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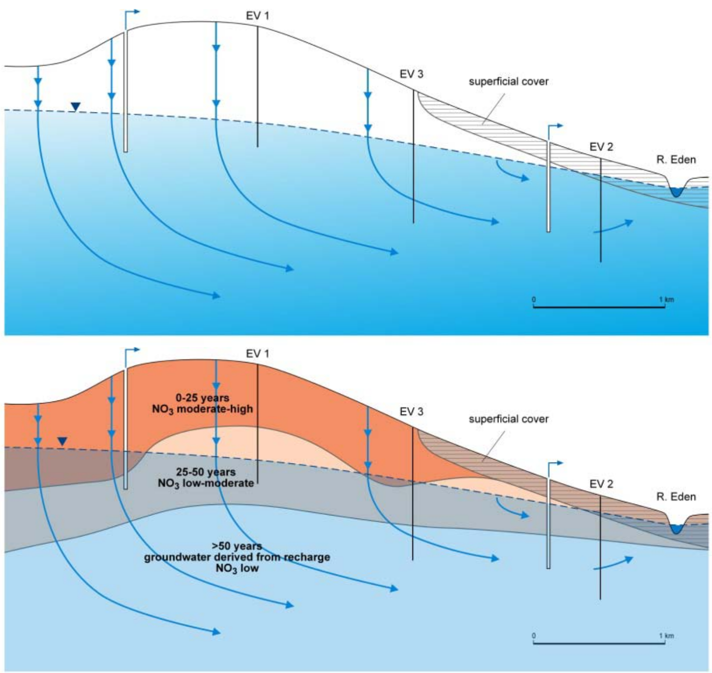
Investigation of rising nitrate concentrations in groundwater in the Eden Valley, Cumbria:

3. Saturated Zone Studies

Groundwater Systems and Water Quality
Commissioned Report OR/08/024

Environment Agency Science Group
Project SC030113



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BRITISH GEOLOGICAL SURVEY
Commissioned Report OR/08/024

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Investigation of Rising Nitrate Concentrations in Groundwater in the Eden Valley, Cumbria:

3. Saturated Zone Studies.

A. Butcher[1], A. Lawrence[1], A. Gallagher[1], S. Burke[2], J. Ingram[3], & P. Merrin[4].

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Cover illustration
View of a borehole test site in the Eden Valley west from near Penrith

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EXECUTIVE SUMMARY

This component Work Package of the Eden Valley Project was undertaken with the objective of determining the hydrogeological regime and hydrochemical stratification in selected boreholes. The subsequent aim is to apply this to better understand timescales for water movement through the saturated zone along a transect ending near to the River Eden where the Permo-Triassic sandstone aquifer is exposed or underlies thin superficial deposits.

A previous report in this series confirmed rising nitrate trends in groundwater in the study area, and suggested that with continued land use practices and with no evidence of denitrification, that this trend would continue. Another concluded that the average recharge rate is probably in the range 425-470 mm/y and the rate of water movement through the unsaturated zone is c. 3.5-3.85 m/y. Based on this estimate of water movement in the unsaturated zone, the travel time for recharge to migrate from the soil to the water table (or the delay imposed by the unsaturated zone) over most of the area where the sandstone is free of superficial deposits in the Eden Valley is c. 14 years. However if the higher fells are not considered - closer to 10 years.

Given the inherent uncertainties and limitations associated with the various methods for determining the hydrogeological regime in a boreholem, methods proposed were:

(i) to date the pore water profile within the saturated zone using CFC and SF_6 tracers

(ii) to determine the variation of aquifer properties with depth, for the matrix (using laboratory techniques) and the aquifer (using field pumping techniques).

(iii) To use groundwater models to estimate groundwater travel times in the saturated zones (this part of the project has not yet been funded).

A transect approach was adopted using existing boreholes to the east of Penrith to the Eden floodplain and addressing gaps with infill drilling. Despite early promise other boreholes (on a ‘southern’ transect) were discounted due to inaccessibility or unsuitable construction. A c. 4km transect from the east of Penrith in a north-western direction to the floodplain of the River Eden was selected starting at previously drilled project borehole.

The earlier borehole was drilled in a location where the unsaturated zone was relatively deep (c. 120 m). The second borehole, close to the floodplain was drilled to a depth of c. 90 m of which 85 m was below the water table on completion. A third borehole was drilled at a location between these two boreholes to a depth of 114 m and where the water table is c. 50 m below the surface.

Laboratory testing for core provided a range of determined porosity values of 4.4 % to 29.2 % averaging 19.4 % in EV2 and 11.7 to 32.3 % and averaging 21.1 % in EV3.

Horizontal permeability was between 0.02 mD and 18400 mD (K c.8 m/d) averaging 1340 mD in EV2 and 70 mD to 24200 mD (K c.16 m/d) and averaging 1530 mD in EV3.

Geophyscial borehole logging, BHTV and optical imaging were conducted to evaluate the geophysical properties and flow regimes and support the design of open hole and interval pump testing.

Borehole pump testing conducted on isolated intervals using packer testing suggested hydraulic conductivity up to 41 m/d and averaging 6.2 m/d in EV2 and upto 7.2 m/d and averaging 3.3 (2008 tests) in EV3.

The pumped interval water CFC/SF6 results indicated that concentrations, associated with less than 10% modern (1960 recharge), had penetrated to about 50 m depth in EV2 (at the outflow end of the study transect) and to c. 85 m depth in EV3 (the intermediate transect borehole).

1. INTRODUCTION

1.1 Project objectives

The objectives of the project 'Investigation of Rising Nitrate Concentrations in Groundwater in the Eden Valley' are to identify the causes of rising nitrate concentrations in groundwater in the Permo-Triassic sandstone aquifer of the Eden Valley area and to gain a better understanding of the groundwater and surface water flow system. This includes identifying the sources of the nitrate contamination and the processes controlling nitrate movement, so that possible management options for reversing this trend can be considered.

A previous report Work Package 1 'Catchment Water Quality Survey' concluded that diffuse pollution from agriculture is a widespread problem in the Eden Valley. There is no evidence to suggest that denitrification is a significant process in the sandstone aquifer and therefore nitrate concentrations in many boreholes will increase with time. There is no clear direct relationship between the age of the groundwater and the nitrate concentration, although there is a general trend for the older waters to have lower nitrate concentrations. There has been an increase over the past 10 to 30 years of both chloride and nitrate concentrations in pumped groundwater for most of the major abstraction boreholes. The catchment areas to most of the major abstraction boreholes have a significant fraction of cropped land (> 40%) and estimated nitrate concentrations in recharge averaged over large areas of the Eden Valley exceed current pumped nitrate concentrations. As a consequence, nitrate concentrations in many abstraction boreholes will increase with time. There are a large number of factors that influence the amount of nitrate leached to groundwater such as the history of farming practises and degree of farming intensity. This makes accurately predicting the nitrate concentration in pumped groundwater problematic. Nevertheless over a large area of the Eden Valley catchment, the nitrate concentration in recharge is estimated to be approximately 30 to 50 mg/l (as NO_3). The implication is that many of the major abstraction boreholes will eventually pump water with nitrate concentrations approaching 30 to 50 mg/l (as NO_3).

Another report in this series, Work Package 2 'Unsaturated Zone Studies' concluded that the average recharge rate is probably in the range 425-470 mm/y and the rate of water movement through the unsaturated zone is c. 3.5-3.85 m/y. Based on this estimate of water movement in the unsaturated zone, the travel time for recharge to migrate from the soil to the water table (or the delay imposed by the unsaturated zone) over most of the area where the sandstone is free of superficial deposits in the Eden Valley is c. 14 years. However if the higher fells are not considered - closer to 10 years.

The main objectives of this work package (Work Package 3) 'Saturated Zone Studies' are to determine the hydrogeological regime an hydrochemistry along a flowpath and estimate the nitrate flux in the saturated zone of the aquifer to help predict nitrate concentrations at groundwater discharge points. (e.g. abstraction boreholes, rivers).

Early Planned Work:

- Conceptualise a groundwater flow path from recharge zone to outlet (one possible flow path has been identified (Figure 5); for much of its length the sandstones are overlain by thin superficial deposits.
- Sample existing boreholes along the flow path (for nitrate, CFCs).
- Identify borehole sites and supervise drilling of two cored boreholes (to c. 100 m depth), log and sample core, extract porewaters from drilled core.
- Undertake 'packer-testing' of the boreholes to determine permeability and head distribution and water quality (including residence time indicators) with depth.
- Determine permeability/porosity of sandstone core samples (through aquifer properties laboratory testing).
- Estimate rate of groundwater flow within the sandstone (and its distribution with depth), using the Darcy flow equation (and compare with estimate from residence time indicators).
- Generate Data for a groundwater flow model using a particle-tracking program to quantify travel distances and travel times from the watertable to the discharge points. These results to

be compared with estimates using residence time indicators.

- Estimate nitrate flux in saturated zone based on the groundwater flow model and nitrate concentration depth profiles from packer-testing.
- Make completed boreholes available as monitoring boreholes
- Prepare report.

1.2 Background

The Eden Valley lies between two upland areas; the Pennines to the east and the Lake District to the west. Rainfall in the region is high and the average annual rainfall is approximately 1000 mm/y in the Eden Valley and is in excess of 1500 mm/y on adjacent higher ground. Runoff from the adjacent uplands drains to the River Eden, which flows northwards from Kirkby Stephen through Appleby and Penrith to the Carlisle Basin (Figure 1).

The Eden Valley, which is aligned approximately northwest-southeast, is 56 km long and varies in width from 5 to 15 km. The valley floor is underlain by Permo-Triassic sandstone, which forms the major aquifer in the region (Figures 2 and 3). Approximately 20% of the sandstone outcrop is free of superficial deposits. The remainder is covered by various superficial deposits, including Till (dominant), glacial sands and gravels and river alluvium (Figure 2). The superficial cover is generally thin; comprising Till deposits, less than 2m thick, which occur over 60% of the bedrock. Deposits are thicker around Appleby and also to the west of Brough where a distinctive “hummocky” topography with mounds in excess of 30m of relief can be identified (Humpage 2005). The till is variable in composition but can be surprisingly sandy and therefore potentially permeable. The water table is relatively deep over most of the Eden Valley and, in areas free of superficial deposits, virtually all the water that passes below the root zone can be assumed to continue downwards to the water table.

Groundwater in this aquifer is used by industry, for minor farm supplies and for public water supply. Much of the study area is within the Environment Agency Groundwater Management Unit 5 (River Eden from Eamont to Great Corby) where the groundwater resource availability status is classified as ‘water available’ (Environment Agency 2005).

Groundwater was first used for public water supply in the late 1960s and early 1970s, and licensed groundwater abstractions from the sandstone aquifer have not increased much since this period. In recent years, a number of private farm supplies have been drilled, although the quantities pumped are quite small.

Monitoring of abstraction boreholes in the Permo-Triassic sandstone aquifer in the Eden Valley by the Environment Agency has shown that whilst most have low nitrate concentrations, there are a significant number of boreholes where nitrate concentrations are above 20 mg/l (as NO_3) and show a rising trend. Some groundwater nitrate concentrations even exceed the EC Drinking Water Directive (80/778/EEC) maximum admissible concentration (MAC) of nitrate in potable water supplies of 50 mg NO_3/l (11.3 mg NO_3-N/l). However, there does not appear to be a systematic distribution of these higher nitrate groundwaters, the implication being that either the source of nitrate is localised (point source) or the travel times for water to move from the ground surface to the water supply boreholes are variable. Long travel times may result in current pumped groundwaters originating as infiltration from the surface prior to the intensification of agriculture (which is the most likely source of high nitrate) and thus be of low nitrate concentration.

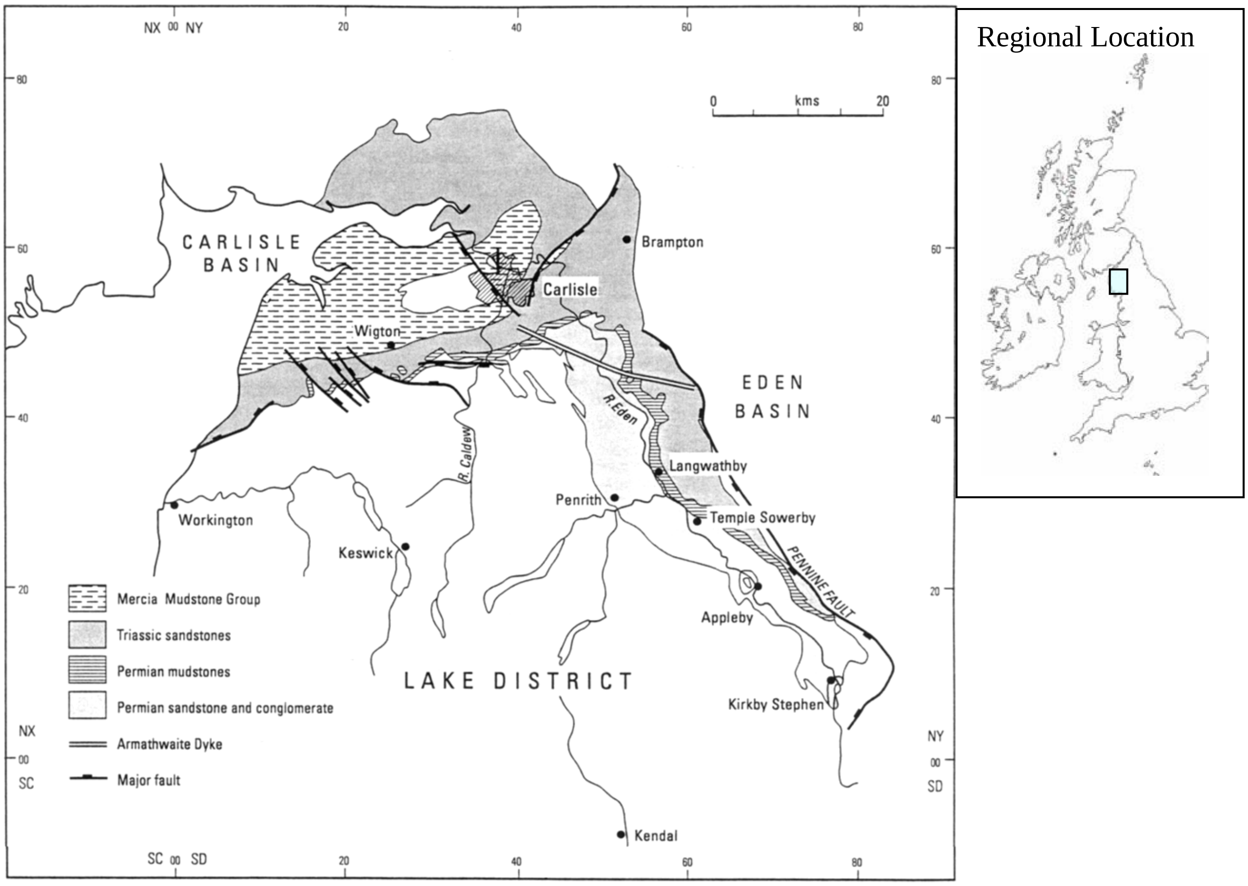


Figure 1. Location map

The Eden Valley is largely rural with a low population density of about 0.2 persons/ha. Agriculture, tourism and some industry are the major sources of income. Livestock rearing is the main agricultural activity; in recent years the improvement of grasslands, cereal cropping and higher stocking densities have resulted in greater applications of fertilisers to grassland and fodder crops. The spreading of slurry wastes on grassland has increased, sometimes contravening Codes of Good Agricultural Practice, e.g for the Protection of Water, 'The Water Code' (MAFF, 1998). Both the timing and quantities applied are more dictated by the need to dispose of the slurry than to meet the crops nutrient needs. However, within the Eden catchment there are also significant areas of semi-natural habitat including unimproved grassland and woodland.

1.3 Potential sources of groundwater nitrate

Nitrate pollution of groundwater arising from agricultural activities has increased largely as a result of the intensification of farming and the increasing use of fertilisers. The consumption of nitrogen fertilisers in the UK has increased more than six fold since 1950, whilst the total number of livestock in the UK increased from 108 million in 1940 to 188 million in 1987 (Hooda et al, 2000).

In a review of post-war changes in farming systems, (Hooda et al, 2000) describe how, because of intensified farming practices where large numbers of animals are reared on relatively small areas, the disposal of wastes (e.g. farm manure, slurry, etc.) is becoming an increasing concern. Such wastes are considered as a disposal problem rather than a useful source of plant nutrients. As a consequence, quantities of farm manure and slurry, far in excess of crop requirements, are frequently applied to soils, with storage and weather considerations often determining the timing and rate of application.

An assessment of groundwater quality beneath dairy cattle farms in California demonstrated that the most important source of groundwater nitrate was the application of manure and slurry to forage fields (rather than point sources such as slurry ponds or stores) (Harter et al, 2002). An earlier study in the UK to evaluate the risk to groundwater from unlined livestock slurry pits concluded that the contribution of nitrate from such sources was relatively small (compared with that derived from intensively cropped arable or grassland) (Gooddy et al, 2001).

In the late 1980s the DoE commissioned research to estimate rates of nitrate leaching from grassland soils overlying both the Chalk and Permo-Triassic sandstone aquifer. This research showed that for lightly fertilised grass pasture, rates of nitrate leaching to groundwater were low. However, when applications of nitrogen fertilisers exceeded 100 kg N/ha/y, then losses of nitrate from the soil to deep percolation became appreciable (Chilton and Foster, 1991). Nitrate concentrations in the porewater of the unsaturated zone beneath grass pasture receiving fertiliser applications approaching 250 kg N/ha/y were similar to, or even higher than, intensively cropped arable soils (Parker et al, 1989).

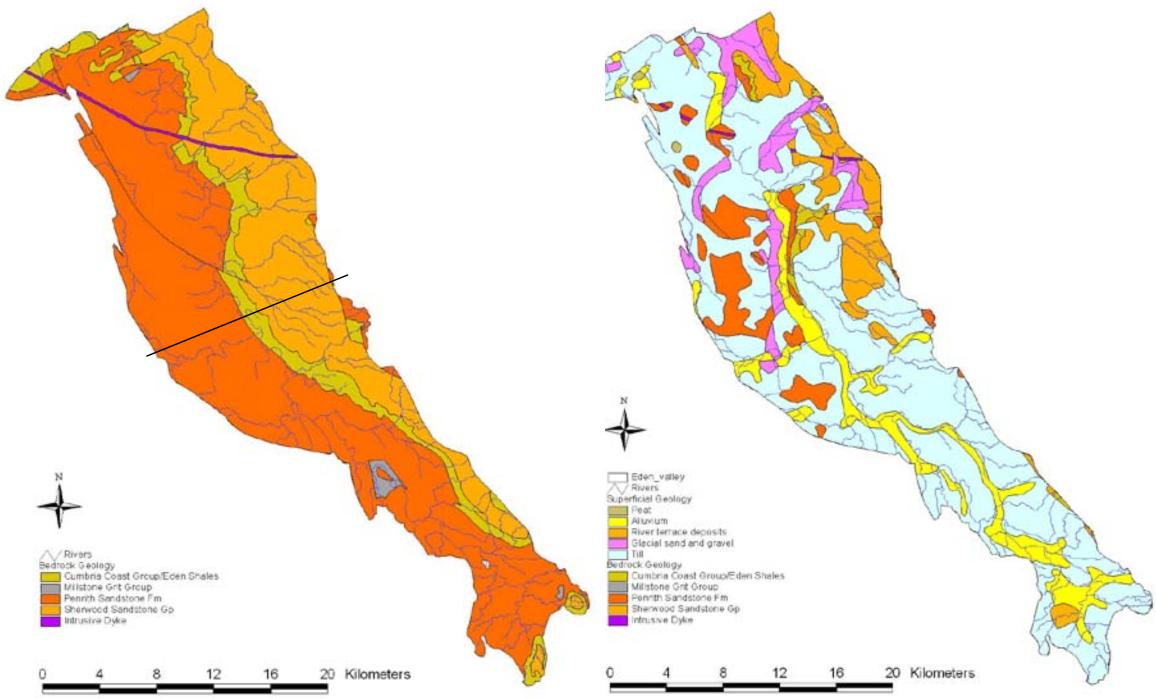


Figure 2. Bedrock and superficial geology, Eden Valley

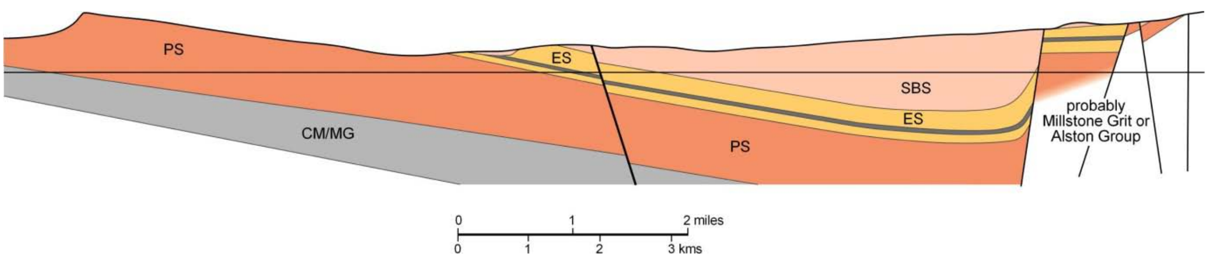


Figure 3. Geological Cross Section in Penrith area

1.4 Conceptualisation and Work Package design

Conceptualisation of the flow regime in the study area involved considering the regional peizometry, geological maps and geological cross section. Recharge, discharge and abstraction mechanisms were also considered through more permeable Superficial Deposits, thinner deposits or from a confined part of the aquifer (Figure 4).

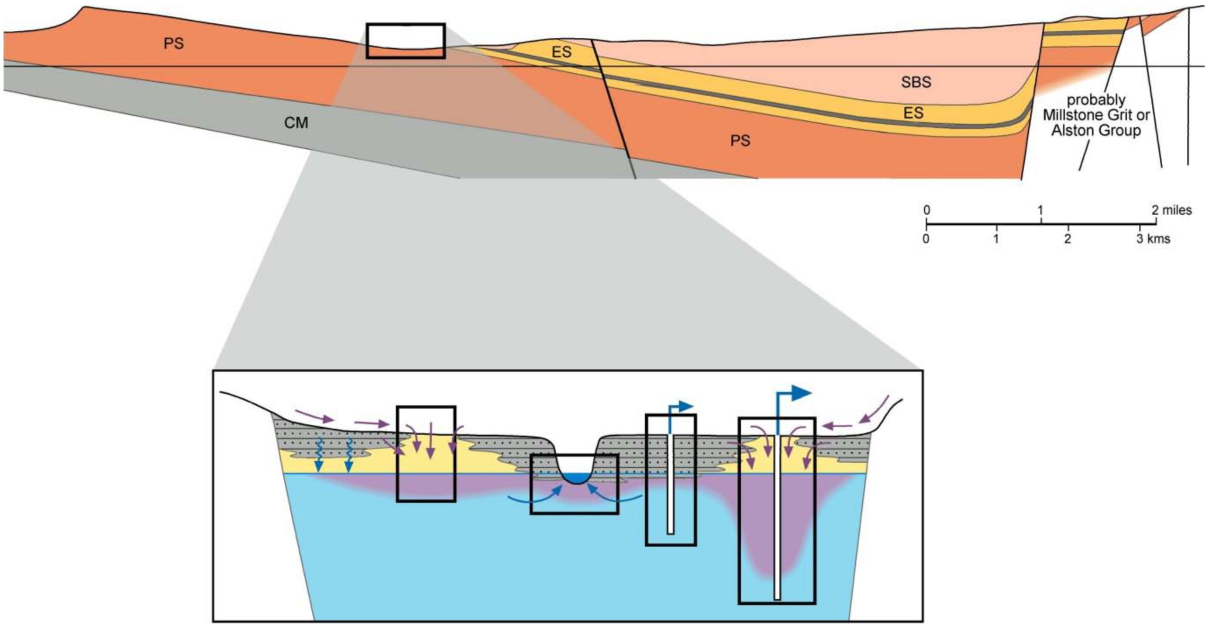


Figure 4. Conceptual groundwater flow paths adjacent to River Eden in Penrith area

A transect approach was adopted using existing boreholes to the east of Penrith to the Eden floodplain and addressing gaps with infill drilling. Despite early promise other boreholes (on a 'southern' transect) were discounted due to inaccessibility or unsuitable construction. A transect was selected subsequently starting at a previously drilled project borehole (Figure 5).

The drilling and characterisation of two boreholes were planned. The first borehole (EV2) at the edge of the floodplain of the River Eden was drilled in late 2005 and tested in 2006. Core was recovered and tested, a porewater hydrochemical profile determined and borehole geophysics and packer pump testing and sampling was conducted. The second (EV3) was located between the floodplain and site of the first borehole (EV1) drilled earlier in the study at Greengill Head Farm, approximately 4 km to the west of the Eden floodplain. Borehole EV3 was drilled in 2006 and tested in 2006 and again in 2008. Core was recovered and tested to determine physical properties and sampled for analysis of the porewater hydrochemistry. Geophysical borehole logging, imaging and packer pump testing were also conducted.

A conceptual section was created (Figure 6). The objective was the attribution of hydrogeological properties to this section, to determine the hydrogeological regime and the hydrochemical profile in the saturated zone of the boreholes.

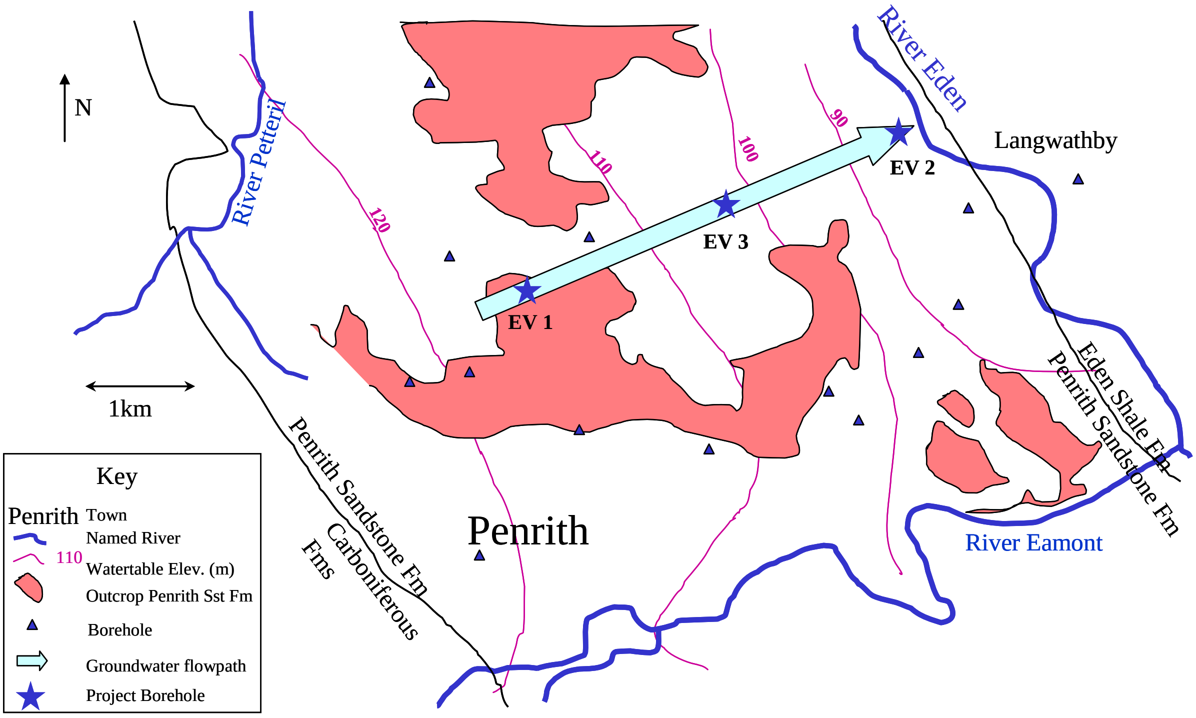


Figure 5. Conceptual groundwater flow path transect in Penrith area

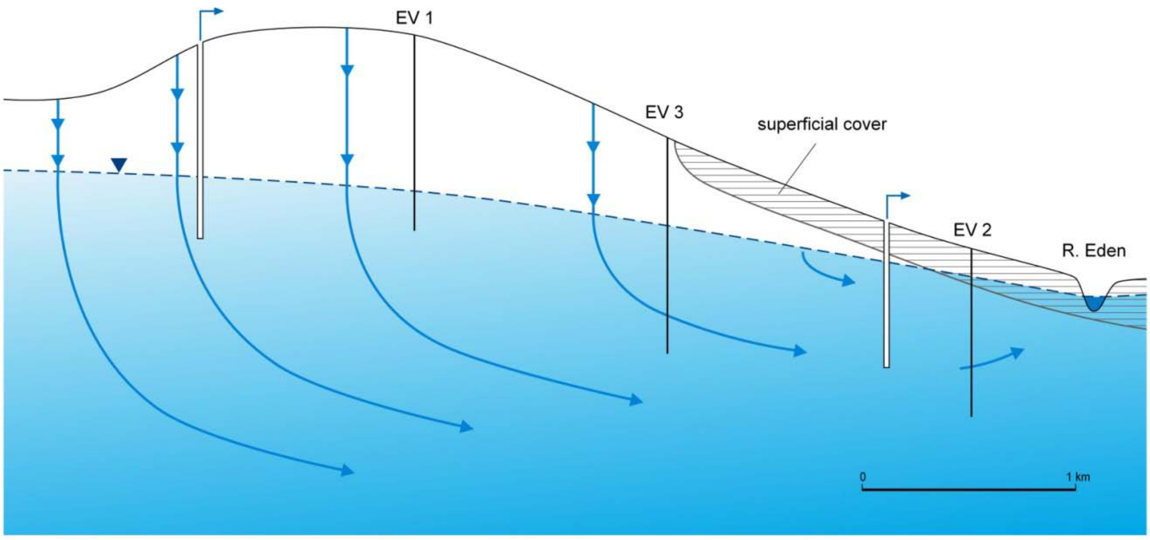


Figure 6. Conceptual groundwater flow path transect in Penrith area with project boreholes.

2. METHODS

2.1 Core drilling and testing

2.1.1 Field programme

The purpose of the drilling was to obtain core with as little disturbance as possible. This core was sub-sampled to a prioritised regime (Table 1) to obtain pore water chemistry (major ions, including nitrate and chloride), the physical characteristics of the rock (porosity and permeability) and fracture characteristics.

Rotary coring using airflush was selected as the preferred drilling method to ensure minimum contamination of the pore waters in the rock core. For both EV2 and EV3 boreholes a Knebel drilling rig with a wireline 'Geobor S' coring system was used. Where drilling could only proceed with the addition of a fluid, a water-mist was used. This occurred only in the strongest sandstones but nevertheless required five diamond core drilling bits for EV2 and two for EV3. Samples of the water were taken for chemical analysis to help identify depth intervals where the pore waters might have been contaminated. The use of water mist for drilling was kept to a minimum.

EV2 'Salkeld Road Borehole' (Langwathby) NY 55404 34281

Drilling started in October 2005 following site clearance and the development of a 'bund' to prevent water drainage off the site. It was estimated that a thickness of c. 10 m of superficial deposits comprising glacial sands and gravels would be encountered at the drillsite. In fact the site was also underlain by cobbles and boulders up to 40 cm long which could not be returned to the surface with the rotary drilling rig. A percussion rig was introduced to drill these strata and to establish temporary 200mm diameter casing to a depth of c. 13 m bgl. Drilling then continued successfully down to a depth of 89.2 m below casing top (bct): the total length of core recovered was from 12.9 to 89m bct. A fire destroyed the drilling rig and it and the drilling rods were removed.

The standing water level on completion was 5.34 m below datum (taken as temporary casing top, c. 0.3m above ground level). On periodic measurement over the course of two years this ranged from 5.3 to 5.47 mbct. Surface elevation was c. 93 m OD taken from spot heights and map contors. Photographs in Figures 7 to 14 detail site activities and the borehole completion.

EV3 'Edenhall Grange Borehole' (Maidenhill Nr Penrith) NY 54598 33146

Drilling commenced in November 2006 and continued successfully down through c. 4m of till cover and then through sandstone to a depth of 114.5 m bct. The total length of core recovered was from 40 m to 114 m bct. Three separate cores of 2 m length drilled at depths of c. 10, 20 and 30 m were also taken.

The water table was encountered at a depth of 49.5 m bct. On periodic measurement over the course of two years this ranged from 49.3 to 50.05 mbct (temporary datum 0.35m above ground level). Surface elevation was c. 154 m OD taken from spot heights and map contors.

Photographs in Figures 15 to 22 capture site activities and the borehole completion.

Core handling

The diameter of the cores recovered from both sites was c. 96 mm which provided sufficient pore water (by centrifugation) to satisfy laboratory requirements (c. 2 ml per cm of core length). The core was obtained using 'Geobore S' 102mm core barrel with pvc sleeve lining.

The core was geologically logged at BGS Wallingford conforming to British Standard 5930: Code of Practice for site investigations, (British Standards Institution 1999). Lithology, fractures and colour were noted with percentage core recovery.

The core was then sub-sampled, as described in Table 1. Samples for physical characterisation were selected and sealed in labelled plastic bags

Samples for moisture content determinations were sub-sampled, weighed, crushed and placed in an oven for a minimum of 24 hours prior to re-weighing. Moisture content was expressed as the weight of water per weight of wet rock and dry rock. This could be converted to moisture content per unit volume of wet rock and dry rock.

Samples of core for porewater major ion analysis were selected and the outer edges of the core, which are more susceptible to disturbance/contamination, were removed. The inner portion of the core was crushed, weighed and packed into centrifuge cups. These were then placed in a Beckman J2 21 high speed centrifuge and spun at 14,000 rpm for 40 minutes. The centrifuged porewater samples were filtered, pH, SEC and HCO_3 were determined and then samples were split for subsequent analyses with a proportion acidified by 1% nitric acid and then the samples were collated for laboratory analyses.

2.1.2 Physical characterisation

Samples selected for physical characterisation were sub-sampled by drilling c. 25mm diameter core plugs in vertical and horizontal orientations. These were oven dried for a minimum of 24 hours prior to testing for porosity, vertical- and horizontal-permeability.

Permeability

Gas permeability tests were performed on samples under steady-state conditions using a pressurised coreholder. A full description of the methodology and discussion of the correlation between gas and liquid permeability in sandstones can be found in Bloomfield and Williams (1995).

In the standard test, samples are constrained in a core holder and a pressure-regulated supply of nitrogen gas was applied to one end of the sample (the downstream end of the sample was held at atmospheric pressure). A soap-foam flow meter was used to measure the outflow of nitrogen from the downstream end of the sample. Gas permeability was calculated using the measured sample dimensions, differential pressure, and the steady-state gas flow rate as follows:

$$k_g = \mu\, Q\, L\, P_o/[A\,(P_i^2 - P_o^2)]$$

where k_g is gas permeability, μ is gas viscosity, Q is the volumetric gas flow rate measured at atmospheric pressure, L and A are the sample length and area respectively, P_o is the downstream (atmospheric) pressure, and P_i is given by $P_i = P_o + P_g$, where P_g is the absolute pressure of the regulated nitrogen permeant. The effective errors associated with the gas permeability measurements are about +/- 2.5% of measured sample permeability.

Porosity

Porosity (and bulk and grain density) were measured using a liquid resaturation method based on the Archimedes principal. The methodology is described in detail in Bloomfield et al. (1995). A sample to be tested is weighed and then placed in a resaturation jar. The jar is evacuated then flooded with propanol. Propanol is used as it is relatively inert with respect to the core and reduces the potential for swelling clays to modify the porosity during testing. The sample is allowed to saturate for at least 24 hours. The saturated sample is then weighed, firstly immersed in the propanol and then, still saturated with propanol, in air. For each sample its dry weight (w), its propanol saturated weight in air (S_1) and its saturated weight immersed in propanol (S_2) are recorded, in addition the density of the propanol (ρ_f) is noted. From these values sample dry bulk density (ρ_b), grain density (ρ_g) and effective porosity (ϕ) can be calculated as follows:

$$\rho_b = (w\rho_f)/(S_1 - S_2)\ \mathrm{g\ cm^{-3}}$$

$$\rho_g = (w\rho_f)/(w - S_2)\ \mathrm{g\ cm^{-3}}$$

$$\phi = (S_1 - w)/(S_1 - S_2)$$

The effective errors on the porosity measurements are approximately ± 0.5 porosity percent.

Data is presented as depth profiles of physical characteristics and crossplots.

Figure 7. EV2: drillsite, preparing retaining bund prior to drilling.

Figure 8. EV2: drillsite looking east over Eden Valley floodplain towards Pennine uplands.

Figure 9. EV2: rig during drilling.

Figure 10. EV2: starting core drilling.

Figure 11. EV2: rig damage following fire

Figure 12. EV2: geophysical logging

Figure 13. EV2: lowering packer test string

Figure 14. EV2: completed borehole

Figure 15. EV3: drillsite airlifting

Figure 16. EV3: drillsite.

Figure 17. EV3: major flow below 100m.

Figure 18. EV3: packer testing.

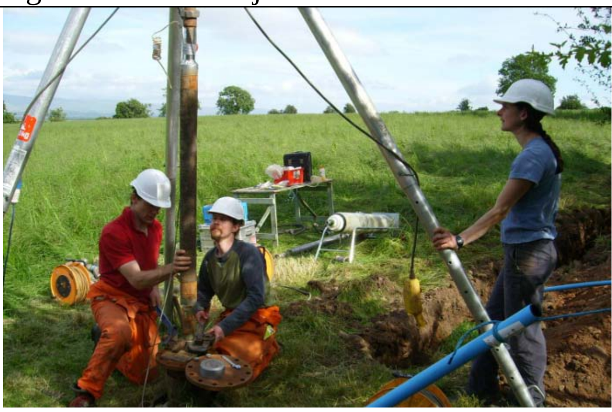


Figure 19. EV3: site lowering packer string

Figure 20. EV3: packers inflated and deflated.

Figure 21. EV3: pumping test headworks

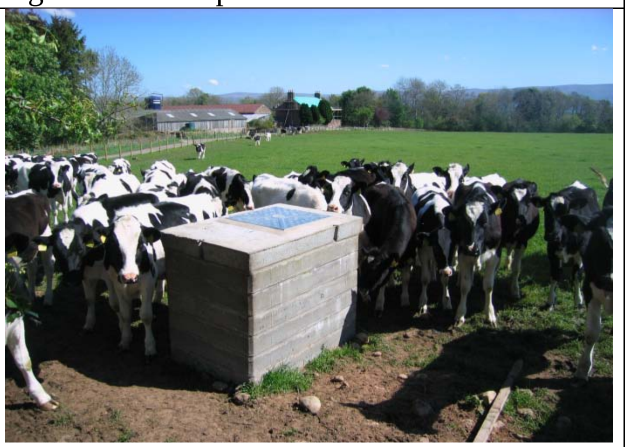


Figure 22. EV3: completed borehole.

Table 1. Sampling regime for drilled core

PRIORITY	REQUIREMENT	SAMPLING INTERVAL	SAMPLE SIZE	SAMPLE HANDLING
1	Centrifuging of porewater	Every metre on the metre. Extra samples at obvious changes in lithology	Sufficient to provide required amount of porewater (see table above), dependant on saturation	Process as soon as possible. Store pending samples (bagged and heat sealed) in fridge until processed. Return residue to core run.
2	Moisture content	As above, plus extra samples to cover range of lithologies	Regular = c.100 gm Extra = c.30gm lump from uncentrifuged sample	As above
3	Aquifer Properties	Every 2m from GL to TD	Stick of core c.0.30-0.50m long	Store (bagged, heat sealed or taped) until transported to Wallingford
4	"Alternate samples"	Every 2m from GL to TD, alternating with AP samples above	Stick of core c.0.30-0.50m long	Store (bagged, heat sealed or taped) until transported to Wallingford
5	"Additional detailed sampling"	Three to be chosen between (say): 10 and 20m 60 and 70m 100 and 120m	Complete c.2m between centrifuge samples.	Store (bagged and heat sealed) in fridge until transported to Wallingford
6	Geochemical Samples	Selected number – to be advised	Can be spun residue from centrifuging	Store (bagged and heat sealed).

2.2 Geophysical testing and imaging

2.2.1 Introduction

The aim of this part of the field testing was to use borehole geophysical techniques to indentify structural features and inflows in order to target the pump testing and sampling regime. At the start of the drilling programme BGS operated a downhole CCTV system. Subsequently, optical and acoustic imaging sondes were commissioned. Optical imagery was interpreted as part of the project.

The aim of the fluid and flowmeter logging was to identify the position of the water inflows and to quantify their contribution to the total yield. Water samples were collected from the pump discharge (bulk sample) and from selected depths determined by interpretation of the fluid log profiles (usually from just above significant inflows) for chemical analysis determination and to examine chemical variation with depth.

The fluid logging measurements were processed and compiled into composite fluid-plots to display the pumped fluid and flowmeter profiles alongside the stratigraphy and the Formation logs.

For the logging of borehole EV2 the submersible pump was placed within the blank casing so that the fluid log profiles represented water moving up to the pump from below. In borehole EV3 the pump was placed in an open-hole section

The flowmeter profiles shown represents the pumping velocity profile minus the pre-pumping profile multiplied by the cross-section area of the borehole. It represents the net effect of pumping presented as an area-corrected cumulative flow rate curve. It gives the flow rate at all depths moving up the pump where it usually matches or is close to the flow rate measured at the surface.

The form of the flowmeter curve indicates the nature of the flow delivery from the rock. In fractured aquifers the flow (and EC/TEMP) profiles are usually stepped reflecting inflows from specific fractured zones, whereas in intergranular aquifers the flow profiles usually display a gradual upward increasing slope supported by intergranular contribution. This latter is suggested by the profile in Figure 29.

2.2.2 Caliper

The caliper probe provides a continuous record of the diameter of the borehole and its casing. It is lowered to the bottom of the hole closed, then opened remotely and the measurements are recorded on the run up to the surface. The caliper used was a Geovista Ltd 2-arm caliper. Caliper probes may have 2, 3 or 4 arms either linked or independent.

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

2.2.3 Natural Gamma

The gamma ray measurements were recorded with a natural gamma ray probe which records the total gamma ray activity within the borehole as a count rate in counts/second received by the detector. It has no radioactive source attached and is simply a crystal detector. Gamma rays are emitted by rocks containing natural radioactive minerals. The natural radioactive elements responsible are potassium (K^{40}) uranium (U^{238}), and thorium (Th^{232}). In clastic sediments these elements preferentially adsorb to finer grained material and relatively high gamma activity is associated with clays. However, potassium, uranium, and thorium are present in the crystalline lattice of igneous deposits that may, therefore, be associated with very high gamma ray activity. The gamma ray log can be run in any borehole and provides a measurement of total gamma ray activity above and below fluid level, through steel or plastic casing.

2.2.4 Focussed resistivity or 'Dual Latero-Log'

The focussed resistivity sonde, also known as the LateroLog directly measures a deep and shallow resistivity of the formation, hence the 'dual'. The resolution of the instrument is 10 cm, which is equivalent to the distance between the central two guard electrodes that ‘focus’ current generated by the current electrode. This current returns to a receiver electrode on the tool itself to provide the shallow measurement, and via the cable above the bridle (10 m of rubber-insulated cable) to provide the deep measurement. The tool is very reliable even in very high resistivity strata where the induction-conductivity sonde is less accurate. However, the bridle must be submerged in an uncased borehole for a measurement to be recorded. Measurement of formation resistivity, therefore, starts approximately 10 m below the base of casing or the water table depending on which is deepest.

2.2.5 Fluid Temperature & Fluid Electrical Conductivity

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

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

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

2.2.6 Impeller Flow-meter

Impeller flowmeter probes can be used on their own, in combination with other sondes. Different size impeller cages can be interchanged to suit different pipe or borehole diameters. An adapter is available to run this sonde in series with a Temperature & Conductivity sonde. The combination with a Temperature & Conductivity sonde is particularly useful during pumping tests.

2.2.7 Heat-pulse Flow-meter

This flow-meter works by detecting a pulse of heat released from a heating grid at an upper or lower thermistor. It is capable of detecting down-flow greater than 9 m/hr and up-flow greater than 5 m/hr.

2.2.8 Optical imaging

The optical image scans were recorded using the Electromind OPTV sonde, which provides a continuous 360 degrees image of the borehole wall exportable in JPEG, BMP or TIFF format with a resolution of less than 1 mm above water or in clear fluid. This high quality output is orientated north-south, and may, therefore, be used for detailed structural, lithological and sedimentary surveys. Best results are achieved when the sonde is well centralised. Any number of features represent by sinusoidal curves can be interactively selected (picked) recording azimuth and dip values. Each pick can be qualified into user definable categories such as bedding, fractures, mineral veins etc. Picks can be displayed as sinusoidal, tadpole or stick plots. Fully interactive structure interpretation can follow where data are displayed using Wulff (equal angle) polar plots and Azimuth Count Rose diagrams for selected borehole intervals. Statistical outputs can alo be presented on plots.

The data is presented as depth profiles of geophysical characteristics, interpreted imagery and borehole cctv images.

2.3 Groundwater quality

2.3.1 Laboratory programme

Water chemistry

Porewater concentrations of Cl, NO_2-N, TON and NH_4-N were determined by automated colourimetry using a Skalar SAN^{++} Analyzer. The samples were filtered through a 0.45 µm filter but were not acidified.

Testing of pH, HCO3 and SEC was conducted using laboratory metres and titration immediately following porewater extraction by centrifuge.

Inductively-Coupled Plasma Optical Emission Spectroscopy (ICP-OES) was used to determine 27 analytes (Table 2). Total concentrations of each element are determined irrespective of different oxidation states. Concentration ranges and detection limits vary for different elements and analyte wavelengths vary with concentration. Samples were acidified with 1 % nitric acid prior to analysis and a minimum volume of 20 ml is usually required for routine analysis. In exceptional circumstances, such as with low volume pore-waters, 5-10 ml is adequate.

Some samples were also analysed by ion chromatography to establish whether all the sulphur determined by the ICP-OES method is attributable to the sulphate ion.

Table 2. Analytes for EV2 and EV3 boreholes porewater samples hydrochemical analysis

Determinands	**Test Method**
Determination of the major and minor cations (27 elements: Ca, K, Mg, Na, S (as SO_4, Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, La, Li, Mn, Mo, Ni, P, Pb, Si, Sr, V, Y and Zn	ICP-OES
Determination of major anions Cl, SO_4, NO_3, NO_2, F, HPO_4	Ion chromatography
Determination of inorganic nitrogen species	Automated colorimetry
Total iodide	Colorimetry analysis
Dissolved organic carbon	OC analyser

The data are presented as summary tables and water quality profiles with depth.

2.4 Interval pump testing

Borehole packers are expanding plugs that can be used to seal and isolate a section of a borehole. The packer system used in the EV2 and EV3 boreholes is a modified and upgraded version of that described by Price and Williams (1993). This incorporates a pump to abstract water from the isolated section between two packers, and a datalogging transducer to measure the pressure within the section. This system allows measurements to be made of the permeability (hydraulic conductivity) of the isolated section and the head within the section. This latter measurement means that a profile can be determined of the natural head within the formation, undisturbed by vertical flow within the borehole. When the packers are inflated, isolating a section of the aquifer from the borehole, the water level in both the isolated interval and the section of borehole above the interval may change from that which was measured in the open hole.

The water level in an open borehole represents a ‘weighted average’ of the head at the different depths penetrated by the hole. The ‘average’ is weighted by the permeability of the different contributing horizons.

For example, if there are two contributing layers A and B of the same thickness with permeabilities of K_A and K_B, and heads of H_A and H_B, the open borehole head (H_O) will be given by:

$$H_O = \frac{K_A H_A - K_B H_B}{K_A - K_B}$$

The head within the aquifer at any depth changes with time. What is measured with a packer system is a ‘relative head change’. Within a section this is recorded as the change in water level which occurs in that section when it is isolated. If the interval has a lower head than that present in the borehole then a negative change is noted. The implication of a negative change is that when the packers are not present, water will flow from the borehole into the formation. The rate of this flow can be calculated as the permeability of the isolated section will have been measured during the subsequent packer test (flow rate is proportional to the permeability and the head difference).

Once the packers have inflated isolating the section to be tested, water is pumped out of the isolated interval at a constant rate. The head in the section is monitored and recorded using the transducer and pumping is continued until a steady-state drawdown is measured. This usually takes no more than 30 minutes. Where possible the pumping rate is then increased and the head monitored using a transducer link to a laptop computer until a new steady-state is reached. The rate is then decreased and a further steady-state achieved. Ideally the permeability calculated for each of these tests will be similar enough for confidence to be placed in the test. After this the packers are deflated and lowered to a new interval. This whole process takes at least two hours (depending on how many pumping rates are used and how long it takes to achieve steady-state) which means that it is difficult to carry out more than three tests in a day.

The calliper logs conducted during geophysical borehole logging are shown in Figure 27. These were used to check that the borehole was of suitable diameter for testing and to select intervals for packer testing. Because boreholes were drilled using a coring method which leaves relatively smooth and uniform borehole surfaces it was not necessary to undertake any additional cutting (reaming) before testing.

Thirty-six intervals were tested in the two boreholes. Sampling for interval water quality and residence time was conducted during the packer pump testing.

The data are presented as summary tables and interval permeability profiles with depth.

2.5 Groundwater residence time

2.5.1 CFCs and groundwater residence time

Samples for CFCs and SF_6 were collected without atmospheric contact and stored in glass bottles within water filled metal tins. Analysis was performed by 'purge-and-trap' gas chromatography at BGS Wallingford.

CFCs can be used to date groundwaters within the past 50 years to a resolution of ±5 years. Concentrations of CFCs have been increasing in the atmosphere at known rates since they began to be used in industrial processes (CFC-12 in the 1930s, CFC-11 in the 1950s). Recharging rainfall contains CFCs dissolved in proportion to the atmospheric concentration at the time of the event. In general the CFCs behave in a conservative way during travel in the subsurface. They, therefore, have the potential to act as indicators of the time elapsed since recharge, in other words the groundwater 'age'.

CFC results can be interpreted in two main ways: either as a bulk age, which assumes that groundwater moves by a piston flow mechanism, or in terms of mixing. In the latter case a simple mixing between 'old' groundwater (> 50 years old) and 'modern' recharge (within the past few years) is often assumed for simplicity. The latter interpretation is usually preferred for fractured aquifers as they are considered more likely to promote mixing than simple intergranular flow.

The residence time of the groundwater is linked to a number of factors, including the depth of the borehole, the thickness of superficial deposits and the thickness of the unsaturated zone. Generally, younger groundwater would have a higher nitrate concentration due to an increase in the intensity of agricultural practises during the last 30+ years. Older groundwaters are more likely to have lower nitrate concentrations as they were mostly recharged prior to the intensification of agriculture. However, partly because the change in land use from unimproved grassland to improved grassland probably occurred over a considerable period (and is likely to vary from farm to farm) and partly because the intensity of farming will vary within the catchment at any specific time, the data are only likely to show broad trends between the age of the groundwater and the nitrate and chloride concentrations.

The data are presented as summary tables, residence 'bow diagrams' and water residence time profiles with depth.

3. RESULTS

3.1 Core drilling and testing

3.1.1 Lithology

EV2

Core recovery of bedrock was generally good (c. 95%); the core consisted of very hard re-cemented sandstone from a depth of c. 13 m to a depth of 25 m. Below that relatively uniform moderately strong to very strong, dark red, well-sorted, well-rounded, medium- to coarse-grained sandstones. Exceptions were observed and these include silt bands and more cemented sandstones and mineralised or bleached structural features (possibly hydrothermally altered) but these made up a relatively small proportion of the total core recovered. The sandstones exhibited dune cross bedding typical of aeolian sandstone.

EV3

Core recovery was generally good (c. 95%); the core consisted of relatively uniform moderately strong to very strong, dark red, well-sorted, well-rounded, medium- to coarse-grained sandstones. Noteable structural features include open sub-vertical joints extending 5 m into the unsaturated part of the borehole and healed high angle fractures/joints in the saturated zone. The sandstones exhibited dune cross bedding typical of aeolian sandstone.

3.1.2 Moisture Content

EV2

Minor water strikes were encountered in mixed Glacial Sands and Gravels and especially at the base of these superficial deposits to c. 16.8 mbct. The moisture content of the sandstones, expressed as weight of pore water per unit weight of wet core was not routinely determined in the very strong sandstone from c. 13 m to c. 25 m but more so in the confined underlying sandstone. . The main water strike was encountered at 25m and water level rose to c. 5.4 m on completion of drilling at a depth of 89m. In the sandstone below 25 m, moisture content ranged from 3.7 to 12.3 % averaging 8.1% by wet weight.

Obvious differences were observed in lithology (and/or degree of cementation) impacting on moisture content.

EV3

The moisture content of the sandstones, expressed as weight of pore water per unit weight of wet core was in the range 1.8 to 5.7 % in the unsaturated zone (above 50 mbct) and 2.3 to 8.25 in the saturated zone.

Moisture content can also be expressed by unit volume (volume of pore water per unit volume of wet core) as mentioned earlier. The estimated moisture content, in the depth interval from 0-49 m, averaged 12.6%. by volume.

As with borehole EV2, differences were observed in lithology (and/or degree of cementation) impacting on moisture content.

3.1.3 Permeability and Porosity

Porosity and permeability results based on the laboratory testing of rock plugs (Tables 3 and 4) are consistent with previous results for Permo-Triassic sandstones in the Eden Valley (Allen et al. 1997).
A c. 10m thick silicified sandstone layer at the contact with the superficial deposits in EV2 exhibited low matrix permeability and porosity. Samples with the highest matric permeability/hydraulic conductivity were coarse-grained, semi-friable sandstones exhibiting close to the theoretical maximum limit for reliable testing using the gas permeameter method. Crossplots in Figures 23 and 24 show similar porosity and hydraulic

conductivity ranges.

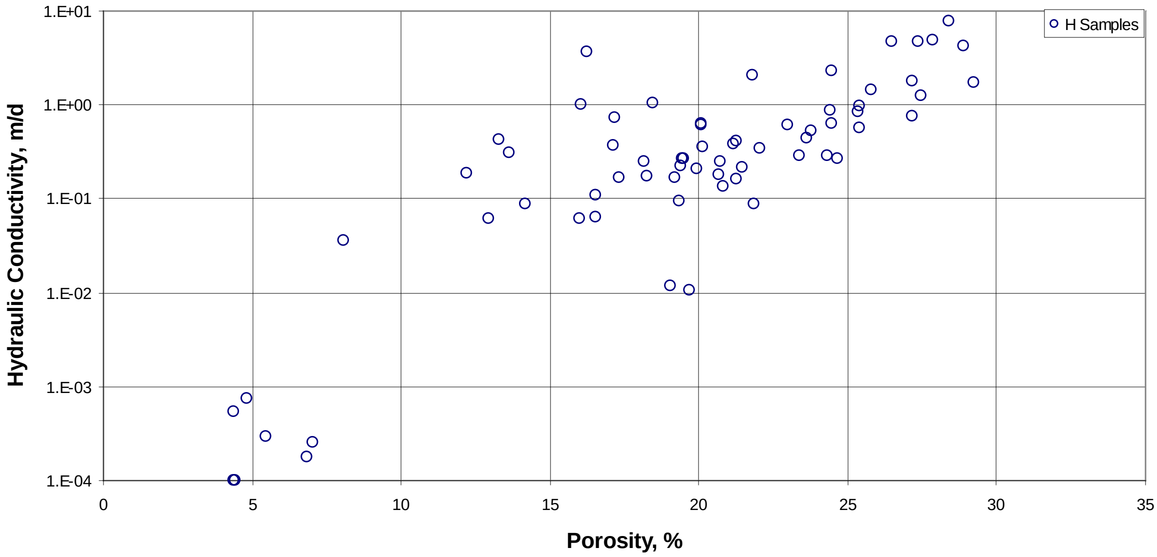
Table 3. EV2: core porosity and permeability

Property	Min	Max	Mean
kh, mD	0.02	18400	1340
Hydraulic Cond, m/d	0	7.8	0.86
Ǿ, %	4.4	29.2	19.4

Table 4. EV3: core porosity and permeability

Property	Min	Max	Mean
kh, mD	70	24200	5030
Hydraulic Cond, m/d	0	15.6	3.27
kv, mD	470	20050	3810
Ǿ, %	11.7	32.3	21.1

On examining the drillcore it is clear that a number of aeolean facies have been intercepted by the boreholes and within these are complex cross-bedded sequences, different grain size distributions and cements. The most significant difference between the aquifer properties of the two boreholes results from the presence of a silicified band at the top of the bedrock in EV2 resulting in reduced porosity and hydraulic conductivity. A more detailed evaluation of borehole core and geophysical image analysis will be undertaken separately.



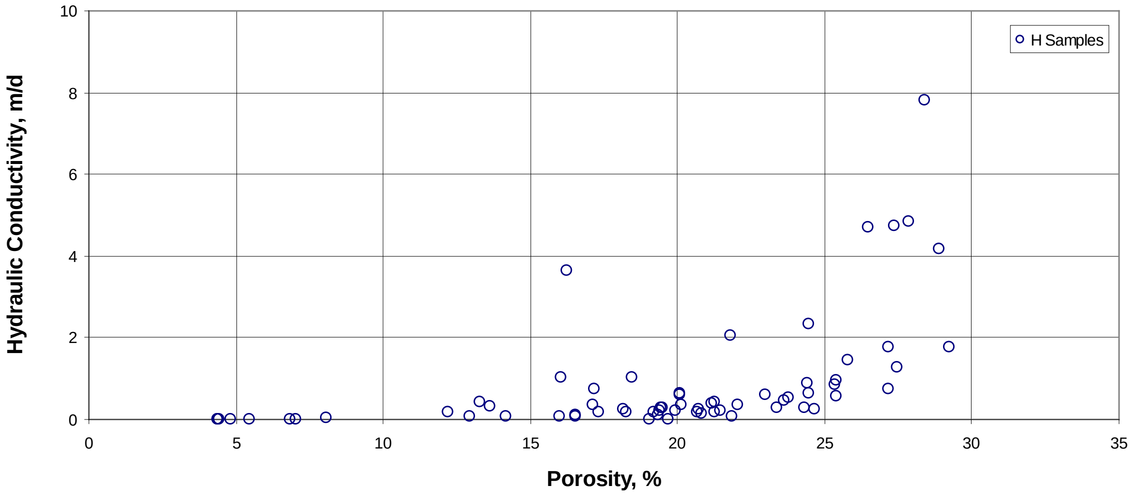
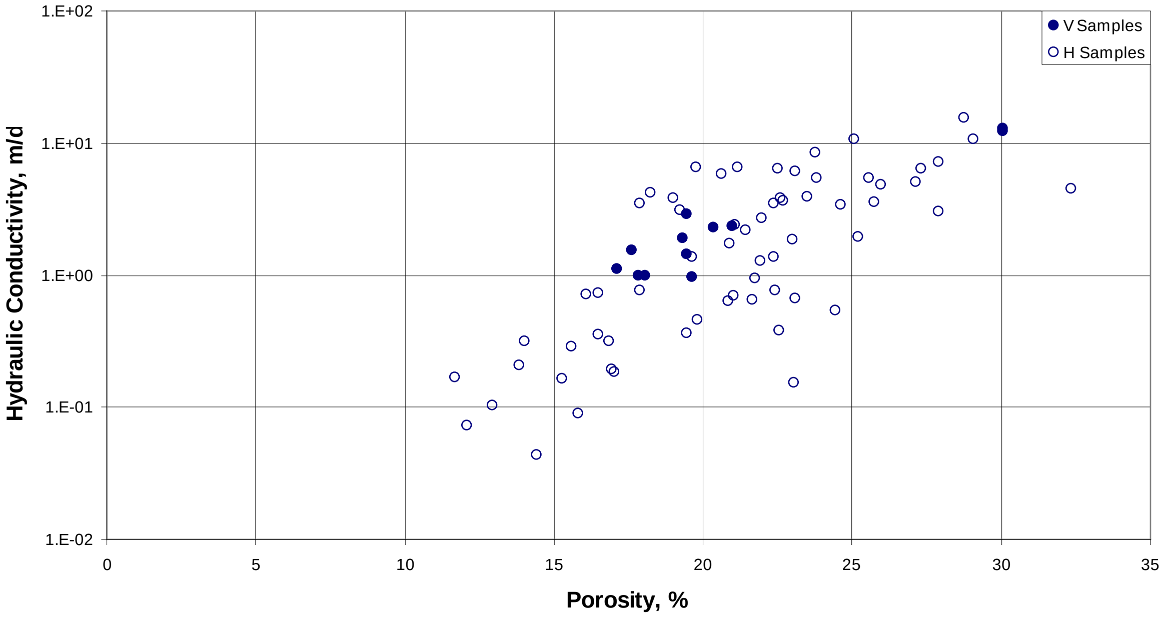


Figure 23. EV2: porosity and hydraulic conductivity (log and linear permeability axes)



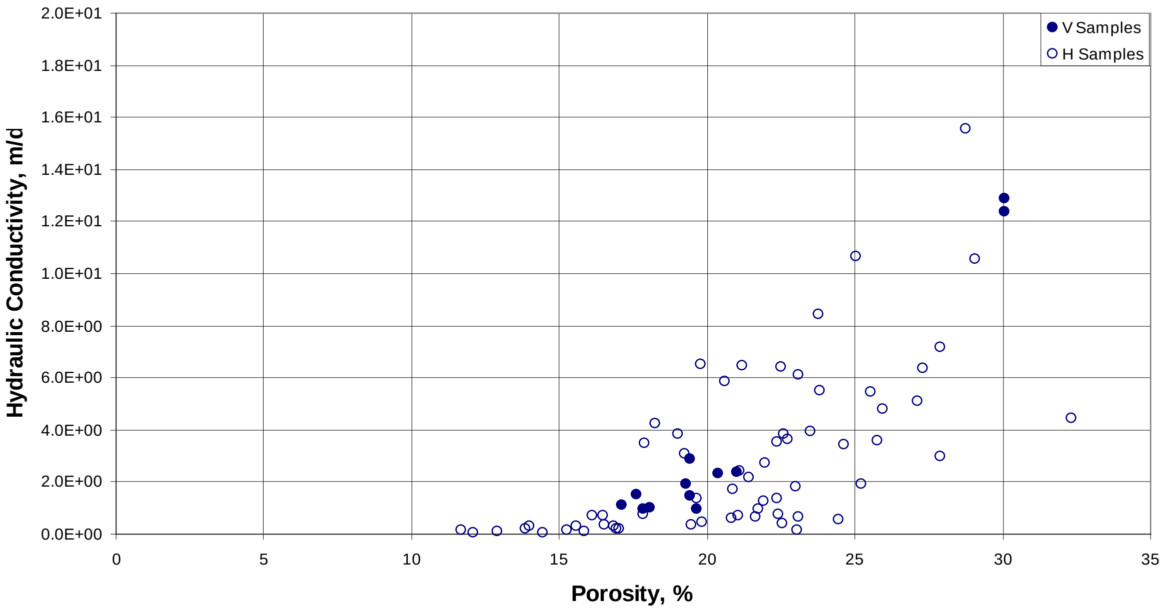


Figure 24. EV3: porosity and hydraulic conductivity cross plots

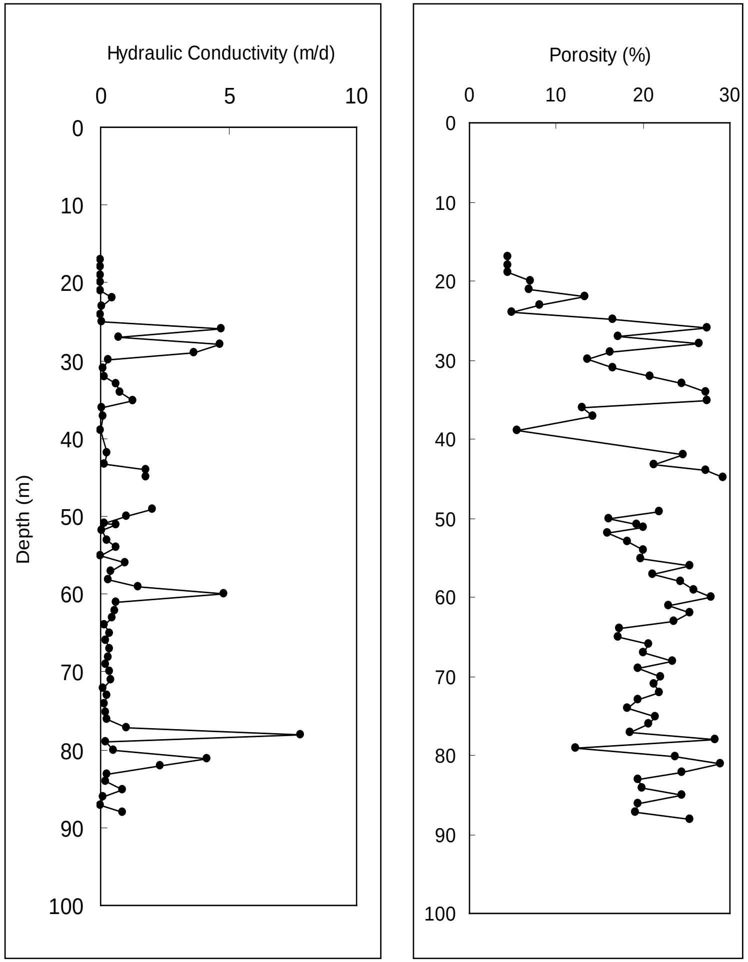


Figure 25. EV2: porosity and hydraulic conductivity profiles

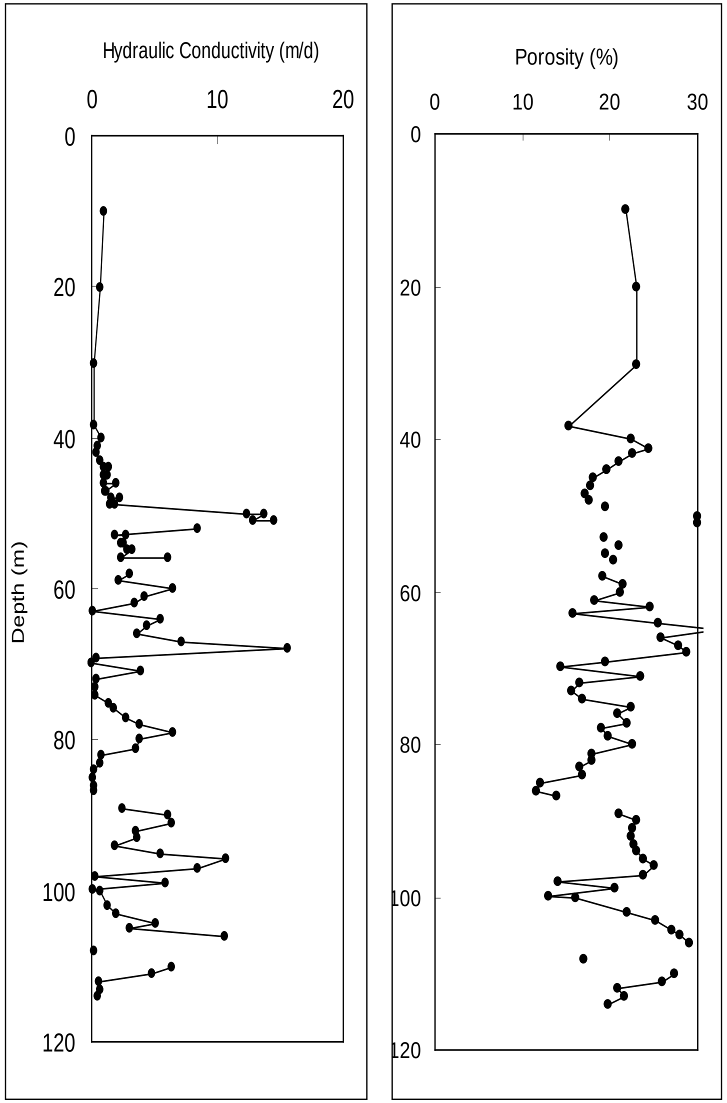


Figure 26. EV3: porosity and hydraulic conductivity profiles

3.2 Interval pump testing

Pumping test results are detailed in Tables 5 to 7. Borehole EV2 was test pumped following borehole development by air-lifting in 2006. Borehole EV3 was test pumped in late 2006 after drilling and development by air-liting and again in 2008 albeit with no further development. The reason for repeat testing was because samples captured for testing the groundwater age were contaminated, probably due to a leak in the pressurised gas line connected to the inflateable packers. Intervals selected for original testing and sampling were repeated after a period of pumping.

It is noteable that for EV2 the mean pumped interval (formation) hydraulic conductivity (K), 6.2 m/d, is almost an order of magnitude greater than mean plug (matrix) K, 0.86 m/d. The highest formation hydraulic conductivities are in intervals *42.7 to 44.8 m bct and* 56.2 to 58.2 m bct.

For EV3 (2008 test pumping) the mean pumped interval (formation) K is 3.34 m/d which is very similar to the mean plug (matrix) K of 3.27 m/d. The highest hydraulic conductivity was measured in the interval 94 - 96.9 m bct but interval tests were more consistent than in EV2.

Table 5. EV2: borehole interval packer test hydraulic conductivity

Interval Depth (bct), m	Hydraulic Conductivity, m/d
17.73 to 19.82	
26.76 to 28.88	*1.32*
26.76 to 28.88	0.98
31.88 to 33.99	0.09
36.23 to 38.34	0.23
38.79 to 40.90	0.37
41.10 to 43.20	4.64
42.73 to 44.84	*41.00*
42.73 to 44.84	35.47
49.74 to 51.85	4.47
51.74 to 53.85	1.25
56.22 to 58.23	19.96
66.65 to 68.65	1.13
73.23 to 75.34	1.79
84.65 to 86.76	4.06
Mean (excl. duplicates)	***6.2***

Table 6. EV3: borehole interval packer test hydraulic conductivity

Interval Depth (bct), m	Hydraulic Conductivity, m/d
53.80 - 56.44	
55.02 - 57.66	
56.75 - 59.39	4.29
57.96 - 60.6	
62.65 - 65.29	0.35
67.60 - 70.24	0.84
70.55 - 73.19	2.63
73.5 - 76.14	0.49
78.41 - 81.05	3.88
85.3 - 87.94	
88.21 - 90.85	1.56
97.55 - 100.19	4.19
102.11 - 104.75	1.7
Mean	***2.21***

Table 7. EV3: borehole interval packer test hydraulic conductivity follow-up testing

Interval Depth (bct), m	Hydraulic Conductivity, m/d
55.8 - 58.7	4.31
68.6 - 71.3	3.34
73.5 - 76.4	1.06
78.5 - 81.4	4.84
82.5 - 85.4	0.27
88.5 - 91.4	3.23
94 - 96.9	7.16
98 - 100.9	3.67
100 - 102.9	2.17
Mean	***3.34***

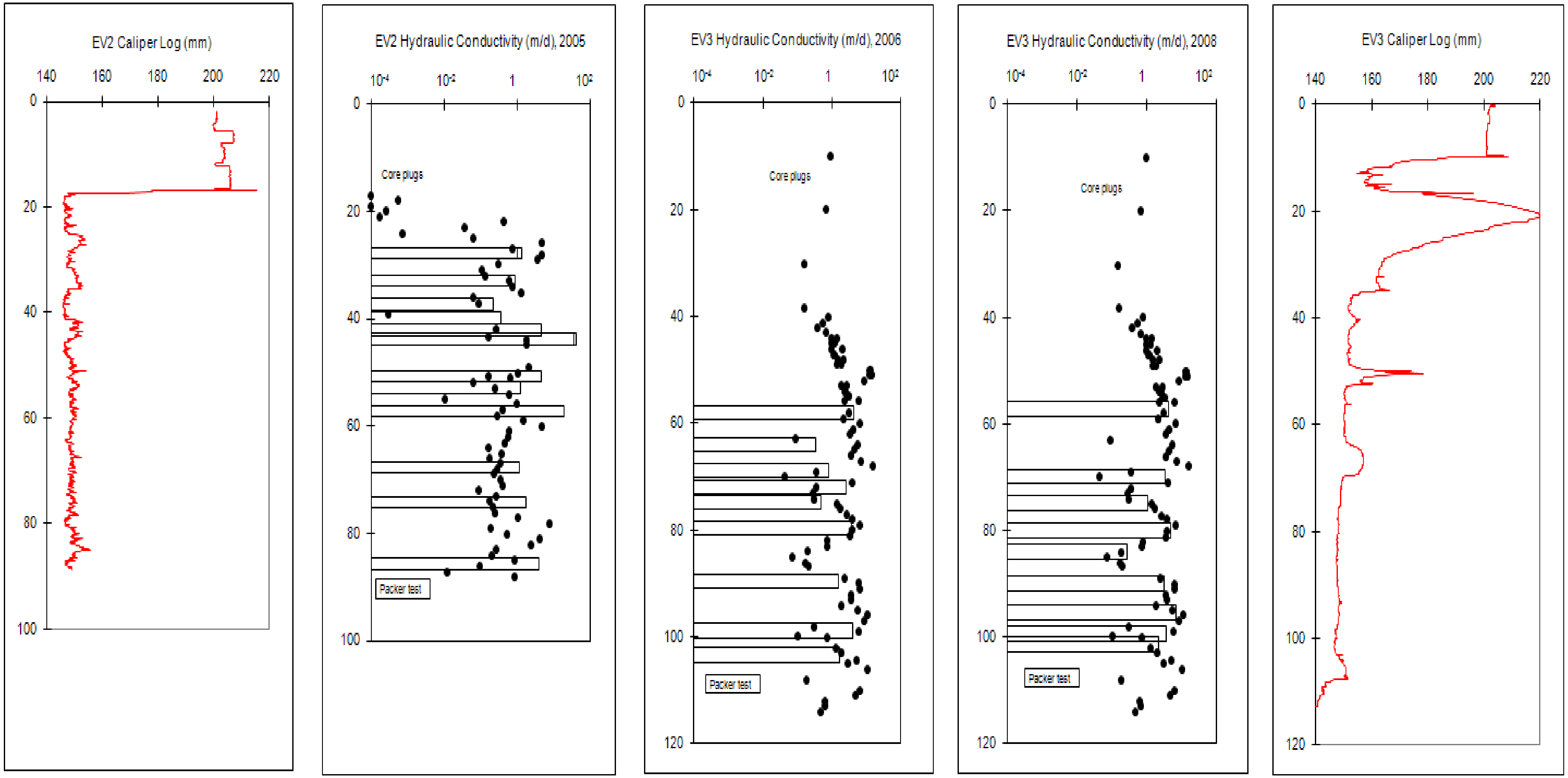


Figure 27. EV2 and EV3: caliper and hydraulic conductivity profiles

3.3 Geophysical testing and imaging

3.3.1 Introduction

Geophyscial borehole logging and imaging was undertaken as soon as possible after completion of drilling of the boreholes using techniques described in section 2.2. Results for each borehole are described separately.

3.3.2 EV2

Geophyscial borehole logging was conducted in November 2005. The borehole is cased to approximately 17 m bgl. Standing water level (SWL) was 5.34 m bgl. Testing under pumped conditions was at a flow rate, Q of 12 m^3/hr with pumped water level (PWL) drawn down to 5.65 m bgl. Data are plotted in Figure 29.

Formation logs

A higher clay content reduces the electrical resistivity of the formation and results in increasing gamma ray emissions. The gamma ray and resistivity logs are, therefore, roughly mirror images of each other. The resistivity readings are plotted on a log-scale. The log-profile is saw-toothed with hard, cemented (high resistivity – low clay content) layers alternating with softer, poorly cemented (low resistivity – high clay content). There is a general pattern of decreasing resistivity (and probably cementation) with depth.

Natural (un-pumped) conditions

Fluid temperature, fluid conductivity, heat-pulse flow-meter (HPFM), and spinner flow-meter (SFM) measurements were recorded during un-pumped/'natural' conditions. The fluid temperature and fluid conductivity log profiles are similar. Readings are quite constant except for minor inflections from 83 m bgl to 40 m to 32 m bgl where fluid temperature and fluid conductivity decrease rapidly. The heat-pulse flow-meter and spinner flow-meter both recorded up-flow over this interval. Up flow recorded by the SFM falls dramatically from 47 to 40 m bgl suggesting that water was flowing out of the borehole over this horizon during un-pumped conditions. The more sensitive HPFM, which does not record flow continuously but at discrete locations, suggests that some water flowed up the borehole past 40 m bgl to exit between 35 to 31 m bgl. The pattern of up-flow suggested by the flow-meter measurements is entirely consistent with the fluid conductivity and fluid temperature log profiles. Indeed the uniformity of fluid conductivity and fluid temperature readings below 40 m is indicative of vertical flow – below 40 m bgl the temperature and conductivity sonde is only ever passing through water that entered the borehole at 83 m bgl. Interestingly HPFM readings suggest that there is some down-flow from approximately 83 m bgl to the base of the borehole, which results in an inflection in the fluid temperature and fluid conductivity log profile.

	Temperature (°C)		Conductivity (µS/cm)	
	Un-Pumped	Pumped	Un-Pumped	Pumped
Min	9.30	9.91	243	267
Max	10.25	10.14	325	323

Figure 28. EV2: summary of fluid logs

Pumped conditions

Fluid temperature, fluid conductivity, and spinner flow-meter (SFM) measurements were recorded during pumping. The SFM results are presented as a percentage of flow measured at the surface. Below the base of the casing water flows into and up the borehole. Virtually zero percent flow is recorded at the base of the borehole and 100% at the base of the casing at approximately 17 m bgl. Below approximately 58 m bgl the fluid temperature and fluid conductivity log profiles are almost identical to those recorded under 'natural' conditions. This is because under natural conditions water is also moving up the borehole. Differences between pumped and un-pumped log profiles observed above 58 m bgl occur as water is drawn into the borehole from horizons that are activated in response to pumping. Significant changes to the fluid conductivity profile in particular correlate with inflows at 58 and 47.5 m bgl. Maximum up-flow is recorded above the upper most inflow horizon at approximately 38 m bgl, above which fluid temperature and fluid conductivity are constant.

Interpreted flow horizons:

^{P} = Horizon active during pumping.
^{N} = Horizon active during 'natural' conditions.
Fracture flow (discrete horizons) at 32-33^{N}, 38 $^{P\&N}$, 42 $^{P\&N}$, 48 $^{P\&N}$, 57 $^{P\&N}$, and 84$^{P\&N}$ m bgl.

Matrix flow from 70 to 84^{N} m bgl, in an interval of softer sandstone.

The majority of flow horizons are located at the junction of soft and hard sandstones, which may help explain why there are fewer at depth.

Optical imaging

The oriented optical image scans were interpreted to identify structural details including bedding, joints fractures lithological and sedimentary features were selected (picked) recording azimuth and dip values. Figure 30 is a composite core image of approximately 10 m in length per core run. Fractures, high angle and low angle features, bleaching and other colour variation can be seen. Notable features in Figure 30 (EV2) are lighter coloured uniform rock with low angle bedding which becomes much more variable exhibiting high angel open fractures, some bleached horizons and open joints, deepening in colour with more subdued sub-horizontal bedded but well jointed beds.

Figure 31 is a vertically compressed composite image which includes picks of identifiable features in borehole EV2.

Identifiable features in the borehole image are classified in the key but are grouped as bedding plain features and joint and fracture features in the graphical analyses. For borehole EV2 three intervals have been selected for description: 0-36 m bd, 36-63 m bd and 63-89 m bd.

Bedding plain features in the upper interval comprise low angle (<30°) 'picks' with a dip azimuth of the greater dips generally to the west. The mean azimuth is WNW. Jont features exhibit a wider spread of dip angles and direction.

Several bedding plain features in the interval between 36 and 63 m bd also comprise low angle (<30°) 'picks' with a dip azimuth generally to the north. The mean azimuth is NNW. Joint features, many of which are altered and with high dip angles exhibit a wider range of orientations.

In the third interval between 63 and 89 m bd a large number of primary bedding features have been identified. These appear to be oriented in two main directions with a mean azimuth towards the northwest. Three altered or healed joints have been identified at a depth between 67 and 70 m bd but most other features have lower dip angles.

BHTV

Figure 32 indicates the base of the casing against apparently hard bedrock with some vertical features. Figure 33 shows a sub-horizontal fracture at 32.6m in which manganese 'spotting' is evident.

Figures 34 and 35 show downhole views of sections illuminated by a suspended lamp. These highlight vertical fractures and a complex network of crossing granulation seams below a horizontal joint or bedding plain. Figure 36 is a horizontal sidewall view of the feature in the preceeding figure including some granular debris

Figures 37 to 39 identify a sequence of weakly-cemented sandstones over which grains are supported by unpumped upflow in the borehole consistent with the flow logging results. This effect looks similar to gas bubbles rising in a fizzy drink.

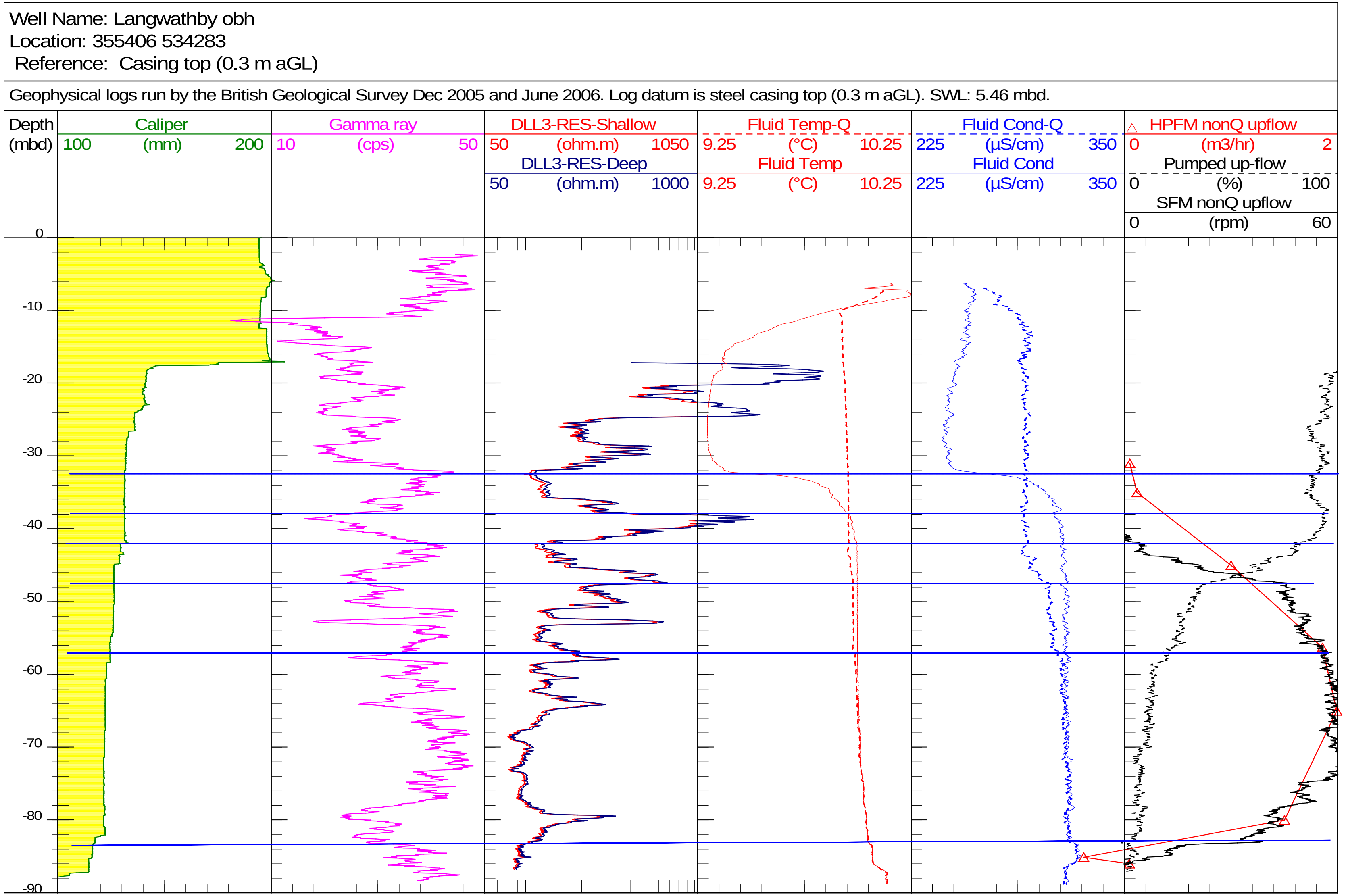


Figure 29. EV2: interpreted logs and inflows

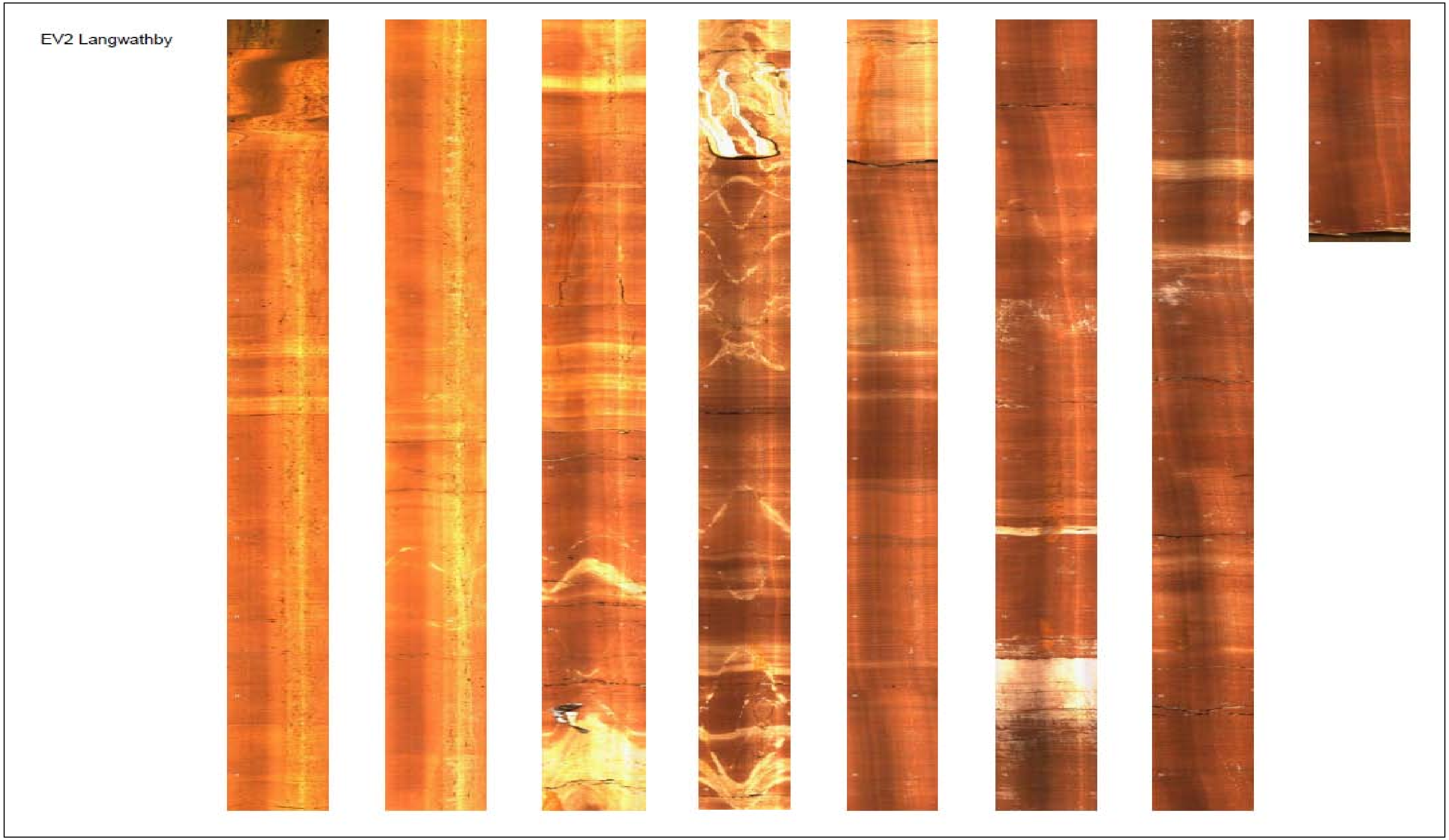


Figure 30. EV2: borehole image composite

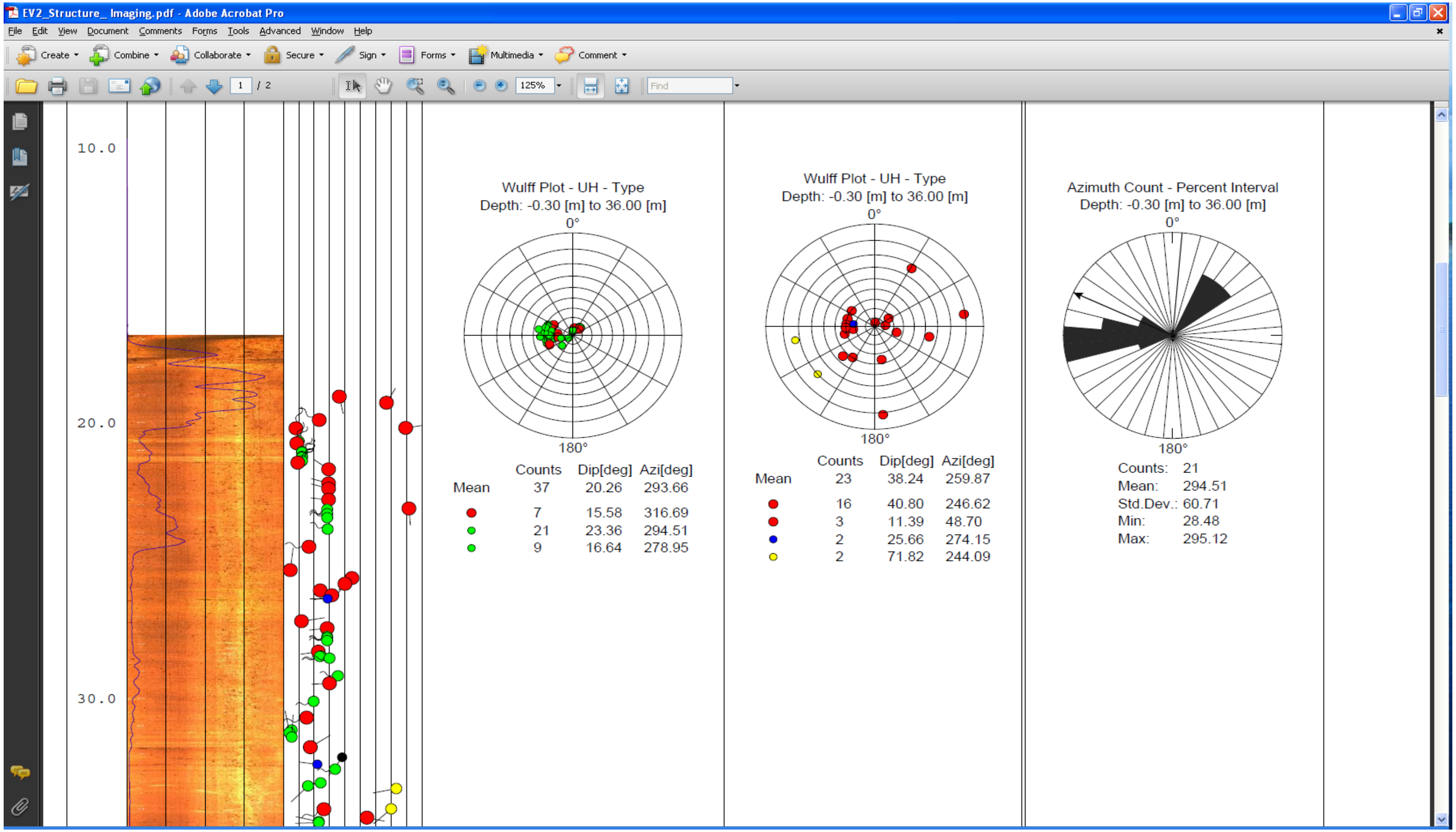
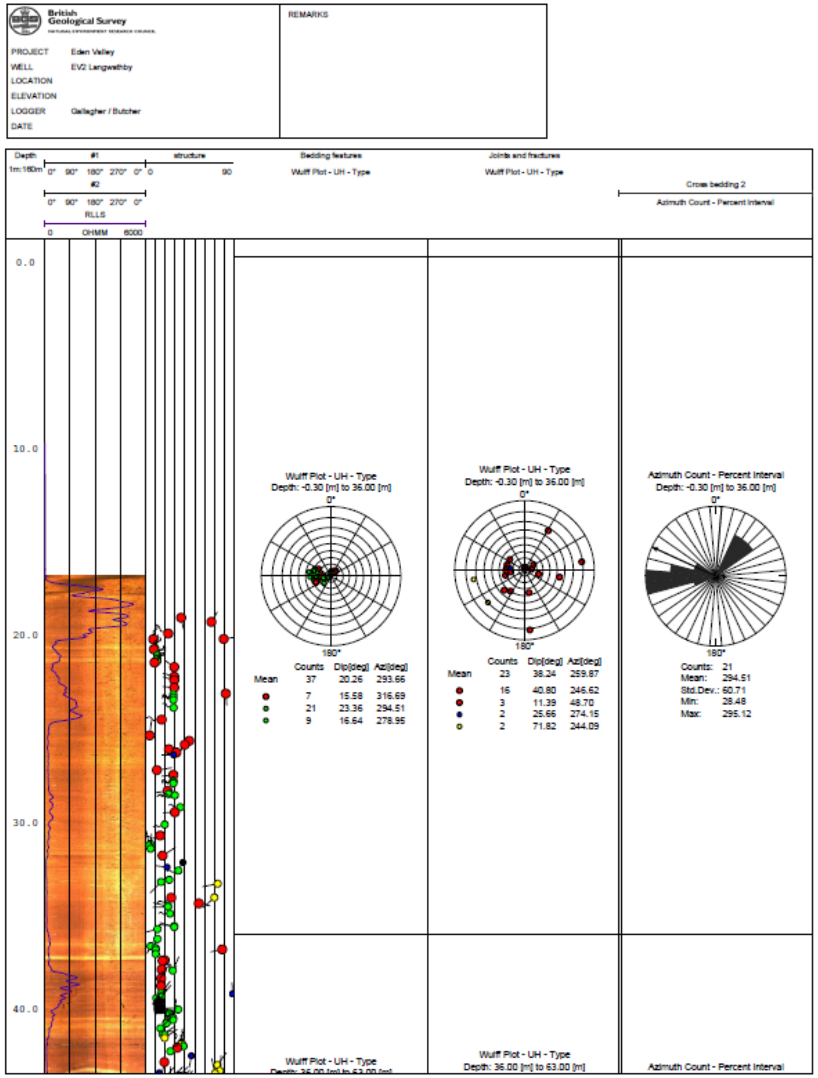
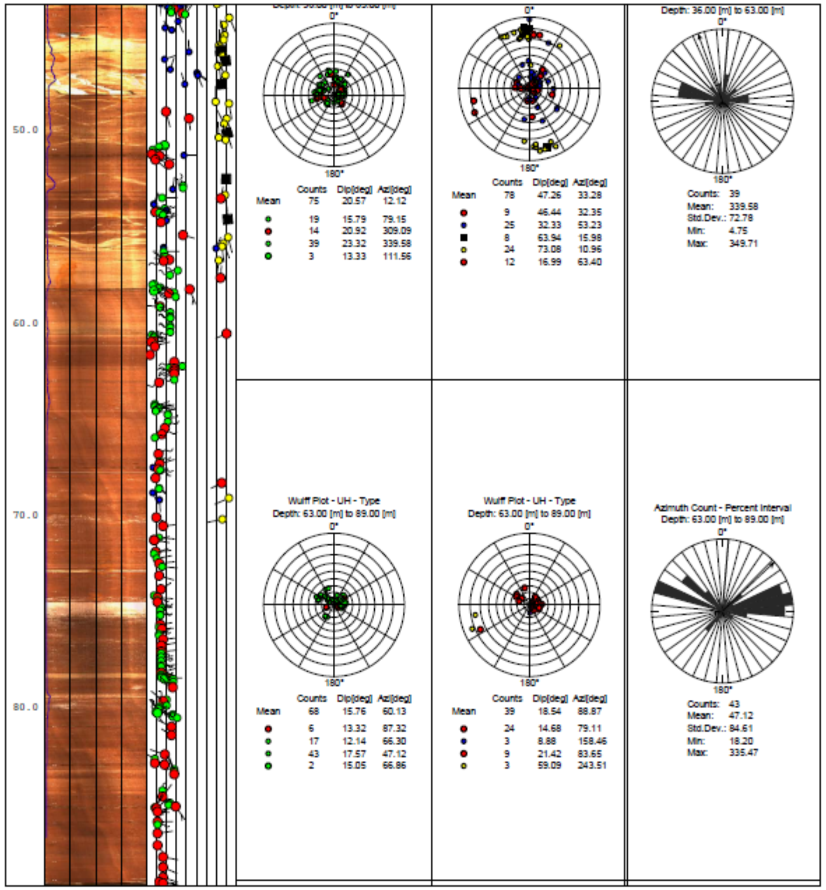


Figure 31. EV2: borehole image interpretation composite A3


British Geological Survey
PROJECT Eden Valley
WELL EV2 Langwathby
LOCATION
ELEVATION
LOGGER Gallagher / Butcher
DATE
REMARKS
Depth 1m:180m
structure
RLLS
OHMM
Bedding features
Wulff Plot - UH - Type
Joints and fractures
Wulff Plot - UH - Type
Cross bedding 2
Azimuth Count - Percent Interval
Wulff Plot - UH - Type
Depth: -0.30 [m] to 36.00 [m]
Counts 37 Dip[deg] 20.26 Azi[deg] 293.66
7 15.58 316.69
21 23.36 294.51
9 16.64 278.95
Wulff Plot - UH - Type
Depth: -0.30 [m] to 36.00 [m]
Counts 23 Dip[deg] 38.24 Azi[deg] 259.87
16 40.80 246.62
3 11.39 48.70
2 25.66 274.15
2 71.82 244.09
Azimuth Count - Percent Interval
Depth: -0.30 [m] to 36.00 [m]
Counts: 21
Mean: 294.51
Std.Dev.: 60.71
Min: 28.48
Max: 295.12
Wulff Plot - UH - Type
Wulff Plot - UH - Type
Depth: 36.00 [m] to 63.00 [m]
Azimuth Count - Percent Interval


Counts 75 Dip[deg] 20.57 Azi[deg] 12.12
19 15.79 79.15
14 20.92 309.09
39 23.32 339.58
3 13.33 111.56
Counts 78 Dip[deg] 47.26 Azi[deg] 33.28
9 46.44 32.35
25 32.33 53.23
8 63.94 15.98
24 73.08 10.96
12 16.99 63.40
Depth: 36.00 [m] to 63.00 [m]
Counts: 39
Mean: 339.58
Std.Dev.: 72.78
Min: 4.75
Max: 349.71
Wulff Plot - UH - Type
Depth: 63.00 [m] to 89.00 [m]
Counts 68 Dip[deg] 15.76 Azi[deg] 60.13
6 13.32 87.32
17 12.14 66.30
43 17.57 47.12
2 15.05 66.86
Wulff Plot - UH - Type
Depth: 63.00 [m] to 89.00 [m]
Counts 39 Dip[deg] 18.54 Azi[deg] 88.87
24 14.68 79.11
3 8.88 158.46
9 21.42 83.65
3 59.09 243.51
Azimuth Count - Percent Interval
Depth: 63.00 [m] to 89.00 [m]
Counts: 43
Mean: 47.12
Std.Dev.: 84.61
Min: 18.20
Max: 335.47

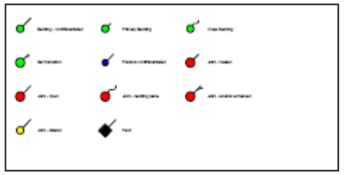


Figure 32. EV2: BHTV base of casing.

Figure 33. EV2: Mn staining.

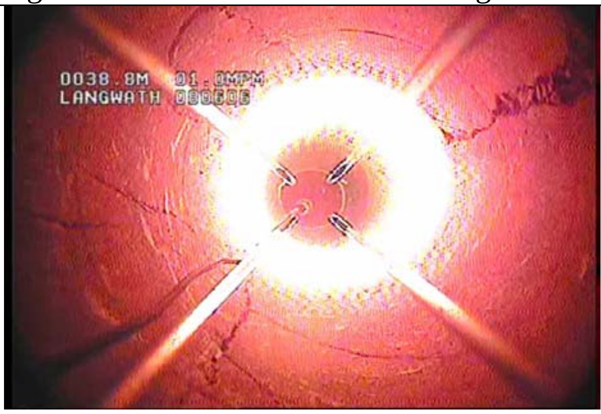


Figure 34. EV2: BHTV vertical fractures.

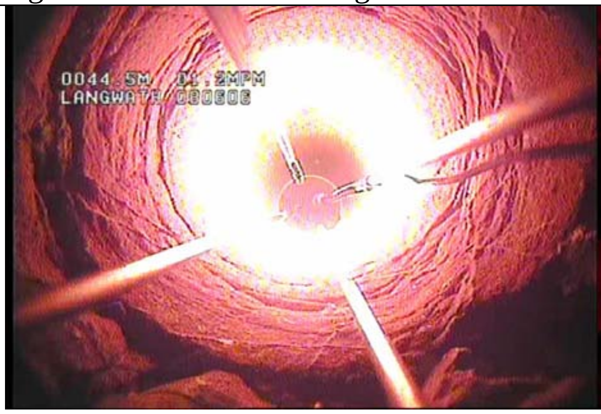


Figure 35. EV2: BHTV granulation seams.

Figure 36. EV2: debris in fracture/bedding

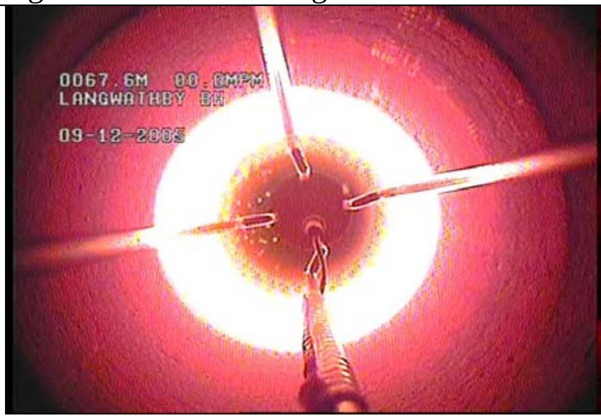


Figure 37..EV2: top of inflow of grains 67.6 m

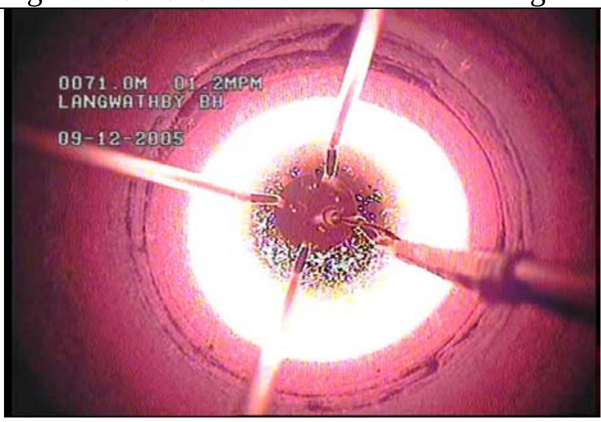


Figure 38.. EV2: upflow transporting grains.

Figure 39. EV2: base of grain inflow 77.5 m.

3.3.3 EV3

Geophysical borehole logging was conducted in November 2006. The borehole is cased to approximately 10 m bgl. Standing water level (SWL) was 49.56 m bgl. Testing under pumped conditions was at a flow rate, Q of 3.43 m^3/hr with pumped water level (PWL) drawn down to 49.88 m bgl.

Formation logs

Gamma ray is recorded throughout the borehole but formation resistivity may only be recorded below the water table. There is a similar range in the values of both formation logs, however, the sandstone appears more homogenous; the log profiles are less ‘saw-toothed’ in character than in EV2, changes occur over a different scale, i.e. individual units of either harder or softer sandstone are generally thicker than in EV2.

Natural (un-pumped) conditions

Fluid temperature (Fluid Temp), fluid conductivity (Fluid Cond) and spinner flow-meter (SFM) logs were recorded during ‘natural’ conditions. There was insufficient vertical flow to register on the spinner flow meter log and it is not presented. Fluid temperatures and fluid conductivities are lower than at EV2 and exhibit a far smaller range. There is a marked change in the character of both the fluid temperature and fluid conductivity logs above approximately 74 m bgl, between 74 m bgl and 108.5 m bgl values are much more constant which suggests a component of vertical flow over this interval.

	Temperature (°C)		Conductivity (µS/cm)	
	Un-Pumped	Pumped	Un-Pumped	Pumped
Min	8.53	8.57	152	148
Max	8.62	8.62	168	153

Figure 40. EV3: summary of fluid logs

Pumped conditions

Fluid temperature (Fluid Temp-Q), fluid conductivity (Fluid Cond-Q), and spinner flow-meter (SFM) measurements were recorded during pumping. The SFM readings suggest that approximately 1 m^3/hr was entering the borehole at its base. This inflow at the base of the borehole explains the difference between the bottom hole pumped and un-pumped fluid conductivities, which should otherwise be the same. The increase in up-flow between 108.5 and 100 m bgl is gradual and indicative of intergranular/ matrix flow, as may be expected from more poorly cemented, soft sandstone indicated over this interval by the resistivity log profile. Between 88 and 74 m bgl there is a slight reduction in up-flow which suggests that water flows out of the borehole over this interval, most probably around 79.5 m bgl. The pronounced inflow at 67 m correlates with a cavity in the borehole wall, a change in the un-pumped temperature log, but no significant change in the pumped fluid logs. Although it should be noted that there is very little variation in the whole profile of the pumped logs, and any minor changes in them should not be over interpreted.

Interpreted flow horizons:

These are harder to interpret than in EV2 due to the smaller changes observed in the fluid temperature and fluid conductivity logs and the lack of clear steps in the SFM log (which may be due to the lower pumping rate compared to EV2).

^{P} = Horizon active during pumping.
^{N} = Horizon active during ‘natural’ conditions.
Fracture flow (discrete horizons) at 67 $^{P\&N}$, 74 $^{P\&N}$, 79.5 $^{P\&N}$, 100^{P}, and 108$^{P\&N}$ m bgl.
Matrix flow at 84 $^{P\&N}$, 100 to 108 $^{P\&N}$, and possibly 80 $^{P\&N}$ m bgl.

The majority of flow horizons are located at the junction of soft and hard sandstones, which may help explain why there are fewer at depth

Optical Imaging

The oriented optical image scans were interpreted to identify structural details including bedding, features joints and fractures lithological and sedimentary features were selected (picked) recording azimuth and dip values. Figure 42 is a composite core image of approximately 10m in length per core run.

In Figure 42 (EV3) a sub-vertical joint extending over 4m in length in the near to the top of the borehole is obvious. A colour change above and below the water table is also evident. Interpreted borehole images include compressed vertical scales and some care should be taken in identifying features from these outputs.

Figure 43 is a vertically compressed composite image which includes picks of identifiable features

The geophysical logging data are presented as depth profiles of geophysical characteristics, interpreted imagery and borehole cctv images.

Figure 43 is a vertically compressed composite image which includes picks of identifiable features in borehole EV3.

Identifiable features in the borehole image are classified in the key but are grouped as bedding plain features and joint and fracture features in the graphical analyses. For borehole EV3 four intervals have been selected for description: 10-34.5 m bd, 34.5-58 m bd, 58-84.5 m bd and 84.5-114.5 m bd.

Bedding plain and cross-bedding features in the upper interval comprise moderate angle (<50°) features possibly in two groups with a mean azimuth direction just west of north. Joint features exhibit a wider spread of dip angles joint and directions including a near vertical joint.

Several bedding and cross-bedding plain features in the interval between 34.5 and 58 m bd also comprise moderate angle (<50°) ‘picks’ with a dip azimuth generally between west and southwest although some are towards the north. The mean azimuth is west. Joint features include several more altered, healed or undifferentiated features often with high dip angles and azimuths towards the west.

In the third interval between 58 and 84.5 m bd cross-bedding features have slightly more modest dip angles (<40°), and exhibit a similar average azimuth to the interval above in a direction just north of west. Fewer altered joint features are noted in an interval with scattered features.

The lowest interval in the borehole between 84.5 and 114.5 exhibits bedding plain joints of up to 30° dip but no dominant direction. Other bedding features have greater dip angles and these are more generally to the northwest. Few joint features are identified of which two open joints and two healed faults between 104 and 105 m bd have high dip angle in a narrow azimuth towards the northwest.

BHTV

Figure 44 indicates the base of the casing against fractured bedrock which in downhole views in Figures 45, 46 and 49 are seen to be complex and oriented in vertical and horizontal angles. In Figure 46 the borehole wall collapse has exposed a long sub-vertical joint with a subdued possibly weathered or eroded face. In contrast Figures 48 and 50 show an absence of vertical jointing/fracturing but either horizontal joints or minor bedding features perhaps related to grain-size changes. These features are particularly obvious in Figures 52 and 54. Sub horizontal fractures or joints are shown in Figures 52 and 54. In these examples, the apertures exceed 3mm and some debris is present. Figure 55 illustrates settled drilling debris at the base of the borehole.

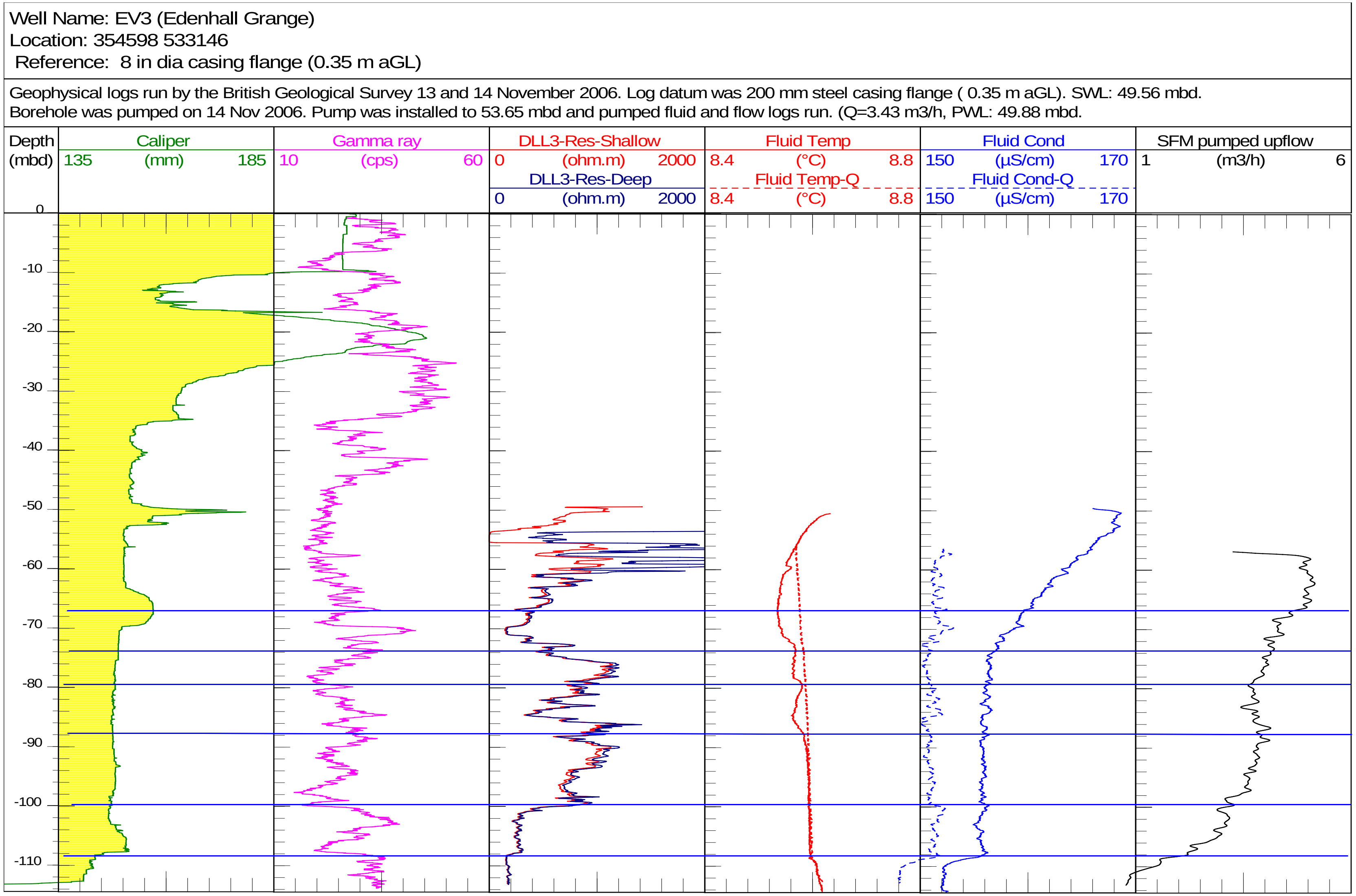


Figure 41. EV3: interpreted logs and inflows

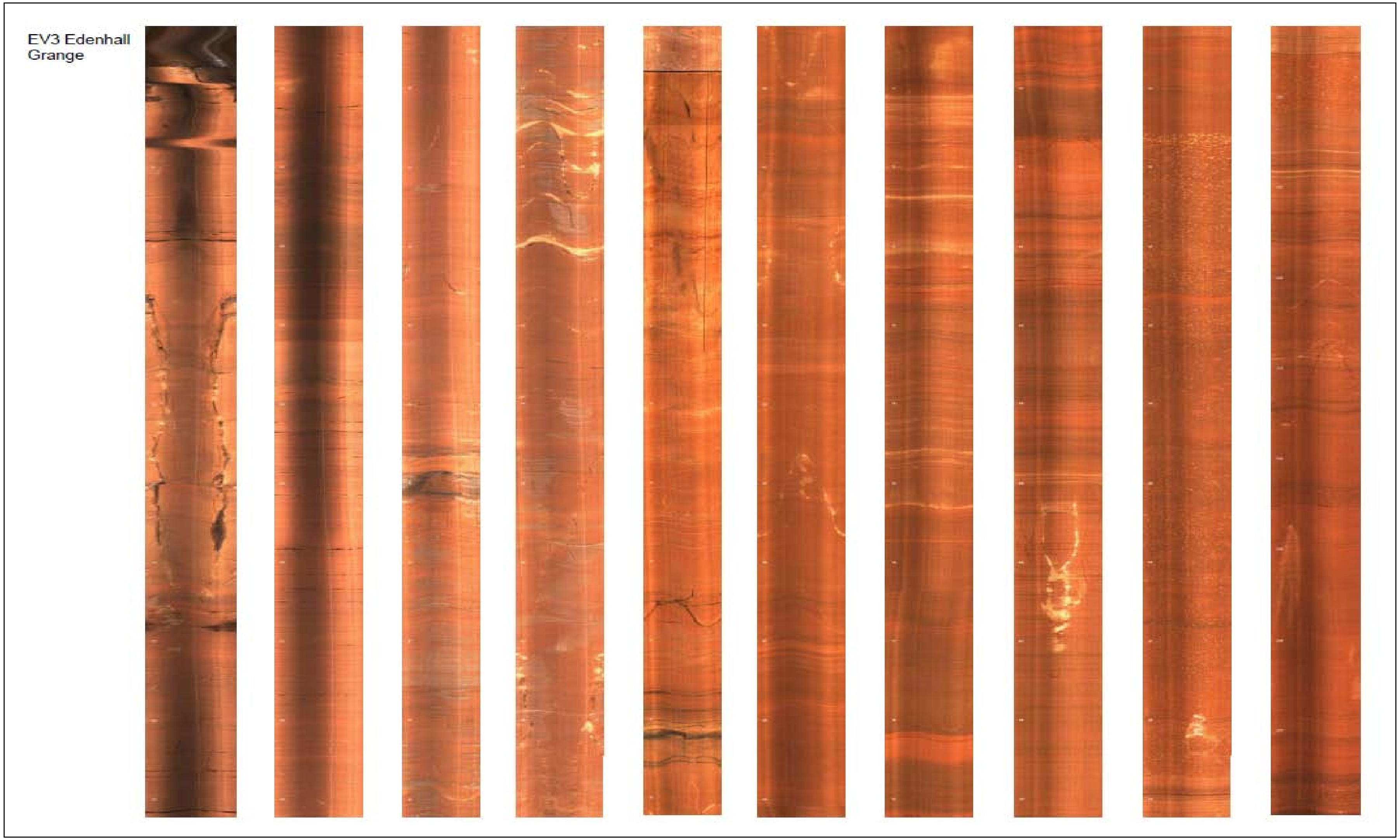


Figure 42. EV3: borehole image composite

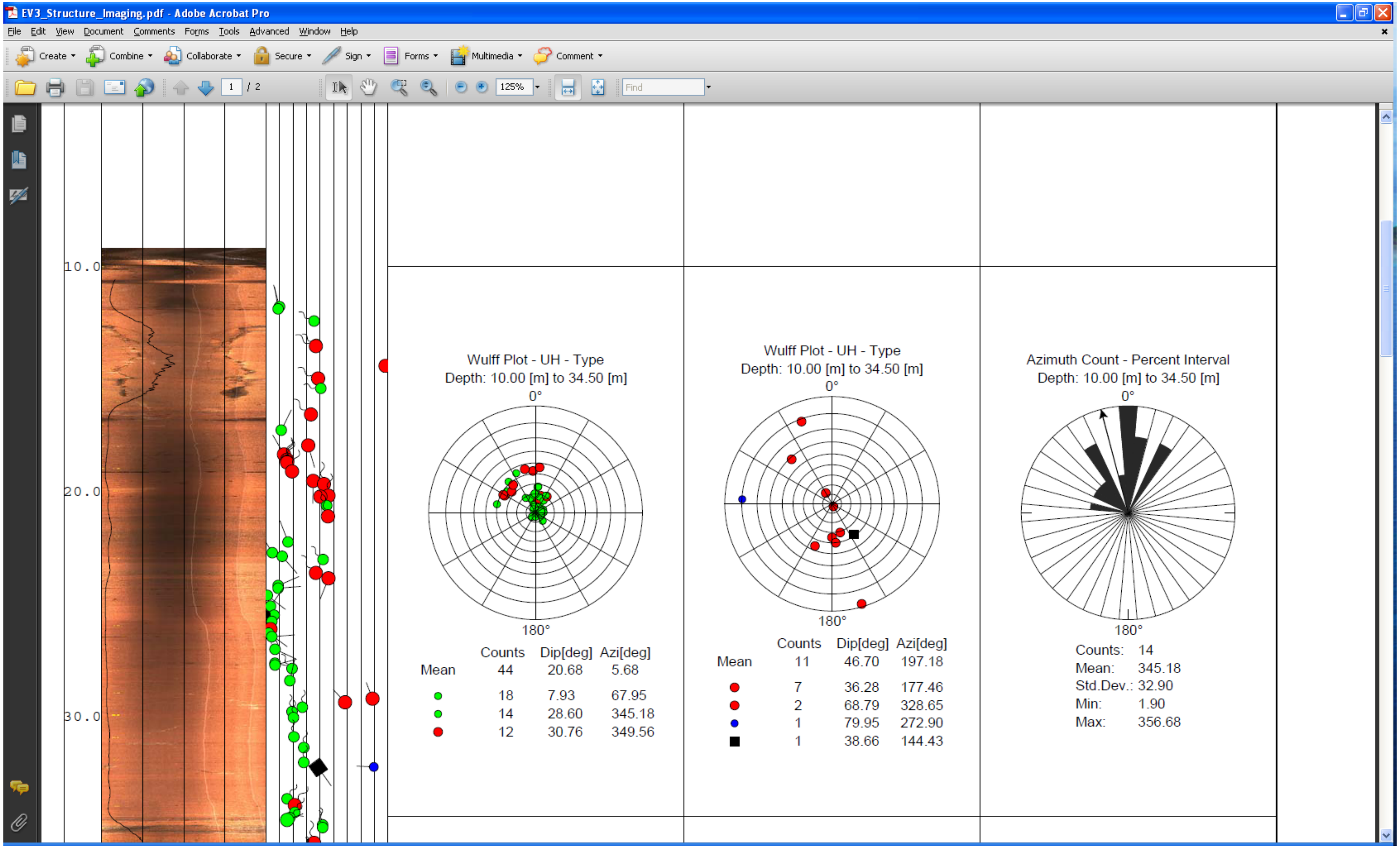
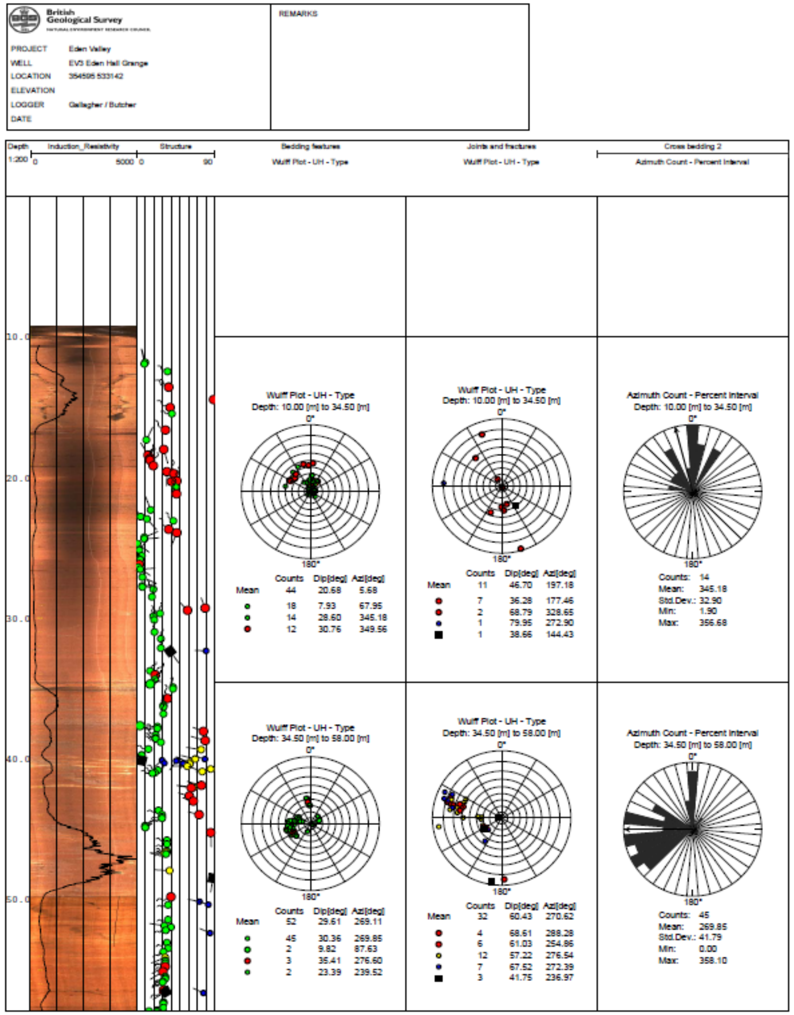
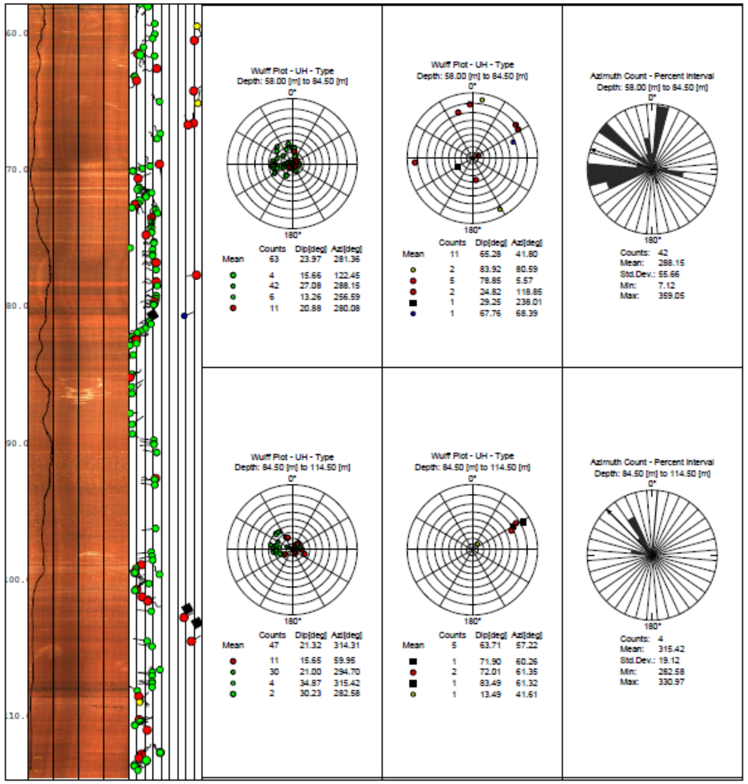


Figure 43. EV3: borehole image interpretation composite A3


British Geological Survey
REMARKS
PROJECT Eden Valley
WELL EV3 Eden Hall Grange
LOCATION 354595 533142
ELEVATION
LOGGER Gallagher / Butcher
DATE
Depth
Induction_Resistivity
Structure
Bedding features
Joints and fractures
Cross bedding 2
Wulff Plot - UH - Type
Azimuth Count - Percent Interval



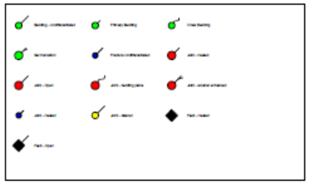


Figure 44. EV3: base of casing

Figure 45. EV3: casing shoe and fractures.

Figure 46. EV3: vertical fractures

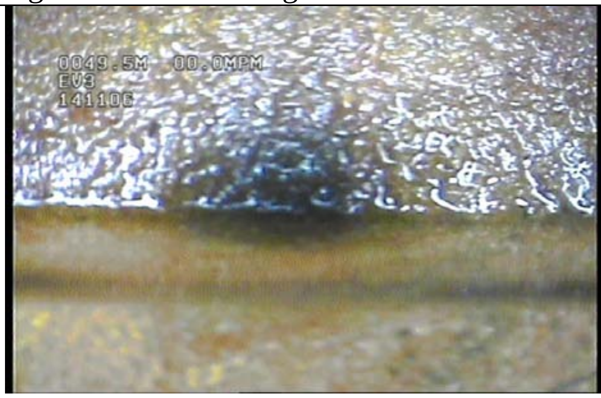


Figure 47. EV3: water table .

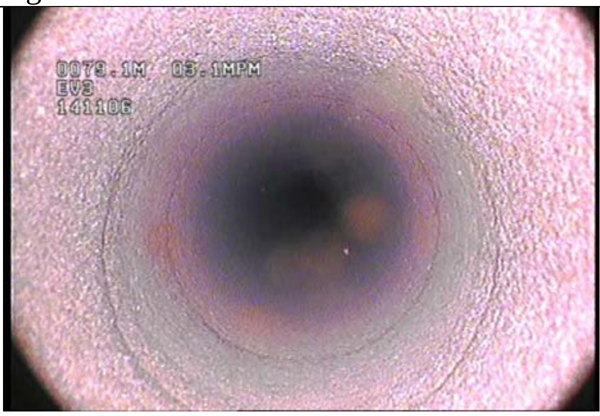


Figure 48. EV3: coarse sandstone matrix flow

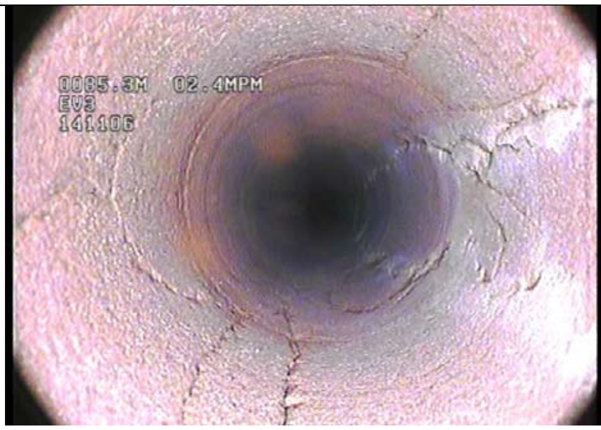


Figure 49. EV3: complex vertical fractures.

Figure 50. EV3: coarse sandstone matrix flow

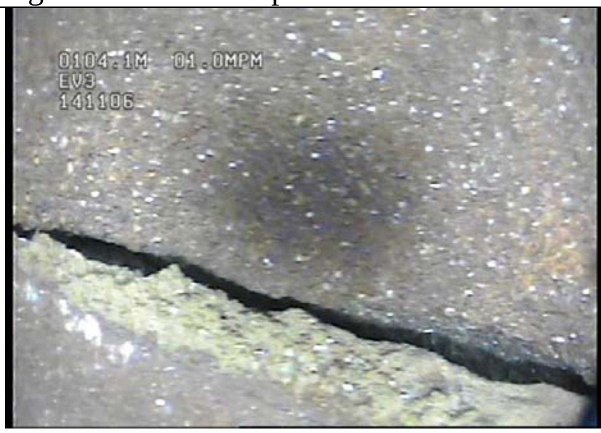


Figure 51. EV3: mineralised fracture fill.

Figure 52. EV3: thin coarse bands

Figure 53. EV3: coarse band above fracture .

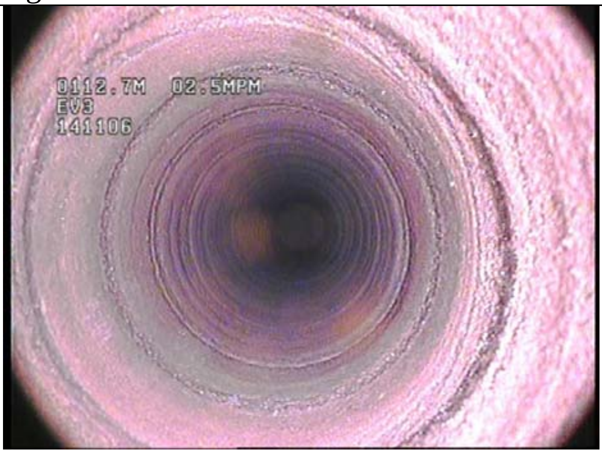


Figure 54. EV3: coarse sandstone matrix flow

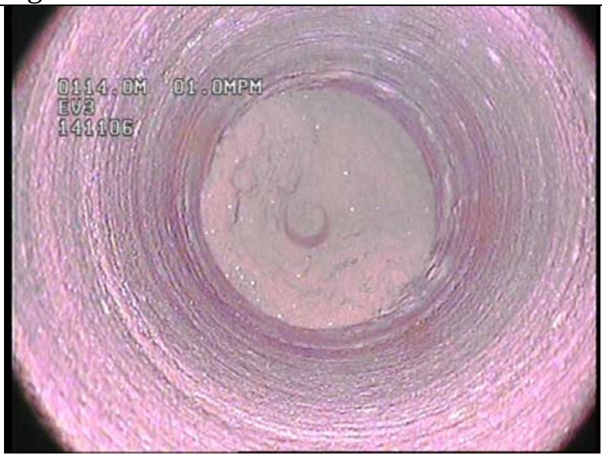


Figure 55. EV3: borehole base.

3.4 Groundwater quality

3.4.1 Water types, sources of contamination and ionic balances

The porewater analyses for the major and some minor ions are presented in Tables 8 and 9; full analyses are presented in Appendix 1.

Analyses of porewaters from drilled core have been compromised in the past by the covert use of foam additives or water mist by contractors whilst drilling. In a previous project phase it was found that the use of foam had not introduced nitrate or chloride into the porewaters and thus concentrations of these are probably representative of inputs derived from agriculture even if some contamination by water/foam is evident (for instance in Na and SO_4 concentrations).

Table 8. EV2 Porewater analyses for major and selected minor ions

Parameter	**Abbreviation**	**Unit**	**Min**	**Max**	**Mean**
conductivity	SEC	µS/cm	182	528	275
calcium	Ca	mg/l	20.1	46.7	31.6
magnesium	Mg	mg/l	2.9	9.6	6.4
sodium	Na	mg/l	11.1	23.7	14.3
potassium	K	mg/l	1.8	4.0	2.5
chloride	Cl	mg/l	18.6	48.6	26.8
sulphate	SO_4	mg/l	10.2	39.4	16.2
bicarbonate	HCO_3	mg/l	20	154	92
nitrate as NO3	NO_3	mg/l	5.3	15.2	10.6
iron	Fe	mg/l	<0.005	0.08	<0.005
manganese	Mn	mg/l	<0.002	0.025	<0.002

Sample size 43 except HCO_3 64 and pH 62

Table 9. EV3 Porewater analyses for major and selected minor ions

Parameter	**Abbreviation**	**Unit**	**Min**	**Max**	**Mean**
conductivity	SEC	µS/cm	184	845	352
calcium	Ca	mg/l	14.2	71.4	37.7
magnesium	Mg	mg/l	1.9	10.0	4.6
sodium	Na	mg/l	14.5	50.6	26.0
potassium	K	mg/l	1.7	7.4	3.8
chloride	Cl	mg/l	21.7	90.0	48.8
sulphate	SO_4	mg/l	16.2	167	51.1
bicarbonate	HCO_3	mg/l	3.0	52	23.9
nitrate as NO3	NO_3	mg/l	1.1	82.4	31.9
iron	Fe	mg/l	<0.005	0.07	<0.005
manganese	Mn	mg/l	<0.002	0.11	0.01

Sample size 43 except HCO_3 64 and pH 62

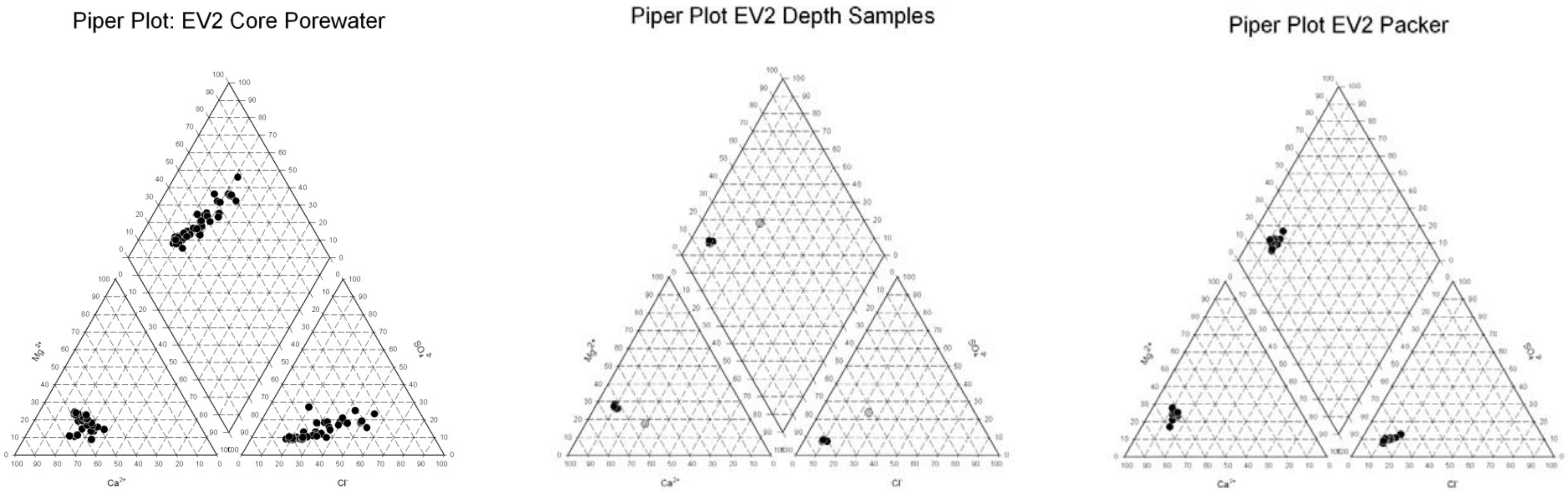


Figure 56. Piper diagram for waters from borehole EV2

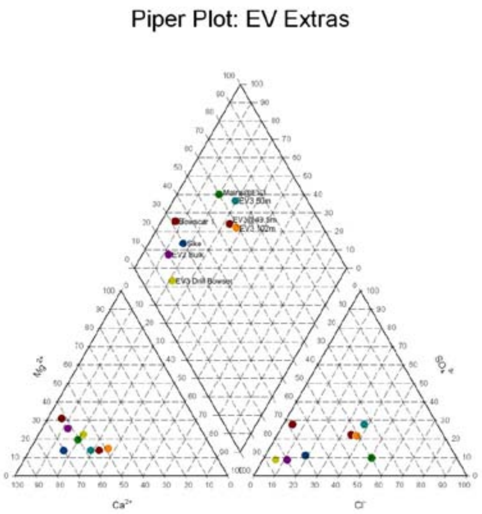


Figure 57. Piper diagram for additional samples

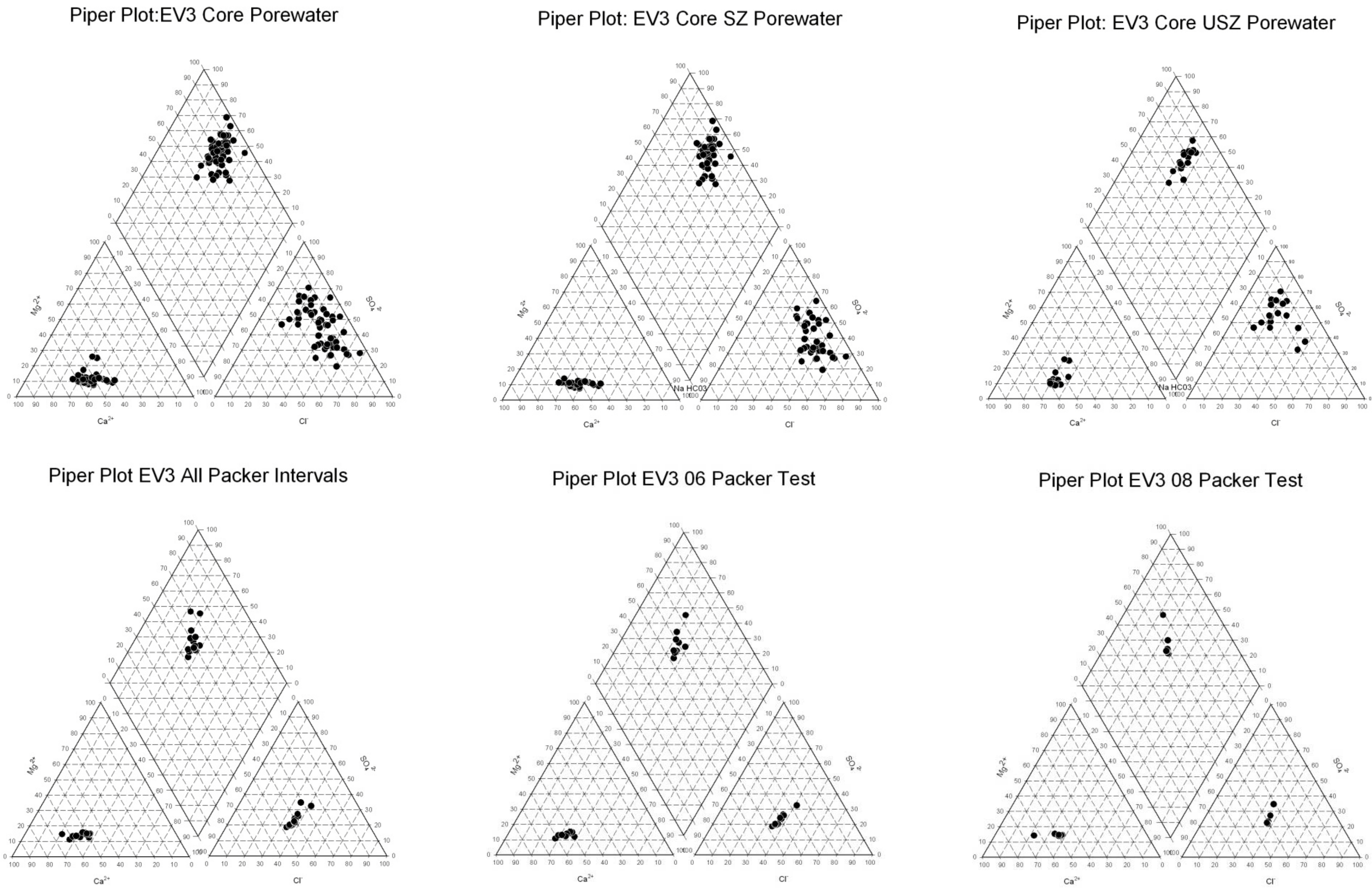


Figure 58. Piper diagram for waters from borehole EV3

EV2

EV2 core porewater

The porewaters in the saturated zone are of a mixed water type (Ca - Cl/HCO_3), with subordinate SO_4 concentrations Fig 56a. These contrast with the groundwater sampled as part of the Catchment Water Quality Survey (Butcher et al 2005) which were predominantly of Ca - HCO_3 type. There appears to be an evolution of the groundwater anions from Cl to HCO_3 with depth.

Figure 57 shows EV2 core porewater and depth samples in comparison with bulk water from Tarn Wood (Nord Vue) public supply borehole (*grey marker*).

EV2 packer

These pumped interval groundwaters are dominated by calcium bicarbonate (Ca/Mg - HCO_3) water

EV2 depth samples

These open borehole waters sampled by switched bailer are similar to packer interval groundwaters dominated by (Ca/Mg - HCO_3) water.

EV3

EV3 core unsaturated zone (USZ) porewater

The porewaters in the unsaturated zone are of a mixed water type dominated by calcium - sulphate to calcium - chloride and contrasts with the groundwater sampled as part of the Catchment Water Quality Survey (Butcher et al. 2005) which were predominantly of Ca – HCO_3 type.

EV3 core saturated zone (SZ) porewater

The porewaters in the saturated zone are of a mixed water type dominated by calcium/sodium sulphate to calcium/sodium chloride with lower magnesium and higher Cl concentrations than in the unsaturated zone.

EV3 packer

Pumped interval groundwaters exhibit no dominant type although calcium is the dominant cation and bicarbonate is slightly higher in these samples than from porewaters. Pump testing sampling in 2006 and 2008 exhibit similar sample hydrochemistry.

EV3 extras

These represent a variety of samples, some of which (EV2 Sike (stream), EV2 Bulk, EV3 Bowser and Bowscar new no.1 borehole) and have a calcium bicarbonate nature and were sampled as the opportunity arose during drilling. The others included bailed samples from EV3 and one from the mains supply are more mixed. The bowser and mains water were sampled in case they were introduced as drilling fluid.

3.4.2 Solute porewater depth profiles

EV2

The principal interest in this study is the movement of chloride and nitrate (derived from chemical fertilisers and animal slurry) through the saturated zone following the conversion of rough unfertilised grazing to intensive cropping (mostly grass).

Porewater concentration – depth profiles for a range of solutes are presented in Figure 59, summarised in Table 8 (and tabulated in Appendix 1).

Original water strikes were encountered in superficial deposits from c. 7 to 16 m below borehole casing top (bct) and then c. 25 m bct in bedrock with water rising to c. 5 m bct.

Nitrate (as NO_3) concentration in porewaters are relatively low and range from c. 5 to 15 mg/l. These exhibit a steady decline with depth downhole to about 89 m where concentrations reach baseline values (5 ≤mg NO_3/l), Shand et al. (2003). Sources of nitrate are principally anthropogenic and derived from agriculture.

A lower concentration at a depth of c. 30 m contrasts with increased concentration in many other determinands. This is may be due to the introduction of treated water, added to the borehole to improve drilling progress at this depth.

Depth samples taken by a sealed bailer from selected depths in the borehole adjacent to inflows (identified during geophyscial testing) are generally consistent with the porewater profile.

Chloride (Cl) concentration in porewaters are modest, ranging from c. 18 to 48 mg/l. These exhibit a steady decline downhole and become quite consistent below a depth of 50 m where concentrations vary only slightly around c. 22 mg/l with no apparent trend.

Baseline concentrations of≤10mg/l (Shand et al. 1997) were sampled in the borehole at selected depths although it should be noted that there was significant upflow in the borehole at the time.

Higher concentrations above a depth of c. 30 m compares with increased concentration in many other determinands except nitrate. An unusually high ‘outlier’ at a depth of c. 79 m compares with other determinand profiles. Sources of chloride (Cl) in groundwater recharge can be both natural (including rainfall), and anthropogenic (principally derived from chemical fertilisers and animal slurry).

Porewater specific electrical conductance (SEC) ranges from c. 180 to 330 µS/cm with a pronounced ‘spike’ >500 µS/cm at a depth of c. 24 m and lesser spikes in common with other determinands at c. 29m and 79m. The profile exhibits a steady increasing trend downhole to about 320 µS/cm at the base.

Porewater sulphate (SO_4) ranges from c. 3.5 to 6.3 mg/l. A pronounced low spike at c. 28 m is consistent with one in the calcium profile. Elevated concentrations are also indicated above 25 m and at c. 29-31, 50 and 79 m, some of which are in common with other determinands. The profile exhibits a gently rising trend downhole but with greater variation between depths of 80 and 90 m

Porewater calcium (Ca) concentrations range between c. 20 and 47 mg/l. Concentrations are subdued at depths of c. 28, 32, 34 and 51 m and notably raised at 22m and also at 57 and 79 m. The profile shows an increasing trend downhole albeit with a relatively broad range.

Porewater sodium (Na) concentrations range from c. 12 to 24 mg/l. There is a notable peak and c. 30 m, a lesser ‘spike’ at c. 79 m and the profile otherwise exhibits a relatively consistent range below 50 m.

Porewater bicarbonate (HCO_3) ranges from c. 20 mg/l at 50 m to 160 mg/l at 83 m. There is a pronounced ‘low’ concentration at c. 50 m in a profile exhibiting an increasing trend but with less variation at depth.

Porewater potassium (K) ranges from c. 2 to 4 mg/l with peaks at 22, 30-31, 36 48 and 79 m. The variability and general trend reduces with depth.

Porewater magnesium (Mg) ranges from c. 3 mg/l at 24 m to c. 9 mg/l at 57 m. The porewater profile exhibits an increasing trend with depth following a similar pattern to the pH profile.

Porewater pH ranges from c. 7.5 to 8.6. The porewater profile exhibits an increasing trend with depth to about 70 m which reverses below 70 m.

EV3

The principal interest in this study is the movement of chloride and nitrate (derived from chemical fertilisers and animal slurry) through the unsaturated zone and saturated zone following the conversion of rough unfertilised grazing to intensive cropping (mostly grass).

Porewater concentration – depth profiles for a range of solutes are presented in Figure 60, and summarised in Table 9 (and tabulated in Appendix 1).

The water table was encountered at c. 50 m bct with no recorded perched water levels.

Nitrate (as NO_3) concentration in the unsaturated zone ranges from c. 1 to c. 80 mg/l. The particularly low concentration at c. 40 m and similarly at c. 52 m is consistent with an unauthorised use of drilling fluid (derived from a water main and containing a greater HCO_3 content). Saturated zone porewater concentrations between depths of 50 and 76 m are in the range 5-70 mg/l and relatively low values c. 5 to 15 mg/l below 76 m.

Chloride (Cl) concentration in porewaters in the unsaturated zone range from c. 25 to 75 mg/l. In the saturated zone below a depth of 50 m the values reduce to below 25 mg/l but with more irregularity than for nitrate, particularly below c. 80m.

Porewater specific electrical conductance (SEC) ranges from c. 200 to 300 µS/cm down to a depth of 40m in the unsaturated zone and peaks at c. 530 mg/l a little above the water table. Below the water table to c. 76m values lie in the range 200-500 and then apart from a sharp peak at c. 90 m these decline to less than 200 mg/l at the base of the borehole.

Porewater sulphate (SO_4) in the unsaturated zone ranges from c. 30 to 50 mg/l to a depth of 40 m and is elevated up to 120 mg/l closer to the water table. In the saturated zone the typical range is c. 25 to 75 mg/l with elevated levels at c. 73, 77 and particularly so at 90 m where the concentration is c. 170mg/l. At the base of the borehole SO_4 reduces to c. 20 mg/l.

Porewater calcium (Ca) concentrations in the unsaturated zone ranges from c. 26 to 40 mg/l to a depth of 40 m and between c. 30 and 70 mg/l just above the water table. Concentrations reduce at the water table and then reduce gradually to the base of the borehole ranging from 18 to 60 mg/l with an isolated peak of c. 70 mg/l at 90 m.

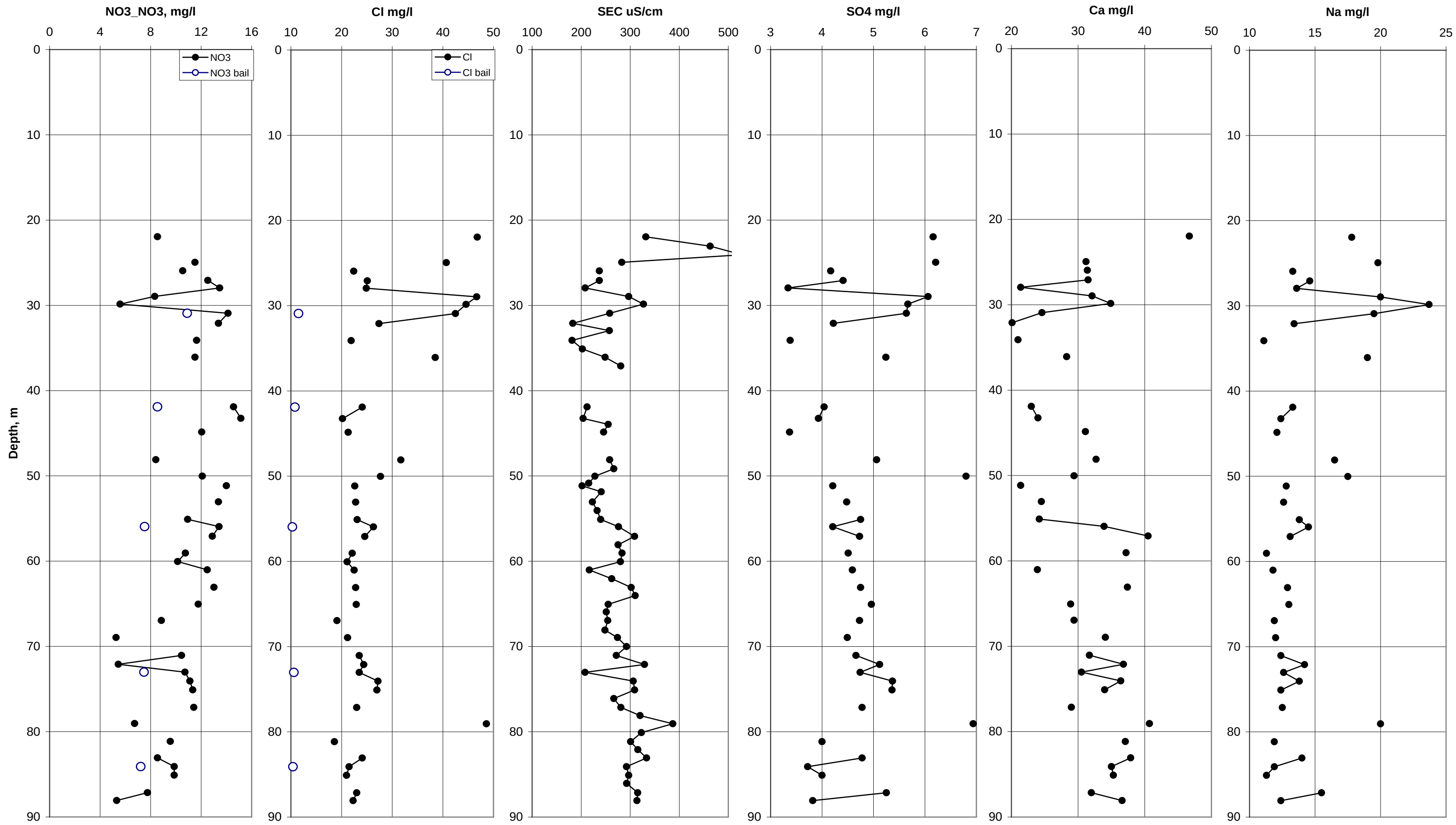
Porewater sodium (Na) concentrations range from c. 12 to 38 mg/l with an isolated elevated peak at 90m. The profile resembles a subdued form of the calcium profile.

Porewater bicarbonate (HCO_3) ranges from c. 10 to 52 mg/l in the unsaturated zone with a peak at 40 m. Below the water table there is a notable ‘low concentration of c. 2 mg/l at 59 m but generally there is a gradual increase and a range between c. 10 and 40 mg/l.

Porewater potassium (K) content ranges from c. 2 to 3 mg/l in the unsaturated zone above 40 m, a range of 2.5 to 7 mg/l through and below the water table decreasing toward the base of the borehole.

The porewater magnesium (Mg) profile exhibits a relatively rapid decline from c. 10 mg/l to c. 3.5 mg/l at c. 30 m. Below this a similar profile to several of the other determinands is shown in the unsaturated zone and below the water table with a notable high value of c. 9.5 mg/l at c. 90 m.

Porewater pH ranges from c. 7.5 to 8.6. The porewater profile exhibits an increasing trend with depth to about 70 m which reverses below 70 m.



NO3_NO3, mg/l
Cl mg/l
SEC uS/cm
SO4 mg/l
Ca mg/l
Na mg/l
NO3
NO3 bail
Cl
Cl bail
Depth, m

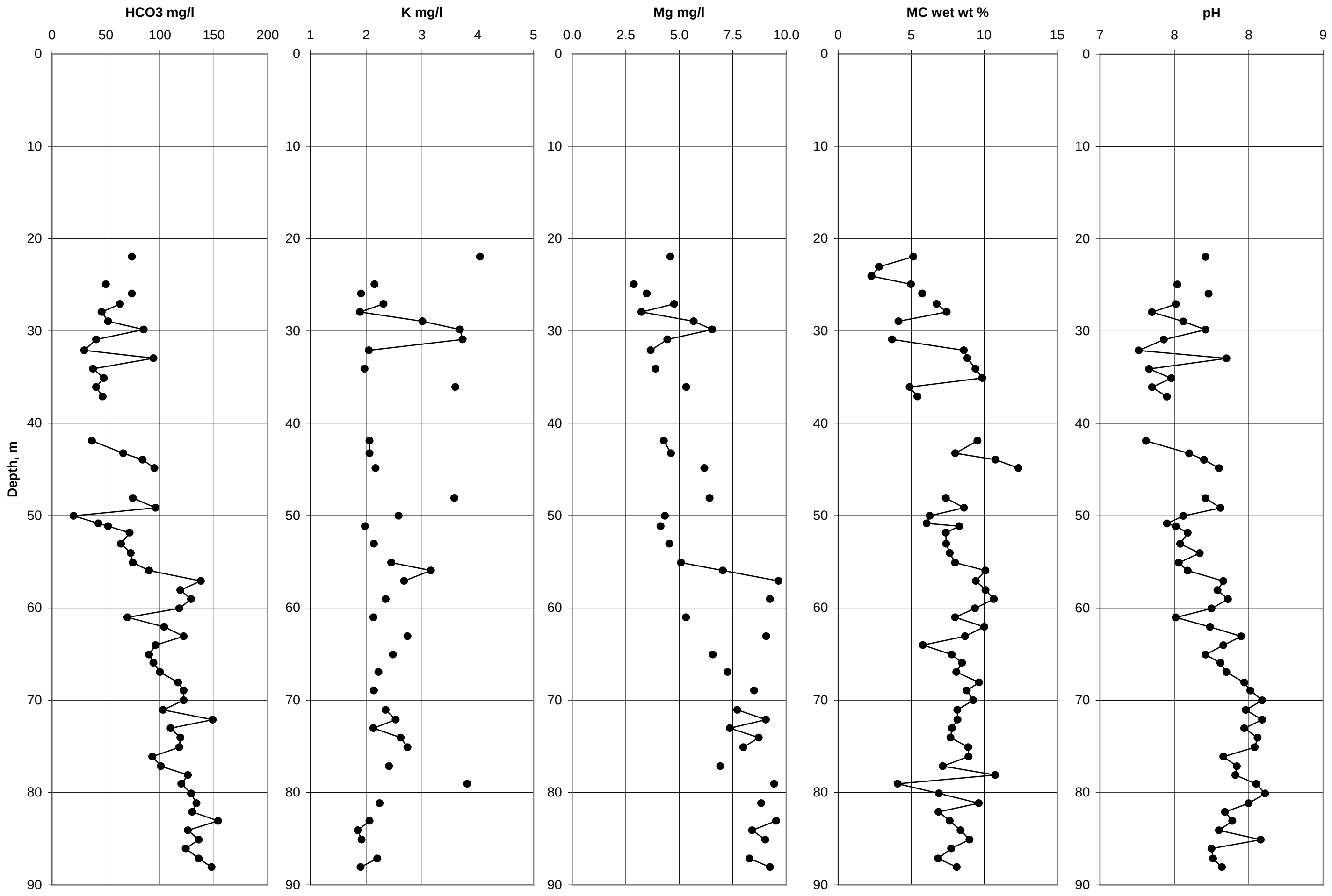
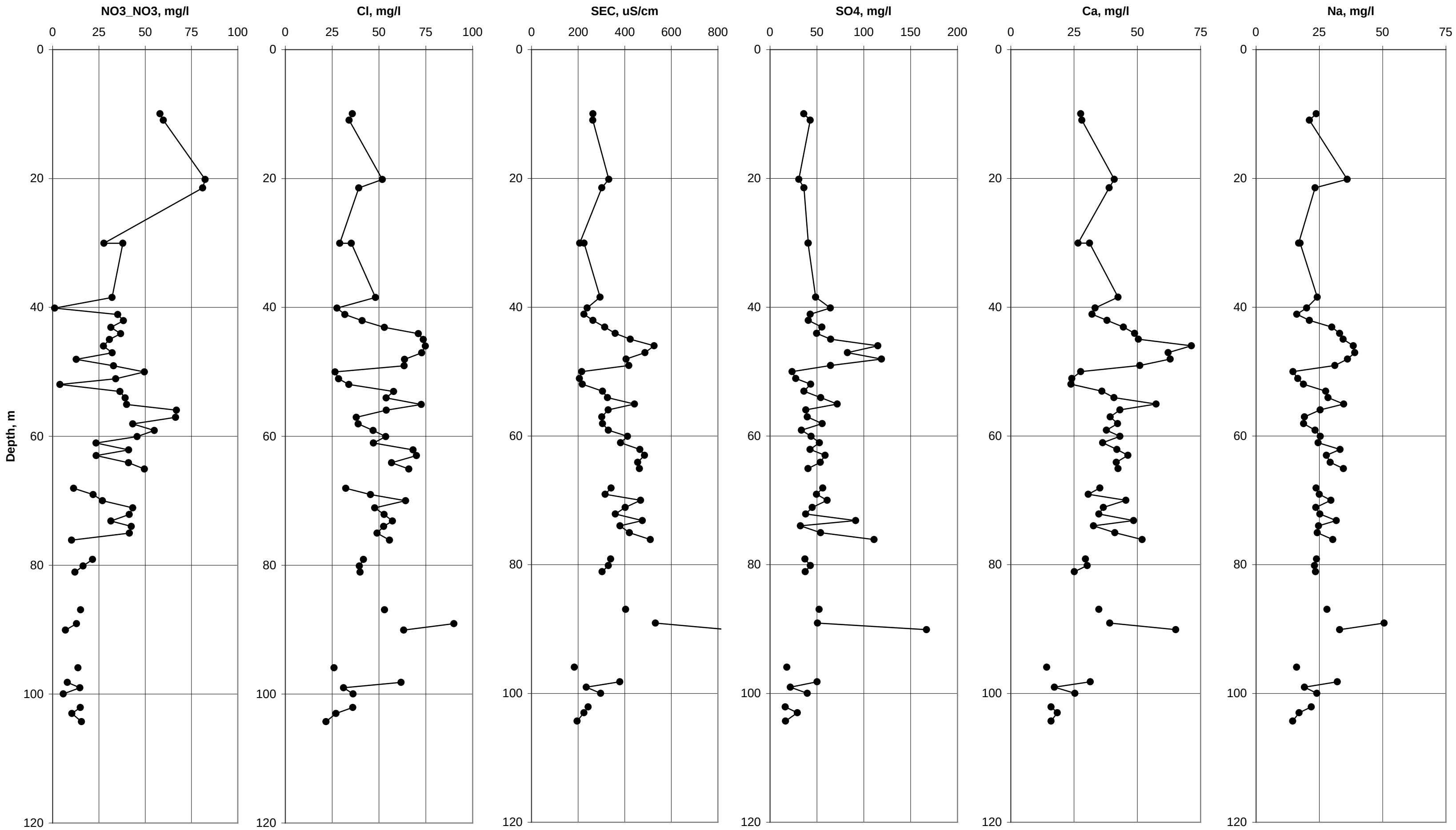


Figure 59. EV2: porewater chemistry profiles


NO3_NO3, mg/l
Cl, mg/l
SEC, uS/cm
SO4, mg/l
Ca, mg/l
Na, mg/l
Depth, m

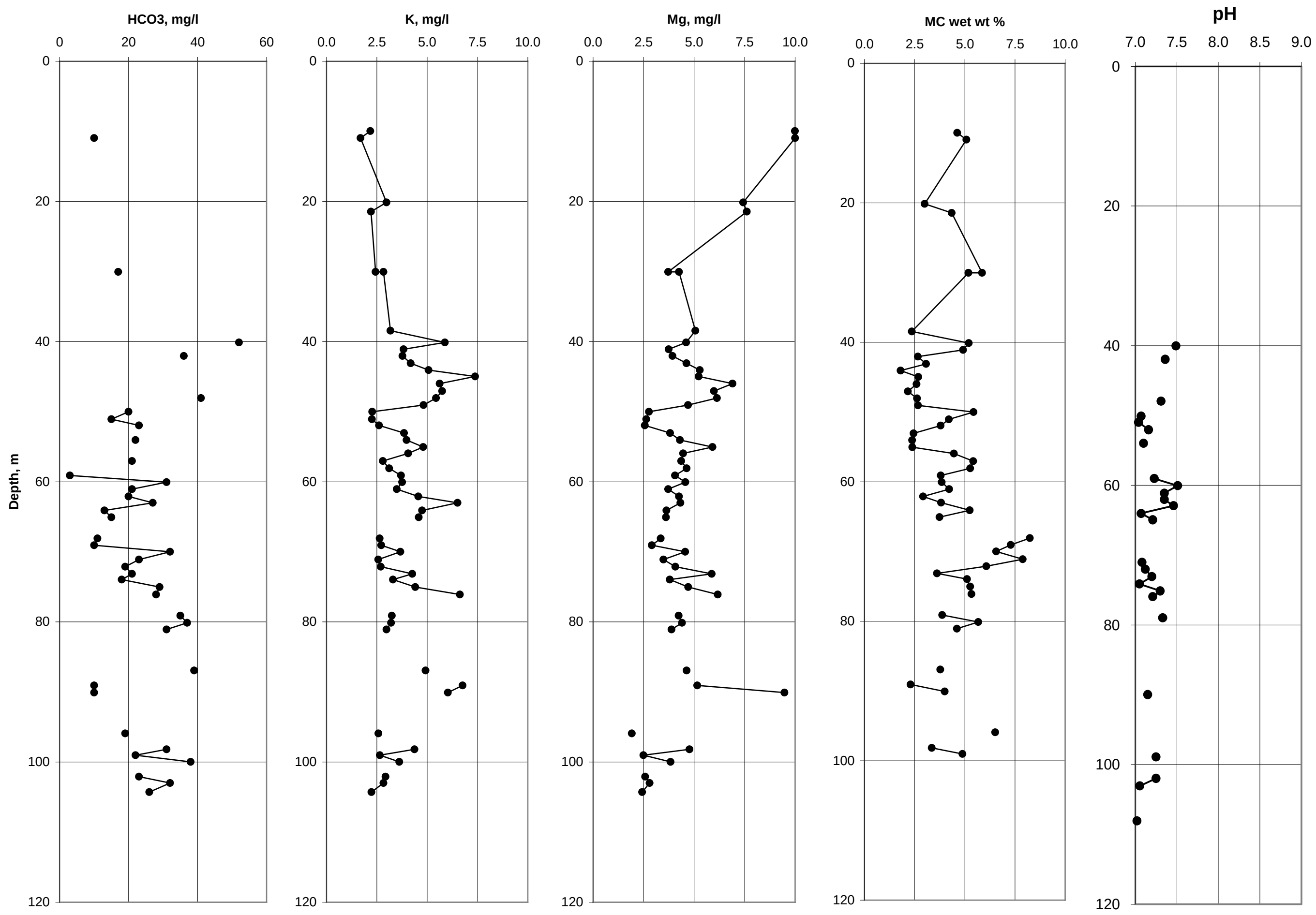


Figure 60. EV3: porewater chemistry profiles

3.5 Groundwater residence time

Overview

CFCs and SF_6 - porewaters have generally low concentrations in comparison to modern (i.e. 2008) recharge. From the borehole logs it is likely that fracture flow is important in this aquifer, so the results are interpreted to mean that the water is basically 'old' but with varying small amounts of modern recharge mixing with it. Table 10 shows the proportion of modern recharge calculated for each indicator.

There is moderately good agreement between the CFCs and more modern dates for year of recharge suggested by SF_6. Since it is present at exceedingly low concentrations in groundwater (10^3 times lower than the CFCs), measurement is inherently less precise and its main use is to show when CFC concentrations may have been raised by contamination. Since there is no evidence for this at any of the sampled sites, the CFC average has been taken to represent the percentage of modern water.

Tables 10 and 11 show the results of the SF6 and CFC analysis for the intervals sampled in boreholes EV2 and EV3.

The pumped interval water CFC/SF6 results indicated that concentrations, associated with 10% modern / 1960 recharge, had penetrated to about 50 m depth in EV2 (transect outflow end) and c. 85 m depth in EV3 (the intermediate transect borehole).

Table 10. EV2 summary of SF6 and CFC analyses for pumped intervals

Top of interval	**Modern Fraction**			**Year of Recharge**		
m bct	*CFC-12*	*CFC-11*	*SF6*	*CFC-12*	*CFC-11*	*SF6*
26.8	0.78	0.46	0.71	1987	1975	1998
36.2	0.25	0.17	0.35	1970	1968	1989
38.8	0.19	0.18	0.09	1968	1968	1977
31.9	0.11	0.10	0.09	1964	1965	1977
42.7	0.09	0.12	0.06	1963	1966	1973
56.2	0.08	0.09	0.04	1962	1964	1971
66.7	0.15	0.15	-	1966	1967	<1970
49.7	0.05	0.12	-	1958	1966	<1970
51.7	0.05	0.09	-	1957	1964	<1970
73.2	0.03	0.02	-	1955	1957	<1970
84.7	0.02	0.03	-	1951	1958	<1970

Table 11. EV3 summary of SF6 and CFC analyses for pumped intervals

Top of interval	**Modern Fraction**			**Year of Recharge**		
m bct	*CFC-12*	*CFC-11*	*SF6*	*CFC-12*	*CFC-11*	*SF6*
57.3	0.63	1.19	0.17	1982	>modern	1982
57.3	0.56	1.03	0.25	1980	1988	1986
70	0.38	0.54	0.16	1974	1976	1982
70	0.16	0.25	0.12	1967	1970	1979
75	0.04	0.04	0	1956	1960	<1975
75	0.03	0.04	0	1954	1960	<1975
79.9	0.10	0.16	0.14	1963	1967	1981
79.9	0.06	0.16	0.09	1959	1967	1978
83.9	0.05	0.13	0.09	1957	1966	1978
83.9	0.05	0.08	0.08	1958	1963	1976
89.9	0.02	0.05	0	1953	1961	<1975
89.9	0.08	0.15	0.08	1962	1967	1977
93.9	0.02	0.05	0	1953	1961	<1975
93.9	0.02	0.04	0	1953	1960	<1975
99.4	0.08	0.04	0.12	1961	1960	1980
99.4	0.02	0.06	0	1951	1962	<1975
101.3	*0.96*	*0.18*	*0.34*	*1992*	*1968*	*1990*
101.3	*0.75*	*0.14*	*0.38*	*1986*	*1967*	*1991*

Pumping level at 101.3m fluctuated wildly and is probably contaminated

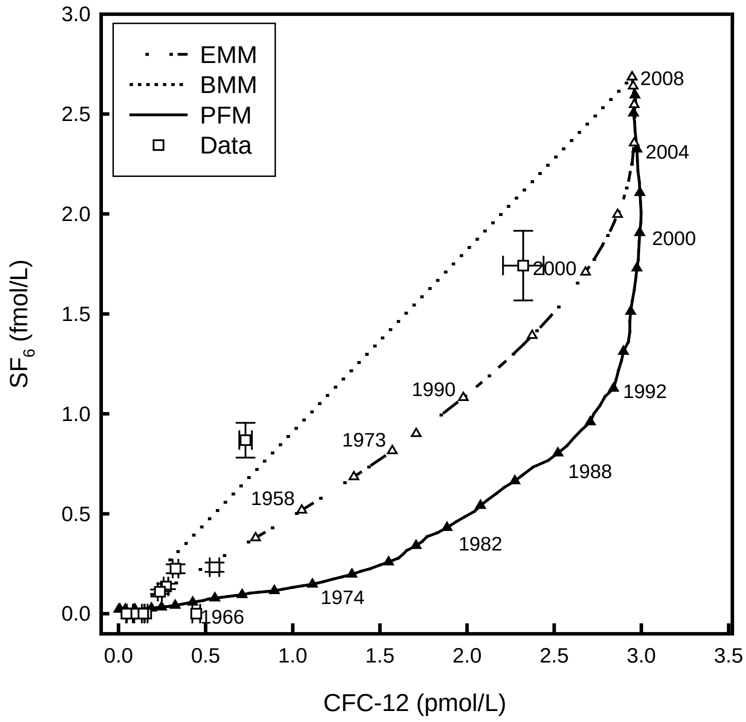
CFC 12 and SF6 Bow diagrams

Data for sampled intervals for the two boreholes are plotted on 'Bow Diagrams' in Figure 61. These diagrams are used to help indicate the process of groundwater flow and mixing according to an Environmental Mixing Model (EMM), Binary Flow Model (BMM) or Piston Flow Model (PFM).

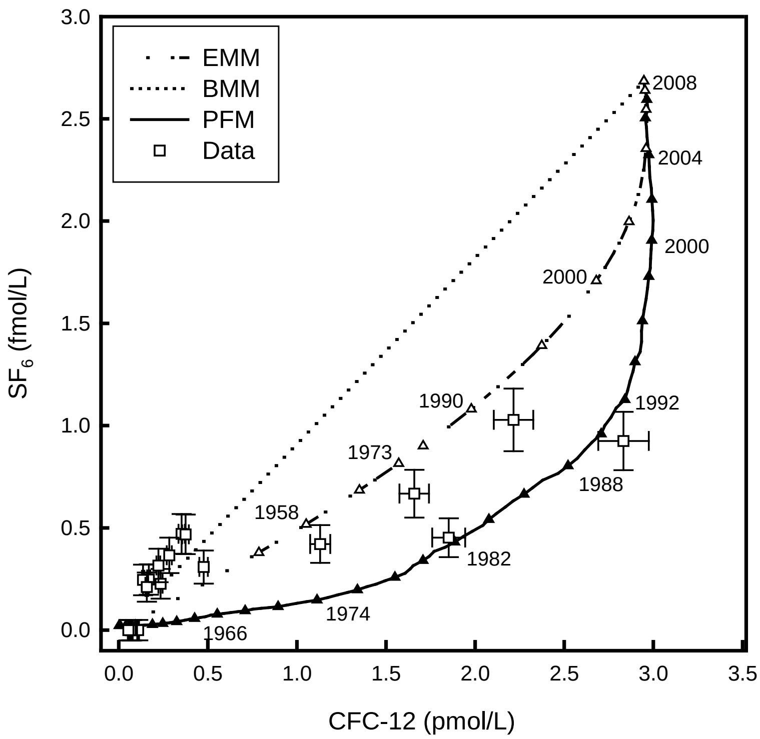
For sampled interval groundwaters from EV2, the datapoints plot generally between the BMM and EMM paths. Data for samples from intervals in EV3 plot close to the BMM for low concentration (less modern waters) and between the EMM and PFM for more modern waters. Aside from determining definitive flow processes in the two boreholes, the flow processes are identified as being different at different parts of the groundwater transect.

CFCs and nitrate concentration

The crossplot of nitrate concentration against the residence time of the groundwater for CFCs in Figure 63 shows a trend of higher nitrate concentrations with younger groundwaters although the correlation relies on few points for the modern water. Depth profiles of interval porewater CFCs, SF6, NO3 and Cl from packer pumping tests in Figures 62, 64, 65 and 66.



EV2



EV3

Figure 61. Packer interval CFC SF6 curves

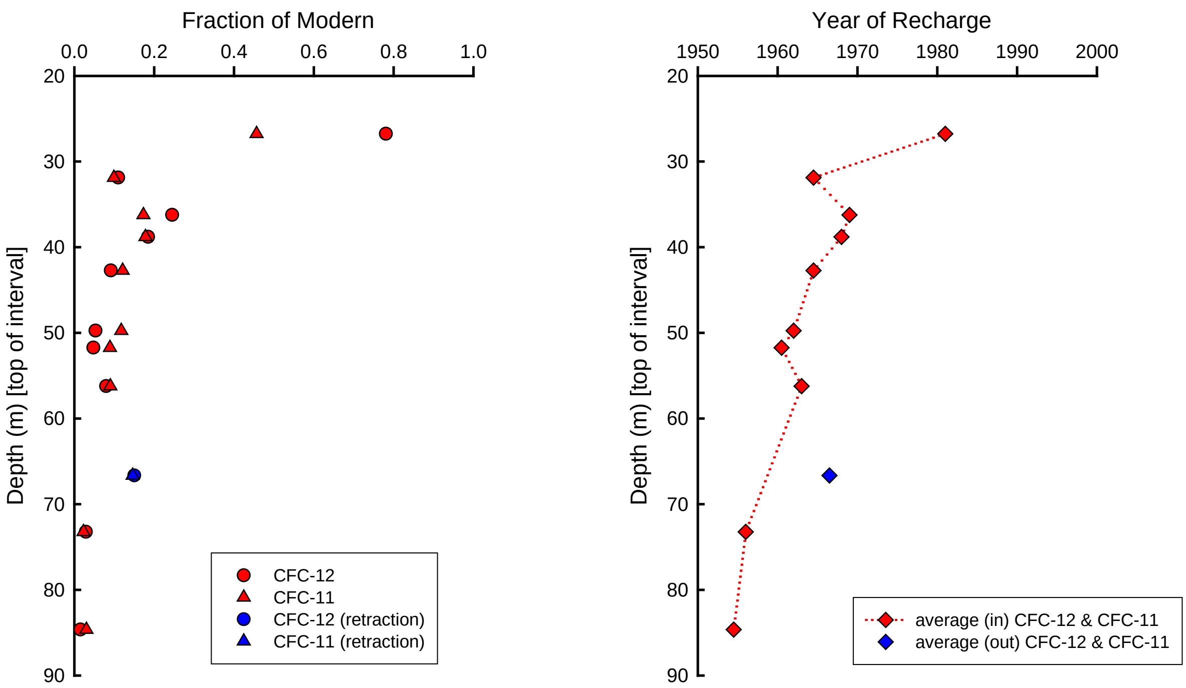


Figure 62. EV2: packer interval CFC SF6 profiles

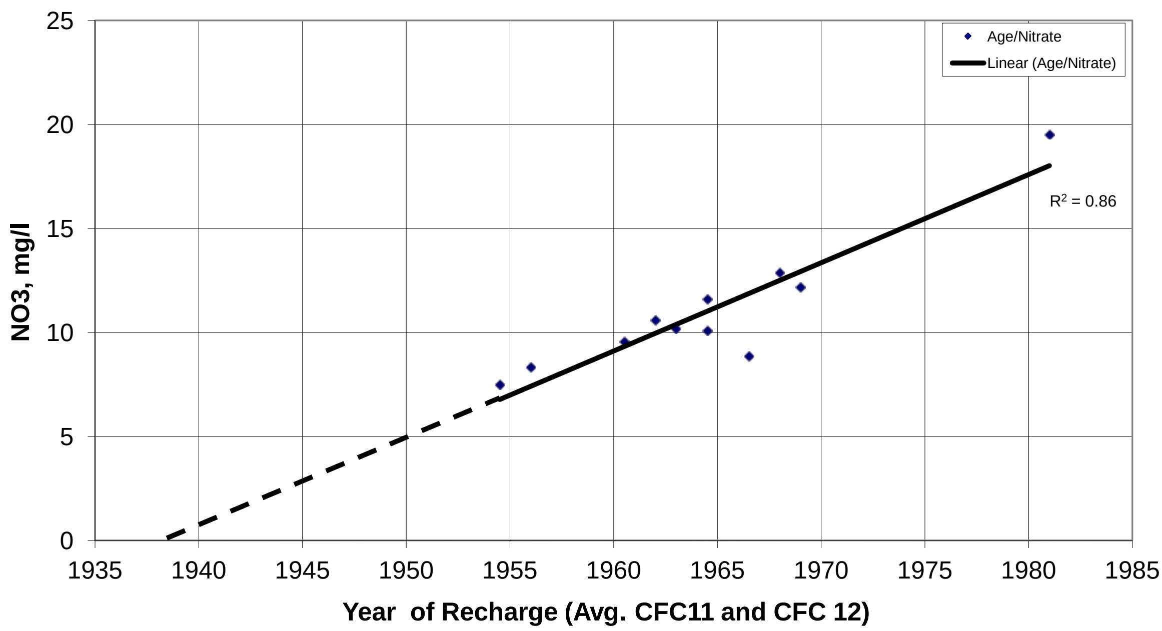


Figure 63. EV2: packer interval NO_3 concentration vs. average recharge year

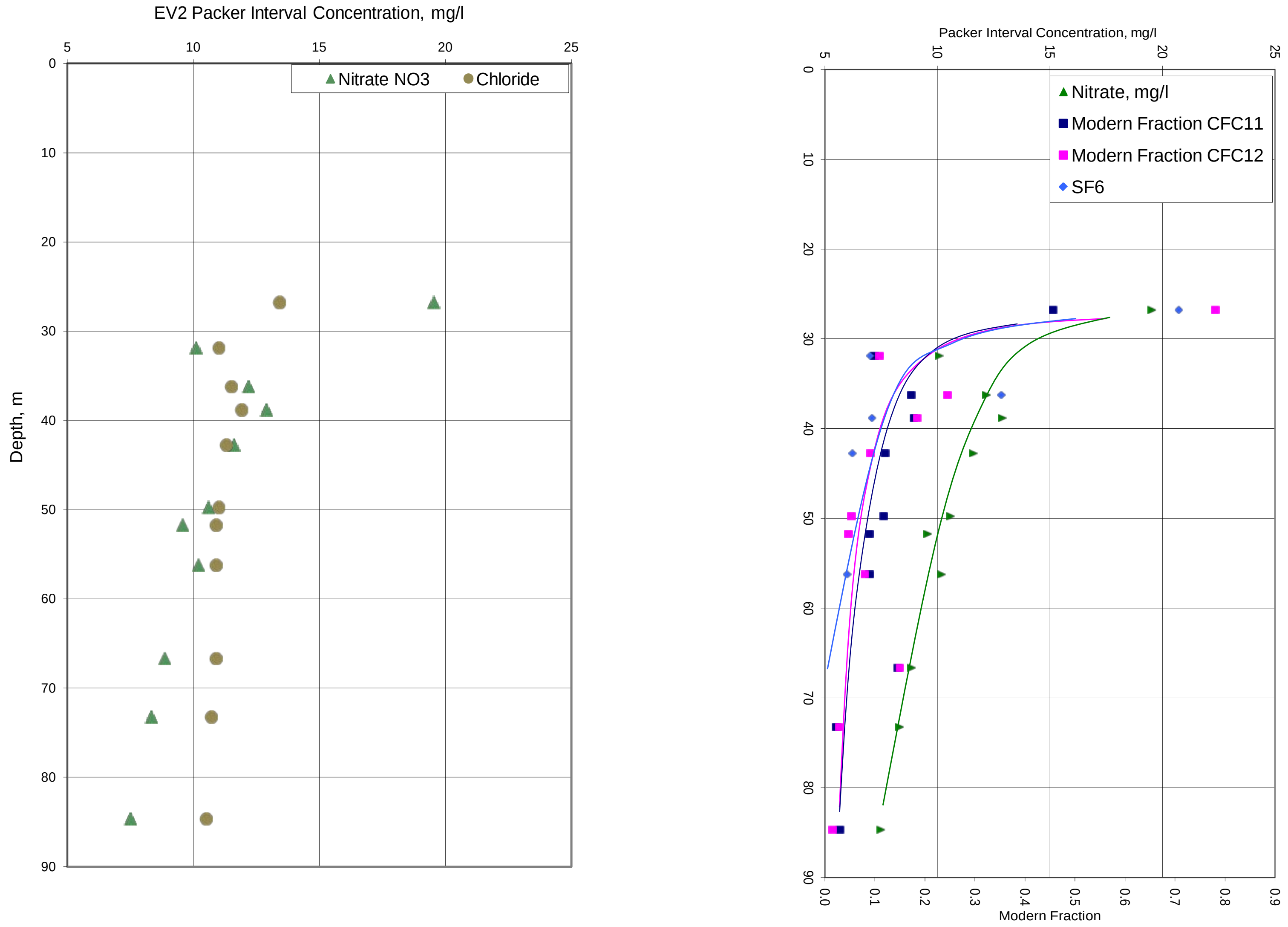
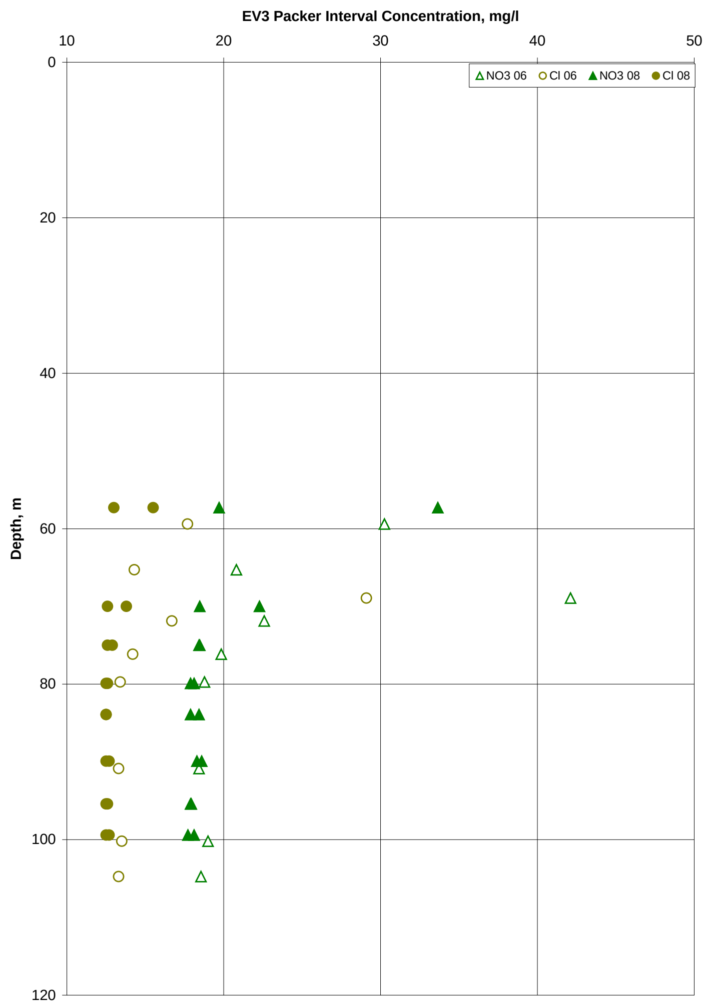


Figure 64. EV2: packer interval NO3, Cl, CFC and SF6 profiles



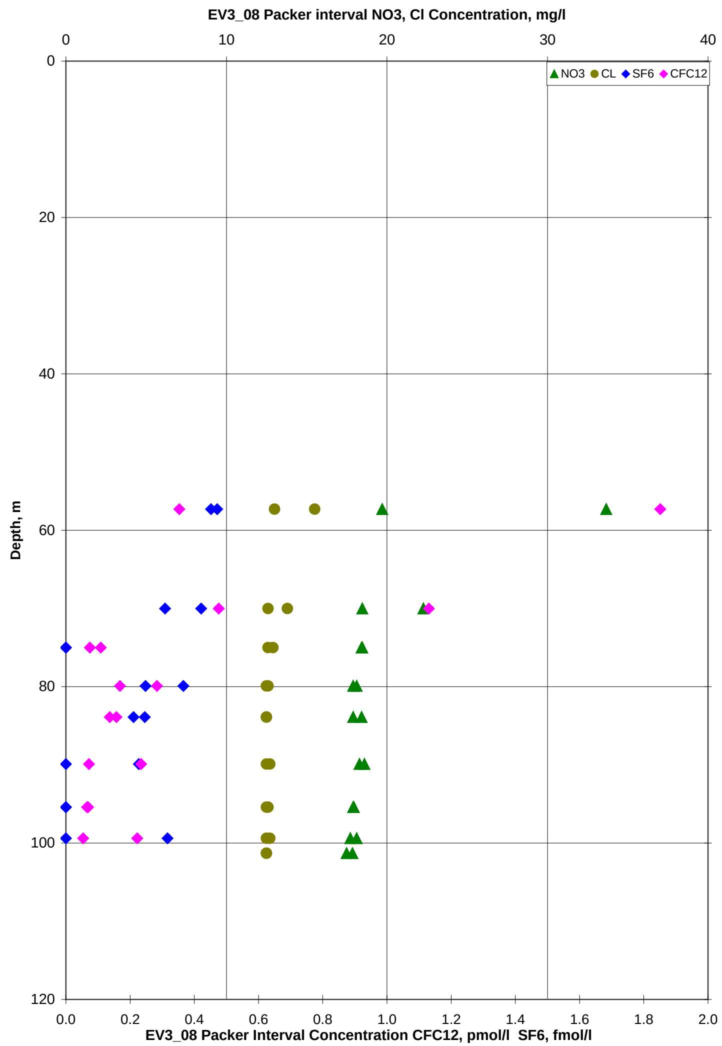
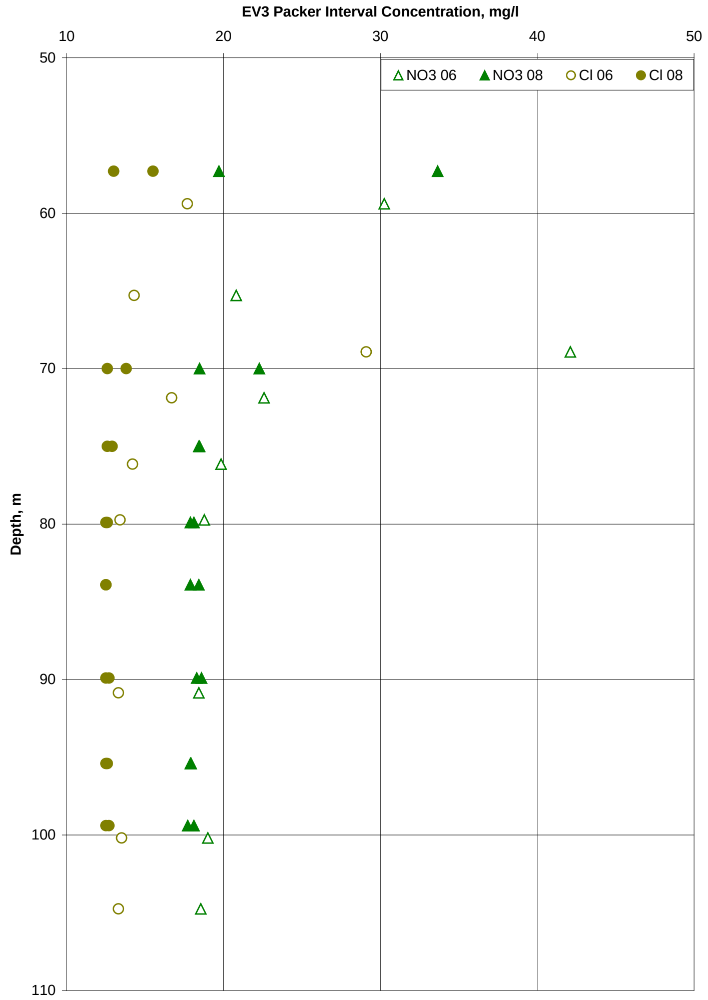


Figure 65. EV3: packer interval NO3, Cl, CFC and SF6 profiles



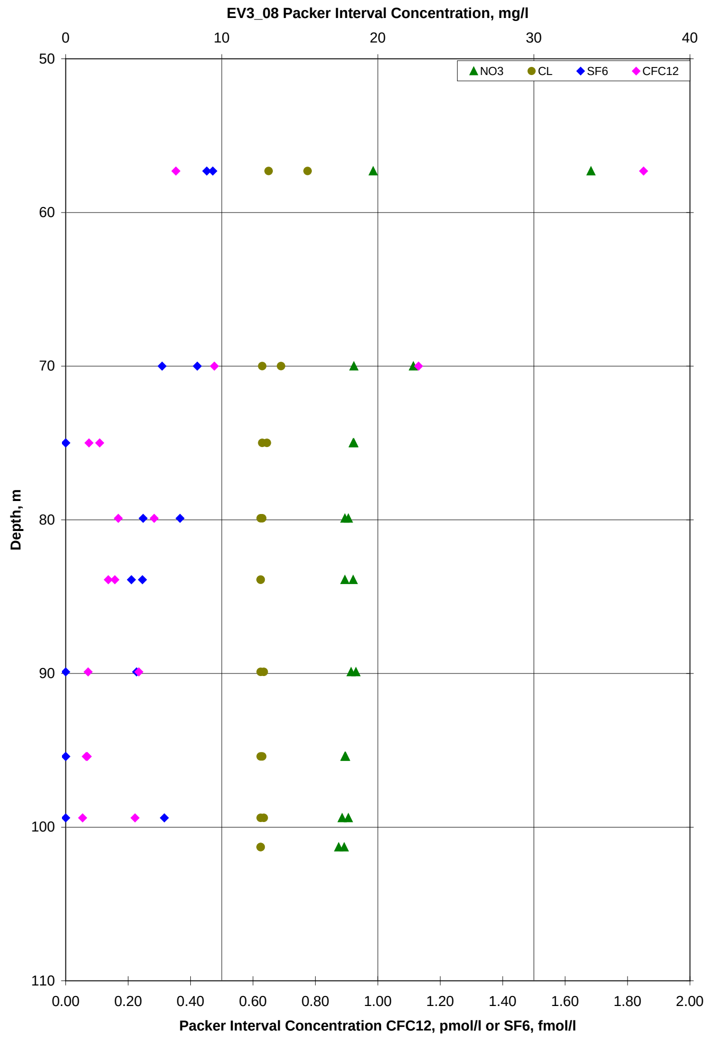


Figure 66. EV3: packer interval NO3, Cl, CFC and SF6 profiles

4. DISCUSSION

On the basis of data profiles developed, an amendment to the earlier conceptual groundwater flow path transect has been possible. Figure 67 incorporates generalised groundwater age and nitrate concentration ranges.

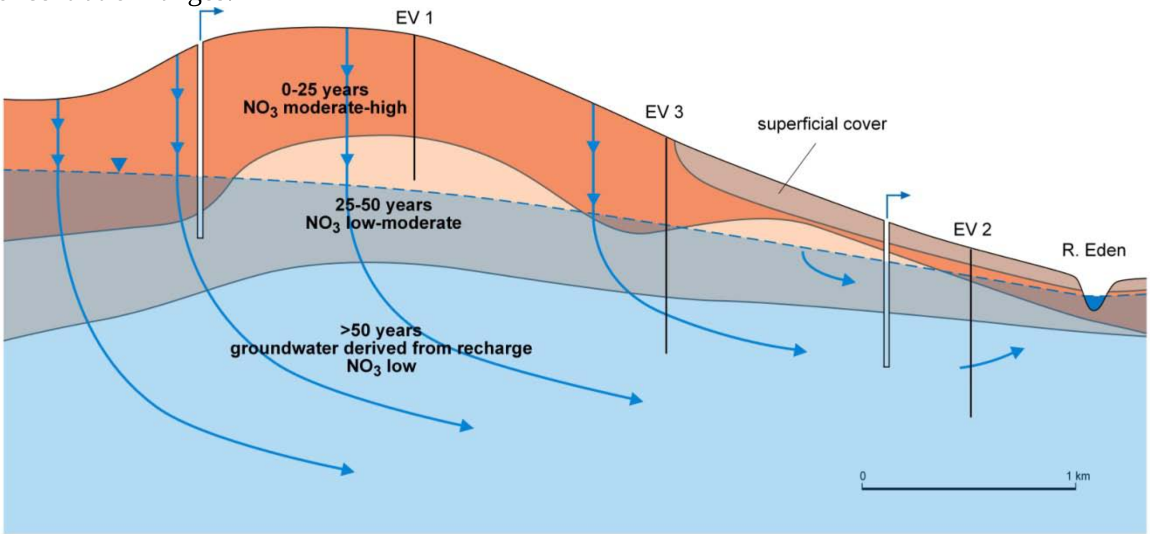


Figure 67. Conceptual groundwater flow path transect in Penrith area with project boreholes and interpreted water quality interpretation

Physical Characteristics (EV2)

Horizontal permeability determined on core samples was between 0.02 mD and 18400 mD (K c.8 m/d) averaging 1340 mD (K, 0.86 m/d).

It is notable that the mean pumped interval (formation) hydraulic conductivity (K), 6.2 m/d, is almost an order of magnitude greater than mean plug (matrix) K, 0.86 m/d. The highest formation hydraulic conductivities up to 41 m/d are in intervals *42.7 to 44.8 m bct.*

A key question is how extensive are these fractures? A radius of 500 m was used as a default fracture extent. It is uncertain now why this value was selected (but thought to be used to exceed values from basic calculations following discussion of evidence from Price and Williams, 1993 and Price 1994). Fractures or fracture networks extending from tens to several hundred metres based on correlation between observation and pumping boreholes were considered.

Related to the question of fracture extent is what controls these fractures? Are fractures associated with specific stratigraphic horizons, with elevation and structural movement, or with lithologies (e.g. friable, loosely cemented horizons?). The presence of slickenside features in nearby outcrops and quarries and apparent fault gouge structures including cataclatic cementation (granulation seams) e.g. in EV2 suggest a complex flow mechanism probably affected by low permeability boundaries and thus potentially by compartmentalism. This would form the basis of some interesting and worthwhile research as there is a considerable amount of data from this project; the previous BGS research activities at Cliburn and using Environment Agency monitoring boreholes. The Environment Agency have allowed access to some of their monitoring boreholes for further investigation (and BGS have subsequently undertaken imaging on surrounding boreholes at Staffield and Cliburn). In addition, discussions with Dr Mike Price and Prof. John Barker regarding their previous aspirations to test fracture dimensions and extent by injecting air into fractures using a packer system would offer one approach to investigating these.

According to Barker and Tellam (*2006*) it is clear that very little is known about fracture extent or controls on fracture development in the Permo-Triassic sandstones. A review of Nirex/NDA Permo-Triassic research data would be worthwhile, particularly in advance of potential new repository investigations in Permo-Triassic rocks.

Also of value would be a review of different model scenarios (for different fracture extents, Price 1994) using data from the aquifer (fracture T, matrix T and porosity (based on borehole data) and estimate what is the minimum fracture dimension required to explain observed porewater nitrate concentration and residence time data in the boreholes.

During the borehole geophysical logging, the heat-pulse flowmeter indicated an upwards flow (not unexpected) with inflow occurring above 50m depth. Further efforts aimed at interpreting chemistry results could be useful in understanding other Permo-Triassic settings. This would be appropriate at public supply boreholes where a time series record of nitrate concentration was available.

Water Quality (EV2)

Porewater chemistry profiles of major determinands are plotted in Figure 59 and packer interval test profiles in Figure 64. In general, the packer test nitrate data agree well with porewater nitrate. This suggests little cross-contamination.

In figure 63 the packer interval NO_3 concentration vs. average recharge year (CFC) exhibits a coefficient of determination R^2 of 0.82. In contrast, during the earlier catchment water quality survey, the R^2 value was a much poorer 0.02. This probably reflects the broad range of hydrogeological environments and regimes encountered in the latter.

The profile can probably be subdivided into three main sections:

70-90 m depth

Nitrate porewaters vary 5-11 mg/l (as NO_3). Higher nitrate (c. 11 mg/l) occur at 75-78 and c. 85m which appear to coincide with higher hydraulic conductivity (possibly fracture supplied?). These waters appear to show very little nitrate above background (or the start of penetration of the nitrate front associated with recharge post 1950s). This agrees with CFC data (e.g. 1955 recharge or 0.05 fraction of modern recharge).

30-70 m depth

Nitrate in this section of the aquifer is slightly higher (and increases towards shallow depth). Nitrate is c. 8-15 mg/l (as NO_3).

Porewater nitrate concentration is elevated at 32m, 42-43m, 51-52m, 57m. It would be interesting to explore how well these correlate with fracture intervals e.g. more modern water flowing through fractures and (possibly) diffusing into adjacent matrix? The profiles of CFCs suggest water of 1960-1972 origin equivalent to a fraction of modern water 0.1-0.3.

Above 30 m depth

Porewater nitrate concentration ranges from 8-14 mg/l. The packer test water at c. 28m is significantly higher (19 mg/l). This would be great evidence for more modern high nitrate water if there were more results!

CFCs suggests pumped water is relatively modern, c. 1980 origin. Percent modern c. 80% but there is only one clear result from this zone. Sampling was complicated by the presence of a silicified zone.

For groundwater modelling approaches it may be better to simplify the profile in Figure 62.

Fraction Modern Water	Year of recharge
0.4-0.8	1980
0.1-0.2	1960-1970
<.1	Pre 1960

Physical Characteristics (EV3)

Horizontal permeability determined on core samples ranged from 70 mD to 24200 mD (K c.16 m/d) and averaging 5030 mD (K 3.3 m/d) in EV3.

Borehole pump testing conducted on isolated intervals using packer testing suggested hydraulic conductivity up to 7.2 m/d. The mean pumped interval (formation) K is 3.34 m/d which is very similar to the mean plug (matrix) K of 3.3 m/d. The highest hydraulic conductivity was measured in the interval 94 - 96.9 m bct but interval tests were more consistent than in EV2. On examining the borehole images and core, it would appear that the complexity of fractures and fault gouge structures as well as the strongly cemented section of the aquifer in EV2 to a depth of c. 25m could account for the greater variability in aquifer properties.

A similar key question to that above is how extensive are these fractures?

A preceding study involved the drilling of a borehole, EV1 to a depth of 120 m at Greengill Farm, Maidenhall (Butcher et el, 2005). Due to the collapse of the cored borehole on reaching the water table and the loss of the drillstring this borehole was not geophysically logged. It would have been very valuable to correlate the stratigraphy and possible extensive fractures between boreholes EV1, EV2 and EV3, perhaps using a natural gamma log. Simple attempts at correlation between EV2 and EV3 have not been successful. More recent geophysical logging conducted at other nearby boreholes may still provide sufficient information to do this.

Water Quality (EV3)

Porewater chemistry profiles of major determinands are plotted in Figure 60 and packer interval test profiles in Figures 65 and 66.

It is interesting that the nitrate profile is very different to that in EV2 and demonstrates that higher (and more modern) nitrate groundwater appears to have penetrated this profile. Determining this was actually one of the objectives of the project.

80-100+ m depth

NO3 porewaters similar to packer test results and c 8-17 mg/l (NO_3). This corresponds with values in interval 30-70m in EV2 (in terms of NO_3 and CFC data).

50-80 m depth

Porewater nitrate concentrations 10-60 mg/l (NO_3) clearly suggest modern recharge. The question is how long this recharge takes to reach the water table if we assume a similar rate of movement through unsaturated zone as in borehole EV1 (see preceding study, Butcher et al 2005).

Nitrate concentrations in porewaters greater than those pumped during the packer test are notable. This could mean that more modern water with elevated nitrate is present in the unsaturated zone (and more modern water is leaching from the unsaturated zone than is entering laterally (and where the water table is even deeper).

Further annotations to the conceptual groundwater flow path transect with project boreholes and water quality interpretation are indicated in Figure 68.

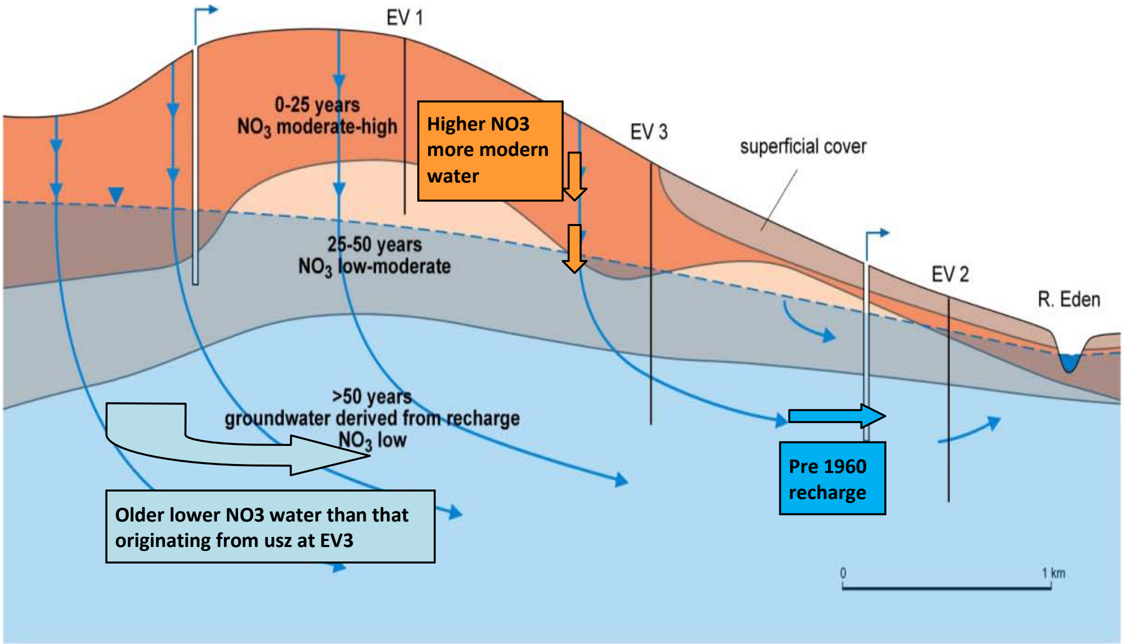


Figure 68. Annotated conceptual groundwater flow path transect in Penrith area with project boreholes and water quality interpretation

5. CONCLUSIONS

This component Work Package of the Eden Valley Project was undertaken with the objective of determining the hydrogeological regime and hydrochemical stratification in selected boreholes. The aim is to apply this to better understand timescales for water movement through the saturated zone along a transect ending near to the River Eden where the Permo-Triassic sandstone aquifer is exposed or underlies thin superficial deposits.

Previous reports in this series concluded that the average recharge rate is probably in the range 425-470 mm/y and the rate of water movement through the unsaturated zone is c. 3.5-3.85 m/y. Based on this estimate of water movement in the unsaturated zone, the travel time for recharge to migrate from the soil to the water table (or the delay imposed by the unsaturated zone) over most of the area where the sandstone is free of superficial deposits in the Eden Valley is c. 14 years. However if the higher fells are not considered - closer to 10 years.

Given the inherent uncertainties and limitations associated with the various methods for determining the hydrogeological regime in a borehole; methods proposed were:

- (i) to date the pore water profile within the saturated zone using CFC and SF_6 tracers
- (ii) to determine the variation of aquifer properties with depth, for the matrix (using laboratory techniques) and the aquifer (using field pumping techniques).
- (iii) To use groundwater models to estimate groundwater travel times in the saturated zones (this part of the project has not yet been funded).

A transect approach was adopted using existing boreholes to the east of Penrith to the Eden floodplain and addressing gaps with infill drilling. Despite early promise other boreholes (on a 'southern' transect) were discounted due to inaccessibility or unsuitable construction. A c. 4km transect from the east of Penrith in a north-western direction to the floodplain of the River Eden was selected starting at previously drilled project borehole.

The earlier borehole was drilled in a location where the unsaturated zone was relatively deep (c. 120 m). The second borehole, close to the floodplain was drilled to a depth of c. 90 m of which 85 m was below the water table on completion. A third borehole was drilled at a location between these two boreholes to a depth of 114 m and where the water table is c. 50 m below the surface.

Laboratory testing of drilled rock core provided a range of determined porosity values of 4.4 % to 29.2 % averaging 19.4 % in EV2 and 11.7 to 32.3 % and averaging 21.1 % in EV3.

Horizontal permeability was between 0.02 mD and 18400 mD (K c.8 m/d) averaging 1340 mD in EV2 and 70 mD to 24200 mD (K c.16 m/d) and averaging 1530 mD in EV3.

Geophyscial borehole logging, BHTV and optical imaging were conducted to evaluate the geophysical properties, structure, fractures and flow regimes and support the design of open hole and interval pump testing.

Borehole pump testing conducted on isolated intervals using packer testing suggested hydraulic conductivity up to 41 m/d and averaging 6.2 m/d in EV2 and up to 7.2 m/d and averaging 3.3 in EV3 (*2008 tests*).

The pumped interval water CFC/SF6 results indicated that concentrations, associated with less than 10% modern (1960 recharge), had penetrated to about 50 m depth in EV2 (at the outflow end of the study transect) and to c. 85 m depth in EV3 (the intermediate transect borehole).

A further study, designed to determine the impact of superficial deposits on the rate of recharge has commenced and will be reported separately.

Preliminary modelling of groundwater nitrate concentration histories at abstraction boreholes has commenced.

A network of 20+ hydrochemical monitoring sites around the study area has been established in order to establish the seasonal range of nutrient concentrations in shallow groundwater, springs and streams in order to provide nutrient input functions for modelling purposes. Some sites are on the River Eden floodplain adjacent to the study area transect.

A transport modelling code is being commissioned to explore the sensitivity of pumped nitrate concentrations to changes in aquifer physical properties.

Some other possible studies are included in the discussion in Chapter 4.

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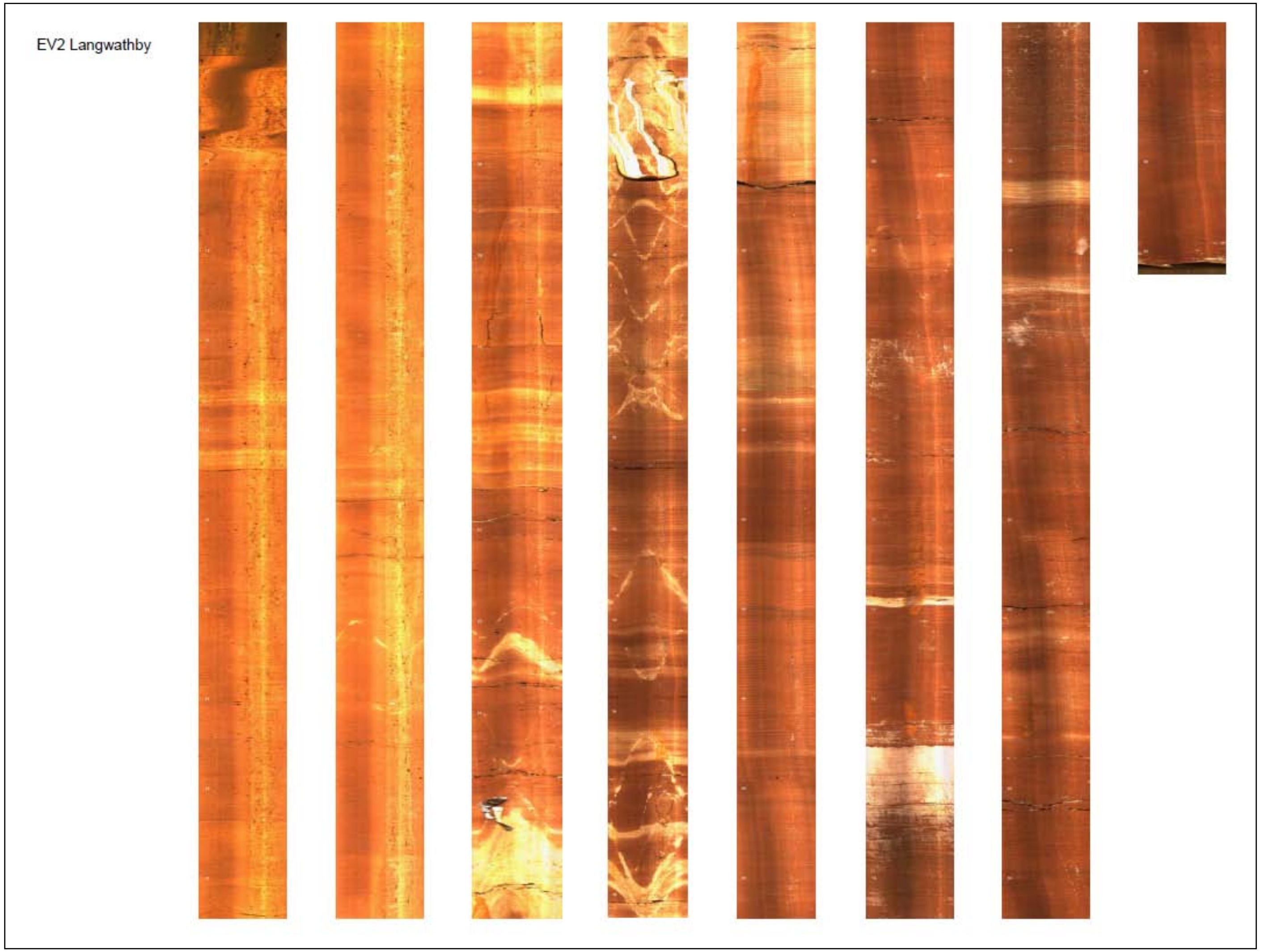
APPENDICES

Boreholes EV2 &EV3 profile porewater and packer sample hydrochemical data (A3).

Available from lead author



A3 Size

A3 Size

Boreholes EV2 EV3 additional data (A3).

Available from lead author