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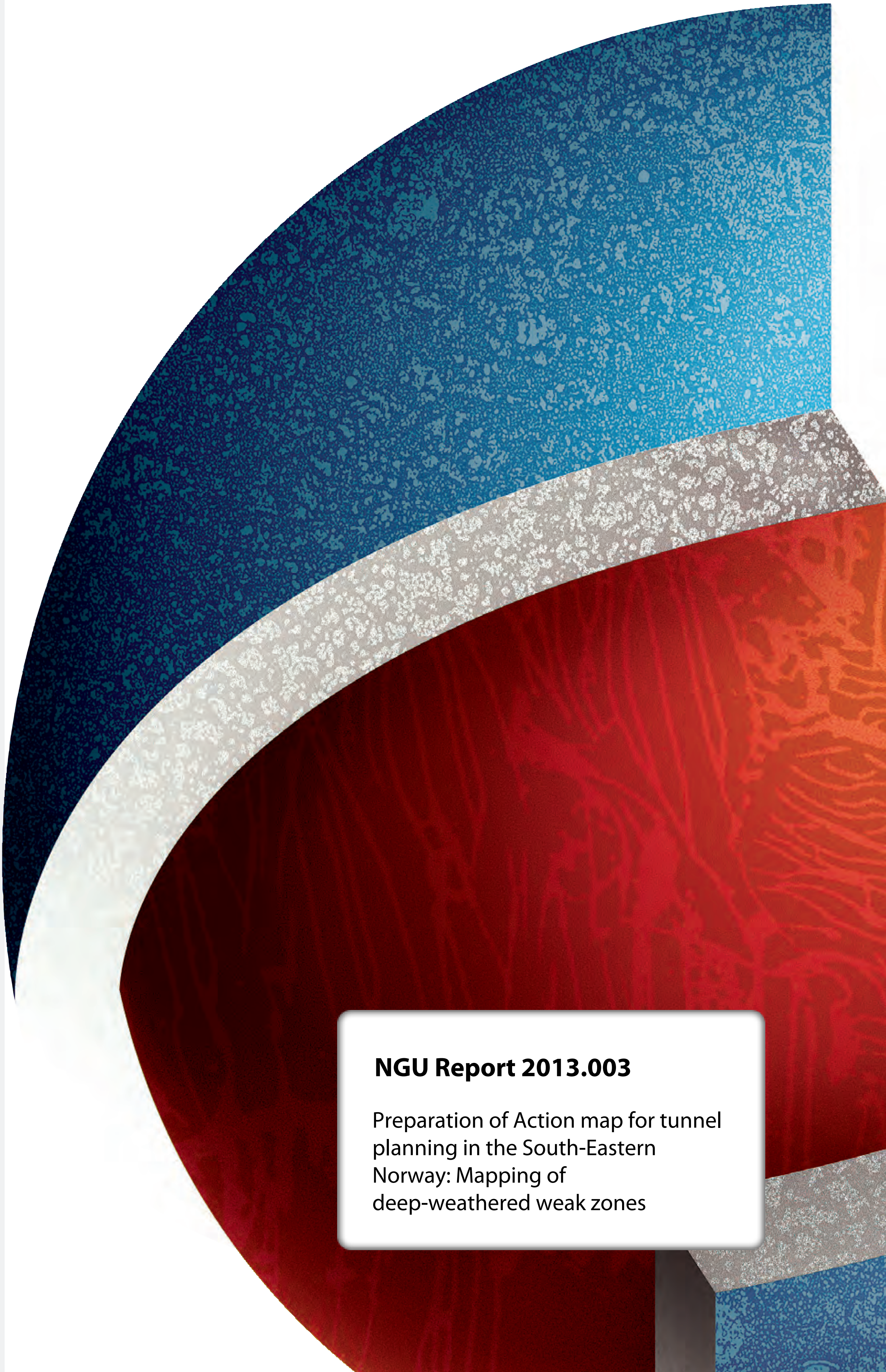

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Preparation of Action map for tunnel planning in the South-Eastern Norway: Mapping of deep-weathered weak zones

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REPORT

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Title:
Preparation of Action map for tunnel planning in the South-Eastern Norway: Mapping of deep-weathered weak zones

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Summary:
Joints and fractures were weathered during a sub-tropical climate regime and thus may contain smectite and kaolinite. The presence of such minerals increases instability in fracture and fault zones. The clay-bearing zones may cause mechanical problems during both tunnel construction and later operation. Due to the chemical alteration of magnetic minerals during weathering, weak zones are characterized by negative magnetic anomalies. Such zones are also prone to 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 referred as the AMAGER method (Olesen et al. 2007). We introduced AGC (Automatic Gain Correction) to the magnetic data to improve signals from areas having low/medium magnetic anomalies. The improved AMAGER method has produced a new map that is furthermore extended to the west of the Oslofjord area relative to the Olesen (2006) version. The method has successfully mapped known weak zones in the Lieråsen and the Romeriksporten railway tunnels and the Hvaler road tunnel, as shown in the previous version by Olesen (2006). In addition, it has identified known weakness zones causing tunnel collapse reported in the Hanekleiv tunnel at E 18 and in the "Bygarasjen" in Skien area. This has resulted in an awareness map for tunnel planers ("aktsomhetskart for tunnelplanlegging"), and was first published in 2006 (Olesen 2006), with a refurbished and expanded version published in 2012 (Baranwal & Olesen 2012).

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 will have a new tool to map potential clay-bearing weakness zones for tunnel planning purposes. The intention of the map is to initiate caution around zones that are indicated. 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 fulfilled. This can be achieved through evaluation of the magnetization of the bedrock, either by inspecting the relevant aeromagnetic map or susceptibility data acquired in the field, or from laboratory measurements of collected bedrock samples. There should be a contrast in magnetic properties between weathered and un-weathered rock. In areas with thick Quaternary overburden, there may not be any topographical expression of the weathered joint valleys but these zones may still be recognized as negative aeromagnetic anomalies.

Keywords:	Geophysics	Tunnel planning
Deep weathering	Aeromagnetic data	Topographical data
	Action map	Scientific report

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1. INTRODUCTION

There has been lots of investment in tunnel construction and in its developments in Norway because of Norway's rough topography. Many problems were reported during tunnel construction in the Oslofjord area and other parts of Norway. Draining of groundwater and rock fall in clay-bearing zones was reported in construction of Holmenkollen railway tunnel in Oslo (Kirkemo 2000). The marine clay above the tunnel subsided and was compacted due to lowering of the groundwater table and therefore damaged houses. Another example of a failed tunnel project was the railway tunnel through Lieråsen between Asker and Drammen, which was started in 1962, but only half of the tunnel was completed in five years (Huseby, 1968, Palmstrøm et al. 2003). The main problem in that area was clay alteration along linear weak zones resulting in rock fall. The original path of the tunnel was deviated to complete the tunnel construction. Water leakage and rock fall were also faced during the construction of the Romeriksporten and the Oslofjord tunnels. The additional cost in Romeriksporten tunnel amounted to approximately one billion NOK.

The Geological Survey of Norway (NGU) started the GEOS Programme (Geology in the Oslo Region) in 2003 to provide geological information necessary to facilitate the large-scale urbanization process in the greater Oslofjord Region. The TIGRIS (The Integration of Geophysical Relations Into Society) research and mapping project was initiated within the framework of the GEOS programme to improve our understanding of how clay alteration formed and to develop a method to map such clay bearing zones. This resulted in an awareness map for tunnel planers ("aktsomhetskart for tunnelplanlegging"), and was first published in 2006 (Olesen 2006), with a refurbished and expanded version published in 2012 (Baranwal & Olesen 2012).

Lipponen & Airo (2006) had 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. On the same line, Olesen et al. (2007) developed a geophysical method referred to as the AMAGER (AeroMAgnetic and GEomorphological Relations) to map the occurrence of deep clay-alteration in the bedrock of the Oslo Region. They related the coinciding depressions in topography and aeromagnetic data to clay alterations areas. The present map includes a westward extension of the map presented by Olesen (2006) with a methodological improvement using the automatic gain correction (AGC).

2. DEEP TROPICAL WEATHERING

The tectonic history of the Proterozoic Sveconorwegian terrain and the Permian Oslo Rift is described by Bingen et al. (2001), Olaussen et al. (1994) and Sundvoll & Larsen (1994). Ramberg & Larsen (1978) and Lutro & Nordgulen (2004) mapped fault and fracture zones within the greater Oslo Region. Lidmar-Bergström (1989, 1995) proposed that the joint valley landscape of Southwestern Sweden was formed during the Neogene exhumation of the Fennoscandian Shield. Erosion of a thick Jurassic/Early Cretaceous saprolite along regional fault and fracture zones formed extensive valleys in the Scandia Region. The weakness zones in this sub-Cretaceous etch-surface were partly due to the presence of clay minerals such as kaolinite and smectite, which were results from chemical weathering under sub-tropical

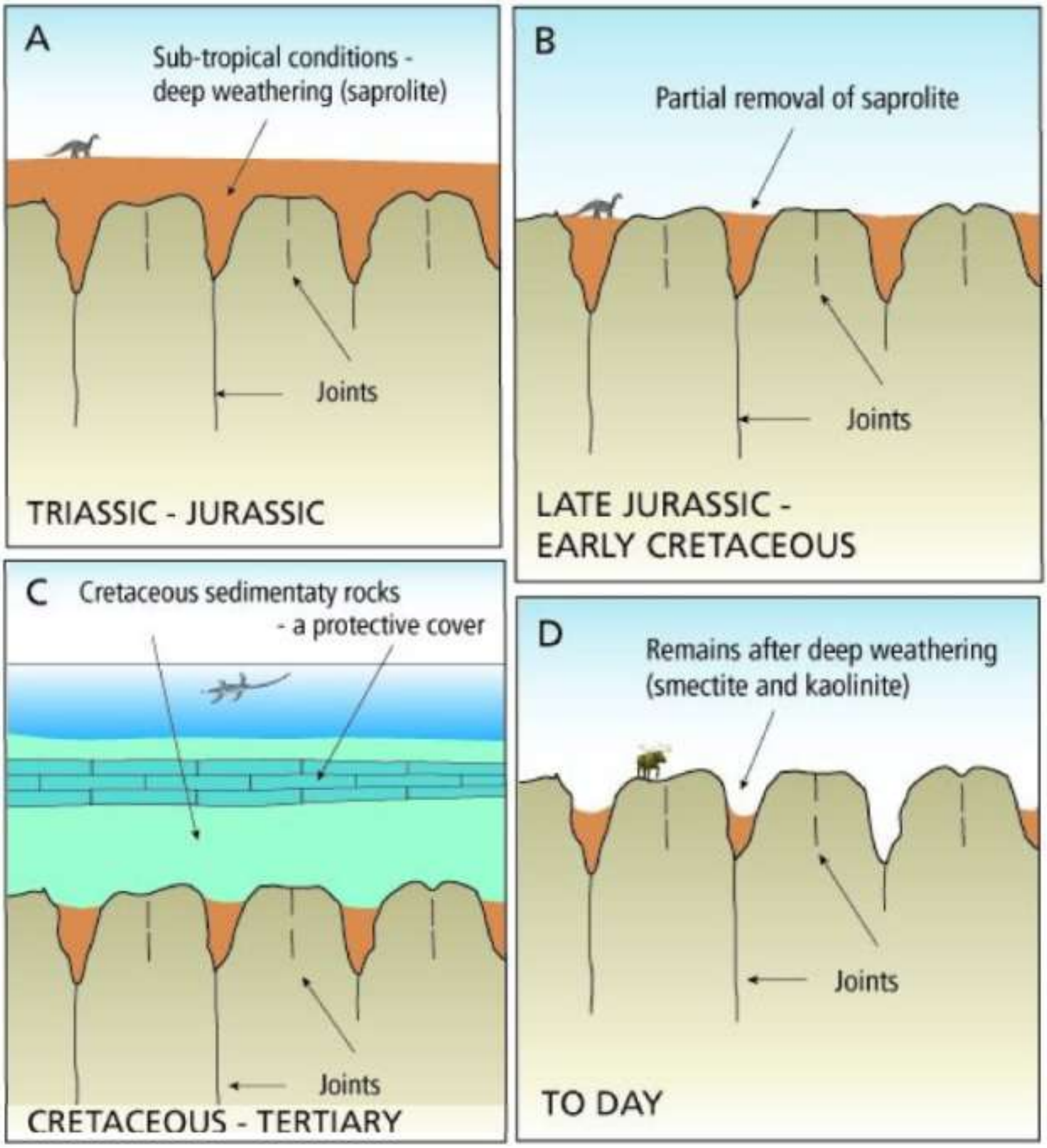

Figure 1. Schematic illustration of the process leading to the present day deep-weathering products from the start in the Triassic to present time.

conditions in the Triassic and Jurassic (Lidmar-Bergström 1982, Lidmar-Bergström et al. 1999). The weathering occurred originally across the entire paleo-surface during the Triassic and Jurassic, but gradually penetrated deeper into pre-existing fracture zones (Fig. 1A). The saprolite was partially eroded before the Cretaceous (Fig. 1B), 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, Fig. 1C). 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 meters along the fracture zones (Fig. 1D)

The occurrence of clay minerals in crystalline bedrock in the greater Oslo Region is 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. (1992 a, b, 1994), and Kocheise (1994). Most of these researchers favored that a low-temperature fluid has acted as the dominating alteration agent in the formation of the Permian Oslo Rift. However, Lidmar-Bergström et al. (1999) provided an alternative explanation for the widespread occurrence of clay minerals in the coastal areas of southern Norway and western Sweden. They argued that 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), on the continental shelf (Roaldset et al. 1993) and lately at Lista (Øverland 2012, Larsen 2012, personal communication). K/Ar dating in the 1970s and 1980s of assumed hydrothermal clay alteration associated with Permian fluorite and sulphide vein deposits, as well as regional fault zones in eastern and southern Norway (e.g. at Lassedalen, Gjerpen, Heskestad, Skreia and Feiring) yielded Mid and Late Triassic ages (Ineson et al. 1975, 1978, Ihlen et al. 1978, 1984). These ages most likely represent the same phase of deep weathering as recently reported from two exploration wells on the Utsira High (Fredin et al. 2012) and not hydrothermal alternation associated with the formation of the mineral deposits.

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 meters above sea level, Fig. 2) 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. Reusch (1903b) also studied kaolinite deposits in Norway (including deposits in Hurdal, Seljord and Flekkefjord).

There is also undisputed hydrothermal clay alteration (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). Therefore all clay-bearing fractures in the Norwegian bedrock may not be related to sub-tropical weathering. However, Olesen et al. (2007) found from the work by Lidmar-Bergström (1989) and Lidmar-Bergström et al. (1999) that most of the clay alteration associated with fracture zones in the greater Oslofjord Region represented remnants of an originally extensive saprolite layer. This model could also explain why the clay-bearing weakness zones seemed to occur as frequently outside the Oslo Rift as within it. During tropical weathering, iron oxides such as magnetite altered to hematite and iron-hydroxides and at the same time silicate minerals were converted into clay minerals (e.g. Henkel & Guzmán 1977, Grant 1984). Deep weathering would therefore create a negative deviation in the Earth's magnetic field. However it would generate a positive anomaly in the regions having a negative remnant magnetization.

3. THE AMAGER METHOD

The AMAGER (AeroMAgnetic and GEomorphological Relations) method to map the occurrence of deep clay alteration in the bedrock of the Oslo Region is based on coinciding depressions in topography and aeromagnetic data to clay alterations areas.

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 break lines. This TIN was then resampled onto a regularly spaced grid (25x25m). The bathymetry of the inner Oslofjord 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 the outer Oslofjord 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 using Geosoft software. The final grid is shown in Fig. 2.

The results of various aeromagnetic surveys as shown in Fig. 3 and detailed in Table 1, are compiled together. Aeromagnetic data from the northern and southwestern areas were acquired by helicopter surveying conducted by the Geological Survey of Norway during the time period 1981-2011. The pattern of flight lines generally provides data along EW- 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 meters, respectively the magnetic sensor was however installed in a bird towed 30 m below a helicopter. Fugro Airborne Surveys (2003) carried out a larger survey of c. 24.000 km to cover the relatively flat areas mainly to the east and north of Oslofjord (Oslo Region 1, Fig. 3). The flight altitude was here 60 and 100 meters in rural and urban areas, respectively. The line spacing was 250 meters. A relatively small area in the outer part of Oslofjord was flown with a line spacing of 500 m (Oslo Region 2, Fig. 3). All the grids were merged into one grid using suture method of Gridknit, developed by Geosoft (2010a). The final grid with cell size 50 x 50 meters of the magnetic anomaly map is shown in Fig. 4.

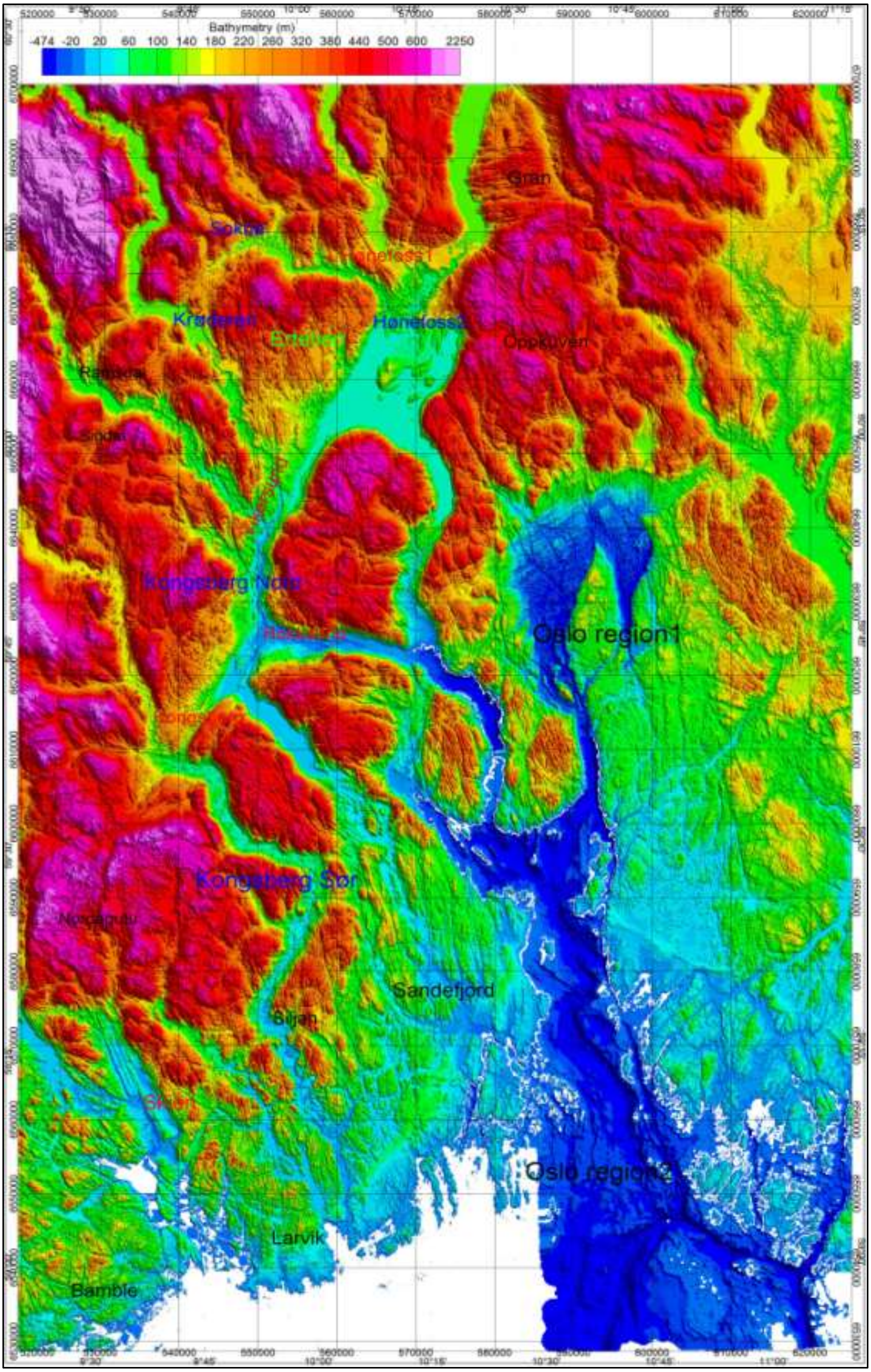

Figure 2. Topography and bathymetry from the greater Oslofjord Region displayed using the shaded-relief technique with illumination from the east.

We used the filtering technique to enhance the magnetic signal from the weathered zones originally presented by Olesen et al. (2007) with slight modification. We have applied automatic gain correction (AGC) to magnetic data to enhance the signal for weak magnetic area besides other steps followed by Olesen et al. (2007). Magnetic data were IGRF corrected magnetic field anomaly. Part of surveys covered by fix-wing aircraft were downward continuated using a frequency-domain filtering package (Geosoft 2010b) from an altitude of 60 meters to 30 meters. The downward continuation brought both fix-wing airborne magnetic data collected at approximately 60 m height and helicopter-borne magnetic data collected at approximately 30 m height at same level. All the data were stitched together using Gridknit and reduced to the magnetic pole (RTP). A 1 km Gaussian high-pass filtering was used on both the topography/bathymetry (Fig. 2) and the magnetic (Fig. 4) grids. The magnetic data from low magnetic areas were also enhanced using AGC. Coinciding negative anomalies in the two high-pass filtered datasets were used as indications of deep weathering. The resulting signal was classified as ‘probable’ or ‘less probable’ weathering depending on the signal to noise ratio. Pronounced anomalies with amplitudes below -5 m (topography) and -100 nT (magnetic) were classified as ‘probable’, while less pronounced anomalies between -5 m and -2 m and between -100 nT and 0 nT were classified as ‘less probable’.

In the map by Olesen (2006), only 1 km Guassian high pass filtered magnetic and topographic data were considered to delineate the deeply weathered fracture zones without automatic gain correction (AGC). We used same 1 km Gaussian high pass filtered data for topography (Fig. 5) but we applied AGC to the 1 km Gaussian high pass filtered magnetic data.

There were various options available for stitching of the grids but we found the suture method considering all the points to calculate the trend as most suitable for the continuation and smoothness at the boundaries. A static trend was removed from both the grids (two grids were stitched at a time and the same process continued until all the grids were stitched). The stitched magnetic map was reduced to pole relative to a point in the centre of the map (59.6844º N, 10.3143º E). The IGRF values for this point were calculated as total field 50914.69 nT, inclination 72.56º and declination 1.846º. The stitched map was filtered using a 1 km Gaussian high-pass filter to discard higher wavelength components (Fig. 6). We observed some regions mostly in the eastern parts of the map (yellowish areas in Fig. 6) were showing moderate magnetic features with almost no variation. Therefore to enhance the signal from such regions, we applied AGC of 50 point length for local amplitude and a maximum gain of 100 (Rajagopalan & Milligan 1994, Geosoft 2010c). We experimented with different length, full and local amplitude options in Geosoft and various gain correction values and found these parameters as most suitable. We observed that application of AGC increased the general amplitude of signals to 30 times and minimum and maximum limit to 2-4 times, respectively (Fig. 7). Finally, negative anomalies from both topography and magnetic data were correlated to produce a map indicating weak and deep weathered zones (Fig. 8). The application of the more strict thresholds (-5 m and -100 nT) in the filtering process provided a result that coincided mostly with linear zones with known clay-alteration zones, e. g. in the Drammen granite (Huseby 1968). The less strict criteria of -2 m and 0 nT also revealed alteration zones in relatively low-magnetic bedrock but in addition produced some artifacts that were unlikely to be related to clay alteration since some of them occurred as isolated patches spread out in the terrain. It was possible to select thresholds that would provide a better result for a restricted area. However, the chosen parameters represented a compromise to produce acceptable results in most of the greater Oslofjord Region.

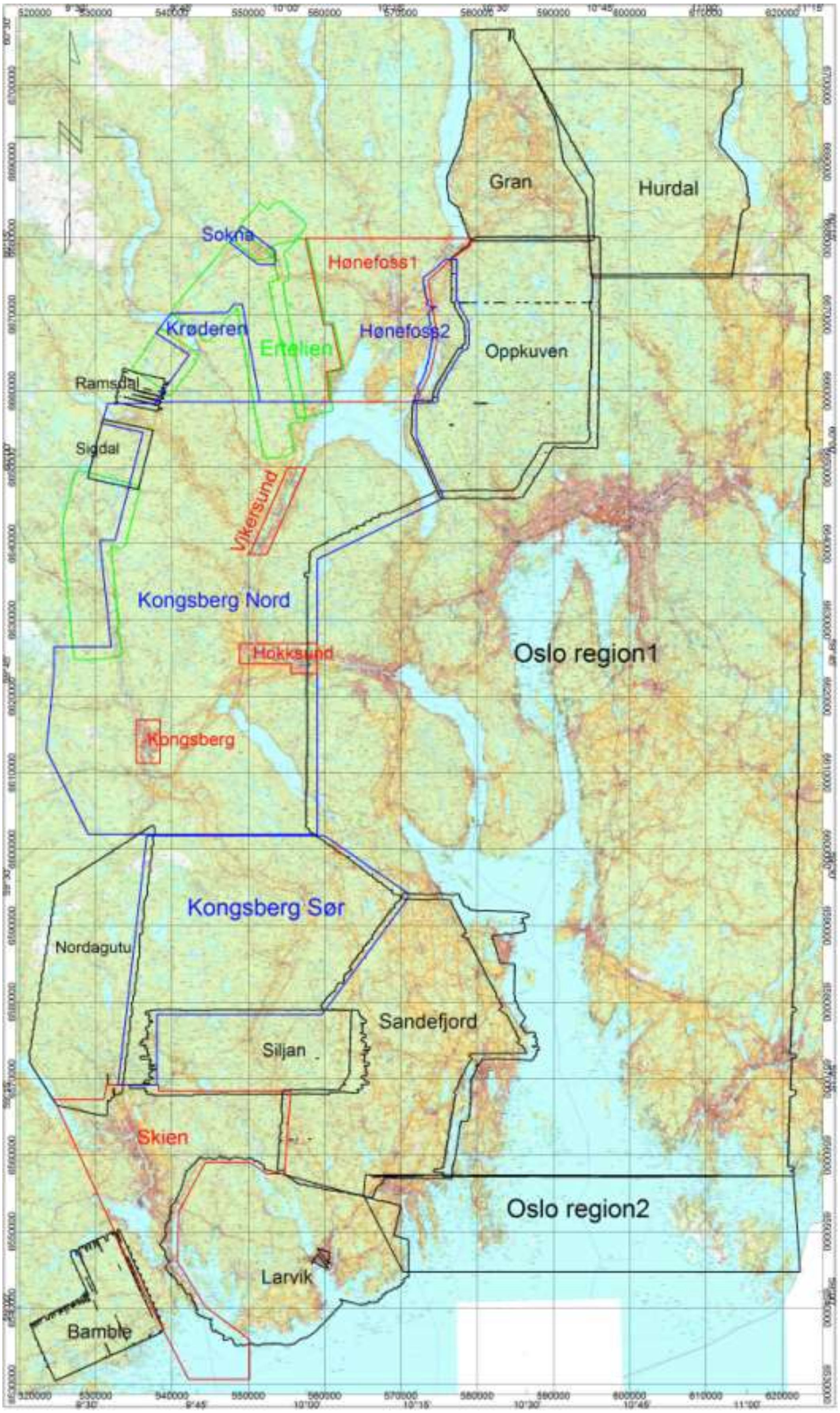

Figure 2. Location of the helicopter and fixed-wing surveys in the Oslofjord region. The data were collected in different campaigns; in 2005 by helicopter and fixed-wing, areas shown in black, in 2006 by helicopter are areas shown in green, in 2009 by fixed-wing are areas shown in red and in 2010-2011 by helicopter are areas shown in blue. Details of the surveys are given in Table 1.

Region	**Type of Survey**	**Year of Survey**	**Surveying company**	**Client**	**References**
Siljan	Helicopter	1981	NGU	BTV/NGU	Håbrekke1982
Gran	Helicopter	1997	NGU	NGU	Beard 1998
Oppkuven	Helicopter	1997-1999	NGU	NGU	Beard 1998 Beard & Rønning 1997 Beard & Lutro 2000
Larvik	Helicopter	1997-1998	NGU	BTV/NGU	Mogaard 1998 Beard 1999
Nordagutu	Helicopter	1999	NGU	BTV/NGU	Mogard & Beard 2000
Sandefjord	Helicopter	2000	NGU	BTV/NGU	Mogaard 2001
Hurdal	Helicopter	2000	NGU	NGU	Beard & Mogaard 2001
Bamble	Helicopter	2005	NGU	F/B	Mogaard 2006
Sigdal & Ramsdal	Helicopter	2005	NGU	F/B	Mogaard 2006
Ertelien	Helicopter	2005-2006	NGU	F/B	Mogaard 2006
Oslo Region 1& 2	Fixed-wing	2003	Fugro airborne surveys	NGU	Fugro 2003
Kongberg Nord & Sør	Helicopter	2009 - 2011	NGU	BTV/NGU	Baranwal et al, 2013
Krøderen, Sokna and Hønefoss2	Helicopter	2011	NGU	BTV/NGU	Baranwal et al. 2013
Skien, Kongsberg, Hokksund, Virkesund, Hønefoss1	Fixed-wing	2009	Geological survey of Sweden (SGU)	BTV/NGU	SGU 2009

Table 1. Description of the helicopter and fixed-wing surveys around the Oslofjord Region. BTV = Buskerud, Telemark and Vestfold counties, F/B = Falconbridge/Blackstone.

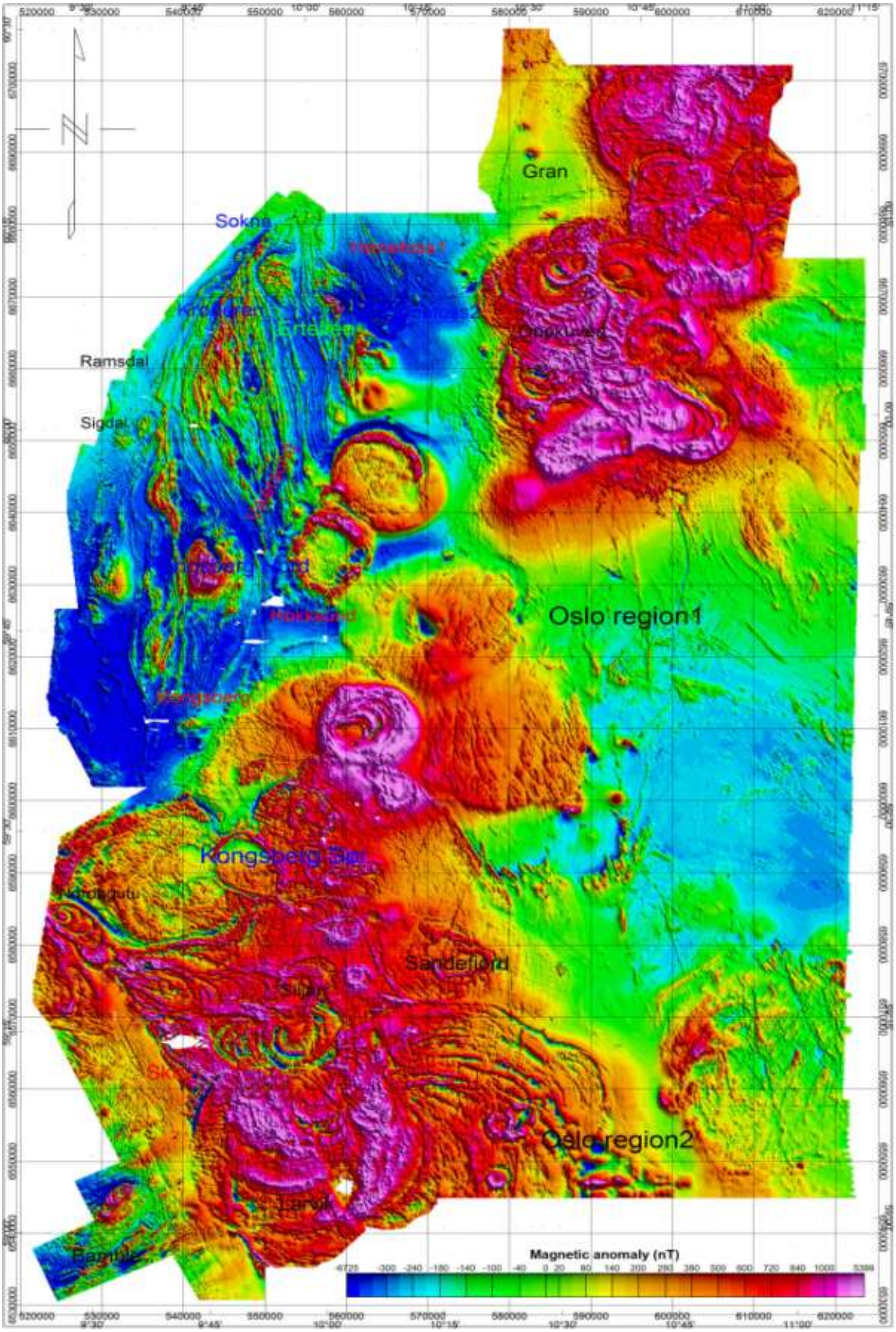

Figure 3. Compilation of aeromagnetic surveys around the greater Oslofjord region. A shaded relief version of total magnetic field anomaly is presented. White areas represent lack of data.

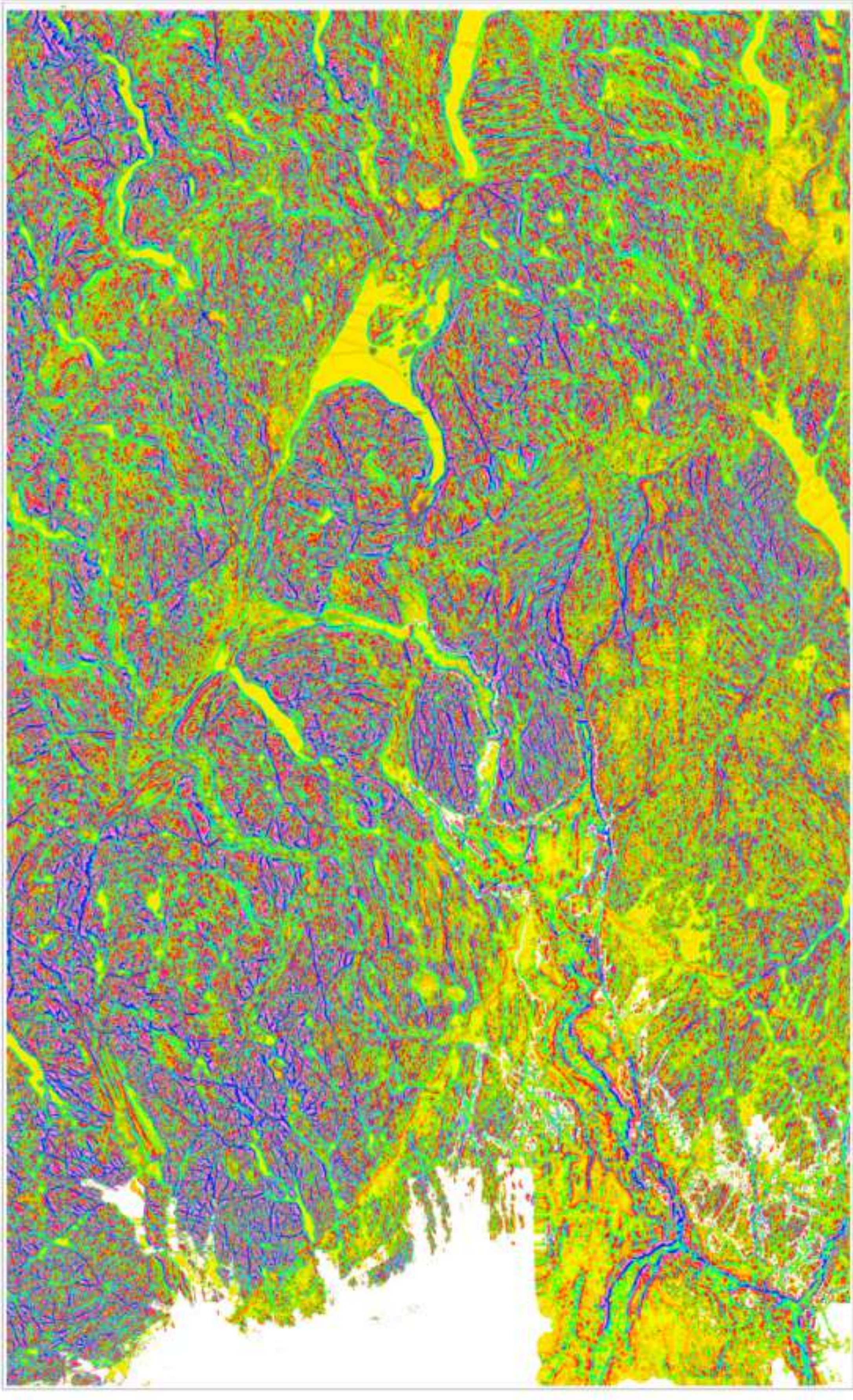

Figure 4. 1-km Gaussian high-pass filtered topography data around the greater Oslofjord region.

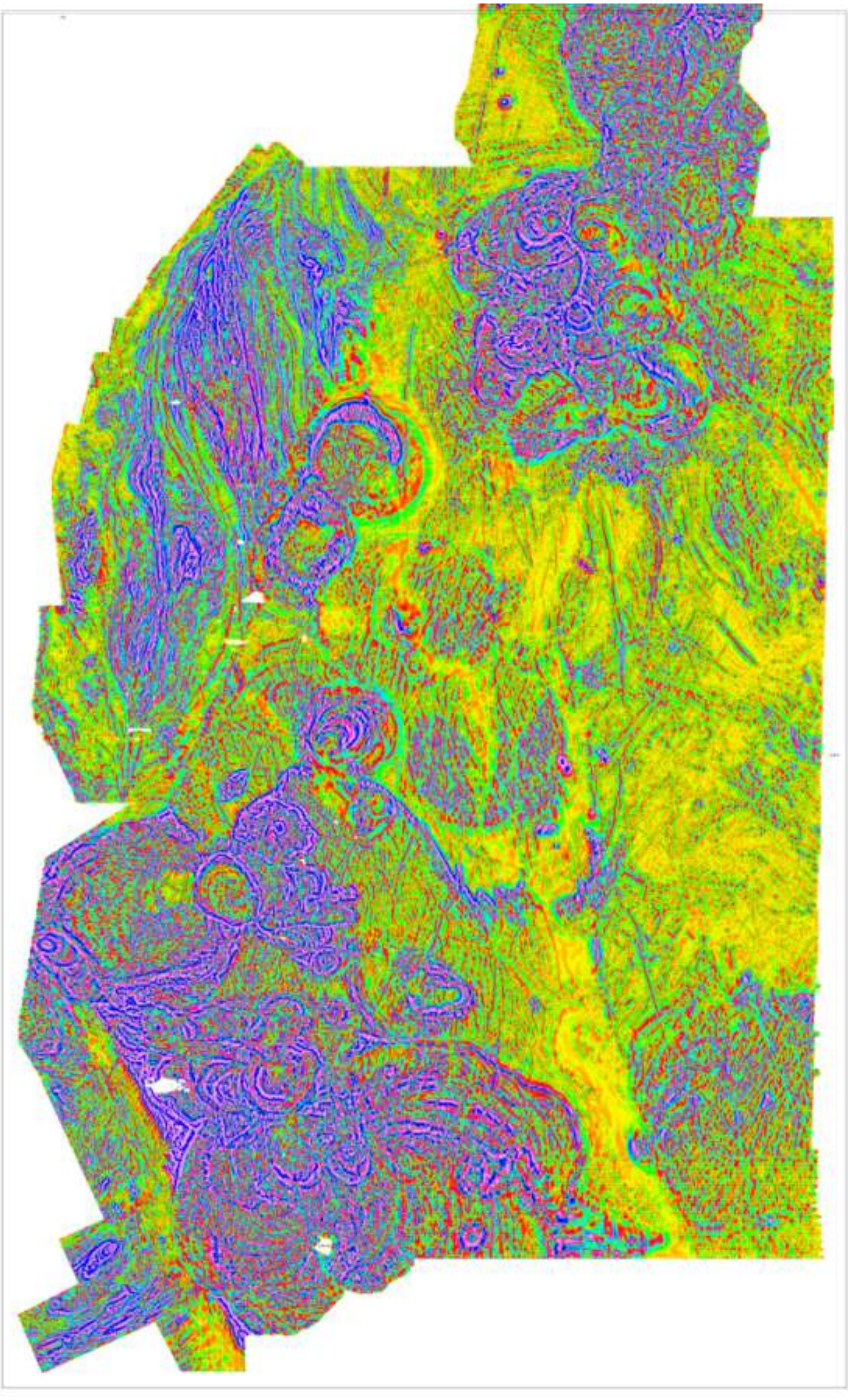

Figure 5. Reduce to pole and 1-km Gaussian high-pass filtered magnetic anomaly data around the greater Oslofjord region.

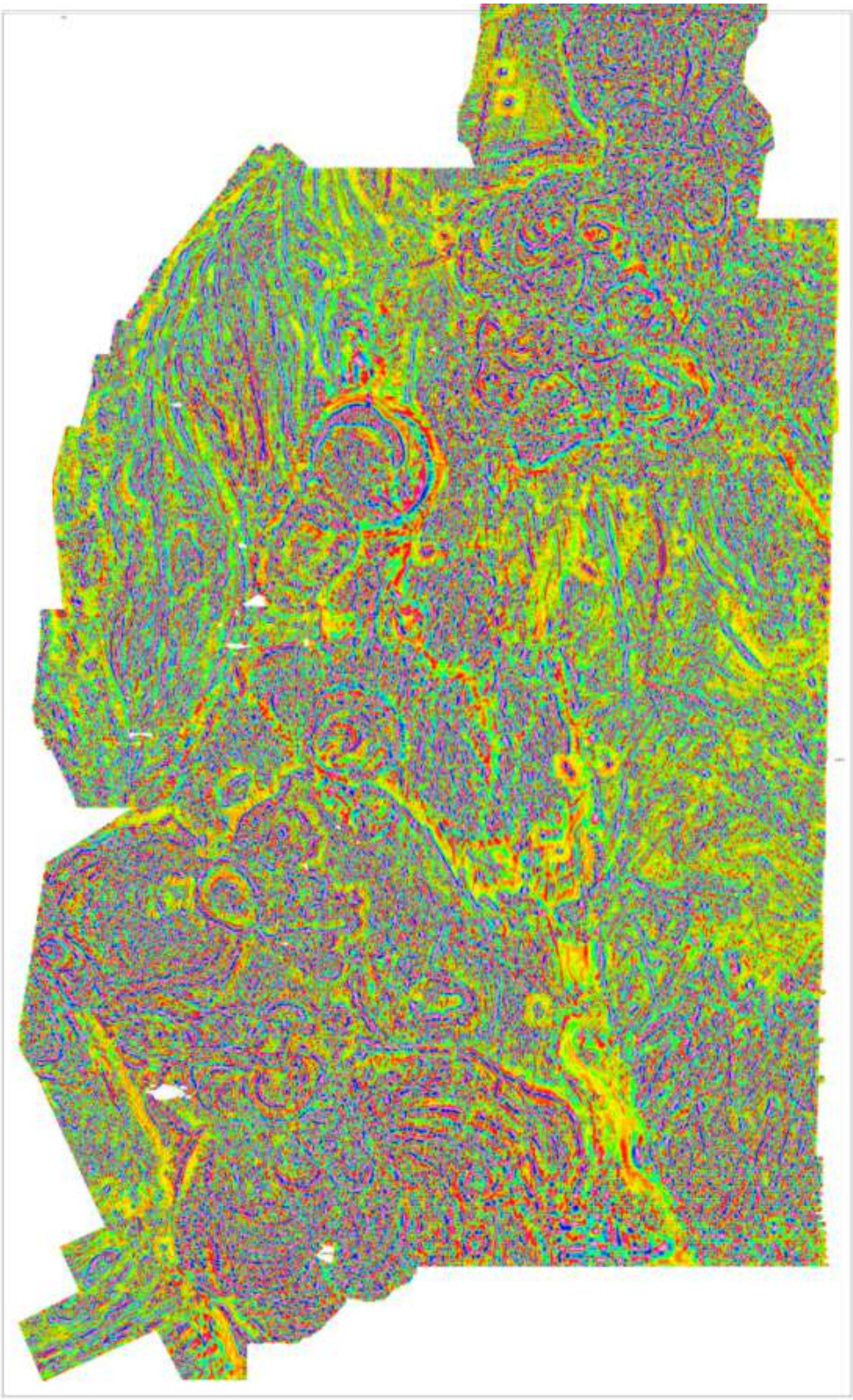

Figure 6. Automatic gain correction (AGC) using 50 point local amplitude window of the grid presented in Fig. 6.

4. RESULTS

The new attention map for tunnel planers ("Aktsomhetskart for tunnelplanlegging Østlandsområdet") is presented in Fig. 8. This map is available in printed version in scale 1: 150.000 from NGU (Baranwal & Olesen 2012). A georeferenced version will be presented at www.ngu.no. Examples from areas where there has been tunnel construction and drift problems are shown in the Figures 9 to 13.

The new map represents a westward extension of the Olesen (2006) map further to the area around Kongsberg. However, the whole map should be considered as new due to the application of the AGC. We notice that we have detected all of the weak zones reported in the literature e.g. weak zones encountered in the Lieråsen and Romeriksporten railway tunnels (Figs. 9 and 10). Weakness zones observed in the Oslofjord road tunnel (Palmstrøm et al. 2003) also appear on our deep weathering interpretations even though these tunnels are located c. 100 meters below sea level (Fig. 11). In addition, we also identified tunnel collapse reported in Hanekleiv tunnel at E18 in 2008 (Rønning et al. 2010) and in Bygarasjen in Skien reported in 2009 (Figs 12 and 13). The indication of probable and less probable deeply weathered zones do not necessarily show up at the tunnel or collapse location, but at the lineament close to the site.

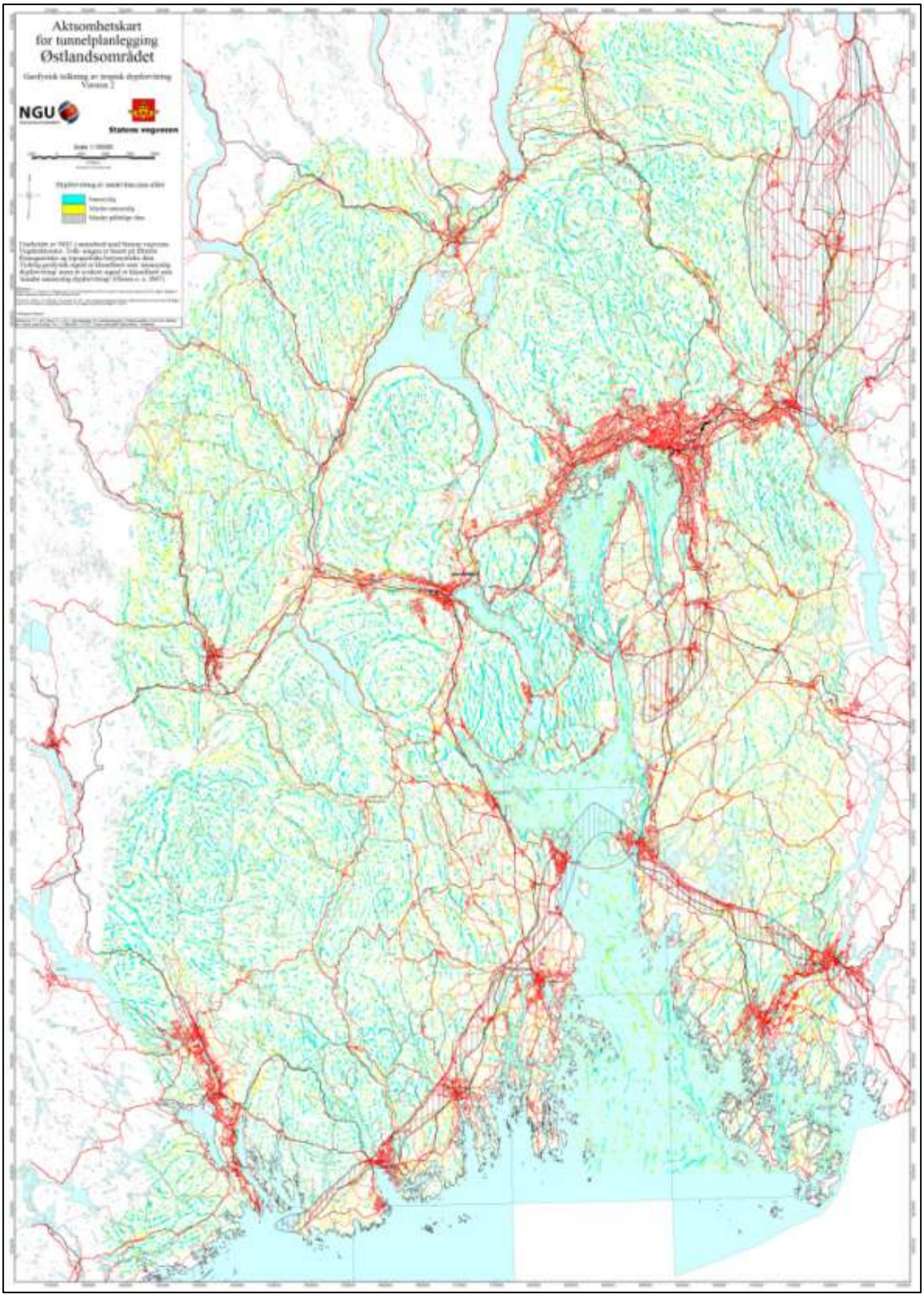

Figure 7. Attention map for tunnel planners indicating zones with deep-weathering around the greater Oslofjord Region. Predicted zones of deep weathering based on processed magnetic and topographic data are shown in blue (probable) and yellow (less probable). Polygons with grey vertical hatching depict areas where interpretation is not reliable due to the presence of a thick Quaternary overburden.

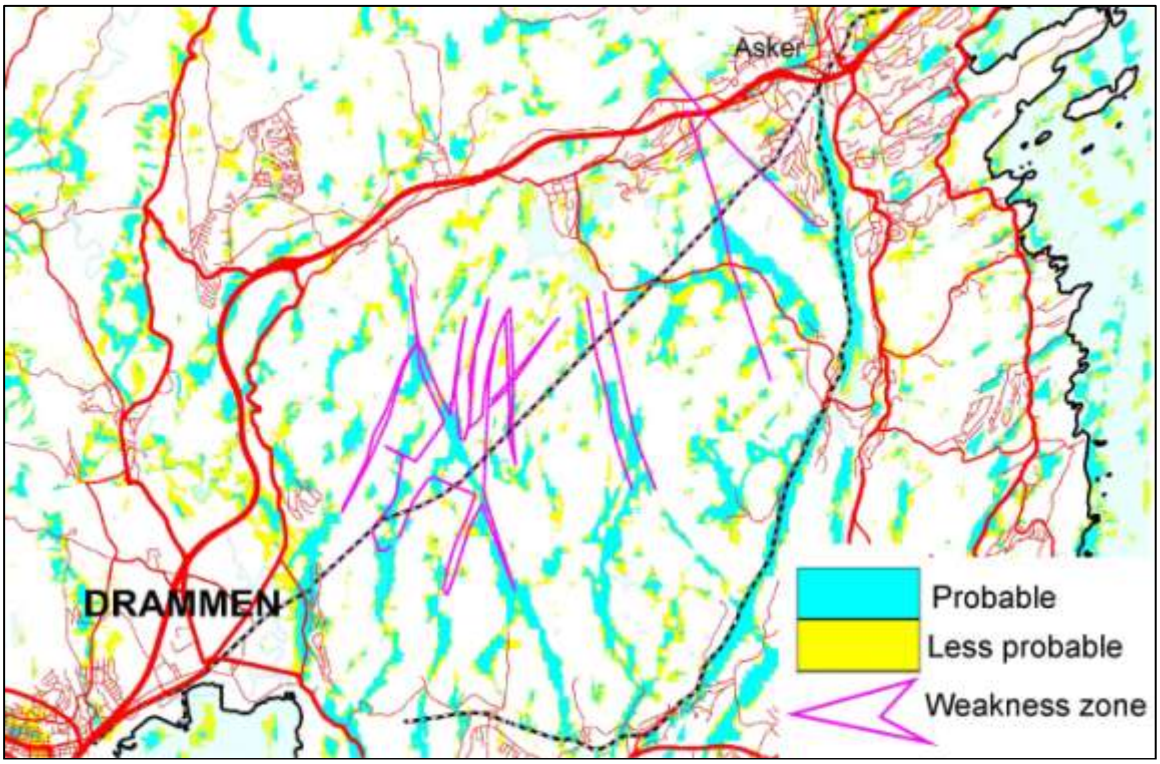

Figure 8. Interpreted deep weathering zones in the Lier-Asker area with the 10.7 km long Lieråsen railway tunnel. Previously mapped weakness zones are marked with purple polygons and lines, while predicted zones of deep weathering based on processed magnetic and topographic data are shown in blue (probable) and yellow (less probable).

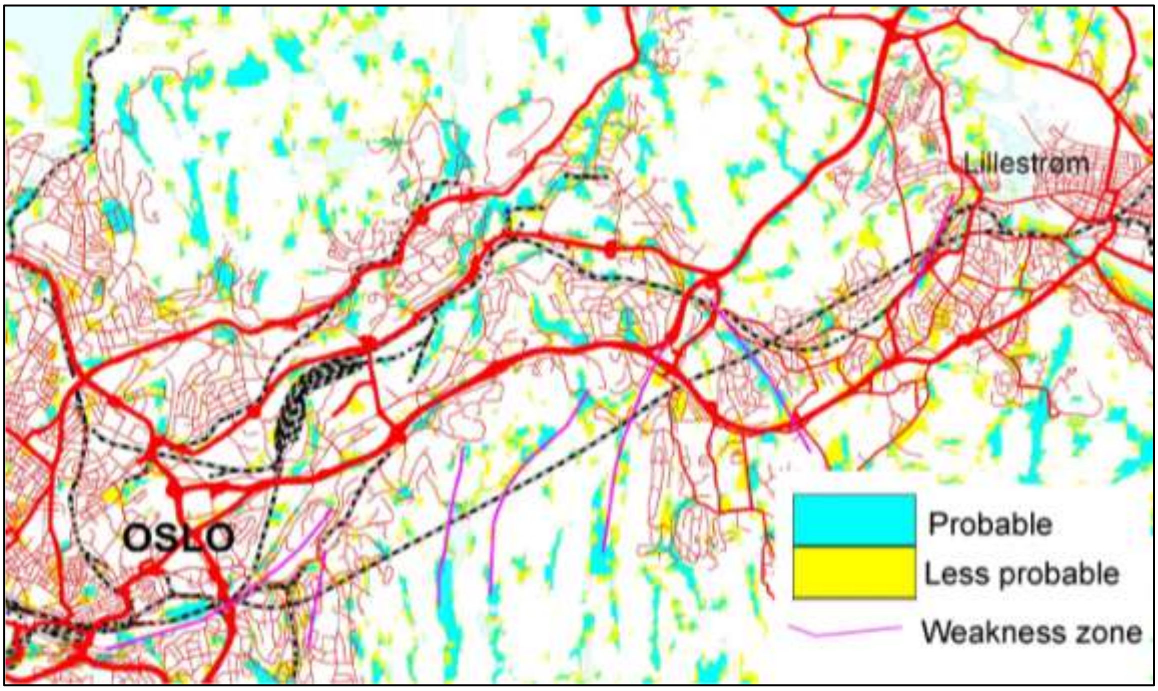

Figure 9. Interpreted deep weathering zones along the 13.8 km long Romeriksporten railway tunnel. There is in general a good correlation between the interpreted zones with deep weathering and the weakness zones observed in the tunnel at a depth of c. 200 m below surface by Bollingmo (1999).

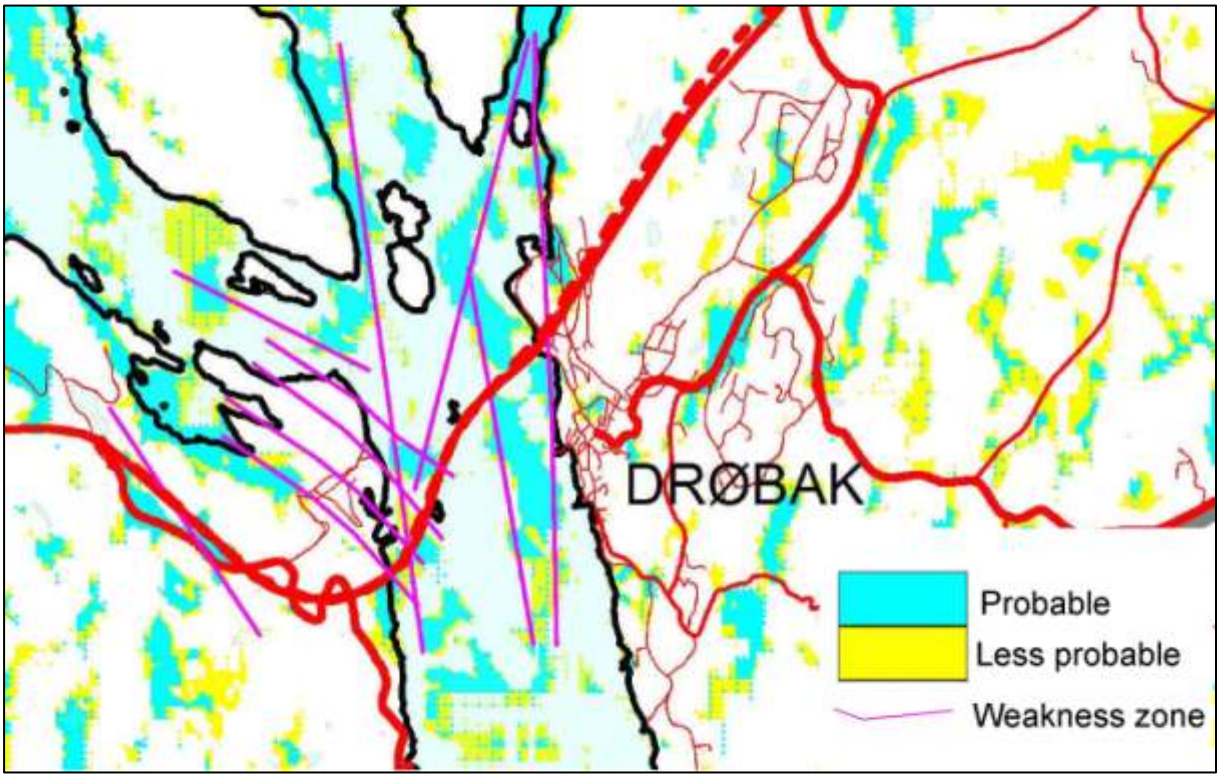

Figure 10. Interpreted deep weathering zones along the Oslofjord road tunnel. Note that the zones seem to have another direction than the geological interpretation (shown in purple color, from Palmstrøm et al. 2003).

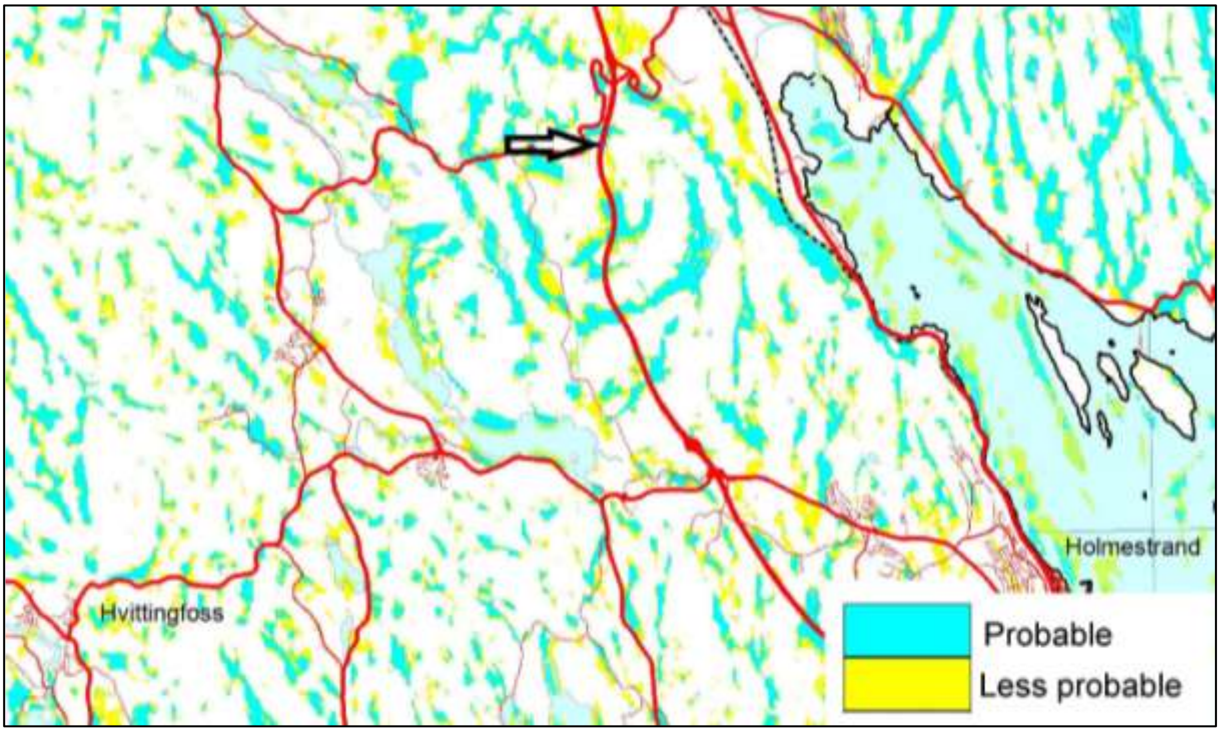

Figure 11. Interpreted deep weathering zones along the Hanekleiv road tunnel. The tunnel collapse shown by the black arrow lies in an area indicated as less probable deep weathering.

Figure 12. Interpreted deep weathered zones in the Skien area where an admit tunnel to an underground parking area in bedrock collapsed in 2009. Note that the method is able to indicate zones of probable and less probable deep weathering in urban areas.

5. DISCUSSION

Olesen et al. (2007) have carried out a detailed study using forward modeling of the magnetic field to interpret the depth extent of the alteration zones and also calculated the average yield of wells located both inside and outside the interpreted weathering zones (classified as 'probable'). Forward modeling of the magnetic data revealed that some of the low-magnetic zones continue to a depth of approximately 300 m below the surface. They reported that average water yield of the 1907 groundwater wells drilled after 1980 located outside the interpreted weathered zones, had a 47% higher average yield than the 58 wells located inside the interpreted deep-weathering zones. This supported their conclusion that the interpreted weathering zones represented remnants of a more extensive saprolite. The abundance of clay minerals such as smectite and kaolinite clogged the fracture zones and therefore reduced the water permeability of the bedrock. Olesen et al. (2007) concluded that stability problems will be more frequent at shallow depths while later leakage most probable will occur at greater depths in weakness zones.

The AMAGER method will not produce valid results in bedrock with very low magnetization since there will be no magnetic ferro-oxides to oxidize to low-magnetic ferrohydroxides. Weathering of a reversely magnetized 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 to note that an experienced geologist or geophysicist should assess the magnetization 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 Oslofjord Region, however, has shown that the bulk of the anomalies are caused by rocks with normal magnetization (Lundin et al. 2005, Ebbing et al. 2007).

In areas with thick Quaternary overburden, e.g. Raet an end moraine around the outher Oslofjord, delta sediments at the lake Øyern 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. These areas are marked with hachure (Fig. 8) and referred to as less reliable interpretation zones.

The cell size used in the AMAGER method was 25 x 25 meters for the topography and 50 x 50 meters for the magnetic data. Higher cell size of magnetic data reduces the resolution of the method and therefore thin zones may not be indicated. On the other hand, lack of high resolution may overestimate the thickness of the weathered zones.

As shown in the examples (Figs. 9-13), the indication of deep weathering may not be continuous along a lineament. Several examples have shown that construction and drift problems may arise without any indication directly at the site. However, in these cases deep weathering is indicated along the lineament close to the problem area.

In urban areas, technical installations may influence the measured magnetic field values, and this can ruin the possibilities for high quality interpretations. However, the example from Skien (Fig. 13) shows that analyses in densely populated areas is possible.

Variations in the measuring height may also give false anomalies. If the terrain changes rapidly it is difficult to drape the terrain correctly, especially with fixed-wing aircrafts. Increasing distance to the magnetic sources (hundred meters or more) may result in a reduced magnetic field, which in terms gives false indications of weathered zones.

When the first version of the action map was released (Olesen 2006), a discussion arose on deep weathering versus hydrothermal alteration in the Hanekleiva tunnel collapse. For the Oslofjord tunnel, it was claimed that the most problematic zone, indicated with the AMAGER method, was an infill of sand and gravel in a previous eroded zone. These two processes will both reduce the magnetic field, and from an engineering point of view, the discussion is irrelevant.

Due to the uncertainties with the AMAGER method, it is recommended that an experienced geologist or geophysicist should be present to ensure that the conditions necessary of using the method are satisfied. The method cannot describe the quality of bedrock in detail, but act as a tool to pinpoint areas for further investigation.

6. CONCLUSIONS

During a tropical to sub-tropical climate joints and fractures were prone to weathering and thus may contain clays such as smectite and kaolinite. The presence of such minerals prohibits groundwater flow in fracture and fault zones. The clay-bearing zones may cause problems of instability both during tunnel construction and at later operation. Due to the chemical alteration of magnetic minerals during weathering, weak zones are characterized by negative magnetic anomalies. 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 referred as the AMAGER method (Olesen 2006, Olesen et al. 2007). This has resulted in an awareness map for tunnel planners ("aktsomhetskart for tunnelplanlegging"), and was first published in 2006 (Olesen 2006). We introduced AGC (Automatic Gain Correction) to the magnetic data to improve signals from areas having low/medium magnetic anomalies. The improved AMAGER method has produced a better map of these low magnetic regions and extended the map area to the west relative to the previous version (Baranwal & Olesen 2012). The AMAGER method has successfully mapped known weak zones in the Lieråsen and the Romeriksporten railway tunnels and the Hvaler road tunnel as indicated in the earlier map by Olesen (2006). In addition, it has also identified known weakness zones causing tunnel collapse reported in the Hanekleiv tunnel at E 18 and in an underground parking lot (Bygarasjen) in Skien city.

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 a new tool to map 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 magnetization of the bedrock, either by inspecting the relevant aeromagnetic map or susceptibility data acquired in the field, or from laboratory measurements of collected bedrock samples. There should be a contrast in magnetic properties between weathered and un-weathered rock. In areas with thick Quaternary overburden, there may not be any topographical expression of the valleys, but zones may still be recognized by the negative aeromagnetic anomalies.

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