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Petrology, Lithology, Bedrock Structures, Glaciation and Sea Level. Important Factors for Groundwater Yield and Composition of Norwegian Bedrock Boreholes?

NGU
Norges geologiske undersøkelse
Geological Survey of Norway

Postboks 3006 - Lade
7002 TRONDHEIM
Tlf. 73 90 40 11
Telefaks 73 92 16 20

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Forfatter: Geir Morland

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A fact in itself is nothing. It is valuable only for the idea attached to it, or for the proof which it furnishes.

Claude Bernard

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CONTENTS

Appendices (separate volume)

Abstract

In Norway approximately 87% of the population receives drinking water from surface water sources. The vulnerability of many such sources to increasing regional environment pollution and the phenomena of bacteriological problems and high humus contents occurring regularly in the spring and autumn, has led Norwegian authorities to look for alternative water supply possibilities. However, there exist a number of unique problems with respect to water supply in Norway. It is a large country (323,758 km^2 , N-S extent 1,752 km) with a small population (4,391,966 people pr. 1. January 1997). Although 73% of the population live in cities and communities larger than 200 people, there are still almost 1.2 million people living in remote areas. In the 40 towns with more than 10,000 inhabitants, groundwater accounts for only 3,6% of the water supply, and all of this is derived from Quaternary glaciofluvial and fluvial sedimentary aquifers. However, groundwater use can reach some 30% in remote areas where hard rock groundwater is the most important alternative to surface water. When establishing a bedrock borehole, the drilling costs, water yield and quality are all elements of great importance for both the drilling entrepreneur and the borehole owner. It will be a major step forward in understanding the occurrence of groundwater in bedrock if it becomes possible to predict the groundwater yield and the groundwater quality in terms of statistical probabilities in different bedrock types in different areas of Norway.

More than 100,000 private drinking water boreholes are in use in Norway today and between 2,000 and 4,000 new boreholes are drilled every year. The Geological Survey of Norway (NGU) is in possession of information on more than 20,000 bedrock boreholes. To be able to handle such a large number of data from the existing Bedrock Borehole Database (BBD), a complete reorganised BBD has been established as a result of this thesis. The new database is implemented using the ORACLE relational database system. In the BBD there exists information on location, borehole depth and borehole yield for approximately 14,000 boreholes in hard rock. The use of a geographical information system (ArcView 3.0 GIS) and modern statistical techniques based on exploratory data analysis has made it possible to investigate different geological factors influencing the groundwater yield of Norwegian bedrock boreholes.

The groundwater chemistry of selected bedrock boreholes shows a clear relationship with bedrock types for several analytical parameters, although some parameters show stronger relationships with topographical or climatic factors (e.g. distance to coast).

The investigation suggests the existence of a statistically significant relationship between groundwater yield and different bedrock types (Bedrock types are defined in Figure 2.1.1). In the context of this thesis, a particular type of bedrock often consists of several different bedrock entities (Bedrock entities are defined in Table 2.3.1). The investigation also suggests a statistically significant relationship between groundwater yield from bedrock boreholes and these entities.

The exploitable porosity and permeability of hard rocks are for every practical water-resource purpose controlled by the existence of fracture systems. Norway has therefore by somewhat subjective assessment been divided into 36 different fracture system subareas. The pattern of groundwater yield from bedrock boreholes in these different tectonic sub-areas is similar to the pattern obtained for groundwater yield in different bedrock types.

It is a common opinion among Norwegian hydrogeologists that bedrock boreholes in the vicinity of, or intersecting a fracture zone or lineament have a more favourable potential groundwater yield than bedrock boreholes situated in a distance from such a lineament. Using the current BBD, it has not been possible to confirm this hypothesis as a general rule. Nevertheless, with some of the investigated lineaments, there does appear to be an increase in groundwater yield with proximity, and such lineaments may reward more detailed hydrogeological investigation.

The postglacial isostatic uplift of Fennoscandia has recently been considered as an important factor in keeping fractures open and transmissive in Norwegian hard rock aquifers. The hypothesis of an approximately linear relationship between present uplift rates and groundwater potential in Norwegian hard rock aquifers is supported on the basis of the latest data on present uplift rates.

As a result of the Fennoscandian postglacial uplift, more dry land is becoming available along the coastal part of Norway. The areas vertically underlying the maximum extent of the sea just after the ice started to melt, the postglacial Marine Limit (ML), are often covered by marine clay. It has not been possible to statistically confirm or reject a relationship between groundwater yield and location of bedrock boreholes in relation to the ML.

Kurzfassung

Rund 87% der norwegischen Bevölkerung werden mit Trinkwasser aus Oberflächengewässern versorgt. Die Empfindlichkeit dieser Resourcen gegenüber der generell stetig ansteigenden Verschmutzung der Umwelt und dem Phänomen der regelmäßig im Frühling und Herbst auftretenden erhöhten bakteriologischen Belastung und hohen Humusgehalten, veranlaßten die norwegischen Behörden, nach alternativen Wasserversorgungsmöglichkeiten zu suchen.

In Bezug auf die Wasserversorgung gibt es in Norwegen eine Zahl von einzigartigen Problemen. Norwegen ist flächenmäßig ein ausgedehntes Land (323,758 km², Nord-Süderstreckung 1,752 km) mit einer geringen Einwohnerzahl (4,369,957 Menschen, Stand vom 1. Jannuar 1996). Obwohl 73% der Bevölkerung in Städten und Gemeinden mit mehr als 200 Einwohnern leben, wohnen 1,2 Millionen Einwohner in dünn besiedelten Gebieten. In den 40 Städten mit mehr als 10,000 Einwohnern werden nur 3,6% des Trinkwasserbedarfs durch Grundwasser gedeckt, welches aus quartären glaziofluvialen und fluvialen sedimentären Aquiferen stammt. Die Nutzung von Grundwasser als Trinkwasser in dünn besiedelten Gebieten kann lokal 30% erreichen, wobei aber Wasser aus Festgesteinen die wichtigste Alternative zur Oberflächenwassernutzung ist.

Wird eine Grundwasserbohrung im Muttergestein abgeteuft, sind vor allem die Bohrungskosten, die geförderte Wassermenge und die Wasserqualität die Faktoren, welche im Hauptinteresse der Bohrfirma und des Auftraggebers stehen. Es wird ein wesentlicher Schritt vorwärts im Verständnis über das Auftreten von Grundwasser in Muttergesteinen sein, wenn es möglich ist, Vorraussagen bezüglich der erwarteten Grundwassermenge und -qualität in Form von statistischen Wahrscheinlichkeiten in unterschiedlichen Gesteinstypen in unterschiedlichen Gebieten Norwegens zu treffen.

In Norwegen sind heute mehr als 100,000 private Trinkwasserbrunnen in Betrieb und zwischen 2,000 und 4,000 Brunnen werden jährlich neu errichtet. Der Norwegische Geologische Dienst (NGU) ist im Besitz von Informationen zu mehr als 20,000 Bohrungen im Festgestein. Um diese große Anzahl von Daten zu bearbeiten, wurde eine beim NGU bestehende Bohrungsdatenbank (Bedrock Borehole Database = BBD) vollständig reorganisiert und die Daten in eine neue Datenbank überführt. Diese Überführung bildet ein Ergebnis dieser Dissertation. Die neue Datenbank wurde unter Zuhilfenahme des relationalen Datenbanksystems ORACLE entwickelt. In der BBD sind im wesentlichen Informationen zur Lage, zur Bohrungstiefe und zur erschroteten Fördermenge von 14,000 Bohrungen in Festgesteinen enthalten. Durch die Verwendung eines geographischen Informationssystems (ArcView 3.0 GIS) und moderner statistischer Techniken, basierend auf der explorativen Datenanalyse, wurde es möglich, jene geologischen Faktoren zu bestimmen, welche die Fördermengen der Brunnen in den Muttergesteinen Norwegens beeinflussen.

An ausgewählten Brunnen im Festgestein kann eindeutig gezeigt werden, daß für zahlreiche Parameter eine Abhängigkeit des Wasserchemismus vom Muttergesteinstyp gegeben ist, obwohl einige Parameter stärkere Beziehungen zu topographischen oder klimatischen Faktoren (z. B. Distanz zur Küste) aufweisen.

Ein Untersuchungsergebnis läßt darauf schließen, daß eine statistisch signifikante Beziehung zwischen warteter Fördermenge und Muttergesteinstyp (die Muttergesteinstypen sind in Abbildung 2.1.1. definiert) gegeben ist. Selbst die unterschiedlichen Gesteinsserien (die Gesteinsserien sind in der Tabelle 2.3.1. definiert), welche einen speziellen Muttergesteinstyp aufbauen, zeigen eine statistisch signifikante Beziehung zur Fördermenge.

Die effektive Porosität und die Permeabilität von Festgesteinen sind für jeden praktischen Aspekt der Wassergewinnung bedeutend und sind durch das Vorhandensein von Bruchsystemen kontrolliert. Dementsprechend wurde

Norwegen nach eher subjektiven Gesichtspunkten in 36 bruchtektonische Einheiten gegliedert. Das Muster, das sich aus der statistischen Verteilung der Wasserfördermengen aus Brunnen innerhalb dieser Einheiten ergibt, ist ähnlich dem Muster, welches aus der Verteilung der Fördermengen bezogen auf die Muttergesteinstypen resultiert.

Unter norwegischen Hydrogeolgen herrscht die Meinung vor, daß Brunnen in Muttergesteinen, welche in der Nähe von Kluftzonen liegen, oder diese durchörtern, ein höheres Potential an pumpbarer Wassermenge haben, als solche, welche abseits dieser Kluftzonen liegen. Mit der Auswertung der Daten in der neuen Bohrungsdatenbank war es nicht möglich, diese Hypothese als generelle Regel zu unterstützen. Vielmehr kann die "Nullhypothese" - keine Beziehung zwischen Fördermenge und Entfernung zu wichtigen Lineamenten - bestätigt werden. Dennoch scheint es einige Lineamente zu geben, bei welchen nahegelegene Brunnen höhere Förderraten aufweisen und bei welchen sich nähere hydrogeologische Untersuchungen lohnen würden.

Es wurde erachtet, daß die postglaziale isostatische Hebung Fennoscandias ein wesentlicher Faktor dafür ist, daß Klüfte im Bereich der Wasservorkommen in den norwegischen Festgesteinen offen gehalten werden und hydraulisch durchlässig bleiben. Die Hypothese einer ungefähr linearen Beziehung zwischen den aktuellen Hebungsraten und dem Wasserpotential in den Festgesteinen wird aufgrund der letzten Daten über die gegenwärtigen Landhebungsraten unterstützt.

Aufgrund der postglazialen isostatischen Hebung Fennoscandias werden zunehmend trockene Landflächen entlang der Küste Norwegens freigelegt. Diese Bereiche, welche das postglaziale "Marine Limit" (=ML - die Küstenlinie, welche sich unmittelbar nach Abschmelzen des Eises entwickelte) ursprünglich vertikal unterlagerten, sind meist durch marine Tone überdeckt. Es war nicht möglich eine Beziehung zwischen Wasserfördermenge und Lage der Bohrung bezüglich des ML statistisch zu bestätigen oder zu verwerfen.

Chapter 1

Introduction

1.1 Background

In 1992 the author was given responsibility for the Bedrock Borehole Database (BBD) at the Geological Survey of Norway (NGU). The database contained information on about 20,000 of the existing 100,000 boreholes in Norway and has never been used to its full potential. In 1993 Dr. Clemens Reimann, with experience in system analysis and use of geo-databases from his work at the Institute for Technical Ecosystem Analysis Joanneum Research at the Mining University Leoben, joined NGU. At this time it was agreed to carry out a thorough system analysis to decide how a really useful hydrogeological database should be structured and to assess which other readily available (from NGU or other State organisations) digital or easily digitisable data could be linked to the database existed (Morland et al. 1992). Very soon it became clear that this task involved a major research effort, covering many different aspects of earth sciences, and a PhD-project was agreed with O. Univ. Prof. Dr. Eugene F. Stumpfl of the Institute for Geosciences at the Mining University of Leoben.

System analysis showed that the existing BBD did not contain any data that could be used for research purposes other than the location of the borehole, the depth of the borehole and the yield of the borehole. Even these data were not quality-controlled. The first question thus were:

- How can these data, having been entered for 46 years by different people, be quality-controlled before trying to make use of them?
- Are there statistical methods that can actually handle data of such poor quality?
- What other data exist that could be successfully linked to the existing database?

- What kind of useful information could be extracted from such a database?
- How should the new database then be structured?

To answer these questions, a review of the different levels of information that might be interesting to include in a hydrogeological database was necessary. Thus, the first part of this thesis provides a review of the geology of Norway, the history of hydrogeology and the issue of why bedrock boreholes are so important in the Norwegian context. The review also covers the petrology and geochemistry of some rocks containing boreholes and, last but not least, data available from the central statistical office of Norway. A new database structure was developed from scratch, including a new field form for the future original registration of data at the time a new borehole is drilled. The necessary links to a geographical database system were analysed and then established, and statistical software able to handle the special kind of data collected was tested and implemented.

In the second part of this work, some of the most important uses of the new database are presented, partly based on the linkage of the whole data set to other digital information (e.g. bedrock geology, distance to regional lineaments, land uplift rates, the postglacial Marine Limit) and partly based on smaller subsets of boreholes where additional information was available (e.g. geochemistry). These examples show how powerful a functioning database system will be in the future in terms of predicting:

- The yield in different lithologies.
- The optimum depth of a Norwegian bedrock borehole.
- Lithologies where problems with regards to groundwater quality might be expected
- The types of additional data which are needed to further improve the utility of a BBD.

In addition to its practical appliances, the BBD can be used in hydrogeological research into topics such as, for example:

- Tectonic and petrological factors influencing the yield of bedrock boreholes.
- Factors influencing the chemical composition of bedrock groundwater.

As an important result of this thesis, NGU's BBD is now ready for future use. It is linked with the necessary geographical information system and statistical tools to handle the data and to extract as much meaningful information as possible. Over time it will now be filled with new (hopefully quality-controlled) additional data. The prospects in terms of practical and scientific gains from the use of the database are huge.

1.2 The Problem and its Context

The hydrogeological conditions in Norway are very different from most European countries. The natural opportunities for exploitation of groundwater for water supply are generally lower in Norway. Most of the people living in urban areas consume a water supply based on surface water. It is believed that groundwater from bedrock boreholes supplies a significant part of the population living in more rural areas, although data for making a precise assessment of the extent of its use are lacking (Ellingsen 1992, Morland 1996a). Groundwater flow in Norwegian bedrock is solely dependent on open, hydrologically communicating fractures and joints.

Streams, rivers and dug wells in tills have traditionally yielded the water supply of minor communities, single households and huts in many parts of Norway. These types of drinking water sources often have a high bacteriological content and are nowadays being replaced by municipal waterworks based on surface water, properly constructed wells in Quaternary deposits or drilled wells in bedrock. Between 3,000 and 4,000 bedrock boreholes are drilled every year and the total annual construction cost may exceed 200 million NOK (353 million ATS) (Klemetsrud 1997). Today it is thought that there exist between 80,000 and 100,000 bedrock boreholes in daily use supplying between 150,000 and 300,000 people (3.4% - 6.8% of the population) (NGU 1992). The majority of these bedrock boreholes are located in rural areas where no municipal waterworks can offer any alternative water supply (Morland 1996a).

Many people therefore have no alternative than to use the groundwater from their bedrock borehole. The chemical composition of such groundwater has traditionally been assumed to be very good. In some areas it was, however, recognised that the groundwater may have an excessive content of fluoride. For example, in the Hurum municipality of Buskerud county, the municipality dentist Rognerud (1973) analysed groundwater from 15 bedrock boreholes in the Drammen granite in 1966. His analyses revealed a fluoride content of up to 2 mg/L (relative to the presently recommended maximum of 1.5 mg/L, Sosial- og helsedepartementet [Ministry of Health and Social Affairs] 1995). It was not, however, until recent years that a spotlight was placed on groundwater quality in bedrock. There has been an increasing interest in particular in the content of elements with possible significance to human health (Banks et al. 1993a, Morland et al. 1995, Sæther et al. 1995, Gropen 1996, Reimann et al. 1996, Bjorvatn et al. 1997). The Geological Survey of Norway (NGU), in co-operation with the Norwegian Radiation Protection Authority (NRPA), are today in the process of analysing more than 2,000 samples from bedrock boreholes from the whole of Norway to obtain a better overview of the distribution of a wide range of elements, particularly those of possible significance to human health. The author initiated the participation of NGU in this project during the spring of 1996, but the results will not be available until the end of 1997. The results of this survey will be of major importance for the prediction of water quality in different lithologies in Norway.

Until today there has not been any national scientific investigation on the subject of borehole yields in different lithologies in Norway. There exist, however, three

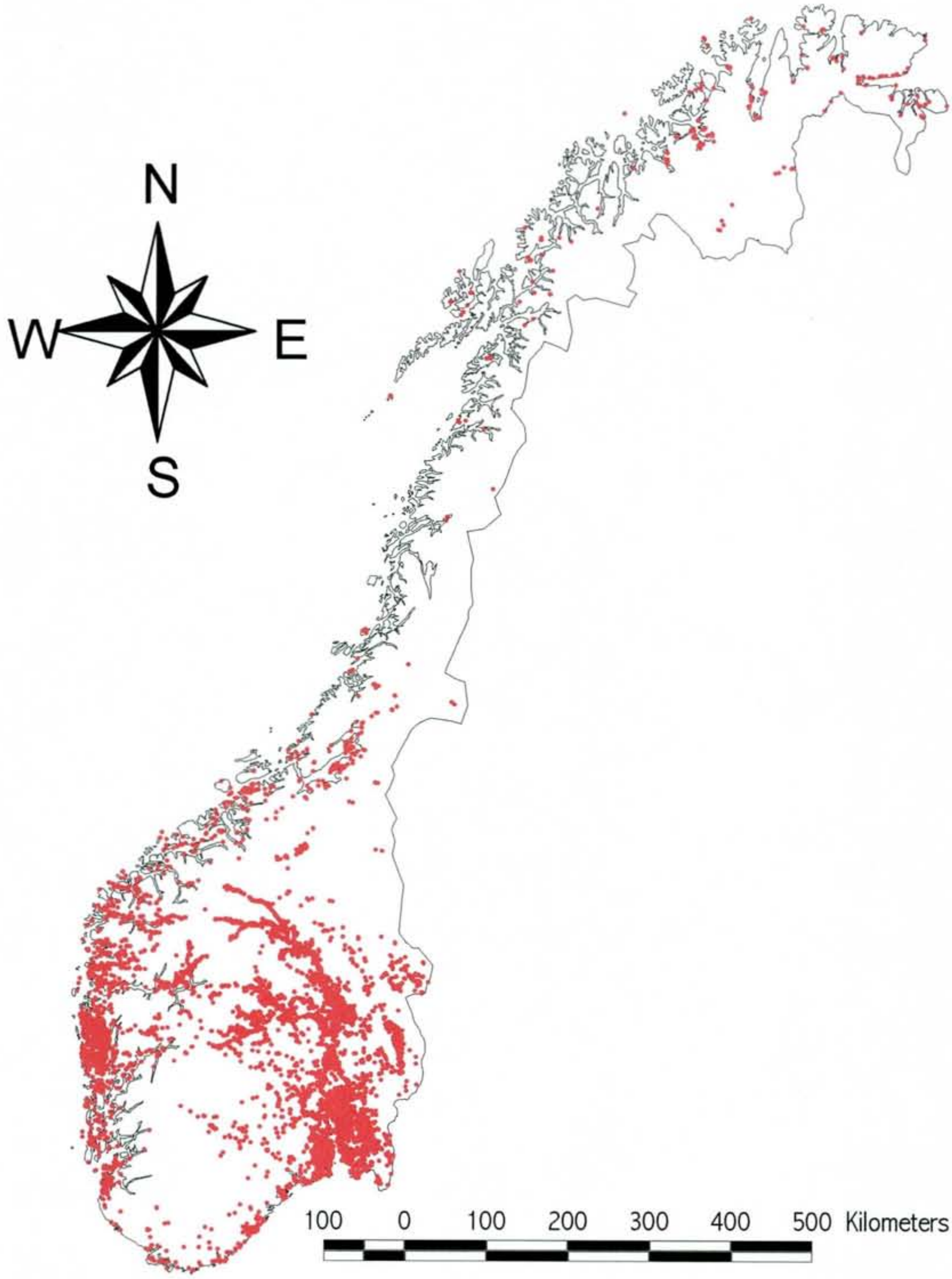


Figure 1.2.1 *Location and distribution of the 15,054 bedrock boreholes that have coordinates in the Bedrock Borehole Database of Norway (BBD). The BBD contains some degree of information from almost 20,000 bedrock boreholes in Norway.*

hydrogeological maps in the scale of 1:1,500,000 covering most of Norway (Persson et al. 1979, 1985a,b). The objective of these maps was to give a representation of different lihologies and occurrence of groundwater. The bedrock of Norway is generally characterised by these maps as consisting of areas with only local groundwater or areas without groundwater resources worth mentioning. Only parts of the Permian Oslo Rift and some limestone areas in the county of Nordland have been given a light green colour in the map, representing local or discontinuous aquifers (Persson et al. 1979 and 1985a). Except for the classification mentioned above, these maps do not indicate the variability of groundwater yield within the different rocks in Norway. Many scientists have investigated lithologies in different regional or local areas in Norway with respect to the groundwater potential (e.g. Skjeseth 1952 and 1956, Holmsen 1956, Hagemann 1959 and 1961, Bryn 1961, Englund 1966, Ellingsen 1978, Persson et al. 1979 and 1985a,b, Rohr-Torp 1987, Banks et al. 1992b and 1993b, Henriksen & Kyrkjeeide 1993, Henriksen 1995), but this information has not been systematically compiled.

There have been relatively few investigations of tectonic or other geological controls on the variation of borehole yield from different lithologies and regions in Norway (Banks et al. 1992a, Banks et al. 1993a, Braathen 1996). The only regional study in this field in Norway has been carried out by Rohr-Torp (1994) concerning the influence of postglacial isostatic uplift on groundwater potential.

In other countries, especially in the United States, several authors have studied the relationship between groundwater yield from a large number of boreholes compared to, for example, lithology, topography, groundwater chemistry and proximity to fracture zones (e.g. Sager 1995 [Canada], Sami 1996 [South Africa], Wikberg et al. 1991 [Sweden], Ali 1994 [United States], Wallace 1996 [United States], McKelvey 1994 [United States], Helvey & Rauch 1993 [United States], Huntley et al. 1991 [United States], Zewe & Rauch 1991 [United States], Carter 1991 [United States], Fiedler 1991 [United States], Schmitt 1989 [United States], Daniel 1989 [United States], Kastrinos & Wilkinson 1995 [United States]). They have found that systematic differences in borehole yield can be related to different lithologies (e.g. Wikberg 1991), and that there is a notable increase in borehole yield for boreholes in close proximity to fracture zones (e.g. Sager 1995, McKelvey 1994 and Fiedler 1991). They also indicate that the topographic setting may be important (Wallace 1996).

This thesis aims to elucidate the above mentioned themes by the applicaton of simple statistical analysis to the information contained in the Bedrock Borehole Database of Norway. This database contains some degree of information on almost 20,000 bedrock boreholes distributed throughout the country (Figure 1.2.1). In particular, the author will focus on information on location, drilled depth and yield. The database does not as yet contain any information on groundwater quality, but data collected from the Oslo and Bergen areas in a recently completed project will be used to elucidate the importance of knowledge of groundwater chemistry in bedrock boreholes used for drinking water supply. These chemical analyses will also be used to investigate the relationship of groundwater chemistry and lithology.

The aims of this thesis are to

- develop a quality-controlled procedure for extracting some, previously identified, important categories of data from the Bedrock Borehole Database of Norway.
- document the probable distribution of the population of Norway according to its source of water supply.

Additionally, the thesis aims to test the following hypotheses concerning boreholes in bedrock aquifers in Norway

- that lithology (petrology and geochemistry) is a dominating factor for the inorganic chemical composition of groundwaters in the Oslo and Bergen areas

- that there exist statistically significant, lithology-dependent differences in distributions of borehole yield from different lithologies
- that borehole yield is enhanced by the presence of favourable tectonic structures
- that there is a statistically significant correlation between borehole yield and postglacial isostatic uplift
- that there is a statistically significant difference in yield of boreholes above and below the Marine Limit.

1.3 Methods

To be able to accomplish a thorough investigation of the subjects mentioned in Chapter 1.1, use has been made of the geographical information system (GIS) program ArcView 3.0 GIS for the capture, storage, retrieval and analysis of different types of spatial data. (see Chapter 3.5 and Table 3.5.1). To handle the geological information in a statistically robust manner, the exploratory data analysis program DAS (by EDAS, Institute for Technical Statistics, University of Vienna, see Dutter et al. 1992 and also Chapter 3.5) has been used.

All figures that do not have a reference in the figure text were prepared using the ArcView 3.0 GIS.

Appendix E contains an overview of all rocktypes and entities used in this thesis and should be of considerable assistance to the reader. Appendix A contains maps showing the location of all these rocktypes and entities.

1.4 Definitions

Definitions of terms used in this thesis are given below.

Bedrock	"Bedrock" means "hard rock" or "solid rock" of (at least in Norway) Precambrian or Palaeozoic age. The term is used in

	contrast to unconsolidated sands, gravels and clays etc. which are termed "superficial deposits" or "Quaternary depostis". There are no significant outcrops of Mesozoic or Cenozoic rocks on mainland Norway.
Bedrock Entity	The term "bedrock entity" describes a polygon derived from the digitised bedrock map of Norway (Sigmond 1992). Each polygon is assigned a rocktype and represented by a numerical code.
Borehole	"Borehole" means a constructed hole in bedrock and/or superficial deposits intended for use as a source for water supply.
Normalised yield	Volume of water derived from a borehole per time unit per metre drilled depth (i.e. L/h per drilled metre, L/s per drilled metre etc.)
Regional lineament	Lineaments as defined by Gabrielsen at al. (1979).
Rocktype	The term "rocktype" refers to a lithological group according to the legend of the "Bedrock map of Norway and adjacent ocean areas" (Sigmond 1992). Each rocktype may consist of several polygons corresponding to different bedrock entities. The rocktype is identified by a numerical code taken from the legend of Sigmond's (1992) bedrock map.
Significant	In this thesis, the concept of statistical significance has been assessed by the use of boxplots based on techniques of exploratory data analysis (EDA). Significant difference is accepted when the median value of a parameter displayed in a box-plot differs (at a 95% level) from the medians of the same parameter for another group of boreholes (i.e. another boxplot). The notches (or horizontal aquare parentheses) in all box-plot diagrams in this thesis are a visual indication of the significance interval for each box-plot. If the notches of two box-plots do not

	overlap, this indicates significantly differing median values at a 95% confidence limit.
Yield	Volume of water derived from a borehole per time unit (i.e. L/h, L/s etc.), usually assessed on the basis of a short-term pumping test. This parameter thus reflects the transmissivity of the main fractures feeding the borehole, but does not necessarily reflect the wider transmissivity/storage properties of the aquifer, nor the sustainable long-term yield.

Chapter 2

Geology of Norway

2.1 Bedrock Geology

Norwegian bedrock geology can be divided into four main units based on the age of the rocks and their tectonic significance:

- Precambrian rocks, mostly gneisses, granites and amphibolites (older than c. 600 mill. years)
- Sedimentary, volcanic and plutonic rocks of the Caledonian mountain chain (orogenic belt) (mostly 600 - 400 mill. years)
- Devonian sedimentary rocks of western and middle Norway (400 - 350 mill. years)
- The Upper Carboniferous-Permian igneous and subordinate sedimentary rocks of the Oslo Region (280 - 230 mill. years).

In addition to these main units, there are extremely small areas consisting of Mesozoic deposits on the Norwegian mainland. Reported locations are:

- The island of Andøya (see Figure 4.2.4)
- At Bjorøy, near Bergen (Fossen et al. 1995)

These deposits are equivalent of the sediments that comprise Norway's continental shelf and parts of Svalbard.

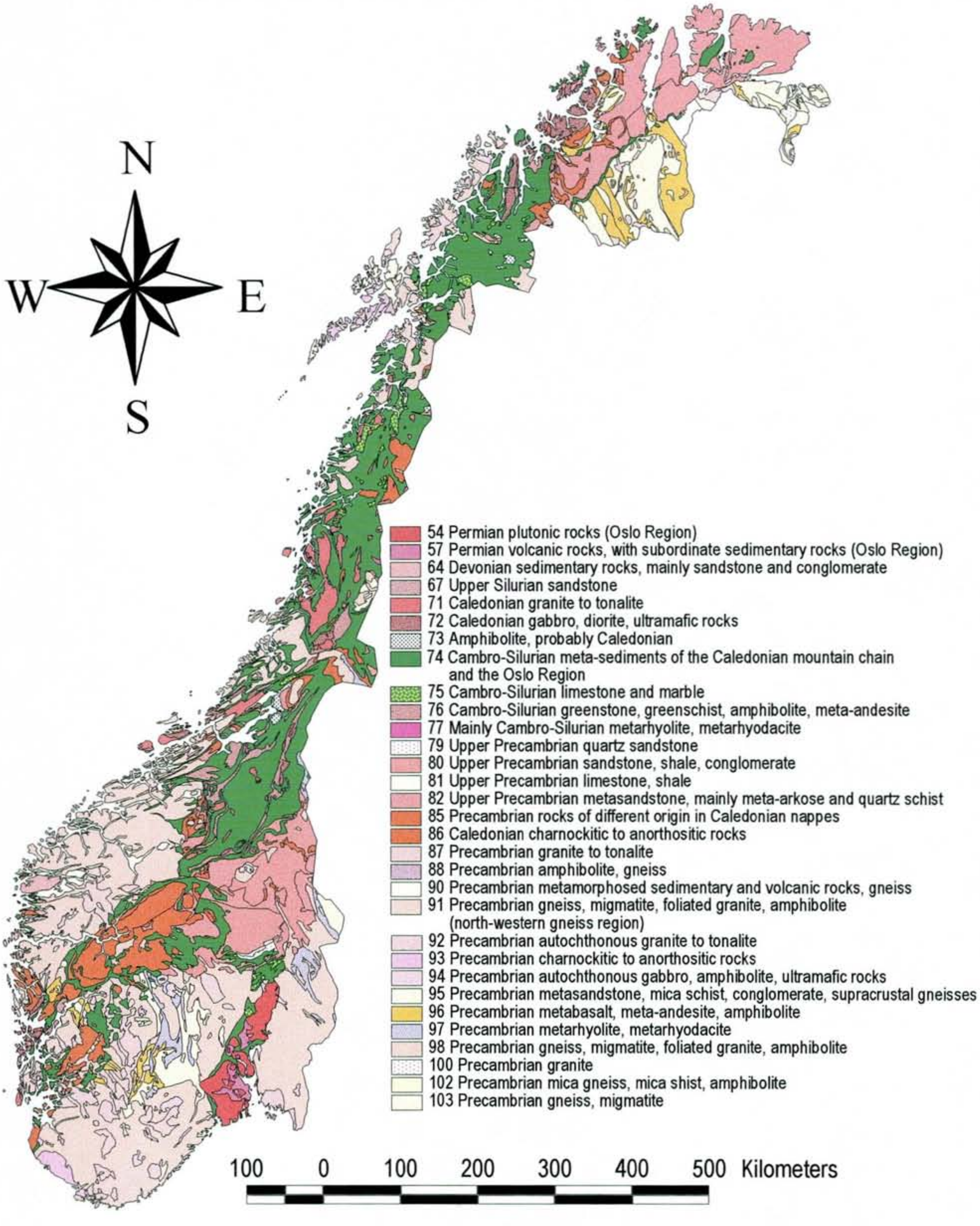


Figure 2.1.1 *Bedrock map of Norway. The map is derived from the digitised bedrock map of Norway and adjacent ocean areas (Sigmond 1992).*

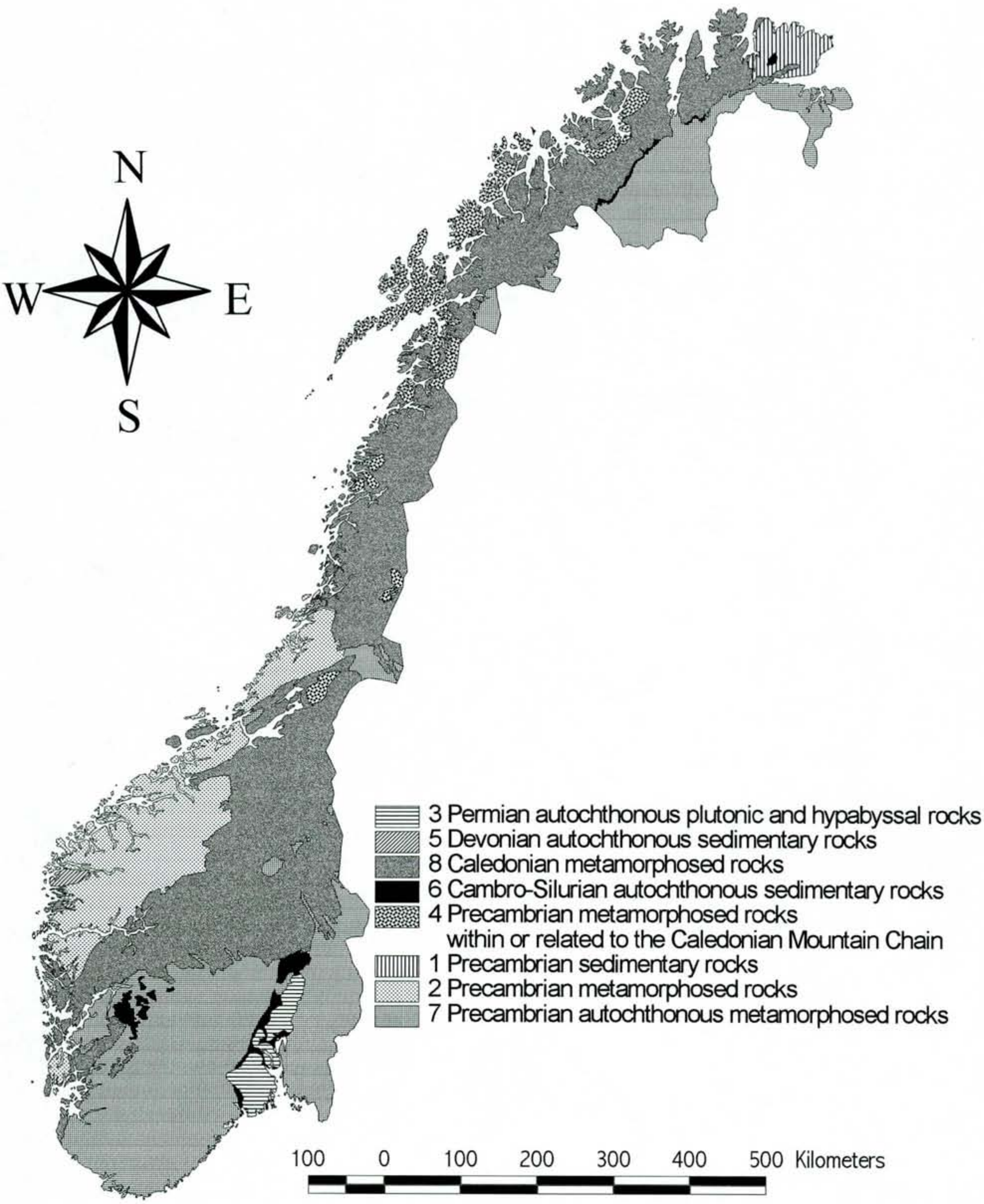


Figure 2.1.2 *Simplified geological map showing the location of autochthonous and allochthonous rocks. The map is derived from the digitised bedrock map of Norway and adjacent ocean areas (Sigmond 1992).*

Table 2.1.1. Areal distribution of different geological units on the Norwegian mainland. The distribution is derived from the digitised bedrock map of Norway and adjacent ocean areas (Sigmond 1992).

Geological units	**Percentage of the total area**
Precambrian rocks	68.5 %
Cambro-Silurian metasediments/igneous rocks	29.2 %
Devonian sediments	0.4 %
Permian igneous and subordinate sedimentary rocks	1.9 %
Total area	100.0 %

Precambrian rocks

Of the Archaean of Fennoscandia, the granite-greenstone province in Karelia (Finland/Russia) is the only part that returns ages in excess of 3,000 million years (Gorbatschev & Bogdanova 1993). The continental crust of the Baltic Shield was formed between 3,500 and 1,500 million years ago during several periods of orogenic activity (Gaál & Gorbatschev 1987). Rifting and break-up between 2,500 and 2,000 million B.P. strongly affected and partly dispersed the Archean Domain. In the north, the resultant basins were closed by collisional orogeny between 1,950 and 1,820 million years ago. Almost simultaneously, the Sveco-fennian orogeny created the continental crust in the central Baltic Shield (Gorbatschev & Bogdanova 1993). The final stage of major crust formation in the Baltic shield occurred in western Scandinavia between 1,750 and 1,550 million years ago (Gorbatschev & Bogdanova 1993). After its formation, the continental crust of Fennoscandia underwent a major reworking during the Sveconorwegian-Grenvillian and Caledonian orogenies (1,200 - 900 million B.P. and 500 - 400 million B.P., respectively).

In total, Precambrian rocks outcrops (or subcrops below Quaternary cover) over 68% of the area of the mainland of Norway (Table 2.1.1). Allegedly autochthonous (in relation to Caledonian events) Precambrian rocks occupy almost 36% of the mainland. The main occurrences of are in the north-western part, the southern part and the south-eastern part of Southern Norway. Precambrian bedrock also occur in the county of Finnmark, in the Lofoten - Vesterålen area, and are found in a number of smaller areas. The latter occur as windows in tectonic culminations/domes the Caledonian mountain chain of northern Norway (Figure 2.1.1 and 2.1.2) (Strand and Kulling 1972). The Precambrian rocks consists mainly of gneisses, granitic rocks and amphibolites. In addition slightly metamorphosed metasediments and -volcanites occur.

The oldest Precambrian rocks are located in the county of Finnmark and in the Lofoten - Vesterålen area. In the Sør-Varanger area, south of the town of Kirkenes, the "Bjørnevatn"-group consists of lightly metamorphosed sediments and volcanites dated to 2,600 million B.P. (type 7 furthest to the north-east in Figure 2.1.2) (e.g. Dobrzhinetskaya et al. 1995, Siedlecka et al. 1985). Among the rocks in this group are conglomerates, quartzites and mica schists together with iron ores, the latter including the resource forming the basis of the largest iron mine in Norway. The "Bjørnevatn"-group rests on an even older basement (2,800 mill. B.P.) of gneissic granite and migmatite which are recognisable as clasts in the conglomerate of the "Bjørnevatn"-group. A series of conglomerates and greenstones of the Pasvik-Pechenga Greenstone Belt (e.g. Melezhik et al. 1995) directly overlie the "Bjørnevatn"-group. These rocks are derived from sedimentary and volcanic processes related to rifting, followed by a period of folding and metamorphism at c. 1,800 million B.P.

The Precambrian rocks of Southern Norway has been dated to a maximum age of 1,700 million B.P. (Andresen 1994). In the north-western gneiss region (NWGR) of Southern Norway (type 2 in Figure 2.1.2) various ortho-gneisses contain occurrences of granulite, eclogite and garnet periodotite, lithologies indicating higher pressures of formation than any other outcropping Norwegian rock type (Griffin et al. 1985). In addition to the gneisses there are occurrences of marble-, olivine- and titanium-bearing minerals, all of which are currently, or have been, exploited (Oftedahl 1980). Two crust-forming events dominate the Precambrian history of the NWGR. They took place at about 1,800 - 1,600 and 1,550 - 1,400 million B. P (Koenemann 1993).

The large Precambrian bedrock area in Southern Norway is divided by the Oslo Rift into a larger western and a smaller eastern part (type 7 in Figure 2.1.2). In addition to gneiss and granite, this region also contains quartz-feldspar pegmatites and gabbronorites containing occurrences of nickel ores. Associated with the Egersund province are occurrences of important ilmenite (i.e. titanium) ores. Near the town of Kongsberg, silver-bearing dykes once gave rise to a prosperous mining industry. Knaben mine in the Kvinesdal area exploited occurrences of molybdenite in the gneissic granite. The Telemark area contains metavolcanics and quartzites of age 1,500 million years. The granites of the large Precambrian region of Southern Norway are between 900 and 1,100 million years of age. A lightly metamorphosed red sandstone (the Trysil Sandstone) in the north-eastern part of this area occurs together with volcanic rocks (the Trysil Porphyry). The Trysil porphyries are dated at around 1,640 million years of age (Oftedahl 1980).

Caledonian rocks

In the Caledonian mountain chain there occur greenstones, often with ophiolitic texture, various shelf sediments and intrusive rocks of Upper Precambrian to Upper Silurian age together with allochtonous Precambrian thrust sheets, all thrust in an easterly to south-easterly direction (type 8 in Figure 2.1.2). The Caledonian belt stretches from Jæren and the Stavanger area in the south-west to the Varanger Peninsula in the county of Finnmark. Deformation and metamorphism of the rocks generally increases towards the west. In contrast, almost non-metamorphosed feldspar-rich sandstone (sparagmite), dolomites and shales occur at the edges of the

Caledonian belt in the east and south-east. Lithified diamictites (tillites) formed during an Upper Precambrian ice-age occur within these rocks (Oftedahl 1980).

A sub-Cambrian peneplain was established and a sedimentary sequence of mud, sand and carbonates were then deposited on this surface. These are preserved within the Oslo Graben, where fossil-bearing slate, sandstone and different types of limestone occur. In a period from Upper Silurian to possibly Middle Devonian, the folded Cambro-Silurian sequence in South-eastern Norway was eroded. A new peneplain, which was established in Upper Carboniferous and early Permian time, was then covered with Permian basalts, rhomb porphyry lavas and subordinate sedimentary rocks in the Oslo Region (for more information, see chapter 4.3).

In the more central parts of the Caledonian belt, similar sediments are metamorphosed into phyllites, mica schists, quartzites and marbles (Oftedahl 1980). Sediments deposited in deep water also occur together with metavolcanics in these areas. It is believed that the greenstones and greenschists in the Karmøy/Hardanger-fjord area, Bergen area, Sunnfjord area and in the Trøndelag area have originated from deep sea eruptions (Andresen 1994). In Northern Norway there are thick layers of marble and mica schist. Datable fossils are sparse, but occur in the county of Finnmark, near the Sulitjelma mine in the county of Nordland, in the Trøndelag area, along the western coast of Norway and in the Gausdal-Valdres areas in the middle of Southern Norway. During the Caledonian orogeny, parts of the continental basement were thrust over the younger sediments by up to several hundreds of kilometres. The remains of these thrust sheets form high and steep mountains, such as those of the Jotunheimen area (Oftedahl 1980).

Devonian rocks

During late stages of the Caledonian Orogeny, central parts of the orogen underwent tectonic extension, either from collapse of the mountain chain or from plate readjustments. This extension allowed the accumulation of Devonian sediments in (often fault-controlled) subsiding basins, which mark the end of the

Table 2.1.2 Geological chronology of Norway. After Oftedal, 1980.

M.y.	Period		Areas, rocks, etc.	
0		Holocene	A series of glaciations	
2.5		Pleistocene		
5		Pliocene	Continental:	No rocks
22.5		Miocene		
	Cenozoic	Oligocene	Norwegian shelf:	Thick sedimentary sequences
		Eocene		in the North Sea and the Mid-
		Paleocene		Norwegian shelf
65		Cretaceous	Continental:	Local areas of deposition
140	Mesozoic	Jurassic		
195		Triassic	Norwegian shelf:	Thick sequences in all shelf areas
230				
280		Permian	Oslo igneous rocks	Shelf rocks
345		Carboniferous	(Some sediments)	Little known
395	Paleozoic	Devonian	Upper Caledonian folding. Small molasse basins of	
			sandstone and conglomerate	
435		Silurian	Main phase of the Caledonian orogeny	
			Marine sediments and volcanics over most of Norway	
500		Ordovician	Platform in the Oslo Region, thick sequenses in the	
			Caledonian geosyncline	
		Cambrian	Arenig phase in latest Cambrian/earliest Ordovician	
			time. Gabbros, greenstones, granites etc.	
570		Vendian	Younger	Arkoses in Southern Norway
			and	Sandstones in Northern Norway
650		Upper		
		Riphean	Older	
900			Post-tectonic granite phase	
1150	Proterozoic	Middle	Metamorphism, folding and granite intrusion in	
		Riphean	Southern Norway (Sveconorwegian)	
1350			Quartzites and metarhyolites	
			1500: Kongsbergian orogeny, strong metamorphism	
			1600: Supracrustals in Southern Norway, no	
			basement known	
		Lower	1700: Formation and metamorphism of supracrustal	
		Riphean	gneisses in coastal area Bergen-Møre-Namsos	
			1800: Karelian orogeny Finnmark-Lofoten	
2500			2500: Bjørnevatn group with iron ore in Sydvaranger.	
	Archean		Strong metamorphism Sydvaranger-Lofoten	
			2800: Precambrian basement, Finnmark-Lofoten	

Caledonian orogeny (type 5 in Figure 2.1.2). These sediments consists of thick layers of sedimentary breccia, conglomerates, sandstone and siltstone, and occur mainly in the Sognefjord and Nordfjord area (see Figure 4.2.4). Minor occurrences are located between the bay of Hustadvika and the outlet of Trondheimfjord and at Røragen, east of the town of Røros. The Devonian strata were mainly deposited in fresh water from braided rivers. Fossil plants and fish have been found in these sediments (Steel 1995).

Permian rocks

The Oslo Rift divides the large Precambrian regions of Southern Norway. It is essentially a half-graben structure. As discussed above, early Palaeozoic strata are preserved in the graben. Additionally, one can find fossil-bearing Permian strata; fossils of fish and non-marine flora and fauna occur (Oftedahl 1980).

Overlying these Permian sediments are up to 1,500 m of volcanic rocks, in particular basalts and rhomb porphyry (Oftedahl 1952). The Permian period also saw the intrusion of alkaline plutonic rocks such as Oslo-essexite, larvikite, nordmarkite, the Drammen granite, lardalite and nepheline syenite pegmatite. These intrusions occupy some 60% of the Oslo Region (Sigmond 1992).

During the Mesosoic, the bedrock of Norway was eroded to a peneplain, with only minor hills and valleys (Riis 1996). The land was uplifted again in the Tertiary period. A geochronological representation of the bedrock geology of Norway is shown in Table 2.1.2.

2.2 Quaternary Geology

A characteristic feature of the Quaternary geology of Norway is the widespread occurrence of relatively thin superficial deposits covering the bedrock. The largest quantities of these deposits occurs in the mountainous regions of Southern Norway, on the Finnmarksvidda area in the county of Finnmark in Northern Norway and as thick sedimentary sequences in valleys in lower-lying regions. There have been several periods of glaciation during the Quaternary period covering the entire Norwegian land mass and the adjacent areas. The superficial deposits observed today are mainly clays, sand, gravel and tills deposited during and after the last glaciation, the Weichselian glaciation. This glaciation started about 115,000 years B.P., although climatic changes have caused large variations in the thickness and extent of this ice-sheet. During the period of 17,000 to 21,000 B.P. the ice reached its last maximum extent. Some 12,000 to 11,000 years ago, the coastal areas of Norway were deglaciated and by 8,500 B.P. most of the ice-sheet was gone.

The weight of the ice-sheet caused a depression of the land mass of Fennoscandia. As the ice melted, this depression was gradually isostatically compensated, resulting in a rise of the land surface relative to the sea level. As a result, marine deposits laid down immediately after deglaciation, when the sea level also was higher than today, can now be found at significant elevations above the present sea level. The upper limit of these deposits is called the Marine Limit (ML) (see Figure 9.1.1). During the deglaciation enormous amounts of eroded bedrock material and superficial deposits were transported by melt-water rivers along and under the ice towards the sea. Under the ML there exist therefore wide plains of clay, interfingering in some areas with fluvial fans of sand and gravel. These deposits underlie the majority of the agricultural landscape of Norway today.

Till forms a relatively thin or discontinuous cover over the bedrock across large areas of Norway. During the deglaciation, re-advances of the ice and shorter periods with little or no retreat occurred. This caused marginal moraines to be built up along the ice margin. The Younger Dryas moraine is the most continuous and can be traced along the entire coast of Norway. The moraine is in many cases related to the occurrence of rock thresholds or islands in the fjords. The marginal moraine from Younger Dryas time is, in Southern Norway called the "Ra" moraine.

In the more central parts of the country, large lakes were dammed up by the remains of the ice-sheet. Fine sand and silt deposits from these large lakes are a particularly characteristic Quaternary feature in the major East-Norwegian valleys.

Widespread deposits of clay occurs in areas formerly inundated by the sea. The areas with such glaciomarine sediments have typically been heavily eroded due to postglacial isostatic uplift and often have a ravine character. Infiltrating fresh water tends to wash out the saline pore waters of the marine clay, altering its geotechnical properties and making the clay unstable. This unstable clay (quick clay) has caused large landslides in Norway. The quick clay slides with the largest known impact on people and daily life were those in Verdalen in the county of Nord-Trøndelag in 1893 and in Gauldalen in the county of Sør-Trøndelag in 1345. The slide in Verdalen contained 55 million m^3 of clay and killed 112 people (Thoresen 1990).

In the valleys of the coastal parts of Norway large screes have formed at the base of steep mountainsides. Gravel, stones and boulders form alluvial and avalanche fans. Transport of material to such fans is usually connected with periods of heavy rainfall or melting of snow.

Peat and bogs represent some of the youngest superficial deposits. They are most common in areas with high precipitation along the coast, normally underlain by bedrock. The organic deposits are normally quite small. Larger bogs may be found in depressions and basins in mountain areas, where they are underlain by till. Fluvial deposits cover most of the valley bottoms in Norway and are generally associated with present-day rivers and streams.

2.3 *Bedrock Types and Entities*

To be able to use the Bedrock Borehole Database (BBD) in connection with the digital bedrock map of Norway (Sigmond 1992), it was necessary to assign to each borehole a code indicative of the lithology of the bedrock at the borehole site. One way of doing this is to use the predefined polygons in the digitised bedrock map.

Table 2.3.1 *Bedrock entities identified from the digitised bedrock map of Norway and adjacent ocean areas (Sigmond 1992). Only bedrock entities containing more than nine bedrock boreholes are listed. The rocktype (sorted in ascending order) and the number of boreholes within each bedrock entity are also listed.*

Entity	Number of boreholes	Rock-type	Entity	Number of boreholes	Rock-type	Entity	Number of boreholes	Rock-type	Entity	Number of boreholes	Rock-type
836	187	54	795	24	74	803	25	80	789	135	91
958	159	54	806	25	74	745	13	81	829	123	91
971	178	54	814	20	74	754	49	81	962	42	91
1032	37	54	862	140	74	7	35	82	812	22	92
906	100	57	869	336	74	651	158	82	1029	295	92
923	16	57	875	15	74	100	19	85	1082	13	92
975	434	57	894	368	74	638	12	85	817	72	94
1031	13	57	920	27	74	664	135	85	868	17	94
646	11	64	946	12	74	731	53	85	680	10	95
788	43	67	1035	77	74	772	27	85	809	15	95
810	13	67	808	82	75	840	19	85	811	11	95
820	12	67	884	231	75	858	18	85	851	49	95
891	56	71	485	10	76	1019	37	85	115	10	96
861	40	72	625	31	76	1059	32	85	867	18	96
919	32	72	693	11	76	658	240	86	670	42	97
951	13	72	696	13	76	659	14	86	760	52	97
98	10	74	870	18	76	785	1075	86	807	11	97
456	103	74	880	39	76	647	33	87	815	66	97
650	86	74	993	28	76	721	50	88	692	12	98
656	87	74	751	34	79	517	11	90	717	2402	98
694	363	74	777	14	79	610	12	90	744	13	98
726	20	74	16	14	80	612	16	90	776	619	98
755	18	74	551	24	80	635	22	90	828	28	98
761	29	74	640	46	80	643	31	90	844	70	98
767	150	74	698	563	80	515	525	91	849	28	98
778	11	74	727	48	80	679	21	91	850	33	98
791	19	74	759	271	80	683	266	91	1007	127	98
794	40	74	792	24	80						

Chapter 3.5 describes how each of the 12,757 selected boreholes have been assigned a rocktype and entity. The bedrock map consists of 1,020 different polygons, each of them representing one type of bedrock and a unique part of the total area of Norway.

These polygons are referred to as bedrock *entities* in the reminder of this thesis. Each entity has a unique identification number. The size of these polygons or bedrock entities varies between 2.43 km^2 and 31,700 km^2. In many of the predefined rock types on the digitised map there exist no known bedrock boreholes. The bedrock boreholes selected from the BBD for use in this study are located within a total of 316 different bedrock entities. 110 bedrock entities contain more than nine bedrock boreholes, and these are listed in Table 2.3.1. These 110 bedrock entities occupy approximately 60% of the total area of Norway. Due to lack of information on groundwater yield in bedrock boreholes in the rest of Norway, only bedrock types associated with these 110 entities are considered in this thesis.

The rocktypes in Table 2.3.1 are all defined in the digital bedrock map of Norway. Not included in this table are the six rocktypes that host less than 10 bedrock boreholes. These six bedrock types (namely rocktypes 73, 77, 93, 100, 102 and 103) are not used for further discussion in this thesis. The remaining 25 rocktypes are identified in Figure 2.1.1 and referred to in Table 2.3.1.

The location of each rocktype, with entities, is shown in appendix A.

Chapter 3

Hydrogeology of Norway

3.1 *Introduction*

During Antiquity and in the Middle Ages, Aristotle's belief concerning the origin of groundwater was uncontested (Rekstad 1922). He believed that the earth's crust attracted the sea water like a sponge, thereby creating groundwater. He explained the lack of salt in the water by the effect of filtration, an opinion widespread among certain sectors of the public today. During the course of history, several more or less famous individuals raised their voices against this doctrine, and towards the end of the 18th century, the French physicist Mariotte finally proved that most groundwater has its origin in precipitation (Rekstad 1922). Ironically, hydrogeologists have recently realised that Aristotles's salt filtration effect is not entirely crazy. Ion filtration is accepted as a possible explanation for the evolution of chemical composition of deep esoteric sedimentary formation waters today (e.g. Downing & Howitt 1969).

History of Drilling Bedrock boreholes

The history of drilling boreholes in bedrock extends back to before 2,500 years B.C. when the Chinese developed the cable tool drilling method (Driscoll 1986). This method, although using a more modern cable tool rig (Figure 3.1.1), enjoyed a monopoly status in Norwegian bedrock drilling, from its advent in Norway in the late 1890s up to around 1960 (Jansen 1995). Inspired by the success of bedrock drilling in USA and Europe (in the 1870s) and in Sweden and Finland (1890s), the geologist A. Helland initiated the drilling of bedrock boreholes in some minor fishing communities along the coast of Northern Norway in the late 1890s (Rekstad 1922). These boreholes, with depths of 30 to 45 m, yielded generally good water quality, except for one borehole at Henningsvær, which had an excessive content of chloride. Helland also suggested that water-bearing faults and joints might exist below 30 m, which at that time was the commonly accepted maximum depth of drilling.

The Swedish company "Svenska Diamantsbergbornings Aktiebolag" represented by "Backe & Bonnevie" in Kristiania (Oslo) had a near monopoly in drilling bedrock boreholes in Norway until 1920. In 1916, the company published a brochure which summarised more than 20 years of drilling boreholes in Sweden, Finland and Norway. It

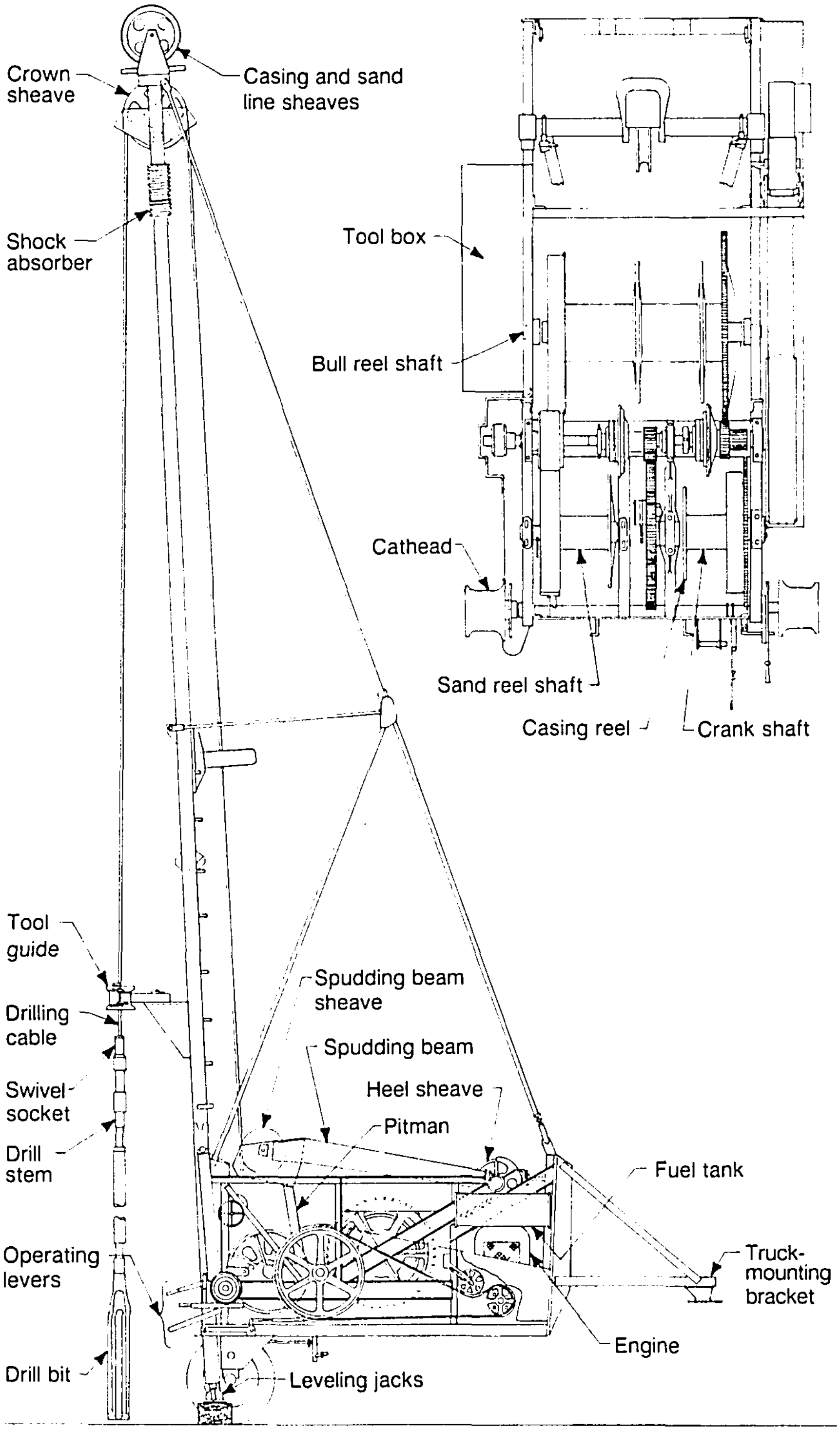


Figure 3.1.1 *Engineering drawing of a typical cable tool rig. The spudding action is imparted to the drill line by the vertical motion of the spudding beam. The shock absorber mounted beneath the crown block helps control the impact of the bit on the rock. (From Driscoll 1986).*

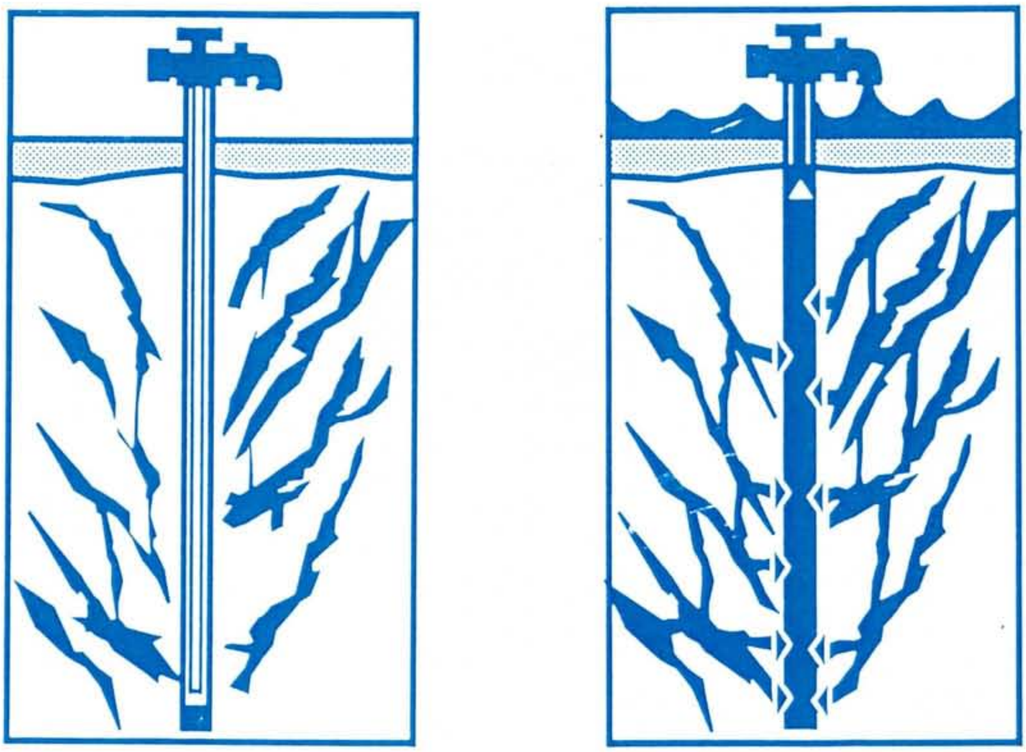
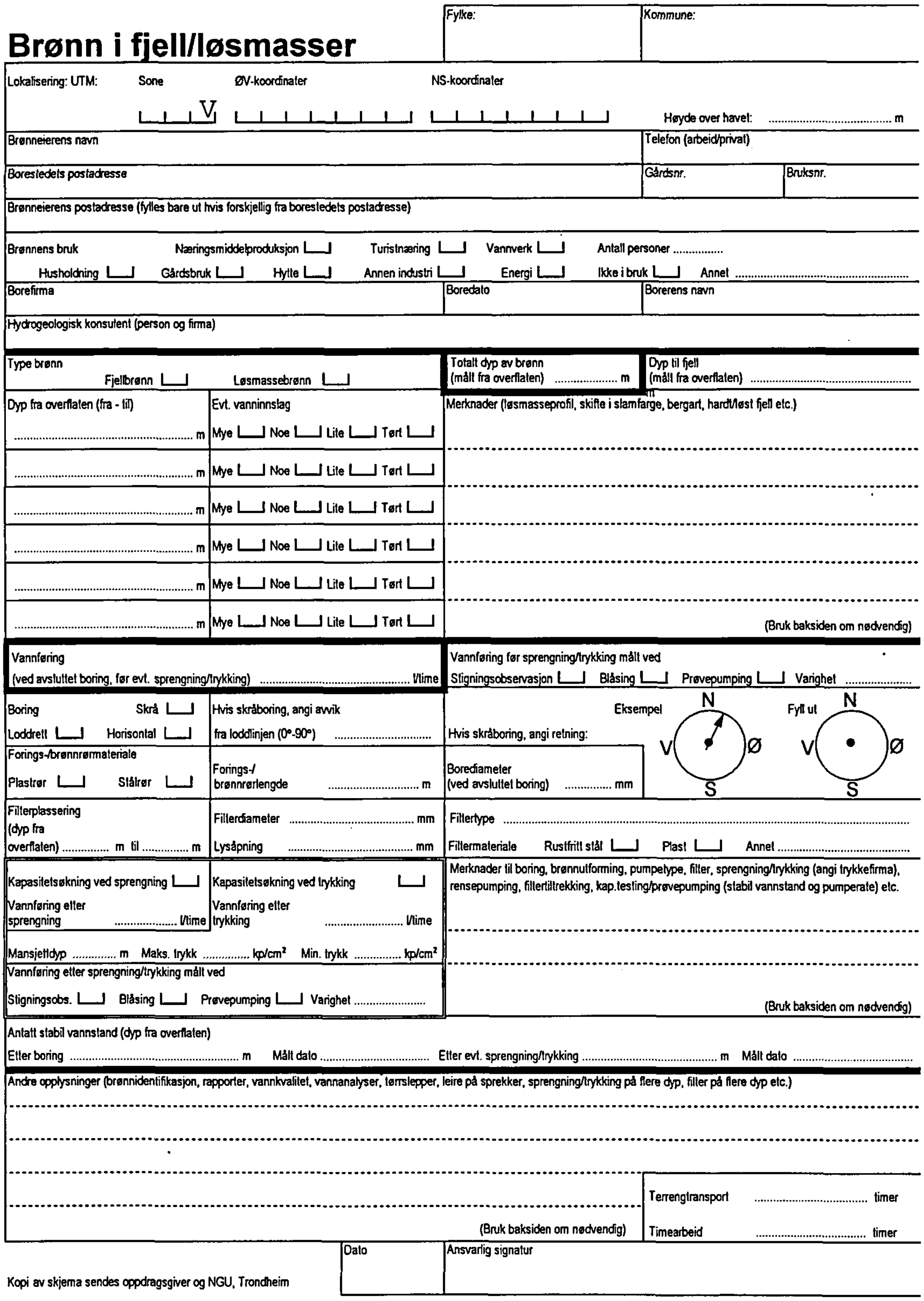


Figure 3.1.2 *Drawing showing the principle of hydraulic fracturing in a bedrock borehole. From a brochure from Flatwater Fleet Inc.*

concluded that of all the boreholes drilled in this period, 90% supplied more than 100 L/h and only 2% yielded absolutely no groundwater.

The first Norwegian company to drill bedrock boreholes was "Norsk Diamantboring", which started operating in the 1920s. The drilling was performed using 4" (10 cm) diameter core drilling. This method required two men to operate. In 1946 their chief driller suggested the use of the cable tool method which only needed one man to operate. He did not succeed in persuading the company owners and consequently he founded his own company, "O. Jansen Maskin og Brønnboring" (Jansen 1995). In its heyday, this company operated ten drilling rigs. In the 1950s several other companies were founded and by 1st January 1960, more than 20 companies were operating more than 50 cable tools rigs. In the 1960s most companies started to use the more efficient method of down-the-hole-hammer drilling. For example, one company took three days to drill only 35 cm in a very hard quartzite using a cable tool drilling rig. Upon returning to the site with down-the-hole-hammer drilling rig, they drilled 100 m in two days (Jansen 1995).

4" (10 cm) diameter boreholes were gradually replaced by 6" (15 cm) boreholes. There are several advantages in enlarging the diameter of the borehole. A 6" borehole contains for example a larger storage capacity and allows more freedom in specification of pumps. From the mid-1970s the use of dynamite and other explosives to increase the yield of boreholes became more frequent. This was not a new concept; already at the turn of the century the German geologist Keilhack suggested the use of dynamite in the bottom of a



Brønn i fjell/løsmasser

Fylke:

Kommune:

Lokalisering: UTM: Sone ... V ØV-koordinater NS-koordinater Høyde over havet: .... m

Brønneierens navn

Telefon (arbeid/privat)

Borestedets postadresse

Gårdsnr.

Bruksnr.

Brønneierens postadresse (fylles bare ut hvis forskjellig fra borestedets postadresse)

Brønnens bruk Næringsmiddelproduksjon ☐ Turistnæring ☐ Vannverk ☐ Antall personer ....

Husholdning ☐ Gårdsbruk ☐ Hytte ☐ Annen industri ☐ Energi ☐ Ikke i bruk ☐ Annet ....

Borefirma

Boredato

Borerens navn

Hydrogeologisk konsulent (person og firma)

Type brønn Fjellbrønn ☐ Løsmassebrønn ☐

Totalt dyp av brønn (målt fra overflaten) .... m

Dyp til fjell (målt fra overflaten) .... m

Dyp fra overflaten (fra - til)	Evt. vanninnslag	Merknader (løsmasseprofil, skifte i slamfarge, bergart, hardt/løst fjell etc.)
.... m	Mye ☐ Noe ☐ Lite ☐ Tørt ☐	
.... m	Mye ☐ Noe ☐ Lite ☐ Tørt ☐	
.... m	Mye ☐ Noe ☐ Lite ☐ Tørt ☐	
.... m	Mye ☐ Noe ☐ Lite ☐ Tørt ☐	
.... m	Mye ☐ Noe ☐ Lite ☐ Tørt ☐	
.... m	Mye ☐ Noe ☐ Lite ☐ Tørt ☐	(Bruk baksiden om nødvendig)

Vannføring (ved avsluttet boring, før evt. sprengning/trykking) .... l/time

Vannføring før sprengning/trykking målt ved Stigningsobservasjon ☐ Blåsing ☐ Prøvepumping ☐ Varighet ....

Boring Skrå ☐ Loddrett ☐ Horisontal ☐

Hvis skråboring, angi avvik fra loddlinjen (0°-90°) ....

Hvis skråboring, angi retning:

Eksempel

Fyll ut

Forings-/brønnrørmateriale Plastrør ☐ Stålrør ☐

Forings-/brønnrørlengde .... m

Borediameter (ved avsluttet boring) .... mm

Filterplassering (dyp fra overflaten) .... m til .... m

Filterdiameter .... mm

Lysåpning .... mm

Filtertype ....

Filtermateriale Rustfritt stål ☐ Plast ☐ Annet ....

Kapasitetsøkning ved sprengning ☐

Vannføring etter sprengning .... l/time

Kapasitetsøkning ved trykking ☐

Vannføring etter trykking .... l/time

Mansjettdyp .... m Maks. trykk .... kp/cm² Min. trykk .... kp/cm²

Vannføring etter sprengning/trykking målt ved

Stigningsobs. ☐ Blåsing ☐ Prøvepumping ☐ Varighet ....

Merknader til boring, brønnutforming, pumpetype, filter, sprengning/trykking (angi trykkefirma), rensepumping, filtertiltrekking, kap.testing/prøvepumping (stabil vannstand og pumperate) etc.

(Bruk baksiden om nødvendig)

Antatt stabil vannstand (dyp fra overflaten)

Etter boring .... m Målt dato .... Etter evt. sprengning/trykking .... m Målt dato ....

Andre opplysninger (brønnidentifikasjon, rapporter, vannkvalitet, vannanalyser, tørrslepper, leire på sprekker, sprengning/trykking på flere dyp, filter på flere dyp etc.)

(Bruk baksiden om nødvendig)

Terrengtransport .... timer

Timearbeid .... timer

Dato

Ansvarlig signatur

Kopi av skjema sendes oppdragsgiver og NGU, Trondheim

Figure 3.1.3 The current form for registration of information on drilling of bedrock wells in Norway (Morland 1996b).

dry borehole to increase yield (Rekstad 1922). Explosives create new fractures in the vicinity of the borehole and thus open new pathways for groundwater flow. Another method of increasing the yield of bedrock boreholes is hydraulic fracturing (Figure 3.1.2) (Less et al. 1993). This method consists of pumping water, with or without additives, under extremely high pressure into a sealed borehole causing faults and joints to open. This is the most frequently used method for increasing yield in bedrock boreholes today. During recent years it is estimated that between 3,000 and 4,000 bedrock boreholes have been drilled annually in Norway (Klemetsrud 1997).

History of Groundwater Databases

Groundwater has been part of the responsibility of NGU for several generations. NGU has collected information and stored it in a groundwater archive since 1951. By that time about 800 bedrock boreholes had been drilled in Norway (NGU 1952). Since 1983 all information has been stored in an electronic Bedrock Borehole Database (BBD) at NGU.

Since the beginning in 1951 a total of five different forms or questionaires have been used to collect information about the bedrock boreholes. The complexity of the forms has generally increased with time. The presently used form (Figure 3.1.3) represents the optimum amount of relevant information agreed between NGU and the Bedrock Well Borer Association of Norway (MEF). Although the presently used form appears rather complex, it is constructed and explained in a logical way. The returned forms which NGU receives from the bedrock well borers also confirm that it is easy to use in practice.

The information stored in the BBD is of varying quality. This is partly due to the development in drilling technology, but the main reasons lie in the frequent changes of forms, the non-existant or variable routines for quality control and the fact that reporting of information to NGU has, until 1992, been voluntary (See Groundwater Legislation). This means that borehole data registered in the BBD can contain errors connected to, for example, the actual position of the borehole, the depth of the borehole, the thickness of superficial deposits drilled through or the yield.

During the past 46 years, information on a total of almost 20,000 bedrock boreholes has been stored in the BBD at NGU. The amount of information about each borehole varies from almost nothing to very comprehensive.

In the period 1989 to 1992 NGU was responsible for the largest groundwater project ever carried out in Norway, the GiN-prosject (GiN = Grunnvann i Norge *[Groundwater in Norway]*). The GiN-project was the result of the recognition of an increasing gap between the actual use of groundwater and the demand for good quality resources. One objective of the GiN-project was the construction and implementation of a groundwater database. All information collected during the project was supposed to be stored in this database. Due to technical, economical and structural difficulties, the database was only used as a tool for production of reports for the 316 municipalities and counties involved in this project. The main hydrogeological information from this project is still not stored in a electronic database and has not been used to supplement the existing BBD.

Groundwater Legislation

The majority of countries in Europe have a thorough legislative framework concerning groundwater. The prospective use of groundwater has to be evaluated and licensed in many countries. In Norway there has never been any legislation regulating the use of groundwater, and for all practical purposes the principle of "First come, first served" has dominated. The Watercourses Act Committee declined in 1940 to include any legislation concerning groundwater in the new Watercourses Act (Hagemann 1989). Since then no further action was taken to address the judicial uncertainty concerning groundwater until Ass. Professor B. Stordrange of the University of Oslo completed his report of 1988 on possible new Norwegian legislation concerning groundwater (Stordrange 1988). This report was distributed to a number of public and private interest groups. Some of these organisations then called for the introduction of a new Act obliging well borers to provide information about newly drilled boreholes. NGU was one of these organisations and in 1992 the Watercourses Act (*Vassdragsloven)* was changed to include a paragraph stating that everyone who drills for groundwater must provide information to NGU (Ot.prp. nr. 50, 1992). It was not specified in detail what type of information was to be sent to NGU. NGU and MEF therefore agreed to make a proposal to the former Ministry of Oil and Energy regarding the precise type of information required on bedrock boreholes. The Ministry accepted this proposal in late 1994. Since 1995 NGU has collected information about bedrock boreholes in Norway in accordance with this proposal, although it is recognised that some drilling entrepreneurs are more conscientious than others in fulfilling their legal obligations.

A new committee was appointed to review the Watercourse Regulation Act in November 1990. In 1994 the committee submitted a draft bill for an Act relating to watercourses and groundwater, the Water Resources Act (NOU 1994). The new Act will replace the 1940 Watercourses Act and some other pieces of special legislation. Compared with the Watercourses Act, the draft bill is considerably simplified. Chapter IX of the draft bill contains the most important new provisions relating to groundwater. According to section 49, the surface owner's rights to groundwater are restricted to use of groundwater for activities/purposes which are considered "natural" for the type of property concerned, although the term "natural" is not clearly defined. Any further rights to groundwater belong to the State. Groundwater rights do not override and may not contravene the general provisions relating to the minimum permitted rate of surface water flow, surface water abstraction and drainage measures. Rules requiring the issuing of a licence for groundwater abstraction and other activities that affect groundwater, are laid down. The State will also require a license if it wishes to exercise its rights to groundwater resources. The paragraph stating that everyone who drills for groundwater must provide information to NGU, is adopted more or less unchanged in the new Water Resources Act. It is likely that the Act will be approved by the Norwegian Parliament, the "Stortinget" in late 1997.

3.2 The Present Water Supply Situation

Norway has traditionally been reliant on its abundant resources of surface water. These surface waters have generally high raw water quality compared with the rest of Europe. It can also be argued that this high raw water quality has led to some complacency on the issue of drinking water quality in Norway. Norway has been reluctant to invest in comprehensive water treatment systems partly due to complacency, partly due to the highly decentralised water industry which is run by local municipalities and partly due to the high capital investments required to link a sparsely distributed population to centralised water treatment works.

In fact, although surface water quality is quite good, it is not quite good enough to be used as drinking water with only minimal or no treatment. Despite the efforts of the health authorities in recent years to raise drinking water quality to an acceptable level, a considerable number of people (an estimated 1 million, NGU 1992), many food processing factories and tourist destinations still have unsatisfactory water supplies. The largest problems are connected with waterworks based on surface water (Ellingsen 1988). The most problematic parameters are high colour, turbidity, smell and taste of the water. Unacceptable content of humic substances and/or bacterial contamination are related to these problems and are the two most common causes of non-compliance of Norwegian waterworks. Many of these waterworks have no, or only minimal, water treatment.

Investigations have estimated that around 87% of Norway's population is supplied from waterworks based on surface water (Ellingsen 1992). Figure 3.2.1 shows that almost 50% of the inhabitants of both Finland and Sweden and almost 100% of the inhabitants of Denmark are supplied by drinking water from waterworks based on groundwater. The figure also shows that Norway is using less groundwater than any of the other listed countries.

The bedrock and Quaternary geology of Norway are very different from the geology of many other European countries. The natural conditions for exploitation of groundwater for water supply are somewhat less suitable in Norway than elsewhere. Norway also has an entirely different population distribution compared with other countries. It is a large country (323,758 km^2, N-S extent 1,752 km) with a small population (4,391,966 people pr. 1st January 1997). Except for a small number of relatively large cities, the population live in smaller towns and villages,

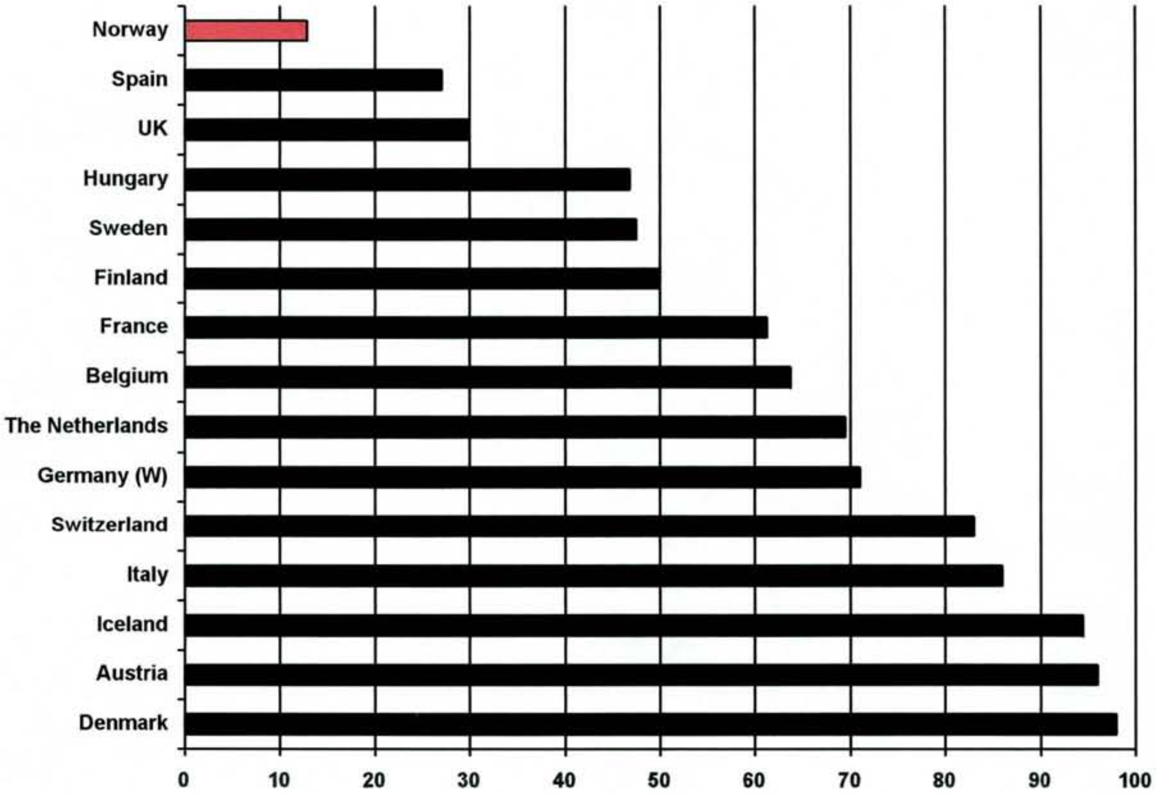


Figure 3.2.1 *Groundwater use as a percentage of all water supplied in selected European countries. NGU (1992).*

sparsely distributed in rural districts and often separated by fjords, lakes, hills and mountains. Today, approximately one third of Norway's population lives in villages in rural districts with less than 200 inhabitants. Because of Norway's abundant resources of supposedly "clean" surface water, health concerns and practical needs have traditionally not resulted in a demand for alternative sources of drinking water. As a result, there has been no incentive for larger scale co-ordination of the water supply and no or very limited use of groundwater. As awareness of the possibility of groundwater use increases, local authorities, private consultants and the public at large is beginning to regard groundwater in several ways as a preferable source of drinking water to surface water. The main advantages usually are:

- Good and stable water quality and temperature
- Groundwater requires less sophisticated water treatment
- Groundwater is often located closer to the users
- Groundwater is better protected from pollution
- Source protection areas are usually smaller than for surface waters
- Waterworks based on groundwater are often cheaper to establish and operate
- Groundwater works can be established in several phases as demand increases. Surface water works are often one-off investments

The distribution of the population of Norway based on the census of 1980 has been digitised (Statistisk sentralbyrå [SSB] 1980). Numbers of people living in urban areas are derived from information from the SSB (1994), the central institution for producing official statistics in Norway. The population distribution is not believed to have changed dramatically during the last 17 years. For example, in 1980 there were 842 towns and villages defined as "urbanised areas", while in 1994 the equivalent number was 878. SSB defines "urbanised areas" as communities with at least 200 inhabitants where the distance between each house does not generally exceed 50 metres. Today these areas include approximately 73% of Norway's population. The median and mean numbers of inhabitants in these "towns and villages" in Norway are 747 and 3,600 persons, respectively. In Norway there are only 40 "cities" exceeding 10,000 inhabitants. These "cities" house 47% of the total population. Figure 3.2.2 shows the distribution of the population on 1st January 1996.

Information on water quality from different waterworks has been related to the size and location of cities, towns and villages in urban areas (Morland 1996a). Of the more than 3.2 million inhabitants in these areas (SSB 1994) 86% (448 cities, towns and villages) are supplied by waterworks based on surface water and 6% (108 cities, towns and villages) are supplied from waterworks based on groundwater. For 8% (322 towns and villages) there is no information available, but the majority are

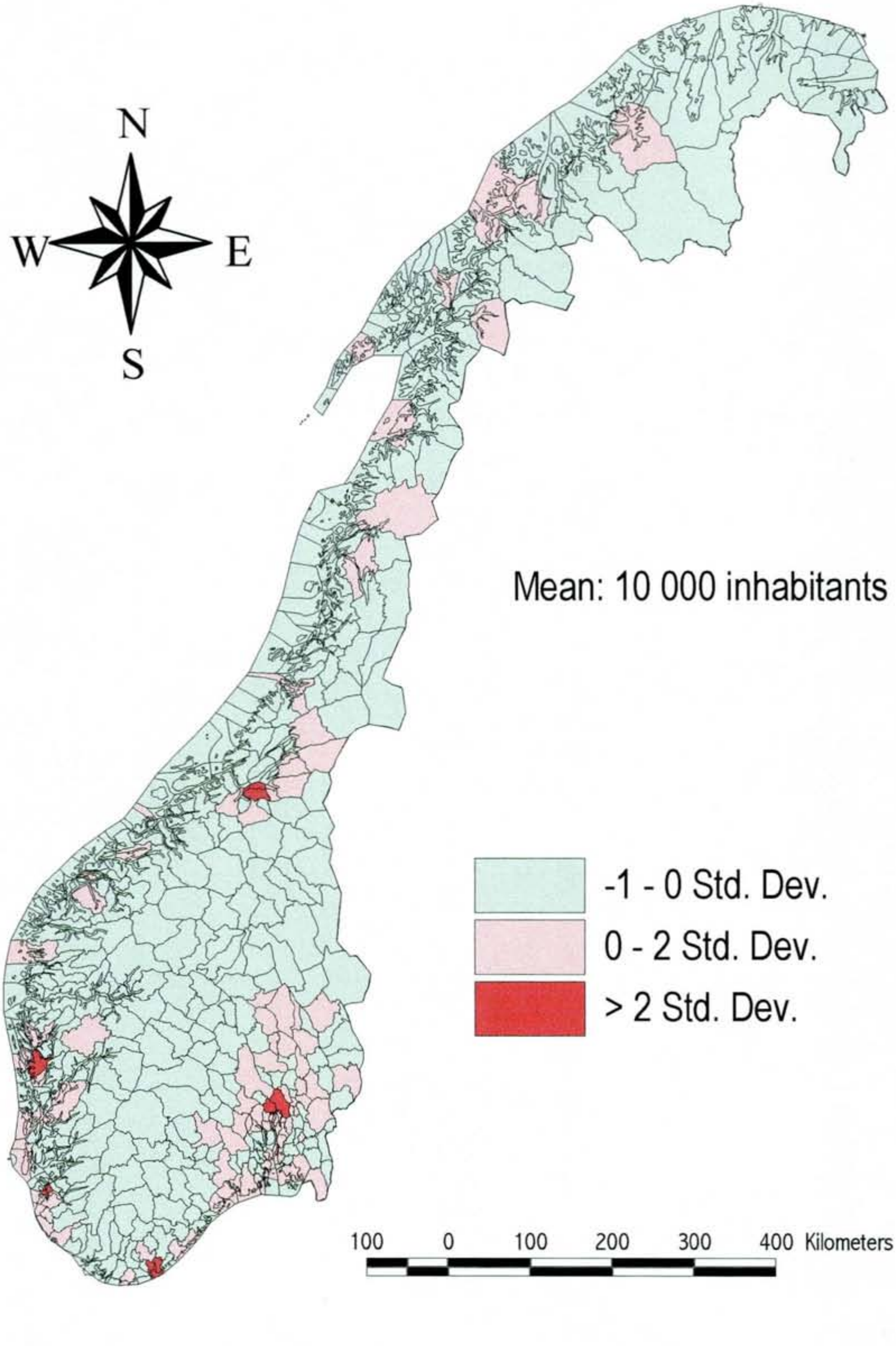


Figure 3.2.2 *Distribution of the Norwegian population on 1st January 1996 using standard deviation (Std. Dev.) of inhabitants in all municipalities as the mapping object. 1 Std. Dev. equals 28,000 inhabitants (ih). Minimum = 214 ih, maximum = 490,000 ih, median = 4,300 ih. Based on information from SSB (1997).*

assumed to be supplied by surface water. The rest of the population (1.2 million persons) live in rural areas. Some of these are connected to waterworks already described above, but there exists no reliable information on the type of water supply and water quality for the majority of these 1.2 million.

The inhabitants of many of the 448 cities, towns and villages mentioned above as being supplied by surface water, enjoy generally good water quality. Nevertheless, 400,000 persons (187 cities, towns and villages) have an unacceptable water quality in relation to Norway's drinking water regulations. A thorough investigation in the archives of NGU has shown that almost 190,000 of these 400,000 persons (109 cities, towns and villages) live in places which have geologically favourable conditions for groundwater supply (Morland 1996a).

Of the 40 Norwegian cities with more than 10,000 inhabitants, only six cities/towns (namely Lillehammer, Kongsberg, Elverum, Kongsvinger, Hønefoss and Alta) enjoy water supply based on groundwater (3.6% of the total population of these cities/towns). All of these large groundwater works are based on Quaternary glaciofluvial and fluvial sedimentary aquifers.

In total, 13% of Norway's population are supplied by groundwater (Ellingsen 1992). This fact, combined with the results mentioned above, indicates that the majority of groundwater used for water supply in Norway is derived from small and single household waterworks in rural areas. Groundwater use may reach some 30% in remote areas where hard rock groundwater is the most important alternative to surface water. This is one major reason for attempting to obtain a better knowledge about the quantity and quality of groundwater from bedrock boreholes.

3.3 Bedrock and Quaternary Aquifers

To be able to locate the different lithologies occurring in different parts of Norway, Figure 3.3.1 has been created. The figure shows the location and name of all the counties in Norway. Figures 2.1.1, 2.1.2 and appendix A are also helpful in

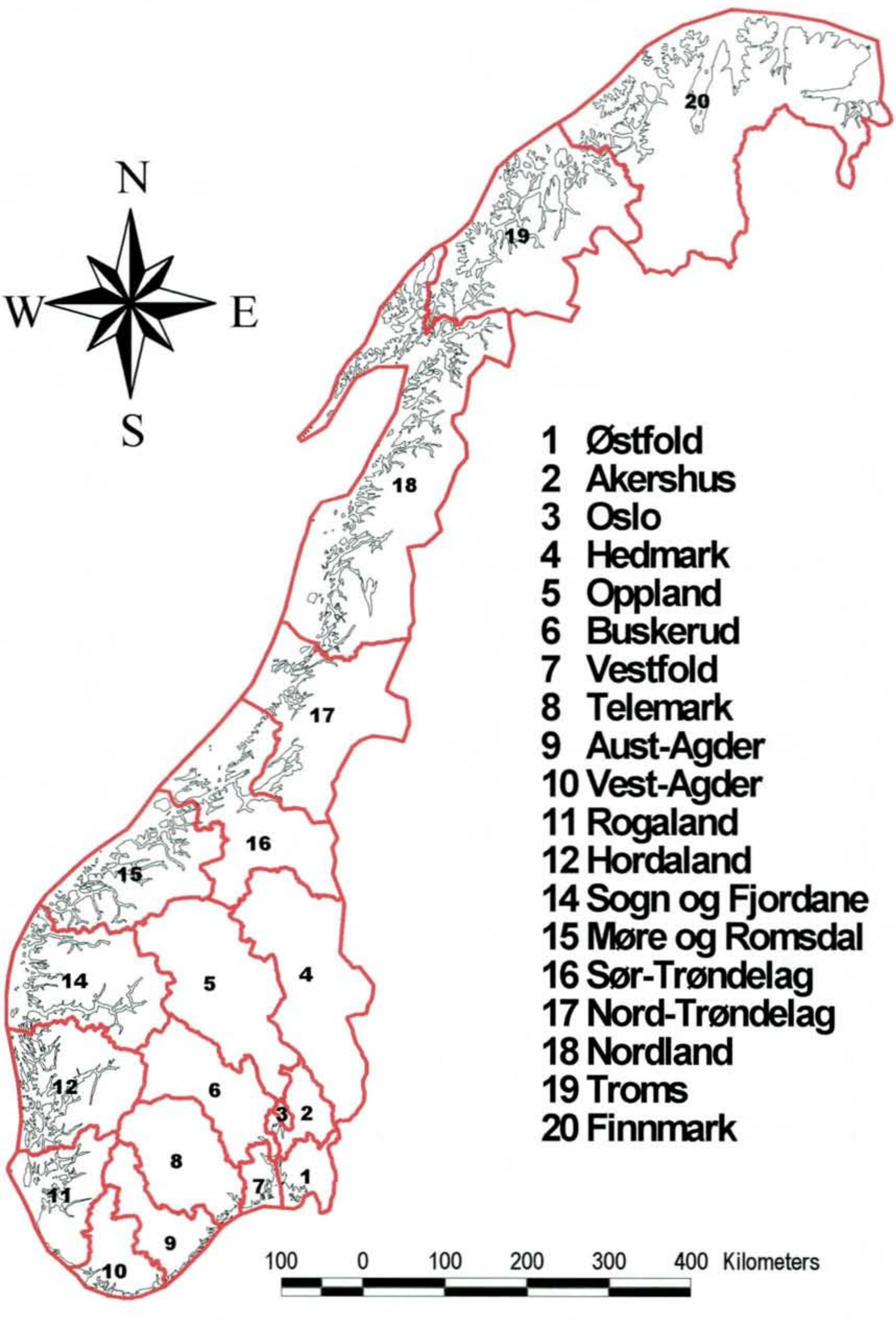


Figure 3.3.1 *The counties of Norway.*

identifying the location of the lithologies mentioned. The main source for the hydrogeological description of both bedrock and Quaternary aquifers has been groundwater guidebook No. 8 from the GiN-project (see History of Groundwater Databases) (NGU 1991). This chapter represents a compiled version of the known hydrogeology of bedrock and Quaternary aquifers in Norway, and it is intended to serve as a background information chapter. No information retrieved from the BBD in this thesis is used in this chapter. The "received wisdom" described in this section may thus be based on several different sources. The different authors of this "received wisdom" have used information both from the BBD and from other sources (municipalities, consultant companies, universities, bedrock well borers etc.). There has, however, never been any consensus among Norwegian hydrogeologists about how to present the information about drilled depth and yield of bedrock boreholes. Mean, median, interquartile range (middle 50%) or other more or less subjective methods have been used to illustrate the drilled depth and the yield "typically" obtained in different lithologies throughout Norway. In this chapter, the sources of information are cited without examining in detail how the figures have originated.

Bedrock aquifers

In the lower lying areas of south-eastern Norway, there are two regions of Precambrian crystalline rock divided by the Oslo Rift (type 7 in Figure 2.1.2). The Rift contains rocks of Cambrian to Permian age (type 3+6 in Figure 2.1.2). The two Precambrian regions consists mainly of gneiss and granite. The area of Norway with the densest occurrence of bedrock boreholes is the Precambrian area east of the Oslo Rift. Boreholes drilled in this area tends to yield more than boreholes in the Precambrian region west of the Oslo Rift. Yields of 3,000 to 10,000 L/h have been obtained by drilling along prominent fracture zones (Gaut 1993). It is believed that such good results are at least partly caused by the development of feather fractures (i.e. series of fractures branching diagonally from a larger fracture, as en echelon tension gashes induced by sheer-stress, often in connection with strike slip faults [Blès et al. 1986]). Yields in excess of 36,000 L/h are known from the

Rakkestad area in the county of Østfold in the eastern Precambrian region. This area also has a water supply based on groundwater from bedrock boreholes.

In the Oslo Rift there are various sedimentary rocks of Cambro-Silurian age overlain and intruded by plutonic, volcanic and sedimentary rocks of Permian age (type 6 and 3 respectively in Figure 2.1.2). The oldest sedimentary rocks include phyllites, shales, schists, sandstones and limestone, all with very different yields from groundwater boreholes. The phyllites, shales and schists yield very little groundwater, the sandstones a little more (Nystuen et al. 1993). Massive limestones are known to yield 3,000 to 6,000 L/h in this area. Fold structures in the limestone are also known to be of great importance for borehole yield. A borehole located on the top of an anticline tends to yield less water than a borehole located in a syncline (NGU 1991). A syncline may also form a larger "water reservoir" than an anticline.

The Permian plutonic rocks of the Oslo Region are often assumed to have comparable hydrogeological characteristics to the surrounding Precambrian rocks, but as in most rocks in Norway the yield of bedrock boreholes varies greatly. Boreholes associated with major fault zones are known to have yields of up to 10,000 L/h, but other boreholes located within the same zones may hardly yield enough water for a small hut. Permian hypabyssal rocks tend to have a better yield to their host rocks. This may be due to the metasomatic effect of intrusion on the surrounding rock, rendering it more competent and with more open fractures. Dykes are thus regarded as very favourable hydraulic features.

The Permian volcanic rocks in the Oslo Region are also known to be good aquifers. Yields of 6,000 to several tens of thousands L/h from the rhomb porphyry lavas are quite usual (Nystuen et al. 1993). The water bearing zones are typically the discontinuities between the massive volcanic beds. The volcanic beds themselves may be almost impermeable.

In the Telemark area, in the middle of the Precambrian region covering most of the south-western part of Norway (type 7 in Figure 2.1.2), the rocks have a lower grade of metamorphism than the rest of the rocks of this region. The rocks here consists mainly of quartzites and metamorphosed volcanic rocks. Little is known about borehole yields in this area, but the Precambrian rocks further east tend to have higher borehole yields than the quartzites in this area.

Further north in the eastern part of Norway (South-east part of type 8 in Figure 2.1.2) the bedrock consists mainly of sedimentary rocks of Precambrian to Palaeozoic age, the so-called sparagmite area. The rocks vary from shales and schists to sandstones and conglomerates with some limestones and quartzites in the north-east. The shales and schists tends to have very low borehole yields but the massive sandstones, conglomerates and quartzites to the north and east often have borehole yields of 3,000 to 6,000 L/h. The Caledonian orogeny resulted in the occurrence of the latter rocks in several thrust sheets, the nappe decollements often coinciding with horizons of compact shales and schists. These structural changes have proven to be very favourable for high yielding bedrock boreholes since the sandstones are fractured by shear and tension faults and acts as independent reservoirs between the more compact shales and schists.

The municipality of Ringsaker in Hedmark county has several waterworks based on groundwater from bedrock boreholes. The largest one is based on groundwater from the Brummunddal Sandstone of Permo-Triassic age and supplies over 8,000 persons in the vicinity of the town of Brummunddal. This sandstone is the only bedrock aquifer in Norway with a significant intergranular porosity, estimated as 15% by Englund and Jørgensen (1980).

The southernmost part of the main Precambrian region in south-western Norway consists mainly of gneiss with some granitic to charnockitic or anorthositic metamorphosed plutonic rocks. Most bedrock boreholes in this area tend to have generally low borehole yields. The anorthositic areas of southern Rogaland tends to yield somewhat better.

The bedrock geology in the western part of Southern Norway is very complex. The main conclusions from a hydrogeological point of view are that the gneissic region (the south-western part of type 2 in Figure 2.1.2) generally exhibits low yields from bedrock boreholes. The hydrogeological map of Bergen, located in the county of Hordaland (Ellingsen 1978) shows that the median yield of bedrock boreholes in most lithologies in this area is between 300 and 500 L/h. The "phyllite" (actually a mica schist) has a median yield of 250 L/h. Experience during the last ten years of drilling bedrock boreholes in this area shows that hydraulic fracturing (see Figure 3.2.1) tends to increase yield very effectively in this area.

The northern part of the gneissic region and the areas influenced by the Caledonian orogeny in the central part of Norway (types 2 and 8 in Figure 2.1.2) are also very variable hydrogeologically. The outermost gneissic areas have poorly yielding boreholes (although even poorly yielding boreholes of 100 - 200 L/h are usually enough to supply single households with water). Nevertheless, there are some bedrock boreholes with yields of up to 15,000 L/h in this area. A common problem in coastal areas is the possibility of intrusion of saline water into high yielding boreholes. In the municipality of Vikna, in the county of Nord-Trøndelag, only 50% of the bedrock boreholes yield water of acceptable water quality because of the intrusion of saline water.

The metamorphosed volcanic and sedimentary rocks in the so-called Trondheim Region, mainly in the Sør-Trøndelag and Nord-Trøndelag counties, usually have very low borehole yields, often too little to supply even single households with water. The exceptions are boreholes in limestone which may yield several hundred L/h. The plutonic rocks, especially Trondhjemite, tend to be better aquifers with borehole yield of 1,800 L/h or more.

In the counties of Nordland and Troms the mountains are dominated by mica schists and mica gneisses with the intercalations of limestone. The mica schists and gneisses have generally low borehole yields, ranging from zero to 1,500 L/h. However, if even thin beds of limestone occur within the mica bedrock, the yields are dramatically improved. Massive limestone occurrences have the highest borehole yields in this area. This is due to the karstic character of the lithology. Groundwater boreholes yielding in excess of 30,000 L/h are reported from the Mo i Rana-district in the middle of the county of Nordland. A borehole in a lithologically slightly different shaly limestone in the municipality of Fauske, a little further north, yields only 350 L/h. This large difference may be due to differing extents of karstification or may simply be due to the boreholes intersecting or not intersecting transmissive flow pathways. Karstic systems are also the reason for the existence of numerous springs in many parts of the county of Nordland.

Bedrock boreholes intersecting major faults in the metamorphosed Precambrian bedrocks (type 4 in Figure 2.1.2) yield up to 3,500 L/h in Hamarøy area (in the north of the county of Nordland) decreasing to approximately one third of this yield in the Lofoten area and on the large islands of the county of Troms. A borehole through the Caledonian nappe succession and into the underlying Precambrian bedrock in the middle of the county of Troms yields 10,000 L/h. This relatively high groundwater yield may be due to the elevated permeablility of the thrust fault itself or permeablility enhancement due to paleo-weathering of the Precambrian basement bedrock. Bedrock boreholes with a similar location in the nappe sequence on the island of Senja have not, however, given the same high yields. A number of drillings on the smaller islands have not been entirely successful. This is probably due to the combination of massive bedrock with few joints and faults, inaccurate location and drilling direction of the borehole and high extraction rate during pumping tests, causing saline sea water to intrude into the boreholes. On the largest island south of Lofoten in the county of Nordland, Værøy, 10-12 bedrock boreholes yield in excess of 6,000 L/h. This is probably due to the large screes formed on the base of the steep mountainsides on the island. Large springs are often observed at the bottom of such screes and there may be good possibilities of drilling high yielding bedrock boreholes at such locations.

The lithology of the central and eastern parts of the county of Finnmark consists mainly of sandstones and shales (equivalent to types 1, 4 and 6 in Figure 2.1.2). The yields of bedrock boreholes in the sandstones are generally high, often in the range of 3,000 L/h to 6,000 L/h, decreasing to a general maximum of 700 L/h in the shales. Bedrock boreholes in the Precambrian area in the south-eastern parts of the county of Finnmark yield 700 L/h to 1,800 L/h.

Quaternary aquifers

Quaternary deposits generally occur in Norway as relatively thin or discontinuous cover over the bedrock. A large part of the low-lying areas of Norway were inundated by the sea at the end of the last glaciation (se Figure 9.1.1) resulting in a widespread occurrence of marine deposits in especially the south-eastern and middle parts of Norway.

Till deposits usually have little importance as groundwater resources though dug wells in tills have yielded the traditional water supply of single households and huts in many parts of Norway. These dug wells often have a high bacteriological content and are nowadays being replaced by municipal waterworks based on surface water, groundwater from other Quaternary deposits or boreholes in bedrock.

The hydrogeologically interesting Quaternary deposits are generally glaciofluvial and fluvial in nature and are often in hydraulic continuity with rivers and lakes. In some areas fossil shore deposits occur wich may be suitable for groundwater extraction.

Groundwater extraction from Quaternary deposits in Norway is in most cases related to aquifers which are in hydraulic continuity with surface water bodies; the water is thus so-called "bank infiltrated". There are, nevertheless, some exceptions;

for example, the large glaciofluvial deposit of Øvre Romerike (in the county of Akershus) is the largest aquifer in Norway which is solely recharged by infiltrating precipitation. The capital of Norway, Oslo, has a water demand of around 3,500 L/s (Enander 1994). The glaciofluvial deposit of Øvre Romerike has a theoretical groundwater yield of 570 L/s, only 16% of Oslo's demand (Snekkerbakken 1992). Realistically, however, even 570 L/s would be difficult to achieve because of pollution caused by a wide range of activities on the deposit, including the current Gardermoen airport and the planned main airport serving the Oslo area (under construction), 70 years of military presence and military and municipal waste disposal pits, extensive gravel workings in the protective unsaturated zone, asphalt factories, a railway and a motorway. All these activities limit this aquifer's utility as an important national hydrogeological resource. Today the aquifer only supplies a couple of minor waterworks with groundwater.

The largest waterworks in Norway based on groundwater is located in the Olympic city of Lillehammer and supplies around 25,000 persons. The yearly average amount of groundwater produced by this waterworks is less then 8 million m^3 (c. 250 L/s), rather small compared with many European waterworks based on groundwater. The water is largely derived from bank infiltration from the "Lågen" river.

In fluvial and glaciofluvial deposits in coastal areas of Norway saline groundwater can be extracted. Aquaculture has become an important industry in Norway, in which access to large quantities of high quality water is a basic requirement. Occurrence of water quality-related problems such as infectious diseases, parasites etc. has made the use of saline and fresh groundwater in land-based aquaculture attractive as a way to reduce problems for the industry itself and also to reduce negative impacts on the marine environment. The fjord delta aquifer at Sunndalsøra in the county of Møre og Romsdal is the most famous example of the use of groundwater in aquaculture in Norway. Because of the high groundwater recharge from two rivers flowing over the fjord delta, the salinity of groundwater is too low to be used in onshore aquaculture of, for example, salmon (Soldal 1993).

3.4 The Bedrock Borehole Database

NGU implemented the electronic Bedrock Borehole Database (BBD) in 1983. This first version of the database had major limitations with respect to the insertion and update of information, flexibility and data visualisation.

In 1987 a new version of the BBD was constructed which added support for geographic coordinates as the most important enhancement (Flaa 1987). More flexibility was introduced in searching the database and a totally new set of graphical and tabular reports was included in this new release. The BBD was built using the Hewlett-Packard database system IMAGE/3000.

The author has been responsible for the database since 1992 and in 1995 the BBD was moved to the Oracle relational database management system platform, Oracle7. This was a major upgrade resulting in a much more flexible data structure giving the users more freedom in choosing appropriate front end tools for manipulation and inspection of the database content.

The Oracle RDBMS

The Oracle Relational DataBase Management System (RDBMS) is one of the market leaders of open database systems. The BBD is run on the Oracle7 Server, a robust and reliable database server.

A database server is the key to solving the problems of information management within the BBD. In general, a server must reliably manage a large amount of data in a multi-user environment so that many users can concurrently access the same data. All this must be accomplished while delivering high performance. A database server must also prevent unauthorised access and provide efficient solutions for failure recovery.

The Oracle Server provides efficient and effective solutions with the following features:

- client/server (distributed processing) environments
- large databases and space management
- many concurrent database users
- high transaction processing performance
- high and controlled availability
- openness, industry standards
- manageable security
- database enforced integrity
- distributed systems
- portability, compatibility and connectibility
- replicated environments

The Oracle Server is a relational database management system that provides an open, comprehensive, and integrated approach to information management of the BBD.

SQL is the programming language that defines and manipulates the BBD. SQL databases are relational databases, this means simply that data is stored in a set of simple relations. A database can have one or more tables, and each table has columns and rows. The BBD has, for example, a table called "Brønn" (Borehole), which constrains a column called "Brønntype" (Type of Borehole). Each row in this column represents a value indicating whether the borehole is a bedrock borehole or a borehole in Quaternary deposits.

Database Structure

The BBD has both a physical and a logical structure. Because the physical and logical server structure are separate, the physical storage of data can be managed without affecting the access to logical storage structures.

The physical structure of the BBD is determined by the operating system files that constitute the database. Each Oracle database is made of three types of files, one or more datafiles, two or more redo log files, and one or more control files. The files of an Oracle database provide the actual physical storage for database information.
The logical structure of the BBD is determined by

- one or more tablespaces (a tablespace is a logical area of storage)
- the schema objects. A schema is a collection of objects. Schema objects are the logical structures that directly refer to the data of the BBD.

The logical storage structures dictate how the physical space of the database is used. The schema objects and the relationships among them comprise the relational design of the BBD.

Design of the Database

The BBD is designed using well-known structured methods supported by the Oracle Designer/2000 tool. This is an integrated life cycle analysis, design and maintenance tool based on a comprehensive repository. It is one of the best CASE (Computer-Aided Systems Engineering) tools available today having won all of the awards in Computerworld's evaluation of CASE tools in 1996 (IDG Research Services Group 1996). Entity-relationship modelling has been used to structure the information in the BBD. The author has introduced the hydrogeological database concept at NGU and the BBD is a part of this concept which is currently being developed. Thus the BBD has interconnections with other parts of this overall database system.

The design of the hydrogeological database is centred around three main geographical categories; points, lines and areas. Thus, it is easy to present information in Graphical Information Systems (GIS). A bedrock borehole is a subtype of a point. It is connected to coordinates and is thus one of the geographical categories. The database consists of 140 domains, 130 entities and more than 140 tables containing more than 900 attributes.

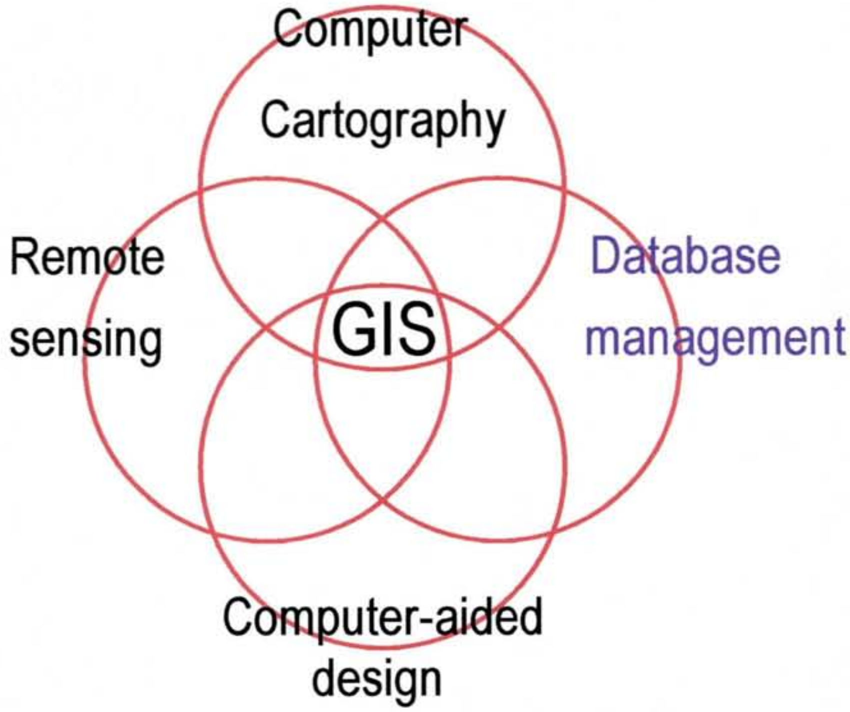


Figure 3.5.1 *The relationship between GIS, Computer-aided design, computer cartography, database management and remote sensing information systems (Maguire et al. 1991).*

3.5 Interfacing the Bedrock Borehole Database

The Geographical Information System

Data that describe any part of the Earth's surface or the features found on it can be called geographical data. These include not only cartographic and scientific data, but also business data, land records, photographs, customer databases, travel guides, real estate listings, legal documents, videos, etc. Geographical information systems (GIS) have proved themselves ideal for the capture, storage, retrieval and analysis of different types of spatial data. GISs have commonly been used only for production of maps and data tables in the final stages of a project, rather than for the extensive spatial analysis capabilities for which they were designed. According to Maguire et al. (1991), a true GIS (as opposed to other mapping systems) has the ability to search and analyse spatial data with reference to geographic location as well as the possibility of creating new geographical data through the combination of two or more geographical data layers. A GIS can be seen as a combination of other information systems as illustrated in Figure 3.5.1. This figure illustrates the concept of thematic data layers in a GIS.

Table 3.5.1 *Geographic information used in this thesis. AVS=ArcView 3.0 GIS shapefiles, AI=ARC/INFO coverages, TD=Tabular data.*

Description
Digital map of all municipalities (AVS)
Digital map of all counties (AVS)
Digital map of Norway (AVS)
Digital Bedrock map of Norway (AI)
Digital map of the distribution of the population in Norway (AI)
Digital map of the isostatic uplift (AI)
Digital map of the location of the Marine Limit (AI)
Digital map of the borders of the map-series of M711 (AI)
Digital map of lineaments (AI)
Digital Bedrock map of Norway and adjacent ocean areas (AI)
Digital map of Norway transformed from Admin32 (AVS)
Digital map of tectonic subtypes (AI)
Extraction of all suitable bedrock boreholes from the BBD (TD)
Number of inhabitants in Norwegian municipalities (TD)
Chemical analyses from the Oslo Area (TD)
Chemical analyses from the Bergen Area (TD)

To handle the different geographical information represented in this thesis (Table 3.5.1), the author has used the geographic desktop information program ArcView 3.0 GIS, a powerful, easy-to-use tool. ArcView 3.0 GIS gives the power to visualise, explore, query and analyse data spatially. Spatial data is geographic data that stores the geometric location of particular features, along with attribute information describing what these features represent. Spatial data are also known as digital map or digital cartographic data. ArcView 3.0 GIS is made by Environmental Systems Research Institute (ESRI), the makers of ARC/INFO, the leading geographic information system (GIS) software. The main advantage using ArcView 3.0 GIS compared to using ARC/INFO is that there is no need to know how to create geographic data. ArcView 3.0 GIS supports the use of geographic data sets created by ARC/INFO and enables the user to access all these resources, including vector coverages, map libraries, grids, images and event data. ArcView 3.0 GIS enables the user to display, query, summarise, and organise data geographically.

ArcView 3.0 GIS works with views, tables, layouts, charts and scripts stored in one file called a project. Projects enables the user to keep all the components needed together for a specific task or application. Table 3.5.1 lists all the information examined and presented using ArcView 3.0 GIS projects in this thesis.

Exploratory Data Analysis

Data analysis was carried out using the DAS-program produced by edas, Institute for Technical Statistics, University of Vienna (Dutter et al. 1992). This program package is based on methods of exploratory data analysis (EDA) (Tukey 1977, Velleman and Hoaglin 1981, Kürzl 1988, O'Connor et al. 1988, O'Connor and Reimann 1993, Rock 1988) that are especially well suited for the handling of non-normally distributed data that are likely to contain a high number of errors - both typical characteristics of many geological data sets. General sources of errors are for example:

- Errors in assigning lithology/natural variability in the geological unit being studied. This is a possible source of error concerning all aspects of this thesis.
- Field sampling errors, e.g. wrong place visited, samplers not obeying sampling procedures or developing their own submethods. This is a possible source of error specially concerning Chapters 4 and 5.
- Errors due to incorrect coordinate location of boreholes, coordinate systems which have been redefined.
- Sample preparation errors, e.g. contamination, sample mix-ups. This is a possible source of error especially concerning Chapters 4 and 5. Also the use of simplified digital and conventional maps in analysing data spatially have possibilities of errors equivalent to traditional sample preparation errors.
- Analytical errors, e.g. contamination, wrong sequence of samples loaded into instrument, sample mix-ups. This is a possible source of error especially concerning Chapters 4 and 5. Again, the use of simplified digital and conventional maps in analysing data spatially have possibilities of errors equivalent to traditional analytical errors.
- Data processing errors, e.g. entry of field/laboratory number and coordinates. This is a possible source of error in the process of storing information on a form into an electronic database and it may therefore influence the accuracy of the registered information. This is a possible source for error in the BBD, in all analytical results presented in Chapters 4 and 5 in addition to leading to errors in the construction of digital maps.

All these errors can never be avoided in the course of a large project. Thus, data analysis techniques created to cope with such errors - i.e. the methods of exploratory data analysis - should be preferred over classical statistics. For example, a modern geochemical survey will be carried out using a number of quality control and assurance procedures (McGrath 1987, Reimann and Wurzer 1986, Reimann 1989) while no quality assurance was up to now used in connection with the data of the BBD. Knowing that, for example, all borehole information in the BBD are connected with uncertainties in depth and yield (depending on the type of drilling equipment and the procedure for estimation the borehole yield) and location coordinates, made it a challenge to investigate how EDA-methods are able to cope with such a "worst case" scenario in terms of data quality.

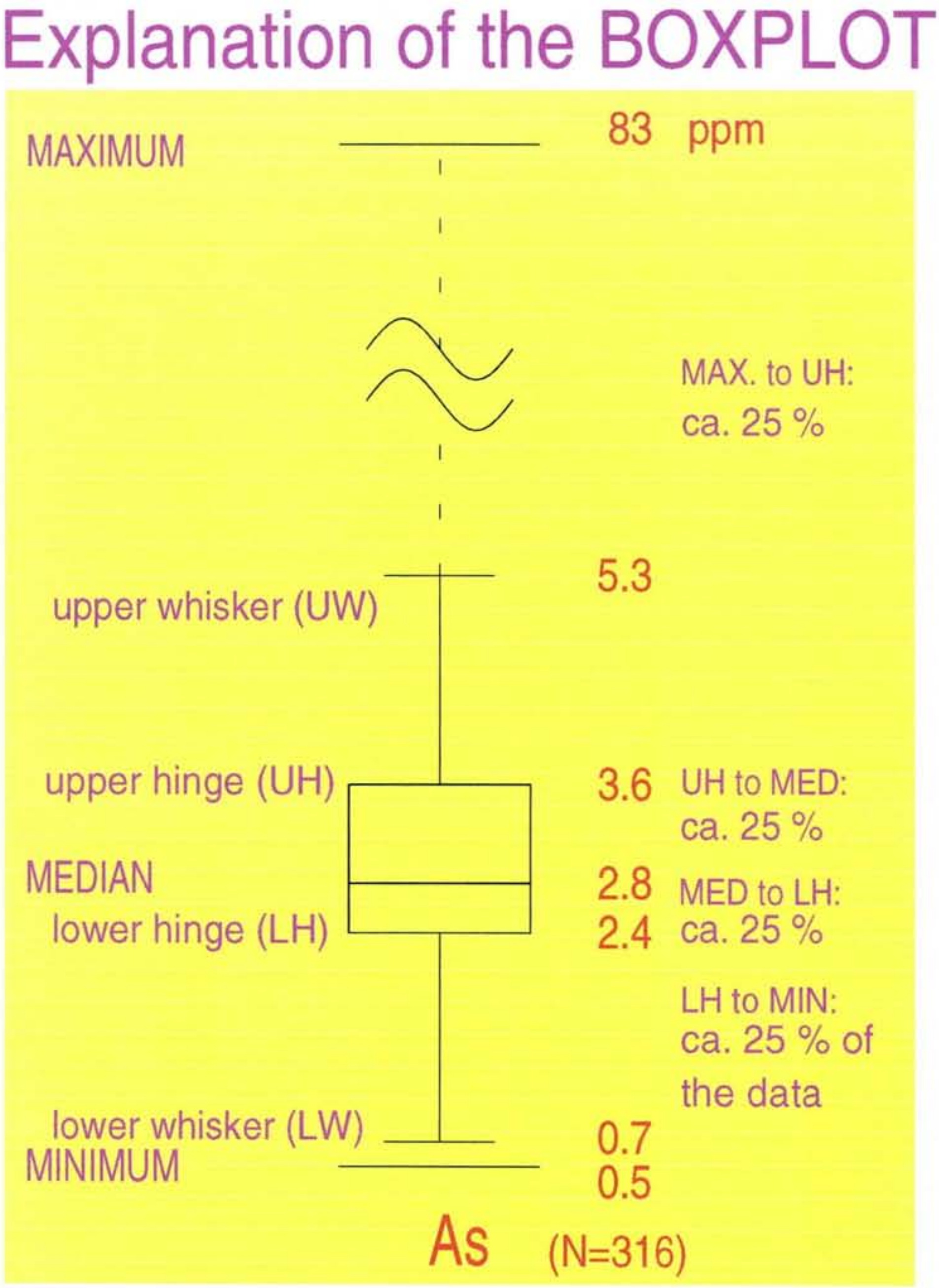


Figure 3.5.2 *Explanation of the BOXPLOT. The example data set is for concentrations of As in the uppermost 5 cm of soil in a Norwegian town (fraction < 2 mm, aqua regia digestion). Definitions: Hinge spread (HS) = UH - LH, upper whisker (UW) = UH + 1.5 x HS, lower whisker (LW) = LH - 1.5 x HS. The whiskers are drawn at the last actual data point falling within the whisker range. Outliers are defined as plotting outside the whisker range. Modified from Reimann (1997).*

Modern geologists are trained to use classical statistics to treat their data. It is rarely recognised that many of these techniques require that the data set shows a normal (or at least a log-normal) distribution. It is, however, a well-documented fact that geological data sets almost never follow the laws of a normal distribution (Davies 1980, McBratney et al. 1982). To overcome non-normality, geologists often use a log-transformation of their data set to approach a normal distribution. Surprisingly, they often then forget to apply the necessary statistical tests to assure that the resulting data distribution now follows Gaussian laws. If they did these tests - as for example McGrath and Loveland (1992) did for the data of the geochemical atlas of England and Wales - they would realise that (as a rule) this transformation does not produce normally distributed data at all. This would spell the end for classical treatment of geological data and of the received wisdom usually taught at university (Rock 1988). It is rarely realised that continuing to use classical statistics on a data set which shows neither a normal nor a log-normal distribution must lead to misleading results.

In all procedures in this thesis requiring data presentation and statistical treatment the techniques of EDA are used. EDA makes no assumptions on data distribution but is strongly based on rank statistics and the use of graphics to discover "unusual" data behaviour. EDA relies solely on the inherent structure of the data. This has several important advantages, including the clear delineation of the spread and the skewness of the data and the objective definition of data outliers. Experience using these methods has shown that analysing data using EDA-techniques readily brings out relations between, for example, chemical measurements and geographic and geological features (O'Connor et al. 1988, McGrath and Loveland 1992, O'Connor and Reimann 1993). An explanation of the boxplot used by the DAS-program is given in figure 3.5.2.

Extracting Data from the Bedrock Borehole Database

The quality of the information contained in the existing Bedrock Borehole Database (BBD) is very variable. It was therefore not possible to use the content of the BBD without critical examination of its quality. In principle, information about each borehole ought to have been confirmed before further use. NGU has not prioritised this type of quality control procedure, and, due to limited time, it would not be possible to check the information about every borehole for the purpose of this thesis. Therefore the extraction program ORACLE Browser 2.0 was used to extract some, previously identified, important categories of data from the BBD. Table 3.5.2 lists these extracted categories and the query options used to extract this information. The query options used in this initial extraction were purely to ensure that information exists about the geographical location of each borehole.

Table 3.5.2 Categories, description, query options and format used in retrieving boreholes from BBD.

Categories	Description and query options	Format
***Id**	Identification (unique string-variable)	String(6)
Zone	Universal Transverse Mercator System Zone	Numeric(2.0)
UTMX	East-West coordinates (in metres) is not null	Numeric(6.0)
UTMY	North-South coordinates (in metres) is not null	Numeric(7.0)
Totdepth	Total depth (in metres) of the bedrock borehole	Numeric(3.1)
Rockdepth	Thickness (in metres) of superficial deposits	Numeric(3.1)
Yield	Yield (in L/h)	Numeric(5.0)
Ddate	Date of drilling the borehole	Date

Groundwater yield of boreholes are usually assessed by blow-out tests at the termination of the drilling. In the blow-out tests the water blown out of the bedrock borehole using compressed air from the drill bit, is collected in a bucket or barrel of known volume. The duration of a blow-out test is normally 1-2 hours, and the driller makes several such estimations of the yield during the test. Yield of low-yielding bedrock boreholes (i.e. less than 100 L/h) are often measured using rising-level tests. In these tests the bedrock borehole is blown dry using compressed air from the drill bit and the rise of water level per time unit in the borehole is measured. Normally the driller performs this test after the water level in a bedrock borehole has reached a static level following drilling.

The short-time blow-out yields are not directly comparable with the yields measured by long-term pumping tests. The difference varies depending on local geology, duration of the pumping test and the amount of draw-down during the pumping test (Banks 1992). Long-term pumping tests have, however, generally not been carried out in bedrock boreholes in Norway. The measure of groundwater yield using blow-out tests or rising-level tests must nevertheless reflect the transmissivity of the hydraulic system in the near vicinity of the bedrock borehole and should, provided that the number of observations in different bedrock boreholes is large, be considered an adequate basis for the estimation of median short-term yield of bedrock boreholes in a rocktype.

A total of 15,054 boreholes were retrieved from the BBD. These boreholes were exported as a SYLK-file (Symbolic Link File) to Excel and stored as an Excel-file (XLS-file). To validate the quality of the total data set and examine it for possible errors, the boreholes were exported as a DBF4-file to the desktop geographic information system ArcView 3.0 GIS. To ensure correct transfer of all the columns in the DBF4-file, it was necessary that the first record contained a value in every column. Otherwise ArcView 3.0 GIS would transfer all columns with no value in the first record into string-format. This would occur independently of previous formatting in Excel.

Quality Control

After importation into ArcView 3.0 GIS, a total of four new categories were attached to the data set. An overview of the new categories is given in Table 3.5.3. The following describes how all boreholes with a possible information error were identified and deleted from the data set. All boreholes with no values in the two categories of depth and yield were also deleted.

The values in the categories totdepth and rockdepth were compared and 25 boreholes had identical values. It was assumed these duplicate registrations in the category of rockdepth were due to human error in the registration process but that the values itself were correct with respect to totdepth. For these 25 boreholes the value of depth was set to the value of totdepth and the value of rockdepth was set to zero.

Comparing the categories yield and totdepth, 57 boreholes had identical values. It was assumed that this also was due to human error in the registration process, and all 57 boreholes were deleted from the data set since one of the main categories did not contain any values. For the rest of the boreholes the value of depth was set to the subtracted value of rockdepth from totdepth. Checking the extreme values of depth, there were still 609 boreholes with no value. All these boreholes were deleted from the data set.

The next comparison revealed 42 boreholes with a higher value of rockdepth than depth. A closer investigation of the values showed that this probably was due to human error in the registration process and that the value of rockdepth actually should be the subtracted value of rockdepth from totdepth. For these 42 boreholes the value of depth was set to the value of rockdepth and the value of rockdepth to the subtracted value of rockdepth from totdepth. A new look at the extreme values of depth revealed 73 boreholes with a value of depth less than 10 metres. It is supposed that the registration of boreholes over the period of 46 years also includes some boreholes in Quaternary deposits. Since a bedrock borehole is usually deeper than 10 metres and the possibility exists that boreholes in Quaternary deposits are represented in the data set, all 73 boreholes were deleted from the data set.

Examination of the extreme values of yield revealed 1,431 boreholes with no yield or with yields between zero and 10 L/h (including 37 boreholes with yields between zero and 10 L/h). Low values in the category of yield may also be due to human errors in the registration process or to a unintended use of litres per second or minute instead of litres per hour. These boreholes were therefore deleted from the data set together with all boreholes with no declared value of yield.

The category of normalised yield was set to the value of yield divided by depth (drilled depth). Examination of the extreme values of normalised yield revealed 120 boreholes with both a value of normalised yield higher than 100 litres per hour per

Table 3.5.3 New categories attached to the data set retrieved from BBD.

Categories	Description
Depth	Thickness of superficial deposits deducted from the total depth of the borehole, i.e. the drilled depth in bedrock
Normalised Yield	Yield divided with drilled depth, (in Litres/hour per drilled metre)
Entity	Polygon identification in the digitised bedrock map of Norway (unique values for each polygon)
Rocktype	Bedrock type according to legend given in the digitised bedrock map of Norway (unique values for each type)

drilled metre and a value of depth less than 20 metres. It was possible that these boreholes actually were boreholes in Quaternary deposits, and to prevent errors in future calculations all 120 boreholes were deleted from the data set.

The coordinates registered in the BBD are connected to five different zones in the Universal Transverse Mercator System (UTM). In this system the globe is divided into sixty zones, each spanning six degrees of longitude. This projection is a specialized application of the Transverse Mercator projection. Each zone has its own central meridian from which it spans 3 degrees west and 3 degrees east. X- and Y-coordinates are recorded in metres. The (N-S) origin for each zone is the Equator and the E-W origin its central meridian. To be able to use the geographic part of ArcView 3.0 GIS, all coordinates had to be converted from their actual zone to zone 32, which has been chosen as the standard UTM zone for this thesis. To enable this conversion, all boreholes in UTM zones 33, 34, 35 and 36 were exported from and then again imported into ArcView 3.0 GIS using separate DBF4-files. Using an optional extension in ArcView 3.0 GIS, Projector!, the coordinates were converted into the chosen standard UTM zone 32. All five DBF-files were taken into ArcView 3.0 GIS for further geographic evaluation. An examination of the geographic location of the boreholes revealed three boreholes with coordinates locating them far away from Norway. These boreholes were deleted from the data set.

Using the attribute-file of the digitised bedrock map of Norway and adjacent ocean areas (Sigmond 1992), all boreholes were assigned a value representing the categories of entity and rocktype. It was not possible to use a digitised bedrock map containing fjords and islands because the inaccuracy of the map combined with some inaccuracy in the coordinates of the boreholes and the fact that a lot of boreholes are drilled in the vicinity of the sea, led to more than 1,000 boreholes appearing to be located in the ocean. Entity is a unique value identifying the different polygons in the digitised bedrock map of Norway and rocktype is a unique value according to the legend given in the same digitised bedrock map. Due to some inconsistency in the digitised map, four boreholes were not given any values in the categories of entity and rocktype. These boreholes were deleted from the data set. A further description of the content of the categories of entity and rocktype is given in Chapter 2.3.

Having completed this quality assessment of the initial data set, a total of 12,757 boreholes were considered to have satisfactory data accuracy and quality to be used in this thesis. 2,297 boreholes (15,3 % of the initial number of extracted boreholes) had been deleted. The remaining boreholes were exported into Excel using a DBF4-file.

Chapter 4

The Petrology and Geochemistry of Norwegian Bedrock with special emphasis on the Oslo and Bergen Areas

4.1 Introduction

An increased use of groundwater from bedrock boreholes in Norway (Chapter 3.2) has enabled the investigation of possible relationships between different lithologies and the chemistry of the groundwater they contain. There are at least seven important factors influencing the chemistry of groundwater in bedrock:

- Degree of weathering/alteration
- Hydraulic conditions (e.g. residence time, fracture aperture)
- Chemical composition of the recharge water
- Superficial Quaternary sediments
- Rock-water and water-water chemical interactions
- Stability of the bedrock minerals, mineralogy and mineral chemistry
- Fracture mineralization

The potential for groundwater flow and interaction with bedrock minerals is dependent on the hydraulic conditions at the surface and within the bedrock. Groundwater is in contact with the open faults and joints within the rock in which it is flowing. These fractures vary enormously in terms of their width, length, direction, the presence of clay and other minerals and their relationship with other faults and joint systems in the bedrock. The physical characteristics of joint systems are controlled by the physical properties of the bedrock itself and the processes influencing the bedrock during its geological evolution.

Table 4.1.2 *Average composition of igneous rocks and glacial clay (percent as oxides). From Goldschmidt (1954).*

Element	Igneous rocks	Glacial clay
SiO_2	59.12	59.19
TiO_2	1.05	0.79
Al_2O_3	15.34	15.82
Fe_2O_3	3.08	3.41
FeO	3.80	3.58
MnO	0.12	0.11
MgO	3.49	3.30
CaO	5.08	3.07
Na_2O	3.84	2.05
K_2O	3.13	3.93
H_2O	1.15	3.02
P_2O_5	0.30	0.22
SO_3	-	0.08
S	0.05	0.07
CO_2	0.10	0.54

In addition to the influence of superficial deposits, chemical interaction between the groundwater and bedrock and the stability of the rock.forming minerals are usually considered to be the most important factors governing groundwater chemistry. In order to understand the different types of chemical interaction occurring between groundwater and bedrock minerals, it is necessary to have a knowledge of the mineralogical and chemical composition of the bedrock and fracture minerals.

The chemical composition of different rocks has always been of primary interest for geologists. E.g. Goldschmidt (1954) referred to the average composition of igneous rocks found by Clarke & Washington (1924) and compared their results with the average composition of glacial clay (see Table 4.1.2). There exists no national overview of the geochemistry of Norwegian bedrocks, although such a lithogeochemical mapping has been carried out in Finland and will be presented in a Finnish geochemical bedrock atlas (in prepararion). In Norway there exists two data sets which may to some extent reflect the pattern of element content of Norwegian bedrock. These are the geochemical atlas of Norway based on overbank sediments (Ottesen et al. in prep.) and the geochemical atlas of stream sediments in Southern Norway (Nilsen & Reimann 1996). The work of Ottesen et al. (in prep.) divides Norway into 29 different regions based on geological rather than lithological criteria. The results of Ottesen et al. (in prep.) are therefore not easily related to different lithologies, and are only used here to illustrate the elements enriched in the Oslo Region. The work of Nilsen & Reimann (1996) has related the element content of the stream sediments in Southern Norway to the underlying lithologies, using the digital map derived from Sigmond (1992), i.e. the same digital map used in the assignment of lithologies to bedrock boreholes in Chapter 2.3. Another three national data sets based on samples of soils (A- and B- horizons) and moss (Njåstad et al. 1994) also exists. These data sets also shows a similar distribution of element content compared to the data set of Nilsen & Reimann (1996). The element content of stream sediments are therefore used in Chapter 4.2 to give an impression of the relatively varying element content in different lithologies (however, the absolute element content in stream sediments will significantly differ from that of the pristine bedrock, due both to weatering and sorting of the sediments and to non-total analytical extraction techniques). The user's guide to the bedrock map of Norway (Sigmond et al. 1984) has been used as a basis for Chapter 4.2.

4.2 Petrology and Geochemistry of Norway

James Hutton (1727–1797), the eminent 18th century gentleman farmer and one of the founders of modern geoscience, pioneered the concept of the rock cycle (Figure 4.2.1), which depicts the interrelation between igneous, sedimentary and

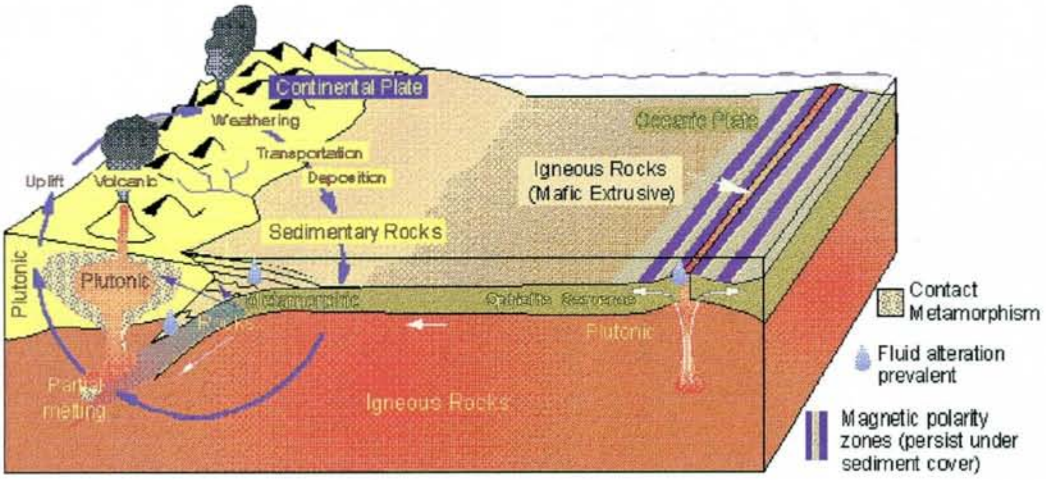


Figure 4.2.1 *The rock cycle. Redrawn and modified from Montgomery (1990) and Monroe and Wicander (1994).*

metamorphic rocks (Hutton, 1970). In Norway, most rocks have been subject to metamorphism to a greater or lesser degree.

Igneous rocks

Several types of volcanic rocks and phenomena occur in the Oslo Region, including the remains of volcanic craters and large calderas such as those at Glitrevann, Drammen and Ramnes (see Figure 4.2.2 and Type 3 in Figure 2.1.2). Today, the calderas are not seen as depressions in the landscape. After the Permian period the upper rocks were removed by erosion, so that a deeper section of the calderas is exposed today.

According to Ottesen et al. (in prep.), the Oslo Region is enriched geochemically in Be, Ce, K, La, Mo, Nb, Zn and W compared to the total median element content of all their analysed overbank sediment samples (687). According to the work of Nilsen & Reimann (1996), the stream sediments overlying plutonic rocks (rocktype 54) of the Oslo Region (see Figure 4.2.3) have a higher content of Pb compared to stream sediments overlying most of the other rocktypes. The use of stream

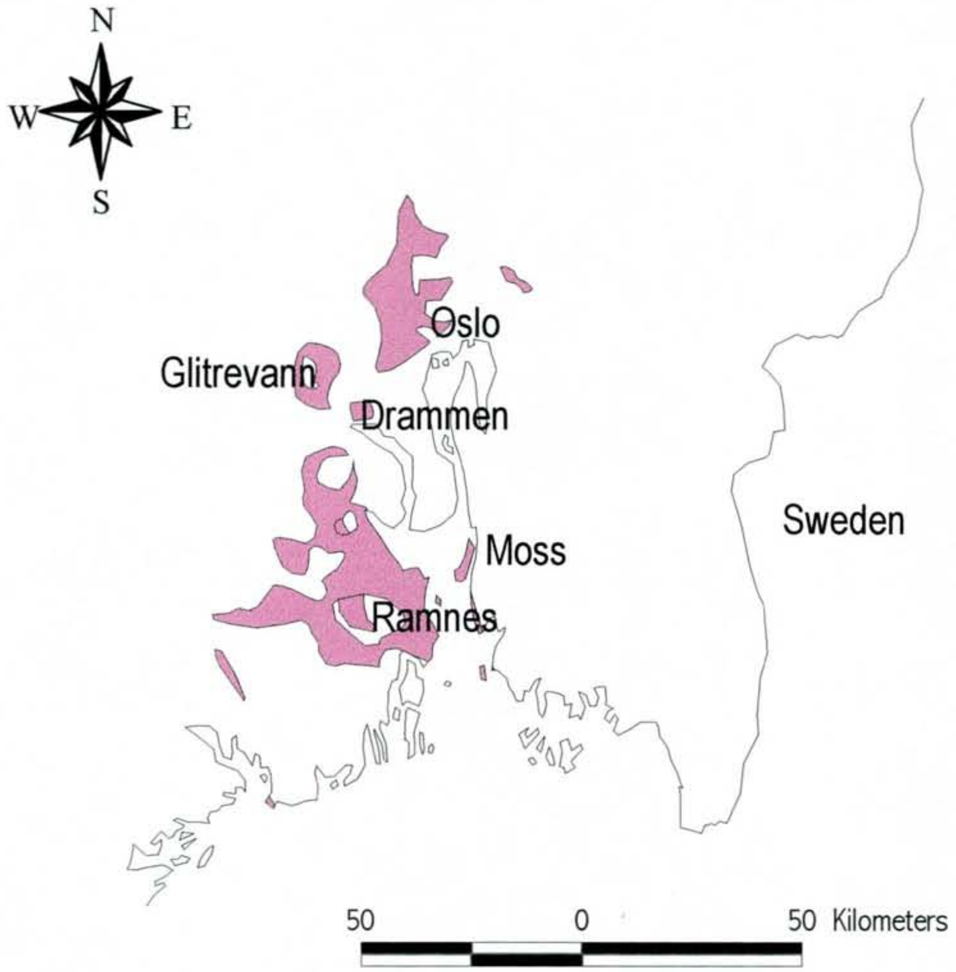


Figure 4.2.2 *The distribution of extrusive rocks, explosion craters and large calderas in the Oslo Region.*

sediments to compare the composition of underlying lithologies may be difficult, since the element content may vary over several orders of magnitude within the bedrock itself and between different outcrops of similar bedrocks. According to Stumpfl & Sturt (1964), the element content of two geographically different gabbroic rocks at Sørøy, in the county of Finnmark, varies due to compositional variations of the respective local magmas and/or granitization. The element content of stream sediments is, however, believed to reflect the regional trends of the bedrock composition. A geological assessment of this problem have been carried out by Nordgulen (1996). He points out that areas of high or low element content in stream sediments for most of the elements, with some exceptions, may be explained by the underlying lithology. Some geological provinces differ from this general pattern with respect to groups of elements or the whole data set (for further information, see Nilsen & Reimann 1996). Based on this assumption, Nilsen & Reimann's (1996) data set has therefore been used in this chapter to illustrate possible differences in litho-geochemical composition between different lithologies in Southern Norway.

Norwegian plutonic, hypabyssal and extrusive rocks can be divided into several sub-groups based on their quartz content (Table 4.2.1). Plutonic rocks are generally medium- to coarse-grained whereas hypabyssal and extrusive rocks, which have cooled and crystallised more rapidly, are fine-grained. For example, in Permian dykes in the Oslo Region there are larger crystals scattered in a finer grained ground mass. Plutonic rocks are particularly prevalent in the Oslo Region (Figures 4.2.3 and 2.1.2). An example is the biotite granite of the Drammen Granite (see analyses in Tables 4.3.3 and 4.3.4). These rocks were originally formed deep in the Earth's crust but now occur at the surface, as the previously overlying rocks were removed by erosion over millions of years.

Hypabyssal rocks are common in Norway, but most of their exposures are too small to be shown on Figure 4.2.3. The Permian dykes of syenite and rhomb porphyry, which occur between Tyrifjorden and Valdres, are unusual, however, simply because of their length. The longest of these dykes can be followed over some 115 km!

Extrusive rocks occur, for example, on the island of Jeløya, west of Moss (Figure 4.2.2) where basalt covers most of the island. These basalts were extruded during a volcanic eruption during the Permian period, approximately 250-290 million B.P. Analyses of the basalts have been carried out by Neumann et al. (1990) and Grimmer (1991). The analyses of Neumann et al. (1990) are given in Table 4.3.2. According to the work of Nilsen & Reimann (1996), the stream sediments overlying extrusive rocks (rocktype 57) of the Oslo Region (see Figure 4.2.3) have

Table 4.2.1 *Sub-groups of Norwegian plutonic and extrusive rocks classified according to their quartz-content (SiO_2). The SiO_2-content is calculated as the percentage of light-coloured minerals present in the rock. Compiled from Sigmond 1984.*

SiO_2-content	**Plutonic rocks**	**Extrusive rocks**
> 20%	granite, charnockite, quartz porphyry, granodiorite, enderbite, tonalite, trondhjemite	rhyolite, dacite, trachyte, latite
5-20%	syenite, monzosyenite, monzonite, quartz monzonite, mangerite, quartz diorit, monzodiorite, monzogabbro, diorite	dacite, andesite
< 5%	nepheline syenite, gabbro, monzonorite, jotunite, norite, anorthosite, dolerite	basalt

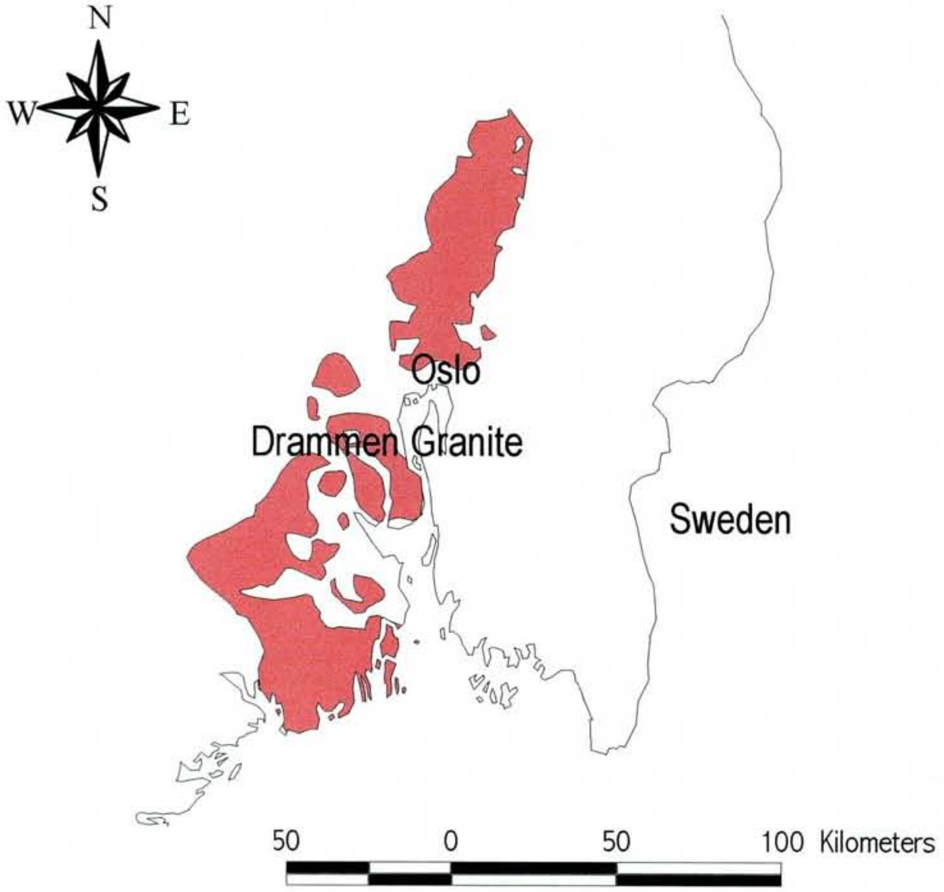


Figure 4.2.3 *The distribution of Permian plutonic rocks in the Oslo Region (rocktype 54)*

a similar composition to stream sediments overlying rocktype 54. Stream sediments overlying rocktype 54 have elevated contents of Fe and Mo compared to stream sediments overlying rocktype 57, possibly reflecting the high Mo content of e.g. the Drammen Granite.

Sedimentary rocks

In Norway, there are thick sequences of sandstones, conglomerates and sedimentary breccias. Examples of these can be found in the Devonian sediments occurring between Sognesjøen and Nordfjord (Figure 4.2.4 and Type 5 in Figure 2.1.2). According to the work of Nilsen & Reimann (1996), stream sediments overlying Devonian sedimentary rocks (rocktype 64) have a higher content of Cr, Pb and Ti and a lower content of Ba, Mo, Na and Zn than stream sediments overlying most other rocktypes. Quartz sandstone of Precambrian age occur in the Moelv-Rena area and on the Varanger Peninsula (Figure 4.2.4 and Type 6 in Figure 2.1.2). The occurrence of such rocks shows that the area was covered by glaciers or ice-sheets in Upper Precambrian time - that is more than 600 million years ago. According to the work of Nilsen & Reimann (1996), stream sediments overlying such quartz sandstones (rocktype 79) have a higher content of Ba, Mn and Zn and a lower content of Ca, Cr, Cu and Ti than stream sediments overlying most of the other rocktypes.

Other sedimentary rocks, which are also economically important, include limestone and dolomite. Limestones are particularly prevalent in the Oslo-Mjøsa district (Figure 4.2.4 and Type 6 in Figure 2.1.2). According to the work of Nilsen & Reimann (1996), stream sediments overlying Cambro-Silurian limestone and marble (rocktype 75) in the Oslo-Mjøsa district have a higher content of Ba, V and Zn and a lower content of Ti than stream sediments overlying most of the other rocktypes.

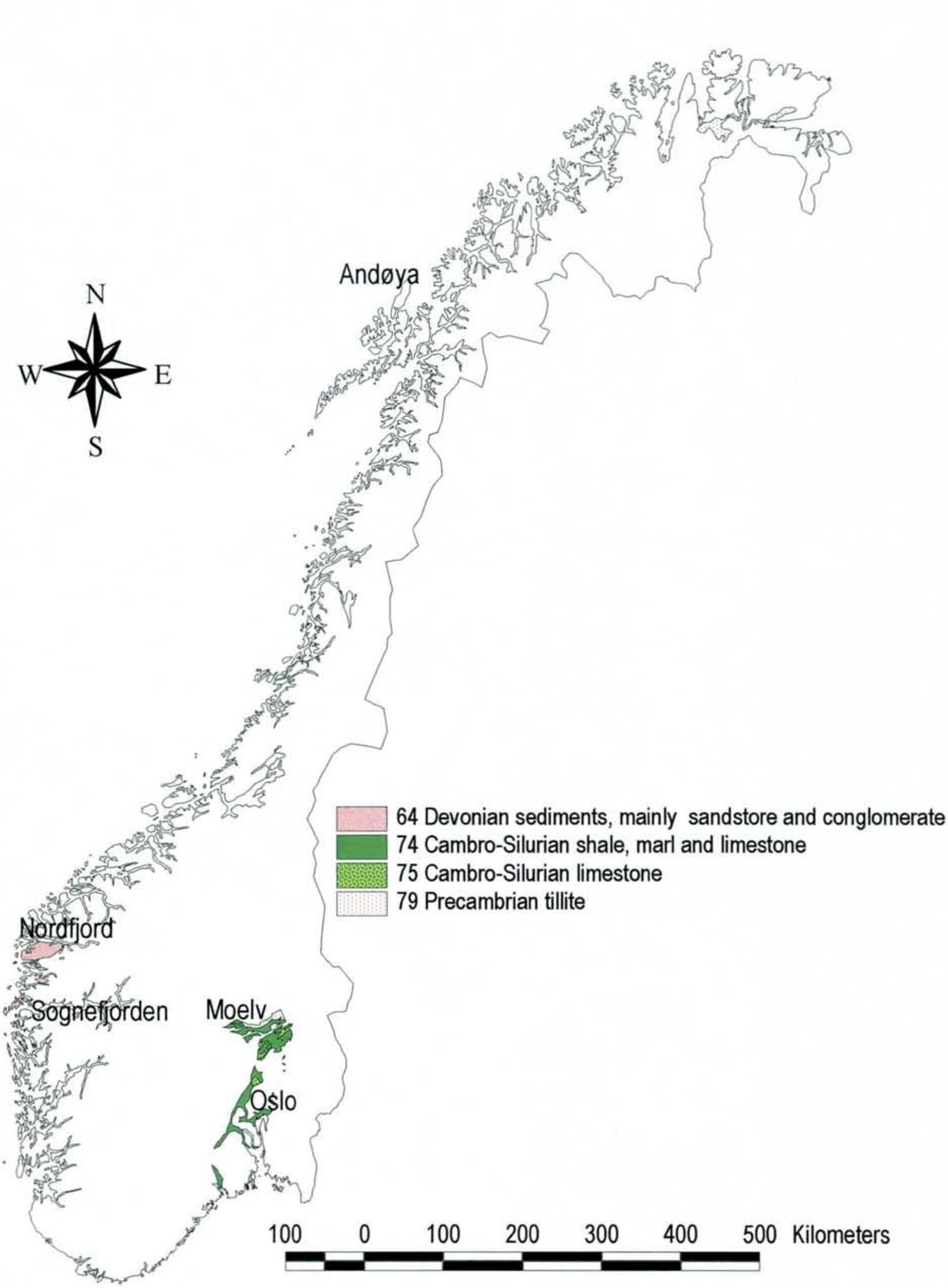


Figure 4.2.4 *The distribution of some sedimentary rocktypes in Norway mentioned in the text. On the island of Andøya, the youngest sedimentary rocks on the Norwegian mainland occur.*

Metamorphic rocks

Most of the rocks exposed in Norway are between 250 and 2,800 million years old and show varying degrees of metamorphism. During the long period since their formation many of these rocks have been affected by folding and thrust deformation. Often these rocks have been buried to great depths in the crust on one or more occassions and subjected to high pressures and temperatures. Some may also have partially or completely melted before re-crystallisation.

As a result of high temperature and pressure, rocks undergoing metamorphism generally acquire a new internal texture in the form of a parallel orientation of minerals. They therefore become foliated or schistose and original internal structures, such as bedding, may be partially or totally destroyed. The prefix "meta" is commonly used to indicate that the rock has been metamorphosed; for example a metasandstone is a metamorphosed sandstone. For convenience we can divide the metamorphic rocks into three main groups.

Metamorphosed igneous rocks

Metamorphosed plutonic rocks occur in many places in Norway (see Type 7 in Figure 2.1.2). Examples of such rocks include the foliated granite occurring at the northern end of Tinnsjø and at Flavatnet in Telemark. Where Norway is at its narrowest, between Hellemofjorden and the Swedish border in the coounty of Nordland, the exposed bedrock is composed solely of foliated granite. According to the work of Nilsen & Reimann (1996), stream sediments overlying rocktype 98 have a composition which does not differ greatly from the average composition of stream sediments overlying the other rocktypes.

Metamorphosed extrusive rocks occur in stratigraphic sequences of Archaean to Silurian age, while unmetamorphosed extrusive rocks are found in the Devonian and Permian successions (see Types 3 and 5 in Figure 2.1.2; locations given in Figure 4.2.2 and 4.2.4). Volcanic eruptions have occurred in Norway throughout

Table 4.2.2 *Element analyses of samples taken from greenstones in the Trøndelag area by Nilsen et al. (1993). For the analyses of major elements by XRF (top eleven results), and of F, S and C by combustion, the results are given in percent. For trace elements (XRF), the results are given in ppm. The sample names refers to Nilsen et al. (1993).*

	GK7	GK20	JA12	LN09	LN14	SS09	SS20
Si	27.39	29.91	23.78	27.74	20.91	28.32	22.01
Al	4.4	4.55	7.04	9.13	7.55	7.07	7.57
Fe	14.42	11.68	8.76	4.25	7.97	6.62	9.81
Ti	0.13	0.22	0.74	1.37	0.73	0.71	0.91
Mg	1.95	2.07	4.58	1.2	6.3	1.98	4.66
Ca	2.02	1.47	3.55	1.39	4.92	2.31	2.79
Na	-	-	3.69	3.98	3	3.89	1.93
K	0.11	0.03	0.20	2.08	0.07	0.04	0.02
Mn	0.09	0.10	0.15	0.02	0.10	0.09	0.36
Zn	0.037	0.005	0.360	0.44	0.011	0.015	0.081
Cu	0.133	0.068	0.045	0.005	0.010	0.006	0.005
F	-	-	-	-	-	-	-
S	3.16	0.72	2.18	0.04	0.00	0.16	0.85
C	0.66	0.47	0.15	0.08	0.92	0.54	0.90
Ag	-	-	-	-	-	-	-
As	24	16	25	29	15	15	26
Ba	92	26	33	72	14	18	16
Cd	-	-	-	-	-	-	-
Ce	11	-	35	38	14	25	20
Co	39	27	35	17	38	12	28
Cr	-	-	322	18	178	-	15
La	-	-	11	14	-	-	-
Mo	-	-	-	-	-	-	-
Ni	-	-	113	7	38	-	18
Pb	12	-	-	-	-	-	-
Sb	-	-	-	-	-	-	-
Sc	19	21	34	32	34	26	45
Sn	-	-	-	-	-	-	-
Sr	38	-	41	37	43	117	50
V	27	70	252	209	234	121	390
W	-	-	-	-	-	-	-
Zr	99	66	105	243	78	127	69

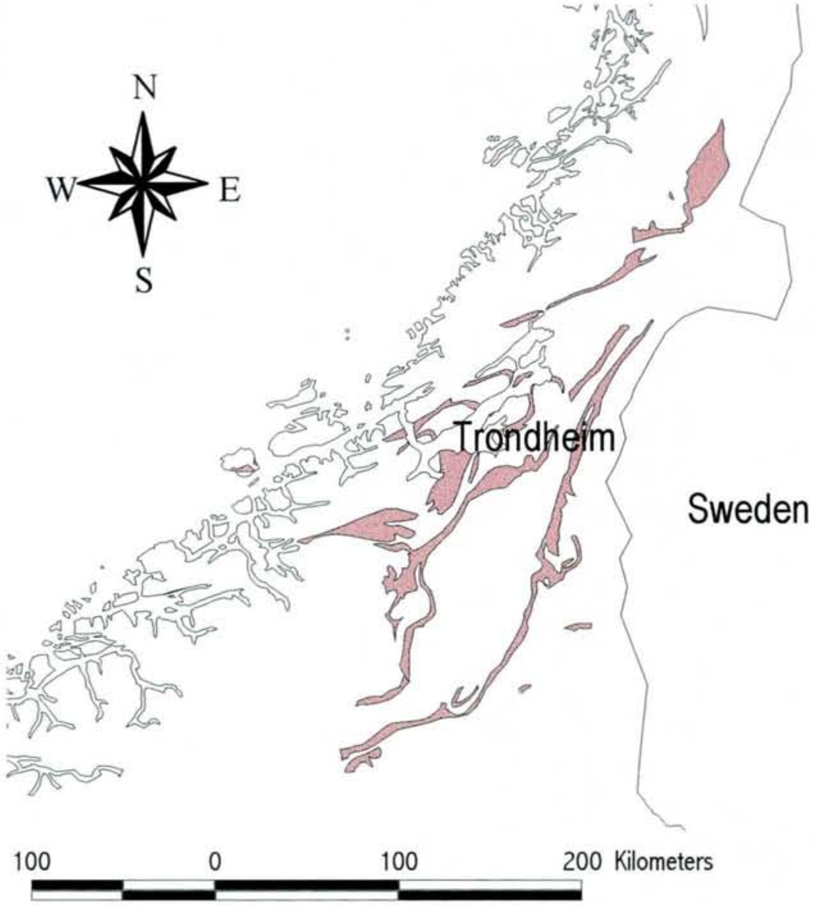


Figure 4.2.5 The distribution of greenstone rocks in the Trøndelag region.

the Earth's history from Archaean to Permian time, and metamorphosed volcanic rocks can be found in almost every county. The most common volcanic rock type on Earth is basalt. Weakly metamorphosed basalt (greenstone) covers large areas of Norway, e.g. in Trøndelag (see Figure 4.2.5 and Type 8 in Figure 2.1.2). In terms of internal structure and chemical composition these greenstones are very similar to the basalts which are found on the ocean floor today. The greenstone rocks in and around Trondheim (Figure 4.2.5), for example, were originally basaltic lavas which flowed out on to the ocean floor in Cambrian or Early Ordovician time. Many of Norway's most important occurrences of pyritic massive sulphide ores are found in association with these metamorphosed basalts. According to the work of Nilsen &

Reimann (1996), stream sediments overlying greenstone (rocktype 76) have a higher content of Cr, Cu, Mg, Na, Ni, Ti and V and a lower content of Pb than stream sediments overlying most of the other rocktypes. Analyses of greenstone from the Trøndelag area (Nilsen et al. 1993) are given in Table 4.2.2.

Amphibolite is formed as a result of the regional medium-grade metamorphism of basic igneous rocks such as basalt or dolerite; such rocks occur extensively in the northern part of Setesdal and in Telemark (see Type 7 in Figure 2.1.2). Ultramafic lava (very low SiO_2-content) and a variety of volcanic rocks with exceptional chemical compositions, occurs in the vicinity of Karasjok (see Type 7 in Figure 2.1.2).

Metamorphosed sedimentary rocks

Large areas of Norway consist of metamorphosed sedimentary rocks. Meta-sandstones, for example, occur at Gaustatoppen, Lifjell, Seljord, in the area from Gudbrandsdalen to the Swedish border and in the region from Reisadalen to Varangerfjorden. In places, where these rocks have been particularly strongly deformed, they have been transformed into flagstones. These flagstones are quarried as dimmension stones and used for various construction purposes, e.g. at Oppdal and Alta. According to the work of Nilsen & Reimann (1996), stream sediments overlying such sandstones and shales (rocktype 80) have a composition which does not greatly differ from the average composition of stream sediments overlying the other rocktypes.

The progressive metamorphism of shales or clay-rich rocks leads to the formation of slate, phyllite, mica schist and mica gneiss. Such rock types occur beneath the overthrust gneisses from Stavanger to western Hardangervidda and Hallingskarvet and are also found extensively from Dombas to Kvikne, Gauldal, Tydal and Verdal and further north to Lyngen (Type 8, Figure 2.1.2). Metamorphosed limestone and dolomite, calcite marble and dolomitic marble, occur in many places throughout the country, but are particularly common in northern Norway (Type 8, Figure 2.1.2).

Metamorphosed rocks of unknown origin

In many places, the rocks are so strongly metamorphosed that it is difficult to determine their precise origin, e.g. gneisses and migmatites. Gneiss is perhaps the most common rock type in Norway. Terms such as granitic gneiss and dioritic gneiss refer to gneisses which contain the same minerals as in granite and diorite, respectively, but these rocks are not necessarily metamorphosed granite or diorite. A granitic gneiss, for example, can be of completely unknown origin. It may be a metamorphosed granite but it may equally originate from a sandstone. Amphibolite is another metamorphic rock type which can be derived from a variety of rocks. It can be formed from a plutonic or extrusive rock or from a sediment. Granulite is formed at very high temperatures, has a gneiss-like structure and covers large areas north-west of the Tana river in the county of Finnmark (Type 8 in Figure 2.1.2).

Migmatite and migmatitic rocks are the products of intense metamorphism and partial melting of pre-existing rocks. Migmatites consist of a darker, generally gneissose older part (paleosome) and a lighter newly-crystallised granitic part (neosome). The neosome is generally seen as irregular veins and dykes which transect older structures in the paleosome.

Migmatitic gneiss and migmatite are common rock types in the extensive north-western gneiss region (NWGR) from Sognefjorden to Vikna (Type 2, Figure 2.1.2). The rocks in this region have been metamorphosed at such great depths in the Earth's crust that in some places the unusual rock type eclogite can be found. The origin of eclogite is of special interest to research geologists from all parts of the world. People living in Stadlandet have this rock type, formed at crustal depths of around 60-70 km, right outside their doorstep.

Mylonite is a fine-grained, fissile flint-like rock which is formed by intense ductile deformation and recrystallisation of various other rock types along thrusts and other high-strain movement zones.

The simplified geological map in Figure 2.1.2 shows which rocks are autochthonous and which are allochthonous. For example, the autochthonous Precambrian (basement) rocks (Type 7) occur in south-eastern Norway and the eastern part of Finnmark. Rocks of Precambrian to Silurian age, which were thrust over the Precambrian basement and overlying autochthonous sedimentary rocks during the development of the Caledonian mountain chain, occur in a wide belt from the Stavanger district in the south to Finnmark in the north (Type 8).

4.3 The Oslo Region

The term "Oslo Region" is here used to refer to an area of about 100,000 km^2 centred on the City of Oslo (Figure 5.1.1). Extending from the Mjøsa District in the north to the southern part of Oslofjord in the south, the Oslo Region is approximately 220 km long and varies in width from 35 to 65 km (Dons 1978). In contrast to its surrounding Precambrian rocks, the sedimentary sequences of the Oslo Region are mainly of Cambrian, Ordovician and Silurian age, but there are also sediments, plutonic and volcanic rocks of Permian age, possibly also of Upper Carboniferous and Triassic age (Ramberg 1976).

The term "Oslo Graben" refers to the on-land part of a larger rift structure called the "Oslo Rift" that continues towards the south into Skagerrak (the North Sea). This graben was formed in Carboniferous-Permian times. The term "Oslo Area" is used as a purely non-generic, geographic term referring to the urban area of Oslo and its immediate surroundings. In the context of this thesis, the term “Oslo Area” relates mainly to the area of bedrock boreholes described in Chapter 5 .

The Oslo Region is tectonically dominated by the Carboniferous-Permian Oslo rift. Within the rift Precambrian basement rocks and Cambro-Silurian sedimentary rocks occur, including U-rich alum shales near the bottom of the sequence. These sediments are unconformably overlain by volcanic rocks (basalts, latites and trachytes) and sediments of Carboniferous-Permian age. The Precambrian basement rocks and the sedimentary and volcanic cover are intruded by younger igneous rocks (monzonites, syenites and granites) of mainly Permian age. The volcanics in the Oslo Rift are a very favourable lithology for drilling hard rock groundwater boreholes with exceptionally high yields. To the east and west of the Oslo rift, autochthonous Precambrian basement consisting mainly of gneisses, granites and amphibolites dating from the time of the Sveconorwegian orogeny or earlier are found.

The Permian igneous rocks in the Oslo Region have a clear alkaline affinity. The basic lavas include ankaramites and nefelites as well as basanites, alkali-basalts and tholeiittic types. There are also trachyte lavas which can be interpreted as differentiates of basaltic magmas. The frequent occurrence of rhomb porphyry lavas was probably formed by differentiation of a deep alkali-basaltic magmatic reservoir. There are also some ryholitic vulcanites present, partly developed as ignimbrites.

Studies of trace elements and isotopic relationships suggest that the magmatic rocks of the Oslo Region have not been contaminated to any great extent by crustal rocks but have originated from a relatively rare magmatic type. The same rare magma type has also been found in other parts of the world in connection with major faults, for example in Eastern Africa. The Larvikite rock is the most common plutonic rock in the Oslo Region and is chemically almost identical to the rhomb porphyry lavas (monzonittic).

The entire Oslo Region has been exposed to a high degree of hydrothermal alteration during the tectonic evolution of this area. This is particularly evident in the Drammen granite. This structurally destructive metamorphism can hardly be recognised on the surface, but is the reason why this so-called "hard rock" terrain has caused major difficulties during the excavation of the railway tunnel from Drammen to Oslo (Rohr-Torp pers. comm.).

Previous Investigations in the Oslo Region

The first studies of the Oslo Region were carried out by the Department of Geology at Oslo University (founded in 1811). The University's first professor, J. Ersmark (1763-1839), had gained a good knowledge of the area by the time the famous German geologist Leopold von Buch (1774-1853) visited Oslo in 1806 and 1808. Through von Buch's report ("Christiania Übergangsterritorium"), the area was brought to the attention of an international scientific audience.

In the middle and late 19th century, the Oslo Region was studied by several famous geologists including B.M. Keilhau, F.L. Hausmann, C.Fr. Naumann, Charles Lyell and Th. Kjerulf. During a period of more than 60 years, Professor W.C. Brøgger (1851-1940) wrote about 60 publications covering almost every subject relating to the geology of the region. A number of other well-known geologists have contributed to the geological understanding of the Oslo Region and work to increase our understanding of the geology of the region is continuing today.

Petrology of Selected Rocks of the Oslo Area

The lithologies described here are those in which bedrock boreholes have been drilled in the Oslo Area (see Chapter 5). As shown in Figure 4.3.1, most of the boreholes are located in the Drammen Granite and in the volcanic rocks north of the Ramnes Caldera. The digital bedrock map of Norway (Sigmond 1992) is not sufficiently detailed to be used to determine the lithology of each borehole in order to compare the lithology and hydrochemistry of the boreholes (Morland et al. 1995).

A more detailed lithological assessment was therefore carried out. In the Oslo Area, the bedrock boreholes were divided into five main categories (Table 4.3.1). Four of these categories cover 96% of all the boreholes examined in this area. Two of the main lithological categories, the Permian basalts and the Drammen Granite, will be described more in detail with regards to petrology and geochemistry. For the

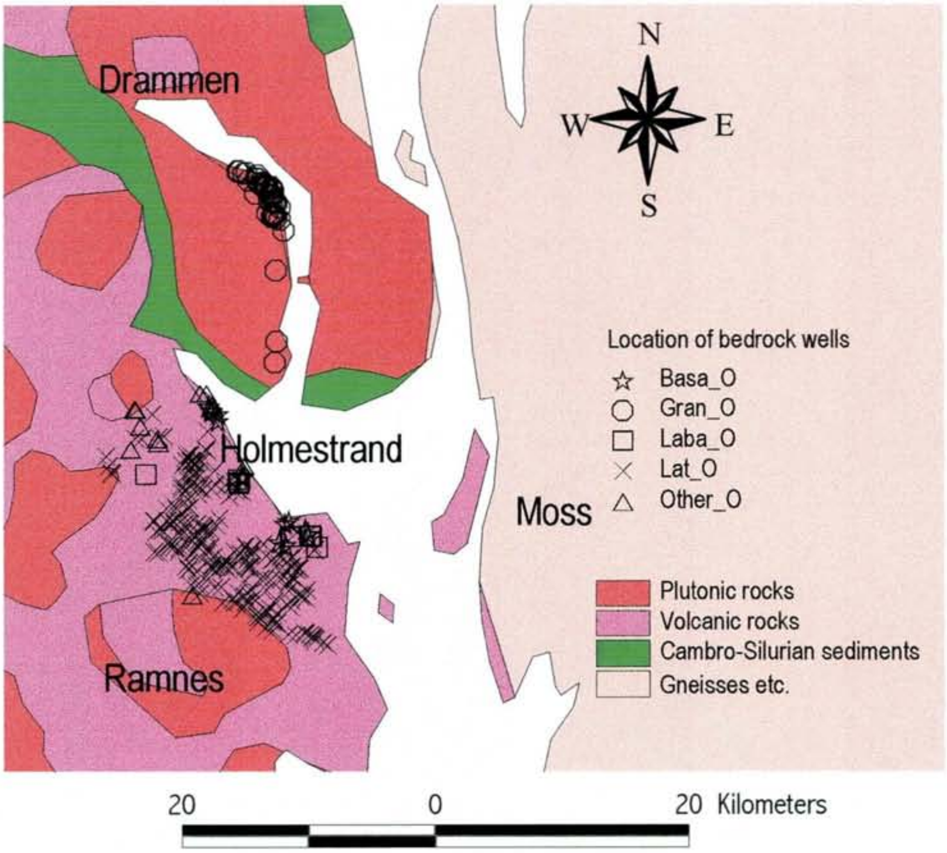


Figure 4.3.1 *Map of part of the Oslo Region indicating the location of different rock types. The location and lithology of all sampled boreholes is also shown.*

Table 4.3.1 *The five main lithological types containing sampled bedrock boreholes in the Oslo Area.*

Lithological category	**Number of boreholes**	**Rocks**
Basa_O	18	Permian basalts
Gran_O	44	Drammen Granite
Laba_O	10	Permian latites and basalts
Lat_O	227	Permian latites and rhomb porphyry lavas
Other_O	12	Basic igneous rocks, trachyte, syenite, metasandstone

other main rock categories the author has been unable to locate any geochemical analyses. According to Dr. R.G. Trønnes of the Mineralogisk-Geologisk Museum in Oslo, no litho-geochemical analyses exist from these lithologies.

Permian Basalts

Magmatism in the Oslo Rift occurred from about 280 to 230 million years B.P. The extensional period started with the formation of grabens and the simultaneous extrusion of large volumes of basaltic lavas, the so called B_1 series. These basalts are almost entirely covered by younger lavas (Figure 4.2.2), but are now exposed in the Skien area, along the eastern margin of the Vestfold lava field, at Jeløya outside Moss (Figure 4.2.2) and along the western and southern margin of the Krokskogen Lava Field just north of Oslo.

The B_1 lavas decrease in thickness and alkalinity towards the north (Neumann et al., 1990). In the Vestfold-Jeløya area, the B_1 lava sequence is sub-alkaline to mildly alkaline and shows large local variations in thickness (180 - 1,500 meters). The B_1 volcanism was succeeded by the extrusion of numerous flows of rhomb-porphyry lavas. This extrusive period culminated in the formation of volcanoes, many of which developed into calderas (e.g. Brøgger 1933, Oftedahl 1953, Ramberg et al. 1978 and Larsen et al. 1983). A series of small intrusions of layered gabbro (Oslo-essexite) may represent feeders to basaltic volcanoes (Neumann et al. 1985).

During and after the time of caldera formation, a number of large, nearly circular, felsic batholiths were emplaced in the shallow crust (Figure 4.2.3). The igneous activity in the Oslo Rift was accompanied by extensive dyke emplacement. The major dykes are contemporaneous with the main phase of magmatic activity (Neumann 1990). It has been estimated that uplift and erosion have removed the upper 1-3 km of the Permian upper crust, exposing the roots of the Oslo magmatic complex (Oftedahl 1952).

Table 4.3.2 *Element analyses of samples taken from the B_1 basaltic lava sequence in the county of Vestfold by Neumann et al. (1990). For the analyses of major elements (the top eleven results), the results are given in weight percent. For trace elements, the results are given in ppm. LOI = loss on ignition, n.a. = not analysed. From Neumann et al. (1990).*

	OB102	OB101	OB100	OB99	OB98	OB97	OB96
SiO_2	46.06	44.51	45.30	45.03	47.78	47.95	47.16
TiO_2	4.48	3.03	4.66	3.36	3.26	2.45	2.44
Al_2O_3	7.55	12.87	10.03	8.12	9.38	16.05	11.21
Fe_2O_3	14.23	13.25	14.78	15.11	14.14	11.51	13.81
MnO	0.16	0.20	0.20	0.19	0.19	0.16	0.28
MgO	11.71	9.18	7.49	11.40	9.18	5.83	8.30
CaO	10.71	11.38	10.97	11.84	10.88	8.71	11.91
Na_2O	1.34	2.31	2.11	1.53	2.30	3.74	2.35
K_2O	1.29	1.14	1.94	1.61	1.72	1.99	1.12
P_2O_5	0.50	0.58	0.72	0.58	0.60	0.48	0.42
LOI	0.89	0.28	0.50	n.a.	n.a.	n.a.	n.a.
Sc	33.2	23.2	27.2	32.9	28.2	18.5	43.3
Cr	876	330	403	769	551	111	304
Co	44.5	54.7	56.7	67.7	60.0	41.2	55.0
Ni	262	68	149	275	163	34	57
Rb	24.8	14.5	45.0	28.7	28.5	62.9	18.2
Sr	174	2390	1002	921	778	1452	573
Y	26.8	19.4	41.1	30.9	36.1	20.6	30.4
Zr	282	218	402	252	283	201	179
Sb	0.11	0.15	0.13	0.13	0.15	0.06	0.02
Cs	0.48	1.31	0.25	0.43	0.24	1.68	2.49
Ba	438	1139	410	439	447	556	326
La	58.0	60.8	79.1	59.7	58.0	44.0	36.4
Ce	117.7	105.7	148.4	110.8	110	82.4	72.8
Sm	10.9	9.5	16.4	11.1	9.8	7.1	7.9
Eu	3.3	2.9	4.4	3.5	3.2	2.3	2.3
Tb	1.03	0.86	1.39	1.03	1.15	0.76	0.88
Dy	6.3	4.3	8.0	5.7	6.5	4.5	n.a.
Yb	1.9	1.1	2.3	2.2	1.9	1.4	2.1
Lu	0.25	0.18	0.36	0.27	0.27	0.22	0.33
Hf	9.8	7.5	10.8	9.8	9.9	6.7	5.7
Ta	4.62	4.51	4.62	4.38	4.37	3.05	2.58
Th	6.09	4.82	8.05	5.06	6.35	4.29	3.06
U	2.0	1.5	1.5	0.90	2.1	1.2	0.85

The B_1 basaltic lava sequence in the county of Vestfold has been sampled by Neumann et al. (1990) and Grimmer (1991). Due to uncertainty in the location of the analyses of Grimmer (1991), only the analyses from Neumann et al. (1990) have been used in the following comparison. The samples were collected from a 90 m thick exposure of seven successive lavas near the town of Holmestrand. Table 4.3.2 shows the results of analysis of these samples. Figure 4.3.1 and Table 4.3.1 show only 10 boreholes located in this lithology

Drammen Granite

The major outcrop of the Drammen Granite is called the Drammen batholith, which intrudes Precambrian gneisses to the east and Cambro-Silurian sedimentary rocks to the north, west and south (see Figure 4.3.1). Permian extrusives of the Glitrevann Caldera (Figure 4.2.2) border the north-western corner of this granite complex. The emplacement of the Drammen batholith pre-dates the subsidence of the Drammen and Glitrevann Calderas (Gaut 1981).

Interpretation of available gravimetric data indicates that the batholith is probably relatively thin (about 3 km thick) but the data may also be interpreted as indicating a pseudo-cylindrical body grading downwards into a mixture of blocks and intrusives (Trønnes et al. 1992). Trønnes et al. (1992) also outline the various granite types within the Drammen Granite.

These granite types seems to represent separate intrusive phases with gradual transitions and some sharp contacts occurring along the junction of two separate petrographic types. Trønnes et al. (1992) explain this variation as a result of the intrusion of a new magma into an already emplaced, but only partially solidified magma. The sharp contact boundaries may be caused by new magma intruding into an early intrusion where the solidification was nearly complete. Where the early intrusion was still predominantly liquid, the conditions may have been favourable for a more extensive mixing and mutual assimilation resulting in a transitional

Table 4.3.3 *Major element analyses of samples taken by Martinsen (1986) and Trønnes et al. (1992) of the Drammen granite by XRF. Values in weight percent. LOI = loss on ignition, n.d. = not detected. The T and M in front of the sample names refers to the work of Trønnes et al. (1992) and Martinsen (1986), respectively.*

	T_4B	T_7	T_M5	T_M6	M_I9
SiO_2	76.3	77.0	78.9	76.9	76.1
TiO_2	0.11	0.14	0.16	0.09	0.20
Al_2O_3	12.8	12.7	12.5	13.2	13.3
Fe_2O_3	0.99	0.53	0.24	0.56	0.47
FeO	0.27	0.44	0.33	0.16	0.35
MnO	0.03	0.04	0.03	0.01	0.04
MgO	0.07	0.02	n.d.	n.d.	0.25
CaO	0.55	0.51	0.39	0.18	0.55
Na_2O	3.95	3.89	3.57	4.28	4.20
K_2O	4.34	4.14	4.71	4.64	4.26
P_2O_5	n.d.	n.d.	n.d.	n.d.	<0.01
LOI	0.46	0.39	0.45	0.33	0.47

boundary. Partial remelting of an early intrusive phase may also have led to gradual transitions between the different intrusion phases.

The coarse-grained, medium- to coarse-grained and cumulophyric granites seem to represent the earliest intrusives of the Drammen batholith currently exposed. The transition between these different petrographic types are mostly gradual, and may therefore be part of the same intrusive event. The micro-crystalline porphyries are chemically similar to the coarse-grained granite (especially in the central parts of the batholith). These two lithologies may therefore be genetically related. The

Table 4.3.4 *Trace element analyses of samples taken by Martinsen (1986) and Trønnes et al. (1992) of the Drammen granite. Values in ppm. n.a. = not analysed. The T and M in front of the sample names refers to the work of Trønnes et al. (1992) and Martinsen (1986), respectively.*

	T_4B	T_7	T_M5	T_M6	M_I9
F	2250	2200	400	300	n.a.
Rb	372	408	427	548	682
Sr	49	41	6	8	47
Ba	n.a.	n.a.	30	20	n.a.
Y	61	33	53	55	55
Zr	120	117	148	190	187
Nb	73	58	78	116	105
La	n.a.	n.a.	n.a.	27	n.a.
Ce	n.a.	n.a.	n.a.	38	n.a.
Nd	n.a.	n.a.	n.a.	8	n.a.
Sm	n.a.	n.a.	n.a.	1.9	n.a.
Eu	n.a.	n.a.	n.a.	n.d.	n.a.
Tb	n.a.	n.a.	n.a.	0.2	n.a.
Yb	n.a.	n.a.	n.a.	9.5	n.a.
Lu	n.a.	n.a.	n.a.	1.6	n.a.
Li	n.a.	n.a.	n.a.	n.a.	45
Co	n.a.	n.a.	n.a.	n.a.	36
Cu	n.a.	n.a.	n.a.	n.a.	6
Zn	n.a.	n.a.	n.a.	n.a.	17
Mo	n.a.	n.a.	n.a.	n.a.	39
Pb	n.a.	n.a.	n.a.	n.a.	34

intrusion of the porphyries, the rapakivi and the medium- to fine-grained granite appear to post-date the first intrusion of coarse-grained granite (Trønnes et al. 1992).

The bedrock boreholes shown in Figure 4.3.1 in the Drammen batholith are almost all located in the medium to fine-grained granites in the central parts of the batholith. Trønnes et al. (1992) have analysed four samples taken in the vicinity of these boreholes from this special type of the Drammen Granite. Martinsen (1986) has mainly analysed samples from and around molybdenum-mineralisation zones, but one of his samples is taken from the medium-grained granite in the vicinity of the bedrock boreholes shown in Figure 4.3.1. Table 4.3.3 shows the results of the analysis of these samples with respect to the major elements. Table 4.3.4 shows the results of the analysis of trace elements in the same samples.

4.4 The Bergen Area

The hard rock lithologies in the surroundings of Bergen are very variable. In the west (Øygarden Gneiss Complex) and north, Proterozoic rocks of the north-western gneiss region (NWGR) are present. The rocks of the NWGR are overlain by a variety of allochthonous rocks assigned to the Lower, Middle and Upper Allochthons of the Caledonian nappe succession. These rocks are present in the so-called Bergen Arcs. The Bergen Arcs are a major convex-towards-the-east, arc-like structure extending from Bergen towards the north-east. The Bergen Arcs consists of a series of arcuate belts containing rocks with different lithologies and tectono-metamorphic histories. From west to east, the following units are found, all separated by tectonic contacts (Ingdahl 1985):

- The Øygarden Gneiss Complex (an extension of the NWGR)
- The Minor Bergen Arc
- The Ulriken Gneiss Complex

- The Anorthosite Complex
- The Major Bergen Arc

The Øygarden Gneiss Complex contains a great variety of grey and red orthogneisses and lesser amounts of paragneisses together with supracrustals (Kolderup and Kolderup 1940). In the legend of Figure 4.4.1 these lithologies are represented by the lithological group named migmatitic gneiss.

The Minor Bergen Arc consists of metasedimentary and meta-igneous rocks of supposed Lower Palaeozoic age, and also includes a number of rocks which have strong mylonitic fabrics (Sturt et al. 1975). In the legend of Figure 4.4.1 these lithologies are represented by the lithological group named phyllite and meta-arkose.

The Ulriken Gneiss Complex consists of several thrust-slices of migmatitic gneisses separated by zones of blastomylonites and younger meta-sediments (conglomerates and quartz schists) (Sturt and Thon 1978). In the legend of Figure 4.4.1 these lithologies are represented by the lithological group named migmatitic mica gneiss.

The Anorthosite Complex is very heterogeneous, consisting of anorthosites, anorthositic gabbros, gabbroic rocks and mangeritic rocks as well as gneisses and some meta-sediments (quartzite) (Ingdahl 1985). In the legend of Figure 4.4.1 these lithologies are represented by the lithological group named charnockitic to anorthositic gneisses.

The Major Bergen Arc consists of meta-sediments, meta-volcanics and meta-igneous rocks as well as slices of basement gneisses. It is now established that the allochthonous Caledonian sequence consists of two major complexes, the Gulfjellet Ophiolite Complex and the Samnanger Complex separated from the overlying Holdhus Group by a major stratigraphic unconformity (Thon 1984). In the legend of Figure 4.4.1 the Gulfjellet Ophiolite Complex is represented by the

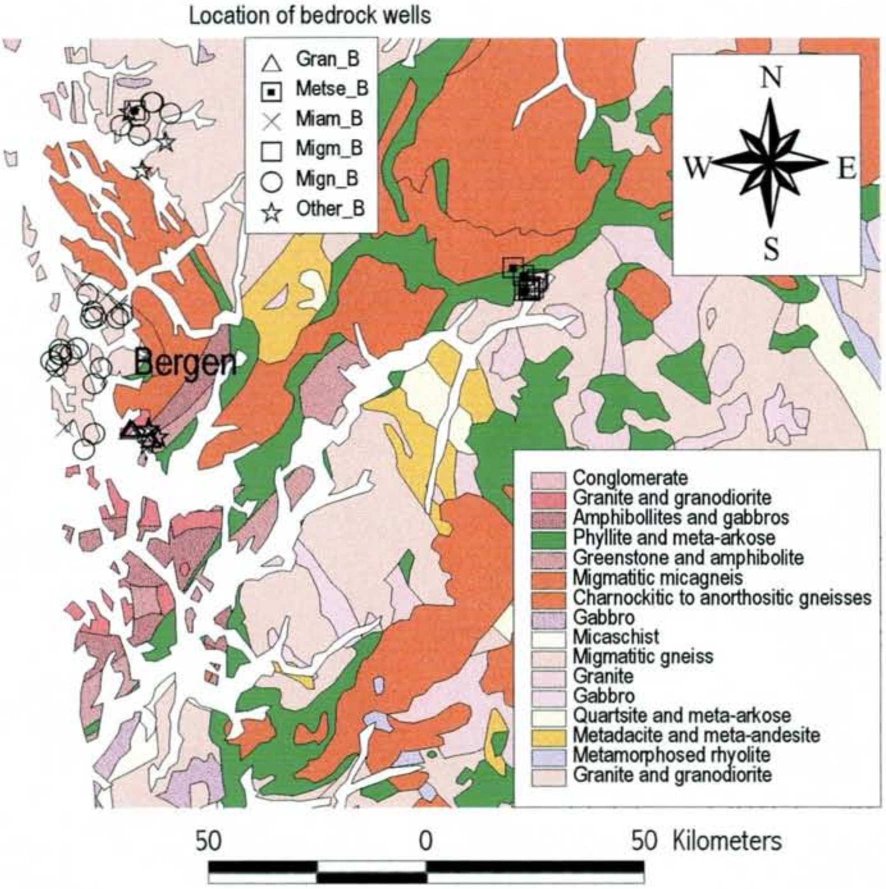


Figure 4.4.1 *A map of the Bergen Area indicating the distribution of different rocktypes. The location of all sampled boreholes and their lithologies are shown.*

Table 4.4.1 *The six main lithological categories with sampled bedrock boreholes in the Bergen Area.*

Lithological category	**Number of boreholes**	**Rocks**
Gran_B	7	Granite and/or granodiorite
Metse_B	4	Metasediments as phyllite and meta-arkose
Miam_B	7	Migmatitic gneisses with amphibolites and metagabbros
Migm_B	7	Migmatites
Mign_B	23	Migmatitic granitic or granodioritic gneisses
Other_B	8	Miscellaneous rock types

lithological groups named amphibolites and gabbros, the Samnanger Complex by the groups named greenstone, amphibolite, phyllite and meta-arkose.

In the eastern part of the Bergen area, north of Hardangerfjorden, phyllites and migmatitic gneisses are present. In the legend of Figure 4.4.1 these lithologies are represented by the lithological groups named phyllite, meta-arkose and migmatitic gneiss. In the south-east, south of Hardangerfjorden, various Proterozoic gneisses and metavolcanic rocks, which are part of the Sveco-norwegian basement of Southern Norway, are present adjacent to scattered outliers of Caledonian nappe rocks consisting of Cambro-Ordovician phyllites.

Bedrock boreholes drilled in lithologies in the Bergen region tend to display considerably lower groundwater yields than boreholes in the Oslo Region (see Chapter 6).

Petrology of Selected Rocks of the Bergen Area

The rocks described here are the rocks of the Bergen Area in which boreholes have been drilled, as described in Chapter 5. As shown in Figure 4.4.1, most of the selected bedrock boreholes are located within the Bergen Arcs in the vicinity of Bergen (37 of 58 boreholes). 24 of these are located in the Øygarden Gneiss Complex, 5 in the Anorthosite Complex and the rest (8 boreholes) in the Major Bergen Arc. A total of 10 boreholes are located north of Bergen, in the municipality of Masfjorden, in the Western Gneiss Region whilst 10 boreholes have been drilled east of Bergen, in the municipality of Ulvik, located in phyllites and migmatitic gneisses north of Hardangerfjorden.

The digital bedrock map of Norway (Sigmond 1992) is not sufficiently detailed to be used to determine the bedrock lithology of each borehole in order to compare the lithology and hydrochemistry of the boreholes (Morland et al. 1995).

Table 4.4.2 *Element analyses of tonalite intrusive rocks. For the analyses of major elements (the upper 12 results), the results are given in weight percent. For the trace elements, the results are given in ppm. LOI = loss on ignition, n.d. = not detected. From Ingdahl (1985).*

	O-226	**O-228**	**O-241**	**O-242**	**O-243**
SiO_2	63.61	64.24	68.88	70.88	66.76
TiO_2	0.72	0.37	0.23	0.12	0.35
Al_2O_3	17.45	17.85	17.10	16.32	18.33
Fe_2O_3	2.17	0.53	0.53	0.51	0.92
FeO	2.18	1.84	0.71	0.68	0.85
MnO	0.18	0.07	0.18	0.04	0.20
MgO	1.39	0.48	0.35	0.30	0.31
CaO	4.38	2.73	1.77	1.26	2.75
Na_2O	3.94	5.05	5.54	5.07	4.54
K_2O	3.73	3.11	2.28	2.73	2.55
P_2O_5	0.36	0.18	0.05	0.03	0.10
LOI	0.09	3.37	1.98	1.43	2.34
V	68	39	18	18	27
Cr	59	114	78	93	59
Co	21	11	4	2	6
Ni	224	596	411	403	258
Cu	122	211	140	221	129
Zn	84	84	41	22	39
Rb	77	76	53	80	62
Sr	1630	1917	1072	977	1534
Y	19	13	11	8	12
Zr	299	205	191	139	211
Nb	15	21	10	13	12
La	43	46	6	n.d.	11
Ce	71	76	19	n.d.	26
Nd	39	41	12	n.d.	16

Table 4.4.3 *Element analyses of mafic rocks. For the analyses of major elements (the upper 12 results), the results are given in weight percent. For the trace elements, the results are given in ppm. LOI = loss on ignition, n.d. = not detected. From Ingdahl (1985).*

	O-24	O-222	O-223
SiO_2	52.15	52.92	49.59
TiO_2	2.32	2.39	2.37
Al_2O_3	13.37	13.43	13.26
Fe_2O_3	3.33	2.55	3.73
FeO	7.24	7.82	8.28
MnO	0.19	0.24	0.21
MgO	5.76	5.89	6.74
CaO	8.89	8.29	9.44
Na_2O	4.74	5.15	3.74
K_2O	0.25	0.20	0.25
P_2O_5	0.26	0.25	0.23
LOI	0.76	1.69	1.10
V	350	358	360
Cr	228	225	225
Co	64	64	72
Ni	44	45	44
Cu	174	102	186
Zn	73	86	85
Rb	7	8	7
Sr	96	78	121
Y	30	29	27
Zr	142	153	145
Nb	8	3	9
La	2	3	3
Ce	7	20	13
Nd	11	18	15

A more detailed lithological assessment has therefore been carried out. In the Bergen Area, the bedrock boreholes are separated into six main categories (Table 4.4.1 and Figure 4.4.1).

There are even fewer litho-geochemical analyses relating to the Bergen Area available than for the Oslo Area. The area itself is geologically very complicated, and existing analyses have mainly been carried out on unrepresentative rock samples. According to Ø. Nordgulen of the Section for Bedrock Geology at NGU in Trondheim, no analyses of the lithologies mentioned in Table 4.4.1 are available with the exception of analyses of the lithologies in the Os area south of Bergen in the Major Bergen Arc. These analyses have been performed by Ingdahl (1985) as a part of his thesis at the University of Bergen. In Table 4.4.2, his results of five analyses of tonalite intrusive rocks are presented. These analyses may be compared to lithology Gran_B in Table 4.4.1. In Table 4.4.3, his results of three analyses of mafic rocks (pillow lavas) are presented. These analyses may be compared to lithology Other_B in Table 4.4.1 since five of eight bedrock boreholes in this lithology are located within these mafic rocks.

4.5 Comparison of Element Contents

All borehole water samples analysed in the study by Morland et al. (1995) (see also Chapter 5) have been divided into 11 groups according to the lithology of the host rock of the bedrock boreholes (Tables 4.3.1 and 4.4.1). For the four lithologies with existing geochemical analyses mentioned in the Chapters 4.3 and 4.4, element contents presented in Tables 4.3.2, 4.3.3, 4.3.4, 4.4.2 and 4.4.3 are compared with results of groundwater sample analyses (Morland et al. 1995) of the bedrock boreholes defined to be located in these lithologies.

Generally, the Permian basalts (Table 4.3.2 and defined to be equal to the lithological group Basa_O) shows a ultrabasic to basic character compared to the more basic to intermediate mafic rocks (pillow lavas) in the Major Bergen Arc (Table 4.4.3 and defined to be equal to the lithological group Other_B). The

Drammen granite (Table 4.3.3 and defined as the lithological group Gran_O) is more acidic than the tonalite rocks in the Major Bergen Arc (Table 4.4.2 and defined as the lithological group Gran_B). These four lithological groups may be divided into two groups according to their origin. In the following comparisons the lithological groups Gran_O are therefore compared with Gran_B and Basa_O are compared with Other_B.

Titanium

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of titanium than groundwater from boreholes in the lithological group Gran_O. In Tables 4.3.3 and 4.4.2, the same tendency is present in the geochemical analyses of the rocks. It is also a tendency that groundwater from boreholes in the lithological group Basa_O have a higher content of titanium than groundwater from boreholes in the lithological group Other_B. This also reflects lithological composition, as can be seen by comparing Table 4.3.2 and 4.3.3.

Aluminium

Groundwater from boreholes in the lithological group Gran_O tends to have a higher content of aluminium than groundwater from boreholes in the lithological group Gran_B. This is in contrary with the geochemical results shown in Tables 4.3.3 and 4.4.2. It is a tendency that groundwater from boreholes in the lithological group Other_B have a higher content of aluminium than groundwater from boreholes in the lithological group Basa_O. In Table 4.4.3, the concentrations of aluminium are also generally higher than the results shown in Table 4.3.2.

Iron

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of iron than groundwater from boreholes in the lithological group Gran_O. In Tables 4.3.3 and 4.4.2, the same tendency is present in the geochemical analyses of the rocks. It is also a tendency that groundwater from boreholes in the lithological group Other_B have a higher content of iron than groundwater from boreholes in the lithological group Basa_O. This is in contrary with the geochemical results shown in Tables 4.3.2 and 4.4.3.

Manganese

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of manganese than groundwater from boreholes in the lithological group Gran_O. In Tables 4.3.3 and 4.4.2, the same tendency is present in the geochemical analyses of the rocks. For the two other lithological groups, the opposite tendency is present; groundwater from boreholes in the lithological group Basa_O tends to have a higher content of manganese than groundwater from boreholes in the lithological group Other_B. The results in Tables 4.3.2 and 4.4.3 suggests an almost similar content in these two lithologies.

Magnesium

Groundwater from boreholes in the lithological group Gran_O tends to have a higher content of magnesium than groundwater from boreholes in the lithological group Gran_B. This is in contrary with the geochemical results shown in Tables 4.3.3 and 4.4.2. There is also a tendency, although not significant, that groundwater from boreholes in the lithological group Basa_O has a higher content of magnesium than groundwater from boreholes in the lithological group Other_B. In Tables 4.3.2 and 4.4.3, the same tendency is present in the geochemical analyses of the rocks.

Calcium

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of calcium than groundwater from boreholes in the lithological group Gran_O. In Tables 4.3.3 and 4.4.2, the same tendency is present in the geochemical analyses of the rocks. Although the content of calcium in groundwater from boreholes in the lithological groups Basa_O and Other_B seems to be quite similar, it is possible to see a tendency, although not significant, that groundwater from boreholes in the lithological group Basa_O has a higher content of calcium than groundwater from boreholes in the lithological group Other_B. In Tables 4.3.2 and 4.4.3, the same tendency is present in the geochemical analyses of the rocks.

Sodium

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of sodium than groundwater from boreholes in the lithological group Gran_O. In Tables 4.3.3 and 4.4.2, the same tendency is present in the geochemical analyses of the rocks. The same tendency is also present in the other two lithologies. Groundwater from boreholes in the lithological group Other_B tends to have a higher content of sodium than groundwater from boreholes in the lithological group Basa_O. In Tables 4.3.2 and 4.4.3, the same tendency is present in the geochemical analyses of the rocks.

Potassium

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of potassium than groundwater from boreholes in the lithological group Gran_O. This is in contrary with the results shown in Tables 4.3.3 and 4.4.2 The same tendency is present for the two other lithological groups; a higher content of potassium in groundwater from boreholes in the lithological group Other_B while the lithological group Basa_O shows a higher content of potassium in the geochemical analyses of the rocks.

Phosphorus

Groundwater from boreholes in the lithological group Gran_O tends to have a higher content of phosphorus than groundwater from boreholes in the lithological group Gran_B. In Table 4.3.3, the content of phosphorus has not been detected, while detectable levels are found in the results in Table 4.4.2. Groundwater from boreholes in the lithological group Basa_O tends to have a higher content of phosphorus than groundwater from boreholes in the lithological group Other_B. The same tendency is present in Tables 4.3.2 and 4.4.3.

Chromium

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of chromium than groundwater from boreholes in the lithological group Gran_O. This element is, however, not analysed in Table 4.3.4. Groundwater from boreholes in the lithological group Basa_O tends to have a higher content of chromium than groundwater from boreholes in the lithological group Other_B. The same tendency is also present in Tables 4.3.2 and 4.4.3.

Cobalt

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of cobalt than groundwater from boreholes in the lithological group Gran_O. Only one sample of the latter lithological group have been analysed. This result suggests, however, that this lithology have a higher content of cobalt than the lithological group Gran_B. Groundwater from boreholes in the lithological groups Basa_O and Other_B is quite similar with respect to the content of cobalt. This is also reflected in Tables 4.3.2 and 4.4.3.

Nickel

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of nickel than groundwater from boreholes in the lithological group Gran_O. No samples of this latter lithological group have been analysed with respect to nickel, and it is therefore not possible to compare these two groups. Groundwater from boreholes in the lithological group Basa_O tends to have a higher content of nickel than groundwater from boreholes in the lithological group

Other_B. In Tables 4.3.2 and 4.4.3, the same tendency is present in the geochemical analyses of the rocks.

Rubidium

Groundwater from boreholes in the lithological group Gran_O tends to have a higher content of rubidium than groundwater from boreholes in the lithological group Gran_B. In Tables 4.3.3 and 4.4.2, the same tendency is present in the geochemical analyses of the rocks. Groundwater from boreholes in the lithological group Other_B tends to have a higher content of rubidium than groundwater from boreholes in the lithological group Basa_O. This is contrary to the results of the geochemical analyses of the rocks shown in Tables 4.3.2 and 4.4.3.

Strontium

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of strontium than groundwater from boreholes in the lithological group Gran_O. In Tables 4.3.4 and 4.4.2, the same tendency is present in the geochemical analyses of the rocks. Groundwater form boreholes in the lithological group Basa_O tends to have a higher content of strontium than groundwater from boreholes in the lithological group Other_B. In Tables 4.3.2 and 4.4.3, the same tendency is present in the geochemical analyses of the rocks.

Yttrium

Groundwater from boreholes in the lithological group Gran_O tends to have a higher content of yttrium than groundwater from the lithological group Gran_B. In Tables 5.3.4 and 4.4.2, the same tendency is present in the geochemical analyses of the rocks. Groundwater from boreholes in the lithological groups Basa_O and Other_B have a quite similar content of yttrium. This is also in accordance with the results shown in Tables 4.3.2 and 4.4.3.

Zirconium

Groundwater from boreholes in the lithological group Gran_O tends to have a higher content of zirconium than groundwater from the lithological group Gran_B. This is in contrary with the results of the geochemical analyses of the rocks shown in Tables 4.3.4 and 4.4.2. Groundwaters from boreholes in the lithological groups Basa_O and Other_B have a quite similar content of zirconium, but the content of zirconium shown in Tables 4.3.2 tends to be higher than in Table 4.4.3.

Lanthanum

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of lanthanum than groundwater from boreholes in the lithological group Gran_O. Only one sample of the latter lithological group has been analysed. This result suggests that this lithology have a lower content of lanthanum than the lithological group Gran_B. Groundwater from boreholes in the lithological group Basa_O tends to have a higher content of lanthanum than groundwater from boreholes in the lithological group Other_B. In Tables 4.3.2 and 4.4.3, the same tendency is present in the geochemical analyses of the rocks.

Cerium

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of cerium than groundwater from boreholes in the lithological group Gran_O. Only one sample of the latter lithological group has been analysed. This result suggests that this lithology have a lower content of cerium than the lithological group Gran_B. Groundwater from boreholes in the lithological group Basa_O tends to have a higher content of cerium than groundwater from the lithological group Other_B. In Tables 4.3.2 and 4.4.3, the same tendency is present in the geochemical analyses of the rocks.

Neodymium

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of neodymium than groundwater from boreholes in the lithological group Gran_O. Only one sample of the latter lithological group have been analysed. This result suggests that this lithology has a lower content of neodymium than the lithological group Gran_B. Groundwater from boreholes in the lithological group Basa_O tends to have a higher content of neodymium than groundwater form the lithological group Other_B. No samples of the lithological group Basa_O have been analysed with respect to neodymium, and it is therefore not possible to compare these two groups.

Niobium

Groundwater from boreholes in the lithological group Gran_O tends to have a higher content of niobium than groundwater from the lithological group Gran_B. In Tables 4.3.4 and 4.4.2, the same tendency is present in the geochemical analyses of the rocks. Groundwater from boreholes in the lithological group Other_B tends to have a higher content of niobium than groundwater from boreholes in the lithological group Basa_O. No samples of the lithological group Basa_O have been analysed with respect to niobium, and it is therefore not possible to compare these two groups.

Copper

Groundwater from boreholes in the lithological group Gran_B tends to have a higher content of copper than groundwater from boreholes in the lithological group Gran_O. Only one sample of the latter lithological group has been analysed. This result suggests that this lithology has a lower content of copper than the lithological group Gran_B. Groundwater from boreholes in the lithological group Other_B tends to have a higher content of copper than groundwater from boreholes in the lithological group Basa_O. No samples of the lithological group Basa_O have been analysed with respect to copper, and it is therefore not possible to compare these two groups.

Zinc

Groundwater from boreholes in the lithological group Gran_O tends to have a higher content of zinc than groundwater from boreholes in the lithological group Gran_B. Only one sample of the lithological group Gran_O have been analysed. This result suggests that this lithology has a lower content of zinc than the lithological group Gran_B. Groundwater from boreholes in the lithological group Other_B tends to have a higher content of zinc than groundwater from boreholes in the lithological group Basa_O. No samples of the lithological group Basa_O have been analysed with respect to zinc, and it is therefore not possible to compare these two groups.

4.6 Discussion

The results mentioned in Chapter 4.3, 4.4 and 4.5 are based on relatively few rock analyses. The comparison between element content in groundwater and in the rock itself is also connected to several sources of errors. This may be the errors in assigning lithology to the sampled boreholes in addition to natural variability within the lithology. Field sampling errors or contamination from pipework or particulate matter may have influenced both the results in Morland et al. (1995) and the results shown in Tables 4.3.2, 4.3.3, 4.3.4, 4.4.2 and 4.4.3. Errors due to incorrect coordinate location of the sampled boreholes and uncertainties in the location of the where the rock-samples were taken may also have influence on the comparison between element content in groundwater and in the host rock as shown in Chapter 4.5. Sample preparation errors and analytical errors may also be a possible source of errors. For example, it is believed that all the analyses of yttrium and zirconium presented in Table 4.3.3 are too low. This has been due to errors in the calibration curve stored in the computer of the XRF-equipment (Ingdahl 1985). The comparisons in Chapter 4.5 have been performed visually, which also may have introduced errors related to observing the graphics.

Bearing all these possible sources of errors in mind, the results of Chapter 4.5 shows an interesting pattern. Out of 44 comparisons in Chapter 4.5, 27 (61%) shows an equivalent relationship between element content in rocks and in groundwater derived from boreholes in comparable lithological groups. 10 comparisons (23%) have shown an opposing relationship and 6 comparisons (14%) have not been possible due to lack of analyses of some of the elements in one or more of the lithological groups. The elements exhibiting opposing relationships between groundwater and whole rock concentrations are aluminium, magnesium, potassium, cobalt and zirconium for the lithological groups Gran_O and Gran_B and iron, manganese, potassium, rubidium and zirconium for the lithological groups Basa_O and Other_B.

The content of an element in groundwater is not only dependent on the content of that same element in the host rock itself. Bearing in mind that groundwater flow in Norwegian bedrock is solely dependent on open, hydraulically communicating fractures and joints, the importance of fracture-filling minerals present in these fractures and joints should not be underestimated (Gascoyne et al. 1993). Vortisch et al. (1983) describe an enrichment of As at the Cambro-Ordovician boundary in south Sweden which is thus not dependent on the host rock but related to stratigraphy. Two further important aspects concerning elements dissolutions are (Mandel 1979):

- In a complex solution, such as groundwater, where many dissolved species inter-react with each other, the solubility of each potential mineral phase will depend on the content of all the dissolved species. Rather complex iterative hydrochemical techniques are required to simulate the processes taking place in such waters.

- Minerals that possibly might be precipitated from a complex solution are not necessarily identical with the originally dissolved minerals. This means that the chemical composition of a secondary mineral is determined by chemical reactions between dissolved elements and not by their origin.

The groundwater residence time is also believed to be of major importance in controlling the extent of water-rock interaction. Morland (1988) showed that the element content increased in a well defined pattern, probably due to increasing residence time in the Quaternary deposit of Kaldvella in the county of Sør-Trøndelag. The same controls in the evolution of groundwater chemistry have also been noted in crystalline aquifers (e.g. Gascoyne et al. 1993, May et al. 1993, Banks et al. 1993a).

To gain more knowledge about the composition of groundwater in bedrock boreholes, it is necessary to analyse both the element content of the groundwater from a large number of bedrock boreholes in addition to the element content of the host rock lithology and the element content of fracture-filling minerals. As mentioned in Chapter 1.1, NGU, in co-operation with the Norwegian Radiation Protection Authority (NRPA), is in the process of analysing more than 2,000 samples from bedrock boreholes from the whole of Norway. This is done without having the financial possibility to include analyses of host rock and fracture-filling minerals. The results will, nevertheless, be of major importance in increasing our knowledge of the relationship between groundwater chemistry and bedrock lithology.

Chapter 5

Groundwater Chemistry in the Oslo and Bergen Areas

5.1 Introduction

This chapter is a modified version of an article entiteled "The Hydrochemistry of Norwegian Bedrock Groundwater - Selected Parameters (pH, F^-,Rn, U, Th, B, Na, Ca) in Samples from Vestfold and Hordaland, Norway", by Morland, G., Reimann, C., Strand, T., Skarphagen, H., Banks, D., Bjorvatn, K., Hall, G.M. and Siewers, U. The article is submitted to the journal "Norges geologiske undersøkelse Bulletin" with a view to publication.

In the 1980s NGU undertook an extensive investigation of the chemical composition of surface and groundwater samples from almost all Norwegian waterworks supplying more than 1,000 people with drinking water. This undertaking resulted in data on the chemical composition of water drunk by 70% of the Norwegian population for major and some trace parameters (Flaten 1991). Since that time, increasingly sensitive methods have become available (e.g. inductively coupled plasma mass spectrometry - ICP-MS) for determining very low levels of trace elements. Interest has also increased in the significance of some, previously seldom analysed, health-related parameters and also in the use of surface and groundwaters as a geochemical mapping medium (e.g. the Norwegian survey of 473 lakes - Skjelkvåle et al. 1996).

NGU and the Norwegian Radiation Protection Authority (NRPA) have invested significant effort in recent years in investigating concentrations of radionuclides in groundwater abstracted from Norway's crystalline bedrock (Strand & Lind 1992, Banks et al. 1995a,b). These studies have confirmed that a significant proportion of bedrock groundwaters in some lithologies (particularly granites and gneisses)

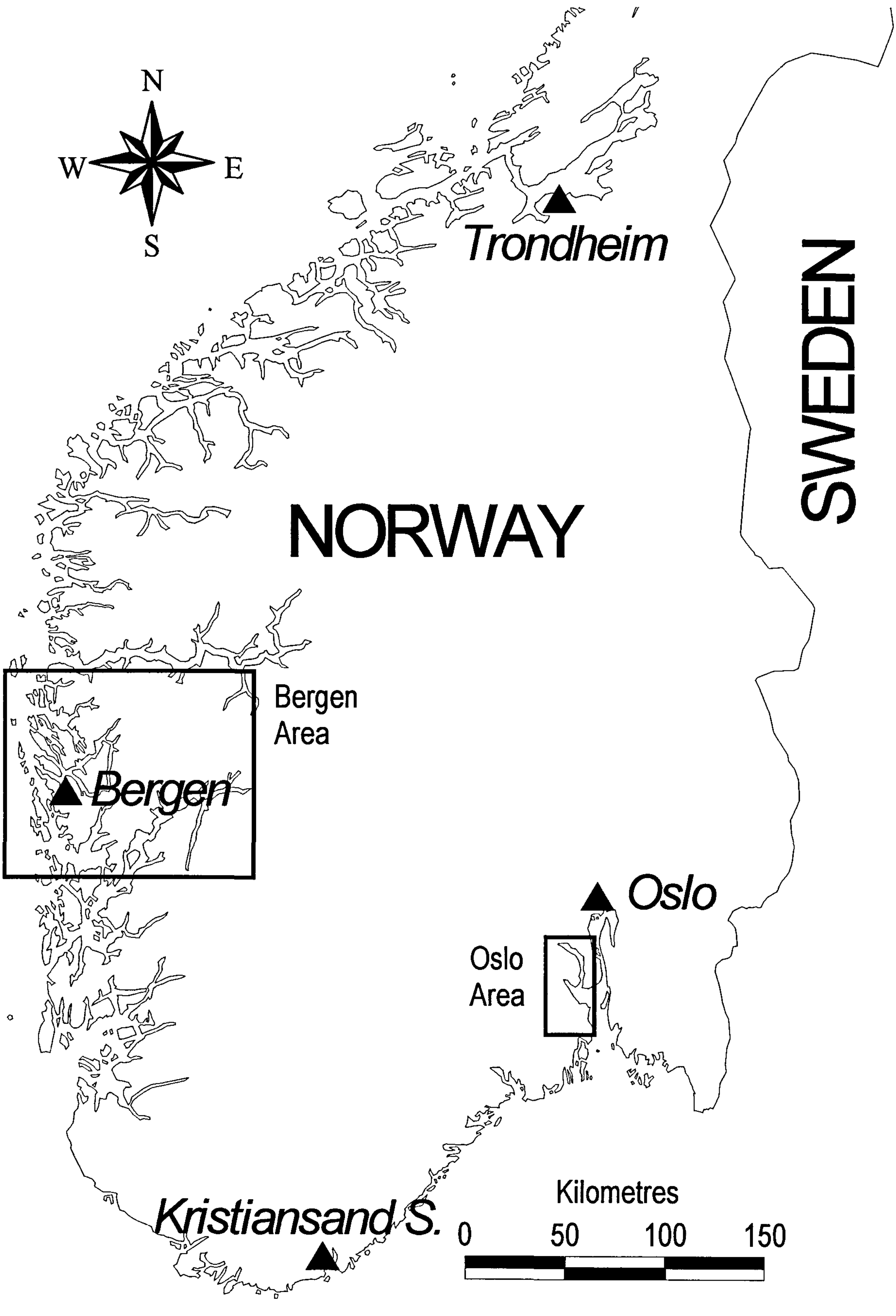


Figure 5.1.1 Map of Southern Norway, showing location of the study areas.

exhibit radon concentrations of several hundred or even thousand Bq/L. Such concentrations may have a direct health impact via ingestion or an indirect one via degassing within a house and subsequent inhalation (Swedjemark 1993). The investigations resulted in the NRPA (1995) recommending an action level of 500 Bq/L for Rn in drinking water.

The work of Banks et al. (1995b) and Sæther et al. (1995) also revealed that concentrations of other trace elements such as F^-, Be, Th, U in bedrock may be significant in a health context. In fact, Bjorvatn et al. (1992 and 1994) have documented cases of dental fluorosis in Southern and Western Norway ascribable to the consumption of fluoride-rich bedrock groundwater.

This chapter presents selected results from a recent, more extensive survey (Morland et al. 1995, Reimann et al. 1996) of over 300 bedrock boreholes in the Oslo and Bergen areas, dominated by granitic and gneissic lithologies. Figure 5.1.1 shows the general location of the study areas, in the southern half of Norway, and the figures 4.3.1 and 4.4.1 shows the location of the different rocktypes and sampled boreholes in the Oslo and Bergen areas, respectively. This study uncovered significant levels of Rn (up to 6,840 Bq/L) and U (up to 2 mg/L) in bedrock groundwaters. This chapter attempts to discuss the results of selected parameters (pH, F^-, Rn, U, Th, B, Na, Ca). The connection between the results of the groundwater analysis and the rock lithology of the bedrock boreholes is discussed in Chapter 4.

5.2 Materials and Methods

In 1994, groundwater sampling from all known boreholes in bedrock in Hordaland county (ca. 1,000 boreholes) and in three municipalities in Vestfold county (Våle, Svelvik and Holmestrand - 314 boreholes) was undertaken as a collaboration between the health and environment authorities of northern Vestfold and the Department of Dental Research, University of Bergen. The full results of the fluoride analyses of these waters have recently been reported by Bårdsen et al.

(1996). By request from NGU, additional samples were taken from a selection (all 314 boreholes from the Oslo Area, 58 from the Bergen Area) of the boreholes for more detailed chemical analyses. These were subject to radon analysis at the Norwegian Radiation Protection Authority and fluoride analysis at the Institute for Dental Research in Bergen. A selection of 150 of the samples were submitted for ICP-MS analysis of trace elements at the laboratories of the Geological Survey of Canada (GSC) and the Federal Institute for Geosciences and Natural Resources (BGR) in Germany. The full results of the study are reported in Morland et al. (1995) and Reimann et al. (1996).

All samples were taken by representatives of the local health authorities in the Oslo Area and by the Institute for Dental Research in the Bergen Area. Samples were taken from boreholes which were in regular use (hence ensuring that fresh groundwater was sampled). Immediately prior to sampling, the tap (which may have been at the well-head or indoors) was run for at least five minutes prior to the acquisition of a 100 mL aliquot of sample. Temperature was monitored during sampling to ensure fresh groundwater was being sampled. The samples were not filtered or acidified in the field in order that the total element content of the water, as drunk, was measured. This decision was consciously chosen to meet the objectives of the project as a whole (i.e. to assess the *total* intake of the analysed elements by people using the groundwater as drinking water).

Analytical Methods

For sampling of radon, a plastic funnel was inserted below the running water tap such that the tap mouth was under water and there were no air bubbles in the funnel. Using an adjustable automatic pipette, with disposable tips, a quantum of 10 mL water was taken from the funnel and injected slowly into a 20 mL vial containing 10 mL of pre-filled scintillation liquid (Lumagel). The ampoule of scintillation liquid and water was then sealed and shaken. The liquid gels in contact with water, immobilising the radon. Samples were delivered to NRPA within 3 days and analysed using an LKB Wallac 1215 scintillation counter, calibrated using a standard radium solution. Results were back adjusted for radioactive decay to give a radon concentration in Bq/L at the time of sampling.

Table 5.2.1 Elements analysed by ICP-MS at GSC with method detection limits in µg/L (D.L.).

Element	D.L.	Element	D.L.	Element	D.L.
Ag	0.05	Al	2	Ba	0.2
Be	0.005	Cd	0.05	Ce	0.01
Co	0.02	Cr	0.1	Cs	0.01
Cu	0.1	Dy	0.005	Er	0.005
Eu	0.005	Fe	5	Gd	0.005
Ho	0.005	In	0.01	La	0.01
Li	0.005	Lu	0.005	Mn	0.1
Mo	0.05	Nd	0.005	Ni	0.1
Pb	0.1	Pr	0.005	Rb	0.05
Sb	0.01	Sm	0.005	Sr	0.5
Tb	0.005	Tl	0.005	Tm	0.005
U	0.005	V	0.1	Y	0.01
Yb	0.005	Zn	0.5		

Afterwards, a 30 mL sample was taken in a polyethylene (PE) bottle for fluoride determination at the local health authorities and at the Institute of Dental Research, University of Bergen, using an ion-sensitive electrode (Orion 960900 combined F electrode).

Finally, two new PE bottles (120 mL) were thoroughly rinsed three times with running tap water and then filled to the top. At NGU the final selection of the 150 samples for ICP-MS analysis was made. The samples were sent by courier to the Geological Survey of Canada's (GSC) laboratory where the sample bottles were opened for the first time since sampling, acidified with ultrapure nitric acid (at the rate of 1 mL per 100 mL sample) and shaken for 24 hours. They were then analysed by ICP-MS (VG PlasmaQuad 2+) for the elements listed in Table 5.2.1.

Details of the analytical methodology, with associated figure of merit (typical accuracy and precision), can be found in Hall et al. (1996). In addition (detection limits in brackets) Ca (0.2 mg/L), K (0.1 mg/L), Mg (0.2 mg/L) and Na (1 mg/L) were analysed by ICP-AES. International standards as well as GSC-in-house standards and sample blanks were run for quality control purposes. Aliquots of 20 samples (17 samples and 3 standards) were then shipped to BGR's ICP-MS laboratory for analysis. Samples were shipped back to NGU and stored in a refrigerator.

Table 5.2.2 Elements analysed by ICP-MS at BGR with method detection limits in µg/L (D.L.).

Element	D.L.	Element	D.L.	Element	D.L.
Ag	0.001	Al	0.05	As	0.025
B	0.01	Ba	0.002	Be	0.002
Bi	0.001	Br	0.1	Ca	10
Cd	0.002	Ce	0.001	Co	0.005
Cr	0.01	Cs	0.001	Cu	0.005
Dy	0.001	Er	0.001	Eu	0.001
Fe	2	Ga	0.001	Gd	0.001
Hf	0.002	Hg	0.005	Ho	0.001
In	0.001	K	10	La	0.001
Li	0.002	Lu	0.001	Mg	10
Mn	0.1	Mo	0.001	Na	10
Nb	0.002	Nd	0.001	Ni	0.002
Total P as PO_4^{3-}	1	Pb	0.002	Pr	0.001
Rb	0.002	Sb	0.002	Sc	0.005
Se	0.01	Sm	0.001	Sn	0.005
Sr	0.01	Ta	0.001	Tb	0.001
Te	0.001	Th	0.001	Ti	0.1
Tl	0.002	Tm	0.001	U	0.001
V	0.01	W	0.002	Y	0.001
Yb	0.001	Zn	0.01	Zr	0.002

Several month later, when the results of the initial interlaboratory comparison and the first results from the whole data-set were available, BGR became interested in analysing the whole set of 150 samples. The original samples that had been in Canada and then stored refrigerated at NGU for about 6 months were then shipped to BGR and analysed within two weeks after arrival. They were then analysed at BGR's laboratory by ICP-MS (SCIEX ELAN 5000) for the elements listed in Table 5.2.2.

Results of interlaboratory comparison and storage effects on water chemistry are reported in Morland et al. (1995). Generally the results obtained from the two laboratories are in excellent agreement, with the exception of Al, Fe, Cr and Ni (see Reimann et al. 1996 for further details). Rare earth element hydrochemistry is discussed by Banks et al. (in prep.).

Data Analysis

Analytical results were classified on the basis of the aquifer geology at the borehole location into one of 11 main categories (Figures 4.3.1 and 4.4.1, Tables 4.3.1 and 4.4.1). During statistical treatment, any data below the detection limits of the technique were set to half the detection limit.

5.3 *Investigation of Selected Parameters*

5.3.1 pH

The pH of the 58 waters from the Bergen Area and of 123 of the groundwaters from the Oslo Area was determined in the field using a portable pH metre. Figure 5.3.1.1 indicates that the distribution of pH is almost perfectly normal (i.e. log-normal distribution of hydrogen ion activity). The median pH of the Oslo waters was found to be 7.3, all measured samples falling in the range 6.0 to 8.4. The median pH in the Bergen Area is somewhat higher at 7.7, although the range is greater, stretching from 5.8 to 9.1. Compared with hard rock lithologies from other areas (e.g. the Carnmenellis granite [Smedley 1991] or Scilly granite of Cornwall, U.K. [range 5.2 - 6.4] [Banks et al. 1997]), these pH values are rather high, probably due to rather high aquifer residence times and the fact that mafic minerals have not been removed by prolonged subaerial weathering, as is the case in areas which have not been recently glacially scoured.

The correlation of pH with aquifer lithology is not immediately clear, although it will be noted that two acidic lithologies (Oslo granite and Bergen migmatites) have the lowest pH values. The migmatitic gneisses, amphibolites and metagabbros of the Bergen Area are the group with the highest pH. The majority of groundwaters fall well within the limits allowed by the Norwegian drinking water standards (Sosial- og helsedepartementet [Ministry of Health and Social Affairs] 1995), namely $6.5 < \mathrm{pH} < 8.5$, although a minority of samples (13%) fall either above or below these limits (Table 5.3.1.1).

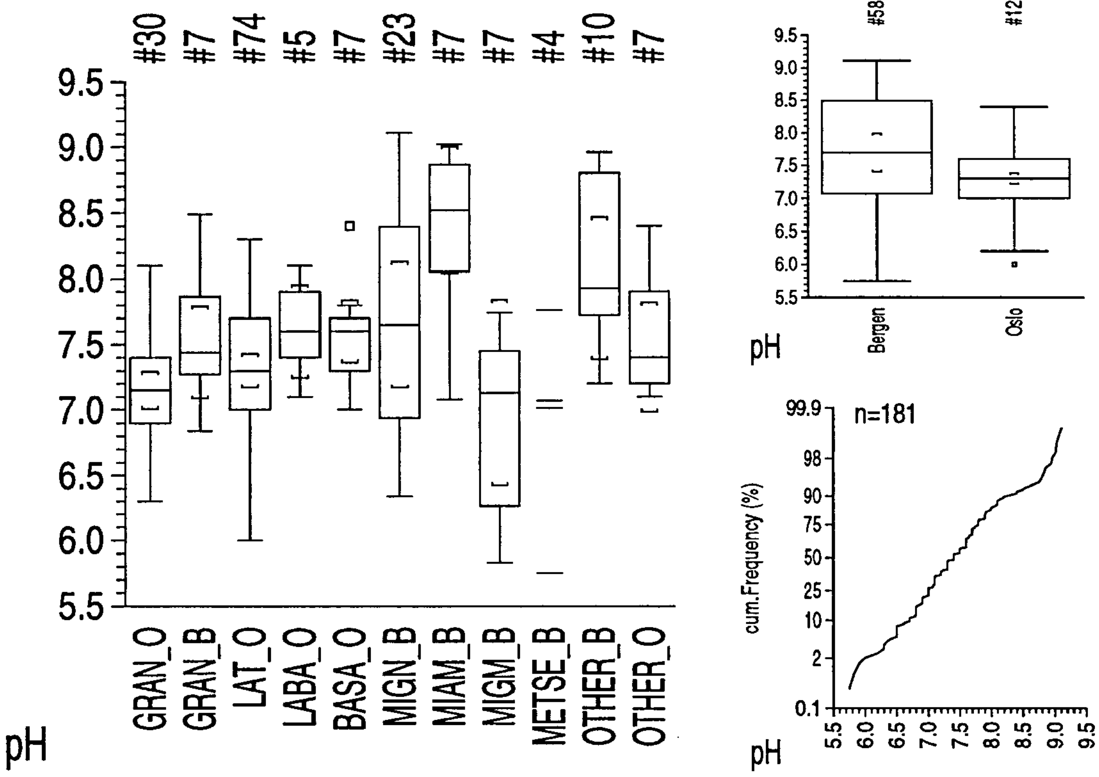


*Figure 5.3.1.1 Diagram showing: **left**, boxplots for distribution of pH among bedrock groundwaters of the various lithological groups (see text for explanation): **top right**, boxplots for distribution of pH among the Oslo Area and the Bergen Area: **bottom right**, cumulative probability distribution plot for pH for the entire data set (n = 181). # = total number of samples in boxplot group.*

5.3.2 Fluoride

Water may be a significant source of fluoride in the diet. It is known that fluoride is required in certain quantities for normal tooth and bone development. Deficiency can result in malformation of bones and decreased resistance to dental caries.

Table 5.3.1.1 Summary table showing proportion of bedrock groundwater samples from the study samples failing with respect to drinking water norms.

Parameter	Norm	Source	Bergen Area failures/total	Oslo Area failures/total	Total failures/total
pH	> 8.5	1	14/58	0/123	14/181
	< 6.5	1	4/58	5/123	9/181
U_BGR	< 20 μg/L	3	11/58	9/92	20/150
U_GSC	< 20 μg/L	3	10/58	9/92	19/150
Rn	< 100 Bq/L	4	41/56	211/265	252/321
	< 500 Bq/L	6	15/56	40/265	55/321
	< 1000 Bq/L	5	4/56	24/265	28/321
F^-	< 1.5 mg/L	1	20/58	40/313	60/371
Na	< 20 mg/L	2	34/58	36/92	70/150
	< 150 mg/L	1	4/58	2/92	6/150
Combined norms for pH, U, Rn (500 Bq/L), F and Na (150 mg/L)	Compliance		20/56	18/25	38/81
	Failure		36/56	7/25	43/81
Ca	> 25 mg/L	2	16/58	61/92	77/150
	< 15 mg/L	2	29/58	16/92	45/150
K	< 12 mg/L	1	0/58	3/92	3/150
Mg	< 20 mg/L	1	0/58	7/92	7/150
Ba	< 100 μg/L	2	2/58	15/92	17/150

1: Maximum (or minimum) permitted concentration, Norway (Sosial- og helsedepartementet [Ministry of Health and Social Affairs] 1995)
2: Guideline value, Norway (Sosial- og helsedepartementet 1995)
3: Canadian drinking water limit (Barnes 1986)
4: Swedish 'concern' level (SIFF 1987)
5: Swedish maximum level (SIFF 1987)
6: Norwegian recommended maximum (NRPA 1995)

Several studies (e.g. Rock et al. 1981) seem to demonstrate that artificial fluoridation of naturally fluoride-poor drinking water can decrease incidence of caries. Many children are indeed recommended to take fluoride supplement tablets in Norway today. Nevertheless, excessive fluoride may cause negative health effects, referred to as fluorosis. Dental fluorosis results in chalkiness and mottling of the teeth, osteofluorosis results in rough, thickened and chalky bones,

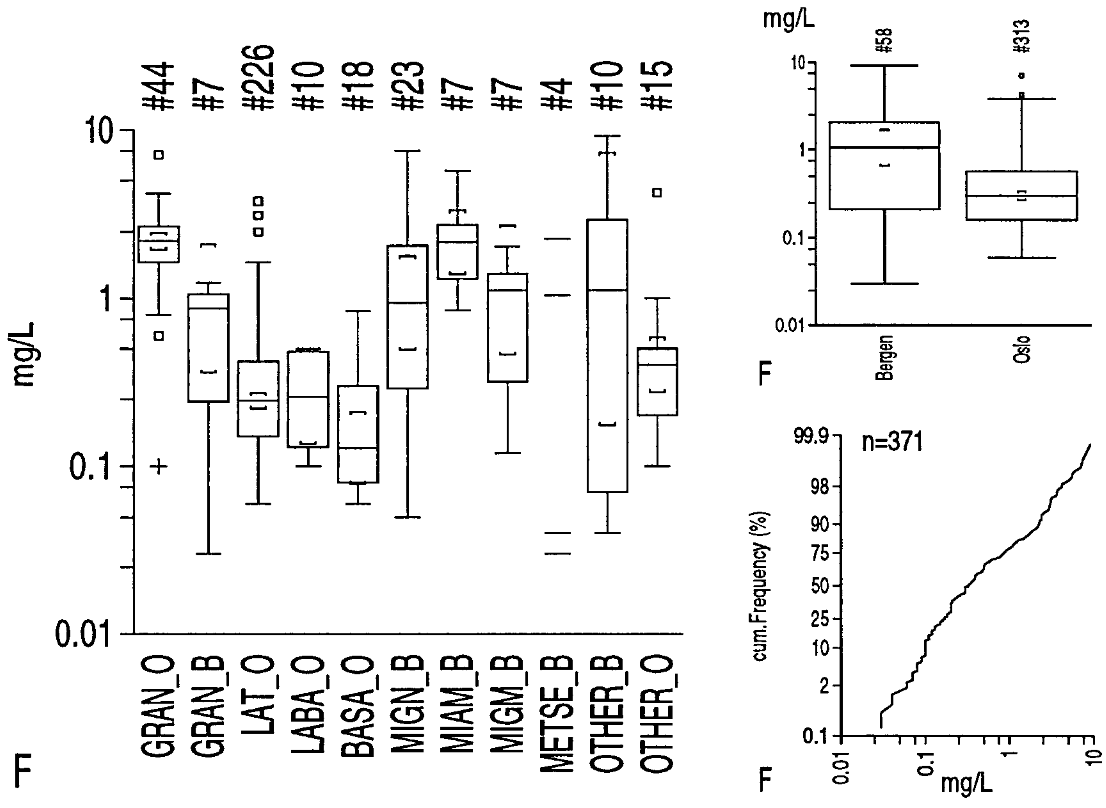


Figure 5.3.2.1 Diagram showing (note the log scales): ***left,*** *boxplots for distribution of fluoride (mg/L) among bedrock groundwaters of the various lithological groups (see text for explanation):* ***top right,*** *boxplots for distribution of fluoride among the Oslo Area and the Bergen Area:* ***bottom right,*** *cumulative probability distribution plot for fluoride for the entire data set (n = 371). # = total number of samples in boxplot group.*

particularly in the jaws, fingers and ribs. Fluorosis may also cause lameness and limb stiffness in cattle and sheep (first observed in volcanic terrain in Iceland in c. 1000 AD - Shupe et al. 1979). Cases of dental fluorosis have been identified by Bjorvatn et al. (1992, 1994) in some parts of western Norway and appear to be

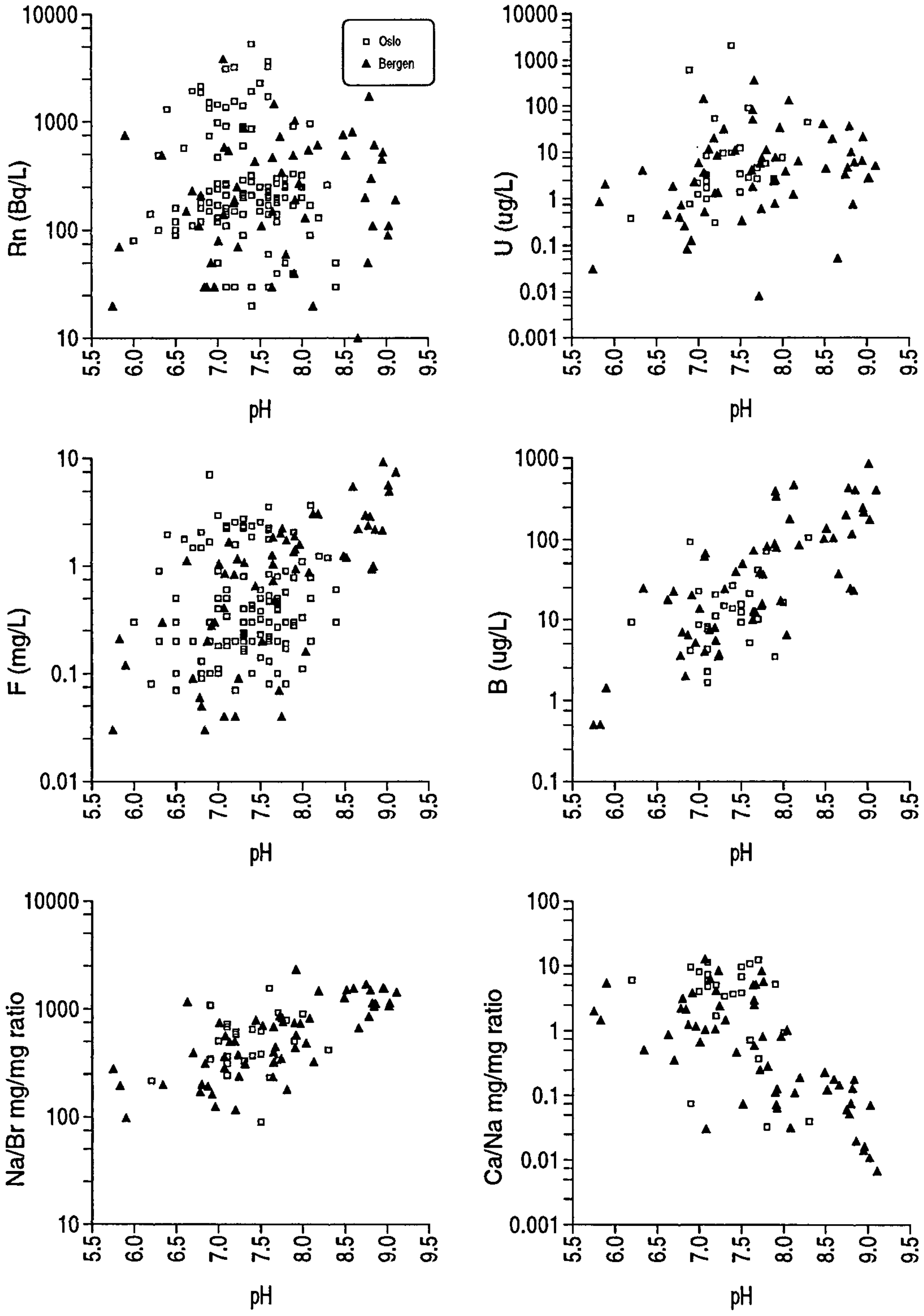


Figure 5.3.2.2 *XY graphs (note the log scales) showing the relations of (a) Rn, (b) U (Canadian values), (c) F, (d) B, (e) Na/Br ratio and (f) Ca/Na versus pH for the data sets from the Oslo Area and the Bergen Area.*

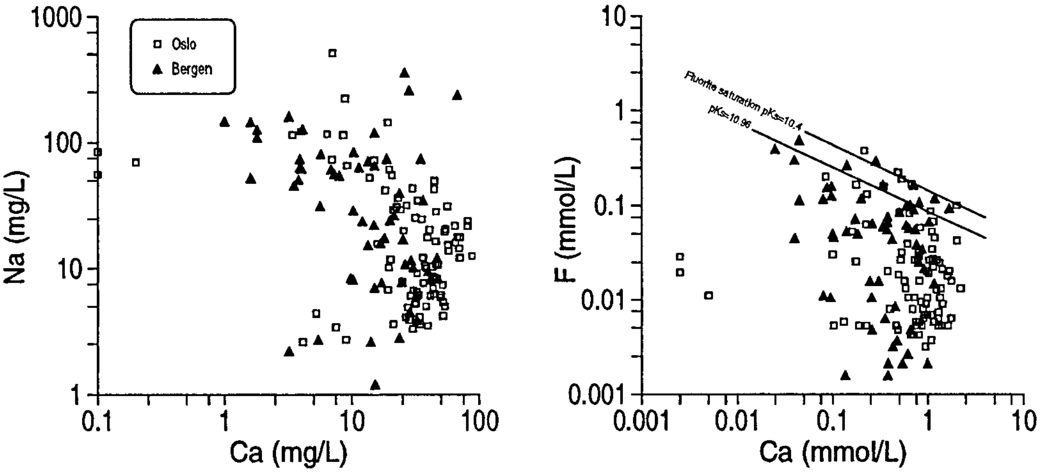


*Figure 5.3.2.3 X-Y graphs showing (note the log scales) (**left**) concentrations in mg/L of the relations between Ca and Na in the waters from the Oslo Area and the Bergen Area and (**right**) relations between molar concentrations of Ca and F^- in the same areas. The upper line shows saturation with respect to fluorite according to Krauskopf (1979)'s value of $pK_s = 10.4$ while the lower line uses Nordstrom & Jenne (1977)'s value of 10.96, both at 25°C. Both lines are adjusted to $T = 6°C$ using the Van't Hoff isotherm. Corrections for activity have not been made.*

linked to consumption of fluoride-rich bedrock groundwater, in a region where levels may exceed 9 mg/L (Bjorvatn 1996, Figure 5.3.2.1).

Previous studies of the regional distribution of fluoride in bedrock groundwater in cool temperate areas include that of Corbett & Manner (1984) in Ohio, United States, where levels of up to 5.9 mg/L were recorded. In the current study, the highest concentrations were recorded in samples from the Bergen Area (Figure 5.3.2.1), where around one third (20 of 58 samples) of all samples exceeded the Norwegian drinking water limit of 1.5 mg/L (Sosial- og helsedepartementet

[Ministry of Health and Social Affairs] 1995) and a maximum concentration of 9.2 mg/L was recorded (Table 5.3.1.1). These high levels are typically derived from the gneissic lithologies and especially from the lithological group consisting of migmatitic gneisses, metagabbros and amphibolites. In the Oslo Area, levels were generally lower, although a significant number of outliers (40 out of 313 samples), mostly from the Drammen Granite and some from the latites, exceeded the 1.5 mg/L limit (Table 5.3.1.1). Figure 5.3.2.2c reveals that in the Bergen samples of elevated pH (>8.5) there are considerably elevated concentrations of fluoride. These high pH values are typically related to the migmatitic gneisses with metagabbro and amphibolite and it is likely that the fluoride is being derived by anion exchange for hydroxide ions on sites on amphiboles or sheet silicates. An observation of a positive correlation with pH has been made several times previously in Norwegian bedrock groundwaters, with a similar explanation (Banks et al. 1993a, Englund & Myhrstad 1980).

Figure 5.3.2.3 reveals no clear correlation of F with Ca, although it will be noted that the most fluoride- and calcium-rich waters impinge upon the line defining fluorite saturation. A plausible model for fluoride evolution in these waters thus involves the derivation of fluoride by anion exchange on amphiboles, sheet silicates and, possibly, apatite, at elevated pH, with an upper limit being defined by the locus of fluorite saturation.

5.3.3 Radon

Apparent correlations have emerged between the incidence of lung cancer and the concentration of radon in household air. Hitherto, some 20 epidemiological studies have been carried out in mines (the most important in uranium mines) and some 30 studies in residential environments. The most important of these are described by ICRP (1993), UNSCEAR (1994), Lubin et al. (1994) and WHO (1996). Although radon-containing water was once thought to have positive health-effects (Albu et al. 1997), there now exist epidemiological studies which appear to link radon concentration in water with incidence of gastric cancer (Mose et al. 1990). Water

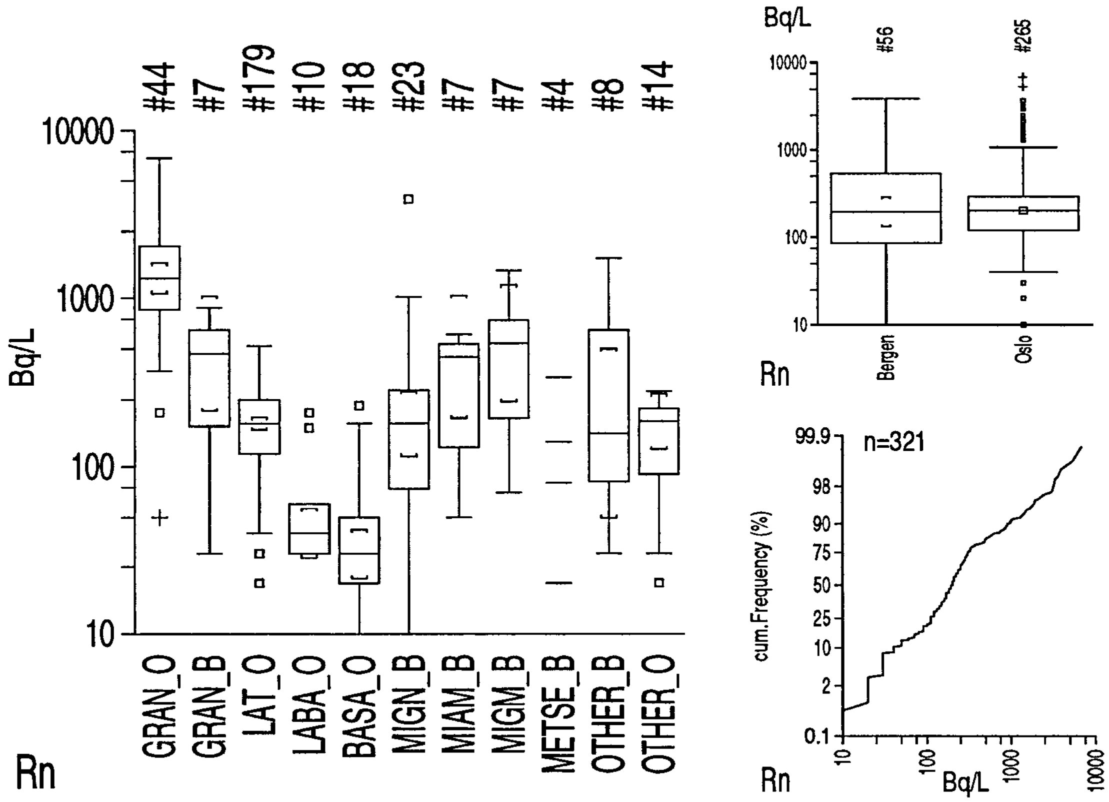


Figure 5.3.3.1 *Diagram showing (note the log scales):* ***left,*** *boxplots for distribution of Rn (Bq/L) among bedrock groundwaters of the various lithological groups (see text for explanation):* ***top right,*** *boxplots for distribution of Rn among the Oslo Area and the Bergen Area:* ***bottom right,*** *cumulative probability distribution plot for radon for the entire data set (n = 321). # = total number of samples in boxplot group.*

with elevated radon concentrations can, according to recent research, result in significant radiation doses, particularly for young children (UNSCEAR 1993, Swedjemark 1993).

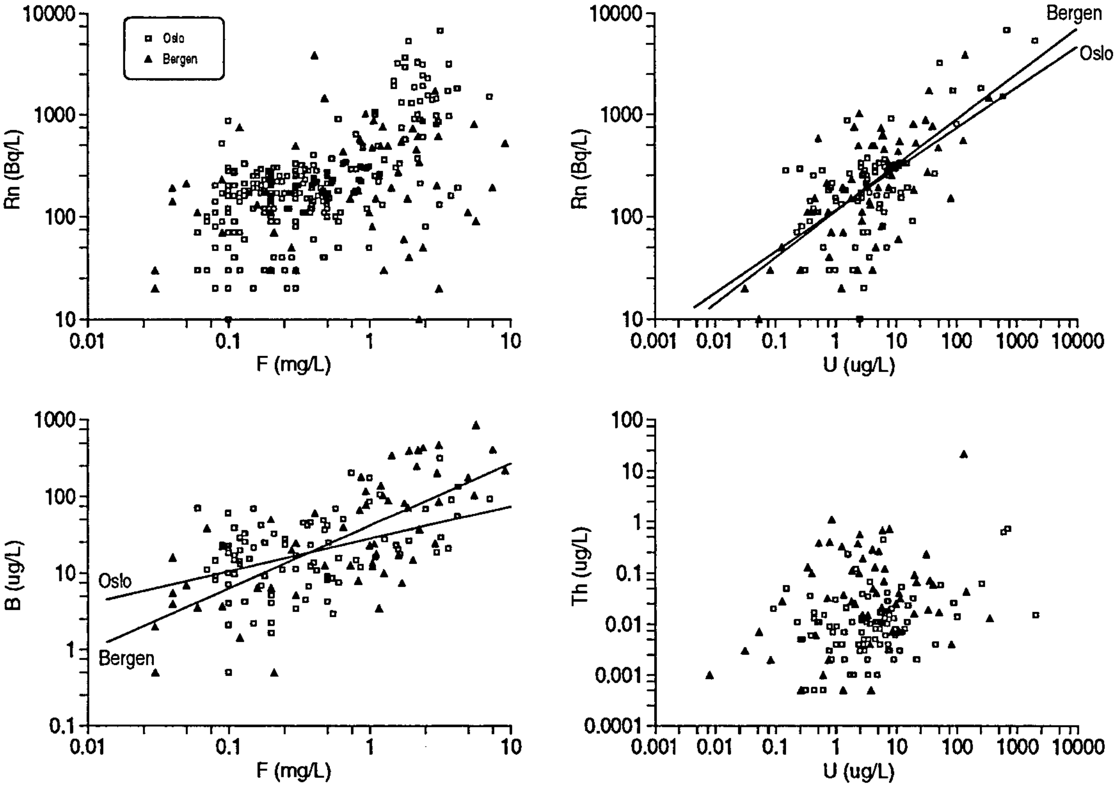


Figure 5.3.3.2 *X-Y graphs (note the log scales) showing covariation (a) of F⁻ and Rn, (b) of U and Rn. Correlation coefficients are 0.537 (Bergen) and 0.777 (Oslo). Standard faults are 503 (Bergen) and 643 (Oslo). The functions describing the correlation lines are Rn = 285 + 5.93*U (Bergen) and Rn = 279 + 3.24*U (Oslo). (c) of F and B. Correlation coefficients are 0.593 (Bergen) and 0.438 (Oslo). Standard faults are 131 (Bergen) and 41.9 (Oslo). The functions describing the correlation lines are B = 21.5 + 51.7*F (Bergen) and B = 19.8 + 17.2*F (Oslo). (d) U and Th in the waters from the Oslo Area and the Bergen Area.*

Hitherto, the highest radon activity reported from Norwegian waters is from the Precambrian Iddefjord Granite of south-eastern Norway (Banks et al. 1995a), with c. 8,500 Bq/L. NRPA (Lind 1996) has analysed a groundwater sample from the same lithology, near the town of Fredrikstad, with an activity of 19,900 Bq/L. Almost 80% of samples taken from this lithology exceeded 1,000 Bq/L (Banks et al. 1995a). Even these values are modest compared with the maxima recorded in drinking water in Sweden (57,000 Bq/L - Åkerblom & Lindgren 1996) and Finland (77,500 Bq/L - Salonen 1994).Sweden operates with an "concern" level of 100 Bq/L for household drinking water, above which it is recommended that the possible effects of the radon on water users should be considered. For groundwater extracted from a private borehole to use in a single household, the similar limit is 500 Bq/L. Sweden has a maximum limit of 1,000 Bq/L, above which action to limit the dose from radon is recommended (Statens strålskyddsinstitut 1996). Norway (NRPA 1995) has recently introduced a recommended maximum level of 500 Bq/L. These levels are based on radiation doses to children and adults due to ingestion and inhalation of degassed radon (Strand & Lind 1992). For children, ingestion results in the most significant dose; for adults, inhalation is the critical pathway.

On the basis of 56 boreholes in the Bergen Area and 265 boreholes in the Oslo Area (Figure 5.3.3.1), around 80% of boreholes (252 out of 321) had a radon activity in excess of 100 Bq/L, while some 17% (55 out of 321) had a concentration in excess of 500 Bq/L. The highest recorded level was 6,840 Bq/L. The most problematic lithological group from the point of view of radon, are the Oslo granites (dominated by the Permian Drammen Granite) where almost 90% of all boreholes exceeded 500 Bq/L and over 50% of all boreholes exceeded 1,000 Bq/L. The lowest radon activities are related to the basalts of the Oslo Area. The latites and rhomb porphyries which, with their relatively high permeability, form the dominant bedrock groundwater supply around Oslofjord, exhibit radon concentrations typically in the range 100-500 Bq/L.

Figure 5.3.3.2a suggests that there are a significant number of cases, especially in the Oslo Area, where high Rn is accompanied by high F^-. Positive correlation between Rn and F^- has been noted by Banks et al. (1995a,b). A possible coexistence of fluoride and uranium in various mineral assemblages (e.g. apatite and sheet

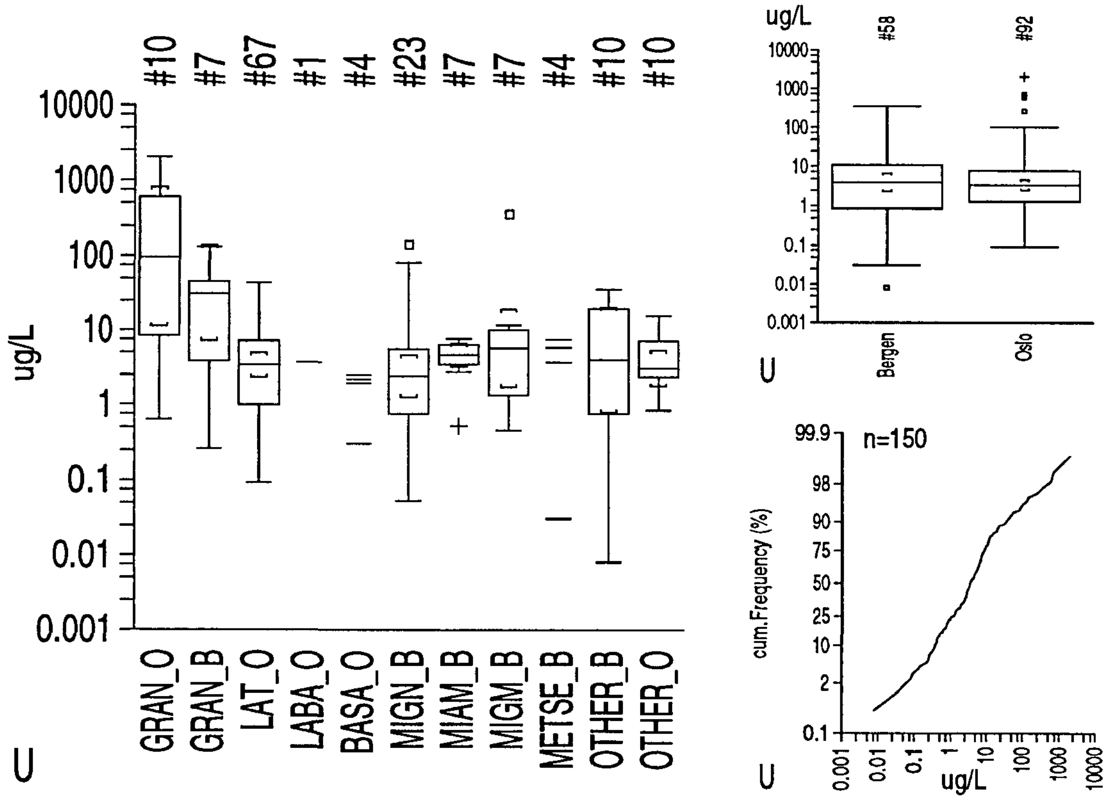


Figure 5.3.4.1 Diagram showing (note the log scales): ***left,*** *boxplots for distribution of U (µg/L) among bedrock groundwaters of the various lithological groups (see text for explanation):* ***top right,*** *boxplots for distribution of U among the Oslo Area and the Bergen Area:* ***bottom right,*** *cumulative probability distribution plot for uranium for entire data set (n = 150). # = total number of samples in boxplot group. In all cases, the figures refer to uranium analyses carried out by GSC in Canada.*

silicates such as biotite) is well known. No radium analyses have, as yet, been performed on the waters, but Strand & Lind (1992) note that there is generally no clear correlation between radon and radium in Norwegian groundwater.

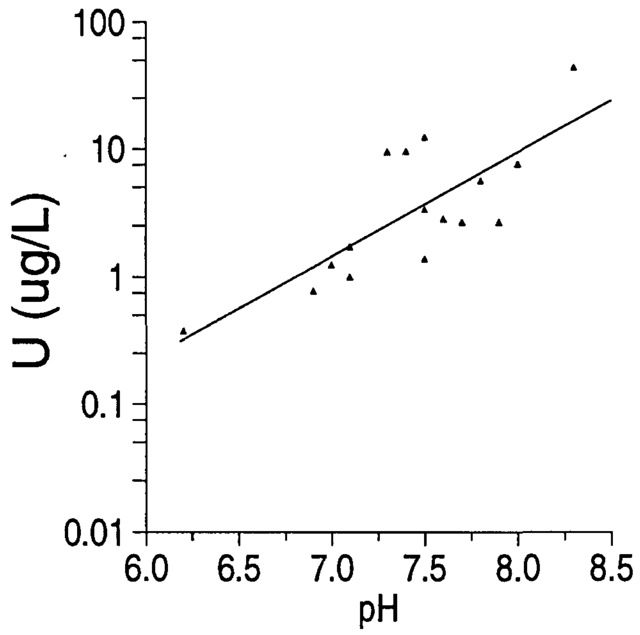


Figure 5.3.4.2 *XY-diagram showing (note the log scale) the correlation between U and pH in the Permian latites and the rhomb porphyry lavas from the Oslo Area. Correlation coefficient is 0.565, standard fault is 9 and the function describing the correlation line is* $U = -81.5 + 11.9 * pH$.

5.3.4 Uranium and Thorium

Previously, the highest reported uranium concentration in Norwegian bedrock groundwater was from the Iddefjord granite (170 µg/L - Banks et al. 1995a), although levels of over 14 mg/L have been reported from granites near Helsinki in Finland (Asikainen & Kahlos 1979). For thorium, Banks et al. (1995a) reported a maximum of 2 µg/L. No Norwegian drinking water limit exists for uranium or thorium whereas Canada uses a maximum of 20 µg/L (Barnes 1986) for uranium.

In this survey, uranium was determined both in Canada and Germany. Below 100 µg/L, the interlaboratory calibration is good. Above this level, the Canadian results exceed the BGR results to a degree which increases with concentration. The highest concentration was found in a sample returning a value of some 2,020 µg/L from

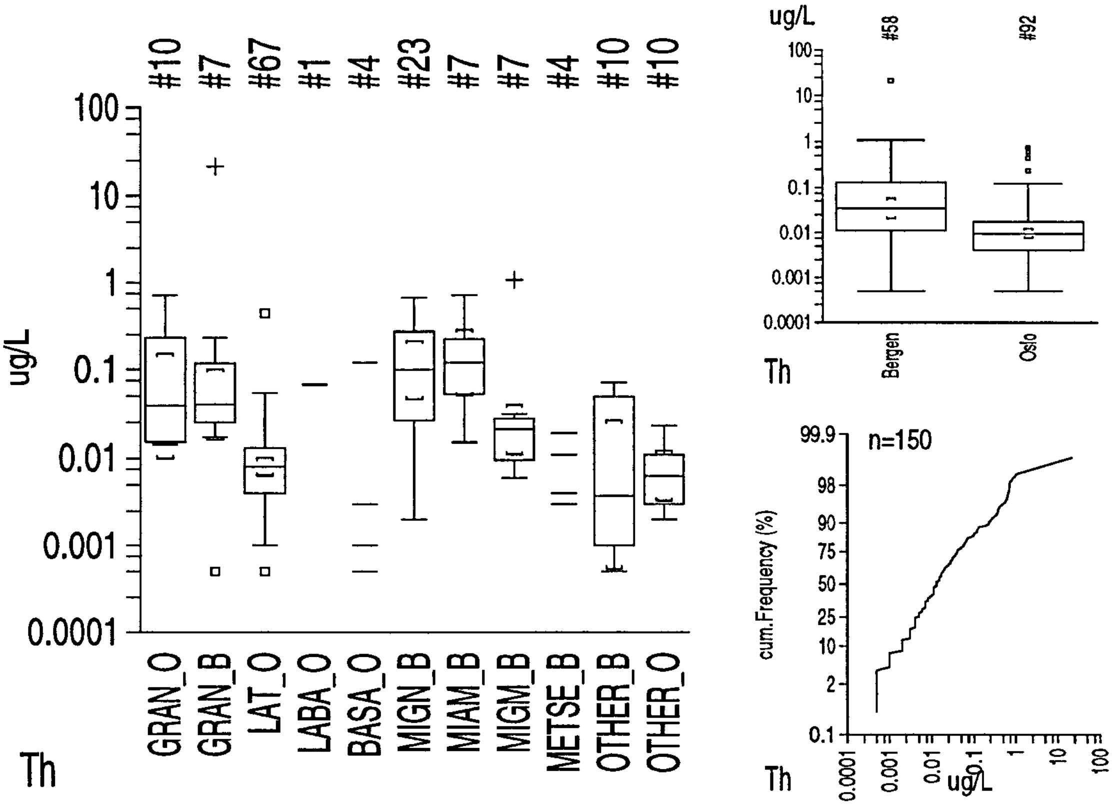


Figure 5.3.4.3 Diagram showing (note the log scales): ***left,*** *boxplots for distribution of Th (µg/L) among bedrock groundwaters of the various lithological groups (see text for explanation):* ***top right,*** *boxplots for distribution of Th among the Oslo Area and the Bergen Area:* ***bottom right,*** *cumulative probability distribution plot for thorium for the entire data set (n = 150). # = total number of samples in boxplot group. In all cases, the figures refer to thorium analyses carried out by BGR in Germany.*

Canada and 890 µg/L from Germany. In the diagrams and in the subsequent discussion, the Canadian values are referred to because these are the values measured shortly after sampling. The distribution of uranium seems to follow that of radon quite closely (Figure 5.3.3.2b). Figure 5.3.4.1 shows that the highest concentrations (with a median of some 100 µg/L and a maximum of 2 mg/L) are derived from the Oslo granites. The next highest levels are derived from the Bergen granites. Some 13% (19 out of 150 samples) of all groundwaters exceed the Canadian limit of 20 µg/L, and these are dominantly from the granite lithologies.

Although there exists a clear correlation in Figure 5.3.3.2b between Rn and U for the total data set, the large differences in Rn and U contents between the different lithologies (Figure 5.3.3.1 and 5.3.4.1) cause the correlation in Figure 5.3.3.2b. This is in accordance with Banks et al. (1995a), and indicates that, although aquifer U content may act as a coarse control on both dissolved Rn and U contents in groundwater, other factors (hydrodynamic factors such as residence time, fracture aperture, redox conditions, weathering history etc.) control the distribution of these parameters within a given aquifer type. There may be a weak positive correlation of U with pH (Figure 5.3.2.2b). The correlation is considerably stronger in the Permian latites and rhomb porphyry lavas from the Oslo Area (Figure 5.3.4.2). Thorium in groundwater seems to exhibit a very weak positive correlation with uranium (Figure 5.3.3.2d), probably reflecting a coarse co-variation in Th and U content in host rocks. Thorium is generally rather insolubl, particularly so in reducing conditions, so redox potential is likely to be a major factor in controlling thorium distribution in groundwater. In this survey almost all samples contain < 1 µg/L thorium (Figure 5.3.4.3), although a single sample from the Bergen granites returned a value of some 20 µg/L. Again the highest concentrations are derived from the acidic lithologies (gneisses and granites). The low solubility of Th probably implies that it presents less of a concern in the context of human health than U or Rn, but given that Th is significantly more toxic than either of the above, the health impact of µg/L-levels of Th cannot necessarily be disregarded as insignificant.

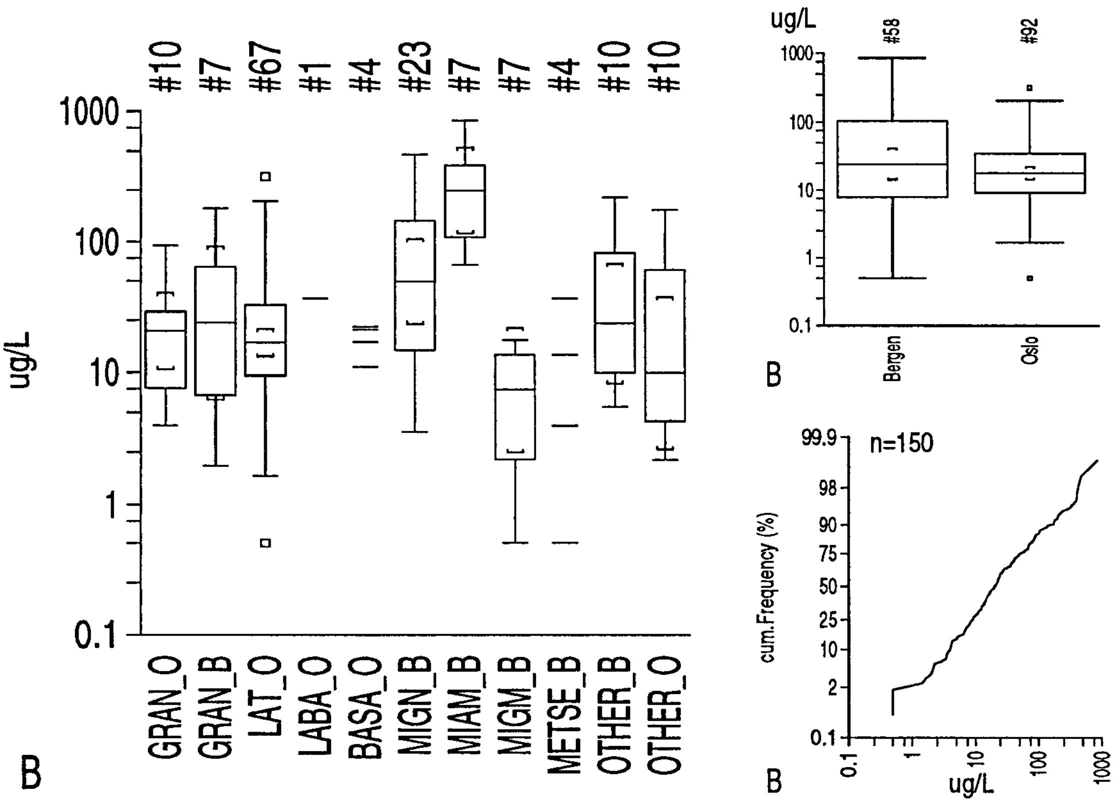


Figure 5.3.5.1 Diagram showing (note the log scales): ***left,*** *boxplots for distribution of B (µg/L) among bedrock groundwaters of the various lithological groups (see text for explanation):* ***top right,*** *boxplots for distribution of B among the Oslo Area and the Bergen Area:* ***bottom right,*** *cumulative probability distribution plot for boron for the entire data set (n = 150). # = total number of samples in boxplot group. In all cases, the figures refer to boron analyses carried out by BGR in Germany.*

5.3.5 Boron

Boron (Figure 5.3.5.1) is an essential element for plants but becomes phytotoxic in high concentrations. Concentrations of boron may thus be of concern regarding the use of groundwater for irrigation. Its essentiality for human health has not been clearly demonstrated, but its utility as a tracer of sewage leakage or of leachate from waste disposal sites renders knowledge of background concentrations in groundwater of considerable interest. Studies of a single lithology, the Iddefjord Granite, by Banks et al. (1993a) indicate that boron in groundwater in coastal regions is partly derived from marine salts in recharge water and partly from water-rock interaction. Boron concentrations recorded in this survey vary between approximately 1 µg/L and 850 µg/L. They show a positive co-variation with fluoride (Figure 5.3.3.2c) and also with pH (Figure 5.3.2.2d). As with fluoride, the highest concentrations are clearly derived from the lithological group containing migmatitic gneisses, amphibolites and metagabbros from the Bergen region.

5.3.6 Sodium and Calcium

Both sodium and calcium have been problematic parameters in the context of Norwegian water resources for some time. The former Norwegian guideline level for sodium (SIFF 1987) was set at a level of only 20 mg/L, which was frequently exceeded in the bedrock groundwater of a country with a high degree of marine influence (marine-derived salts in recharge water) and an abundance of rocks containing sodic plagioclase. The maximum concentration for sodium has been recently defined (Hellesnes 1995, Sosial- og helsedepartementet [Ministry of Health and Social Affairs] 1995) at the more realistic level of 150 mg/L (although the guideline value of 20 mg/L is retained). Calcium has also long been regarded as undesirable from an aesthetic point of view in Norway (scaling of kettles and problems with foaming of soap), and former guidelines (SIFF 1987) stipulated

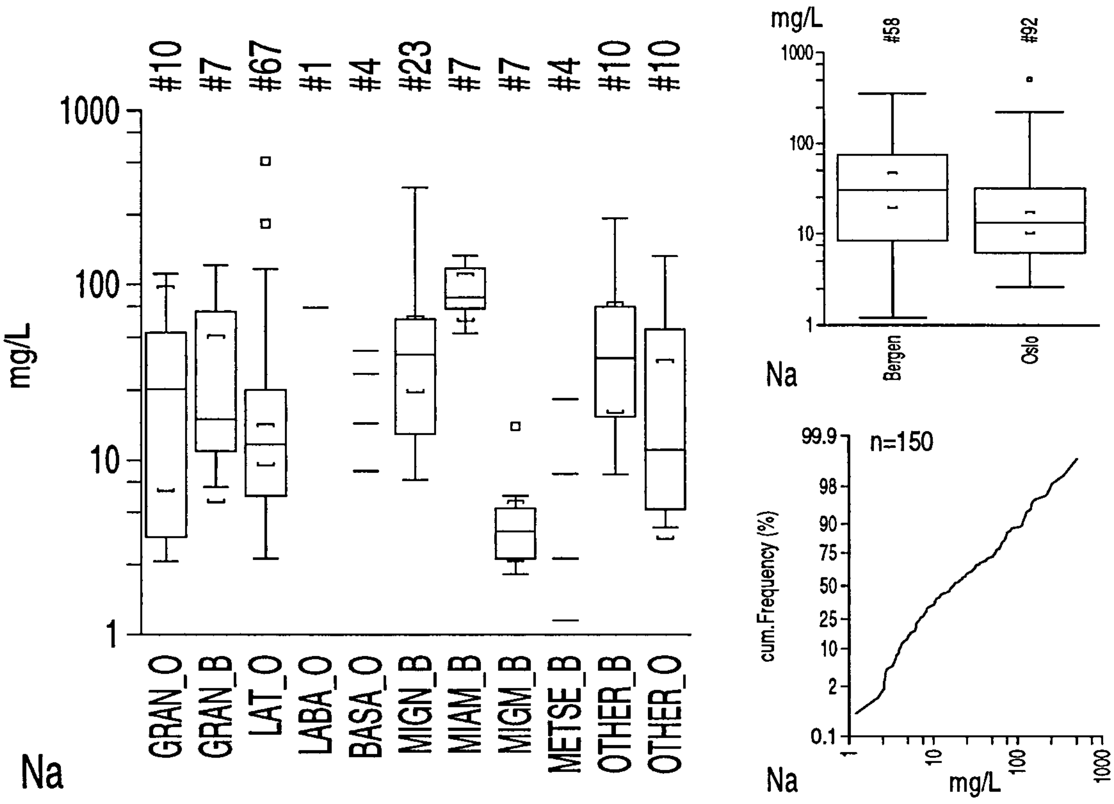


Figure 5.3.6.1 Diagram showing (note the log scales): ***left,*** *boxplots for distribution of Na (mg/L) among bedrock groundwaters of the various lithological groups (see text for explanation):* ***top right,*** *boxplots for distribution of Na among the Oslo Area and the Bergen Area:* ***bottom right,*** *cumulative probability distribution plot for sodium for the entire data set (n = 150). # = total number of samples in boxplot group.*

maximum limits for calcium in drinking water, despite the fact that calcium is not regarded as toxic in drinking water. This despite the fact that several other European nations have set minimum levels for hardness in drinking water (a concept now accepted in Norway - see below). These minimum levels have been

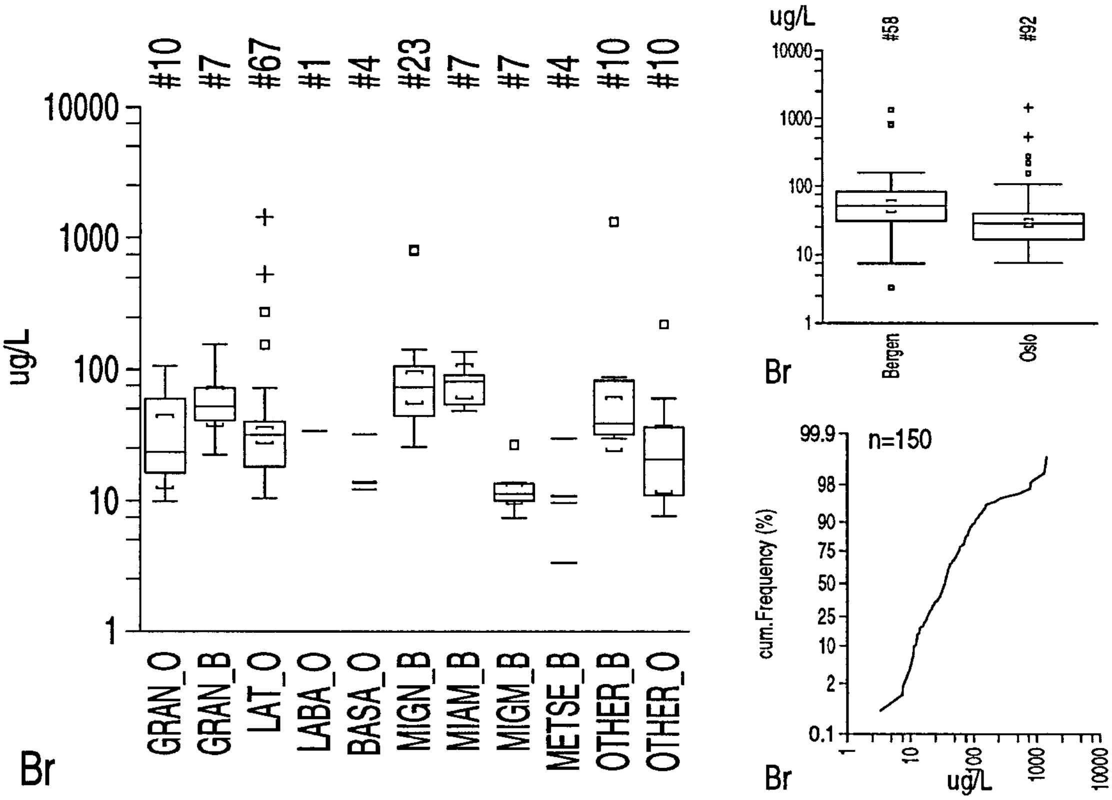


Figure 5.3.6.2 Diagram showing (note the log scales): ***left,*** *boxplots for distribution of Br (µg/L) among bedrock groundwaters of the various lithological groups (see text for explanation):* ***top right,*** *boxplots for distribution of Br among the Oslo Area and the Bergen Area:* ***bottom right,*** *cumulative probability distribution plot for bromide for the entire data set (n = 150). # = total number of samples in boxplot group. In all cases, the figures refer to bromide analyses carried out by BGR in Germany.*

ostensibly promoted by the observation that the incidence of heart disease in several countries (e.g. the UK [Crawford et al. 1971, Lacey 1981] and Norway [Glattre et al. 1977]) is inversely correlated with water hardness. The reasons for this remain unclear, although several possible causative models have been proposed:

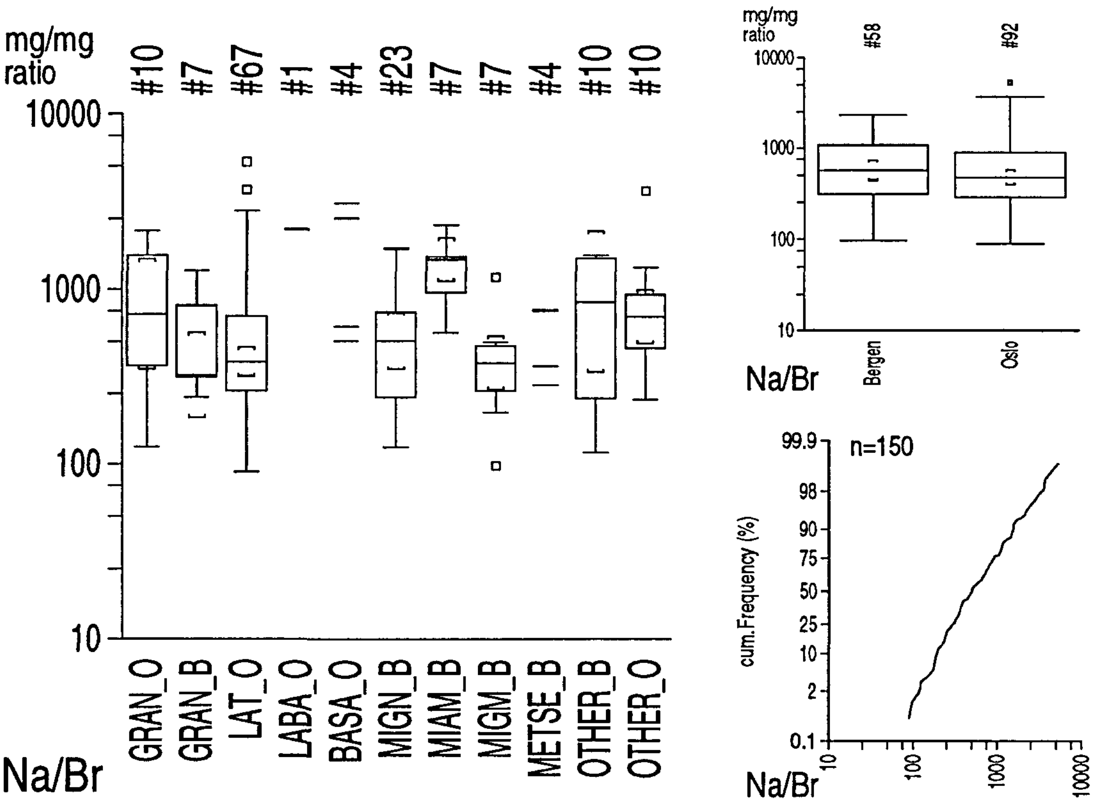


Figure 5.3.6.3 *Diagram showing (note the log scales):* ***left,*** *boxplots for distribution of Na/Br (mg/mg) among bedrock groundwaters of the various lithological groups (see text for explanation):* ***top right,*** *boxplots for distribution of Na/Br among the Oslo Area and the Bergen Area:* ***bottom right,*** *cumulative probability distribution plot for the sodium to bromide ratio for the entire data set (n = 150). # = total number of samples in boxplot group. In seawater the ratio Na/Br = 161-162 (mg/mg) - Rösler & Lange (1975), Open University (1989).*

- that calcium-rich waters are often poor in sodium, a high dietary content of which is known to exacerbate hypertensive disorders.
- that a high water hardness hinders the solubility of many toxic metals (such as lead), which otherwise may be solubilised from geological materials or from the distribution network (Crawford & Clayton 1973).
- that heavy industry, particularly in the UK, has grown up in areas with soft water supplies suitable for textiles manufacture and boiler feed water (i.e. it is the industrial environment rather than the water per se which leads to the disease).

Currently (Sosial- og helsedepartementet [Ministry of Health and Social Affairs] 1995) Norway advises a guideline range of 15-25 mg/L for calcium, yet (slightly perversely) sets a minimum level of 60 mg/L calcium-equivalents (Ca or Mg) for artificially softened water.

Figure 5.3.6.1 displays the sodium concentrations recorded during this study and it will be noted that around 50% of waters (70 out of 150) exceed the Norwegian guideline of 20 mg/L and 4% (6 out of 150) exceed the limit of 150 mg/L, while the maximum observed is 508 mg/L. Banks et al. (1993a) demonstrated that sodium in groundwater in a coastal granite lithology was partly derived from marine salts (from precipitation or direct intrusion) but was in many cases largely derived from silicate weathering or possibly iron exchange. The effect of marine influence can be assessed by examining Figure 5.3.6.2, showing the distribution of bromide in the waters, assumed to be a good indicator of sea salts in groundwater. It will be noted that there is a considerable degree of correlation between Na and Br. The groups with a clear sodium-excess are also clearly identified on Figure 5.3.6.3, which shows the Na/Br ratios (with a value of c. 160 mg/mg in ideal sea water [Rösler & Lange 1975, Open University 1989]).

The range of calcium concentrations extends to higher values in the Oslo Area than in the Bergen Area (Figure 5.3.2.3). There appears to be a general inverse relation between Na and Ca. Samples with > 60 mg/L Na generally contain < 30 mg/L Ca. This relationship is further elaborated by the correlation of the Ca/Na ratio with pH in Figures 5.3.2.2e and 5.3.2.2f. While it will be noted that Ca is dominant over Na in many samples of pH < 8, beyond pH = 8, calcium falls to very low values and the Na/Br ratio increases dramatically (i.e. a lithological source of Na). It will be noted that almost all of the samples of pH > 8 are derived from Bergen, dominantly from the lithological group of "migmatitic gneiss/metagabbro/amphibolite". The changes observed here are reminiscent of those described by, for example, Edmunds (1981) and Banks (1996) in classic sedimentary aquifers of the UK (the Lincolnshire Limestone and the Coal Measures). In these cases, at a given stage in groundwater evolution, reducing conditions commence with a decline in Eh, reduction of sulphate, generation of alkalinity and a slight rise in pH. Commensurate with this is the exchange of Ca for Na (possibly related to the presence of reduced sulphide-phase exchange surfaces in the aquifer). The removal of Ca from the aquifer raises the fluorite saturation "ceiling" permitting increased solubility of fluoride. The data from the Bergen and Oslo areas are consistent with a similar step in groundwater evolution, but in the absence of redox indicators (Eh, sulphate, nitrate) and alkalinity, the model must remain speculative in this case. This should underline the necessity of future groundwater chemical surveys to include analysis of anions and alkalinity in the analytical programme, despite the costs associated with these analyses, if a full understanding of groundwater genesis is to be achieved.

5.4 *Discussion*

By examining the contents of several potentially undesirable parameters in Norwegian bedrock drinking water from the Oslo and Bergen areas, it has been demonstrated that 53% of all waters contravene recognised drinking water limits for one or more of the following parameters: pH, U, Rn, F^- and Na (Table 5.3.1.1). The majority of these contraventions were identified in the Bergen Area (64% contravention), with a rate of only 28% contravention in the Oslo Area.

It is clear from the results of this investigation that there is some cause for concern over the suitability of some untreated groundwaters from bedrock aquifers as drinking water resources. Concentrations of Rn, U and F^- have been presented which exceed accepted drinking water norms, in some cases very significantly. Other elements with possible health (Be, Al) or aesthetic (Fe, Mn) implications, which exceed accepted norms in these waters, are presented and briefly discussed by Reimann et al. (1996). Studies by Sæther et al. (1995) and Morland et al. (1996) have demonstrated that water quality problems associated with Rn and F^- (and presumably U) are not normally encountered in Quaternary aquifers in Norway, which form the basis for most large-scale waterworks. Morland et al. (1996) demonstrate that the radon activity in Quaternary groundwater from 31 large Norwegian waterworks does not exceed 80 Bq/L.

Even in bedrock groundwater, many geochemical parameters exhibit a heavily skewed, quasi-log-normal distribution. This implies that the health-related parameters usually only exceed drinking water norms in a minority of waters, and these are typically in relatively well-defined lithologies. In the case of Rn, F^- and U, for example, granitic groundwater can be predicted to carry a greater risk of limit-exceedance than basaltic lithologies. From Table 5.3.1.1, it can be seen that from the areas of Bergen and Oslo studied, 53% yielded water which did not satisfy at least one of the following: Norwegian drinking water limits for pH, Na, Rn and F^- or the Canadian limit for U. It is almost certainly the case that these results are not representative of Norwegian bedrock groundwater as a whole, as the areas chosen do seem to contain a high proportion of "high-risk" lithologies. For example, the counties of Nord- and Sør-Trøndelag have recently been subject to studies of radon in groundwater in some 30 bedrock boreholes in Caledonian metasediments and metavolcanics and Precambrian gneisses without any groundwater exceeding the 500 Bq/L limit (Strand 1996)

Finally, it must be remembered that most "problem-parameters" can be treated. For radon, treatment is available for domestic water supplies. Several methods are available, including simple aeration and carbon adsorption. The methods are assessed by Nazaroff et al. (1988), Kinner et al. (1990) and Boox (1995a,b). Fluoride is more problematic to treat, the most effective, but expensive, technologies being anion exchange and ultrafiltration.

Chapter 6

Yield of Bedrock Boreholes in Norway

6.1 Introduction

The groundwater yield of a bedrock borehole is usually defined in Norway as the volume of water extracted per unit time, expressed for example in litres per hour (L/h) (e.g. Banks et al. 1993b, Ellingsen 1978 and 1992, NGU 1991, Persson et al. 1979, 1985a and 1985b and Rohr-Torp 1987). This definition of the yield of a bedrock borehole does not however take into consideration the depth of the borehole. Due to the fact that a bedrock well borer usually will cease drilling when a satisfactory borehole yield has been obtained, a normalisation of yield with respect to borehole depth is required in order to be able to compare the yields of boreholes in different lithologies.

The concept of normalised yield has therefore been used in this thesis. This term takes into account both the actual groundwater yield of the bedrock borehole and the drilled depth (in bedrock) of the borehole. The advantages of using normalised yield instead of yield (litres per unit time) has also been exploited by Rohr-Torp (1994) as a better method for comparing bedrock boreholes. Henriksen (1995) also uses normalised yield in a study of the relationship between topography and borehole yield in boreholes in the county of Sogn og Fjordane.

6.2 Materials and Methods

All the 12,757 bedrock boreholes extracted from the BBD (Chapter 3.5) have been assigned a rocktype and entity as defined in Chapters 2.1 and 2.3 (Figure 2.1.1 and Table 2.3.1). The normalised yield of each borehole has been calculated using the value of yield divided by the drilled depth of the borehole, resulting in units of litres/hour per drilled metre. A total of 25 different rocktypes and 110 different bedrock entities have been identified (Chapter 2.3). As the assignment of boreholes to rocktype categories and entities was performed using a digitised geological map at the large scale of 1:3,000,000 (compared to geological maps at a scale of 1:1,000,000 or smaller, e.g. Sigmond et al. 1984), the possibility exists for the erroneous allocation of lithology to boreholes. The exploratory data analysis program DAS is well-suited in dealing with this kind of "non-ideal" data set and has been used to prepare graphical statistical presentations of all rocktypes and entities. ArcView 3.0 GIS was used to prepare the maps.

6.3 *Results*

The median values of depth, yield and normalised yield for the 25 different rocktypes were calculated using the DAS-program. The results are shown in Table 6.3.1. Arithmetic mean values are not cited in this thesis as means of distributions such as those considered in this thesis, which are typically highly skewed towards low values, are very sensitive to the outlying high values of high-yielding boreholes. If we consider all rocktypes in Table 6.3.1 with a median yield of around 1,000 L/h, the variation in median depth (i.e. drilled depth) among these rocktypes exceeds 40%. Normalised yield is therefore the only parameter which can be used to reliably compare the yield obtained from boreholes in different bedrock types.

The results shown in Table 6.3.1 are also presented graphically in Figures 6.3.1, 6.3.2 and 6.3.3. These figures show the information as box-plots for each rocktype. The notches within each box-plot indicate the 95% confidence limit about the median. The median depth of the entire data set is 56 m. The 95% confidence limit ranges from 55.42 to 56.57 m. The median yield of the entire data set is 600 L/h with a 95% confidence limit ranging from 583 to 617 L/h. The median normalised yield of the entire data set is 12.037 L/h per drilled metre with a 95% confidence limit ranging from 11.65 to 12.42 L/h per drilled metre. The horizontal lines in Figures 6.3.1, 6.3.2 and 6.3.3 indicate these upper (red line) and lower (light blue line) confidence limit ranges for the entire data set. The location of the entities for each rocktype is shown in Appendix A. Graphical statistical plots for all boreholes located within each bedrock entity and rocktype are shown in Appendix B. These

Table 6.3.1 *Variation in the median depth (metres) of bedrock boreholes with corresponding median groundwater yield (litres/hour) (sorted in descending order) for the various bedrock types. The rocktype number refers to the digitised bedrock map of Norway and adjacent ocean areas (Sigmond 1992). Normalised yield is in litres/hour per drilled metre*

Rock-type	Definition	Number of boreholes	Median yield	Median depth	Median normalised yield
57	Permian volcanic rocks, with subordinate sedimentary rocks (Oslo Region)	568	2500	45	58.3
79	Upper Precambrian quartz sandstone	58	1020	50	23.2
75	Cambro-Silurian limestone and marble	335	1000	45	22.5
54	Permian plutonic rocks (Oslo Region)	561	1000	50.5	22.4
67	Upper Silurian sandstone	68	1000	63.5	17.6
87	Precambrian granite to tonalite	50	800	61	13.8
98	Precambrian gneiss, migmatite, foliated granite, amphibolite	3378	750	48	16.7
81	Upper Precambrian limestone, shale	63	700	41	16.8
97	Precambrian metarhyolite, metarhyodacite	182	700	54.5	14.0
80	Upper Precambrian sandstone, shale, conglomerate	1036	600	50	12.7
85	Precambrian rocks of different origin in Caledonian nappes	374	600	57	11.4
74	Cambro-Silurian meta-sediments of the Caledonian mountain chain and the Oslo Region	2098	600	57	11.4
82	Upper Precambrian metasandstone, mainly meta-arkose and quartz schist	238	600	61	10.7
92	Precambrian autochthonous granite to tonalite	360	590	53	11.4
88	Precambrian amphibolite, gneiss	70	575	68	10.9
95	Precambrian metasandstone, mica schist, conglomerate, supracrustal gneisses	113	550	58	10.3
90	Precambrian metamorphosed sedimentary and volcanic rocks, gneiss	114	525	73.5	8.3
96	Precambrian metabasalt, meta-andesite, amphibolite	66	500	67.5	10.3
94	Precambrian autochthonous gabbro, amphibolite, ultramafic rocks	109	420	55.5	9.4
91	Precambrian gneiss, migmatite, foliated granite, amphibolite (north-western gneiss region)	1140	420	71	6.6
76	Cambro-Silurian greenstone, greenschist, amphibolite, meta-andesite	175	360	65	5.6
86	Caledonian charnockitic to anorthositic rocks	1341	310	71	5.1
71	Caledonian granite to tonalite	88	300	78.5	4.1
64	Devonian sedimentary rocks, mainly sandstone and conglomerate	22	290	67	4.5
72	Caledonian gabbro, diorite, ultramafic rocks	103	250	80	3.5

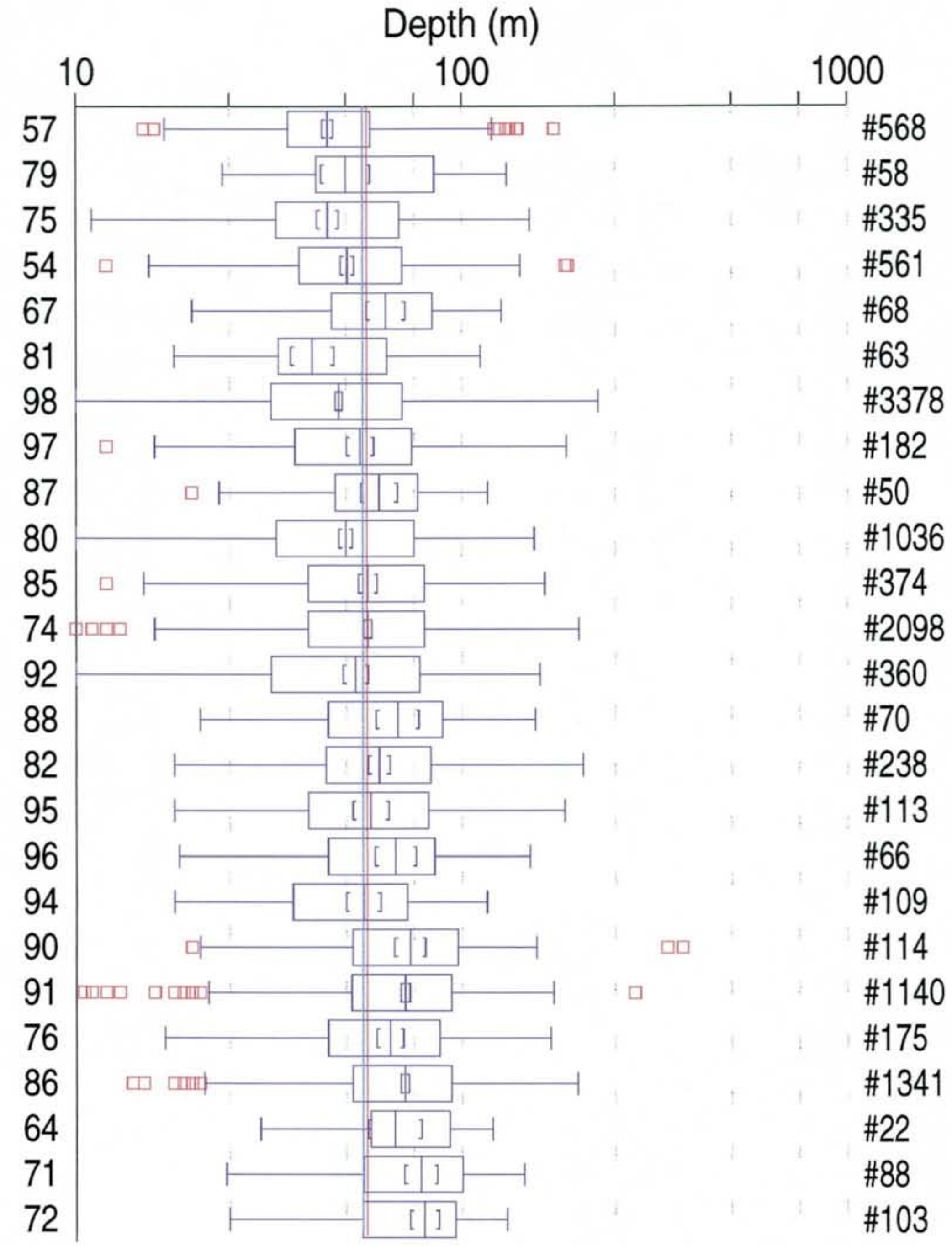


Figure 6.3.1 *Boxplots showing the drilled depth in metres of all 12,757 boreholes extracted from the BBD as a function of bedrock type (left). The 95% confidence limits of the overall median of 56 m are marked as horizontal lines. # = total number of samples in boxplot group. The boxplots are sorted as in Figure 6.3.3.*

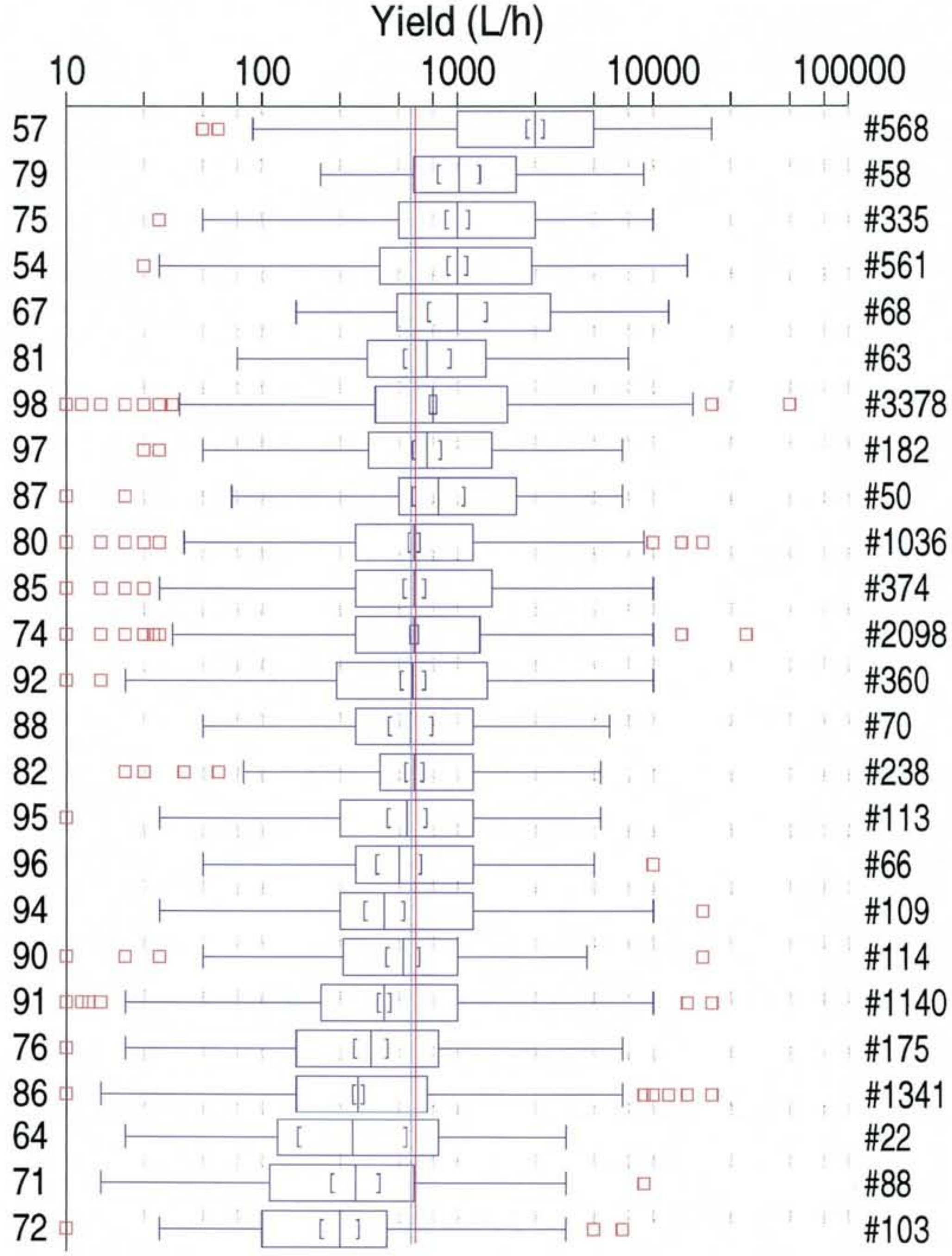


Figure 6.3.2 *Boxplots showing the yield in litres per hour of all 12,757 boreholes extracted from the BBD as a function of bedrock type (left). The 95% confidence limits of the overall median of 600 L/h are marked as horizontal lines. # = total number of samples in boxplot group. The boxplots are sorted as in Figure 6.3.3.*

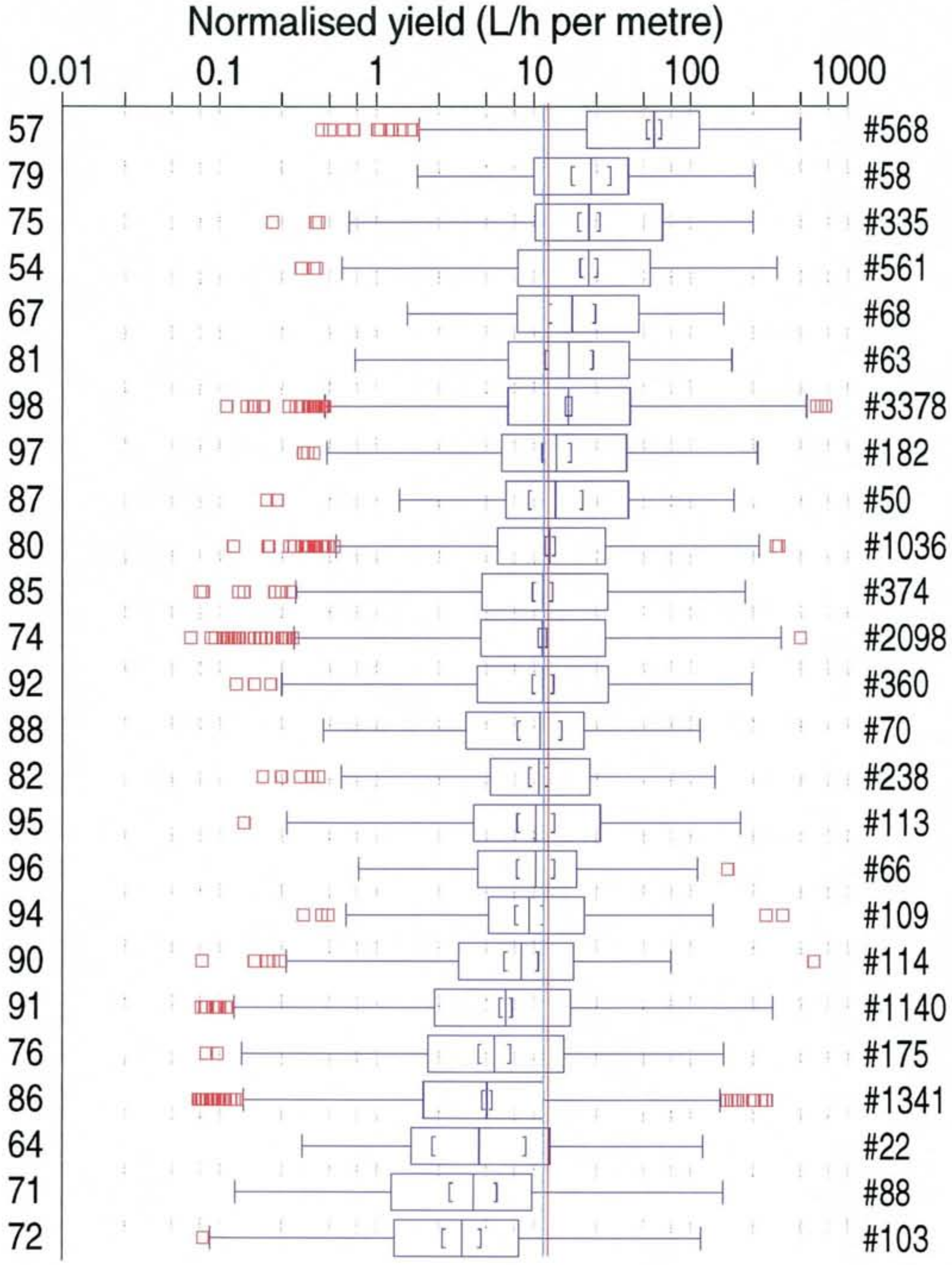


Figure 6.3.3 *Boxplots showing, in descending order, the normalised yield in litres/hour per drilled metre of all 12,757 boreholes extracted from the BBD as a function of bedrock type (left). The 95% confidence limits of the overall median of 12.0 L/h per drilled metre are marked as horizontal lines. # = total number of samples in boxplot group.*

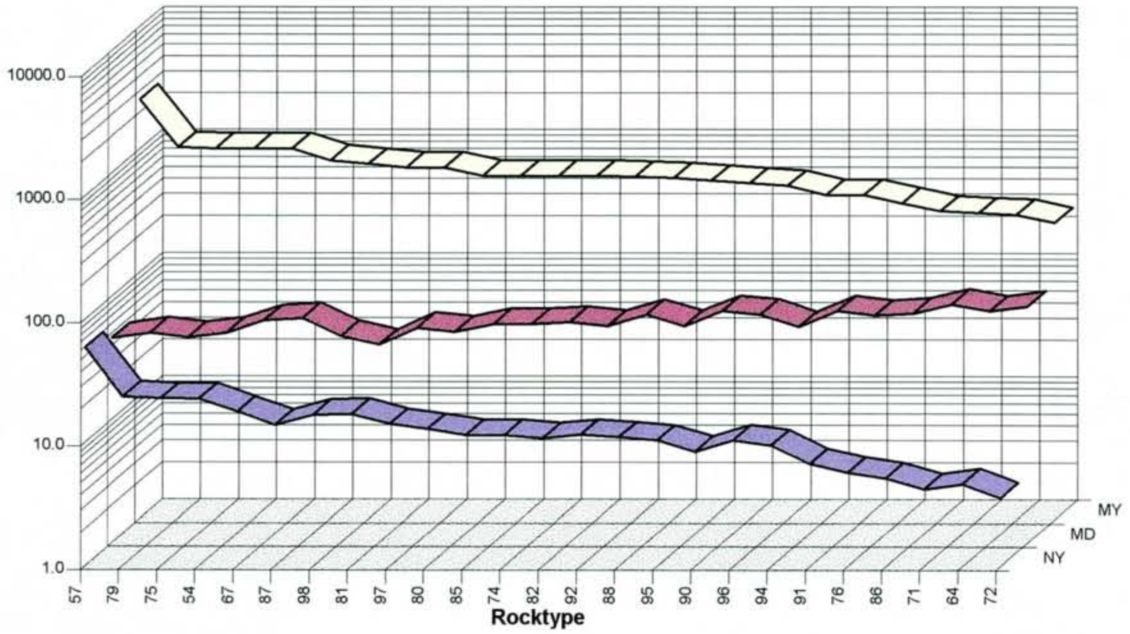


Fig. 6.3.4 *The median values of depth (MD - red color) (m), yield (MY - yellow color) (L/h) and normalised yield (NY - blue color) (L/h per drilled metre) of the various rocktypes compared on a logarithmic scale.*

plots include cumulative frequency curves, density traces, boxplots and XY-plots with respect to depth and yield with corresponding correlation coefficients.

Figure 6.3.4 shows a marked increase in the median value of depth as the median value of yield decreases. This is probably due to the effect of the discontinuation of drilling when a satisfactory supply has been obtained, even at a relatively shallow depth, as previously mentioned in Chapter 6.1. It also highlights the bedrock well borers habit of drilling boreholes too deep in rocks with high values of normalised yield. In other words, the drilled depth is very poorly related to the required yield in rocks with low groundwater yield. This also illustrates the importance of considering both yield and depth when classifying the groundwater yield potential of different bedrock types.

Figure 6.3.5 (Appendix D) shows XY-plots of depth versus normalised yield for all bedrock boreholes within each of the 110 bedrock entities. The smoothing function in the DAS-program has been used (moving median 4, then 2, 5, 3 and finally applying the Hanning method). The results of the smoothing process are represented by the black line in each entity diagram. Figure 6.3.5 shows the same trend in the correlation coefficients as in Appendix B, but gives a more detailed picture of the relationship between depth and normalised yield for each bedrock entity. Normalised yield was estimated for both shallow and deep bedrock boreholes within each entity. These normalised yield values were used to calculate the spread of the normalised yield of shallow bedrock boreholes versus normalised yield of deep boreholes within each entity.

The results indicate that only 18 bedrock entities show a general increase with depth in the yield of deep boreholes compared to shallow boreholes. The majority (74) of the bedrock entities show a clear decrease in the median normalised yield of deep boreholes compared to shallow boreholes. For 18 entities no clear relationship between normalised yield and depth could be identified. A median reduction factor was calculated by dividing the median normalised yield of deep bedrock boreholes by the corresponding value for shallow boreholes, both estimated from Figure 6.3.5. This reduction factor was calculated to be approximately 0.4. Each of the entity diagrams in Figure 6.3.5 is discussed below under the corresponding rocktype. The median values of depth, yield and normalised yield of different rocktypes and entities are also discussed below.

Figures 6.3.1, 6.3.2 and 6.3.3 and the box-plots in Appendix B were used to determine if median values are equal or significantly different between different box-plots. The notches in these figures indicate the 95% confidence limits based on the distribution of the data.

Rocktype 54

Bedrock boreholes in this rocktype are located within the Permian plutonic rocks of the Oslo region. The median depth of bedrock boreholes in this rocktype is significantly lower than the median depth of 56 m for the entire data set (see definition in Chapter 1.3). The median yield is significantly higher than the overall median yield of 600 L/h and the median normalised yield is significantly higher than the overall median of 12.0 L/h per drilled metre for the entire data set (see Table 6.3.1). A total of 66% of all boreholes located in this rocktype have a higher normalised yield than the median for the entire data set.

Rocktype 54 consists of four bedrock entities (see Table 6.3.2). There are only minor differences between three of the four entities in this rocktype. Entity 1032 differs, however, from the other entities in having a significantly higher median yield resulting in a higher median normalised yield of 57.7 L/h per drilled metre. Approximately 81% of all boreholes in entity 1032 have a higher normalised yield than the median of the entire data set.

The median depth, yield and normalised yield of entities within this rocktype are given in Table 6.3.2 together with the upper hinge and lower hinge values (see Figure 3.5.2 for explanation). The upper and lower hinges define the interquartile range (i.e. the central 50%) of the data for boreholes located in this rocktype. The maximum yield of bedrock boreholes within the plutonic rocks of the Oslo region was previously thought to be around 10,000 L/h (see Chapter 3.3). The data set considered here does not conflict with this statement as only 6 boreholes (or 1%) within rocktype 54 exceed this yield. Hagemann (1961) indicates a median yield of boreholes in the plutonic rocks in the county of Vestfold of 1,000 L/h (entities 971 and 1032). Rohr-Torp (1987) calculated the median value of 314 bedrock boreholes within different granitic rocks within the area of the 1:50,000 map sheet for Drøbak as being in the range 580 L/h to 750 L/h.

Table 6.3.2 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 54 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 54	38	50.5	70	400	1000	2400	7.9	22.4	55.0
Entity 836	35	49	67	400	950	2450	8.9	20.9	58.4
Entity 958	35	50	70	500	900	2000	7.4	20.0	50.0
Entity 971	40	55	70	400	1000	2400	7.0	22.0	43.1
Entity 1032	40	51	61	1000	2400	5000	18.2	57.7	111.1

Approximately 71% of the bedrock boreholes within rocktype 54 have yields in the range 400 L/h to 5,000 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.2). In Figure 6.3.5 the bedrock entities within rocktype 54 all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors for all these entities are between 0.2 and 0.4.

Rocktype 57

Bedrock boreholes in this rocktype are located within the Permian volcanic rocks and subordinate sedimentary rocks of the Oslo region. The median depth of bedrock boreholes in this rocktype is significantly lower than the median depth of 56 m for the entire data set. The median yield is however significantly higher than the overall median yield of 600 L/h and the median normalised yield is significantly higher than the median of 12.0 L/h per drilled metre of the complete data set (see

Table 6.3.3 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 57 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			**Yield**			**Normalised yield**		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 57	35.5	45	58	1000	2500	5000	28.8	58.3	113.6
Entity 906	30	40	52.5	600	1200	2800	13.2	31.1	80.0
Entity 923	30	40	47	570	1000	1500	12.8	23.1	37.2
Entity 975	37	46.5	59	1250	3000	6000	28.8	68.7	122.6
Entity 1031	44	51	60	900	1500	2000	18.2	30.0	39.5

Table 6.3.1). A total of 87% of all boreholes located in this rocktype have a higher normalised yield than the median for the entire data set.

Rocktype 57 comprises four bedrock entities (see Table 6.3.3). There are only minor differences between three of the four entities in this rocktype. Entity 975 differs however from the other entities by having a significantly higher median yield and a consequently higher median normalised yield of 68.7 L/h per drilled metre. A total of 90% of all boreholes in entity 975 have a higher normalised yield than the median for the entire data set. The spread in depth, yield and normalised yield for boreholes in entities 923 and 1031 is smaller than the corresponding spreads in entities 906 and 975. This may be due to a greater homogeneity in the bedrock lithology within these entities than in the other entities of this rocktype.

The median depth, yield and normalised yield of entities within this rocktype are given in Table 6.3.3, together with upper hinge and lower hinge values (see Figure 3.5.2 for explanation), which envelop the central 50% of the data for boreholes located in this rocktype. Nystuen et al. (1993) mention that the yield of boreholes in the Permian rhomb porphyry lava at Sollihøgda (entity 906) is typically between 2,000 L/h and 5,000 L/h. Hagemann (1961) suggested a median yield of more than 4,000 L/h in the same lithology. It was mentioned in Chapter 3 that borehole yields in the rhomb porphyry lava are generally considered to range from 6,000 L/h to several tens of thousands of L/h. Given the current data set, these statements seem somewhat optimistic. A total of 73% of the bedrock boreholes within rocktype 57 have yields between 570 L/h and 6,000 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.3).

Figure 6.3.5 shows that the bedrock entities in rocktype 57 all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The exception is bedrock entity 923 for which no correlation is observed between normalised yield and depth. The reduction factors for all entities lie between 0.3 and 0.4.

Rocktype 64

Bedrock boreholes in rocktype 64 are located within the Devonian sedimentary rocks of the west coast of Norway. The median depth of bedrock boreholes in this rocktype is significantly higher than the median depth of 56 m for the entire data set. The median yield is significantly lower than the overall median of yield of 600 L/h and the median normalised yield is significantly lower than the overall median of 12.0 L/h per drilled metre (see Table 6.3.1). Only 27% of all boreholes located in this rocktype have a higher normalised yield than the median for the entire data set.

Table 6.3.4 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 64 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			**Yield**			**Normalised yield**		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 64	58	67	93	120	290	800	1.7	4.5	12.7
Entity 646	57	75	96	160	280	450	1.9	3.2	7.8

This rocktype contains only one bedrock entity (see Table 6.3.4). The median depth, yield and normalised yield of the rocktype are given in Table 6.3.4 together with the upper hinge and lower hinge values (see Figure 3.5.2 for explanation) which envelop the central 50% of the data. Approximately 55% of the bedrock boreholes within rocktype 64 have yields in the range 120 L/h to 800 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.4). A total of 22 bedrock boreholes occur in rocktype 64. Of these only 11 boreholes are located in entity 646.

In Figure 6.3.5 the bedrock entity of rocktype 64 shows a tendency for a reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factor for this entity is estimated at around 1. This means that some deep bedrock boreholes within this rocktype may have a yield exceeding the yield of shallow bedrock boreholes.

Rocktype 67

Bedrock boreholes in this rocktype are located within the Upper Silurian sandstones (entities 810 and 820) and fine-grained granitic gneiss of the Nes Precambrian

Table 6.3.5 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 67 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	M	UH	LH	M	UH	LH	M	UH
Rocktype 67	46	63.5	84	490	1000	3000	7.8	17.6	47.0
Entity 788	40	60	78	700	1400	2500	10.7	21.0	54.1
Entity 810	64	97	112	210	460	900	4.6	7.8	8.3
Entity 820	49.5	66.5	77.5	490	1200	7500	11.0	18.0	125.1

Horst (possibly metamorphosed rhyolite) (entity 788) of the Mjøsa area. The median depth of bedrock boreholes in this rocktype is not significantly higher than the median depth of 56 m for the entire data set. The median yield is significantly higher than the overall median yield of 600 L/h but the median normalised yield is not significantly higher than the median of 12.0 L/h per drilled metre for the entire data set (see Table 6.3.1). Approximately 59% of all boreholes located in this rocktype have a higher normalised yield than the median for the entire data set.

Rocktype 67 contains three bedrock entities (see Table 6.3.5). There are only minor differences between two of the three entities in this rocktype. Entity 810 differs from entity 788 in having both a lower median yield and a higher median depth resulting in a significantly lower median normalised yield of 7.8 L/h per drilled metre. Only 15% of all boreholes in entity 810 have a higher normalised yield than the median for the entire data set. The spread (i.e. the difference between the whiskers in Figure 3.5.2) in depth, yield and normalised yield of this entity is smaller than for entities 788 and 820. This may be due to a greater homogeneity in the lithologies within this entity as compared to entities 788 and 820.

The median depth, yield and normalised yield of boreholes within the entities of this rocktype are given in Table 6.3.5, together with upper and lower hinge values (see Figure 3.5.2 for explanation), enveloping the central 50% of the data. Englund & Myhrstad (1980) cite borehole yields obtained from this rocktype in the range of 500 L/h to 2,000 L/h. Rohr-Torp (in Nystuen et al. 1993) indicated that borehole yields obtained in areas of interbedded sandstone and shale are typically in the range 250 L/h to 2,000 L/h. Rohr-Torp also indicates a range of borehole yields in sandstones and conglomerates from 1,000 L/h to 2,500 L/h. A total of 90% of the bedrock boreholes within rocktype 67 have yields in the range 210 L/h to 7,500 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.5), broadly supporting the estimates of Englund et al. and Rohr-Torp.

In Figure 6.3.5 only entity 788 shows a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factor for this bedrock entity is estimated to be 0.2. Entities 810 and 820 show no correlation between normalised yield and depth.

Rocktype 71

Bedrock boreholes in this rocktype are located within the Caledonian granite and granodiorite in the Bergen area. The median depth of bedrock boreholes in this rocktype is significantly higher than the median depth of 56 m of the entire data set.

The median yield is lower than the overall median yield of 600 L/h and the median normalised yield is significantly lower than the median of 12.0 L/h per drilled metre for the entire data set (see Table 6.3.1). Only 18% of all boreholes located in this rocktype have a higher normalised yield than the overall median.

Table 6.3.6 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 71 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	M	UH	LH	M	UH	LH	M	UH
Rocktype 71	55.5	78	100.5	110	300	600	1.2	4.1	9.8
Entity 891	61	84	102	90	275	500	0.9	2.7	7.0

This rocktype contains only one entity. The median depth, yield and normalised yield of this rocktype are given in Table 6.3.6, together with upper hinge and lower hinge values (see Figure 3.5.2 for explanation) which envelop the central 50% of the data from boreholes located in this rocktype. A total of 64% of the bedrock boreholes within rocktype 71 have yields in the range 90 L/h to 600 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.6).

In Figure 6.3.5 the bedrock entity of rocktype 71 shows a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factor for this entity is 0.3.

Rocktype 72

Bedrock boreholes in this rocktype are located within the Caledonian gabbroic and ultramafic rocks in the Bergen area. The median depth of bedrock boreholes in this rocktype is significantly higher than the median depth of 56 m for the entire data set. The median yield is significantly lower than the overall median yield of 600 L/h and the median normalised yield is significantly lower than the median of

Table 6.3.7 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 72 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			**Yield**			**Normalised yield**		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 72	55	80	96	100	250	435	1.3	3.5	9.1
Entity 861	56	80.5	90	100	235	410	1.2	3.2	6.0
Entity 919	71	91	110	55	120	375	0.7	1.6	3.9
Entity 951	26	40	60	150	200	300	1.7	5.0	10.5

12.0 L/h per drilled metre for the entire data set (see Table 6.3.1). Only 17% of all boreholes in this rocktype have a higher normalised yield than the median for the entire data set.

Rocktype 72 is comprised of three bedrock entities (see Table 6.3.7). Entity 951 differs from the other two entities in having a significantly lower median depth. The median yield and median normalised yield of entity 951 are not significantly different from those of the other entities. The spread (the difference between the whiskers in Figure 3.5.2) in depth, yield and normalised yield of this entity is smaller than for entities 861 and 919. This may be due to a greater homogeneity in the lithologies within this entity than in the other entities within this rocktype.

The median depth, yield and normalised yield of entities within this rocktype are given in Table 6.3.7, together with the upper and lower hinge values (see Figure 3.5.2 for explanation), which envelop the central 50% of data from boreholes located in this rocktype. Approximately 62% of the bedrock boreholes within rocktype 72 have yields in the range 55 L/h to 435 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.7).

In Figure 6.3.5 the bedrock entities of rocktype 72 all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors for entities 861 and 919 are both around 0.3. The reduction factor for entity 951 is estimated to be approximately 1. This means that deep bedrock boreholes within this entity may have a yield exceeding the yield of shallow bedrock boreholes.

Rocktype 74

Bedrock boreholes in this rocktype are located within the Cambro-Silurian meta-sediments of the Caledonian mountain chain and the Oslo region. The median depth, yield and normalised yield are quite close to the overall median values for the entire data set (see Table 6.3.1). Approximately 48% of all boreholes located in this rocktype have a higher normalised yield than the overall median.

Rocktype 74 contains 22 bedrock entities (see Table 6.3.8). Six entities (98, 694, 726, 761, 795 and 862) have significantly greater depths and four entities (894, 920, 946 and 1035) have significantly lesser depths than the median depth of this rocktype as a whole. Eight entities (767, 778, 794, 806, 814, 869, 894 and 920) have significantly higher median yields and five entities (456, 694, 862, 875 and 1035) have significantly lower median yields than the median yield of the rocktype as a whole. A combination of relatively large depth and relatively low yield results in five entities (456, 694, 795, 862, and 1035) having significantly lower median normalised yields than the median for the rocktype as a whole.

Table 6.3.8 *The median (M), lower and upper hinge values (LH and RH respectively) for boreholes located in rocktype 74 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	M	UH	LH	M	UH	LH	M	UH
Rocktype 74	40	57	80	300	600	1300	4.6	11.4	28.6
Entity 98	68.5	80	98	300	780	2000	3.8	9.2	25.0
Entity 456	41	60	80	200	400	800	3.8	7.0	16.6
Entity 650	38	53	85.5	250	600	1000	4.0	10.2	25.0
Entity 656	38	61	81	250	500	1800	3.9	8.6	30.5
Entity 694	46	65.5	96.5	170	430	1050	2.6	7.3	19.9
Entity 726	61.5	82	98	248	555	1750	2.5	8.1	27.1
Entity 755	30	48	88	200	450	800	5.6	9.5	18.2
Entity 761	55	68	84	200	600	1300	2.3	8.8	20.6
Entity 767	39	55	70	400	800	1200	7.1	13.8	25.0
Entity 778	35	43	59.5	700	1650	3000	19.3	28.0	66.1
Entity 791	38.5	47	62.5	285	700	1500	4.2	13.5	23.6
Entity 794	42.5	59	75	500	938	1625	7.8	16.4	33.3
Entity 795	67.5	76.5	102	400	600	900	4.5	7.1	12.9
Entity 806	35	50	64	900	2000	3000	20.0	33.3	96.0
Entity 814	29.5	53	64	480	1750	2400	12.1	28.2	77.0
Entity 862	50	70	89	125	300	600	1.8	4.7	10.6
Entity 869	41	57	79.5	500	800	1800	7.4	14.0	35.1
Entity 875	45.5	65	82	197	320	725	3.0	5.4	15.5
Entity 894	32	45	60	300	930	2000	7.6	21.8	49.2
Entity 920	27	40	60.5	700	1200	2000	19.9	35.0	66.6
Entity 946	25.5	30	56.5	275	850	2150	7.0	35.7	76.3
Entity 1035	32	46	61	210	375	600	4.4	8.0	15.3

However, a combination of relatively low depth and elevated yield results in six entities (778, 806, 814, 869, 894 and 920) having significantly higher normalised yields than the median for the rocktype as a whole. All these entities are located in the Oslo region. All entities with a significantly lower median normalised yield are located within the Caledonian mountain chain. The median normalised yield of entity 920 in the Oslo region is for example over 7 times greater than that of entity 862 in the Bergen area.

The median depth, yield and normalised yield of entities within rocktype 74 are presented in Table 6.3.8, together with upper and lower hinge values (see Figure 3.5.2 for explanation), which envelop the central 50% of the data from boreholes located in each entity. Rohr-Torp (Nystuen et al. 1993) states that typical borehole yields obtained in the shale and phyllite areas of the Mjøsa region are in the range 0 L/h to 500 L/h. Rohr-Torp also gives a typical borehole yield range of 250 L/h to 3,750 L/h for limestones in this area (entity 794). It has been stated that a typical yield for bedrock boreholes in the Cambro-Silurian sediments of the Oslo region in areas containing massive limestone is of the order of 3,000 to 6,000 L/h (see Chapter 3). No entity in the data set consists solely of massive limestone in this rocktype, but the majority of boreholes in entity 806 are located within such massive limestones and show an interquartile range in yield of between 900 L/h and 3,000 L/h (see Table 6.3.8), somewhat lower than the 3,000 to 6,000 L/h stated above.

It has also previously been stated that borehole yields in entity 98 are typically up to 1,000 L/h. This entity consists mainly of mica schist and mica gneiss. Ellingsen (1978) states that the phyllites of the Bergen area (Entities 862 and 875) have median yields of 250 L/h. Other evidence suggests that these estimates may be a little pessimistic. Englund & Myhrstad (1980) indicate typical yields of between 50 L/h and 2,000 L/h for the various Cambro-Silurian shales of the Mjøsa district (entities 767, 778, 794, 795, 806 and 814). Nystuen et al. (1993) suggest typical yields of between 500 L/h and 800 L/h for the phyllites of the Øystre Slidre area (entity 694). They also indicate a range in yield from 700 L/h to 4,000 L/h in the Ordovician and Silurian limestones in the central Ringerike district (entity 894). Henriksen (1995) estimated the median normalised yield of the lower Palaeozoic para-autochthonous phyllite located within entity 640 at 14.3 L/h per drilled metre. This lies within the uncertainty in the median normalised yield shown in Appendix B.

In Figure 6.3.5 the bedrock entities in rocktype 74 all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The exception is entity 920 which is estimated to have virtually identical normalised yields at all borehole depths. The reduction factors for the majority of bedrock entities in this rocktype vary from almost zero and 0.5. Five of the bedrock entities have a reduction factor higher than 1 (entities 456, 755, 761, 767 and 920) implying that some deep bedrock boreholes within these entities may have a yield exceeding the yield of shallow bedrock boreholes. Entities 778 and 946 show no correlation between normalised yield and depth.

Rocktype 75

Bedrock boreholes in this rocktype are located within the Cambro-Silurian limestone and marble of the Oslo region. The median depth of bedrock boreholes in this rocktype is significantly lower than the median depth of 56 m of the entire data set. The median yield is significantly higher than the overall median yield of 600 L/h, resulting in a median normalised yield which is also significantly higher than the median of 12.0 L/h per drilled metre for the entire data set (see Table 6.3.1). Approximately 71% of all boreholes in this rocktype have a higher normalised yield than the median for the entire data set.

Rocktype 75 consists of two bedrock entities (see Table 6.3.9). There are only minor differences between these two entities, but the median depth of entity 884 is significantly higher than that of entity 808. The almost identical distribution in

Table 6.3.9 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 75 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 75	33	45	69	500	1000	2500	10.2	22.5	65.9
Entity 808	27	35.5	55	600	1000	2600	12.3	28.6	83.3
Entity 884	36	46	64	500	1000	2500	10.9	22.5	65.9

borehole yields in these two entities indicates that the difference in median depth does not result in any significant variation in the median normalised yield.

The median depth, yield and normalised yield of entities within this rocktype are given in Table 6.3.9, together with upper and lower hinge values (see Figure 3.5.2 for explanation), which envelop the central 50% of the data from boreholes located in this rocktype. As mentioned above (under rocktype 74), a typical yield for bedrock boreholes in the Cambro-Silurian sediments of the Oslo region is generally regarded as being between 3,000 L/h and 6,000 L/h in areas containing massive limestone. Neither of the two entities comprising rocktype 75 consist solely of massive limestone, but the majority of boreholes in entity 808 are located within such a limestone and have an interquartile range ranging from 600 to 2,600 L/h (see Table 6.3.9). This is somewhat lower than previously supposed. Englund & Myhrstad (1980) for example suggests typical yields of between 1,000 L/h and 5,000 L/h for the Mjøsa limestone (entity 808).

In Figure 6.3.5 the two bedrock entities of rocktype 75 both show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors range from 0.3 and 0.4.

Rocktype 76

Bedrock boreholes in this rocktype are located in the Cambro-Silurian greenstones, silty shales and ultramafic rocks of western and mid-Norway. The rocktype also includes the metamorphosed Precambrian quartzite of the Sparagmite Group in the Rondane area. The median depth of bedrock boreholes in this rocktype is significantly higher than the median depth of 56 m for the entire data set. The median yield is significantly lower than the overall median of yield of 600 L/h, resulting in a significantly lower median normalised yield than the median of 12.0 L/h per drilled metre for the entire data set (see Table 6.3.1). Only 31% of all boreholes located in this rocktype have a higher normalised yield than the median for the entire data set.

Rocktype 76 contains seven bedrock entities (see Table 6.3.10). There are only minor differences between six of the seven entities in this rocktype. Entity 625 differs from the other entities in having a significantly higher median yield compared to the median normalised yield of this rocktype, resulting in a significantly higher median normalised yield of 15.4 L/h per drilled metre.

Approximately 58% of all boreholes in entity 625 have a higher normalised yield than the median for the entire data set. Entity 625 consists mainly of the Precambrian metaquartzite of the Sparagmite Group in the Rondane area, and is therefore lithologically very different from the other entities in this rocktype which mainly consist of mafic and ultramafic rocks. Closer inspection revealed that the assignment of entity 625 to rocktype 76 is due to an error in the digitising of the geological map. On the equivalent conventional map, this entity belongs to rocktype 82.

Table 6.3.10 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 76 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 76	45	65	87.5	150	360	800	2.1	5.6	15.7
Entity 485	36	48.5	80	120	450	600	2.2	8.3	25.0
Entity 625	40	51.5	68.5	490	800	1200	8.8	15.4	26.6
Entity 693	45	74	83	208	450	675	2.4	5.6	6.5
Entity 696	45	62	90	250	300	1100	3.4	4.9	17.7
Entity 870	48	65	100	240	500	850	3.0	6.5	15.4
Entity 880	46.5	65	90	105	190	450	1.3	2.9	7.4
Entity 993	52	70	85	125	297	535	2.1	3.6	13.4

The median depth, yield and normalised yield of entities within this rocktype are presented in Table 6.3.10, together with upper and lower hinge values (see Figure 3.5.2 for explanation), which envelop the central 50% of data from boreholes located in this rocktype. Approximately 65% of the bedrock boreholes within rocktype 76 have yields in the range 105 L/h to 1,100 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.10). Entity 625 is compared with the other entities of rocktype 82 under the section covering this rocktype.

In Figure 6.3.5 the bedrock entities of rocktype 76 all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors vary between 0.1 and 0.4. Entity 693 shows no correlation between normalised yield and depth.

Rocktype 79

Bedrock boreholes in this rocktype are located within the metamorphosed Upper Precambrian quartz sandstones of the Moelven area. The median yield of boreholes in this rocktype is significantly higher than the overall median yield of 600 L/h resulting in a median normalised yield significantly higher than the overall median of 12.0 L/h per drilled metre (see Table 6.3.1). Approximately 66% of all boreholes located in this rocktype have a higher normalised yield than this overall median.

Rocktype 79 consists of two bedrock entities (see Table 6.3.11). There are only minor differences in borehole properties between these two entities. The median depth, yield and normalised yield of these entities are given in Table 6.3.11, together with upper and lower hinge values (see Figure 3.5.2 for explanation) which envelop the central 50% of the data from boreholes. Englund et al. (1980) suggest typical yields of between 300 L/h and 3,000 L/h for the lithologies represented by these entities. Approximately 71% of the bedrock boreholes within rocktype 79 have yields in the range 500 L/h to 2,000 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.11).

In Figure 6.3.5 the bedrock entities in rocktype 79 all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors vary from 0.2 to 0.6.

Table 6.3.11 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 79 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 79	42	50	85	600	1020	2000	10.0	23.2	40.0
Entity 751	40	46	75	600	1100	2000	10.6	24.5	40.0
Entity 777	50	50.5	80	500	1000	2000	10.0	18.9	37.5

Rocktype 80

Bedrock boreholes in this rocktype are located within the metamorphosed Upper Precambrian Sparagmite Group of the counties of Oppland and Hedmark and the Varanger Peninsula in the county of Finnmark. The lithology of these rocks is dominated by sandstones, conglomerates, quartz schists and meta-arkoses, and on the Varanger Peninsula also shales and claystones. The median depth of bedrock boreholes in this rocktype is significantly lower than the median depth of 56 m for the entire data set. The median normalised yield is however only slightly higher than the overall median of 12.0 L/h per drilled metre (see Table 6.3.1). Approximately 52% of all boreholes in this rocktype have a higher normalised yield than the median for the entire data set.

This rocktype consists of eight bedrock entities (see Table 6.3.12). There are no significant differences in borehole characteristics between seven of the eight entities in rocktype 80. Entity 640 has a particularly low median normalised yield and only 33% of boreholes in this entity have a higher normalised yield than the overall median for the data set.

Table 6.3.12 The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 80 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.

	Depth			Yield			Normalised yield		
	LH	M	UH	LH	M	UH	LH	M	UH
Rocktype 80	33	50	75	300	600	1200	5.9	12.7	28.6
Entity 16	40	64.5	78	600	1025	2000	15.0	25.9	57.7
Entity 551	35.5	57.5	75.5	600	1000	2000	6.5	18.5	36.2
Entity 640	40	55	71	150	285	700	3.2	6.5	14.8
Entity 698	33	50	75	300	550	1000	6.0	18.8	24.1
Entity 727	41	54.5	77	600	1000	2000	9.3	21.6	45.8
Entity 759	30.5	45.5	69.5	355	600	1500	6.4	14.7	41.3
Entity 792	40.5	64.5	79	400	800	1550	6.4	13.3	32.7
Entity 803	44	64	85	300	500	900	4.4	8.6	16.7

The median depth, yield and normalised yield of entities within this rocktype are presented in Table 6.3.12, together with the upper and lower hinge values (see Figure 3.5.2 for explanation) which envelop the central 50% of the data. In Chapter 3 it was stated that the typical yield of boreholes in the lithologies of this rocktype is considered to be between 3,000 L/h and 6,000 L/h. Consideration of the data set used in this study however suggests that these estimates are extremely optimistic. Rohr-Torp (in Nystuen et al. 1993) indicated that typical yields obtained in these areas lie between 1,000 L/h and 3,600 L/h; a closer estimate but still an overestimate. Englund & Myhrstad (1980) suggest more realistic values of typical yield of between 300 L/h and 1,000 L/h in the Brøttum Formation (Entity 698). Hagemann (1959) cites a mean yield of almost 2,900 L/h in the eo-Cambrian rocks of eastern Finnmark (entity 16). Approximately 83% of the bedrock boreholes within rocktype 80 have yields of between 150 L/h and 2,000 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.12).

In Figure 6.3.5 the bedrock entities in this rocktype all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors for the majority of bedrock entities within this rocktype vary from 0.1 to 0.4. Five of the bedrock entities have a reduction factor close to 1 or higher (entities 16, 792 and 803). This means that deep bedrock boreholes within these entities may have a median yield exceeding the median yield of shallow bedrock boreholes.

Rocktype 81

Bedrock boreholes in this rocktype are located within the metamorphosed Upper Precambrian limestones and shales of the Biri and Rena areas. The median depth of bedrock boreholes in this rocktype is significantly lower than the median depth of 56 m of the entire data set. The median normalised yield is however not significantly higher than the overall median of 12.0 L/h per drilled metre (see Table 6.3.1). Approximately 62% of all boreholes located in rocktype 81 have a higher normalised yield than the overall median.

Rocktype 81 consists of two bedrock entities (see Table 6.3.13). Entity 745, located in the Rena area, has a significantly lower median depth and a consequently higher median normalised yield of 40.0 L/h per drilled metre compared to 13.7 L/h per drilled metre of entity 754. Approximately 92% of all boreholes in entity 745 have a higher normalised yield than the overall median for the data set. The spread in depth, yield and normalised yield for entity 745 is less than for entity 754. This may be due to a greater homogeneity of the lithologies within this entity.

The median depth, yield and normalised yield of entities within rocktype 81 are shown in Table 6.3.13, together with upper and lower hinge values (see

Table 6.3.13 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 81 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			**Yield**			**Normalised yield**		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 81	33.5	41	64	350	700	1400	6.9	16.8	40.5
Entity 745	30	32	39	500	1200	1500	16.8	40.0	43.8
Entity 754	36	45	75	300	600	1100	6.7	13.7	30.0

Figure 3.5.2 for explanation) which envelop the central 50% of the data. Rohr-Torp (in Nystuen et al. 1993) suggested that typical yields obtained from boreholes in these rocks ranged from 250 L/h to 3,750 L/h. Englund & Myhrstad (1980) indicated typical yields of between 300 L/h and 1,000 L/h in the Biri Limestone (Entity 754). Approximately 68% of all boreholes in rocktype 81 have yields in the range 300 L/h to 1,500 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.13).

In Figure 6.3.5 the bedrock entities within rocktype 81 all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors vary between 0.1 and 0.4.

Rocktype 82

Bedrock boreholes in this rocktype are mostly drilled in the Upper Precambrian meta-sandstone of the Ringebu-Koppang area. The rocktype also includes entity 625, in the Rondane area, already mentioned under the description of rocktype 76.

Table 6.3.14 The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 82 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.

	Depth			Yield			Normalised yield		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 82	44.5	61	83	400	600	1200	5.3	10.7	22.8
Entity 7	45	64	85	400	500	1000	4.8	10.2	21.4
Entity 625	40	51.5	68.5	490	800	1200	8.8	15.4	26.6
Entity 651	47	62	83	380	675	1200	5.3	10.6	22.8

The median depth of bedrock boreholes in this rocktype is only slightly higher than the median depth of 56 m for the entire data set and the median normalised yield is not significantly different from the overall median of 12.0 L/h per drilled metre (see Table 6.3.1). Approximately 46% of all boreholes located in this rocktype (including entity 625) have a higher normalised yield than this overall median.

Rocktype 82 contains three bedrock entities (including entity 625, see Table 6.3.14). There are only minor differences between the borehole characteristics of these three entities. The median of depth, yield and normalised yield of entities within this rocktype are presented in Table 6.3.14, together with upper and lower hinge values (see Figure 3.5.2 for explanation) which envelop the middle 50% of the data. Rohr-Torp (in Nystuen et al. 1993) indicated that typical yields of boreholes in entity 651 ranged from 250 L/h to 3,000 L/h. The commonly accepted values given in Chapter 3 for typical yields in the lithologies of this entity of between 3,000 L/h and 6,000 L/h are optimistic. In fact, 57% of the bedrock boreholes within rocktype 82 have yields in the range 380 L/h to 1,200 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Tables 6.3.14 and 6.3.10).

In Figure 6.3.5 the bedrock entities within rocktype 82 (including entity 625) all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors vary between 0.2 and 0.7.

Rocktype 85

Bedrock boreholes in this rocktype are located within the Caledonian mountain chain, in lithologies consisting mainly of Precambrian gneisses and metamorphosed granites. The median depth, yield and normalised yield are quite similar to the median values for the entire data set (see Table 6.3.1). Approximately 48% of all boreholes located in this rocktype have a higher normalised yield than the overall median value of 12.0 L/h per drilled metre.

Rocktype 85 consists of nine bedrock entities (see Table 6.3.15). There are only minor differences in the borehole characteristics of seven of these nine entities. Entity 664 differs from the total data set of rocktype 85 in having a significantly higher median yield resulting in a higher median normalised yield of 23.7 L/h per drilled metre. Entity 840 differs however in having a significantly lower median yield causing a lower median normalised yield of 1.7 L/h per drilled metre. Approximately 70% of all boreholes in entity 664 have a higher normalised yield than the overall median compared with only 11% of all boreholes in entity 840. The spread in depth and normalised yield for entity 100 is significantly less than those of the other entities. This may be due to a greater homogeneity in the lithologies within this entity compared to the other entities of rocktype 85.

The median of depth, yield and normalised yield of entities within rocktype 85 are given in Table 6.3.15, together with upper and lower hinge values (see Figure 3.5.1 for explanation) which envelop the central 50% of the data. Ellingsen (1978) suggests typical yields of between 250 L/h and 500 L/h for boreholes in this

Table 6.3.15 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 85 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 85	40	57	80	300	600	1500	4.7	11.4	29.5
Entity 100	50.5	82	105	525	600	1005	6.4	10.0	13.5
Entity 638	65	88	104	440	750	2750	5.7	10.9	26.6
Entity 664	36	51.5	68	500	1000	2000	9.1	23.7	50.8
Entity 731	48	62.5	76	350	600	1500	5.8	9.4	23.1
Entity 772	40	50	77	185	300	1900	3.3	10.7	26.3
Entity 840	68.5	100	124.5	30	120	375	0.4	1.7	5.9
Entity 858	49	81.5	99	150	365	1500	1.8	7.4	16.9
Entity 1019	23	40	60	200	375	600	4.1	8.7	17.5
Entity 1059	33	45	67	168	325	750	3.6	8.2	20.1

rocktype in the Bergen area. Approximately 90% of the bedrock boreholes within rocktype 85 have yields in the range 30 L/h to 2,750 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.15).

Figure 6.3.5 shows that the bedrock entities within rocktype 85 all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors for the majority of bedrock entities within this rocktype vary between 0.2 and 0.8. Two of the bedrock entities have a reduction factor close to 1 or higher (entities 1019 and 1059). This means that deep bedrock boreholes within these entities may have a yield exceeding the yield of shallow bedrock boreholes. Entities 638, 772 and 858 show no correlation between normalised yield and depth.

Rocktype 86

Bedrock boreholes in this rocktype are located within the Caledonian mountain chain, in lithologies consisting mainly of charnockitic to anorthositic rocks. The median depth of bedrock boreholes in this rocktype is significantly higher than the median depth of 56 m for the entire data set. The median yield is significantly lower than the overall median yield of 600 L/h and the median normalised yield is also lower than the median of 12.0 L/h per drilled metre for the entire data set (see Table 6.3.1). Only 24% of all boreholes located in this rocktype have a higher normalised yield than this overall median.

This rocktype consists of three bedrock entities (see Table 6.3.16). Entity 658 differs from entity 785 in having both a higher median yield and a lower median depth, resulting in a significantly higher median normalised yield of 14.0 L/h per drilled metre. Approximately 54% of all boreholes in entity 658 have a higher normalised yield than the median for the entire data set compared to only 17% of all boreholes in entity 785.

The median values of depth, yield and normalised yield of entities within this rocktype are presented in Table 6.3.16, together with upper and lower hinge values (see Figure 3.5.2 for explanation) which envelop the central 50% of the data. Ellingsen (1978) suggested a typical range in borehole yield from 250 L/h to 500 L/h in most lithologies, including those of rocktype 86, in the Bergen area. Henriksen (1995) has estimated the median normalised yield of the charnockitic and anorthositic rocks contained in entity 658 to be between 8.8 and 23.8 L/h per drilled metre depending on the degree of detail used in grouping the rocktype.

Table 6.3.16 The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 86 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.

	Depth			Yield			Normalised yield		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 86	52	71	94	150	310	700	2.0	5.1	11.7
Entity 658	39	53	72.5	350	700	1250	5.8	14.0	30.2
Entity 659	37	84.5	91	300	500	1200	3.5	8.7	13.8
Entity 785	56	75	100	130	300	600	1.6	4.2	8.9

Approximately 68% of the bedrock boreholes within rocktype 86 have yields in the range 130 L/h to 1,250 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.16). Figure 6.3.5 shows that the bedrock entities of rocktype 86 all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors vary between 0.2 and 0.4. Entity 659 shows no correlation between normalised yield and depth.

Rocktype 87

Bedrock boreholes in this rocktype are located within the north-western gneissic region, in lithologies consisting mainly of Precambrian migmatitic gneiss of granitic to granodioritic composition. The median depth, yield and normalised yield are all quite close to the median values for the entire data set (see Table 6.3.1). Approximately 54% of all boreholes located in this rocktype have a higher normalised yield than the overall median value of 12.0 L/h per drilled metre.

Table 6.3.17 The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 87 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.

	Depth			Yield			Normalised yield		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 87	47	61	77	500	800	2000	6.7	13.8	40.0
Entity 647	47	52	77	600	500	2000	9.7	17.8	28.8

This rocktype contains only one entity (see Table 6.3.17). The median depth, yield and normalised yield of the rocktype are given in Table 6.3.17, together with upper and lower hinge values (see Figure 3.5.2 for explanation) which envelop the central 50% of the data. Henriksen (1995) has estimated the median normalised yield of the granite also contained in entity 647 at 9.9 L/h per drilled metre. This is significantly lower than the lower limit of the median normalised yield shown in Appendix B. This anomaly may however be due to the differences in the number and location of boreholes in these two data sets. Approximately 58% of the bedrock boreholes within rocktype 87 have yields in the range 500 L/h to 2,000 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.17). In Figure 6.3.5 the bedrock entity within rocktype 87 shows a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factor is 0.3.

Rocktype 88

Bedrock boreholes in this rocktype are located within the north-western gneissic region, in lithologies consisting mainly of Precambrian amphibolite and banded gneiss. The median depth of bedrock boreholes in this rocktype is significantly

Table 6.3.18 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 88 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 88	45	68	89	300	575	1200	3.7	10.9	20.8
Entity 721	48	68.5	88	300	650	1200	4.7	9.5	20.8

higher than the median depth of 56 m for the entire data set. However, both the median yield and normalised yield are quite close to the overall median values for the data set (see Table 6.3.1). Approximately 47% of all boreholes located in this rocktype have a normalised yield higher than the overall median value of 12.0 L/h per drilled metre.

Rocktype 88 consists of only one entity (see Table 6.3.18). The median values of depth, yield and normalised yield of this rocktype are given in Table 6.3.18, together with upper and lower hinge values (see Figure 3.5.2 for explanation) which envelop the central 50% of the data. Approximately 57% of the bedrock boreholes within rocktype 88 have yields in the range 300 L/h to 1,200 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.18).

In Figure 6.3.5 the bedrock entity of rocktype 88 shows a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factor is 0.6.

Rocktype 90

Bedrock boreholes in this rocktype are located within the north-western gneissic region, in lithologies consisting of Precambrian metamorphosed sedimentary and volcanic rocks. The median depth of bedrock boreholes in this rocktype is significantly higher than the median depth of 56 m for the entire data set resulting in a significantly lower median normalised yield compared to the median of 12.0 L/h per drilled metre for the entire data set (see Table 6.3.1). Approximately 39% of all boreholes located in this rocktype have a higher normalised yield than this overall median.

Rocktype 90 consists of five bedrock entities (see Table 6.3.19). There are only minor differences in borehole characteristics between four of the five entities in Rocktype 90. Entity 517 differs however from the other entities in having a significantly lower median yield resulting in a lower median normalised yield of 2.1 L/h per drilled metre. Only 18% of all boreholes in entity 517 have a higher normalised yield than the median for the entire data set.

The median depth, yield and normalised yield of entities within this rocktype are given in Table 6.3.19, together with upper and lower hinge values (see Figure 3.5.2 for explanation) which envelop the central 50% of the data. Approximately 71% of the bedrock boreholes within rocktype 90 have yields in the range 104 L/h to 1,450 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.19).

Figure 6.3.5 illustrates that the bedrock entities of rocktype 90 all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors for the majority of bedrock entities within this rocktype vary between 0.3 and 0.6. Entity 635 has a reduction factor of 1.4. This means that deep bedrock boreholes within this entity may have a yield exceeding the yield of shallow bedrock boreholes. Entity 517 shows no correlation between normalised yield and depth.

Table 6.3.19 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 90 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			**Yield**			**Normalised yield**		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 90	52	73	97.5	260	525	1000	3.3	8.3	18.0
Entity 517	57	75	113	104	120	950	1.3	2.1	6.0
Entity 610	33	60.5	91	390	750	1450	7.4	13.8	35.3
Entity 612	28	44.5	62.5	490	600	950	9.7	15.6	34.0
Entity 635	53	71	90	450	650	1000	4.7	9.4	19.2
Entity 643	58	84.5	104	300	500	775	4.0	7.1	12.7

Rocktype 91

The bedrock boreholes in this rocktype are also located within the north-western gneissic region, in lithologies consisting mainly of Precambrian migmatitic gneiss of granitic to granodioritic composition. The median depth of bedrock boreholes in this rocktype is significantly higher than the median depth of 56 m for the entire data set. The median yield is significantly lower than the overall median of yield of 600 L/h and the median normalised yield is also significantly lower than the median of 12.0 L/h per drilled metre for the entire data set (see Table 6.3.1). Only 34% of all boreholes located in this rocktype have a higher normalised yield than this overall median.

Rocktype 91 consists of six bedrock entities (see Table 6.3.20). The entities appear to fall naturally into two groups on the basis of their borehole characteristics. The entities of the first group (entities 515, 683 and 962) all have significantly higher

Table 6.3.20 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 91 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	M	UH	LH	M	UH	LH	M	UH
Rocktype 91	52	71	94	200	420	1000	2.4	6.8	17.2
Entity 515	44	63	88	250	500	1500	3.6	9.5	26.3
Entity 679	79	100	120	100	300	750	0.7	4.0	8.5
Entity 683	58	72.5	91	250	600	1200	3.6	8.1	20.7
Entity 789	61	81	100	60	200	400	0.7	2.9	6.4
Entity 829	75.5	90	102	95	200	475	1.0	2.6	5.4
Entity 962	39	60	63	225	425	800	4.0	7.4	18.5

median normalised yields than the entities of the second group (entities 789 and 829). It is generally accepted that yields in the coastal area of the outcrop of entity 515 usually exceed 180 L/h. Ellingsen (1978) states that most rocks in the Bergen area have typical values of median yield of between 250 L/h to 500 L/h (entities 789 and 829). The median normalised yields of the two groups of entities in this rocktype are 9.0 and 2.7 L/h per drilled metre respectively. Approximately 42% of all boreholes in the group consisting of entities 515, 683 and 962 have higher normalised yields than the median for the entire data set, compared with only 10% in the second group.

The median depth, yield and normalised yield of entities within this rocktype are given in Table 6.3.20, together with upper and lower hinge values (see Figure 3.5.2

for explanation) which envelop the central 50% of the data. Henriksen (1995) has estimated the median normalised yield of bedrock boreholes in the undifferentiated gneisses also covered by entity 683 to be approximately 9 L/h per drilled metre. This is within the limit of uncertainty shown in Appendix B. Approximately 74% of the bedrock boreholes within rocktype 91 have yields in the range 60 L/h to 1,500 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.20).

Figure 6.3.5 illustrates that the entities within rocktype 91 all show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors vary between 0.1 and 0.4.

Rocktype 92

Bedrock boreholes in this rocktype are located in Sør-Aurdal municipality in Oppland county (entity 812), in Østfold county (entity 1029) and in the Farsund area near Lindesnes, the southernmost point of Norway (entity 1082). The lithology is dominated by Precambrian fine- to medium-grained granites (entity 812), granite (entity 1029) and hornblende granite (entity 1082). The median depth, yield and normalised yield are all quite close to the overall median values (see Table 6.3.1). Approximately 48% of all boreholes located in this rocktype have a higher normalised yield than the overall median value of 12.0 L/h per drilled metre.

Rocktype 92 consists of three bedrock entities (see Table 6.3.21). Entity 1029 differs from the other entities in having a significantly lower median depth. The median normalised yield is, however, not significantly different from that of the other entities. Approximately 50% of all boreholes in this entity have a higher normalised yield than the median for the entire data set, compared to 34% for the other entities.

Table 6.3.21 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 92 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	M	UH	LH	M	UH	LH	M	UH
Rocktype 92	32	53	78	240	510	1420	4.4	11.4	29.8
Entity 812	62	83	104.5	400	800	1000	4.0	9.3	15.4
Entity 1029	30	50	72.5	240	600	1500	4.9	12.2	31.5
Entity 1082	57	62	76	240	500	1000	2.6	7.6	12.5

The median depth, yield and normalised yield of entities within this rocktype are presented in Table 6.3.21, together with upper and lower hinge values (see Figure 3.5.2 for explanation) which envelop the central 50% of the data. Approximately 53% of the bedrock boreholes within rocktype 92 have yields in the range 240 L/h to 1,500 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.21).

Figure 6.3.5 illustrates that bedrock entity 1029 and 1082 within rocktype 92 shows a reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors for entities 1029 and 1082 are 0.2 and 1 respectively. This means that deep bedrock boreholes within entity 1082 may have a yield exceeding the yield of shallow bedrock boreholes. Entity 812 shows no correlation between normalised yield and depth.

Rocktype 94

Bedrock boreholes in this rocktype are located in the eastern part of Norway and are drilled in lithologies consisting of Precambrian autochthonous gabbro, amphibolite and ultramafic rocks. The median yield is significantly lower than the overall median of yield of 600 L/h. The median normalised yield is however not significantly different from the median of 12.0 L/h per drilled metre for the entire data set (see Table 6.3.1). Approximately 45% of all boreholes located in this rocktype have a higher normalised yield than this overall median.

Rocktype 94 contains two bedrock entities (see Table 6.3.22). Entity 817 has a significantly greater median depth than entity 868, although the median normalised yield is not significantly different from that of entity 868. Only 40% of all boreholes in entity 817 have a higher normalised yield than the median for the entire data set, compared to 59% in entity 868. The spread of data for depth, yield and normalised yield within entity 868 is less than that within entity 817. This may be due to a greater homogeneity in the lithologies of the bedrock boreholes within this entity.

Examination of a more detailed conventional bedrock map of Norway (at a scale of 1: 1,000,000) indicated that a number of the bedrock boreholes in entity 817 lie within a quartzite. The scale of the digitised 1: 3,000,000 map did not permit this quartzite to be identified as a separate entity.

The median depth, yield and normalised yield of boreholes within the entities of this rocktype are given in Table 6.3.22, together with upper and lower hinge values (see Figure 3.52. for explanation) which envelop the central 50% of the data. Approximately 61% of the bedrock boreholes within rocktype 94 have yields in the range 245 L/h to 1,200 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.22).

Table 6.3.22 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 94 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			**Yield**			**Normalised yield**		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 94	36.5	55.5	72	250	420	1200	5.2	9.4	21.0
Entity 817	47	61.5	73	245	475	1200	4.1	8.1	19.5
Entity 868	31	36	45	350	400	800	8.3	14.5	21.0

Figure 6.3.5 illustrates that bedrock entity 817 shows a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factor is 0.5. Bedrock entity 868 shows no correlation between normalised yield and depth.

Rocktype 95

Bedrock boreholes in this rocktype are located in the southern part of Norway, in lithologies consisting of Precambrian quartzite, granitic gneiss, sandstone and conglomerate. The median depth, yield and normalised yield are all quite close to the median values for the entire data set (see Table 6.3.1). Approximately 44% of all boreholes located in this rocktype have a higher normalised yield than the median value of 12.0 L/h per drilled metre for the entire data set.

Rocktype 95 consists of four bedrock entities (see Table 6.3.23). There are only insignificant variations in borehole characteristics between these entities. The median depth, yield and normalised yield of entities within this rocktype are given in Table 6.3.23, together with upper and lower hinge values (see Figure 3.5.2 for explanation) which envelop the central 50% of the data. Approximately 58% of the

Table 6.3.23 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 95 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	M	UH	LH	M	UH	LH	M	UH
Rocktype 95	40	58	82	250	550	1200	4.1	10.3	26.5
Entity 680	24	32	40	400	950	1200	14.8	27.7	45.0
Entity 809	32	44.5	80	225	550	970	5.7	8.6	23.8
Entity 811	33.5	40	45	280	600	1250	6.7	15.4	28.3
Entity 851	50	70.5	89.5	200	500	1100	2.1	6.7	24.5

bedrock boreholes within rocktype 95 have yields in the range 200 L/h to 1,250 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.23).

In Figure 6.3.5 the bedrock entities within rocktype 95 all (except entity 811) show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors vary between 0.3 and 0.4. Bedrock entity 811 shows no correlation between normalised yield and depth.

Rocktype 96

Bedrock boreholes in this rocktype are located in the Caledonian mountain chain, in lithologies consisting of Precambrian meta-basalt and meta-andesite. The median depth of bedrock boreholes in this rocktype is significantly higher than the median

Table 6.3.24 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 96 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			Yield			Normalised yield		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 96	45	67	85	300	500	1200	4.4	10.3	18.8
Entity 115	65	71	90.5	500	950	2000	5.5	15.2	33.7
Entity 867	34	49	75	240	450	1200	4.4	10.3	23.1

depth of 56 metres for the entire data set, although the median normalised yield is very close to the median of 12.0 L/h per drilled metre for the entire data set (see Table 6.3.1). Approximately 45% of all boreholes located in this rocktype have a higher normalised yield than this overall median. This rocktype contains two bedrock entities with insignificant differences (see Table 6.3.24).

The median depth, yield and normalised yield of entities within this rocktype are presented in Table 6.3.24, together with upper and lower hinge values (see Figure 3.5.2 for explanation) which envelop the central 50% of the data. Approximately 89% of the bedrock boreholes within rocktype 96 have yields in the range 240 L/h to 2,000 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.24).

In Figure 6.3.5 neither of the two bedrock entities within rocktype 96 show correlation between normalised yield and depth.

Rocktype 97

Bedrock boreholes in this rocktype are located in southern Norway in lithologies consisting of Precambrian metarhyolite and metabasalt. The median depth, yield and normalised yield are all quite close to the median values for the entire data set (see Table 6.3.1). Approximately 58% of all boreholes located in this rocktype have a higher normalised yield than the overall median value of 12.0 L/h per drilled metre.

Rocktype 97 consists of four bedrock entities (see Table 6.3.25). The entities fall naturally into two different groups on the basis of their borehole characteristics. The entities in the first group (670 and 807) have a significantly higher median normalised yield than the entities in the second group (760 and 815). The median normalised yields of the two groups are 41.7 and 12.3 L/h per drilled metre respectively. Approximately 74% of all boreholes in the first group (entities 670 and 807) have higher normalised yields than the median for the entire data set compared with only 52% for the second group.

The median depth, yield and normalised yield of the entities within rocktype 97 are shown in Table 6.3.25, together with upper and lower hinge values (see Figure 3.5.2 for explanation) which envelop the central 50% of the data. Approximately 71% of the bedrock boreholes within rocktype 97 have yields in the range 240 L/h to 2,000 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.25). Figure 6.3.5 shows that the bedrock entities within rocktype 97 all (except entity 807) show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors vary between 0.3 and 0.9. Bedrock entity 807 displays no correlation between normalised yield and depth.

Table 6.3.25 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 97 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			**Yield**			**Normalised yield**		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 97	37	54.5	74	350	700	1500	6.3	14.0	39.0
Entity 670	24	34	50	500	950	1500	13.2	40.2	54.2
Entity 760	47	67	87	360	650	1950	5.0	13.1	27.0
Entity 807	23	35.5	44.5	350	1500	2000	10.0	69.0	80.1
Entity 815	43	57	79.5	240	475	1100	3.9	9.3	19.3

Rocktype 98

Bedrock boreholes in this rocktype are located within the two Precambrian regions of Southern Norway, in lithologies consisting of gneiss, migmatite and foliated granite. The median depth of bedrock boreholes in this rocktype is significantly lower than the median depth of 56 m for the entire data set. The median yield is significantly higher than the overall median yield of 600 L/h and the median normalised yield is also significantly higher than the overall median of 12.0 L/h per drilled metre for the entire data set (see Table 6.3.1). Approximately 59% of all boreholes located in this rocktype have a higher normalised yield than this overall median.

Rocktype 98 consists of nine bedrock entities (see Table 6.3.26). The eastern entities (i.e. those located east of the Oslo Rift) generally have a higher median normalised yield than the western entities. The exceptions to this generalisation are

Table 6.3.26 *The median (M), lower and upper hinge values (LH and UH respectively) for boreholes located in rocktype 98 with respect to depth (m), yield (L/h) and normalised yield (L/h per drilled metre). The number of boreholes within each bedrock entity is given in Table 2.3.1.*

	Depth			**Yield**			**Normalised yield**		
	LH	**M**	**UH**	**LH**	**M**	**UH**	**LH**	**M**	**UH**
Rocktype 98	32	48	70	380	750	1800	6.9	16.7	41.1
Entity 692	30	46.5	65.5	710	950	1000	9.3	20.8	31.2
Entity 717	31	44	64	400	800	2000	8.5	20.0	47.4
Entity 744	45	51.5	58	400	1000	2000	10.1	18.9	39.2
Entity 776	38	58	80	300	600	1200	5.0	11.6	25.0
Entity 828	34	50	64	260	400	925	4.4	8.9	19.1
Entity 844	45	57	67	500	800	2000	8.2	14.7	44.4
Entity 849	33	41.5	57	300	500	1280	7.0	12.9	25.2
Entity 850	31.5	41	59	400	1200	2500	12.8	27.8	58.8
Entity 1007	43.5	61	82	150	300	700	2.1	5.4	11.8

the relatively higher yield entities of 744 and 850 in the western area. These entities have median normalised yields comparable with entities in the eastern region. The entities of the eastern region (see appendix A) have a group median normalised yield of 20 L/h per drilled metre compared to a group median of 10.7 L/h per drilled metre in the western region (see appendix B). Approximately 64% of all boreholes in the eastern region have a higher normalised yield than the median for the data set, compared with 46% in the western region. The spread of depth, yield and normalised yield data for entities 692, 744, 828 and 849 is less than for the other entities. This may be due to a greater homogeneity in the lithologies within these entities compared to the other entities of this rocktype.

The median depth, yield and normalised yield of entities within this rocktype are presented in Table 6.3.26, together with upper and lower hinge values (see Figure 3.5.2 for explanation), which envelop the central 50% of the data. Rohr-Torp (in Nystuen et al. 1993) stated that typical yields from boreholes in the Precambrian granite and gneiss of the Mjøsa-Gudbrandsdalen-Valdres region (entities 717, 828, 844 and 776) are in the range 250 L/h to 2,600 L/h.

Nystuen et al. (1993) also suggest a typical yield of 500 L/h to 2,000 L/h in the migmatitic gneisses of the Begna-area (entity 776). Bryn (1961) cites median yields of 1,100 L/h for the Precambrian gneiss and 700 L/h for granitic rocks in the area corresponding to entity 717. Approximately 79% of the bedrock boreholes within rocktype 98 have yields in the range 150 L/h to 2,500 L/h (i.e. the range between the lowest hinge of the poorest aquifer and the upper hinge of the best aquifer in Table 6.3.26).

In Figure 6.3.5 most bedrock entities within rocktype 98 show a clear reduction in the median normalised yield from shallow to deeper bedrock boreholes. The reduction factors for the majority of bedrock entities connected to this rocktype vary between 0.2 and 0.7. Two of the bedrock entities have a reduction factor close to 1 or higher (entities 692 and 849). This means that deep bedrock boreholes within these entities may have a yield exceeding the yield of shallow bedrock boreholes. Bedrock entity 828 shows no correlation between normalised yield and depth.

6.4 Discussion

The results documented above confirm that interesting and statistically significant variations in drilled depth, yield and normalised yield exist between many of the 110 different bedrock entities containing 10 or more bedrock boreholes. Moreover, statistically significant differences occur between the yields of many of the 25 rocktypes included in this study, confirming that borehole yield from bedrock boreholes is dependent on lithology. The results indicate that by using information contained in the existing BBD, it is possible to predict a range of typical yield, drilled depth and normalised yield for bedrock boreholes.

The lithologies yielding most groundwater per drilled metre are the metamorphosed rhyolites (in the Telemark area in Southern Norway) dominating entity 807 (median normalised yield of 69 L/h per drilled metre [only 11 boreholes]), the Permian volcanic rocks and subordinate sedimentary rocks in the Oslo Rift dominating entity 975 (median normalised yield of 68.7 L/h per drilled metre [434 boreholes]) and the Permian plutonic rocks within the Ramnes Caldera (see Figure 4.2.2 and 4.2.3) in the Oslo region dominating entity 1032 (median normalised yield of 57.7 L/h per drilled metre [37 boreholes]).

The lithologies having the lowest groundwater yield per drilled metre are the gabbroic and ultramafic rocks in the Bergen area dominating entity 919 (median normalised yield of 1.6 L/h per drilled metre), the complicated lithological group of gneiss, migmatite, granite, metamorphosed volcanic and sedimentary rocks (in the Bergen area) dominating entity 840 (median normalised yield of 1.7 L/h per drilled metre) and the foliated quartz diorite (in the NWG-region) dominating entity 517 (median normalised yield of 2.1 L/h per drilled metre).

Some rock types show higly varying median yields. The granites, for example, have median normalised yields which vary from 1.7 L/h per drilled metre (entity 840 of rocktype 85) to 27.8 L/h per drilled metre (entity 850 of rocktype 98).

The fact that almost all bedrock entities show a decreasing median normalised yield with increasing depth of the boreholes results in a varying median normalised yield (Figure 6.3.5). The median normalised yield in fact varies within a bedrock entity by a factor of between 1 and 100 between the highest median normalised yield for

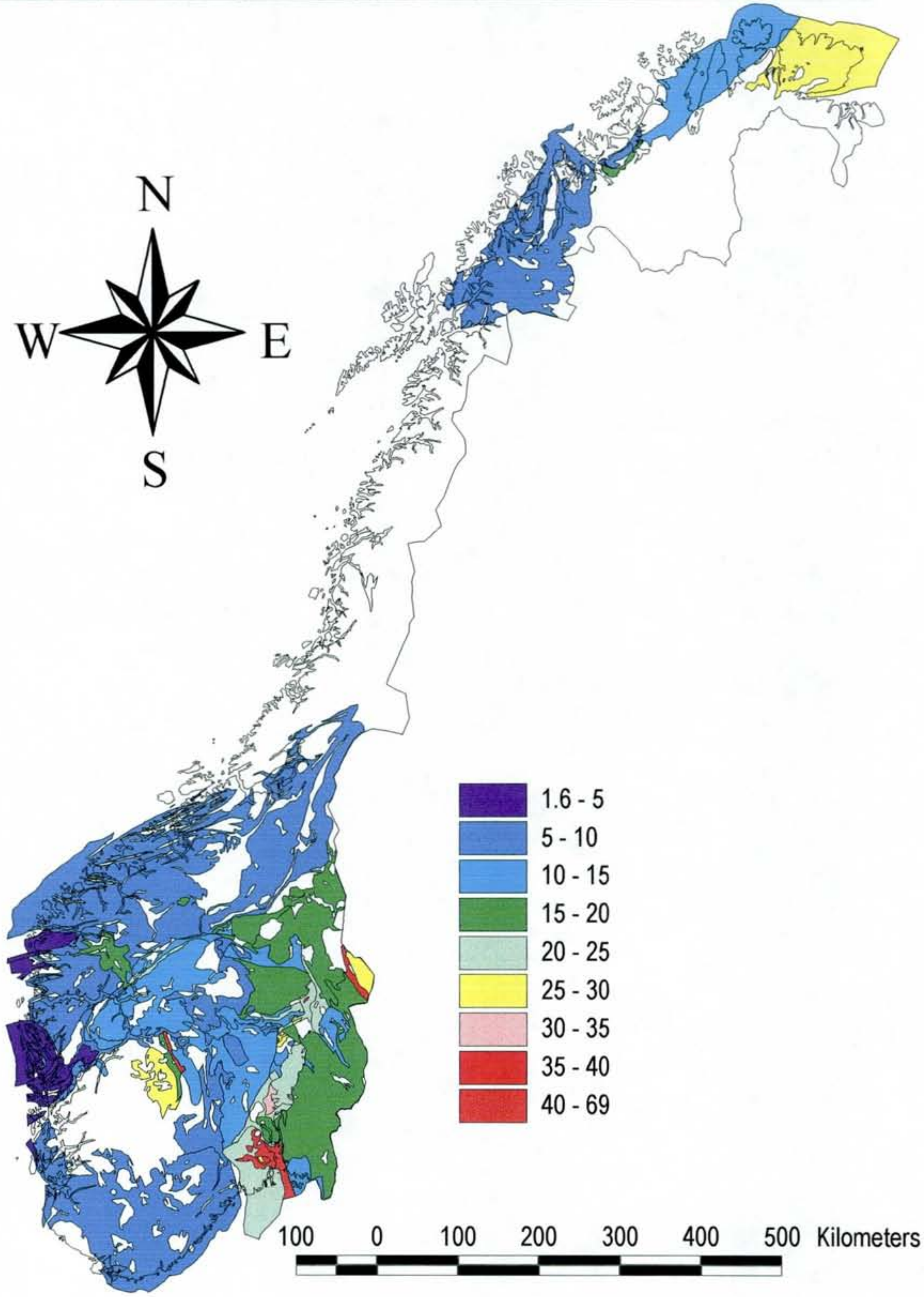


Figure 6.4.1 *Map of Norway showing the median normalised yield (L/h per drilled metre) for each entity containing information from 10 or more bedrock boreholes.*

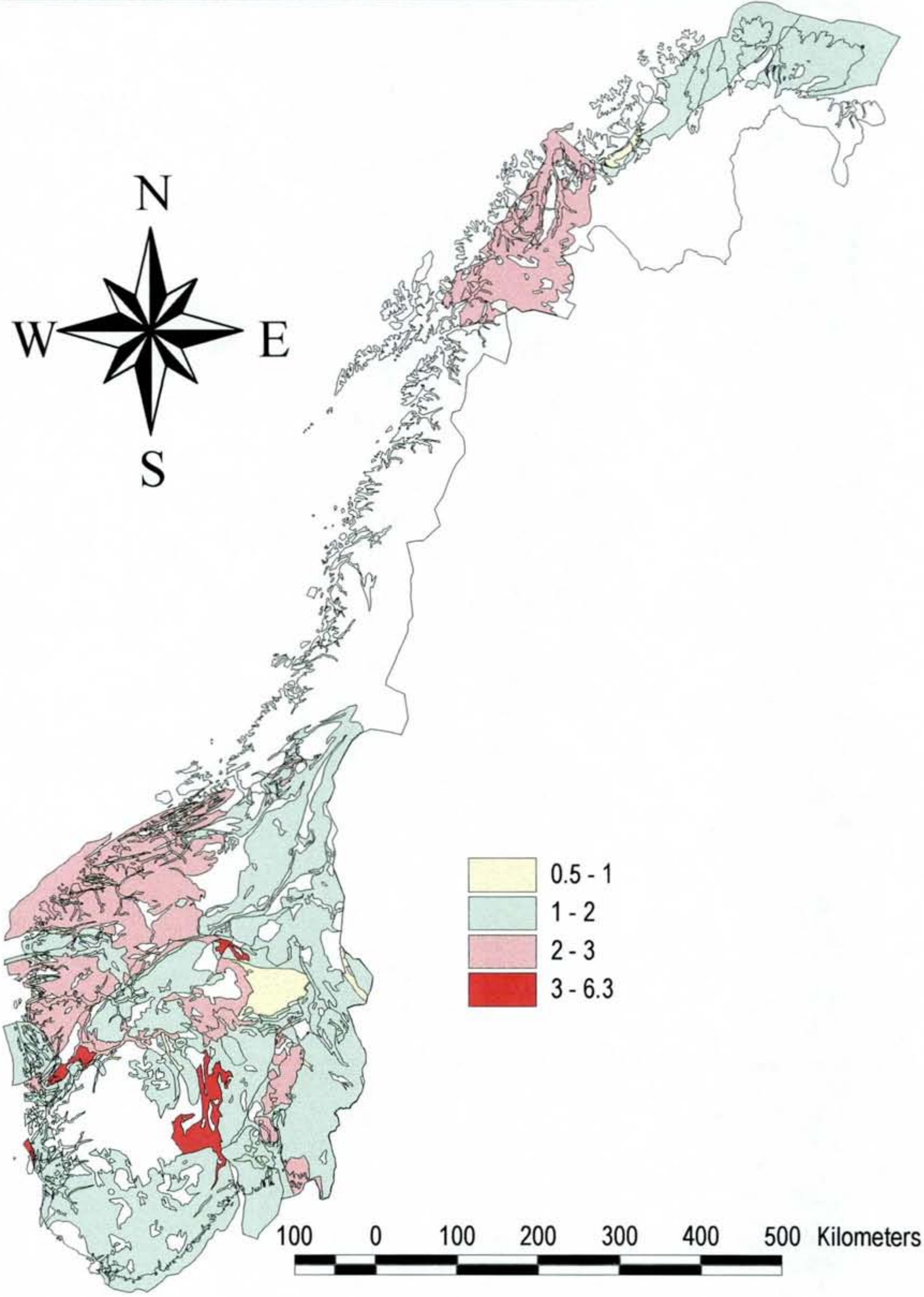


Figure 6.4.2 Map of Norway showing the homogeneity factor for normalised yield (UH - LH / median) for all entities containing information from 10 or more bedrock boreholes.

shallow bedrock boreholes compared to that of deep bedrock boreholes. This makes it difficult to find a single parameter capable of adequately describing the hydrogeological properties of each bedrock entity. Nevertheless, the median normalised yield can be used to give an indication of the likely short-term groundwater yield which can be expected from single boreholes in each bedrock entity. An indication of the variability in the expected yield can be obtained from the tables for each bedrock entity in Chapter 6 giving the interquartile range (i.e. the range of normalised yield across the central 50% of the bedrock boreholes (i.e. upper hinge [UH] - lower hinge [LH]).

Only six bedrock entities out of 110 have an interquartile range for normalised yield which is less than the absolute value of their median. The ratio of the interquartile range to the median normalised yield varies from 0.5 (entity 810 of rocktype 67) to 3.3 (entity 851 of rocktype 95) with an outlier of 6.3 (entity 820 of rocktype 67). This "homogeneity factor" can be used as an indication of how hydrogeologically homogenous the lithologies within each entity are. The median value of the homogeneity factor is 1.8. According to the conventional bedrock map of Norway (at a scale of 1: 1,000,000), entity 820 (of rocktype 67) consists of granodioritic migmatitic gneiss, limestone and Silurian sandstone. These lithologies are very different with respect to groundwater yield from bedrock boreholes. The granodioritic migmatitic gneiss dominating entity 776 (which has a homogeneity factor of 1.7) has a median normalised yield of 11.6 L/h per meter. Entity 808 (which has a homogeneity factor of 2.5) consists of limestones in addition to Silurian sandstone, shale and marl and has a median normalised yield of 28.6 L/h per drilled metre. The Silurian sandstone dominating entity 810 (which has the overall lowest homogeneity factor of 0.5) has a median normalised yield of 7.8 L/h per drilled metre. These examples reflects the tendency for the lithologies within entities with a low hydrogeological homogeneity factor to be more lithologically uniform than those within entities with a high homogeneity factor.

Figure 6.4.1 shows the entities containing information from 10 or more bedrock boreholes, superimposed on a map of Norway, together with the median normalised yield for each entity. This map therefore gives some indication of the variation in median borehole yield *between* different bedrock entities. Figure 6.4.2 shows the homogeneity factor plotted for each entity, thus giving an impression of the degree of variation in borehole characteristics *within* each entity. A high homogeneity factor indicates a large interquartile range relative to the absolute median normalised yield.

The general decrease in median normalised yield with increasing depth is a puzzling phenomenon. As mentioned at the beginning of Chapter 6, Figure 6.3.4 shows a significant increase in the median value of depth as the median value of yield decreases. This is probably a result of the fact that bedrock well borers often will cease drilling a borehole when a sufficiently high yield has been obtained (see Chapter 6). It may also be the result of bedrock well borers drilling excessively deep boreholes in rocks with high yield whilst drilling boreholes more adjusted to the required yield in rocks with low values of yield. This does however not explain the clear tendency in almost all bedrock entities to show a significantly lower median normalised yield in deep bedrock boreholes compared to shallow bedrock boreholes.

This pattern of decreasing median normalised yield with increasing depth has not been discussed in any detail within Norway. Skjeseth (1956) mentions briefly that the frequency and size of joints in crystalline bedrock decrease with depth and consequently advises against drilling boreholes deeper than a specified depth. Skjeseth does not however specify this depth. Hagemann (1961) shows a diagram suggesting that the capacities of bedrock boreholes in plutonic rocks in the Oslo Region decrease with depth. He explains this as the result of drilling deep bedrock boreholes where the yield of the borehole is too low at "normal" depth. Hagemann goes on to say that such deep drilling is not normally cost-effective due to the tendency of bedrock to become more massive with depth. Englund (1966) also shows a diagram suggesting an increase in the yield of a typical borehole in Cambro-Ordovician schist in the Mjøsa area down to around 60 m followed by a decrease in yield.

In Figure 6.3.5 it is possible to identify a number of bedrock entities with a tendency for the normalised yield to increase or remain stable up to a depth of around 70 metres. Bedrock entity 788 in particular shows a dramatic increase in median normalised yield from 15 L/h per drilled metre at depths of around 25 m to 75 L/h per drilled metre at depths of around 35 m. Similar trends can also be found for bedrock entities 850, 975, 1029 and 1035. The main trend is however not for a significant increase in the median normalised yield with depth but rather a decrease starting at very shallow depth.

Henriksen (1995) plotted normalised borehole yield versus borehole depth for bedrock boreholes in the county of Sogn og Fjordane. The resulting plots indicate a general decrease in normalised yield with borehole depth and Henriksen notes that this trend is similar to trends displayed in scatter-plots of hydraulic conductivity versus depth in crystalline rocks (i.e. Carlsson et al. 1983, Black 1987, Soulios et al. 1990).

The reason for this observed decrease in median normalised yield with depth for almost all entities is probably attributed to the variations in the frequency of horizontal joints within the bedrock. These sub-horizontal fractures or sheet-jointing have been described in Scandinavia by Vogt (1897), Ljungner (1927), Hausen (1944) and Larsson (1984) and others. Such sub-horizontal fractures have been interpreted as the result of surficial stress-relief exaggerated by the hydraulic relief of the retreating Quaternary ice sheets (Rohr-Torp 1994). Myrvang (1996) mentions that during the period 1950-60, the Swedish professor Hast suggested that the reason for the high horizontal stress exceeding the vertical stress component was due to the isostatic uplift after the last deglaciation.

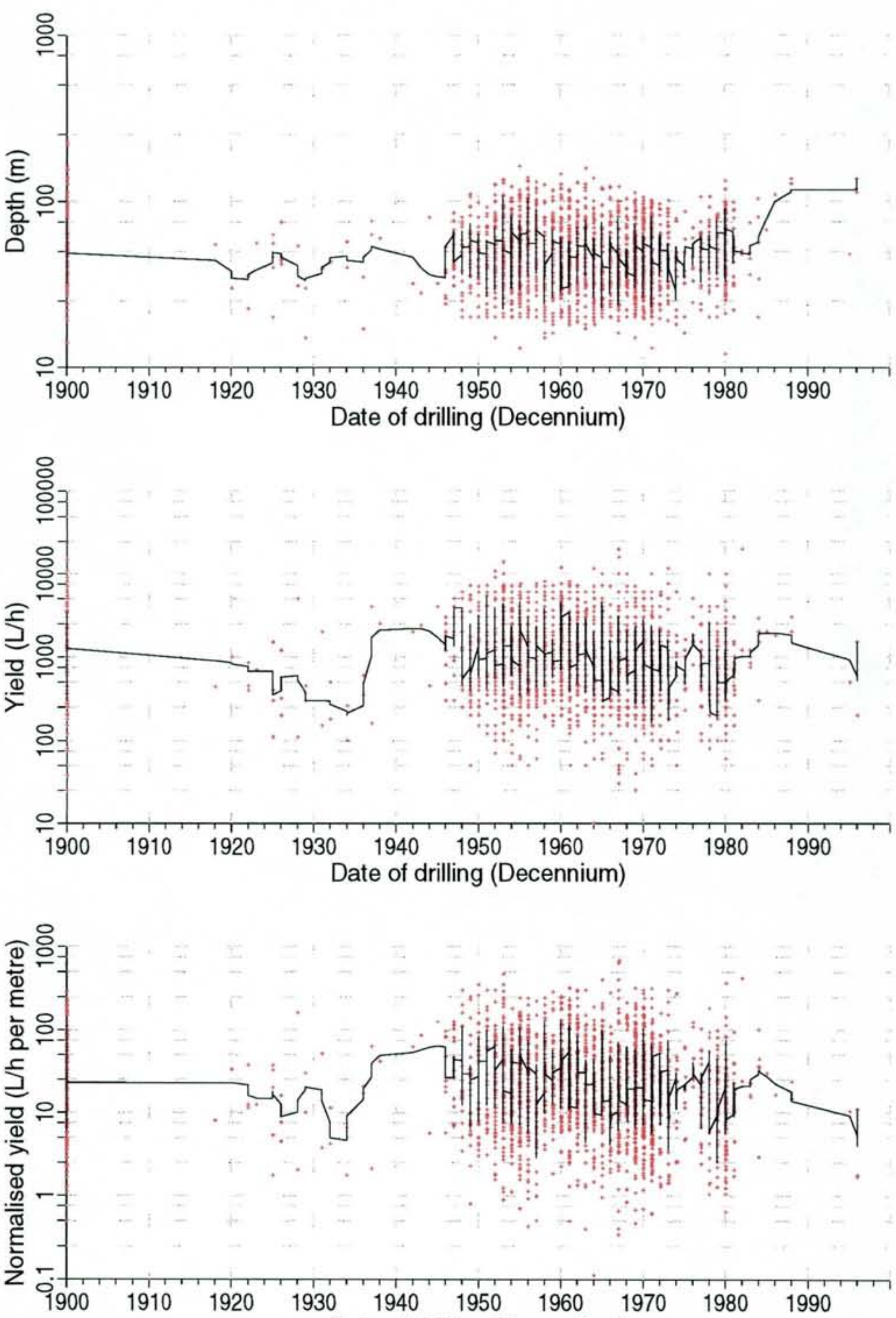


Figure 6.4.3 *XY-plots of drilling date compared to depth (m), yield (L/h) and normalised yield (L/h per drilled metre) for all bedrock boreholes within bedrock entity 717 (rocktype 98). The solid line was constructed using the smoothing method of the DAS-program (see text for explanation).*

However, Gustafson et al. (1988) have observed that many of the early aplites in the Simpevarp area in south-eastern Sweden are sub-horizontal, indicating that the two largest principal stresses were sub-horizontal in the thrust regime very early in the tectonic history. Talbot et. al (1987) concludes that "experience elsewhere in Sweden indicates that the most significant hydraulic conductors are likely to be sub-horizontal fracture zones in the top 500 metres, although tests deeper than this indicate that they can be deeper still".

It has been noted by several authors (Persson et al. 1985b, Banks et al. 1994, 1996, Banks 1997) that the distribution of yield from bedrock boreholes also has an approximately log-normal character. This observation has been supported by this study. Several investigations have also documented that the permeability of crystalline rocks decreases with increasing depth (e.g. Carlsson 1983, Gustafson et al. 1984, Ahlbom et al. 1991, Gustafson & Krasny 1994, Henriksen 1995). This decrease in permeability may be explained by increasing stress within the rock or the reduced occurrence of sub-horizontal joints due to rock mechanical properties. The frequency of such joints has been reported to be almost logarithmic, decreasing with depth (Gustafson et al 1984). Gustafson assumes that the present joint systems are the result of a very large number of tectonic episodes and that this processes is still continuing.

E.g. the reduced occurrence of sub-horizontal joints may explain the almost linear character of the median normalised yield shown in the logarithmic diagrams of Figure 6.3.5. The existence of sub-horizontal joints down to depths of perhaps 500 m, decreasing exponentially in frequency, would therefore appear to be an important factor in explaining the relationship of normalised yield with depth in bedrock boreholes in Norway. Other important factors may be (1) the location of tectonic features and regional lineaments in the vicinity of bedrock boreholes, (2) the influence of isostatic uplift due to the last glaciation period, (3) the location of bedrock boreholes relative to the highest sea level (the Marine Limit) and (4) the local topography and hydrology in the vicinity of the bedrock borehole.

The first three factors mentioned were investigated and will be discussed in Chapters 7, 8 and 9. However, sheer number of bedrock boreholes has made it extremely time-consuming to relate each of them to local topography and hydrology. Henriksen (1995) considered the topography of about 760 bedrock boreholes in the county of Sogn og Fjordane. He concluded that in high-relief areas the lithological factor may be subordinate to factors related to the local topography and hydrology of the catchment area of the bedrock borehole. This has also been noted by Uhl & Sharma (1978) and Yin & Brook (1992).

The majority of the 12,757 bedrock boreholes used in this study were drilled during the period 1946 to 1982. During this period, developments in drilling equipment have caused a major increase in drilling speed and efficiency. In particular the introduction of down-the-hole-hammer drilling in 1960 was revolutionary. Figure 6.4.3 presents smoothed XY-diagrams (see the explanation for Figure 6.3.5) for all boreholes in bedrock entity 717 (rocktype 98) based on their date of construction, drilled depth (m), yield (L/h) and normalised yield (L/h per drilled metre).

From the upper diagram in Figure 6.4.3 it is not possible to detect any relationship between construction date and drilled depth in either shallower or deeper boreholes up to 1974. From 1974, however, the diagram suggests an increase in median drilled depth. The middle diagram concerning drilling date and yield suggests a stable median yield up to around 1960. From around 1960 the diagram seems to suggest a decrease in the median yield. The same pattern is also seen in the bottom diagram showing drilling date and normalised yield. This pattern is interpreted as being the result of the introduction of faster and more efficient down-the-hole-hammer drilling techniques by Norwegian bedrock well borers around 1960. These faster drilling techniques may result in clogging of fissures and joints relative to the less violent slower traditional cable tool method.

The petrophysical differences between the rocktypes used in this thesis are assumed to be of major importance for the development of horizontal fractures in the rock. However, the rocktypes are not as homogenous as one would ideally wish because of the scale of the digitised map. Ideally, a representative sample of the host rock of every bedrock borehole should be analysed with respect to its petrophysical properties. As far as the author knows, no samples from host rocks from groundwater boreholes have been analysed with respect to their petrophysical parameters. As has also been seen in Chapters 4.3 and 4.4, it has been very difficult to track down any representative petrochemical analyses of host rock at the sites of bedrock boreholes.

The results of several thousand petrophysical analyses have been stored in the petrophysical database at NGU. There exists, however, one fundamental problem with the database: the samples have not been taken with the intention that they should be representative for their host lithology. The majority of samples are usually taken in connection with a particular unusual petrological or lithological phenomenon occurring within the host lithology. In addition, very few of the samples have reliable coordinates, which would have made it very difficult to assign petrophysical properties to the 12,757 bedrock boreholes used in this thesis. These factors are the main reasons for not placing more emphasis on possible petrological and petrophysical controls on bedrock borehole yield in this thesis. The fact that there exist two independent databases at NGU which could give valuable insights if linked, however, highlights the need for more discussion and co-operation even within an organisation such as NGU.

Chapter 7

Tectonics and the Yield of Norwegian Bedrock Groundwater Boreholes

7.1 Introduction

Mapping of tectonic fracture zones and other lineaments has been an integral part of many groundwater exploration programmes in hard rock terrain. In areas where bedrocks have negligible low primary porosity, as in Norway, the interception of transmissive secondary structural features is held to be of crucial importance for a successful bedrock borehole. Many scientists working in countries other than Norway have investigated various tectonic features with respect to their groundwater potential, several with an emphasis on arid or semi-arid hard rock areas (Greenbaum 1992a,b, Boeckh 1992, Gustafsson 1993, Gustafsson 1994, Wladis et al. 1994, Sander et al. 1996, Wolfbauer 1996 and others). In Norway some work has been performed by Banks et al. (1993b) and Misund (pers. comm.).

7.2 Materials and Methods

The exploitable porosity and permeability of crystalline hard rocks is, for every practical water-resource purpose, controlled only by the existence of fracture systems. More than 5,300 regional lineaments have thus been digitised from from Gabrielsen et al. (1979) (Figure 7.2.1). It is believed that the overwhelming majority of these lineaments represent faults and fracture zones, although other origins for some lineaments (lithological boundaries etc.) cannot be excluded. Norwegian researchers have, by visual assessment, divided Norway into 36 different fracture system sub-areas (Gabrielsen et al. 1979). These tectonic sub-areas are shown in Figure 7.2.2. Each sub-area should ideally be homogenous with respect to lineament directions. Although the outlines of the sub-areas were not defined by geological criteria (but simply by systematic plotting of the lineament orientations), many of the boundaries appear to be closely related to known

Figure 7.2.1 *Regional lineaments in Norway. Digitised from Gabrielsen et al. (1979) in the scale 1: 1,000,000.*

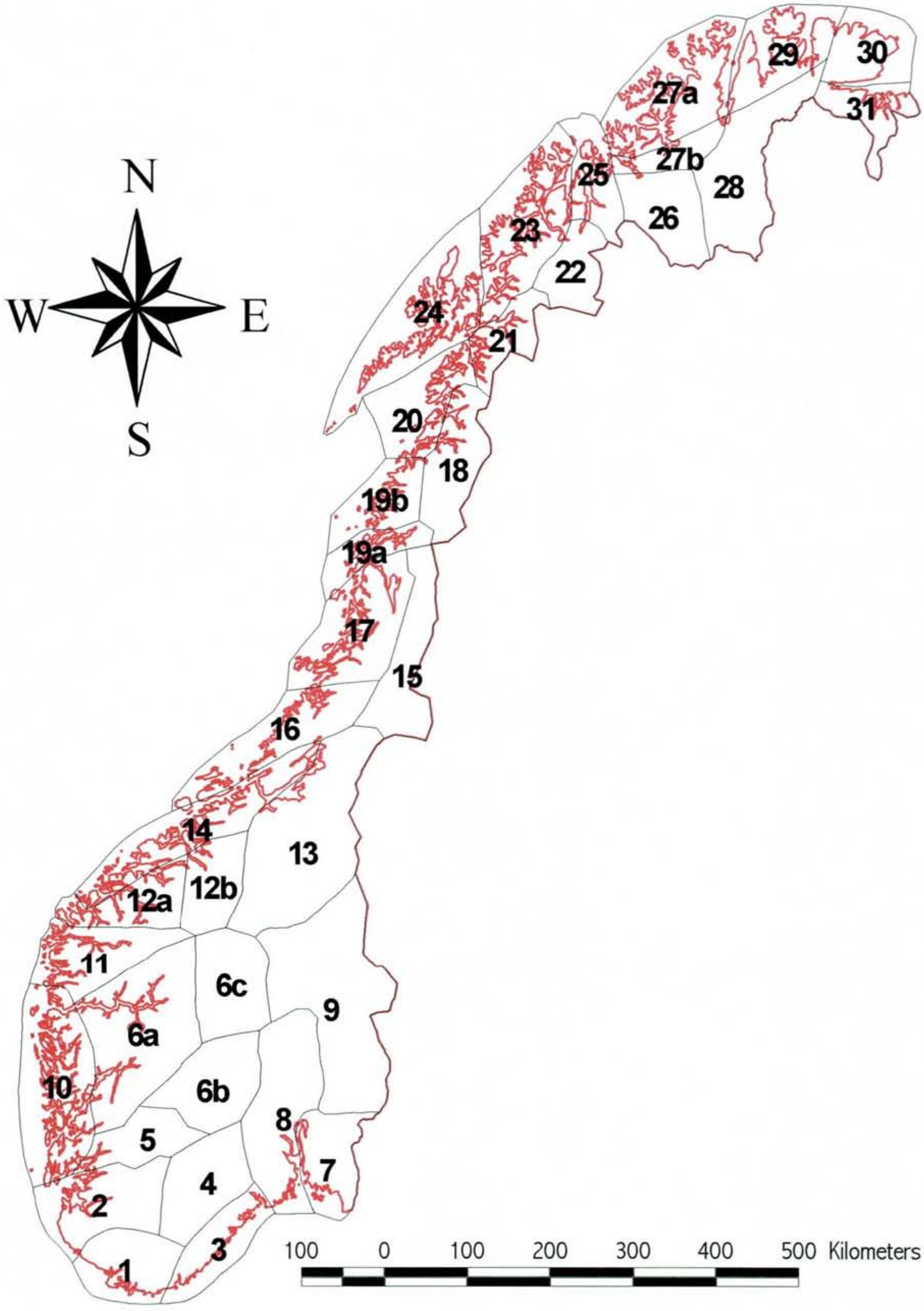


Figure 7.2.2 *Tectonic sub-areas in Norway. Digitised from Gabrielsen et al. (1979).*

geological features, such as lithological boundaries, structural provinces etc. Some of the sub-areas exhibit rather complex fracture patterns, and analysis of such sub-areas has demonstrated that this is due to the occurrence of several superimposed fracture sets (Gabrielsen et al. 1979).

Three fracture zone sets are almost ubiquitous (see figure 7.2.1), namely the N-S, NE-SW and NW-SE directions. In some areas an E-W direction is also recognised. "Double orthogonal" systems of this kind have been reported by several authors (e.g. H. Cloos 1928, Rieldel 1929, E. Cloos 1932 and 1935, Tchalenko 1970, Wilcox et al. 1972, Holmgren 1976, Fiedler et al. 1976) as a world-wide phenomenon, and have been termed the G-system by Katterfeld (1976). In the further use of these sub-areas, emphasis will be placed on differences occurring in the median normalised yield of boreholes in different sub-areas, rather than on the directional differences of fracture sets within each sub-area.

It is commonly believed by Norwegian hydrogeologists that bedrock boreholes in the vicinity of, or intersecting a fracture zone or lineament have a more favourable potential yield than bedrock boreholes situated away from such lineaments. The digitised lineaments in Figure 7.2.1 have been obtained by Gabrielsen et al. (1979) using Landsat images. The images have been subject to visual analysis, generally at a scale of 1:1 mill. The possible error in the location of the lineaments incurred during digitising is believed to be less than 1,000 metres (Ekremsæther 1997). Wladis et al. (1994) suggest that the zone of influence (i.e. favourable hydrogeological potential) around a lineament extends to a distance of about 500 metres, considerably further than found by other authors (e.g. Clark 1985). It should be noted that almost every recent paper which has undertaken this kind of correlation study has stressed the importance of positional accuracy for both boreholes and lineaments (for example Gustafsson 1994 and Sander et al. 1996). This has been difficult to achieve using the Norwegian BBD and the above-mentioned Landsat images, although no other data were available for this study.

All of the 12,757 bedrock boreholes extracted from the BBD (Chapter 3.5 and Figure 1.2.1) have been given a representative value according to which regional sub-area they are located within. The distance to the nearest regional lineament has also been calculated and assigned to each borehole. This situation clearly falls short of an ideal data set in terms of positional accuracy and it is exactly such data sets for which the exploratory data analysis program DAS is suited. ArcView 3.0 GIS has been used to visualise the data in the form of maps.

7.3 Results

7.3.1 Regional Sub-Areas

Figure 7.3.1.1 shows a map of the tectonic sub-areas containing information on 10 or more bedrock boreholes. The median normalised yield of each sub-area has been plotted on the map. The map indicates the variation in borehole yield characteristics in these sub-areas containing boreholes registered in the BBD. Although the map in Figure 7.3.1.1 shows a generally similar pattern to the map in Figure 6.4.1 (normalised yield for bedrock lithological entities), there are also several differences. A graphical presentation of all boreholes located within each entity covered by each sub-area are shown in Appendix C. The presentation contains cumulative frequency curves, density traces, boxplots and XY-plots with respect to depth and yield, together with the relevant correlation coefficients (Pearson's r).

7.3.2 Regional Lineaments

All of the 12,757 bedrock boreholes extracted from the BBD (Chapter 3.5 and Figure 1.2.1) have been related (in terms of distance) to their nearest regional lineament (Figure 7.2.1) using ArcView 3.0 GIS. Of a total of 5,342 digitised regional lineaments, 1,095 of them are related to one or more bedrock boreholes. The majority (75%) of these 5,342 regional lineaments have each been related to fewer than 10 bedrock boreholes. 272 regional lineaments are each related to between 10 and 672 bedrock boreholes. Only 18 regional lineaments have each

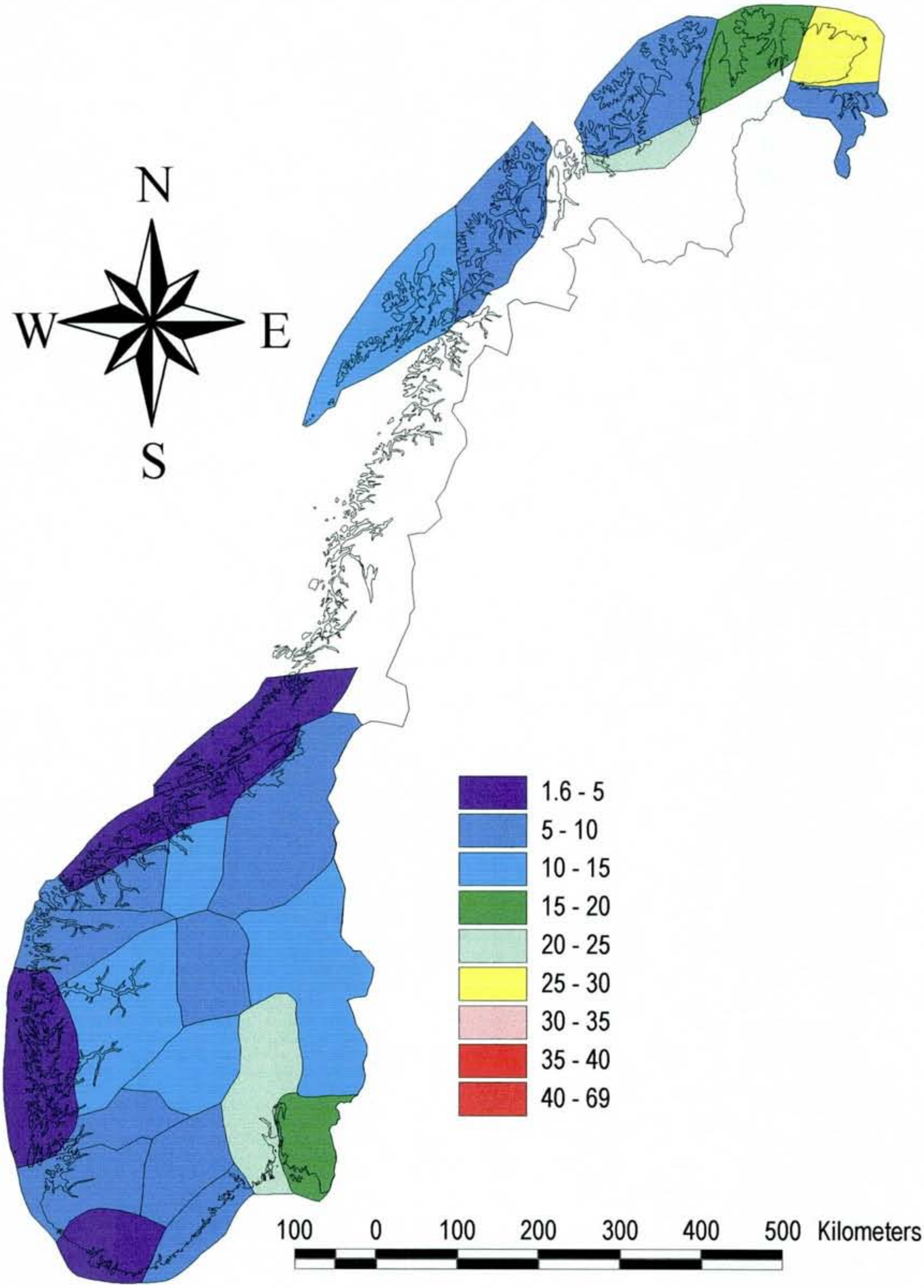


Figure 7.3.1.1 Map of Norway showing tectonic sub-areas containing information on 10 or more bedrock boreholes. For each sub-area, the median normalised yield (L/h per drilled metre) is plotted.

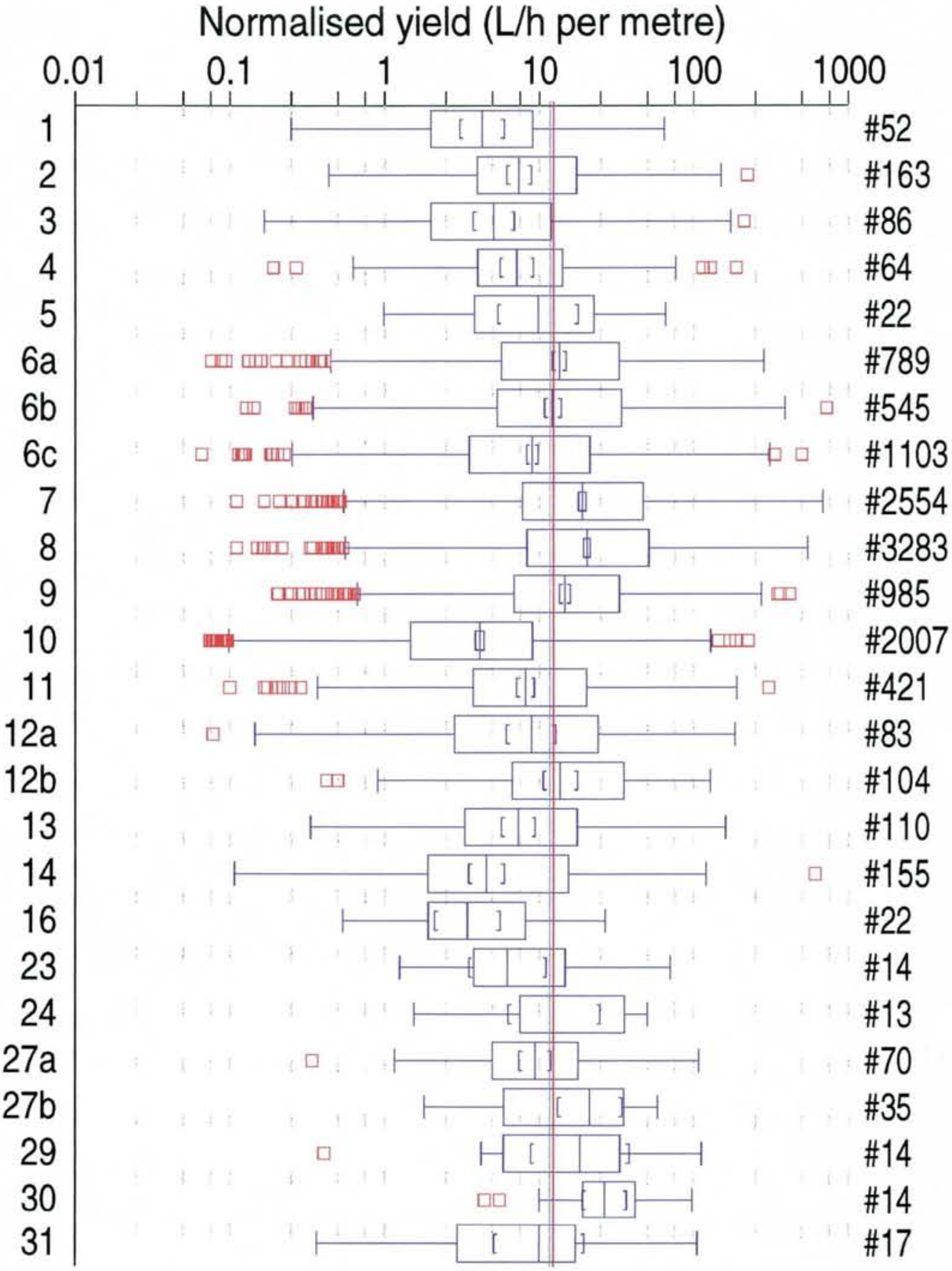


Figure 7.3.1.2 *Boxplots showing, in descending order, the normalised yield in litres/hour per drilled metre of all the 12,757 extracted boreholes from the BBD as a function of tectonic sub-areas (left). The 95% confidence limits of the overall median of 12.0 L/h per drilled metre for the entire data set are marked as horizontal lines. # = total number of samples in boxplot group.*

Table 7.3.2.1 *Tabular presentation of the selected 18 regional lineaments. LNR = lineament number, L = length of the digitised regional lineament (kilometres), No = number of bedrock boreholes related to the regional lineamen, NY = median normalised yield of these boreholes (L/h per drilled metre), MY = median yield of these boreholes (L/h), MD = median depth of these boreholes (metre), MDIS = median distance from the regional lineament to each of the related bedrock boreholes (metres).*

LNR	No	NY	MY	MD	MDIS	L
112	112	8.2	365	46	4724	22
391	672	22.4	800	40	914	97
392	259	17.0	740	48	698	40
393	122	15.0	680	40	742	12
395	161	23.8	1000	45	370	19
398	201	16.5	670	44.5	1502	38
411	110	12.8	60	49	1787	37
784	158	18.1	820	43	1299	70
904	255	14.5	800	52	1647	25
993	101	3.3	280	79.5	1248	8
1295	101	8.2	500	61	1526	23
1369	116	25.9	1000	39	466	8
1370	126	7.8	500	68.5	737	45
1430	118	14.5	700	49.5	1232	12
1431	191	22.2	1000	46	1006	14
1433	184	18.1	950	47.5	1493	43
1742	126	10.0	700	63	2603	8
1995	101	7.8	350	57	2131	16

been related to more than 100 bedrock boreholes. This chapter will focus on these 18 lineaments to assess the relationship of borehole yield to proximity of these lineaments. The 18 lineaments in question are dominantly situated in the south-eastern areas of Norway, where the bedrock borehole density is highest.

Table 7.3.2.1 presents some features of the selected 18 regional lineaments, which are related to a total of 3,214 bedrock boreholes. All boreholes related to one of these regional lineaments have been divided into sub-groups according to which bedrock entity they are located within. Only sub-groups (12 in total) containing 10 or more bedrock boreholes nearer than 500 metres from a regional lineament are used. In Figure 7.3.2.1, all the 12 sub-groups are presented as boxplot-diagrams; in addition, boxplots are shown for the bedrock entities containing the various sub-groups. The boxplots in this figure reveal that the majority of the sub-groups (7 out of 12) do not exhibit any significant difference in the median normalised yield as compared with the total data set for the bedrock entity to which they belong. Four sub-groups have a significantly higher median normalised yield and two sub-groups have a median normalised yield that is significantly lower than the median normalised yield for the total data set of the bedrock entity to which they belong.

An analysis of the distribution of median normalised yield of boreholes at varying distances from a regional lineament is presented in Figure 7.3.2.2. The locations of the regional lineaments and bedrock boreholes in the sub-groups defined in Figure 7.3.2.2 are shown in Figure 7.3.2.3. The diagrams in Figure 7.3.2.2 present all boreholes, on both sides of a regional lineament. In Figure 7.3.2.2, all sub-groups defined in Figure 7.3.2.1, containing 10 or more bedrock boreholes within a distance of less than 500 metres from a regional lineament, are presented.

For eight of the twelve sub-groups presented in Figure 7.3.2.2 it is possible to identify an increase in median normalised yield with decreasing distance from the regional lineaments. Boreholes related to one regional lineament (759_1370) shows a tendency towards decreasing median normalised yield with decreasing distance from the regional lineament. From the other diagrams it is not possible to identify any significant positive or negative correlation of distance with median normalised yield. The presumed positive influence of the regional lineament on the median normalised yield of bedrock boreholes has an extent of between 50 metres (sub-group 717-393) and 350 metres (sub-group 975-391), measured perpendicularly from the regional lineament.

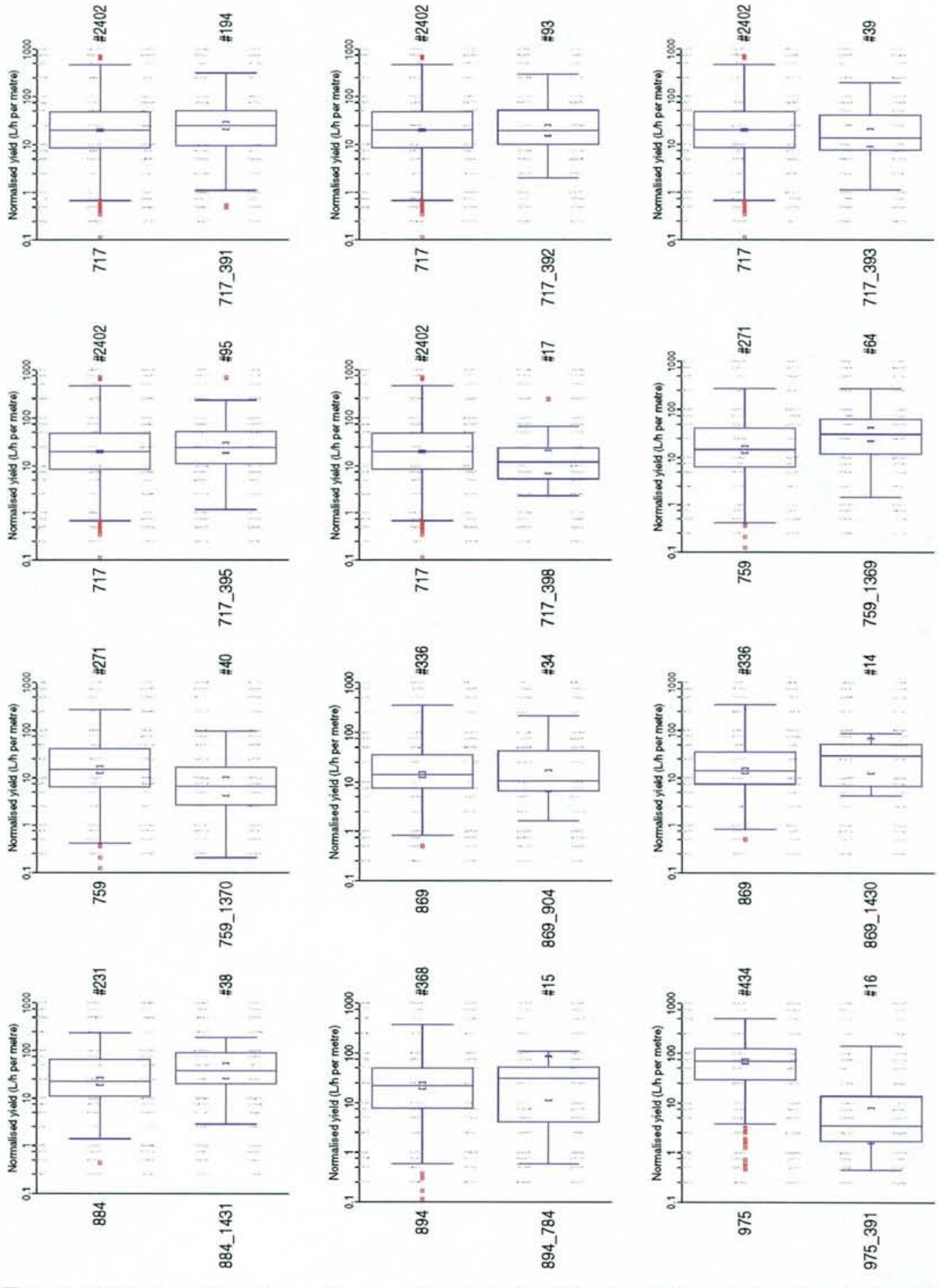


Figure 7.3.2.1 *Boxplots of normalised yield of bedrock boreholes located within a distance of 500 metres from a regional lineament. Sub-group 717_391 contains boreholes drilled in bedrock entity 717 (see Table 2.3.1, Chapter 6.3 and appendix A and B), within 500 metres the lineament whose identification number end in 391.*

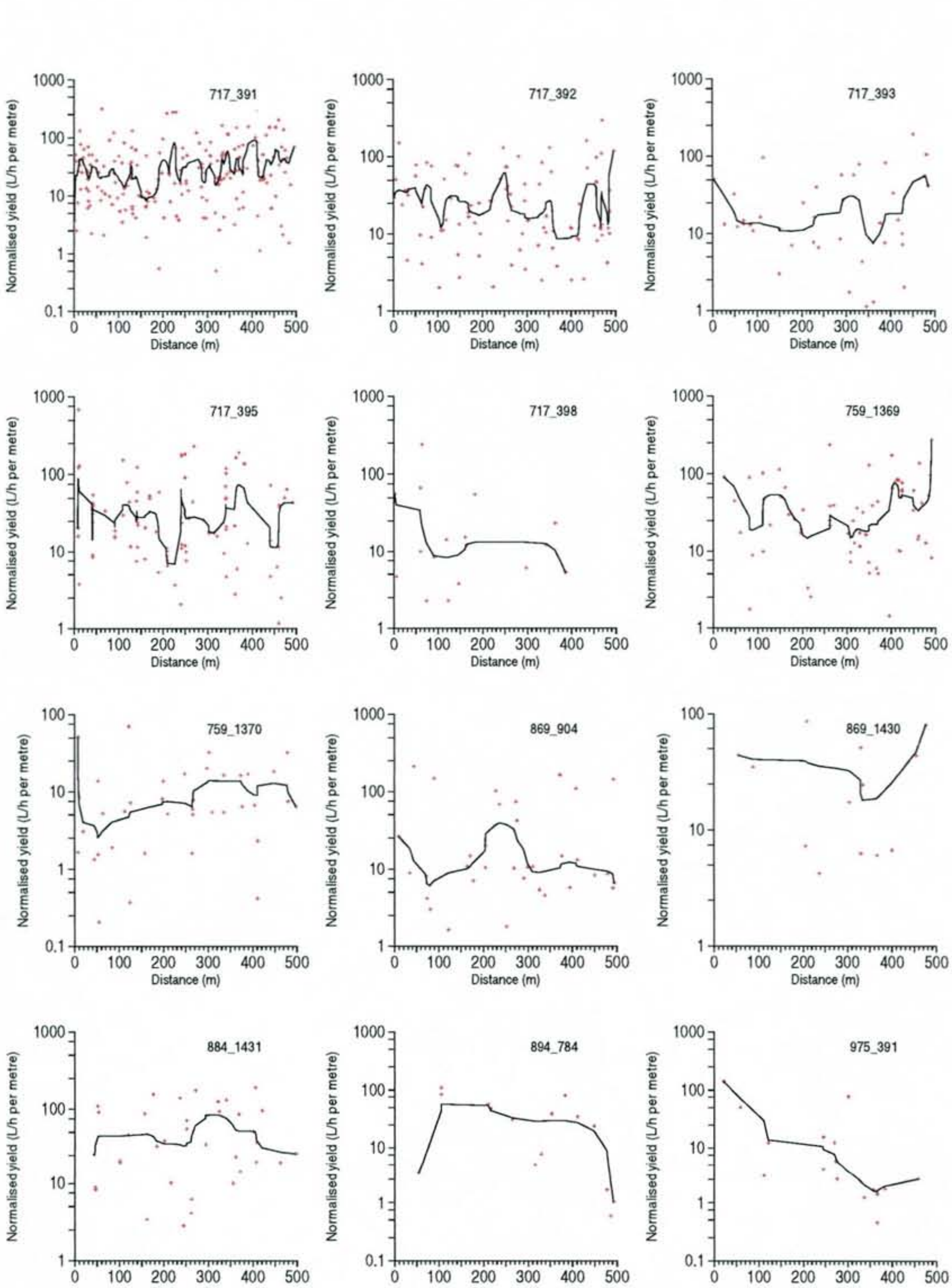


Figure 7.3.2.2 XY-plots of the distance (metres) from a bedrock borehole to the nearest regional lineament and the borehole's normalised yield (L/h per drilled metre) (see text for explanation). The solid line has been constructed using the smoothing method of the DAS-program (see Chapter 6.3 for explanation).

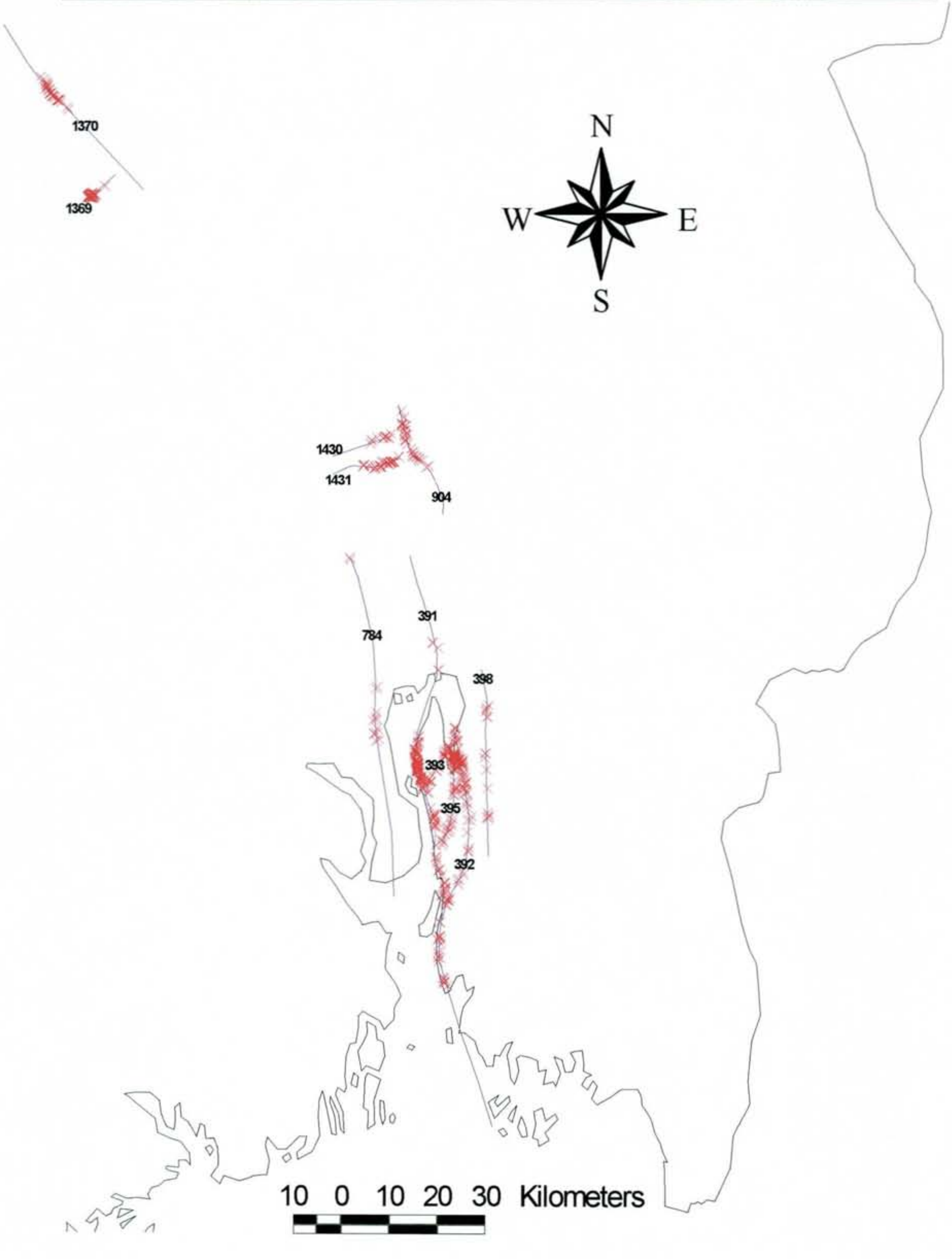


Figure 7.3.2.3 Location of the regional lineaments (blue lines) and bedrock boreholes (red crosses) within a distance of less than 500 metres from regional lineaments.

Sub-group 717_391 indicates an increase in median normalised yield from around 10 L/h per drilled metre at a distance of around 150 metres from the regional lineament to around 40 L/h per drilled metre close to the lineament. Sub-group 717_392 indicates a similar increase, although the positive effect can only be identified up to distances of around 100 metres.

Sub-group 717_393 is the sub-group indicating the narrowest zone of influence around a regional lineament. The median normalised yield increases from around 12 L/h per drilled metre to around 50 L/h per drilled metre within a zone of only 50 metres width from the lineament.

Sub-group 717_395 indicates an increase in the median normalised yield from around 10 L/h per drilled metre at a distance of around 200 metres from the lineament to around 75 L/h per drilled metre close to the lineament.

Sub-group 717_398 contains only 17 boreholes, but it is possible to see a tendency towards increasing median normalised yield with decreasing distance from the regional lineament. The median normalised yield increases from around 10 L/h per drilled metre at a distance of 100 metres up to around 50 L/h per drilled metre close to the lineament. Sub-group 759_1369 exhibits a similar pattern.

Sub-group 896_904 may be interpreted as showing an increasing median normalised yield from around 6 L/h per drilled metre at a distance of around 75 metres to some 25 L/h per drilled metre close to the regional lineament.

Sub-group 975_391 indicates a similar increase from a median normalised yield of around 2 L/h per drilled metre at a distance of around 350 metres to between 50 and 100 L/h per drilled metre close to the regional lineament. The only sub-group to show a clear tendency towards decreasing median normalised yield with decreasing distance from the regional lineament, is sub-group 759_1370.

It is not possible to identify any correlation between median normalised yield and distance from a regional lineament for the three sub-groups 869_1430, 884_1431 and 894_784.

7.4 Discussion

Regional sub-areas

Each tectonic sub-area (average area 9,326 km^2) generally covers a larger area than a typical bedrock entity (average area 172 km^2). This has a smoothing effect on the borehole yield map and masks the smaller areas of high-yielding entities in Figure 7.3.1.1. If one compares the eastern part of Southern Norway on maps in Figures 7.2.2, 7.3.1.1 and 6.4.1, it is not surprising that sub-area 8 has a higher median yield than the other sub-areas. The median normalised yield of this sub-area is, however, only 20.4 L/h per drilled metre. This is due to a majority of relatively low-yielding boreholes within this sub-area. The significantly high-yielding bedrock entities within this sub-area (see Appendix C) represent only 20% (664 of 3,283) of all boreholes located within this sub-area. The significantly low-yielding bedrock entities within this sub-area represent almost 40% (1,252 boreholes). The rest of the bedrock entities located within this area do not have a significantly different median normalised yield to the median normalised yield of sub-area 8.

It is a little surprising that sub-area 7 has a significantly higher median normalised yield than sub-area 9, the difference being almost 5 L/h per drilled metre. Figure 6.4.1 gives the impression that the median normalised yield of bedrock entities in the area covered by sub-area 9 is generally higher than in the bedrock entities covered by sub-area 7. Close inspection of the data reveals that the difference is due to an overweight of boreholes within specific lithologies. 89% (2,130 boreholes or 83% of all the boreholes located in sub-area 7) of the boreholes located within bedrock entity 717 are located in the area covered by sub-area 7. Only 254 boreholes (26% of all boreholes located in sub-area 9) in bedrock entity 717 are located in the area covered by sub-area 9. The other bedrock entities within sub-area 9 with an elevated normalised yield account for only 65 boreholes. On the other hand, two bedrock entities with a low median normalised yield, contribute a total of 476 boreholes (48% of all boreholes located in sub-area 9) to sub-area 9.

Another interesting feature of the map in Figure 7.3.1.1 is the low yield of sub-area 1. Figure 6.4.1 gives the impression that the whole area occupied by bedrock entities 1007 and 1082 have a median normalised yield of between 5 and 10 L/h per drilled metre. The graphical presentation of sub-area 1 in Appendix C reveals that the nine boreholes (17% of all boreholes in this sub-area), not included in either of the entities mentioned above, must have a significantly lower yield and normalised yield compared to the other boreholes in this sub-area.

Comparing the boxplots of sub-area 1 and sub-area 3 in figure 7.3.1.2 reveals that the median normalised yields of these two sub-areas are not significantly different. The median normalised yield of sub-area 3 is 5.1 L/h per drilled metre. 11 boreholes located within the generally high-yielding bedrock entity 971, are the reason for a median normalised yield exceeding 5 L/h per drilled metre in this sub-area. Excluding these 11 boreholes from sub-area 3 results in a median normalised yield of less than 5 L/h per drilled metre.

An other notable feature of the map in Figure 7.3.1.1 is that the median normalised yield of sub-areas 23 and 24 are significantly different. The median normalised yield of sub-area 24 is twice the median normalised yield of sub-area 23. Figure 6.4.1 contains no indication of elevated yields in the Lofoten area. Figures 2.1.1 and 2.1.2 show that the Lofoten area consists mainly of Precambrian rocks which is not heavily affected by the Caledonian orogeny. This is in contrast to the majority of Troms county, which is underlain by mica schist and mica gneiss, both known as low-yielding lithologies. This is probably the reason for the differences between these two sub-areas.

The northernmost part of Northern Norway in Figure 7.3.1.1 reveals possibly more information concerning the distribution of median normalised yield than all the information contained in Figure 6.4.1. Both sub-areas 27a and 31 have median normalised yields significantly lower than the median normalised yield of the surrounding sub-areas (Figure 7.3.1.2). The median normalised yields of sub-areas 27b and 29 are not significantly different, but that of sub-area 30 is significantly higher than sub-areas 29 and 31.

All sub-areas classified in Figures 7.3.1.1 and 7.3.1.2 as having a median normalised yield of less than 5 L/h per drilled metre are located in the coastal areas of Southern Norway. Figure 7.3.1.1 also gives the impression that the value of median normalised yield of bedrock boreholes exhibits a radial pattern with normalised yields increasing towards central Southern Norway. It is not possible, without examining the data set in more detail, to draw any definite conclusion about this apparent pattern. One possibility is that different tectonic features in these sub-areas may influence the yield; this could be assessed by superimposing the median normalised yield per rocktype (as defined in Chapter 6) on Figure 7.3.1.1. Another possible explanation may relate to the emergent nature of the coastal areas and the fact that, until recently, some of these rocks were under sea level. This may have had implications for weathering and dissolution of fractures and may also have affected the properties (swelling etc.) of any clay minerals in fractures. The pattern may also reflect differential isostatic rebound, which was most intense in Central Norway; these possibilities are dealt with further in Chapter 9 and 8, respectively.

Regional lineaments

The relationship between major fracture zones and borehole yield is in general obscure (Banks et al. 1992a, Greenbaum 1992), although it is generally accepted by hydrogeologists in Norway that the drilling of a bedrock borehole to intercept a fracture zone is beneficial with respect to the expected yield of the borehole (NGU 1992). One would therefore have expected a study of the relationship between borehole yield and distance from a regional lineament to reveal a higher median normalised yield in boreholes near to lineaments than the overall median normalised yield of the bedrock entities within which the boreholes are located.

The results presented in Figure 7.3.2.1 do not clearly indicate any positive influence of a regional lineament on the median normalised yield of bedrock boreholes located in the vicinity. This figure shows that 20% of all sub-groups have a significantly lower normalised yield in the vicinity of a regional lineament compared to only 10% with a significantly higher normalised yield. The results presented in Figure 7.3.2.2 indicate, however, that a majority of the sub-groups (8 out of 12) exhibit a pattern of increased median normalised yield in the immediate vicinity of the regional lineaments. Wolfbauer (1996) suggests that an elevated median yield occurs in boreholes located within a distance of 200 - 400 metres from the lineament, but his results also exhibit a large degree of uncertainty. Wladis et al. (1994) conclude that any correlation of yield and proximity to a lineament vanishes beyond distances of approximately 200 - 300 metres (depending on the source of lineament detection; SAR-imagery, SPOT-imagery or aerial photographs).

There may be several causes of error influencing the result presented in Figure 7.3.2.2. A possible technical error in the location of the lineaments may have been introduced during digitising. This error is believed to be less than 1,000 metres (Chapter 7.2). If the actual location error on the original lineament map (as opposed to the digitising error) for a regional lineament is of this order of magnitude, then the relationships between bedrock boreholes and regional lineaments shown on Figure 7.3.2.2 are almost meaningless. The fact that 8 sub-groups in Figure 7.3.2.2 suggests an increasing median normalised yield of bedrock boreholes with proximity to a regional lineament might indicate that the actual location error is generally rather small. As mentioned in Chapter 7.2, the positional accuracy of both bedrock boreholes and digitised lineaments is of great importance, and this accuracy is difficult to improve from image analysis or map interpretation alone. Field studies, preferably using a Global Positioning System (GPS), would be necessary to achieve a marked improvement in positional accuracy.

Finally, further sources of error in the analyses described in this Chapter include:

- Errors in positional accuracy of the boreholes, themselves
- Errors in estimation (especially overestimation - see Chapter 3.3) of borehole yield.
- That the lineaments identified in Landsat images have only been so-called large, regional lineaments. Lineaments and fracture zones in crystalline bedrock exists at all scales (Odling 1993). It is possible that hydrogeologically relevant lineaments in Norway may not have been included in the digitisation due to the small scale of the base map. To be able to include the majority of hydrogeologically relevant lineaments, Wolfbauer (1996) recommends the use of a base map at a scale not exceeding 1 : 100,000.
- The lineament map (being a plan view) tends to overemphasise the importance of sub-vertical lineaments and fracture zones. Several studies have indicated that sub-horizontal fracture zones may be important from a hydrogeological point of view.
- Landsat images tends to favour certain lineament directions.

Similar correlation studies of lineaments and borehole yields made by Sander et al. (1996) indicate that linear features mapped from various images are clearly important for groundwater availability in hard rock terrain. He also stresses the importance of positional accuracy for the lineaments and boreholes considered, and concludes that errors in accuracy can have a serious impact on the analysis of lineament structures of only a few tens of metres width. The same conclusion is drawn by Wladis et al. (1994), who suggest the use of GPS to reduce locational errors.

The possible positional error in the location of the bedrock boreholes themselves is also a potential source of error in the results described in Chapter 7.3.2. Norwegian hydrogeologists commonly believe that bedrock boreholes in the vicinity of, or intersecting, a fracture zone or lineament have a more favourable potential yield than bedrock boreholes away from such structures. One might thus argue that this has resulted in some bias in the data, as boreholes are likely to have been located in accordance with this assumption, with only a few boreholes being located in areas not influenced by tectonic lineaments. In fact, this argument is probably only valid for a limited number of boreholes. Most bedrock boreholes in Norway usually supply single houses or country cottages and are thus located by bedrock well borers rather than hydrogeologists, typically near the point of use using criteria of convenience and practicability rather than hydrogeology. In other words, bedrock well borers usually construct a bedrock borehole as near the user as possible, generally not seriously taking into consideration other (e.g. geological) factors which might influence the yield.

One explanation of why one of the sub-groups indicates a decreasing median normalised yield in bedrock boreholes approaching the regional lineament, may be the fact that the digitised regional lineaments represent major tectonic structures which have been reactivated several times during the tectonic evolution of Norway. Also, it is likely that many of the fracture zones (e.g. in the Oslo Region, see Chapter 4.3) have acted as conduits for thermal fluids. Cataclasis and hydrothermal alteration may thus have caused the development of a high content of secondary clay minerals in these lineaments. Such a high clay content, particularly if it includes swelling clays such as smectites, will result in a significantly lower yield in boreholes located within (and possibly also in the vicinity off) such lineaments (Banks et al. 1992a).

Chapter 8

Postglacial Isostatic Uplift and the Yield of Norwegian Bedrock Groundwater Boreholes

8.1 Introduction

The youngest Quaternary ice age, the Weichselian, started 150,000 - 120,000 years ago and lasted up to 10,000 years B.P. The ice has not covered the whole of Norway continuously during the Weichselian glaciation. Periods of warmer climate, during which the ice sheet has almost completely retreated, have alternated with cold periods of ice-advance. The ice-sheet over Norway and the rest of Fennoscandia reached its maximum extent at between 17,000 and 21,000 years B.P. (Sveriges Nationalatlas 1994) The thickness of the ice-sheet reached such a magnitude that in several areas, the direction of ice movement was independent of the underlying topography.

The thickness of the ice is not precisely known, but is believed to have reached a maximum of between 2,000 and 3,000 metres in the Gulf of Bothnia between Sweden and Finland. The weight of this enormous thickness of ice is generally accepted to have caused an isostatic depression of the underlying crust by 800-850 metres in this area (Mörner 1980). The magnitude of this depression decreased towards zero at the outer limits of the maximum extent of the ice-sheet.

The coastal areas of Norway were deglaciated first at around 12,000 years B.P., while by around 8,500 years B.P. the large, continuous continental ice-sheet had, apart from some residual mountain areas, melted away. This deglaciation was thus extremely rapid, in the context of geological history, compared to, for example, the Caledonian orogeny (Rohr-Torp 1994). It resulted in an isostatic uplift or rebound of the crust in the area previously covered by ice. This uplift accelerated dramatically after the deglaciation and reached a maximum rate of up to 0.5 metres per year in the Gulf of Bothnia (Mörner 1978, 1980). This rate gradually decreased again to the present uplift rate of less than 10 mm per year.

Rohr-Torp (1994) has described the consequences of changes in stress and strain rates in the crust connected to this isostatic uplift; namley seismic activity, fracturing and reactivation of old fracture systems. As mentioned in Chapter 6.4, Gustafson (1984) believes that fracture systems, which we observe today in bedrock, are the result of a large number of tectonic episodes and that the process of fracture creation and reactivation still continue today. Bearing in mind the several periods of glaciation and deglaciation during the Quaternary, one might argue that the Quaternary has been the single most hydrogeologically important period of fracture formation and reactivation. We can see the direct evidence of this today in the occurrence of relatively shallow seismic activity and neotectonic fault movement in many areas of Scandinavia and Canada.

To the author's best knowledge, only one scientific publication exists on the possible influence of isostatic uplift on the yield of bedrock boreholes in Norway. Using information from 1,278 boreholes in five separate areas in Precambrian bedrock, Rohr-Torp (1994) concluded that it seems possible to predict the "typical" median yield of a randomly placed bedrock borehole in the Precambrian rocks of Fennoscandia. He suggests a rule of thumb which states that in areas with zero annual uplift, a 80 - 85 metres deep bedrock borehole is expected to yield a baseline value of 180 L/h. For each mm increase in annual uplift, 100 L/h can be added to the total yield at the same time as the depth required to achieve this yield is reduced by 6 metres.

8.2 Materials and Methods

Rohr-Torp (1994) assume that there is a significant correlation between the total isostatic uplift pattern since the end of the last glaciation (8,500 years B.P.) and the present uplift rates in Fennoscandia. Figure 8.2.1 shows the estimated present isobase pattern of annual land uplift in relation to the mean sea level (Statens

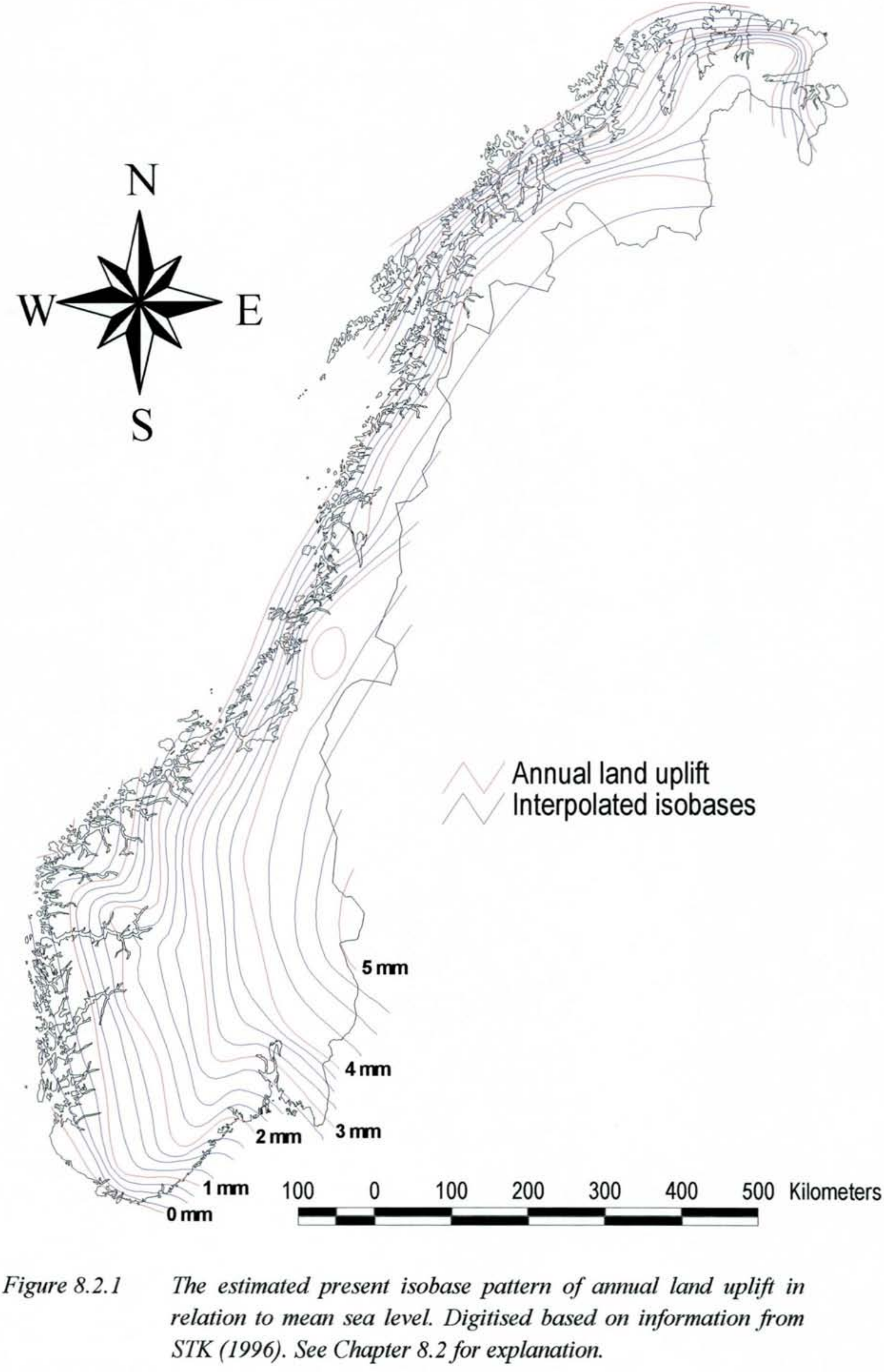


Figure 8.2.1 *The estimated present isobase pattern of annual land uplift in relation to mean sea level. Digitised based on information from STK (1996). See Chapter 8.2 for explanation.*

Kartverk [STK], 1996). The red lines represent digitised isobases of annual land uplift (based on a map from the STK) while the blue lines represent interpolated isobases at an interval of 0.25 mm per year.

The location of the isobases shown in this latest presentation from STK is in many ways different from previously published interpretations of annual uplift (Sørensen 1987). There are relatively few data points for annual uplift in the northern part of Norway and in the mountainous region of Southern Norway, causing the isobases in this area to be rather unreliable. There also exist some local variations in annual land uplift, which appear to be overlooked by these isobases. For example, the annual uplift in the Ski area (30 km south-east of Oslo) is observed to be 7 mm per year (Danielsen 1996). It is also known that neotectonic activity may result in even larger anomalous local uplift rates in several other locations in Norway and elsewhere in Fennoscandia (Mörner 1978 and 1980, Olesen 1988, Olesen et al. 1992 and 1995 and others).

All of the 12,757 bedrock boreholes extracted from the BBD (Chapter 3.5 and Figure 1.2.1) have been allocated a representative value according to the annual land uplift represented by the nearest isobase. The distance between a borehole and the nearest isobase line has also been recorded. This data forms another example of a "non-ideal" data set which is borehole suited to the exploratory data analysis program DAS. ArcView 3.0 GIS has been used to prepare the maps.

8.3 Results

As a matter of curiousity, it would be interesting to know more about the behaviour of the the database material forming the foundation of the study by Rohr-Torp (1994), and resulting in his "rule of thumb". Thus a similar investigation in the same five areas of Precambrian bedrock was executed. Due to different methods of bedrock borehole information extraction from the BBD, only 961 "valid" boreholes (according to the criteria of Chapter 3.4.3) were extracted from these areas, compared with the 1,278 bedrock boreholes used in Rohr-Torp's (1994) study. This

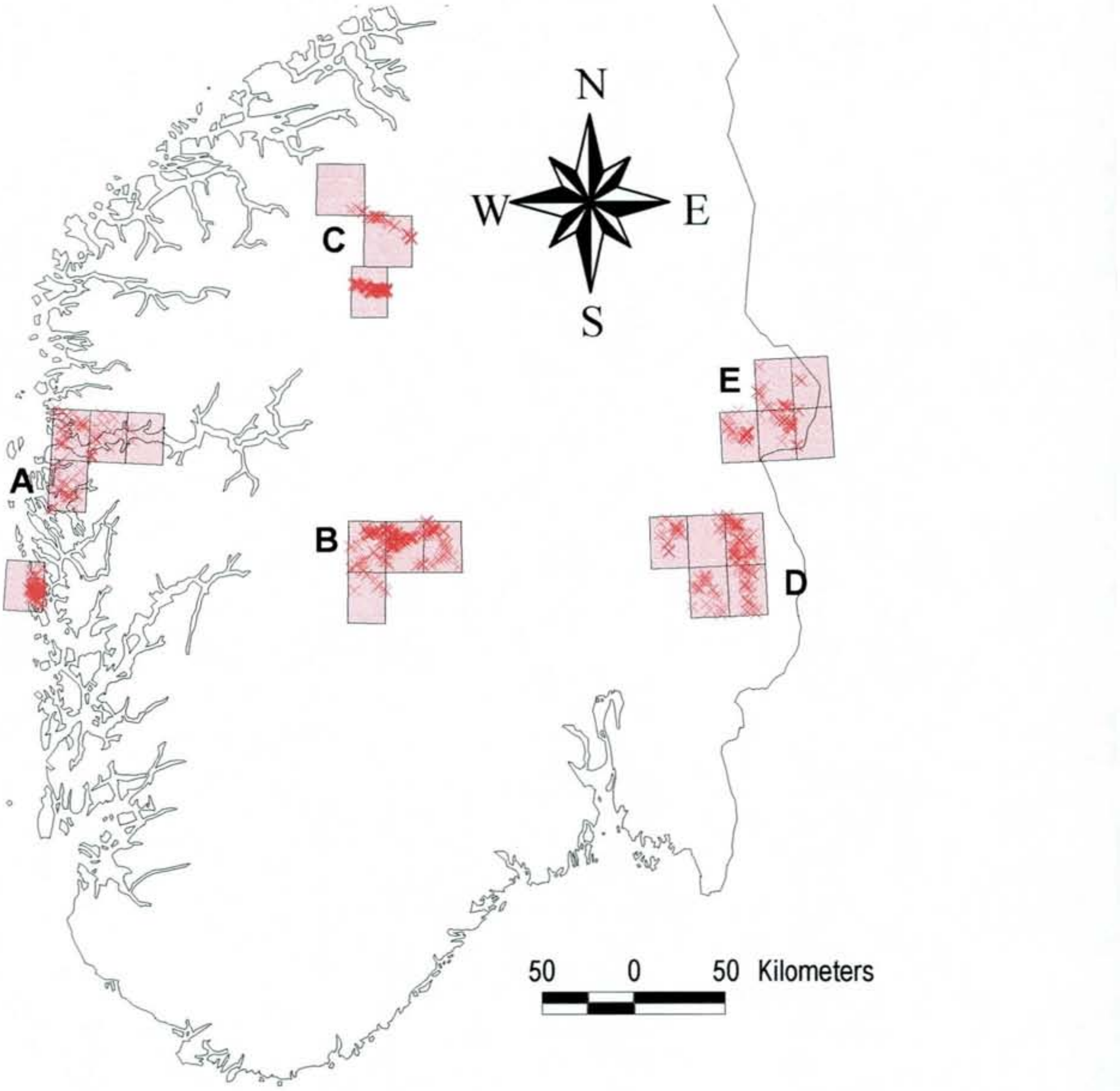


Figure 8.3.1 *A - E represents the five areas investigated by Rohr-Torp (1994). The locations of boreholes extracted from the BBD according to Chapter 3.5 and Figure 1.2.1 are represented with red crosses.*

is mainly due to one of the basic criteria (Chapter 3.4.3) being the existence of borehole coordinates. Rohr-Torp (1994) used all boreholes registered in the BBD, including boreholes without coordinates, but whose location was known to fall within Precambrian rocks of a given map-sheet in the topographic M711 map-series.

Table 8.3.1 *Approximate annual land uplift (mm), number of boreholes and median values of yield (L/h), depth (m) and normalised yield (L/h per drilled metre) of bedrock boreholes located in the five areas used by Rohr-Torp (1994), and compared to his results (2^{nd} sub-columns).*

Area	Approx. Uplift		No. of boreholes		Median yield		Median depth		Median normalised yield	
A	0.5	0.4	224	263	300	250	80.5	81.5	4.2	3.1
B	2.75	3.5	273	454	450	500	56.5	57	8.7	8.8
C	2.5	4	185	197	600	600	49	55	12.2	10.9
D	4.5	5.8	165	239	700	800	59	55	15.0	14.6
E	5	7.5	114	125	950	1000	34	35	31.5	28.6

Figure 8.3.1 shows the location of these map-sheets for the five areas considered. Rohr-Torp (1994) mentions that the selected areas were not ideal in several aspects, but were the only areas containing a sufficient number of boreholes in Precambrian rocks in Norway at the time of the study. Rohr-Torp (1994) chose to use bedrock boreholes in Precambrian areas in order to attain a more uniform set of borehole lithologies than would have been the case if all bedrock boreholes in Norway had been included. He also chose to omit the areas adjacent to the Oslo Region, to preclude possible interference from the intense Permian igneous and tectonic activity in this region. Table 8.3.1 presents further information on the five areas according to the current author's data set, compared with the information published by Rohr-Torp (1994).

Table 8.3.1 reveals that, although the numbers of boreholes used by Rohr-Torp and the current author differ by up to 40%, the median values of yield, depth and

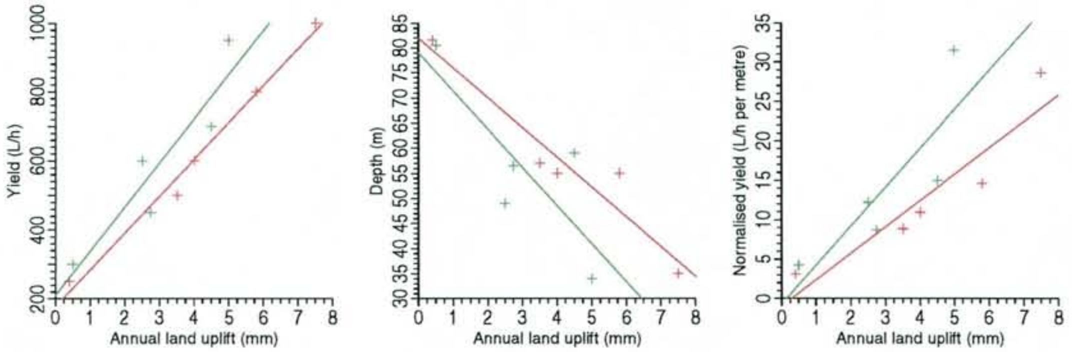


Figure 8.3.2 *Comparison of correlations between the results of this investigation and those of Rohr-Torp (1994). For this study (green crosses and lines) the relevant correlation coefficients (Pearson's r) are: 0.925 (yield), 0.805 (depth) and 0.847 (normalised yield). Standard errors are 109 (yield), 11.6 (depth) and 6.39 (normalised yield). The functions describing the correlation lines are: median yield = (210+128*annual land uplift), median depth = (79-7.6*annual land uplift) and median normalised yield = (-0.726+4.93*annual land uplift). For Rohr-Torp's (1993) study (red crosses and lines) correlation coefficients are: 0.994 (yield), 0.956 (depth) and 0.932 (normalised yield). Standard errors are 36.6 (yield), 5.57 (depth) and 4.01 (normalised yield). The functions describing the correlation lines are median yield = (177+107*annual land uplift), median depth = (81.8-5.93*annual land uplift) and median normalised yield = (-0.974+3.34*annual land uplift).*

normalised yield are quite similar for the two investigations. The major difference lies in the values used for annual land uplift in the five areas. This is due to the use of two different base maps (as described in Chapter 8.2).

Table 8.3.2 *Approximately annual land uplift (mm), number of boreholes and median values of yield (L/h), depth (m) and normalised yield (L/h per drilled metre) of all bedrock boreholes located in Precambrian rocks.*

Approx. uplift	No. of boreholes	Median yield	Median depth	Median normalised yield
0	119	400	57	7.5
0.25	135	480	60	8.7
0.5	1278	300	78	4.2
0.75	491	350	79	4.9
1	184	700	70	10.4
1.25	89	600	71	8.8
1.5	129	500	68	8.3
1.75	91	600	68.5	10.5
2	283	700	62.5	12.0
2.25	256	700	55	13.4
2.5	231	600	49	13.4
2.75	580	500	55.5	10.0
3	726	650	50	14.6
3.25	1363	800	43	19.4
3.5	758	800	45	17.5
3.75	342	600	54	11.4
4	838	600	60	11.5
4.25	458	700	43	16.9
4.5	174	955	50	19.5
4.75	85	900	60	15.4
5	107	900	36	26.3

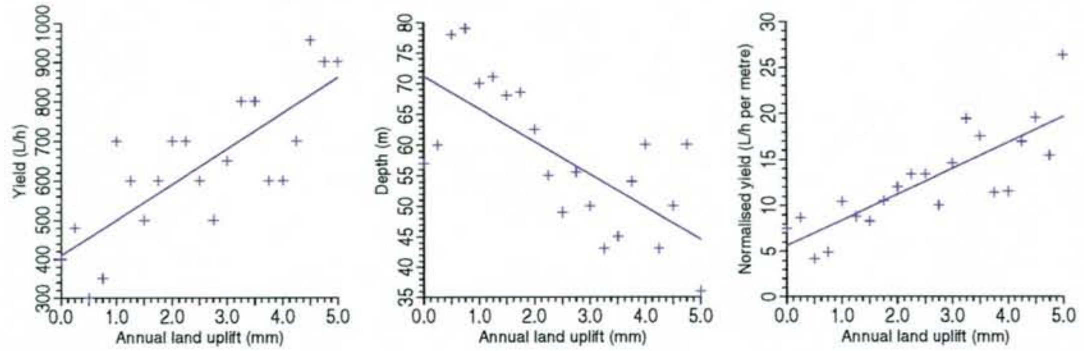


Figure 8.3.3 *Correlation of median borehole characteristics with annual uplift for all bedrock boreholes located in Precambrian rocks. Correlation coefficients are: 0.789 (yield), 0.705 (depth) and 0.822 (normalised yield). Standard errors are: 112 (yield), 8.52 (depth) and 3.1 (normalised yield). The functions describing the correlation lines are: median yield = (409+90.2*annual land uplift), median depth = (71.1-5.32*annual land uplift) and median normalised yield = (5.59+2.8*annual land uplift).*

Figure 8.3.2 shows three diagrams comparing the results described in Table 8.3.1. The results show a significant correlation between annual land uplift and yield, depth and normalised yield, but not as good as the correlation obtained using the median values from Rohr-Torp (1994). The differences are almost entirelly due to the use of other values (Sørensen 1987) for annual land uplift by Rohr-Torp (1994). Diagrams using the same values of annual uplift have almost identical correlation lines.

Rohr-Torp (1994) used only 1,278 bedrock boreholes in Precambrian bedrock in his investigation. A total of 8,726 of the 12,757 bedrock boreholes extracted from the BBD in this study (as described in Chapter 3.5), are located in Precambrian rocks

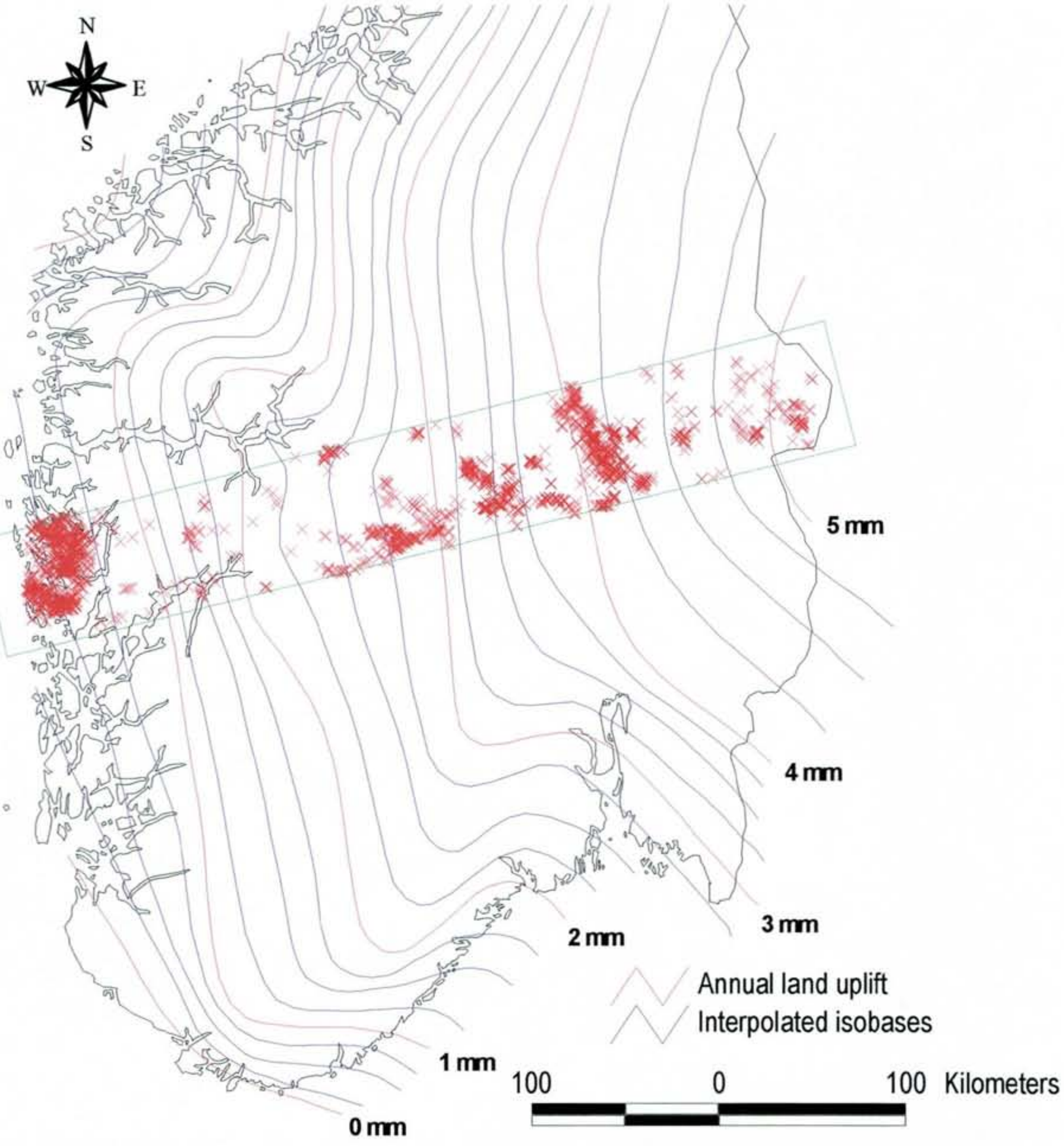


Figure 8.3.4 *Location of boreholes in Precambrian rock within a corridor approximately perpendicular to the uplift isobases through Southern Norway.*

(Rocktype > 78), according to the bedrock map of Norway (Sigmond 1992). Table 8.3.2 shows the number of boreholes associated with each uplift isobase and their median values of yield, depth and normalised yield. The data in Table 8.3.2 are presented graphically in Figure 8.3.3. This figure presents a correlation very similar

Table 8.3.3 *Approximate annual land uplift (mm), number of boreholes and median values of yield (L/h), depth (m) and normalised yield (L/h per drilled metre) of all bedrock boreholes in Precambrian rock located within the corridor defined in Figure 8.3.4.*

Approx. uplift	No. of boreholes	Median yield	Median depth	Median normalised yield
0.5	922	300	79	4.0
0.75	208	250	85	3.2
1	9	250	90	1.7
1.25	6	320	53.5	9.6
1.5	43	450	51.5	10.7
1.75	11	850	60	18.0
2	7	600	66	12.5
2.25	9	1200	39	17.9
2.5	94	700	40	19.7
2.75	181	450	59.5	8.2
3	97	450	52.5	9.5
3.25	82	500	63.5	7.2
3.5	207	800	42.5	16.9
3.75	92	700	61.5	10.4
4	261	600	57	11.0
4.25	324	700	44	17.1
4.5	59	1000	41	21.4
4.75	30	1000	44	31.8
5	105	900	35	29.9

Table 8.3.4 *Approximate annual land uplift (mm), number of boreholes and median values of yield (L/h), depth (m) and normalised yield (L/h per drilled metre) of all bedrock boreholes extracted from the BBD.*

Approx. uplift	No. of boreholes	Median yield	Median depth	Median normalised yield
0	198	400	52.5	7.5
0.25	200	400	60	7.1
0.5	1604	300	75.5	4.0
0.75	605	350	80	4.9
1	199	600	70.5	9.7
1.25	96	575	71.5	7.9
1.5	150	500	68	8.4
1.75	96	600	70	9.4
2	333	600	62	11.3
2.25	365	800	55	14.5
2.5	478	1200	50	25.0
2.75	1067	1000	50	18.2
3	973	600	54	13.1
3.25	1787	800	45	17.8
3.5	1144	800	46	16.7
3.75	614	600	54	11.6
4	1376	750	55	13.4
4.25	726	800	49.5	17.5
4.5	183	900	48	19.6
4.75	85	900	60	15.4
5	118	900	39.5	24.6

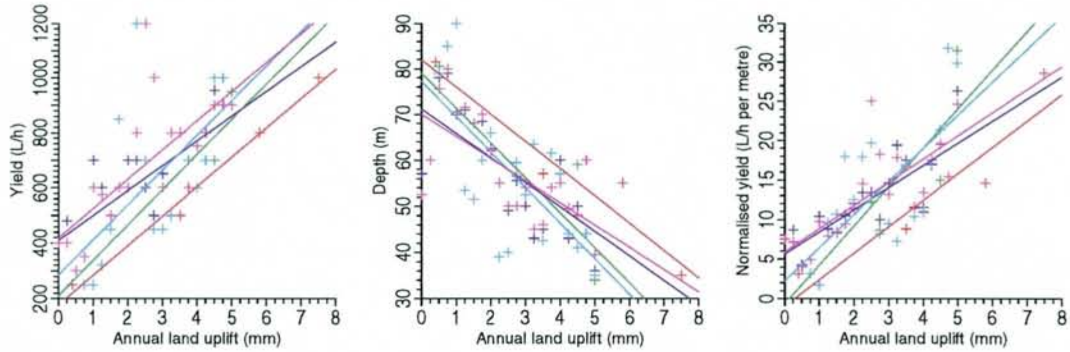


Figure 8.3.5 *Correlation of median borehole characteristics with annual uplift for all bedrock boreholes in Precambrian rocks located within the corridor defined in Figure 8.3.4 (light blue). Correlation of median borehole characteristics with annual uplift for all bedrock boreholes extracted from the BBD (pink). Correlation lines and data points (crosses) from Figures 8.3.2 and 8.3.3 are also shown, using the same colour coding as in these figures.*

*Correlation coefficients for the boreholes in the Precambrian corridor (light blue) are: 0.644 (yield), 0.689 (depth) and 0.714 (normalised yield). Standard errors for the correlation lines are: 217 (yield), 11.7 (depth) and 5.95 (normalised yield). The correlation lines are described by: median yield = (285+127*annual land uplift), median depth = (77.2-7.72*annual land uplift) and median normalised yield = (2.19+4.19*annual land uplift).*

*Correlation coefficients for the entire BBD data set (pink) are: 0.715 (yield), 0.678 (depth) and 0.769 (normalised yield). Standard errors for the pink correlation line are: 166 (yield), 8.32 (depth) and 3.88 (normalised yield). The correlation lines are describing by: median yield = (419+106*annual land uplift), median depth = (70-4.82*annual land uplift) and median normalised yield = (5.88+2.94*annual land uplift).*

to the correlations shown in Figure 8.3.2. The main difference between the two figures is that the gradients of the correlation lines for all parameters are 30% to 40% less than the green correlation lines in Figure 8.3.2. The correlation coefficients for both depth and normalised yield differ by less than 3%, while the correlation coefficient for yield is 24% less than that derived from Figure 8.3.2.

To test this relationship between uplift and yield from bedrock boreholes in Precambrian rocks from another angle, 2,747 bedrock boreholes in a particular geographical corridor (Figure 8.3.4) were selected. This corridor extends from the 5 mm/a isobase approximately perpendicularly through the isobases towards the Bergen area. The boreholes within this corridor correspond to annual land uplift rates of between 0.5 mm and 5 mm. Figure 8.3.4 shows the location of the corridor and the Precambrian bedrock boreholes within it. Table 8.3.3 shows the number of boreholes within each uplift class and their median values of yield, depth and normalised yield. Table 8.3.4 shows the same parameters for all bedrock boreholes (irrespective of lithology) extracted from the BBD according to the criteria defined in Chapter 3.5 The results of Tables 8.3.3 and 8.3.4 are presented graphically in Figure 8.3.5, where the previous results (from Figures 8.3.2 and 8.3.3) are also shown for comparison. The results of Tables 8.3.3 and 8.3.4 for the Precambrian corridor and for the entire data set exhibits the lowest correlation coefficients between yield and uplift of the five investigations described in this Chapter. The functions describing the correlation lines for the Precambrian bedrock boreholes within the corridor (light blue lines) are very similar to those describing the correlation lines for the investigation presented in Figure 3.2.2 (green lines). The functions, describing the correlation lines for all bedrock boreholes located in Precambrian rocks (dark blue lines) are very similar to those for all bedrock boreholes extracted from the BBD (pink lines).

8.4 Discussion

At the outset, the author did not expect to find such a good overall correlation between annual land uplift and median yield, depth and normalised yield of bedrock boreholes. The result is in accordance with the general pattern shown in Figures 6.4.1 and 7.3.1.1. This finding supports the hypothesis of elevated bedrock borehole yields being related to elevated isostatic uplift rates. One may thus speculate that the postglacial isostatic uplift has resulted in the bedrock being more permeable in approximate proportion to the uplift rate. It should also be remembered that "what comes up must have gone down"; i.e. the apparent permeability enchancement could equally be due to the process of isostatic depression during glaciation or be related to stress-induced fracturing or hydraulic fracturing under the ice-sheet itself (Banks et al. 1996). Several periods of glaciation and deglaciation during the Quaternary is, however, believed by the author to be the most important factor for the apparent permeability enchancement.

As mentioned in Chapter 6.4, Talbot et. al (1987) conclude that the most significant hydraulic conductors in parts of Sweden are likely to be sub-horizontal fracture zones within 500 metres of the surface. One possible explanation of the genesis of such sub-horizontal fractures (at least 50-150 m beneath the surface) may be vertical stress-relief (Rohr-Torp 1994). Sweden has generally experienced a larger total isostatic uplift and has thus a larger current annual postglacial isostatic uplift rate than Norway. It may thus be that such sub-horizontal fracture zones occur more frequently in Sweden. Deeper sub-horizontal fracture zones indicate a tectonic origin (Gustafson et al. 1988).

As mentioned in Chapters 6.4 and 8.1, Gustafson (1984) has hypothesised that the joint and fracture systems which we observe today are the result of a large number of tectonic incidents of varying geological age and that the processes of fracture creation and reactivation still continues today. For example, the several periods of glaciation which have taken place in the Quaternary, will have led to the repeated reactivation and formation of fractures. It is possible that this repeated stressing/ stress-relief effect on the bedrock might specifically have induced an increased number of sub-horizontal fractures in areas covered by thick ice-sheets during the Quaternary.

Table 8.4.1 *Recommended expected yield and drilled depth according to the modified "rule of thumb" (based on the idea of Rohr-Torp 1994). Uplift = annual land uplift (mm), yield = calculated median value of yield (L/h) and depth = calculated median value of depth (m).*

Uplift	**Yield**	**Depth**
0	270	74
1	400	67.5
2	530	61
3	660	54.5
4	790	48
5	920	42.5

Nevertheless, there are also other natural physical factors which may result in a similar pattern to that of land uplift (Figure 8.2.1). Such factors potentially include all those that are related to altitude or to proximity from the coast. For example, precipitation (Førland 1993b), its frequency (Førland 1993a) and chemical quality (Rosenqvist 1976), air temperature (Sælthun et al. 1994), river water temperature (Asvall et al. 1994) and groundwater temperature (Kirkhusmo et al. 1988) all tends to have a distribution in Norway similar to that of uplift. The precipitation is, however, generally high over the parts of Norway containing the vast majority of the bedrock boreholes extracted from the BBD (eastern Norway and along the coast). There is thus no indication that lack of precipitation in general may influence the yield of Norwegian bedrock boreholes or that the air, river water and groundwater temperature, also reflecting the duration of the winter period and ground frost, may be of any critical importance for the differences in yield of bedrock boreholes in Norway.

Using the diagrams in Figure 8.3.5, it is possible to suggest a modified "rule of thumb" (based on the idea of Rohr-Torp 1994), which states that for zero annual isostatic uplift a typical bedrock borehole has a median yield of 270 L/h for a borehole depth of around 74 metres. For each one mm increase in annual land uplift, 130 L/h can be added to the median yield at the same time as the depth required to achieve this yield is reduced by 6.5 metres (for examples, see Table 8.4.1). This "rule of thumb" is believed to be valid for annual land uplift rates varying from zero to 5 mm. The main difference from Rohr-Torp (1994) is that this "rule of thumb" includes all rocktypes in Norway!

Chapter 9

Marine Limit and the Yield of Norwegian Bedrock Groundwater Boreholes

9.1 Introduction

The maximum extent of the sea immediately after the ice started to melt is called the Upper Marine Limit (ML). This is, in general, the highest elevation of that marine sediments could have been deposited at following the last glaciation. Deglaciation occurred at differing times along the coast in different areas of Norway. The ML was therefore not established at the same time and level across Norway. The ML may have been established at lower levels relative to the present sea-level inland than closer to the present day coast. This is due to the fact that post-glacial isostatic uplift continued during the progressive deglaciation. The ML in any region is therefore dependent on the history of the deglaciation process in that part of the country.

The ML is presently around 195 m above the present sea level at Minnesund (Selmer-Olsen 1976), 221 m at Aker in the Oslofjord (Thoresen 1990) and around 150 m in the Larvik area (Selmer-Olsen 1976). In eastern parts of the county of Finnmark, near Kirkenes, the ML is approximately 70-80 m above the present sea level, near Tromsø about 50 m, near Trondheimsfjord around 180 m, in the east end of the Hardangerfjord around 120 m. In the coastal areas of Jæren, on the south-western tip of Norway, and Stad, in the western part of the country, the ML is around 20 and 4-5 m above the present sea level respectively (Thoresen 1990).

In some parts of western Norway and the counties of Troms and Finnmark where the isostatic uplift has been relatively modest, incidences of land subsidence caused by the rapid intrusion of the sea have occurred. These incidences took place 4,500 and 6,500 years B.P. and are called tapes-transgressions.

Hagemann (1961) mentions that saline water can be found in bedrock boreholes and springs below the ML. He interprets this as being the result of the influence of marine-deposited clays or ancient sea water in sealed fissures in the rocks penetrated by the borehole. Bryn (1961) suggests that bedrock boreholes containing saline water originating from ancient sea water in sealed fissures may show a decline in salinity during intensive pumping. He suggests furthermore that saline water originating from marine clays does not show this decline in salinity despite intensive pumping.

There have been a number of reports of bedrock boreholes located below the ML yielding saline groundwater. For example, bedrock boreholes in the volcanic rocks of the county of Vestfold were once the main water source for the municipalities of Ramnes and Våle. Problems relating to a high content of salt and fluoride have led to the closure of these waterworks. Several boreholes located close to the present sea level have also had problems concerning saline groundwater. This is however not necessarily related to the location of the borehole below or above the ML. The main reason is often an excessive abstraction rate from bedrock boreholes near the sea. In the municipality of Vikna in the county of Nord-Trøndelag, a municipality consisting of several islands, a total of 20 bedrock boreholes are registered. Eight of these boreholes yield saline water with a composition close to ordinary sea water (NGU 1991).

The author has been unable to trace any scientific investigations on the possible relationship between the groundwater yield of bedrock boreholes and the location of these boreholes above or below the ML. It has been, however, a common belief among Norwegian hydrogeologists that fracture zones tend to have more clay minerals beneath the ML compared to fracture zones above the ML (Rohr-Torp pers. comm.).

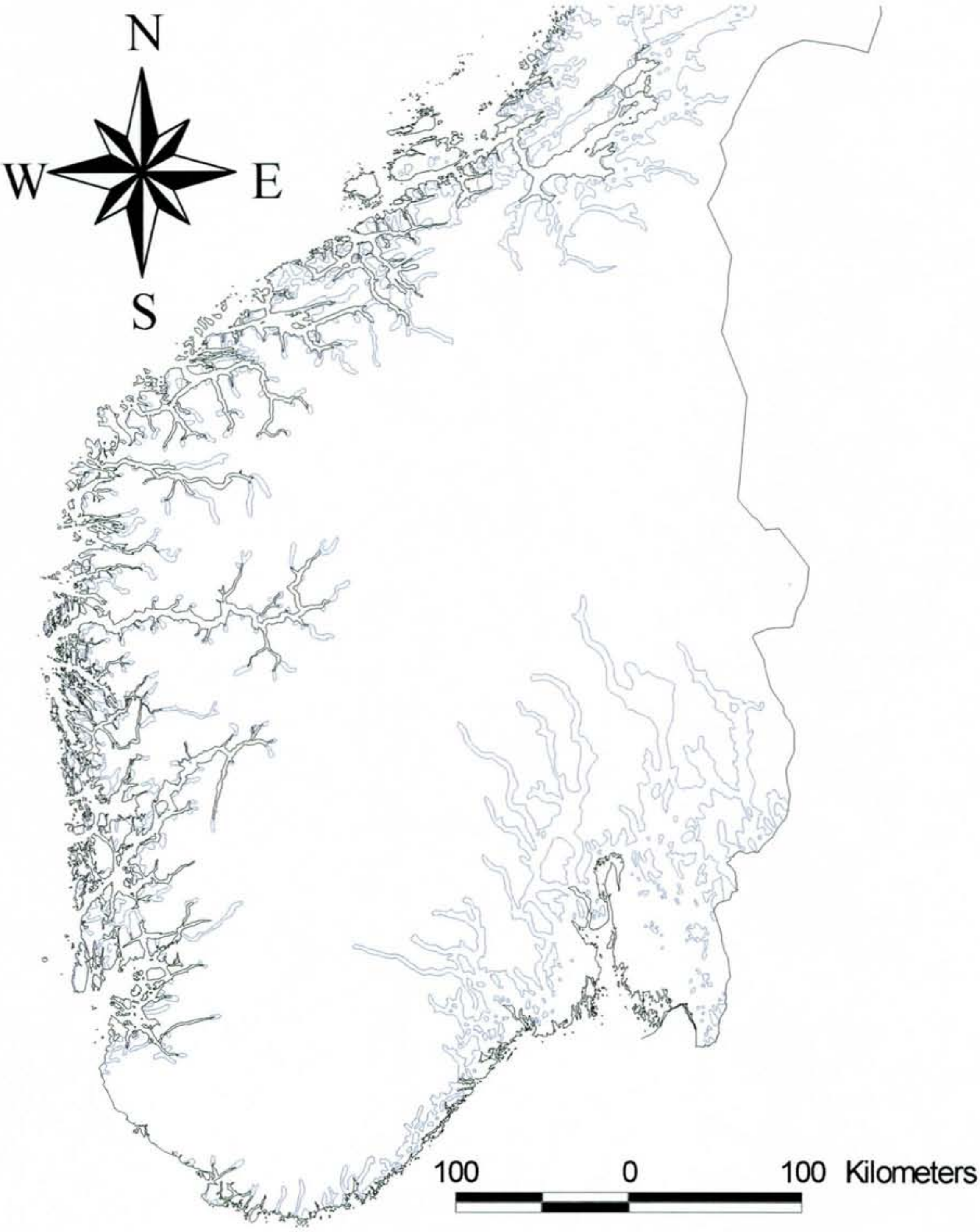


Figure 9.2.1 *Marine Limit (ML) in Southern Norway. The blue lines represents the maximum extend of the ML. In some areas the ML is not possible to separate from the coast. The coast is marked as a black line. The map is derived from Sørensen et al. (1987).*

9.2 Materials and Methods

Figure 9.2.1 shows the location of the ML in Southern Norway. The blue lines represent the location of the ML. The map was digitised at a scale of 1:1,000,000 from the 1:5,000,000 map of Sørensen et al. (1987). Due to the relatively small scale of the original map, the accuracy of the map is to some degree questionable. It was however considered to be of sufficient accuracy for the purpose of comparing the yield of bedrock boreholes above and below the ML.

Each of the 12,757 bedrock boreholes extracted from the BBD (see Chapter 3.4.3 and Figure 1.2.1) were given a representative value according to their location above or below the ML. This is another example of a "non-ideal" data set well suited for use with the exploratory data analysis program DAS. The GIS system ArcView 3.0 was used in the production of the map.

9.3 Results

Almost all the 110 bedrock entities (Chapter 2.3) have a majority of boreholes either above or below the ML, making it difficult to statistically compare bedrock boreholes located below the ML with those above the ML. Only four bedrock entities have a geographical distribution suitable for such a comparison with the number of boreholes in each of these categories exceeding nine bedrock boreholes. The fraction of bedrock boreholes in these entities located below the ML varies from 34% to 67%. More information on the entities is given in Table 9.3.1.

Bedrock boreholes within each entity are divided into two groups depending on whether they are located above or below the ML. Table 9.3.2 presents the median values of depth, yield and normalised yield for these two groups for all bedrock boreholes within the four entities. Figure 9.3.1 presents the depth, yield and normalised yield of all the boreholes as a boxplot in addition to boxplots of the boreholes located above and below the ML within each entity.

Table 9.3.1 *Selected entities used to compare borehole yields in areas above and below the Upper Marine Limit. No = number of boreholes within the bedrock entity, >ML = number of boreholes located in areas above the ML, <ML = number of boreholes located in areas below the ML*

Entity	Rocktype	No	>ML	<ML
776	98	619	409	210
836	54	187	106	81
760	97	52	26	26
1007	98	127	42	85

Table 9.3.2 *Median values of depth (m), yield (L/h) and normalised yield (L/h per drilled metre) for the four selected entities. The bedrock boreholes within each entity are divided into two groups depending on whether they are located below or above the ML.*

	Median depth		Median yield		Median normalised yield	
Entity	Above ML	Below ML	Above ML	Below ML	Above ML	Below ML
760	61,5	74	770	600	13.3	12.6
776	59	56	600	600	11.9	11.3
836	43	54	600	1500	15.2	31.6
1007	58	69	320	300	6.0	4.9

Figure 9.3.1 indicates that one bedrock entity (entity 836) contains boreholes with significant differences between yield, drilled depth and normalised yield above and below the ML. Entity 836 belongs to rocktype 54, the Permian plutonic rocks of the Oslo Rift area.

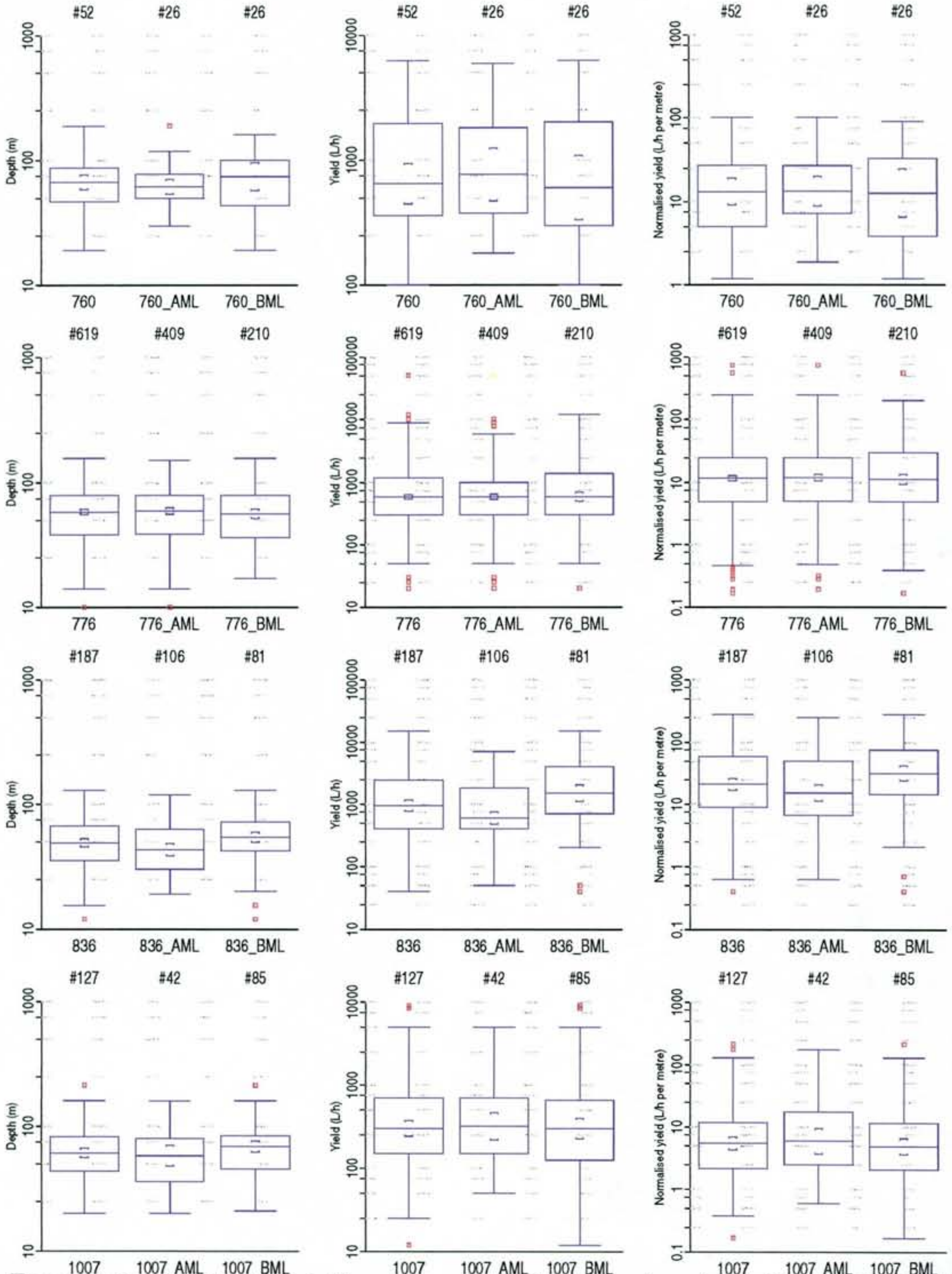


Figure 9.3.1 *Depth, yield and normalised yield as boxplots of boreholes within each entity and box-plots for boreholes located both above and below the ML.*

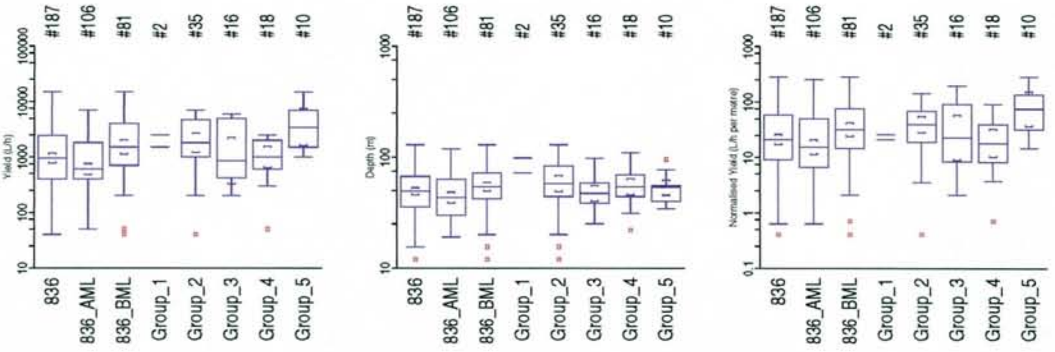


Figure 9.3.2 Depth, yield and normalised yield as boxplots of the five groups of boreholes within entity 836 and boxplots for boreholes located both above and below the ML.

The boreholes within this entity located below the ML are divided into five groups depending on their geographic location. Group 1 contains two boreholes in the northern area of the outcrop of the entity. A closer investigation of the exact location of these boreholes using the 1 : 1,000,000 bedrock map of Norway reveals that these two boreholes are in fact drilled in Cambro-Silurian sediments and not in plutonic rocks.

The bedrock boreholes contained in Group 2 are located in the valley bottom along the main E4 road. The bedrock in this area consists mainly of syenite rocks. Boreholes in Groups 3 and 4 are located in the vicinity of Maridalsvannet and Bogstadvannet, respectively. The bedrock boreholes around Maridalsvannet are predominantly drilled in syenite rocks but the boreholes in the vicinity of Bogstadvannet are located both in the Drammen granite and syenite rocks. Bedrock boreholes in Group 5 are located in the area of Gjelleråsen and are mainly drilled in syenite rocks.

Figure 9.3.2 presents boxplots of these five groups in addition to a box-plot showing all bedrock boreholes located in each entity and boxplots of boreholes located above and below the ML. The boxplot of boreholes in Group 5 shows a significantly higher median normalised yield compared to those in Group 4. This may be due to the proximity of these boreholes to the contact zone between the Permian rocks and the Precambrian basement rocks east of the Oslo Rift.

9.4 Discussion

The results presented in Chapter 9.3 comparing bedrock boreholes located below and above the ML are subject to several sources of error.

Errors in the location of the ML may have been introduced during the digitising process. Given that the base map used for digitising was enlarged from a map at a scale of 1: 5,000,000, the possibility exists for significant errors in the location of the ML. It is not possible to quantify this error but errors occurring during the digitising process at a scale of 1: 1,000,000, are considered to be less than 1,000 meters. If the actual error relating to the location of the ML is of this order of magnitude or larger, then the location of bedrock boreholes above and below the ML can only be approximate.

As mentioned in Chapter 7 the accuracy of bedrock borehole locations is also of great importance. The positional accuracy of bedrock boreholes may be improved by using a Global Positioning System (GPS). Furthermore, borehole yield estimates can also be a source of error due to the possibility of overestimation (see Chapter 3.3).

The results presented in Figure 9.3.1 and 9.3.2 suggest that bedrock boreholes within bedrock entity 836 located below the ML, have a higher normalised yield than boreholes above the ML. Given that the ML is over 200 m above the present sea level in the vicinity of Oslo, this means that the majority of the population lives in low-lying areas or in valleys penetrating into upland areas. Bedrock boreholes located within Groups 2, 3 and 4 are all drilled in such areas. Henriksen (1995) has also found significant differences between bedrock boreholes drilled in valley bottoms and those drilled in valley slopes or on ridges/hills. This may also explain the significantly elevated median of normalised yield in the bedrock boreholes located below the ML compared to those above the ML. The other entities show no significant difference in borehole yields above and below the ML. The data set thus does not allow us to reject the "null hypothesis" of "no significant influence of the marine limit on borehole yield" as a general rule.

This investigation of possible differences between the groundwater yields of bedrock boreholes has highlighted a major problem; in the Oslo area, the majority of the population live in areas below 220 m above the present sea level. This means that the majority of boreholes in this area are located below the ML. It is possible that a thorough investigation in this area, including the accurate location of bedrock boreholes and the ML, may show a statistically significant difference between borehole yields above and below the ML. Considering the very high ML in this area, it would perhaps be an idea to pinpoint areas with a lower ML, for example in the fjords of western Norway, and to consider only bedrock boreholes located in similar geomorphological environments above and below the ML.

In summary, the existing data do not clearly indicate that there is a significant difference between the yields of boreholes drilled above and below the ML.

Chapter 10

Discussion

Over many years (since 1951) NGU has been collecting data on bedrock drinking water boreholes in a database. Recently (1992), NGU became officially responsible for management of information on Norway's bedrock groundwater resources. This responsibility includes ensuring that all bedrock well borers submit information from all newly-drilled drinking water boreholes to NGU. Today the main drinking water resource in Norway is surface water. Only some 150,000 to 300,000 people (3.4% - 6.8% of the population) have their water supply based on groundwater from bedrock boreholes. However, in rural areas this percentage may be as high as 30% (Chapter 3.2). NGU has for some time promoted the use of bedrock boreholes as a safer water supply for the Norwegian population. Presently there exists about 100,000 bedrock drinking water boreholes in Norway. The economic importance of bedrock groundwater is highlighted by the fact that between 3,000 and 4,000 bedrock boreholes are drilled every year at a total annual construction cost exceeding 200 million NOK (353 million ATS) (Chapter 1.1).

At this point the question arises of what a database actually is and what kind of information one wants to extract from it. Up to now, NGU's database could be compared with a stamp collection, where instead of stamps, borehole coordinates, depths and some further data were collected in a computer without considering what these data should be used for and without any quality control. When the author became responsible for the database in 1992, the database thus bore more resemblance to a data graveyard than to a modern database system. To construct a database system that provides useful information, and (hopefully) information that will be cost-effective for society, one has to start working with the data instead of only collecting data. The first step in this thesis was therefore to develop quality control procedures for the old data, that had been entered by different people over more than 40 years.

Checking carefully the existing data in the database showed that there were actually only three types of stored information that really had practical use: coordinates, depth of the borehole and the yield. Thus a thorough review of the existing regional geological, petrological and geochemical knowledge, preferably in digital form or in a form that could easily be digitised and that could thus be linked to the database, was necessary. It was then possible to link additional information, e.g. bedrock lithology, distance to regional lineaments etc. to each borehole, making it possible to commence scientific investigations and develop ideas on the kind of data desirable for a functional, "living" database.

The electronic Bedrock Borehole Database (BBD) at NGU has existed since 1983. The idea was to collect hydrogeologically relevant information from all bedrock boreholes being constructed in Norway. The information from the bedrock well borers has been based on voluntary submission and was completely dependent on an active relationship with those at NGU responsible for the BBD. Since around 1980, cultivating contacts with bedrock well borers has not been prioritised by NGU, and the amount of new bedrock boreholes being reported to the BBD decreased rapidly (see Figure 6.4.3). In 1992, a new paragraph was included in the Watercourses Act stating that everyone who drills for groundwater must provide information to NGU (Ot.prp. nr. 50 1992) (see Chapter 3.1). Since then, NGU has, in co-operation with the bedrock driller branch organisations, tried to introduce this new act. This has not been easy, but today, the majority of borehole drilling companies realise the importance of having a national database of bedrock boreholes containing information about, for example, yield, chemistry, lithology and fracture zones. Publishing of "worked up"-information from the BBD, as presented in this thesis has been one of the major demands from bedrock well borers and the public at large. The implementation of a new and updated BBD (Chapter 3.4) based on "easy to use" graphical interfaces and accessible for both bedrock well borers and the public through the World Wide Web, will mark a new and dynamic era for the BBD.

To prevent errors in the data set being incorporated into the statistical investigations presented here, an pilot quality control procedure was performed on the data set (Chapter 3.5). The possible errors discovered led to the exclusion of more than 15% of the initially extracted boreholes. This demonstrates:

1. The importance of established quality control routines when working with any database.
2. How important it is to understand the possible sources of error connected to any large data set, collected over an extended time frame.

The absolute necessity of objective statistical evaluations of such a database is highlighted by the fact, that even after deleting all bedrock boreholes with none or very low yield (< 10L/h) in the data control procedure, the median yield in several typical lithologies is still considerably lower than what was believed to be the case according to the estimates of hydrogeological experts (Chapter 3.3 - see for example rocktype 80 in Chapter 6.3).

There exist many petrological text-books dealing with theoretical petrology (e.g. Blatt & Tracy 1996, Boggs, S. 1992, Bucher 1994, Cawthorn 1996, Coleman & Wang 1995, Deer, Howie & Zussman 1992, Demaiffe 1996, Guéguen & Palciauskas 1994, Hibbard 1995, Johannes & Holtz 1996, Mason 1990, Miyashiro 1994, Perchuk 1991, Philpotts 1990, Wilson 1989, Yardley 1989). However, to the author's best knowledge, no text-book has yet investigated the influence of petrophysical properties on groundwater yield or quality in crystalline rocks. The only publication the author has been able to identify dealing with the relationship between groundwater yield and different geological properties as rocktype and regional lineaments (Wolfbauer 1996), also lacks information and consideration of the influence of petrophysical properties on groundwater yield. Petrophysical properties such as the rocks' mineral content, composition and grain side, metamorphic facies and history, history of stress inducements, resistance to weathering and mechanical properties as strength and ductility may all have an influence on groundwater yield and/or quality. It is clearly time to initiate studies at these more practical aspects of petrology. A database containing much more information on the petrology of the host rock of a borehole would be of great help in such an undertaking. The complete lack of this information highlights again the importance of a thorough systems analysis before constructing a database.

Water quality in groundwater from bedrock boreholes is an important issue, previously poorly investigated in Norway. The existing boreholes have been drilled without much concern for the possible content of more "esoteric" elements which might have a negative health impact such as Be, F^-, Mo, Rn, Tl, Th and U. All of these may have toxic or carcinogenic effects on humans (Reimann et al. 1996). Petrologists know that these elements are enriched in certain rocks, but they are, however, seldom consulted in questions of surface or Quaternary groundwater supply and thus the geological knowledge was just "forgotten" in the context of bedrock groundwater boreholes. However, groundwater from bedrock boreholes is often considerably enriched with respect to a large number of elements of toxicological importance when compared to surface water or even groundwater from Quaternary deposits (Reimann et al. 1996). For a Geological Survey, being responsible for information on groundwater in a country like Norway (Chapter 3.2), it is of utmost importance to employ, if at all possible, existing information on petrochemistry to predict the element content of groundwater extracted from boreholes in various lithologies (Chapter 4 and 5). In particular, children have a large daily water intake compared to their weight. Society might therefore start to ask unpopular questions if geochemists are not able to apply their accumulated knowledge on mineral deposits, petrology and geochemistry to the prediction of drinking water quality in lithologies where, for example, high U, Th or F^- levels might be expected.

For the reasons mentioned above, groundwater, particularly from bedrock boreholes, should not be presented as a universal panacea for drilling entrepreneurs, house owners, consultant companies and municipalities. Alternative resources to vulnerable Norwegian surface water intakes should be assessed, including high altitude lakes and lower altitude deep lakes with well-defined thermoclines and long residence times in addition to bedrock and drift groundwater. Nevertheless, it would be wrong to place too much emphasis on the negative aspects of groundwater quality. In summary, groundwater from bedrock boreholes can continue to be regarded as a very attractive alternative water resource in many areas. The risk due to elevated concentrations of health-related parameters can be reduced by

- access to a comprehensive database on the occurrence of geochemical parameters in bedrock groundwaters of differing lithologies in order to identify "risk-lithologies".
- the application of analytical programs which include the more important health-related parameters (F^-, Rn, U and Be) that are often not analysed as "standard" by conventional analytical laboratories.
- the willingness to accept and invest in cost-effective water treatment facilities for "problematic" parameters, rather than to expect the "perfect" resource, where no form of treatment is necessary.

To test whether or not there exists statistically significant yield differences in boreholes drilled in different lithologies, it was necessary to link the BBD to a digitised geological map (Chapter 6). Due to no other existing alternative, a digitised geological map derived from a conventional map in the scale 1:3,000,000 was used. This digitised map turned out to maybe have too coarse a resolution for the purpose, although statistically significant, lithology-dependent differences in distributions of borehole yield from different lithologies can still be shown to exist. To be able to gain more knowledge based on the content of the BBD, it is absolutely necessary to use more detailed digitised geological maps (actually, "lithological" maps, which are to date not produced at all, would be best suited for this applied purpose!). A good test area might be the county of Oppland. Although the approach to a possible relationship between yield of bedrock boreholes and location above or below the Upper Marine Limit (ML) is not possible to investigate in this county, Erik Rohr-Torp (Nielsen et al. 1990) has accomplished the most complete survey of existing drilled bedrock boreholes of any county of Norway in Oppland. An investigation should use, for example, large scale satellite images or aerial photos combined with a field investigation to assign bedrock boreholes to different lithological and topographic features, determination of proximity of fracture zones and their origins and investigations of secondary fracture-fill minerals and directions. Sampling of both groundwater and the bedrock itself should be carried out to compare the possible relationship between the element contents of groundwater and bedrock. In co-operation with bedrock well borers operating in Oppland, it will also be possible to sample drilling cuttings and groundwater samples from newly drilled boreholes for comparison. Accurate positioning of bedrock boreholes and fracture zones using GPS is to be preferred.

Most of the studies on bedrock groundwater in Norway have been performed within limited geographical areas using only a few boreholes. The results of this thesis and of, for example, Henriksen (1995) shows the need for large data sets to identify, for example, differences between borehole yields in different lithologies. To be able to gain more knowledge about bedrock groundwater, future projects should be accomplished using a national or regional approach based on a large number of boreholes. In this thesis, the lower limit of the number of boreholes required for meaningful statistical analysis was generally set to ten boreholes within a bedrock entity. Due to the large natural variation in drilled depth, borehole yield and lithologies, the number of bedrock boreholes in future investigations should be considerably larger.

The most important factor hindering acquisition of new knowledge about groundwater in bedrock boreholes in Norway is actually the lack of digitised maps covering the areas where people live and work. To produce geological maps of inhabited areas, is a surprisingly new concept for many Geological Surveys (one suspects the former emphasis on sparsely populated areas may be related to geologists' aesthetic preferences, local politics and, possibly, factors related to travel expenses!). NGU is trying to implement this idea; one of its strategic goals for the years 1998 - 2000 is "to digitise all the bedrock maps in the scale 1:250,000" (NGU 1997). Unfortunately, NGU has, however, no intentions of digitising the bedrock map of Norway in the scale 1:1,000,000.

The relatively poor quality of the data set as well as the poor resolution of the current available digitised information (geology and tectonics) create serious problems in investigating the influence of regional lineaments and the Marine Limit on water yield in bedrock boreholes.

There exists a very interesting, statistically significant correlation between borehole yield and postglacial isostatic rebound (Chapter 8). If this is a causitive relationship related to the degree of actual vertical uplift, loading and unloading stresses, or whether it is related to stresses resulting from friction along the base of moving glaciers and hydraulic fracturing resulting from huge water pressures within inter-ice conduits (Banks et al. 1996), is not known. The correlation is, nevertheless, so strong for all the data sets used in Chapter 8, that an inter-Scandinavian study on the practical application of this theory seems justified (compare Rohr-Torp 1994).

Figure 6.3.5 in Chapter 6 reveals that almost all bedrock entities show a decreasing median normalised yield with increasing depth of the bedrock boreholes. This fact makes it difficult to suggest median values of yield/normalised yield or ranges of such for different rocktypes or entities. Such typical values would, at least have to be standardised for a given borehole depth. The distribution of yield compared to drilling depth seems to be approximately log-normal, and can be observed in Figure 6.3.5 as both a one or a two line logarithmic distribution (e.g. entity 515 and entity 785, respectively). This behaviour of the data set suggests that there exists an optimum depth of drilling in different rocktypes and entities. Almost every bedrock well borer in Norway has adopted the practice of giving a water guarantee to customers. A drilling company being aware of this optimum depth could save considerable amounts of money by stopping a dry borehole once this depth is reached and commencing a new borehole instead of increasing the borehole depth beyond the optimum. The annual total bedrock borehole construction costs in Norway exceed 200 million NOK (353 million ATS). If the results of this thesis or continued research based on the presented ideas can reduce this cost by only 0.3%, this alone will recover the total cost of constructing and running the suggested database.

As shown above, the BBD of NGU cannot function in solitude from other geological information. There exists a clear demand for even more detailed, large scale, digital geological maps (both bedrock and Quaternary geological maps [surficial deposit maps]). It is quite surprising how often a collection of very many completely useless data is named a "database" just because of sheer size. A database should be regarded as a living organism. It needs steady care, use, development and consideration based on a solid system analysis by an expert in the field of the use of the data. A database should not be used for storing away the largest possible amounts of data. Correctly linked with the right kind of other digital data (e.g. geology, lithology, petrology, geochemistry, Quaternary geology), readily available at a modern Geological Survey, and an easy to handle graphical statistical data analysis package, it becomes a very powerful tool indeed. It has been shown in this thesis that the rewards from skilfully using such a tool can be high, both scientifically and in terms of economic savings to society.

Chapter 11

Conclusions

The results of this thesis may be summarised by the following conclusions:

1. All groundwater from newly drilled boreholes should be analysed with respect to their element content. As analyses may be affected by the presence of drilling cuttings (Banks et al. 1993a), analysis should take place after several months of pumping.
2. The results confirm that interesting and statistically significant variations in drilled depth, yield and normalised yield exist between many of the bedrock entities. Moreover, statistically significant differences occur between the yields of many of the 25 rocktypes included in this study, confirming that borehole yield from bedrock boreholes is dependent on lithology.
3. Almost all bedrock entities show a decreasing median normalised yield with increasing depth of the bedrock boreholes. This behaviour of the data set suggests that there exists an optimum depth of drilling in different rocktypes and entities.
4. Using the current BBD it has not been possible to confirm that bedrock boreholes in the vicinity of, or intersecting a fracture zone or lineament have a more favourable potential yield than bedrock boreholes situated in a distance from such a lineament.
5. There is a statistically significant positive correlation between normalised yield of bedrock boreholes and annual isostatic uplift.
6. It has not been possible to statistically confirm or reject a relationship between yield and location of bedrock boreholes in relation to the marine limit.
7. Petrologists, geochemists and hydrogeologists should form joint working groups to present easily understandable information on risk-lithologies

with respect to high element contents of elements with a possible health impact.

8. Petrologists and hydrogeologists should also form joint working groups to study the influence of petrology and petrophysical properties on groundwater yield in different lithologies.
9. In addition to the present project of analysing groundwater samples from c. 2,000 bedrock boreholes throughout Norway, there is a need for a continuous national survey of water quality, in co-operation with, for example, the National Radiation Protection Agency (NRPA), the borehole drilling organisations and municipal health authorities.
10. There is a need to produce digital bedrock maps in the scale of 1:50,000 to 1:250,000. Even a digital version of the bedrock map of Norway in the scale 1:1,000,000 (Sigmond 1984), would be a major advance in the study of drilled depth, yield and hydrochemistry from bedrock boreholes in different lithologies.
11. Future groundwater investigation projects should be accomplished using a national or regional approach based on a large number of boreholes. An thorough investigation in the county of Oppland is perhaps the most effective way to gain more knowledge about groundwater in crystalline rocks in Norway.
12. Cost savings due to more knowledge about lithologies and groundwater quality, even in the order of only less than one percent, will result in a considerable social-economic saving, exceeding the expense of having the BBD at NGU. This is very much in line with NGU's motto "Geology for society"!

Chapter 12

References

Ahlbom, K., Andersson, J.-E., Nordqvist, R., Ljunggren, C., Tirén, S. & Voss, C. (1991): Fjällveden study site. Scope of activities and main results. SKB TR 91-52, Stockholm.

Åkerblom, G. & Lindgren, J. (1996): Mapping of ground water radon potential. Proc. IAEA Tech. Committee Meeting "The advantages and pitfalls of using uranium exploration data and techniques as well as other methods for the preparation of radioelement and radon maps for baseline information in environmental studies and monitoring". Vienna, May 1996.

Albu, M., Nash, H. & Banks, D. (1997): Mineral and Thermal Groundwater Resources. Chapman and Hall (in press).

Ali, A. (1994): Application of a Geographic Information System (GIS) for evaluation of groundwater pollution potential using DRASTIC; an empirical assessment methodology. Masters Thesis at Murray State University, United States, 110 pp.

Andresen, A. (1994): En kort oversikt over hovedtrekkene i Norges berggrunn [A brief description of the main aspects of the bedrock geology of Norway - in Norwegian]. Unpublished. Inst. of Geology, University of Oslo, 56 pp.

Asikainen, M. & Kahlos, H. (1979): Anomalously high concentrations of uranium, radium and radon in water from drilled boreholes in the Helsinki region. Geochimica et Cosmochimica Acta 43, 1681-1686.

Asvall, R.P & Tvede, A.M. (1994): Water Temperature Regimes in Norwegian Rivers. In "Nordic Hydrological Conference 1994" (eds. C. Kern-Hansen, D. Rosbjerg & R. Thompsen). NHP-report 34, 131-139.

Aune, B., Det norske meteorologiske institutt (1993): Årstemperatur 1 : 2 mill. [Annual temperature]. Nasjonalatlas for Norge, kartblad 3.1.5, Statens kartverk.

Banks, D. (1992): Boring og prøvepumping av hydrogeologiske testhull i en grønnstein akvifer - Østmarkneset, Trondheim. Med appendiks om kapasitetstesting av borehull i fjell [Drilling and test pumping of hydrogeological boreholes in a greenstone aquifer - Østmarkneset, Trondheim. Including appnedices on capacity testing of boreholes in bedrock - in Norwegian]. Norges geologiske undersøkelse report 91.213, 107 pp.

Banks, D. (in.prep.): Hydrochemical variation in groundwaters of the Millstone Grit and Coal Measures aquifers of South Yorkshire and North Derbyshire. Submitted to Quarterly Journal of Engineering Geology.

Banks, D. (1997): Predicting the probability distribution of yield from multiple boreholes in crystalline bedrock. Submitted to Ground Water.

Banks, D., Hall, G., Reimann, C., Siewers, U. (in prep.): Distribution of Rare Earth Elements, Yttrium and Scandium in Crystalline Bedrock Groundwaters: - Oslo and Bergen Regions, Norway. Submitted to Applied Geochemistry.

Banks, D., Solbjørg, M.L. & Rohr-Torp, E. (1992a): Permeability of fracture zones in a Precambrian granite. Quarterly Journal of Engineering Geology, London 25, 377-388.

Banks, D., Rohr-Torp, E. & Skarphagen, H. (1992b): An integrated study of a Precambrian granite aquifer, Hvaler, Southeastern Norway. Norges geologiske undersøkelse 422, 47-66.

Banks, D., Rohr-Torp, E., & Skarphagen, H. (1993a): Groundwater chemistry in a Precambrian granite island aquifer, Hvaler, Southeastern Norway. In S.B. Banks & D. Banks (eds.), Hydrogeology of Hard Rocks. Mem. XXIV Congress of the International Association of Hydrogeologists, Ås, Oslo, Norway (1993), 395-406.

Banks, D., Rohr-Torp, E. & Skarphagen, H. (1993b): Groundwater resources in hard rock; experiences from the Hvaler study, Southeastern Norway. In S.B. Banks & D. Banks (eds.), Hydrogeology of Hard Rocks. Mem. XXIV Congress of the International Association of Hydrogeologists, Ås, Oslo, Norway (1993), 39-51.

Banks, D., Rohr-Torp, E. & Skarphagen, H. (1994): Groundwater resources in hard rock; experiences from the Hvaler study, Southeastern Norway. Applied Hydrogeology, 2, No. 2/94, 33-42.

Banks, D., Reimann, C., Røyset, O., Skarphagen, H. & Sæther, O.M. (1995a): Natural concentrations of major and trace elements in some Norwegian bedrock groundwaters. Applied Geochemistry 10, 1-16.

Banks, D., Røyset, O., Strand, T. & Skarphagen, H. (1995b): Radioelement concentrations in Norwegian bedrock groundwaters. Environmental Geology, 25, 165-180.

Banks, D., Odling, N.E., Skarphagen, H. & Rohr-Torp, E. (1996): Permeability and stress in crystalline rocks. Terra Nova 8, 223-235.

Banks, D., Reimann, C., Skarphagen, H. & Watkins, D. (1997): The comparative hydrogeochemistry of two granitic island aquifers: the Isles of Scilly, UK and the Hvaler Islands, Norway. Norges geologiske undersøkelse report 97.xxx (in prep.)

Barnes, A.J. (1986): Water pollution control; national primary drinking water regulations; radionuclides. U.S. Federal Register, 51/189, 30/9/86, 34836-34862.

Bjorvatn, K. (1996): Fluor og radon i grunnvann. Helsemessige implikasjoner [Fluoride and radon in groundwater. Implications for health - in Norwegian]. Lecture at the seminar "Drinking water research towards the year 2000", Norwegian Research Council, Bergen 5/9/96.

Bjorvatn, K., Thorkildsen, A.H. & Holteberg, S. (1992): Sesonmessige variasjoner i fluoridinnholdet i sør og vestnorsk grunnvann. [Seasonal variations of the fluoride content in south and west Norwegian groundwaters - in Norwegian]. Den norske Tannlegeforenings Tidende 102, 128-133.

Bjorvatn, K., Bårdsen, A., Thorkildsen, A.H. & Sand, K. (1994): Fluorid i norsk grunnvann - en ukjent helsefactor. [Fluoride in Norwegian groundwater - an unknown health factor - in Norwegian]. Vann 2/94, 120-128.

Bjorvatn, K., Bårdsen, A., Reimann, C., Morland, G., Skarphagen, H., Sæther, O., Siewers, U., Hall, G., Strand, T. (1997): Grunnvann og helse [Groundwater and health - in Norwegian]. Tidsskrift for den Norske Lægeforening 1, 61-65.

Black, J.H. (1987): Flow and flow mechanisms in crystalline rock. In: Goff, J.C. and B.P.J. Williams (eds.). Fluid Flow in Sedimentary Basins and Aquifers. Geological Society Special Publication No. 34, 185-199.

Blatt, H. & Tracy, R.J. (1996): Petrology : igneous, sedimentary, and metamorphic. Freeman, New York, 529 pp.

Blés, J.L. & Feuga, B. (1986): The fracture of Rocks. North Oxford Academic Publishers Ltd., 132 pp.

Boeckh, E. (1992): An exploration strategy for higher-yield boreholes in the West African crystalline basement. In: Wright, E.P. & Burgess, W.G. (eds.) 1992, Hydrogeology of Crystalline Basement Aquifers in Africa, Geological Society Special Publication No. 66, 87-100.

Boggs, S. (1992): Petrology of sedimentary rocks. Macmillan, New York, 707 pp.

Boox, C. (1995a): Orienterande undersökning av effekten av vattenbehandlings-utrustning på radonhalten i från borrade brunnar [Preliminary assessment of the effectiveness of water-treatment equipment for radon in bedrock boreholes - in Swedish]. Statens Strålskyddsinstitut report 95-14, Stockholm. 9 pp.

Boox, C. (1995b): Radon i vattnet - olika åtgärder att sänka halterna [Radon in water - various approaches to reduction in concentration - in Swedish]. Borrsvängen, 3/95, 21-24.

Bryn, K.Ø. (1961): Grunnvann øst for Oslo-feltet [Groundwater east of the Oslo Region - in Norwegian]. Norges geologiske undersøkelse 213, 5-19.

Brøgger, W.C. (1933): Om rombeporfyrgangene og de dem ledsagende forkastninger i Oslofeltet [About rhomb porphyry dykes and accompanying faults in the Oslo Region - in Norwegian]. Norges geologiske undersøkelse 139, 51 pp.

Braathen, A. (1996): Bruddsoner og grunnvann i Sunnfjord - prosjektforslag [Faults and groundwater in Sunnfjord - project proposal - in Norwegian]. Norges geologiske undersøkelse, 4 pp.

Buan, J.E. (1983): Vannkvalitet i fjellbrønner i Nord-Trøndelag [Water quality in bedrock boreholes in Nord-Trøndelag - in Norwegian]. Dep of Appl. Geol., The Norwegian Institute of Technology (NTH), Trondheim, 97 pp.

Bucher, K. (1994): Petrogenesis of metamorphic rocks. Complete revision of Winkler's textbook. Springer, Berlin, 318 pp.

Bøe, R. & Bjerkli, K. (1989): Mesozoic sedimentary rocks in Edøyfjorden and Beitstadfjorden, central Norway: Implications for the structural history of the Møre-Trøndelag fault zone. Marine Geology, 87, 287-299.

Bårdsen, A., Bjorvatn, K. & Selvig, K.A. (1996): Variability in fluoride content of subsurface water reservoirs. Acta Odontologica Scandinavica 54, 343-347.

Carlsson, L., Winberg, A. & Grundfelt, B. (1983): Model calculations of the groundwater flow at Finnsjn, Fjällveden, Gidea and Kamelunge. SKBF-KBS, Stockholm, Technical Report 83-45, 208 pp.

Carter, G.L. (1991): Hydrogeologic framework of a saprolite-fracture crystalline rock system related statistically and spatially to radon-222 concentrations and borehole yield in Clark and Oconee counties, Georgia. Master's Thesis at Georgia State University, Atlanta, United States. 116 pp.

Clark, L. (1985): Groundwater abstraction from Basement Complex areas of Africa. Quarterly Journal of Engineering Geology 24, 437-451.

Corbett, R.G. & Manner, B.M. (1984): Fluoride in the groundwater of Northeastern Ohio. Ground Water, 22/1, 13-17.

Crawford, M.D., Gardner, M.J. & Morris, J.N. (1971): Changes in water hardness and local death rates. The Lancet, 14/8/71, 327-329.

Crawford, M.D. & Clayton, D.G. (1973): Lead in bones and drinking water in towns with hard and soft water. British Medical Journal 2, 21-23.

Cawthorn, R.G. (1996): Layered intrusions. Elsevier, Amsterdam, 531 pp.

Coleman, R.G. & Wang, X. (1995): Ultrahigh pressure metamorphism. Cambridge University Press, Cambridge, 528 pp.

Daniel, C.C. (1989): Correlation of borehole yield to borehole depth and diameter in fractured crystalline rocks, North Carolina. In "Proceedinds of a conferance on Ground water in the Piedmont of the Eastern United States" (eds. C.C. Daniel, R.K. White & P.A. Stone). Clemson University, South Carolina, United States, 638-653.

Danielsen, J. (1996): Annual uplift in the Ski area. Pers. comm.

Davies, B.E. (1980): Trace element pollution. In B.E. Davies (ed.): Applied soil trace elements. John Wiley & Sons, Chichester, 297-351.

Deer, W.A., Howie, R.A. & Zussman, J. (1992): An introduction to the rock-forming minerals. Longman Scientific & Technical, Harlow, Essex, 696 pp.

Demaiffe, D. (1996): Petrology and geochemistry of magmatic suites of rocks in the continental and oceanic crusts : a volume dedicated to professor Jean Michot. Université Libre de Bruxelles, Bruxelles, 385 pp.

Dobrzhinetskaya, L.F., Nordgulen, Ø., Vetrin, V.R., Cobbing, J. & Sturt, B.A. (1995): Correlation of the Archaean rock between the Sørvaranger area, Norway and the Kola Peninsula, Russia (Baltic Shield). In (eds. D. Roberts & Ø. Nordgulen) 'Geology of the eastern Finnmark - western Kola peninsula region'. NGU Special Publications 7, 7-27.

Dons, J.A. (1978): Terminology and History of Investigations. Norges geologiske undersøkelse 337, 9-16.

Downing, R.A. & Howitt, F. (1969): Saline groundwaters in the Carboniferous rocks of the English East Midlands in relation to geology. Quarterly Journal of Engineering Geology 1, 241-269.

Driscoll, F.G. (1986): Groundwater and Boreholes. Second Edition. Third printing 1989. Johnson Filtration Systems Inc., St. Paul, Minnesota 55112, 1108 pp.

Dutter, R., Leitner,T., Reimann, C. & Wurzer, F. (1992): Grafische und geostatistische Analyse am PC. Beiträge zur Umweltstatistik. Schriftenreihe der Technischen Universität Wien 29, 78-88.

Edmunds, W.M. (1981): Hydrogeochemical investigations. In Lloyd, J.W. (ed.), Case Studies in Groundwater Resources Evaluation, Oxford Science Publications, 87-112.

Ekremsæther, J. (1997): Inaccuracy introduced in the digitising process (pers.comm.)

Ellingsen, K. (1978): Bergen: Beskrivelse til hydrogeologisk kart 1115 I, M.: 1 : 50,000 [Bergen: description to hydrogeological map 1115 I, scale 1 : 50,000 - in Norwegian]. Norges geologiske undersøkelse 342, 44 pp. + map.

Ellingsen, K. (1988): Norsk vannforsyning - Status [Norwegian Water Supply - Status - in Norwegian]. Vann 4/88, 590-596.

Ellingsen, K. (1992): Norske kommuners bruk av grunnvann til vannforsyning [The use of groundwater in Norwegian municipalities - in Norwegian]. Norges geologiske undersøkelse report 91.248, 57 pp.

Ellingsen, K. & Banks, D. (1992): Norway's tonic. World Water & Environmental Engineering Nov. 1992, 31-32.

Enander, L. (1994): Grunnvann fra Gardermoen, ikke et alternativ for Osloregionen [Groundwater from Gardermoen, no alternative to supply the Oslo Region - in Norwegian]. Teknisk Ukeblad, p. 5.

Englund, J.-O. (1966): Grunnvann i Sparagmittgruppens bergarter i Syd-Norge [Groundwater in the Sparagmitegroup bedrocks in southern Norway - in Norwegian]. Norges geologiske undersøkelse 242, 5-18.

Englund, J.-O. & Jørgensen, P. (1980): Weathering and hydrogeology of the Brumunddal Sandstone, Southern Norway. Nordic Hydrology 6, 43-62.

Englund, J.-O. & Myhrstad, J.A. (1980): Groundwater chemistry of some selected areas in southeastern Norway. Nordic Hydrology 11, 33-54.

Fiedler, A.C. (1991): A statistical study of the adequacy of crystalline rock water boreholes of the Colorado Front Range. Master's Thesis at Colorado State University, Fort Collins, United States, 105 pp.

Flaten, T.P. (1991): A nation wide survey of the chemical composition of drinking water in Norway. The Science of the Total Environment 102, 35-71.

Flaa, R.A. (1987): Veiledning i bruk av hydrogeologisk database. EDB-register for borebrønner i fjell [Guidebook to the hydrogeological database. EDB-register for bedrock boreholes - in Norwegian]. Norges geologiske undersøkelse report 87.104, 70 pp.

Fossen, H., Holter, K.G., Hesthammer, J., Mangerud, G., Martinsen, O., Gabrielsen, R.H. (1995): Jurassic Park - nærmere enn vi tror. Problemer i Bjorøytunnelen [Jurassic Park - closer than we imagine. Problems in the Bjorøy tunnel - in Norwegian]. Geonytt 3, 3-6.

Førland, E., Det norske meteorologiske institutt (1993a): Nedbørhyppighet 1 : 7 mill. [Frequency of Precipitation]. Nasjonalatlas for Norge, kartblad 3.1.3, Statens kartverk.

Førland, E., Det norske meteorologiske institutt (1993b): Årsnedbør 1 : 2 mill. [Annual Precipitation]. Nasjonalatlas for Norge, kartblad 3.1.1, Statens kartverk.

Gabrielsen, R.H. and I.B. Ramberg (1979): Fracture patterns in Norway from LANDSAT imagery: Results and potential use. Norwegian Sea Symposium, Proceedings, Norwegian Petroleum Society. NSS/23, 1-28.

Gascoyne, M. & Kamineni, D.C. (1993): The hydrogeochemistry of fractured plutonic rocks in the Canadian shield. In S.B. Banks & D. Banks (eds.), Hydrogeology of Hard Rocks. Mem. XXIV Congress of the International Association of Hydrogeologists, Ås, Oslo, Norway (1993), 440-449.

Gaál, G. & Gorbatschev, R. (1987): An Outline of the Precambrian Evolution of the Baltic Shield. Precambrian Research 35, 15-52.

Gaut, A. (1981): Field relations and petrography of the biotite granites of the Oslo Region. Norges geologiske undersøkelse 367, 39-64.

Gaut, A. (1993): Guide to Field Excursion II: The Oslofjord Area 28. June - 2.. July 1993. International Association of Hydrogeologists XXIVth Congress. 97 pp.

Glattre, E., Askevold, D. & Bay, I.G. (1977): Letter, The Lancet, ii, 12/11/77.

Gorbatschev, R. & Bogdanova, S. (1993): Frontiers in the Baltic Shield. Precambrian Research 64, 3-21.

Goldschmidt, V.M. (1954): Geochemistry. Oxford at the Claredon Press. 730 pp.

Greenbaum, D. (1992a): Structural influences on the occurrence of groundwater i SE Zimbabwe. In: Wright, E.P. & Burgess, W.G. (eds.) 1992, Hydrogeology of Crystalline Basement Aquifers in Africa, Geological Society Special Publication No 66, 77-85.

Greenbaum, D. (1992b): Remote sensing techniques for hydrogeological mapping in semi-arid basement terrains. British Geological Survey, Technical Report WC/92/28.

Griffin, W.L., Austrheim, H., Brastad, K., Bryhni, I, Krill, A.G., Krogh, E.J., Mørk, M.B.E., Qvale, H & Tørudbakken, B. (1985): High-pressure metamorphism in the Scandinavian Caledonides. In Gee, D.G. & Sturt, B.A. (eds.): The Caledonide Orogen - Scandinavia and related areas. Wiley. New York. 783-801.

Grimmer, S.C. (1991): Geochemistry and Petrography of Alkali Volcanics from the Oslo Palaeorift, Norway. Thesis submitted for the degree of Doctor of Philosophy. University of Keele, Great Britain.

Gropen, A.-M. (1996): Fluoridinnholdet i drikkevannet i Akershus [The content of fluoride in drinking water in Akershus - in Norwegian]. Fylkestannlegen i Akershus. 60 pp.

Guéguen, Y. & Palciauskas, V. (1994): Introduction to the physics of rocks. Princeton University Press, Princeton, N.J., 294 pp.

Gustafson, G. (1984): Geohydrologiska förundersökningar i berg [Geo-hydrological pre-investigations in bedrock - in Swedish]. Swedish Rock Engineering Research Foundation. BeFo 84: 1/86, 125 pp.

Gustafson, G. et al. (1984): Mongstad development project. Complementary Report, Fuelstore, 1984.

Gustafson, G. & Krasny, J. (1993): Crystalline rock aquifers: Their occurrence, use and importance. In S.B. Banks & D. Banks (eds.), Hydrogeology of Hard Rocks. Mem. XXIV Congress of the International Association of Hydrogeologists, Ås, Oslo, Norway (1993), 3-20.

Gustafson, G., Stanfors, R., Wikberg, P. (1988): Swedish hard rock laboratory first evaluation of preinvestigations 1986-87 and target area characterisation. Swedish Nuclear Fuel and Waste Management Co., SKB technical report 88-16, 99 pp.

Gustafsson, P. (1993): Satellite Data and GIS as a Tool in Groundwater Exploration in a Semiarid Area. Licentiate Thesis. Department of Geology, Chalmers University of Technology, Publ. A 74.

Gustafsson, P. (1994): Spot Satellite Data for Exploration of Fractured Aquifers in a Semi-Arid Area in Southeastern Botswana. Applied Hydrogeology 2/94, 9-18.

Hagemann, F. (1959): Vannboring i Øst- og Midt-Finnmark [The construction of bedrock boreholes in the eastern and middle areas of Finnmark - in Norwegian]. Norges geologiske undersøkelse 205, 84-89.

Hagemann, F. (1961): Grunnvann i Vestfold [Groundwater in Vestfold - in Norwegian]. Norges geologiske undersøkelse 213, 29-48.

Hagemann, O.Chr. (1989): Rettslige spørsmål knyttet til grunnvann [Legislative questions concerning groundwater - in Norwegian]. Vann 1/90, 15-24.

Hall, G.E.M., Vaive, J.E. and Pelchat, J.C. (1996): Performance of ICP-MS methods used in the determination of trace elements in surface waters in hydrogeochemical surveys. Journal of Analytical Atomic Spectrometry 9, 779-786.

Hausen, H. (1944): Die Bankung als regionale Oberflächenerscheinung in Präkambr. Felsgrund des Schärenhofes im Südwestfinland [The sheet-jointing in Precambrian bedrock in south-western Finland - in German]. Fennia 63, No. 3.

Hellesnes, I. (1995): Ny drikkevannsforskrift. Betydning for næringsmiddelbedrifter. [New drinking water guidelines: significance for the food industry - in Norwegian]. Vann 2/95, 313-319.

Helvey, S.W. & Rauch, H. (1993): The influence of lineaments and hydrogeologic setting on water borehole yield in Greene County, Pennsylvania. Ground Water Management 16, 497-511.

Henriksen, H. & Kyrkjeeide, K. (1993): Regional analysis of data from groundwater boreholes in hard rocks with the aid of statistical significance tests and a geographical information system. In S.B. Banks & D. Banks (eds.), Hydrogeology of Hard Rocks. Mem. XXIV Congress of the International Association of Hydrogeologists, Ås, Oslo, Norway (1993), 1042-1050.

Henriksen, H. (1995): Relation Between Topography and Borehole Yield in Boreholes in Crystalline Rocks, Sogn og Fjordane, Norway. Ground Water 33/4, 635-643.

Hibbard, M.J. (1995): Petrography to petrogenesis. Prentice Hall, New Jersey, 587 pp.

Holmsen, P. (1956): Oppsprekning, topografi og vannføring i massive dypbergarter [Fracturing, topography and capacities in massive plutonic rocks - in Norwegian]. Norges geologiske undersøkelse 195, 37-42.

Huntley, D., Pollack, J., Perce, S.W., McHugh, J.A. (1991): Relations between borehole yield , fracturing, and depth in crystalline rock systems, San Diego County, California. In "Environmental perils; San Diego region" (eds P.L. Abbot & W.J. Elliott), San Diego Assoc. of Geologists, California, United States, 173-178.

Hutton, J. (1970): System of the earth, 1785. Theory of the earth, 1788. Observations on granite, 1794. Together with Playfair's Biography of Hutton / Introd. by Victor A. Eyles. Foreword by George W. White. [Darien, Conn.] :. Hafner Pub. Co., 1970, 203 pp.

IDG Research Services Group (1996): Application Development Tools Brand Preference Study. http://www.oracle.com:80/products/tools/, 6 pp.

ICRP (1993): Protection against radon-222 at home and at work: a report of a task group of the International Commission on Radiological Protection / adopted by the commission in September 1993. International Commission on Radiological Protection Publication 65, Pergamon Press, Oxford, 45 pp.

Ingdahl, S.E. (1985): Stratigraphy, Structural Geology and Metamorphism in the Os Area, Major Bergen Arc. Institute of Geology, Dep. A, University of Bergen. Cand. Real. Thesis, 666 pp.

Jansen, O. (1995): Moments in bedrock drilling in Norway. Pers. comm.

Johannes, W. & Holtz, F. (1996): Petrogenesis and Experimental Petrology of Granitic Rocks. Springer, Berlin, 335 pp.

Kastrinos, J.R. & Wilkinson, B.A. (1994): Geological controls on high-yield bedrock boreholes in Massachusetts. Journal of the New England Water Works Association 108/1, 8-25.

Kinner, N.E., Quern, P.A., Schell, G.S., Lessard, C.E. & Clement, J.A. (1990): Treatment technology for removing radon from small community water supplies. In Cothern CR and Rebers, P. (eds.), Radon, radium and uranium in drinking water. Lewis Publishers, Chelsea, Michigan, 39-50.

Kirkhusmo, L. & Sønsterud, R. (1988): Groundwater temperature in Norway. Map, unpublished.

Klemetsrud, T. (1997): Average construction cost of bedrock boreholes. Pers. comm.

Koenemann, F.H. (1993): Tectonics of the Scandian Orogeny and the Western Gneiss Region in Southern Norway. Geologische Rundschau 82, 696-717.

Kolderup, C.F. & Kolderup, N.H. (1940): Geology of the Bergen Arc System. Bergens Museums Skrifter No. 20, 137 pp.

Krauskopf, K.B. (1979): Introduction to geochemistry. 2nd edn. McGraw-Hill, 617 pp.

Kürzl, H. (1988): Exploratory data analysis: recent advances for the interpretation of geochemical data. Journal of Geochemical Exploration 30/3, 309-322.

Lacey, R.F. (1981): Changes in water hardness and cardiovascular death rates. Water Research Centre (UK), Technical Report TR171, 35 pp.

Larsen, B.T. and Sundvoll, B. (1983): The Oslo Rift, a high-volcanicity continental rift formed from a Hercynian continent-continent collision. IUGG XVIII General Assembly, Hamburg, Program Abstract 2, p. 594.

Larsson, I. (1984): Rock Fractures - a Ground Water Storage. In Hydrology for planning and construction. Bulletin No TRITA-VB-130, The Royal Institute of Technology, Stockholm, Sweden, 22 pp.

Less, C. & Andersen, N. (1993): Hydrofracture - State of the Art in South Africa. In S.B. Banks & D. Banks (eds.), Hydrogeology of Hard Rocks. Mem. XXIV Congress of the International Association of Hydrogeologists, Ås, Oslo, Norway (1993), 717-723.

Lind, B. (1997): Maximum radon concentration analysed in Norway. Pers. comm.

Ljugner, E. (1927): Spaltentektonik und Morphologie der schwedishen Skagerak-Küste, I, II [Fractures and morphology of the Swedish Skagerrak coast - in German]. Bulletin of the Geol. inst., Uppsala, vol. XXI.

Lubin, J.Y., Boice, J.D., Edling, C., Hornung, R.W., Hoew, G., Kunz, E., Kusiak, R.A., Morrison, I., Radford, E.P., Samet, J.M., Tirmarche, M., Woodward, A., Xiang, Y.S. & Pierce, D.A. (1994): Radon and lung cancer - a joint analysis of 11 underground miners' studies. National Institute of Health Publication 94-3644, US Department of Health and Social Services, 136 pp.

Maguire, D.J., Goodchild, M.F. and Rhind, D.W. (1991): Geographical, Technical Information Systems. Principles and Applications. Longman Scientific and Technical UK. 649 + 447 pp.

Mandel, S. (1979): Groundwater Resources. Investigation and Development. Academic Press. 254 pp.

Martinsen, M. (1986): Den permiske metallogenese i Drammensgranitten, Oslofeltet: Mineralogiske, geokjemiske, genetiske og sturkturelle studier [The Permian Metallogenesis of the Drammen Granite in the Oslo Rift area: Mineralogical, geochemical, genetical and structural investigations - in Norwegian]. Dep. of Appl. Geol., Norwegian Institute of Technology (NTH), 202 pp.

Mason, R. (1990): Petrology of the metamorphic rocks. Unwin Hyman, London, 230 pp.

May, F., Hoernes, S. & Neugebauer, H.J. (1993): Origin of mineral waters in the Rheinish Massif; analytical and numerical results. In S.B. Banks & D. Banks (eds.), Hydrogeology of Hard Rocks. Mem. XXIV Congress of the International Association of Hydrogeologists, Ås, Oslo, Norway (1993), 498-506.

McBratney, A.B., Webster, R., McClaren, R.G. & Spiers, R.B. (1982): Regional varaition of extractable copper and cobalt in the topsoil of south-east Scotland. Agronomie 2, 969-982.

McKelvey, J.R. (1994): Application of geomorphic and statistical analysis to site selection criteria for high yield water boreholes in the North Carolina Piedmont. Masters Thesis at the University of North Carolina, United States,

McGrath, S.P. (1987): Computerized quality control, statistics and regional mapping of the concentrations of major and trace elements in the soils of England and Wales.- Soil use and management 3, 31-38.

McGrath, S.P. & Loveland, P.J. (1992): The soil geochemical atlas of England and Wales. Blackie Academic & Professional, London, 101 pp.

Melezhik, V.A., Sturt, B.A., Mokrousov, V.A., Ramsay, D.M., Nilsson, L.P. & Balashov, Y.A. (1995): The Early Proterozoic Pasvik-Pechenga Greenstone Belt: 1:200000 geological map, stratigraphic correlation and revision of stratigraphic nomenclature. In (eds. D. Roberts & Ø. Nordgulen) 'Geology of the eastern Finnmark - western Kola peninsula region'. NGU Special Publications 7, 81-91.

Misund, A. (1997): Results of drilling towards neotectonic zones in the Rana area. Pers. comm.

Miyashiro, A. (1994): Metamorphic petrology. UCL Press, London, 404 pp.

Monroe, J.S. & Wicander, R. (1994): The changing earth, exploring geology and evolution. Minneapolis, West, c1994. 46 pp.

Montgomery, C.W. (1990): Physical geology. 2nd ed. Dubuque, IA : Wm C. Brown Publishers, c1990. 555 pp.

Morland, G. (1988): Hydrogeologiske undersøkelser i Kaldvellafeltet med vekt på grunnvannskjemi [Hydrogeological investigations in the Kaldvella area with special emphasis on groundwater chemistry - in Norwegian]. Dep. of Appl. Geol., Norwegian Institute of Technology (NTH), 94 pp.

Morland, G. (1995): Water quality of waterworks in Norway. Unpublished.

Morland, G. (1996a): Bruk av grunnvann i Norge [Use of groundwater in Norway - in Norwegian]. Norges geologiske undersøkelse report 96.082, 25 pp.

Morland, G. (1996b): Registreringsskjema for borebrønner i løsmasser og fjell [Form for registration of information connected to drilled boreholes in Norway - in Norwegian]. Norges geologiske undersøkelse, 4 pp.

Morland, G., Morland, E., Kirkhusmo, L., Bjerkli, K. (1992): Hydrogeologisk databasesystem ved NGU [Hydrogeological database system at NGU - in Norwegian]. Norges geologiske undersøkelse Internal Report 92.047, 19 pp.

Morland, G., Reimann, C., Skarphagen, H., Bjorvatn, K., Hall, G.E.M., Siewers, U. & Strand, T. (1995): Grunnvannskvalitet i borebrønner i fjell fra områder nær Oslo og Bergen [Groundwater quality in bedrock boreholes in bedrock from areas near Oslo and Bergen - in Norwegian]. Norges geologiske undersøkelse report 95.161, 165 pp.

Morland, G., Strand, T., Furuhaug, L., Skarphagen, H. & Banks, D. (1996): Radon concentrations in groundwater abstracted from Quaternary deposits at major Norwegian waterworks. In preparation for submission to Ground Water.

Mose, D.G., Mushrush, G.W. & Chrosniak, C. (1990): Radioactive hazard of potable water in Virginia and Maryland. Bulletin of Environmental Contamination and Toxicology 44, 508-513.

Myrvang, A. (1996): Kompendium i bergmekanikk [Compendium in rock mechanics - in Norwegian]. Faculty of geology and rock mechanics, Norwegian University of Science and Technology, Trondheim, 226 pp.

Mörner, N.A. (1978): Faulting, fracturing and seismicity as functions of glacio-isostasy in Fennoscandia. Geology 6, 41-45.

Mörner, N.A. (1980): The Fennoscandian uplift: geological data and their geodynamical implication. In Mörner, N.A. (ed.): Earth Rheology, Isostacy and Eustacy, John Wiley & Sons. New York, 251-284.

Nazaroff, W.W., Doyle, S.M., Nero, A.V. & Sextro, R.G. (1988): Radon entry via potable water. In W.W. Nazaroff & A.V. Nero (eds.), Radon and its decay products in indoor air. Wiley and Sons, New York, 131-157.

Neumann, E.-R., Larsen, , B.T. & Sundvoll, B. (1985): Compositional variations among gabbroic intrusions in the Oslo Rift. Lithos 18, 35-59.

Neumann, E.-R., Sundvoll, B. & Øverli, P.E. (1990): A mildly depleted upper mantle beneath southeast Norway: evidence from basalts in the Permo-Carboniferous Oslo Rift. Tectonophysics 178, 89-107.

Nielsen, J.T., Sand, K., Rohr-Torp, E. (1990): Grunnvannskartlegging - metodeutvikling [Mapping of groundwater resources - development of methodology - in Norwegian]. Norges geologiske undersøkelse report 90.138, 50 pp.

Nilsen, R. & Reimann, C. (1996): Geokjemisk atlas over bekkesedimenter i Sør-Norge [A Geochemical Atlas of Stream Sediments in Southern Norway]. Norges geologiske undersøkelse report 96.137, 147 pp.

Njåstad, O., Steinnes, E., Bølviken, B. & Ødegård, M. (1994): Landsomfattende kartlegging av elementsammensetningen i naturlig jord: Resultater fra prøver innsamlet i 1977 og 1985 oppnådd ved ICP emisjonsspektrometri [National survey of the element content in natural soil: Results of samples collected in 1977 and 1985 and analysed by ICP-AAS - in Norwegian]. Norges geologiske undersøkelse report 94.027, 114 pp.

Nordgulen, Ø. (1996): Geochemical atlas of southern Norway. Norges geologiske undersøkelse internal message 11.04.96.

Nordstrom, D.K. & Jenne, E.A. (1977): Fluorite solubility equilibria in selected in selected geothermal waters. Geochimica et Cosmochimica Acta 53, 1727-1740.

NGU (1952): Årsmelding 1951 [Annual Report 1951 - in Norwegian]. Norges geologiske undersøkelse, 71 pp.

NGU (1991): Grunnvannsmuligheter i Norge [Groundwater possibilities in Norway - in Norwegian]. Norges geologiske undersøkelse 107, 20 pp.

NGU (1992): Grunnvann i Norge (GiN) - Sluttrapport [Groundwater in Norway (GiN) - Final report - in Norwegian]. Norges geologiske undersøkelse 111, 35 pp.

NGU (1997): Virksomhetsplan 1997. Handlingsplan 1998-2000 [Activity plan 1997. Strategic plan 1998-2000 - in Norwegian]. Norges geologiske undersøkelse, 22 pp.

Nystuen, J.P., Kirkhusmo, L.A., Naterstad, J. (1993): Excursion No. 1. Geology and Hydrogeology in South Central Norway 3.-5. July 1993. International Association of Hydrogeologists XXIVth Congress. Norges geologiske undersøkelse, 62 pp.

NOU 1994: Lov om vassdrag og grunnvann [Water Resources Act - in Norwegian]. Norges offentlige utredninger 12, 521 pp.

NRPA (1995): Anbefalte tiltaksverdier for radon i bo- og arbeidsmiljø [Recommended action limits in living and working environments - in Norwegian]. Statens Strålevern brochure No. 5, 11 pp.

O'Connor, P.J., Reimann, C. & Kürzl, H. (1988): An application of exploratory data analysis techniques to stream sediment surveys for gold and associated elements in County Donegal, Ireland.- in: MacDonald, D.R. and Mills, K.A.(eds.): Prospecting in areas of glaciated terrain 1988; The Canadian Institute of Mining and Metallurgy, 449-467.

O'Connor, P.J. & Reimann, C. (1993): Multielement regional geochemical reconnaissance as an aid to target selection in Irish Caledonian terrains. Journal of Geochemical Exploration, 47/1-3, 63-89.

Odling, N.E. (1993): An investigation into the permeability of a 2D natural facture pattern. In S.B. Banks & D. Banks (eds.), Hydrogeology of Hard Rocks. Mem. XXIV Congress of the International Association of Hydrogeologists, Ås, Oslo, Norway (1993), 290-300.

Oftedahl, Chr. (1952): Studies on the igneous rock complex of the Oslo Region, XII. The lavas. Skr. Nor. Vidensk.-Akad. Oslo, I: Mat.-Naturv. Kl. 1952, 3, 64 pp.

Oftedahl, Chr. (1953): Studies on the igneous rock complex of the Oslo Region, XIII. The cauldrons. Skr. Nor. Vidensk.-Akad. Oslo, I: Mat.-Naturv. Kl. 1953, 3, 108 pp.

Oftedahl, Chr. (1980): Geology of Norway. Norges geologiske undersøkelse 356, 3-114.

Olesen, O. (1988): The Stuoragurra Fault, evidence of neotectonics in the Precambrian of Finnmark, northern Norway. Norsk Geologisk Tidsskrift 68, 107-118.

Olesen, O., Henkel, H., Lile, O.B., Mauring, E., Rønning, J.S. & Torsvik, T.H. (1992): Neotectonics in the Precambrian of Finnmark, northern Norway. Norsk Geologisk Tidsskrift 72, 301-306.

Olesen, O., Gjelle, S., Henkel, H., Karlsen, T.A., Olsen, L. & Skogseth, T. (1995): Neotectonics in the Ranafjorden area, northern Norway. Norges geologiske undersøkelse 427, 5-8.

Open University (1989): Seawater: its composition, properties and behaviour. Pergamon Press, p. 24.

Ot.prp. nr. 50 (1992): Om endringer i vassdragsreguleringsloven m.fl. [About changes in the Watercourse Regulation Act and other acts - in Norwegian]. Odelstingsproposisjon nr. 50, Stortinget, 101-103.

Ottesen, R.T., Bogen, J., Bølviken, B. & Volden, T. (in prep.): Geokjemisk atlas for Norge [Geochemical atlas of Norway]. Norges geologiske undersøkelse.

Perchuk, L.L. (1991): Progress in metamorphic and magmatic petrology : a memorial volume in honor of D.S. Korzhinskiy. Cambridge university press, Cambridge, 503 pp.

Persson, G., Karrenberg, H., Dubertret, L, Andersen, L.J., Bryn, K.Ø., De Geer, J., Kelstrup, N. & Kirkhusmo, L.A. (1979): Explanatory notes for the hydrogeological map of Europe. Sheet C3, Oslo. International Association of Hydrogeologists. Unesco, Paris. 47 pp.

Persson, G., Kirkhusmo, L.A., Olson, T. & Wikner, T./Persson, G., De Geer, J., Egorov, S.V., Kirkhusmo, L.A., Olsson, T., Panova, Z.P., Taka, M. & Wikner, T. (1985a):): Explanatory notes for the hydrogeological map of Europe. Sheet C2, Trondheim. International Association of Hydrogeologists. Unesco, Paris. 41 pp.

Persson, G., Kirkhusmo, L.A., Olson, T. & Wikner, T./Persson, G., De Geer, J., Egorov, S.V., Kirkhusmo, L.A., Olsson, T., Panova, Z.P., Taka, M. & Wikner, T. (1985b):): Explanatory notes for the hydrogeological map of Europe. Sheet D2, Haparanda. International Association of Hydrogeologists. Unesco, Paris. 67 pp.

Philpotts, A.R. (1990): Principles of igneous and metamorphic petrology. Prentice Hall, Englewood Cliffs, 498 pp.

Ramberg, I.B (1976): Gravity interpretation of the Oslo Graben and associated rocks. In The Oslo Paleorift: A Review and Guide to Excursions (J.A. Dons and B.T. Larsen (Eds.)). Norges geologiske undersøkelse 337, 41-53.

Ramberg, I.B. and Larsen, B.T. (1978): Tectonomagmatic ecolution. In The Oslo Paleorift: A Review and Guide to Excursions (J.A. Dons and B.T. Larsen (Eds.)). Norges geologiske undersøkelse 337, 55-73.

Rekstad, J. (1922): Grunnvatnet [The Groundwater - in Norwegian]. Norges geologiske undersøkelse 92. 30 pp.

Reimann, C. (1989): Reliability of geochemical analyses: recent experiences.- Transactions of the Institution of Mining and Metallurgy, 98, B123-B130.

Reimann, C. (1997): Explanation of the BOXPLOT. Pers. comm.

Reimann, C. and Wurzer, F. (1986): Monitoring accuracy and precision - improvements by introducing robust and resistant statistics. Mikrochimica Acta, 1986 II/1-6, 31-42.

Reimann, C., Hall, G.E.M., Siewers, U., Bjorvatn, K., Morland, G., Skarphagen, H. & Strand, T. (1996): Radon, fluoride and 62 elements as determined by ICP-MS in 145 Norwegian hard rock groundwater samples. The Science of the Total Environment 192, 1-19.

Riis, F. (1996): Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data. Global and Planetary Change 12, 331-357.

Rock, N.M.S. (1988): Numerical Geology. Lecture Notes in Earth Sciences, 18. Springer Verlag, Berlin, 427 pp.

Rock, W.P., Gordon, P.H. & Bradnock, G. (1981): Caries experience in West Midland school children following fluoridation of Birmingham water in 1964. British Dental Journal 150, 269-273.

Rognerud, E. (1973): Utbredelsen av fluor i drikkevannet, sammenholdt med en kariesepidemiologisk undersøkelse av skole-elever i Hurum [The distribution of fluoride in the drinking water compared to a cariesepidemiologic evaluation of pupils in Hurum - in Norwegian]. Munnpleien, 5/6, 98-107.

Rohr-Torp, E. (1987): Drøbak 1814 II: Beskrivelse til hydrogeologisk kart, M: 1:50,000 [Drøbak: description to hydrogeological map 1814 II, scale 1:50,000 - in Norwegian]. Norges geologiske undersøkelse, Skrifter 78, 19 pp. + map.

Rohr-Torp, E. (1994): Present uplift rates and groundwater potential in Norwegian hard rocks. Norges geologiske undersøkelse 426, 47-52.

Rosenqvist, I. Th. (1976): Et bidrag til analyse av geologiske materialers bufferegenskaper mot sterke syrer i nedbørsvann [A contribution to the analysis of buffer characteristics of geological materials against strong acids in precipitation - in Norwegian]. NAVF report, 124 pp.

Rösler, H.J. & Lange, H. (1975): Geochemische Tabellen (2nd edn.) VEB Deutscher Verlag für Grundstoffindustrie, Leipzig, 700 pp.

Sager, K.E.A. (1995): Groundwater flow patterns in the Manotick area; a GIS perspective. Master Thesis at the Carleton Universtity, Ottawa, Canada. 172 pp.

Salonen, L. (1994): ^{238}U series radionuclides as a source of increased radioactivity in groundwater originating from Finnish bedrock. In: "Future Groundwater Resources at Risk", Proc. Helsinki Conf. June 1994, IAHS Publ. 222, 71-84.

Sami, K. (1996): Evaluation of the variations in borehole yield from a fractured Karoo Aquifer, South Africa. Ground Water 34/1, 114-120.

Sander, P., Minor, T.B., Chelsley, M. (1996): Lineament analysis for groundwater assessment in a rural water project in Ghana. In: Sander, P. (1996): Remote sensing and GIS for groundwater assessment in hard rock areas. Doctorate Thesis. Department of Geology, Chalmers University of Technology, Publ. A 80. 23 pp.

Schmitt, T.J. (1989): Intersecting lineaments and water borehole yield in the crystalline rocks of Rabun County, Georgia. In "Geological Society of America, Southeastern Section, 38th annual meeting". Geological Society of America 21/3, p 57 (abstract).

Selmer-Olsen, R. (1976): Ingeniørgeologi. Del I. Generell geologi [Engineering geology. Part I. General geology - in Norwegian]. Tapir, 281 pp.

Shupe, J.L., Arland, E.O. & Sharma, R.P. (1979): Effects of fluorides in domestic and wild animals. In F.W. Oehme (ed.) "Toxicity of heavy metals in the environment - Part 2". Marcel Dekker, New York.

Siedlecka, A., Iversen, E., Krill, A.G., Lieungh, B., Often, M., Sandstad, J.S., Solli, A. (1985): Lithostratigraphy and Correlation of the Archean and Early Proterozoic Rocks of Finnmarksvidda and the Sørvaranger District. Norges geologiske undersøkelse 403, 7-36.

SIFF (1987): G2. Kvalitetsnormer for drikkevann [Quality norms for drinking water - in Norwegian]. Statens institutt for folkehelse, Oslo, 72 pp.

Sigmond, E.M.O. (1992): Bedrock map of Norway and adjacent ocean areas. Scale 1:3 million. Norges geologiske undersøkelse

Sigmond. E.M.O., Gustavson, M., Roberts, D. (1984): Berggrunnskart over Norge [Bedrock map of Norway]. M 1:1 million. Norges geologiske undersøkelse, 31 pp.

Skjelkvåle, B.L., Henriksen, A., Vadset, M. and Røyset, O. (1996): Sporelementer i norske innsjøer - Foreløpig resultat for 473 sjøer [Trace elements in Norwegian lakes - preliminary result from 473 lakes - in Norwegian]. Norsk institutt for vannforskning (NIVA) Rapport 3457-96, Oslo, Norway, 18 pp.

Skjeseth, S. (1952): Vannboringer utført i traktene omkring Mjøsa og Randsfjorden 1950-52 [Construction of bedrock boreholes in the Mjøsa and Randsfjorden areas 1950-52 - in Norwegian]. Norges geologiske undersøkelse 184, 12-22.

Skjeseth, S. (1956): Kambro-silurbergartenes hydrogeologi i Mjøs- traktene [The hydrogeology of the Cambrosilurian bedrock in the Mjøsa area - in Norwegian]. Norges geologiske undersøkelse 195, 15-36.

Smedley, P.L. (1991): The geochemistry of rare earth elements in groundwater from the Carnmenellis area, southwest England. Geochimica et Cosmochimica Acta 55, 2767-2779.

Snekkerbakken, A.M. (1992): Grunnvannsmagasinet på Gardermoen - beregning av kapasitet [The groundwater aquifer at Gardermoen - estimation of yield - in Norwegian]. Vann 1C, 150-157.

Soldal, O. (1993): Hydrogeology of a fjord delta aquifer, with emphasis on saline groundwater, Sunndalsøra, Norway. Dr. Scent. Thesis, Institute of Geology, University of Bergen, 85 pp.

Sosial- og helsedepartementet [Ministry of Health and Social Affairs] (1995): Forskrift om vannforsyning og drikkevann m.m. [Directive on water supply and drinking water - in Norwegian]. Forskrift No. 68 (I-9/95), Oslo, Norway, 38 pp.

Soulios, G., Christaras, B., Kilias, A., Athanasias, S., Christou, O., Kontzoglou, J. (1990): Decrease of the permeability regarding to the depth in crystalline rocks; data from Elassona area (Greece). Bulletin of the International Association of Engineering Geology No. 42, 95-99.

Statens kartverk (1996): Annual land uplift. Map in the scale of 1: 5 mill. Statens kartverk. Not published.

Statens strålskyddsinstitut (1996): Radon i vatten [Radon in water - in Swedish]. Swedish Radiaton Protection Institute report 96-03, 12 pp.

Statistisk sentralbyrå (1980): Maps showing the distribution of the population based on the census in 1980. Scale 1:250,000. Statistisk sentralbyrå, Norway.

Statistisk sentralbyrå (1994): Numbers of people living in urban areas the 1. January 1994. Excel-file received from Statistisk sentralbyrå, Norway.

Statistisk sentralbyrå (1997): Numbers of people living in the municipalities the 1. January 1996. Received from the Internet Server of the Statistisk sentralbyrå, Norway. (http://www.ssb.no/www-open/ukens_statistikk/utg/9708/1-3t.txt).

Steel, R, Siedlecka, A., Roberts, D. (1985): The Old Red Sandstone basins of Norway and their deformation: a review. In Gee, D.G. & Sturt, B.A. (eds.): The Caledonide Orogen - Scandinavia and related areas. Wiley. New York. 293-315.

Stordrange, B. (1988): Rettslige og rettspolitiske aspekter ved utnytting av grunnvann [Juridical and Political Aspects concerning the exploitation of groundwater - in Norwegian]. Lov og Rett, 391-420.

Strand, T. (1996): Results of radon analysis in the counties of Sør- and Nord-Trøndelag. Pers. comm.

Strand, T. & Kulling, O. 1972: Scandinavian Caledonides. A volume in the Regional Geology Series edited by L. U. De Sitter. Wiley - Interscience, 302 pp.

Strand, T. & Lind, B. (1992): Radon in tap water from drilled boreholes in Norway. Proc. Intnl. Symp. On Radon and Radon Reduction Technology, 22-25/9/92, Minneapolis, USA.

Stumpfl, E.F. & Sturt, B.A. (1964): A preliminary account of the geochemistry and ore mineral parageneses of some Caledonian basic igneous rocks from Sørøy, northern Norway. Norges geologiske undersøkelse 234, 196-230.

Sturt, B.A., Skarpenes, O., Ohanian, A.T. & Pringle, I.R. (1975): Reconnaissance Rb/Sr isichron study in the Bergen Arc System and regional implications. Nature 253, 595-599.

Sturt, B.A. & Thon, A. (1978): Caledonides of Southern Norway. Geol. Surv. of Canada, IGCP Project 27, 39-47.

Sveriges nationalatlas (1994): Berg och jord [Rock and Soil - in Swedish]. Sveriges nationalatlas. 208 pp.

Swedjemark, G.A. (1993): Radon och radium i vatten. Underlag för bestämmelser [Radon and radium in water. Basis for directives - in Swedish]. Statens Strålskyddsinstitut report 93-34, Stockholm, 10 pp.

Sælthun, N.R., Bergström, S., Einarsson, K., Thomsen, T., Vehviläinen, B. (1994): Simulation of Climate Change Impact on Runoff in the Nordic Countries. Part B - Climate and Runoff Scenarios. In "Nordic Hydrological Conference 1994" (eds. C. Kern-Hansen, D. Rosbjerg & R. Thompsen). NHP-report no. 34, 13-25.

Sæther, O.M., Reimann, C., Hilmo, B.O., Taushani, E. (1995): Chemical composition of hard- and softrock groundwaters from central Norway with special consideration of fluoride and Norwegian drinking-water limits. Environmental geology 26/3, 147-156.

Sørensen, R, Bakkelid, S. & Torp, B. (1987): Landhevning. Nasjonalatlas for Norge. Hovedtema 2: Landformer, berggrunn og løsmasser. Kartblad 2.3.3 [Land uplift. National atlas of Norway. Main theme 2: Morphology, bedrock and superficial deposits. Map No. 2.3.3]. Map - 1: 5,000,000. Statens kartverk.

Talbot, C., Riad, L. (1987): Natural fractures in the Simevarp area. Swedish Nuclear Fuel and Waste Management Co., Project Report 25-87-03.

Thon, A. (1984): The Gulfjellet Ophiolite Complex and the Structural Evolution of the Bergen Arcs, West Norwegian Caledonides. In Gee, D.G. & Sturt, B.A. (eds.): The Caledonide Orogen - Scandinavia and related areas. Wiley. New York. 671-677.

Thoresen, M. (1990): Kvartærgeologisk kart over Norge. Tema: Jordarter [Quaternary map of Norway. Theme: Surficial deposits - in Norwegian]. Map M. 1:1 million with description. Norges geologiske undersøkelse, 64 pp.

Trønnes, R. & Brandon, A.D. (1992): Mildly peraluminous high-silica granites in a continental rift: the Drammen and Finnemarka batholiths, Oslo Rift, Norway. Contributions to Mineralogy and Petrology 109, 275-294.

Tukey J.W. (1977): Exploratory Data Analysis. Addison-Wesley, Reading, 506 pp.

Uhl, Jr. V.M. & Sharma, G.K. (1978): Results of Pumping Tests in Crystalline-Rock Aquifers. Ground Water 16/3, 192-203.

UNSCEAR (1993): Sources and effects of ionizing radiation. 1993 report to the General Assembly, with scientific annexes. Annex A - exposures from natural sources of radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, United Nations, New York. 922 pp.

UNSCEAR (1994): Sources and effects of ionizing radiation. 1994 report to the General Assembly, with scientific annexes. Annex A - epidemiological studies of radiation carcinogenesis. United Nations Scientific Committee on the Effects of Atomic Radiation, United Nations, New York, 11-184.

Velleman, P.F and Hoaglin, D.C. (1981): Applications, basics and computing of Exploratory Data Analysis. Duxbury Press, Boston, Mass., 354 pp.

Vogt, J.H.L. (1897): Granitens og svenitens Baenkning i Forhold til den nuvaerende overflade [The sheet-jointing of granite and svenite compared to the surface - in Swedish]. Geologiska Föreningens i Stockholm Förhandlingar, Bd IV, 439-446.

Vortisch, W., McMinn, J., Lindström, M. & Starke, K. (1983): Arsenic enrichment at the Cambro-Ordovician boundary in south Sweden. Geologiska Föreningens i Stockholm förhandlingar, 104, 3, 211-218.

Wallace, J.Y. (1996): Statistical analysis of data from water supply boreholes in Orange County, NC. Bachelor's Thesis at the University of North Carolina, United States, 38 pp.

WHO (1996): Indoor air quality: a risk-based approach to health criteria to radon indoors. World Health Organisation, Regional Office for Europe, Report EUR/ICP/CEH 108(A).

Wikberg, P (ed.), Gustafson, G., Rhén, I. & Stanfors, R. (1991): Äspö Hard Rodk Laboratory Evaluation and conceptual modelling baseed on pre-investigations 1986-1990. SKB Technical Report 91-22, Stockholm.

Wilson, M. (1989): Igneous petrogenesis. Unwin Hyman, London, 466 pp.

Wladis, D. & Rosenbaum, M.S. (1994): Remotely sensed data allowing a multi-indicator approach to groundwater assessment. In "Nordic Hydrological Conference 1994" (eds. C. Kern-Hansen, D. Rosbjerg & R. Thompsen). NHP-report no. 34, 99-112.

Wolfbauer, J. (1996): Erforschung und Bewertung des Grundwasserpotentials im Kristallin der Böhmischen Masse in Oberösterreich [Investigation of different aspects connected to groundwater potential in crystalline rocks in the Bohemian Massif - In German]. Abteilung für Technische Ökosystemanalyse, Montanuniversität Leoben, Austria. Technical Report OA26/95, 46 pp.

Yardley, B. W. D. (1989): An introduction to metamorphic petrology. Longman Scientific & Technical, Harlow, Essex, 248 pp.

Yin, Z.-Y. & Brook, G.A. (1992): The Topographic Approach to Locating High-Yield Boreholes in Crystalline Rocks: Does It Work? Ground Water 30/1, 96-102.

Zewe, B.T. & Rauch, H.W. (1991): Influence of hydrogeologic setting and lineaments on water-borehole yield in the Great Valley karst terrane of eastern West Virginia. In "Appalachian karst" (eds. E.H. & K.M. Kastning), National Speleological Society, Huntsville, United States, 223-230.