Aeromagnetic mapping of deep-weathered fracture zones in the Oslo Region – a new tool for improved planning of tunnels

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A new method referred to as the AMAGER Method (AeroMAgnetic and GEomorphological Relations) has been developed to map the occurrence of deep clay alteration in the bedrock of the Oslo Region. Rock instability and water leakage have caused significant problems during tunnel construction in this particular area of southern Norway. Structural weakness zones contain clay minerals, including smectite and kaolinite, and are to a large extent the result of chemical weathering of pre-existing fracture zones during sub-tropical conditions in the late Triassic, Jurassic and Early Cretaceous. The weathering penetrated deeper into the fracture zones and was preserved below Late Jurassic and Cretaceous sediments. Subsequent exhumation removed most of the deep weathering, however clay zones occurring at depths of 200-300 metres were preserved.

Deep weathering produces negative magnetic anomalies because ferromagnetic minerals such as magnetite are altered to less magnetic hematite and ironhydroxide minerals. In situ measurements at four different locations show that the magnetic susceptibility in the weathered zones is reduced by 35-93 % compared to fresh rocks. We have developed a filtering technique to enhance the magnetic signal from the weathered zones. Coinciding negative lows in the high-pass filtered topography/bathymetry and magnetic data are used as indications of deep weathering. The resulting signal is classified as 'probable' or 'possible' depending on the signal to noise ratio. The new AMAGER method has been able to detect more than 90 % of the known fracture zones inside the Lieråsen and Romeriksporten railway tunnels and the Hvaler road tunnel. Modelling of the observed magnetic field suggests that some of the low-magnetic zones continue to a depth of c. 300 metres below the surface. Engineering geologists have consequently been presented with a new tool that can facilitate the mapping of potential clay-bearing weakness zones in tunnel planning. We will, however, recommend that an experienced geologist or geophysicist is at hand to ensure that conditions necessary for using the method are satisfied before the results are applied in planning of new tunnels.

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Introduction

Experience has shown that tunnels in the greater Oslo Fjord region tend to be technically more demanding and expensive to construct than elsewhere in Norway. Problems with tunnel construction can be traced back to the beginning of the century. Building of the Holmenkollen railway tunnel in Oslo, for example, experienced many difficulties such as draining of groundwater and rock falls in clay-bearing zones (Kirkemo 2000). The lowering of the groundwater table caused compaction and subsidence of the marine clay above the tunnel, which in turn led to damage to a large number of houses. The local railway company went bankrupt because of the large amounts of money needed to compensate the house-owners. Oslo municipality had to take over the operation of this particular underground railway system.

The railway tunnel through Lieråsen, between Asker and Drammen, is another example of a failed project. Construction started in 1962 but only half of the tunnel had been completed after five years (Huseby 1968, Palmstrøm et al. 2003). The delay was caused by clay alteration along linear weakness zones resulting in rock falls and spalling. The course of the tunnel had to be altered to allow completion of the tunnel.

Water leakage and rock falls during the construction of the Romeriksporten and the Oslo Fjord tunnels are well known problems experienced during the last decade. The additional costs related to the building of the Romeriksporten tunnel amounted to approximately one billion NOK.

New tunnels in the Oslo Region represent the largest investments outside the petroleum sector in Norway. It is therefore economically profitable to map the weakness zones and improve knowledge about them.

The Geological Survey of Norway launched the GEOS Programme (GEology in the OSlo Region) in 2003 to provide geological information necessary to facilitate the large-scale urbanisation process in the greater Oslo Fjord region. Over one third of the Norwegian population lives in this area. Road and railway authorities are currently working on more than 40 different plans for the construction of new tunnels. The TIGRIS (The Integration of Geophysical Relations Into Society) research and mapping project was initiated within the framework of the GEOS Programme with the objective of improving our understanding of how clay alteration zones formed and to develop new methods of mapping these zones.

Consequently, the present paper deals with two subjects; geological processes producing substantial clay alteration and a new geophysical method to map these clay-rich zones. The tectonic history of the Proterozoic Sveconorwegian terrain and the Permian Oslo Rift has been described previously by Bingen et al. (2001), Olaussen et al. (1994), and Sundvoll & Larsen (1994). Fault and fracture zones within the greater Oslo Region have been mapped by Ramberg & Larsen (1978) and Lutro & Nordgulen (2004).

Lipponen & Airo (2006) have produced an overview of airborne geophysical methods for hydrogeological investigations. They concluded that the combination of digital terrain data and aeromagnetic data was a powerful tool for mapping fracture zones in hard crystalline rocks in southern Finland. They relate the coinciding depressions in topography and aeromagnetic data to brittle deformation along fracture zones and not to clay alteration.

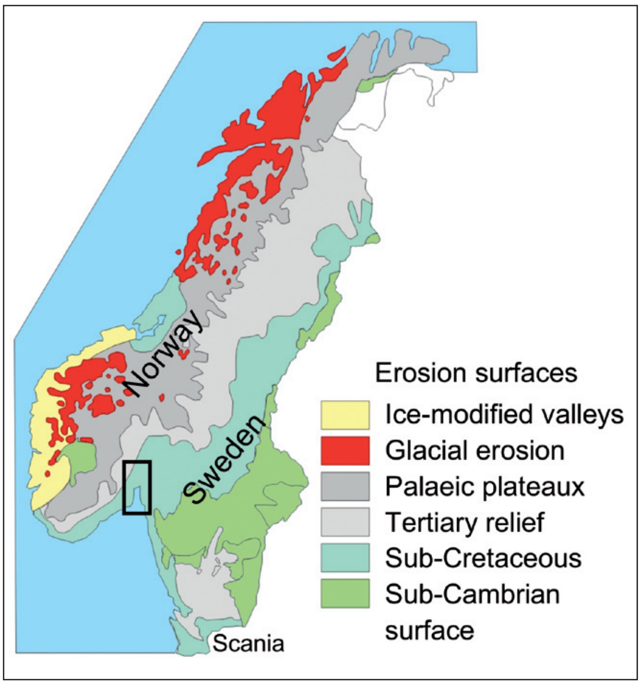

Fig. 1. Geomorphological map of western Fennoscandia (Lidmar-Bergström et al. 1999). The sub-Jurassic/Cretaceous etch-surface extends from Scania northwards along the coasts of western Sweden and southern Norway. The black frame denotes the greater Oslo Fjord region.

Saprolite – deep tropical weathering

Lidmar-Bergström (1989, 1995) proposed that the joint valley landscape of southwestern Sweden was formed during the Neogene exhumation of the Fennoscandian Shield. She studied how erosion of a thick Jurassic/Early Cretaceous saprolite along regional fault and fracture zones had caused the formation of extensive valleys in the northern Scania region. This system of joint-aligned valleys could be traced north along the west coast of Sweden all the way to eastern Norway and southwestwards along the coast of southern Norway (Figs. 1 & 2). The weakness zones in this sub-Cretaceous etch-surface are partly due to the presence of clay minerals such as kaolinite and smectite which are to a large extent the result of chemical weathering under subtropical conditions in the Jurassic and Early Cretaceous (Lidmar-Bergström 1982; Lidmar-Bergström et al. 1999). The weathering occurred originally across the entire paleo-surface, but gradually penetrated deeper into pre-existing fracture zones (Fig. 3). The saprolite was partially eroded before the Cretaceous, and the remnants of this chemical weathering were preserved below shales and carbonates deposited during the Late Jurassic and Cretaceous transgressions (c. 400 meter higher sea level). Up to 60 metre thick bodies of saprolite have been found in joint valleys in Scania (Lidmar-Bergström et al. 1999). Exhumation of southeastern Norway was initiated during the Early Cenozoic and the uplift and erosion accelerated during the Neogene. Although glacial erosion removed more of the remaining chemically weathered materials, the clay zones were preserved to depths of 200-300 metres along the fracture zones.

The occurrence of clay minerals in crystalline bedrock in the greater Oslo Region has also been studied by a large number of geologists, e.g. Låg (1945, 1963), Sæther (1964), Selmer-Olsen (1964), Rokoengen (1973), Bergseth et al. (1980), Sørensen (1988), Banks et al. (1992a,b, 1994), and Kocheise (1994). Most of these researchers favoured low-temperature fluids related to the formation of the Permian Oslo Rift as the dominating alteration agent. We think, however, that Lidmar-Bergström et al. (1999) provide a more plausible explanation for the widespread occurrence of clay minerals in the coastal areas of southern Norway and western Sweden. The strand-flat that is formed by an erosion mechanism involving freezing, thawing and wave-abrasion (e.g. Holtedahl 1953) does not cut into the etch-surface area of southern Norway and western Sweden, indicating that the exhumation can be quite young, perhaps only a few hundred thousand years.

Riis (1996) concluded from a correlation between offshore geology and onshore morphological elements that a peneplain with related deep weathering was formed during the Jurassic. His study supported the conclusions from Lidmar-Bergström (1995) that the relief in Sweden bordering southeastern Norway had an extensive cover of Late Jurassic and Cretaceous sediments. Remnants of sub-tropical weathering can also be found below Mesozoic sedimentary rocks on Andøya, northern Norway (Sturt et al. 1979) and on the continental shelf (Roaldset et al. 1993).

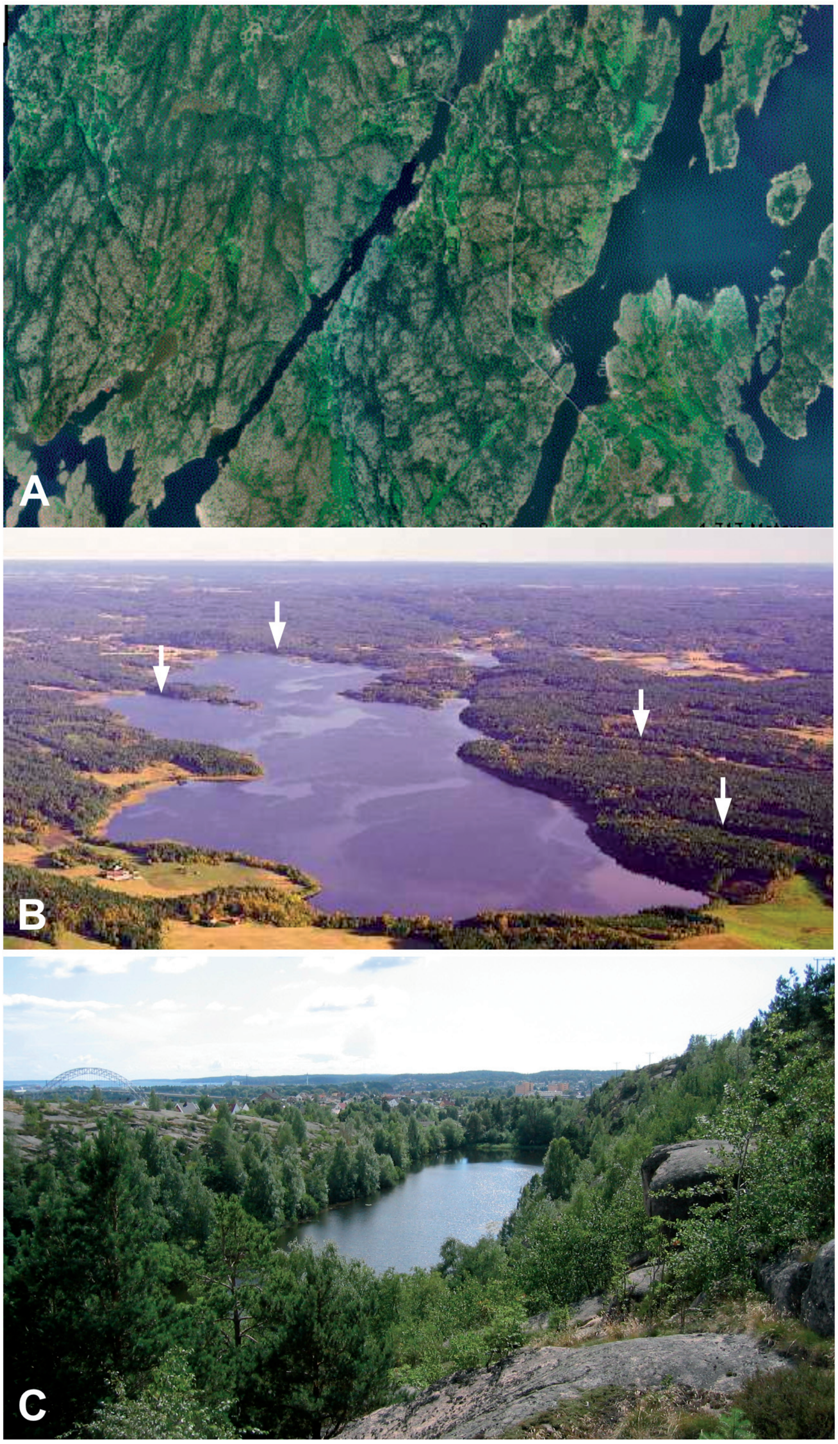

Fig. 2. Sub-Cretaceous weathered (etch-) surfaces in the southern Østfold county. The local linear depressions are interpreted to represent deeply eroded weathering along faults and fracture zones. (A) Valleys and sounds between islands in the Hvaler area. (B) Small valleys and escarpments (indicated by white arrows) around Isesjøen lake in the Sarpsborg area. (C) Linear joint valley along the Bingedammen lake in the Fredrikstad area. The centre of Fredrikstad and the Glomma road bridge can be seen in the background to the left.

This conclusion, however, is not totally new. Reusch (1902, 1903a) suggested more than a hundred years ago that the Oslo Region had been covered with Cretaceous sedimentary rocks. He based his hypothesis on a geomorphological feature defined as 'superimposed valleys'. He argued that the Numedalslågen river could not have eroded through the relatively high Skrim mountains (700-800 metres above sea level, Fig. 4) if the course was not already defined in relatively soft sedimentary rocks lying on the crystalline rocks. Reusch (1902, 1903a) also concluded that a SSE-trending paleo-river had been flowing from Valdres through Nittedal and Øyeren to the coast. This drainage system was changed after exhumation and erosion along the fault systems of the Oslo Rift and in the more soft, low-metamorphic Cambro-Silurian rocks of the Ringerike-Hadeland district. Reusch (1902, 1903a) argued further that the eroded sedimentary sequence could be of Cretaceous age since flintstones were found in Østfold county and he knew that the Cretaceous rocks in Denmark were flintstone-bearing. Reusch (1878) concluded also that the landscape was relatively little affected by the glacial erosion. Holtedahl (1953) disagreed with the conclusions

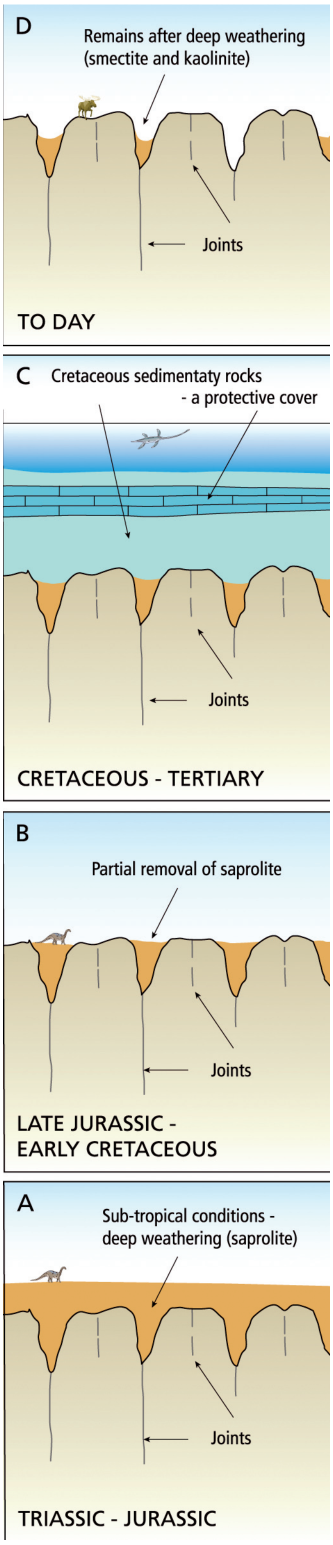

Fig. 3. Schematic illustration of the process leading to the present day deep-weathering products. A) Triassic-Jurassic sub-tropical weathering (etching) across the entire paleo-surface with deeper penetration into pre-existing fracture zones. B) Partly erosion of the weathered material during Late Jurassic or Early Cretaceous. C) Preservation of chemical weathering below shales and carbonates deposited during the Late Jurassic and Cretaceous transgressions. D) Uplift and erosion during the Neogene. The bulk of the chemical weathering was removed leaving an immature etch surface landscape with joints and faults as valleys. The clay zones containing smectite and kaolinite were preserved at depth along the fracture zones (modified after Lidmar-Bergström 1995). Magnetic minerals were selectively altered to iron-hydroxides during the weathering, yielding negative magnetic anomalies. The result is a correspondence between linear topographic depressions and negative magnetic anomalies.

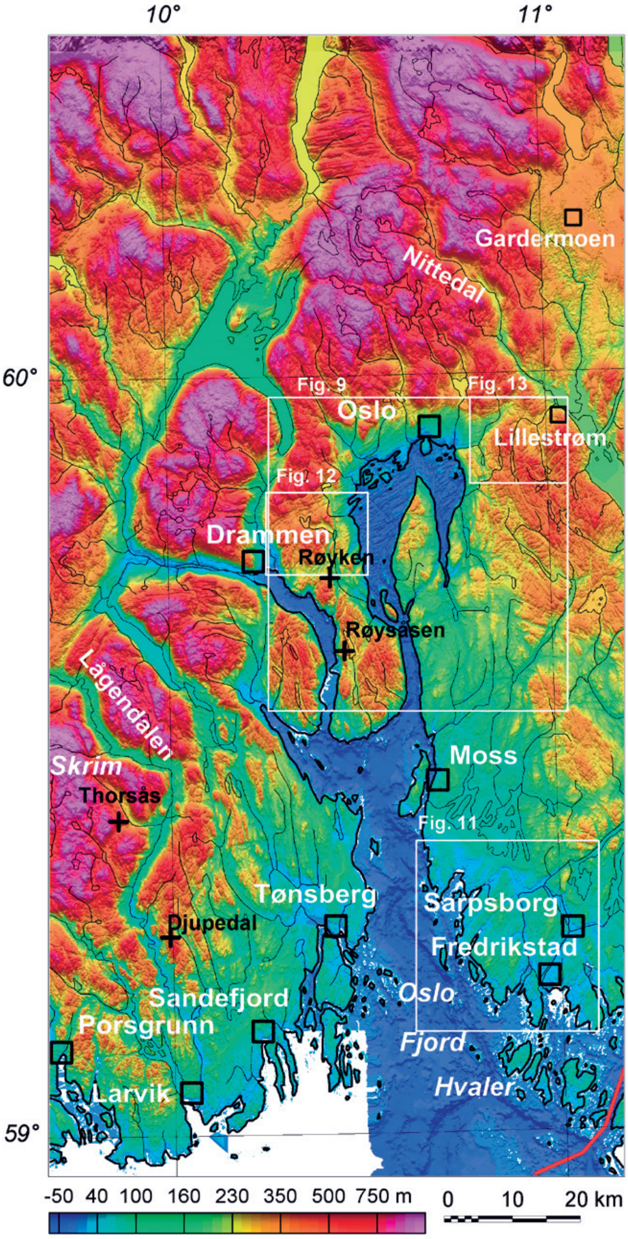

Fig. 4. Topography and bathymetry from the greater Oslo Fjord Region.displayed using the shaded-relief technique with illumination from the east. A shaded-relief version (in grey tones) of the 1 km Gaussian high-pass filtered grid has been produced and superimposed on the coloured total field map to enhance the high wave-number component of the dataset. The white frames show the inner Oslo Fjord, Fredrikstad, Lieråsen and Romeriksporten areas (Figs. 9, 11, 12 & 13, respectively).

presented by Reusch (1902, 1903a) and suggested that the valleys in the Oslo Fjord region developed primarily along regional fracture zones. Aeromagnetic maps (Lundin et al. 2005) and Fig. 8, however, do not indicate any regional fracture zones along the valleys of Lågendalen and Nittedal or the Drammen Fjord. Holtedahl (1953) did not include the correct references to the work by Reusch (1902, 1903a) and many geoscientists working with the Neogene uplift of Fennoscandia during the last two decades have not been aware of this interesting study. Reusch (1903b) also studied kaolinite deposits in Norway (including deposits in Hurdal, Seljord and Flekkefjord). He arrived at the conclusion that the Flekkefjord deposit was a result of hydrothermal activity related to volcanism (Reusch 1900).

There is also undisputed hydrothermal clay alteration

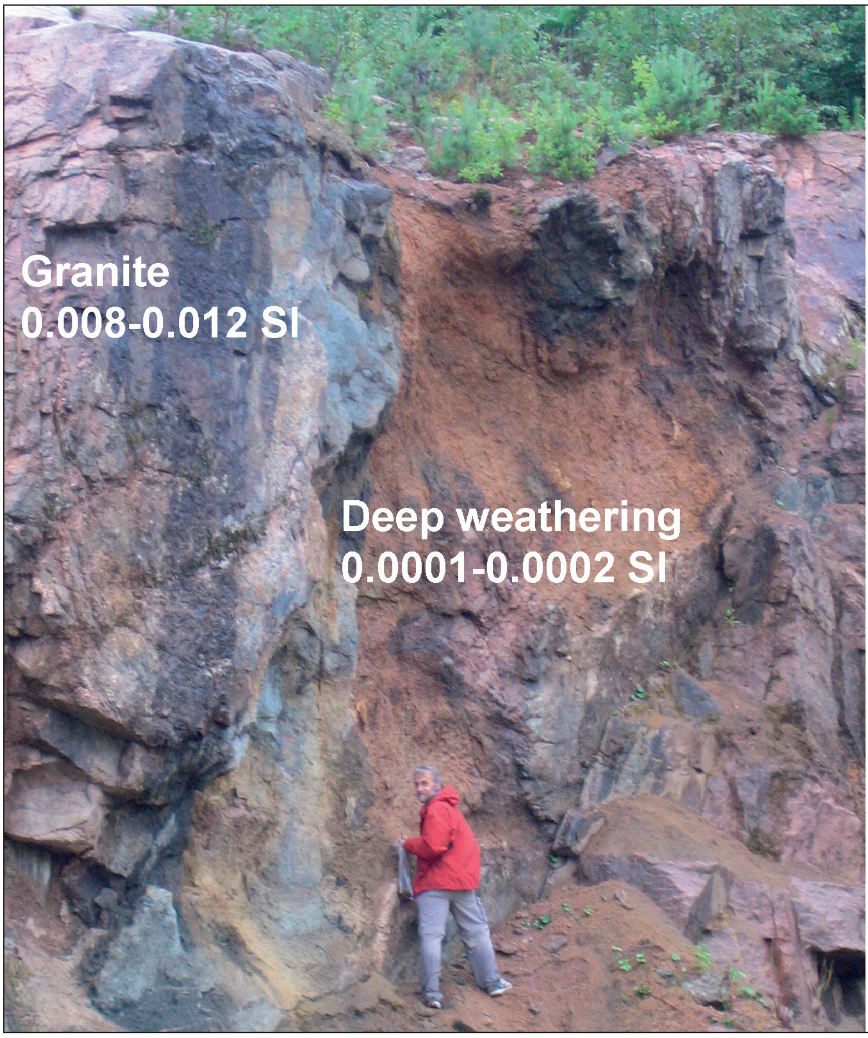

Fig. 5. Deeply weathered diabase and granite along E 23 in Røyken. The average susceptibility of the Drammen granite is 0.00940 SI while the weathered granite and diabase have a susceptibility of 0.00012 SI. Screening X-ray diffraction (XRD) and infrared spectroscopy (IR) examinations of the < 1 mm fraction of the weathered material show a predominance of mechanically disintegrated primary minerals (mainly quartz and feldspar) over newly formed clay minerals. Of the latter, mixed-layer clays, chlorite, illite and smectite dominate, but minor amounts of kaolinite have also been found.

(often referred to as propylite and argillic alteration) associated with sub-volcanic complexes and ore-forming processes in the Oslo Region (Olerud & Ihlen 1986) and some deep-seated (>1000 m) clay-bearing veins in Norwegian mines and hydropower plants (Sæther 1964, Rokoengen 1973). There is consequently no evidence that all clay-bearing fractures in the Norwegian bedrock are related to sub-tropical weathering. We think, however, that the work by Lidmar-Bergström (1989) and Lidmar-Bergström et al. (1999) has shown that most of the clay alteration associated with fractures zones in the greater Oslo Fjord region represents remnants of an originally extensive saprolite layer. This model can also explain why the clay-bearing weakness zones seem to occur as frequently outside the Oslo Rift as within it.

During tropical weathering, iron oxides such as magnetite alter to hematite and iron-hydroxides (Fig. 5) at the same time as silicate minerals are converted into clay minerals (e.g. Henkel & Guzmán 1977, Grant 1984). Ferro-hydroxides have also been observed in clay-alteration zones in the greater Oslo Fjord Region, in Vestfold (Låg 1945), and in Østfold (Kocheise 1994, Banks et al. 1994). Deep weathering will therefore create a negative deviation in the Earth's magnetic field. It is generally observed that the thick layer of weathered rock (saprolite) in tropical areas can be subdivided into several weathering zones (Fig. 6; Acworth 1987). The deeper zones are often dominated by granular friable layers of disintegrated crystal aggregates and rock fragments while a more shallow zone has a massive accumulation of secondary minerals (clays) though some stable primary minerals may still be present in their original form. The shallow zone has low permeability while the deeper zone has intermediate permeability.

Datasets

The topography grid was produced using digital hypsographic and hydrographic vector data at the scales of 1:5.000 and 1:10.000. A TIN (triangular irregular network) was produced, using all elevation data with hydrographic features used as breaklines. This TIN was then resampled onto a regularly spaced grid (25x25m). The bathymetry of the inner Oslo Fjord was acquired by the Marine Geology Group of the Geological Survey of Norway using the multi-beam echo-sounder instrument on board the research vessel R/V Seisma. The bathymetry of

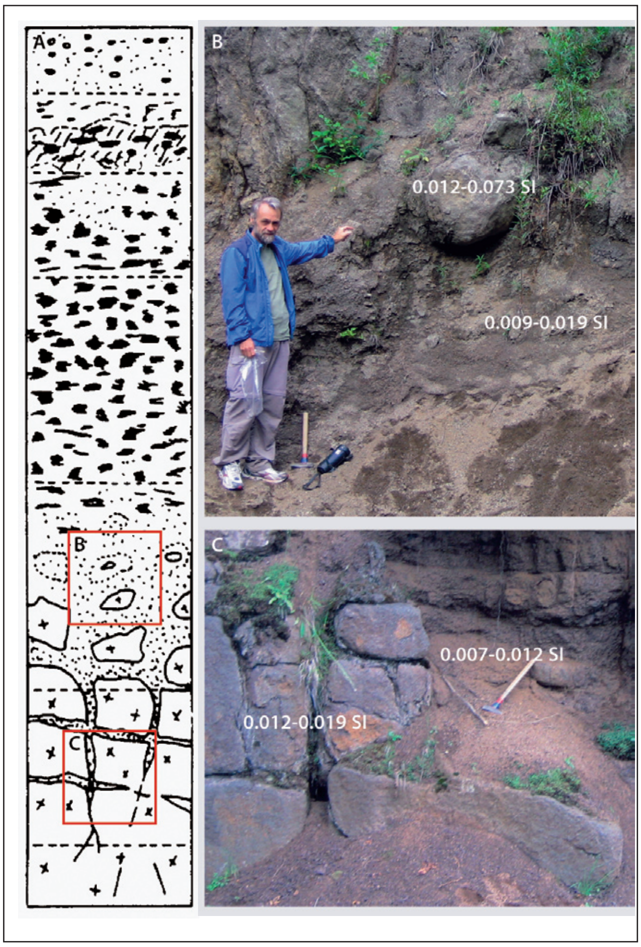

Fig. 6. (A) Generalised tropical weathering profile (Acworth 1987) separated into two upper soil horizons (red sandy soil and laterite) and four lower alteration zones (two clay zones, a granular friable layer and a lowermost zone of fractures and fissured rock). The total thickness of the profile may reach 100 metres in normal bedrock but may be significantly thicker along regional fracture zones. Photograph B and C which are from field localities in the southern Oslo Region, illustrate examples of weathering from the two lowermost zones. Screening X-ray diffraction (XRD) and infrared spectroscopy (IR) examinations show that the < 1mm fraction of the weathered material consists of a mixture of mechanically disintegrated primary minerals and newly formed clay minerals including chlorite, illite and mixed-layer clays. The mechanically disintegrated minerals are the most abundant. The locations have also been described by Sørensen (1988). The white numbers show that the magnetic susceptibility is lower within the weathered zones compared to the fresh larvikite. (B) Remnants of weathering in a regional fracture zone in Djupedal, Larvik. Core-stones of relatively fresh larvikite can be found in a granular layer of disintegrated crystal aggregates. The mean of susceptibility measurements on the core stones is 0.02620 SI, while the mean of the weathering is 0.01400 SI. (C) Weathering along fracture zones in larvikite at Thorsås, Siljan. The mean susceptibility on the apparently fresh larvikite is 0.01510 SI, while the mean of the weathered zones is 0.00980 SI.

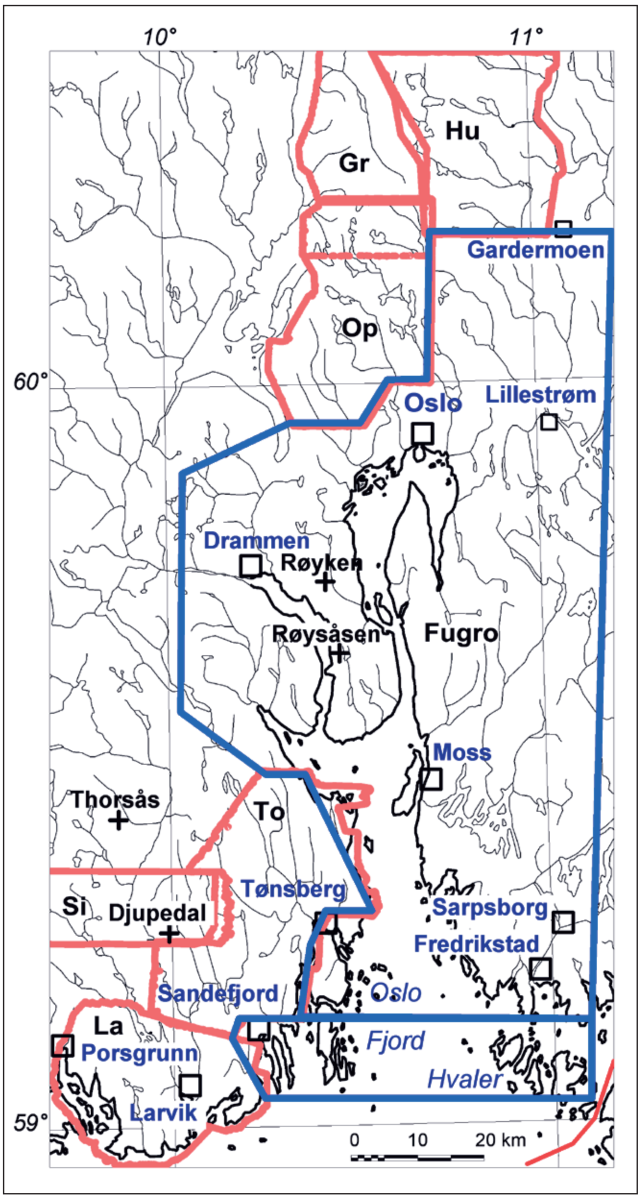

Fig. 7. Location of the helicopter and fixed-wing surveys in the Oslo Fjord Region, shown with red and blue colours, respectively. Abbreviations for individual helicopter surveys: Gr - Gran (Beard 1998), Hu - Hurdal (Beard & Mogaard 2001), Op - Oppkuven (Beard 1998, Beard & Rønning 1997, Beard & Lutro 2000), La - Larvik (Mogaard 1998, Beard 1999), Si - Siljan (Håbrekke 1982) and To - Torp (Mogaard 2001). The fixed-wing survey acquired by Fugro Airborne Surveys (2003) is shown with two blue frames.

the outer Oslo Fjord was compiled by the Norwegian Mapping Authority (SK) and the Norwegian Institute of Nature Research (NINA) (Lars Erikstad, pers. comm. 2004). The different grids were merged into one grid using Boolean operation (Geosoft 2004). The final grid is shown in Fig. 4.

The results of a total of 7 aeromagnetic surveys (Fig. 7) have been compiled in the present study. Aeromagnetic data from the northern and southwestern areas were acquired by helicopter surveying conducted by the Geological Survey of Norway during the time period 1982-2001 (c. 16.000 km). The pattern of flight lines generally provides data along E-W-trending profiles (except for the Gran survey that was flown along N-S trending lines). The line spacing and flight altitude were 200 and 60 metres, respectively. Fugro Airborne Surveys (2003) carried out a larger survey of c. 24.000 km to cover the relatively flat areas to the east and north of Oslo Fjord (Fig. 7). The flight altitude was here 60 and 100

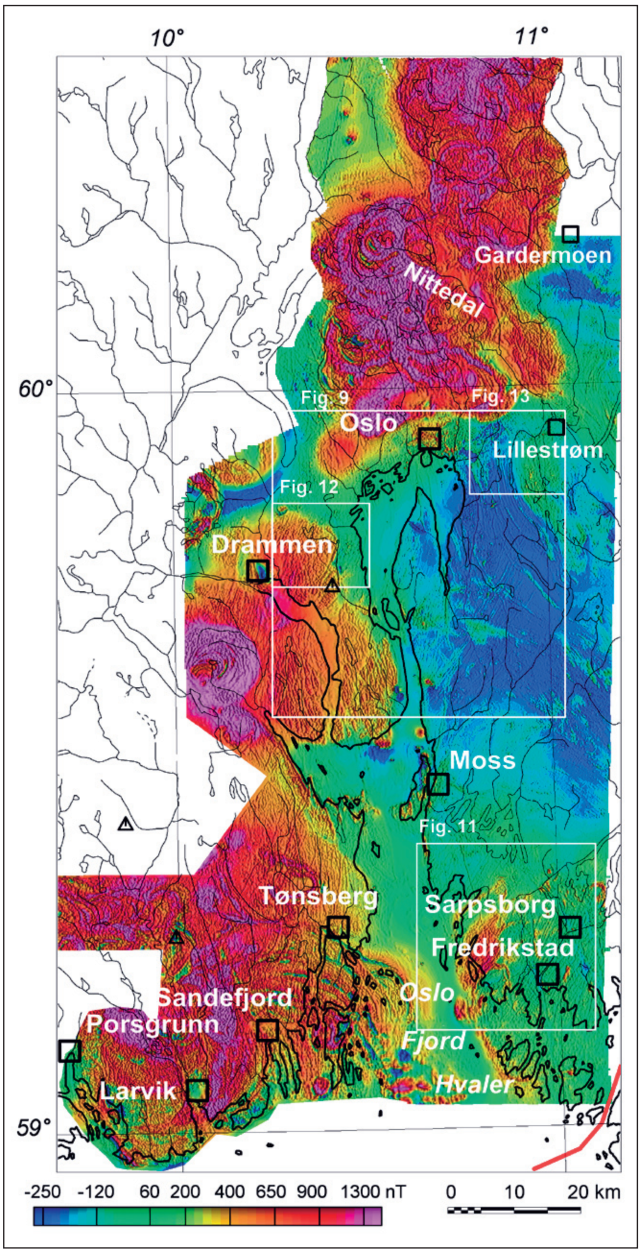

Fig. 8. Compilation of aeromagnetic surveys in the greater Oslo Fjord Region. To enhance the high wave-number component of the compiled dataset, a shaded relief version (in grey-tones) of the 1 km Gaussian high-pass filtered grid has been produced and superimposed on the coloured total field map. The white frames show the inner Oslo Fjord, Fredrikstad, Lieråsen and Romeriksporten areas (Figs. 9, 11, 12 & 13, respectively).

metres in rural and urban areas, respectively. The line spacing was 250 metres. A relatively small area in the outer part of Oslo Fjord (Fig. 7) was flown with a line spacing of 500 m. The horizontal and vertical gradients were measured using optical pumping cesium magnetometers. The measured transverse horizontal gradient was applied in the gridding process to improve the resolution of the grid.

The grids were merged into one grid of 25x25 metre cells using the minimum curvature algorithms, Gridknit, developed by Geosoft (2005a). The final grid is shown in Fig. 8.

Methods

We have developed a filtering technique to enhance the magnetic signal from the weathered zones. The magnetic field has been reduced to the magnetic pole and continued downwards from an altitude of 60 metres to 30 metres to enhance the magnetic anomalies using a frequency-domain filtering package (Geosoft 2005b). We have further carried out a 1 km Gaussian high-pass filtering of both the magnetic (Fig. 8) and topography/bathymetry (Fig. 4) grids. Coinciding negative anomalies in the two high-pass filtered datasets are used as indications of deep weathering. The resulting signal is classified as 'probable' or 'possible' weathering depending on the signal to noise ratio. Pronounced anomalies with amplitudes below -5 m and -5 nT are classified as 'probable', while less pronounced anomalies between -5 m and -2 m and between -5 nT and -2 nT are classified as 'possible'. The result has been displayed at a scale of 1:100.000 (Olesen 2006).

We carried out forward modelling of the magnetic field to interpret the depth extent of the alteration zones, applying the interactive forward modelling software IGMAS (Götze & Lahmeyer 1988, Schmidt & Götze 1998). The program uses parallel vertical cross-sections with a polygonal structure and triangulates between the sections. A susceptibility of 0.00010 SI was applied to the weathered zone and 0.01500 SI to the host rock. These two numbers are based on average values of *in situ* measurements on weathered Drammen granite within the Oslo Fjord region and fresh bedrock exposures of the Iddefjord granite in the Fredrikstad area, respectively.

The *in situ* magnetic susceptibility has been measured on both fresh bedrock and weathered bedrock to check that the magnetisation has decreased due to the sub-tropical weathering alteration. We applied the Microkappa (Model KT-5) from Geofyzika Brno that is based on electromagnetic induction utilising an air-cored coil with a diameter of 55mm. The accuracy of the instrument is 1x10-5 SI. We measured four different locations: at the Røysåsen mine in Hurum, the E 23 in Røyken, Thorsås in Siljan and Djupedal north of Larvik (Fig. 4, Table 1). The results from the latter three locations are also shown in Figs. 5 & 6.

We have also calculated the average water yield of wells located both inside and outside the interpreted weathering zones (classified as 'probable'). The data were extracted from the national groundwater database at NGU (Gundersen & Gaut 2005).

Results

The linear anomalies in the aeromagnetic dataset (Figs. 8 & 9) have several origins and can be related to:

a) faults of various age and origin (with or without Permian dike intrusions)
b) Permian dikes
c) joints and fractures deeply weathered in the Mesozoic (mainly Jurassic and Early to Middle Cretaceous).

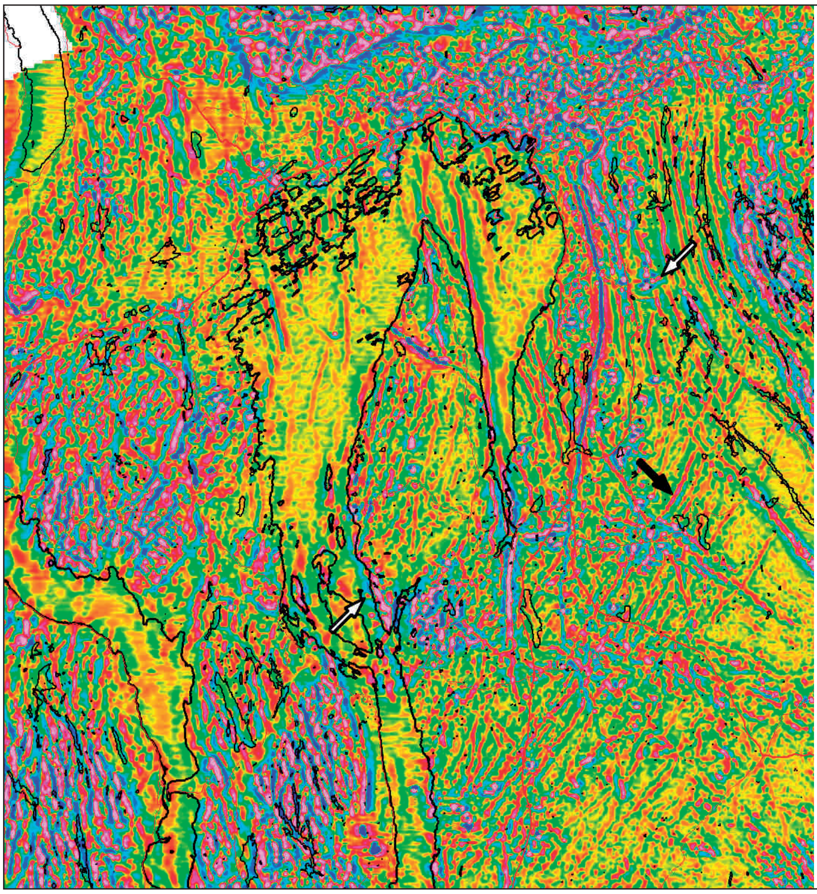

Fig. 9. Gaussian 1-km high-pass filtered aeromagnetic data from the inner Oslo Fjord – Drammen Fjord region. A large number of the negative aeromagnetic anomalies are caused by deep weathering. Other negative anomalies are contact anomalies to positive anomalies e.g. related to Permian dyke intrusion. The black arrow points to a Permian diabase dyke in the central eastern part of the map area. Two anomalies, marked with white arrows can be related to man-made structures, the shipwreck of the warship Blücher and the waste disposal area, Grønmo.

Deeply weathered joints and fractures are characterized by negative anomalies due to the oxidation of iron-bearing minerals. These anomalies, therefore, show a good correlation with linear topographic depressions (Figs. 10 & 11). This phenomenon is also observed along fracture zones in northern Sweden and southern Finland by Henkel & Guzmán (1977) and Lipponen & Airo (2006), respectively. Henkel & Guzmán (1977) suggested that the alteration of magnetite to hematite and Fe-hydroxides was related to near-surface alterations at low temperature, high oxygen fugacity and the presence of water.

We have measured the magnetic susceptibility at four different locations with outcrops of weathered rocks: at the Røysåsen mine in Hurum, the E 23 in Røyken, Thorsås in Siljan and Djupedal north of Larvik (Fig. 4, Table 1). The results from these locations show that the susceptibility in the weathered zones is reduced by 35-93 % compared to the fresh rocks (Table 1). The susceptibility data from the latter three locations are also shown in Figs. 5 & 6. The mean susceptibility measurements of the apparently fresh Drammen granite at the fourth location (the entrance portal at Røysåsen mine) is 0.00116 SI, while the mean value of the weathered zone on the left side of the entrance is 0.00008 SI (Table 1). The weathered material has a gravelly to sandy structure and consists mainly of mechanically disintegrated rock fragments together with primary quartz and feldspar grains. Screening infrared spectroscopy (IR) examinations of the < 1 mm fraction of the weathered material indicate that smectite is the most abundant secondary clay mineral. Smaller amounts of kaolinite are also present. The Røysåsen and Djupedal locations are situated within 4-5 km long zones of 'probable deep weathering' on the interpretation map (Olesen 2006). The Thorsås location is situated outside our survey area (Fig. 7) while the new E 23 location in Røyken is too local (1 m wide) to show up on the interpretation map, i.e. it does not have any topographical signature.

The application of the more strict thresholds (-5m and -5 nT) in the filtering process provides a result that coincides mostly with linear zones with known clay alteration zones, for example in the Drammen granite (Huseby 1968). The less strict criteria of -2m and -2 nT also reveal alteration zones in relatively low-magnetic bedrock but in addition produce some artefacts that are unlikely to be related to clay alteration since some of them occur as isolated patches spread out in the terrain. It is possible to select thresholds that will provide a better result for a restricted area. The chosen parameters, however, represent compromises that produce acceptable results in most of the greater Oslo Fjord Region (e.g. the Lieråsen and Romeriksporten areas Figs. 12 & 13). We notice that most of the weakness zones encountered in the Lieråsen and Romeriksporten railway tunnels are also mapped in the interpreted deep weathering zones. Weakness zones observed in the Oslo Fjord road tunnel (Palmstrøm et al. 2003) and Hvaler road tunnel (Larsen 1990) also appear on our deep weathering interpretations even though these tunnels are located

Table 1: Magnetic susceptibility measurements on fresh and weathered rocks at four different localities (Figs. 4, 5 & 6) in the grater Oslo region. UTM coordinates are shown with datum WGS-84 and the susceptibility data are in SI units. The geology of the Thorsås and Djupedal localities is described by Sørensen (1988) and the Røysåsen locality is reported by Ihlen & Martinsen (1986).

Location	Rock type	UTM coord. WGS-84	Fresh rock			Weathered rock		
			No	Min. max.	Mean	No	Min. max.	Mean
Røysåsen, Hurum	Granite	582110-6611920	10	0.00019-0.00273	0.00116	16	0.00002-0.00060	0.00008
E 23, Røyken	Granite, diabase	579970-6622641	23	0.00803-0.01180	0.00940	16	0.00001-0.00069	0.00012
Thorsås, Siljan	Larvikite	548920- 6586790	13	0.01200-0.01870	0.01510	13	0.00667-0.01240	0.00980
Djupedal, Larvik	Larvikite	556540-6569790	30	0.01130-0.06920	0.02620	24	0.00927-0.01890	0.01400

c. 100 metres below sea level. The directions of some of the interpreted extensions of the weathering zones deviate, however, to some extent from the previous interpretations. It is not possible to determine which of these interpretations is the correct one since none are based on observations within the fracture zones. The interpreted deep weathering zones are less continuous than the mapped weakness zones (Figs. 13 & 14). This may relate to heterogeneous alteration along the fracture zones but is most likely caused by a reduced resolution of the method due to varying magnetisation of the adjacent bedrock.

The new AMAGER method detects 15 of 16 (i.e. 94 %) of the known fracture zones in the Lieråsen and Romeriksporten railway tunnels and the Hvaler road tunnel. Modelling of the observed magnetic field suggests that some of the low-magnetic zones continue to a depth of c. 300 metres below the surface (Fig. 14).

The average water yield of the 5438 groundwater wells located outside the interpreted zones of deep weathering (classified as 'probable') is 24% higher than the yield of the 127 wells located within the weathering zones (Table 2). The water yield is normalised by calculating the yield per meter of the well depth. We also restricted our study to wells drilled later than 1980 because we assume that younger wells have a more accurate location than the vintage wells. We found that 1907 wells located outside the interpreted weathered zones had a 47 % higher average yield than the 58 wells located inside the interpreted deep-weathering zones. This supports our conclusion that the interpreted weathering zones represent remnants of a more extensive saprolite. The abundance of clay minerals such as smectite and kaolinite clogs the fracture zones and reduces the water permeability of the bedrock. This conclusion is supported by the fact that most water leakage occurs at great depths (c. 200 m) in the Romeriksporten tunnel, i.e. below the lakes Lutvann and Puttjern (Palmstrøm et al. 2003). Fig. 15 shows a conceptual model of how stability problems and water leakage are dependant of the depth of the tunnel. Stability problems will be more frequent at shallow depths while water leakage most likely will occur at greater depths in weakness zones.

Table 2: Average water yield of groundwater wells within and outside the interpreted zones of deep weathering (classified as 'probable'). The water yield is normalised by calculating the yield per meter of the well depth.

	Number of wells	Average yield l/hr pr. meter	Difference %
Within weathered area	127	32	- 19
Outside weathered area	5438	39	+ 24

Discussion

Banks et al. (1992a,b, 1994) pointed out that regional fracture zones in the Iddefjord granite on the island of Hvaler in Østfold county had a low transmissivity and were filled with swelling-clay mineral infillings. They concluded that interpretation by geophysical and remote sensing methods might not always be a satisfactory method for locating groundwater resources in hard rock aquifers. Banks et al. (1992a, 1994) considered both a deep weathering process and hydrothermal alteration to explain the observed clay alteration, but favoured hydrothermal fluids originating from the Permian Oslo Rift and its associated volcanism as the alteration agent. Our study of deep weathering in the Oslo Fjord Region explains these low transmissivity zones as remnants of deep weathering rather than being caused by low-temperature alteration by Mg- and Ca-rich fluids as sug-

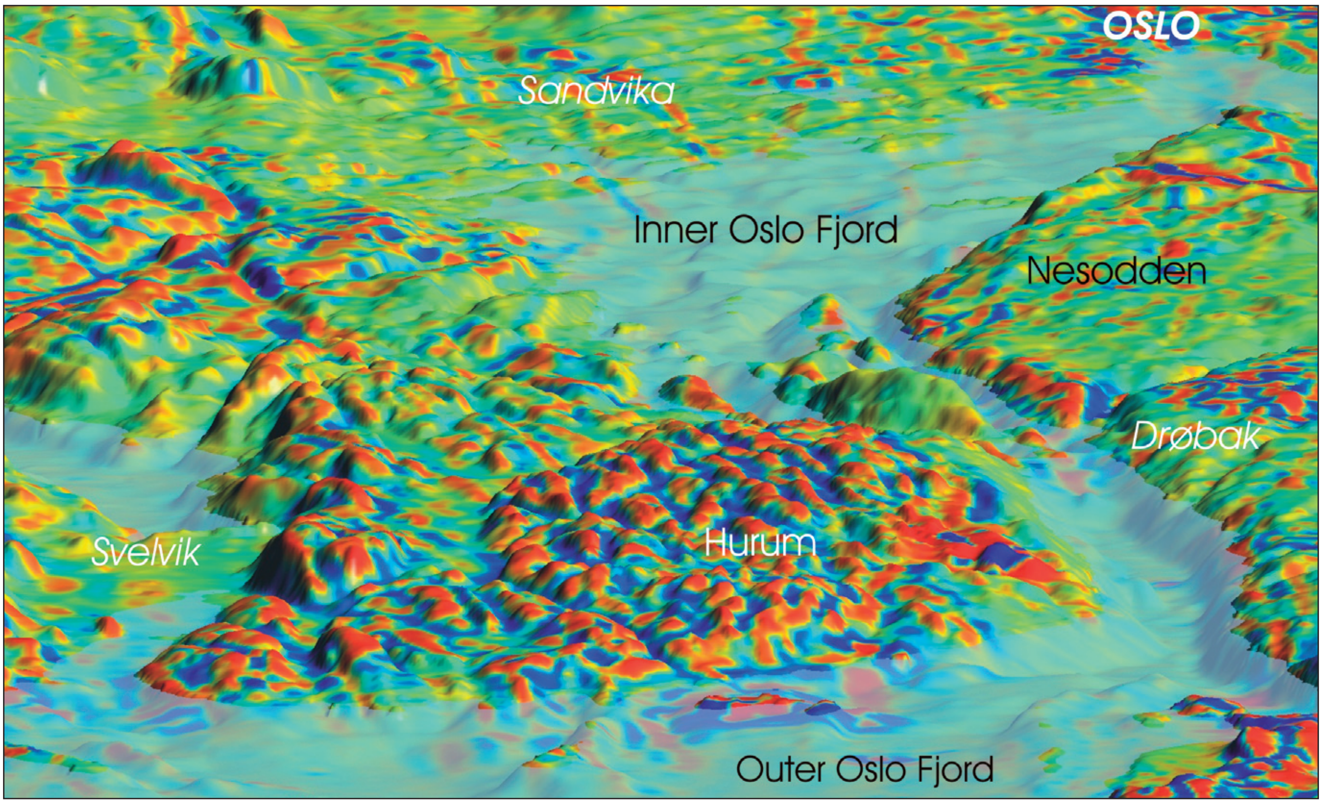

Fig. 10. 1-km high-pass filtered aeromagnetic data draped on the digital terrain-model of the inner Oslo Fjord Region. Note that the negative magnetic zones associated with the joint valleys can be traced into the Oslo Fjord. We have applied a vertical exaggeration of 3 to visualise better the relationship between topography and aeromagnetic data.

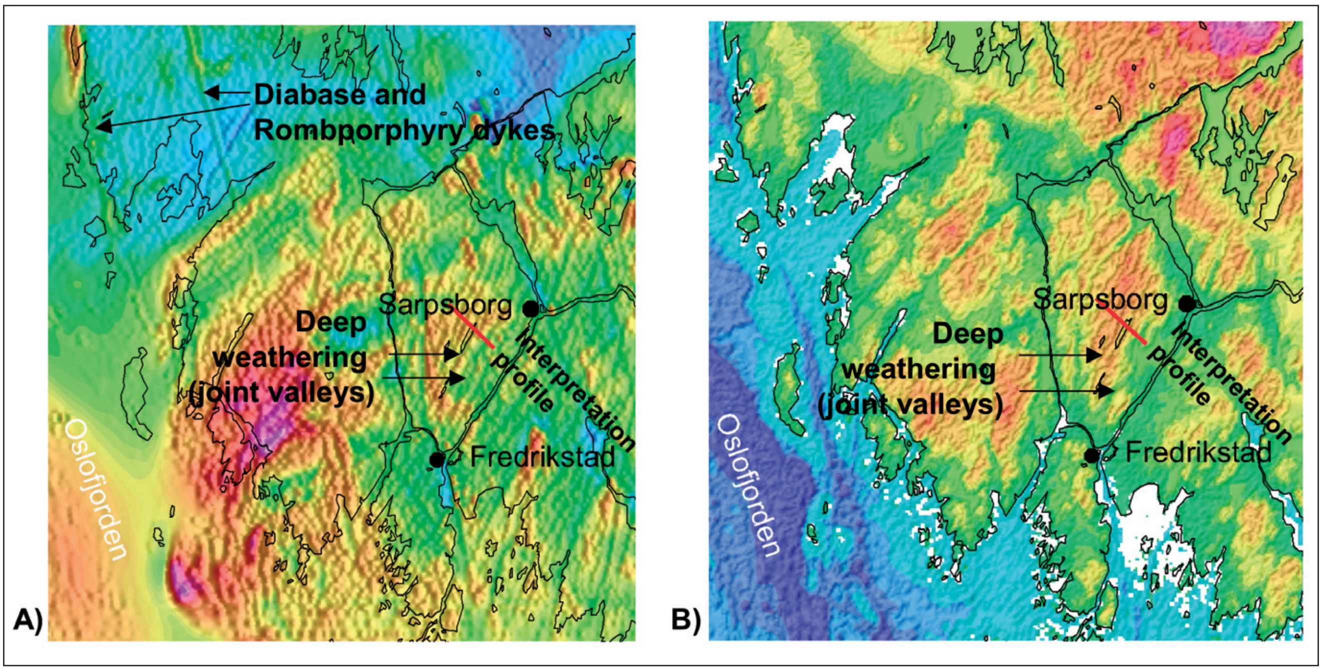

Fig. 11. Aeromagnetic data and topography of the southern Østfold county. A) Aeromagnetic data displayed with the total field referred to IGRF-2003 in colour and a shaded-relief version of the 1-km high-pass residual in grey tones. B) A shaded relief version of the 1-km high-pass filtered topography and bathymetry superimposed on a colour version of the same dataset. The so-called 'joint valleys' are caused by erosion along deeply weathered fracture- and fault-zones. The red line denotes the location of the interpretation profile in Fig. 14.

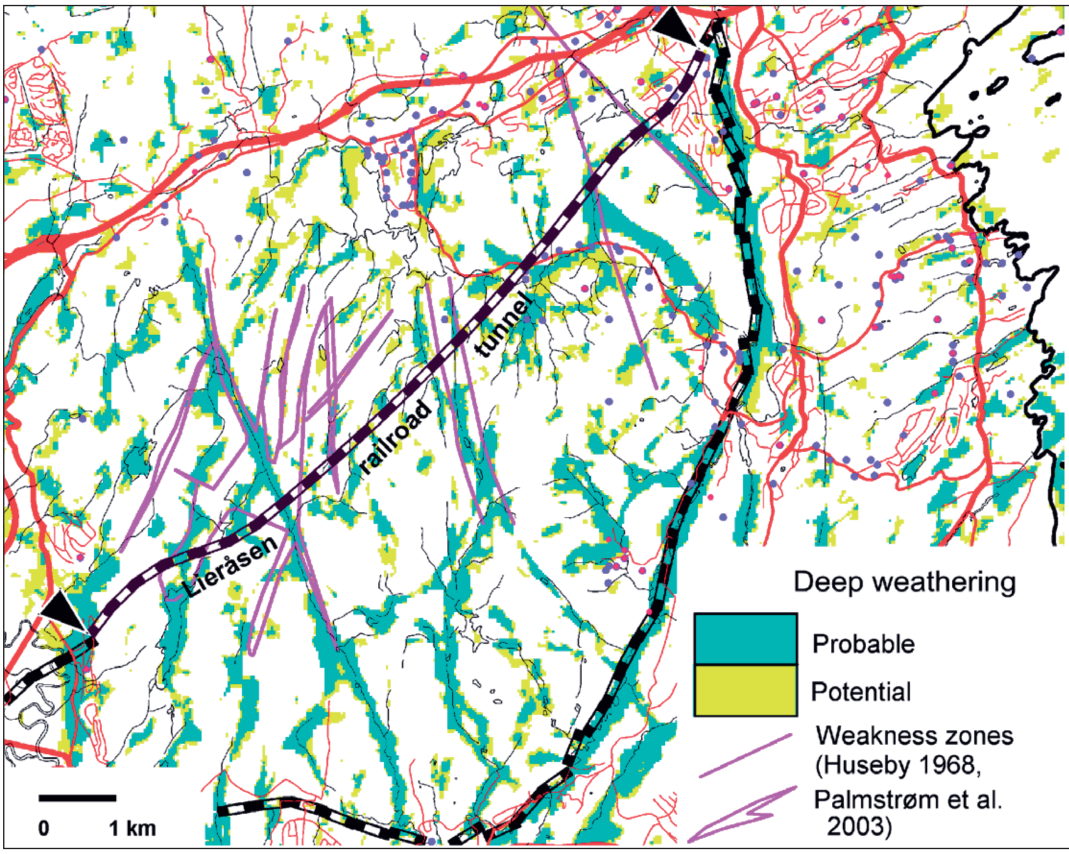

Fig. 12. Interpretation map of Lier-Asker area with the 10.7 km long Lieråsen railway tunnel. Previously mapped weakness zones are marked with purple polygons and lines, while predicted zones of deep weathering based on processed magnetic and topographic data are shown in blue (probable) and yellow (possible). Violet and purple dots represent locations of wells from NGUs national well database drilled before and after 1980, respectively.

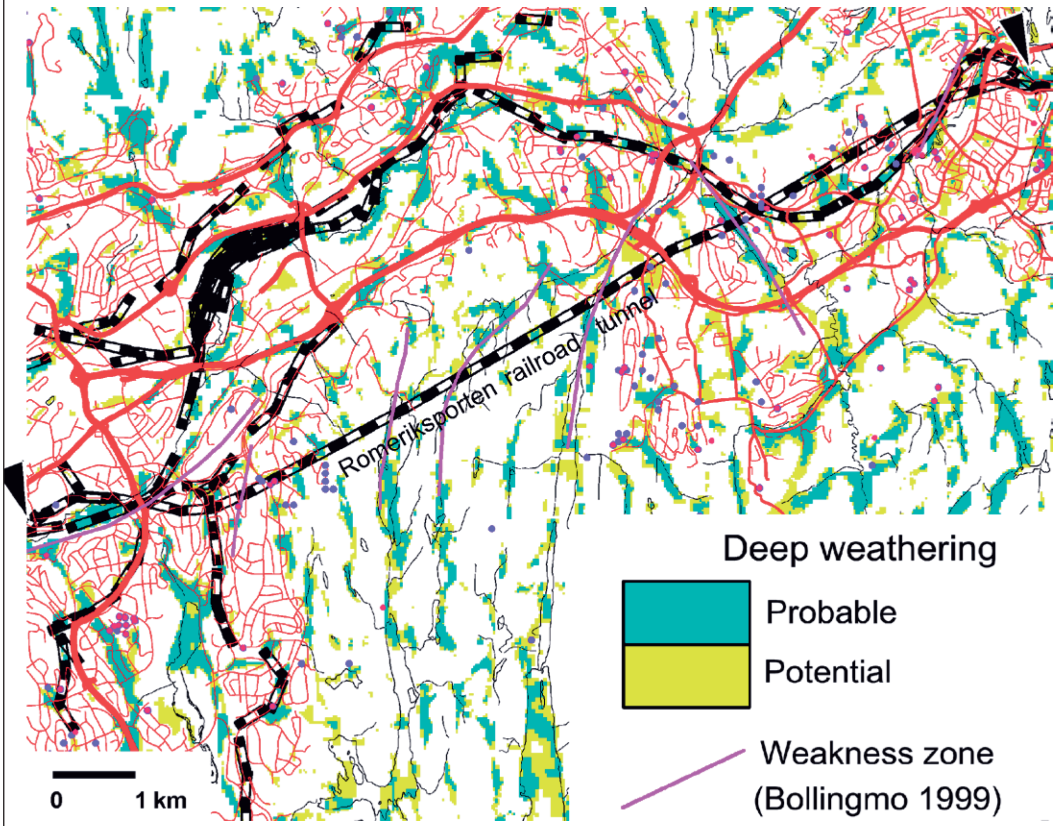

Fig. 13. Interpreted deep weathering zones along the 13.8 km long Romeriksporten railway tunnel. There is in general a good correspondence between the interpreted zones and the weakness zones observed in the tunnel at a depth of c. 100 m below the ground surface by Bollingmo (1999). Violet and purple dots represent locations of wells from NGUs national well database drilled before and after 1980, respectively.

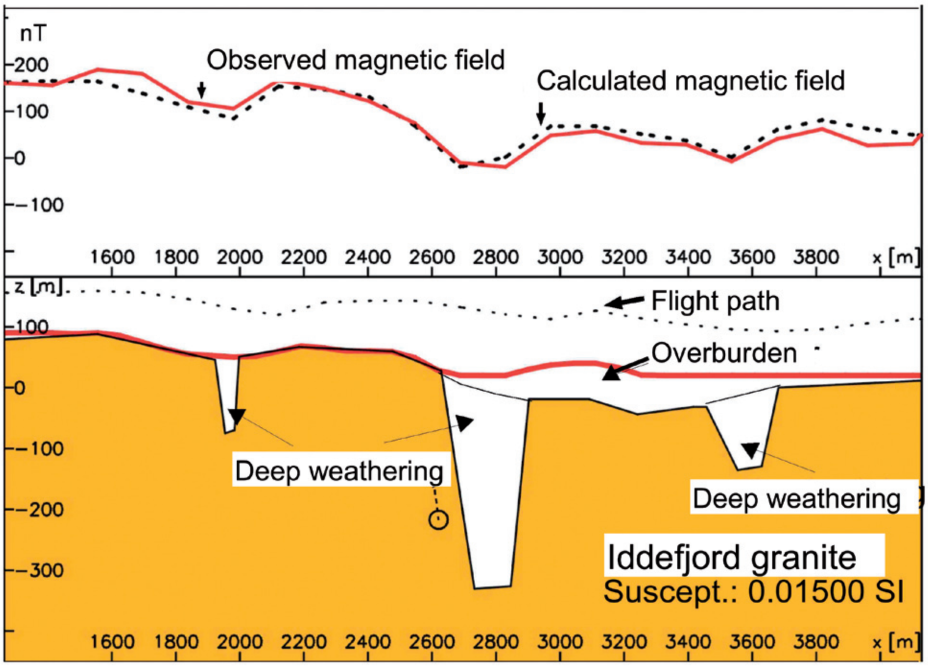

Fig. 14. Magnetic modelling of a profile (see Fig. 11 for location), of deeply weathered fracture zones in the Fredrikstad area in Østfold county. The modelling supports the conclusion that deep weathering is responsible for the linear negative magnetic anomalies associated with linear topographic depressions. The topographic depressions mark weathered faults, fractures, and joints. The white non-magnetic material represents weathering products (smectite and kaolinite) in which magnetic minerals (magnetite in particular) have been oxidized by chemical weathering and leaching (e.g. Grant 1984). The vertical exaggeration factor is 1.9.

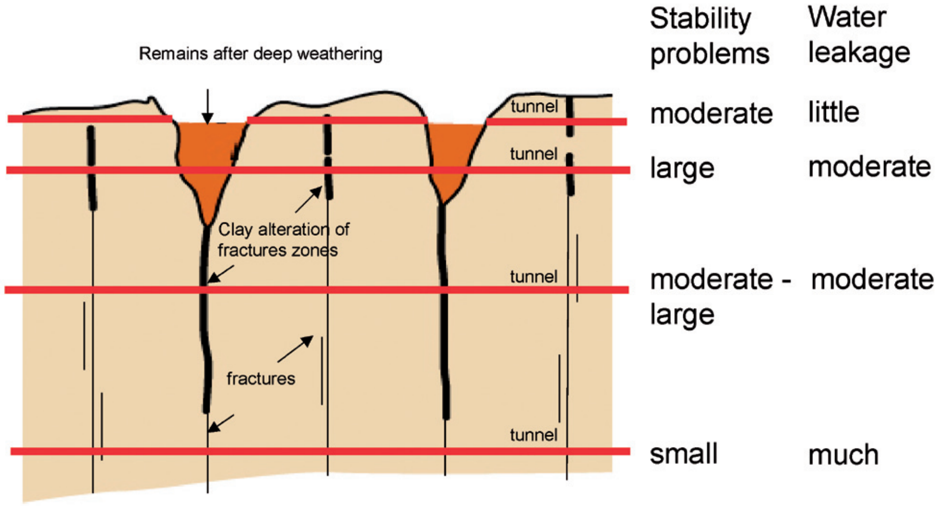

Fig. 15. Sketch illustrating the depth dependence of tunnel problems in areas with subtropical weathering. Stability problems will occur more frequently at shallow depths while water leakage most will most likely prevail at greater depths in weakness zones.

gested by Banks et al. (1994). There is also evidence from seismic studies and drilling through the weakness zones in the Lieråsen railroad tunnel that the width of the zones decreases with depth (Huseby 1968) supporting an alteration process operating from above and penetrating downwards. It is, however, important to note that hydrothermal propylite and argillite alteration will decrease the magnetisation of the bedrock in a similar way as subtropical weathering does (Grant 1984, Clark 1997).

Ihlen & Martinsen (1986) argued initially that the argillic alteration at the entrance to the Røysåsen mine (Fig. 4) within the Drammen granite was formed during the final stage of the Permian hydrothermal activity in the area. This alteration is according to present day interpretations (P.M. Ihlen pers comm. 2006), thought to have taken place during Mesozoic sub-tropical weathering conditions partly because it occurs along regional fracture zone in the greater Oslo Region.

During construction of the Hvaler tunnel, in the Iddefjord Granite, it was observed that leakage of groundwater occurred between the observed "zones of weakness" rather than within them (Banks et al. 1992b, Kocheise 1994). This phenomenon has also been observed in a large number of other tunnels along the coast of Norway (Nilsen 1988, Banks et al. 1992b)

Østfold Brønnboring, a drilling company in Østfold county, has also experienced low groundwater yield from wells located within regional fracture zones. The drillers, therefore, generally try to avoid these zones in their groundwater exploration campaigns (R. Lie, pers. comm. 2005). The clogging of such fracture zones by clay products has been known to groundwater drillers for quite some time from practical experience, although the geological reason for this clay content has not been recognised.

The AMAGER method will not produce valid results in bedrock with very low magnetisation since there will be no magnetic ferro-oxides to oxidize to low-magnetic ferro-hydroxides. Weathering of a reversely magnetised rock will in most cases produce a positive anomaly within a negative magnetic anomaly. Beard & Lutro (2000) reported this phenomenon from the Krokskogen lava sequence immediately to the northwest of Oslo. It is therefore important that an experienced geologist or geophysicist should assess the magnetisation of the bedrock either by petrophysical measurements in the field or on collected bedrock samples, or by inspection of the aeromagnetic map. Interpretation of aeromagnetic data in the greater Oslo Fjord region, however, has shown that the bulk of the anomalies are caused by rocks with normal magnetisation (Lundin et al. 2005, Ebbing et al. submitted).

In areas with thick Quaternary overburden, e.g. Raet terminal moraine around the Oslo Fjord and the Gardermoen glaciofluvial deposit there will of course be no topographical expression of the weathered fracture zone and the assumptions of the AMAGER method will consequently not be fulfilled. It will, however, still be possible to recognize the weathered fracture zones as negative aeromagnetic anomalies.

The original application of the AMAGER method (Olesen 2004a,b) involved utilisation of a 50x50 metre grid acquired by gridding the 20-metre contours on the 1:50.000 scale topography map series of Norway. The results from processing the present improved topography dataset from 1:5.000 and 1:10.000 scale maps reveal some more details but do not deviate significantly from the initial interpretation. This conclusion shows that the method is quite robust and not fully dependent on a high-resolution topography/bathymetry dataset to produce reliable results.

The AMAGER method is supposed to work on Fennoscandian bedrock that was exposed to Mesozoic weathering and exhumed during the Neogene. Lidmar-Bergström et al. (1999) have identified two such areas in Norway; the Skagerrak-Kattegat coast (including the greater Oslo Fjord region) and the Fosen peninsula and Trondheimfjord areas in Mid Norway (Fig. 1). Rueslåtten et al. (1984) found surprisingly little water when drilling in prominent fracture zones in a variety of Precambrian and Palaeozoic bedrock lithologies on the island of Hitra and in Leksvik municipality in mid Norway (including locations within the Møre-Trøndelag Fault Complex). They concluded that the fracture zones were clogged by clay minerals, supporting the conclusion from exhumation of deeply weathered bedrock in this area (Lidmar-Bergström et al. 1999).

Conclusions

Joints and fractures were weathered during a sub-tropical climate regime and thus contain smectite and kaolinite. The presence of such minerals prohibits groundwater flow in fracture and fault zones. The clay-bearing zones may cause mechanical problems during both tunnel construction and later operation. Water break-through in tunnels crossing deeply weathered joints and fractures tend, however, to occur between such structural features.

Due to the chemical alteration of magnetic minerals during weathering, these weakness zones are characterized by negative magnetic anomalies. In situ measurements at four different locations showed that the magnetic susceptibility in the weathered zones is reduced by 35-93 % compared to fresh rocks. Such zones are also generally marked by topographic depressions. The recognition of this relationship has led to a method involving the combined analysis of magnetic and topographic data to predict zones of deep weathering.

The new AMAGER method has proved capable of detecting more than 90 % of the known fracture zones in the Lieråsen and Romeriksporten railway tunnels and the Hvaler road tunnel. Modelling of the observed magnetic field indicates that some of the low-magnetic zones continue to a depth of c. 300 metres below the surface. We conclude that high-resolution aeromagnetic data should be acquired prior to planning of long tunnels in bedrock subjected to tropical weathering or hydrothermal alteration.

Engineering geologists have consequently acquired a new tool with which to facilitate the mapping of potential clay-bearing weakness zones for tunnel planning purposes. It is, however, important to note that an experienced geologist or geophysicist should be present to ensure that the conditions necessary of using the method are satisfied. This can be achieved through evaluation of the magnetisation of the bedrock, either by inspecting the relevant aeromagnetic map or susceptibility data acquired in the field, or from laboratory measurements on collected bedrock samples. There should be a contrast in magnetic properties between weathered and unweathered rock. In areas with thick Quaternary overburden there will most likely not be any topographical expression of the weathered joint valleys but these zones may still be recognized as negative aeromagnetic anomalies.

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