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Mapping of caesium fallout from the Chernobyl accident in the Jotunheimen area.

Geological Survey of Norway
NO-7491 Trondheim, Norway
Tel.: 47 73 90 40 00
Telefax 47 73 92 16 20

REPORT

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Title:

Mapping of caesium fallout from the Chernobyl accident in the Jotunheimen area.

Authors: Vikas C. Baranwal, Frode Ofstad, Jan S. Rønning and Robin J. Watson	Client: Reindeer Hubandry Administration Sør-Trøndelag / Hedmark
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Summary:

As a consequence of the Chernobyl accident, several areas in Norway received radioactive fallout. One of these areas is the eastern part of Jotunheimen in central Norway. Immediately after the accident in 1986, the Geological Survey of Norway (NGU) performed airborne gamma-ray spectroscopy in central Norway. At that time, it was not possible to calculate reliable radionuclide concentrations, and the data were presented as total counts per second. Several man-made radionuclides were present in the initial fallout, but due to short half-lives, most of these have now disintegrated into stable isotopes. ^{137}Cs, with a half-life of 11.000 days (≈ 30 years) is still present in the environment in significant quantities, leading to high radioactivity levels in meat from reindeer and sheep. To obtain a detailed map of the caesium fallout concentration in Jotunheimen, an airborne gamma-ray spectrometry (AGRS) survey was carried out, focussing on reindeer grazing areas. This project was a cooperation between Reindeer Husbandry Administration, Norwegian Radiation Protection Authority and the Geological Survey of Norway.

Based on experience from previous measurements, line spacing was fixed to 1000 meters, and measuring altitude was nominally 60 meters. A total of 85 lines in east-west direction were measured, covering an area of about 3900 km^2.

Caesium concentrations in kBq/m2 are reported based on calibrations performed at NGU in 2010. The highest concentrations (more than 50 kBq/m^2) are found in a 100 km2 area north of the lake Vinsteren, with a maximum value of around 70 kBq/m^2. About 50 % of the area has concentrations higher than15 kBq/m^2. These compare with concentrations greater than 40kBq/m^2 previously measured in central Norway. All element concentrations represent an average value for an oval footprint of approximately 120 meters by 150 meters due to flying altitude and speed. Heavy rainfall shortly before data collection may have contributed to a reduction in the measured concentrations.

Keywords: Caesium	Fallout	Chernobyl
Geophysics	Airborne	Mapping
	Gamma-ray spectrometer	Scientific report

CONTENTS

FIGURES

1. INTRODUCTION

As a consequence of the Chernobyl accident, several areas in Norway received radioactive fallout. One of these areas is the eastern part of Jotunheimen in central Norway. Immediately after the accident in 1986, the Geological Survey of Norway (NGU) performed airborne gamma-ray spectroscopy in central Norway. At that time, it was not possible to calculate reliable radionuclide concentrations, and the data were presented as total counts per second. The map of the southern part of Norway (Figure 1) showed considerable fallout in Jotunheimen and other areas. However, this map was based on relatively few flight lines, and therefore does not provide the same level of detail available in the present study.

Initially, several man-made radionuclides were present in the fallout from the nuclear accident. However, most of them have disintegrated into stable isotopes due to their short half-lives. Only ^{137}Cs with a half-life of 11,000 days (≈ 30 years) is still present in the environment in significant quantities, and constitutes a potential health hazard due to high levels of radioactivity in the meat from reindeer and sheep. The Geological Survey of Norway (NGU) has previously prepared a map of caesium fallout in parts of Trøndelag (Smethurst et al. 1999) which is presented in Figure 2.

A discussion between NGU and the Reindeer Husbandry Administration on the practical use of caesium deposition mapping in countermeasure planning in reindeer husbandry was initiated in 2006. With reference to the caesium maps from Trøndelag, the Reindeer Administration in South Norway obtained financial support from the Ministry of Agriculture and Food for a helicopter borne gamma-ray spectrometric survey in and around Jotunheimen in 2009. However, due to new aviation regulations NGU was not able to conduct this survey until the summer of 2011.

Based on experience from the Nord-Trøndelag measurements, the line spacing was fixed at 1000 meters, with a nominal measuring altitude of 60 meters. The region of interest, specified by Lavrans Skuterud representing the Reindeer Administration, is shown in Figure 3. In total, the profile length was approximately 2600 line km. This area was extended towards the northeast in order to adjoin previously mapped areas. Magnetic and electromagnetic surveys were performed in addition to the radiometric survey. However, we present the data only from the radiometric and magnetic surveys in this report.

This project was a cooperation between Reindeer Husbandry Administration, Norwegian Radiation Protection Authority and the Geological Survey of Norway.

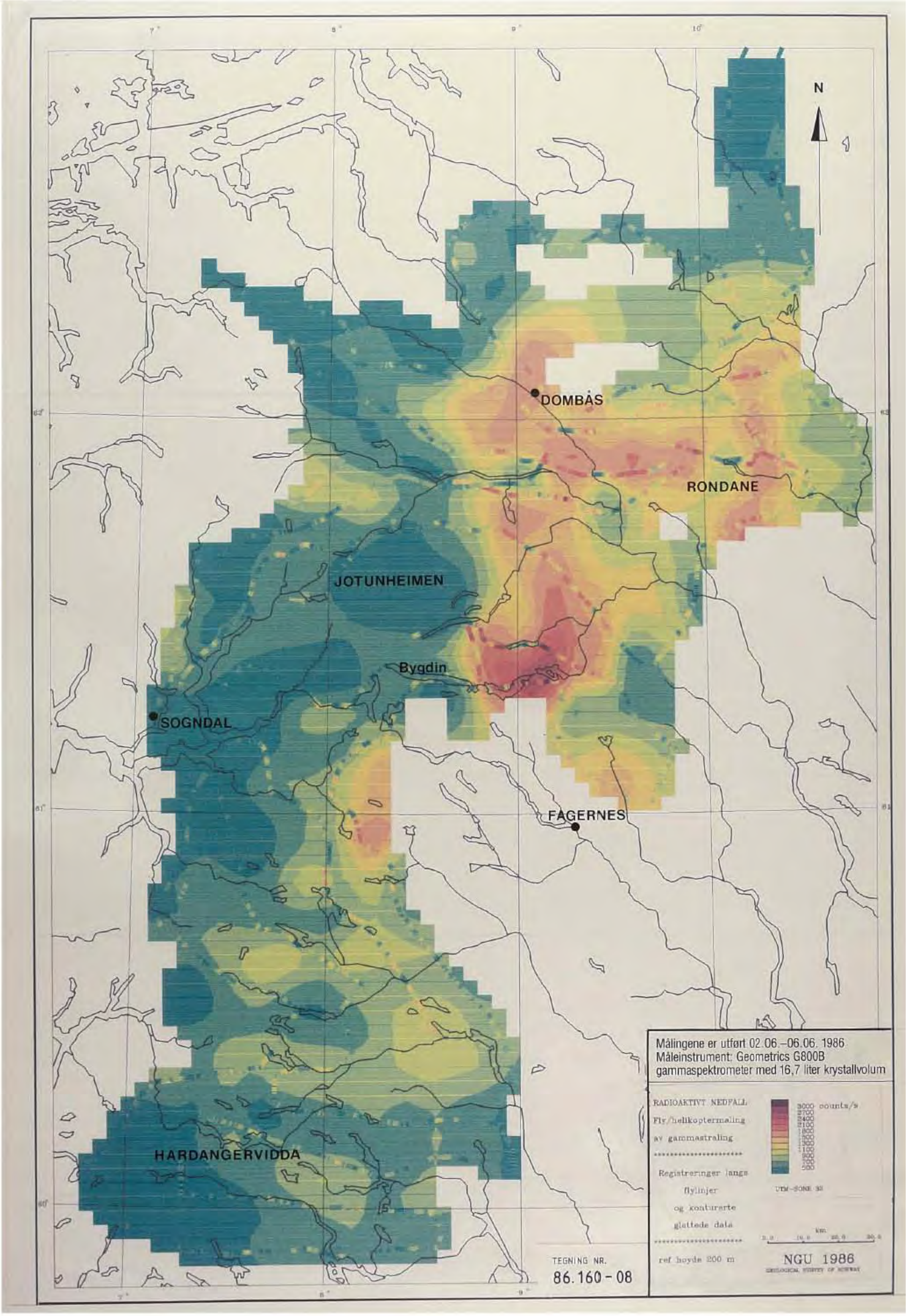

Figure 1: Fallout from the Chernobyl accident in counts per second based on data measured from a fixed wing aircraft in the summer of 1986. The coloured lines represent the flight lines while the coloured areas are gridded data From Lindahl & Håbrekke 1986).

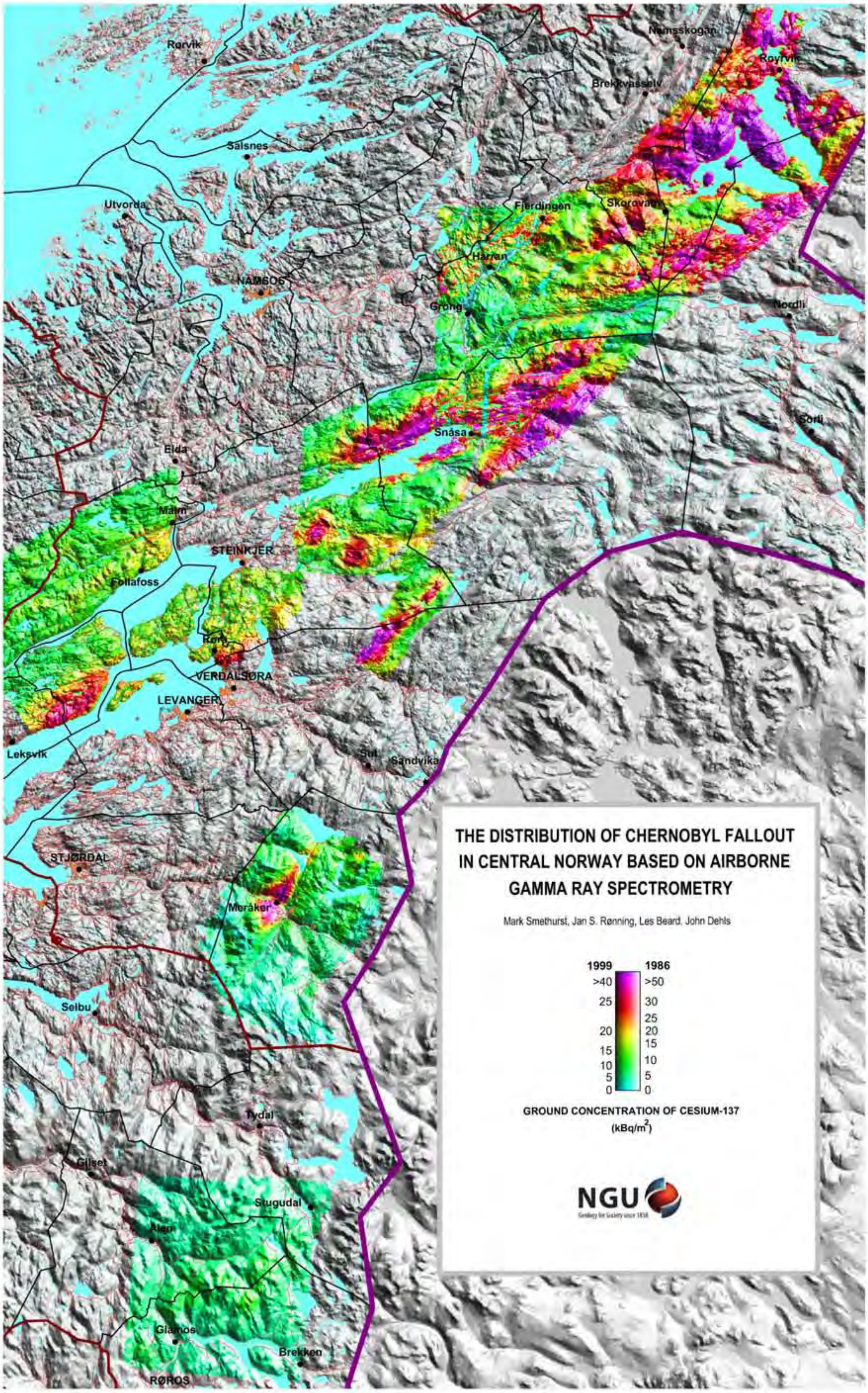

Figure 2: Ground concentration of ^{137}Cs in central Norway area (Smethurst et al. 1999).

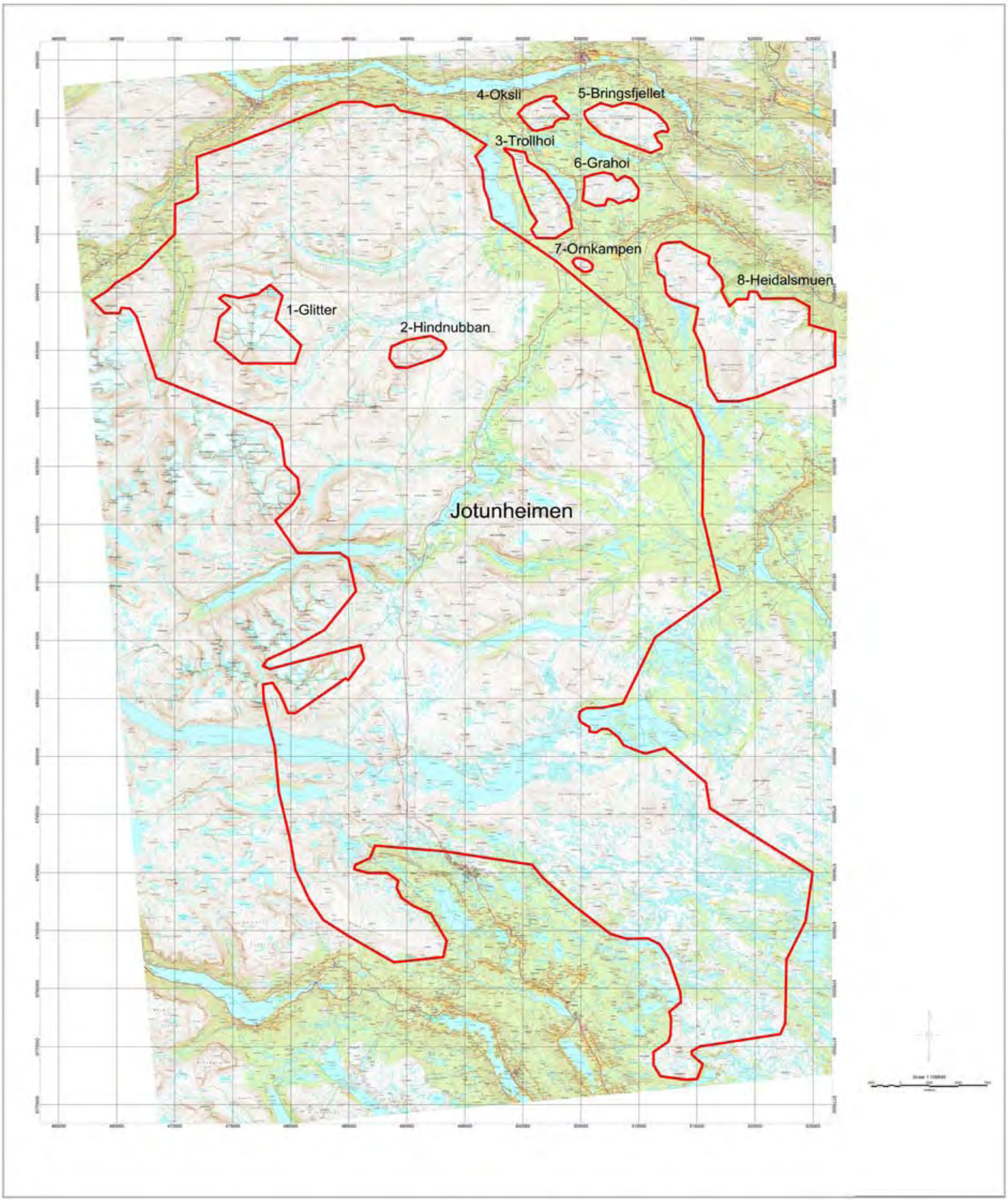

Figure 3: Proposed areas for airborne gamma-ray spectrometer measurements in Jotunheimen..

2. MEASURING METHOD AND PROCEDURE

Radiometry, magnetic and electromagnetic data were measured in the area. Due to the sparse line spacing, the electromagnetic data has not been processed. A brief description of radiometric and magnetic methods is given in Appendix A.

2.1 Measuring equipment

The radiometric measurements were carried out using a 1024 channel RSX-5 gamma ray spectrometer with sodium iodide detector packs of total crystal volume 20.9 l (16.7 l downward and 4.2 l upward directed). Energies from 0.2 MeV to 3 MeV were collected in the channels 1 to 1023. The channel 1024 (cosmic channel) covers energies above 3 MeV.

Total magnetic field was recorded using a Scrintex Cs-2 caesium magnetometer. The magnetometer resolution was 0.001 nT. The base station was a Scrintex ENVI proton magnetometer with a resolution 0.1 nT. Electromagnetic fields originating from coplanar and co-axial dipoles were also measured to investigate the ground conductivity.

For navigation, a Topcon Legacy E GPS system with an antenna at the tail tip of the helicopter was used. The GPS was sampled twice per second. The system had accuracy better than ±5 m. A Bendix/King radar-altimeter was also mounted on the helicopter to measure the height of sensors from the ground. Its accuracy was 5 % of the measured altitude.

2.2 Calibrations

The RSX-5 gamma-ray spectrometer was calibrated for Cs, K, U and Th sensitivity at NGU during 2010. Stripping ratios and sensitivities for K, U and Th were calculated using NGU's radiometric calibration pads in July 2010 (Grasty 1987, Appendix A). Sensitivity for caesium was calculated in June 2010 using a point caesium source moved in a grid pattern to approximate an infinite source (Appendix B3). Cosmic, aircraft and height attenuation coefficients were determined from a special survey as recommended by IAEA (2003) close to Narvik airport in August, 2011. Upward detectors were calibrated to correct for atmospheric radon measurements.

2.3 Data Acquisition

All the geophysical data were collected simultaneously. The crystal for the radiometric measurements was mounted directly on the underside of the helicopter, while the magnetometer was mounted in a bird hanging 30 m below the helicopter during the flights. The GPS system was used for positioning and the radar altimeter was used to determine height above surface topography.

To cover the survey area efficiently and economically, three base locations were used for the survey: Beitostølen, Gjende and Lemonsjøen. The field campaign lasted from 21.07.11 until 31.07.11, with seven days of production due to adverse weather conditions on several days.

The surveyed region has an area of about 2934 km^2. The measurements were performed along 85 east-west directed, parallel lines with a line spacing of 1000 m (Figure 4). The average flying altitude over the flight lines was 65 m and the average production speed was about 85 km/h. However, due to the relatively strong topography variations (400 to 2400 m above mean sea-level) it was not always possible to keep the speed and flying altitude constant.

For the radiometry, a recording time of one second for each measurement was used. This provides a compromise between an acceptable measuring interval (of about 30 m) and collecting sufficient counts for a representative spectrum. We expect that about 70% percent of the gamma ray counts for a single measurement originates from an oval (or footprint) of width twice the flying height, and length twice the flying height and the distance travelled during the accumulation, i.e. roughly 120m by 150m. Full coverage could therefore have been obtained using 200-250 m line spacing. Prior to this survey, NGU and the Reindeer Husbandry Administration assessed the effect and needs of various line spacings (200 to 1600 m) from a small area in the Trøndelag survey (Figure 2). A line spacing of 1000 m was chosen to cover a larger area at the cost of lower resolution.

For the magnetic mapping, five samples per second were recorded resulting in a data spacing of about 6 m during data acquisition. For removal of the diurnal magnetic field variation, a base magnetometer was placed in Beitostølen; however this failed to record any magnetic data due to technical problems. Instead, magnetic data from Dombås observatory (http://www.tgo.uit.no/), approximately 100 km NE of Jotunheimen, was used to remove diurnal variations from the magnetic data.

The company *Heliscan as* provided the helicopter (AS 350 B2) and pilot for the airborne measurements.

3. PROCESSING

For most processing stages the commercial software "Geosoft" was used (Oasis Montaj Geosoft, 2007).

In processing of the airborne gamma ray spectrometry data, spectral windows for various elements (Cs, K, U, Th) were first live time corrected, and then aircraft and cosmic background values were eliminated (e.g. Grasty, 1987; IAEA, 2003). The upward detector method as discussed in IAEA (2003), was applied to remove the effects of radon in the air below and around the helicopter. Window stripping was used to isolate count rates from the individual radio-nuclides Cs, K, U and Th (IAEA, 2003). The topography in the region was rough, and the sensor was not always at a constant altitude. Stripped window counts were therefore corrected for variations in flying height to a constant height of 60 m. Finally, count rates were converted to effective ground element concentrations using calibration values derived from calibration pads at the Geological Survey of Norway in Trondheim. A list of the parameters used in the processing scheme is given in Appendix B1. For further reading regarding standard processing of airborne radiometric data, we recommend the publication from Minty et al. (1997).

The total magnetic field data was filtered with a non-linear filter of three fiducials to remove spikes. Remaining spikes in the data were removed manually. To correct for diurnal variations of the external magnetic field a spiking and low-pass filtered version of the total magnetic field data from the Dombås observatory was subtracted, and an average regional field of 51095 nT was added. The IGRF values were calculated (using Geosoft) and subtracted from base corrected data to obtain magnetic anomaly data. We could not see any inconsistencies between adjacent flight lines, or along the flight lines, and therefore no micro-leveling was applied. A flow chart of the magnetic data processing (including the used parameters) is given in Appendix B2. An overview of standard processing for airborne magnetic data is given by e.g. Luyendyk (1997).

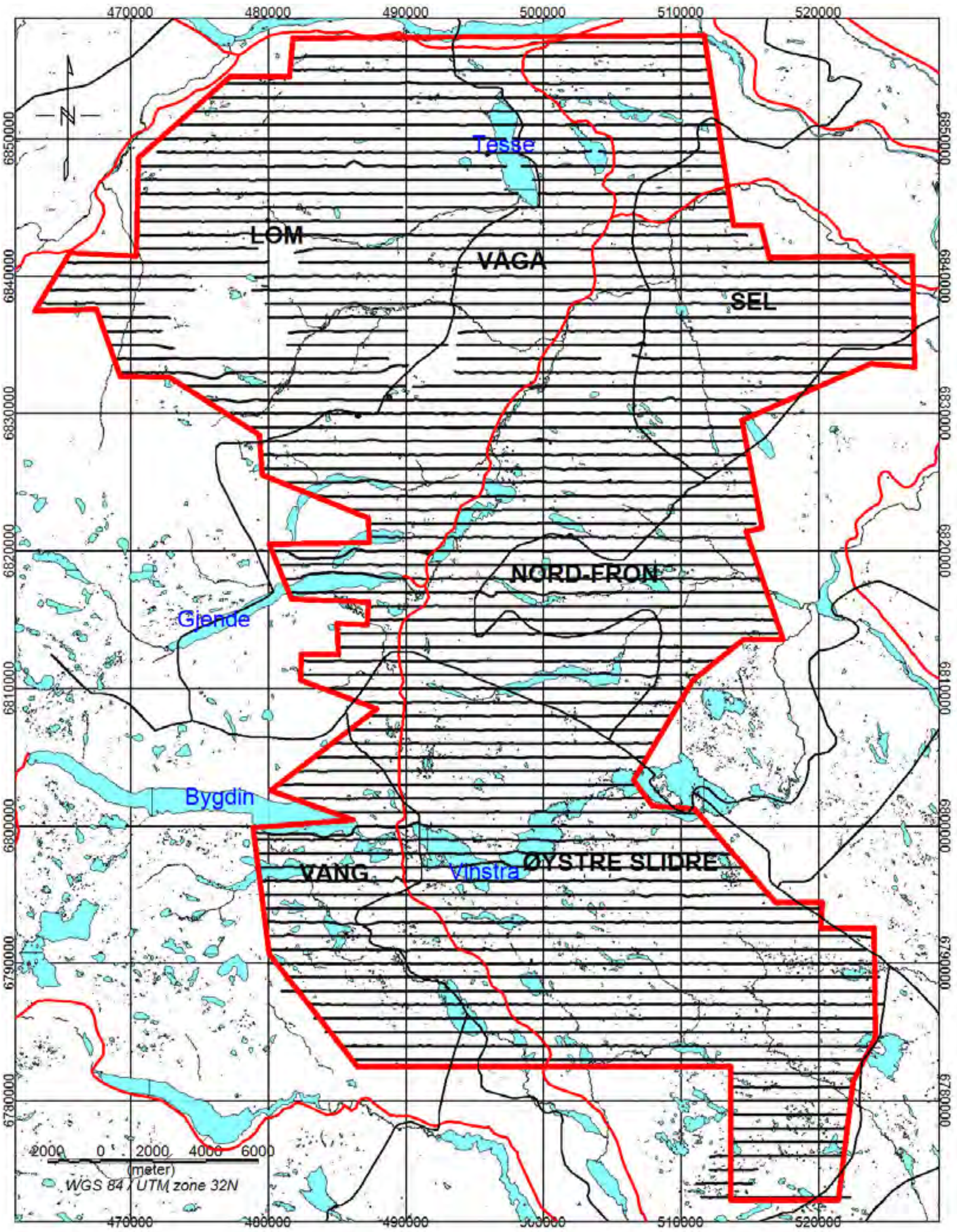

Figure 4: Survey area around Jotunheimen. The thick black and red lines indicate the flight lines of the helicopter survey and boundary of the survey area, respectively. The thin black and red lines represent municipality boundaries and roads, respectively.

4. RESULTS

Radiometric and magnetic data were processed and maps produced. Due to sparse line spacing, electromagnetic data were not processed. Final data are presented either as grids (using minimum curvature gridding) or as profile plots. The gridded data have a sampling interval of 200 m in both x and y directions. Final grids for total counts of Cs, K, U, Th and magnetic total field anomaly are shown in figures 5 to 10.

The following maps in scale 1: 100.000 are produced as a part of this study:

2011.062-01:	Jotunheimen, Ground concentration of Caesium-137 (kBq/m^2) in June 2011 (Equal area distribution colour scale)
2011.062-02:	Jotunheimen, Ground concentration of Caesium-137 (kBq/m^2) in June 2011 (Linear distribution colour scale)
2011.062-03:	Jotunheimen, Ground concentration of Caesium-137 (kBq/m^2) in June 2011 (Profile plot)
2011.062-04:	Jotunheimen, Radiometric data, total counts (c/s)
2011.062-05:	Jotunheimen, Ground concentration of Potassium in weight %.
2011.062-06:	Jotunheimen, Ground concentration of Uranium in ppm.
2011.062-07:	Jotunheimen, Ground concentration of Thorium in ppm.
2011.062-08:	Jotunheimen, Total magnetic field.

Only the caesium maps at scale 1:100.000 are included in this report. The other maps, at scale 1: 100.000, can be ordered from NGU. Maps of Cs concentration at reduced scale are presented in Figures C-1 to C-3 (Appendix C) in three different ways to highlight salient features. Figure C-1 show the Cs grid with equal area distribution which highlights ranges of the variations. Figure C-2 shows the Cs grid with linear distribution which highlights absolute values. Figure C-3 shows Cs concentration as a profile plot along the flight lines.

5. DISCUSSIONS

The radiometric measurements in the Jotunheimen area in 1986 (Figure 1) and in 2011 were not carried out with the same sensor, but with the same sensor type and volume. The total count maximum reading from 1986 was approximately 3000 c/s while the maximum reading in 2011 was about 1800 c/s. This is not inconsistent with a half-life of around 30 years, but a more detailed comparison is difficult as we do not know the exact positions for the 1986 readings. Several effects have an influence on the data in addition to the physical disintegrations. Data from 1986 were measured during the summer several weeks after the Chernobyl accident. Short lived radioisotopes such as Iodine-131, Tellurium-132, Barium-140 and Molybdenum-99 with half-lives less than 13 days (Smethurst 1995) had disintegrated to stable isotopes, but others such as Caesium-134 (half-life 730 days), Ruthenium-106 (368 days) and Ruthenium-103 (40 days) were still present during the earlier survey. In the present study, radionuclide concentrations will also have been reduced relative to the earlier study through wash-out and animal grazing.

Concentration of all radioisotopes mapped by gamma-ray spectroscopy is heavily dependent on the calibration of the sensors. The NGU has followed standard spectrometer calibration procedures (IAEA 2003).

Lakes are clearly visible in radiometry maps as areas exhibiting no gamma radiation. The Cs concentration shows a transition from high values to low values around the lakes or water bodies because parts of the footprint of the measurements were over water.

Moisture in the ground/soil has a significant attenuating effect on gamma radiation from all radio-elements. As the data acquisition was performed immediately after a period of heavy rain, wet ground might have reduced the number of gamma-rays from the ground resulting in a reduced apparent element concentration, including that for caesium. The effect of this is difficult to quantify.

The caesium concentration is calculated in kBq/m^2. Effective potassium concentrations are given in weight % and effective uranium and thorium concentrations are given in ppm. In a first view the ground concentrations of U and Th correlate with each other. Such a rough first-order correlation of thorium and uranium nuclides is typical for many rock types (IAEA, 2003).

The maximum concentration of the caesium fallout in Jotunheimen is about 70 kBq/m^2. Concentrations greater than 40 kBq/m^2 were mapped in the Trøndelag area in an earlier study (Smethurst 1999).

The Cs distribution is not correlated with the occurrence of natural radioelements (Uranium, Thorium and Potassium) and has highest concentrations in the centre of the study area. The concentrations of Cs are reduced in the northwest part of the map, possibly due to presence of high altitude mountains. We also observe higher Cs concentrations over mountainous regions than over forests.

Statistical uncertainties in the reported caesium concentrations are estimated to be of the order of a few percent; the dominant source of uncertainty is likely to be a systematic uncertainty in the caesium sensitivity factors (Bq/m^2 per count-per-second) derived from calibrations performed at NGU (Appendix B3). We estimate this systematic uncertainty to be around 15%.

6. CONCLUSION

Caesium concentrations in kBq/m^2 are calculated from airborne gamma-ray spectrometry in a 3900 km^2 area in Jotunheimen, central Norway. The maximum value is about 70 kBq/m^2 which is slightly higher than concentrations previously mapped in central Norway. The highest values (more than 50 kBq/m^2) are concentrated in a 100 km^2 area north of lake Vinstra. About 50 % of the area has concentrations higher than 15 kBq/m^2. All element concentrations represent an average value for an oval footprint of approximately 120 m times 150 meters due to flying altitude and speed.

7. REFERENCES

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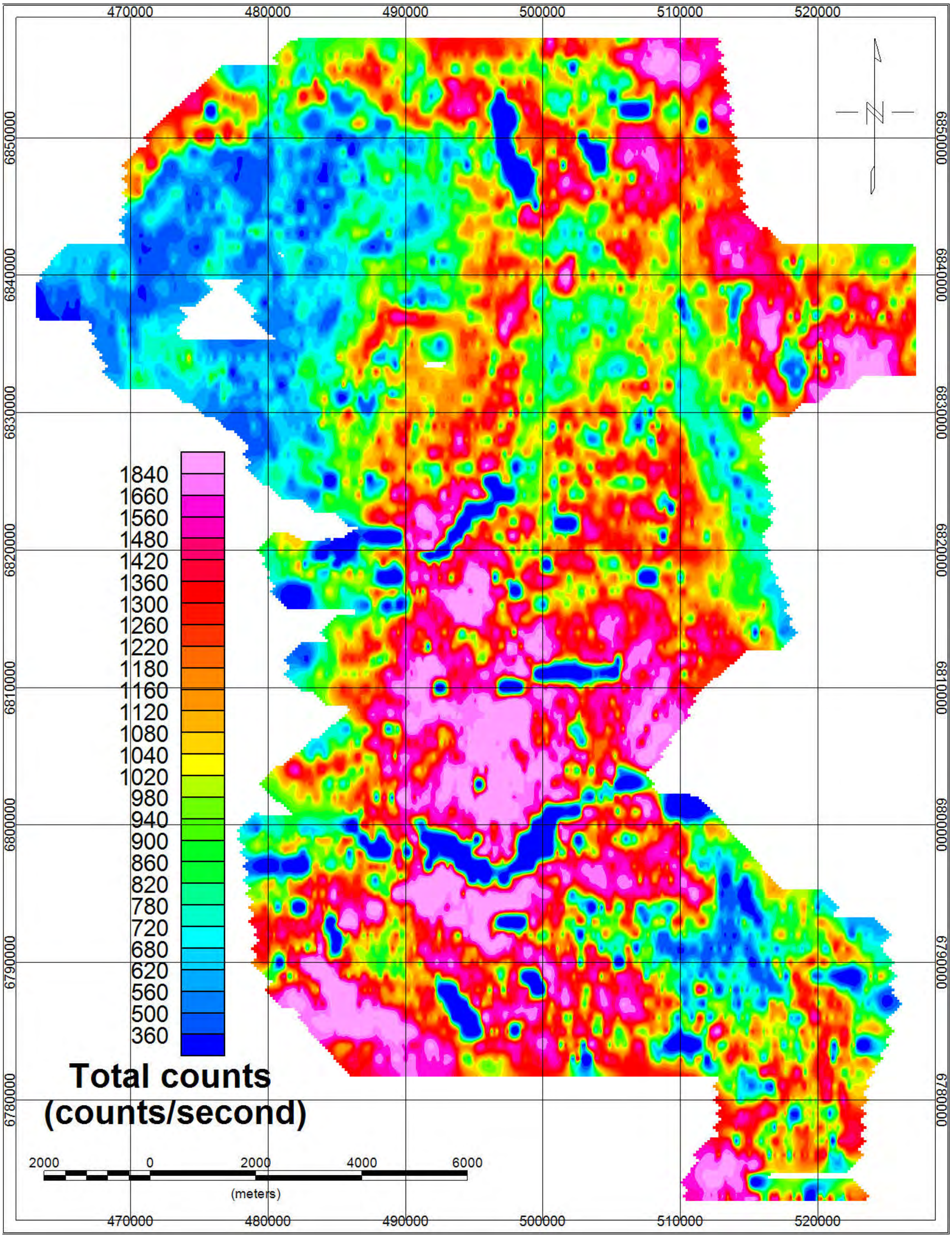

Figure 5: Total counts grid of the Jotunheimen area.

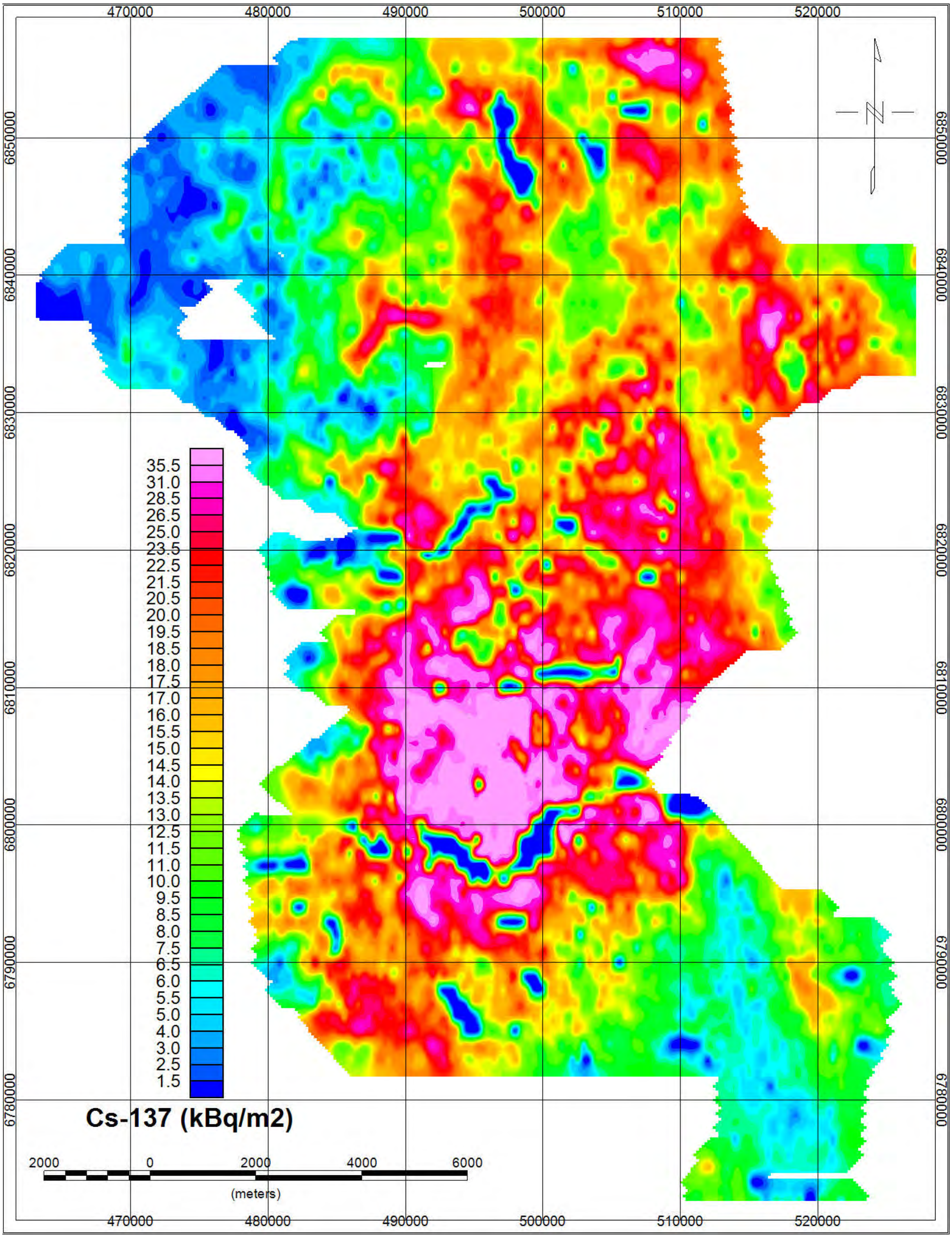

Figure 6: Caesium grid of the Jotunheimen area.

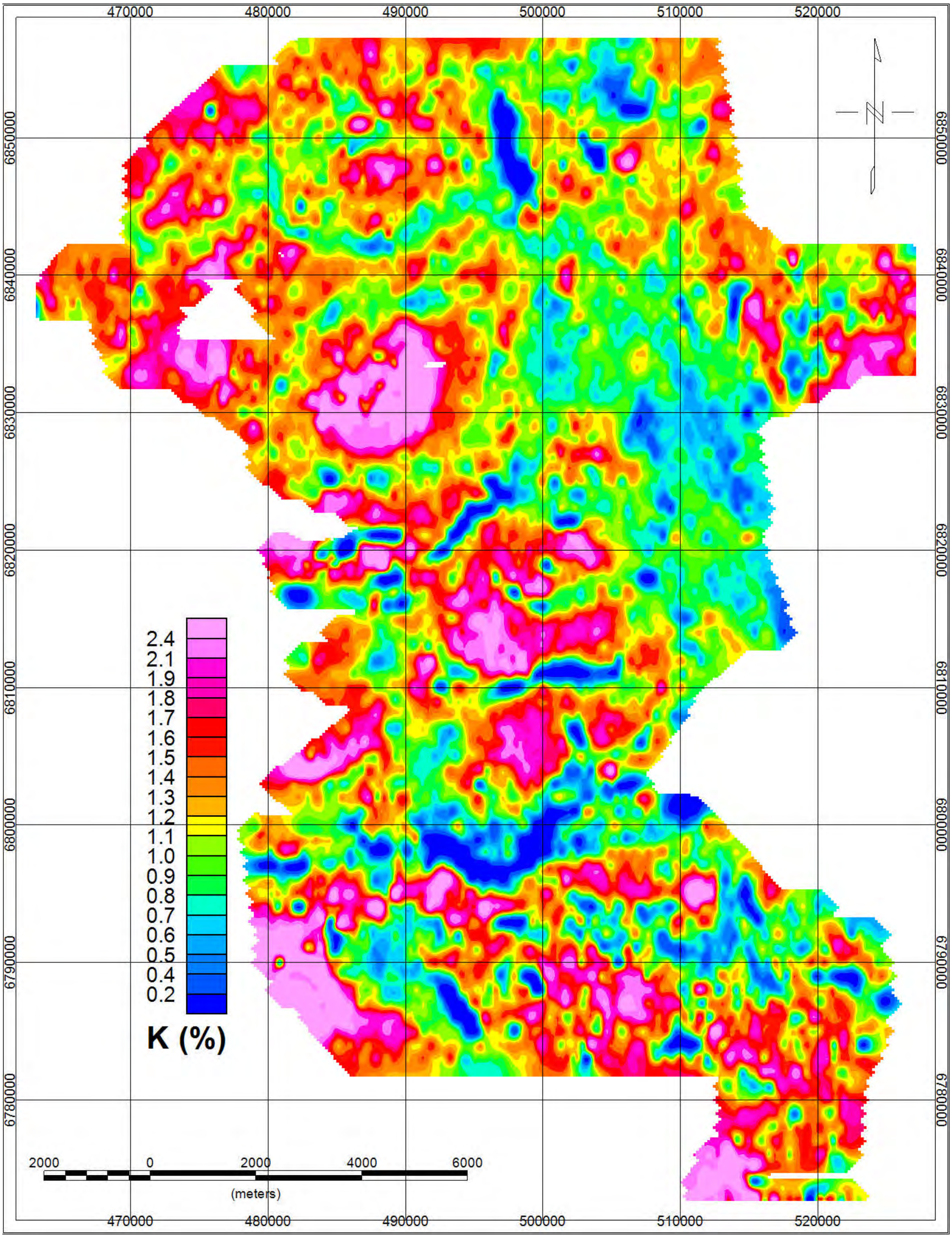

Figure 7: Potassium grid of the Jotunheimen area.

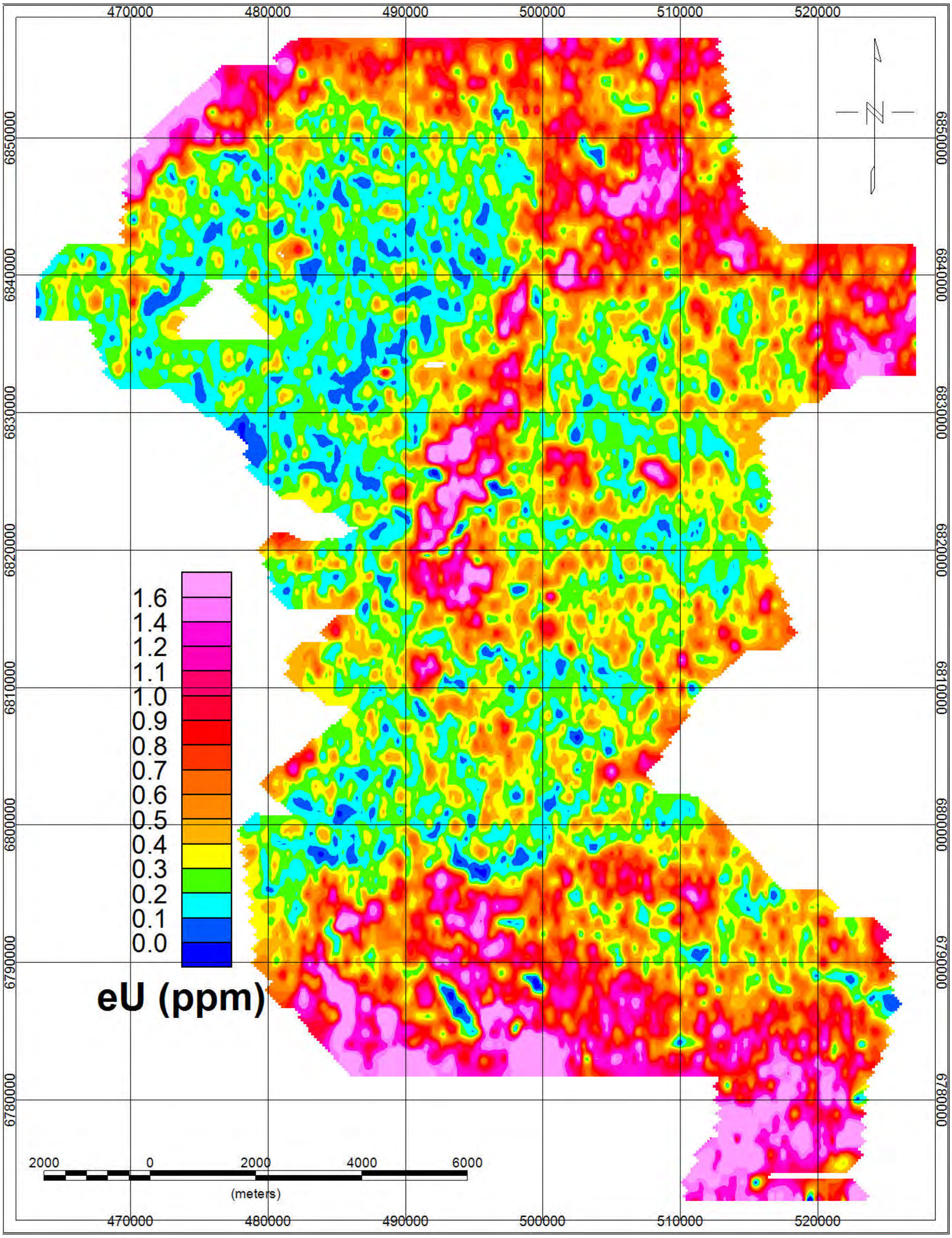

Figure 8: Uranium grid of the Jotunheimen area.

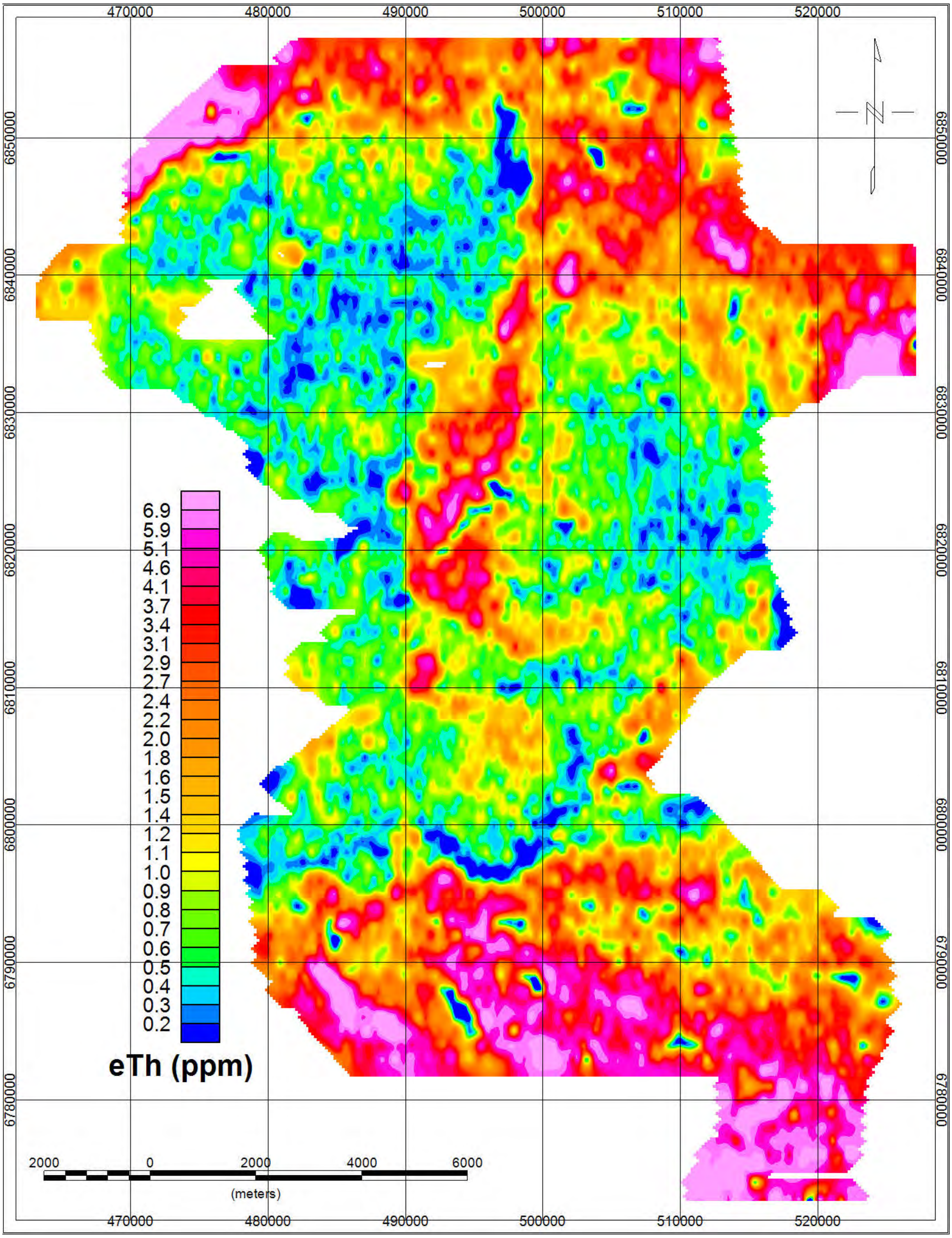

Figure 9: Thorium grid of the Jotunheimen area.

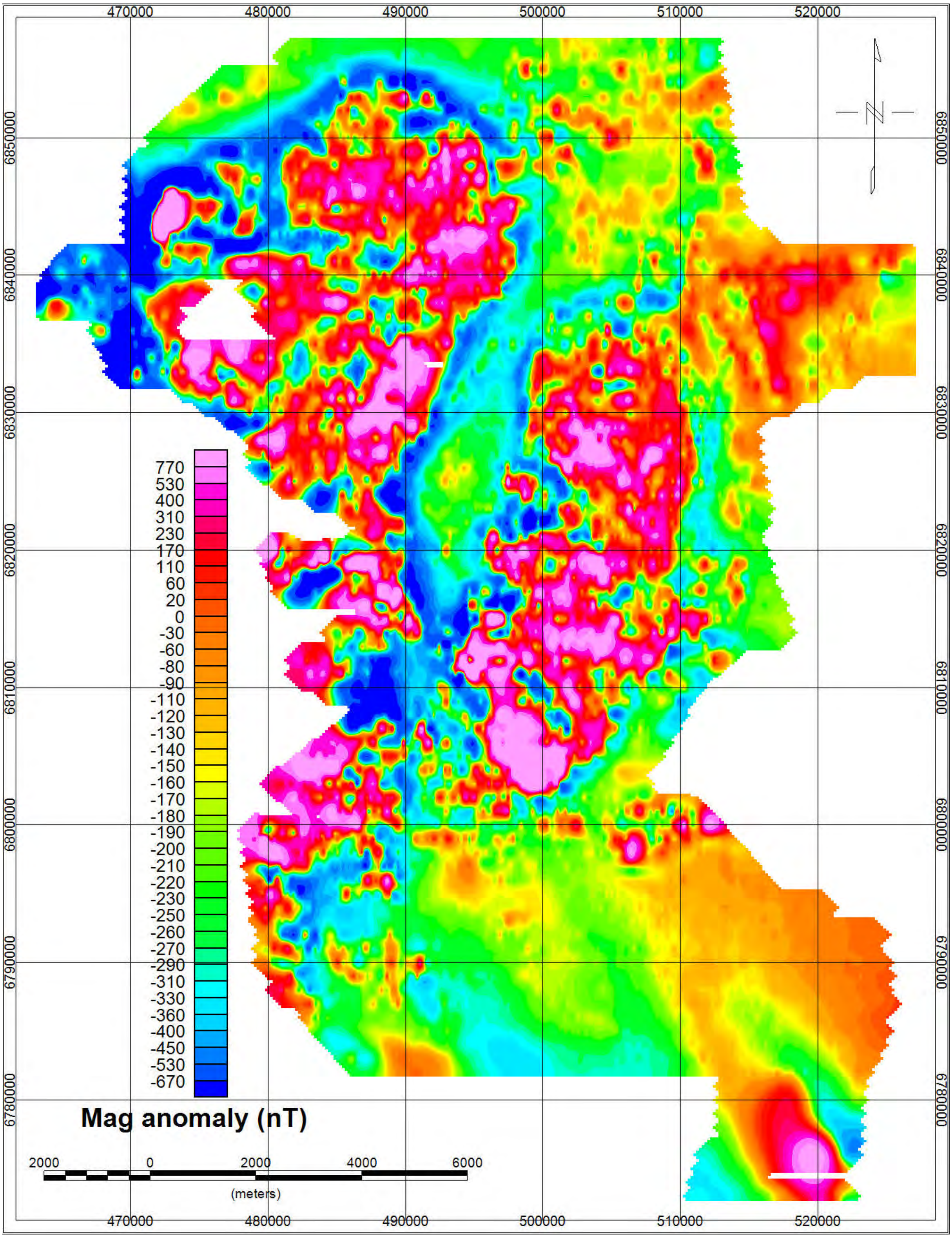

Figure 10: Total amgnetic field anomaly grid of the Jotunheimen area.

Appendix A: Short description of magnetic and radiometry methods

Radiometry:

Airborne gamma ray spectrometry (AGRS) is generally used for mapping of the near-surface concentration of the natural isotopes Thorium-232, Uranium-238 and Potassium-40, whose decay series are responsible for mostly all radioactivities from natural sources. ^{40}K has only one daughter product (^{40}Ar), but ^{238}U and ^{232}Th decay in a series of 18 and 11 daughter isotopes until the stable isotopes ^{206}Pb and ^{208}Pb are reached. AGRS can also be used for environmental surveys e.g. to map Cs fallout from the Chernobyl accident. In case of Cs mapping, two isotopes of Cs could be present, ^{134}Cs and ^{137}Cs; however ^{134}Cs has a half-life of only 730 days. All ^{134}Cs from Chernobyl would have effectively disappeared, and so we map only ^{137}Cs which has a longer half-life of 11000 days.

Every product in the decay series has its own specific alpha, beta and/or gamma radiation. During measurements the gamma radiation is recorded by a scintillation detector and arranged into a spectrum of 1024 equally sized energy channels. In the processing, it is possible to separate the contribution of the K, U and Th from the total spectra by using the gamma ray counts in windows around the most significant energy maxima of the decay series. For uranium and thorium series the maxima from the daughter products ^{214}Bi and ^{208}Tl are used. The counts in these windows represent the Uranium and Thorium ground concentrations assuming that the products in the decay series are in equilibrium (it is assumed that no products are depleted or added)[1]. For determining Potassium ground concentrations, counts in a window around the ^{40}K peak are used. Cs concentration is determined from counts in a window around the ^{137}Cs peak.

Any spectrum measured with an airborne system will be a mixture of spectra from various sources including cosmic radiation, aircraft background, atmospheric radon background, naturally occurring ^{40}K, ^{238}U, ^{232}Th from ground, ^{137}Cs from nuclear accidents, and other man-made radioactive nuclides. In natural radioelement surveys, the cosmic, aircraft and atmospheric radon signals are considered as background: for fallout mapping, the gamma rays from natural radioelements in the ground will also be considered as background.

Gamma radiation is strongly attenuated by any type of shielding/covering materials and therefore only the gamma radiation from the upper one meter of the subsurface is recorded by helicopter-borne gamma ray spectrometry. This means that information from gamma ray spectrometry is always limited to the shallow features. Soil and sediments (but also high water concentrations in the shallow ground) can significantly attenuate gamma radiation from underlying rock. However, in region with no or thin overburden, radiometry data can often provide accurate "geological maps", because uranium, thorium and potassium concentrations are closely linked to individual rock types and their origin/development. Because the number of radiation counts from surface material decreases exponentially with the altitude above the ground, data quality of radiometric airborne data is strongly dependent on the flight heights. Weather conditions and air radon concentrations (^{222}Rn) also have a large impact on the data quality and can complicate the data processing. A complete overview (including theory, calibration, acquisition, processing and interpretation) of gamma ray spectrometry methods is given in IAEA (2003).

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[1] To emphasize that ^{238}U and ^{232}Th concentrations are not directly measured, finally determined uranium and thorium concentrations are presented in "eU" and "eTh" . The prefix "e" stands for "equivalent" or "effective".

Magnetic:

Airborne magnetic surveying is an efficient method to determine the main geological, near surface structures and lineaments provided that the associated rock types have measurable magnetic properties[2]. Although a magnetic field is a vector field, essentially all modern instruments in common use measure only the total magnetic field. Local magnetic anomalies related to the magnetization of near-surface rock types are superimposed with the much larger main earth fields (in the order of 50000 nT), other regional anomalies and time-varying external fields (usually in the range of ~ 60 nT). The so-called diurnal magnetic field is mainly caused by the interaction of charged particles emitted from the sun with the geomagnetic field. By using a magnetic base station situated close to the surveyed region, the effect of this slowly varying external field can be measured and removed from the magnetic helicopter data. However, in some periods so-called magnetic storms occur that are responsible for strong high-frequency magnetic noise which is difficult to remove using base station corrections. Magnetic surveying should not be carried out during these periods.

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[2] The local magnetic field of rocks is typically sensitive to the magnetite content. Therefore classification based on magnetic anomalies varies from other geological classification methods which are often silica based.

Appendix B1: Flow chart of radiometry processing

Underlined processing stages are not only applied to the K, U and Th window, but also to the total count and Cs window. Meaning of parameters is described in the referenced literature.

Processing flow:

1) Quality control

2) Live time correction (IAEA, 2003)

3) Airborne and cosmic correction (IAEA, 2003)

Used parameters:
(determined by high altitude calibration flights near Narvik airport in August, 2011)

Aircraft background counts:

Cs window	7
K window	9
U window	3
Th window	0
Uup window	0
Total counts	150

Cosmic background counts (normalized to unit counts in the cosmic window):

Cs window	0.0749
K window	0.0610
U window	0.0454
Uup window	0.0237
Th window	0.0626
Total counts	1.0536

4) Radon correction using upward detector method (IAEA, 2003)

Used parameters (determined from survey data over water and land):

a_u: 0.4 $b_{u:}$ 1.18
a_K: 0.8 b_K: 2.98
a_T: 0.04 b_T: 1.02
a_{cs}: 6.5 b_{cs}: 5.91
a_I: 23.7 b_I: 24

a_1: 0.066 a_2: 0.040

5) Stripping correction (IAEA, 2003)

Used parameters (determined from measurements on calibrations pads at the NGU):

a	0.0482
alpha	0.3087
beta	0.4807
gamma	0.7953

K in Cs	0.272
U in Cs	1.817
Th in Cs	1.251

6) Height correction to a height of 60 m

Used parameters (determined by height calibration flight at near Narvik airport in August, 2011):

Attenuation factors in 1/m:
Cs: 0.0088
K: 0.0107
U: 0.0067
Th: 0.0062
Total counts: 0.0076

7) Converting counts at 60 m heights to element concentration on the ground

Used parameters (determined from NGU calibration pads):

Counts per elements concentrations:
Cs: 18.7 counts/kBq/m^2
K: 69.1 counts/%
U: 7.71 counts/ppm
Th: 4.38 counts/ppm

8) Microlevelling using Geosoft menu and smoothening by a convolutuion flitering

Used parameters for microlevelling:
Decorrugation cutoff wavelength: 4000 m
Cell size for gridding: 200 m
Naudy Filter length: 5000 m

3X3 Convolution filter:
Predefined filter: Hanning
No.of passes: 1

Appendix B2: Flow chart of magnetic processing

Meaning of parameters is described in the referenced literature.

Processing flow:

1) Quality control

2) Non-linear filter (Naudy and Dreyer, 1968): 3 fiducials and manual removal of rest of the spikes

3a) Subtraction of spiked removed version of the magnetic field of the base station

3b) Adding a constant shift of 51095 nT (mean/median of base magnetic data)

4) Calculation of IGRF values and subtraction

Appendix B3: Caesium calibration

The airborne system was calibrated for sensitivity to caesium at NGU during June 2010 using a Cs-137 source of activity 433 kBq. With the detector mounted on a stand 0.9 metres off the ground and facing downwards, the caesium source was moved in a 1 metre grid pattern around one side of the detector, and a caesium spectrum recorded at each grid point. To save time and space, symmetry in the long-axis of the detector was assumed, and so only grid points lying on one side of the detector were considered. Background-corrected spectra were used to obtain the total caesium-window counts for each grid point. Each grid point in a 9m by 5m grid was recorded, together with several additional grid points from a larger 15m by 11m grid. Counts at each grid point where the recorded counts exceeded 2% of the maximum value were summed (and doubled where appropriate to account for symmetry effects) to provide an estimate of the detector response from a uniform Cs-137 concentration of 433 kBq/m^2 .

The resultant sensitivity for the caesium window was 1cps = 31.7 Bq/m^2 at 0.9 m height.

Given the sparseness of the measurement grid and the limited area over which counts were recorded, we estimate a systematic uncertainty of around 15% in the sensitivity.

Appendix C: Produced and delivered maps

Down-scaled image of maps originally produced in scale 1: 100 000.

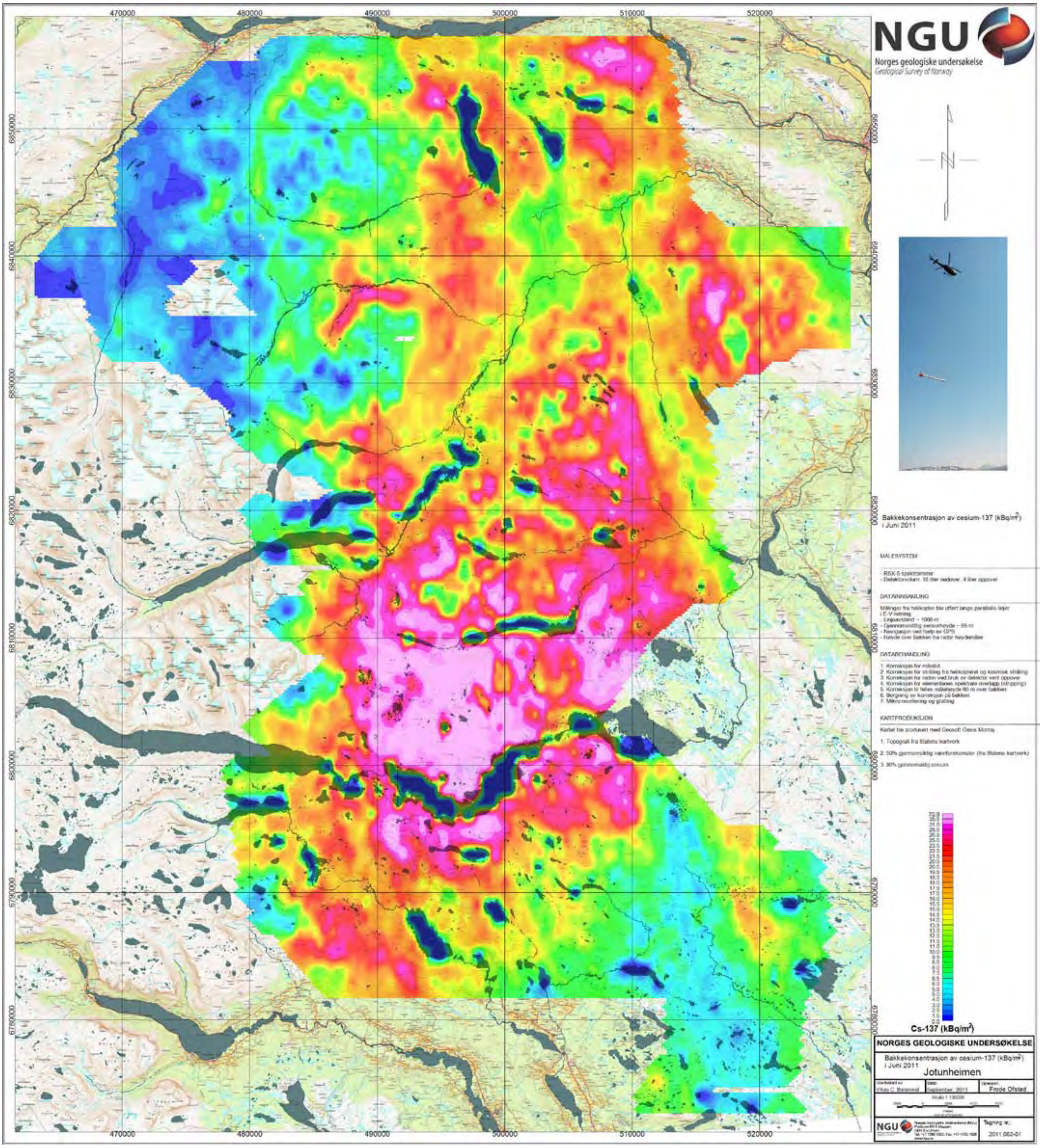

Figure C-1: Caesium map of the Jotunheimen area with equal area distribution plotting.

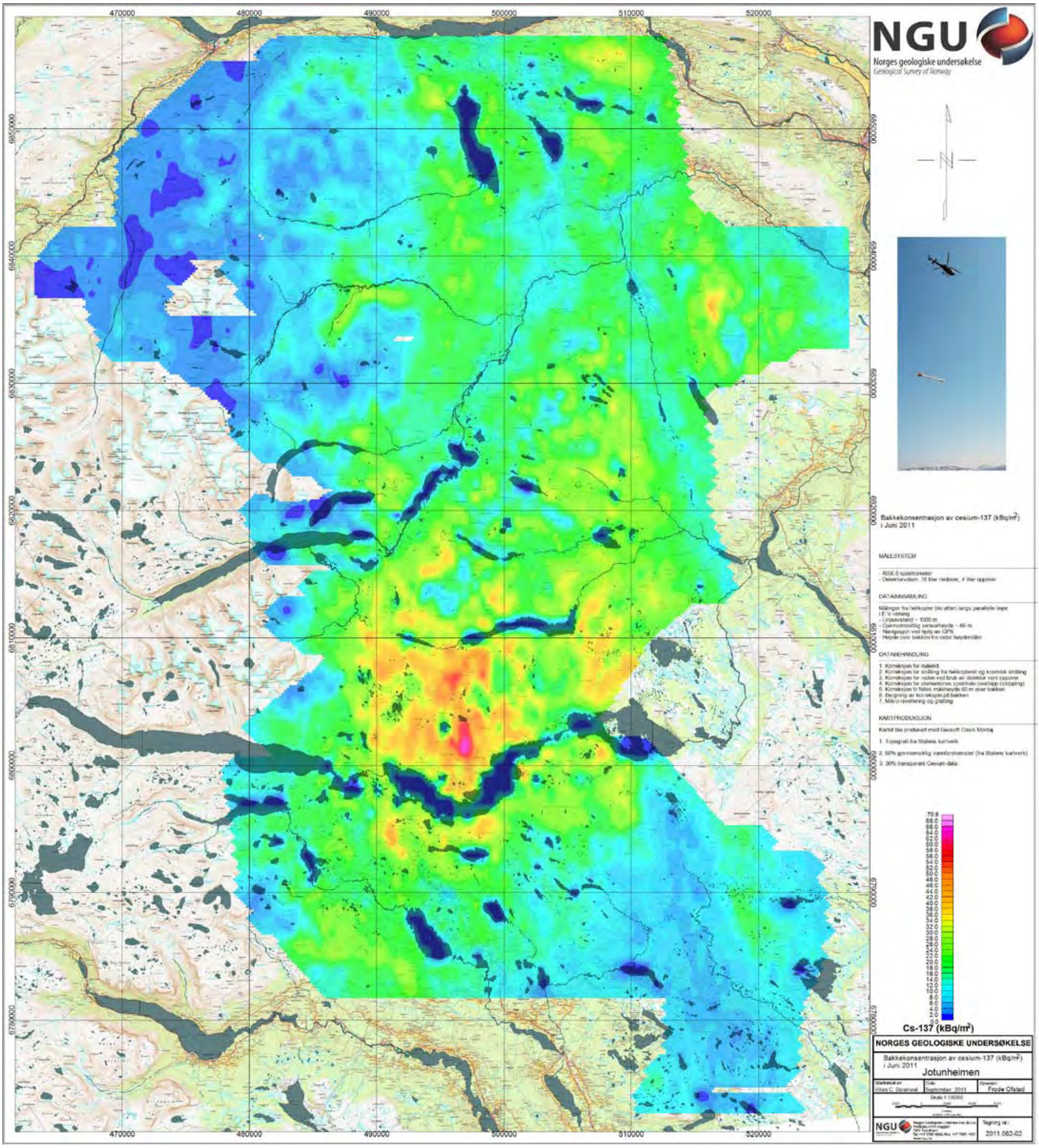

Figure C-2: Caesium map of the Jotunheimen area with linear distribution plotting.

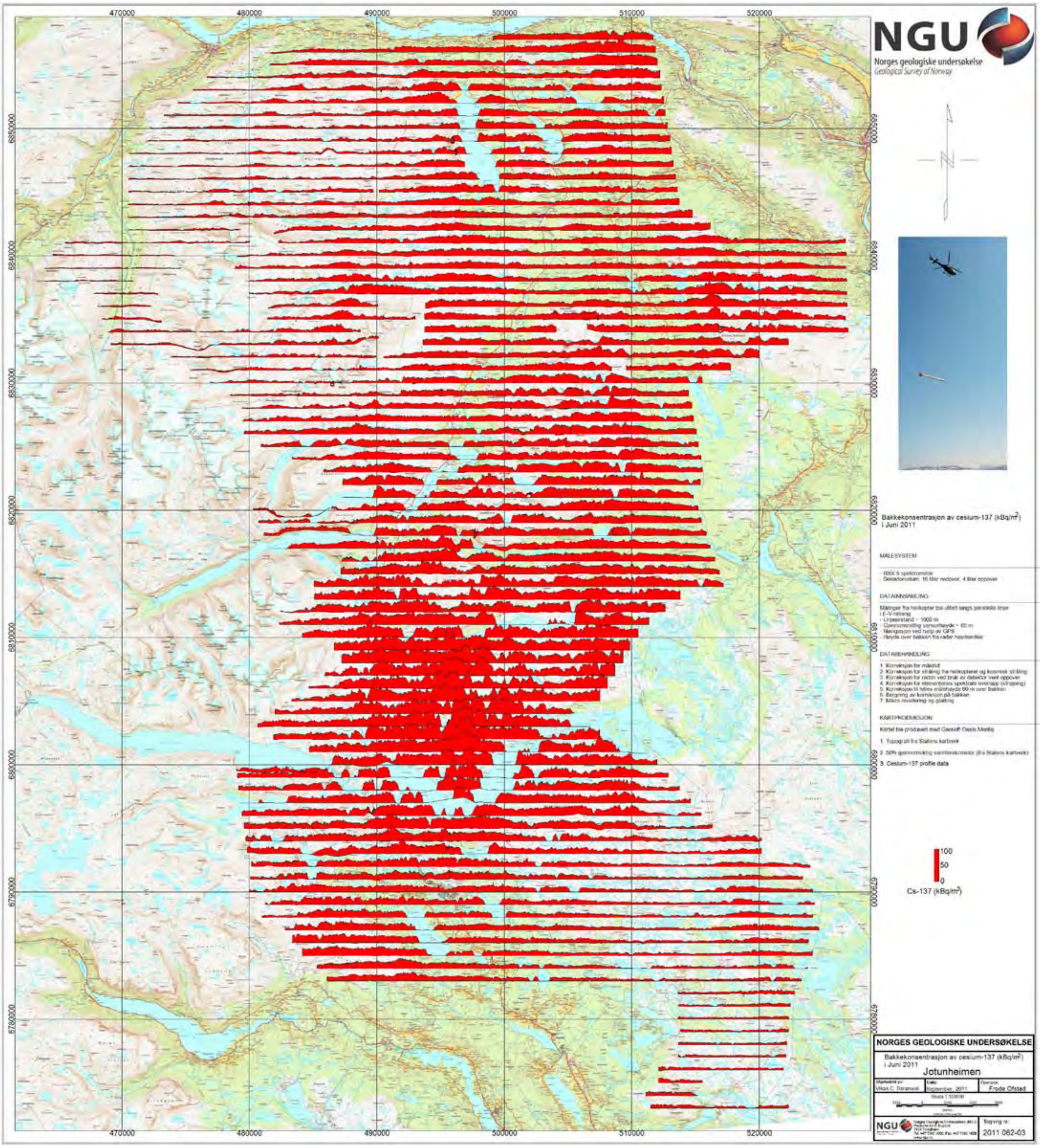

Figure C-3: Caesium map of the Jotunheimen area with profiles along flight lines.