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THE COMPARATIVE HYDROCHEMISTRY OF TWO GRANITIC ISLAND AQUIFERS: THE ISLES OF SCILLY, U.K. AND THE HVALER ISLANDS, NORWAY

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THE COMPARATIVE HYDROCHEMISTRY OF TWO GRANITIC ISLAND AQUIFERS: THE ISLES OF SCILLY, U.K. AND THE HVALER ISLANDS, NORWAY.

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Sammendrag:

A comparative study is presented of granitic groundwaters from the Hvaler islands, southeastern Norway (11 samples) and the Scilly islands, southwestern England (10 samples). The islands display similar bulk lithologies and land use, but differing glaciation and hence weathering histories. The groundwater of both groups bears a strong marine signature, although the Hvaler islands display less marine influence and a greater degree of water-rock interaction. The most interesting hydrochemical dissimilarities concern the health related trace elements Rn, U and F. These display median (and maximum) values of 2510 Bq/l (8520 Bq/l), 15 mg/l (170 mg/l) and 3.3 mg/l (4.4 mg/l) respectively for Hvaler, compared with 140 Bq/l (200 Bq/l), 1.5 mg/l (4 mg/l) and 0.1 mg/l (0.27 mg/l) for Scilly. Commonly employed drinking water limits for these parameters are 500 Bq/l (Norwegian action level), 20 mg/l (Canadian limit) and 1.5 mg/l. The differences in contents of these elements between Hvaler and Scilly may be ascribed to (i) differing trace element compositions of the granites and fracture mineralisations; (ii) radically differing recent weathering histories; (iii) hydrodynamic factors.

Emneord: Hydrogeologi	Grunnvann	Granitt
Fjell	Drikkevann	Borebrønner
Uran	Radon	Fagrapport

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FOREWORD

This study was carried out as a joint study by NGU and the University of Sheffield, U.K. Field work in Hvaler was carried out in the period autumn 1992 and winter 1992/93 and the results of sampling in Hvaler are reported extensively in Banks et al. (1995a,b). Field work on Scilly was carried out in the period summer 1995 by David Banks and Helge Skarphagen. Clemens Reimann assisted greatly with the statistical processing of data.

Information on water supply on the Isles of Scilly was kindly provided by David Watkins of the Camborne School of Mines (University of Exeter), Trevenson, Pool, Redruth, Cornwall, TR15 3SE, U.K.

1. INTRODUCTION

Aquifers in granitic rocks contain important groundwater resources in many parts of the world. In arid regions of Africa and India, they may form the only reliable supply of drinking water. Even in some temperate and sub-arctic regions underlain by crystalline massifs, such as Scandinavia and the Czech Republic, granitic lithologies have been recognised as containing significant resources. In the U.K., granitic aquifers play a very minor role in a nationwide groundwater perspective, serving only relatively few remote properties and small communities in western and northern Britain and Northern Ireland. For those communities, however, the granitic groundwater resource may underpin their very livelihood. Such is the case in the Isles of Scilly where water resources are required to support the islands' main industries of tourism and agriculture and where they are now stretched to their limit.

Groundwater derived from granitic rocks is not an unalloyed blessing. It is widely recognised from several studies (e.g. Banks et al. 1995a,b; Reimann et al. 1996) that they may contain minor and trace elements such as fluoride, some heavy metals, radioelements (U, Th, Ra) and the dissolved radioactive gas radon at levels which may exceed recognised drinking water norms. The island situation complicates the situation still further, with its attendant risk of unacceptable salinity.

The current study aims to compare the aquifers of two granitic island groups. These islands exhibit many similarities in land-use and geology, but also considerable differences in terms of recent geological and weathering history and in detailed mineralogy (Tables 1 & 2). The study was undertaken so that a comparison of the two aquifer systems could shed light on the important controlling processes for the hydrochemistry of shallow granitic groundwaters.

2. GEOLOGY, GEOCHEMISTRY AND MINERALOGY

2.1 Isles of Scilly

The Isles of Scilly lie 45 km to the west-southwest of Land's End. They consist of five inhabited islands: St Marys, St Agnes, Bryher, Tresco and St Martins, and some 140 smaller rocky islets. The Isles are the most south-westerly outcrop of a genetically related chain of granite bodies stretching through southwestern England from Dartmoor to Scilly. These are believed to be linked at depth to form the Cornubian granite batholith, intruded in Carboniferous times some 270 Ma ago. The granite outcrops form the moors of Devon and Cornwall. The islands consist almost entirely of granite; the surrounding "Killas" slates of Devonian age, into which the granite was intruded, only being exposed as a narrow altered strip on St Martins.

The Scilly Isles granite consists of at least two separate intrusions, a coarse-grained Outer Granite, with porphyritic feldspar, comprising the bulk of the islands of St Agnes, Gugh, St. Marys, St Martins and the northern parts of Tresco and Bryher. This was subsequently intruded by a medium-grained non-porphyritic granite, the Inner Granite, outcropping on the island of Samson and the southern parts of Tresco and Bryher. As all of the sampled boreholes are drilled into the Outer Granite, the Inner Granite will not be discussed in greater detail here. In both granites, the dominant minerals are quartz, potassium feldspar, plagioclase and lithium-rich biotite and muscovite. Tourmaline is concentrated locally, with the development of schorl (black tourmaline, often in radiating clusters of crystals). Accessory minerals include iron oxides, apatite, zircon, andalusite, rutile, monazite, anatase, topaz, chlorite and brookite. Minor tin deposits are reported on the islands (Barrow 1906). The granites are cut by sheets and dykes of biotite microgranite, aplite and mica-quartz-feldspar-schorl pegmatite.

The distribution of radioactive elements in the Scilly granites is unknown, and it may be dangerous to extrapolate geochemical data from other parts of the Cornubian batholith complex. Nevertheless, Zaghloul (1958) notes that, in the Lamorna Granite of Land's End (the southwestern tip of mainland Britain), of related age and genesis to the Scilly granite, 73 % of the total α-emissions are derived from accessory mineral inclusions, especially within biotite, feldspars and apatite/topaz. The nature of the inclusions was unknown but suspected to be largely zircon and uraninite. Ball et al. (1991) suggest that the main U-host in the Hercynian granites of southwestern Britain is low-thorium uraninite, with some contribution from zircon, monazite and apatite. They contend that there is also a small irresolvable uranium component at grain boundaries which may be particularly important in terms of the dynamics of radon emanation. The total radium content was reported by Zaghloul (1958) as 9.35 x 10^{-12} Ra g/g. This may remain in the granite in a mixture of plumbogummite, iron oxides and clay minerals, even when the uraninite is weathered and mobilised out of near-surface rock under oxidising conditions (Ball et al. 1991, Ball & Miles 1993).

2.2 Hvaler

The Hvaler islands (Hvalerøyene) lie in the mouth of Oslofjord in south-east Norway (Fig. 1a). The hydrogeology is reported by Banks et al. (1992a,b; 1993; 1994). The dominant geological unit is the Precambrian Iddefjord Granite, described by Oxaal (1916). The granite is intruded into Precambrian gneisses, and consists of 13 separate plutons (Pedersen and Maaløe 1990), some of the youngest of which yield a Rb/Sr age of 918 ± 7 Ma, corresponding to the end of the Sveconorwegian orogeny. Quartz, microcline and plagioclase dominate in the granite, with accessory biotite, hornblende, muscovite, iron-oxides, chlorite, apatite, titanite, zircon and garnet.

Across the Swedish border, the continuation of the Iddefjord Granite (the Bohus Granite) has been investigated in great detail in connection with a geothermal energy project at Fjällbacka. Both at Fjällbacka (Eliasson et al. 1990) and Hvaler, fracture mineralisations consisting of calcite, fluorite, smectite, hematite, chlorite, quartz, biotite, muscovite, epidote and iron oxyhydroxide (rust) have been found (see Banks et al. 1994 for further details). In the Iddefjord Granite, uranium and thorium mineralisation has been reported, including uranium (IV) oxide, thorite, samarskite, monazite and xenotime (Banks et al. 1995b).

3. GLACIATION AND QUATERNARY SEDIMENTS

3.1 Isles of Scilly

The Isles of Scilly represent a submergent landscape. A mere 5000 a.B.P. (years before present), most of the islands would have formed a single island mass and it was not until the Roman period that today's islands would have been recognisable. As late as 1000 a B.P., they would have been joined at low tide (Fig. 1b). The mean sea level rise has been calculated as 2.1-2.6 mm/a for the period datable by archaeological remains (Ratcliffe 1992). The islands have thus been subject to relatively prolonged subaerial weathering.

The Scilly Isles represented the southernmost limit of the maximum extent of glaciation in the U.K. Limited patches of till, containing exotic fragments such as sandstone and flint, are found on the northern parts of the archipelago, where granite outcrops are characterised by physical weathering. Periglacial conditions prevailed during much of Pleistocene, however, and these are represented, particularly on the southern part of the island group (St Agnes, St Marys) by the widespread occurrence of soliflucted head or "ram", consisting of angular frost-shattered granite fragments in a sandy matrix. Here, granite tors exhibit distinctive features of chemical weathering.

Other Quaternary deposits include limited tracts of clayey alluvium at Higher and Lower Moors, near Old Town, St. Mary's. Wells in coarser grained horizons associated with these form the basis of much of the island's water supply. Blown sand forms beaches and bars between granite massifs. Raised beaches indicate that the submergent character of modern Scilly is only a comparatively recent phenomenon, complex relative sea level fluctuations throughout the glacial period having shaped Scilly's topography.

3.2 Hvaler

In contrast to Scilly, the Hvaler islands have undergone substantial isostatic uplift in the past 10,000 years or so. The highest marine limit is c. 170 m above current sea-level (Selmer-Olsen

1964). The islands have therefore only emerged from the sea within the last several thousand years. The islands have thus been glacially scoured; fresh granite outcrops in large areas, with typically only a thin cover of humus. There is no substantial development of a disaggregated surficial layer of weathered granite.

The Iddefjord Granite area is dissected by a pattern of linear valleys resulting from preferential (largely glacial) erosion along zones of fractured and crushed rock. These valleys are usually partially infilled by Quaternary deposits, typically shallow marine or littoral silts and sands. Limited deposits of peat and wind-blown sand also exist (Olsen & Sørensen 1990).

4. LAND USE AND WATER SUPPLY

4.1 Isles of Scilly

The only significant town is Hugh Town, on St Marys island. The islands support a population of about 2000 people, but this figure is at least doubled by the tourist influx in summer. The Scilly Isles are ecologically very sensitive, a delicate balance existing between permanent habitation and the provision of an unspoilt, pollution-free environment.

The dominant industries on Scilly are flower and bulb cultivation during the winter half of the year, and tourism during the summer. The land area consists of open heathland, pasture for grazing and cultivated land (mostly for the flower industry).

The huge expansion in population during the summer creates significant problems related to water demand. The available groundwater recharge to the islands is obviously limited, while intensive land use poses quality problems related to agricultural contamination. Nitrates cause a particular problem, accumulating in recirculated groundwater used for irrigation. The low level of the land and proximity to the sea implies a shallow halocline and salinity problems related to saline intrusion and sea spray. These problems have been known for many years, as illustrated by the analyses in Table 3, culled from the British Geological Survey well archive. The risk of elevated radon, uranium and heavy metal levels in granitic waters in southwestern England has been recognised (Ball et al. 1991, Heath 1991), although the extent of any problem is largely unknown and no specific results from Scilly have been reported.

The backbone of supply on the most populated island, St. Marys, comprises shallow wells in the alluvial deposits of Lower and Higher Moors, near Old Town and Porth Hellick. Sensitive management of these supplies, particularly that at Lower Moors, is crucial to prevent saline intrusion. To supplement these wells during peak demand, and to provide a source of low-nitrate water for blending, saline groundwater boreholes adjacent to the shore near Porth Hellick have been commissioned, coupled to a reverse osmosis desalination plant. Formerly, many private boreholes in the granite were used for supply but, now that most properties are connected to the public supply, only a handful of these are still operational.

On Bryher and Tresco, the small populations are served by central wells in Quaternary deposits (blown sands). On St Martins and St Agnes private boreholes into the granite prevail.

Some of the islands contain permanent large inland pools of water in low lying areas but these tend to be contaminated by sea spray rendering them unsuitable for water supply. The island of St Mary's contains two important wetlands which are ecologically important, attracting rare bird life.

Wastes on St Marys are managed carefully and an incinerator is now used to dispose of the majority of wastes produced. Nevertheless, leachate from the Porthmellon rubbish tip, just east of Hugh Town, has led to concern over contamination of groundwater (Young 1991).

4.2 Hvaler

Hvaler's land use displays many similarities to that of Scilly. Most of the land underlain by Quaternary sediments is used for agriculture, this activity being favoured by relatively mild winters. During the summer a major influx of tourists takes place, although, unlike Scilly, this takes the form of individually owned or rented holiday "huts" rather than centralised hotels. Many of these huts have their own boreholes or wells. On Kirkeøy, the island providing the focus of the Hvaler study, the main town is supplied by wells in Quaternary deposits. As on Scilly, this system is highly stressed during the summer and must be carefully managed to prevent saline intrusion.

Groundwater quality from the granite is known to be problematic regarding salinity, high Fe and Mn concentrations and in some circumstances high hardness and the presence of hydrogen sulphide. Less widely recognised are the elevated concentrations of radionuclides (Rn, U and Th) and fluoride.

5. WATER SAMPLING AND ANALYSIS

Similar procedures were followed during the Hvaler and Scilly studies. The methods and equipment used are detailed in Banks et al. (1995a,b). In brief, however, bedrock boreholes or wells were chosen (Table 4a,b) with emphasis being given to the following criteria:

(i) borehole should be in regular use or should be naturally overflowing, such that "fresh" groundwater is sampled.
(ii) borehole should not be newly drilled. Investigations (e.g. Banks et al. 1993) have indicated that newly exposed rock surfaces and drilling cuttings can substantially affect water chemistry.
(iii) borehole should give low possibility for degassing, i.e. sampling points at borehole head, or sampling points which are part of a closed system (e.g. pressure tank) were preferred.
(iv) the water should not contain particulate matter or humic material.

In practice, however, some boreholes did not satisfy all criteria (i.e. minor infringements of (iii) and (iv)). These are highlighted in Table 4a,b. In particular, it should be noted that most boreholes in Hvaler employ pressure tank systems. At Scilly, this is not the case and samples were mostly taken from a hose directly from the pump. The wellhead arrangements are considered, in general, to give greater possibilities for degassing at the Scilly sites than at Hvaler.

Sampling took place in autumn 1992 and winter 1992-93 in Norway and in summer 1995 in Scilly (samples Sc1-10 of groundwater and Sc11 of rainwater). Prior to sampling, the tap was allowed to run for at least 5 minutes. All polythene flasks were rinsed thoroughly three times with groundwater, and (for filtered samples) twice with filtered water before sampling.

The following samples were then taken in polythene bottles with screw caps:

(a) 2 x 100 ml unfiltered, unacidified
(b) 2 x 100 ml field-filtered (0.45 μm Millipore filter and polythene syringe) and acidified (0.5ml/100 ml of 65% Ultrapur nitric acid).
(c) 1 x 500 ml unfiltered, unacidified.

One quantum of sample (a) was analysed for anions (F^-, Br^-, Cl^-, $SO_4^=$, NO_3^-) by ion chromatography, in Norway by the Geological Survey of Norway and in the U.K. by the University of Sheffield's Department of Animal and Plant Sciences. One quantum of sample (b) was analysed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) for a suite of elements, in Norway by the Geological Survey of Norway and in the UK by the University of Sheffield Department of Earth Sciences. Three control samples from Scilly were also run by ICP-AES at the Geological Survey of Norway, and also for the elements Cd, Se and As by atomic absorption spectroscopy (AA - contract number 1996.0175). The second quantum of sample (b) was analysed by ICP Mass Spectrometry for a suite of elements including Pb, U and Sn. In the UK, this was performed by the University of Sheffield joint ICP-MS facility, in Norway by the Norwegian Institute of Air Research (NILU).

The 500 ml sample (c) was used for laboratory determinations of pH, electrical conductivity (EC) and alkalinity, in Norway by the Geological Survey of Norway and in the U.K. by the University of Sheffield Department of Animal and Plant Sciences. In the Scilly study, pH and temperature were measured in the field using a Palintest Microcomputer 900 meter. In neither study was Eh (redox potential) determined, the nature the pumping and wellhead arrangements precluding the acquisition of a meaningful measurement.

For sampling of radon, a plastic funnel or other similar container was inserted below the running sampling tap such that the tap mouth was under water and there were no air bubbles. A quantum of 10 ml water was taken from the funnel and injected slowly into a 20 ml vial containing 10 ml of prefilled scintillation liquid. Flasks were delivered to the Norwegian Radiation Protection Authority (NRPA) in the case of the Norwegian samples, and to the British Geological Survey in the case of the Scilly samples and analysed by scintillation counter, calibrated using a standard radium solution. Results were corrected for radioactive decay to give a radon concentration in Bq/l at time of sampling.

The Scilly samples were left for 6 months, allowing excess Rn to decay and an equilibrium to be established between dissolved radium and radon in the sample. The samples were reanalysed by liquid scintillation to yield an activity of radium in solution.

Determination of fluoride by ion chromatography in the Scilly samples proved impossible due to interference with organic species. Samples were thus delivered to the British Geological Survey for determination using a fluoride ion specific electrode. The methodology incorporated a total ionic strength buffer solution to convert complex F to F^- and to maintain a constant ionic strength. The measured fluoride is thus assumed to closely represent the total fluorine in solution.

The Hvaler and Scilly studies formed parts of independent projects and hence direct inter-laboratory comparisons was not possible within the project framework.

6. GROUNDWATER CHEMISTRY

The following discussion will focus on the chemistry of the groundwaters of the Scilly Islands. These are compared (Table 4a,b) with minimum, median and maximum values from the Hvaler study, details of which can be found in Banks et al. (1995a,b).

Comparative box-and-whisker plots (Tukey 1977) for Scilly and Hvaler are presented in Figures 2a and 2b. Comparison is further aided by Figure 3, on which median values of parameters for Hvaler and Scilly are plotted on opposing axes. Parameters falling above the central diagonal 1:1 line are elevated at Scilly with respect to Hvaler, points below the line are more elevated at Hvaler.

For the purposes of plotting and statistical analysis, all chemical analyses falling below detection limit have been set to a value of half the detection limit.

6.1 Ionic Balance

Ionic balances for the Hvaler data are discussed by Banks et al. (1995a) and were broadly found to be acceptable. Ionic balances for the Scilly data were within ± 5% (indicating valid analysis), except for sample Sc9 (7.5 %). The Scilly samples afforded the opportunity for comparison of laboratory and field pH values. Extremely good correspondence was observed, the largest deviation being only 0.3 pH units (Sc6).

6.2 Rainfall & Surface Run-off

Table 5 presents data from sample Sc11, a sample taken from a roof-catchment derived rainwater storage tank on St Marys, compared with sea water, the average rainfall composition for Hvaler and spot samples of rainfall and storm surface run-off on a granite surface taken from Hvaler.

The rainwater from the storage tank on St Marys is clearly not pure rainfall. The concentrations of chloride are similar to those of the least saline of the St Marys groundwater samples indicating some degree of evapotranspiration and acquisition of dry salts from the roof catchment. The water has also acquired significant concentrations of fluoride, silica, calcium and an elevated pH, indicating some degree of interaction with the walls of the granitic storage tank and or cement lining/mortar.

It will also be noted from Table 5 that non-marine sources of sulphur account for less than 30 % of the total sulphate for the Scilly rainfall, whereas the non-marine component is > 65 % for the Hvaler rainfall and surface run-off. Such a non-marine excess of sulphate in precipitation in southern Norway is ascribed by many workers to anthropogenic contamination (i.e "acid rain" - Tørseth 1996). Interestingly, nitrate concentrations do not appear to reflect the differing postulated "acid rain" components.

Finally, comparison of rainfall and run-off compositions for Hvaler indicates the considerable up-concentration effect of evapotranspiration and acquisition of dry fallout and residual evapotranspired salts in near-marine environments. The concentration factor between rainfall and run-off is between 10 and 20 for conservative parameters. Nitrate and potassium are relatively depleted between rainfall and surface run-off, probably reflecting uptake by vegetation.

6.3 Sodium and Chloride

In all cases, the granitic groundwaters on Scilly are sodium chloride waters. On Hvaler, the least evolved granitic waters are sodium chloride (the signature being derived from the marine component of rainfall - the so-called type I and II waters of Banks et al. 1993), as were those waters affected by sea water mixing (type IV). There was also a large class of more evolved waters (Type III) with typically sodium (or even calcium) bicarbonate composition, indicative of feldspar or carbonate weathering. This class (III) is absent on Scilly.

Type III waters on Hvaler could be distinguished by elevated Na/Cl equivalent ratios, reaching 3.8 in the data considered in this study, but sometimes exceeding 7 (Banks et al. 1993). In the Scillies, most waters display ratios of just less than 1, reflecting marine dominance and relatively little sodium input from plagioclase weathering.

In terms of absolute salinity, the Scilly groundwaters exceed those of Hvaler, with median values of 166 mg/l and 94.5 mg/l Cl^- respectively and minimum values of 97 and 25 mg/l respectively. The higher salinity at Scilly may reflect several factors:

(i) the position of Scilly in the open Atlantic, leading to a greater component of sea spray in recharge
(ii) the higher salinity of the open Atlantic compared to the somewhat brackish water in the Hvaler area, situated outside the estuary of the Glomma, one of Norway's main rivers.
(iii) the considerably greater tidal range at Scilly (c. 4 m) compared with the rather negligible tides at Hvaler (0.3 m), forcing a greater degree of penetration of saline water into the aquifer.

The distribution of chloride concentrations in Scilly (Fig. 1b) indicates that the values in wells on St Agnes, receiving the brunt of the prevailing westerly wind, are higher than those on St Martins and St Marys, on the lee side of the island group. The highest salinity is at well Sc3, a dug well in both drift and granite, situated only c. 10 m from the ocean shore. This well is used for flushing/washing purposes and not for potable supply.

The UK standard for drinking water quality is 150 mg/l for Na and 400 mg/l for Cl^-. The sodium standard is exceeded by Sc1 and Sc 3 on Scilly and the chloride standard by Sc3 (a non-potable supply - see above).

The Norwegian maximum admissible concentration (MAC) of 150 mg/l for Na (Sosial- og Helsedepartementet 1995) is exceeded by all the Hvaler samples. No MAC exists for chloride although a recommended maximum of 200 mg/l is implied, which is exceeded by two of the eleven Hvaler samples.

6.4 Magnesium and Sulphate

In most cases, magnesium and sulphate are the next most abundant cation and anion (as meq/l) respectively at Scilly, reflecting the dominance of marine-derived salts.

On figure 3, the points for Cl^-, $SO_4^=$, and EC all lie a similar distance above the 1:1 line, reflecting the greater marine component in Scilly groundwaters. The point for Mg, however, lies even further above the line, reflecting an enrichment at Scilly which cannot be fully explained by the marine component.

In Fig. 4 it can be seen that all Scilly groundwaters show an excess of both magnesium and sulphate compared with concentrations expected from the ratio between these elements and chloride in sea water. The excess non-marine values of elements ($SO_4^=$*, Mg*, Ca*, K*) can be calculated from the observed chloride concentrations. One possible explanation of the sulphate excess in groundwater might be an observed sulphate excess in precipitation (possibly derived from "acid rain" - Tørseth 1996); alternatively, a lithological source (possibly sulphide), soil source or an anthropogenic (agricultural) source might be suspected.

An excess of Mg is observed in all samples from Scilly except Sc3, where a considerable deficit of some 8 meq/l is observed. This confirms that a significant part of the dissolved magnesium in the Scilly waters (except Sc3) is non-marine. Figure 4 indicates a positive correlation of Mg* and $SO_4^=$* with nitrate, suggesting that there may be a link with agricultural or sewage contamination.

All of the Hvaler samples contain less Mg than the Scilly samples. The Hvaler samples, tend to exhibit, with Sc3, a significant Mg* deficit, indicating loss of Mg in the geological environment, possibly as secondary magnesium silicates or by ion exchange.

The UK drinking water standard of 50 mg/l for magnesium is not exceeded by the Scilly samples, while the sulphate limit of 250 mg/l is only exceeded by Sc3. None of the Hvaler samples exceed the even more stringent Norwegian MACs of 20 mg/l Mg or 100 mg/l sulphate.

6.5 Nitrate and Potassium

Both nitrate and potassium show considerably higher concentrations at Scilly than at Hvaler. At Hvaler, nitrate concentrations seldom rise above 1 mg/l, whereas, on Scilly, the majority of waters appear to exhibit significant contamination, two waters exceeding the UK drinking water limit of 50 mg/l. Five samples exceed the limit of 12 mg/l for potassium. A plot of K* (corrected for marine input) against NO_3^- confirms a correlation between these two parameters for Scilly (Fig. 4). The contamination is most likely to be derived either from sewage infiltration or from agrochemicals. A limited quantity of potassium is thought to be derived from weathering of silicate minerals; this is likely to correspond to the 1-4 mg/l typical of the Hvaler groundwaters.

The nitrate concentrations in the Hvaler groundwaters are puzzlingly low. One reason may be that the bulk of agriculture takes place in areally limited drift-filled fracture-controlled valleys which may have the character of groundwater discharge rather than recharge zones. Another explanation may be nitrate reduction in more reducing groundwater conditions at Hvaler. Neither of these hypotheses can be confirmed on the basis of the present data. No samples from Hvaler exceed the Norwegian MACs of 44 mg/l nitrate and 12 mg/l potassium.

6.6 Calcium

The median calcium concentrations for Scilly and Hvaler are similar, although the range at Scilly is considerably smaller, most waters containing 10-20 mg/l. At Hvaler, the range spans 1.3 to 45 mg/l. No Scilly samples exceed the UK limit if 250 mg/l Ca. On Hvaler, only two samples fall within the Norwegian recommended range of 15-25 mg/l Ca.

At both Scilly and Hvaler, calcium in groundwater displays a significant excess over that attributable to a marine component (Fig. 4). The excess (Ca*) shows no correlation with NO_3^-. Calcium is considered to be derived from a lithological source. Calcium displays no clear correlation with alkalinity (Fig. 5).

6.7 Alkalinity and pH

Weathering of both carbonate and silicate minerals by dissolved carbon dioxide produces alkalinity in the form of bicarbonate and elevates the pH of the solution. Carbonic weathering of sodic/potassic/calcic feldspar would release sodium/potassium/calcium, bicarbonate and silica to solution, while weathering of calcium carbonate would release calcium and bicarbonate. This does not necessarily apply if silicate weathering is dominated by anthropogenic acids rather than carbon dioxide.

At both Hvaler and Scilly, alkalinity displays the expected good correlation with pH (Fig. 5). In most Scilly groundwaters, however, both pH and alkalinity are low (c. 5.5 and 0.2 to 0.3 meq/l respectively), indicating very little water-rock interaction in the form of weathering. There is, however, no clear correlation between alkalinity and Na* (Fig. 5). Speciation modelling (using MINTEQA2, see below) of inorganic carbon in Scilly groundwaters indicates that the bicarbonate would be expected to be in equilibrium with significant carbonic acid concentrations. The Scilly groundwaters are thus aggressive and still contain significant potential for weathering.

The Hvaler groundwaters show a clear correlation between Na* and alkalinity, indicating carbon dioxide weathering of plagioclase feldspars to be the likely major source of alkalinity.

Median pH is two units higher in Hvaler than at Scilly, while alkalinity is typically ten times as high. This is again indicative of a considerably greater degree of water-rock interaction at Hvaler. The elevated pH and alkalinity may be due to a greater carbonate shell fragment content in the superficial deposits in some areas of Hvaler. The limited extent of such deposits and the similar median levels of groundwater calcium to Scilly would suggest, however, that elevated alkalinity and pH are due to a greater degree of silicate weathering at Hvaler, rather than carbonate weathering.

Half of the Scilly samples fall below the minimum recommended pH of 5.5 in the UK. All, except one, of the Hvaler samples fall within the Norwegian limits of 6.5 - 8.5. For alkalinity, all except two of the Scilly samples fall below the recommended minimum (for artificially softened waters) of 30 mg/l HCO_3^- (0.5 meq/l). All of the Hvaler samples exceed this value.

6.8 Silicon

Dissolved silicon may be derived from silica dissolution, or from weathering of silicates such as feldspars. There is no clear correlation between silicon and either alklinity, pH or Na* (Fig. 5), although Banks et al. (1993) did find some suggestion of a relationship between Si and Na* using a different dataset from Hvaler.

Silicon levels are typically slightly lower at Scilly than at Hvaler, again possibly indicating a lower degree of silicate weathering. Most groundwaters are slightly oversaturated with respect to quartz, but are slightly undersaturated or near saturation with respect to chalcedony, which may be a more likely control on silica content.

6.9 Fluoride

The levels of dissolved fluorine at Scilly are low, the maximum recorded being 0.27 mg/l. In contrast, all except two of the Hvaler samples exceed the (British and Norwegian) drinking water limit for fluoride of 1.5 mg/l, reaching a maximum of 4.4 mg/l. In fact, in others studies (Banks et al. 1993), concentrations of around 6 mg/l have been encountered at Hvaler and up to 10 mg/l in other hard rock lithologies of S. and W. Norway (Reimann et al. 1996). Cases of dental fluorosis have also been identified in families using bedrock groundwater in some areas of Norway (Bjorvatn et al. 1992). The sources of fluoride in Hvaler's groundwater may include the common occurrence of fluorite as a fracture mineral on some fracture sets, fluorine in silicate mineral phases such as amphiboles or micas or fluorine in accessory minerals such as apatite. The high fluoride concentrations are possible due to the relatively low calcium concentrations in many Hvaler groundwaters, although in some Hvaler samples, saturation with respect to fluorite is approached, presumably imposing an upper limit on fluorite concentrations.

At Hvaler, some positive correlation (r = 0.77) between fluoride and pH is noted in this and earlier (Banks et al. 1993) data sets. This relationship may purely reflect covariation due to increasing residence time, but may possibly be indicative of anion exchange with OH^- at elevated pH. No significant correlation with pH is observed at Scilly (Fig. 6).

In the Scilly samples, groundwater fluorine concentrations are of a comparable order of magnitude to aluminium. Speciation modelling by MINTEQA2 of the Al-F system indicates that much of the fluorine is complexed by aluminium, the dominant complex usually being AlF^{2+}. Free fluoride (F^-) as a percentage of total fluorine is modelled as ranging from 88% in Sc10 to only 4% in Sc3. This modelling exercise is, however, very sensitive not only to the accuracy of Al determinations but also to the validity of the assumption that the ion electrode determination represents total fluorine (see above).

At Hvaler, the fluoride significantly exceeds aluminium, and the majority of fluorine is F^-, whilst Al tend to exist as hydroxyl complexes due to the higher pH of the waters.

6.10 Minor Metals (Fe, Mn, Al)

On both Scilly and Hvaler, concentrations of iron, manganese and aluminium display negative correlations with pH (Figure 6). This may reflect these elements' greater solubility at lower pH, although a substantial proportion of these elements may be present in colloidal form, even after filtering at 0.45 µm.

Iron concentrations on Scilly are relatively low compared with those at Hvaler, none of them exceeding the British and Norwegian drinking water MAC of 200 µg/l. On Hvaler, 7 of 11 samples exceeded this level, with a maximum of 1.34 mg/l.

Iron concentrations are likely to be derived from silicate (e.g. biotite) or non-silicate (e.g. oxide) phases. The Iddefjord granite is known as a rather magnetic granite due to its content of magnetite, often oxidised to iron (III) oxides along fracture zones. Concentrations of manganese are also significantly higher on Hvaler than Scilly. Four samples from Scilly exceed the UK limit and Norwegian guideline of 50 µg/l compared with seven out of eleven at Hvaler. Regarding aluminium, concentrations are of a similar order of magnitude at Scilly and Hvaler, although the median is slightly higher at Scilly (107 µg/l) than at Hvaler (84 µg/l). There is, however, a greater range at Hvaler than Scilly, with only two samples exceeding the UK MAC of 200 µg/l on Scilly, but four exceeding this level on Hvaler.

The most plausible explanation of these distributions is that groundwaters are generally less oxidising at Hvaler than Scilly, permitting greater solubility of Fe and Mn. Due to the fact that active boreholes were sampled, meaningful Eh measurements could not be acquired. Indirect evidence (e.g. the not-uncommon occurrence of H_2S in boreholes at Hvaler) tends to support the above hypothesis. An alternative hypothesis is that mafic (Fe-containing) minerals have been largely removed from zones of active groundwater circulation at Scilly during prolonged subaerial weathering, whereas they are still present in the largely unweathered rocks of Hvaler.

6.11 Boron

Boron occurs at similar levels on Hvaler and Scilly. Boron occurs at significant concentration in seawater (Table 5), although correction for marine component suggests that there may also be a significant component of non-marine boron in most samples (Fig. 5). Boron may be lithologically derived or from sewage contamination (being present in some detergents). Previous studies of data from Hvaler suggested some degree of correlation with Si (Banks et al. 1993) but this is not observed in this sample set.

The Norwegian drinking water limit of 300 µg/l is exceeded by two samples from Scilly and four from Hvaler. The UK drinking water limit of 2000 µg/l is not exceeded in any sample.

6.12 Radioactive elements

Radon poses one of the more significant groundwater quality problems in Hvaler. All except one of the samples exceed the Swedish action level of 100 Bq/l (SIFF 1987), while 9 of 11 exceed the Norwegian recommended action level of 500 Bq/l (NRPA 1995). At Scilly, seven out of ten samples exceeded 100 Bq/l but the maximum was only 200 Bq/l.

The problem due to radon is potentially more acute on Hvaler as most consumers use enclosed pressure tanks rather than open loft tanks (which give a possibility for degassing during storage). Also Norwegians tend to have better insulated (and hence more poorly ventilated) houses and tend to spend more time indoors than dwellers on Scilly.

It might be argued that the observed differences in radon are due to different sampling conditions. It is certainly true that most of the Hvaler samples were taken from pressure tanks or directly from boreholes. On Scilly, samples were often from long (in some cases, > 100 m) hoses leading from borehole to point of use. For various reasons, samples on Scilly were typically taken under more turbulent conditions. The water of sample Sc6 is believed to have passed through a loft tank. To assess the effects of sampling, a "star-rating" system for various sampling factors (turbulent conditions, vicinity of sampling point to borehole, intervening tanks, type of pump) has been indicated in Table 4a,b. Temperature may also be seen as an indicator of groundwater "freshness". There is seen to be no clear relationship between the rating and radon concentration, indicating that the effect of sampling conditions may only be of minor importance in this case.

Significant differences are also observed in dissolved uranium concentrations. Concentrations range from 2 - 170 µg/l on Hvaler, with only < 2 - 4 µg/l being observed at Scilly. The Canadian MAC for drinking water is 20 µg/l (Barnes 1986), being exceeded by four samples from Hvaler. The higher uranium concentrations at Hvaler can clearly not be attributed to elevated mobility due to lower pH, to complexation with chloride, carbonate or nitrate. They are also unlikely to be attributed to higher mobility at elevated redox potential, as several indirect redox indicators (dissolved Fe, Mn, H_2S indicate generally more reducing waters on Hvaler). Fluorine complexation of uranium could conceivably be a factor, although there is no significant positive correlation between these two parameters within either the Scilly or the Hvaler data groups. In addition to purely hydrochemical factors, the elevated uranium concentration at Hvaler could be due to (a) the generally more evolved nature of the waters (longer residence time); (b) slightly higher concentrations of U in the granite at Hvaler than at Scilly (Table 2); (c) differences in U mineral phases between Hvaler and Scilly; (d) uranium having been removed by prolonged weathering under oxidising conditions at Scilly.

Both at Hvaler (Banks et al. 1995b) and at Scilly (Fig. 6) no significant correlation between dissolved U and Rn are observed. The two parameters are controlled by very different factors, uranium by whole rock content of uranium and by hydrochemical factors; radon by whole rock content of radium (ultimately derived from U) and by hydrodynamic factors.

Radium concentrations were determined for the Scilly groundwaters. Only three samples yielded detectable radium and none more than 0.1 Bq/l. Thus all samples fall below the USEPA limit of 2.2 Bq/l Ra in drinking water (Milvy & Cothern 1990).

6.13 Trace Metals

Barium is present in generally higher concentrations at Scilly than at Hvaler, with levels of up to 140 μg/l being observed. In no case do levels exceed the U.K. drinking water limit of 1000 μg/l. Only a weak degree of correlation with Ca is observed (Fig. 5).

Copper is also present in generally higher concentrations in Scilly than at Hvaler, with levels of up to 126.5 μg/l being observed (although this sample Sc6 may be affected by copper pipes). This does not, however, approach the UK MAC of 3000 μg/l.

Lead at Scilly and Hvaler is consistently below the detection limits of ICP-ES (88 and 50 μg/l respectively). Analysis by ICP-MS indicates that lead only exceeds 1 μg/l in one sample (Sc3) at Scilly. All samples thus lie well within the drinking water limit of 50 μg/l.

Strontium shows the expected correlation with calcium in both the Scilly and Hvaler groundwaters (Fig. 5), although the ratio Sr/Ca is higher in the Scilly waters, possibly reflecting the ratio in the mineral phase. No drinking water limit applies to this parameter.

Tin was analysed by ICP-MS at Scilly as one might suspect its presence due to the known tin mineralisation in Cornish granites. In all cases it was below the detection limit of 3 μg/l.

Zinc exhibits generally similar levels in the Scilly and Hvaler waters, reaching 134 μg/l in Sc3 at Scilly. There is a weak negative correlation with pH in both data sets (Fig. 6). In no case is the U.K. drinking water limit of 5000 μg/l exceeded.

6.14 Speciation Studies

All the groundwater samples from Scilly and two selected samples from Hvaler (Sample 9 of Banks et al. (1995b), exhibiting the highest U concentration, and sample 11, exhibiting the highest alkalinity, fluoride and salinity of the Hvaler samples) have been subject to speciation modelling using the MINTEQA2 code. Due to lack of redox information, manganese and iron were assumed to exist in the +II state. Selected results are displayed in Table 6.

The majority of Scilly waters are substantially undersaturated with respect to many mineral phases (reflecting their unevolved nature and shorter residence times). For example, all waters are considerably undersaturated with respect to all common carbonate phases, including calcite. In contrast, some of the Hvaler waters have been shown to approach calcite saturation (Banks et al. 1993), including samples 9 and 11.

Assessment of fluorite saturation assumed that the fluoride determinations approximated total fluorine concentrations in solution. All Scilly waters were found to be significantly undersaturated with respect to fluorite. Significant proportions of fluorine were found to be complexed with aluminium. In contrast, Banks et al. (1993). have demonstrated that the most fluoride-rich waters of Hvaler are saturated with respect to fluorite, an interpretation confirmed by MINTEQA2 results for samples 9 and 11. In these samples > 99 % of fluorine is in the form of F^-.

Aluminosilicates are more difficult to model due the high sensitivity of aluminium speciation to assumptions made about fluoride determinations. MINTEQA2 indicates, however, that all the waters are significantly oversaturated with respect to secondary phases such as kaolinite, possibly implying that kinetic factors limit the precipitation of aluminosilicate secondary mineral phases. The Scilly waters are undersaturated with respect to albite and anorthite, but approach saturation with respect to microcline (although this is partly due to the high anthropogenically derived potassium concentrations in the water). The two Hvaler waters are oversaturated with respect to albite and microcline.

The results of the speciation studies confirm that the Hvaler waters are generally much more evolved than the Scilly waters, and approach equilibrium with primary silicate and other mineral phases. This is likely to reflect a longer residence time than for the Scilly waters, which are still agressive with respect to carbonate and silicate phases.

7. CONCLUSIONS

A comparative study of the granitic island aquifer complexes of Hvaler and Scilly reveals significant differences in groundwater chemistry which can be summarised as follows:

- the Scilly groundwaters are dominantly sodium chloride waters, whilst many of the Hvaler waters are dominated by sodium or even calcium bicarbonate.
- The Scilly waters exhibit considerably elevated concentrations of nitrate, potassium and magnesium relative to Hvaler. These are believed to be related to intense agriculture on Scilly or possibly to contamination by sewage infiltration.
- Non-marine excesses of sulphate on Scilly are most likely related to agriculture or sewage, whilst those on Hvaler may be related to a sulphate excess in precipitation (Tørseth 1996) or possibly to lithology.
- the Hvaler waters exhibit elevated pH, alkalinity, dissolved silicon and Na/Cl ratios in comparison to Scilly. All of these are indicative of more mature waters on Hvaler, with a considerably greater degree of silicate weathering. The correlations between Na*, alkalinity and pH at Hvaler, and a lack of significant correlation between $SO_4^{=}$* and Na*, suggest that this is likely to be related to long residence time rather than to intensified silicate weathering due to "acid rain".
- Concentrations of fluoride, radon and uranium in waters from Hvaler are all at least one order of magnitude higher than those from Scilly.

Salinity due to the marine-dominated environment is problematic for drinking water supply at both Scilly and Hvaler. In addition, on Hvaler, potential infringements of drinking water quality standards arise from high levels of radon, uranium, fluoride, iron, manganese, sodium (in excess of marine component) and alkalinity. Potential problems on Scilly are related to agricultural contamination (NO_3^- and K) and to low pH (potential for corrosion, particularly when coupled to high salinity).

The differences in hydrochemistry can be ascribed to one or several of the following factors:

- Scilly's more marine dominated position in the open Atlantic compared to Hvaler's more sheltered position in an estuary in Skaggerak.
- differences in hydrodynamic character (i.e. residence time and fracture aperture). Topographical gradients in Scilly are higher than at Hvaler, due to smaller island area with similar elevation. Although no detailed borehole statistics exist for Scilly, the authors have the impression (Table 1) that boreholes are generally higher yielding than at Hvaler, implying greater fracture aperture. Both factors will result in shorter groundwater residence times at Scilly, and less mature waters. Fracture aperture, in particular, will affect groundwater radon concentrations (Nelson et al. 1983). Hydrodynamic factors may, in turn, partly control redox conditions, differences in which would help to explain differences in Fe and Mn concentrations.
- differences in weathering history. The relatively longer subaerial weathering history of Scilly may have had several effects: (a) enhancement of fracture permeability leading to shorter residence times; (b) depletion of region of active groundwater flow (i.e. the zone of circulation of rainfall-derived "fresh" groundwater) in mafic minerals and fracture mineralisations; (c) depletion of region of active groundwater flow in uranium.
- differences in whole rock geochemistry and mineralogy, although Table 2 suggests that the differences are not significant enough to account for the major hydrochemical differences.
- differences in agricultural intensity are likely if the major differences in NO_3^- and K concentrations are to be explained, but further research is required on this aspect.

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	Hvaler	Scilly
Main industries	Tourism, agriculture	Tourism, floriculture, agriculture
Rainfall Evaporation	740 mm (mean 1961-90)[1] 500-550 mm (Penman calculated)[2]	750 - 1000 mm/a 450 mm/a (estimated actual)
Marine environment	Brackish, situated at mouth of Glomma estuary	Atlantic ocean
Tidal range	0.15 - 0.30 m	c. 2 - 6 m
Lithology	Granite with limited superficial deposits	Granite with limited superficial deposits
Landscape type	Emergent	Submergent
Dominant Pleistocene environment	Glaciated	Periglacial
Maximum topography	c. 70 m a.s.l.	50 m a.s.l.
Borehole yields	Short term yields: Mean = 745 l/h (Banks et al. 1992b) Median = 400 l/h	Long term yields: maximum 3600 l/h (Robins 1996) typical 700 l/h

[1] Station 1080 Hvaler, 17 m above sea level.

[2] Stations 17150 Rygge (40 m a.s.l.) and 27500 Ferder Lighthouse (6 m a.s.l.)

Table 1: Comparison of land-use, topography and hydrogeological factors at the Scilly Isles and the Hvaler Islands.

Weight %	Scilly[1]	Bohus Granite[2]	Iddefjord Granite[3]	Hvaler[4]
SiO_2	71.52			67.75-72.04
Al_2O_3	14.84			14.95-16.36
Fe_2O_3	0.53			0.24-0.97
FeO	1.02			1.08-2.09
MgO	0.36			0.23-0.73
CaO	0.81			1.42-1.74
Na_2O	2.94			3.04-3.57
K_2O	5.42			5.08-5.56
P_2O_5	0.23			0.02-0.1
F	0.24			
TiO_2	0.24			0.2-0.47
ppm				
As	9			
Ba	420			
Ce	78			
Cs	30			
La	25			
Li	293			
Mn	236			230-620
Pb	37			
Rb	441			
Sn	9			
Sr	108			
Th	27	13-77 (44.7)	50.2	
U	7	3-20 (9.5)	9.9	
V	16			
Y	16			
Zn	37			
Zr	117			

	Bohus (modal)[5]	Scilly (modal)[6]	Scilly (actual)[7]
Quartz	20.4-31.6	28.7 ± 10.9	31.3-34.5
K-feldspar	32.5-44.0	32.3 ± 9.3	) 48.6-51.7
Plagioclase	16.3-29.8	26.0 ± 4.0	)
Biotite	3.8-7.0	5.1 ± 3.8	5.7-10.1
Muscovite/Sericite	0.6-6.5	5.6 ± 2.3	5.3-9.5
Titanite	0.1-1.0		
Apatite	0.1-0.2	0.67 ± 0.49	
Magnetite	0.6-2.4	0.05 ± 0.1	0.03-0.16

[1] Mean values, Outer Granite - Stone & Exley (1989)
[2] Range (arithmetic mean), Swedish Bohus Granite - Landström et al. (1980)
[3] Arithmetic mean, Iddefjord Granite- Killeen & Heier (1975)
[4] Range of values, Fredrikstad Granite (part of the Iddefjord Granite), after Pedersen & Maaløe (1990).
[5] Range of modal composition (%) in Bohus Granite - Landström et al. (1980)
[6] Outer Granite, arithmetic mean ± standard deviation, after Jones (1963): total iron ores included with magnetite.
[7] Outer Granite, estimated composition from microscopic analysis, Osman (1928)

Table 2. The geochemical and mineralogical composition of the Scilly and Hvaler Granites.

	Old Well Old Moors St Marys	New Well Old Moors St Marys	Abbey Well Tresco	Church Well Tresco	St Marys Coastguard
Date	4/2/39 Well, c.17 ft	4/2/39 Well, 26 ft	1946 Well, 6 ft	1946 Well, 30 ft	20/4/58 Bore 168 ft
pH	6.9	6.0	6.5	5.9	
Alkalinity (meq/l)	0.90	0.4			0.3
Total hardness (mg/l $CaCO_3$)					155
SiO_2 (mg/l)	13	12			
Amm-N (mg/l)					0.17
Ca^{++} (mg/l)	37	35			
Mg^{++}	25	30			
Fe (total)					0.7
$SO_4^{=}$ (mg/l)	84	108	70	32	
NO_3^-	53	66.5	16	15	133
Cl^-	192	232	223	148	123
F^-					0.1

Table 3. Historical analyses from wells in Drift deposits and one borehole in granite. Information from the British Geological Survey National Well Archive, Wallingford, Oxon.

Index	Date	Pump	Turbulent/exposed sampling	Vicinity	Intervening tanks	T (°C)	pH (field)	Lab determination pH (lab)	EC (µS/cm)	Alkalinity (meq/l)	IC determination (mg/l) Cl^-	Br^-	NO_3^-	SO_4^{--}	mg/l F^-	ICP-ES determination (mg/l) Ca	K	Mg	Na	Si	Ionic Balance Error (%)
Detection Limit (Scilly)																0.003	0.053	0.005	0.0177	0.007	
Sc1	04-Jul-95	Sub	xx	xxx	No	15.8	5.26	5.27	1191	0.22	269	1.11	30.3	56.2	0.09	16.8	14.7	20.8	156	3.90	1.4
Sc2	04-Jul-95	Sub	x	xx	No	14.1	5.36	5.26	1094	0.18	250	1.18	14.0	64.2	0.13	17.7	10.4	20.2	150	6.72	3.0
Sc3	04-Jul-95	Surface	x	x	No	11.6	5.28	5.24	7610	0.20	1818	9.76	45.5	281.3	0.18	88.1	56.5	21.5	1052	3.16	-4.2
Sc4	04-Jul-95	Sub	xx	xx	No	12.7	6.1	6.03	1026	1.02	182	0.86	49.8	47.3	0.08	26.5	26.6	17.6	115	4.04	3.1
Sc5	04-Jul-95	Sub	x	x	No	12.3	5.52	5.46	989	0.26	223	0.87	21.2	41.2	0.27	13.0	10.9	17.8	135	3.99	3.3
Sc6	11-Jul-95	Sub	x	xxxx	Pressure + loft	18.1	6.66	6.36	821	1.02	144	0.62	39.5	36.4	0.10	13.2	10.3	15.0	115	5.60	5.0
Sc7	11-Jul-95	Sub	x	x	No	12.5	5.47	5.44	626	0.30	97	0.52	62.5	38.5	0.07	11.0	44.5	10.8	63	4.45	4.6
Sc8	11-Jul-95	Sub	x	xx	No	13.5	5.46	5.38	674	0.20	110	0.68	71.6	35.8	0.07	11.4	9.2	14.0	87	7.05	5.0
Sc9	14-Jul-95	Sub	x(x)	xxx	No	13.2	5.73	5.54	666	0.40	139	0.58	19.7	28.2	0.05	13.7	14.9	13.0	90	4.22	7.5
Sc10	14-Jul-95	Sub	xxx	xx	No	13.6	5.51	5.50	682	0.26	150	0.68	7.5	30.4	0.10	9.4	6.1	12.1	92	7.45	3.6
Maxium						18.1	6.66	6.36	7610	1.02	1818	9.76	71.6	281.3	0.27	88.1	56.5	21.5	1052	7.45	
Median						13.35	5.49	5.45	905	0.26	166	0.77	34.9	39.8	0.10	13.4	12.8	16.3	115	4.34	
Minimum						11.6	5.26	5.24	626	0.18	97	0.52	7.48	28.2	0.05	9.4	6.1	10.8	63	3.16	
Hvaler Maximum								8.41	1610	3.79	390	0.85	6.4	62.9	4.44	45.9	7.3	10	317	7.19	
Hvaler Median								7.61	481	2.75	95	0.18	0.1	21.7	3.26	10.5	2.9	2.5	111	5.38	
Hvaler Minimum								6.43	244	0.88	25	<0.02	<0.05	11.6	0.82	1.3	<0.2	0.7	28	3.31	

Table 4a. Analytical results for Scilly Samples Sc1-Sc10. Statistical summaries are also given for the 11 granitic groundwaters from Hvaler. Key: Turbulent/exposed sampling - x = low opportunity for degassing, xxx = high opportunity for degassing: Vicinity - x = sample point near borehole, xxx = sample point far from borehole: Pump - sub = submersible, surface = centrifugal suction pump.

	ICP-ES determinations (µg/l)											ICP-MS determination (µg/l)			Bq/l		meq ratio
Index	Al	As	B	Ba	Cd	Cu	Fe	Mn	Se	Sr	Zn	Pb	Sn	U	Rn	Ra	Na/Cl
Det. Limit (Scilly)	22.8	(by AA)	2.7	0.6	3.3 (0.02 by AA)	4.2	1.8	0.4	(1 by AA)	0.1	13.2	1	3	2		0.07	
Sc1	340	1.0	106	20	0.17	28	58	31	1.1	484	36	< 1	< 3	< 2	120	0.08	0.90
Sc2	188		97	24	< 3.3	8	19	84		347	36	< 1	< 3	< 2	140	< 0.07	0.93
Sc3	591	4.8	318	140	2.3	36	107	86	1.4	3696	134	4	< 3	< 2	80	< 0.07	0.89
Sc4	74		164	14	< 3.3	6	17	2		580	< 13.2	< 1	< 3	< 2	160	< 0.07	0.98
Sc5	127		87	11	< 3.3	< 4.2	55	56		285	< 13.2	< 1	< 3	< 2	160	0.1	0.94
Sc6	< 23		341	22	< 3.3	127	22	14		249	23	< 1	< 3	3	97	< 0.07	1.23
Sc7	88		164	42	< 3.3	7	33	9		325	20	< 1	< 3	2	150	0.08	1.00
Sc8	41	9.5	106	15	0.05	7	48	7	< 1	227	< 13.2	< 1	< 3	3	200	< 0.07	1.22
Sc9	175		166	13	< 3.3	51	95	8		340	18	< 1	< 3	3	44	< 0.07	1.01
Sc10	< 23		93	6	< 3.3	< 4.2	5	359		175	35	< 1	< 3	4	140	< 0.07	0.95
Maxium	591		341	140	15	127	107	359		3696	134	4	< 3	4	200	0.1	1.23
Median	107		135	17	< 3.3	8	40	22		333	21	< 1	< 3	< 2	140	< 0.07	0.96
Minimum	< 23		87	6	< 3.3	< 4.2	5	2		175	< 13.2	< 1	< 3	< 2	44	< 0.07	0.89
Hvaler Maximum	729		408	22	< 10	27	1340	301		362	116	12		170	8500		3.77
Hvaler Median	84		129	8	< 10	4	292	106		76	15	1.2		15	2500		1.89
Hvaler Minimum	< 20		35	2.6	< 10	< 2	16	18		10	< 5	0.38		2.4	65		0.92

Table 4b. Analytical results for Scilly Samples Sc1-Sc10. Statistical summaries are also given for the 11 granitic groundwaters from Hvaler.

	Standard seawater Lloyd & Heathcote (1985)	Rainfall storage tank, St Marys (sample Sc11)	Typical rainfall, Hvaler, after data presented by Storrø 1990	Rainfall during storm event,Kirkeøy, Hvaler[4]	Granite surface run-off during storm event, Kirkeøy, Hvaler[4]
Cl^- mg/l	19000	85.6	c. 2	2.95	41.8
Na	10500	57.8		1.2	23.8
$SO_4^{=}$ (total)	2700	17.2	c. 2.8	2.03	16.8
$SO_4^{=}$ (non marine)		5.0	c. 2.4	1.61	10.9
Mg	1350	4.9		0.21	3.11
Ca	400	21.7	c. 0.2	0.36	2.06
K	380	5.8		0.47	0.65
Alkalinity (as HCO_3^-)	142			0	0
Br^-	65	0.36		<0.02	0.083
Sr	8	0.18		< 0.002	0.024
Si	6.4 / 3.7	1.34		<0.02	2.42
B	4.6	0.073		< 0.02	< 0.02
F^-	1.3	0.04		<0.1	0.33
Inorganic N µg/l	500	880[1]	400-500	900[2]	49[3]
Li	170			< 2	4
Ba	30	32		< 2	16
Al	10	<23		68	1350
Fe	10	19		53	495
Zn	10	144		14	89
Cu	3	<4.2		112	8
Mn	2	6		19	44
pH		7.31	4.2 - 4.3		3.53

[1] = 3.9 mg/l NO_3^-, [2] = 4.01 mg/l NO_3^-, [3] = 0.22 mg/l NO_3^-, [4] samples from near testhole 3, Pulservik, Kirkeøy, described in Banks et al. 1992b.

Table 5. Comparison of seawater, rainfall and surface run-off; Hvaler and Scilly.

	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10	Hvaler 9	Hvaler 11
Calcite	-4.00	-3.99	-3.62	-2.34	-3.82	-1.99	-3.84	-4.00	-3.36	-3.92	+0.20	-0.36
Barite	-0.37	-0.19	+0.86	-0.54	-0.68	-0.48	-0.05	-0.56	-0.74	-1.03	-1.21	-0.53
Gypsum	-2.19	-2.10	-1.18	-2.04	-2.39	-2.42	-2.43	-2.46	-2.48	-2.60	-2.37	-2.28
Fluorite	-5.72	-4.27	-4.77	-3.25	-2.93	-3.28	-4.36	-3.97	-4.63	-3.43	+0.20	+0.10
Quartz	+0.30	+0.56	+0.28	+0.36	+0.36	+0.42	+0.41	+0.59	+0.37	+0.61	+0.47	+0.58
Chalcedony	-0.23	+0.03	-0.26	-0.17	-0.17	-0.10	-0.13	+0.06	-0.16	+0.08	-0.09	+0.02
Amorphous SiO_2	-0.73	-0.48	-0.77	-0.68	-0.68	-0.60	-0.64	-0.45	-0.67	-0.43	-0.60	-0.49
Kaolinite	+5.36	+4.88	+4.81	+5.72	+3.30	+5.29	+4.30	+3.74	+6.02	+2.30	+4.90	+6.08
Anorthite	-8.22	-8.63	-8.62	-6.26	-10.18	-5.36	-9.31	-9.78	-6.92	-11.19	-3.19	-3.09
Albite	-1.71	-1.39	-1.35	-0.79	-2.52	-0.16	-2.30	-2.05	-1.07	-2.65	+0.81	+1.92
Microcline	-0.87	-0.67	-0.70	+0.48	-1.70	+0.62	-0.54	-1.13	+0.05	-1.93	+1.60	+2.27

Table 6. Saturation indices of selected mineral phases for Scilly samples Sc1-Sc10 and Hvaler samples 9 and 11 (from Banks et al. 1995a and b), estimated using the MINTEQA2 code. Where parameters (notably Al) are below detection limits, the input value has been set to half the detection limit).

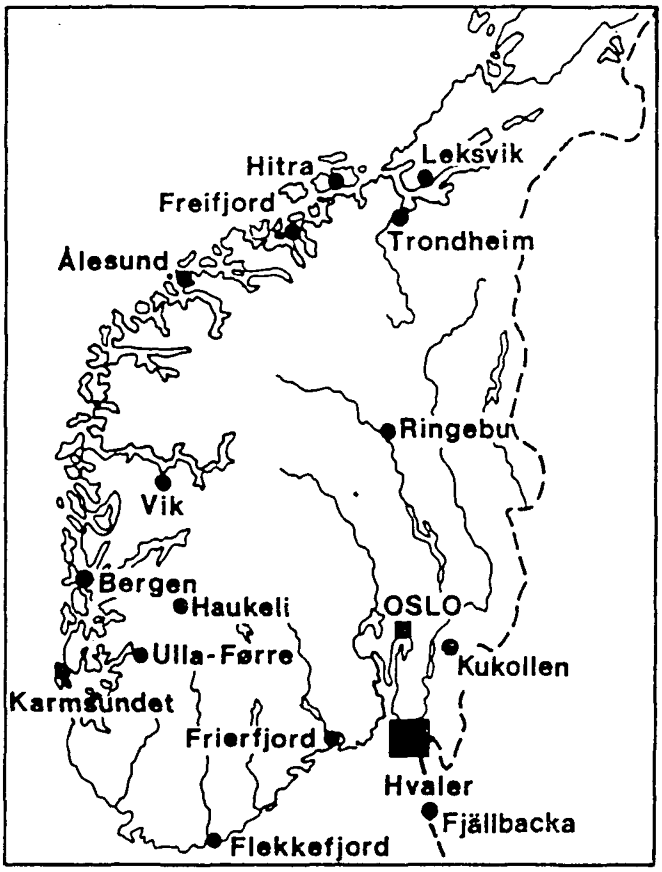


Figure 1a: Location map of the Hvaler Island area, Norway.

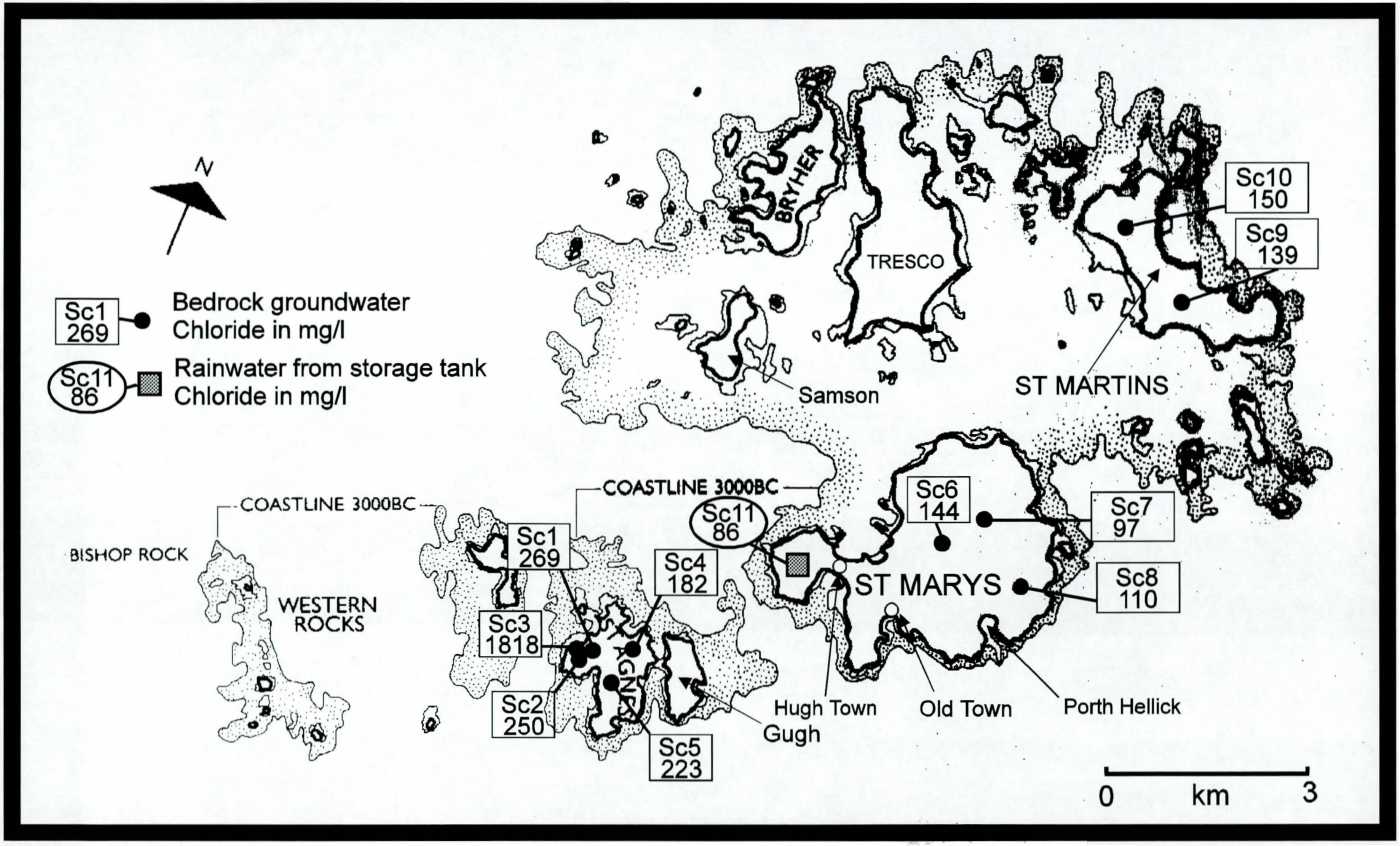
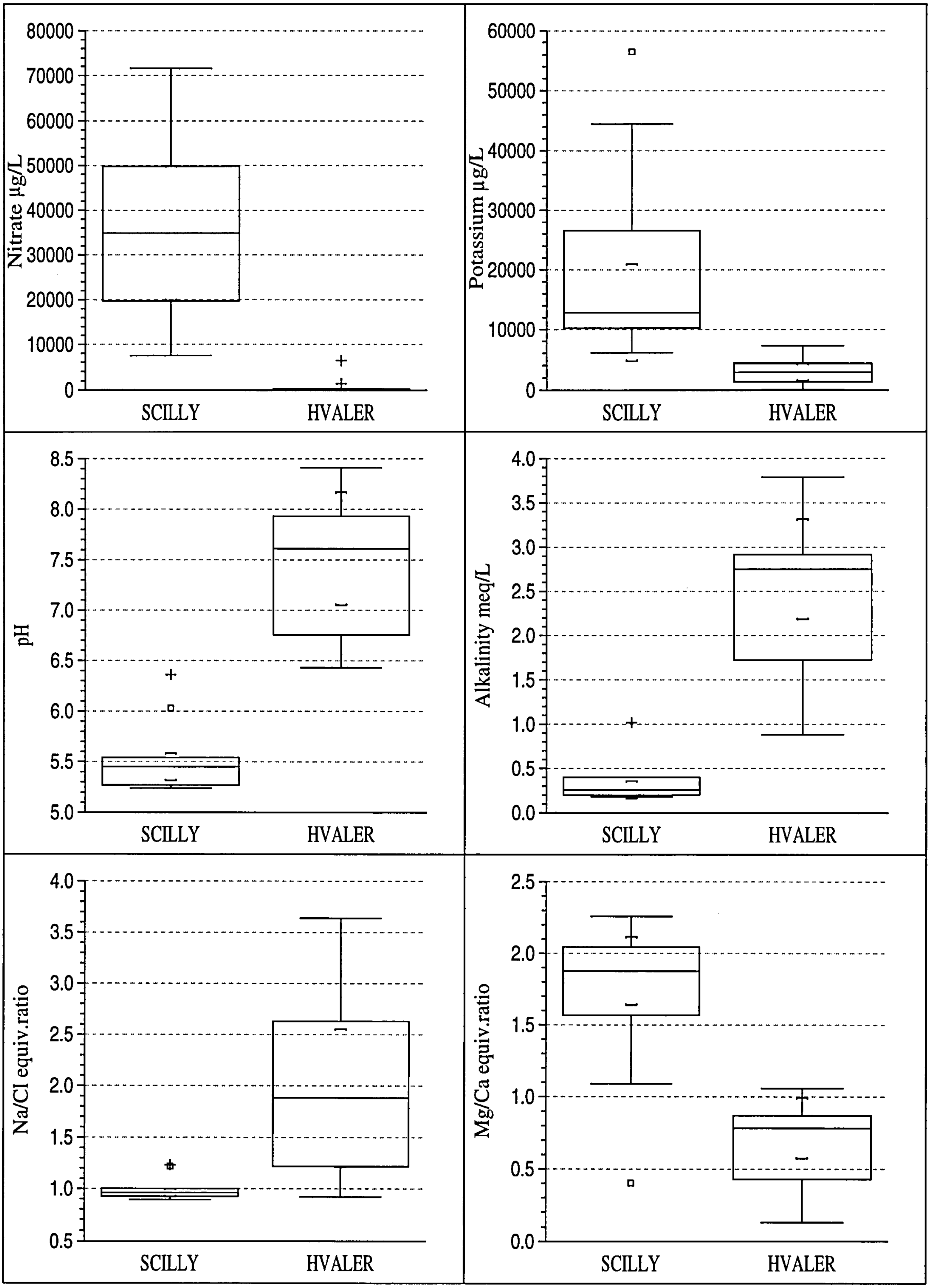


Figure 1b: Map of the Scilly island group, showing sampling localities, chloride concentrations and location of coastline 5000 a.B.P. (modified after Ratcliffe, 1992, and published with the permission of Twelveheads Press, Truro).

Figures 2a : Comparative box plots of selected parameters in granitic groundwaters from Scilly (n=10) and Hvaler (n=11). Boxes show interquartile range, with line at median value, whiskers show extraquartile range (excepting near and far outliers shown by squares and crosses respectively).



Figures 2b: Comparative box plots of selected parameters in granitic groundwaters from Scilly (n=10) and Hvaler (n=11). Boxes show interquartile range, with line at median value, whiskers show extraquartile range (excepting near and far outliers shown by squares and crosses respectively).

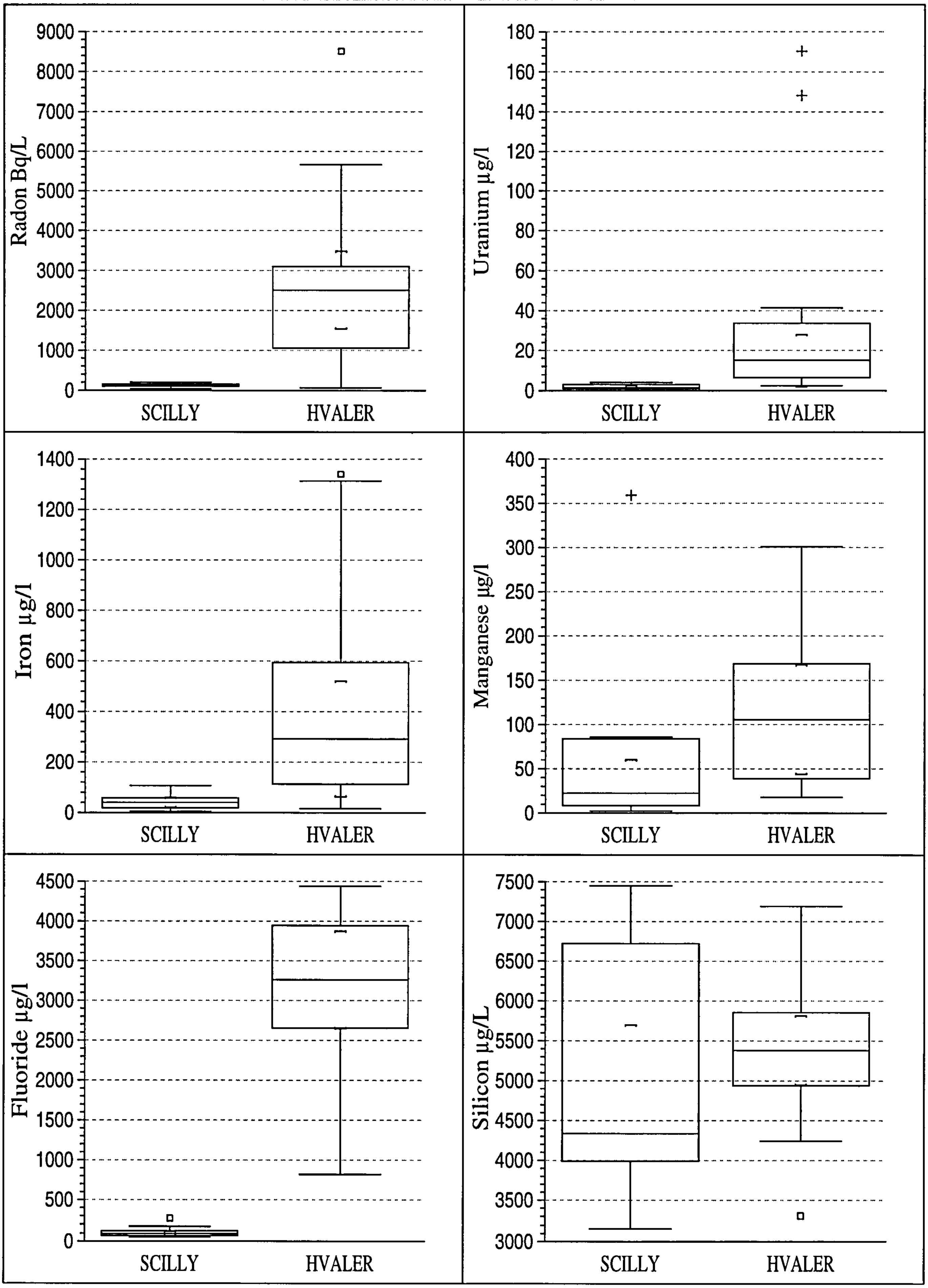


Figure 3. Logarithmic plot of median values of selected parameters at Scilly and Hvaler. All concentrations in μg/l, excepting Rn in Bq/l and EC in μS/cm. H^+ estimated from field pH and HCO_3^- estimated on the basis of alkalinity.

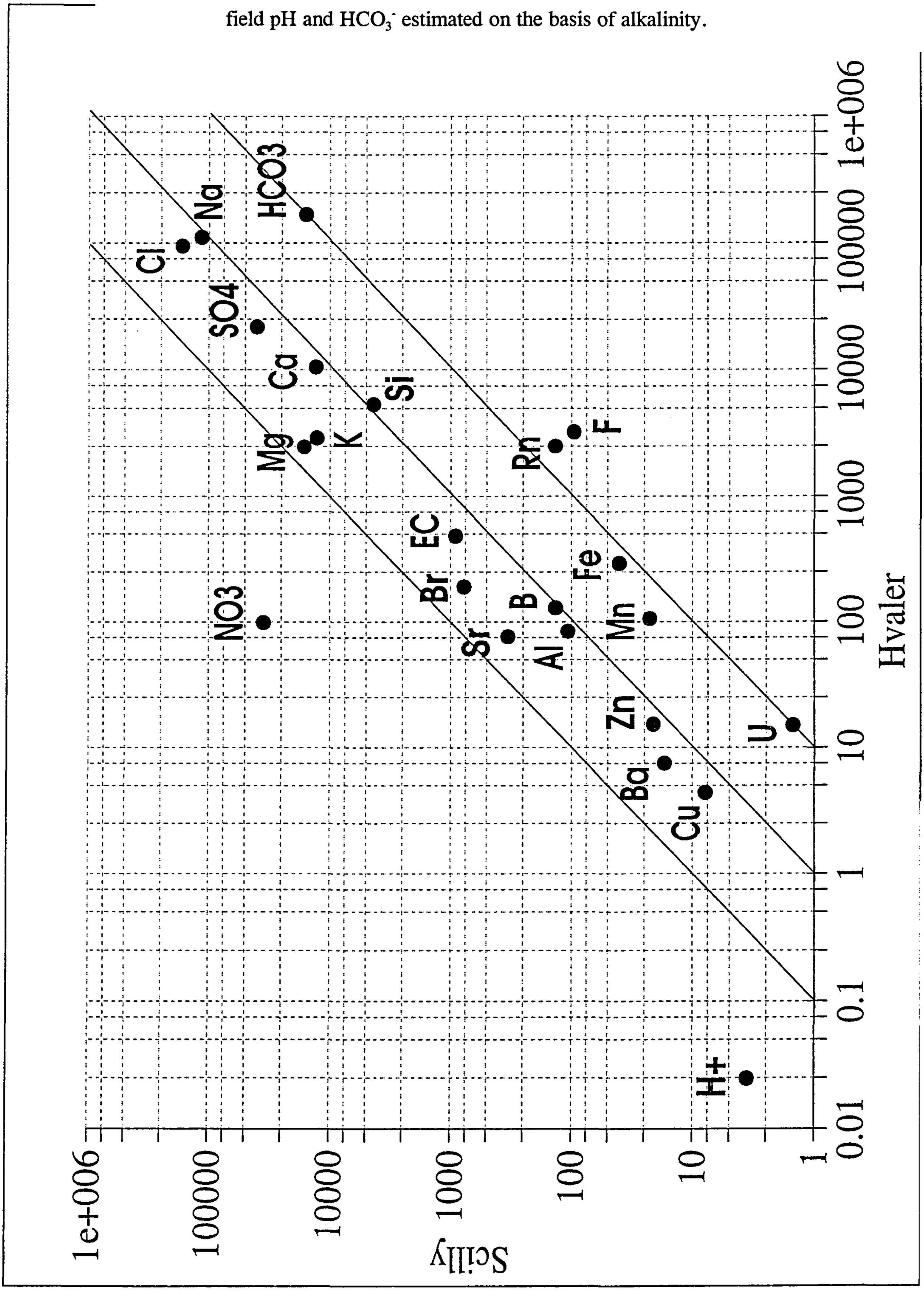


Figure 4. Plots of non-marine components of calcium, magnesium, sodium and potassium in Scilly and Hvaler groundwaters, against nitrate, all values in meq/l.

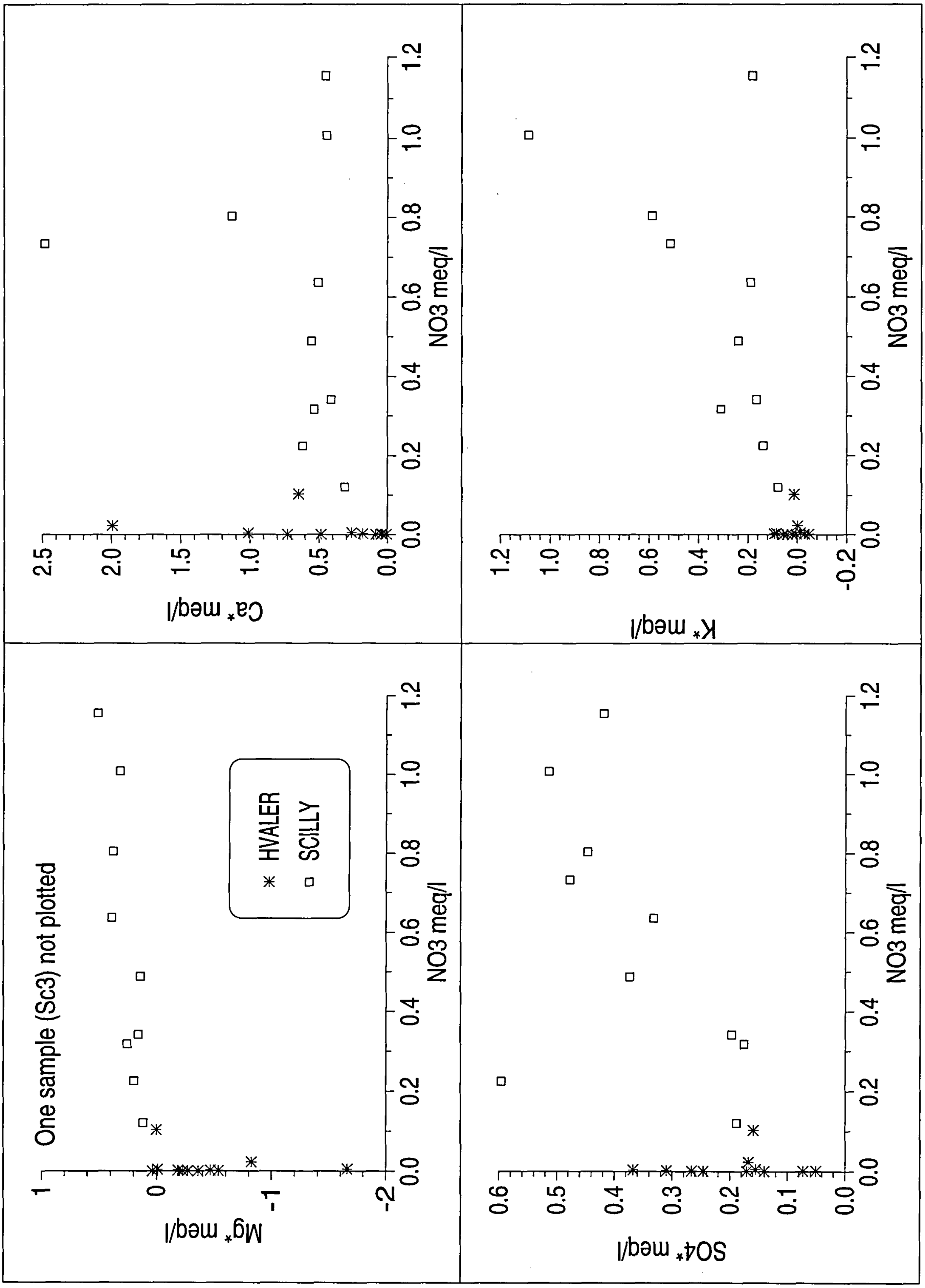


Figure 5. Selected cross plots related to alkalinity, pH, silicon, non-marine (Ca*) and total (Ca) calcium, non-marine sodium (Na*), non-marine boron (B*) barium and strontium in Scilly and Hvaler groundwaters; alkalinity, Na* and Ca* in meq/l, Si and Ca in mg/l, B*, Sr and Ba in μg/l.

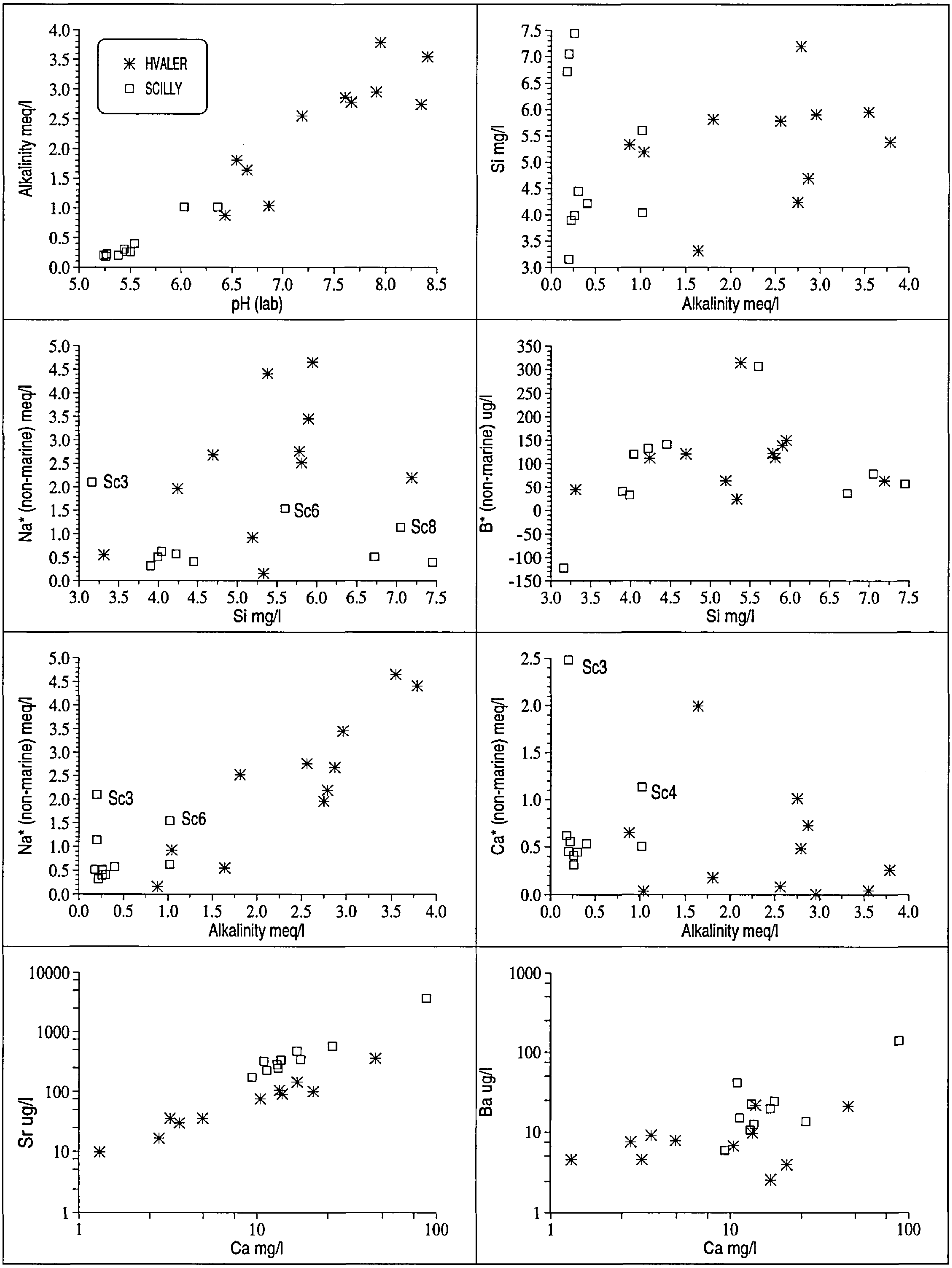


Figure 6. Cross plots of selected metals (Fe, Al, Mn, Zn, Cu and U) in µg/l against pH for Scilly and Hvaler groundwaters. Lines show best fit linear regressions. Cross plots of uranium against radon and fluoride against pH.