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An introduction to Groundwater in Crystalline Bedrock

David Banks & Nick Robins

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An introduction to Groundwater in Crystalline Bedrock

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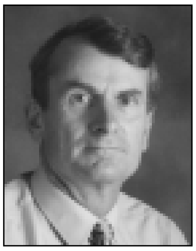
Nick Robins



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Prologue

"Therefore a miner, since we think he ought to be a good and serious man, should not make use of an enchanted twig, because if he is prudent and skilled in the natural signs, he understands that a forked twig is of no use to him.....So if *Nature* or *Chance* should indicate a locality suitable for mining, the miner should dig his trenches there; if no vein appears, he must dig numerous trenches until he discovers an outcrop of a vein."

Agricola (1556). De Re Metallica.

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Cover photos:

1. *Shedding light on rock and water. Corbiere Lighthouse, Jersey, Channel Islands.* Photo by Joe Bates.
2. *Geologist Helge Skarphagen examines springs from gneisses exposed in a road cutting near Herefoss, southern Norway. Note that groundwater tends to emerge along the boundaries of pegmatites (light rocks)*. Photo by David Banks. See Figures 25a,b for locations of sites mentioned in the text.
3. *Winter drilling, near Glasgow, Scotland*. Photo by Nick Robins.

Introduction

This small book has a big ambition. It aims to present practical information and a little philosophy to those involved in locating groundwater resources in areas underlain by crystalline bedrock, that is to say:

- Private groundwater users, potential well owners and water bottlers
- Local authorities
- Water companies and local water supply undertakings
- Drillers
- and Consultants

Each of these users will inevitably have different requirements and this volume may be considered to be a "maximum version", hoping to provide something for everyone. We have consciously mixed practical advice with some hydrogeological theory. Pick and choose the parts that you find useful. We have also provided a comprehensive reference list for those of you who wish to delve further into the subject. We aim to try to communicate Scandinavian findings (often largely published in Nordic languages) to an international audience. A Norwegian version of this book will be published later.

Almost all of Norway (Figure 25b) is underlain by some type of crystalline bedrock, and groundwater from such rocks is an important drinking water resource in rural areas, with over 100,000 bedrock wells thought to exist in a country with a population of somewhat over 4 million! In the United Kingdom, crystalline bedrock groundwater is probably an underused resource. Such rocks underlie much of the U.K.'s "Celtic Fringe" - Cornwall, Wales, Scotland and parts of Northern Ireland (see Figure 25a: Robins 1990, 1996a,b, Robins and Misstear 2000), as well as the Channel Islands (Robins & Smedley 1994, Blackie et al. 1998). A number of small British communities are almost entirely dependent on bedrock groundwater, such as several of the islands of Scilly (Banks et al. 1998e), and such groundwater provides an attractive alternative resource for other communities with a currently unsatisfactory water supply (Ellingsen & Banks 1993).

Bedrock aquifers are also exploited widely in tropical climes; in much of Africa and India, for example. There, however, the hydrogeological conditions are very different. The rocks are deeply weathered and rainfall recharge may be scarce. We will thus largely, though not exclusively, restrict ourselves to consideration of bedrock aquifers in the glaciated terrain of Norway and the northern U.K., where rock outcrops are relatively fresh and where the quantity of precipitation is depressingly abundant.

Groundwater in bedrock is a difficult resource to understand and pin down. It is very difficult to predict the yield or water quality of a new borehole with any degree of certainty. It is, however, possible to quantify the chances of being successful. We will attempt to guide you through the maze of fractures and uncertainties comprising a bedrock aquifer in such a way as to allow you to make an informed choice about its potential as a water resource.

1. What is Groundwater in Crystalline Bedrock?

There are, of course, two parts to this question:

1.1 What is Groundwater?

Groundwater is simply water that occurs in the ground; in the pore spaces between mineral grains or in cracks and fractures in the rock mass. It is usually formed by rain water or snow melt-water that seeps down through the soil and into the underlying rocks. Unfortunately, we have a very poor understanding of exactly what proportion of rainfall ends up entering a crystalline rock aquifer, although Robins & Smedley (1994), Blackie et al. (1998) and Olofsson (1993) shed some light on the problem. Sometimes, where a pumping well is close to a river or lake, a well may also "suck" river- or lake-water into the river banks and bed, so that it enters the adjacent sediments and rocks and becomes groundwater.

In recent sediments, such as sands or gravels, groundwater flows through the many pore spaces between sand grains. The *permeability* of the sediment is governed by the distribution of grain sizes in the sediment and the yield of a well in such deposits is relatively easy to predict.

1.2 What is crystalline bedrock ?

When we use the term *crystalline bedrock* (or *hard rock* or *bedrock*) in this book we refer to igneous or metamorphic rocks, such as granites, basalts, metaquartzites or gneisses, where the intergranular pore spaces are negligible and where almost all groundwater flow takes place through cracks and fractures in the rocks.

As fractures are not homogeneously distributed in the rock mass, and because the permeability of the fracture system is very sensitive to the fracture aperture and degree of fracture connectivity, it is very difficult to predict the yield of a well or borehole in crystalline bedrock. To be successful, we need to understand, as Agricola recommended in 1556 (see Prologue) both Nature (in the guise of geology) and the element of Chance.

Further reading on groundwater:

Banks & Banks (1993a), Domenico & Schwartz (1990), Downing (1998), Ellingsen (1992a), Ellingsen & Banks (1993), Fetter (1994), Grundfos (1988), ISIS (1990), Knutsson (2000), Lloyd (1999), Olsson (1979), Price (1996), Robins (1990, 1996a,b), Todd (1990).

Hydrogeological Maps of Groundwater in Crystalline Rock

In Norway:
Ellingsen (1978), Rohr-Torp (1987).
In Sweden: Maps for each county, of which Karlqvist (1985) is an example.
In the UK: BGS (1990)

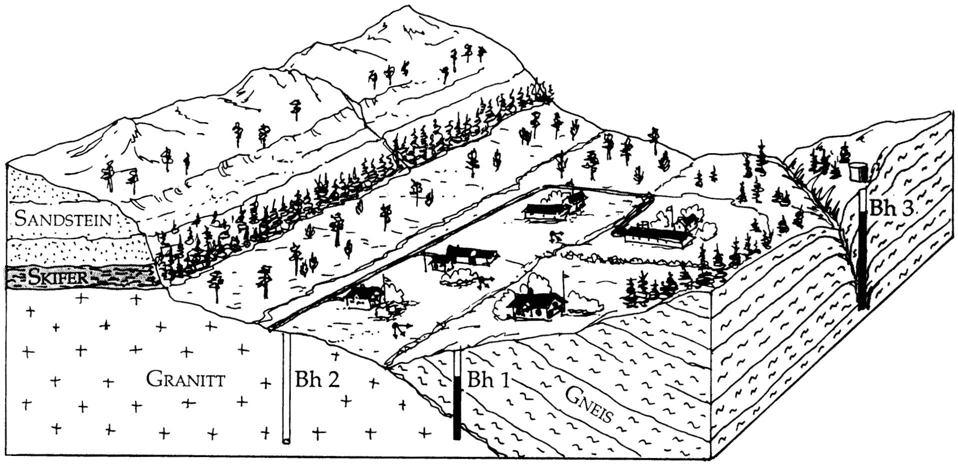


Figure 1. Schematic diagram of boreholes in a crystalline bedrock aquifer (from Eckholdt & Snilsberg 1992). Borehole 1 intersects a thrust fault between granite and gneiss and may thus have a good yield. Nevertheless, a stream receiving agricultural run-off runs along the fault outcrop, rendering the well vulnerable to pollution. Borehole 2 is less vulnerable but does not intersect a fracture zone and may thus have a lower yield. Borehole 3 is located up-gradient of polluting activities and intersects a fracture zone (expressed in the topography as a linear valley).

2. How to Get Groundwater out of the Ground

2.1 Springs

Under natural conditions, groundwater flows from regions of high groundwater *head* to low groundwater head. In practice, this usually means, from areas of high topography to the coast or to river valleys. Because rainfall is entering the bedrock aquifer, groundwater has to come out somewhere. Very often it emerges as springs in low-lying areas, which springs typically drain into streams or to the sea. Alternatively, groundwater may discharge directly into the bed of a stream. In either case, this groundwater baseflow maintains some degree of flow in the streams during prolonged dry weather.

Groundwater flow generally follows the gradient of the *water table*. This is essentially the surface separating water-saturated from unsaturated rocks. In other words, it is the level of water in the huge natural storage tank that an aquifer represents. In crystalline bedrock of low permeability, the water table reflects a subdued version of the natural topography. A spring discharge area can be thought of as a location where the water table intersects ground level.

Springs have historically been important water supplies. Very often they have been excavated, lined with timber, brick or stone and maybe covered by a roof or small house to form a well that is protected from contamination by surface run-off and animals. Today, they can still be ideal water supplies, provided that the land-use in the surrounding area is such that it does not contaminate the spring.

2.2 Wells and boreholes

Unfortunately, springs only occur at the whim of nature and topography. While, in historic times, "Mohammed has come to the mountain" and people have settled around springs, more recent

Figure 2. (a) A spring from Precambrian Hecla Hoek marbles, Bockfjord, Svalbard (photo: David Banks).

settlements have grown up in areas devoid of springs and it has been necessary to use technology to access the water table.

In many rocks (e.g. the Chalk of southern England), wells may be dug to considerable depths to reach the water table, but this is not possible in the hard crystalline rocks we are considering. In hard rock terrain, dug wells are at best dug down through superficial soils and sediments to reach a bedrock spring, or are excavated to a few metres depth by the judicious use of explosives.

In crystalline bedrock it is normal to drill a narrow (e.g. 150 mm diameter) borehole to several tens of metres depth below the water table. A pump may then be installed in the borehole. As it pumps out water, the water level in the borehole is depressed, lowering the groundwater head in the adjacent

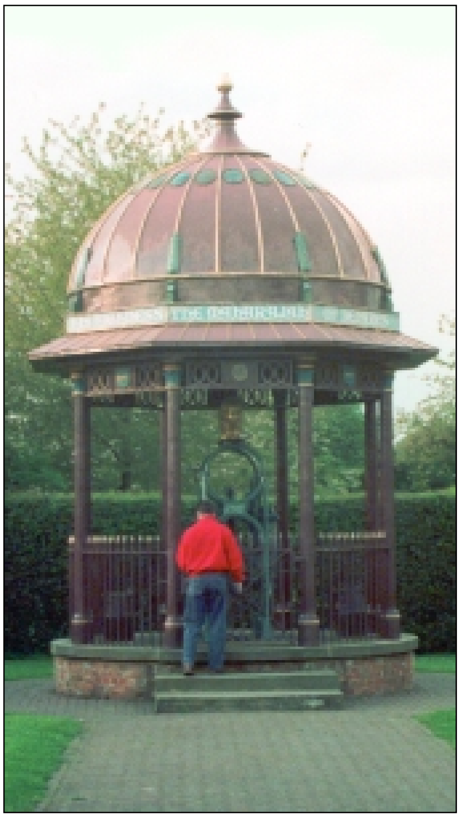


Figure 2. (b) The Maharajah's Well, Stoke Row U.K. A deep dug well in the Chalk, donated to the drought-stricken villagers of the Chilterns by the Maharajah of Benares (photo: David Banks).

Figure 2. (c) an artesian (overflowing) borehole in Carboniferous rocks at Catcraig, near Dunbar, Scotland. The photo features the geologist C.T. Clough and derives from c. 1908 (after Robins 1990). Printed with permission from British Geological Survey.

Figure 2. (d) A modern, angled borehole in granite, Hvaler Islands, Norway (photo: David Banks).

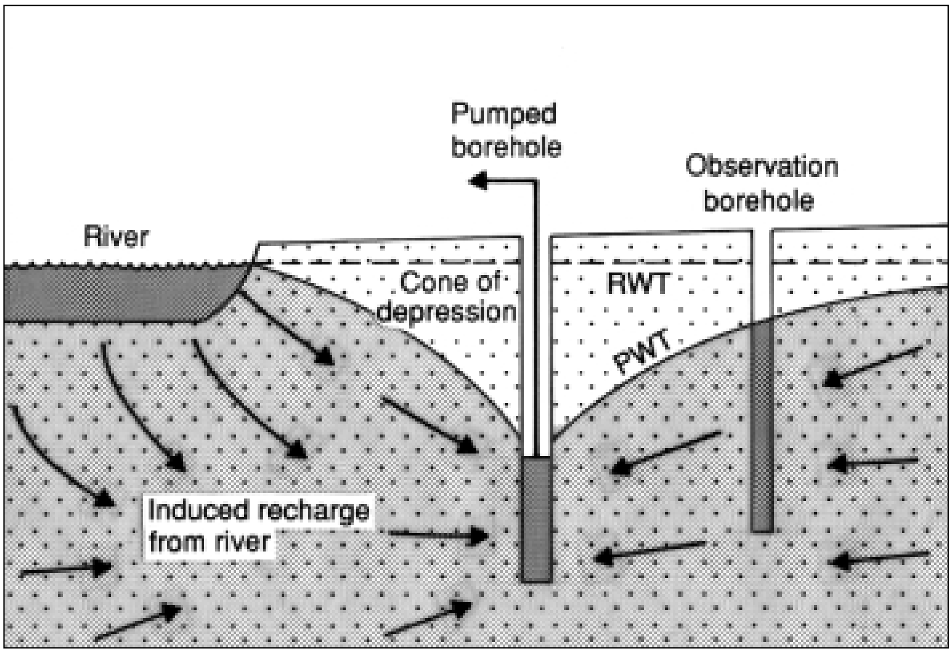


Figure 3. Groundwater flow in the vicinity of a pumped borehole, RWT = rest water table before pumping, PWT = water table during pumping (after Banks 1992d, printed with permission from Blackwell Science Ltd.).

aquifer. This causes groundwater flow to be induced towards the borehole and alters the natural groundwater flow and water balance in the aquifer. Provided we do not try to take too much water, the aquifer will settle down to a new dynamic equilibrium situation. This equilibrium will govern the long-term yield of the borehole. Usually, the long term yield is somewhat lower that the yield initially estimated by drillers on the basis of short-term testing, because in the latter case, the aquifer has not had time to reach its new equilibrium.

Further reading on spring protection, groundwater abstraction and borehole drilling

Clark (1988), Commonwealth Science Council (1987), Lloyd (1999), Skjeseth (1955), Waterlines, UNESCO (1984).

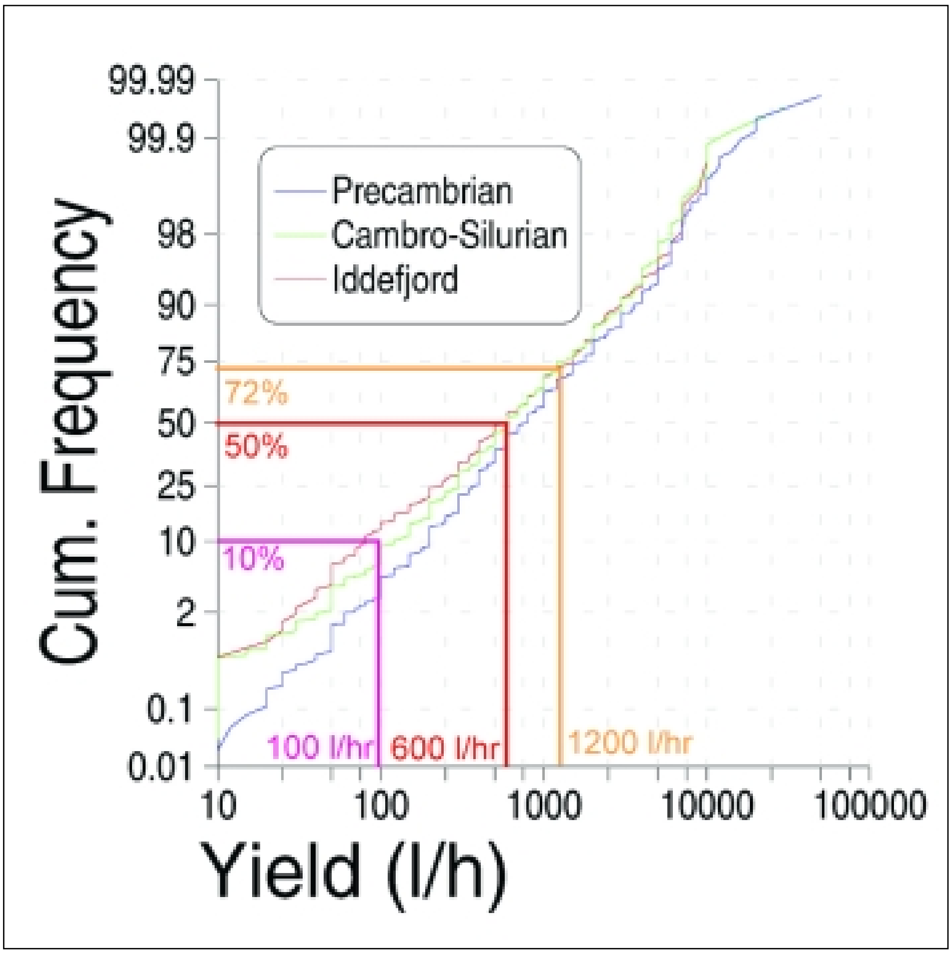
3. Well Drilling in Bedrock. Bingo, Poker or Chess?

It is tempting to regard well-drilling in bedrock as a game where the prize is a high quality, cheap water supply. But is it a game like chess, where a geologist's skill and knowledge can find the right borehole location and drilling strategy, or is it like bingo, where the outcome is solely determined by a random selection of unpredictable numbers? Most hydrogeologists would probably make a comparison with poker, which is mostly determined by a blind selection of random cards, but where a sensible playing strategy can increase our chances of success. And like hardened card-sharps, many professional hydrogeologists and water-witches have expended considerable effort in building up a reputation and bluffing that their "infallible systems" can overcome the random element. You, as customers and well-drillers, should treat such claims with great caution. Well drilling in bedrock always bears a greater or lesser risk: what we hydrogeologists can do is estimate that risk and quantify your chances of success.

3.1 Yield distribution curves

If we examine a particular rock type, such as the Iddefjord Granite of southern Norway, we can take the yields of all the boreholes in the granite and plot them on a cumulative probability diagram, such as that in Figure 4. From such a diagram, we can see that the median yield is 600 l/hr (follow the red line horizontally from the 50% mark to the curve for the Iddefjord Granite, and

Figure 4. Cumulative frequency diagram showing yield distribution curves for Norwegian wells in the Iddefjord Granite ("Iddefjord"), Cambro-Silurian metasediments of the Norwegian Caledonian terrain ("Cambro-Silurian") and Precambrian gneisses ("Precambrian"). The added purple guide-line shows the approximate 10% yield for most lithologies (i.e. 90% of wells yield better than this figure). The red and orange guide-lines show the median yield (50%, red) and the 72% yield (orange) for the Iddefjord Granite. (Figure prepared by Geir Morland, using data from his thesis of 1997).



then vertically down to where it meets the x-axis at 600 l/hr). For a well drilled randomly in the granite, there is thus a 50% chance that a yield of 600 l/hr will be achieved. Similarly, we can assess the 25 % or 75 % yields. Or if, we wish to obtain 1200 l/hr we can see (by following the orange line vertically up from the 1200 l/hr mark to the Iddefjord Granite curve, and then horizontally across) that we have a 72 % chance of *not* achieving this amount (28 % chance of achieving it).

However, different rock types have different yield distribution curves. For example, Caledonian slates and schists of Norway have a lower yield distribution. This is because permeability is determined by fracture aperture, which is, in turn, governed by the rock's geomechanical properties. In fact, theory can show that a single fracture of 1 mm aperture can transmit more water than 900 planar, parallel fractures of 0.1 mm aperture (the transmissivity of such fractures is proportional to the *cube* of the aperture). Brittle, hard rocks, such as granite, are better able to sustain fractures with wide apertures than soft, deformable rocks, such as shales and slates.

A word of caution, however. The construction of such yield distribution curves pre-supposes the existence of an adequately comprehensive well database (data for the UK, for example, are not good enough to be used for this purpose). The yields submitted by drillers to such databases are often short-term yields. The sustainable, long-term yields may be considerably less. Additionally, dry boreholes may not have been reported at all, so inducing a positive spin to the statistics. It is also important also to know whether such databases include wells whose yield has artificially been stimulated by explosives or hydraulic fracturing (see Chapter 12).

3.2 Dowsers and Water-Witches

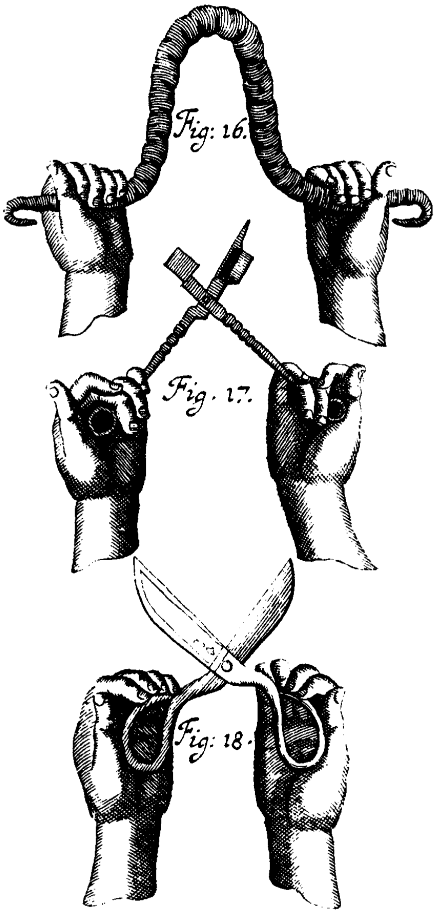
In hard-rock terrain, whether it be in Nigeria, Norway or Cornwall, dowsers are very often used to locate ground water and often seem to achieve similar results to hydrogeo-logists (see Text Boxes 1 and 2). The authors would venture to argue that this is not because of special prowess on behalf of the dowser, but often because of lacking insight on the part of the hydrogeologist. Dowsers will often try to locate water using forked twigs, bent clothes hangers, German sausages or pendula (Figure 5). Some may even ply their skills in the office over a map, without venturing into the terrain. The most honest dowsers will admit that it is difficult to conceive of a physical explanation for dowsing and that their skill is purely "spiritual". Agricola (1556) tells us that, "..wizards, who also make use of rings, mirrors and crystals, seek for veins with a divining rod shaped like a fork; but its shape makes no difference... for it is not the form of the twig that matters, but the wizard's incantations which it would not become me to repeat". It is likely that customers use dowsers for three reasons:

(i) They are cheaper than hydrogeologists
(ii) The subject of groundwater is difficult to understand and has always been associated with magic and mysticism – see Kubla Khan by Samuel Taylor Coleridge
(iii) In a field where the uncertainty of the result is so great, people feel drawn to mystical, rather than scientific, methods.

Nevertheless, some dowsers often seem to enjoy considerable success (although others, in the authors' experience, have cost their clients large sums of money). Why should this be so ? We offer two explanations:

(i) Most dowsers work for domestic clients where the water demand is only maybe 100 l/hr (most people use 300-400 l water every day). From Fig. 4, it will be seen that there is usually a c. 90 % chance of achieving this yield wherever one drills (follow the purple line from the 10% mark).

Figure 5.Three subtle and esoteric implements of the Hermetic art of dowsing: (a) the Knackwurst (or German Sausage); (b) the Liechtputze (or candle trimmer); (c) the Schneiderscheer (the tailor's scissors) (from Zeidler 1700, reproduced in Prokop & Wimmer 1985).



The Unacceptable Face of Dowsing

While we would argue that many dowsers are honest and have a good intuitive understanding of groundwater, a few dowsers can cause great distress to their clients. A Norwegian dowser is cited in the newspaper "Agder" (20/4/90) as saying (in English translation):

"The dowsing twig is on the way out, many say. The reason is supposedly that there is no scientific evidence for its many uses. In my opinion, that is utter rubbish....Hundreds of years before we began drilling boreholes, we used the forked twig to find water....No, the dowsing rod is by no means outdated."

Fair enough, one might say, but now things become macabre:

"the dowsing rod can be used .....to find all sorts of radiation. One thing's for sure. Many people have back problems due to "veins of water", which run under their house. The radiation from these can be drawn away by cheap and effective means."

Luckily, the solution to such problems does not involve digging up the foundations of the house to find the offending fracture. A simple "radiation damper" can be placed under the bed ! One may find such psychobabble amusing, but for some it is definitely not a joke. One of the authors was contacted in the UK by a distraught woman several years ago, whose husband was suffering a serious illness. In desparation, she turned to a dowser who told her that the illness was caused by a "groundwater vortex" beneath the property. So, as well as her uncertainty and distress over her husband's health, she now was being asked to consider moving house or some serious engineering geology. Our advice to you is the same at that we gave to her - "Stay away from such practicioners and trust your doctor. Dowsing and medicine do NOT mix".

(ii) Most dowsers operate in a geographically limited area. They get to know their terrain and gain an instinctive (often subconscious) feel for how the hydrogeology of the area functions.

Dowsers can, however, create and perpetuate grave misconceptions. On the Channel Island of Jersey, for instance, rainfall on the Pyrenees is reputed to flow underground and beneath the Bay of Biscay to rise up onto Jersey to discharge as springs 200 m above sea level. This is an improbable situation given the abundance of local rainfall and local recharge and the friction (or head loss) in driving the water underground all the way from the Pyrenees!

Our advice: for small domestic supplies, the best person to site a borehole is often a local well driller. He usually has a reasonable hydrogeological understanding and is able to assess the logistical and well-head protection factors that maybe far more important than the merely geological. For larger supplies, use the services of a hydrogeologist with experience of hard rock terrains.

Further Reading on Dowsing and Well Yield Statistics

Agricola (1556), Banks (1998), Henriksen (1995), Knutsson (2000), Morland (1997), Persson et al. (1985), Prokop & Wimmer(1985), USGS (1993), Wladis & Gustafson (1999).

Water Divining in Kosova

Our colleague Habib Meholli tells us about the following methods for locating groundwater in Kosova.

Method 1: *First catch your chicken. Remove its head with an axe. Let the headless chicken run around for a few minutes and where it falls motionless, dig your well.*

Method 2: *Provide your horse with salty feed. The horse will soon become thirsty. It will start looking around for water or damp soil. The place where it starts pawing the ground with its hooves may be a good place to dig a well, as groundwater is likely to be close to the surface.*

4. Where Should I Drill My Borehole?

The location of a borehole should take into account at least three factors:

(i) Logistical factors, including access
(ii) Vulnerability factors
(iii) Geological factors

For small domestic supplies, where it is possible to drill a well with satisfactory yield almost anywhere, the first two factors are likely to be paramount. For larger supplies, where the yield of the well is critical, finding a sensible geological location becomes increasingly important.

Logistics and access prevent a number of sources from being developed. In the North-Western Highlands of Scotland, the Precambrian limestones of the Durness and Assynt areas offer karst conditions and the prospects of high-yielding groundwater sources. These are little used simply because few people live in these areas.

4.1 Logistical Factors

It is necessary to consider:

- proximity of the borehole to the point of use, or
- proximity of the borehole to an existing water distribution network
- availability of a power supply for the pump.
- ease of access for a drilling rig.

4.2 Vulnerability Factors

Here, one should consider potential sources of pollution; the borehole should not be located in the immediate vicinity of:

- sewerage pipes, which may leak.
- pit latrines, cesspits, septic tanks, leaking tight tanks
- unbunded oil or paraffin storage tanks
- land subject to intensive use of organic or inorganic fertilisers, pesticides or other chemicals
- surface waters, particularly those known to be bacterially (or otherwise) contaminated
- the sea.

If possible, boreholes should be located at least 50 m (and preferably more, depending on aquifer characteristics and yield) up any topographical gradient from the above, or any other forms of contaminative human activity. In the case of surface waters, the location of a borehole will always be a compromise between the hydraulic advantages that location near a river or lake can offer (a plentiful source of groundwater recharge) and the disadvantages in terms of vulnerability to pollution.

Where an aquifer is covered by a significant thickness of low-permeability materials (e.g. boulder clay), less stringent conditions may apply to locating a borehole near to potential contaminant sources. There should be a presumption against such a location, however, unless it can be clearly demonstrated that the cover offers adequate protection.

It should be noted that the concept of source vulnerability also applies to existing surface water sources (eg. river or stream intakes). It is often these that, due to their vulnerability to pollution, need to be replaced by new groundwater sources. Care needs to be taken to ensure that the new groundwater well does not draw on the surface water, unless a sufficient residence time and "filtration effect" are present to ensure that water quality is safeguarded. Some fluvial sand and gravel deposits act as efficient water purifiers, however, and peat-stained river water may appear as crystal clear "bank infiltration" in a well only 5 m from the bank of the river (a fact now being exploited in the replacement of rural village supplies in Scotland, wherever peat stained surface water supplies existed and which are now outlawed by current EC legislation). Note, however, that appearances may be deceptive, and thorough chemical, bacteriological and hydraulic testing may be necessary before a source can be approved for supply. Fractured bedrock does not necessarily have these same powers of attenuation and purification and riverside boreholes into bedrock exposures should be avoided unless water treatment is available.

4.3 Geological Factors

As previously explained, the hydrogeological factors influencing well yield can be difficult to predict. Ideally one wishes a borehole to intersect one or more fractures of high groundwater *transmissivity*, which also are interconnected with a wider system of fractures or with superficial deposits that provide adequate groundwater *storage*. Most hydrogeologists agree that it is sensible to target:

- zones of intense fracturing. These may be vertical, horizontal or with an intermediate dip and are generally referred to simply as *fracture zones*.
- areas with a moderate (2-5 m thick) cover of superficial deposits (e.g. moraine). These deposits confer a degree of protection to the underlying bedrock groundwater, and may also act as a reservoir for water. The superficial deposits should not be too thick though - they are considerably more costly to drill through than the bedrock itself.

Further Reading on Well Location

Robins & Ball (1998).

5. Fracture Zones

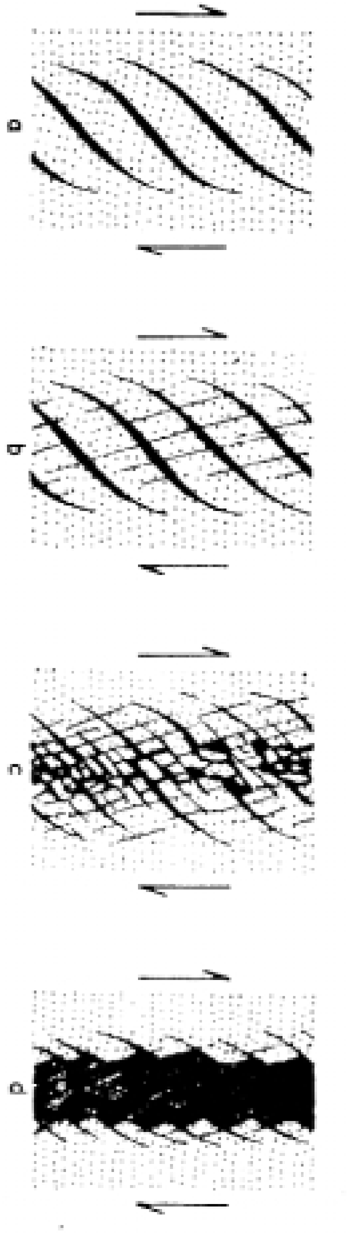


Figure 6.The development of a fracture zone (after Selmer-Olsen 1976, printed with permission from Tapir forlag): (a) the development of en-echelon tension gashes (fiederspalten), (b) the development of shear fractures across the fiederspalten, (c) and (d) breakdown of the central portion of the zone to yield fault breccia and gouge.

A fracture zone is a planar feature, where the density of fractures is very high. It is usually an abortive or actual fault where some shear movement has occurred between the rocks on either side. If the fracture zone is vertical or sub-vertical it may be seen as an approximately linear depression or valley in the terrain, on maps or on aerial photos. If the fracture zone is horizontal it may not be seen at the surface at all!

Aerial photographs of Loch Fleet in south-west Scotland revealed a distinct, but short lineament in granite which contains tight joints 0.5 to 3 m apart (Figure 7a). Seepages of soil water and groundwater flowing into the loch were located early one frosty morning using a thermal imaging or thermal infra-red linescan camera which highlighted the relatively warm groundwater (c 8°C as opposed to the loch water's 2°C). The largest inflows were discovered around the lineament intersection with the loch shore, but underwater discharge was also suspected as this corner of the loch had an enhanced temperature of some 3°C. Total discharge into the loch amounted to some 2 l/s (Cook et al. 1991).

The fractures that make up a fracture zone may not have the same orientation as the zone itself (Fig. 6). The most intense fracturing is usually at the centre of the zone. It may be so intense here that the rock has been broken into a fault gouge consisting of rock fragments set in a fine grained, low permeability rock "flour".

Furthermore, some faults have been subject to hydrothermal activity or secondary mineralisation after their formation. This seems to be particularly common in the region of the Oslo rift. Hot and/or mineralised waters passed through the fractures and altered existing minerals to clays or deposited new minerals. In this way fractures may have become sealed and fault gouge may have been turned into very low permeability clays.

The phenomena of fault gouge and secondary clay mineralisation are two reasons why not all fracture zones are very permeable. In a sub-sea tunnel in the islands of Hvaler in SE Norway, the biggest water leakages came not from the biggest fracture zones but from smaller fractures between them (Fig. 7b). On the islands themselves, many

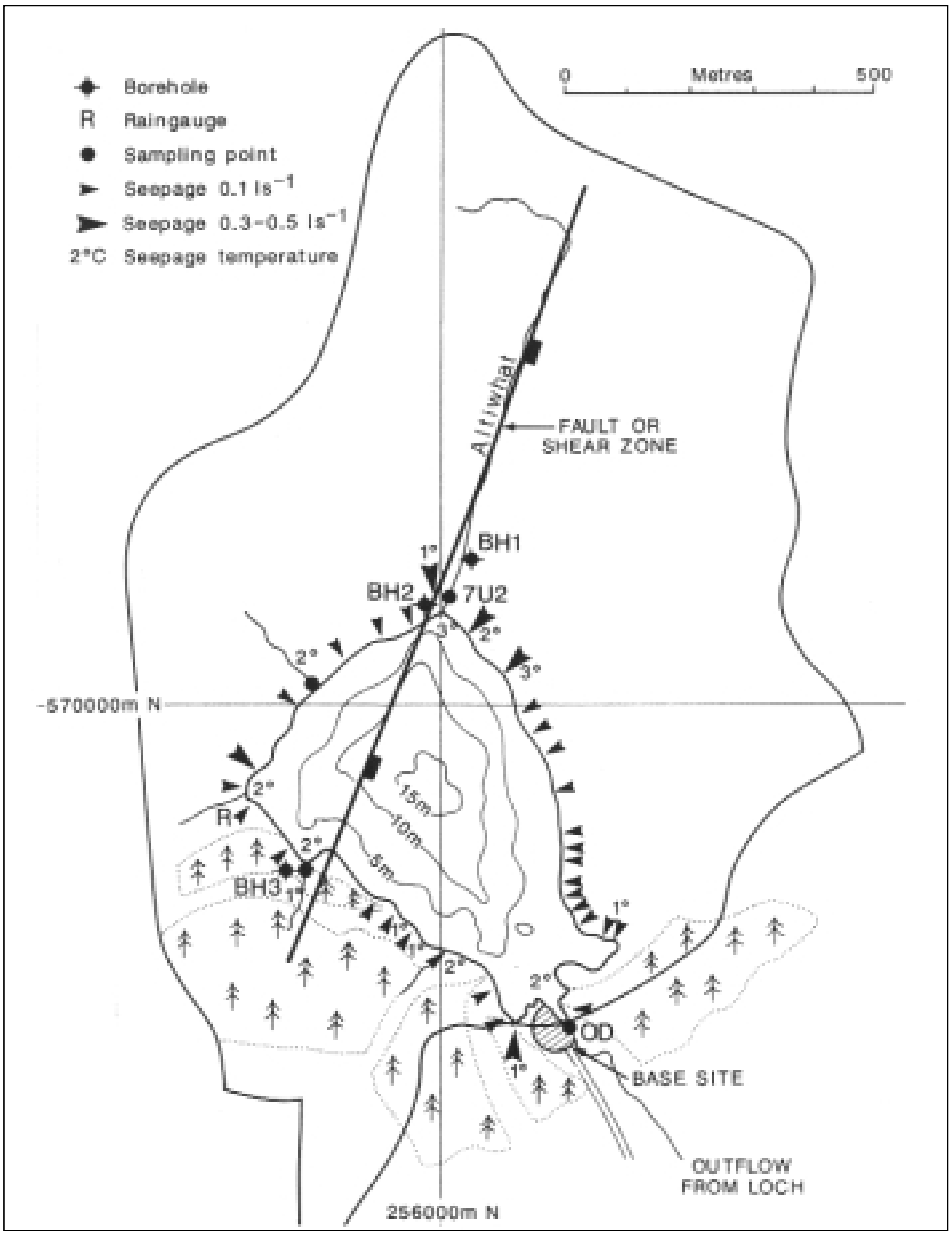


Figure 7a. Map of Loch Fleet, Scotland, based in the results of an infra-red linescan survey, showing boreholes, sample sites and inflows of groundwater (and soil water from peaty soils), which are greatest around the fracture zone at the north of the Loch (after Cook et al. 1991, printed with permission from Elsevier Scientific Publishing Company).

wells drilled into apparently major fracture zones have had very disappointing yields.

There is some structural geological evidence to suggest that the margins of a fracture zone, where fracturing is less intense, may be more permeable than the core of the zone, where fracturing and secondary mineralisation may have been so intense that permeability has been reduced.

5.1 Dykes

Dykes are essentially extensional fractures that have been filled with magma. Because of the intense temperature difference between the magma and the host rock during emplacement, a chill margin may have developed, where expansion and contraction have caused the host rock and the dyke rock to crack. These chill margins may be very permeable and, at least in the Oslo area, are good targets for boreholes for water supply.

Further reading on fracture zones and dykes

Banks et al. (1992a, 1994), Braathen et al. (1998), Braathen & Gabrielsen (2000), Cloos (1955), Cook et al. (1991), Hancock (1985), Leveinen et al. (1998), Mead (1920), Selmer-Olsen (1976).

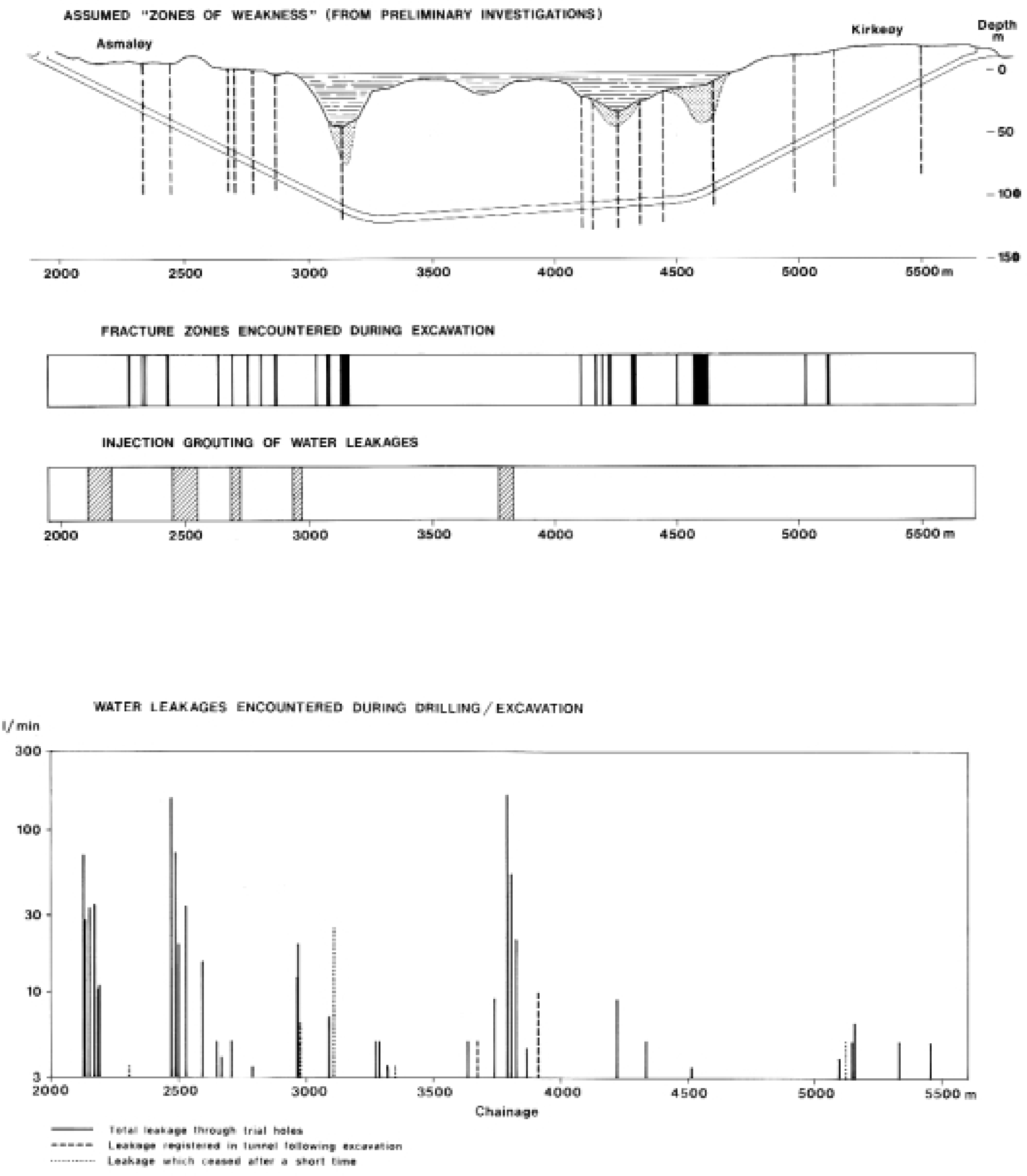


Figure 7b. Water leakages in the Hvaler tunnel (after Banks et al. 1992a, printed with permission from Geological Society Publishing House). Note that zones of water leakage and injection grouting do not necessarily coincide with fracture zones as detected by geophysics and in the tunnel itself.

6. Superficial Deposits

The importance of deposits that overlie bedrock, such as moraine material, marine or beach deposits or glacio-fluvial sand and gravel, is fourfold:

(1) Groundwater often flows more slowly in granular aquifers than in bedrock fractures. Granular aquifers offer greater potential to attenuate and retard pollutants. Overlying deposits may thus protect a bedrock aquifer from pollution.

(2) Superficial granular deposits tend to have larger groundwater storage coefficients than bedrock aquifers. They may thus represent a substantial reservoir of groundwater to feed the underlying bedrock.

(3) Some superficial deposits, especially marine clays, may affect underlying groundwater quality due to leaching of salts.

(4) In bedrock, the shallowest sub-horizontal fractures in the top 1 - 2 metres are often very permeable. In exposed bedrock, however, they are either dry, or their water is vulnerable to surface pollution or they are excluded from the borehole by surficial casing. In bedrock below a thickness of superficial deposits, however, these fractures are more likely to be exploitable, and may make a significant contribution to a well's yield (Fig. 8).

The various roles that the superficial (or "drift") deposits fulfil are currently the subject of intense investigation. The nature and integrity of the deposit, particularly in the case of a glacial till, is often not known, and the effect which clay horizons may have on inhibiting recharge or protecting the bedrock from surface pollutants is largely unquantifiable. Considerable efforts in drift and drift 'domain' mapping will help our understanding of this complex area of hydrogeology (McMillan et al. 2000).

Recent work in west Wales has revealed a complex system of glacio-lacustrine deposits in a number of valleys including Afon Teifi above the town of Cardigan. Granular deposits are, for the most part, saturated and capable of yielding small amounts of water for domestic and farm use. However, difficulties with actually drilling the deposits mean that most boreholes case out the drift and draw water from fractures in the underlying Lower Palaeozoic shales and grits. To the north, in the Rheidol valley, however, a high yielding shallow borehole supplies the town of Aberystwyth with filtered river water from terrace gravels.

Further Reading on the Role of Superficial Deposits

Foster (1998).

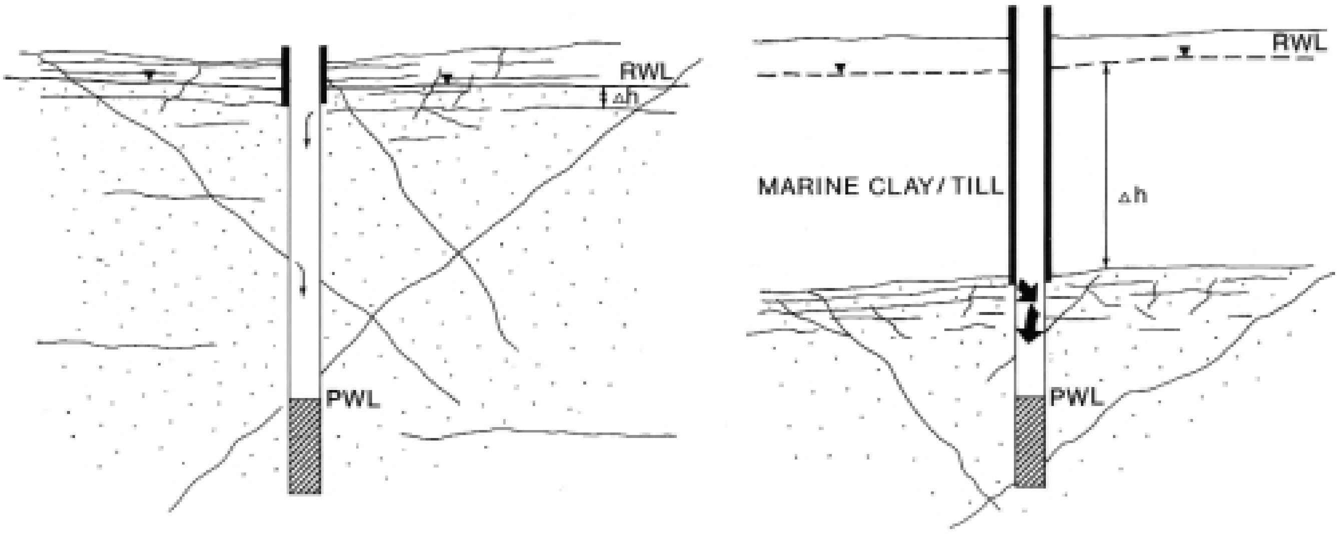
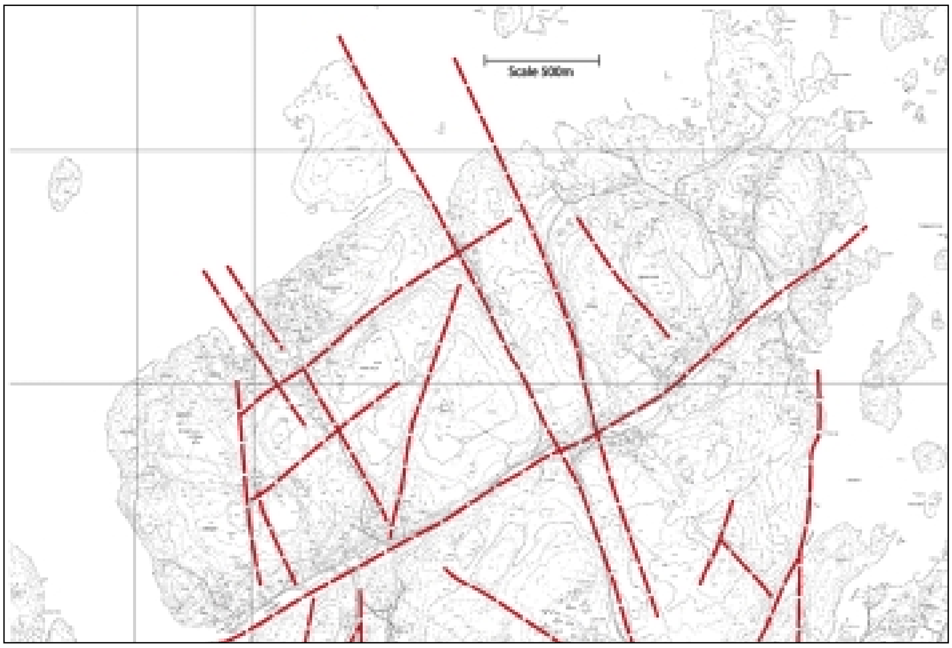
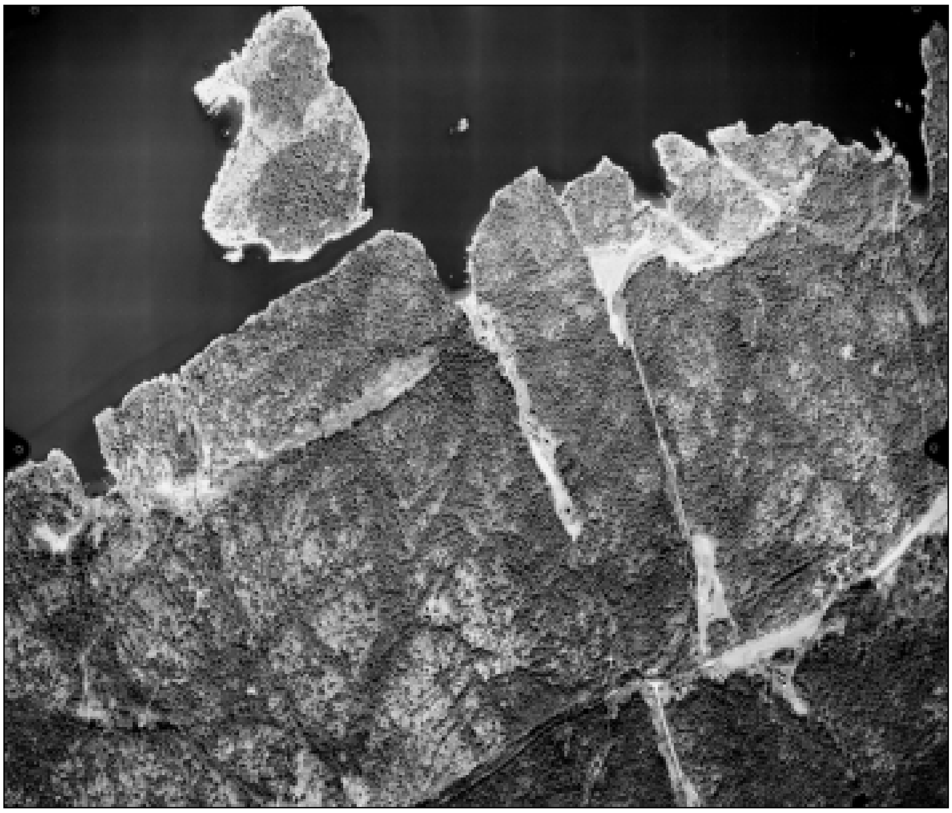


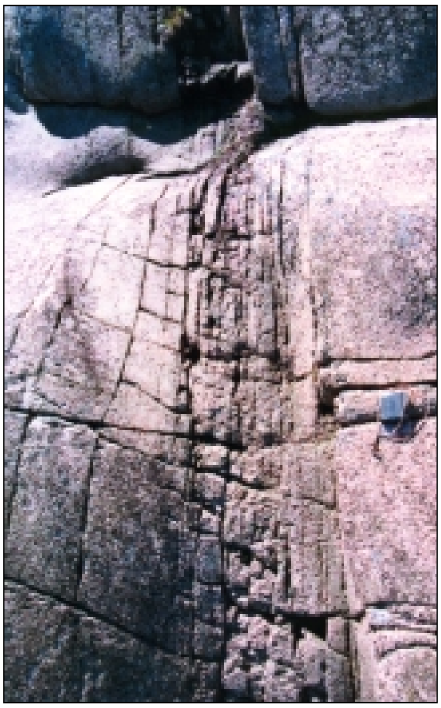
Figure 8. Exploitation of fractures near the bedrock surface. In (a) without a superficial cover, these are difficult to exploit (they may be dry or cased out) and the hydraulic gradient achievable between fracture and borehole is low. Below superficial deposits (b) they are exploitable and a significant hydraulic gradient (Dh) may be applied.

7. Fracture Mapping

Figure 9. Fracture zones on (a) a topographic map (fracture zones marked as broken lines) printed with permission from the Norwegian Mapping Authority and (b) an aerial photo (photo: Fotonor AS). (c) A fracture zone in the field (photo: D. Banks) and (d) a weathered-out basalt/dolerite dyke at Skams Klove, Kjøkøy (photo: E. Rohr-Torp). All examples come from the Iddefjord Granite terrain of the Hvaler Islands, Norway.) a and b with permission from the Norwegian mapping authority.







Fracture zones and fractures may be mapped (Fig. 9):

- from satellite images or aerial photographs
- from maps
- by direct measurement, in the field

On maps and aerial photos, sub-vertical fracture zones will usually appear as *lineaments*. Beware, however, not all lineaments are fracture zones; they may also represent lithological boundaries, beds of readily-weathered rock, glacial features or anthropogenic features such

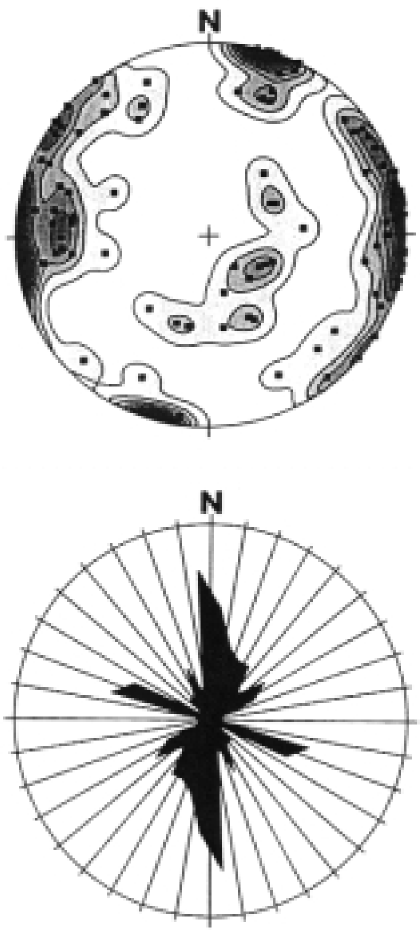


Figure 10. Fracture orientations (n = 105) represented on (a) a fracture rose and (b) a lower hemisphere stereographic projection. In the latter, poles (i.e. the direction at right angles) to the fracture planes are plotted and contoured. From Jondal, Hordaland County, Norway. After Midtgård et al. (1998).

as trenches, roads or zones of cleared vegetation along power lines.

Fractures are measured, in the field, with a compass and clinometer. The apparent frequency of fractures will, however, be determined by the angle between the fracture and the surface being observed. For example, on a horizontal land surface, vertical fractures will be very well observed but horizontal fractures will not be seen.

7.1 Presentation of fracture data

Fractures may be represented as directions on a rose-diagram, where the length of the "petal" is proportional to the frequency of fractures in that direction. They may also be presented as "poles to planes" on a lower hemisphere stereographic projection. Here, horizontal fractures plot in the centre of the hemisphere, while a north-to-south vertical fracture plots at the edge of the diagram (equator) in the east or west position (Fig. 10).

7.2 Common fracture patterns

A group of fractures or fracture zones of the same direction is known as a *fracture set*. Normally it is possible to identify two or three main fracture "sets" or orientations in a terrain. These may vary from scale to scale, such that the fracture zone directions identified from an aerial photo are likely to bear some relation to, but not be identical to, the fracture sets mapped at field scale.

One common pattern of fracture zones in ancient crystalline terrain is a pattern consisting of four sub-vertical directions at c. 45° to each other Tirén & Beckholmen (1989). There may be very good structural geological reasons for this: such a pattern can "absorb" a wide variety of tectonic stresses.

Two commonly occurring fracture patterns at a more detailed scale are (Figure 11):

- the orthogonal pattern, consisting of one horizontal and two vertical fracture sets at 90° to each other.
- the classic conjugate shear pattern consisting of a tension fracture and two shear fracture directions at an acute angle to this. A horizontal stress release fracture set may also occur.

Further Reading on Fracture Zone and Fracture Mapping

Banks et al. (1992b), Braathen & Gabrielsen (2000), Broch (1979), Ellingsen (1978), Lloyd (1999), Ramberg et al. (1977), Rohr-Torp (1987), Tirén & Beckholmen (1989).

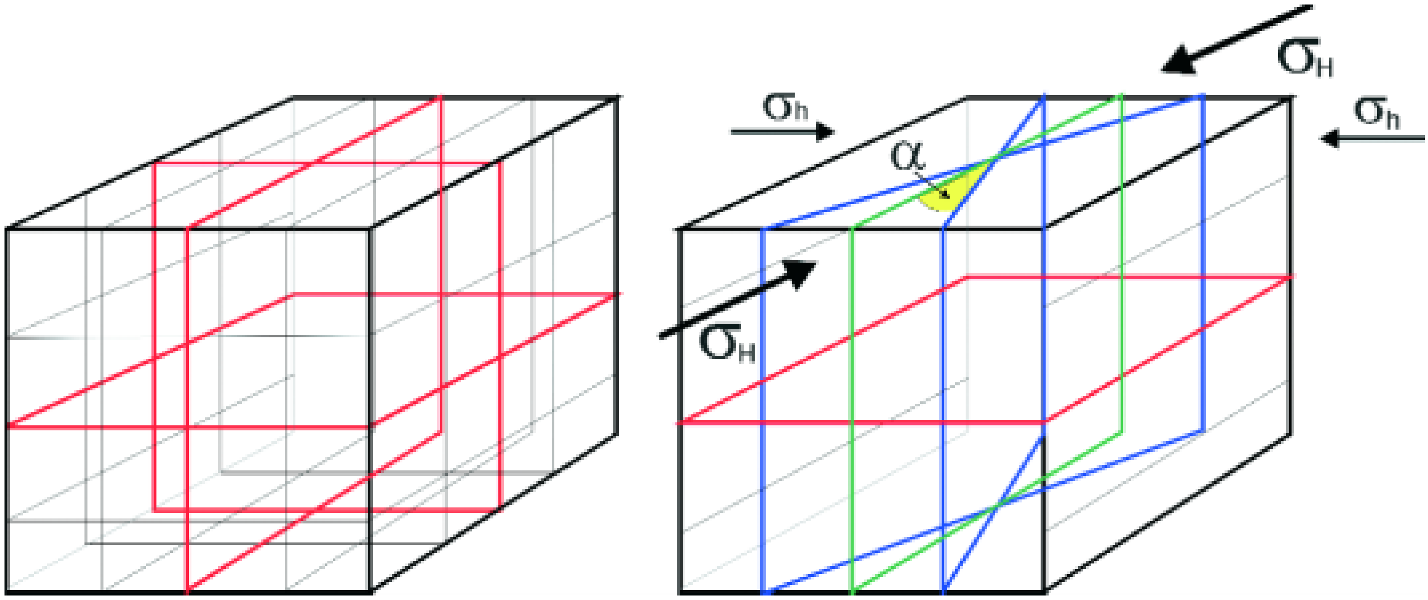


Figure 11. Two common fracture patterns. (a) Orthogonal fracture pattern and (b) idealised conjungate shear / tension fracture pattern. In (b), the shear fractures are blue, the tension fractures are green and the horizontal stress release fracture set red. The angle a is acute, typically around 30°. sH and sh are maximum and minimum horizontal stress directions, respectively.

8. Geophysics

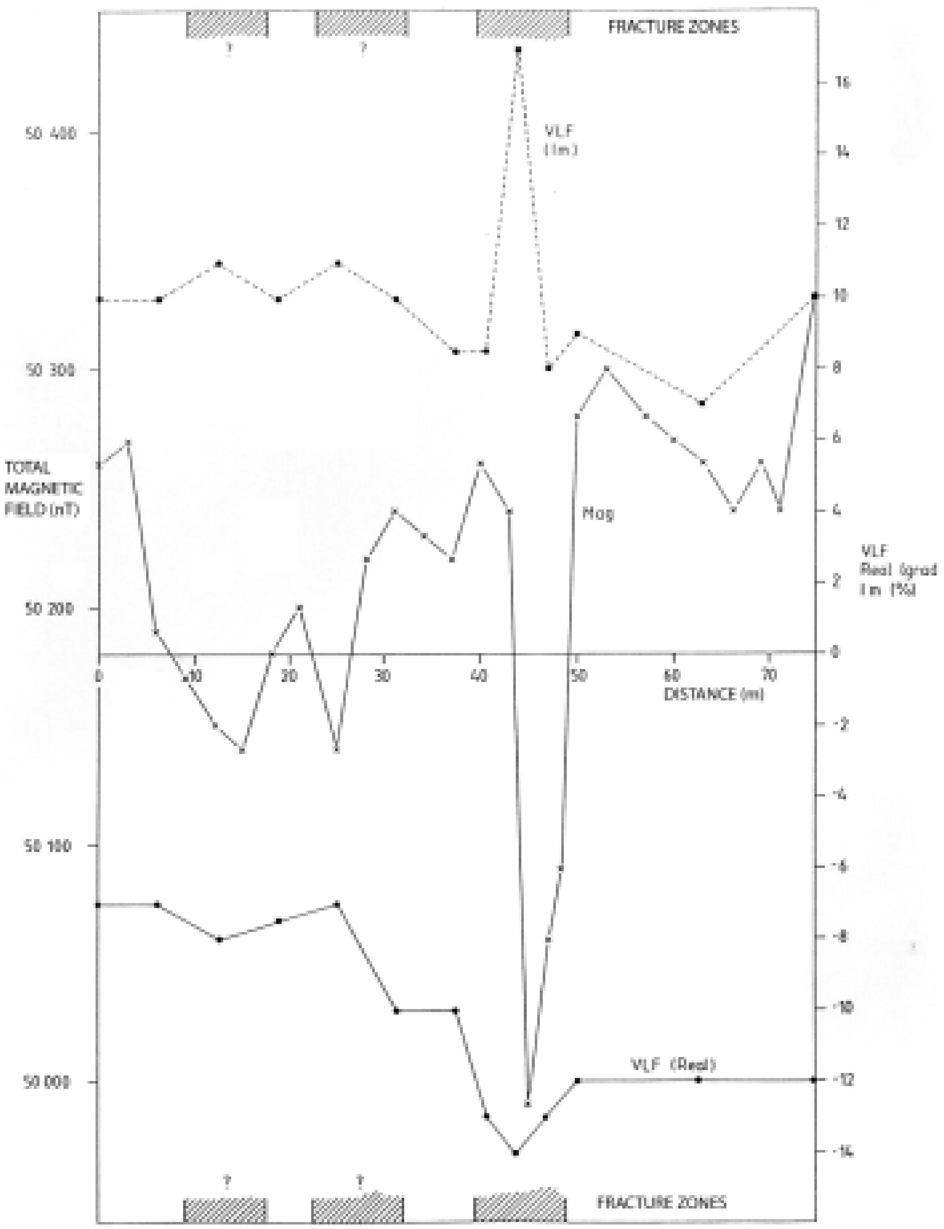


Figure 12. VLF and magnetic field profiles across fracture zones in the Iddefjord Granite of the Hvaler Islands, Norway. The negative anomalies in the VLH (real signal) and magnetic field define the zone (after Banks et al. 1991).

8.1 Surface Geophysical Methods

In terrain where no deep weathering profile occurs, the following methods are likely to be of use in locating zones of intense fracturing.

- Very Low Frequency (VLF) electromagnetic induction profiling. This measures the electromagnetic response of the rocks to radio/microwave signals from a network of powerful transmitters placed around the globe. A negative anomaly indicates conductive (water- or clay-rich) rocks (Figure 12).
- Total magnetic field anomaly. In rocks rich in magnetite, a negative anomaly may be observed over fracture zones, where the magnetite has been oxidised to non-magnetic iron (III) oxides (Figure 12).
- Resistivity profiling. Here, electrical resistivity between two electrodes of constant separation is measured to

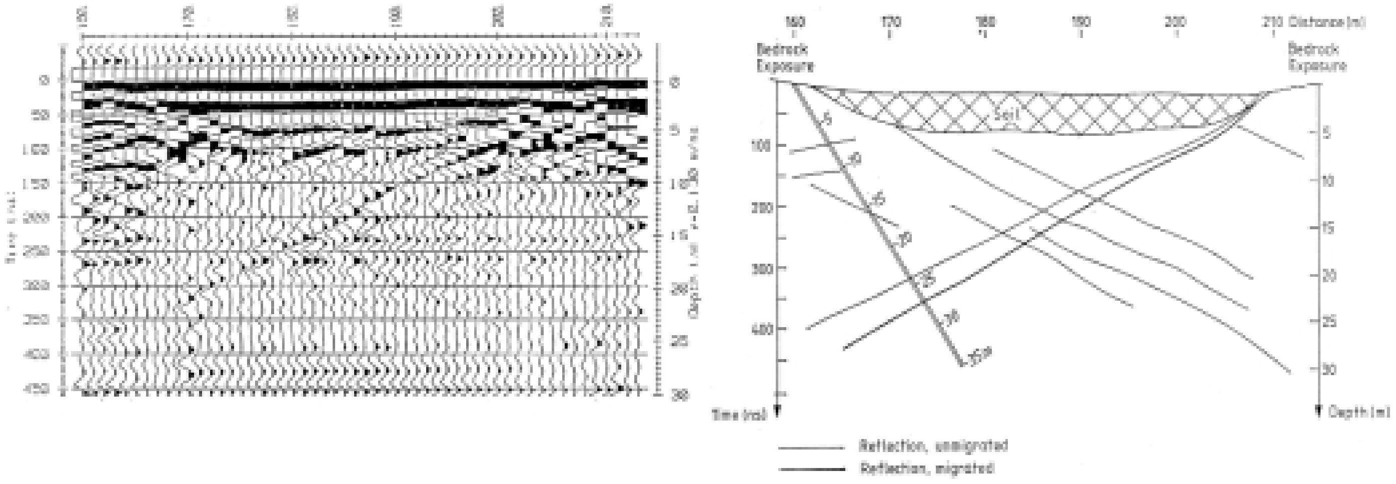


Figure 13. (a) The use of electromagnetic inductance (EM31) equipment in the field to measure conductivity (photo: Ingemar Aamo); (b) a Georadar profile and its interpretation, showing the bedrock surface below superficial deposits (hatched) and low angle fractures in the underlying bedrock (from Hvaler, Norway - Banks et al. 1993b)

give a lateral profile of resistivity. A negative anomaly (low resistivity) indicates conductive rocks, as in VLF.

- Vertical electrical resistivity sounding (VES). Here the separation of an electrode array is varied, such that a vertical profile of resistivity is built up. This is a common technique in weathered terrain in Africa, but in glaciated terrain, its main use is to locate depressions (possible fracture zones) in the bedrock surface beneath superficial deposits.
- Georadar (ground radar). This works on the radar principle and detects reflecting underground surfaces. It may be used to map the bedrock surface beneath covering sediments or to identify low-angle fractures (Figure 13b).

It should be remembered that many major fracture zones form valleys which may be useful communication conduits for roads, buried services (pipes, cables) and for overhead telephone or power lines. All of these may disturb electrical methods.

Secondly, you should be aware that none of these methods can adequately distinguish between water-filled (permeable) and clay-filled (impermeable) fractures.

8.2 Downhole Geophysical Logging

After a well has been drilled, various geophysical probes or *sondes* may be lowered into the borehole, to ascertain the depths of water-bearing fractures (Figure 14). These sondes include:

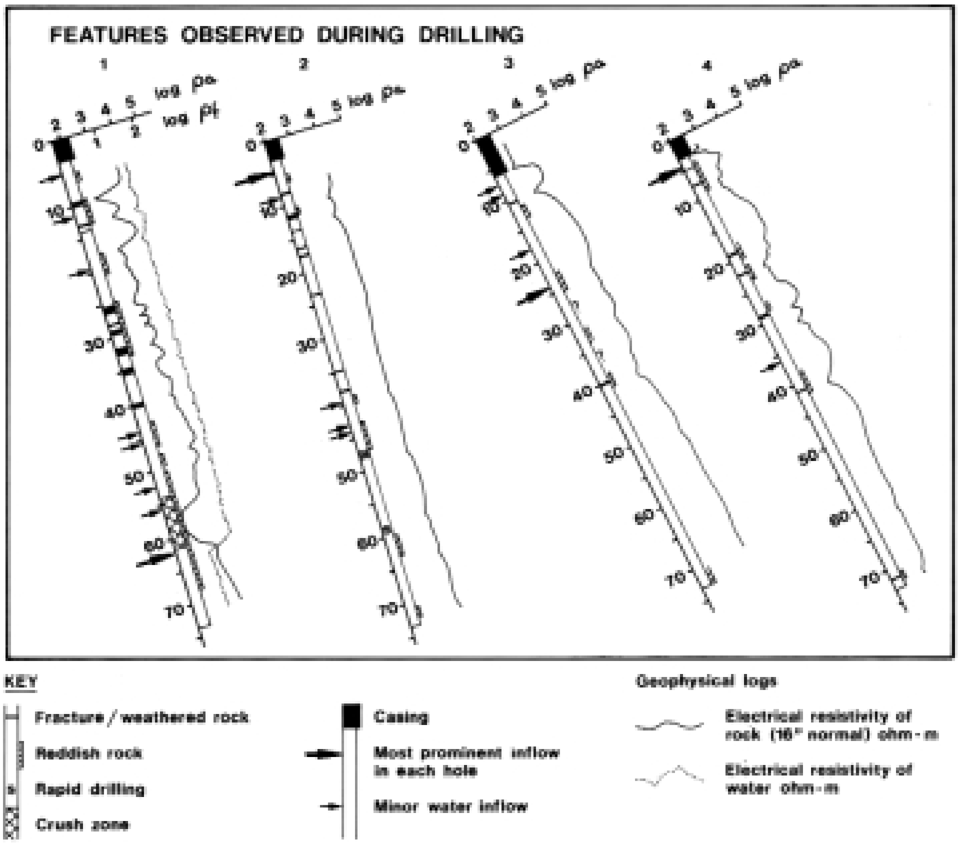


Figure 14. Drillers' logs , fluid resistivity log and resistivity logs of boreholes at Hvaler, Norway. In borehole 1 there is a clear low-resistivity anomaly adjacent to the clay filled fracture zone at 54 - 62 m. There is abrupt change in fluid resistivity at 62 m indicating an inflow of water (after Banks et al. 1992b).

- the *caliper sonde*, where sprung arms measure the diameter of the borehole. Fractures can be seen as irregularities of larger diameter in the borehole wall.
- *resistivity sondes*, which measure the electrical resistivity of the borehole walls and which readily detect zones of intense fracturing (but cannot distinguish whether these are clay- or water-filled).
- *fluid sondes*, which measure the temperature and electrical conductivity of the water column in the borehole. A jump in these signals at particular depths can indicate inflowing groundwater from a permeable fracture.
- the *gamma sonde*, which detects rock types, clays and fracture infill minerals or pegmatites which are rich in radioactive elements: uranium, thorium or potassium.
- The complex *acoustic televiewer* tool uses acoustic signals to profile the wall of the borehole. Fractures show up very clearly, and from the profile it is possible to calculate their orientation.

Further Reading on Geophysics

Blikra et al. (1991), Davis & Annan (1989), Griffiths & King (1981), Houtkamp & Jacks (1972), Lloyd (1999), Mullern & Eriksson (1981), Olesen et al. (1992a), Sclumberger (1969), Tate et al. (1970).

9. Stress

The rocks below the earth's surface are in a constant state of *stress* due to:

- gravitational forces. The deeper one goes, the greater the weight of the overlying rocks. The weight from these tends to close fractures up and permeability decreases with depth (Fig. 17).
- tectonic forces. Continents collide and break up. These immense disturbances may induce very strong regional horizontal stresses in the lithosphere. In Southern Norway for example, the lithosphere is in a state of high stress (around 10 Mpa have been measured at only several tens of m depth - Banks et al. 1996) due to the opening of the Atlantic Ocean.
- topographic stresses. The weight of mountains exerts stress on the rocks of the valley below. For example, near the foot of a mountain there will be a large stress parallel to the slope of the mountainside. Near the top of the mountain slope there may be reduced stress (or even tension) parallel to the slope as the mountainside tries to slip away.

Large compressional stresses perpendicular to a fracture will tend to close it up and reduce its permeability. Compressional stresses parallel to a fracture will, however, tend to open it. Thus, permeability will be enhanced in a direction parallel to the mountain slope near the foot of a mountain, and parallel to the contours near the top. If one is able to drill angled boreholes, one should drill parallel to the contours at the base of a hillside and parallel to the slope near the top to encounter the most open fractures.
Recent research using computer models shows that this directional permeability-enhancing effect is likely to be real, but relatively small in comparison with other factors. Odling (1993) argues that the decisive factor for permeability anisotropy (or directionality) is not stress, but the way in which fractures are connected.

9.1 Regional Studies

Regional overviews of rock stress measurements do exist (Klein & Barr 1986, Stephansson et al. 1986). One of the most interesting recent findings relates, however, to post-glacial stress release. Rohr-Torp (1995) and Morland (1997) found a very clear correlation between well yield and amount of post-glacial isostatic rebound in Norway. Such isostatic rebound is a geologically recent and rather traumatic event, probably involving the creation of large numbers of sub-horizontal stress release fractures and the reactivation of older fracture systems. In practice, this finding means that rocks in inland Norway have, on average, higher yields than those on the coast (Fig. 15).

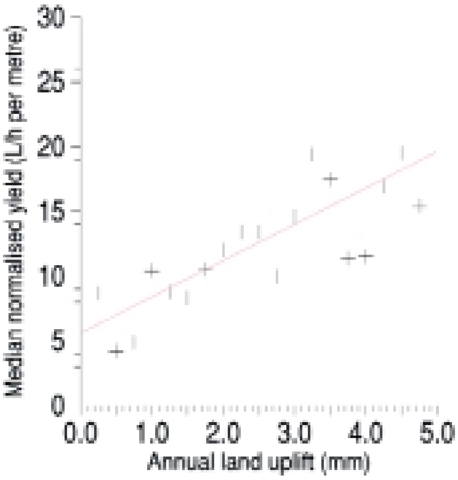


Figure 15. Correlation between well yield and total postglacial isostatic uplift; the diagram shows the yield of wells in Norwegian Precambrian rocks per metre drilled depth as a function of annual land uplift. The figure was prepared by Geir Morland using data from his thesis (Morland 1997).

Further Reading on Stress and Neotectonics

Banks et al. (1996), Bott & Kusznir (1984), Klein & Barr (1986), Knutsson (2000), Midtbø (1996), Morland (1997), Mörner (1979), Myrvang (1979), Odling (1993), Olesen et al. (1992b, 1997), Rohr-Torp (1994), Stephansson et al. (1986).

10. Borehole Orientation

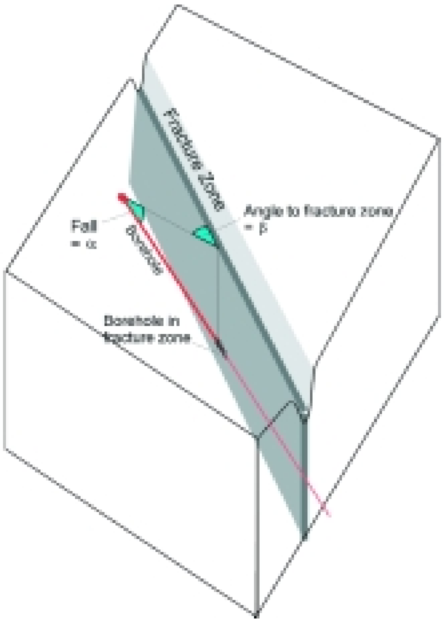
Most modern down-hole hammer drilling rigs are able to drill at angles of up to 45° from the vertical in any direction (Fig 16a). Some rigs can even drill horizontal holes. Boreholes do not have to be vertical and a non-vertical borehole offers significant advantages over a vertical one. Boreholes should be orientated with the following in mind, in order of priority:

1) A borehole should encounter a fracture zone with certainty, at the desired depth and so as to insert the greatest possible drilled length into the zone. It is recommended to drill, with a fall of some 45°-60°, at an acute angle across the zone. The angle should not be too acute, however, for fear of "missing" the zone if it is not completely vertical (Fig. 16b).
2) A borehole should be oriented away from possible sources of pollution, if these exist.
3) A borehole should encounter the greatest possible number of fractures. A vertical borehole will not cross many vertical fractures.
   A borehole should ideally be drilled perpendicularly to the main fracture direction or, if there is more than one fracture set, should be drilled to approximately bisect the obtuse angle between the fracture sets.
   The optimal angle can, in fact be calculated relatively easily (Banks 1992), although a fall of 45° is likely to be a good compromise in the case of poor fracture information.
4) Theory suggests that a borehole drilled perpendicular to the greatest horizontal compressive stress will encounter the most open fractures. Odling (1993) notes, however, that this effect is likely to be subordinate to other factors (see Ch. 9).

Further Reading on Borehole Orientation

Banks (1992c)

Figure 16. (a) A modern downhole hammer rig drills a deviated borehole in the gneisses of Flatanger municipality, Norway. (b) Schematic diagram showing optimum borehole orientation to meet a fracture zone. The angle a (borehole fall) should be such as to meet the fracture zone at a depth of some 40 - 50 m. The lower the angle b, the longer the portion of the borehole within the zone, but the greater the angle b, the less the danger of missing the zone altogether.



11. Drilling

In the past, boreholes have been drilled in hard rocks using simple cable tool rigs or conventional mud-lubricated rotary rigs. These techniques are slow and labour intensive, and it is now usual to drill with a down-hole air hammer.

The hammer is tipped with tungsten carbide buttons and powered by compressed air. During drilling it is rotated slowly. The compressed air which powers the hammer is blown through the bit and carries the drilled rock flour and cuttings to the top of the hole where they may be inspected and logged by the driller or site geologist. Small quantities of water are often added to the drill stem above the water table to cool the bit and dampen the cuttings. Typically, a well is drilled at 127-152 mm diameter.

If commenced directly on a rock

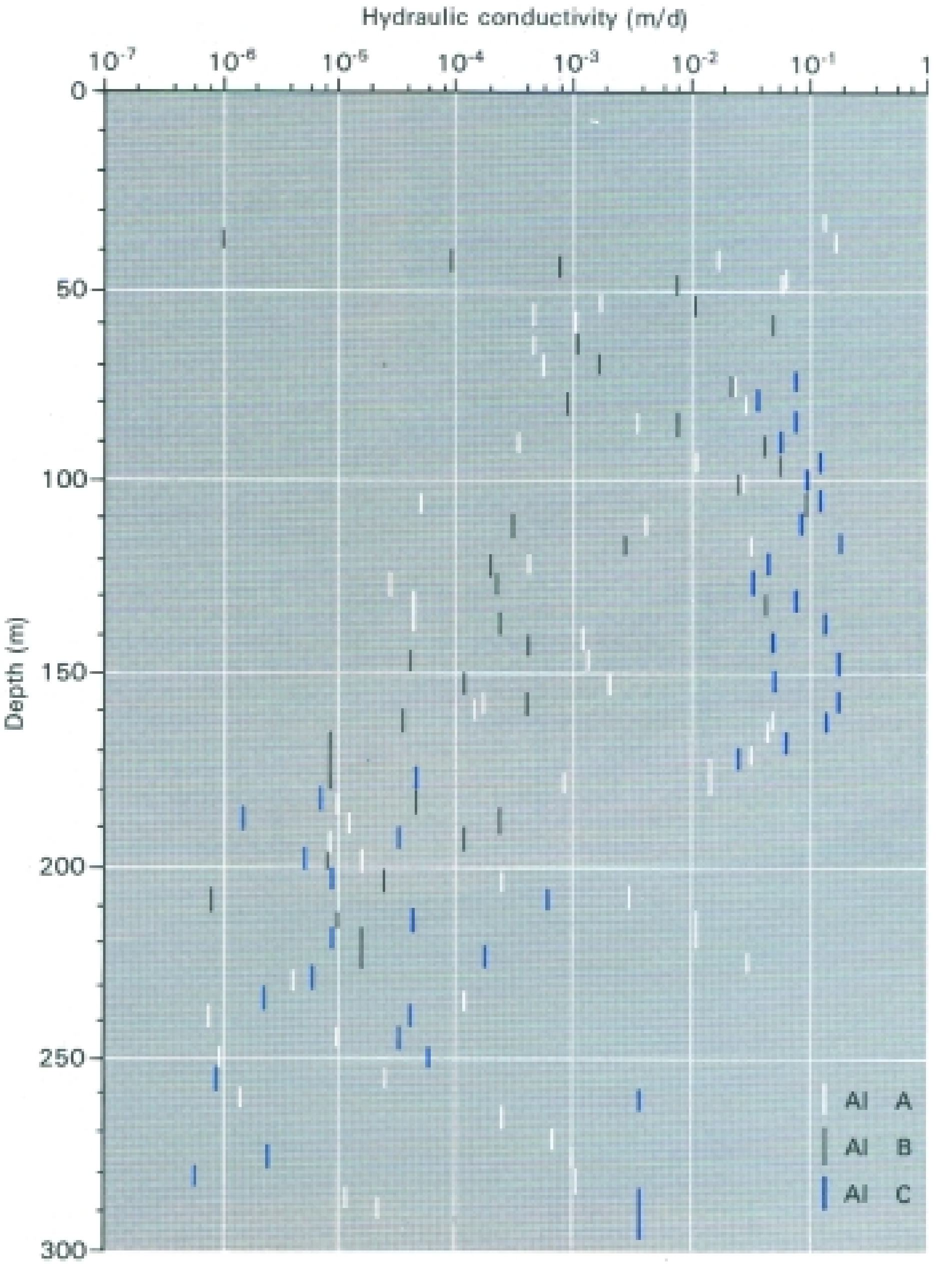


Figure 17. Diagram illustrating the trend to decreasing mean permeability with depth in bedrock (although with very large scatter !), on the basis of data from the Altnabreac granite in Scotland (Holmes 1981). The differing colours refer to different boreholes, A, B and C. Printed with permission from British Geological Survey.

outcrop, the upper 3-5 m of the borehole are usually cased with plain casing (more if the rock is of poor quality). This is often installed by drilling at c. 200 mm diameter using an ODEX ex-centred bit which carries the (e.g. 152 mm diameter) casing down with it. If superficial sediments are present, the casing is usually carried down through these to maybe 1 m into the underlying bedrock (or at least 3 m into bedrock if the superficial deposits are thin, i.e. < 2 m). When the casing is installed it should be grouted into place, preferably by injection from within the casing, and preferably using an impermeable, durable and slightly elastic grout. Drilling may then progress with a bit of, say, 140 mm through the installed casing. Drilling progress may be as fast as 1 m per 4-5 minutes. Most bedrock boreholes may be drilled "open hole". In extremely fractured rock, an inner string of slotted casing may be desirable to support the borehole wall.

The above paragraph describes common drilling practice today. There are indications, however, that many Scandinavian bedrock boreholes are inadequately protected against surficial contamination. Korkka-Niemi (2001) and Gaut et al. (2000) found many such boreholes with bacterial contamination, while Frengstad et al. (in press) decribe boreholes subject to periodic run-in of low-pH surficial water. One possible reason for these observations is inadequate length and sealing of plain casing in the uppermost section of the borehole.

During drilling, one may note the presence of potentially water-bearing fractures by (see Fig. 14):

- "rough" drilling progress, with the bit appearing to catch on broken rock
- very fast drilling progress
- red-brown drilling cuttings, indicating oxidising, circulating groundwater
- the appearance of water or damp drill cuttings in the compressed air.

A driller will be able to estimate the short-term yield of the borehole by the amount of water blown up with the compressed air during drilling. He may also measure the rate of rise of water in the hole on completion of drilling and make an initial estimate of the yield from this. Samples of water taken during or shortly after drilling are almost *never* representative of the final water quality taken from the hole - don't waste money on water sampling at this stage.

11.1 How Deep Should I Drill?

This question is governed by geology, logistics and economics:

- Permeability decreases with depth (Fig. 17, and Carlsson & Olsson 1977)
- Rate of drilling decreases with depth
- A rig carries only a finite amount of drill string

but also

- There are extra costs associated with relocating a rig and starting a new hole

Most drillers drill to depths of between 50 and 90 m on the basis of experience. At depths greater than this it is probably better to start a new borehole than continuing to drill. Thus, two boreholes of 50-60 m are probably preferable to a single hole of 120 m depth.

You should decide the borehole depth before commencing to drill. Never be tempted to abandon an apparently dry hole at less than the agreed depth. Even if no water strike is made before full depth, water may be obtained by artificial stimulation techniques (Chapter 12).

On Jersey (Channel Islands), the average depth of boreholes is much shallower than in Norway, at just less than 30 m. Bearing in mind that the depth to the water table varies by up to 7 or 8 m, this suggests that the top 25 m or so of the saturated aquifer is the main productive zone in many boreholes on Jersey (Robins & Smedley

1994). Nevertheless, there exist two considerably deeper boreholes on Jersey, penetrating Precambrian shales, and yielding good quality water from deep-seated fractures. Other deep boreholes on the island include one which is 145 m deep but situated adjacent to the shore and pumping salt water and another 92 m deep, effectively dry borehole in solid unfractured granite. It is suspected that these may reflect the needs of a driller who has been contracted to drill on a "drilled metres"-related payment system rather than the more normal (and safer) yield guarantee system.

Further Reading about Borehole Construction

Clark (1988), Driscoll (1986), Lloyd (1999), UNESCO (1984).

The Luftwaffe School of Well Drilling

One of the most unusual well-drilling methods practised in the UK is documented in the British Geological Survey's well database, under index number SX-45/1. It concerns a well in Devonian Tamar Slates in Plymouth Devonport Dockyard:

"Royal Naval Barracks - Devonport: At a point in the shillet [slate] near the flagstaff of the Barracks, a shaft made by an unexploded bomb has been explored and a considerable quantity of fresh water found at a level just above the 'tide' apparently floating on top of the salt water. The Superintending Civil Engineer made a pumping test at the rate of 300,000 gallons per day [57,000 l/hr] and the level was reduced by six inches [15 cm]. He did not consider it advisable to pump any heavier owing to the danger of drawing in sea water. The Naval Medical Officer says that this water is potable, although not quite equal to town water.

Dated 7th April 1943."

It's a great story, although we are somewhat suspicious of the enormous yield. Did the bomb in fact fracture a water main ?

12. Borehole Yield Stimulation

As the outcome of drilling is uncertain, it is worth budgeting at the outset for some form of well-stimulation, for all except the very smallest domestic supplies. Well-stimulation is forcing nature's hand in the hydrogeological poker game. It gives us an ace up our sleeve. If transmissive fractures do not exist naturally, we can make them by brute force. There are two main forms of well-stimulation:

- Explosives. These should be used by a skilled operator who can place the right charge at the right level in the borehole. A tamp of sand or similar is often placed above the charge to direct its force into fracturing the rock rather than blowing water out of the borehole. The technique can be effective, but a more subtle and controlled method is
- Hydraulic fracturing (or *hydro-fraccing*). Here, water is injected into the borehole at such a high pressure that the strength of the rock and the ambient stresses are exceeded, and a new fracture is propagated. (Alternatively, existing small fractures may be jacked open and made more transmissive).

For hydraulic fracturing, the best rigs have a dual pump system. One pump applies a high pressure to initiate the fracture, while the secondary pump has a high volume capacity, injecting large flows of water to propagate the fracture as far as possible (Fig. 18). Dispersing agents (to remove clay minerals), or small amounts of sand or glass beads (to hold fractures open) may be added to the hydrofraccing fluid.

Two systems of hydraulic fracturing may be used. The most basic form injects water below a single packer. It is best used in dry or poorly yielding holes. A fracture may be induced anywhere in the section below the packer. In highly-yielding boreholes or boreholes with clay-filled fractures, this method may simply open the existing water-bearing fractures. After the hydrofraccing these may then close up again with little net effect. In such holes, hydraulic fracturing between a pair of packers is recommended. This allows the targeting of hitherto poorly fractured sections of borehole.

In no case should hydraulic fracturing take place at less than 25-30 m depth.

Figure 18. (a) a hydraulic fracturing rig (photo: David Banks).

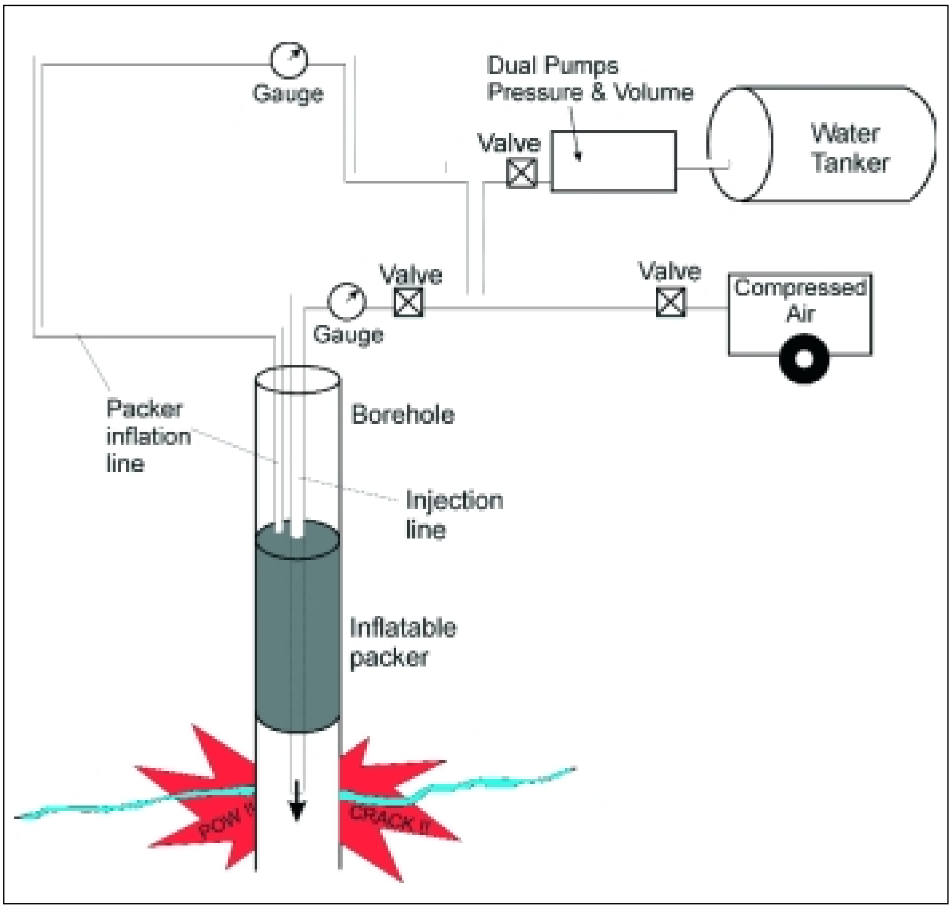


Figure 18. (b) schematic diagram of hydraulic fracturing with a dual pump, dual packer system.

Shallow hydrofraccing runs the risk of creating fractures to the surface, which would be vulnerable to contamination.

Even for boreholes which yield satisfactorily after drilling, some form of yield stimulation may be beneficial. It will usually result in increased well efficiency (yield/drawdown ratio), which reduces pumping costs, although stimulation techniques are themselves expensive..

Further Reading on Well Stimulation

Less & Andersen (1994), Smith (1989), Banks et al. (1996).

13. Test Pumping

Figure 19. A wind-pump used for pumping groundwater at Stonehaven, Scotland (photo: Nick Robins).

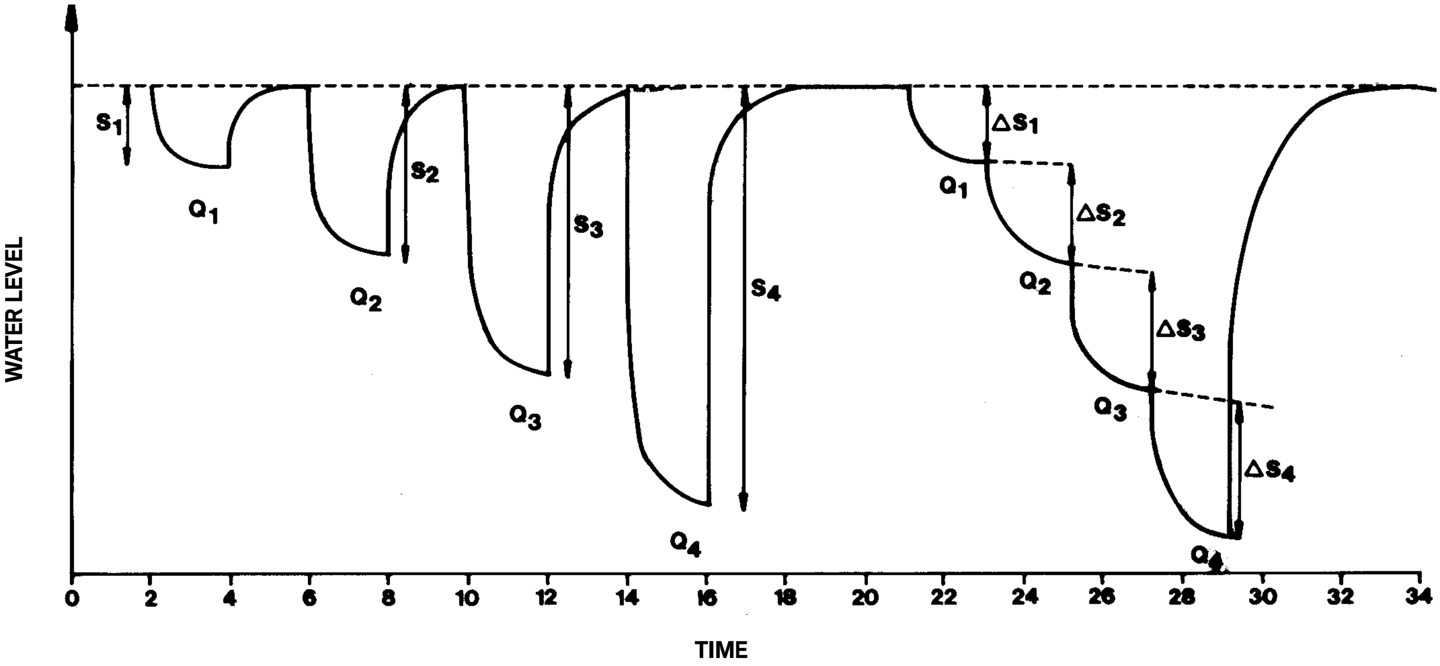


Figure 20. (a) Yield/drawdown curves for a conventional step test: in the left-hand method, a recovery period is allowed between each step and drawdowns (s1-s4) are measured directly for each pumping rate (Q1-Q4). In the right-hand method, steps follow directly on from each other, and the 2-hour drawdown for a rate Q_n is calculated by $s_n = \Delta s_1 + \Delta s_2 + ... + \Delta s_n$. (after Banks 1992a).

13.1 Drillers' Estimates

Experienced drillers are usually able to give a reasonable assessment of a borehole's short-term yield on the basis of the quantities of water blown up out of the borehole during drilling or by measuring the rate of rise of water level in the borehole following drilling. Remember, however, that such estimates are likely to overestimate the borehole's long-term yield. Such estimates will often only be sufficient for making a decision about well stimulation and for designing a longer-term test pumping.

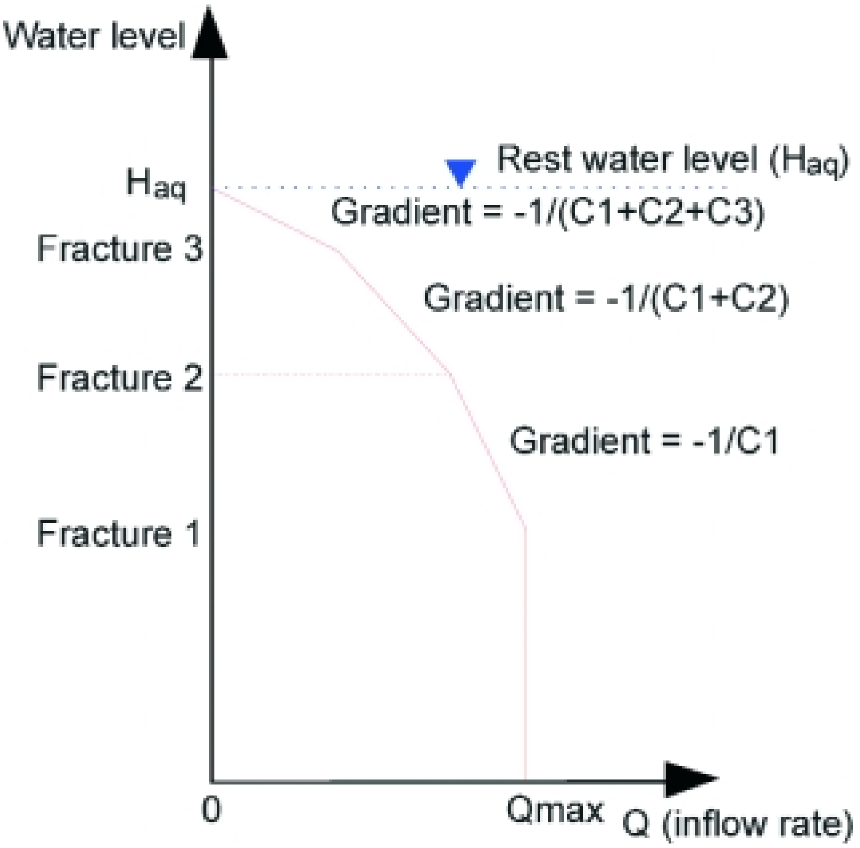


Figure 20. (b) Idealised inflow / water level curves for a rising level test, where three water-yielding fractures, with specific capacities C1, C2 and C3 occur at differing levels, and where Haq = aquifer head / rest water level (modified after Banks 1992b).

Figure 21. (a) An elegant Steinar Skjeseth assists a driller in measuring water flow during the test-pumping of a well.

13.2 Short-Term Test Pumping

If a more accurate measurement of yield is necessary, a short-term test pumping may be necessary. For larger municipal supplies, such a test is regarded as a necessary documentation of the performance of a capital investment. To use the analogy of a car, test pumping is like logging the fuel consumption, to ensure the vehicle is properly tuned and performing at optimum efficiency. Such a test may take two forms:

1) For high-yielding boreholes, a conventional step test may be carried out (Fig. 20a). This involves pumping the well at four different (increasing) rates (Q) for two hour steps, and measuring the water level during pumping. The specific capacity Q/s may be determined for each step, where s is the drawdown (total decrease in water level in borehole, relative to natural water level, at the end of each step). This test is described by Kruseman & de Ridder (1987).
2) For moderate or low-yielding boreholes, a pump is set in the borehole at, say, 50 m depth. It is pumped until the water level is drawn down to the intake (the pump draws air). The pump is then operated for another 1 hour and the rate of water pumped (Q) is measured using a bucket / barrel and stopwatch (Fig. 21a). The drawdown is known (50 m less natural water level) and the specific capacity may be calculated. The pump is then turned off and removed from the borehole. The rise in water level (Dh/Dt) is then regularly measured and the inflow rate (Q) can be estimated by:

   $Q = \pi . r^2 . (\Delta h / \Delta t)$, where r is the radius of the bore.

This rise in water level may be used to calculate the specific capacity for various drawdowns. Abrupt changes in the rate of rise indicate the presence of yielding fractures and can be seen on a plot of Q vs. water level (Fig. 20b). The yields and apparent transmissivities of these

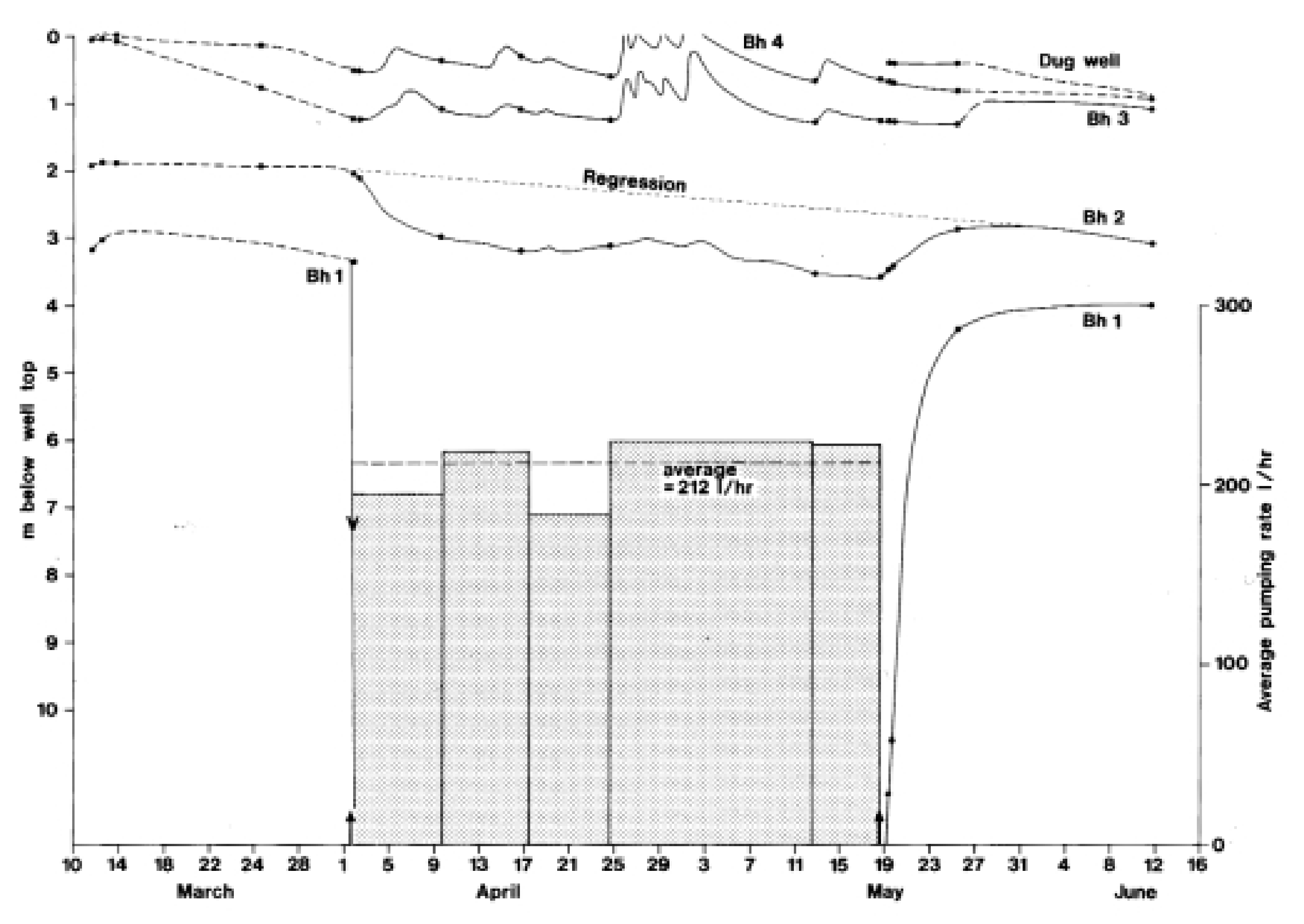
Figure 21. (b) test-pumping a borehole at Turriff, North-East Scotland (photo: Nick Robins).

fractures may be estimated from the rising-level test using the method of Banks (1992b).

13.3 Long Term Test-Pumping

A longer term test pumping of a duration of several weeks to one year is necessary to ascertain the water quality and to ensure that the long-term yield is sustainable. An extended period of pumping will also ensure that the borehole is adequately cleared of drilling cuttings.

The length of test pumping for public water supplies may be determined by national standards or legislation. For public supplies in Norway, a period of 6 months - 1 year is desirable in order to encompass both a major recharge event (snow-melt or autumn rain, when boreholes may be susceptible to bacterial contamination) and a low recharge period (summer or, in inland Norway, midwinter) when the yield will be at its most critical).



During long term pumping, the pump operation is usually controlled by water level-sensitive switches in the borehole, while the yield may be measured manually, via an on-line flowmeter or (for small supplies) by a tipping bucket gauge.

After the water has become clear of cuttings, a programme of regular water sampling for microbiological components may commence. A less regular programme for chemical constituents should also be undertaken which should, in addition to standard major and minor parameters, also include fluoride, radon, and uranium as these may present particular problems in groundwater from bedrock. Water quality may change throughout the test-pumping period (Fig. 22).

Further Reading on Test Pumping

Banks (1992b), Banks et al. (1993a, 1994), Driscoll (1986), Jetel & Kràsny (1968), Kruseman & de Ridder (1989), Wladis & Gustafson (1999).

Figure 22. Water level responses in three observation boreholes during the long term pumping of a borehole at Pulservik on the Hvaler Islands, Norway. All the boreholes are around 70 m deep and within c. 100 m of each other. The dug well is shallow and in superficial Quaternary deposits. Only borehole 2 obviously affected by pumping at around 212 l/hr in borehole 1. The small fluctuations in the hydrographs around the end of April are probably rainfall events. Note the yield along the base of the diagram. During the test, the hydrochemistry of the water changed from sodium-bicarbonate to sodium-chloride due to the wells drawing either on seawater or deep "fossil" saline water.

14. Water Quality

The chemical quality of groundwater from bedrock is often very different from that of water from superficial drift deposits. Bedrock groundwater is often more mature, more basic, more reducing, more sodium-rich and contains more of most minor/trace elements than drift groundwater. In Norway, the median pH of groundwater from bedrock is around 8.1, almost irrespective of lithology. Except in coastal areas, where sodium chloride may dominate, the most important anion is usually bicarbonate (HCO3-), while the main cation is calcium in less mature waters or sodium in more mature waters.

14.1 Natural Health-Related Parameters

Norwegian bedrock groundwaters can contain significant concentrations of parameters which, from the point of view of health or aesthetic acceptability, can be undesirable. For example, in a recent survey (from 1998) of bedrock boreholes in Norway:

- 115 of 1604 boreholes (7%) had a pH outside the Norwegian acceptable range (6.5 - 8.5). Most of these had a pH that was too high.
- 222 of 1601 samples (14%) had a radon (Rn) concentration over the Norwegian recommended norm of 500 Bq/l.
- 258 of 1604 (16%) had fluoride (F-) concentrations exceeding the Norwegian drinking water maximum of 1.5 mg/l.
- 46 of 1604 (3%) had sodium (Na) concentrations in excess of 150 mg/l.
- In 58 of 476 (12%) samples, uranium (U) concentrations were above the

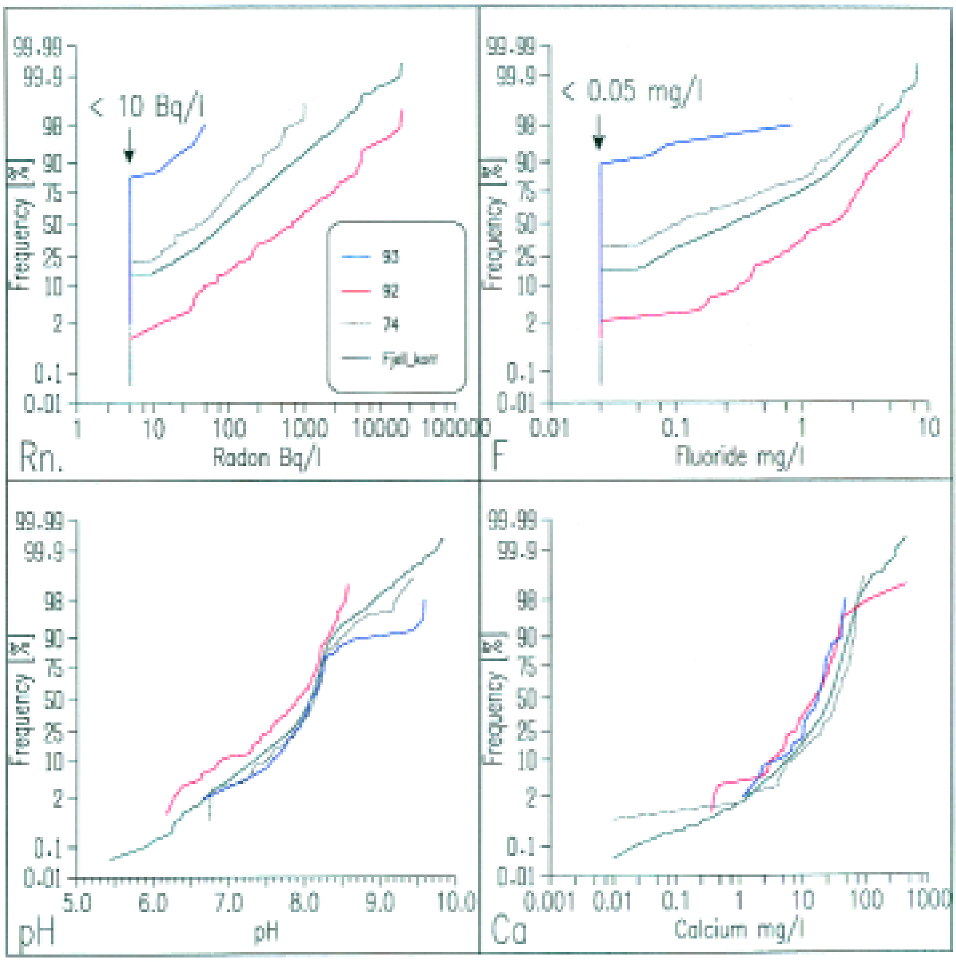


Figure 23. Cumulative probability plots for groundwater chemistry (radon, fluoride, pH and calcium) in Norwegian bedrock groundwater wells for all analysed bedrock wells (All; n=1604), wells in Caledonian metasediments (Rock group 74; n= 114), wells in Precambrian granites (Rock group 92; n= 76) and wells in Precambrian anorthosites (Rock group 93; n= 34). Based on the dataset reported by Banks et al. (1998a,b,c,d). Note that fluoride and radon concentrations below the analytical detection limit are plotted at a value of half the limit.

American drinking water norm of 30 µg/l, while only 3% exceeded the less conservative Canadian norm of 100 µg/l.

- Only 1 of 476 samples exceeded the American limit of 4 µg/l for beryllium (Be).
- Barium (Ba) concentrations exceeded the Norwegian guideline value (100 µg/l) in 122 of 1604 sources (8%).

Iron (Fe) and manganese (Mn) were also problematic in a substantial number of boreholes. All the above parameters should be analysed during the long term test-pumping of a new borehole.

Although it is possible to say that the above problem parameters exceed drinking water norms more frequently in particular areas and rock types (e.g. particularly granites in the case of Na, Rn, F, U and Be, it is impossible to predict the water quality of an individual well in just the same way as it is impossible to predict the yield. We can, however, estimate probabilities of violation of drinking water norms from cumulative probability curves (Fig. 23).

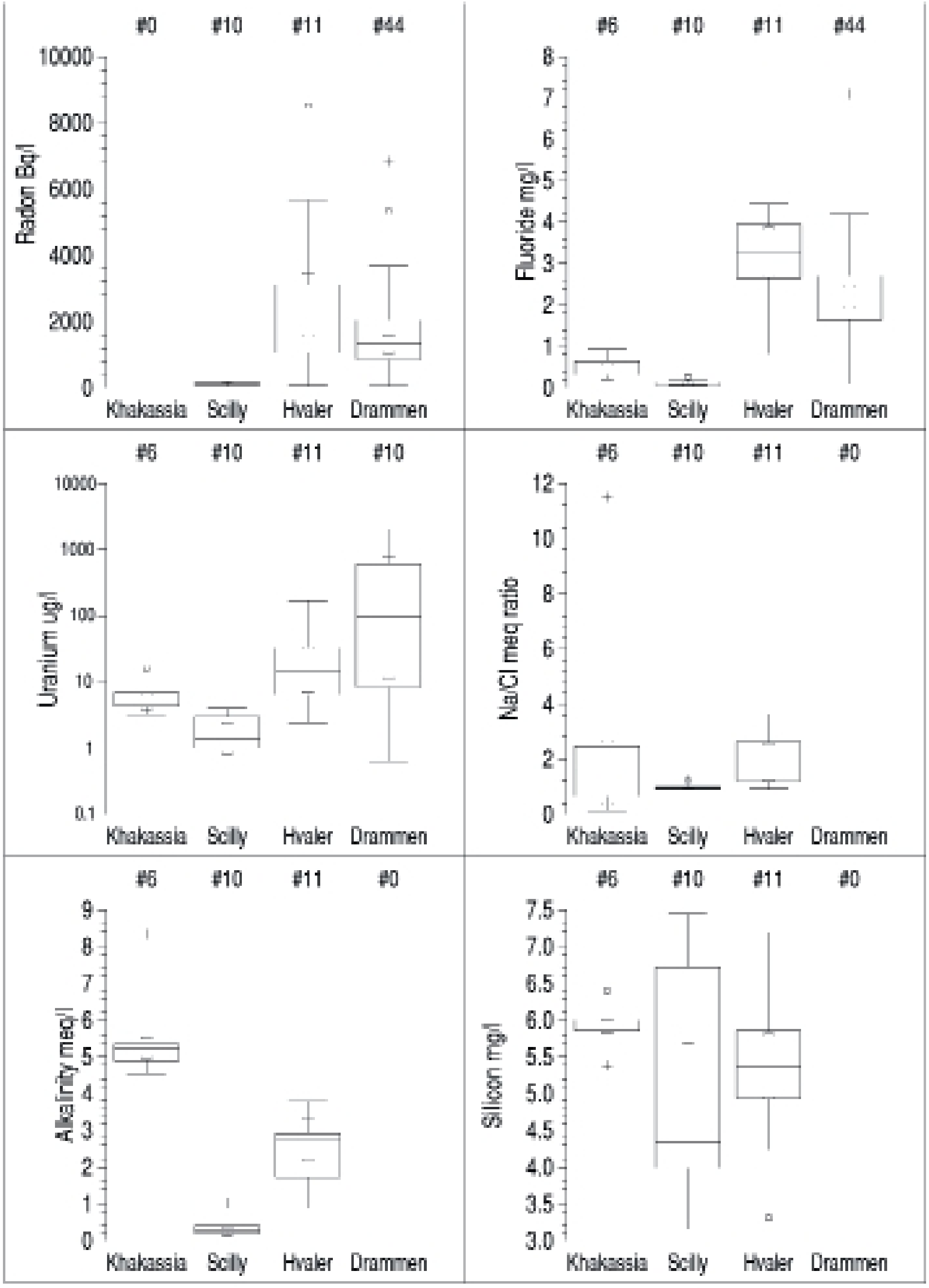
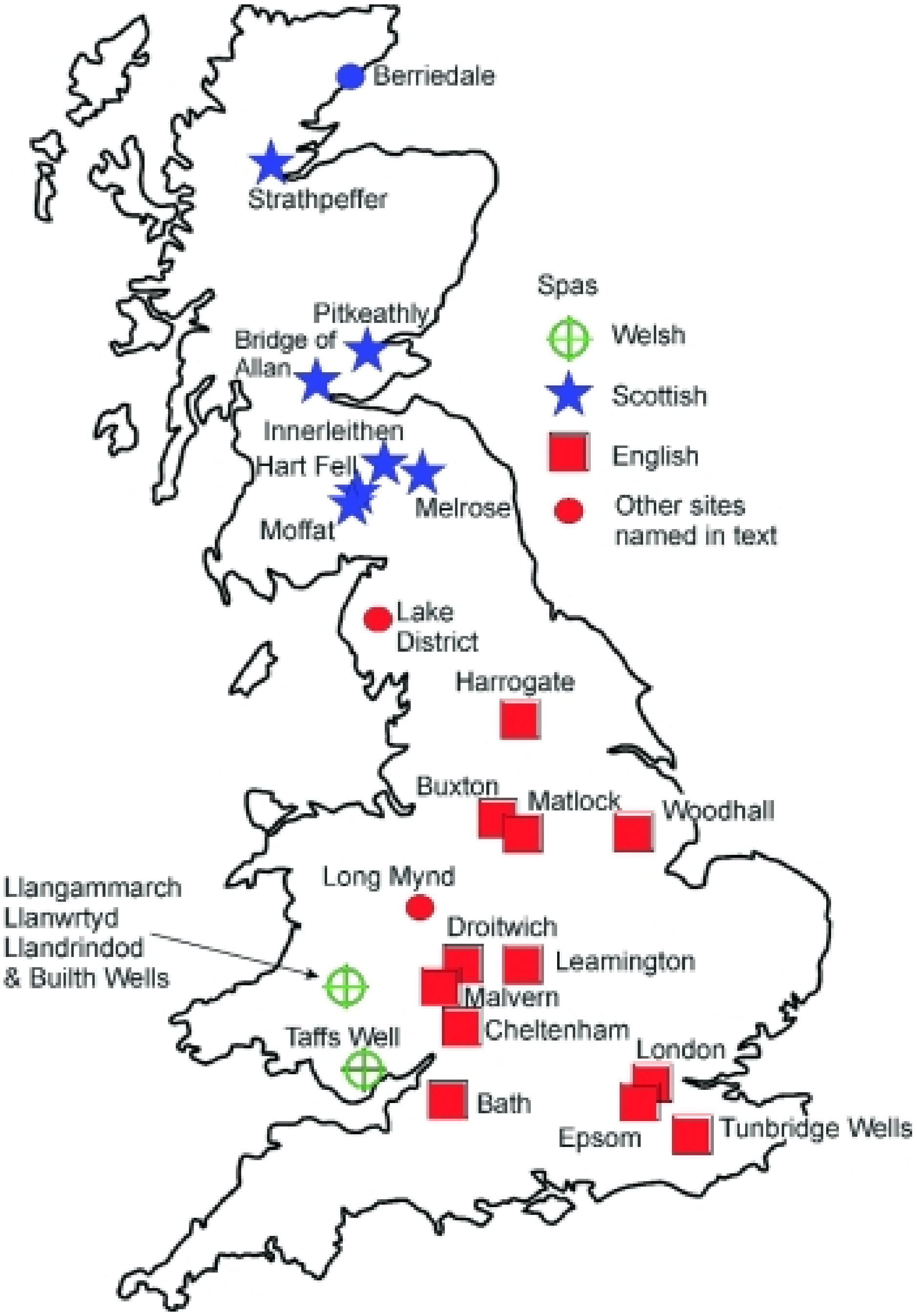


Figure 24. Statistical boxplots comparing concentrations of various parameters (Rn, F, U, Na/Cl ratio, alkalinity and silicon) for groundwaters from four different granites, (i) the British Isles of Scilly granite, (ii) the granites of the Shira region, Khakassia, southern Siberia, (iii) the Norwegian Iddefjord granite of Hvaler and (iv) the Permian granites of the Oslo Rift, dominated by the Drammen Granite. Data from Banks et al. (1995), Morland et al. (1997), Banks et al. (1997), Parnachev et al. (1999). No radon data are available from Siberia.

Figure 25a. Map showing locations of some spas in the U.K. and other locations mentioned in the text.



Although it is possible to make some general statements about groundwater chemistry related to rock-type, such generalisations can be very misleading. Fig. 24 compares groundwater chemistry from the British Isles of Scilly Granite, granites from the Shira region of southern Siberia, the Norwegian Iddefjord Granite of the Hvaler Islands and the Norwegian Drammen granite of the Oslo Rift. It will be seen that the Scilly Granite groundwaters contain far less radon, fluoride, uranium and sodium (relative to chloride) than the Norwegian waters. The Scilly waters are far less hydrochemically mature. This may be due to:

- more permeable fractures and steeper topography at Scilly causing faster groundwater flux and less mature waters
- the Scilly granite not having been intensively glaciated. Basic and trace-element-bearing minerals may thus have been removed by prolonged sub-aerial weathering to a greater extent at Scilly than on Hvaler (Banks et al. 1997, 1998e).

In the UK, drinking water standards comply with maximum admissible concentrations (MAC) or prescribed concentrations of values (PCVs) laid down by the European Union and interpreted by the UK Government for many individual chemical constituents. For several trace consitituents (e.g. uranium, thallium) no European MACs or PCVs have yet been developed.

14.2 Pollution-Related Parameters

Pollution from anthropogenic, rather than natural, sources may be of many forms and come from many sources. In the rural areas where bedrock boreholes are most common, the following types of pollution should be considered:

- Pollution from sewage, cesspools, slurry lagoons or pit latrines, indicated by faecal bacteria, high concentrations of nitrate and/or ammonium and maybe potassium. One common source of such pollution is farmyard run-off entering a borehole because of a poorly sealed and protected well top.
- Pollution from leaking fuel tanks or lines. Indicated by high hydrocarbon contents, oily smell or taste.
- Pollution from agricultural activity (fertilisers, manure, silage liquor, pesticides). May be indicated by the presence of faecal bacteria, high concentrations of nitrate and/or ammonium, dissolved organic carbon and maybe potassium. If these are found, pesticides should also be analysed.

- Road salt. Characterised by sodium (or maybe potassium) and chloride.

14.3 Spas and deep groundwater circulation, bottled waters

Although the pressure of overlying rock tends to reduce the numbers of open fractures with depth, there may be some deep groundwater circulation, although generally of modest volume, along selected flow paths. The emergences of such deep flow paths often represent mineral water springs or spas. Such flowpaths may occur in an area of tectonic disturbance such as a major fault, but also require sufficient head to drive water down into the earth. It can take many years for the water to re-emerge from a deep circulatory system; radiometric dating estimates of the groundwater rising at Buxton in the English Peak District suggest an age of 10,000 years. Clearly, such old water should be free from modern day contaminants, and is likely to be in mature hydrochemical equilibrium with the rocks through which it has passed. It could, therefore, be quite saline, but happily the Buxton water is only modestly mineralised and is widely enjoyed as a bottled table water.

In Central Wales, the spa resorts of Builth Wells, Llandrindod Wells and the lesser known Llanwrtyd Wells and Llangammarch Wells (Figure 25) all relied on old upwelling groundwater from Silurian/Ordovian rocks, driven by the head provided by the surrounding hills. The sources are of variable hydrochemical type, from saline to iron-rich (chalybeate) and sulphur-rich. These small spring discharges relate geologically to the Tywi Lineament with groundwater circulating down to 300 m before rising to mix with shallower waters. Mixing with the shallower groundwaters tends to disguise the chemistry of the deeper circulating waters (Edmunds et al, 1998). Known to the Romans for their curative powers, the spa waters were drunk warm and by the pint by the Victorians, and are now a novelty on display for visitors. Treatments available at the spas also included the needle shower (high pressure needles of saline water jetted at the naked patient) and other rather odd Victorian remedies.

Other similar deep-seated saline groundwater systems occur in British basement rocks in the Lake District, at Wentnor near the Shropshire Long Mynd and in Scotland.

Few British or Norwegian bottled waters derive from old, deep groundwater circulation, other than that at Buxton. Most come from relatively shallow sources. For example, waters bottled as Natural Mineral Waters (according to EC labelling requirements) in Scotland issue from springs or are pumped from boreholes in Devonian and Carboniferous sandstone and lavas, one (Caithness Spring,

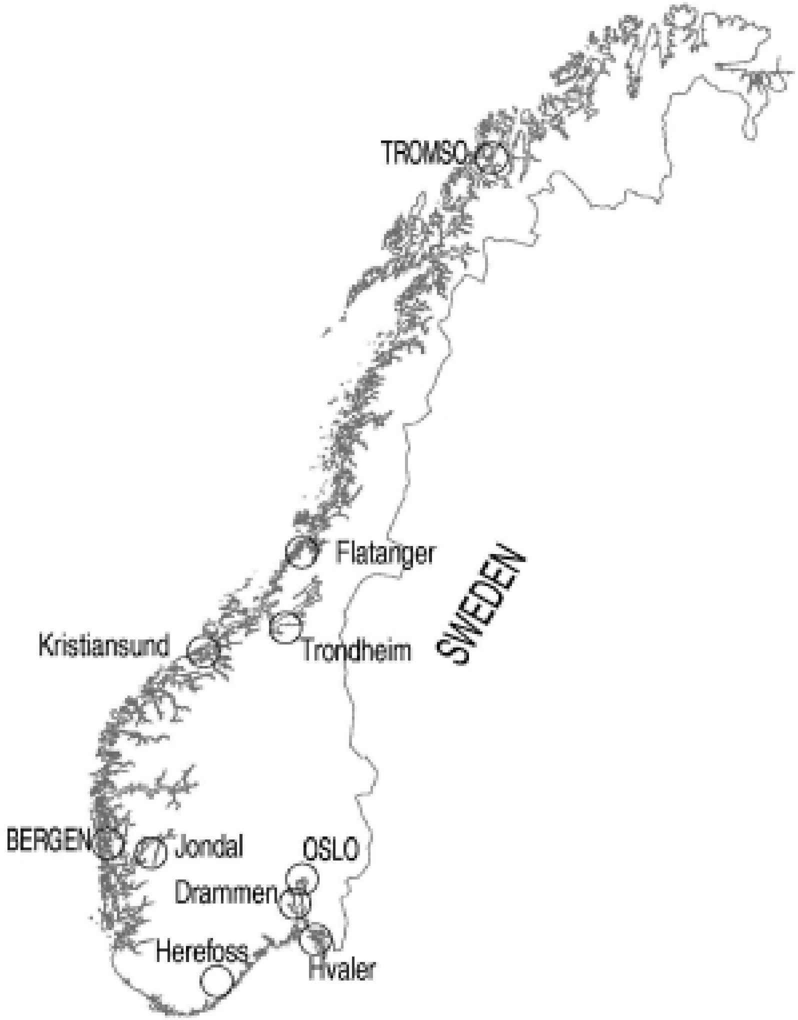


Figure 25b. Map of Norway showing some of the sites mentioned in the text.

Berriedale) from the Precambrian and one (St Ronan's Spring, Innerleithen) from a borehole in Silurian shales. Another source in lavas is extremely weakly mineralised and represents a very young water from a very short flowpath: its attraction as a bottled water eludes the authors who would rather add safe (but boring) tap water to their whisky!

Further Reading on Water Quality

Aastrup et al. (1995), Asikainen & Kahlos (1979), Banks et al. (1993a, 1995, 1997, 1998a-e, 2000), Bucher & Stober (2000), Frengstad & Banks (2000), Frengstad et al. (2000, 2001, in press), Gaut et al. (2000), Lahermo et al. (1990), Morland et al. (1997), Reimann et al. (1996), Sæther et al. (1995).

Further Reading on Mineral Waters and Spas

Albu et al. (1997), Edmunds et al. (1969, 1998), Robins & Ferry (1992)

Water Into Wine - Trondheim Police Pollute Aquifer with Potentially Narcotic Fluids.

The following story was reported in the Norwegian newspaper "Verdens Gang" (14/10/92), in English translation:

"Moonshine on tap

It's swimming with fusel and moonshine liquor in Osveien (Trondheim)...The brew available on tap from the Foss and Kristiansen families is derived from a police raid of over 3500 litres of sats. The fermenting fluid which the police chucked out has ruined the well supplying the two families...."It's bubbling like Alka-Seltzer", sighs Tor Kristiansen and a black thought wings its way to the boys in blue at Trondheim Police Station. The police found an illegal still in the neighbouring house...The fire brigade were called out to dispose of the offending mash and pumped it right out into the ground....*

But it's not just from the 60 m deep borehole that the sats is pumped up. From a rocky slope behind the houses a steady stream of water, with a familiar odour, trickles out."'

*sats = mash, must...the mixture of sugar and yeast so beloved of the practitioners of the traditional Norwegian art of home-distilling.

15. Water Treatment

Most "problem parameters" may be treated. When considering treatment, please remember the following:

(i) Minimise your exposure. If you have fluoride-rich water, you may not need to use fluoride toothpaste or other supplements. Seek advice from your dentist or doctor.
(ii) You are the customer. Don't believe the sales brochures. Insist that a supplier proves that a treatment system is satisfactory by analysing the water, "before" and "after" treatment.
(iii) Most water treatment systems require maintenance. This may entail cleaning, changing of filters, or regeneration of ion exchange resins. Old filters can be breeding grounds for bacteria.
(iv) You don't need to treat all your water - there is often a correspondence between treatment capacity and price. If you have fluoride-rich water, you need only treat the water used for drinking, not that used for showering! Water hardness (calcium and magnesium), on the contrary, is possibly quite good for your health (according to some studies), but may need to be removed before feeding boilers, washing machines and other heated appliances.
(v) Some treatment methods can have negative health consequences. Some water softeners exchange calcium ions for sodium. This is not desirable for people requiring a low-sodium diet.

More specifically, for the most common parameters requiring treatment:

- *Bacteria* may be treated by chemical disinfection (ozone, chlorinating agents) or ultra-violet treatment. The best technique depends on water quantity and water chemistry.
- *Radon* may best be treated by aeration followed by a short (c. 1 hour) storage to allow decay of daughter nuclides. On a domestic scale, several cyclone or filter-cascade units are available, providing effective treatment.
- *Fluoride* may be treated by reverse osmosis, anion exchange or activated alumina adsorption techniques. On a larger scale, aluminium flocculation and precipitation can be effective.
- *Nitrate* may be treated by reverse osmosis or activated carbon filtration, as may *uranium*.
- Undesirable concentrations of *sodium* or *calcium/magnesium* may be treated by cation exchange.

Further Reading on Water Treatment

Banks et al. (1998a, 2000), Ellingsen (1992b), Grundfos (1988), Statens Strålevern (1996).

16. Vulnerability and Source Protection

We have already said that boreholes should not be located too close to pit latrines, agricultural land or oil tanks, but how many metres is "too close" ? The trouble is, we don't really know.

In relatively homogeneous granular aquifers (sand or gravels), we can derive a permeability and porosity from laboratory studies or pumping tests and calculate how far groundwater travels in 50 days (which UK practice suggests is about the time needed for bacterial contamination to "die out" in groundwater; Norway uses a figure of 60 days) or 400 days (the time estimated for some other pollutants to degrade). Using analytical equations or numerical models, we can draw source protection zones based on these distances.

In hard rock aquifers, however, we don't know very much for certain. We have only statistics on fracture patterns and statistics on well yields. We can derive something called an "apparent transmissivity" from pumping tests - a kind of average of the permeability of all the fractures feeding the borehole. But it's not the average that's important in this context, it's the travel time through the most permeable fracture pathway. We often assume an effective porosity of 1% in crystalline bedrock, but there is very little basis for this figure.

The only way to approach a solution is via a statistical or "stochastic" approach. Fracture statistics can be used to generate a range of possible ground-

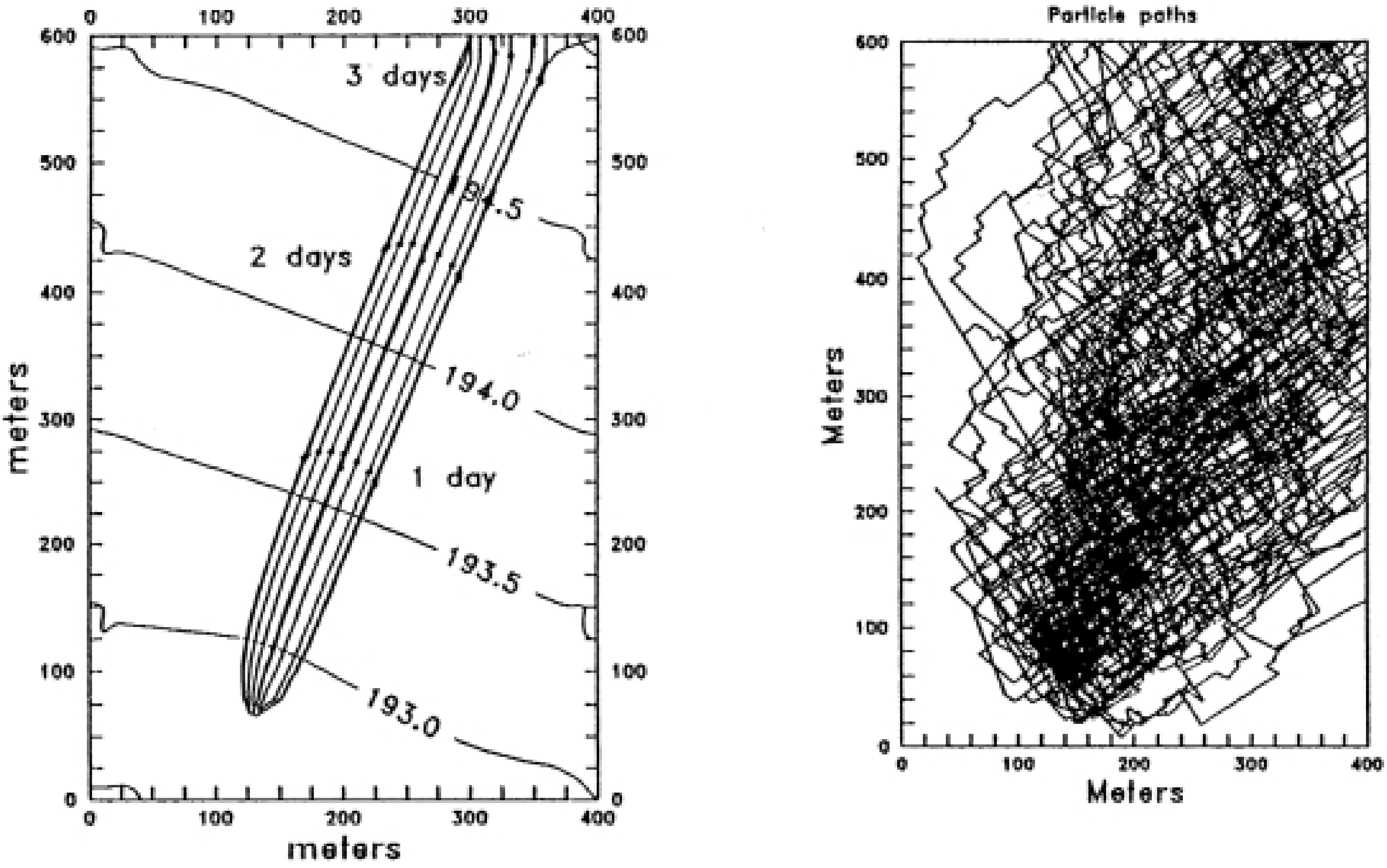


Figure 26. Comparison of groundwater catchment areas (defined by flow paths) for a borehole drilled in a dolomite aquifer in the USA using (left) a deterministic porous medium model (contours in metres OD) and (right) a stochastic model based on twenty realisations of a fracture network. Note that the borehole's capture zone is larger (and the travel times faster) when modelled using the fracture network model. After Bradbury & Muldoon (1994). Printed with permission from Springer Verlag.

water models for the aquifer, allowing median, best-case and worst-case solutions to be examined. Guérin & Billaux (1994) used such an approach and found difficulties in calibrating models - adequate simulation of water levels and groundwater fluxes did not imply adequate simulation of groundwater transport times. Bradbury & Muldoon (1994) also used stochastic fracture network generation models and found that source protection zones were considerably bigger than conventional porous medium models would predict (Figure 26).

What to do ?

- Use common sense
- Use conventional techniques (porous medium models) cautiously and multiply the results by a significant safety factor.
- Support research into development of user-friendly stochastic fracture network models.

16.1 Groundwater Protection Practice in the UK and Norway

In the UK, groundwater vulnerability maps are available at a scale of 1:100,000 for England and Wales and parts of Scotland. These provide a first tier in the risk assessment procedure towards deciding what activities are permissible to avoid serious risk of contaminating groundwater resources. However, for much of the hard rock terrain of these areas, the maps show that vulnerability is "negligible" on the (mistaken) belief that there is no groundwater available within them to be contaminated. These maps are, therefore, of limited value in hard rock areas, although they form a valuable part of the decision support system over the more permeable aquifers.

In Norway a similar situation exists: in theory, wells should be surrounded by "sanitary zones" within which potentially contaminating activities are prohibited or limited. These zones are based on the well's catchment area and on groundwater travel times. In sedimentary aquifers these can be reasonably estimated. In hard rock aquifers, however, it is recognised (Eckholt & Snilsberg 1992, Robins 1999) that such calculations are almost impossible to make. Only very general "common sense" guidance is given for defining sanitary zones in hard rock aquifers and, as we have seen, common sense is not always a particularly reliable guide in such complex hydrogeological environments.

16.2 Soakaways, Septic Tanks and Pit Latrines

One of the commonly asked questions is, "How far do I have to place my waste facility, be it soak-away, septic tank or pit latrine, from my groundwater source?" There is no single correct answer. The optimum spacing between latrines and water sources is often given as 30 - 50 m as a hard and fast rule. In reality, the distance is a function of the prevailing rock type and cover material, the depth to the water table, the local hydraulic gradient, and the design of sanitation and groundwater source. A fractured rock aquifer, such as granite, behaves differently from a porous sandstone aquifer. A fracture may run between groundwater source and waste areas to provide a hydraulic connection and it will thus often be advisable to locate waste facilities down-gradient of and/or approximately perpendicularly to any known fracture trends with respect to a groundwater borehole. Greatest care must be taken where the water table is shallow (ie less than about 3 m below ground surface) as the opportunity for attenuation of waste material in the unsaturated zone is small.

In the Republic of Ireland there are an estimated 300 000 septic tanks serving a population of 1 million people and discharging some 80 million m_ per year of effluent into the ground. The effluent contains faecal bacteria, and high levels of nitrogen and phosphorus. Recent investigations revealed that the safe distance between source and septic tank varied between 30 m and 60 m depending on the prevailing geology, and that the worst conditions were thin soils over fractured bedrock, a situation common in hard rock areas. The study defined a site unsuitable for a septic tank as one:

– where the percolation rate of wastewater to the ground is so fast that it puts groundwater at risk,

– where the percolation rate is so slow that it puts surface water at risk,

– where the water table is within 1.5 m of the surface,

– where the bedrock is within 1.5 m of the surface.

The basis to this important consideration is common sense. In general, the further the waste disposal facility is from the water source the better. In practice, land boundaries may limit available options. The sensible placement of waste down gradient of the water source, with source and septic tank placed at right angles to the prevailing fracture orientation are advisable precautions.

Further precautions include well-head sanitary seals and other means of preventing contaminated surface run-off, for example, getting down the outside of the well casing to contaminate the source. Do not site your borehole in the middle of a farmyard - you would be surprised how many such boreholes exist and how many of them receive nitrogenous surface water as a result. Furthermore, ensure that your fuel tanks are as far from your groundwater source as possible, that they are satisfactorily bunded and check the tanks regularly for spillage and leakage - a very small concentration of hydrocarbons in drinking water taints it and doesn't do you any good either.

Further Reading on Source Protection

Banks et al. (in press), Bradbury & Muldoon (1994), Burgess & Fletcher (1998), Daly et al. (1993), Daly & Warren (1998), Eckholdt & Snilsberg (1992), Guérin & Billaux (1994), NRA (1992), Palmer & Lewis (1998), Robins (1998, 1999).

17. Maintenance & Rehabilitation

A borehole is just like any other piece of equipment. It requires regular checks and maintenance to function at optimum efficiency and to prolong its life. It is a good idea to regularly measure and record the *yield* of the borehole. For municipal supplies this may best be done by means of a yearly, short term pumping test (see above) to measure the borehole's specific capacity.

Many municipal waterworks do not have the possibility to measure water level or drawdown in their boreholes. This is a mistake - it is like driving a car without a "low oil" warning light. Water levels can be measured most effectively via either pressure transducers coupled to data loggers, or simply by an electrical "dipper" through a specially installed "stilling pipe" to avoid tangling the dipper with rising main or cable.

It is also advisable to remove the pump once every few years to inspect it for signs of clogging or corrosion. Provided a flexible rising main hose has been attached to the pump, this should not be a problem for most users.

If a decline in borehole yield is noted, it is important to find out if this is due to:

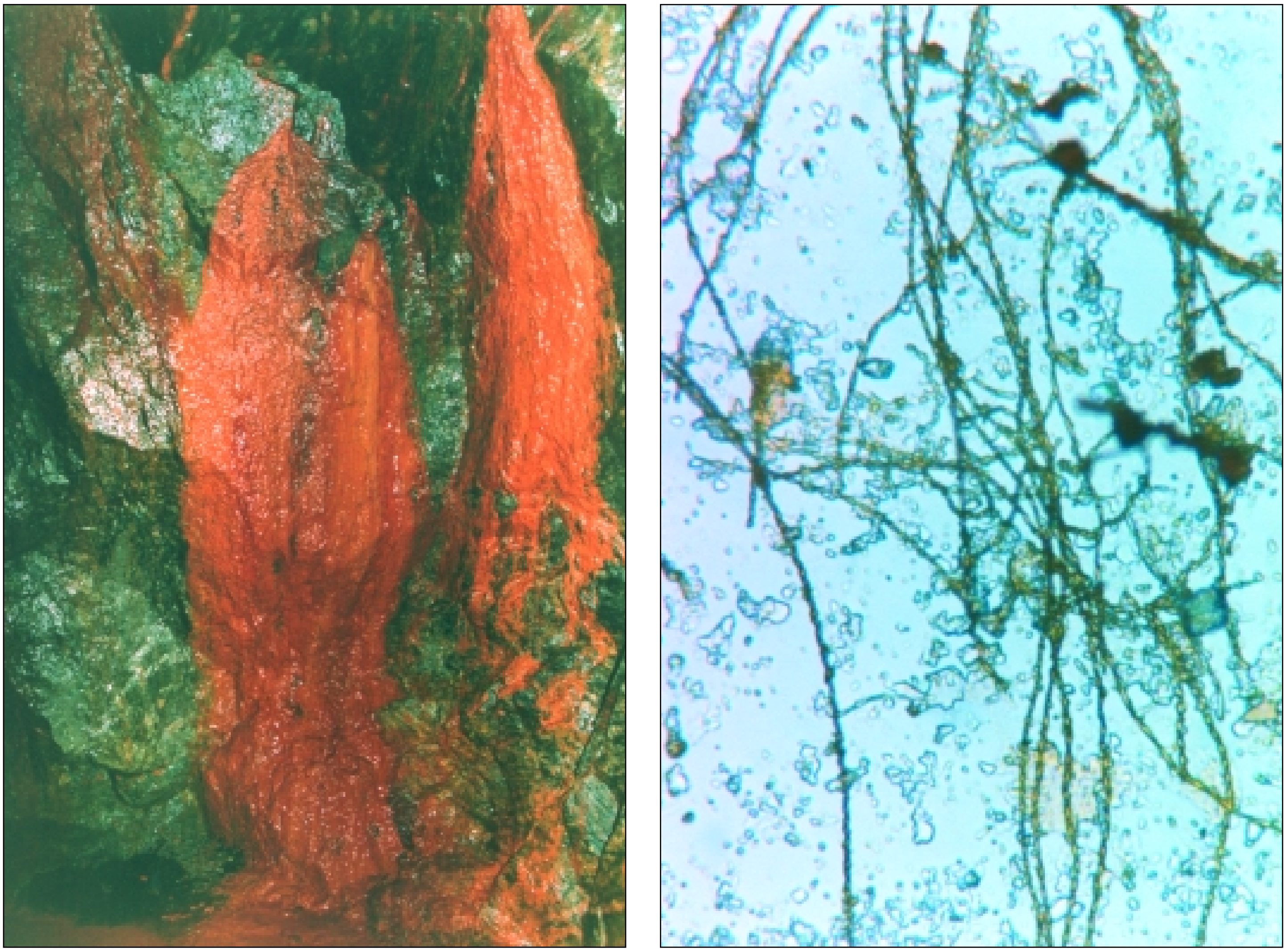


Figure 27(a) Iron bacterial biofilm growths in the Hvaler subsea road tunnel, Granite, (b) growths of Gallionella on a microcope slide suspended in a granite borehole on Hvaler. Both photos: David Banks

- poor performance of the borehole itself (low yield with high drawdown, i.e. declining specific capacity)
- or poor performance of the pump or rising main (low yield, but correspondingly low drawdown, i.e. no decline in specific capacity).

Poor pump or rising main performance may be caused by leakages in the rising main, clogging of the pump or rising main or wear of the pump impellers. The solution is usually straightforward; replacement of worn/corroded parts or some form of physical/chemical treatment to remove clogging.

If the problems lies in the borehole, however, it is important to ascertain whether the low yield is due to:

- abnormally dry / low recharge weather conditions
- increased abstraction from other nearby users
- a problem of fracture clogging or degradation in the borehole.

Water-yielding fractures (and pumps or rising mains) may become clogged with particulate matter, chemical precipitates or, most often, by some sort of bacterial mat comprised of metal-immobilising bacteria (often called *iron bacteria*) and iron oxyhydroxide and/or calcium carbonate precipitates. These look like an orange slime at first, but can harden to a brown crust, and can often be seen in down-hole closed circuit television surveys. Another tell-tale sign of these bacterial biofilms are occasional, very high total bacterial counts in water analyses as pieces of these mats slough off. The bacteria are not dangerous for humans, but cause engineering problems.

If such bacteria and precipitates are found, a course of treatment involving:

- shock chlorination of the borehole to kill the bacteria
- physical agitation, e.g. jetting or wire brushing to remove physical encrustation
- treatment with concentrated hydrochloric, sulphonic or hydroxyacetic acid to dissolve iron hydroxide or carbonate precipitates (this should only be undertaken by skilled personnel)
- clearance pumping to remove displaced and dissolved biofilm
- repeat chlorination to kill any remaining bacteria. (The pump and rising main should also be disinfected before re-emplacement in the borehole).

Some hydrogeologists also recommend hydraulic fracturing in cases of borehole clogging to re-open clogged fractures or create new fractures. In such cases, ensure the water and equipment used is sterile, and disinfect the borehole after treatment.

Further Reading on Well Maintenance and Rehabilitation

Banks (1992a), Banks & Banks (1993b), Driscoll (1986), Howsam (1988, 1990).

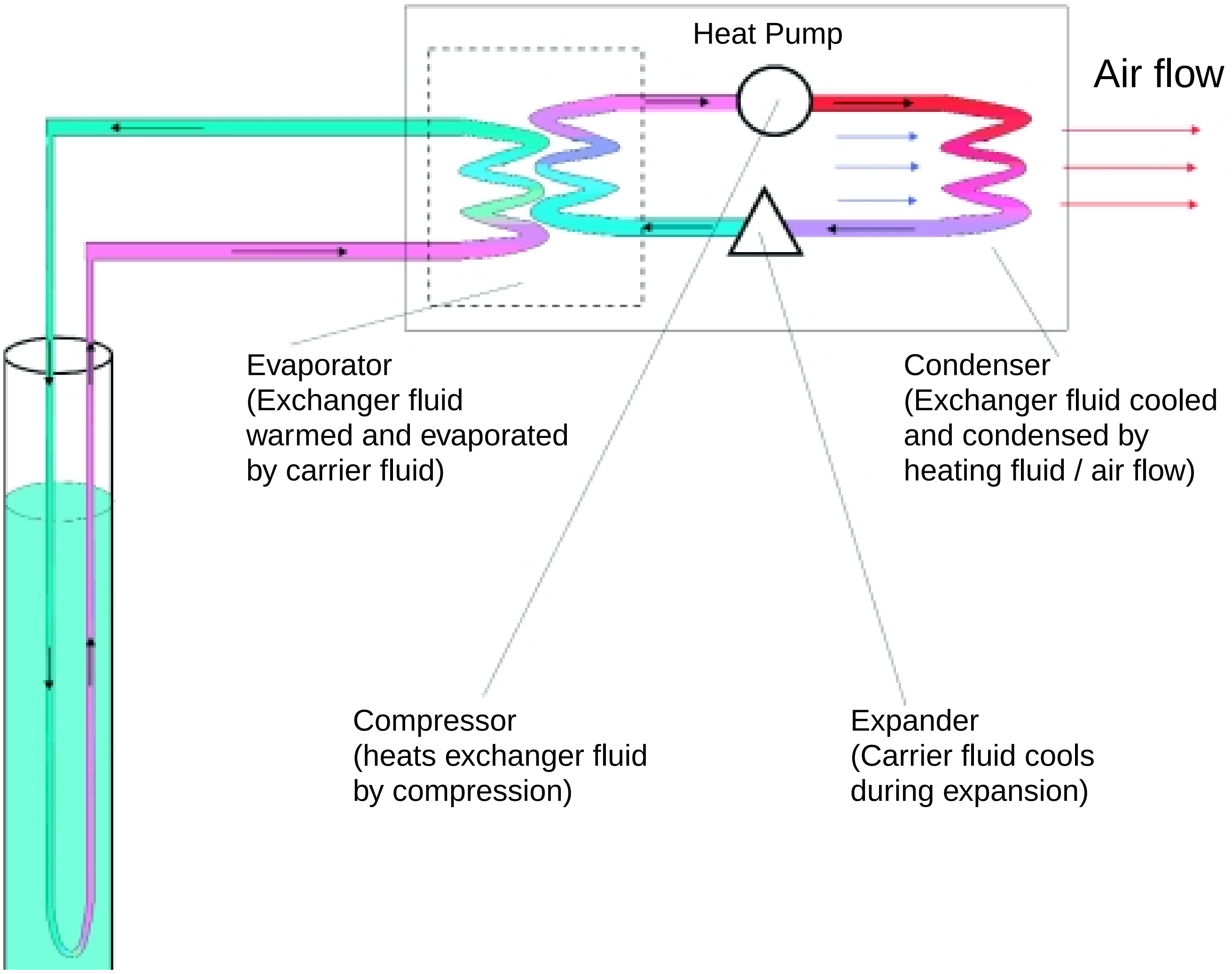
18. Ground Source Heat

Rocks, minerals and groundwater have a huge capacity to store heat. They have an approximately constant temperature throughout the year, although heat from the sun will tend to warm them in the summer. The rocks cool very slowly and they are generally warmer than the air in winter. Conversely, rocks are generally cooler than the air in summer. It is thus possible to extract some of this stored solar heat (and a component of genuine geothermal heat - see 18.4) via boreholes during the winter. This heat energy may be tapped either by:

- pumping groundwater from a borehole and extracting heat from it via a heat pump. This method is best suited to permeable rocks and wells with a high yield.
- circulating a fluid through a closed hose system down the borehole. The fluid is warmed to the temperature of the rocks and, on its return to the surface, may be sent through a heat pump.

A *heat pump* (Figure 28) needs a small amount of electricity to run, and functions like a refrigerator. It takes heat from a low-temperature medium (e.g. Norwegian groundwater at 5 - 6°C) and transfers it to a high temperature space-heating medium at, say, 25°C. The electricity is used to "push" the heat "up" the temperature

Figure 28. Schematic diagram of a groundwater-based heat pump system. A carrier fluid (e.g. glycol) with a low freezing point is circulated in a closed loop in the borehole (left), being warmed to the temperature of the groundwater. This passes through the heat pump evaporator where it heats and vaporises the exchanger fluid (with a very low boiling point), which is in turn futher heated by compression. This heat is then transferred to a heating fluid (e.g. circulating air) which heats the room.



gradient. Heat pump systems may be based on many different sources, such as sea-water, unfrozen rivers, deep lakes or even sewage. However, in inland, rural areas of Norway or Scotland, geology may be the most accessible resource. Heat pumps may be used to warm domestic properties, but are probably most effectively utilised at larger public buildings, vehicle depots, rail stations or residential blocks. Circulating groundwater may also be used for de-icing pavements in winter.

18.1 But is it Ecologically Friendly ?

About as ecologically friendly as is possible ! The heat extracted is essentially solar energy (and a small proportion contributed by the earth's geothermal gradient). Instead of using solar cells, we are using the earth's surface as a huge solar energy collector. The energy is thus sustainable, provided we do not remove more than is replen-ished by nature. Other nations, notably Sweden and the USA, have actively promoted heat pumps as one of the most attractive alternative technologies available for space heating. The only drawback to heat pumps is that they require a small electrical energy input to extract the ground-source heat. However, the net energy benefit is huge, and the electricity consumed by heat pumps is outweighed by savings in electrical energy consumption in conventional heating.

Not only are heat pumps ecologically friendly, they can rapidly save the consumer money. And, as opposed to many alternative energy technologies, heat pumps are proven, and they may be purchased today from a local water engineer. It is also likely that heat pump systems may be implemented at sites such as landfills or abandoned mines, where heat extraction could efficiently be combined with contaminant control programmes.

18.2 How Much Energy can be Extracted ?

The energy extracted from a "heat well" depends on:

- the thermal properties (heat capacity and conductivity) of the rock
- the temperature of the subsurface
- the heat "catchment area" and surface area available for exchange between rock and borehole fluid.
- the solar (major) and geothermal (minor) inputs to the system.
- the thermal efficiency of the heat pump and extraction system

The thermal properties of geological material vary according to mineral composition (Table 1). Quartz content is a decisive factor.

Table 1.
The thermal conductivity of selected rocks and minerals (after Sundberg 1991).

Rock	Mineral	Conductivity in W/(m.°C)
Limestone		1.5 - 3.0
Shale		1.5 - 3.5
Sandstone		2.0 - 6.5
Granite		3.0 - 4.0
Diorite		1.7 - 3.0
Quartzite		5.5 - 7.5
Gneiss		2.5 - 4.5
	Quartz	7.7
	Plagioclase	1.5 - 2.3
	K-feldspar	2.5
	Mica	2.0 - 2.3
	Olivine	3.1 - 5.1

Of course, over the average year, the energy extraction cannot exceed the energy input to the system. During the winter, however, the extraction can exceed the input, provided a sufficient period of recovery is allowed during the summer. In fact, as hydrogeologists will begin to recognise, the physics governing heat flow is highly analogous to that governing groundwater flow, and the scheme just described is directly similar to seasonal exploitation schemes for groundwater management.

As an example, an installation in Kristiansund, mid-Norway, comprising 3 boreholes (two to 50 m, one to 37 m) is reported to have yielded 9 kW space heating effect, (2.5 times more energy was provided by the heat pump than was used to operate it - Oterholm 1990). In the Oslo area, typical yields are reported as 45 W per metre of borehole (Skarphagen 1996), which is not dissimilar to the Kristiansund experience.

In fact it is likely that the heat yield can be significantly enhanced by

- pumping the borehole at a low rate, inducing groundwater flow to the heat borehole. The groundwater transports additional heat to the borehole by advection, effectively increasing the borehole's heat catchment area.
- drilling in areas of significant topography with a high natural groundwater flow and thus higher heat recharge.
- hydraulic fracturing to increase permeability and thus groundwater flow to the borehole. The hydraulic fracturing also increases the fracture contact area between rock and groundwater, permitting more effective exchange of heat between the primary heat store (the rocks) and the heat transport medium (groundwater).

18.3 A Cooling Resource

Circulating groundwater may also be used to *cool* equipment (computers) or offices. The circulating groundwater will thus be warmed up. This "waste" heat may then be reused to heat other parts of a building complex or may be re-injected to the ground via injection boreholes to be used later (e.g. in winter). This is thus a form of artificial heat recharge to the ground. For such heat storage to work, there must not be a high natural groundwater through-flow which can disperse and advect the heat away.

18.4 Geothermal Energy

In sections 18.1 - 18.3, we have discussed the abstraction of dominantly solar energy which is stored in rocks. Of course, there will also be a small component of genuine "geothermal" energy, derived from nuclear decay reactions within the earth. This component becomes more significant in deeper boreholes. Temperature increases with depth according to the geothermal gradioent – typically at least 20°C for every km in many basement rocks.

In some particular areas, the geothermal temperature gradient may be especially high and it may be possible to extract geothermal energy from boreholes (Lindblom 1978, Baria 1990). The possibility of doing this has been explored both in the Bohus Granite of Sweden (Landström et al. 1980) and in the Carnmenellis Granite of Cornwall, U.K. (Downing & Gray 1986). In both cases, although some success was enjoyed during pilot projects, the commercial exploitation of this energy was judged economically inefficient in today's energy climate.

Further Reading on Ground Source Heat & Geothermal Energy

Andersson (1996), Baria (1990), Downing & Gray (1996), Hilmo et al. (1998), IEA Heat Pump Newsletter, Kitching et al. (1992), Landström et al. (1980), Lindblom (1978), Morgan (1997), NGU/NVE (2000), NTH/SINTEF (1992), Oterholm (1990), Skarphagen (1995, 1996), Sundberg (1991), Wikström (1995).

19. Conclusion

Groundwater in crystalline bedrock is a misunderstood resource. Although difficult to predict its behaviour, groundwater in such aquifers remains an excellent solution for potable / agricultural water supply for domestic properties and farms. It is also an attractive, environmentally friendly, decentralised energy resource for space heating, via the use of heat pumps. The low temperature of groundwater, especially in Northern Britain and Scandinavia, renders it suitable for cooling and air-conditioning purposes.

The major challenges in the field of hard-rock hydrogeology today can be summed up as:

- Understanding mechanisms of groundwater recharge and quantities of water entering hard rock aquifers
- Building up statistically significant quantities of data on yield and quality of water from wells in bedrock
- Developing low cost treatment systems for tackling the somewhat "unusual" quality problems (radon, fluoride, uranium) which may occur in hard rock groundwater.
- Promoting ground source energy management and developing off-the-shelf heat pump solutions based on groundwater, in order to minimise the capital investment required to install such systems.
- Developing methodologies for assessing aquifer vulnerability and delineating source protection zones in hard rock terrain.

Groundwater in crystalline rocks remains an under-used resource, particularly in Britain. Hard rock aquifers contain enormous quantities of fresh groundwater, a small fraction of which is used today.

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21. Glossary

Aquifer. A sediment or rock unit that has sufficient groundwater storage and which is sufficiently permeable that it can be used for the viable exploitation of groundwater.

Baseflow. The portion of flow in a river or stream that is maintained during prolonged dry periods. Under natural conditions, this baseflow is normally supported by groundwater entering the watercourse via springs or leakage through the channel bed.

Borehole. See well.

Crystalline bedrock. In this book, the term is used interchangeably with hard rock and bedrock. Rocks comprised of interlocking crystals with very little intergranular porosity. Most groundwater flow thus takes place in fracture systems. These are typically metamorphic (e.g. gneisses) or igneous (basalts, granites) rocks.

Drawdown. When a well or borehole is pumped, the groundwater level is depressed. The drawdown is the difference between the natural non-pumping level and the pumped level.

Dyke. A sheet-like body of igneous rock (such as dolerite) that has been intruded discordantly (i.e. cutting across bedding and other structural features) along a fracture.

Fault gouge. Fine-grained rock debris occurring in a fault zone, and produced by the grinding action of fault motion on the wall rocks.

Fracture set. A collective term encompassing all fractures in a rock unit that have a similar orientation and form and, usually, a common genesis.

Fracture zone. A planar zone of rock which is characterized by an increased density of fractures or joints. A fracture zone may be a fault zone and its core may be comprised of fine-grained fault gouge or rock flour.

Groundwater. Water that occurs in pore spaces and fractures in sediments and rocks in the subsurface. The term groundwater is usually used to refer to water which occurs in saturated strata below the water table, and which can be abstracted from wells, springs or boreholes.

Head. A measure of the potential energy of groundwater at any point in an aquifer system. Head is essentially composed of the sum of pressure head and elevation (or height) head. Groundwater always flows from regions of high head to low head.

Hydraulic conductivity. See permeability.

Lineament. A linear geographical feature that can be observed on maps, aerial or satellite photos. In hard rock terrain, the lineament may correspond with a fracture zone. Alternatively it may correspond with a linear rock outcrop, a lithological boundary, a pipeline trench or other man-made feature.

Moraine. A sediment which was transported by or deposited in contact with a glacier or ice-sheet. A basal moraine or basal till is a deposit formed at the base of a glacier. It often comprises very poorly sorted material with a high content of pebbles or boulders set in a fine-grained clayey matrix.

Permeability. The ease with which a fluid can pass through a porous or fractured medium under a head gradient. When considering water as the fluid in question, the term permeability is effectively interchangeable with hydraulic conductivity (expressed in m/d or m/s).

Post-glacial isostatic rebound. During the ice age, the huge weight of ice covering Fennoscandia pushed the continental crust downwards by a vertical distance of several hundred metres. Following the melting of the ice sheet, the crust started to recover to its original level, a process that continues today. This rebound is accompanied by neotectonic activity, including fault reactivation.

Specific Capacity. The ratio of the yield (or pumping rate) of a well to the corresponding drawdown in the water level. Specific capacity is an expression of the productivity of the well and is related to aquifer transmissivity. Units are typically m^2/s or m^2/d.

Spring. A location where groundwater emerges naturally at the earth's surface. The spring often coincides with the intersection of the water table and the earth's surface.

Storage. The ability of an aquifer to store water within its structure under conditions of increasing groundwater head, and to release it under conditions of decreasing head. The storage coefficient will bear some relation to the rock's porosity and to its elastic properties.

Transmissivity. The product of an aquifer's thickness and its hydraulic conductivity. The ease with which water can flow through an aquifer unit. Expressed in m^2/d.

Water table. The surface in an unconfined aquifer at which the pore water pressure equals atmospheric. Below the water table, an aquifer is fully saturated with groundwater. The water table is analogous to the free water surface in a tank of water (representing an aquifer).

Well. A hole in the ground which provides access to an aquifer and through which water can be abstracted. Wells are typically either dug by hand (dug wells) or drilled with a drilling rig (borehole).

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This small book has a big ambition. It aims to present practical information and a little philosophy to those involved in locating groundwater resources in areas underlain by crystalline bedrock, that is to say:

- Private groundwater users, potential well owners and water bottlers
- Local authorities
- Water companies and local water supply undertakings
- Drillers
- and Consultants

We have consciously mixed practical advice with some hydrogeological theory. We have also provided a comprehensive reference list for those of you who wish to delve further into the subject.
We will largely, though not exclusively, restrict ourselves to consideration of bedrock aquifers in the glaciated terrain of Norway and the northern U.K.

Almost all of Norway is underlain by some type of crystalline bedrock, and groundwater from such rocks is an important drinking water resource in rural areas. In the United Kingdom, crystalline bedrock groundwater is probably an underused resource.

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