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Action mapping for tunnel planning, Oslofjord-Telemark region: mapping of deeply weathered weakness 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 prohibits groundwater flow 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 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 AMAGER method. The first version of "Aktsomhetskart for Tunnelplanlegging, Østlandet" was published in 2006. A second version was published in 2012. In this and version 3 and 4 published in 2016, we have used AGC (Automatic Gain Correction) to the magnetic data to improve signals from areas having low/medium magnetic anomalies and the area has been expanded westwards to Telemark. The present report describes the production of the last maps.

The improved AMAGER method has successfully mapped known weak zones in the Lieråsen and the Romeriksporten railway tunnels, the Oslofjord and the Hvaler road tunnel as shown in the earlier map of Olesen (2006). In addition, it had also identified known weakness zones causing tunnel collapse reported in the Hanekleiv tunnel at E 18 and in the "Bygarasjen" in Skien area. Deep weathering was also identified and confirmed by a 2D resistivity survey at Kjose in the Vestfold area which is presented in this report.

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. 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. There will be uncertainty in the interpretation of the action map depending on some of the geological conditions. There should be a contrast in magnetic properties between weathered and unweathered rock.In areas with thick Quaternary overburden, there may not be any topographical depression of the weathered joint valleys but these zones may still be recognized as negative aeromagnetic anomalies alone. Mountainous and higher elevation regions can also show low topography and low magnetic anomaly, however most of the deep-weathering that occurred in these regions would most likely be removed by erosion. So a good precaution is recommended not to misinterpret the action map in such uncertain areas.

Keywords:	Geophysics	Tunnel planning
Deep weathering	Airborne magnetic 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. A lot of problems were reported in tunnel construction in the Oslofjord and other parts of Norway. Draining of groundwater and rock falls in clay-bearing zones were reported in construction of Holmenkollen railway tunnel in Oslo in the 1920s (Kirkemo, 2000). The marine clay above the tunnel subsided and was compacted due to lowering of the groundwater table and therefore damaged lot of 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 falls. The original path of the tunnel was deviated to complete the tunnel construction. Water leakage and construction problems were also faced during the construction of the Romeriksporten and the Oslofjord tunnels.

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 the hard crystalline rocks of 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. This research resulted in the first version of "Aktsomhetskart for tunnelplanlegging, Østlandsområdet" (Olesen, 2006).

In 2012, new data west of the Oslo region was available and a second version of the tunnel planning map could be created (Baranwal & Olesen, 2012). This map includes a westward extension of the first map present by Olesen (2006). To improve the response in low magnetic areas, the automatic gain correction (AGC) method was used on the magnetic anomalies (Baranwal et al., 2013).

During the years 2011-2015, NGU conducted several helicopter-borne geophysical surveys in the Telemark area and therefore new data were available for AMAGER analysis. As a part of the ForForUT project, a cooperation between "Statens vegvesen, Vegdirektoratet" and NGU, an upgraded version of the tunnel planning maps (Baranwal, 2016; Baranwal & Olesen, 2016) are prepared as it was agreed on. A new deep-weathering location was identified and confirmed by a 2D resistivity survey at Kjose in the Vestforld area (Fredin et al., 2012a; Olesen et al., 2012). This location, together with earlier known locations, is confirmed in our new action map as well. The present report describes the background and the production process of the new tunnel planning maps.

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 Scandinavian 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 resulted from 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 during the Triassic and Jurassic, but gradually penetrated deeper into preexisting fracture zones (Fig. 1A).

The majority of the 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 Triassic to Early Jurassic ages (Ineson et al., 1975, 1978; Ihlen et al., 1978, 1984). Clay-poor grus weathering from breccias and fracture zones was sampled in a large number of these locations (P. Ihlen, pers. comm., 2013; T. Vrålstad, pers. comm., 2013). The Mesozoic ages most likely represent the same phase of deep weathering as has recently been reported from two exploration wells on the Utsira High (Fredin et al., 2012b), and not hydrothermal alteration associated with the formation of the mineral deposits. The magmatic activity in the Oslo Rift had already ceased in the Early Triassic (Sundvoll & Larsen, 1994). 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).

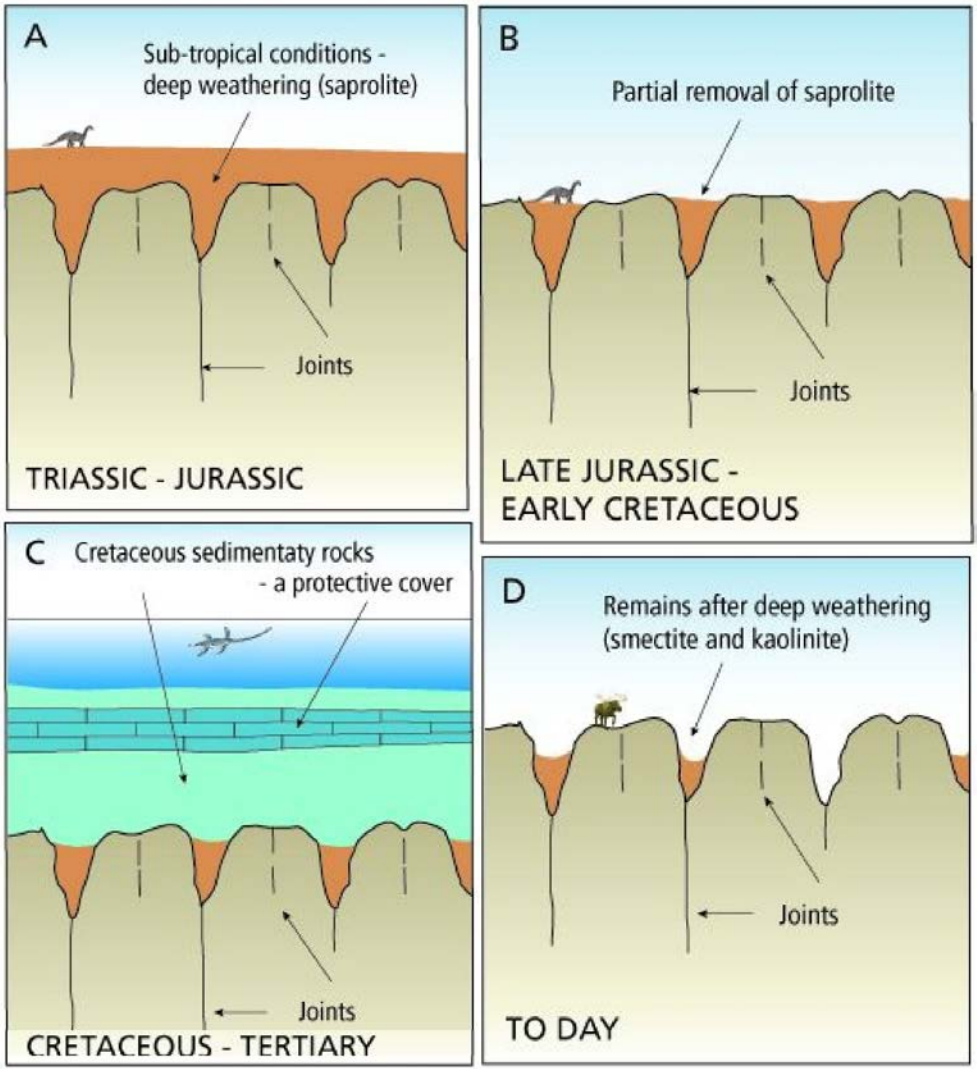


Figure 1: Schematic illustration of the process leading to the present day deep-weathering products from the start in the Triassic/Jurassic to present time (modified after Lidmar-Bergström, 1995).

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. (1992a, 1992b, 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 a better 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 et al., 2012).

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) 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 softer, 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). He concluded that the Flekkefjord deposit was a result of hydrothermal activity related to volcanism (Reusch, 1900).

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). 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 fractures 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 (Grant, 1984). Deep weathering would therefore create a negative deviation in the Earth’s magnetic field. However, breakdown of the remnant magnetization could result in positive anomalies as well if bedrock held a reversed remnant magnetization as reported by Beard & Lutro (2000) in the Krokskogen area. A detail discussion about tropical weathering in Norway was presented in TWIN report (Olesen et al, 2012). A follow-up of ground geophysical methods at some of confirmed deep-weathering location is also detailed by Rønning et al. (2007).

3. IMPROVED AMAGER METHOD

The AMAGER (AeroMAgnetic and GEomorphological Relations) method was presented by Olesen et al. (2007) to map the occurrence of deep clay alteration in the bedrock. It was based on correlating the depressions in topography and aeromagnetic data to detect clay alterations areas. Olesen et al. (2007) had 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 continued 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. The conclusion was also supported by the fact that most water leakage occurs at great depths (c. 200 m) i.e. below the lakes Lutvann and Puttjern (Palmstrøm et al., 2003). 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.

In the improved AMAGER method, automatic gain correction (AGC) was used to enhance the low and medium magnetic field areas. It was first introduced by Brönner et al. (2012). Later, Baranwal & Olesen (2012) and Baranwal et al. (2013) also implemented it with further investigations. They showed that some of the areas (especially in south-western Norway and the eastern part of Oslofjord region) with lower and smoother magnetic anomalies showed almost no variation in magnetic field without application of AGC however there were clear variation in magnetic fields in such areas after the application of AGC. Improved AMAGER method presented a better coverage and larger anomalies for probable and less probable zone of deep-weathering in such areas (Brönner et al., 2012; Baranwal et al., 2013).

A deep-weathering tunnel action map for greater Oslofjord region was presented by Baranwal & Olesen (2012) using the improved AMAGER method and extending the work done by Olesen et al. (2007). It had successfully mapped known weak zones in the Lieråsen and the Romeriksporten railway tunnels and the Hvaler road tunnel as shown in earlier map of Olesen (2006). In addition, it had also identified known weakness zones causing tunnel collapse reported in the Hanekleiv tunnel at E 18 and in the "Bygarasjen" in Skien area (Baranwal et al., 2013). Therefore, after collection of new high-resolution airborne magnetic data form Telemark area in 2012-2014, same technique of Baranwal et al. (2013) is used to extend the action map to further south of the Oslo fjord region till Telemark region.

4. DATA COMPILATION AND PROCESSING PROCEDURE

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

4.1 Topographical data

The topography grid was produced using digital hypsographic and hydrographic vector data at the scales of 1:5000 and 1:10000. A TIN (triangular irregular network) was produced, using all elevation data with hydrographic features used as break lines. This TIN was then re-sampled 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). Topography grid in the format of digital elevation model (DEM) of Telemark region was obtained from Kartverket. The different grids were merged into one grid using MOSAIC grid software in Geosoft (2010a). The final grid is shown in Fig. 2.

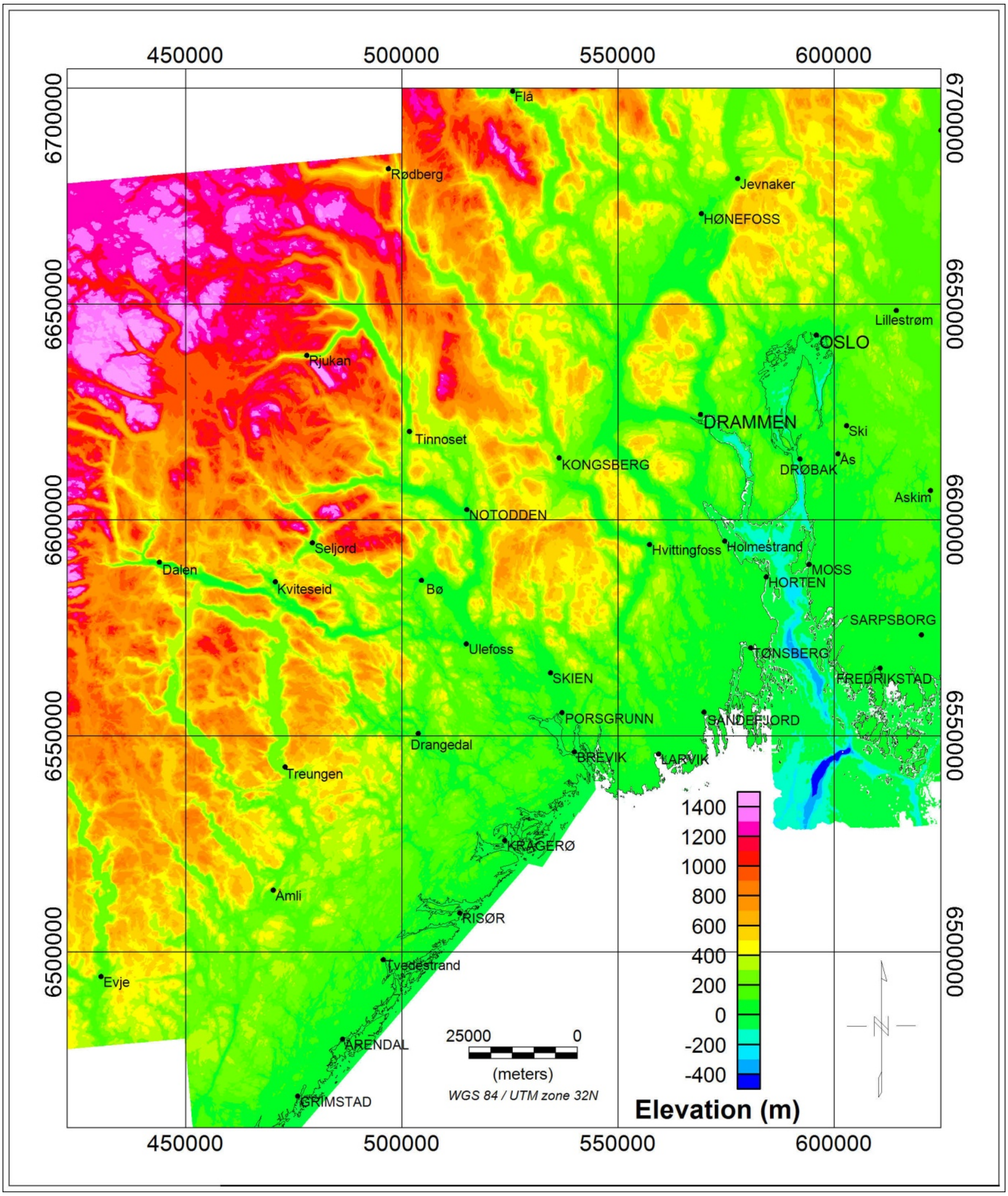


Figure 2: Mosaic of topography and bathymetry from the greater Oslofjord and Telemark Region displayed with shaded-relief.

4.2 Compilation of magnetic data

Aeromagnetic data was collected through various surveys during 1981-2015 as shown in Fig. 3 and also detailed in Table 1.

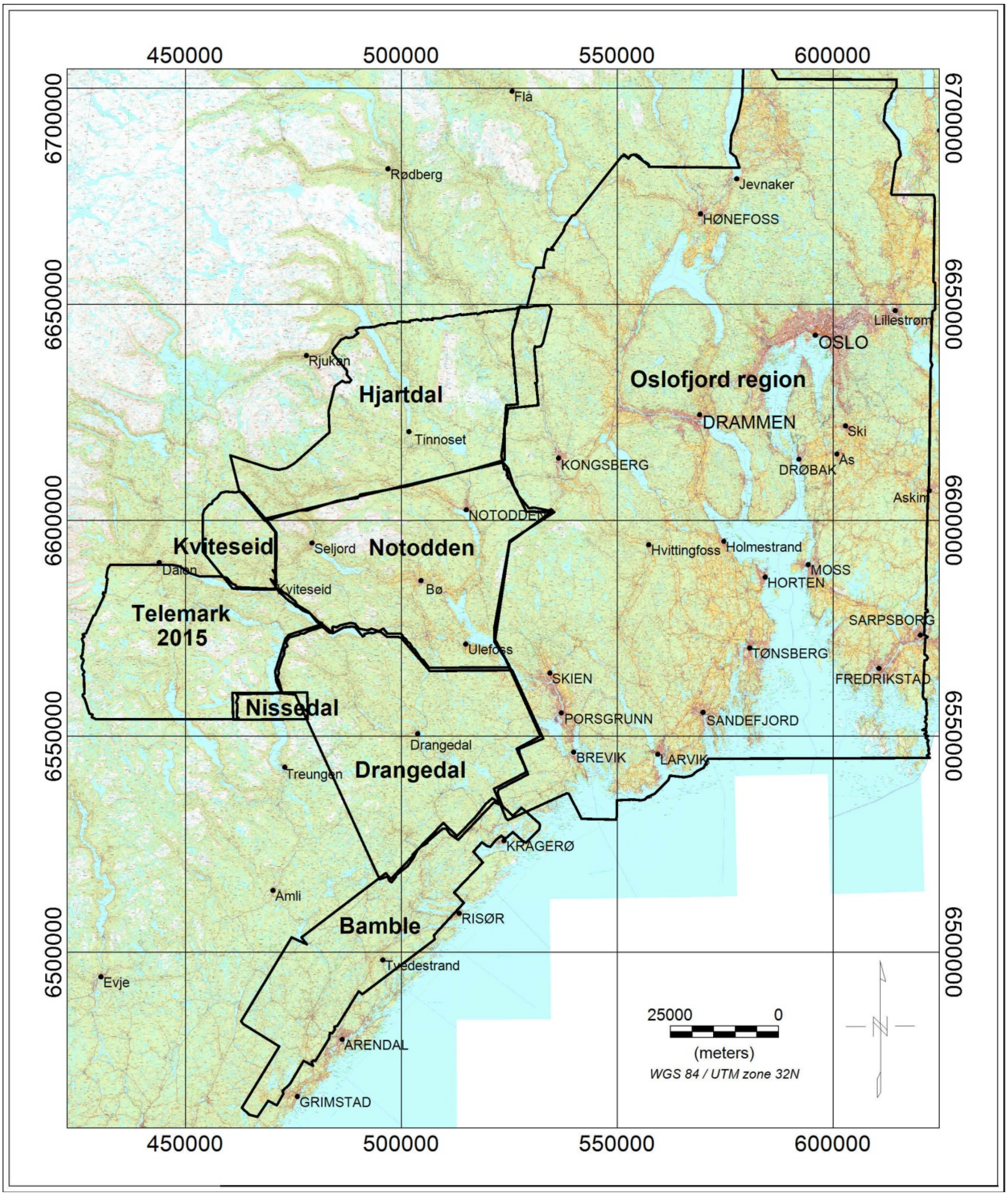


Figure 3: Location of the helicopter and fixed-wing surveys in the greater Oslofjord and Telemark Region. Details of the surveys are given in Table 1.

Processed magnetic data were IGRF corrected to magnetic field anomaly. Details of the data processing of each survey area can be found in respective reports as mentioned in Table 1. Compilation of a large area shown as Oslofjord region was performed earlier and details of surveys within this region can be found in Baranwal et al. (2013). Details of the surveys performed later are tabulated in the table 1. All the grids from the new survey areas and the Oslofjord region were stitched 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.

Table 1: Description of the helicopter surveys around the Oslo-fjord and Telemark region after 2011.

Survey names	**Regions**	**Year of Survey**	**Flight line direction**	**Flight line spacing and sensor height**	**References**
Oslofjord region	Many surveys	1981-2011	mixed	mixed	Olesen et al., 2007; Baranwal et al., 2013
Hjartdal	Hjartdal, Rjukan, Flesberg	2013-2014	140°-320°	200 m & 57 m	Rodionov et al., 2014
Notodden	Kviteseid, Notodden, Ullefoss	2013	140°-320°	200 m & 65 m	Stampolidis et al., 2013
Kviteseid	Kviteseid, Seljord, Tokke	2012	130°-310°	100 m & 65 m	Baranwal et al., 2012
Telemark 2015	Kviteseid, Nissedal, Fyresdal, Dalen	2015	90°-270°	200 m & 65 m	Stampolidis & Ofstad, 2015
Nissedal	Nissedal	2011	90°-270°	200 m & 65 m	Baranwal & Ofstad, 2012
Drangedal	Porsgrunn, Drangedal, Nisser, Bamble	2014	155°-335°	200 m & 50 m	Stampolidis & Ofstad, 2014
Bamble	Bamble	2006	121°-301° 134°-314° 143°-323°	150 m & 28 m	Fugro, 2006

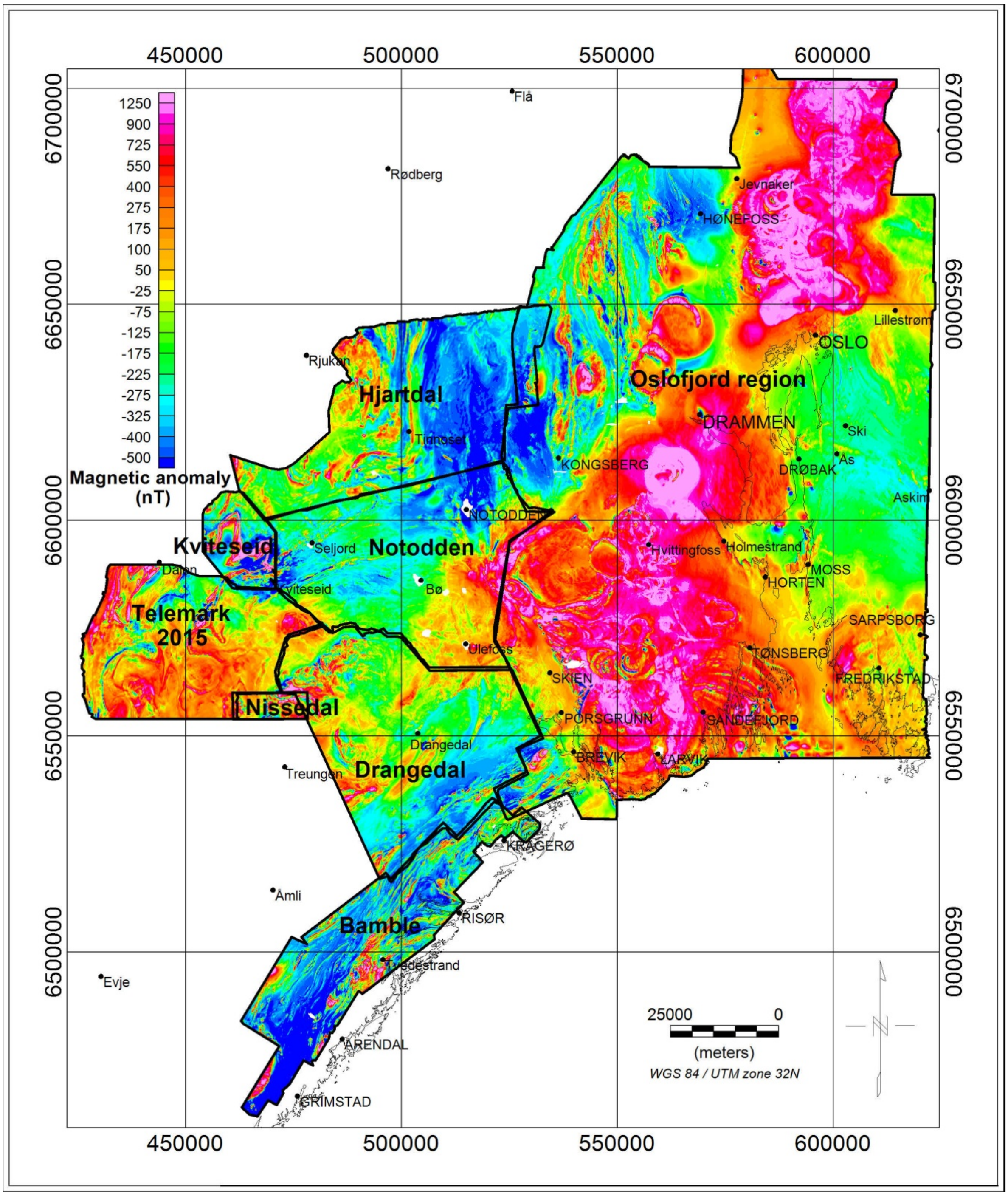


Figure 4: Compilation of aeromagnetic surveys around the greater Oslofjord and Telemark Region. A shaded relief version of total magnetic field anomaly is presented. White areas represent lack of data.

4.3 Processing of magnetic and topographic data

We adapted the filtering technique originally presented by Olesen et al. (2007) with addition of automatic gain correction (AGC) to map possible areas of deep weathering zones. AGC was applied to magnetic data to enhance the signal for weak magnetic area besides other steps followed by Olesen et al. (2007). The same technique was used to create action map in 2013 (Baranwal & Olesen, 2012). First, the stitched magnetic anomaly grid (Fig. 4) was reduced to the magnetic pole (RTP). Then, 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 indicators 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 -50 nT (magnetic) were classified as ‘probable’, while less pronounced anomalies between -5 m and -2 m and between -50 nT and 0 nT were classified as ‘less probable’. It is important to note that these magnetic anomaly and topography values are high-pass filtered values instead of actual magnetic anomaly and topography values.

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 in addition, 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 using overlapping areas to calculate the trend as most suitable for the continuation and smoothness at the boundaries. A static trend was removed from second neighboring and overlapping grid assuming Oslofjord region grid as the basis. 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 (59.53734º N, 9.51278º E, UTM 32N 529 000 - 6600000). The IGRF values for this point were calculated as total magnetic field 50982 nT, inclination 72.48º and declination 2.42º. The stitched map was filtered using a 1 km Gaussian high-pass filter to discard higher wavelength components (Fig. 6). To enhance the signal from low to moderate magnetic field regions, we applied AGC of 50 point length for local amplitude and a maximum gain of 100 (Rajagopalan & Milligan, 1994; Geosoft, 2010b). We experimented with different length, full and local amplitude options and various gain correction values in Geosoft and found these parameters as most suitable. We observed that application of AGC increased the general amplitude of signals to 50 times and minimum and maximum limit to 2-4 times (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 -50 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 region. Some of the areas in the east side with thick soil cover and areas higher than 700 m above m.s.l. (mostly in the west) were hatched to show uncertain interpretation in such regions.

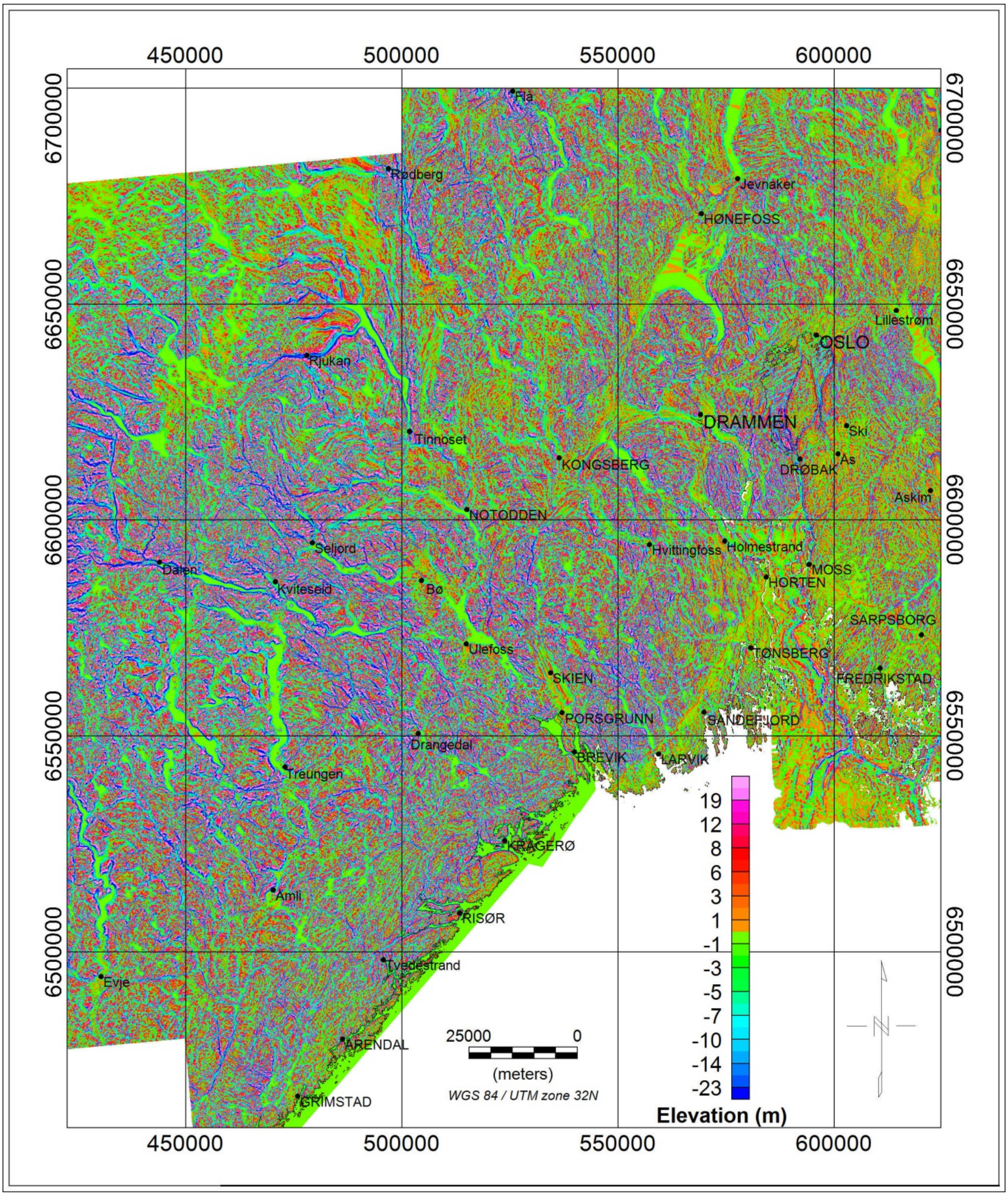


Figure 5: 1-km Gaussian high-pass filtered topography data around the greater Oslofjord and Telemark Region.

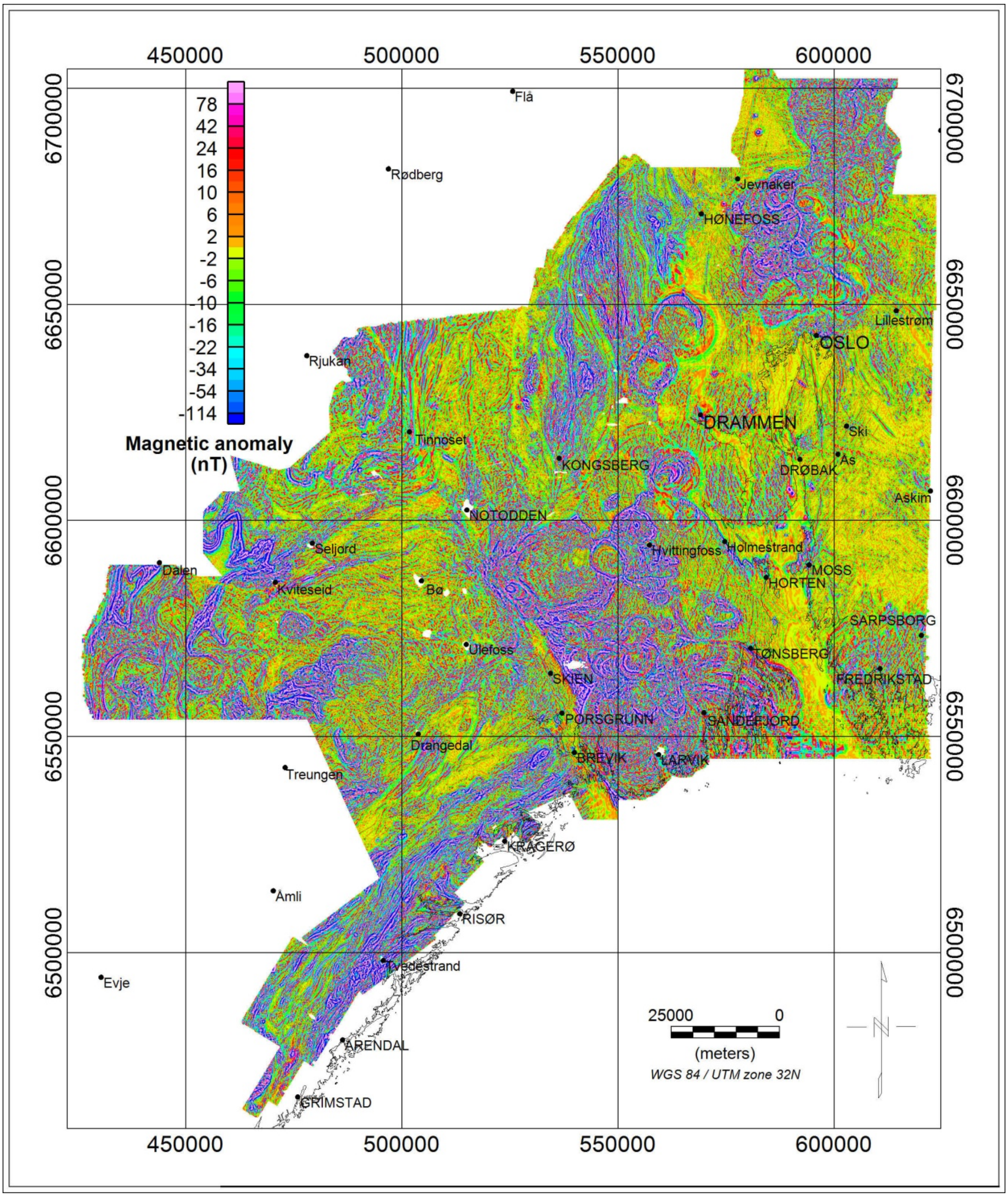


Figure 6: Reduce to pole and 1-km Gaussian high-pass filtered magnetic anomaly data around the greater Oslofjord and Telemark Region.

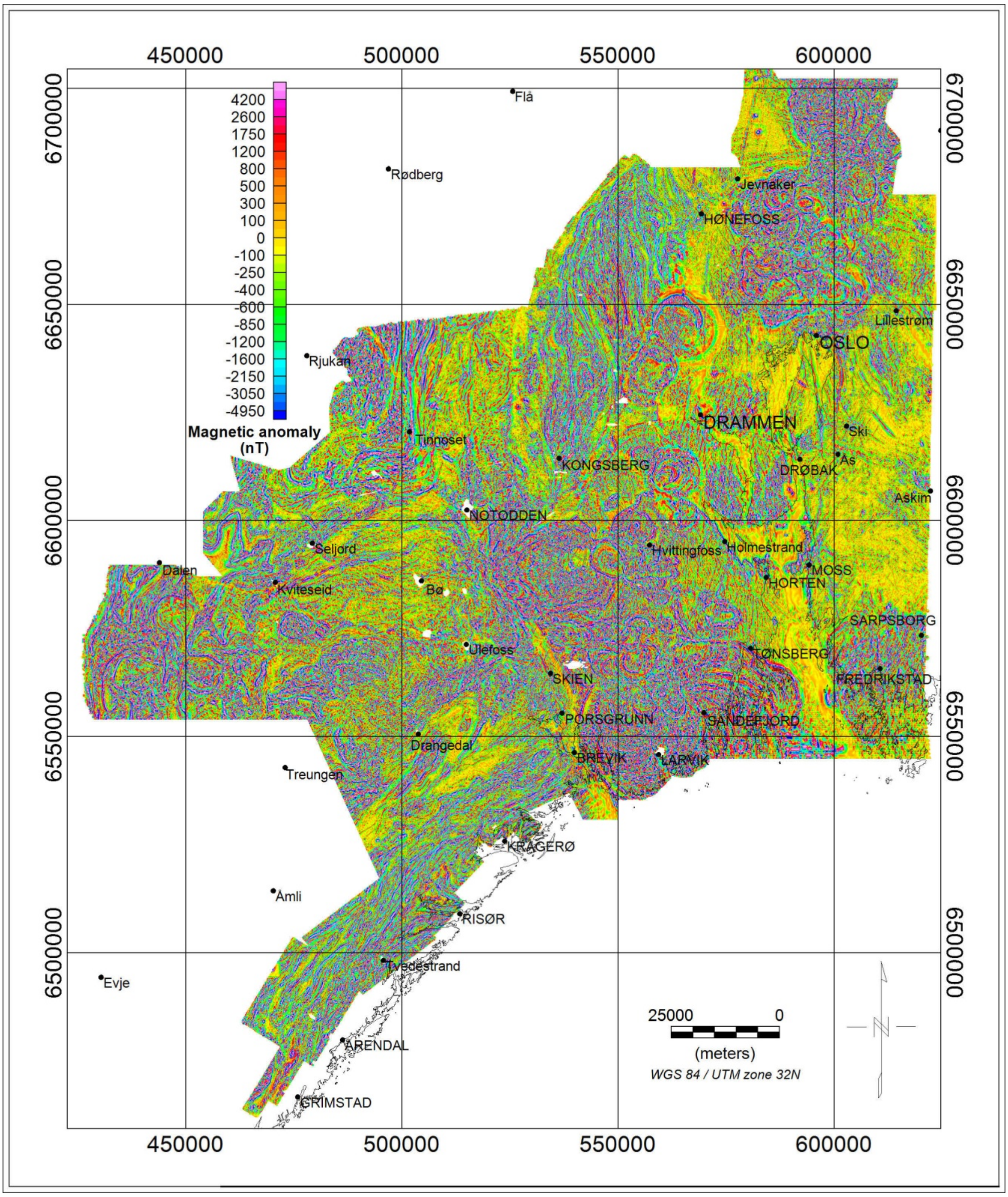


Figure 7: Automatic gain correction (AGC) using 50 point local amplitude window of the magnetic grid presented in Fig. 6.

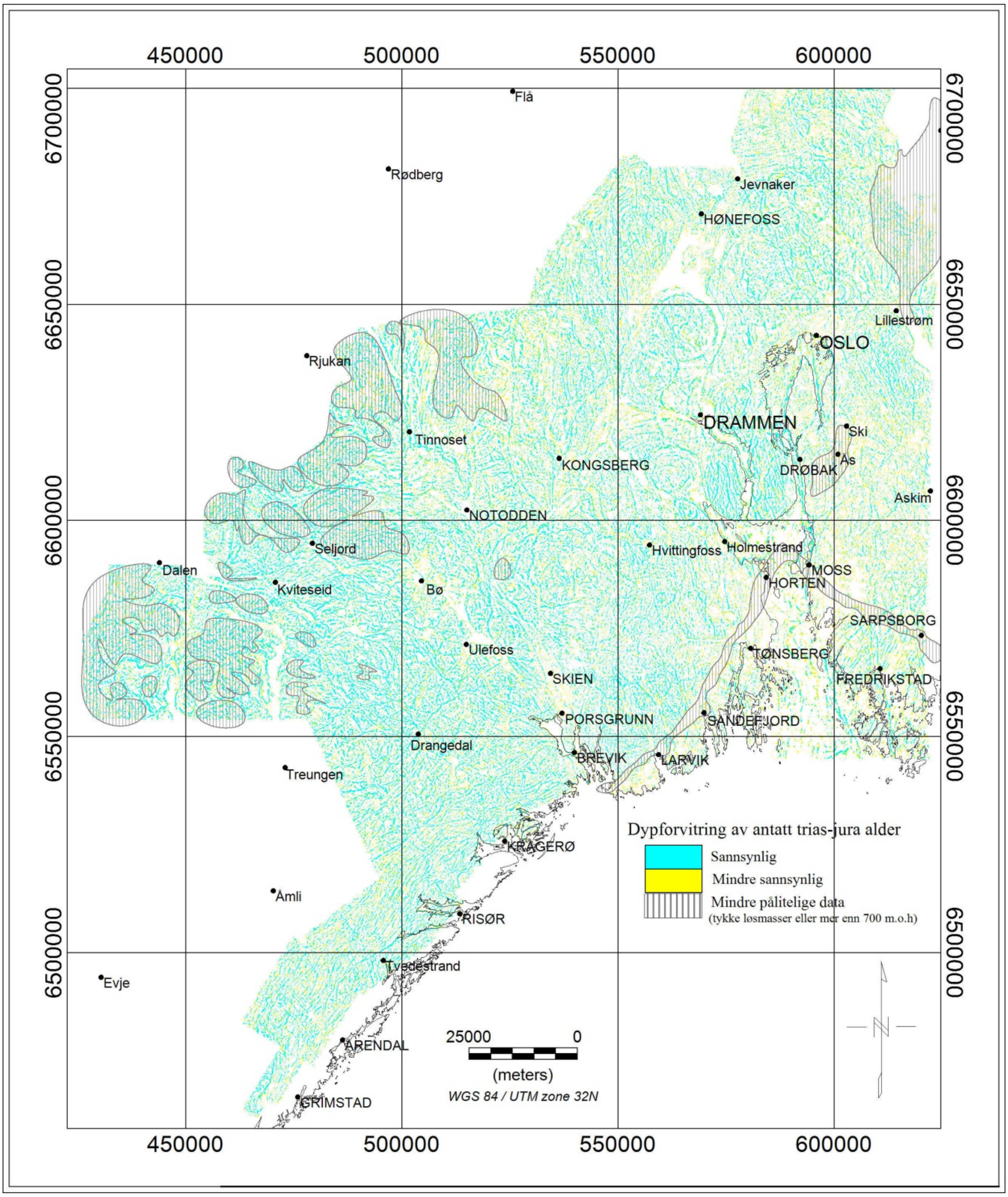


Figure 8: **Action map for tunnel planning** around the greater Oslofjord and Telemark region. Areas with thick soil cover (in the east) and areas higher than 700 m above m.s.l. (in the west) are hatched to show uncertain areas of the interpretation.

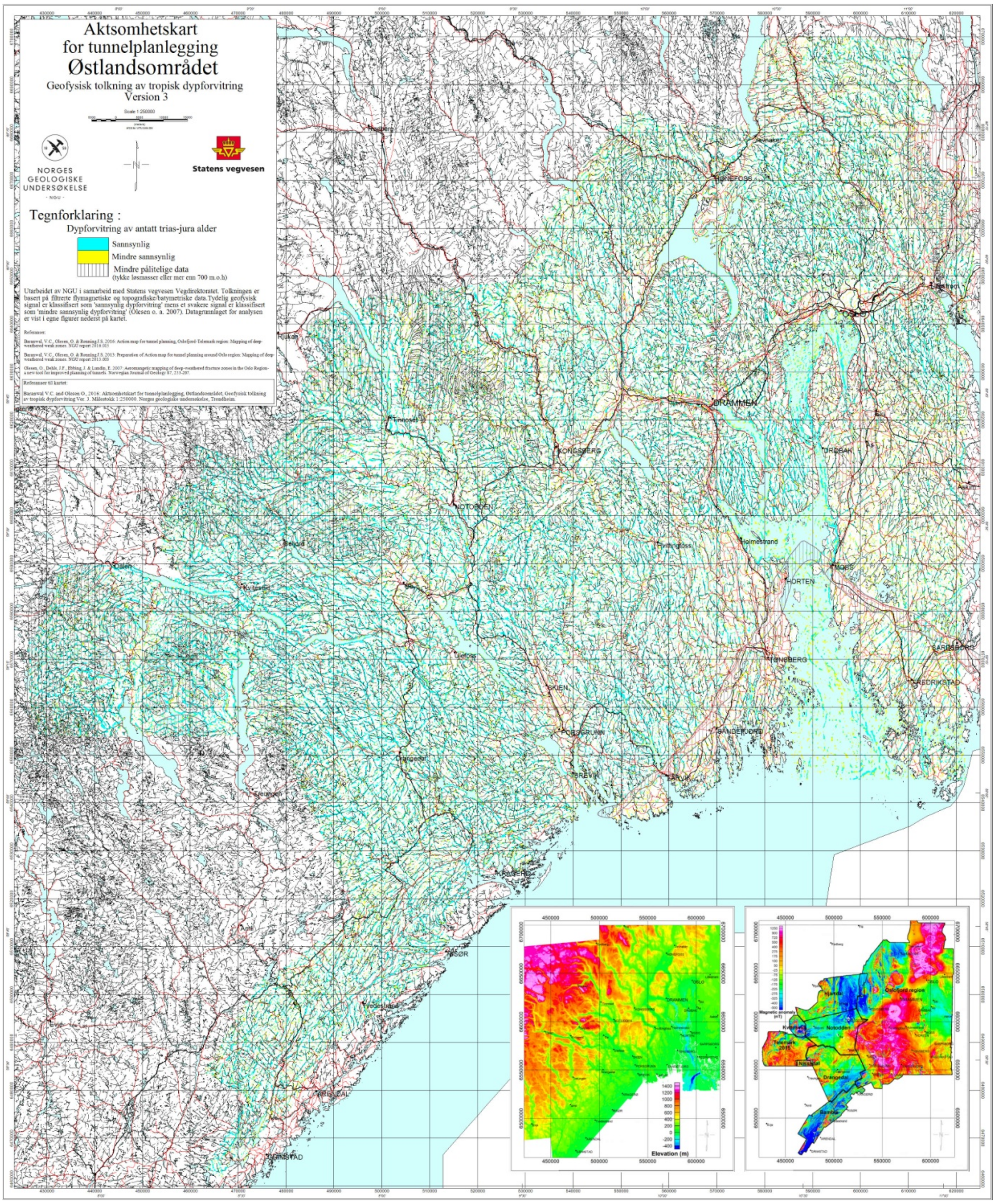
5. RESULTS

5.1 Upgraded tunnel planning maps

The new "Aktsomhetskart for tunnelplanlegging Østlandsområdet" for Oslofjord and Telemark together is presented in Fig. 9 and only for Telemerk region in Fig. 10. These maps are available in printed version in scale 1: 250.000 (Baranwal & Olesen, 2016) and 1: 175000 (Baranwal, 2016) from NGU. The Oslofjord and Telemark map will also be available from NGUs web-site.

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 magnetic anomalies and local topographic depressions. Mountainous and higher elevation regions can also show low topography and low magnetic anomaly, however most of the deep-weathering that occurred in these regions would most likely be removed by erosion. Therefore such areas are hatched with vertical lines in the upgraded maps (Figs. 9 and 10) to indicate that interpretation of deep-weather weak joins could be inaccurate in such areas.

The new map represents a westward extension of the Baranwal & Olesen (2012) map further to the area in Telemark. However, the whole map should be considered as new due to the application of RTP and AGC to the newly stitched grid of extended magnetic map.



Utarbeidet av NGU i samarbeid med Statens vegvesen Vegdirektoratet. Tolkningen er basert på filtrerte flymagnetiske og topografiske/batymetriske data. Tydelig geofysisk signal er klassifisert som 'sannsynlig dypforvitring' mens et svakere signal er klassifisert som 'mindre sannsynlig dypforvitring' (Olesen o. a. 2007). Datagrunnlaget for analysen er vist i egne figurer nederst på kartet.

Referanser:

Baranwal, V.C., Olesen, O. & Rønning J.S. 2016: Action map for tunnel planning, Oslofjord-Telemark region: Mapping of deep-weathered weak zones. NGU report 2016.015

Baranwal, V.C., Olesen, O. & Rønning J.S. 2013: Preparation of Action map for tunnel planning around Oslo region: Mapping of deep-weathered weak zones. NGU report 2013.005

Olesen, O., Dehls, J.F., Ebbing, J. & Lundin, E. 2007: Aeromagnetic mapping of deep-weathered fracture zones in the Oslo Region - a new tool for improved planning of tunnels. Norwegian Journal of Geology 87, 253-267.

Referanser til kartet:

Baranwal V.C. and Olesen O., 2016: Aktsomhetskart for tunnelplanlegging, Østlandsområdet, Geofysisk tolkning av tropisk dypforvitring Ver. 3. Målestokk 1:250000. Norges geologiske undersøkelse, Trondheim.

Figure 9: Tunnel action/deep-weathering weakness zone map around greater Oslofjord and Telemark 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 less reliable due to the presence of a thick quaternary overburden (in the east) and elevated regions higher than 700 m above m.s.l. (in the west).

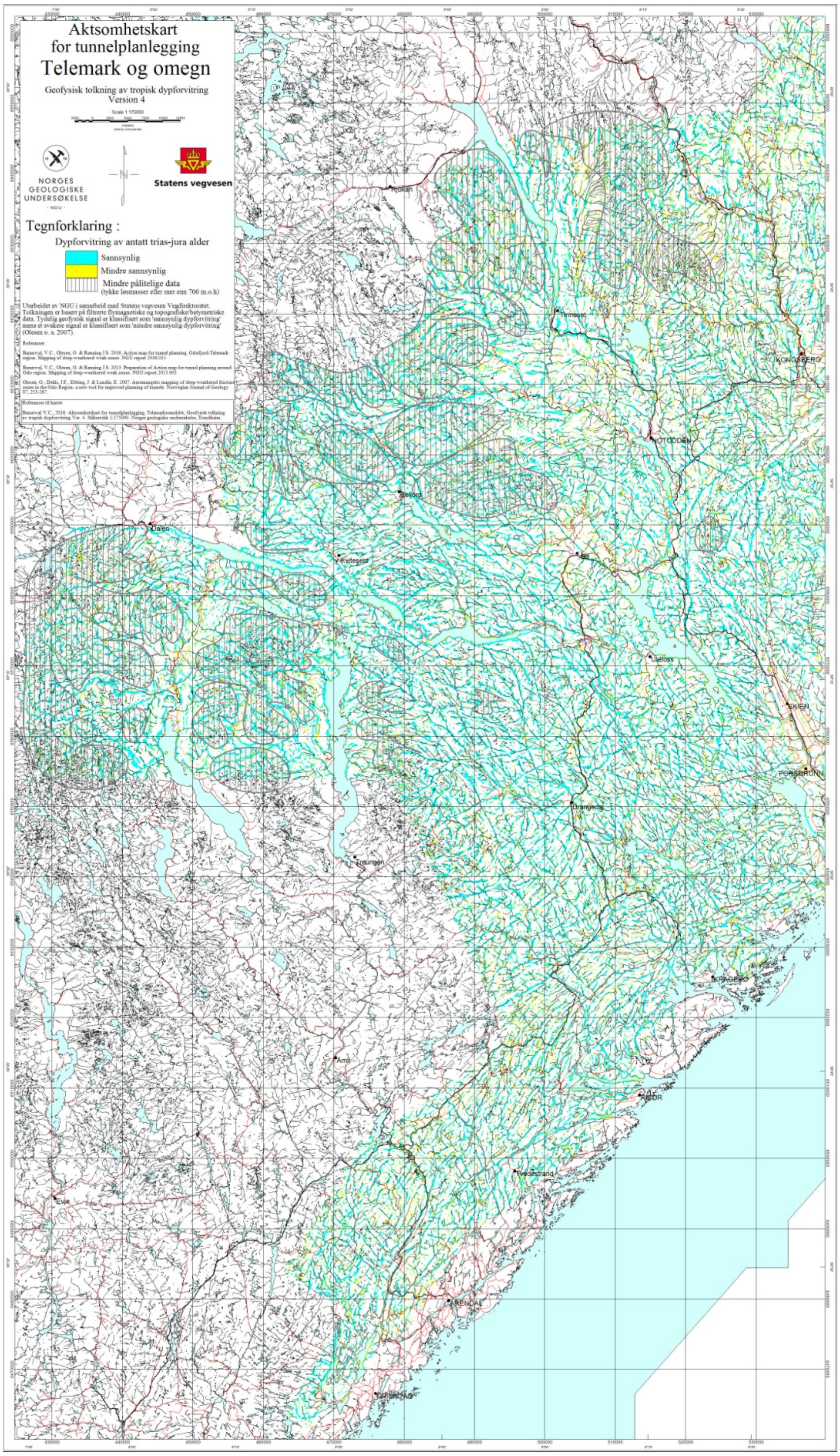


Figure 10: Tunnel action/deep-weathering weakness zone map around Telemark region only. Predicted zones of deep weathering based on processed magnetic and topographic data are shown in blue (probable) and yellow (less probable). Polygons with grey vertical hatching depict areas where interpretation is less reliable due to the elevated regions greater higher than 700 m above m.s.l.

5.2 Verification of AMAGER anomalies

We notice that we have recovered all of the weak zones reported in earlier reports by Olesen et al. (2007), Rønning et al. (2007) and Baranwal et al.(2013) e.g. weak zones encountered in the Lieråsen and Romeriksporten railway tunnels, weakness zones observed in the Oslofjord road tunnel (located c. 100 meters below sea level), tunnel collapse reported in Hanekleiv tunnel at E18 reported in 2007 (Rønning et al. 2007) and in Bygarasjen in Skien reported in 2009 (Baranwal et al., 2013). These areas were shown and discussed in the earlier reports therefore they are not shown again in this report.

In addition, one more site was confirmed with deep weathering by soil sampling and 2D resistivity survey (Låg, 1945; Fredin et al., 2012a; Olesen et al., 2012) near the hamlet of Kjose, located between Larvik and Porsgrunn (Fig. 11). We have zoomed part of the area near Kjose from our present deep-weathering action map (Baranwal & Olesen, 2016) in Fig. 11. As reported by Olesen et al. (2012), soil sample analysis and visual inspection confirmed a highly weathered zone with presence of saprolite near Kjose area. Four 2D resistivity profiles (shown by crossed lines in Fig. 11) confirmed presence of 40 m thick layer of weathered bedrock of saprolite with low resistivity values (100-1000 Ωm in a host bedrock of several thousand Ωm). 2D resistivity interpretation indicated that some of the fault zones cut through the bedrock yielding deep structures down to 160 m (2D resistivity survey had limitation to see down to this depth only). These locations are marked by pink symbols on the resistivity profiles in Fig. 11. These locations correlated well with deep-weathering indicators of AMAGER method (Fredin et al., 2012a, p. 52) and also in our present action map as shown in Fig. 11.

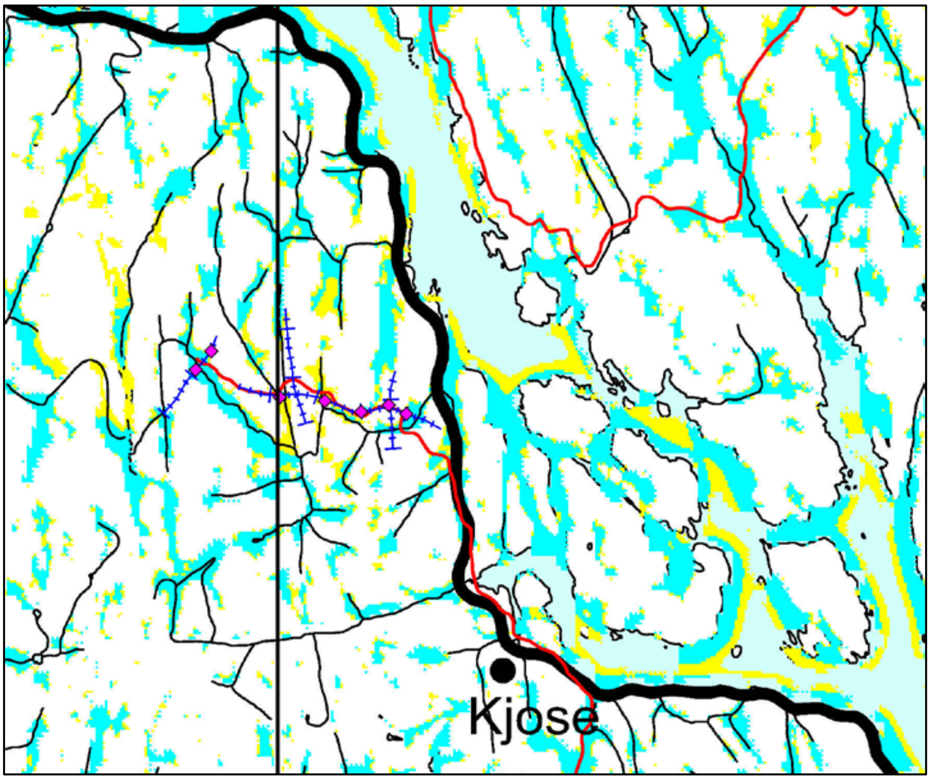


Figure 11: Deep-weathering map zoomed in the Kjose area located in Vestfold between Larvik and Porsgrunn from present map (Baranwal & Olesen, 2016). Resistivity profiles are plotted by crossed lines and deep weathering locations identified from field and resistivity surveys are plotted by pink symbols (Fredin et al., 2012a).

6. DISCUSSION

The AMAGER method in general will not produce valid results in bedrock with very low magnetization since there will be no magnetic ferro-oxides to oxidize to lower 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 terminal moraine around the outer Oslofjord, sediments south of 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. Similarly, mountainous and higher elevation regions can also show depressions in low topography and low magnetic anomaly, however most of any deep-weathering that occurred in these regions would most likely be eroded. An elevation of higher than 700 m above m.s.l. is assumed to represent such regions. Therefore such areas are hatched with vertical grey lines and referred as less reliable interpretation zones.

Sometime, 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 showed that it is possible to do analyses in densely populated areas as well (Baranwal et al., 2013).

Variations in the measuring height may also give false anomalies. If the terrain changes rapidly, it is not possible to drape the terrain especially with fixed wing aircrafts. Longer distance to 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 previously eroded zone. These two processes will both reduce the magnetic field. Therefore, from an engineering geologist point of view, this discussion on the origin of the negative magnetic anomalies is of less importance. Construction problems may arise in such weak zones independent of whichever geological process created the low magnetic field.

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.

7. CONCLUSIONS

Joints and fractures were weathered during a sub-tropical climate regime and thus may contain clay minerals such as 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. 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 to as the AMAGER method (Olesen, 2006). AGC (Automatic Gain Correction) to the magnetic data is used to improve signals from areas having low/medium magnetic anomalies. The improved AMAGER method has produced a better map of these low magnetic regions (Brönner et al, 2012; Baranwal et al., 2013). The map is further extended to the Telemark region in the west since new magnetic surveys data are available. It has successfully mapped all known weak zones in the Lieråsen and the Romeriksporten railway tunnels and the Oslofjord and Hvaler road tunnels as shown in earlier investigations of Olesen (2006, Olesen et al. 2007) and also known weakness zones causing tunnel collapse reported in the Hanekleiv tunnel at E 18 and in the "Bygarasjen" in Skien area as detected in a previous map (Baranwal & Olesen 2012, Baranwal et al. 2013). One deep-weathering site (Kjose) already confirmed by resistivity tomography and reported by Fredin et al. (2012a) is also presented here.

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. 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 unweathered rock. In areas with thick Quaternary overburden, there may not be any topographical expression of the weathered joint valleys and deep fractures. Deep-weathering should be eroded and removed from higher elevation areas by now. However, these zones may still be recognized as negative magnetic anomalies with topographical depressions and can give wrong indications on the deep-weathering tunnel action map.

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