The importance of hydraulic gradient, lineament trend, proximity to lineaments and surface drainage pattern for yield of groundwater wells on Askøy, West Norway

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Lie, H. & Gudmundsson, A. 2002: The importance of hydraulic gradient, lineament trend, proximity to lineaments and surface drainage pattern for yield of groundwater wells on Askøy, West Norway. *Norges geologiske undersøkelse Bulletin 439*, 51-60.

Groundwater and lineament studies were made on Askøy, an island northwest of Bergen. In addition to field measurements of lineaments and associated fractures, a total of 2695 photolineaments and 409 topolineaments were analysed in relation to yield of drilled groundwater wells. The results of statistical analyses in geographical information systems (GIS), as well as numerical modelling of groundwater flow, highlight two parameters that affect yield of groundwater wells. These factors are proximity of groundwater wells to lineaments and lineament trends. The results indicate that, on Askøy, NE-SW-trending lineaments, and those that strike subparallel to the slope of the topography, are most likely to provide high-yield groundwater wells. Although the statistical significance in these analyses is not high, the results indicate that the methods may be generally very useful, particularly for areas with a large number of drilled wells. The surface drainage pattern on Askøy is partly controlled by lineaments and other tectonic elements. In particular, the streams commonly follow topographic lineaments, many of which are fault zones, individual fractures, contacts or other mechanical discontinuities in the rock mass. We conclude that by combining data on lineament trends and surface drainage, it may be possible to characterise hydraulic differences between lineaments of different trends.

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Introduction

There have been several recent studies on the possible correlation between the yield of drilled groundwater wells and their distances to nearby lineaments (Boeckh 1992, Greenbaum 1992, Yin & Brook 1992, Gustafsson 1993, Morland 1997, Braathen et al. 1999). In general, the well yield is expected to increase when approaching lineaments. One reason for this is that most lineaments are depressions that receive water by topography-driven flow. Another reason is that many lineaments have a high fracture frequency, and thus normally high hydraulic conductivity, close to their central parts. However, the correlations between the yield of wells and their distances to lineaments generally show large variations which cannot be entirely explained in terms of proximity to lineaments. These variations suggest that other factors, such as hydraulic properties, lineament trend and influence of topography, must also be considered.

Lineaments are commonly mapped from topographical maps, aerial photographs and satellite images. Here, we define lineaments as all mappable linear or curvilinear features that may represent major discontinuities (mechanical breaks) in the bedrock (Braathen & Gabrielsen 1998, Lie 2001). Major morphological discontinuities at the intersections between surface and foliation are included in this term because these lineaments commonly represent foliation structures that have been reactivated as joints or faults.

The aim of this paper is to evaluate how the lineament trend and the hydraulic gradient affect the groundwater potential on the island of Askøy (Fig. 1). For this purpose we use groundwater well yield data, mapped lineaments, topographical data and simple numerical flow models. Since surface and subsurface drainage is partly controlled by lineaments, we also combine maps of stream systems with those of lineaments to evaluate what possible differences in hydraulic properties exist between the lineament trends.

Hydrogeological background

Geology of the Bergen area

The region around Bergen can be divided into two main units: Precambrian crystalline bedrock and Caledonian thrust nappes. The basement consists of metamorphic Precambrian migmatites, granites and mafic rocks from the cratonic part of Baltica (Milnes & Wennberg 1997, Fossen 1998). The nappes are grouped into the Lower, Middle and Upper Allochthons (Milnes & Wennberg 1997). The two lowermost tectonostratigraphic units include mylonitic, granulitic, granitic and sedimentary rocks while the Upper Allochthon, which dominates in the Bergen region, includes metamorphic Precambrian granulites and anorthosites as well as granitic/migmatitic rocks, meta-arkoses, conglomerates and ophiolitic complexes (Milnes & Wennberg 1997). Most Precambrian rocks in the Bergen area include various

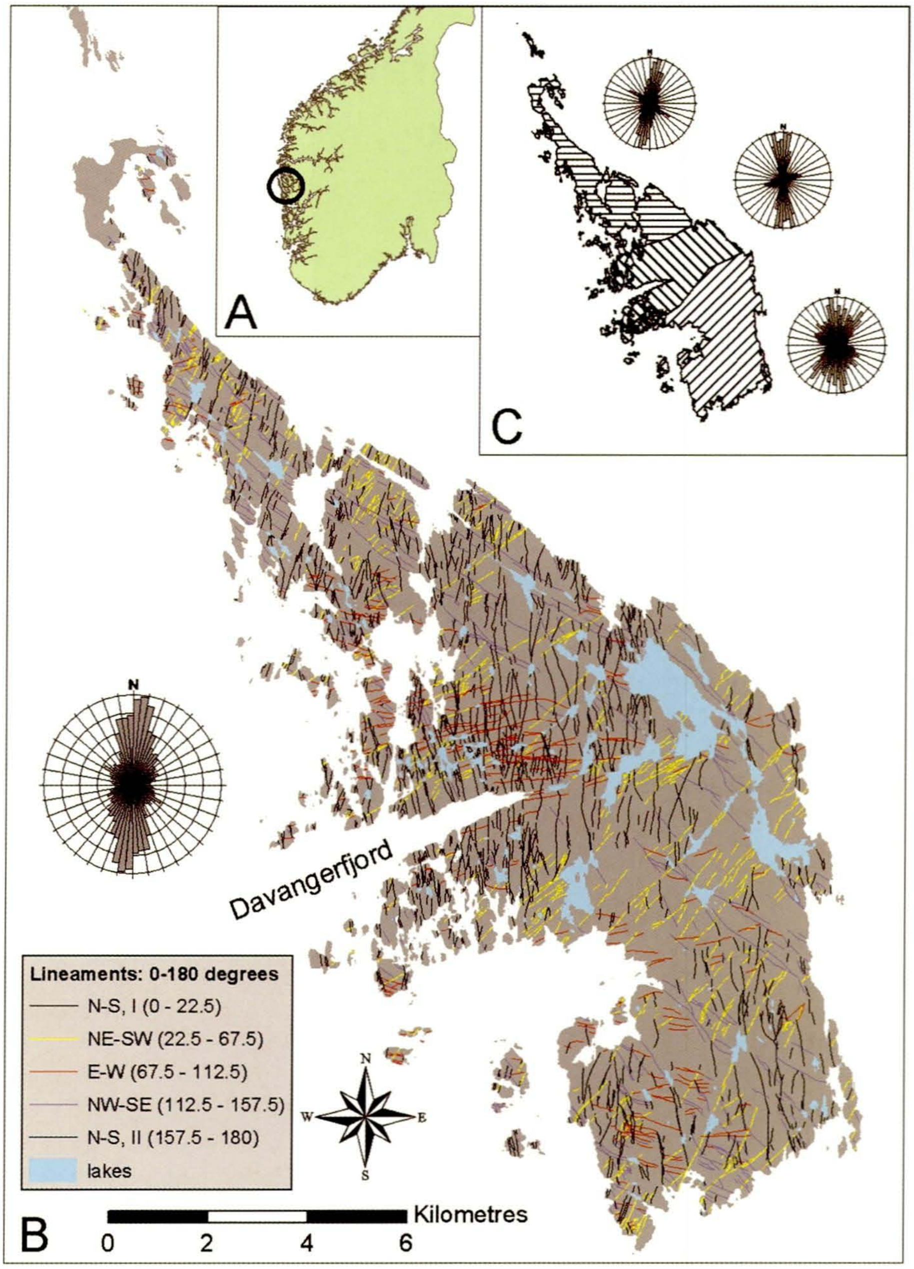

Fig. 1. (A) Map of South Norway showing the location of the study area, Askøy, an island northwest of the city of Bergen on the western coast of Norway. (B) Photolineaments (n=2695) on Askøy are derived from aerial photos at the scale of 1:15,000. The photolineaments are grouped into 4 groups according to trend. N-S-trending lineaments dominate as indicated in the rose diagram. (C) Map of Askøy showing three subareas based on an assessment of the spatial distribution of the 4 lineament groups. The varying distributions of trends indicate different structural histories between the regions.

structures of Precambrian age which are overprinted by Caledonian ductile deformation structures (Fossen 1992, 1998, Milnes & Wennberg 1997).

Around Bergen, the Upper Allochthon is structurally dominated by the Bergen Arc System which is a Caledonian nappe complex (Kolderup & Kolderup 1940, Fossen 1998). The Bergen Arc System consists of arcuate structures that, in map view, are concave to the west (Ragnhildstveit & Helliksen 1997). The pattern of fault and joint traces (lineaments), and especially the orientation of the metamorphic foliation, is related to the arcs. The Precambrian Øygarden Gneiss Complex is the westernmost unit of the Bergen Arc System and consists mostly of gneiss (granitic, amphibolitic, tonalitic and granodioritic, some of which are mylonitised), but also includes metasedimentary, amphibolitic and igneous rocks (Fossen & Ragnhildstveit 1997, Ragnhildstveit and Helliksen 1997). Almost the entire island of Askøy belongs to the Øygarden Gneiss Complex, but along the east coast, where the Main Caledonian Thrust Zone is exposed, there are rocks, mainly metasediments and mylonitic gneiss, from the Minor Bergen Arc (Milnes & Wennberg 1997, Ragnhildstveit & Helliksen 1997, Fossen 1998).

Bedrock hydrogeological studies in Norway

In southern Norway, there is a correlation (on a regional scale) between the yield of groundwater wells and current postglacial uplift rates (Rohr-Torp 1994, Morland 1997). This means that along defined profiles there is a near-linear increase in well yield from the western part of southern Norway to its eastern interior part. One explanation for this increase is that well yield is related to the stress fields generated by postglacial doming (Rohr-Torp 1994, Gudmundsson 1999).

In Norway, several studies have been made of the potential correlation between the yield of drilled wells and surface morphology, bedrock lithology and proximity to lineaments. Henriksen (1995) concluded that there is a positive correlation between valley bottoms/flatlands and well yield. Morland (1997) found significant variations in yield between different lithologies, but a low correlation between well yield and distance to lineaments mapped from satellite images in Norway. However, Braathen et al. (1999) reported no significant correlations between well yield and distance to lineaments, although they concluded that high-yield wells are most likely to be obtained when drilling into the damage zones of fracture zones.

On a local scale, yield of drilled wells in crystalline rocks is generally thought to be spatially related to specific lineaments, particularly those that are fracture zones (Gustafsson 1993). This is because clustered fracturing normally causes increased fracture porosity as well as connectivity and thus increased permeability. Field studies indicate that, for many fracture zones in Norway, the fracture intensity is a function of distance from the central part of the zone (Braathen & Gabrielsen 1998, Berg 2000). Some fracture zones, however, show little or no change in fracture frequency on approaching the centre of the fracture zone. For others, a significantly higher fracture intensity occurs mainly within the morphological escarpments of the fracture zone, compared to the host rock (Lie 2001). These results suggest that the groundwater potential does not always increase linearly when approaching lineaments. For modelling groundwater potential close to lineaments, one must also make field measurements and correlation analyses focusing on lineament trend and hydromechanical structure in relation to the hydraulic gradient.

Commonly, a fault zone can be divided into two main hydromechanical units: a core and a damage zone (Caine et al. 1996, Caine & Forster 1999). Field studies in Norway (Braathen & Gabrielsen 1998, Braathen et al. 1999) indicate that the damage zone is normally the most favourable for conducting water and therefore should be the target zone for the location of potentially high yielding wells.

A groundwater potential map for a part of the Bergen Area (Ellingsen 1975, 1978) covers the southern part of Askøy. Other studies relevant for the hydrogeology of Askøy include Kolderup & Kolderup (1940) and Askvik (1965, 1971) who focus on structural geology and petrography. Comparison of deformation structures in the Øygarden Gneiss Complex and the Jurassic Bjorøy Formation, as well as field studies, indicate a clear mechanical difference between the non-cohesive Late Jurassic or younger gouge zones and the older more brittle and cohesive fracture zones (Fossen et al. 1997, Fossen 1998). Fossen (1998) also correlates NNE-SSW-trending fracture zones on Askøy with the NE-SW-trending faults on Sotra (west of Bergen) which there predate joint systems trending NNW-SSE. This paper is primarily based on the most recent hydrogeological study of Askøy, that by Lie (2001).

Mapping and analysing lineaments

The lineaments were derived from two different data sources, namely as photolineaments and topolineaments, and then analysed in GIS. Aerial photographs were used for stereographic mapping of photolineaments on Askøy (Fig. 1B). To define more clearly the larger topographical lineaments, many topolineaments (Fig. 2) were mapped inside a GIS-interface from digital elevation data. The photolineaments were imported into GIS together with drilled groundwater wells from the bedrock borehole database of the Geological Survey of Norway (NGU). Numerical values for azimuth and length of lineaments, as well as distance from drilled groundwater wells to their nearest lineaments, were provided using spatial GIS operations.

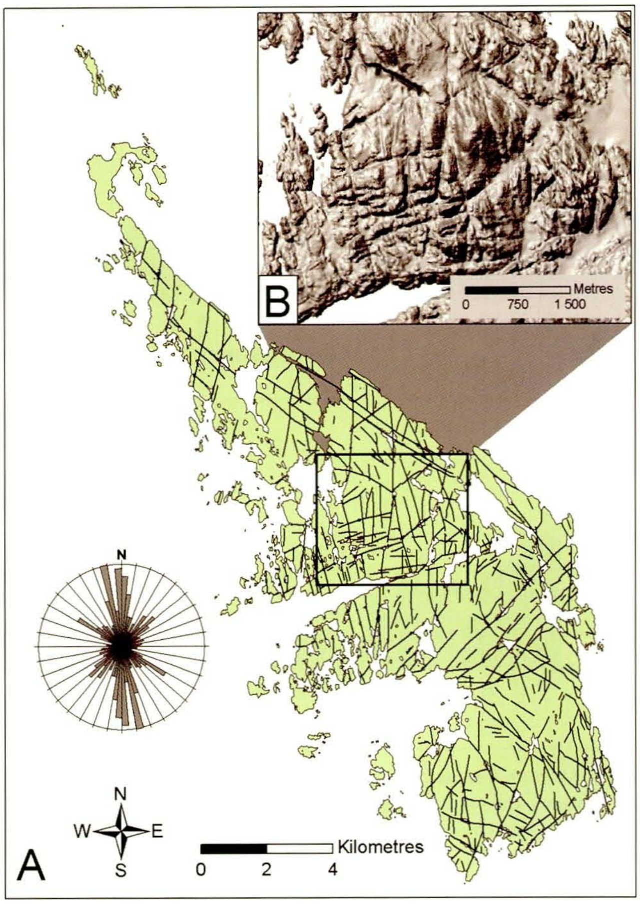

Fig. 2. (A) Map of Askøy showing topolineaments (n=409) mapped from hillshade maps of a digital elevation model (DEM), combined with the original contour lines of elevation. (B) Hillshade map, with illumination from the northwest at an altitude-angle of 45 degrees, emphasises the pattern of lineaments in a part of Askøy.

Photolineaments

A total of 2695 photolineaments longer than 75 m were obtained from aerial photographs at the scale of 1:15,000 (Fig. 1B). Most of the photolineaments on Askøy presumably represent fractures, as indicated by field studies and the morphological charactististics of the lineaments. The N-S-trending photolineaments dominate the frequency distribution, followed by the NW-SE-trending lineaments (Fig. 1B). Normalising the frequency distribution with lineament length, however, provides a different, and perhaps more usable, output for groundwater studies (Fig. 3A). In this way, short lineaments count less than long ones, and the NW-SE-trending photolineaments become more dominating (Fig. 3A). Visual inspection of the map (Fig. 1B) also shows a pronounced NE-SW trend which, however, is not very distinct in the two frequency distributions (Fig. 1B, 3A). Using trends as the only criteria, the photolineaments can be classified into

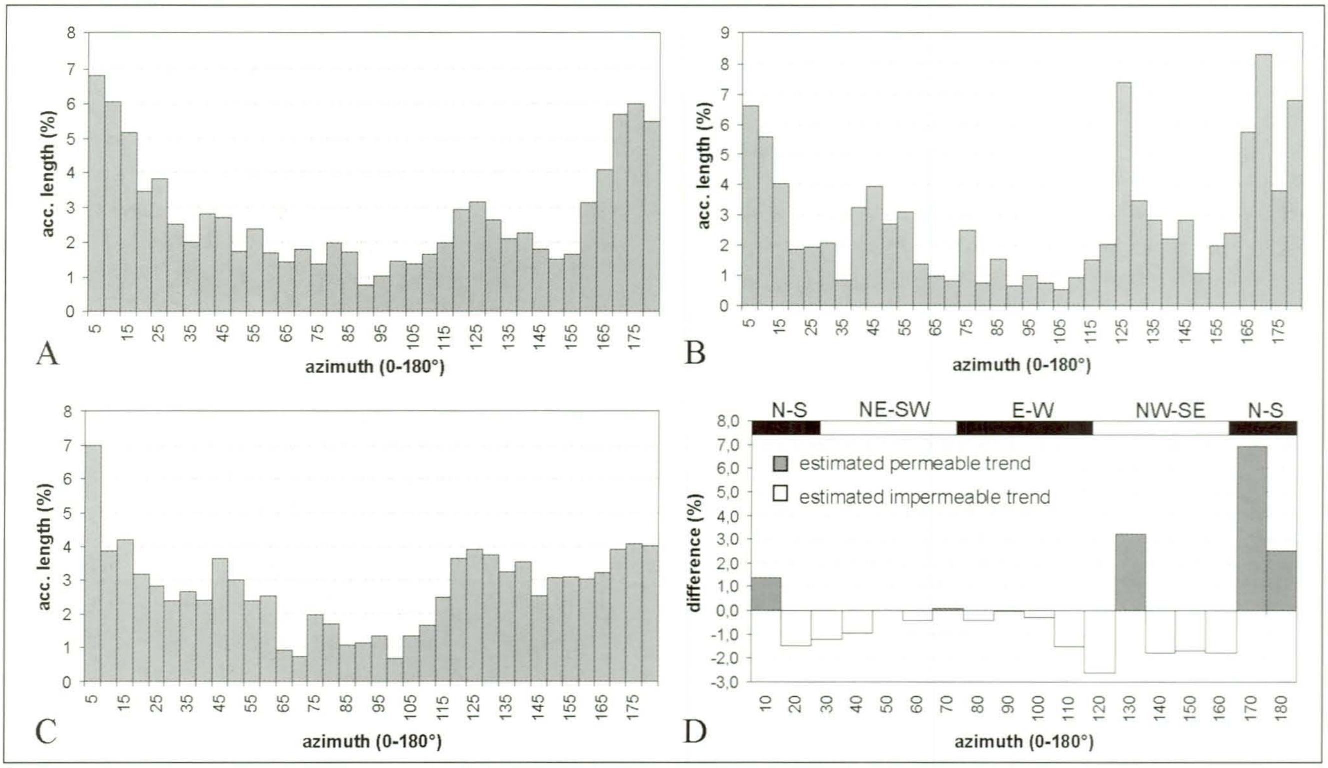

Fig. 3. Azimuth frequency distribution of photolineaments (A), topolineaments (B) and river segments (C) when weighted according to the length of the features. The vertical scale is percentage. The difference between the relative distributions of topolineaments (B) and river segments (C) in each trend class could thus be calculated as in D. This difference is a measure of the relative permeability difference between the lineament trends.

four main groups, striking N-S, NE-SW, E-W and NW-SE (Fig. 1B). These groups show differences in appearance and spatial distribution.

The N-S group dominates on Askøy, but is less intense in the southern part of the island (Fig. 1B, black lines). Some lineaments are curved and may be shallow-dipping faults, or consist of two or more structures with different trends.

The NE-SW group (Fig. 1B, yellow lines) is sparsely but evenly distributed on the island. The group consists partly of long and straight structures, some of which are known to be faults (Askvik 1971, Fossen 1998).

The E-W group is represented by lineaments mainly in two areas, namely around Davangerfjord and in a small area in the southern part of the island (Fig. 1B, red lines) .

Lineaments of the NW-SE group occur throughout the island, but are relatively sparsely represented in the region around Davangerfjord (Fig. 1B, blue lines). The largest NW-SE lineaments occur in the northeastern part of Askøy, possibly with an increasing frequency when approaching the Main Caledonian Thrust Zone (Milnes & Wennberg 1997) to the northeast.

The spatial distribution of the four lineament populations has been used as a basis for a structural classification of Askøy into three subareas (Fig. 1C). The rose diagrams indicate that the N-S-trending lineaments in the north are slightly clockwise rotated relative to those in the central part of the island (Fig. 1B, C). The NE-SW group is most evident in the rose diagram for the southernmost subarea (Fig. 1C). The classification into subareas thus shows that there may be a large local variation in lineament pattern and intensity. On Askøy this is, at least partly, due to the bedrock heterogeneity (Ragnhildstveit & Helliksen 1997), but structural and stress-field variations probably also affect the lineament distribution. These variations include changes in orientation of foliation (Kolderup & Kolderup 1940, Bjørkaas 1951, Lie 2001), proximity to thrust zones, and the somewhat different stress fields, at the time of lineament formation, associated with the different tectonic units. Many lineaments are also thought to have developed parallel to the arc structures of the Bergen Arc System (Kolderup & Kolderup 1940, Ragnhildstveit & Helliksen 1997).

Topolineaments

A total of 409 topolineaments were mapped from a digital elevation model (DEM) that was made using the ArcInfo software (ESRI 1999). Contour elevation data at 5 and 20 m intervals, and spread points of known elevation, were used to compute the DEM with the TOPOGRIDTOOL module (Hutchinson 1989). Hillshade maps (Fig. 2 B) were calculated for four illumination azimuths using Arc View Spatial Analyst (ESRI 1996), and from these maps the major depressions and hills were mapped. The frequency distribution of topolineaments, mostly large topographical depressions, indicates three main trends: N-S, NW-SE and NE-SW (Fig. 2A). They all remain pronounced after being normalised by the lineament lengths (Fig. 3B).

Bedrock borehole database

To explore the spatial well yield distribution on Askøy, groundwater well data were taken from the bedrock borehole database of the Geological Survey of Norway (NGU). In statistical analyses, well yield (litres per hour) is used as an estimator (test variable) for the groundwater potential of the bedrock. Yield values divided by well depth are also analysed, but the results are about the same as for the unmodified yield values. Only high-quality data were used in the analyses. For example, we excluded those drilled wells that due to location errors are situated in the sea, as well as those for which important information (coordinates or well yield) is lacking. A total of 72 wells were used for the analysis on Askøy.

Lineaments and yield of drilled bedrock groundwater wells on Askøy

Proximity analyses

As indicated above, many consider the yield of drilled bedrock groundwater wells to increase when approaching structural lineaments (Boeckh 1992, Greenbaum 1992, Gustafsson 1993, Braathen et al. 1999). However, many investigations show little or no correlation between distance to lineaments and well yield (Morland 1997). This may be partly due to contrasting hydraulic properties in the vicinity of different lineaments. In the following analyses the lineament trend and the hydraulic gradient, as well as the proximity to lineaments, are used to evaluate the characteristics of those lineaments that are most likely to be good conductors of groundwater.

Several factors indicate that individual lineaments have different hydraulic properties. First, most fracture zones are highly permeable only for relatively short periods of time following a seismogenic fault slip (Gudmundsson 2000). Since open, conductive fractures dominate the fluid flow in fractured media, this implies that recently active fracture zones are those most likely to yield much groundwater. Second, the hydraulic properties of lineaments depend on their trends. This is partly because the regional stress field (Hicks et al. 2000) generates different stress concentrations around lineaments of different trends (Lyslo 2000). Only those lineaments with the greatest stress concentrations are likely to be reactivated in the present stress field; and only those that become reactivated are likely to increase significantly, but temporarily, their hydraulic conductivity. The third main factor is the angular relationship between a lineament and the regional hydraulic gradient, which has large effects on the local groundwater flow (Phillips 1991, Gudmundsson 2000). Because the hydraulic gradient commonly coincides with the topographic gradient (Domenico & Schwartz 1998), this suggests that classification of lineaments according to the slope of topography is likely to be useful in groundwater yield studies.

The distance to the nearest photolineament for every single groundwater well is easily calculated in a vector-based GIS. The resulting table, consisting of a distance value and unique identification (ID) numbers for every well and lineament in pairs, allows relating every yield value to the distance to, and azimuth of, the nearest lineament. The distance from every well to the nearest lineament in each of the four trend classes (Fig. 1B) is then calculated and the well yield plotted against the distance to the lineament. The intensity of the local stress field, and thus the associated fracture frequency, falls off with increasing distance from the lineaments. It follows that the permeability and yield of wells

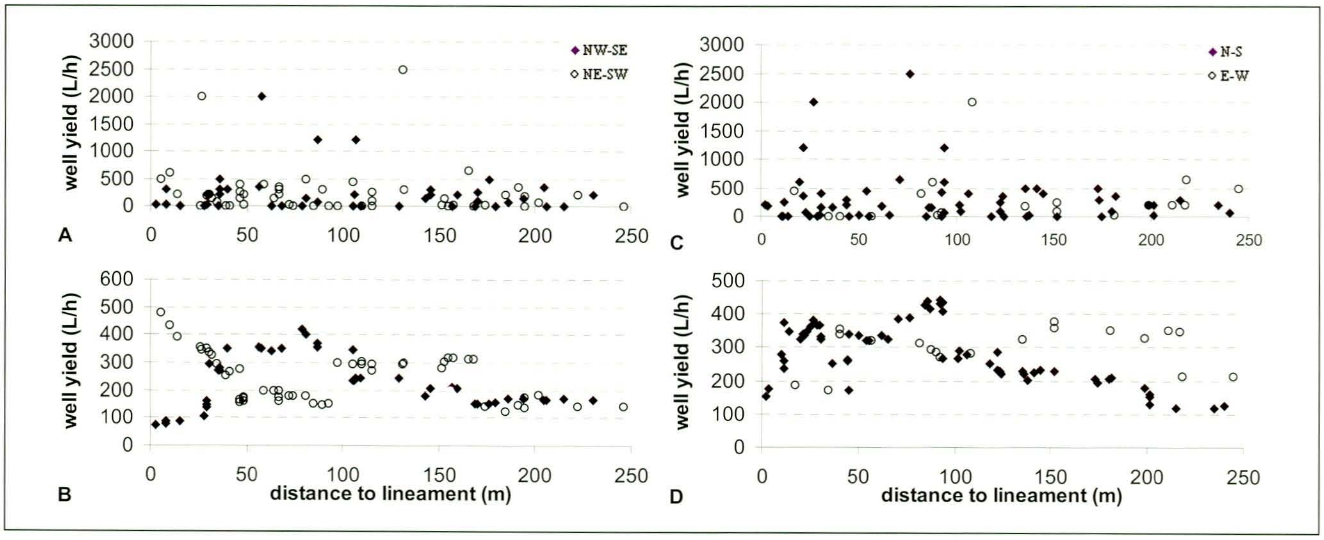

Fig. 4. Scatter plots showing groundwater well yield versus distance to lineaments of different trends. (A) Yield correlated with distance to NW-SE-trending lineaments (filled squares) and NE-SW-trending lineaments (open circles). (B) As in A, but here the data are smoothed by moving averages of 15 values. (C) Yield correlated with distance to N-S-trending lineaments (filled squares) and E-W-trending lineaments (open circles). (D) As in C, but the data are smoothed by moving averages of 15 values.

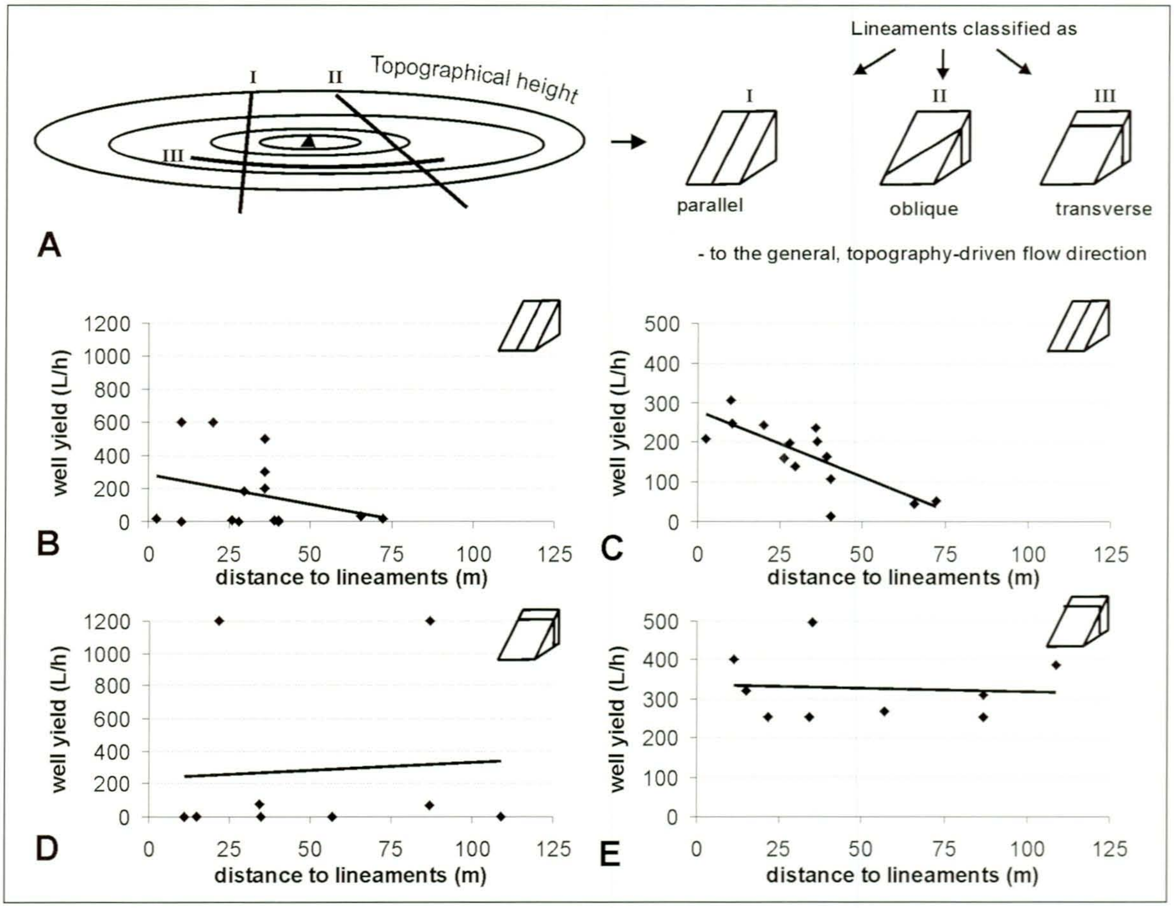

Fig. 5. (A) Lineaments are classified as parallel (group I), oblique (group II) and transverse (group III) to the assumed topography-driven groundwater flow. (B) Scatter plot showing well yield correlated with distance to group I lineaments ($R^2 = 0.085$). (C) Scatter plot showing data in B smoothed by moving averages of 5 values ($R^2 = 0.551$). (D) Scatter plot showing well yield correlated with distance to group III lineaments ($R^2 = 0.004$). (E) Scatter plot showing data in D smoothed by moving average of 5 values ($R^2 = 0.007$). R^2 denotes the goodness-of-fit for linear correlations.

are affected only out to a certain limited distance from a nearby lineament. For many lineaments, this distance would be of the order of several hundred metres. Here, we take the average distance to be 250 m, so that only wells within 250 m of a lineament are considered in the analyses.

Visual inspection of the raw data does not indicate any very clear relationship between well yield and distance to nearby lineaments (Fig. 4A, C). However, after smoothing the data by a moving average of 15 values the pattern appears less accidental (Fig. 4B, D). For the NE-SW group there is a clear increase in the yield of wells from a distance of ~100 m to the central parts of the lineaments (Fig. 4B). For the NW-SE structures, the smoothed data indicate an increase in yield of wells from a distance of ~160 m to ~75 m, but then a decrease to the central parts of the lineaments (Fig. 4B). The N-S-trending lineaments show results similar to those of the former group, except that the increase in yield starts at a distance of ~250 m from the lineament centres and continues to ~20 m from the centres where the yield suddenly decreases (Fig. 4D). The well yield shows little variation on approaching the E-W lineaments (Fig. 4D).

Photolineaments were divided into three groups according to the slope of the topography. Lineaments may be transverse, oblique or parallel to the local topography slope (Fig. 5A). We assume topography-driven flow and open aquifers, in which case the hydraulic gradient is similar to the general slope of the topography close to the lineaments. Well yield was plotted against the distance to the nearest lineament in each of the different groups. The number of wells is quite low and the results have low significance (Fig. 5B, D). Nevertheless, after smoothing the yield values, there are indications of an increase in well yield when approaching lineaments that trend parallel to the estimated hydraulic gradient (topography gradient) (Fig. 5C), while there is little variation in the well yield when approaching lineaments that trend transverse to the hydraulic gradient (Fig. 5E).

Properties of the lineament trends

Fracture profiles

Fracture profiles across fracture zones help to quantify their architecture and the attitude and spatial distribution of associated fractures. Vegetation and sediments, however, cover the important, central parts of many fracture zones on Askøy (Fig. 6 A), and information on the central parts is thus

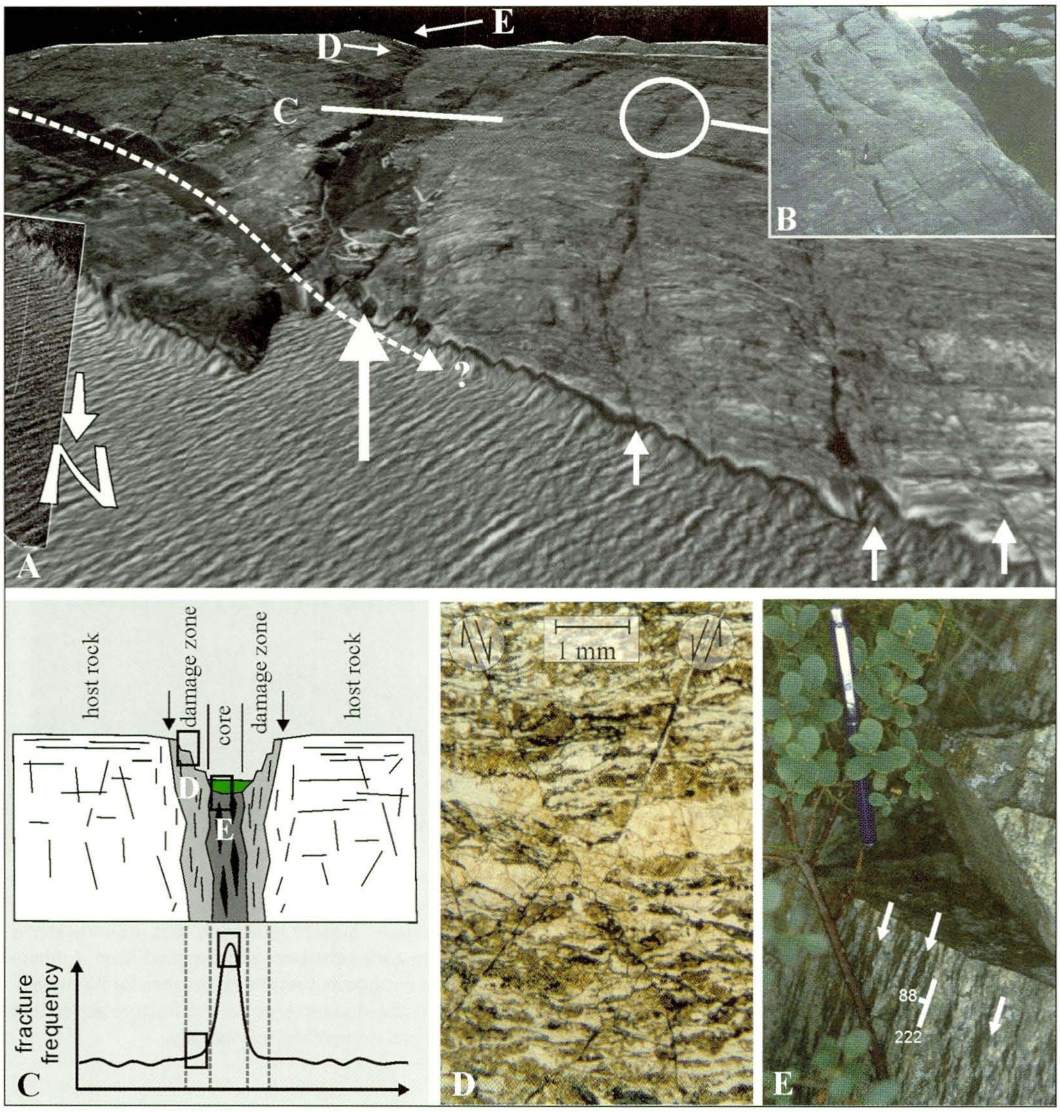

Fig. 6. (A) An aerial photograph (photo: Fjellanger Widerøe AS) of the northern coast of Askøy is put on top of a digital elevation model (DEM). Fracture zones trending N(NE)-S(SW) are indicated with arrows, and a NW-SE-trending lineament is marked with a dashed line. (B) A small N-S-striking fracture zone in A has a central part that is weak and eroded. Minor fractures subparallel to the fracture zone dominate the local fracture frequency distribution. Hammer for scale. View to the SW. For more details on these studies, see Lie (2001). (C) Conceptual model for the major N-S-trending fracture zone in A, showing a damage zone that is limited outwards by the escarpments of the topographic lineament. On Askøy, there is generally a low correlation between fracture frequency and distance to the central part of lineaments outside their morphological escarpments. (D) Many fractures in the damage zone of the fracture zone in A are faults with a dip-slip component. (E) There is evidence of high fracture intensity in the central part of the major lineament in A.

gained only from a few fracture profiles. In the well-exposed areas, that is outside the eroded, inner depressions of the fracture zones, there is little apparent correlation between the fracture frequency and the distance to the central parts of the fracture zones (Lie 2001). There exist, however, examples of very high fracture intensities in the central parts of some lineaments (Fig. 6E). The results presented here indicate that, for most fracture zones on Askøy, the zone of high fracture intensity is narrow and limited outwards by the fracture zone escarpments (Fig. 6A-C). This stresses the importance of accuracy both in field measurements, well positions and location of lineaments when dealing with groundwater flow in fractured rocks. In some fracture zones on Askøy, particularly in small, N-S-trending zones in the southern part of the island, the central parts contain non-cohesive clay minerals which may reduce the zone-transverse permeability.

Lineament and drainage frequency distributions

The distribution of topolineaments provides a large-scale framework for potential groundwater flow (cf. Berg 2000,

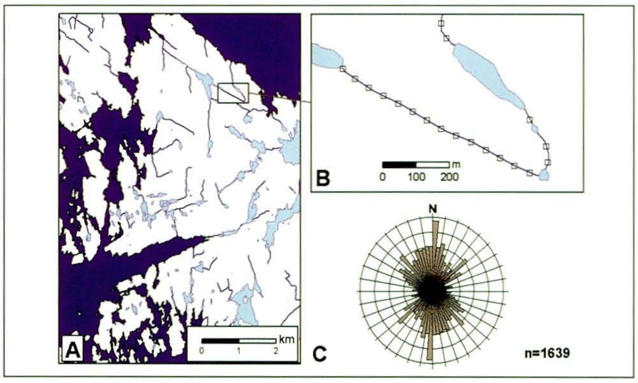

Fig. 7. (A) Rivers and lakes on Askøy (digital map N50, Norwegian Mapping Authority). Rivers are mostly guided by topographical depressions, which are mapped as topolineaments (Fig. 2). (B) The rivers are defined by nodes, indicated by small squares. In GIS, the rivers are split into segments defined by these nodes. The length and azimuth of the segments can be easily calculated. (C) N-S-trending segments dominate in number as for lineaments. Since river bends are normally defined by many points, the importance of short segments may be over-emphasised. Therefore, the azimuth distribution should be normalised with the segment lengths (Fig. 3 C).

Braathen & Gabrielsen 2000). This is because most topographic depressions reflect fracture zones, many of which may consist of open and interconnected fractures of significant permeability.

The topolineaments, being linear or near-linear depressions, also serve as a framework for river flow (Singhal & Gupta 1999). Although only some of them are occupied by rivers, the distribution of river segments is similar to that of the lineaments (Fig. 7), indicating that rivers and streams tend to follow the lineaments. In general, little associated surface runoff along lineaments may indicate high subsurface drainage (Singhal & Gupta 1999, Berg 2000, Braathen & Gabrielsen 2000) and, thus, an integrated evaluation of lineaments and rivers may give indications of the yield potential of nearby wells.

The difference in relative distribution of topolineaments and rivers is calculated in Fig. 3D. For the purpose of comparing the azimuth frequency distributions for river segments and lineaments, the azimuth frequency numbers are weighted according to the lengths of the features, and the numbers are converted into percentages (Fig. 3B, C). The histogram in Fig. 3D is calculated by subtracting the values for the rivers (Fig. 3C) from the values for the topolineaments (Fig. 3B) for each trend class. The results can be used as an indicator for whether there is much or little groundwater transport along a given lineament trend. The N-S- and NE-SW-trending lineaments appear to have the greatest, and the NW-SE-trending lineaments the least, permeability (Fig. 3D). The NW-SE lineaments strike at acute angles to the ESE-directed ridge-push in the area (Hicks et al. 2000) and would thus be expected to concentrate high shear stresses. However, many of the lineaments trending NW-SE are subparallel to, and may also be genetically related to, the penetrative, metamorphic foliation. Thus, these lineaments may have significantly different deformation histories and therefore different hydraulic properties to those of the other lineament trends.

Numerical models

The local groundwater flow pattern around a conductive fracture depends on the angle it makes with the hydraulic gradient. Analytical solutions (Phillips 1991) indicate that an open fracture normal to the general groundwater flow direction has little influence on the flow pattern so long as the fracture aperture is similar to the dimensions of the pores in the host rock. By contrast, a highly conductive fracture at a low angle to the hydraulic gradient may have large effects on the groundwater flow.

The model in Fig. 8, calculated using the MODFLOW code in the PM5 software (Chiang & Kinzelbach 1998, Harbaugh et al. 2000), simulates a vertical active fracture zone that strikes parallel to the slope of the topography. From general field data and laboratory measurements, we estimate the average hydraulic conductivity of the fracture zone as 1×10^{-3} m/s and that of the host rock as 1×10^{-10} m/s (Lee & Farmer 1993, Domenico & Schwartz 1998). Using topographical maps of Askøy, the hydraulic gradient is estimated at 0.05. The modelled fracture zone has a length of 1500 m and a thickness of 10 m. The whole model is 7 km x 4 km. The size of the model is designed to be large enough to avoid that the side-walls affect the flow pattern. The grid is enhanced in the central part of the model to provide more precise solutions close to the fracture zone.

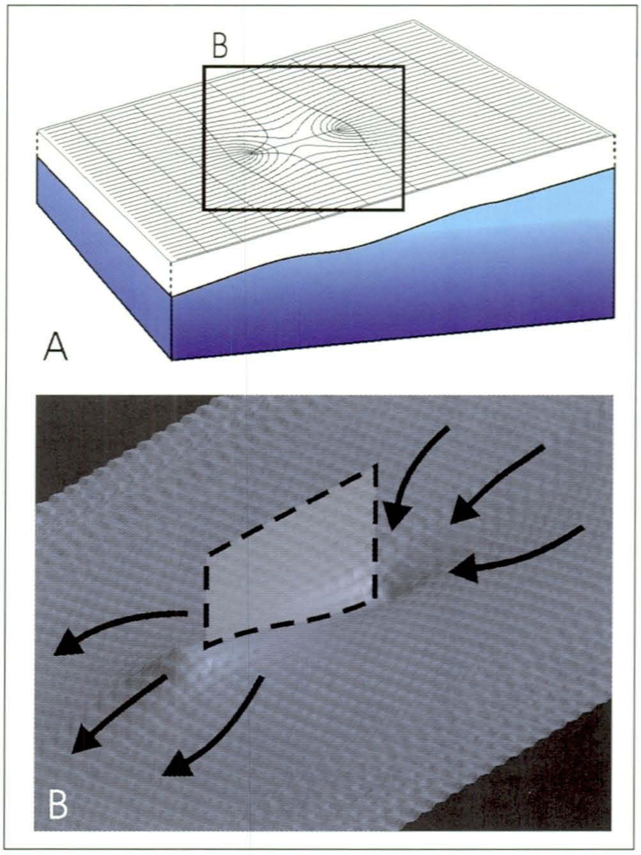

Fig. 8. (A) Simulated flow field around a highly permeable fracture zone that is subparallel to the hydraulic gradient. (B) Three-dimensional view of the estimated groundwater surface indicating that groundwater is drained into the fracture zone upstream and expelled from it downstream. This simple model suggests that the target area for high-yielding groundwater wells is the downstream part of fracture zones that run parallel with the general slope of the topography.

The lineament influences the pattern so that the flow lines converge towards its upstream part and diverge from its downstream part (Fig. 8A, B). This means that groundwater is drained into the fracture zone upstream and expelled from it downstream (Fig. 8B). A similar numerical model, but run for a vertical fracture zone that is oblique to the induced hydraulic gradient, indicates that the groundwater flow pattern is still affected, but to a lesser degree than in Fig. 8. The results indicate that, for maximum yield, groundwater wells should normally be placed inside, or nearby, the downstream parts of active lineaments that trend parallel to the hydraulic (or topographic) gradient.

Discussion

In this paper, we have focused on lineaments as the main targets for the location of groundwater wells that are drilled into bedrock. Many of these lineaments are fracture zones which have been eroded to become topographic depressions. Thus, they gain topography-driven groundwater flow. In addition, because the permeability of lineaments is normally greater than that of the host rock, they are likely to be the main conductors of subsurface water in bedrock.

Lineaments are here grouped according to their trend and their relation to the hydraulic gradient. The analyses indicate that the correlations between well yield and proximity to lineaments depend both on lineament trend and the hydraulic (topographic) gradient. When taking the lineament trend into consideration, we can account for the influence of regional stress (Hicks et al. 2000) as well as the possible different mechanical and hydraulic properties between lineaments of different trends. Topographic variations are partly included in the hydraulic gradient. The importance of the hydraulic gradient, and thus topography, is well known both from numerical (Fig. 8) and analytical groundwater flow models (Phillips 1991, Lie 2001). On Askøy, the greatest increase in well yield occurs when approaching the NE-SW-trending lineaments that strike parallel to the topographic slope.

The integration of lineaments and drainage is based on the assumption that most rivers follow the topographic depressions that are mapped as lineaments. Furthermore, we assume that little surface runoff along lineaments indicates high subsurface drainage. We have made the analysis as simple as possible, and do not consider any quantitative measures from catchment areas or volumetric flow rates in the rivers. Also, we use the drainage maps from the Norwegian Mapping Authority without modifications. For similar analyses in the future, we plan to go into more detail concerning these factors.

This study is, in some ways, similar to the one by Greenbaum (1992) in that we consider variations in well yield as a function of azimuth of associated lineaments. However, in our study the well yield is also analysed according to the distance between wells and lineaments and relationships to the hydraulic gradient. By contrast, Greenbaum (1992) compared well-yield classes, within a certain distance from lineaments, with lineament trend. We conclude that for most active fracture zones, the hydraulic conductivity (and thus the expected well yield) decreases with distance from the centre of the lineament. Aerial photographs, digital elevation data and the fieldwork presented here indicate that, on Askøy, the damage zones of the fault lineaments tend to be narrow and well defined. Because these would commonly be the target zones for groundwater wells, the accurate location of potentially high-yielding wells should normally be easy on Askøy.

In the future, additional results may be provided by improved data collection procedures (yield measurements, and more accurate well coordinates) as well as more detailed mapping of lineaments. For detailed mapping, it is possible to use GIS to combine high-resolution satellite images, orthophotos and DEMs. We suggest that a better understanding of how local and regional stresses affect the permeabilities of lineaments and other structures may be obtained by combining remote-sensing data with numerical models of crustal stresses and groundwater flow.

Acknowledgements

We thank the municipality of Askøy, the Geological Survey of Norway, the Norwegian Mapping Authority and Fjellanger Widerøe AS for data and support, and Helge Askvik, Alvar Braathen, Bjørn Frengstad and Erik Rohr-Torp for helpful and constructive comments. This work was supported by grants from the Research Council of Norway and the European Commission.

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