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Holmedal well field, Sunnfjord.
Tracer tests and borehole geophysics
conducted in 1999

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REPORT

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Summary:

In 1996, the Geological Survey of Norway started the project "Fracture zones and groundwater of Sunnfjord". The aim of the project was to get a regional understanding of deformation along bigger post-Devonian lineaments/fracture zones in crystalline rocks, and the relevance of these lineaments in connection with well capacity

This report presents results from the tracer tests, borehole tomography and electrical conductivity profiles conducted in September 1999.

Tracers injected were DNA, the bacteriophage *Salmonella typhimurium* type 28B, ^{14}C, $^{175}Yb^{3+}$, D_2O and ^{3}H. The purpose of the tracer tests was:

i. Confirming communication between the wells in the well field, as indicated by pumping tests conducted in 1997 and 1998.
ii. Comparing the behaviour of the DNA tracers with the other tracers in order to evaluate the usefulness of DNA as a groundwater tracer in fractured aquifers.

In addition to the tracer tests, NGU wanted to test the usefulness of borehole tomography. Measurements were done between W9 and the wells W3, W5, W6 and W8. NaCl was injected in the wells and the electrical conductivity was logged twice (19th and 26th). The results from the borehole tomography are not included in this report.

The tracer tests confirmed a connection between the pumping well (W9) and the injection wells. Compared to the inactive tracers, DNA behaves like a conservative tracer. The much later arrival of the bacteriophage implies that the DNA tracer is not suitable as a tracer to measure travel time for microbial contamination in a fractured aquifer. However, DNA is a suitable tracer for identification of hydraulic communication and possible flow paths between two groundwater wells or from pollution sources to a groundwater well or spring.

Keywords: Hydrogeology	Bedrock	Fractures
Groundwater	Well	Tracer tests
Pumping	Borehole tomography	

CONTENTS

1. BACKGROUND

In 1996, the Geological Survey of Norway initiated the project "Fracture zones and groundwater of Sunnfjord". The aim of the project was to get a regional understanding of deformation along bigger post-Devonian lineaments/fracture zones in crystalline rocks, and the relevance of these lineaments in connection with well capacity (Braathen et al. 1998).

Mapping of fracture frequency towards lineaments (Braathen et al. 1997, Braathen & Gabrielsen 1998), measurements of rock stress with hydraulic fracturing (Hansen 1996, Midtbø 1996a, Midtbø 1996b) and evaluation of the geological history and relevance of lineaments (Braathen & Henriksen 1997, Braathen 1998, Braathen 1999) in Sunnfjord have been done, and two hydrogeological hypothesis have been established (Braathen & Gabrielsen 1998).

1. In the distal part and in areas with a general background fracturing, water will mainly flow along fractures parallel to the highest in-situ stress field.
2. The greatest potential for groundwater abstraction will be in the marginal zone with high fracture frequency and less clay minerals in the fractures.

A well field with nine wells was drilled in 1997 at Holmedal, Sogn and Fjordane County to evaluate the first hypothesis (Figure 2.1A). Results from this study are described among other places, in this report. The second hypothesis was evaluated by drilling five test boreholes across 4 selected lineaments, also in Sogn and Fjordane, and results are presented by Henriksen & Braathen (2006) and Braathen et al. (1999).

2. SITE DESCRIPTION

Holmedal well field is located at Holmedal, Sogn and Fjordane County (Figure 2.1), and was established in 1997. The well field is situated in and around an old stone quarry (two walls of 50x50 m and < 2 m deep) in the middle of a broad valley. A picture of the stone quarry seen from south-east is shown in Figure 2.2. The closest hills are more than 500 m to the north. A north-south trending lineament is located about 200 m west of the wells.

The main rock is a dark green, fine-grained amphibolite. Locally chlorite schists are developed in zones of strong deformation. In addition, phyllonitic rocks with suspected igneous precursors are found (Henriksen & Braathen 2006). Land use is farmland with pasture and production of grass. A river is located about 300 m west of the well field and a smaller stream flows about 100 m to the south-east.

In total nine wells (W1-W9) were drilled as outlined in Figure 2.1B and C. The field is designed with eight 50-m-deep wells (W1-W8) surrounding the centre well (W9), which is drilled to 100 m depth. All wells were drilled vertically and have a diameter of about 137 mm. Each well has a casing of 3 m, with the top of the casing approximately 0.4 m above surface. The thickness of the superficial deposits varies between 0.2 m and 1.7 m, meaning the casing reaches 0.9-2.4 m into bedrock. Levelling of the wells is shown in Table 2.1. Well number 4 is used as zero level, and based on topographic maps the top of the casing is assumed to be 30 m above sea level.

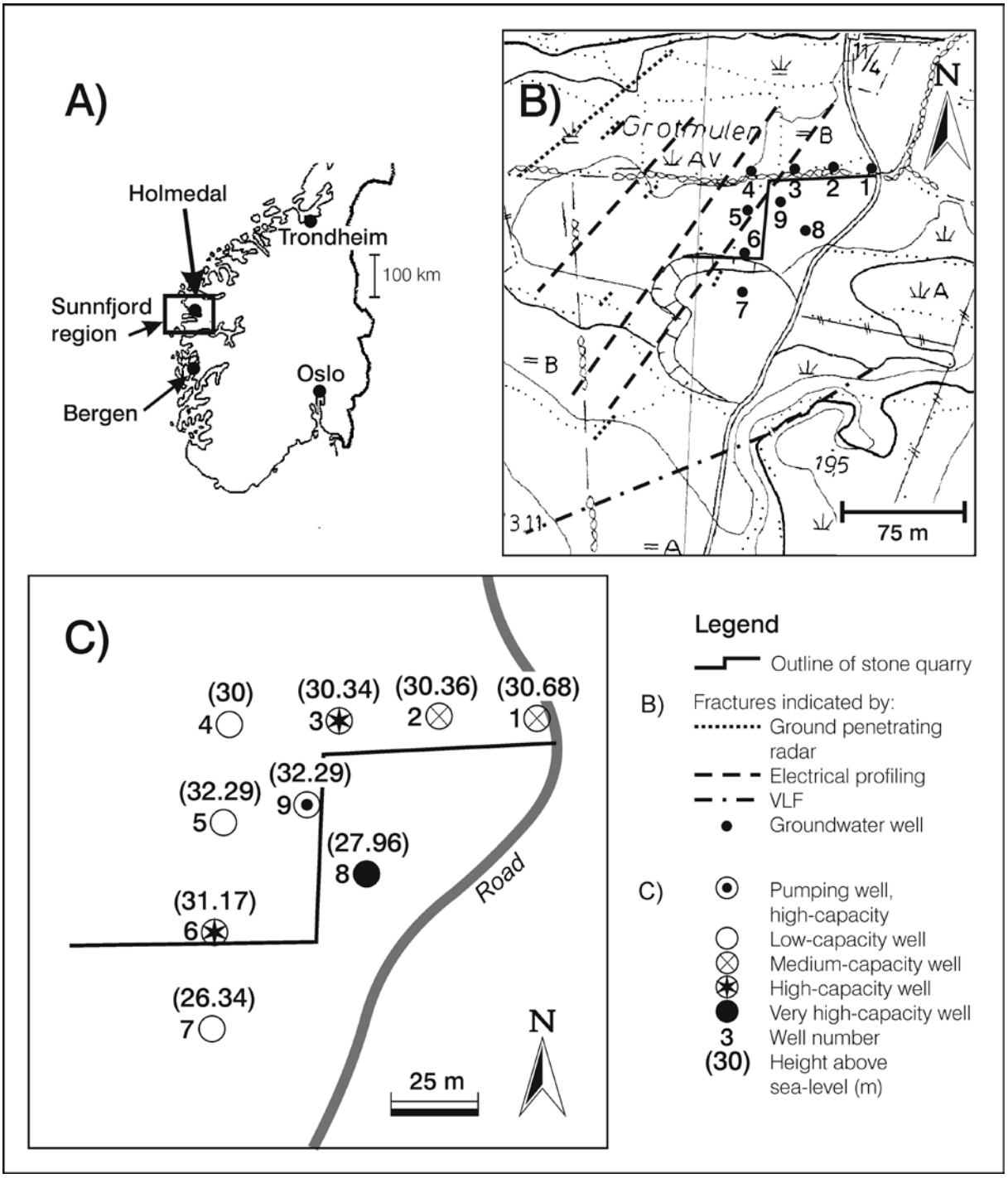

Figure 2.1 A) Map showing the location of Holmedal in western Norway. B) The well field at Holmedal. The wells are numbered 1-9. The dashed lines indicate locations of the geophysical profiles (Elvebakk & Lauritsen 1997). The well field is 75x75 m, i.e. 25 m between each well along two axes. C) Details of the well field. Relative capacity of the wells is indicated by the well symbol. Numbers in parenthesis give the height of the wells above sea level.

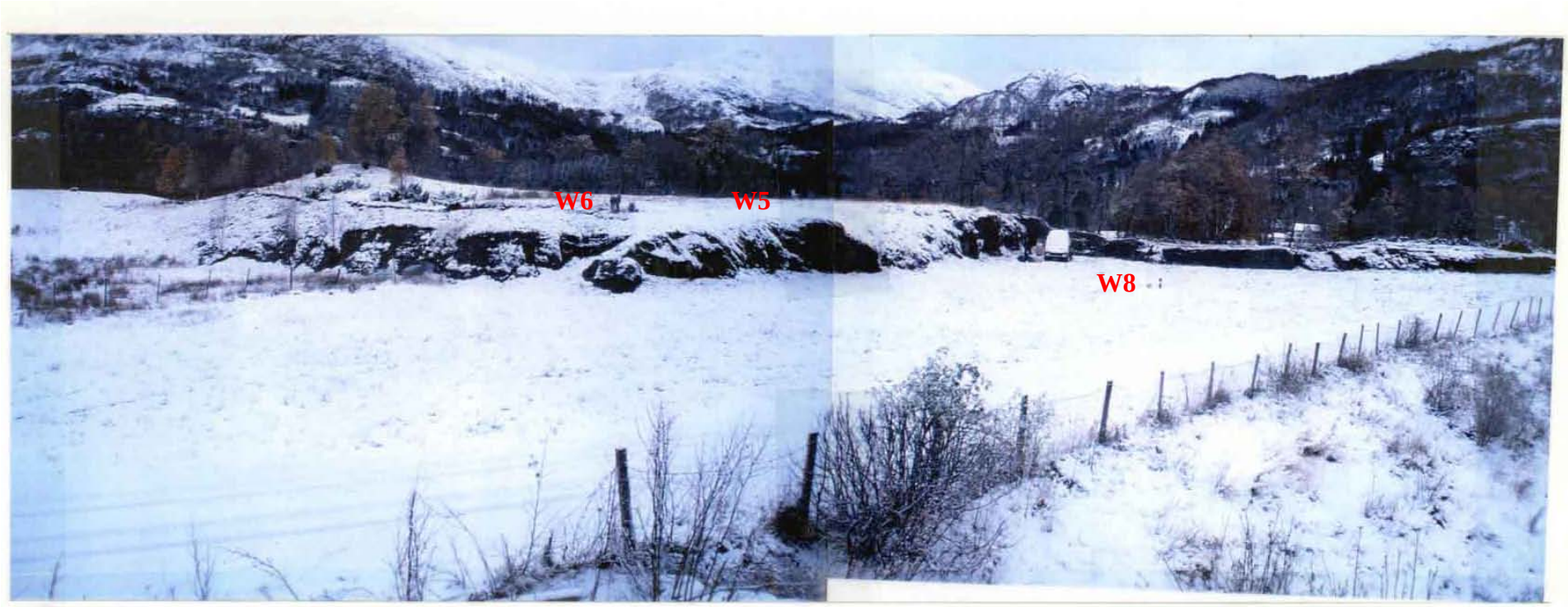

Figure 2.2 Holmedal well field seen from south-east. Wells number 5, 6 and 8 can be seen in the picture. Wells number 1-4 are located behind the quarry edge stretching from behind the car and to the right. Picture is from Braathen et al. (1998).

Table 2.1 The table shows levelling of the wells at Holmedal. Well number 4 is used as level zero. In addition, top of the casing is given as meter above sea level (m.a.s.l.) and the length of the casing above ground is measured (Gaut et al. 1999).

Well number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Levelling (m)	0.68	0.36	0.34	0	2.62	1.17	-3.66	-2.04	2.29
m.a.s.l.	30.68	30.36	30.34	30.00	32.62	31.17	26.34	27.96	32.29
Top casing above ground (m)	0.44	0.41	0.39	0.43	0.40	0.45	0.40	0.42	0.43

3. PREVIOUS WORK

3.1 Fracture measurements and in-Situ stress

3.1.1 Surface fractures

Recorded fractures at the surface are steep to sub-vertical and have a NNW-SSE or NNE-SSW strike (Braathen et al. 1998, Figure 2). There are also fractures along the foliation of the rock, which strikes E-W and dips moderately north at 20°-50°. The foliation is defined by parallel oriented amphibolite, chlorite, mica and occasionally small quartz veins. Secondary fractures related to excavation of the quarry are minor, and superficial. Fracture orientation and frequencies were measured in detail along horizontal scan lines by counting all fractures intersecting 1 m long horizontal sampling lines. The results are shown as rose diagrams and stereographic pole diagrams in Figure 3.2 and Figure 3.3. The two populations of fractures intersect in two main orientations: group 1 which are steeply plunging towards ENE, and group 2 which are plunging in a NNW direction at about 50° (Figure 3.3c and d) (Braathen et al. 1998, Henriksen & Braathen 2006).

Geophysical measurements (electrical profiling, VLF and ground penetrating radar) were carried out before drilling to identify fractures not exposed at the surface (Elvebakk & Lauritsen 1997, Figure 1b). The main fracture orientation found was NNE-SSW (Figure 3.1), whereas VLF indicated a possible water bearing fracture with the direction ENE-WSW.

3.1.2 Borehole logging

Several of the wells have been logged with gamma logger and acoustic and optical televiewers (Dannowski 2001, Hagen & Elvebakk 2001, Kortsch & Elvebakk 2001, Elvebakk & Rønning 2002) as shown in Table 3.1. Data from the televiewers show dominant E-W orientations of fractures at depth and fewer fractures orientated NNW-SSE and NNE-SSW. In addition, some near-horizontal fractures close to the surface are observed. In summary, the dominant fracture strike is NNE-SSW at surface level and E-W at depth (Figure 3.1).

3.1.3 Stress measurements

Part of the Holmedal project has been to examine the possible relationship between in-situ rock stress and fracture flow. Stress measurements are done by hydraulic fracturing (Hansen 1996, Midtbø 1996a, Midtbø 1996b). Measurements at Atløy and Hestad, 8-10 km from

Holmedal (Hansen 1996) show that the largest horizontal stress (σ_H) in the well field has an E-W to ESE-WNW orientation.

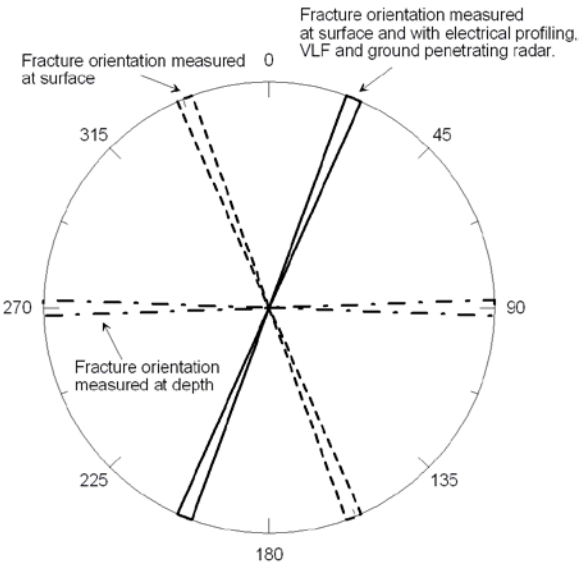

Figure 3.1 Rose diagram showing the main fracture orientations measured at surface and at depth. In summary, the dominant fracture strike is NNE-SSW at surface level and E-W at depth.

Table 3.1 Geophysical measurements conducted in the different wells at Holmedal. Electrical conductivity has also been measured with in all wells with the DATSAM unit. See Chapter 6.

Well number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Optical televiewer		X		X		X		X	X
Acoustic televiewer	X	X	X	X				X	
Resistivity			X					X	X
Temperature								X	X
Electrical conductivity								X	X
Gamma log								X	X
Borehole deviation		X	X	X				X	X

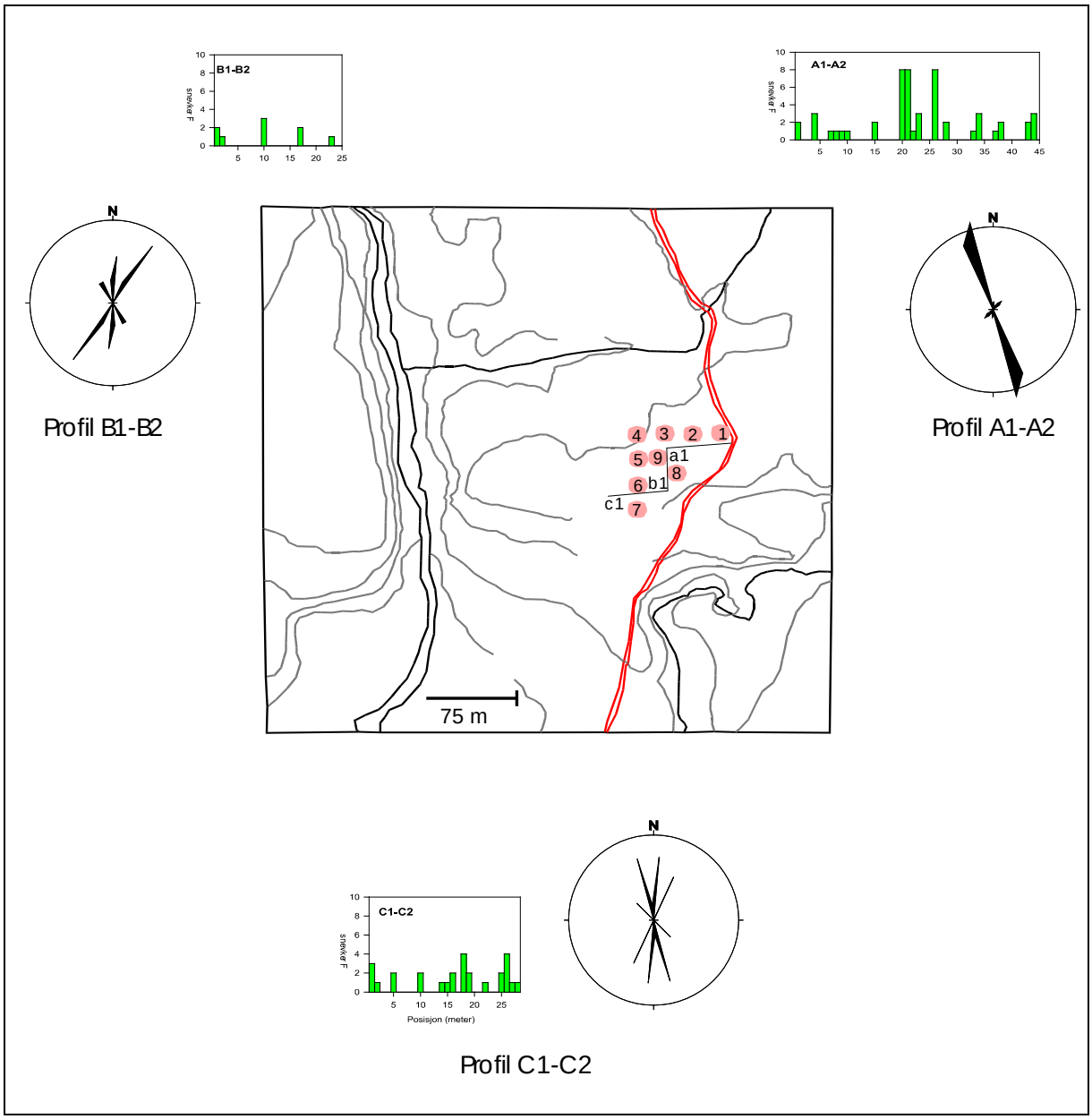

Figure 3.2 Map showing the well field with well 1-9 and sampling lines (a1, b1 and c1) for fracture measurements (Braathen et al. 1998). Fracture frequencies and orientations are shown in the figures outside the map. Sampling lines a1, b1 and c1 corresponds to the profiles A1-A2, B1-B2 and C1-C2.

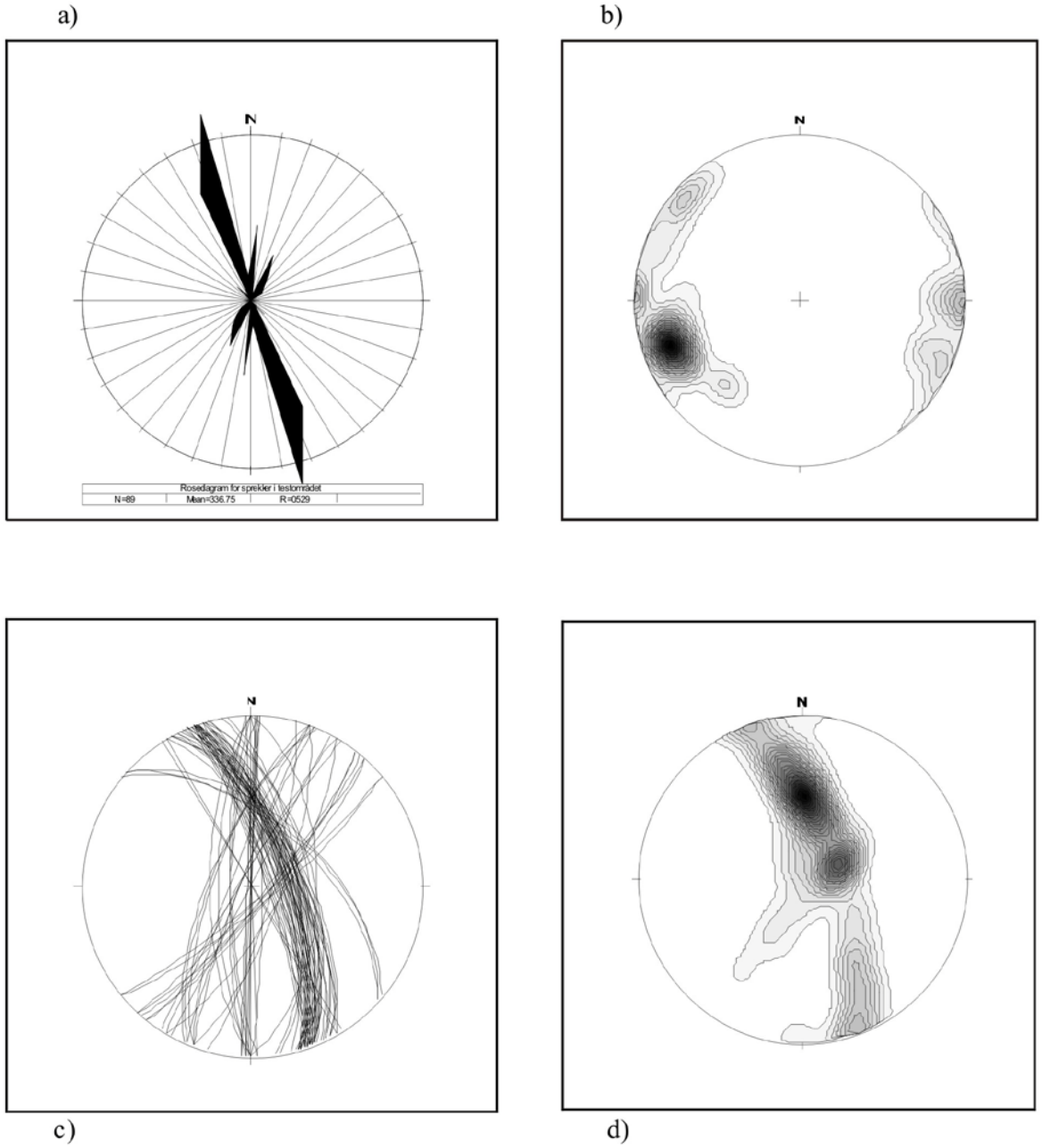

Figure 3.3 Stereographic plots of surface fractures at the well field: a) rose diagrams showing azimuth directions of fractures (N=89) at the test site; b) contoured stereographic projection (lower hemisphere) of the poles to the fracture surfaces; c) stereographic projection of the fracture surfaces and d) contoured plot of fracture surface intersections totalling 3914 intersections (Braathen et al. 1998, Henriksen & Braathen 2006).

3.2 Pumping tests in 1997 and 1998

The approximate capacity of each well was established through recovery tests after short-time (1 hour) pumping tests in 1997 (Braathen et al. 1998). Estimated well capacities are shown in Table 3.2. During the next phase in 1998, a long-time (~14 days) pumping test was carried out in W9 and draw down were measured in the other wells (Gaut et al. 1999). During both pumping tests, the groundwater level was measured automatically at mm-scale with measuring intervals varying from 8 seconds at the start to 15 minutes at the end of each test.

Table 3.2 Estimated well capacity in the wells at Holmedal. The capacity is regarded as very high in W8, high in W3, W6 and W9, medium in W1 and W2 and low in W4, W5 and W7.

Method	Well number	Estimated capacity (l/h)	Relative capacity
Recovery test	W8	> 800	(very high)
Recovery test	W3	80	(high)
Recovery	W6	130	
Recovery	W9	90	
Recovery test	W1	20	(medium)
Recovery	W2	50	
Recovery	W4	7	(low)
Recovery test	W5	4	
Recovery without previous pumping	W7	< 1	(very low)

During both the short- and the long-time pumping tests, alteration in water level in the observation wells during pumping, demonstrated communication between the wells with the highest estimated capacities (W3, W6, W8 and W9, Table 3.2). However, the drawdown in W3 when pumping in W8 and W9 was less significant.

3.3 Tracer tests June 1998

Tracer tests were carried out in the well field in June 1998 (Gaut et al. 1999). The tests were carried out by the Institute for Energy Technology (IFE), and took place at the same time as the long-time pumping test in W9. The aim was to confirm communication between the injection wells (W3, W6 and W8) and the pumping well (W9) as indicated by the short-time pumping tests. Tracers injected were Cl^-, Br^- and I^- in the form of Na-salts, heavy water (D_2O) and the active tracers ^3H and ^{36}Cl.

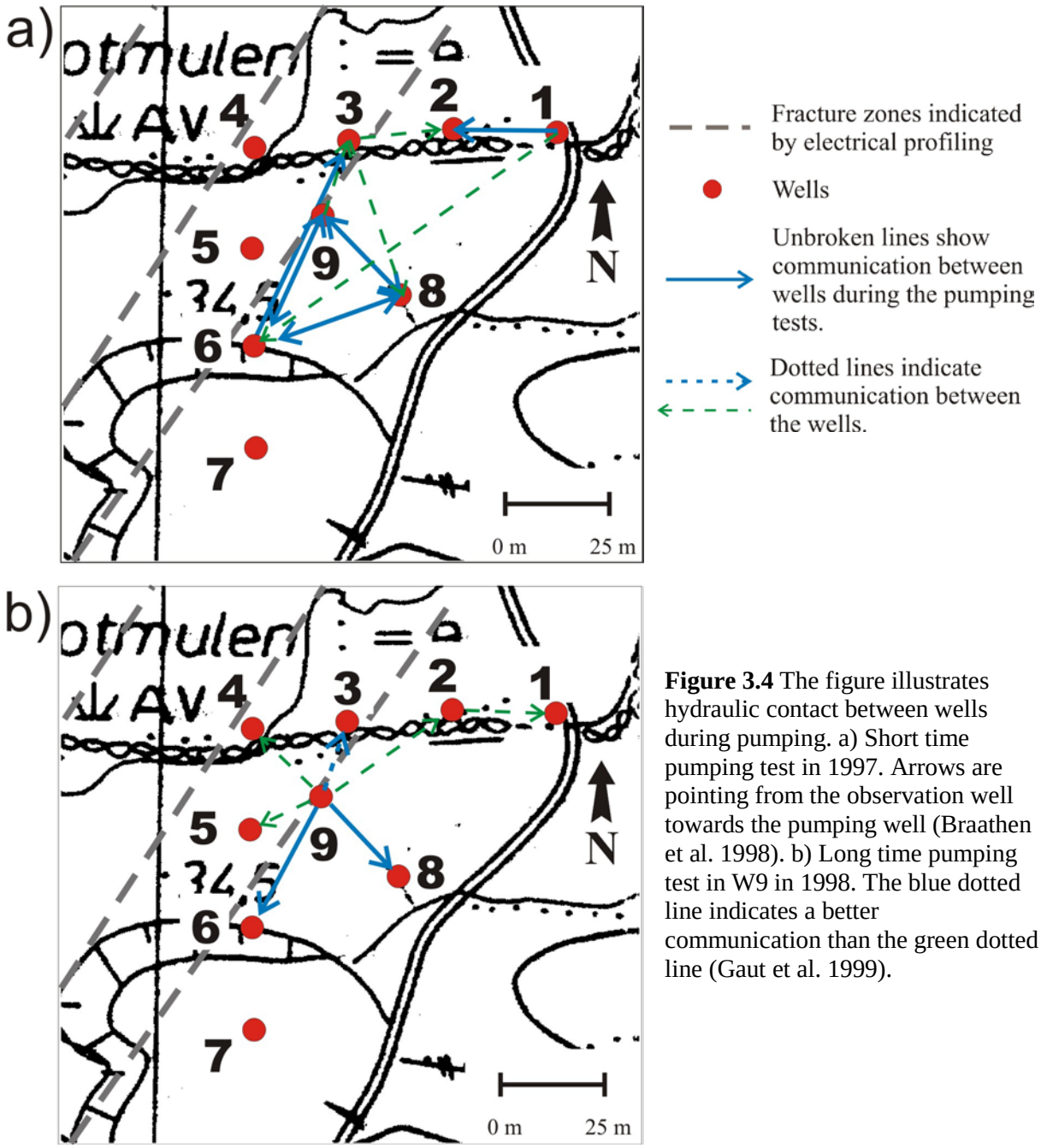

Figure 3.4 The figure illustrates hydraulic contact between wells during pumping. a) Short time pumping test in 1997. Arrows are pointing from the observation well towards the pumping well (Braathen et al. 1998). b) Long time pumping test in W9 in 1998. The blue dotted line indicates a better communication than the green dotted line (Gaut et al. 1999).

4. PUMPING AND GROUNDWATER LEVEL MEASUREMENTS DURING THE TRACER TESTS

Tracer tests were conducted in September 1999 as described in Chapter 5. The pump was installed at about 80 m depth in W9. As for the pumping test in 1998 (Gaut et al. 1999) it was not possible to keep a fixed pumping rate, but the yield was kept more stable. The average pumping rate was about 100 l/hour. The pumping was started on the 14th and ended on the 23rd. Lack of data in Figure 4.1 is due to instrument malfunction.

During the tracer tests the groundwater level was measured automatically at mm scale in wells number 3, 5, 6, 8 and 9. Loggers from ELPRO were used and measuring range**,** installation depth and water level in the wells before pumping started are shown in Table 4.1. Because of problems with the instruments groundwater levels were not measured continuously. The logger in W9 did not work at all after September 16th, and only manual measurements were taken from the 16th to the 19th when sampling of water for tracer analyses ended (Figure 4.1). The water level varied between 47.30 m and 49.54 m during this period.

Groundwater measurements in W3, W5, W6 and W8 during pumping in W9 are shown in Figure 4.2. As expected from the pumping tests in 1997 and 1998 (Braathen et al. 1998, Gaut et al. 1999), the groundwater level immediately drops in W6 and W8 when the pump is started on the 14th. Elevation or stabilization of the groundwater level occurs on the 14th and 22nd due to rain. Time of injection of the different tracers can be seen on the graphs.

Table 4.1 Type of data loggers used to measure water level in the wells during the tracer tests conducted in September 1999. Measuring range, installation depth below ground level and water level in the wells before pumping started are shown.

Well number	Instrument type	Measuring range (m)	Installation depth below ground (m)	Water level measured manually (m)
3	ELPRO	0-10	10	0.87
5	ELPRO	0-10	10	2.31
6	ELPRO	0-10	12	4.97
8	ELPRO	0-20	10	1.64
9	ELPRO	0-75	77	6.33

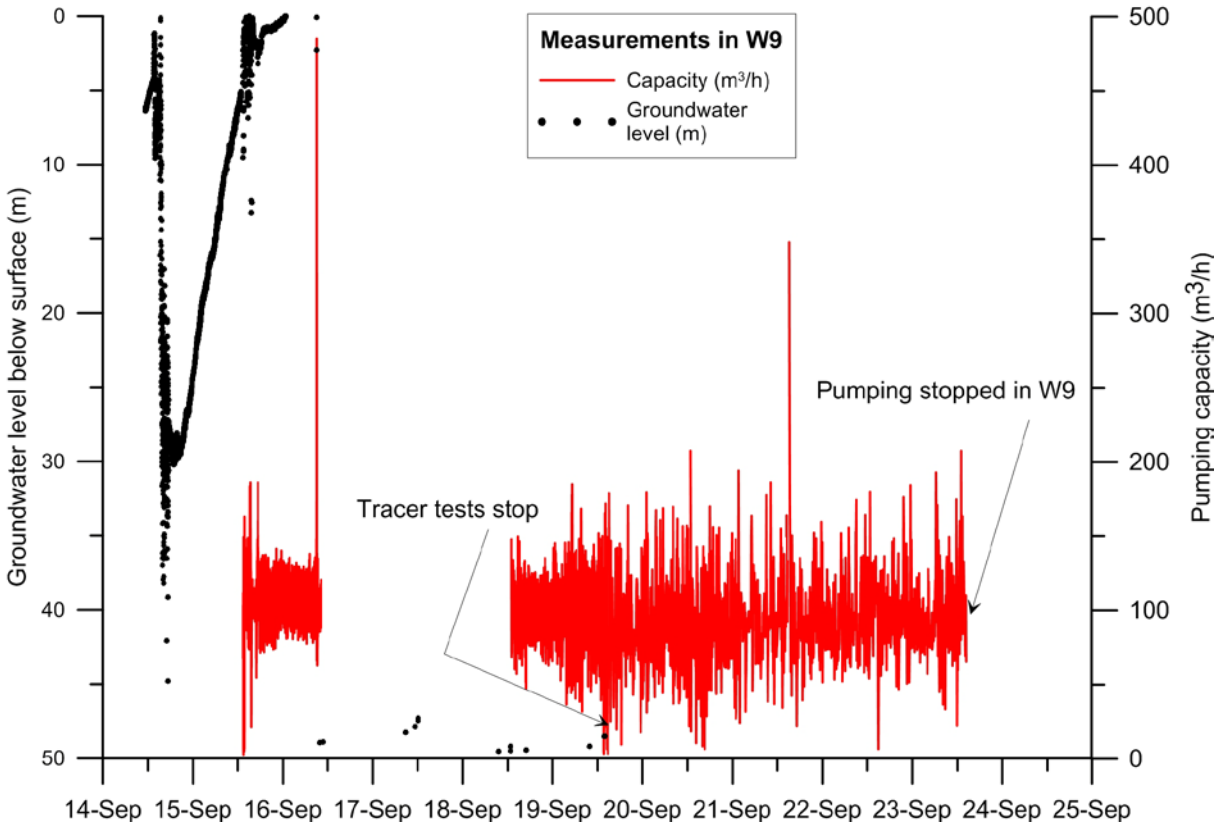

Figure 4.1 The figure shows measurements of groundwater level and pumping capacity in W9 during the tracer tests in September 1999. Because of problems with the instruments the measurements are not continuous. The groundwater level is measured manually from the morning on the 16th. Pumping started on the 14th at about 11:15 and ended on the 23rd at about 14:30. Average pumping rate was approximately 100 l/hour.

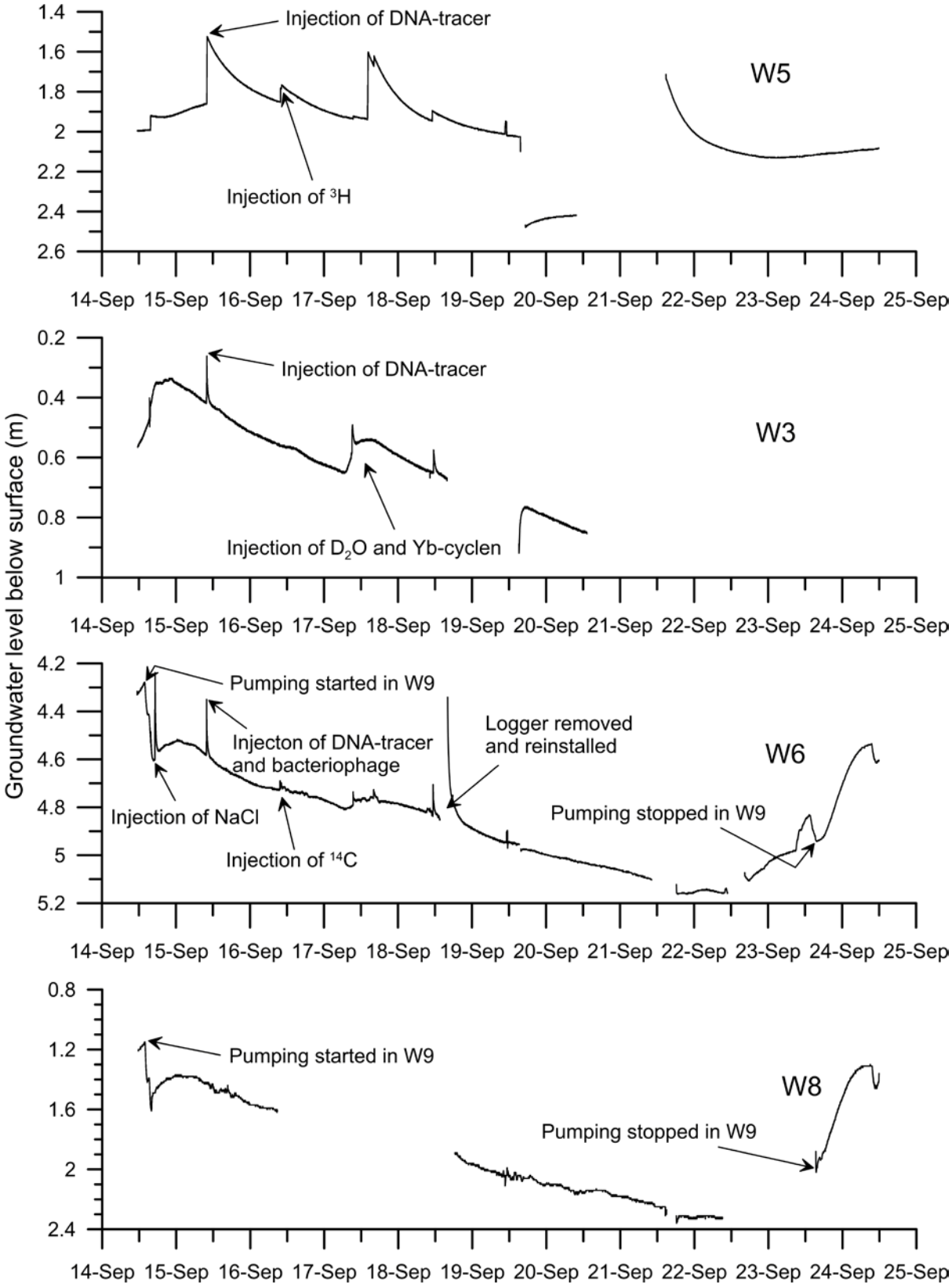

Figure 4.2 Groundwater level measurements in W3, W5, W6 and W8 during pumping in W9. The groundwater level drops immediately in W6 and W8 when the pump is started on the 14th and rises when the pump is stopped on the 23rd. The groundwater level rises in several of the wells due to tracer injection. Examples are W3, W5 and W6 during injection of the DNA-tracer, and in W6 during injection of NaCl. Elevation or stabilization of the groundwater level also occurs on the 14th and 22nd due to rain. Because of problems with the instruments groundwater levels were not measured continuously.

5. TRACER TESTS SEPTEMBER 1999

Tracer tests were carried out in the well field in September 1999. Tracers injected were DNA, the bacteriophage *Salmonella typhimurium* type 28B, ^{14}C, $^{175}Yb^{3+}$, D_2O and ^{3}H. The use of DNA and the bacteriophage is described by Gaut et al. (2005). The purpose of the tracer tests was:

i. Confirming communication between the wells in the well field, as indicated by pumping tests conducted in 1997 and 1998, Figure 3.4.
ii. Comparing the behaviour of the DNA tracers with the other tracers in order to evaluate the usefulness of DNA as a groundwater tracer in fractured aquifers.

5.1 Description of the tracers

The tracers ^{3}H and heavy water (D_2O) are common tracers in hydrogeology. The active tracer ^{3}H is chosen because it can be used in low concentrations and theoretically, will not influence on the water flow.

The synthetic DNA tracers, provided by ChemTAG International AS, are similar to natural DNA in chemical composition hence they will decompose. Each tracer consists of 70 base pairs and is 23.8 nm long. The DNA molecule may curl up into a ball. In a typical DNA tracer test, 10^{16} molecules are injected, corresponding to a few mg of DNA. Other studies using DNA tracers in Norway are described by Sabir et al. (2000).

In appearance, the bacteriophages of the type *Salmonella typhimurium* phage 28B are relatively round (octahedron) with a diameter of 60 nm and have a "doughnut-like" base (Lilleengen 1948). The phage has been used in previous groundwater tracer studies both in the field (Stenström 1996) and in sand- and soil columns in the laboratory (Johansson et al. 1998, Carlander et al. 2000). The phage solution is prepared at the Swedish Institute for Communicable Disease Control (Smittskyddsinstitutet).

The ^{14}C is injected as a labelled thiocyanate (SCN^-). This is a tracer used to better understand the dynamics of oil reservoirs.

A chelate compound was injected in one well. This is a new type of tracer which is originally developed for medical use. It can be labelled with different metal ions. In this study $^{175}Yb^{3+}$ is used because it has a suitable half-life (4.2 days) and low-energy gamma radiation. It is easily detected, but also easy to shield and degenerate relatively fast.

5.2 Method

The tracer tests were conducted under similar conditions as in 1998 (Gaut et al. 1999). A fixed setup was established, with a submersible pump in well number 9 at about 80 metres depth. An average pumping rate of 100-110 l/h was used. Pumping was started at least one day before injection of tracers in order to stabilise the groundwater movement. The groundwater level was measured automatically at mm-scale during pumping in the wells W3, W5, W6, W8 and W9 (Chapter 4). A plastic tube was installed in each of the injection wells to a depth of about 15.2-15.5 m below ground surface. In all tests, tracer solutions were injected through the injection tubes, followed by 1.5-5 litres of water to clean the tube and to ensure that the entire tracer entered into the well (Table 5.1).

Table 5.1 Type and amount of tracer injected in wells W2, W5, W3 and W6 in September 1999. The sodium salts were dissolved in water and the DNA tracers were mixed with ½ litre of water prior to injection.

Date	Injection well	Type and amount of tracer injected	After injection rinsing water (litres)	Measuring method/ Sampling frequency and duration
14th	W6	1 kg NaCl	4	Electrical conductivity measured in the field
15th	W2	DNA (A-9) (about 6.0 x 10^6 molecules)	5	Water samples*[1]
15th	W3	DNA (C-10) (about 6.0 x 10^6 molecules)	5	Water samples*[1]
15th	W5	DNA (B-11) (about 6.0 x 10^6 molecules)	5	Water samples*[1]
15th	W6	DNA (D-12) (about 6.0 x 10^6 molecules)	5	Water samples*[1]
15th	W6	500 ml Bacteriophage solution (about 10^{13} phages)	5	Water samples*[1]
16th	W5	10MBq ^3H	Minimum 1.5	Water samples*[2]
16th	W6	10 MBq ^{14}C	Minimum 1.5	Water samples*[2]
17th	W3	10MBq ^{175}Yb and 1 litre D_2O	Minimum 1.5	Water samples*[2]

*[1, 2]Water samples collected as shown in *[1]Table 5.4 and *[2]Table 5.5

The tracer tests were carried out by both NGU and IFE. NGU injected NaCl, DNA and a bacteriophage solution, whereas IFE injected ^{14}C, $^{175}Yb^{3+}$, D_2O and ^3H.

NaCl was injected in W6 in the afternoon on the 14th (start at 17:07). 1 kg of salt was mixed with 5 litres of water (Table 5.1). After injection the injection tube were rinsed with 4 litres of water. Total time used was 17 min including 90 seconds with tracer injection. Water pumped from W9 was directed through a plastic tank, and electrical conductivity was measured during the night. In addition NaCl were injected in W3, W5, W6 and W8 in connection with borehole tomography (Chapter 6) taking place during and after the tracer tests. Time of injections is shown in Table 5.2. Although these injections are not part of the tracer tests, changes related to them are described in Chapter 5.3.2.

DNA tracers were chosen because each DNA tracer can be constructed with a unique label, and thereby one has the opportunity to inject different tracers with the same physical and chemical properties simultaneously in different wells. In addition, Bacteriophages were used, since this tracer imitate virus- and bacteria transport. The purposes of the tests were (i) to confirm communication between W9 and the wells W2 and W5 and (ii) to compare the behaviour of the DNA tracers with the other tracers injected, thus injection in W3 and W6 as in the previous test in 1998. Different DNA tracers were added in the four chosen wells (W2, W3, W5 and W6) as shown in Table 5.1. About 6.0 x 10^{16} DNA molecules, mixed in ½ litre

of bottled water (type Olden), were injected through the installed plastic tube. In well W6, 500 ml of bacteriophage solution (representing about 10^{13} phages) was added simultaneously as a second tracer. Immediately after injection of tracer(s) 5 litres of water were added to clean the tube in each well. Injection rates are shown in Table 5.3, and the numbers include both injection of water and rinsing of the tube.

Table 5.2 Injection of NaCl in relation to the borehole tomography performed during and after the tracer tests at Holmedal well field in September 1999.

Date	Time of injection	Injection well	Amount of NaCl injected (3‰ salt solution)
18. Sept 99	Not known	W3	Small amount to test the equipment for later salt injection
18. Sept 99	Not known	W5	Small amount to test the equipment for later salt injection
18. Sept 99	Not known	W6	Small amount to test the equipment for later salt injection
20. Sept 99	14:20-17:30	W5	15 litres
21. Sept 99	08:50-15:40	W5	15 litres
22. Sept 99	10:50-15:50	W8	15 litres
23. Sept 99	08:50-15:00	W8	about 5 kg salt

Table 5.3 Tracer injection rates for the DNA tracer.

Well number	Injection rates tracer + water (l/min)
W2	1.1
W3	0.69
W5	0.61
W6	1

Water was sampled from the pumping well (W9) before injection of tracers, thereby determining the background concentrations of the tracers, if any. After injection, water samples were taken every 3 minutes during the first hour, and then less frequent as time passed, as shown in Table 5.4. During the night, an automatic sampler was used to collect 150 ml of water every 30 min and two such samples were collected in the same bottle. Hence samples taken during the night were a combination of two samples. All samples were stored at low temperature. Separate 100 ml samples were taken for DNA and the bacteriophage, and samples taken during the night were split into two 100 ml bottles.

For the DNA analyses 1.5 ml ampoules were used. In the field 4 water samples of 1.5 ml each, were extracted from every 100 ml bottle using disposable plastic pipettes, one for each bottle. Only the ampoules were sent to analyses at NVH.

The PCR- method used to detect DNA in the water samples provides qualitative results. Therefore, all possible precautions were taken in order not to cross-contaminate DNA from one well to the other, or to cross-contaminate the water samples. Different gloves were used when mixing each DNA with bottled water, and the mixing were not done in the field. Gloves were also used during injection and changed between each injection. The analysis also excludes drawing of breakthrough curves, as well as evaluation of time-dependant changes in the DNA concentrations.

Table 5.4 Frequency and duration of each sampling interval used for DNA and bacteriophage analyses.

Sampling frequency (minutes after tracer injection)	Duration of each interval	
	DNA analysis (minutes)	Bacteriophage analysis (minutes)
3	50	61
5	120	116
10	130	270
15	45	45
20	40	40
30	~5 days	210
60		815
360		11 hours

Table 5.5 Frequency and duration of each sampling interval used for tracers injected by IFE.

Sampling frequency (minutes after tracer injection)	Duration of each interval (min)		
	W3	W5	W6
5	120	120	120
6	120	120	120
10	120	240	240

Personnel from IFE started tracer injection at September 16th in W5 and W6 as shown in Table 5.1. Tracers used were 10 MBq ^{3}H in W5 and 10 MBq ^{14}C in W6. ^{3}H were injected with a syringe through the tube wall. The day after 10MBq $^{175}Yb^{3+}$ and 1 litre D_2O were injected in W3. The tracers are described in chapter 5.1. As for DNA and the bacteriophage, a water sample was collected from the pumping well (W9) before injection to determine the background level. After injection water was sampled as shown in Table 5.5. Total sampling time after injection for W3 was 6 hours and 8 hours for W5 and W6. Samples were analysed at IFE.

5.3 Results

5.3.1 Well field behaviour during tracer tests

Figure 4.2 shows the groundwater level measured in W3, W5, W6 and W8 during the tracer tests. Except for an increase or stabilization caused by rain on September 14th and 22nd, the measurements show that the water level in general dropped in these wells during pumping. Compared to W3, W6 and W8, the water level in W5 appear not to be influenced by either precipitation or the pumping in W9. Precipitation on Sept. 14th causes the groundwater level to rise noticeably in W3, W6 and W8, while the water level dropped rapidly in W6 and W8 when pumping was started in W9. In contrast, the groundwater level in W5 increases slowly even after the pump is started.

Several peaks can be observed on the graphs in
Figure 4.2. Most of these are due to injections related to the tracer tests and borehole tomography. The tracer injections done by IFE causes less pronounced increases in the groundwater level because smaller amounts of water are used to rinse the tube afterwards. After the injections, the groundwater level drops fast in W3 and W6, while the level in W5 decreases more slowly. Borehole tomography is done between W9 and some of the wells (Chapter 6). Preparations for salt injections in W3, W5 and W6 were done on the 18th. Some salt (NaCl) were test injected, causing the groundwater level to increase in the three wells.

Table 5.6 First arrivals of tracers in the pumping well (W9) for the tracers injected in W2, W3, W5 and W6. Injection of NaCl in W8 is done in connection with the borehole tomography. Average pumping rate was 100-110 l/h. ND = tracer not detected.

Injection well	Distance from W9 (m)	Tracer	First arrival (min)	First arrival (hours)
W2	38.7	DNA	4066	67.77
W3	21.6	DNA	14*[1]	0.23*[1]
		DNA	29	0.48
		^{175}Yb and D_2O	ND	ND
W5	20.48	DNA	115	1.92
		^{3}H	2400*[2]	40*[2]
W6	39.0	NaCl	50	0.83
		NaCl	180-225	3.0-3.75
		DNA	17	0.28
		Bacteriophage	1417-1776	23.62-29.6
		^{14}C	ND	ND
W8	23.6	NaCl	750*[3]	12.5*[3]

*[1] Uncertain
*[2] Uncertain – small increase, see the text
*[3] After injection started.

5.3.2 The tracer tests

Tracers were injected in wells W2, W3, W5 and W6 (Table 5.1). In addition NaCl was injected in relation to the borehole tomography performed during the same period (Table 5.2). NaCl injected in W6 on the 14th had a possible breakthrough after 50 min (The first peak in Figure 5.1, 5.6 mS/cm) lasting for about 5 min. Afterwards the conductivity in the tank stabilizes on about 0.15 mS/cm. The main pulse seams to arrive after 3-4 hours causing a second increase in the electrical conductivity to a maximum of 0.27 mS/cm. The increase starts after 3 hours, but the conductivity rises more quickly after additional 45 min and the water temperature changes. As shown in Table 5.2, small amounts of NaCl are injected in W3, W5 and W6 on the 18th. This is shown by small increases in the water level in Figure 4.2, but the amount is too small to cause any increase in the conductivity in the water pumped from W9. Not until midnight on the 22nd does the conductivity increase in the tank, probably due to injection in W8 the same day. NaCl injection lasted 5 hours from 10:50-15:50, giving a breakthrough about 12.5 hours after the injection started.

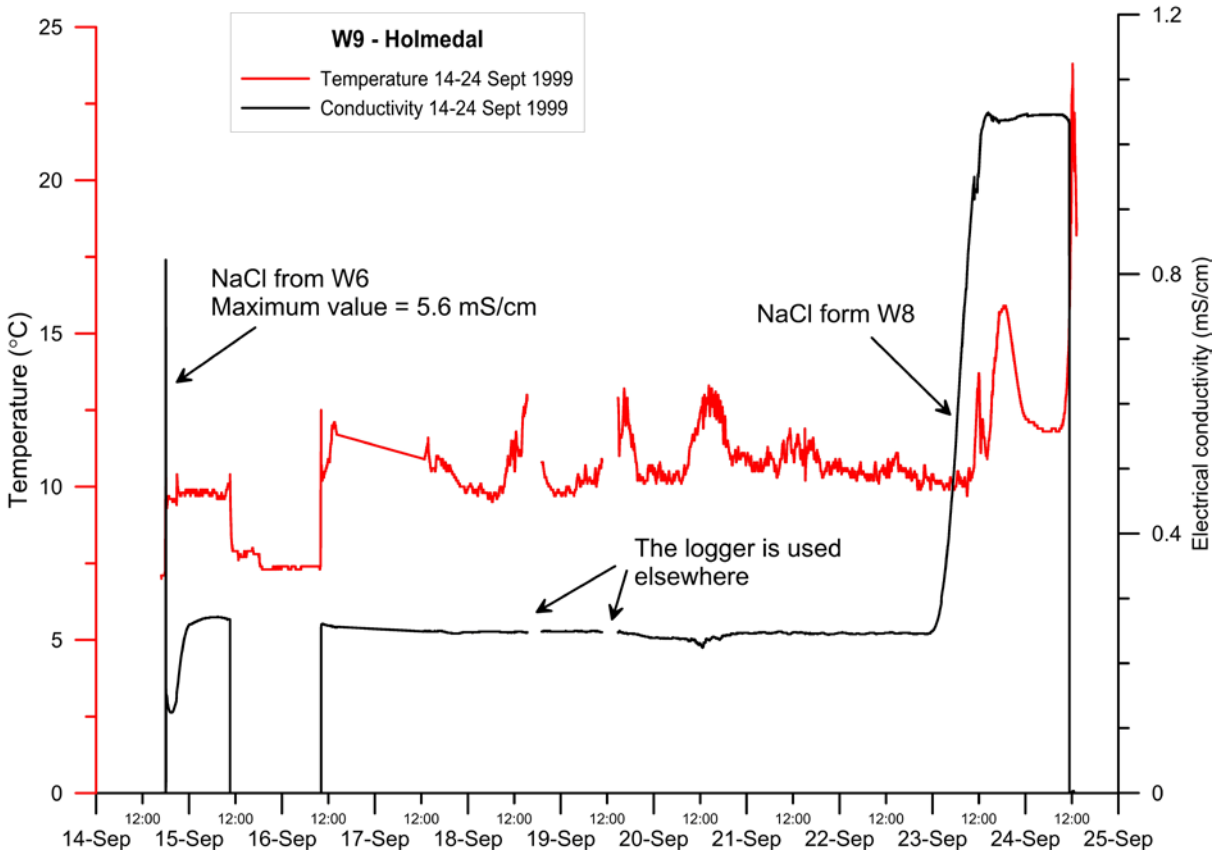

Figure 5.1 Temperature and electrical conductivity measured in the water pumped from W9. The water is flowing through a plastic tank, thus the temperature is influenced by the air temperature and peaks occur during the daytime. The drop in temperature and conductivity between the 15th and 16th is artificial, but the exact cause is unknown.

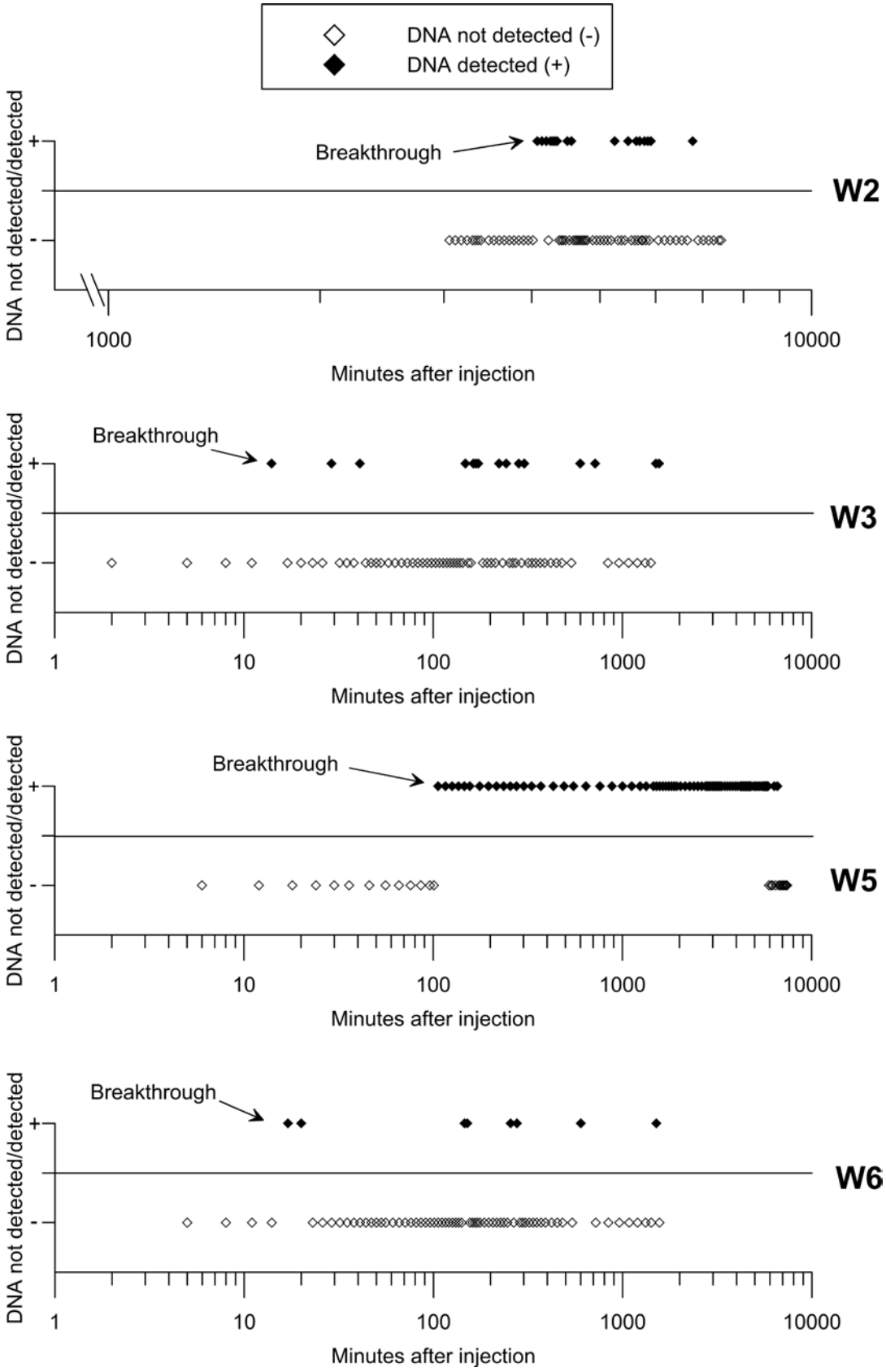

Figure 5.2 Plots showing qualitative breakthrough of the DNA tracer. The Y-axis shows samples where DNA is detected as positive (+) and samples where DNA is not detected as negative (-). The X-axis is logarithmic. Breakthrough in W9 (Table 5.6) is recorded after 14 min from W3, after 17 min from W6, after 115 min from W5, and after 4066 min (2.8 days) from W2 (Gaut 2005 appendix G).

The DNA-tracers proved connection between all the four wells (Table 5.6). First arrival of the DNA-tracer in W9 from W2 occurred after 4066 min (nearly three days), whereas the first indication of arrival from W3 was a weak detection signal after 14 min and a definite detection signal after 29 min. Breakthrough of DNA-tracer from W5 occurred after 115 min and from W6 after 17 min. The results from the analyses are shown in Figure 5.2. For each well, except W5, the samples with positive detection signals occur in between one or more samples were the DNA tracer is not detected, although the results from W2 indicates that the first tracer pulse is more or less continuous.

In contrast to the breakthrough time of 17 min for DNA tracer, breakthrough in W9 of the bacteriophage from W6 occurred between 23.6 and 29.6 hours. Subsequently, the amount of bacteriophage increased steadily, without a noticeable peak in the phage concentration when the sampling was stopped, as shown in Figure 5.3.

None of the tracers injected by IFE was detected in W9. Water samples taken by NGU were also analysed and an increase in the ^{3}H level was observed after about 40 hours (Figure 5.4). The increase is small and the values are lower than the background level of 16 cpm measured before injection in W8 in 1998 (Gaut et al. 1999).

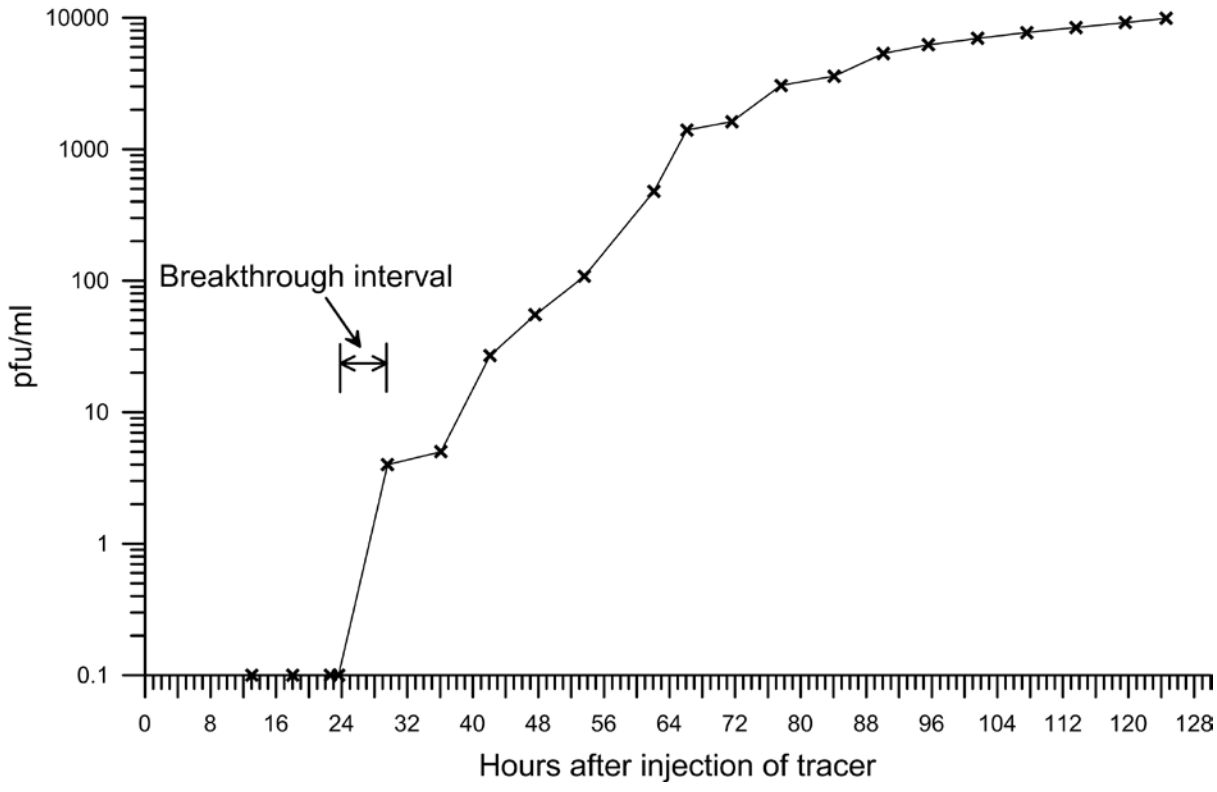

Figure 5.3 Breakthrough curve for the bacteriophage tracer applied in W6. Values plotted as 0.1 pfu/ml (plaque-forming units/ml) are in reality measured below detection (<0.1 pfu/ml). Breakthrough of the tracer occurs between 23.6 h and 29.6 h after injection (Gaut 2005appendix G).

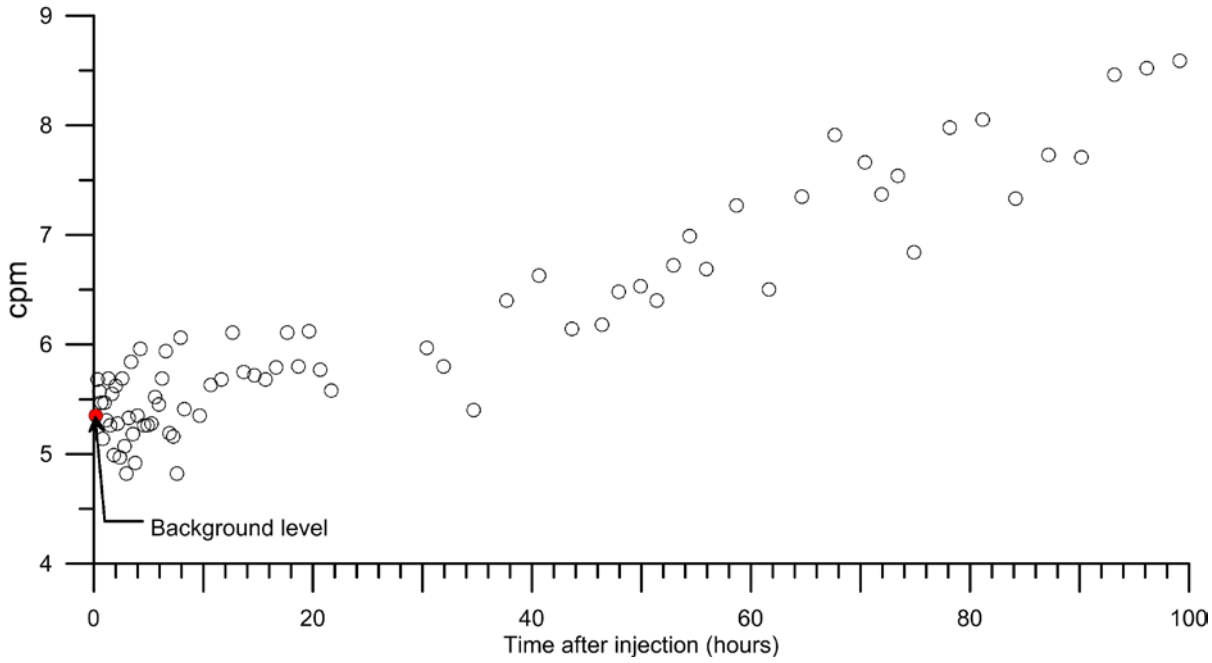

Figure 5.4 Measurements of ^{3}H injected in W5. Possible breakthrough in W9 occurs after about 40 hours. Background level 5.4 cpm (counts per minutes).

6. BOREHOLE TOMOGRAPHY AND ELECTRICAL CONDUCTIVITY

6.1 Borehole tomography

NGU wanted to test the usefulness of borehole tomography and the method was used at Holmedal in September 1999. Measurements were done between W9 and the wells W3, W5, W6 and W8 as shown in Table 6.1. For W5 and W8 measurements were done both before and after injection of 3‰ NaCl, whereas for W3 there was no time to do the measurements with salt. The distance between W9 and W6 was too long to give any results.

Water was pumped in W9 and the salt was injected in W5 and W8 during the measurements. The NaCl solution was injected continuously over an unknown period of time. Data was recorded manually by Torleif Lauritsen and Jomar Gellein. Except for the measurements between W8 and W9, no interpretation of the data has been done, and the data are not reported.

Table 6.1 Borehole tomography conducted in 1999 by Jomar Gellein and Torleif Lauritsen, NGU. Measurements after NaCl-injection were only done in W8 and W5.

Measurements between wells	Date measured		Comments
	Without NaCl	NaCl injected	
W8 and W9	16-18 Sept	22-23 Sept	3^{o}/oo NaCl injected in W8 at about 15 m depth.Salt injected 22^{nd} in the period 10:50-15:50. No increase in the electrical conductivity were measured in W9 until. On the 23^{rd} about 5 kg of NaCl-solution were injected between 08:50 and 15:00. An increase in the electrical conductivity was observed after 12.5 hours.
W6 and W9	18 Sept	None	The distance between the wells is too long to give any results.
W3 and W9	19 Sept	None	Not measured with NaCl
W5 and W9	19-20 Sept	20-21 Sept	3^{o}/oo NaCl - solution injected in W5 at about 15 m depth both 20^{th} (14:20-17:30) and 21^{st} (08:50-15:40).

6.2 Electrical conductivity profiles in the wells

The electrical conductivity was logged in all the wells in September 1999. For most wells the measurements were done twice both on the 19^{th} and the 26^{th}. The results are shown in Figures 6.1-6.5.

Injection of NaCl between the two measurements is clearly shown for the wells W5, and W8. In W5 the small injection on the 18^{th} are also visible as a small increase in the conductivity at about 15m for the measurements carried out on the 19^{th}. In W3 the injection of NaCl occurred on the 18^{th} and the measurements show that most of the NaCl is removed from the well on the 26^{th}, and that the remaining salt has sunk to the bottom of the well. Compared to W3 (Figure 6.2), measurements in W6 (Figure 6.3) show that in this well the NaCl remains for a longer period. The conductivity is still high on the 26^{th}, although NaCl was last injected on the 16^{th}. Wells with no injection of NaCl (W1, W2, and W4) show similar conductivity profile for both measurements. In W2 there is an increase in the conductivity at about 15 m depth, indicating a fracture at this depth.

The temperature is generally stable at about 7°C in all wells below 10 m depth.

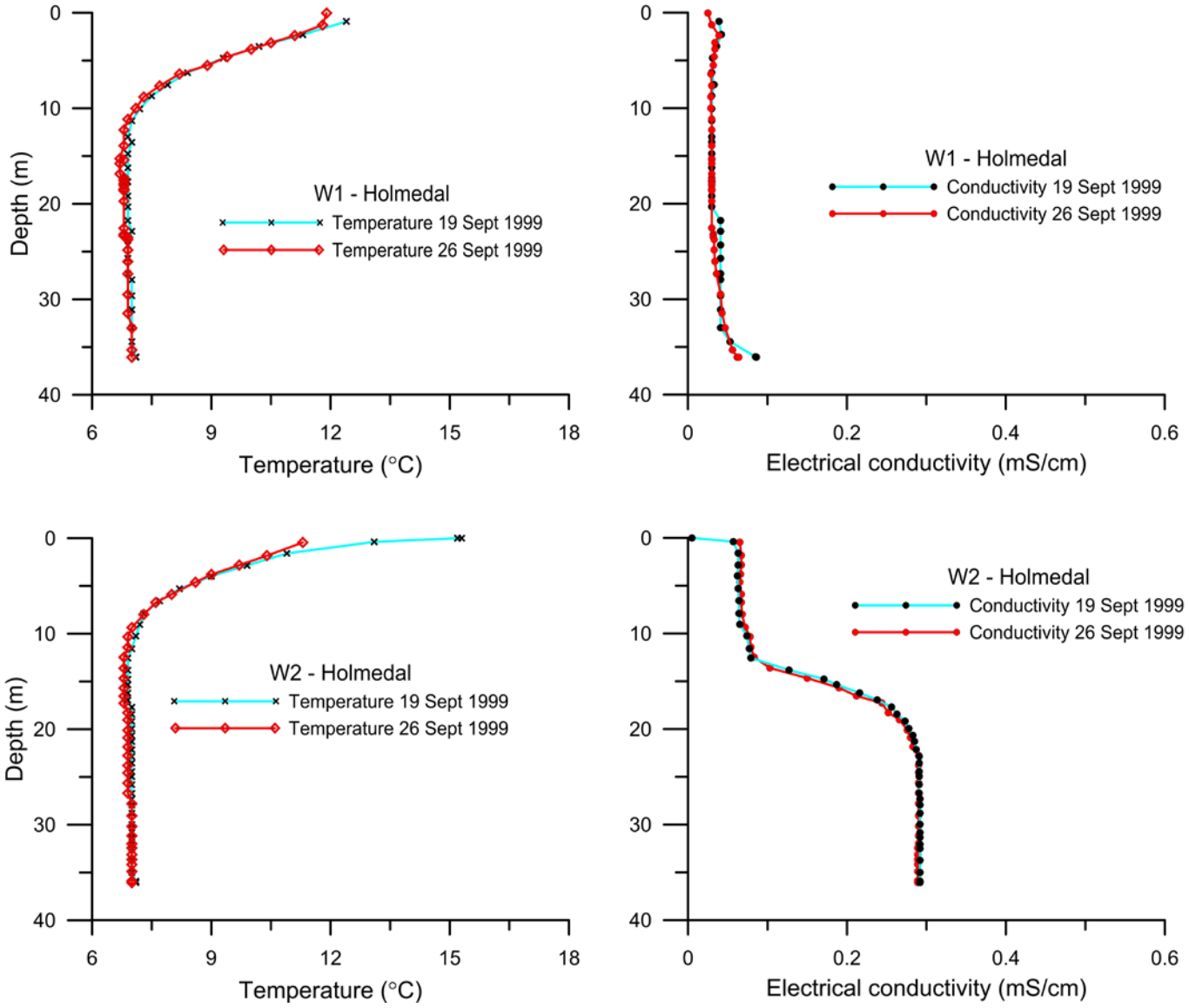

Figure 6.1 Temperature and conductivity logging in W1 and W2, Holmedal well field. The logging is conducted on September 19th and 26th. No NaCl or other types of tracers were injected in W1, whereas DNA was injected in W2 on the 15th. Injection depth was about 15m.

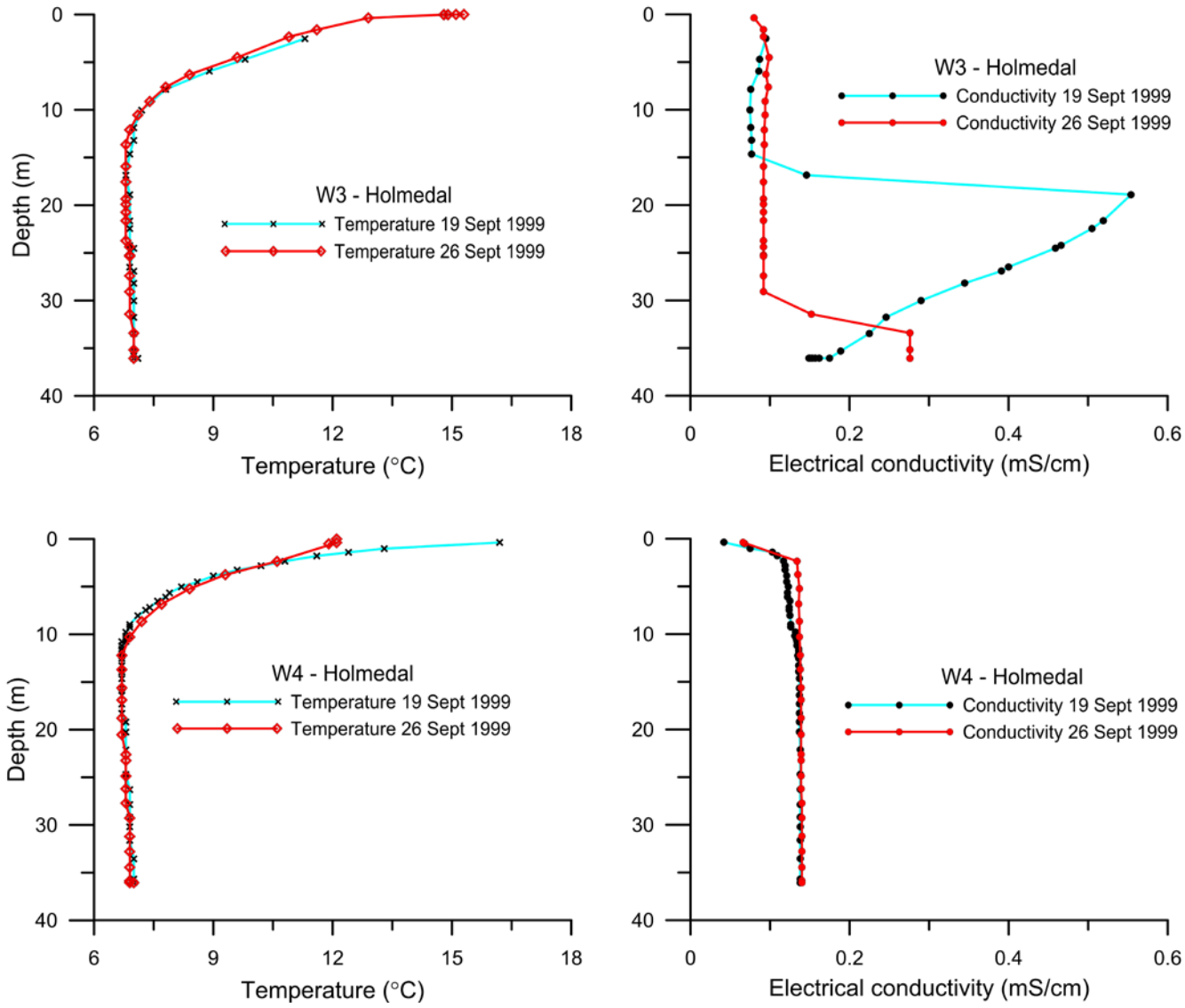

Figure 6.2 Temperature and conductivity logging in W3 and W4, Holmedal well field. The logging is conducted on September 19th and 26th. DNA was injected in W3 on the 15th and 10MBq ^{175}Yb and 1 litre D_2O on the 17th. A small amount of NaCl (3‰ solution) were injected in the well on September 18th. Injection depth was about 15m. No NaCl or any other tracer was injected in W4.

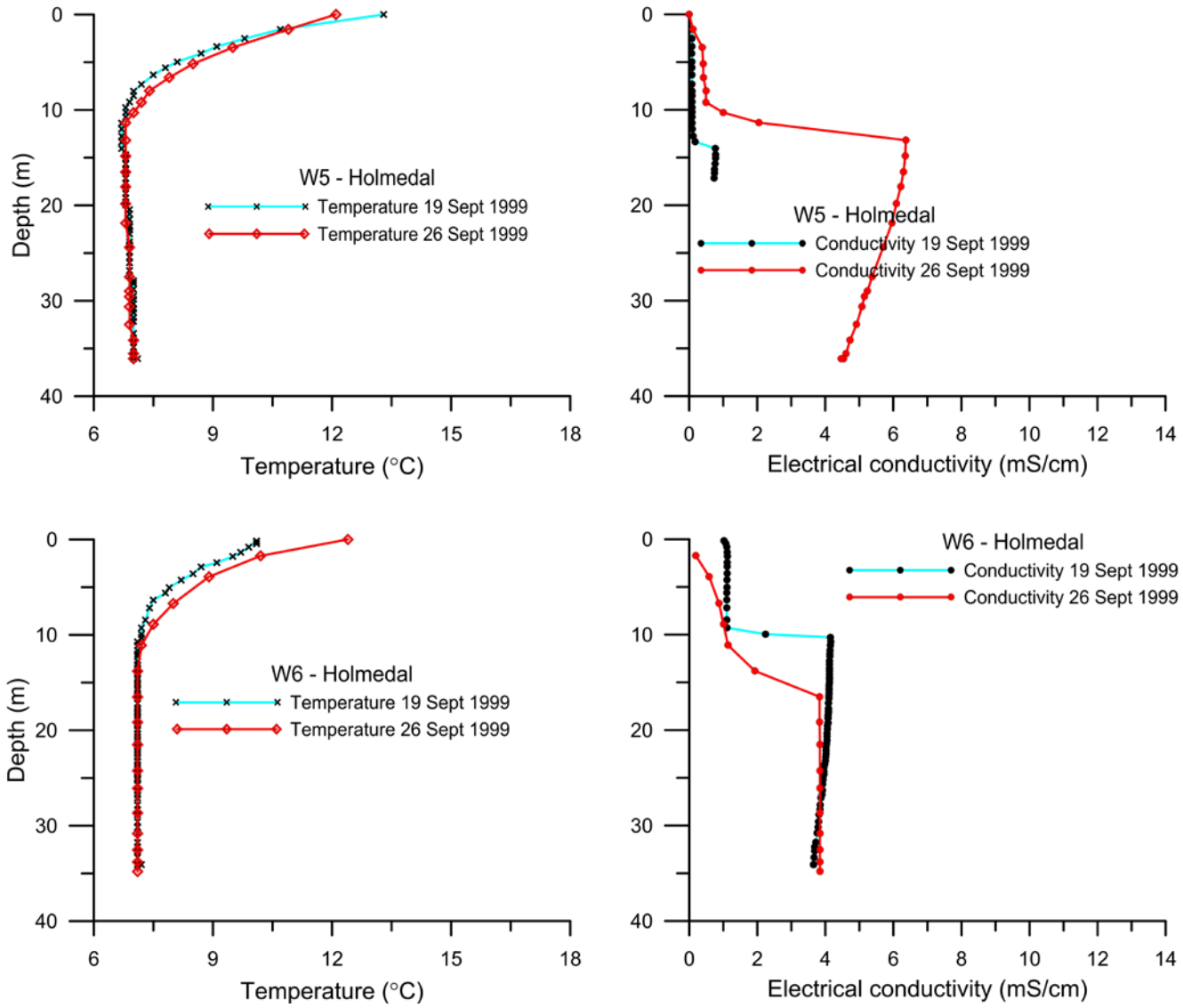

Figure 6.3 Temperature and conductivity logging in W5 and W6, Holmedal well field. The logging is conducted on September 19th and 26th. DNA tracer was injected in W5 on the 15th, whereas NaCl (3‰) was injected on the 18th, 20th and 21st. Only a small amount was injected on the 18th. In W6 NaCl was injected both on the 14th and 16th, whereas DNA and Bacteriophages were injected on the 15th. Injection depth for both wells was about 15m.

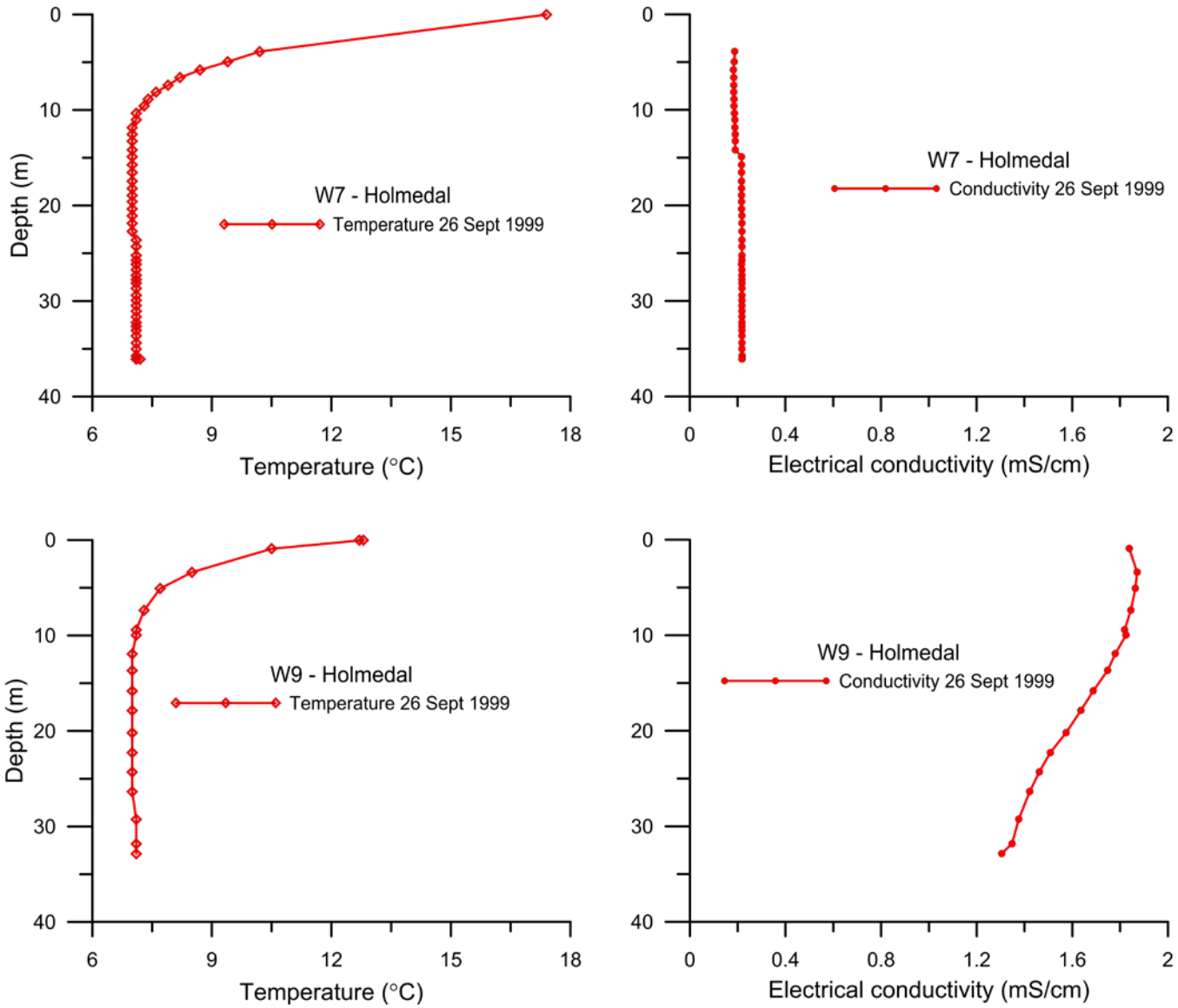

Figure 6.4 Temperature and conductivity logging in W7 and W9, Holmedal well field. The logging is conducted only on September and 26th. No NaCl or any other tracer was injected in the wells.

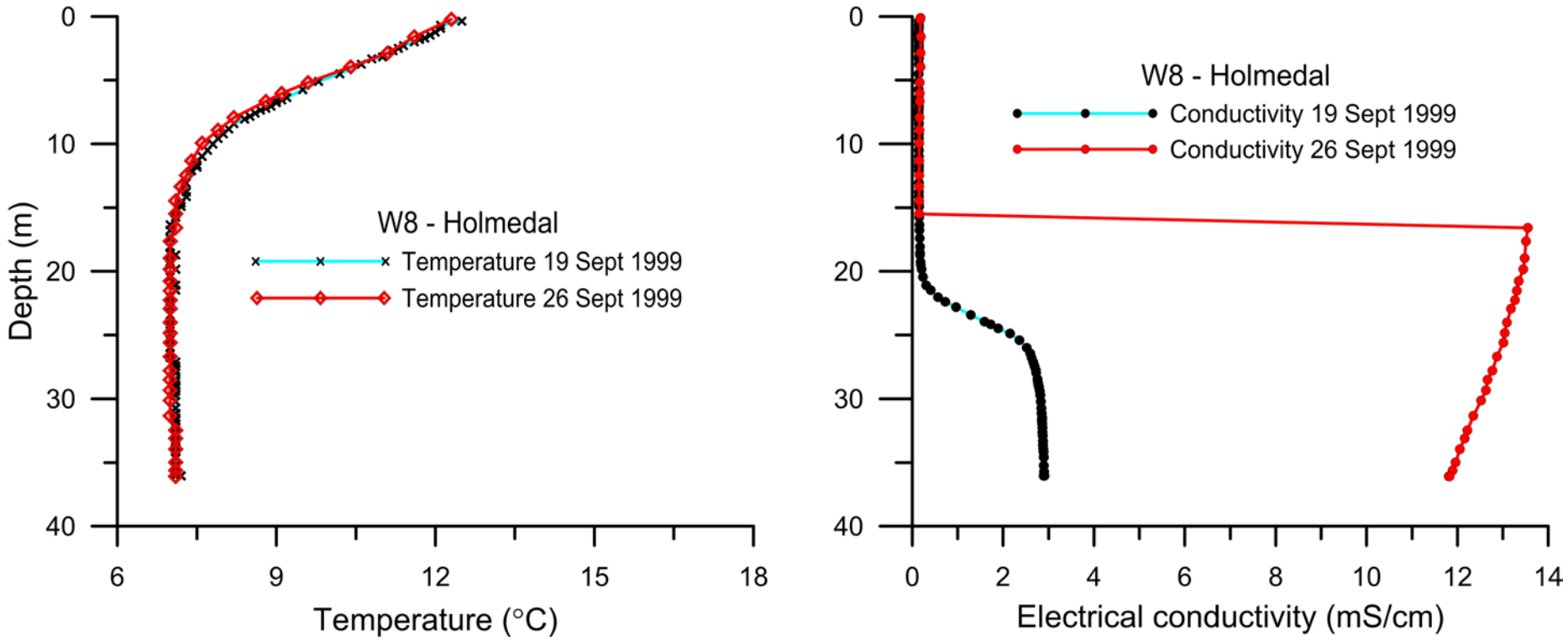

Figure 6.5 Temperature and conductivity logging in W8, Holmedal well field. The logging is conducted on September 19th and 26th. NaCl was injected in the well on the 22nd and 23rd. Injection depth was about 15m.

7. DISCUSSION

The purposes of the tracer tests conducted in 1999 were (i) to confirm communication between W9 and the wells W2 and W5 as indicated by the former pumping tests and (ii) to compare the behaviour of the DNA tracers with the other tracers injected, including the previous test in 1998.

7.1 Communication and flow paths

All tracers (NaCl, DNA and bacteriophage) injected by NGU is detected in the pumping well (W9), thus the tests confirmed the communication between the wells 2, 3, 5 and 6 and W9 as indicated by the pumping tests in 1997 and 1998 Figure 3.4. The tracers injected by IFE in the wells 3, 5 and 6 are not detected, although a tiny increase in the ^{3}H-level is measured after 40 hours.

The DNA tracers injected in W6 show an earlier first arrival in W9 than tracers injected in W3. A similar, early first arrival of the DNA tracer from W5 is observed, though the arrival is later than from W3 and W6. In contrast, the first arrival of the DNA tracer from W2 occurs after nearly three days. In summary, the tracer results suggest that the water flow fastest or at least by a more direct flow path, i.e. shorter flow line, from the wells W3 and W6 to W9 than from the wells W2 and W5. Geophysical measurements show a NNE-SSV striking fracture zone dipping E (Henriksen & Braathen 2006) near W9 that continuous towards W3 and W6 (Figure 2.1). This zone may be a conduit for flow and thereby provide the short flow time. In addition, borehole logging with Optical Televiewer (OPTV) in W9 shows a fracture zone with E-W fracturing in the interval from 54-64 m depth. If this zone is a persisting structure it will intersect W6 and W8 and possibly W5 (Henriksen & Braathen 2006). Water level measurements prior to test pumping in W9 shows that the water level in the wells W6, W8 and W9 is similar and clearly lower than in the wells W1-W5 (Gaut et al. 1999, Henriksen & Braathen 2006). This supports the assumption that the observed fracture zone in W9 intersects W6 and W8, but not the other wells. The intersection with W8 corresponds to a fracture zone at 11-13m depth. The conductivity logs from W8 indicate that there is no mixing of the water column above the injection point at 15m depth, possibly explaining why the tracers injected in W8 in 1998 didn't arrive at W9 as expected from the pumping tests.

Variations in fracture aperture may cause differences in tracer travel time between wells, due to faster advection in wide channels (Zhang et al. 2001) where the friction is less. More water will also flow if the numbers of pathways, i.e. more fractures or interconnected spaces, are increased. Injections of tracers in W3, W5 and W6 caused a rise of the groundwater level (Figure 4.2). In W3 and W6, the groundwater level decreased again momentarily indicating open fractures and/or multiple flow paths transporting the tracer out of the well. The electrical conductivity logs in W3 (Figure 6.2) support this since the conductivity has decreased considerably between the two measurements. However, in W6 the decrease is slow and below 15m depth no decrease can be observed. This indicates one open fracture at this level. In contrast to W3 and W6, the groundwater level after injection in W5 decreased slowly, indicating fractures with smaller aperture and/or few pathways. The first arrivals of DNA tracers and the conductivity logs support these observations.

In general, DNA from the wells is detected in a few samples out of a series, as illustrated by W3 and W6 (Figure 5.2), which in the Holmedal well field, are considered as relatively high-capacity wells (Table 3.2). Hence, samples without DNA appeared in between DNA-arrivals,

consistent with arrival of pulses. Moderate and low capacity wells (e.g. W2, W5) receive either few pulses or one long arrival, respectively. This can also be interpreted as the result of slower, more homogenous flow within a flow path, rather than through numerous flow paths, a scenario more likely for good capacity wells. A similar pattern is observed by Toran & Palumbo (1992), whom describe irregular break through curves (BTC) with multiple peaks representing multiple flow paths.

DNA results are not quantitative and therefore a BTC cannot be drawn. However, arrival of DNA in pulses indicates that attenuation of some of the tracer is taking place. A possible example of absorption is given by the injection of salt the day before injection of DNA (W6), because DNA adsorbs more easily when salt is present (Lorenz & Wackernagel 1987, Toran & Palumbo 1992). This is discussed by Gaut (2005) who concludes that it is most likely that adsorption of DNA (if present) is subordinated other processes and is not important in this study.

Other possible explanations are matrix diffusion and advection processes as discussed by Becker & Shapiro (2000). They found that advection processes caused by differences in hydraulic conductivity in the fracture system, was the reason for tailing of the BTC in fractured crystalline bedrock, and not matrix diffusion. In our study, it is likely that mixing between tracer and the water column occurred in the boreholes after injection of tracer (Pistre et al. 2002). This enhances the probability of the tracer to have entered different fractures and fracture-trajectories, when exiting the injection borehole. If the long continuous signal from W5 corresponds to a BTC tailing, the consistent signals from W5 can be caused by water flowing mainly through one fracture system from W5 to W9. Diffusion-like advection (Becker & Shapiro 2000) can explain the long duration of the signal. Arrival of DNA at various times as seen for the tests conducted in W3 and W6, indicates that the tracers injected instead enter separate fracture systems with different geometric and hydraulic properties. This may cause different advection between fracture systems, and thereby tracer arrival in pulses rather than as a steady flow. This is supported by the drilling and televiewer logs, which show very few fractures or breaks along the borehole in W5, compared to W3 and W6. In W6 this is also supported by the two Cl peaks observed after injection both in 1998 and 1999.

NaCl was injected in both W5 (20^{th} and 21^{st}) and W8 (22^{nd} and 23^{rd}). Conductivity measurements in W9 show a pronounced increase in the electrical conductivity about 12.5 hours after injection in W8. Based on the early breakthrough after DNA injection in W5 and the increased background level of ^{3}H and ^{36}Cl after injection in W8 in 1998 (Gaut et al. 1999), the breakthrough of NaCl is most likely caused by the injection in W8.

7.2 Comparison of tracers

Gaut (2005) has compared the different tracers used at Holmedal. The comparison is approximate because there are uncertainties in the data sets due to sampling intervals and analysis limitations.

The results from 1998 and 1999 indicate that the inactive Br^-, Cl^- and I^- and active ^{3}H and ^{36}Cl tracers are conservative and flow with the water in similar manner. According to Gelhar et al. (1992) and Jensen et al. (1993), Cl^- and Br^- are characterized as conservative or non-reactive tracers, and ^{3}H has also been viewed as a near-ideal tracer (Jensen et al. 1993). Our results suggest that the DNA can be considered as a conservative tracer in fractured aquifers since first arrivals in W3 and W6, as shown in Table 5.6, are within the time range for the breakthroughs observed for the inactive and active tracers injected in 1998 and 1999.

The bacteriophage has a significantly later breakthrough than the other tracers as shown when comparing the results in Figure 5.2 and Figure 5.3. As discussed by Gaut (2005) this can be due to the larger size of the bacteriophage (60nm) compared to the other tracers, excluding the phage from the most direct flow path between the wells if this fracture has a diameter less than 60nm. However a more likely explanation for the difference in travel time for the DNA and the phage is that the latter more easily attaches to fracture walls and fracture fillings as described by Scholl et al. (1990). Although DNA seems to have been little affected by the NaCl-injection in W6, the higher ionic strength of the groundwater may have caused retardation of the bacteriophage. The continuous increase in phage-content shown in Figure 5.3, indicates adsorption and then later detachment of the bacteriophage (Bales et al. 1993, Woessner et al. 2001).

Most tracers injected by IFE in 1999 where not detected in the pumping well. ^{14}C and $^{175}Yb^{3+}$ are tracers utilized in oil reservoirs and medical use respectively and the negative results indicate that they are either not suitable groundwater tracers or that the concentrations injected were too low. It is a possibility that the tracers were influenced by the NaCl injected, causing increased adsorption of the tracers.

Despite the increase in the amount of D_2O injected in 1999 compared to 1998 (about 3 times), no tracer was detected in W9. This indicates that D_2O is not a suitable tracer in fractured aquifers.

To ensure good results, the ^{3}H concentration was increased from 1.2MBq in 1998 to 10MBq in 1999. The tracer was not detected in W5 as expected when comparing with the DNA results. A small, but continuous increase in the concentration is observed after 40 hours (Figure 5.4), but this is below the background level measured in 1998 and is not conclusive. No good explanation has been found. The tracer was injected slightly different than the other tracers since the injection was done with a syringe through the tube wall. This may have influenced on the results. A possibility is that the tracer has been adsorbed to the tube walls before water was injected to rinse the tube or the tracer was not properly injected into the tube.

8. CONCLUSION

Compared to the inactive tracers, DNA behaves like a conservative tracer, and the negatively charged surface of the DNA-molecule may further increase its flow velocity due to anion exclusion. The much later arrival of the bacteriophage implies that the DNA tracer is not suitable as a tracer to measure travel time for microbial contamination in fractured aquifers. However, DNA is a suitable tracer for identification of hydraulic communication and possible flow paths between two groundwater wells or from pollution sources to a groundwater well or spring.

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