

Fracture lineaments and their surroundings with respect to groundwater flow in the bedrock of Sunnfjord, Western Norway

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Assumptions about groundwater flow based on observations from single-well test sites and a multi-well test site were evaluated by statistical methods on a regional data set of borehole flow rates and ground checked, remotely sensed lineaments. The analysis shows that the influence area of lineaments is characterised by a three-partite flow zonation which mirrors that of the hydromechanical fault zone architecture. This flow rate zonation indicates important guide-lines for the siting of water wells in lineaments. But borehole flow rates in the most permeable zone, i.e. the damage zone of the lineaments, cannot be distinguished statistically from borehole flow rates in the less fractured background area. Contrary to the field site results, critically stressed lineaments in the current stress field are statistically equivalent to other lineament directions with respect to groundwater flow. This may relate to topographic perturbations of the regional WNW-ESE stress field, which reorient the maximum compressive stress σ_H into parallelism with fjord- and valley sides in this region. The statistical analyses, which show that topography is the most important explanatory variable for the observed variations in borehole flow rates, support this view.

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Introduction

Groundwater flow in crystalline rocks with no intergranular porosity takes place in a connected fracture network. But far from all fractures are permeable, and fracture permeability varies considerably (Banks et al. 1996). Research conducted at small test sites suggests that fault and fracture zone architecture, fracture orientation, and in situ rock stresses are important in controlling fracture permeability. It is generally recognized that, in the influence area of faults and fracture lineaments, the fault core and central zone have low permeability while the outer damage zone has enhanced permeability compared with the surroundings (Caine et al. 1996; Evans et al. 1997; Henriksen & Braathen 2006). In relation to stresses, fractures most likely to experience enhanced permeability are those parallel to the greatest compressive stress (σ_H) and those prone to reactivation as shear fractures at angles around 30° to σ_H (e.g. Barton et al. 1995; Ferrill et al. 1999; Henriksen & Braathen 2006).

The object of this paper is to examine if the relations referred to above are transferable to groundwater flow on a wider field scale, in an area of ca. 4 000 km². The paper builds upon the results and conceptual framework presented by Braathen et al. (1999) and Henriksen & Braathen (2006). In these works, detailed field mapping (Braathen et al. 1999) shows that the fracture lineaments in the study area are up to 5- 600 m wide deformation zones that consist of an innermost central part (0-40 m wide), followed by a proximal (= marginal) zone (10-50 m wide on either side)

which grades into a distal zone (up to 200 m wide on either side). Together, the proximal and distal zones correspond to the damage zone of Caine et al. (1996). Geophysical logging and test pumping of 5 boreholes across selected lineaments showed that the marginal zone had an enhanced permeability associated with a high fracture frequency of dominantly lineament-subparallel fractures with good connectivity and negligible fracture fillings (Braathen et al. 1999; Henriksen & Braathen 2006). Test pumping and geophysical logging at a field site in Holmedal indicate that outside the influence areas and in the distal zones of lineaments, groundwater flow mainly takes place along fractures prone to reactivation in the in situ stress field (Henriksen & Braathen 2006).

The basis for this follow up work is a high quality database of 697 bedrock boreholes. The database has been integrated in a GIS with other parameters considered important for groundwater flow in hard rocks, e.g. lithology, lineaments, geomorphology and groundwater recharge. The influence of the structural factors and the contemporary stress field, but also other factors considered of importance for groundwater flow in this region, are analysed by statistical methods.

Geology and hydrogeology

The study area lies within the Caledonides of western coastal Norway (Fig. 1). Here, Precambrian gneisses of

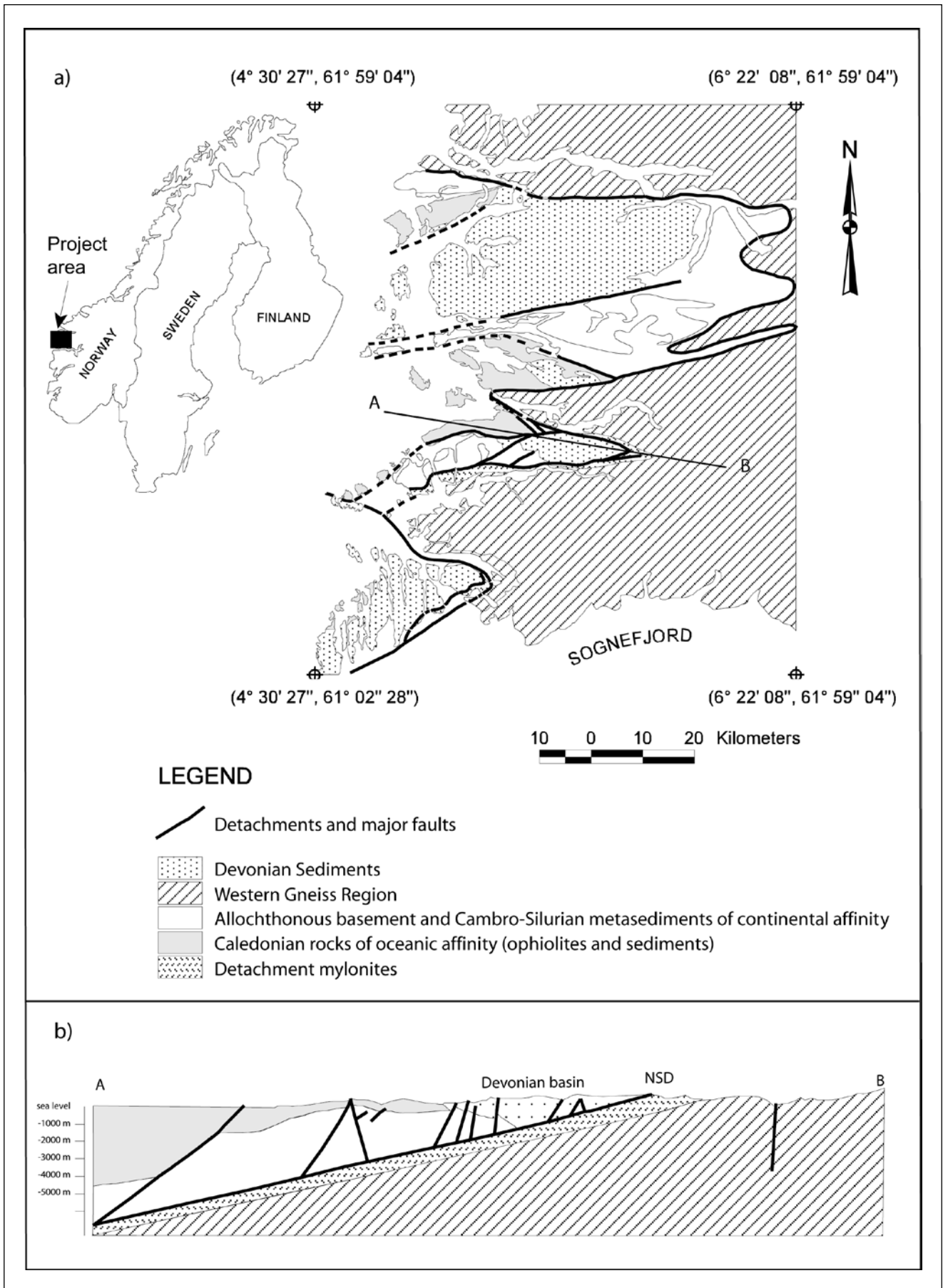


Fig. 1. (a) Simplified geological map of the Sunnfjord area, modified from Osmundsen & Andersen (1994). (b) Profile modified from Osmundsen (1996) and Braathen et al. (2004). NSD = Nordfjord-Sogn Detachment

the Western Gneiss Region (WGR) are structurally overlain by Caledonian thrust sheets, which are locally covered by low-grade metasediments of Middle Devonian age. The rocks of the Western Gneiss Region are heterogeneous quartzo-feldspathic gneisses and migmatites with minor inclusions of supracrustals, basic and ultrabasic rocks (Kildal 1970). The Caledonian thrust sheets comprise Cambrian- Ordovician ophiolite units (greenstones, greenschists and metagabbro with overlying sediments) and tectonic units of Precambrian high grade basement with low-grade sedimentary cover rocks.

A major structural feature of the area is a regional westerly dipping low-angle normal fault, termed the Nordfjord-Sogn Detachment (NSD) by Norton (1987). The NSD is one of several extensional structures related to the denudation of the Caledonides of Western Norway (Andersen 1998). It has a thickness of 1-2 km, and contains a varied succession of ductile and brittle fault rocks formed at different crustal depths and times during progressive fault development (Braathen et al. 2004). The footwall of the NSD is occupied by the Precambrian gneisses of the Western Gneiss Region. Within the hanging wall the Caledonian thrust sheets are unconformably overlain by Lower to Middle Devonian coarse clastic sediments, which are related to tectonically controlled sedimentation in extensional half-grabens during the progressive extension along the detachment zone (Osmundsen & Andersen 2001). The main fault displacement took place during the Devonian, but renewed activity in the Permian and the Late Jurassic- Early Cretaceous are documented (Eide et al. 1997, 1999; Braathen et al. 2004).

Four distinct populations of brittle macroscopic and mesoscopic faults have been distinguished, post-dating the Middle Devonian displacement along the NSD (Braathen & Henriksen 1997; Braathen 1999): (1) E-W thrust faults related to semibrittle- to brittle N-S crustal shortening by Late Devonian-Carboniferous transpression or compression, (2) N-S striking normal faults bisecting conjugate strike-slip faults with dextral NW-SE to NNW-SSE and sinistral NNE-SSW to NE-SW offsets, probably related to a late stage of event (1), (3) N-S striking low- to moderate angle normal faults that mainly bound the eastern margins of the Devonian basins and relate to a Permian E-W extensional event and (4) major E-W striking normal faults, which form the present northern and southern margins of the Devonian basins, and which possibly relate to a Late Jurassic-Early Cretaceous extensional event.

The rocks in the study area were recrystallized during metamorphic conditions ranging from the lower greenschist- to eclogite facies and have no intergranular porosity (e.g. Fetter 1988, p. 296). Hence, groundwater flow is localised to fractures in the rock mass, and it is expected that the fracture systems in this region form important conduits or barriers for groundwater flow.

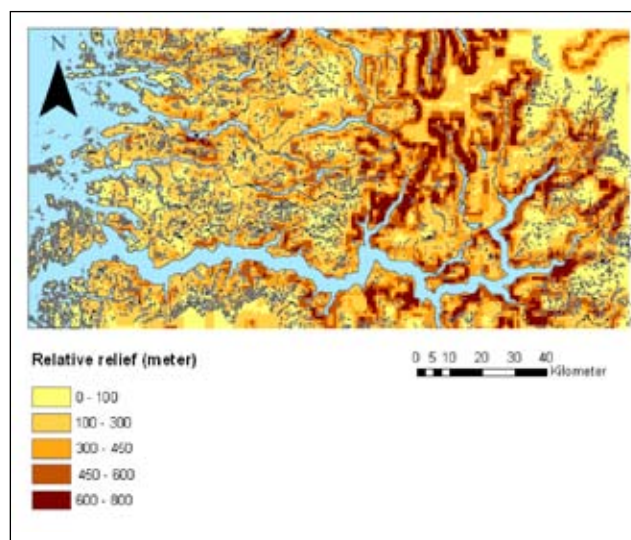


Fig. 2. Relative relief map of the study area based on a 1 km sized grid elevation model

The brittle structures described above are ubiquitously present at all scales from large lineaments on satellite photographs to small scale structures at the outcrop scale. The post- Early Devonian fracture systems are important for the hard rock hydrogeology at the local scale, as they may be prone to reactivation by the high regional compressive horizontal crustal stresses or by postglacial unloading stresses (Gudmundsson 1999).

About 68 % of the study area is exposed bedrock. Thin and discontinuous deposits of glacial till make up 16 %. The remaining part is made up of thicker deposits of glacial till together with small amounts of marine clays and fluvial deposits, all of Holocene age (Klakegg et al. 1989).

In most of the study area, the topography is irregular and hilly with a relief varying between 0-700 meters. In the easternmost parts, however, a typical fjord and valley topography with steeper fjord sides is encountered (Fig. 2).

In situ crustal stresses

In order to evaluate the study hypothesis, that critically oriented faults and fractures in the current stress field are the most permeable, one requires knowledge of the current stress state of the study area.

As a result of oil and gas exploration activities over the last 30 years, a large amount of stress data are available from the North Sea area immediately outside the study area. The data include in situ borehole measurements, borehole breakouts, and stress indicators from earthquakes. These have been compiled by a.o. Dehls et al. (2000), Fejerskov et al. (2000) and Lindholm et al. (2000). The largest horizontal stress (σ_H) is compressive.

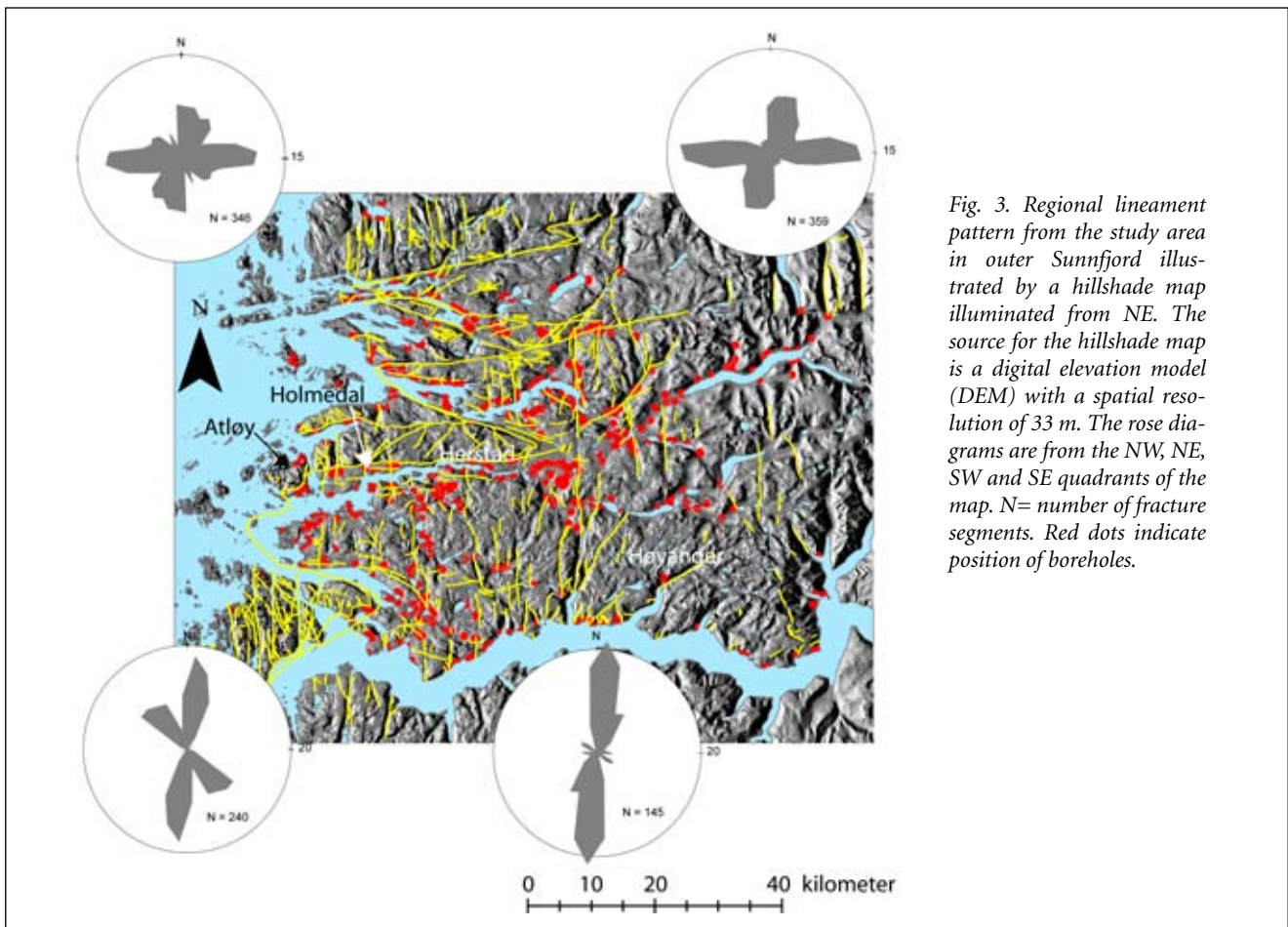


Fig. 3. Regional lineament pattern from the study area in outer Sunnfjord illustrated by a hillshade map illuminated from NE. The source for the hillshade map is a digital elevation model (DEM) with a spatial resolution of 33 m. The rose diagrams are from the NW, NE, SW and SE quadrants of the map. N= number of fracture segments. Red dots indicate position of boreholes.

sive and has a general E-W to ESE –WNW orientation. Ridge push related to sea-floor spreading in the North Atlantic is considered a primary source for the compressive stresses (Fejerskov & Lindholm 2000). In addition, postglacial rebound will produce compressive stresses of the same orientation in this area (Gudmundsson 1999). In the offshore region a NE-SW direction is also recognized by Fejerskov et al. (2000), who relate this direction to reorientation of stresses near major faults.

Onland, in the study area, in situ stress measurements were carried out at three different locations by hydraulic splitting techniques in boreholes of 12-23 meters depth (Hansen 1996; Henriksen & Braathen 2006). At Herstad, (Fig. 3), σ_H was oriented E-W parallel to the topographic grain (valley side) and had magnitudes of 15 and 19.5 MPa. The corresponding magnitudes of σ_h were 8 and 10 MPa respectively. At northern Atløy, the direction of σ_H was E-W with magnitudes of 7.5 and 8 MPa. The corresponding magnitudes of σ_h were 4 and 4.5 MPa. On southern Atløy, σ_H was oriented SW-NE with a magnitude of 7.6 MPa, with a corresponding magnitude for σ_h of 4.2 MPa. The SW-NE direction of σ_H on southern Atløy may relate to stress perturbations near the main Dalsfjord fault (Midtbø 1996a). Further inland, from Høyanger and eastwards (Fig. 3), overcoring measurements in cores in connection with road tunnelling and hydropower plants show that σ_H has either a NW-SE or

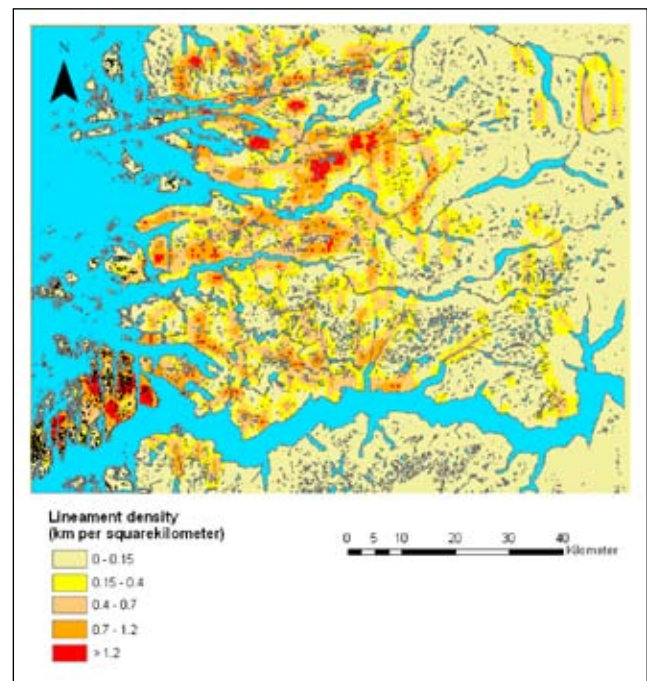


Fig. 4. Lineament length-density map, prepared by IDW interpolation method, with a square grid cell size of 0.5 km². The lineament length-density values (km/km²) are derived from a regular grid of node point values in which the value at each node is the total length of lineaments within a circle area of 1 km radius centered at each node, divided by the area of the circle. These lineament length-densities were calculated with the ArcView Avenue script PL-DENS (Kim et al. 2004).

Table 1. The main variables in the well database	
Borehole site characteristics	
TWD:	Total well depth (m)
DRD:	Total drilled depth (m)
SOT:	Soil thickness (m)
DTOW:	Depth to static water table (m)
LAC:	Length of casing (m)
WDIM:	Well diameter (mm)
Q:	Air-blow flow rate (l/hr)
Topography	
TOPS:	Topographic setting
TOPCON:	Topographic configuration
LREL:	Local relative relief (m)
Geology and hydrology	
LITO:	Lithology
STYP:	Soil type
NETP:	Net precipitation (mm/year)
Relation to structural geological features	
LIND:	Distance to nearest lineament (m)
PELIND:	Perpendicular distance to nearest lineament (m)
LINNB:	Lineament neighbourhood
DINT:	Distance to nearest lineament intersection (m)
LDENS:	Lineament density (m/km ²)

Table 1. The main variables in the well database

a NE-SW direction (Midtbø 1996b). The magnitude of σ_H is 15-20 MPa. When correcting for gravitative stresses, tectonic stresses of 10-15 MPa are obtained (Fejerskov et al. 2000). It is generally considered that the NW-SE and NE-SW stress directions onshore western Norway are due to topographic perturbations of the regional WNW-ESE stress field (Fejerskov et al. 2000; Midtbø 1996a).

Data

Topographical data include a Landsat ETM7 satellite image with 7 multispectral bands of 30 m resolution and a panchromatic band of 15 m resolution, a digital elevation model (DEM) with a spatial resolution of 33 m, and 1: 50 000 scale topographic maps within UTM projection zone 32V. Geological reference data include digital maps of bedrock and loose deposits at the 1: 250 000 scale. Hydrological data include raster maps of annual rainfall, evaporation and runoff within one square km grid cells for the period 1960 -1991 calculated by means of the Nordic HBV model methodology (Beldring et al. 2002; Bergström 1995).

The lineament database

Lineaments in this largely barren region stand out as strong physiographic features (Fig. 3). They were initially detected and extracted into GIS as a separate lineament layer from three sources: the geometrically corrected Landsat ETM7 satellite image, the DEM, and a digital topographic database at 1: 50 000 scale. Later, many of

the lineaments were ground checked and their positional accuracy improved by the use of 1: 5 000 scale maps or GPS. In the field the extracted photo- and topolineaments almost uniquely coincide with deformation zones up to 600 meters in width, that are characterised by increased frequencies of joints, smaller faults, and layers and lenses of fault rocks (Braathen & Gabrielsen 1998; Henriksen & Braathen 2006). Except for the detachment zones, most lineament related fractures have dips in the range 60-90° (Braathen & Henriksen 1997; Braathen 1999). Subtly expressed lineaments, representing foliations and lithological contacts, were excluded from the final lineament map (Fig. 3). Hence, the lineament map classifies as a true fracture lineament map (Gabrielsen et al. 2002) where non-geologic features are absent. Lineament statistics were derived from a standardized lineament map applying the method outlined by Kim et al. (2004). Figure 3 shows the fracture lineament map of the study area with rose diagrams for different sub-regions. Both lineament orientation and density (Figs. 3 & 4) show a spatial variation, indicating different deformation histories and intensities within the study area. Lineaments were initially classified into 8 groups depending on their azimuth directions (N, NNE, NE, ENE, E, ESE, SE and SSE) and into 5 groups based on their lengths (>100 km, 50-100 km, 10-50 km, 1-10 km and < 1km). Only lineaments with lengths greater than 1 km were considered in the statistical analysis.

The majority of lineaments with N-S trends (azimuth sector N340°W – N020°E) are associated with faults of population (2); and those with E-W trends (azimuth sector N60°E – N120°E) correlate with population (4) macro- and mesostructures. Both these lineament trends are recognized as prominent lineament zones in Norway that have been the locus of multiple fault movements and seismic activity from Permian to Recent (Gabrielsen et al. 2002).

The well database

Within the study area, a hard rock borehole database containing 697 well records has been established. The database is based on borehole information supplied by drillers to the national well archive which is maintained by the Geological Survey of Norway (NGU). Technical borehole information in the database includes well yield and depth, depth to water table, overburden thickness, borehole inclination, casing length, well use and positional accuracy. Since 2000, borehole locations have been determined by GPS, which has greatly improved the spatial accuracy of the database. The locations of some of the older boreholes were determined by site inspection either in connection with a previous project (Henriksen 1988) or in this ongoing project. By combining the well database with digital geological, topographical and hydrological data in a GIS each well is given additional attributes; i.e. bedrock type, net precipitation, topographic position and local relative relief in the vic-

Table 2. Categorical grouping variables used in the ANOVA								
Borehole site characteristics								
TWD: Total well depth (m)	<50	50-90	90-130	>130				
DRD: Total drilled depth (m)	<60	60-100	> 100					
SOT: Soil thickness (m)	<1	1-5	>5					
DTOW:Depth to static water table (m)	<2	2-8	8-15	>15				
LAC: Length of casing (m)	<1	1-6	> 6					
WDIM: Well diameter (mm)	< 110	110-140	> 140					
USE: Use of well	DOM	ENE	IND	RES				
Topography								
TOPS: Topographic setting	FS	VS	RI	VB	F			
TOPCON: Topographic configuration	N	NNE	NE	ENE	E	ESE	SE	SSE
LREL: Local relative relief (m)	0-20	20-50	50-100	100-150	>150			
Geology and hydrology								
LITO: Lithology	WG	AB	AC	CO	DEV			
STYP: Soil type	None	Till						
NETP: Net precipitation (mm/year)	<1500	1500-2500	> 2500					
Structural geologic features								
LIND:Distance to nearest lineament (m)	<25	25-100	100-300	>300				
PELIND:Perpendicular distance to nearest lineament (m)	<25	25-100	100-300					
LINNB: Lineament neighbourhood	INN	INNE	INE	TIP	OUT			
DINT:Distance to nearest lineament intersection (m)	<25	25-100	100-300	>300				
LDENS:Lineament density (m/km ²)	<0.14	0.14-0.40	0.40-0.70	0.70-1.14	>1.14			

Table 2. Categorical grouping variables used in the ANOVA. Abbreviations for USE: DOM=Domestic; ENE=Energy; IND=Industry; RES=Research. Abbreviations for LITO: NWG= Precambrian gneisses of the Western Gneiss Region; AB= Allochthonous Precambrian basement rocks; AC= Allochthonous Precambrian cover rocks; CO= Caledonian ophiolite units; DEV= Devonian sandstone and conglomerates. Abbreviations for TOPS: FS=Fjord side; VS=Valley side; RI=Ridge; VB=Valley bottom; F=Flat areas. Abbreviations for LINNB: INN= wells near NNW-NNE lineaments; INNE= wells near NE-ENE lineaments; INE= wells near ENE-ESE lineaments; TIP=wells located at lineament tips; OUT= wells outside the supposed influence area of lineaments (> 300 m).

nity of the well. The distance from each borehole to the nearest lineament and lineament intersection was determined by spatial joining in ArcGIS (Minami 2000 p. 390). Wells within the influence area of lineaments were extracted by applying a buffer of 300 m width around the lineament features, and the perpendicular distance from each well to the nearest lineament was determined in the GIS. Because stress deviations are often concentrated near the tips of discontinuities (Homberg et al. 1997), wells located at lineament tips were also categorized. In summary, each well was characterised by the variables listed in Table 1.

Well yields are reported as air-blow flow rates measured by the driller during and at the termination of the drilling. Compressed air from the drill bit, placed at the bottom of the borehole, is used to blow the water out of the well. The flow rate of water in litres per hour is determined as the water exits the top of the well through a discharge pipe placed at the top of the well casing. Normally, the duration of an air-blow test is from 1 -2 hours. The driller's reports contain, although often incomplete, records of depths to individual fractures with estimates

of their yields. From these data a fracture yield database with information about the depth to individual fractures or water strikes and their yields has been compiled. The bulk of boreholes are intended for private water supplies and most of them have been sited without any hydrogeological consultancy. From a hydrogeological point of view, the data set can be considered as a random sample with respect to well siting, although located in urban areas.

The air-blow tests are indicator tests which only give a rough measure of the actual well yield (Banks 1991; DNRE 1997). Air-blow flow rates have, however, proved to be of great importance in characterizing groundwater potential and the hydraulic properties of hard rocks in different regions of Scandinavia (Rohr-Torp 1994; Morland 1997; Wladis & Gustafson 1999; Henriksen 2003) and elsewhere (Briz-Kishore 1993; Loiseau & Evans 1995). The normalized air-blow flow rate Q/d [l/hr/m] where d is the total drilled depth is a conservative estimate of specific capacity (Wallroth & Rosenbaum 1996). It has been used to obtain estimates of transmissivity that were within an order of magnitude of the transmissivity values based on injection-test data (Wladis & Gustafson 1999). Air-blow flow rates

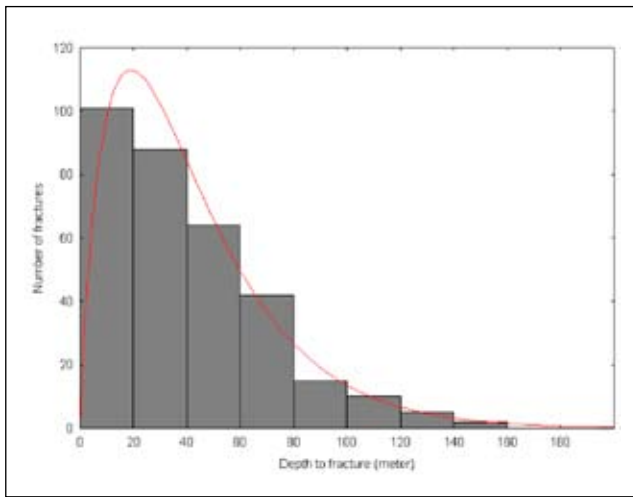


Fig. 5. Plot of depth to the first fracture registered during drilling based on the database of 697 wells. The majority of these fractures are water conducting. The fracture density distribution down to 180 m depth is close to the one-tail exponential gamma distribution. Data are obtained from the original driller's logs submitted by the drilling companies to the Norwegian Geological Survey.

for domestic wells tend to be negatively correlated with drilled rock depth because of socioeconomic factors. The normalized air-blow flow rates may suffer from an additional bias because of a general decline in permeability and fracture frequency with depth in the uppermost 200 m of the Fennoscandian bedrock (Berggren 1998). This is also indicated by the depth distribution of fractures within the study area (Fig. 5).

For these reasons, the raw air-blow flow rates Q [l/hr] were used in this study. However, both this study and other works (e.g. Lie 2001) show a strong positive linear correlation between flow rates and normalized flow rates which suggests that either parameter could be used. As an alternative, yields of the first fracture encountered could be studied as suggested by Loisel & Evans (1995). But only about 10% of the boreholes have data on both fracture yield and depth, which makes the data set unsuitable for the statistical design used in this study.

Statistical analysis

One main objective of the statistical analysis is to investigate whether lineament neighbourhoods have different hydromechanical properties in terms of measured flow rates. However, all the variables listed in Table 1 are explanatory variables that more or less relate to the measured air-blow flow rates. It also appears that the importance of such variables varies from setting to setting (e.g. Mabee 1998). Hence, in order to relate a particular set of key variables to the measured flow rates their relative importance must first be estimated. For a mixture of continuous and categorical variables (i.e. Table 1) this can be done during the routine analysis of variance (ANOVA).

Because the ANOVA is essentially a linear regression on explanatory categorical variables, the coefficient of determination R^2 also gives an indication of how much of the variation in the independent variable that is explained by the regression model (e.g. Johnston 1980). The one-way ANOVA, which is an extension of the t-test for differences in means of two groups, also conducts a simultaneous comparison of the means of multiple groups of categorical data.

The explanatory categorical variables (factors) were classified into groups as shown in Table 2. The classification into topographic setting (TOPS) follows the classification of Henriksen (1995). Topographic configuration (TOPCON) takes into account the grain of the topographic element/setting. The rationale for this grouping is to consider possible effects of topographic perturbations of regional stresses on the hydromechanical bedrock properties. The lithological grouping is the same as the one on the geological map (Fig. 1). The grouping for many of the other variables is based on characteristic breaks in their distribution curves.

The rationale for the grouping into lineament neighbourhood (LINNB) is to consider, at a scale much larger than at the test site at Holmedal (Henriksen & Braathen 2006), the possible reactivation potential of the lineaments given the regional direction (E-W to WNW-ESE) of the current stress field. In this stress field, lineaments in the ENE-SE azimuth sector would be the most critically stressed and/or tend to be open. Lineaments in the NNW-NNE azimuth sector, followed by those in the NNE-ESE azimuth sector would be least amenable for reactivation (Fig. 6).

The analyses were conducted with the computer software STATISTICA 7.0 (StatSoft 2004) on the new boreholes located by GPS after 2000. In this high precision subset of 132 boreholes, the positional accuracy is better than 10 meters.

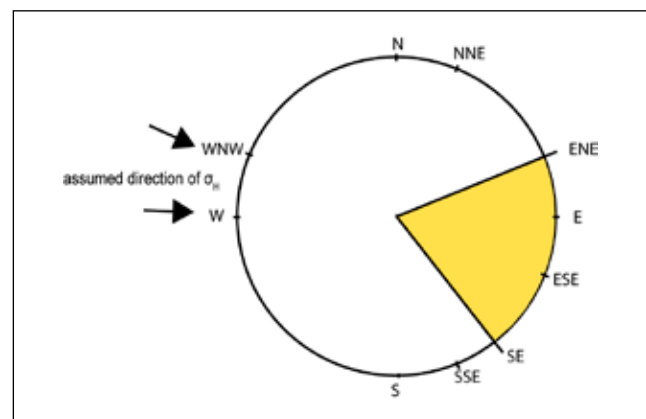


Fig. 6. In a current stress field, with an E-W to ESE-WNW direction, lineaments in the coloured azimuth sector defined by $\sigma_H \pm 30^\circ$ have the highest likelihood of keeping their fracture apertures open or for reactivation.

Table 3. Results of Tukeys test for multiple comparison of group means of log Q for the topographic grouping

	Fjord sides (2.556)	Valley sides (2.867)	Ridges and hills (2.039)	Valley bottoms (3.270)	Flat valley bottoms (3.397)
Fjord sides	x				
Valley sides	0.178	x			
Ridges and hills	0.224	0.007	x		
Valley bottoms	0.001	0.193	<0.001	x	
Flat valley bottoms	0.325	0.758	0.002	0.998	x

Table 3. Results of Tukeys test for multiple comparison of group means of log Q for the topographic grouping. Significant differences (p-level 0.05) are marked in italics. The mean flow rate (log Q) for each group is shown in brackets.

The air-blow flow rates are typically strongly skewed and contain extreme values in either direction. Since one assumption of the ANOVA is that the dependent variable is normally distributed within the groups, a logarithmic transformation of the air-blow flow rates was necessary. ANOVA methods also assume that the grouped data have homogeneous variances. These assumptions were tested by visual inspections of categorised histograms and box-and whisker plots of the groups, and by the Bartlett's and Levene's tests for equal variances (Winer et al. 1991; StatSoft 2004). The tests indicate that the samples in the data set largely comply with these assumptions.

Results

The results of the one-way ANOVA performed on the data sets of groupings (Table 2) indicate that the most important factors are topographic setting (TOPS), drilled rock depth (DRD), topographic configuration (TOPCON) and lineament density (LINDENS). At the 95 %

confidence level, each of these variables explains respectively 25.4, 24.6, 13.7 and 12.7 % of the observed variation in air-blow flow rate. Lithology (LITO) has also a statistical significance on flow rate, but explains only 10.3 % of the observed variation. Taken together in a multiplicative ANOVA, topographic setting and drilled rock depth explain 45.7 % of the total variation.

The result of Tukey's test for pairwise comparison of means from the topographic groups (Table 3) shows that valley bottoms and flat valley bottoms have significantly higher flow rates than the other settings. This is in agreement with the conclusions of Henriksen (1995).

The pairwise comparisons for the drilled rock depth category (Table 4) indicate a significant difference in flow rate between the deeper (DRD >100 meter) and shallower boreholes, the deeper ones having a significantly lower mean.

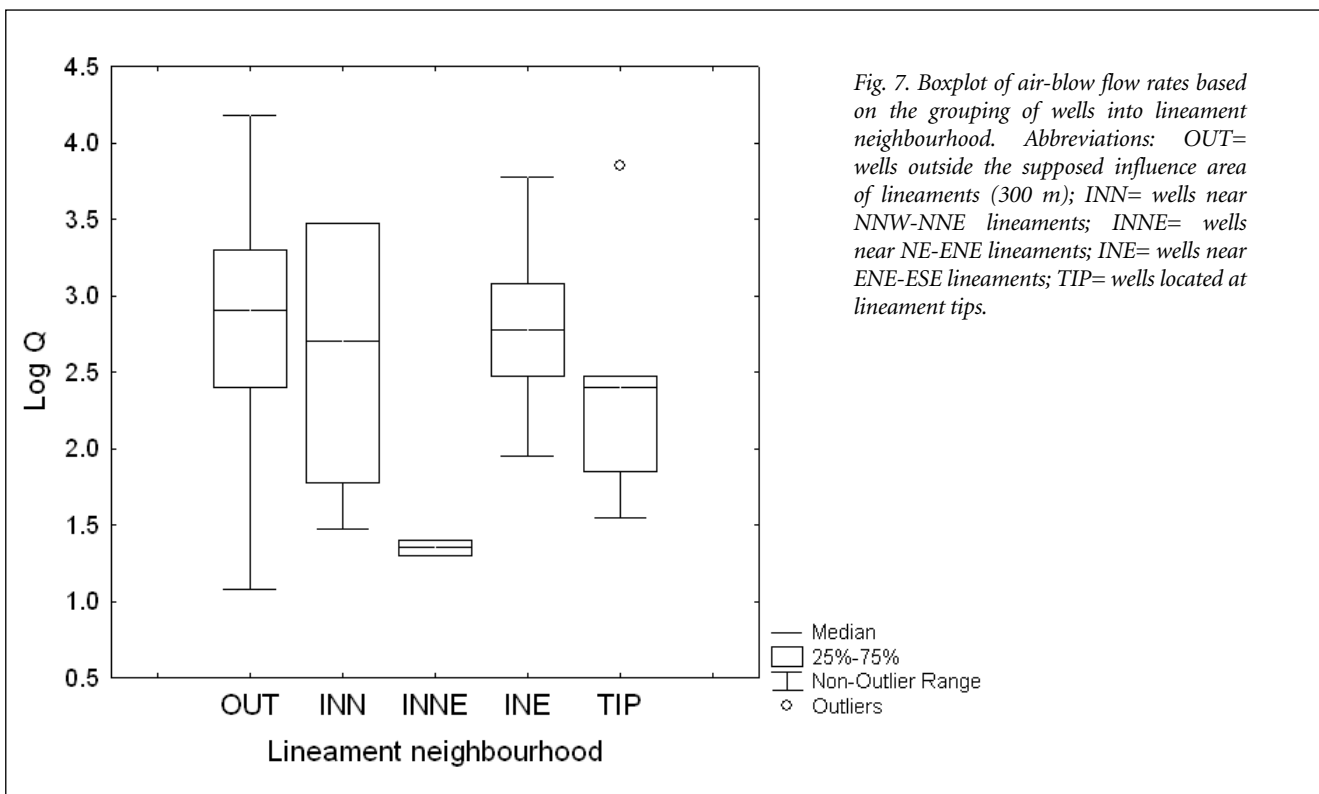


Table 4. Results of Tukeys test for multiple comparisons of group means of log Q for the drilled rock depth grouping

Drilled Rock Depth	≤ 60 (3.036)	60-100 (3.065)	>100 (2.333)
≤ 60	x		
60-100	0.991	x	
>100	0.009	<0.001	x

Table 4. Results of Tukeys test for multiple comparisons of group means of log Q for the drilled rock depth grouping. Significant differences (p-level 0.05) are marked in italics. The mean flow rate (log Q) for each group is shown in brackets.

Figure 7 shows a boxplot of the air-blow flow rates based on lineament neighbourhoods (LINNB) of their wells. The grouping that stands out with the lowest air-blow flow rates is the group associated with lineaments in the NNE-NE and SE-SSE azimuth sector with an average log Q [l/hr] of 1.39. The group of boreholes associated with lineaments in the ENE-SE azimuth sector have the highest flow rates with an average log Q [l/hr] of 2.80. But the results from the one-way ANOVA and the equivalent nonparametric Kruskal-Wallis ANOVA test on this factor are not significant. In the one-way ANOVA, LINNB explains only 7 % of the variation in air-blow flow rates.

In order to study the relationship between flow rate and distance to lineaments, only those wells within an euclidian distance of 300 meter from a lineament were considered. Figure 8a shows a scatterplot of distance (PELIND) versus flow rate for this subset (n=23) of the high precision data set of 132 boreholes. It is difficult to identify any linear trend in the data. But a distance-weighted least square curve (McLain 1974; StatSoft 2004) which was fitted to the data reveals an overall increasing trend for flow rate to about 50 meters lineament distance, followed by a sharp decreasing trend at closer distances. A similar trend is seen on Figure 8b, which is a 5 point running median plot of log Q vs. the perpendicular distance to lineament (PELIND) for the same data set with 23 boreholes. A running median plot of a larger data set (n=129) of boreholes within 300 meter lineament distance, which also includes the boreholes before year 2000 with no GPS coordinates, shows a similar trend (Fig. 8c); but here a subordinate rising trend is indicated for the flow rate in the central zone.

For both data sets, the t-test (significance level 0.05) was used to evaluate the differences in means between the flow rates constituting the two trends within the influence area of the lineaments. The results indicate that boreholes within 50 m distance of the lineaments have significantly lower average flow rates than boreholes positioned at a distance greater than 50 meters.

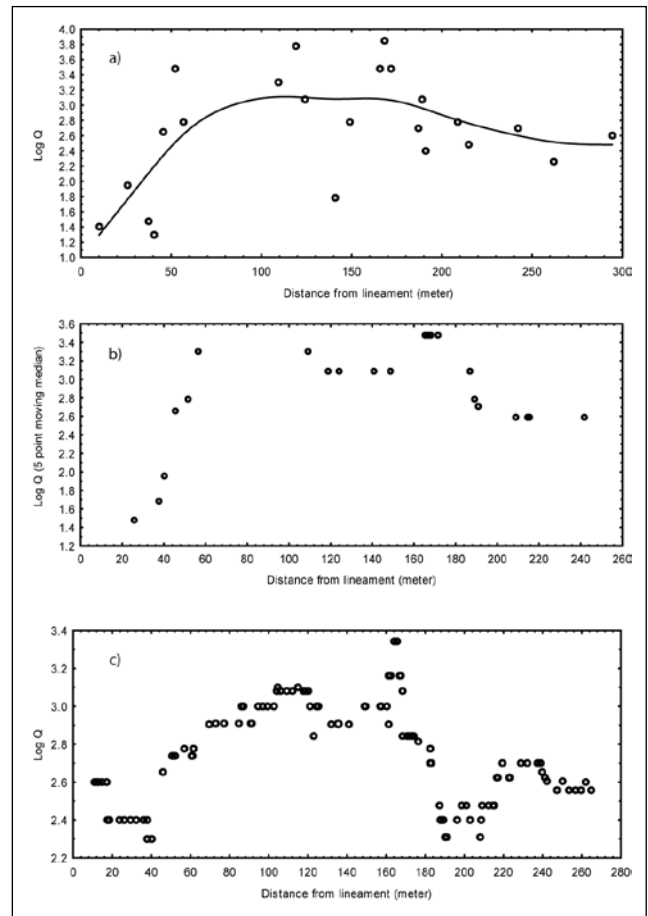


Fig. 8. Scatter plots and moving median plots of borehole flow rates against distance from lineament for wells within 300 meters lineament distance: (a) Scatter plot with a distance-weighted least square curve fitted to flow rate data from the high precision data set (n= 23), (b) 5-point moving median plot of the data in Fig. 8a, (c) 15-point moving median plot of borehole flow rate against lineament distance for a lower precision data set (n= 129) which also includes boreholes before 2000 with no GPS coordinates.

Finally, a new ANOVA was conducted on the complete high precision dataset of 132 boreholes, in which the boreholes constituting the central, less permeable, zone of the lineaments were not considered. Compared with the old ANOVA, as mentioned earlier, the explanatory power of LINNB was reduced from 7% to 1%. This indicates the importance of the central zone in the explanation of the variation in the borehole flow rates. Together, these results from the studies of the well database, indicating a low permeability environment in the central zone of lineaments followed by a more permeable damage zone, are in accordance with the results obtained from the well head studies of test boreholes (Henriksen & Braathen 2006).

Discussion

Proximity analysis, a main focus of this study, calls for the use of high precision data. However, an analysis which only uses the GPS borehole locational data greatly reduces

the size of the data set. Nevertheless, it is believed that the use of the high precision data set of 132 boreholes will give more credible results. The results from the study of the high precision data set of 132 boreholes indicate that topographic setting (25.4 %), drilled rock depth (24.6 %), topographic grain (13.7 %) and lineament density (12.7 %) are the most important predictor variables which account for the variation in the measured air-blow flow rates. The other variables, taken alone or together, account for less than 10% of the variation in flow rates. The lack of influence of technical well constructional factors; i.e. well diameter and well use, is probably related to the small variation in well diameter and well use which make these variables roughly constant. Casing length and soil thickness are strongly positively correlated, but neither of these factors have a significant control on flow rate.

Overburden thickness and type are recognized as an important supply of recharge to the bedrock by Caswell (1987) and Cesano et al. (2000). In this study area, overburden is generally absent or thin. When present, it is mostly low-permeable till. It is considered that these deposits are capable of storing only limited amounts of water and, in addition, have poor hydraulic connection with the underlying bedrock. The air-blow tests of about 1–2 hours duration are probably also too short to draw noticeable amounts of water stored in these overburden deposits. The lack of influence of variables related to recharge, i.e. net precipitation and local relief, is probably also connected with these factors. Depth to water table is not significant at the 10% level. But the small number of boreholes (43) with water level data makes a fair evaluation of this variable difficult.

The negative association between flow rate and drilled rock depth (Table 4) indicates an overall decrease in water-transmitting properties of the bedrock with depth. It is a generally held view that increasing overburden pressure will tend to close fractures and cause a decrease in fracture permeability with depth (Singhal & Gupta 1999, p. 162). But this depth dependence can be related to several factors. Relaxation joints (exfoliation), developed after the last glaciation, are restricted to the upper parts of the bedrock thereby influencing the vertical distribution of hydraulic conductivity and borehole flow rates. Based on model calculations, it has also been suggested that hydrofractures and shear fractures may develop at shallow depths even in massive hard rocks due to the load of the last ice sheet (Boulton et al. 1999, p. 62). Furthermore, the western coast of Norway is subject to high compressive tectonic stresses which may be sufficient to initiate fault reactivation and fracture formation. In a current stress field, existing fractures are more easily reactivated at shallow depths (Alaniz-Álvarez et al. 1999, 2000), and critically stressed faults or fractures at such depths may be structures with enhanced permeabilities (Barton et al. 1995; Rogers 2003). Finally, the upper portion of the bedrock is in a more weathered state, which will also influence well yield in a positive direction.

Topography, in situ stresses and hydraulic bedrock properties

Based on their angular relations with the regional stress field, the most open and critically stressed fractures are likely to be found in the ENE-SE azimuth sector. It follows that the highest borehole flow rates should be associated with lineaments in the ENE-SE azimuth sector, followed by the NE-ENE and NNW-NNE azimuth sectors. The results from the Holmedal field site comply well with this conceptual framework (Henriksen & Braathen 2006). But the analyses of borehole flow rates based on lineament neighbourhood make it difficult to draw similar conclusions for the study area taken as a whole. There is a lack of significant differences between the azimuth groupings, and between these groupings and the background area. Although borehole flow rates in the vicinity of lineaments in the ENE-SE azimuth sector have the highest median and average flow rates, this difference is not as significant as might be expected. These conflicting results can at least be explained partly by considering the effects of perturbations of the regional stress field by faults and topography. Major faults will act as principal stress planes capable of reorienting the regional stress field. Topography, i.e. steep fjord- and valley sides may have a similar effect (Miller & Dunne 1996), and topographic interactions with regional stresses may result in rock fracturing and influence the local hydrogeological properties (Miller & Dunne 1996; Morin & Savage 2002). In western Norway, which experiences high tectonic compressive stresses, it is generally recognized that topographic interactions with the regional stress field rotates σ_H into parallelism with the topographic grain of fjord- and valley sides (Myrvang 1993). In this type of topographic setting, deviatoric stresses in valley bottoms may cause rock fracturing parallel to the ground surface and also favour an open aperture of steeply dipping fractures aligned along the valley axis (Miller & Dunne 1996). In the study area and the immediate adjacent region, this effect was also recognized in a compilation of onland overcoring measurements and numerical simulations by Midtbø (1996b). Because there is a strong correlation between topographic grain and lineament azimuths, the topographic effect referred to above would work towards a leveling out of any differences between borehole flow rates based on the angular relationships between their nearest lineament and the regional E-W to ESE-WNW stress field. By accepting topography as an important modifier for the orientation of the regional stresses, its recorded importance for borehole flow rate in this work and in Henriksen (1995) is readily appreciated. It also follows that the stress-related permeability model may not be applicable at all scales in all areas, which has also been pointed out by Rogers (2003). The lack of association between flow rates in the surroundings of the remotely sensed lineaments and lineament direction (i.e. the orientation of the lineaments in the regional stress field) could probably also reflect that the geometry of the connected fracture network in the damage zone of the lineaments is more important for fluid flow than the in situ anisotropic stresses.

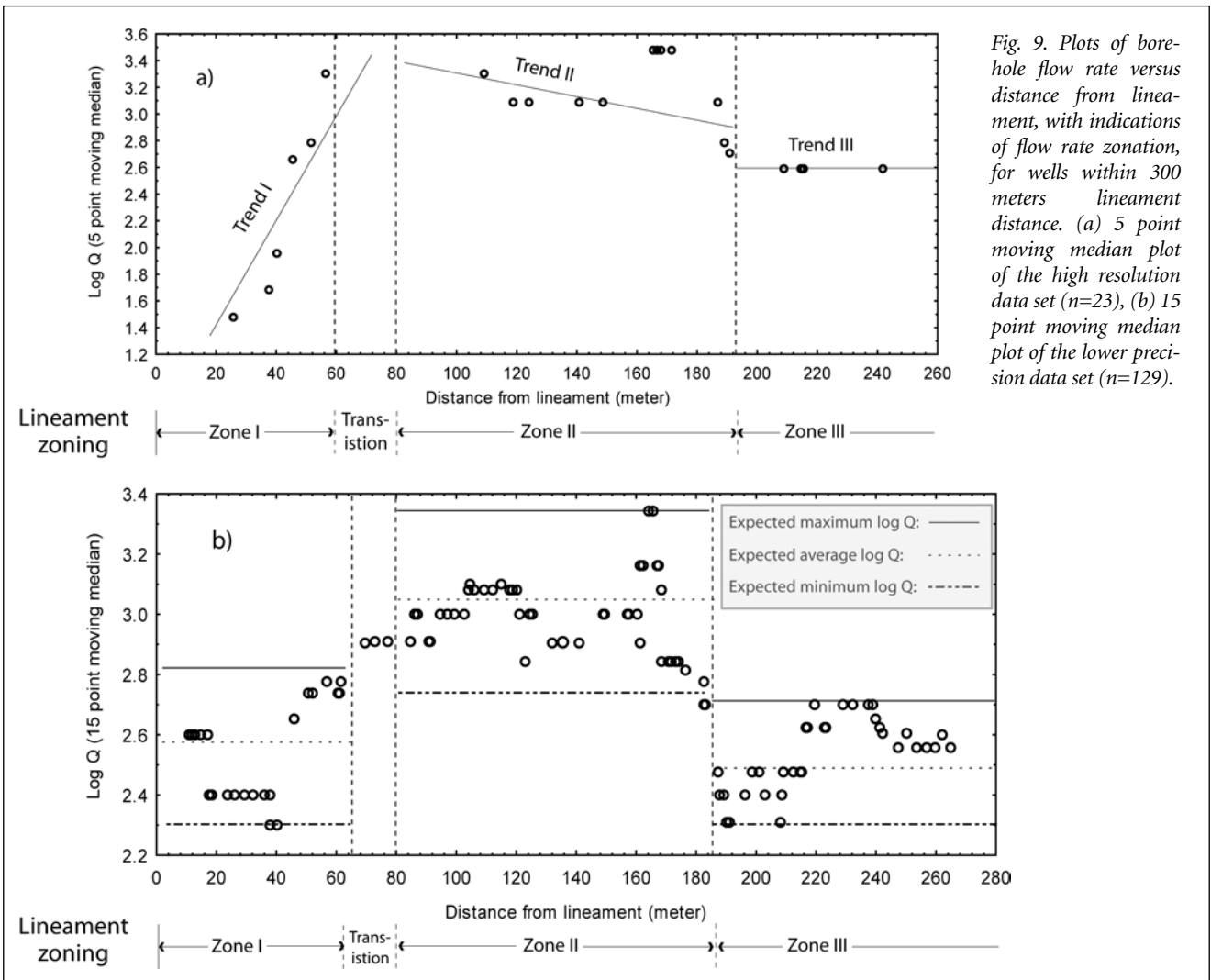


Fig. 9. Plots of borehole flow rate versus distance from lineament, with indications of flow rate zonation, for wells within 300 meters lineament distance. (a) 5 point moving median plot of the high resolution data set (n=23), (b) 15 point moving median plot of the lower precision data set (n=129).

On the other hand, outside the influence areas of lineaments, in areas of known stress orientation, the water conducting properties of smaller fractures comply with the critically stressed fracture model (Henriksen & Braathen 2006). This was also noted by Midtbø (1996a) who, in a survey of small fractures, found that WNW-ESE oriented fractures were the most dominant water conductors in this region.

Hydraulic properties with distance to lineaments

The detailed field studies of lineament architecture and test boreholes (Braathen et al. 1999; Henriksen & Braathen 2006) indicate that, when the low permeable central zone is excluded, a gradual decrease in permeability and measured flow rates of boreholes with distance from lineaments. This same relationship is also indicated by the proximity analysis from the well database of the study area. Although there is a considerable scatter in the flow rate vs. distance plots, a clearer trend emerges when the data sets are smoothed (Fig. 8). For both the high precision (n=23) and lower precision data sets (n=129), the plots of distance versus flow rate indicate a three-partite

division of the lineament surroundings into zones of contrasting flow rates (Fig. 9a, b).

The outermost zone (Zone III) has a constant distance trend with intermediate flow rates. Zone II has a weakly increasing distance trend with increasing and higher flow rates towards the lineament centre. Zone I has a clear decreasing distance trend and the lowest flow rates. This flow rate zonation correlates well with the fracture-mechanical zonation described from fault zones and lineaments by a.o. Caine et al. (1996) and Braathen & Gabrielsen (1998). The work of the latter authors shows a three-partite division of lineaments into deformation zones with marked rock- mechanical contrasts. An innermost central zone (0-40 m width), with low permeable fault rocks, is followed by a marginal zone (10-50 m in width on either side), with a high frequency of open and interconnected fractures, which grades into a distal zone (up to 200 m in width on either side) with low density fracturing.

It is considered that the flow rate zonation (Fig. 9a, b) mirrors that found for the lineament architecture (e.g.

Braathen & Gabrielsen 1998). As such, the results in Fig. 9 may indicate important guide-lines for the siting of boreholes in lineament zones.

The spread in distance vs. flow rate data relate probably in part to an uncertainty regarding the position of the central and marginal zones. One assumption in the proximity analysis is that of ideal lineaments with fixed and constant widths of their central, marginal and distal zones. This is hardly true, as in reality one would expect that the width of the different zones would vary, not only from lineament to lineament, but also along the same lineament (Braathen & Gabrielsen 1998).

The results from this work comply well with proximity analyses at a comparable scale of resolution and in similar lithologies from south western Sweden (Wladis & Rosenbaum 1995) and at a smaller scale (ca. 100 km²) on the island of Askøy area near Bergen (Lie & Gudmundsson 2002). In other studies, distance to lineament intersections is found to exert a major influence on borehole flow rates (Yin & Brook 1992; Magowe & Carr 1999).

On the other hand, neither Morland (1997) nor Kellgren (2002) found any relationship between distance to regional lineaments and borehole yields. This indicates a scale dependence on the outcome of the proximity analyses but also relates to the lack of precision in location of boreholes and regional lineaments.

Lineaments are often considered as zones of enhanced permeability compared with their surroundings (e.g. Siddiqui & Parizek 1971; Yin & Brook 1992). Although the damage zone or marginal zone in the lineament neighbourhoods is recognized as a zone of enhanced permeability in this study, the results from the statistical significance tests indicate no clear differences between the flow rates in the damage zone of lineaments and the background fracture system of the region. These conflicting results are not surprising, as the water transmissive capacity of a fracture lineament depends on a number of factors, a.o. the fracture lineament architecture, secondary fracture fillings and its orientation in the in situ stress field. One should also consider the total geologic history of the fracture lineament in terms of the influence of surficial and near surface processes. Fracture zones are for example favourable sites for enhanced deep weathering processes and often also coincide with topographic depressions that act as sedimentary traps/depositional sites for younger sediments. In Fennoscandia, clay minerals associated with prolonged and deep weathering in the Jurassic and Tertiary as well as marine clays of Holocene age may have a clogging effect on the permeability of the subsurface fracture systems (Olesen et al. 2006). Hence, the recognition of major fracture lineaments as enhanced zones of permeability compared with the surroundings is ambiguous (e.g. Banks et al. 1992; Banks et al. 1996).

Conclusions

Statistical analyses of borehole flow rate data on a large data set covering an area of ca. 4 000 km² are consistent with earlier works with regard to groundwater flow within the influence area of faults and fracture lineaments. In the lineament neighbourhoods, a three-partite flow rate zonation complies well with the general rock mechanical zonation of lineaments. Boreholes within 50-60 m distance of the lineaments have significantly lower average flow rates than boreholes positioned at greater distances, and the results summarised in Fig. 9 may indicate important guide lines for locating water wells in lineament zones. However, the average flow rate in the damage or marginal zone of the fracture lineaments is not statistically different from the surrounding bedrock areas outside the influence areas of the lineaments.

Topography, together with drilled rock depth, are the most important explanatory factors for the observed variations in borehole flow rates. The importance of topography is considered to relate to its ability, within a compressional stress regime, to perturb the regional stress field. Within the study area, this interaction between topography and the regional tectonic stress field acts so as to cause a reorientation of the maximum compressive stress σ_H into parallelism with fjord sides and valley sides. This is demonstrated both by in situ stress measurements and numerical modelling from the study area and immediately adjacent areas. Hence, the local stress field at any site may deviate significantly from the regional WNW-ESE stress field. The most commonly observed directions of σ_H are E-W, NE-SW and NW-SE. This makes it difficult to draw any safe conclusions about groundwater flowpaths based on the critically stressed fracture model from input data of the regional stress field alone.

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