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Helicopter-borne magnetic, electromagnetic and radiometric geophysical survey in Nordreisa, Troms County

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REPORT

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Title: Helicopter-borne magnetic, electromagnetic and radiometric geophysical survey in Nordreisa, Troms County

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August-September 2015	November 2015	342900	Jan S. Rønning

Summary:

NGU conducted an airborne geophysical survey in the Nordreisa area in August-September 2015 as a part of the MINN project. This report describes and documents the acquisition, processing and visualization of recorded datasets. The geophysical survey results reported herein are 4286 line km, covering an area of 857 km^2.

The NGU modified Geotech Ltd. Hummingbird frequency domain system supplemented by an optically pumped Cesium magnetometer and a 1024 channels RSX-5 spectrometer was used for data acquisition.

The survey was flown with 200 m line spacing, line direction 135^o (Northwest to Southeast) and average speed 69 km/h. The average terrain clearance of the bird was 56 m.

Collected data were processed by AR Geoconsulting using Geosoft Oasis Montaj software. Raw total magnetic field data were corrected for diurnal variation and leveled using standard micro leveling algorithm. Final grid was filtered using Butterworth filter.

EM data were filtered and leveled using both automated and manual leveling procedure. Apparent resistivity was calculated from in-phase and quadrature data for two coplanar frequencies (880 Hz and 6606 Hz), and for two coaxial frequencies (980 Hz and 7001 Hz) separately using a homogeneous half space model. Apparent resistivity grids were filtered using 3x3 convolution filter.

Radiometric data were processed using standard procedures recommended by International Atomic Energy Association.

Data were gridded with the cell size of 50 x 50 m and presented as a shaded relief maps at the scale of 1:50000.

Keywords: Geophysics	Airborne	Magnetic
Electromagnetic	Gamma spectrometry	Radiometric
		Technical report

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1. INTRODUCTION

In 2011 the Norwegian government initiated a new program for mapping of mineral resources in Northern Norway (MINN). The goal of this program is to enhance the geological information that is relevant to an assessment of the mineral potential of the three northernmost counties. The airborne geophysical surveys - both helicopter borne and fixed wing- are important integral parts of MINN program. The airborne survey results reported herein amount to 4286 line km (857 km^2) over the Nordreisa survey area, as shown in Figure 1.

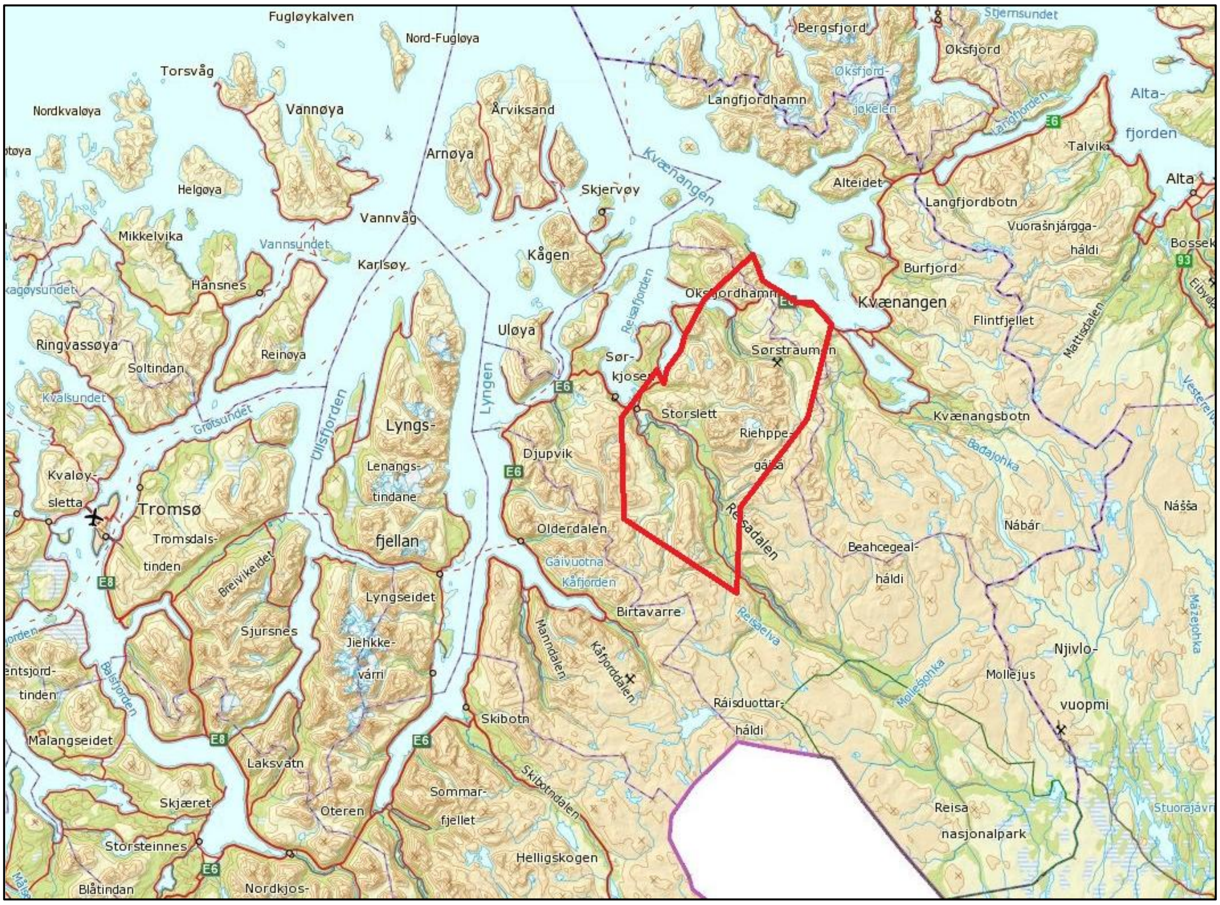

Figure 1: Nordreisa survey area

The objective of the airborne geophysical survey was to obtain a dense high-resolution aero-magnetic, electromagnetic and radiometric data over the survey area. This data is required for the enhancement of a general understanding of the regional geology of the area. In this regard, the data can also be used to map contacts and structural features within the property. It also improves defining the potential of known zones of mineralization, their geological settings, and identifying new areas of interest.

The survey incorporated the use of a Hummingbird™ five-frequency electromagnetic system supplemented by a high-sensitivity cesium magnetometer, gamma-ray spectrometer and radar altimeter. A GPS navigation computer system with flight path indicators ensured accurate positioning of the geophysical data with respect to the World Geodetic System 1984 geodetic datum (WGS-84).

2. SURVEY SPECIFICATIONS

2.1 Airborne Survey Parameters

NGU used a modified Hummingbird™ electromagnetic and magnetic helicopter survey system designed to obtain low level, slow speed, detailed airborne magnetic and electromagnetic data (Geotech 1997). The system was supplemented by 1024 channel gamma-ray spectrometer which was used to map ground concentrations of U, Th and K.

The airborne survey began on August 05th 2015 and was completed on September 10th. A Eurocopter AS350-B3 helicopter from helicopter company HeliScan AS was used to tow the bird. The survey lines were spaced 200 m apart. Lines were oriented at 135°. Due to weather conditions, a small part of the north-east corner of the survey area was flown at 45°.

The magnetic and electromagnetic sensors are housed in a single 7.5 m long bird, which was maintained at an average of 56 m above the topographic surface. A gamma-ray spectrometer, installed under the belly of the helicopter, registered natural gamma ray radiation simultaneously with the acquisition of magnetic/EM data.

Due to instrumental problems, the 34 kHz coplanar coil system was switched off during this survey.

Rugged terrain and abrupt changes in topography affected the aircraft pilot's ability to 'drape' the terrain; therefore the average instrumental height was higher than the standard survey instrumental height, which is defined as 30 m plus a height of obstacles (trees, power lines etc.) for EM and magnetic sensors.

The ground speed of the aircraft varied from 35 – 110 km/h depending on topography, wind direction and its magnitude. On average the ground speed during measurements is calculated to 69 km/h. Magnetic data were recorded at 0.2 second intervals resulting in approximately 4 m point spacing. EM data were recorded at 0.1 second intervals resulting in data with a sample increment of 2 m along the ground in average. Spectrometry data were recorded every 1 second giving a point spacing of approximately 20 meters. The above parameters allow recognizing sufficient details in the data to detect subtle anomalies that may represent mineralization and/or rocks of different lithological and petrophysical composition.

A base magnetometer to monitor diurnal variations in the magnetic field was located at Storslett UTM 506700 E – 7736100 N, central in the survey area. GEM GSM-19 station magnetometer data were recorded once every 3 seconds. The CPU clock of the base magnetometer and the helicopter magnetometer were both synchronized to GMT (Greenwich MeanTime) through the built-in GPS receiver to allow correction of diurnals.

Navigation system uses GPS/GLONASS satellite tracking systems to provide real-time WGS-84 coordinate locations for every second. The accuracy achieved with no differential corrections is reported to be better than ± 5 m in the horizontal directions. The GPS receiver antenna was mounted externally above the cabin of the helicopter.

For quality control, the electromagnetic, magnetic and radiometric, altitude and navigation data were monitored on four separate windows in the operator's display during flight while they were recorded in three data ASCII streams to the PC hard disk drive. Spectrometry data were also recorded to an internal hard drive of the spectrometer. The data files were transferred to the field workstation via USB flash drive. The raw data files were backed up onto USB flash drive in the field.

2.2 Airborne Survey Instrumentation

Instrument specification is given in table 1. Frequencies and coil configuration for the Hummingbird EM system is given in table 2.

Table 1. Instrument Specifications

Instrument	Producer/Model	Accuracy	Sampling frequency
Magnetometer	Scintrex Cs-2	0,002 nT	5 Hz
Base magnetometer	GEM GSM-19	0.1 nT	0,33 Hz
Electromagnetic	Geotech Hummingbird	1 – 2 ppm	10 Hz
Gamma spectrometer	Radiation Solutions RSX-5	1024 channels, 16 liters down, 4 liters up	1 Hz
Radar altimeter	Bendix/King KRA 405B	± 3 % 0 – 500 feet ± 5 % 500 – 2500 feet	1 Hz
Pressure/temperature	Honeywell PPT	± 0,03 % FS	1 Hz
Navigation	Topcon GPS-receiver	± 5 meter	1 Hz
Acquisition system	PC based in house software		

Table 2. Hummingbird electromagnetic system, frequency and coil configurations

Coils:	Frequency	Orientation	Separation
A	7700 Hz	Coaxial	6.20 m
B	6600 Hz	Coplanar	6.20 m
C	980 Hz	Coaxial	6.025 m
D	880 Hz	Coplanar	6.025 m

2.3 Airborne Survey Logistics Summary

Traverse (survey) line spacing: 200 metres
Traverse line direction: 135° NW-SE,
Nominal aircraft ground speed: 30 - 110 km/h
Average sensor terrain clearance EM+Mag: 56 metres
Average sensor terrain clearance Rad: 86 metres
Sampling rates: Magnetometer 0.2 seconds
EM system 0.1 seconds
Spectrometer, GPS, Altimeter 1.0 second

Figure 2: Hummingbird system in air

3. DATA PROCESSING AND PRESENTATION

All data were processed by Alexei Rodionov (AR Geoconsulting Ltd., Canada) in Calgary. The ASCII data files were loaded into three separate Oasis Montaj databases. All three datasets were processed consequently according to processing flow charts shown in Appendix A1, A2 and A3.

3.1 Total Field Magnetic Data

At the first stage the raw magnetic data were visually inspected and spikes were removed manually. Non-linear filter was also applied to airborne raw data to eliminate short-period spikes. Typically, several corrections have to be applied to magnetic data before gridding - heading correction, lag correction and diurnal correction.

Diurnal Corrections

The temporal fluctuations in the magnetic field of the earth affect the total magnetic field readings recorded during the airborne survey. This is commonly referred to as the magnetic diurnal variation. These fluctuations can be effectively removed from the airborne magnetic dataset by using a stationary reference magnetometer that records the magnetic field of the earth simultaneously with the airborne sensor at given short time interval. The data from base station were imported in database using the standard Oasis magbase.gx module. Diurnal variation channel was inspected for spikes and spikes were removed manually if necessary. Minor magnetic storms were observed on August 15th,17th and 20th. Magnetic diurnals exceeded slightly values described in the standard NGU specifications (Rønning 2013) at these dates, but were accepted.

Diurnal variations were measured with GEM GSM-19 magnetometer. The recorded data are merged with the airborne data and the diurnal correction is applied according to equation (1).

$$\mathbf{B}_{Tc} = \mathbf{B}_T + \left(\overline{B}_B - \mathbf{B}_B\right), \qquad (1)$$

where:

$\mathbf{B}_{Tc}$ = Corrected airborne total field readings

$\mathbf{B}_T$ = Airborne total field readings

$\overline{B}_B$ = Average datum base level

$\mathbf{B}_B$ = Base station readings

Corrections for Lag and heading

Neither a lag nor cloverleaf tests were performed before the survey. According to previous reports the lag between logged magnetic data and the corresponding navigational data was 1-2 fids. Translated to a distance it would be no more than 10 m - the value comparable with the precision of GPS. A heading error for a towed system is usually either very small or non-existent. So no lag and heading corrections were applied.

Magnetic data processing, gridding and presentation

The total field magnetic anomaly data ($\mathbf{B}_{TA}$) were calculated from the diurnal corrected data ($\mathbf{B}_{Tc}$) after subtracting the IGRF for the surveyed area calculated for the data period (eq.2)

$$\mathbf{B}_{TA} = \mathbf{B}_{Tc} - IGRF \qquad (2)$$

The total field anomaly data were gridded using a minimum curvature method with a grid cell size of 50 meters. This cell size is equal to one quarter of the 200 m average line spacing. In order to remove small line-to-line leveling errors that were detected on the gridded magnetic anomaly data, the Geosoft Micro-leveling technique was applied on the flight line based magnetic database. Then, the micro-levelled channel was gridded using again a minimum curvature method with 50 m grid cell size. Decorragation Butterworth filter was applied to magnetic data to remove line-to-line leveling errors and 3x3 Hanning filter was passed over the final grid to smooth the image.

The processing steps of magnetic data presented so far, were performed on point basis. The following steps are performed on grid basis. Vertical Gradient (VG), the Tilt Derivative (TD) and Horizontal Gradient (HG) of the total magnetic anomaly were calculated from the micro-levelled total magnetic anomaly grid. The Tilt derivative was calculated according to the equation (3)

$$TD = \tan^{-1}\left(\frac{VG}{HG}\right) \qquad (3)$$

Horizontal gradient (HG) was calculated according to equation (4)

$$HG = Sqrt(HG_x^2 + HG_y^2) \quad (4)$$

Where: HG_x and HG_y are horizontal gradients in X and Y directions.

The results are presented in coloured shaded relief maps:

A. Total field magnetic anomaly
B. Vertical gradient of total magnetic anomaly
C. Tilt angle (or Tilt Derivative) of the total magnetic anomaly
D. Total horizontal gradient

These maps are representative of the distribution of magnetization over the surveyed areas. The list of the produced maps is shown in Table 4.

3.2 Electromagnetic Data

The DAS computer records both an in-phase and a quadrature value for each of the four coil sets of the electromagnetic system. Instrumental noise and drift should be removed before computation of an apparent resistivity.

Instrumental noise

In-phase and quadrature data were filtered with 5 fids non-linear filter to eliminate spheric spikes which were represented as irregular spikes of large amplitude in records and high frequency noise of bird electronics. Simultaneously, the 50 fids low-pass filter was also applied to suppress instrumental and cultural noise. Those filters, however, were not able to suppress the noise completely due to irregular nature of noise. Low speed of helicopter in extremely rugged terrain resulted a swaying of the bird. The pendulum effect of a swaying was clear visible on records especially on 880 Hz data. The period of swaying – 3-8 sec. made application of low pass filter not effective, so some of noise attributed to pendulum effect remains on records in some areas. Shifts of 7000 in phase and quadrature records, with amplitude of 5-10 ppm, was observed almost in all flights, especially, in mountainous areas. Shifts were edited manually where it was possible.

Instrument Drift

In order to remove the effects of instrument drift caused by gradual temperature variations in the transmitting and receiving circuits, background responses are recorded during each flight. To obtain a background level the bird is raised to an altitude of at least 1000 ft above the topographic surface so that no electromagnetic responses from the ground are present in the recorded traces. The EM traces observed at this altitude correspond to a background (zero) level of the system. If these background levels are recorded at 20-30 minute intervals, then the drift of the system (assumed to be linear) can be removed from the data by resetting these points to the initial zero level of the system. The drift must be removed on a flight-by-flight basis, before any further processing is carried out. Geosoft HEM module was used for applying drift correction. Residual instrumental drift, usually small, but non-linear, was manually removed on line-to-line basis.

Apparent resistivity calculation and presentation

When leveling of the EM data was complete, apparent resistivity was calculated from in-phase and quadrature EM components using a homogeneous half space model of the Earth (Geosoft HEM module) for three frequencies 6600, 7000 and 880.

Resistivity for 980 Hz was calculated from quadrature data only. A threshold value of 2 ppm was set for inversion.

Secondary electromagnetic field decays rapidly with the distance (height of the sensors) – as z^{-2} – z^{-5} depending on the shape of the conductors and, at certain height, signals from the ground sources become comparable with instrumental noise. Leveling errors or precision of leveling can lead sometimes to appearance of artificial resistivity anomalies when data were collected at high instrumental altitude. Application of threshold allows excluding such data from an apparent resistivity calculation, though not completely. It's particularly noticeable in low frequencies datasets. Resistivity data were visually inspected; artificial anomalies associated with high altitude measurements were manually removed.

Data, recorded at the height above 100 m were considered as non-reliable and removed from presentation. Remaining resistivity data were gridded with a cell size 50 m and 3x3 convolution filter was applied to smooth resistivity grids. Power lines strongly affected low frequency data – 880 and 980 Hz channels – and areas around most prominent power lines were excluded from maps.

3.3 Radiometric data

Airborne gamma-ray spectrometry measures the abundance of Potassium (K), Thorium (eTh), and Uranium (eU) in rocks and weathered materials by detecting gamma-rays emitted due to the natural radioelement decay of these elements. The data analysis method is based on recommended method for U, Th and K described by the International Atomic Energy Agency (IAEA 1991; 2003). A short description of the individual processing steps of that methodology as adopted by NGU is given bellow:

Energy windows

The Gamma-ray spectra were initially reduced into standard energy windows corresponding to the individual radio-nuclides K, U and Th. Figure 3 shows an example of a Gamma-ray spectrum and the corresponding energy windows and radioisotopes (with peak energy in MeV) responsible for the radiation.

The RSX-5 is a 1024 channel system with four downward and one upward looking detectors and the actual Gamma-ray spectrum is divided into 1024 channels. The first channel is reserved for the "Live Time" and the last for the Cosmic rays. Table 3 shows the channels that were used for the reduction of the spectrum.

Table 3: Specified channel windows for the 1024 RSX-5 systems used in this survey

Gamma-ray spectrum	Cosmic	Total count	K	U	Th
Down	1022	134-934	454-521	551-617	801-934
Up	1022			551-617	
Energy windows (MeV)	>3.07	0.41-2.81	1.37-1.57	1.66-1.86	2.41-2.81

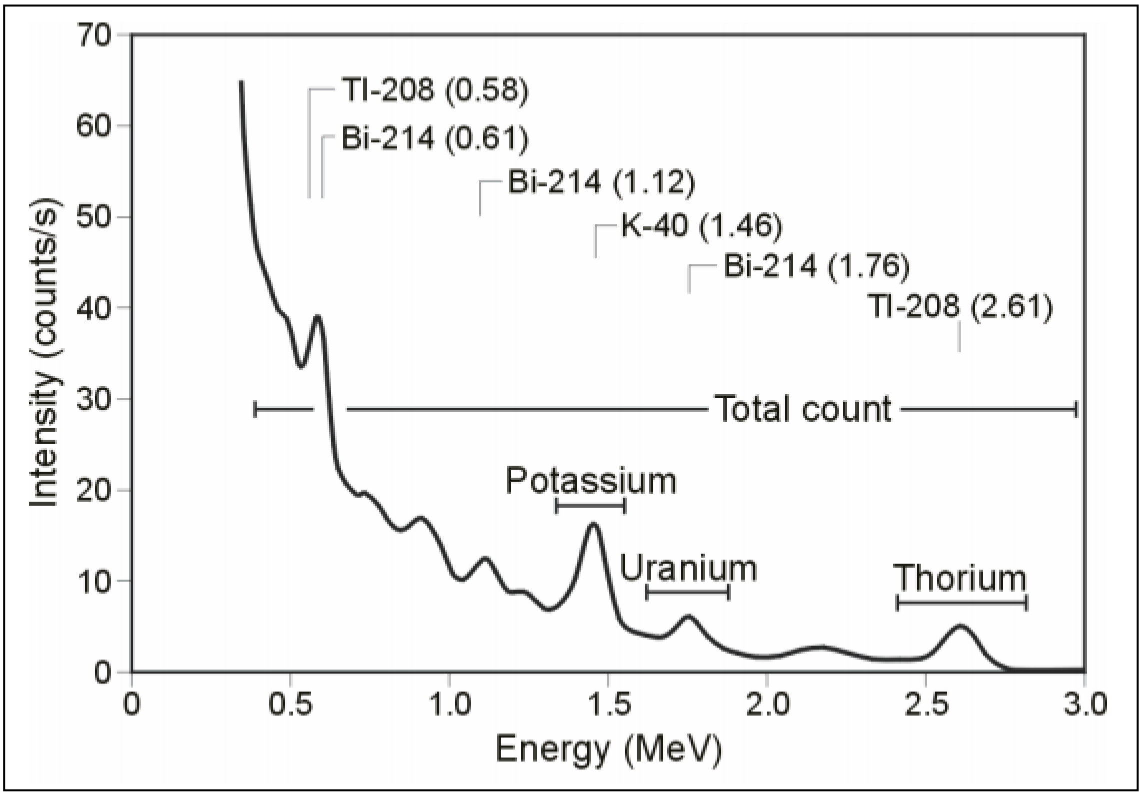

Figure 3: An example of Gamma-ray spectrum showing the position of the K, Th, U and Total count windows.

Live Time correction

The data were corrected for live time. “Live time” is an expression of the relative period of time the instrument was able to register new pulses per sample interval. On the other hand “dead time” is an expression of the relative period of time the system was unable to register new pulses per sample interval. The relation between “dead” and “live time” is given by the equation (5)

$$\text{“Live time”} = \text{“Real time”} - \text{“Dead time”} \tag{5}$$

where the “real time” or “acquisition time” is the elapsed time over which the spectrum is accumulated (1 second).

The live time correction is applied to the total count, Potassium, Uranium, Thorium, upward Uranium and cosmic channels. The formula used to apply the correction is as follows:

$$C_{LT} = C_{RAW} \cdot \frac{1000000}{Live\ Time} \tag{6}$$

where C_{LT} is the live time corrected channel in counts per second, C_{RAW} is the raw channel data in counts per second and Live Time is in microseconds.

Cosmic and aircraft correction

Background radiation resulting from cosmic rays and aircraft contamination was removed from the total count, Potassium, Uranium, Thorium, upward Uranium channels using the following formula:

$$C_{CA} = C_{LT} - (a_c + b_c \cdot C_{Cos}) \tag{7}$$

where C_{CA} is the cosmic and aircraft corrected channel, C_{LT} is the live time corrected channel a_c is the aircraft background for this channel, b_c is the cosmic stripping coefficient for this channel and C_{Cos} is the low pass filtered cosmic channel.

Radon correction

The upward detector method, as discussed in IAEA (1991), was applied to remove the effects of the atmospheric radon in the air below and around the helicopter. Usages of over-water measurements where there is no contribution from the ground, enabled the calculation of the coefficients (a_C and b_C) of the linear equations that relate the cosmic corrected counts per second of Uranium channel with total count, Potassium, Thorium and Uranium upward channels over water. Data over-land was used in conjunction with data over-water to calculate the a_1 and a_2 coefficients used in equation (8) for the determination of the Radon component in the downward uranium window:

$$Radon_U = \frac{Uup_{CA} - a_1 \cdot U_{CA} - a_2 \cdot Th_{CA} + a_2 \cdot b_{Th} - b_U}{a_U - a_1 - a_2 \cdot a_{Th}} \tag{8}$$

where $Radon_u$ is the radon component in the downward uranium window, Uup_{CA} is the filtered upward uranium, U_{CA} is the filtered Uranium, Th_{CA} is the filtered Thorium, a_1, a_2, a_U and a_{Th} are proportional factors and b_U an b_{Th} are constants determined experimentally.

The effects of Radon in the downward Uranium are removed by simply subtracting $Radon_U$ from U_{CA}. The effects of radon in the other channels are removed using the following formula:

$$C_{RC} = C_{CA} - (a_C \cdot Radon_U + b_C) \tag{9}$$

where C_{RC} is the Radon corrected channel, C_{CA} is the cosmic and aircraft corrected channel, $Radon_U$ is the Radon component in the downward uranium window, a_C is the proportionality factor and b_C is the constant determined experimentally for this channel from over-water data.

Compton Stripping

Potassium, Uranium and Thorium Radon corrected channels, are subjected to spectral overlap correction. Compton scattered gamma rays in the radio-nuclides energy windows were corrected by window stripping using Compton stripping coefficients determined from measurements on calibrations pads (Grasty 1991) at the Geological Survey of Norway in Trondheim (for values, see Appendix A3).

The stripping corrections are given by the following formulas:

$$A_1 = 1 - (g \cdot \gamma) - (\mathrm{a} \cdot \alpha) + (\mathrm{a} \cdot g \cdot \beta) - (b \cdot \beta) + (b \cdot \alpha \cdot \gamma) \tag{10}$$

$$U_{ST} = \frac{Th_{RC} \cdot ((g \cdot \beta) - \alpha) + U_{RC} \cdot (1 - b \cdot \beta) + K_{RC} \cdot ((b \cdot \alpha) - g)}{A_1} \tag{11}$$

$$Th_{ST} = \frac{Th_{RC} \cdot (1-(g \cdot \gamma)) + U_{RC} \cdot (b \cdot \gamma - \mathrm{a}) + K_{RC} \cdot ((\mathrm{a} \cdot g) - b)}{A_1} \tag{12}$$

$$K_{ST} = \frac{Th_{RC} \cdot ((\alpha \cdot \gamma) - \beta) + U_{RC} \cdot ((\mathrm{a} \cdot \beta) - \gamma) + K_{RC} \cdot (1-(\mathrm{a} \cdot \alpha))}{A_1} \tag{13}$$

where U_{RC}, Th_{RC}, K_{RC} are the radon corrected Uranium, Thorium and Potassium and a, b, g, α, β, γ are Compton stripping coefficients.

Reduction to Standard Temperature and Pressure

The radar altimeter data were converted to effective height (H_{STP}) using the acquired temperature and pressure data, according to the expression:

$$H_{STP} = H \cdot \frac{273.15}{T + 273.15} \cdot \frac{P}{1013.25} \tag{14}$$

where H is the smoothed observed radar altitude in meters, T is the measured air temperature in degrees Celsius and P is the measured barometric pressure in millibars.

Height correction

Variations caused by changes in the aircraft altitude relative to the ground was corrected to a nominal height of 60 m. Data recorded at the height above 150 m were considered as non-reliable and removed from processing. Total count, Uranium, Thorium and Potassium stripped channels were subjected to height correction according to the equation:

$$C_{60m} = C_{ST} \cdot e^{C_{ht} \cdot (60 - H_{STP})} \tag{15}$$

where C_{ST} is the stripped corrected channel, C_{ht} is the height attenuation factor for that channel and H_{STP} is the effective height.

Conversion to ground concentrations

Finally, corrected count rates were converted to effective ground element concentrations using calibration values derived from calibration pads at the Geological Survey of Norway in Trondheim (for values, see Appendix A3). The corrected data provide an estimate of the apparent surface concentrations of Potassium, Uranium and Thorium (K, eU and eTh). Potassium concentration is expressed as a percentage, equivalent Uranium and Thorium as parts per million (ppm). Uranium and Thorium are described as "equivalent" since their presence is inferred from gamma-ray radiation from daughter elements (^{214}Bi for Uranium, ^{208}Tl for Thorium). The concentration of the elements is calculated according to the following expressions:

$$C_{CONC} = C_{60m} / C_{SENS\_60m} \tag{16}$$

where C_{60m} is the height corrected channel, C_{SENS_60m} is experimentally determined sensitivity reduced to the nominal height (60m).

Spectrometry data gridding and presentation

Gamma-rays from Potassium, Thorium and Uranium emanate from the uppermost 30 to 40 centimetres of soil and rocks in the crust (Minty, 1997). Variations in the concentrations of these radioelements largely related to changes in the mineralogy and geochemistry of the Earth's surface.

The spectrometry data were stored in a database and the ground concentrations were calculated following the processing steps. A list of the parameters used in these steps is given in Appendix A3.

Then the data were split in lines and ground concentrations of the three main natural radio-elements Potassium, Thorium and Uranium and total gamma-ray flux (total count) were gridded using a minimum curvature method with a grid cell size of 50 meters. In order to remove small line-to-line leveling errors appeared on those grids, the data were micro-levelled as in the case of the magnetic data, and re-gridded with the same grid cell size. Finally, a 3x3 convolution filter was applied to Uranium grid to smooth the microlevelled concentration grids.

Quality of the radiometric data was within standard NGU specifications (Rønning 2013). For further reading regarding standard processing of airborne radiometric data, we recommend the publications from Minty et al. (1997).

4. PRODUCTS

Processed digital data from the survey are presented as:

1. Three Geosoft XYZ files: Nordreisa_Mag.xyz, Nordreisa_EM.xyz, Nordreisa _Rad.xyz

2. Coloured maps (jpg-format) at the scale 1:50000 available from NGU on request.

3. Grid-files in Geotiff format

Table 4. Maps in scale 1:50000 available from NGU on request.

Map #	Name
2015.045-01	Total magnetic field
2015.045-02	Magnetic Vertical Derivative
2015.045-03	Magnetic Tilt Derivative
2015.045-04	Magnetic Horizontal Gradient
2015.045-05	Apparent resistivity, Frequency 6600 Hz, coplanar coils
2015.045-06	Apparent resistivity, Frequency 880 Hz, coplanar coils
2014.043-07	Apparent resistivity, Frequency 7000 Hz, coaxial coils
2015.045-08	Apparent resistivity, Frequency 980 Hz, coaxial coils
2015.045-09	Uranium ground concentration
2015.045-10	Thorium ground concentration
2015.045-11	Potassium ground concentration
2015.045-12	Radiometric Ternary Map

Downscaled images of the maps are shown on figures 4 to 15.

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Appendix A1: Flow chart of magnetic processing

Meaning of parameters is described in the referenced literature.

Processing flow:

- Quality control.
- Visual inspection of airborne data and manual spike removal
- Merge magbase data with EM database
- Import of diurnal data
- Correction of data for diurnal variation
- Splitting flight data by lines
- Gridding
- Microleveling
- IGRF removed
- Butterworth filter
- 3x3 convolution filter

Appendix A2: Flow chart of EM processing

Meaning of parameters is described in the referenced literature.

Processing flow:

- Filtering of in-phase and quadrature channels with non-linear and low pass filters
- Selective application of B-spline filter to 880 Hz 7 kHz and 980 Hz data
- Automated leveling
- Quality control
- Visual inspection of data.
- Splitting flight data by lines
- Manual removal of remaining part of instrumental drift
- Calculation of an apparent resistivity using both - in-phase and quadrature channels
- Gridding
- 3x3 convolution filter

Appendix A3: 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.
Meaning of parameters is described in the referenced literature.

Processing flow:

- Quality control
- Airborne and cosmic correction (IAEA, 2003)

  Used parameters: (determined by high altitude calibration flights near Frosta in January 2014)

  Aircraft background counts:

K window	5.3584
U window	1.427
Th window	0
Uup window	0.7051
Total counts	42.726

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

K window	0.057
U window	0.0467
Uup window	0.0448
Th window	0.0643
Total counts	1.0317

- Radon correction using upward detector method (IAEA, 2003)
  Used parameters (determined from survey data over water and land):
  a_u: 0.3282 $b_{u:}$ 0.2076
  a_K: 1.0381 b_K: 0.472
  a_T: 0.1289 b_T: 0.6222
  $a_{Tc:}$ 18.489 $b_{Tc:}$ 0
  a1: 0.003468 a_2: 0.055379

- Stripping correction (IAEA, 2003)
  Used parameters (determined from measurements on calibrations pads at the NGU on April 2015):

a	0.047333
b	-0.0008
g	-0.00155
alpha	0.309065
beta	0.476219
gamma	0.808938

- <u>Height correction to a height of 60 m</u>
  Used parameters (determined by high altitude calibration flights near near Frosta in January 2014):
  Attenuation factors in 1/m:

K:	-0.009523
U:	- 0.006687
Th:	- 0.007393
TC:	-0.00773

- Converting counts at 60 m heights to element concentration on the ground
  Used parameters (determined from measurements on calibrations pads at the NGU on April 2015):
  Sensitivity (elements concentrations per count)::

K:	0.007550 %/counts
U:	0.087568 ppm/counts
Th:	0.156609 ppm/counts

- <u>Microleveling using Geosoft menu and smoothening by a convolution filtering</u>
  Used parameters for microleveling:

De-corrugation cutoff wavelength:	800 m
Cell size for gridding:	200 m
Naudy (1968) Filter length:	600 m

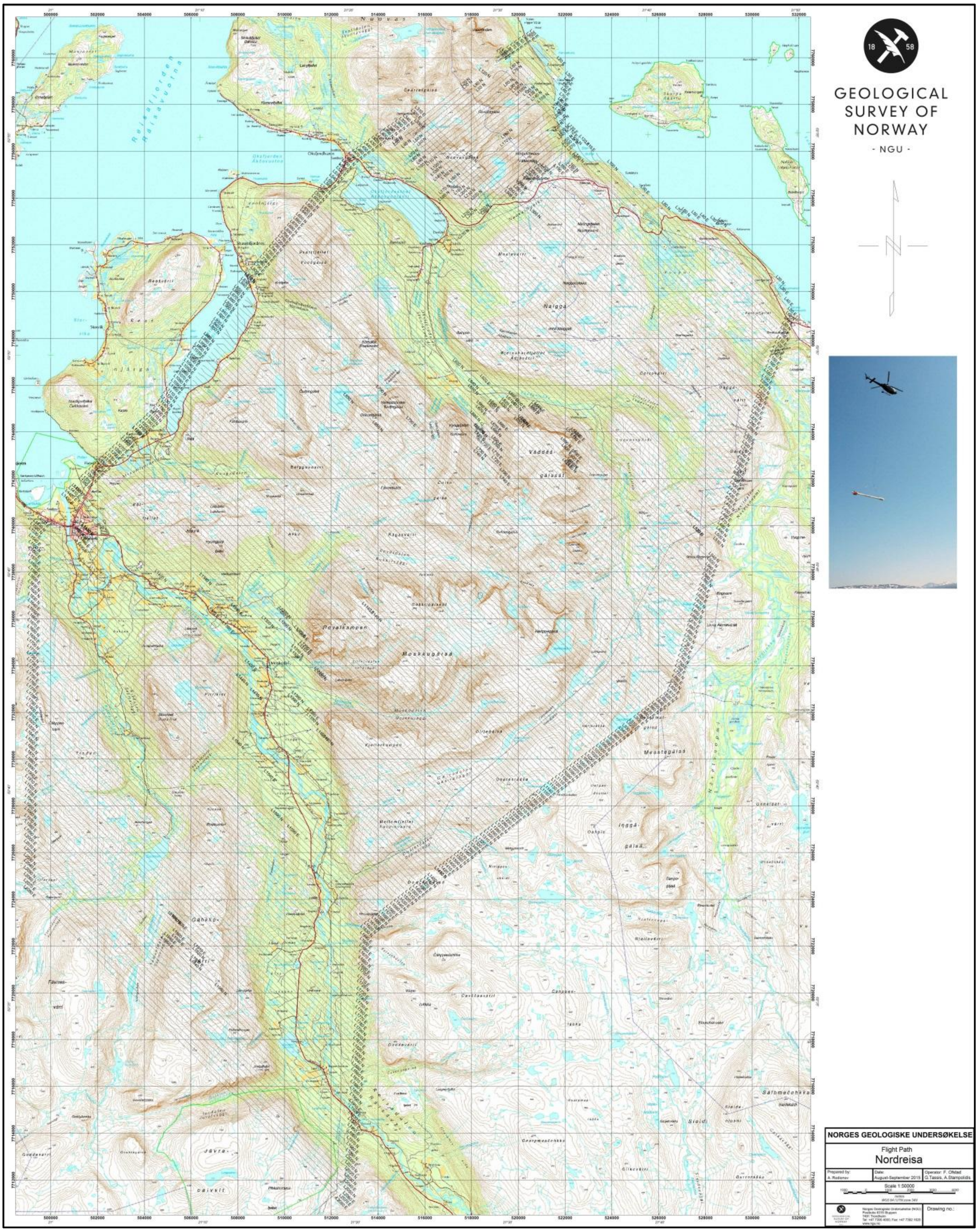

Figure 4: Nordreisa survey area with flight path

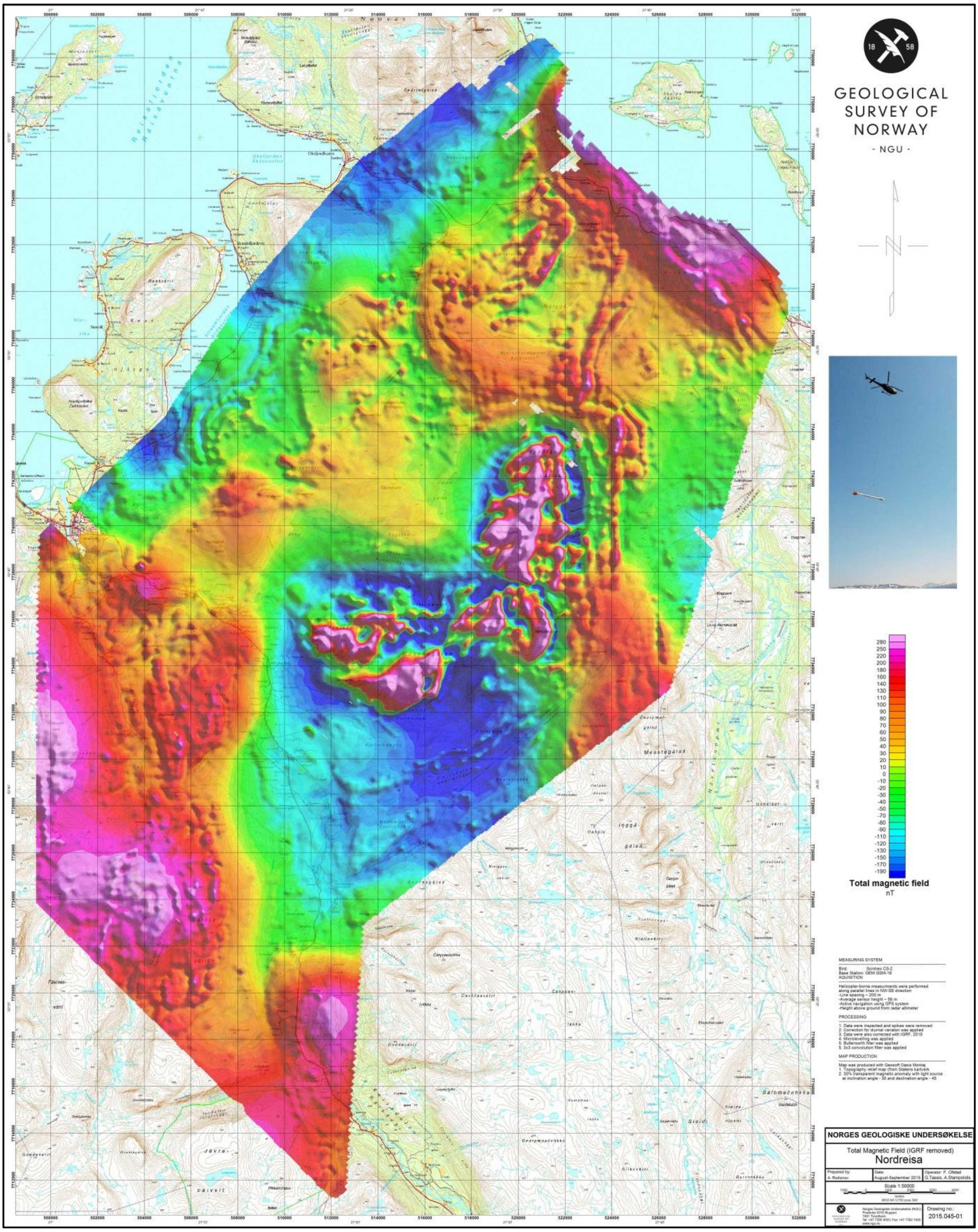

Figure 5: Total Magnetic Field

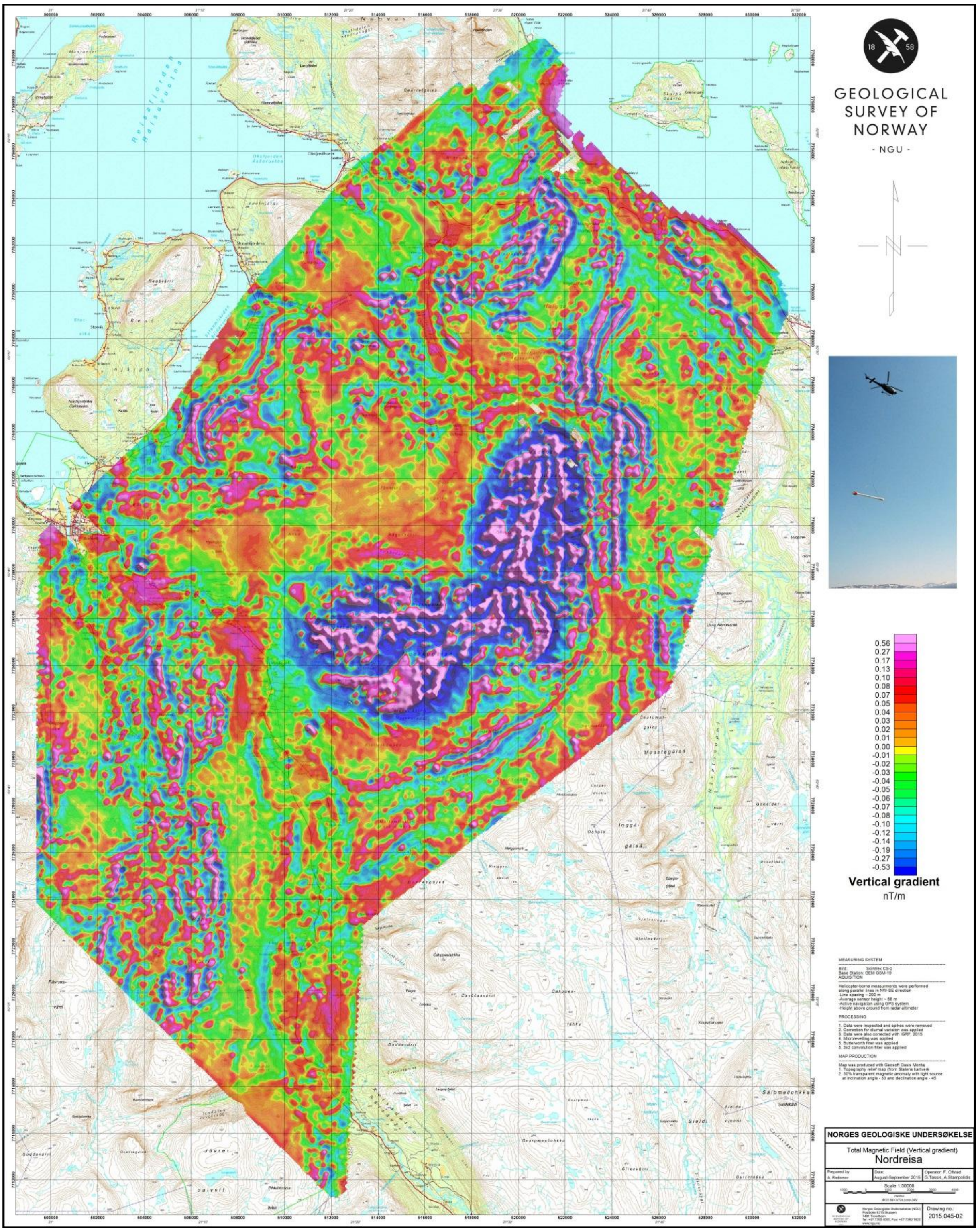

Figure 6: Magnetic Vertical Derivative

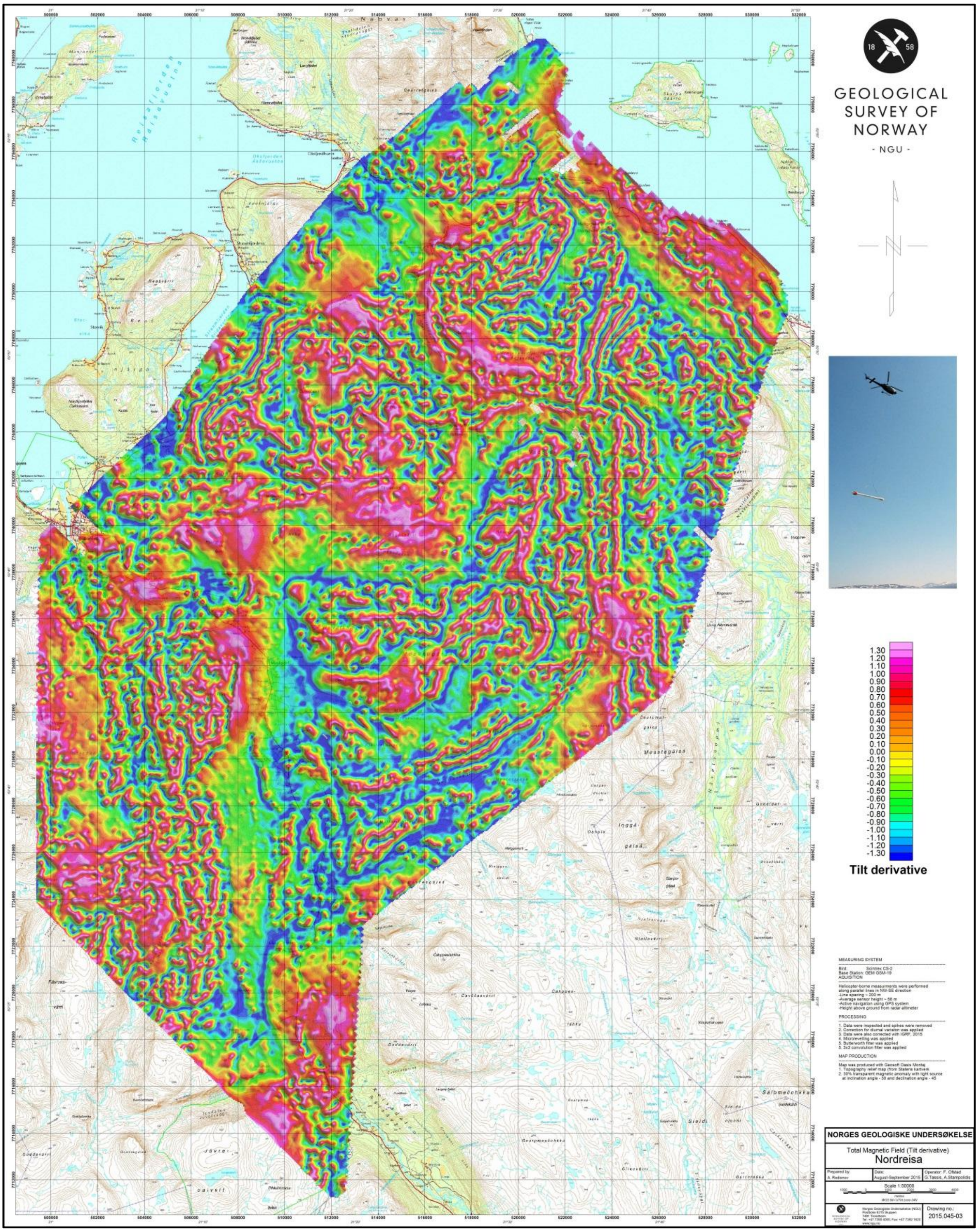

Figure 7: Magnetic Tilt Derivative

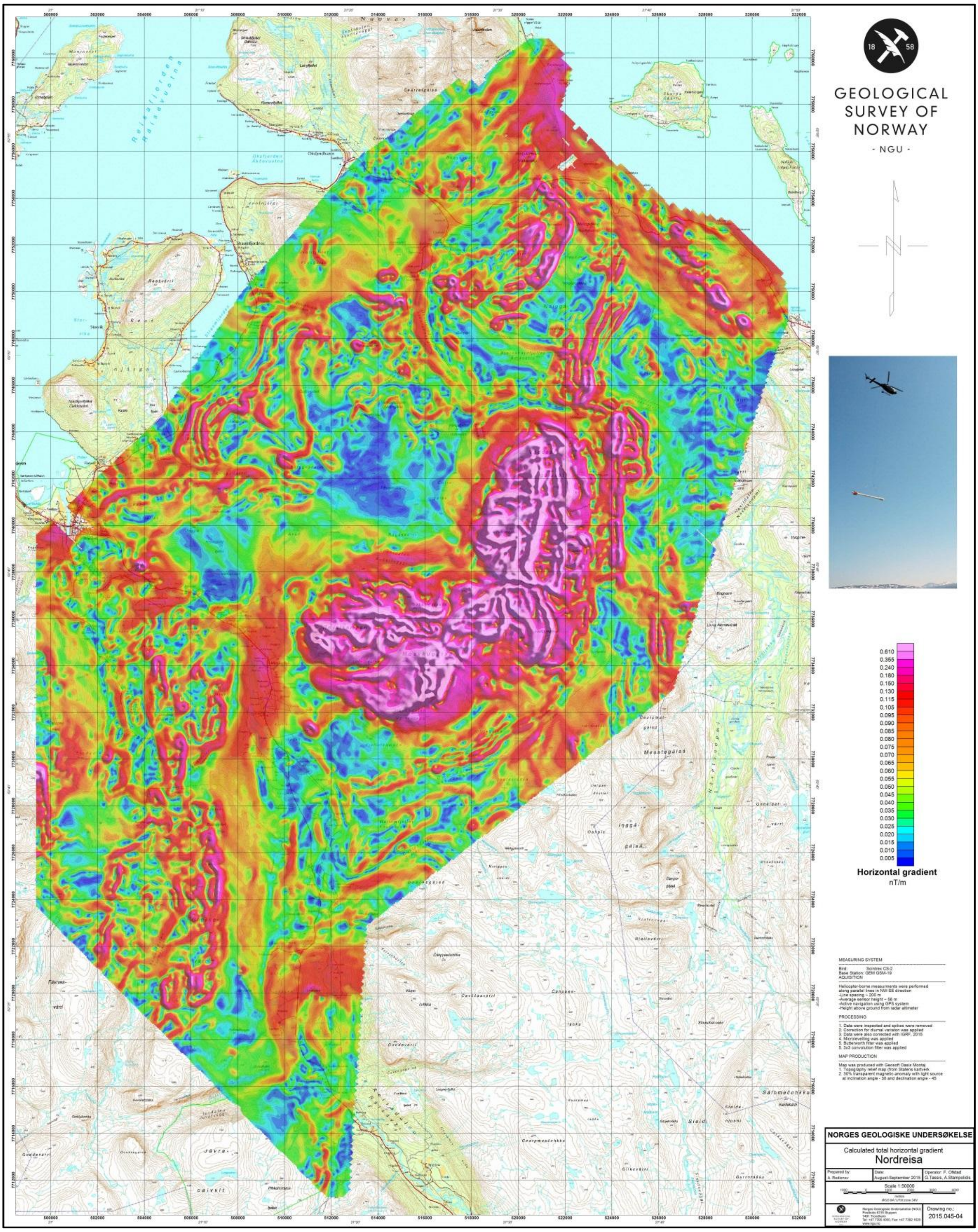

Figure 8: Magnetic Horizontal Gradient

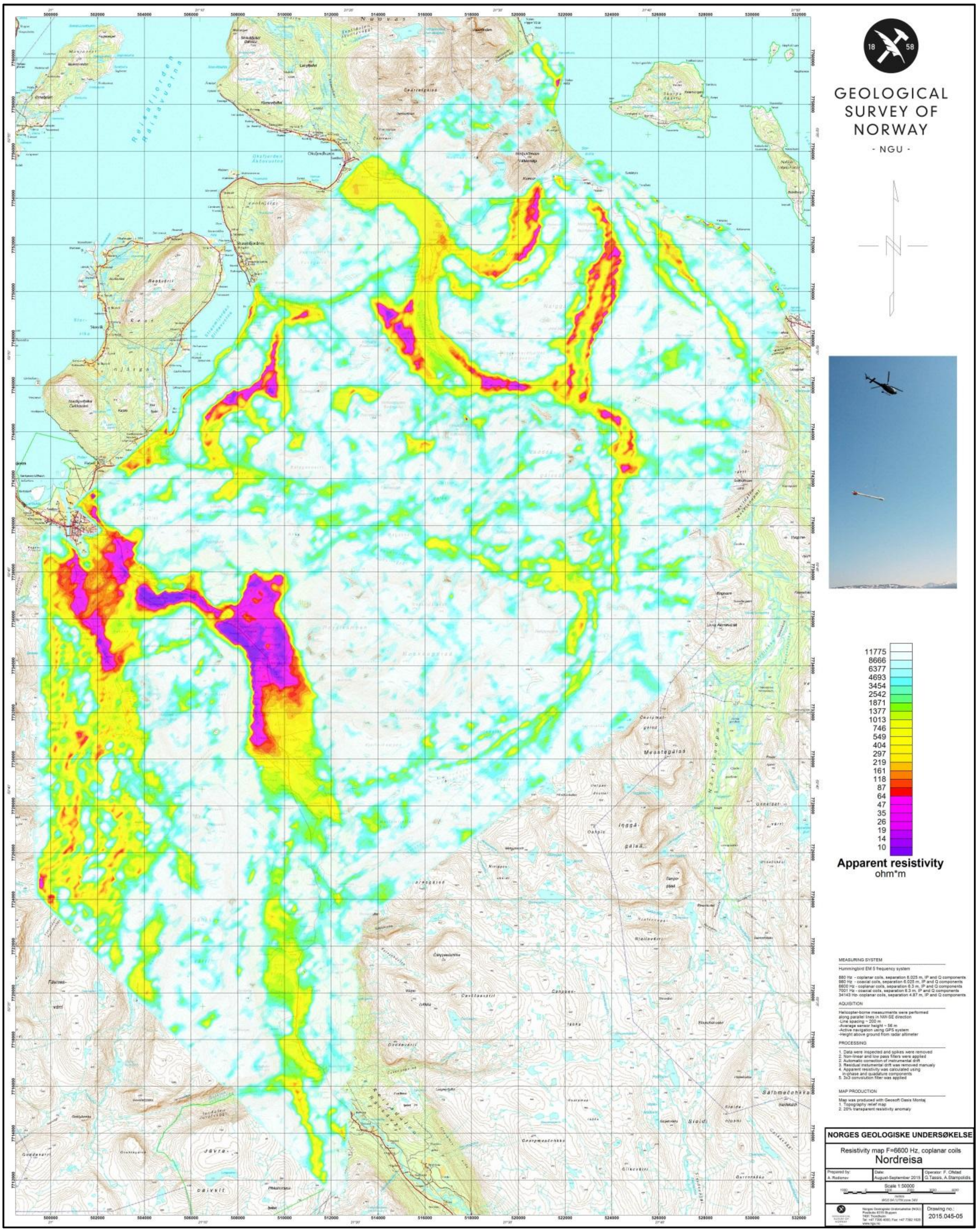

Figure 9: Apparent resistivity. Frequency 6600 Hz, Coplanar coils

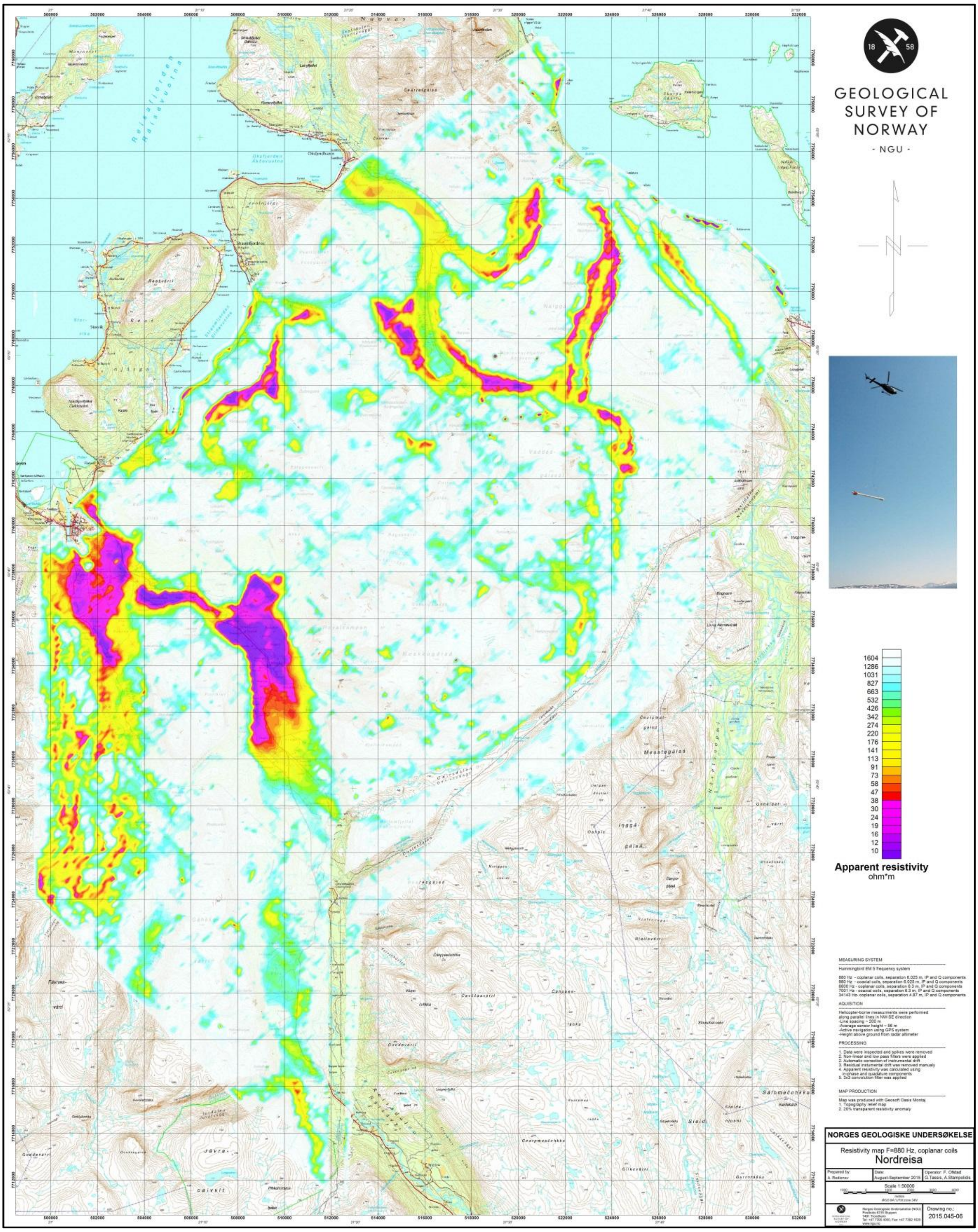

Figure 10: Apparent resistivity. Frequency 880 Hz, Coplanar coils

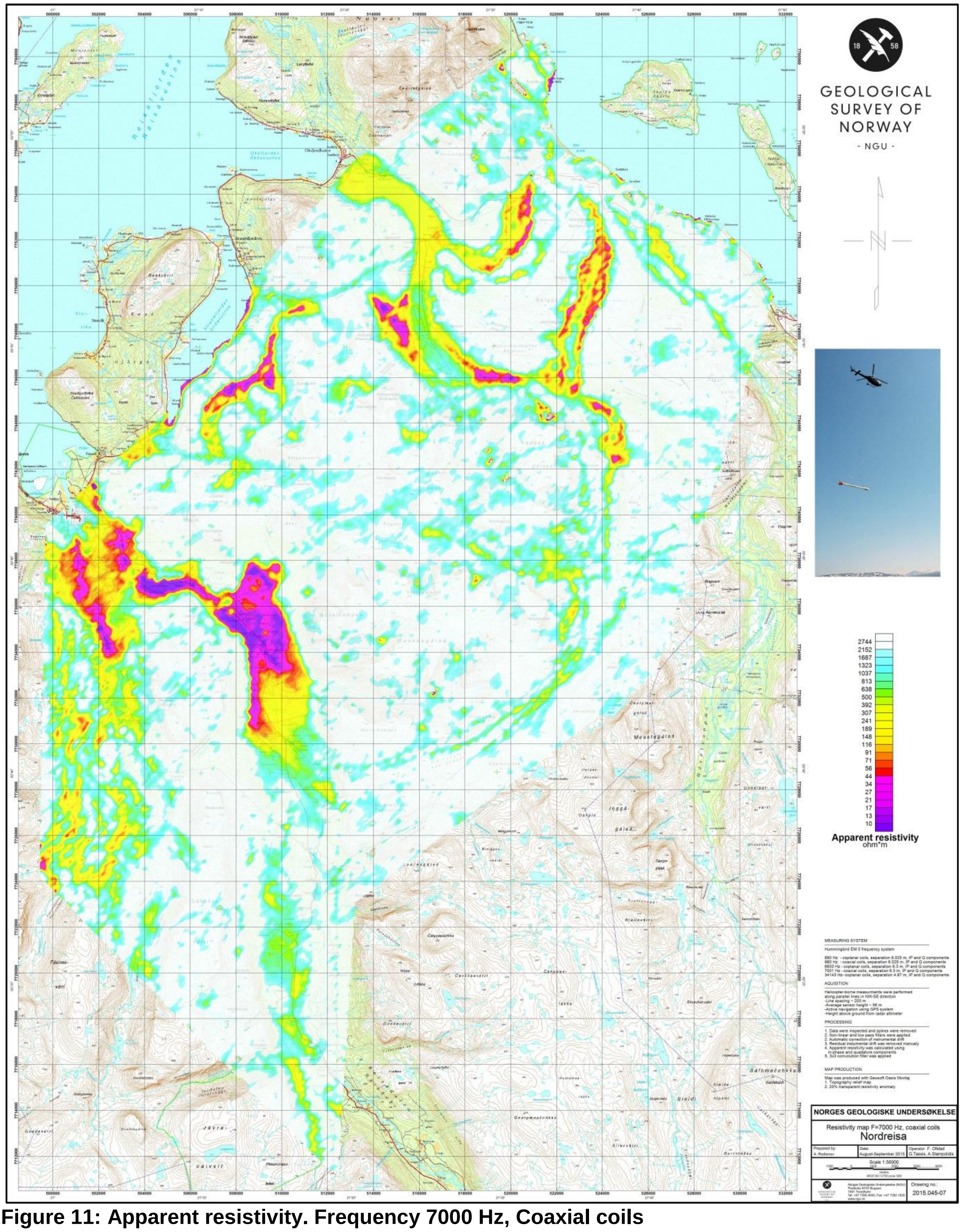

Figure 11: Apparent resistivity. Frequency 7000 Hz, Coaxial coils

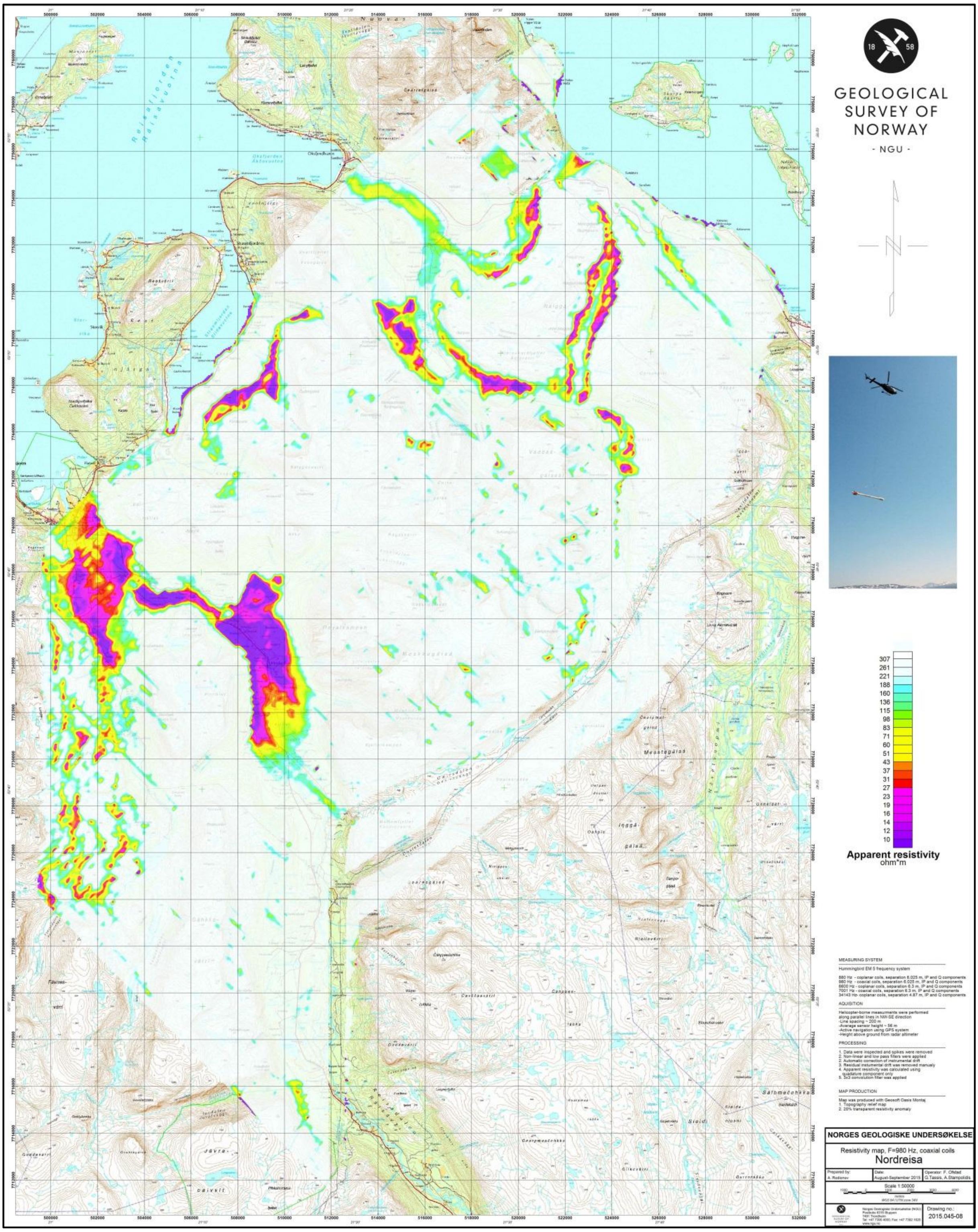

Figure 12: Apparent resistivity. Frequency 980 Hz, Coaxial coils

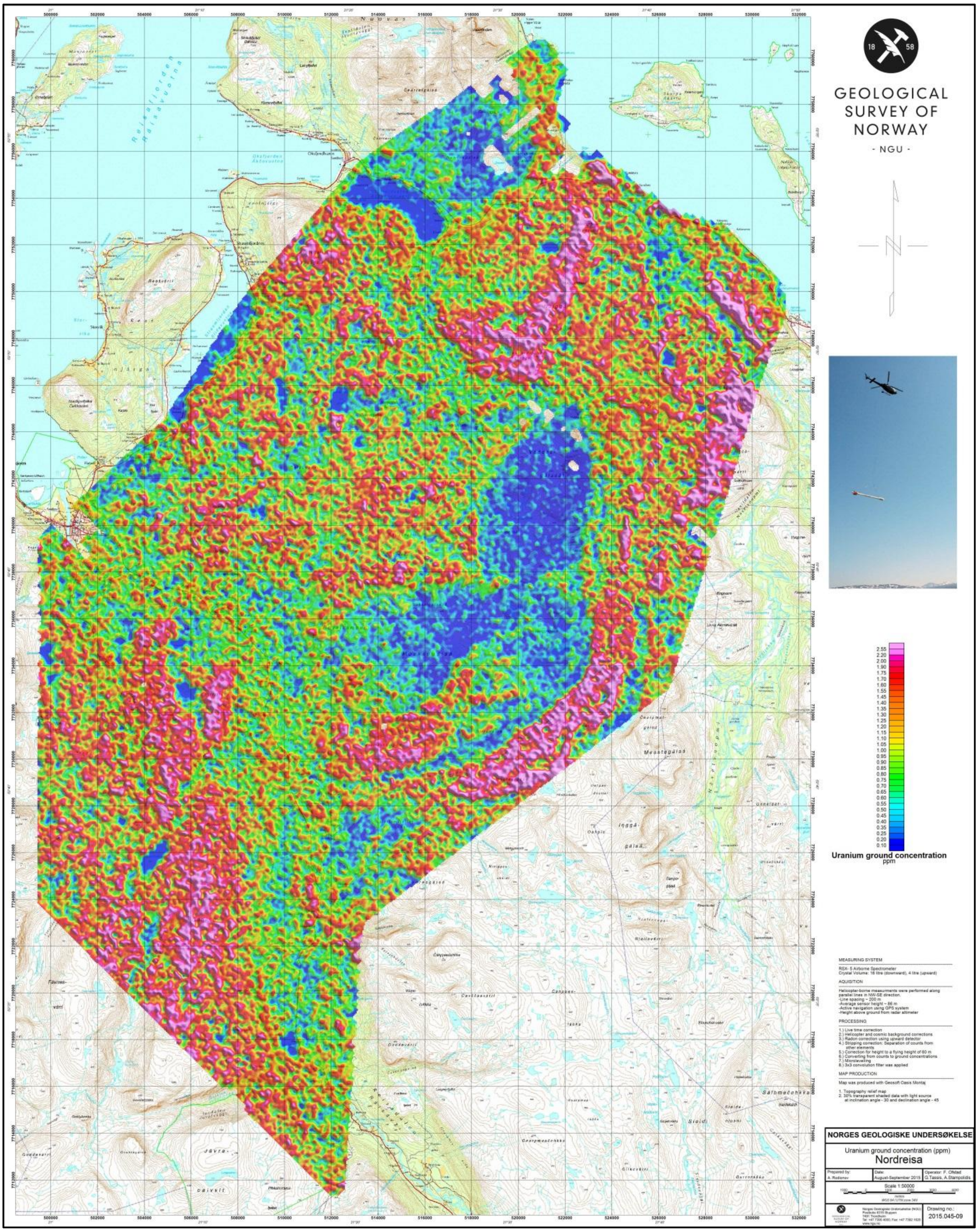

Figure 13: Uranium ground concentration

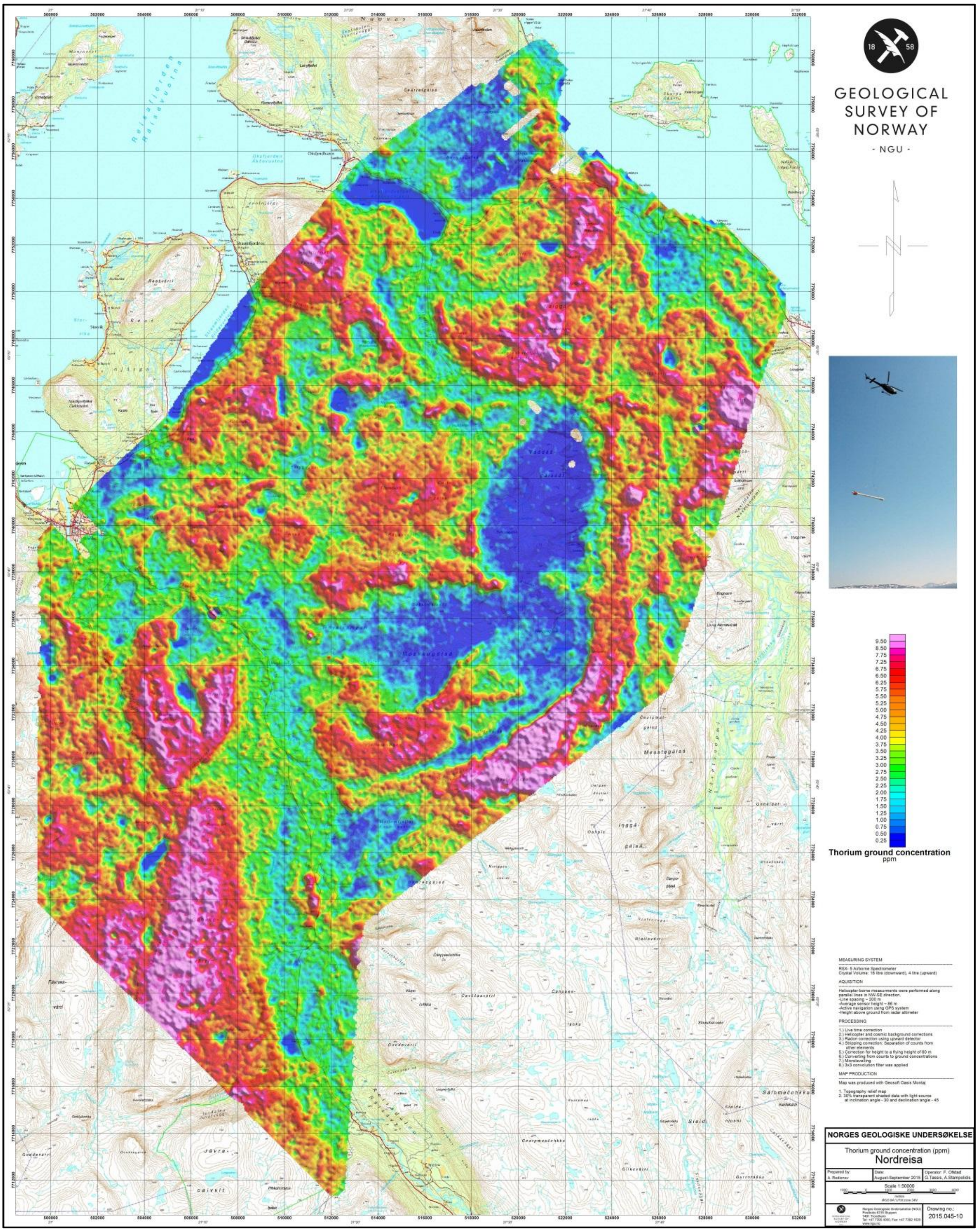

Figure 14: Thorium ground concentration

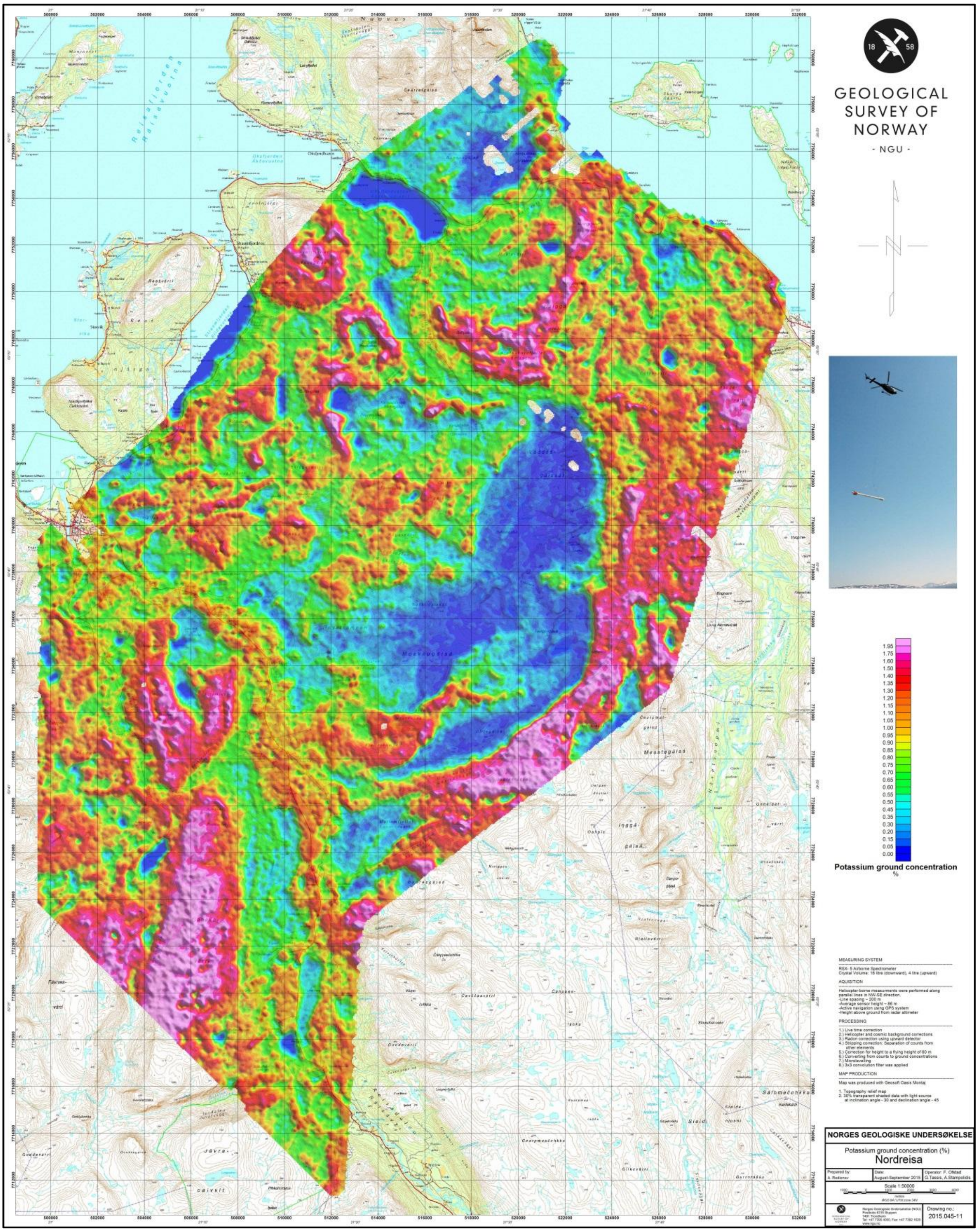

Figure 15: Potassium ground concentration

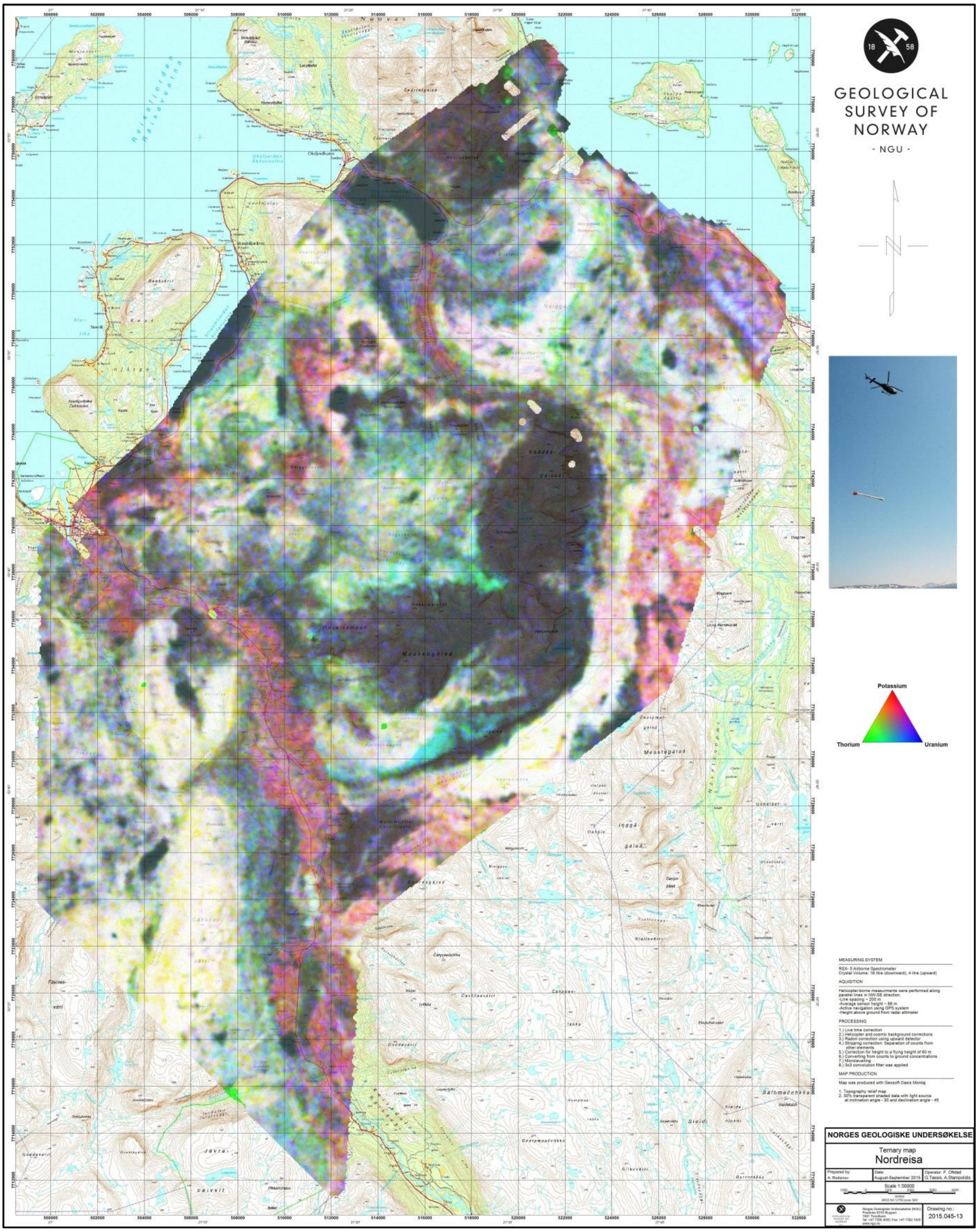

Figure 16: Radiometric Ternary map