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Monitoring of biofilm growth in groundwater boreholes in bedrock aquifers.

NGU
NORGES GEOLOGISKE UNDERSØKELSE
Postboks 3006 - Lade
7002 TRONDHEIM
Tlf. (07) 90 40 11
Telefax (07) 92 16 20

RAPPORT

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Tittel:

Monitoring of biofilm growth in groundwater boreholes in bedrock aquifers.
Overvåkning av biofilmvekst i grunnvannsborehull i fast fjell.

Forfatter: D.Banks	Oppdragsgiver: NGU
Fylke: Østfold, Sør-Trøndelag	Kommune: Hvaler, Trondheim
Kartbladnavn (M=1:250.000) Oslo, Trondheim	Kartbladnr. og -navn (M=1:50.000) 1913-III, 1621-IV Fredrikstad, Trondheim
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Sammendrag:

Four boreholes in granite in Hvaler kommune, and two in greenstone at Trondheim, were test-pumped in 1991. They were subsequently monitored for biofilm growth using suspended slides. They were repeat test-pumped in 1993 to ascertain any decline in capacity. Microscopic observation of the monitoring slides indicated microbial activity (*Gallionella*) in three of the four Hvaler boreholes, but little iron-bacterial growth in one Hvaler borehole and the two Trøndelag boreholes. Repeated test-pumping was not able to indicate any decline in borehole capacity; on the contrary, wet weather activated shallow transmissive fracture systems on Hvaler and increased the boreholes' capacity.

Fire borehull i granitt på Hvaler, og to grønnsteinsborehull i Trondheim ble prøvepumpet i 1991. Alle ble deretter overvåket for jernbakterievekst vha. suspenderte "slides". Hullene ble prøvepumpet igjen i 1993 for å avgjøre evt. nedgang i kapasitet. Mikroskopundersøkelser av "slides"ene viste mikrobiologisk aktivitet (Gallionella) i tre av Hvaler-hullene, men ellers liten jernbakterievekst i det fjerde hullet på Hvaler eller i Trondheimshullene. Prøvepumping i 1993 kunne ikke påvise nedgang i kapasitet; tvert imot forårsaket regnsvær og aktivisering av gruntliggende sprekkesystemer på Hvaler en økning i ytelse.

Emneord: Hydrogeologi	Mikrobiologi	Grunnvann
Berggrunn	Grunnvannskvalitet	Jern
		Fagrapport

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1. Introduction

This report will focus on one particular aspect of groundwater microbiology in hard-rock aquifers, namely the group of bacteria known as the metal-immobilising bacteria (MIB), or more commonly as the "iron-bacteria". These bacteria have recently become the subject of much attention amongst hydrogeologists, due to their ability to form biofilms which can clog groundwater abstraction and drainage systems (Cullimore & McCann 1977, Howsam 1988, Banks 1992a), and their ability to immobilise a range of heavy metals (Banks & Banks 1993).

MIBs appear to be ubiquitous in many groundwater environments, although particular species have different requirements for, for example, pH, oxygen and iron concentrations and organic carbon. The characteristics of the commonest species are summarised in Table 1.

Genus	**Chemoautotrophic (C) or heterotrophic (H)**	**Preferred pH range**	**Other comments**
Gallionella	C	5.5 - 7.6	Oxidises Fe^{II}; microaerophilic; common in biofilms in water supply systems, iron removal plants, hydroelectric power plants.
Leptothrix	H	5.4 - 8.0	Requires low concentrations of soluble organic C; oxidises Mn^{II} and Fe^{II} extracellularly; microaerophilic; often in biofilms together with *Gallionella.*
Sphaerotilus	H	5.4 - 8.0	Similar to Leptothrix, but requires high concentration of soluble organic C; common in sewage sludge.
Thiobacillus ferroxidans	C	1.5 - 3.0	Oxidises Fe^{II} and inorganic S compounds simultaneously; aerophilic; frequent in acid mine drainage waters.
Metallogenium	H	3.5 - 5.0	Oxidises Fe^{II} and Mn^{II}.
Siderocapsa	H	-	Utilises organic part of Fe/Mn humates; common in ground water.
Pseudomonas Arthobacter	H H	-	Utilise organic parts of Fe/organic complexes; some species produce siderophores. Pseudomonas common in groundwater.
Pedomicrobium Hyphomicrobium	H H	-	Most deposit Fe oxides, some deposit Mn oxides.

Table 1. Main features of different genera of ferromanganese depositing bacteria (after Banks 1992b).

Some (but not all) of the most problematic bacteria, in a groundwater context, actively metabolise iron and are microaerophilic, thus typically thriving where relatively reducing iron-containing groundwater encounters a more oxygen rich environment (e.g. in a borehole or tunnel). Although some species can fix CO_2, many species require a source of metabolisable organic carbon, and may particularly thrive in the vicinity of pollution sources or river water infiltration. It is as yet uncertain if these bacteria are introduced to deeper aquifers from soil during borehole drilling, but the weight of opinion seems to suggest that they can survive in pristine aquifers in limited numbers. The occurrence of such bacteria is worldwide, cases being reported from tropical (Cullimore & McCann 1977) and arctic (Asplan 1985) climates as well as from temperate ones.

Despite the comprehensive literature on the subject of MIBs, there is little documentation of MIB clogging problems in fractured aquifers. Harker (1990) reports clogging problems in Chalk boreholes in England but these appear to be due to clogging of slotted casing rather than fractures themselves. Pedersen & Hallbeck (1985) and Pedersen (1987) report the occurrence of thriving populations of *Gallionella ferruginea* in groundwater from two 46 m deep boreholes in sideritic shales and sandstone at Helsingborg in Sweden, and a 60 m deep granitic well at Hindås, near Gøteborg, together with the existence of populations of MIBs in boreholes several hundred metres deep at Ävrö, near Simpevarp, and at Stripa mine.

Due to the importance of groundwater from hard-rock as a water resource for rural areas in Norway, the Geological Survey of Norway (NGU) has commenced a project to ascertain whether the growth of MIB biofilms in fractured aquifers can lead to clogging of fractures. The study consists of four parts:

(a) a questionaire survey of major Norwegian groundwater abstractors to ascertain the degree to which clogging, corrosion and general lack of maintainence pose a problem in Norwegian boreholes. Results are published by Banks (1992c).
(b) publication of a guide to borehole monitoring, maintainence and rehabilitation with emphasis on problems of corrosion and encrustation (Banks 1992a).
(c) monitoring of bedrock boreholes in Trondheim (Banks 1991) and Hvaler (Banks et al. 1993) with repeated test-pumping at two-yearly intervals, and monitoring of bacterial growth using simple "slides".
(d) collection of samples of biofilm and inorganic iron incrustations for chemical and bacteriological analysis (Banks 1992b).

1.1 MIB Occurrence in Scandinavian bedrock aquifers

MIB biofilm growth in Norwegian hydroelectric power tunnels in bedrock was reported by Cullimore and McCann in 1977. Carlsson and Olsson (1977) report ferruginous "sediments" deposited by water leaking from fractures in the Forsmark subsea tunnel in Sweden, which contained up to 73 % iron, 4.5 % manganese and 24 % [organic material + bound water]. These may be biofilms, but, due to the high iron content of the leaking water (ca. 3 mg/l), they may be purely inorganic deposits.

During the course of NGU's studies, biofilms have also been discovered in Norwegian road tunnels. In the Hvaler subsea tunnel, in Precambrian granite, (see Banks et al. 1992a, 1993) several growths, predominantly of *Gallionella* bacteria, can be seen growing on leaking fractures in the walls of the tunnel. In the arctic Vardø subsea road tunnel, in Precambrian metasediments, (Asplan 1985) growths of predominantly *Leptothrix* and *Gallionella,* with associated precipitation of iron, aluminium and manganese, have led to severe clogging of drainage gravels and pipes, necessitating regular maintainence by jetting every two years (Tor-Erik Lynneberg, Veglab., Oslo, pers.comm. 1991). In the Ålesund subsea tunnel (Olsen & Blindheim 1987), reddish brown slimy deposits, presumably, but not confirmed to be, bacterial, cause similar problems (Oddmund Gussiås, Vegkontoret, Molde, pers.comm. 1991), and have necessitated replacement of clogged drainage.

Apparently inorganic iron oxyhydroxide deposits have also caused tunnel drainage problems. At a tunnel complex in pyritic keratophyre at Gråkallen, near Trondheim (Banks & Ottesen 1992), iron-rich drainage water caused incrustations in drainage systems which, after microscopic examination, appeared to be purely inorganic in character.

In boreholes, definite biofilm growth has been observed in only one borehole. A horizontal test borehole drilled in greenstone by SINTEF at Lade, Trondheim, yielding water with ca. 2.4 mg/l iron, exhibits biofilm growths apparently consisting of *Sphaerotilus* and/or *Leptothrix.* The free-draining nature of this borehole in pyrite-rich rock may have been responsible for aerobic, iron-rich conditions favorable for bacterial growth.

NGU's questionnaire investigation also revealed three boreholes in bedrock aquifers where a decline in capacity was tentatively diagnosed as being due to bacterial clogging. In the municipalities of Nes-in-Akershus and Ski, two bedrock boreholes in Precambrian gneiss were successfully rehabilitated by treatment with hydrochloric acid and shock chlorination. The solutions derived during treatment were shown to be iron and manganese-rich, indicating either inorganic or bacterial clogging of fractures. At Gaupen in Ringsaker municipality, a decline in capacity was observed in bedrock boreholes. Slimy red-brown deposits were observed in pipework leading to a diagnosis of bacterial clogging. Treatment by hydrochloric and citric acids, with chlorination, yielded short-term improvements in yield, but after around six months the improvements had been reversed. In none of these three examples was bacterial involvement definitely proven.

Four boreholes at Hvaler (Iddefjord granite) and NGU's two testholes in Trondheim (Støren greenstone), are being monitored for biofilm growth by suspending transparent photographic slide mounts, together with a cylinder of borehole core material, at various depths in the boreholes. All boreholes have been test-pumped, and two have been repeat test-pumped in 1993 to ascertain any decline in yield.

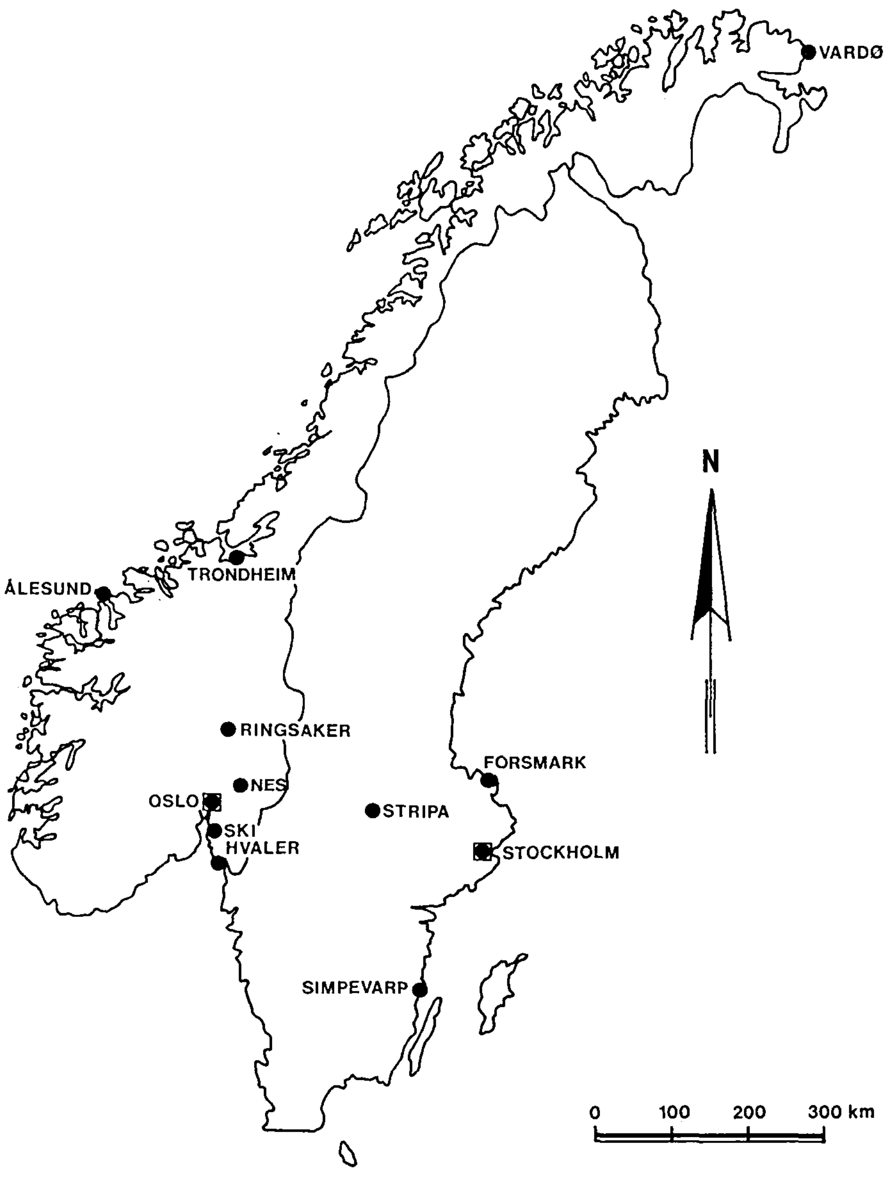

Fig. 1. Map of Norway and Sweden showing localities named in the text

2. Methods

Six boreholes have been selected for study, namely two boreholes in Støren greenstone at NGU's office at Østmarkneset, Trondheim (Banks 1991, 1993), and four boreholes in the Iddefjord granite at Pulservik, Kirkeøy, Hvaler. All boreholes are between 70 and 80 m deep, and are angled at between 3° and 30° away from the vertical. Construction details are given in Table 2.

	Hvaler 1	Hvaler 2	Hvaler 3	Hvaler 4	Trondheim 1	Trondheim 2
Depth	73,5 m	73,5	73 m	73 m	80 m	81 m
Diameter	5½"	5½"	5½"	5½"	5½"	5½"
Fall	73°	73°	60°	60°	64°	87°
Direction	3°	157°	110°	24°	c.288°	c.288°
Lithology	Granite	Granite	Granite	Granite	Greenstone	Greenstone
Casing (Diameter)	0 - 3 m 195 mm	0 - 3 m 195 mm	0 - 6 m 195mm	0 - 3 m 195 mm	0 - 3 m 184 mm	0 - 3 m 153 mm
RWL Spring 1991 (mbwt)	3,75 m	2,65 m	1,13 m	0,86 m	24,56 m	22,86 m

Table 2: Details of borehole construction

	Hvaler 1	Hvaler 2	Hvaler 3	Hvaler 4	Trondheim 1	Trondheim 1
RWL prior to test	3,75 m	2,65 m	1,13 m	0,86 m	24,56 m	22,86 m
Date of test	26/5/91	27/5/91	28/5/91	29/5/91	11/6/91	18/6/91
Duration of drawdown	c. 12 min	c. 10 min	c. 50 min	c. 12 min	5 hrs	3,75 hrs
Pump level	50 m	50 m	50 m	49,5 m	50 m	50 m
Duration of pumping with water level at pump level	3,5 hrs	2 hrs	c. 2 hrs	2,2 hrs	None	None
Duration of recovery monitoring	23 hrs	24 hrs	23 hrs	20 hrs	24 hrs	26 hrs
Yield	360 l/hr	64 l/hr	41 l/hr	21 l/hr	460 l/hr	28 l/hr
Corresponding drawdown	46,25 m	47,35 m	48,87 m	49,14 m	14,8 m	12,1 m
Fracture level(s)	**62 m**	**c. 5 m**	**c. 8 m**	**4,75 m**	**39½-40 m** c. 33½ m 60-61 m	**34,8 m**

Table 3: Details of original borehole test-pumping. All depths are along borehole axis (not vertical).

All boreholes had been test-pumped in 1991, and details of the results are given in Table 3, and reports by Banks (1991) and Banks et al. (1991).

Monitoring units consisting of a plastic-mounted glass slide (with thin stainless steel foil mounting) and a 2 cm diameter rock core were suspended in each of the boreholes at two different depths by thin thread (30 and 50 m in the Trondheim boreholes, c. 22 and 40 m in the Hvaler boreholes). The rock cores were old paleomagnetic cores from similar lithologies (basic igneous rock for the Trondheim boreholes, acidic for the Hvaler holes). No particular sterile methods were used, the objective of the study merely being to examine whether biofilm-forming bacteria could thrive in hard-rock groundwater, it being assumed that they would be introduced in any case during decidedly non-sterile Norwegian drilling practices.

As all of the six boreholes are used by NGU as test-boreholes, the monitoring units were, from time to time, disturbed and removed temporarily from the boreholes, e.g. for geophysical logging etc. During removal, elementary precautions were taken to avoid gross contamination by soil etc. (i.e. use of plastic sheeting to avoid contact with soil, temporary storage in polythene bags). Details of monitoring practices are found in Table 4.

	Hvaler 1	Hvaler 2	Hvaler 3	Hvaler 4	Trondheim 1	Trondheim 2
Emplaced	22 m 30/5/91 40 m 30/5/91	22 m 30/5/91 40 m 30/5/91	22 m 30/5/91 40 m 30/5/91	22 m 30/5/91 40 m 30/5/91	30 m 2/10/91	30 m 2/10/91 50 m 2/10/91
Removed						30 m Jan.92 50 m Jan.92
Re-emplaced						30 m 10/7/92 50 m 10/7/92
Final removal	22 m Mar. 92 40 m Mar. 92	22 m 19/5/92 41 m 19/5/92	22 m 19/5/92 42 m 19/5/92	22 m Mar. 92 42 m Mar. 92	30 m 19/4/93	30 m 23/4/93 50 m 23/4/93

Table 4: Emplacement and removal of biofilm monitoring units

3. Results - Monitoring Units

The slides from the four Hvaler boreholes (at testsite Pulservik; for map see Banks et al. 1992b, 1993) have been examined and limited growth of *Gallionella* bacteria has been demonstrated in all boreholes except borehole 1. Most growth was demonstrated in borehole 4, where matted threads of *Gallionella* on the slide represent potential biofilm growth (Appendix 1, Figs. 2c,d). Borehole 4 was subject to a small oil-leakage during drilling, and it is interesting to speculate whether the

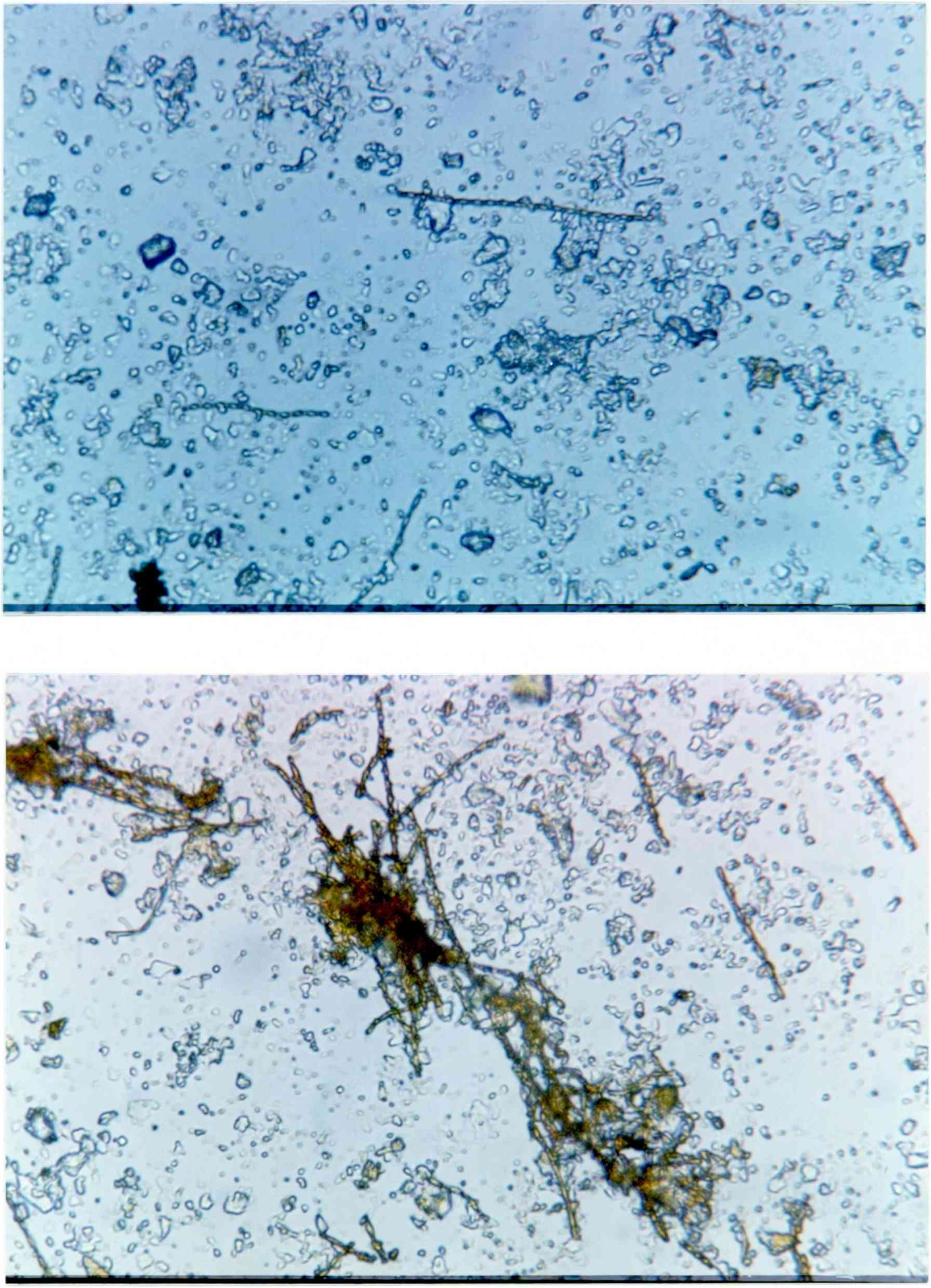

Fig. 2a,b: Microscopic examination of bacteria monitoring slides from borehole 4, Pulservik, Hvaler. Showing corkscrew-like stalks of *Gallionella*, stained with iron oxide.

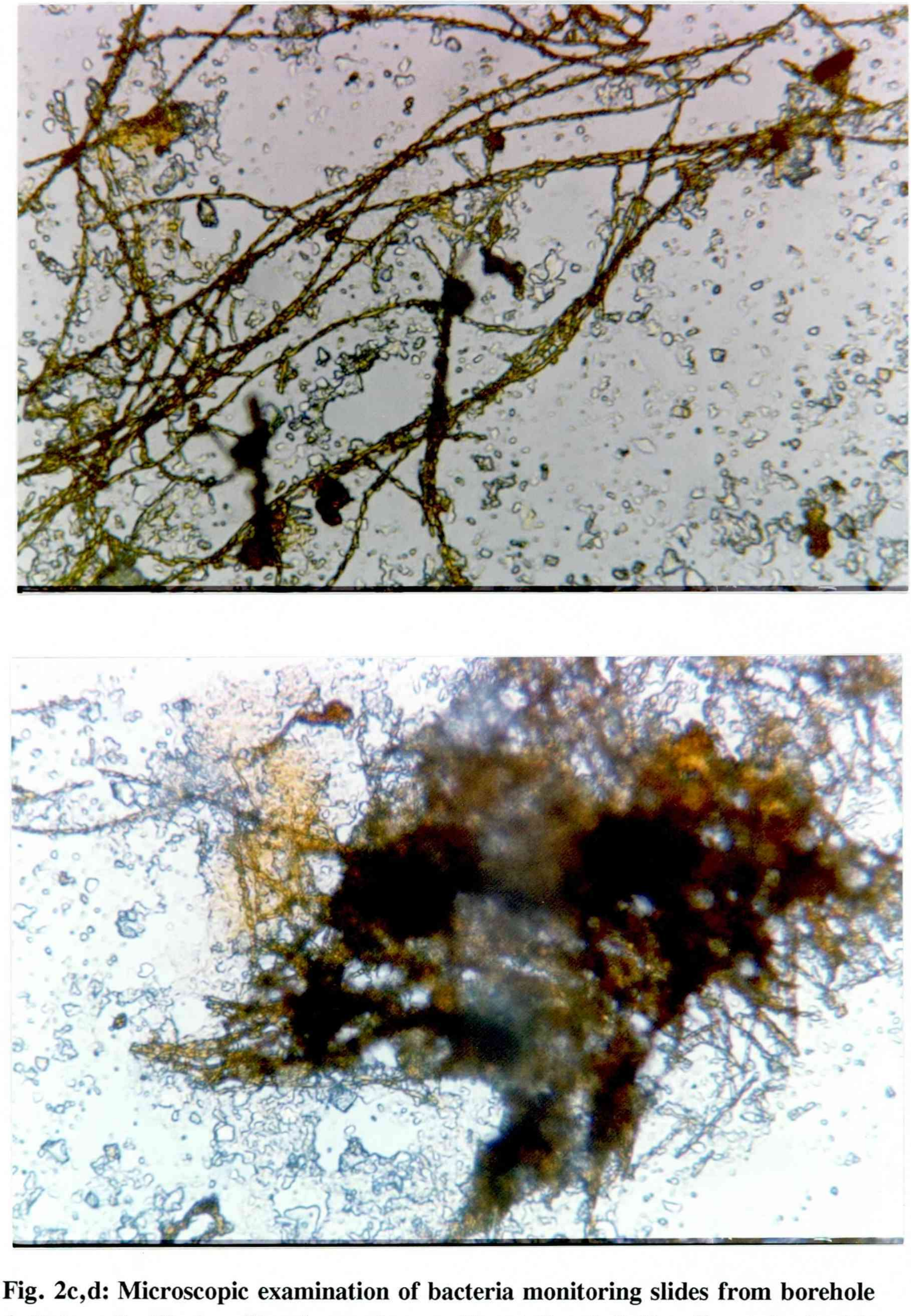

Fig. 2c,d: Microscopic examination of bacteria monitoring slides from borehole 4, Pulservik, Hvaler. Showing corkscrew-like stalks of *Gallionella*, stained with iron oxide. Here, one can see the beginnings of the formation of a proto-biofilm of matted stalks.

presence of oil (an organic carbon source) could have stimulated bacterial growth. It is also interesting to note that borehole 1 is fed by a deep fracture zone at c.62 m depth, yielding relatively uncoloured water. The boreholes 2, 3 and 4 are fed by shallow fractures containing rather humus-rich, brown-coloured groundwater. It is plausible that the organic (humus) content of groundwater in these boreholes has helped to stimulate *Gallionella* growth.

Although the results do not, of course, indicate whether the bacteria are native to the aquifer, have been introduced by drilling or other equipment or were initially present as contamination on the slides, the results do demonstrate that *Gallionella* can survive and form proto-biofilms in the granitic groundwater.

The slides from the boreholes at Trondheim yielded more disappointing results, only a very few *Gallionella* stalks being detected on the slide from 50 m deep in hole 2.

It must be noted that *Gallionella* is a particularly easy bacterium to identify due to its corkscrew-like, often iron-stained, stalk. It is by no means the only biofilm-forming bacterium, nor the only iron-bacterium, and it is quite possible that other, less distinctive bacterial types have been overlooked during the microscopic examination. As a more detailed follow-up to this project, it is recommended that BARTS (Mansuy et al. 1990) kits are used in an attempt to more precisely identify populations present in the various boreholes.

4. Results - test-pumping

The only boreholes to be repeat test-pumped in 1993 were boreholes 2 and 4 at Hvaler. This was due to the fact that borehole 1 had been heavily disturbed by hydrofracturing and chemical stimulation experiments, while borehole 3 had been blocked by a lodged packer. The holes at Trondheim were not re-pumped due the lack of observed biofilm formation.

Methods recommended by Banks (1993) for low-yielding boreholes were employed for test-pumping, namely pumping the water-level down to the pump-intake level (c. 50 m) and then monitoring the recovery. The original test-pumping at Hvaler is described in Banks et al. (1991) and Banks (1993). A large pump was used to sink the water-level rapidly (typically within 10-15 mins.) to the intake level, and then to maintain it there for a short period (c. 2 hrs.) for sampling and to measure the yield from the aquifer (Q_A - as opposed to the yield from borehole storage). In the repeated test-pumping in 1993, a small 2" Grundfos MP1 pump was employed, leading to a somewhat longer pump-out period (c. 30-60 mins.). The water level was then held at around pump-intake level for in excess of 1 hr, by repeated pumping, to measure yield from the aquifer and to take samples. Thus, despite the different pump equipment, a total pumping time of around 2 hours was employed prior to commencement of recovery monitoring in both 1991 and 1993.

Borehole	Hvaler 2	Hvaler 4
Date	15/8/93	16/8/93
Rest water level (m bwt)	2,215 m	0,24 m
Pump level	49 - 50 m	c. 47 m
Pump start	11:06:00	09:59:00
Pumped air (Water level at pump intake) - pump switched off	11:40:00	10:52:01
Pump on	12:15:00	
Pump switched off	12:19:03	
Volume pumped (Time)	< 100 l (39,05 min)	
Calculated Q_A (l/hr)	< 154 l/hr	
Pump on	12:45:00 pm	11:45:00
Pump switched off & removed from borehole	13:00:40 pm	12:00:45
Volume pumped (Time)	150 l (41,62 min)	113 l (68,73 min)
Calculated Q_A (l/hr)	216 l/hr	99 l/hr

Table 5. Details of repeat test-pumping of Hvaler boreholes, August 1993

Recovery curves, in terms of water level vs. time and inflow from the aquifer (Q_A) vs. water level, are presented in Figs. 3 - 5. Raw data from the original and repeat test-pumping are presented in Banks et al. (1991) and Appendix 2 respectively.

Unfortunately, it proved very difficult to reproduce the results of the original pumping tests. It is known that boreholes 2 and 4 are fed by rather shallow fracture systems. The repeat test-pumping was carried out after (and during !) a very wet period, leading to high rest water levels (Table 6). This presumably led to new shallow fracture systems being activated, their transmissivity increasing with elevated water table and the yield of the borehole increasing dramatically. Table 7 shows the short term yields in Autumn 1993 compared with the original yields of Spring 1991, extrapolated to a pumping water-level of 50 m.

In other words, a rise in the water table of 40 - 60 cm has led to a doubling of the boreholes' short term specific capacities. Banks et al. (1991) have shown that the upper 12 metres of the granite have an apparent average hydraulic conductivity two orders of magnitude greater than the deeper aquifer. This is assumed to be due to an abundance of open, near-surface pressure-release fracturing. Under dry conditions, the yield from these is small, as the nearest surface fractures are unsaturated and the achievable hydraulic gradient betwen fracture and borehole is rather small. Under wet conditions, the water table rises and more of these highly transmissive fractures are saturated and activated. Although the achievable hydraulic gradient will still be low, the dramatic increase in transmissivity would still be expected to result in impressive increases in yield. The drawback is, of course, that this water is of very poor, surface-near quality. The water from boreholes 2 and 4 at Hvaler is rather humus rich.

	Hvaler 1	Hvaler 2	Hvaler 3	Hvaler 4
RWL 25/5/91	3,75 m bwt	2,65 m bwt	1,13 m bwt	0,86 m bwt
RWL 15/8/93	3,135 m bwt	2,215 m bwt	0,14 m bwt*	0,28 m bwt

Table 6: Comparison of rest water levels (RWL) betwen first and second test pumping periods. * = Hole bocked by packer, water level may be disturbed. bwt = below well top.

	Borehole 2	Borehole 4
RWL May 1991	2,65 m bwt	0,86 m bwt
RWL August 1993	2,215 m bwt	0,24 m bwt
Depth of yielding fractures	c. 5 m (1991) c. 14 - 15 m (1993)	c. 3 m ?
Fracture transmissivity 1991 1993	2 x 10^{-5} m^2/s 3 x 10^{-6} m^2/s	1 x 10^{-6} m^2/s 4 x 10^{-6} m^2/s
Transmissivity 1991 below fracture 1993	1 x 10^{-7} m^2/s 2 x 10^{-7} m^2/s	6 x 10^{-8} m^2/s 1 x 10^{-7} m^2/s
Short term yield, 1991 PWL = 50 m 1993	64 l/hr 116 l/hr	21 l/hr 41 l/hr

Table 7. Comparison of test pumping in Hvaler boreholes 2 and 4, years 1991 and 1993. RWL = rest water level, PWL = pumping water level.

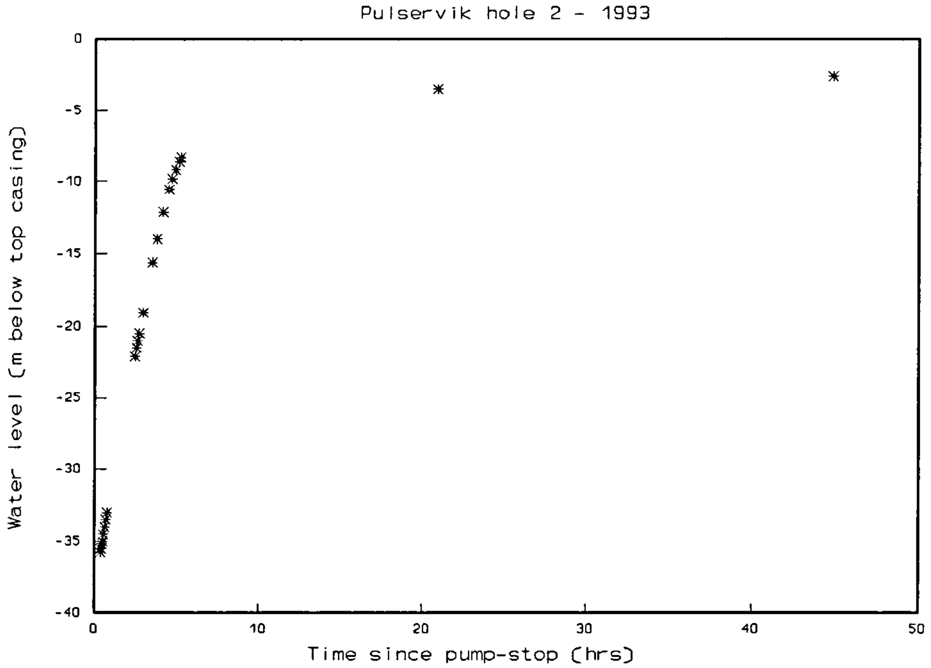

Figure 3a. Water level vs. time plot for recovery from pumping test in Pulservik borehole 2, 1993.

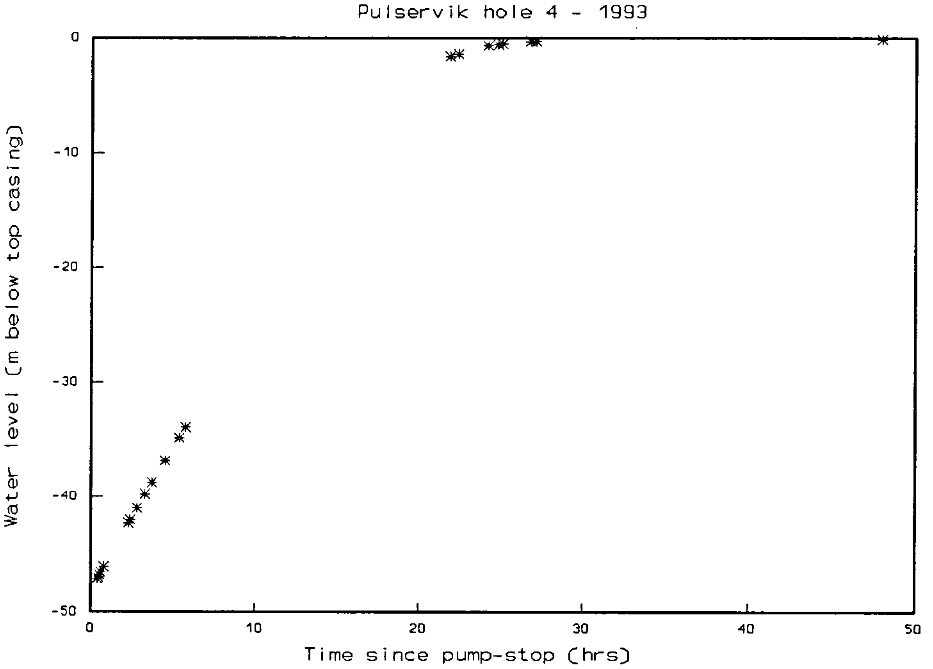

Figure 3b. Water level vs. time plot for recovery from pumping test, Pulservik borehole 4, 1993.

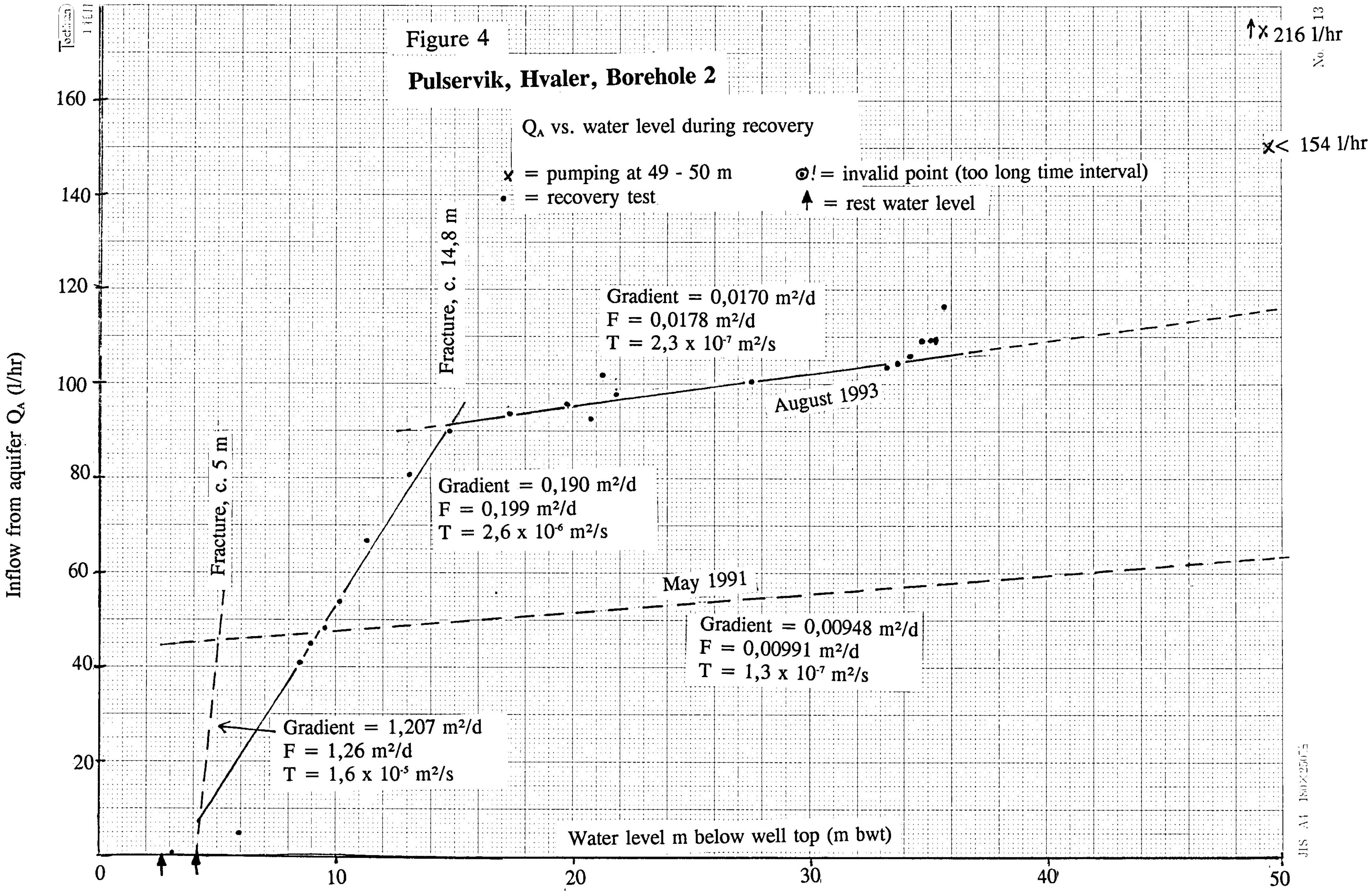

Figure 4

Pulservik, Hvaler, Borehole 2

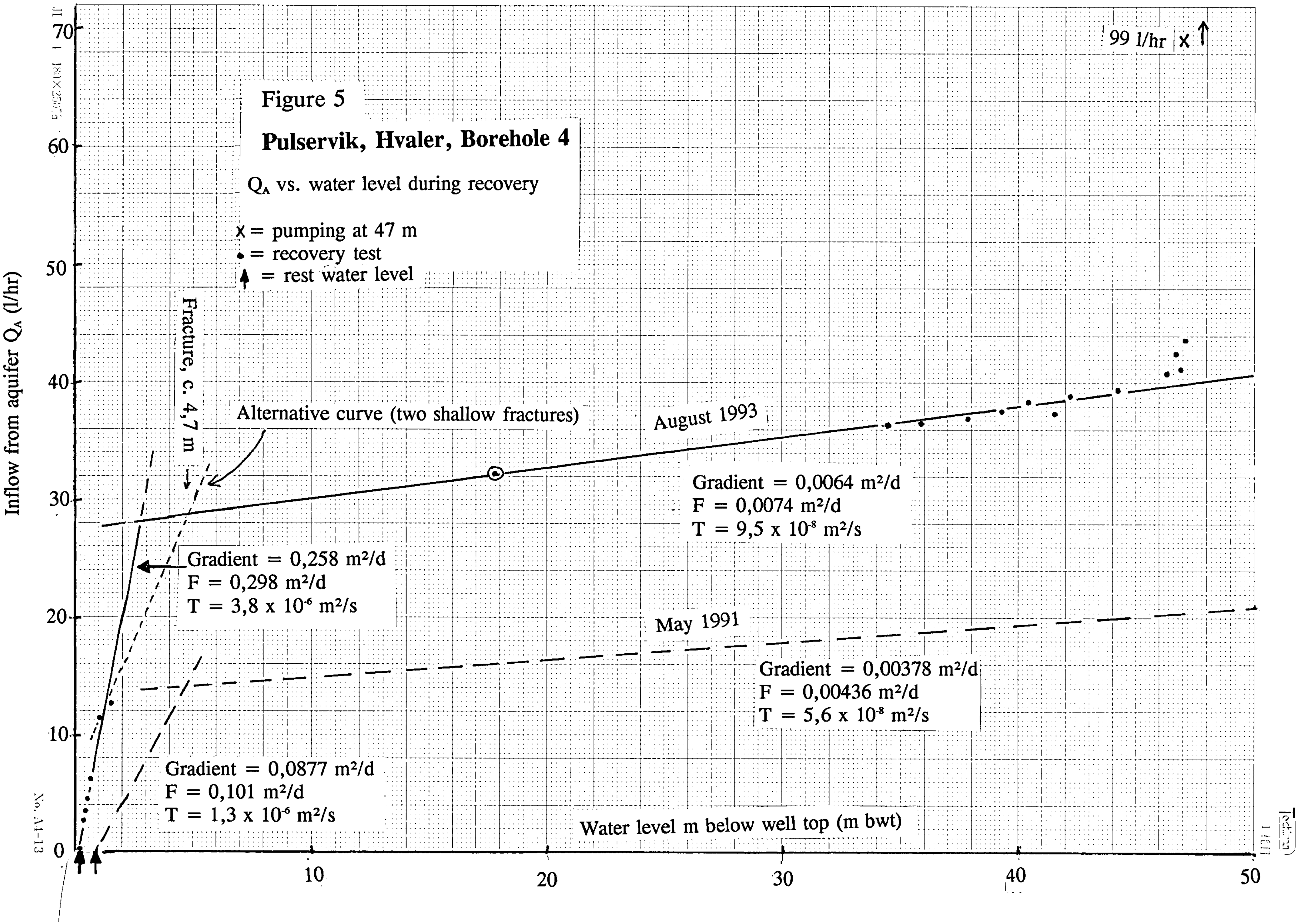

Figure 5

Pulservik, Hvaler, Borehole 4

Q_A vs. water level during recovery

x = pumping at 47 m
• = recovery test
↑ = rest water level

Gradient = 0,0064 m²/d
F = 0,0074 m²/d
T = 9,5 x 10^{-8} m²/s

Gradient = 0,258 m²/d
F = 0,298 m²/d
T = 3,8 x 10^{-6} m²/s

Gradient = 0,00378 m²/d
F = 0,00436 m²/d
T = 5,6 x 10^{-8} m²/s

Gradient = 0,0877 m²/d
F = 0,101 m²/d
T = 1,3 x 10^{-6} m²/s

The results from borehole 4 fit this hypothesis well. Comparing the Q_A vs. water level curves from 1991 and 1993, the gradient of the curve below c. 5 m is low in both periods, indicating that the very low background transmissivity of the deep aquifer has not changed greatly (as would be expected). The break in slope appears to come at c. 3 m, a little above the expected main fracture horizon (4,7 m)[1], but the slope of the line above 5 m is now three times as steep as in 1991, indicating that the majority of the increase in yield is due to the increased tranmissivity of the near-surface fracture system. The curve for borehole 2 is more difficult to interpret. While the deep part of the curve displays a similar slope[2] (background transmissivity) for 1991 and 1993, the break in slope (main fracture horizon) is observed at c. 14½ m, instead of at c. 5 m. This may be due to the increase in water table activating completely new fracture systems (in a not easily explainable manner), or to misinterpretation of the, admittedly rather sparse, data in that region from the 1991 test. In any case, it can be concluded, even for borehole 2, that the increased yield is derived from shallow, rather than deep fracture systems, activated by wet weather.

5. Groundwater Quality

Representative, filtered groundwater samples were collected during the 1991 test-pumping of boreholes 2 and 4 at Pulservik, Hvaler (Banks et al. 1991). During 1993, although the water initially pumped from the boreholes was fairly clear, it rapidly became somewhat turbid (apparently due to drilling cuttings). This is may be not too surprising as the boreholes have never, due to low yields, been subject to proper clearance pumping. Filtration of samples in the field was carried out using 0,45 μm Millipore filters. Acidization was carried out in the lab. to remobilise any precipitated or adsorbed cations/metals.

Sample No.	Borehole	Date	Time	Flask	Filtered	Analysis
P2	Pulservik 2	15/8/93	1245	1x500 ml	N	P
				1x100 ml	N	K
				1x100 ml	Y	A,K,K*
P4	Pulservik 4	16/8/93	1145	1x500 ml	N	P
				2x100 ml	N	A,K
				1x100 ml	Y	A,K,K*

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[1] This level (4,7 m) was based on drilling logs, and not on test pumping results. An alternative interpretation of Fig. 5 could have two yielding fractures, one at 4,7 m and one between 1 and 3 m.

[2] In fact, it can be seen from Table 7 that the background transmissivity appears to have increased from 1991 to 1993. This may be due to (i) the gradient of a very shallow slope being highly sensistive to small errors in measurement, storage effects (time variant yield) etc. (ii) the theory, which assumes that the gradient represents an intrinsic non-variant fracture property, i.e. transmissivity, is not sufficiently valid in this instance.

P = pH, alkalinity, conductivity
A = anions (ion chromatography)
K = cations (ICP)
K^* = standard acidisation of sample in flask (at NGU) by addition of Ultrapure HNO_3, prior to ICP analysis.

Results are summarised in Tables 8a,b, and raw data is documented in Appendix 2.

Unfortunately, during transport to NGU, the samples were inadvertently placed near the vehicle ventilation system and subjected to upwarming. This may render the results for some of the parameters (alkalinity, pH etc.) rather meaningless. The effect of drilling cuttings in raising concentrations of many lithologically derived species (Fe, Al, Ti, and even Ca, Na etc.) has been noticed in many samples from newly drilled boreholes (even filtered samples), including boreholes 2 and 4 in 1991 (Banks et al. 1992b).

In borehole 2, it appears that the water from 1993 test-pumping is less affected than that from 1991 by elevated levels of lithoparameters due to drilling cuttings and newly exposed rock. Concentrations of e.g. Si, Al, Ti, Na, Li, F and heavy metals such as Cu, Zn, Ba and Cr have declined since 1991. The decline in Na levels cannot be due to a higher input of shallow fresh groundwater due to heavy rainfall, as Cl levels have increased. Levels of Fe have increased, possibly associated with increased humus in shallow groundwater. Puzzlingly, levels of Mg, Ca, Sr and Mn have also increased.

In borehole 4, only the concentrations of Zn, F and Li have declined relative to Spring 1991. Other parameters such as Si, Ti, Al, Fe, Na, Ca, Mg, Sr, Mn and Ba have increased. The borehole displays a puzzlingly high salinity; between 100 - 200 mg/l Na and Cl. This must be regarded as strange in a borehole which appears to be fed purely by fractures only 5 m deep. It may be that, as this borehole is drilled into a granitic "massif" in the walls of a fracture zone, the shallow fracture system intercepted is transmitting a large component of essentially deep, mineral-rich granitic groundwater from under the "massif" which has flowed upwards towards a discharge zone in the fracture-controlled valleys at Pulservik.

One other possible reason for the rather different chemical tendencies of the two boreholes could be that borehole 4 has been in an almost stagnant undisturbed state, with very little groundwater throughflow, since the initial pumping in 1991, allowing extensive further reaction with drilling cuttings in the borehole. Borehole 2, although undisturbed by direct pumping, is known to be affected by pumping in borehole 1 (of which there has been a certain amount, including a long term pumping test in Spring 1992, causing a drawdown in borehole 2 of 1 m). This may have induced a greater throughflow of fresher groundwater through the hole, preventing a stagnant "drilling-cutting soup" from accumulating in the borehole.

Locality: Pulservik borehole 2 - Hvaler **Table 8a**

Sampled by: David Banks **Date:** August 1993

Analyzed by: NGU Trondheim

Parameter	Pulservik 2 1991 (FS for ICP)	Pulservik 2 1993 (FS for ICP)	Pulservik 2 1993 (UU for ICP)	**SIFF(G)**	**SIFF(A)**
pH	7,61		7,29	7,5 - 8,5	6,5 - 9,0
Alkalinity (mmol/l)	3,13		2,14	0,6 - 1,0	
Conductivity (μS/cm)	362		290		
Silicon ppm	12.6	7.2	10.2		
Aluminium ppm	3.3	0.35	2.1		
Iron ppm	2.7	4.9	5.4	< 0.1	< 0.2
Magnesium ppm	2.6	3.4	3.3	< 10	< 20
Calcium ppm	6.0	12.2	10.6	15 - 25	
Sodium ppm	80	57	51	< 20	
Potassium ppm	5.8	4.1	4.0		
Manganese ppb	115	240	210	< 50	< 100
Copper ppb	8.6	5.3	7.7	< 100	< 300
Zinc ppb	47	6.4	8.5	< 300	
Lead ppb	< 50	< 50	< 50	< 5	< 20
Cadmium ppb	< 10	< 10	< 10	< 1	< 5
Barium ppb	39	16.3	25	< 1000	
Strontium ppb	47	64	56		
Chromium ppb	19.7	< 10	< 10		
Titanium ppb	149	< 10	75		
Boron ppb	59	36	35		
Beryllium ppb	< 2	< 2	< 2		
Lithium ppb	12.2	< 2	2.1		
Fluoride ppb	2700	1670		< 1500	
Chloride ppm	17.0	19.6		< 100	< 200
Nitrite ppb	< 100	< 1000		< 16	< 164
Nitrate ppb	< 50	< 50		< 11000	< 44000
Phosphate ppb	< 100	< 200			
Sulphate ppm	8.5	7.7		< 100	
Bromide ppb	69	< 100			

FS = field filtered and acidified in flask in laboratory, UU = unfiltered, unacidified.

SIFF(G)/SIFF(A) = Good/acceptable quality according to SIFF (1987) requirements

Locality: Pulservik borehole 4 - Hvaler **Table 8b**

Sampled by: David Banks **Date:** August 1993

Analyzed by: NGU Trondheim. * = contains some particles, thus uncertain alkalinity.

Parameter	Pulservik 4 1991 (FS for ICP)	Pulservik 4 1993 (FS for ICP)	Pulservik 4 1993 (UU for ICP)	**SIFF(G)**	**SIFF(A)**
pH	7,29		6,91	7,5 - 8,5	6,5 - 9,0
Alkalinity (mmol/l)	2,13*		1,50	0,6 - 1,0	
Conductivity (µS/cm)	603		995		
Silicon ppm	7.9	8.0	11.0		
Aluminium ppm	1.1	1.6	3.3		
Iron ppm	1.2	2.9	3.5	< 0.1	< 0.2
Magnesium ppm	3.9	7.6	7.2	< 10	< 20
Calcium ppm	11.4	23	20	15 - 25	
Sodium ppm	116	192	172	< 20	
Potassium ppm	4.6	3.4	3.3		
Manganese ppb	115	183	168	< 50	< 100
Copper ppb	2.1	2.1	4.0	< 100	< 300
Zinc ppb	29	11.4	13.2	< 300	
Lead ppb	< 50	< 50	< 50	< 5	< 20
Cadmium ppb	< 10	< 10	< 10	< 1	< 5
Barium ppb	29	47	54	< 1000	
Strontium ppb	99	270	230		
Chromium ppb	< 10	58	43		
Titanium ppb	60	60	139		
Boron ppb	74	101	98		
Beryllium ppb	< 2	< 2	< 2		
Lithium ppb	11.1	3.2	5.3		
Fluoride ppb	3200	2100		< 1500	
Chloride ppm	103	210		< 100	< 200
Nitrite ppb	< 500	< 5000		< 16	< 164
Nitrate ppb	< 50	< 50		< 11000	< 44000
Phosphate ppb	< 100	< 200			
Sulphate ppm	22	32		< 100	
Bromide ppb	360	520			

FS = field filtered and acidified in flask in laboratory, UU = unfiltered, unacidified.

SIFF(G)/SIFF(A) = Good/acceptable quality according to SIFF (1987) requirements

6. Conclusions

Six boreholes have been monitored using simple techniques for biofilm growth; four in the Precambrian Iddefjord Granite of Hvaler and two in the Caledonian Støren Greenstone at Trondheim. Suspended slides indicated that *Gallionella* bacteria were found in three of the four Hvaler boreholes (interestingly, those fed by rather shallow humus-rich groundwater). In one of these, the growth of a proto-biofilm mat of *Gallionella* stalks could be seen on one of the slides.

Repeat test-pumping was unsuccessful at indicating any decline in borehole yield due to biofilm growth. This was due to the exceptionally wet weather during the repeat test-pumping activating shallow, transmissive fracture systems, thus dramatically increasing the boreholes' specific capacities.

Concrete examples of boreholes where bacterial clogging can be held responsible for decline in borehole yield have thus still not been unequivocally documented in Norway. Several examples exist, however, of iron clogging (potentially bacterial) causing borehole yield reductions, and this study has demonstrated the ability of iron bacteria such as *Gallionella* to survive in crystalline-rock groundwater. The weight of evidence so far suggests that bacterial clogging is a problem expected to affect many of Norway's hundred thousand or more crystalline bedrock boreholes.

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Appendix 1 - Documentation of Biofilm Monitors

On all slides a whitish coating of dried mineral salts from the groundwater could be seen. These could be distinguished as individual crystals under the microscope.

Hvaler borehole 1 - slides examined 18/3/92

22 m Some orange-brown staining on core and thread. No iron bacteria detected on slide.

40 m Nothing seen on core. A small fleck of inorganic "rusty" particle (iron oxyhydroxide, humus ??) on slide. No bacteria detected.

Hvaler borehole 2 - slides examined 3/7/92

22 m. A small amount of brown staining on the core - possibly just scraping of rust from steel casing. Under microscope, occasional *Gallionella* (??) can be seen, but no clusters, or "protobiofilms". Also some other rod-like shapes - possibly bacterial ??. In addition, inorganic flecks of humus/iron oxyhydroxide.

41 m A small amount of brown staining on the core - possibly just scraping of rust from steel casing. Under microscope, very sparse *Gallionella* (often orange-brown-stained) can be seen, but no clusters, or "protobiofilms". In addition, inorganic flecks of humus/iron oxyhydroxide.

Hvaler borehole 3 - slides examined 3/7/92

22 m Very little staining on core. Some brownish coating on slide. Under microscope, this appears to consist of inorganic flecks of red-brown iron oxyhydroxide (possibly related to corrosion of the metal frame around the exterior of the slide). Sparse *Gallionella* (??) can be identified.

42 m Some brownish coating on slide. Under microscope, several flecks of red-brown iron oxyhydroxide/humus. Possible sightings of *Gallionella*.

Hvaler borehole 4 - slides examined 14/4/92

22 m Core lost in borehole. Under the microscope some reddish brown flecks of reddish brown humus/iron oxyhydroxide can be seen. On some parts of the slide, it is possible to see very clear forms of *Gallionella*, with a slight reddish-brown staining.

42 m A slight whitish coating on the slide. Clear reddish brown "growth" on the core. Under the microscope occasional flecks of reddish brown humus/iron oxyhydroxide can be seen. Occasional *Gallionella*. In corner of slide, it is possible to see the growth of a proto-bacterial mat of *Gallionella* consisting of intertwining *Gallionella* stalks (photo - Fig. 2)

Trondheim borehole 1 - slide examined 20/4/93

30 m No incrustation on core. No signs of recognisable bacteria on slide. Some reddish-brown crystals/flecks (iron salts / humus ?).

Trondheim borehole 2 - slides examined 24/4/93

30 m No signs of recognisable bacteria on slide. Some reddish-brown crystals/flecks (iron salts / humus ?). Also some non-bacterial threads. Possibly remains of vegetation or string (!) which has been floating on water surface.

50 m A very few recognizable *Gallionella* on the slide. Some reddish-brown crystals/flecks (iron salts / humus ?). Also some non-bacterial threads. Possibly remains of vegetation or string (!) which has been floating on water surface.

Appendix 2 - Documentation of Raw Data, Repeat test-pumping at Pulservik, Hvaler

Hole 2 - Pulservik							
Date	Time	Time after pump stop		Water level	Qa	Average time	Average water level
		Days	Hours	(m bwt)	(l/hr)	(hrs)	(m bwt)
15-aug-93	10:50:00 am			2,215			
15-aug-93	11:06:00 am	Pump started at 49 - 50 m					
15-aug-93	11:40:00 am	Pump draws air, stopped					
15-aug-93	12:15:00 pm	Pump started					
15-aug-93	12:19:03 pm	Pump draws air, stopped					
15-aug-93	12:45:00 pm	Pump started, sample taken					
15-aug-93	01:00:40 pm	Pump draws air, stopped, removed from hole					
15-aug-93	01:22:50 pm	0,0154	0,369	35,78			
15-aug-93	01:25:03 pm	0,0169	0,406	35,5	116,7	0,388	35,64
15-aug-93	01:28:00 pm	0,0190	0,456	35,15	109,6	0,431	35,325
15-aug-93	01:29:16 pm	0,0199	0,477	35	109,4	0,466	35,075
15-aug-93	01:33:30 pm	0,0228	0,547	34,5	109,1	0,512	34,75
15-aug-93	01:37:52 pm	0,0258	0,620	34	105,8	0,584	34,25
15-aug-93	01:42:18 pm	0,0289	0,694	33,5	104,2	0,657	33,75
15-aug-93	01:46:46 pm	0,0320	0,768	33	103,4	0,731	33,25
15-aug-93	03:26:50 pm	0,1015	2,436	22,11	100,5	1,602	27,555
15-aug-93	03:32:36 pm	0,1055	2,532	21,5	97,7	2,484	21,805
15-aug-93	03:37:08 pm	0,1087	2,608	21	101,9	2,570	21,25
15-aug-93	03:42:08 pm	0,1121	2,691	20,5	92,4	2,649	20,75
15-aug-93	03:56:18 pm	0,1220	2,927	19,03	95,8	2,809	19,765
15-aug-93	04:30:00 pm	0,1454	3,489	15,61	93,7	3,208	17,32
15-aug-93	04:46:50 pm	0,1571	3,769	13,97	90,0	3,629	14,79
15-aug-93	05:08:00 pm	0,1718	4,122	12,12	80,7	3,946	13,045
15-aug-93	05:29:40 pm	0,1868	4,483	10,55	66,9	4,303	11,335
15-aug-93	05:42:00 pm	0,1954	4,689	9,83	53,9	4,586	10,19
15-aug-93	05:54:15 pm	0,2039	4,893	9,19	48,3	4,791	9,51
15-aug-93	06:06:00 pm	0,2120	5,089	8,62	44,8	4,991	8,905
15-aug-93	06:13:00 pm	0,2169	5,206	8,31	40,9	5,147	8,465
16-aug-93	09:55:00 am	0,8711	20,906	3,51	4,7	13,056	5,91
17-aug-93	09:54:00 am	1,8704	44,889	2,62	0,8	32,897	3,065

Hole 4 - Pulservik							
Date	Time	Time after pump stop		Water level	Qa	Average time	Average water level
		Days	Hours	(m bwt)	(l/hr)	(hrs)	(m bwt)
15-aug-93	10:50:00 am			0,28			
16-aug-93	09:50:00 am			0,24			
16-aug-93	09:59:00 am	Pump start at c. 47 m					
16-aug-93	10:52:01 am	Pump draws air, stopped					
16-aug-93	11:45:00 am	Pump start					
16-aug-93	12:00:45 pm	Pump draws air, stopped, removed from hole					
16-aug-93	12:24:57 pm	0,0168	0,403	47,14			
16-aug-93	12:27:55 pm	0,0189	0,453	47	43,6	0,428	47,07
16-aug-93	12:32:25 pm	0,0220	0,528	46,8	41,1	0,490	46,9
16-aug-93	12:36:46 pm	0,0250	0,600	46,6	42,5	0,564	46,7
16-aug-93	12:48:05 pm	0,0329	0,789	46,1	40,8	0,695	46,35
16-aug-93	02:17:00 pm	0,0946	2,271	42,31	39,4	1,530	44,205
16-aug-93	02:23:53 pm	0,0994	2,386	42,02	38,9	2,328	42,165
16-aug-93	02:49:08 pm	0,1169	2,806	41	37,3	2,596	41,51
16-aug-93	03:17:50 pm	0,1369	3,285	39,81	38,3	3,046	40,405
16-aug-93	03:42:42 pm	0,1541	3,699	38,8	37,5	3,492	39,305
16-aug-93	04:30:30 pm	0,1873	4,496	36,89	36,9	4,098	37,845
16-aug-93	05:21:18 pm	0,2226	5,343	34,88	36,5	4,919	35,885
16-aug-93	05:44:40 pm	0,2388	5,732	33,96	36,4	5,537	34,42
17-aug-93	09:50:20 am	0,9094	21,826	1,63	32,2	13,779	17,795
17-aug-93	10:21:40 am	0,9312	22,349	1,41	12,6	22,088	1,52
17-aug-93	12:10:45 pm	1,0069	24,167	0,715	11,4	23,258	1,0625
17-aug-93	12:47:16 pm	1,0323	24,775	0,59	6,1	24,471	0,6525
17-aug-93	01:03:13 pm	1,0434	25,041	0,55	4,5	24,908	0,57
17-aug-93	02:46:20 pm	1,1150	26,760	0,348	3,5	25,900	0,449
17-aug-93	03:08:25 pm	1,1303	27,128	0,315	2,7	26,944	0,3315
18-aug-93	12:00:00 pm	1,9995	47,988	0,16	0,2	37,558	0,2375

N.B. For both holes, diameter = 140 mm below casing. In casing (0 - 3 m) diameter = 195 mm.

Side 2 15.SEP 1993

Prosjektnr: 63.2462.00 Oppdragsnr: 151/93

	R1A	R1B	P1A	P1B	P2 F	P2 F+S	P2	P4 F	P4 F+S	P4
Si	127.2 ppm	34.34 ppm	19.96 ppm	15.98 ppm	7.55 ppm	7.19 ppm	10.24 ppm	8.85 ppm	7.96 ppm	11.00 ppm
Al	57.38 ppm	12.58 ppm	5.97 ppm	4.27 ppm	425.6 ppb	348.1 ppb	2.09 ppm	1.93 ppm	1.63 ppm	3.26 ppm
Fe	40.55 ppm	9.69 ppm	5.43 ppm	4.06 ppm	5.25 ppm	4.91 ppm	5.39 ppm	3.19 ppm	2.88 ppm	3.52 ppm
Ti	2.06 ppm	454.1 ppb	313.5 ppb	221.7 ppb	12.0 ppb	<10.0 ppb	74.7 ppb	82.5 ppb	59.5 ppb	138.8 ppb
Mg	9.45 ppm	2.46 ppm	2.19 ppm	2.24 ppm	3.06 ppm	3.39 ppm	3.31 ppm	7.10 ppm	7.57 ppm	7.15 ppm
Ca	4.74 ppm	2.51 ppm	3.95 ppm	13.60 ppm	10.75 ppm	12.19 ppm	10.63 ppm	20.93 ppm	22.69 ppm	19.98 ppm
Na	81.10 ppm	80.41 ppm	136.9 ppm	148.6 ppm	52.09 ppm	57.27 ppm	50.93 ppm	180.0 ppm	192.4 ppm	172.4 ppm
K	21.02 ppm	5.09 ppm	3.29 ppm	2.27 ppm	3.79 ppm	4.08 ppm	3.96 ppm	3.19 ppm	3.44 ppm	3.33 ppm
Mn	390.3 ppb	97.7 ppb	107.7 ppb	109.9 ppb	212.6 ppb	236.0 ppb	212.2 ppb	172.2 ppb	182.9 ppb	167.7 ppb
P	650.2 ppb	178.5 ppb	110.6 ppb	<100.0 ppb	<100.0 ppb	<100.0 ppb	<100.0 ppb	<100.0 ppb	<100.0 ppb	<100.0 ppb
Cu	57.9 ppb	20.1 ppb	17.7 ppb	12.2 ppb	< 2.0 ppb	5.3 ppb	7.7 ppb	< 2.0 ppb	2.1 ppb	4.0 ppb
Zn	197.9 ppb	46.2 ppb	64.6 ppb	30.9 ppb	5.1 ppb	6.4 ppb	8.5 ppb	9.9 ppb	11.4 ppb	13.2 ppb
Pb	51.4 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb
Ni	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb
Co	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb
V	101.4 ppb	28.8 ppb	18.7 ppb	15.1 ppb	< 5.0 ppb	< 5.0 ppb	9.4 ppb	< 5.0 ppb	5.2 ppb	6.9 ppb
Mo	<10.0 ppb	<10.0 ppb	16.0 ppb	13.7 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb
Cd	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb
Cr	54.4 ppb	11.8 ppb	10.6 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	65.8 ppb	58.0 ppb	42.7 ppb
Ba	357.0 ppb	84.9 ppb	59.2 ppb	59.9 ppb	15.4 ppb	16.3 ppb	25.1 ppb	46.1 ppb	47.3 ppb	54.2 ppb
Sr	59.9 ppb	24.8 ppb	49.5 ppb	178.1 ppb	56.8 ppb	64.1 ppb	56.3 ppb	247.9 ppb	269.2 ppb	234.3 ppb
Zr	215.0 ppb	57.2 ppb	17.9 ppb	13.0 ppb	< 5.0 ppb	44.6 ppb	8.8 ppb	< 5.0 ppb	18.4 ppb	6.8 ppb
Ag	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb
B	86.2 ppb	69.1 ppb	123.9 ppb	120.2 ppb	44.9 ppb	35.5 ppb	35.4 ppb	101.4 ppb	101.4 ppb	97.6 ppb
Be	17.0 ppb	4.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb
Li	30.9 ppb	5.3 ppb	3.7 ppb	3.7 ppb	< 2.0 ppb	< 2.0 ppb	2.1 ppb	4.3 ppb	3.2 ppb	5.3 ppb
Sc	17.9 ppb	4.0 ppb	2.1 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb
Ce	546.5 ppb	127.0 ppb	111.2 ppb	76.7 ppb	<50.0 ppb	<50.0 ppb	61.6 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb
La	278.1 ppb	69.8 ppb	58.8 ppb	35.5 ppb	<10.0 ppb	<10.0 ppb	22.8 ppb	13.4 ppb	13.1 ppb	20.7 ppb
Y	458.6 ppb	131.9 ppb	42.1 ppb	28.5 ppb	8.8 ppb	9.4 ppb	16.8 ppb	9.9 ppb	9.4 ppb	12.0 ppb

Oppdragsnr. 151/93

Nr.	Prøvemrk.	Ledn.evne µS/cm	pH	Alkalitet mmol/l
1.	R1a	338	7.34	2.48 *
2.	R1b	332	7.53	2.47 *
3.	P1a	545	7.76	4.83
4.	P1b	654	7.74	4.97
5.	P2	290	7.29	2.14
6.	P4	995	6.91	1.50
7.	U1	784	8.39	3.88
8.	TL2	223	6.53	0.71
9.	TL3	251	7.28	1.41 *
10.	RB	335	7.25	1.84

*) = Prøvemrk. R1a, R1b og TL3 inneholder det endel uløste fragmenter, og da blir den oppgitte alkalitet noe usikker.

Løpenr.	Prøve mrk.
1	R1a
2	R1b
3	P1a
4	P1b
5	P2 filt.
6	P4 filt.
7	U1 filt.
8	TL2
9	TL3
10	RB filt.

Oppdragsnummer : 151/93 Side 2
Prøve Dato 19.11.93

nr	F^-	Cl^-	NO_2^-	Br^-	NO_3^-	PO_4^{3-}	SO_4^{2-}
1	3.80ppm	16.4ppm	<1.00ppm	<100 ppb	762 ppb	<200 ppb	14.5ppm
2	3.35ppm	14.8ppm	<1.00ppm	<100 ppb	332 ppb	<200 ppb	16.8ppm
3	2.52ppm	28.0ppm	<1.00ppm	<100 ppb	<50.0ppb	<200 ppb	4.85ppm
4	2.15ppm	53.4ppm	<1.00ppm	157 ppb	<50.0ppb	<200 ppb	7.94ppm
5	1.67ppm	19.6ppm	<1.00ppm	<100 ppb	<50.0ppb	<200 ppb	7.72ppm
6	2.07ppm	206 ppm	<5.00ppm	516 ppb	<50.0ppb	<200 ppb	31.6ppm
7	4.30ppm	95.0ppm	<2.50ppm	255 ppb	<50.0ppb	<200 ppb	21.0ppm
8	1.79ppm	15.6ppm	<1.00ppm	<100 ppb	81.3ppb	<200 ppb	31.6ppm
9	3.40ppm	15.6ppm	<1.00ppm	<100 ppb	228 ppb	<200 ppb	15.3ppm
10	187 ppb	27.9ppm	<1.00ppm	<100 ppb	5.13ppm	<200 ppb	15.1ppm

N.B.

F = filtered in field
S = acidified in flask in lab.

U1 = sample from Utengen borehole (see report 93.117)
R1a,b = samples from Reffsgård borehole 1 (see report 93.118)
TL2 = samples from Reffsgård borehole 2 (see report 93.118)
TL3 = samples from Reffsgård borehole 3 (see report 93.118)
P1a,b = samples from test pumping of Pulservik borehole 1 15/8/93 at 1615 hrs & 1714 hrs respectively.
RB = samples from Reffsgård dug well (see report 93.118)

Appendix 3 - Documentation of Chemical Analyses, Repeat test-pumping, Pulservik, Hvaler, August 1993.