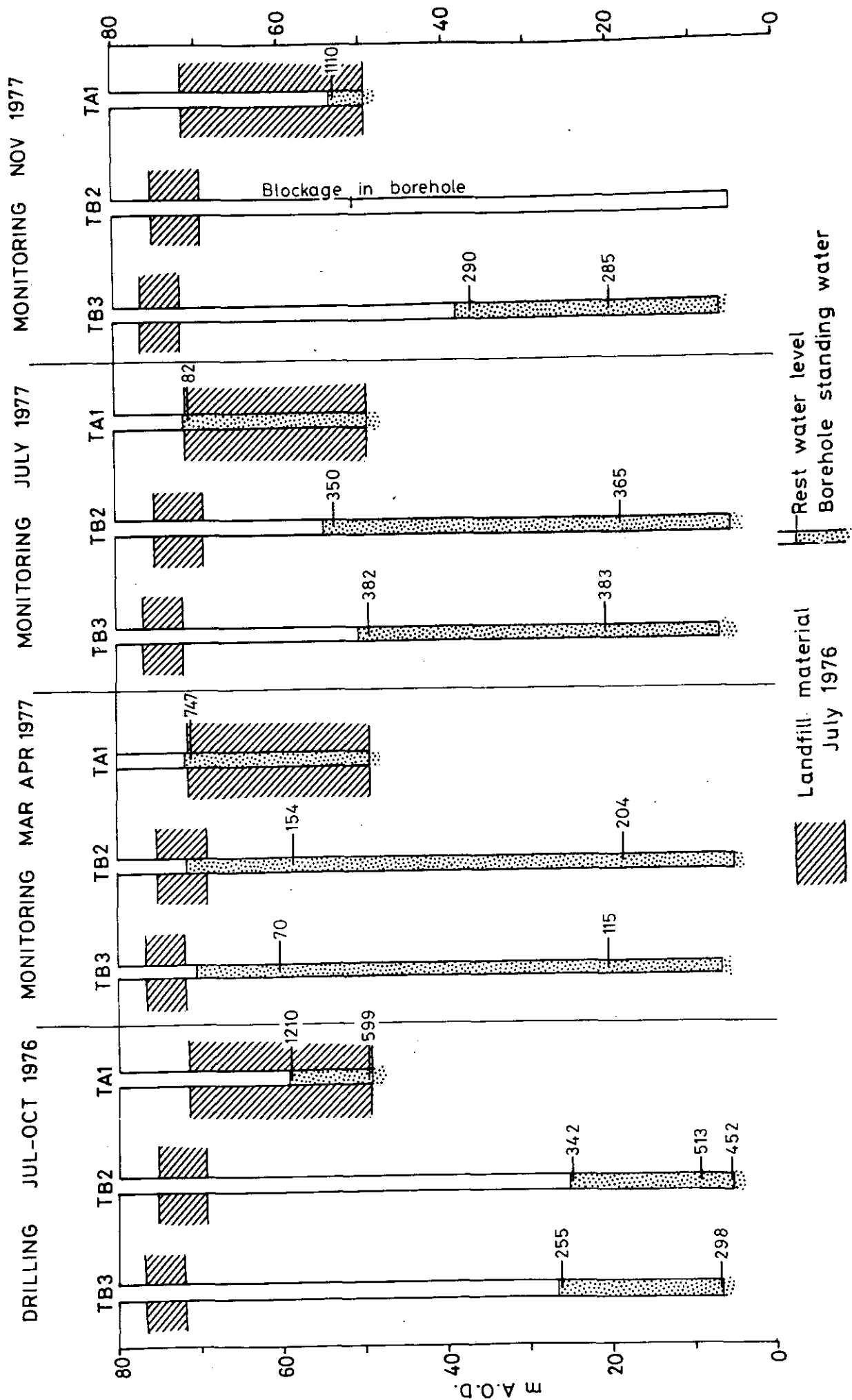
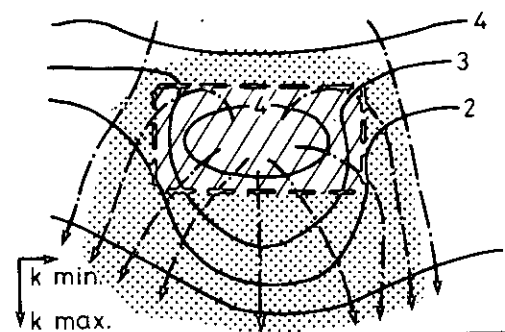
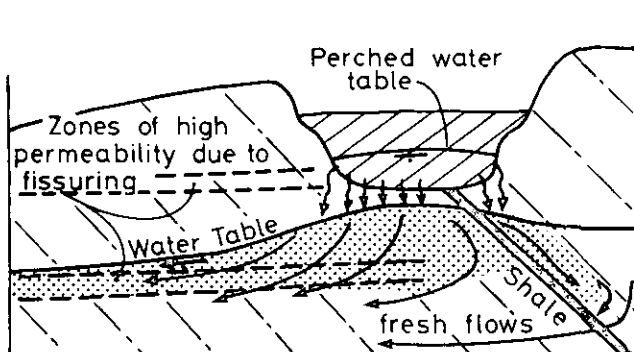


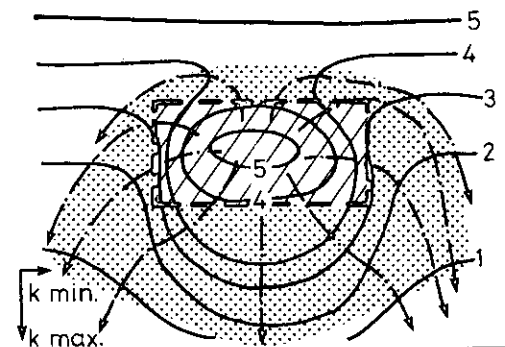
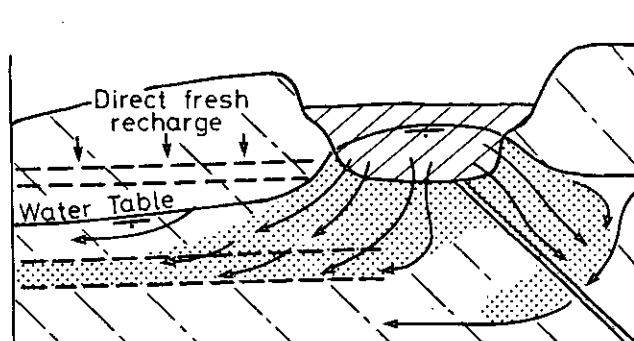
Figure 24. B. Borehole sampling at Tythegston 1976-1977. Variations in chloride concentrations (mg/l) with depth. East-West section.

SECTIONS PARALLEL TO GROUNDWATER FLOW

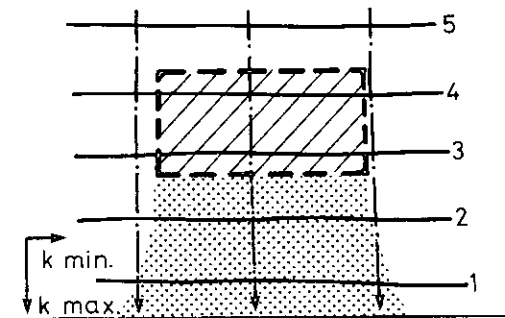
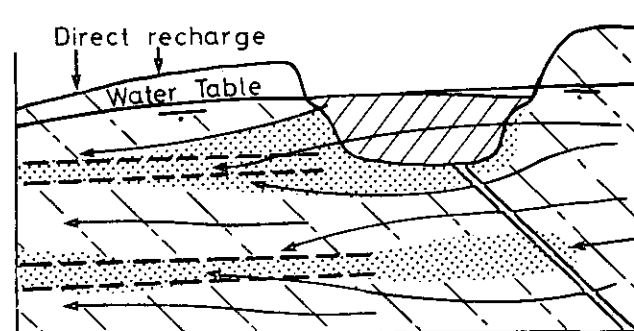
PLANS



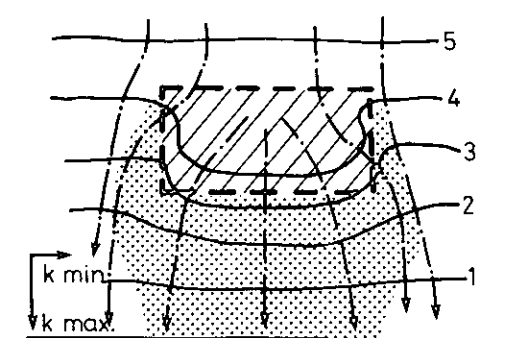
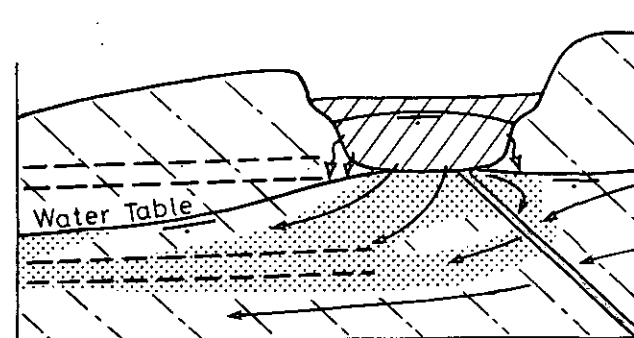
- A. Minimum groundwater level. Decaying recharge mound supported by decreasing leakage from perched water table. Lateral dispersion of leachate into groundwater. Leachate flow confined principally to upper water table and lower preferential flow zone.



- B. Rising groundwater levels. Main and perched water tables united by distinct recharge mound. Lateral dispersion due to head difference at a maximum. Main leachate flow remains in the lower preferential flow zone. Direct recharge of fresh water above contaminated zone.



- C. Maximum groundwater level. Recharge mound overwhelmed. Main leachate flow through upper preferential flow zone. Flushing of lower flow zone by fresh recharge from up-gradient. Lateral dispersion due to head differences at a minimum.



- D. Groundwater recession. Perched water again established. Recharge mound formation commences and lateral dispersion increases. Main leachate flows re-established in lower preferential flow zone.

Figure 25. Summary of postulated groundwater flow system.

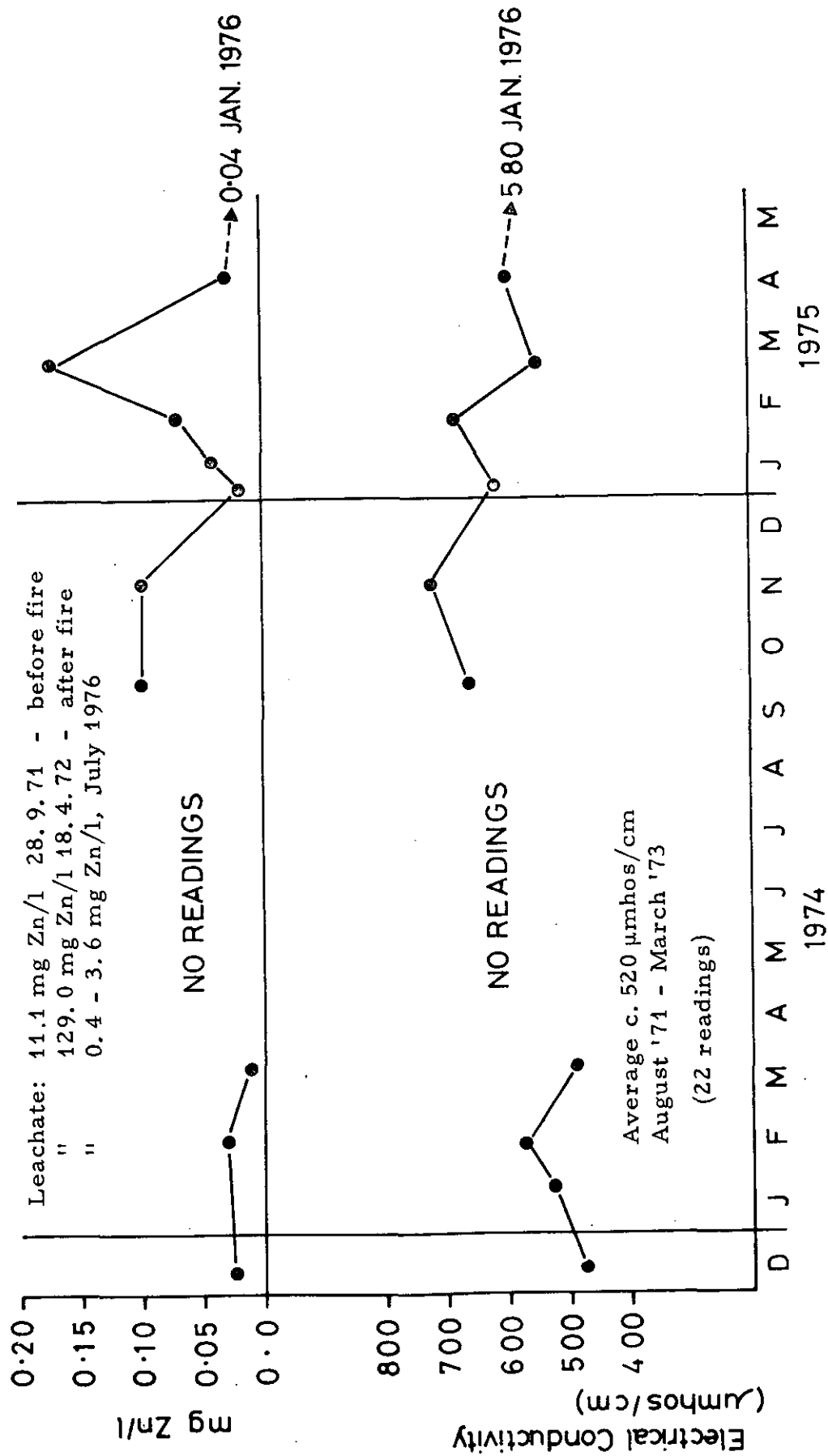


Figure 26. Variations in Zinc concentrations and electrical conductivity, Burrows Well, December 1973 to May 1975.

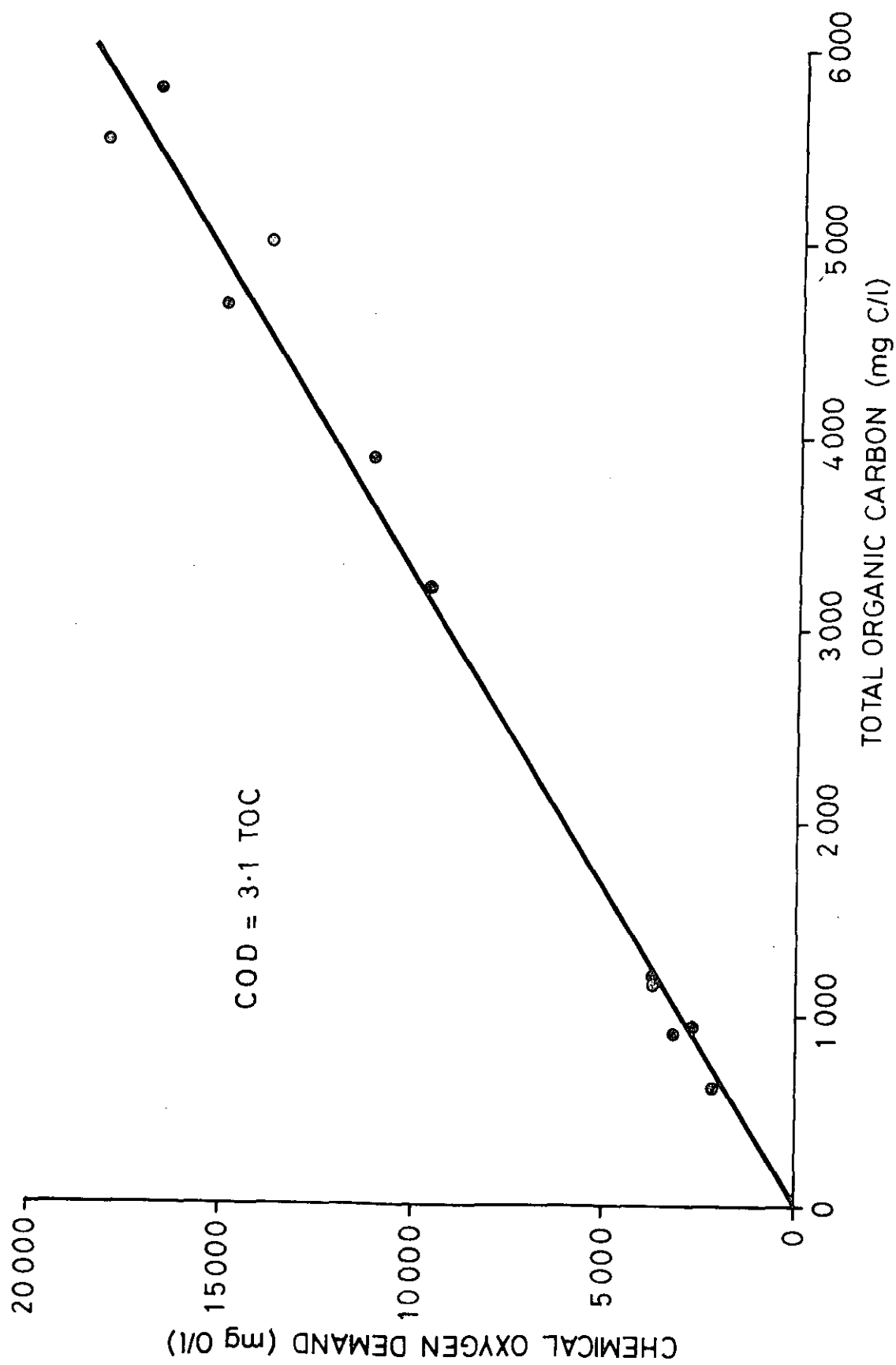


Figure 27. Correlation of COD and TOC, liquid samples from borehole TA 1.

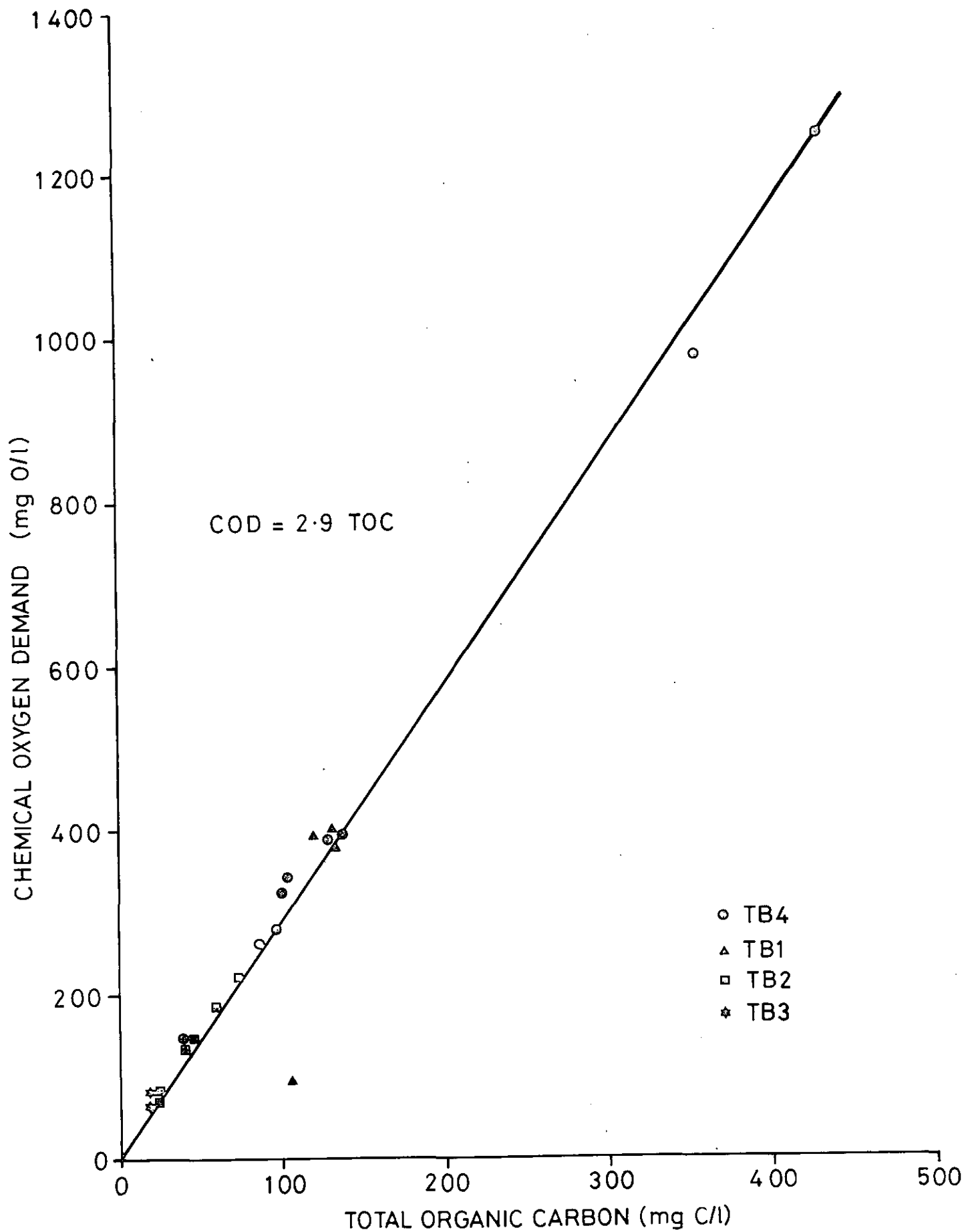


Figure 28. Correlation of COD and TOC, liquid samples from 'B' type boreholes.

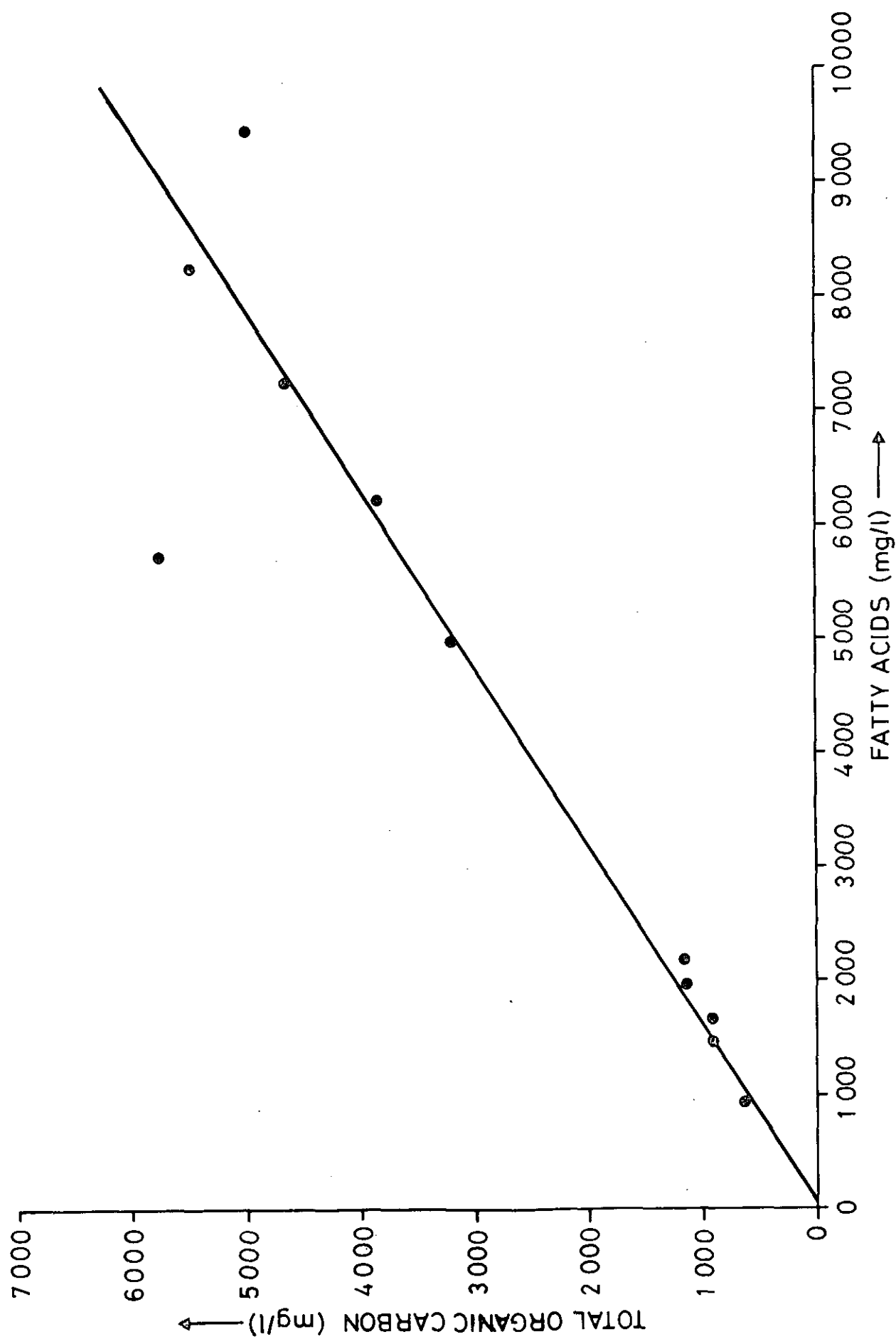


Figure 29. Correlation of TOC and Fatty Acids, standing water samples from borehole TA1.

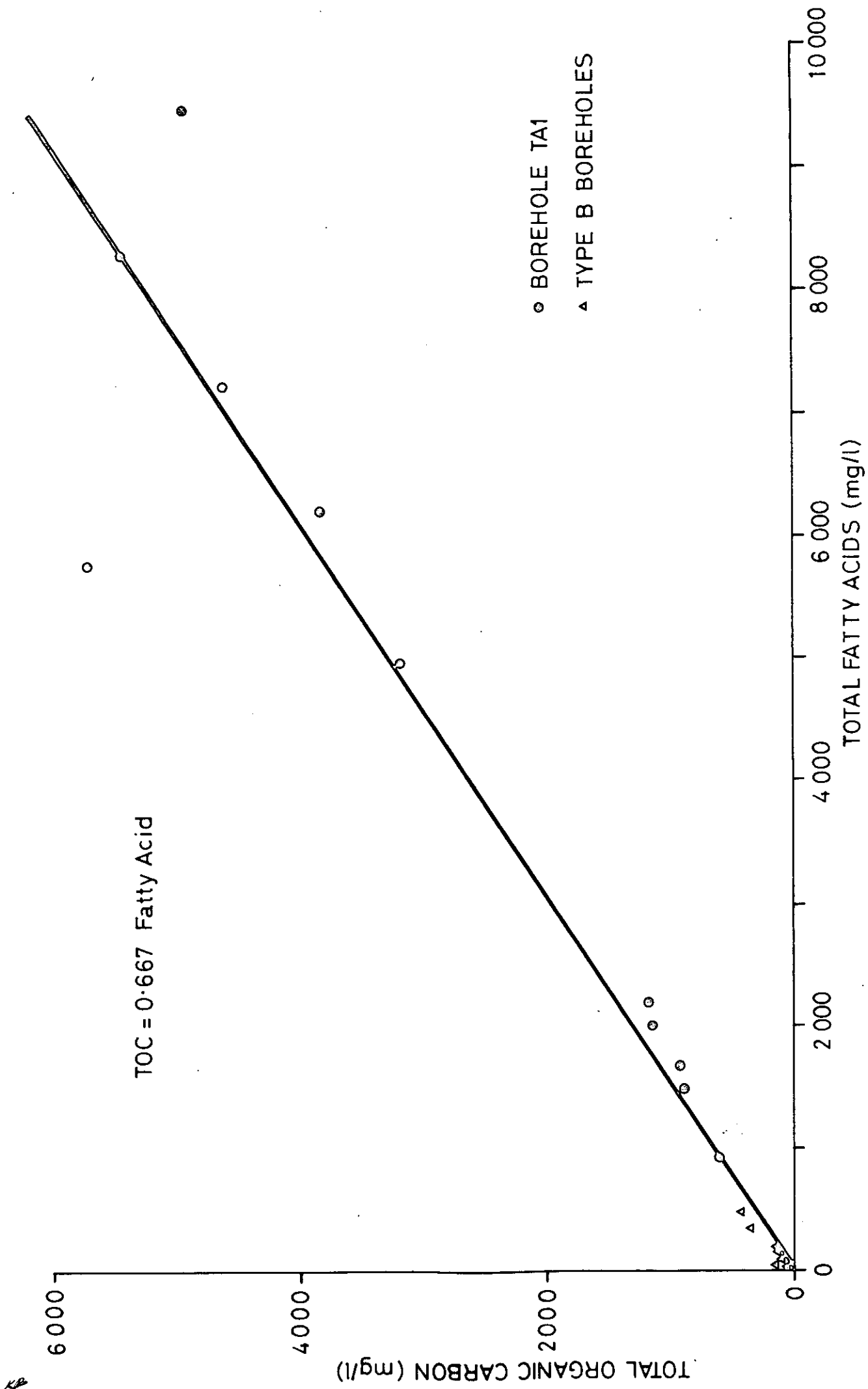


Figure 30. TOC/Total Fatty Acids relationship for Tythegeston borehole waters.