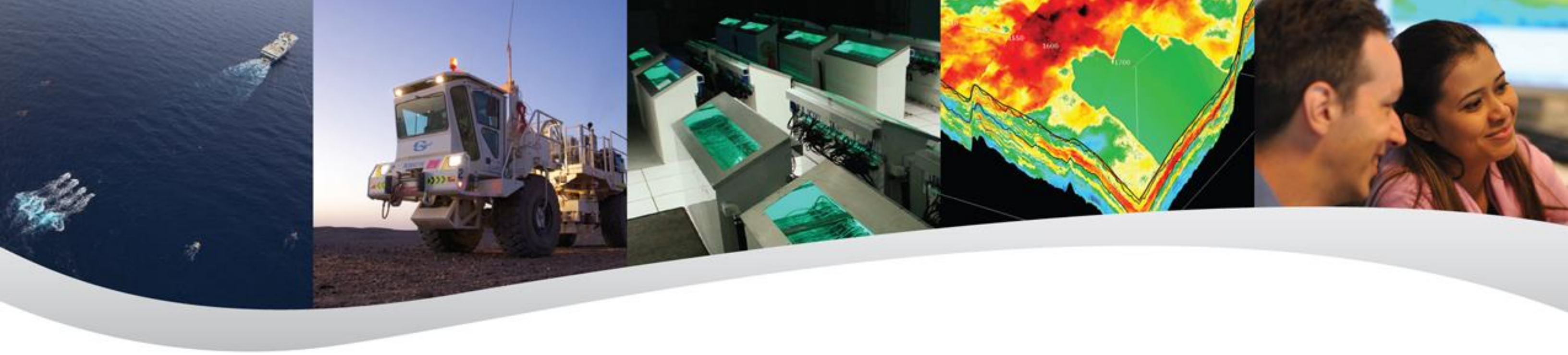

GEOPHYSICAL SURVEY REPORT
AIRBORNE MAGNETIC AND HELITEM SURVEY
SUDBURY AREA
PROJECT 509527
NORTH AMERICAN PALLADIUM LTD.

November 6, 2015

Passion for Geoscience
cgg.com

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Introduction

This report describes the logistics, data acquisition, processing and presentation of results of a HELITEM electromagnetic and magnetic airborne geophysical survey carried out for North American Palladium Ltd. comprising of three blocks (A, B, and C) including two infills (1 and 2) for tie lines over one property near Sudbury, Ontario. Total coverage of the survey block amounted to 1570.2 km. The survey was flown between September 19, 2015 and October 11, 2015.

The purpose of the survey was to map the geology and structure of the area. Data were acquired using a HELITEM electromagnetic system, supplemented by a high-sensitivity cesium magnetometer. The information from these sensors was processed to produce maps and images that display the magnetic and conductive properties of the survey area. A GPS electronic navigation system ensured accurate positioning of the geophysical data with respect to the base map coordinates.

The survey was performed by CGG Canada Services Ltd., Toronto office. Grids and data in digital format are provided with this report.

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Survey Area Description

Location of the Survey Area

Three blocks (A, B, and C) and two tie line infills (1 and 2) near Sudbury, Ontario (Figure 1) were flown between September 19, 2015 and October 11, 2015, with Sudbury, Ontario as the base of operations. Survey coverage consisted of 1347.7 km of traverse lines flown with a spacing of 100 m and 222.5 km of tie lines with a spacing varying from 125 m to 1000 m for a total of 1570.2 km. Tie line infills (1) connecting blocks A and B have a spacing of 250 m and tie line infills (2) connecting blocks B and C have a spacing of 125 m.

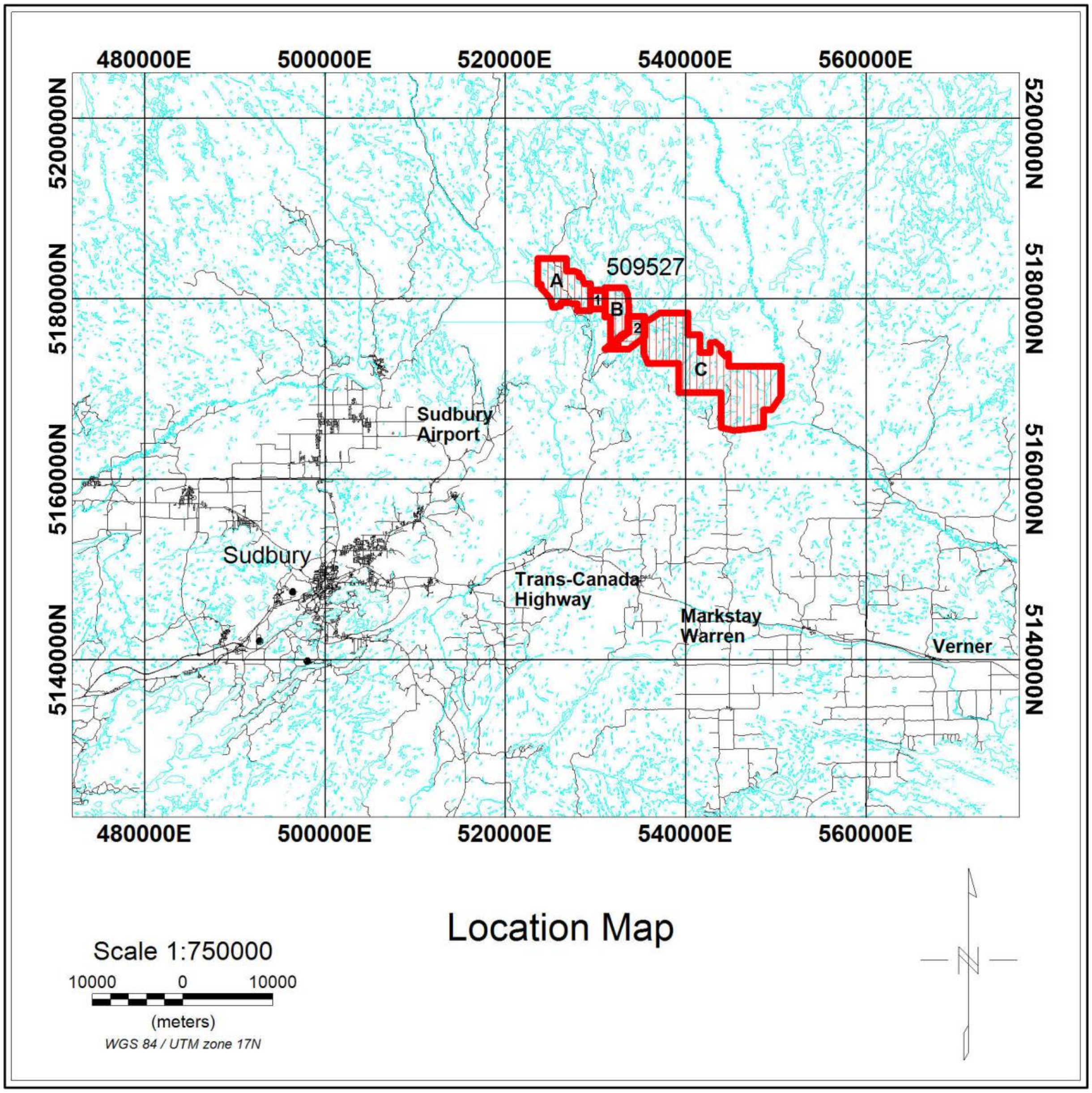


Figure 1 Sudbury Area - Location Map

Table 1 contains the coordinates of the corner points of the survey blocks and infill areas.

Block	Corners	X-UTM (E)	Y-UTM (N)
509527 - A	1	523467	5184520
Sudbury Area	2	526867	5184520
	3	526867	5183115
	4	527685	5183115
	5	528257	5182901
	6	528257	5182525
	7	528536	5182525
	8	528836	5181735
	9	529520	5181735
	10	529520	5178548
	11	528765	5178560
	12	527867	5178576
	13	527867	5179315
	14	527553	5179315
	15	526867	5179503
	16	526867	5179435
	17	526267	5179435
	18	526267	5179070
	19	525767	5179070
	20	525767	5178950
	21	525193	5178950
	22	524877	5179949
	23	524192	5180733
	24	523867	5181096
	25	523867	5181460
	26	523467	5181460
509527 - B	1	530950	5177870
Sudbury Area	2	530950	5181300
	3	533315	5181300
	4	533647	5180526
	5	533800	5179205
	6	533800	5176167
	7	533310	5175835
	8	532600	5175224
	9	532600	5174671
	10	531550	5174658
	11	531550	5177870
509527 - C	1	535250	5173880
Sudbury Area	2	535250	5177775
	3	535971	5177775
	4	537121	5178500
	5	540350	5178500
	6	540350	5176100
	7	541700	5176100

Block	Corners	X-UTM (E)	Y-UTM (N)
509527 - C	8	541700	5174100
Sudbury Area	9	542650	5174100
	10	542650	5175191
	11	543332	5175253
	12	544000	5174696
	13	544000	5174140
	14	544366	5173757
	15	544850	5174053
	16	544850	5172600
	17	547900	5172610
	18	550700	5172599
	19	550700	5169218
	20	549551	5167600
	21	548750	5167600
	22	548750	5165644
	23	546559	5165400
	24	545293	5165299
	25	543800	5165619
	26	543800	5169500
	27	539100	5169500
	28	539100	5172700
	29	535732	5172700
509527 – Infill 1 (250m spacing Tie Lines)	1	529320	5178763
	2	529320	5181033
	3	531150	5181033
	4	531150	5178763
509527 – Infill 2 (125m spacing Tie Lines)	1	533600	5178021
	2	535449	5178019
	3	535450	5175798
	4	533694	5174405
	5	531047	5174408
	6	532805	5175923
	7	532889	5175994
	8	532939	5176030
	9	533409	5176144
	10	533548	5176278
	11	533600	5176293

Table 1 Area Corners NAD83 UTM Zone 17N

Block	Line Numbers	Line direction	Line Spacing	Line km
A	10010 - 10590	0°/180°	100 m	233.9
Sudbury Area	19010 - 191900	90°/270°	1000 m	146.1
B	10760 - 11020	0°/180°	100 m	138.6
2 (Tie Infill 1)	190425 - 190575	90°/270°	250 m	9.9
C	11190 - 12710	0°/180°	100 m	921.8
3 (Tie Infill 2)	190725 - 1910375	90°/270°	125 m	53.9

Table 2 Planned line kilometre summary

During the survey GPS base stations were set up to collect data to allow post processing of the positional data for increased accuracy. The location of the GPS base stations are shown in Table 3.

Status	Location Name	WGS84 Longitude (deg-min-sec)	WGS84 Latitude (deg-min-sec)	Orthometric Height (m)
Primary	Sudbury, Ontario	80° 47’ 31.8602” W	46° 37’ 30.1577” N	350.998
Secondary	Sudbury, Ontario	80° 47’ 28.64699” W	46° 37’ 25.8339” N	347.109

Table 3 GPS Base Station Location

The location of the Magnetic base stations are shown in Table 4.

Status	Location Name	WGS84 Longitude (deg-min-sec)	WGS84 Latitude (deg-min-sec)
Primary	Sudbury, Ontario	80° 47’ 28.64699” W	46° 37’ 25.8339” N

Table 4 Magnetic Base Station Location

System Information

Figure 2 HELITEM System

The HELITEM system is composed of a 50 m cable to which is attached a receiver platform 23 m along the cable below the Helicopter, a magnetometer attached to the transmitter loop 46 m below the helicopter in flight. The top of the cable is attached to a helicopter and when in flight it drags to form a 25 degree angle from the vertical. The real time navigation GPS antenna is on the tail boom of the helicopter, the barometric altimeter, radar altimeter, video camera and data recorder are all installed in the helicopter. GPS antennae are attached to the transmitter loop to give positional information and transmitter orientation.

Aircraft and Geophysical On-Board Equipment

Helicopter:	AS350 B3
Operator:	Canadian Helicopters
Registration:	C-GZIK
Average Survey Speed:	86.5 km/h (24m/s)
EM system:	HELITEM 30 channel multi-coil system
Transmitter:	Vertical axis loop slung below helicopter
Loop area:	708 m^2
Number of turns:	2
Nominal height above ground:	35 m
Receiver:	Multi-coil system (X, Y and Z) with a final recording rate of 10 samples per second, of 30 channels of X, Y and Z component data.
Position:	26.7 m above and 12.9 m forward of transmitter centre
Nominal height above ground:	62 m
Base frequency:	30 Hz
Pulse width:	4 ms
Off-time:	13 ms
Transmitter Current:	1412 A
Dipole moment:	$2.0 \times 10^6 A \cdot m^2$

HELITEM Gate positions 30 Hz / 4 ms pulse width									
Gate	Start time (ms)	End Time (ms)	Midpoint (ms)	Width (ms)			Start time (ms)	End Time (ms)	Midpoint (ms)
1	0.0163	0.1465	0.0814	0.1302	Ontime	Time after pulse shut-off			
2	1.0091	1.9938	1.5015	0.9847	Ontime				
3	1.9857	2.4821	2.2339	0.4964	Ontime				
4	3.8330	3.9714	3.9022	0.1383	Ontime				
5	4.1178	4.1341	4.1260	0.0163	Offtime	5	0.0977	0.1139	0.1058
6	4.1341	4.1585	4.1463	0.0244	Offtime	6	0.1139	0.1383	0.1261
7	4.1585	4.1911	4.1748	0.0326	Offtime	7	0.1383	0.1709	0.1546
8	4.1911	4.2236	4.2074	0.0326	Offtime	8	0.1709	0.2035	0.1872
9	4.2236	4.2643	4.2440	0.0407	Offtime	9	0.2035	0.2441	0.2238
10	4.2643	4.3132	4.2887	0.0488	Offtime	10	0.2441	0.2930	0.2686
11	4.3132	4.3701	4.3416	0.0570	Offtime	11	0.2930	0.3499	0.3215
12	4.3701	4.4434	4.4067	0.0732	Offtime	12	0.3499	0.4232	0.3866
13	4.4434	4.5329	4.4881	0.0895	Offtime	13	0.4232	0.5127	0.4679
14	4.5329	4.6387	4.5858	0.1058	Offtime	14	0.5127	0.6185	0.5656
15	4.6387	4.7689	4.7038	0.1302	Offtime	15	0.6185	0.7487	0.6836
16	4.7689	4.9235	4.8462	0.1546	Offtime	16	0.7487	0.9033	0.8260
17	4.9235	5.1107	5.0171	0.1872	Offtime	17	0.9033	1.0905	0.9969
18	5.1107	5.3385	5.2246	0.2279	Offtime	18	1.0905	1.3184	1.2044
19	5.3385	5.6152	5.4769	0.2767	Offtime	19	1.3184	1.5951	1.4567
20	5.6152	5.9489	5.7821	0.3337	Offtime	20	1.5951	1.9287	1.7619
21	5.9489	6.3477	6.1483	0.3988	Offtime	21	1.9287	2.3275	2.1281
22	6.3477	6.8278	6.5877	0.4801	Offtime	22	2.3275	2.8076	2.5675
23	6.8278	7.4056	7.1167	0.5778	Offtime	23	2.8076	3.3854	3.0965
24	7.4056	8.1055	7.7555	0.6999	Offtime	24	3.3854	4.0853	3.7354
25	8.1055	8.9518	8.5286	0.8464	Offtime	25	4.0853	4.9316	4.5085
26	8.9518	9.9772	9.4645	1.0254	Offtime	26	4.9316	5.9570	5.4443
27	9.9772	11.2142	10.5957	1.2370	Offtime	27	5.9570	7.1940	6.5755
28	11.2142	12.7035	11.9588	1.4893	Offtime	28	7.1940	8.6833	7.9386
29	12.7035	14.5020	13.6027	1.7985	Offtime	29	8.6833	10.4818	9.5825
30	14.5020	16.6667	15.5843	2.1647	Offtime	30	10.4818	12.6465	11.5641

Table 5 HELITEM Gate Positions

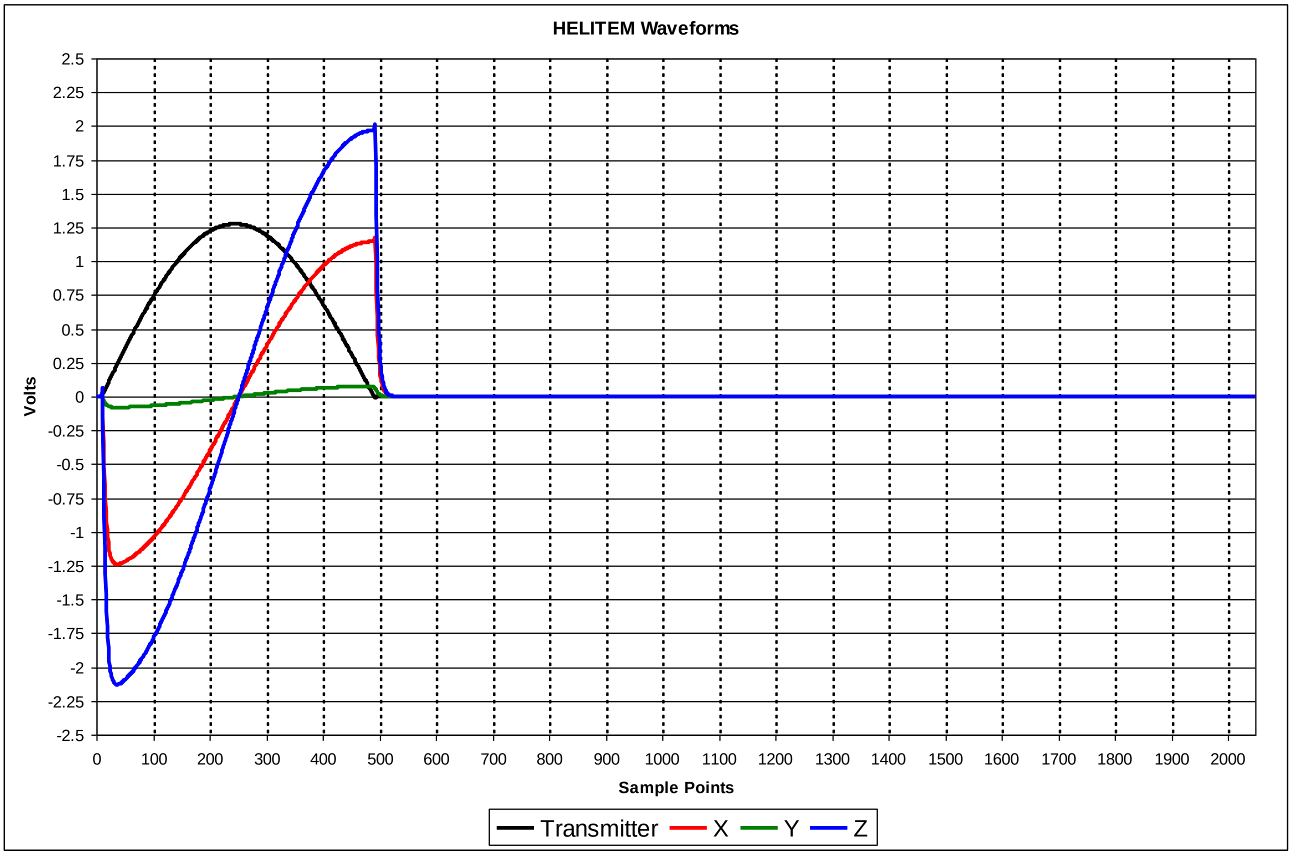


Figure 3 HELITEM System Waveform

Digital Acquisition:	CGG HeliDAS.
Video:	Panasonic WVCD/32 Camera with Axis 241S Video Server. Camera is mounted to the exterior bottom of the helicopter between the forward skid tubes
Magnetometer:	Scintrex Cesium Vapour (CS-3), mounted at transmitter loop;

Operating Range: 15,000 to 100,000 nT
Operating Limit: -40°C to 50°C
Accuracy: ±0.002 nT
Measurement Precision: 0.001 nT
Sampling rate: 10.0 Hz

Radar Altimeter:	Honeywell Sperry Altimeter System. Radar antennas are mounted to the exterior bottom of the helicopter between the forward skid tubes

Operating Range: 0 – 2500ft
Operating Limit: -55°C to 70°C
0 to 55,000 ft
Accuracy:
± 3% (100 – 500ft above obstacle)

	± 4% (500 – 2500ft above obstacle) Measurement Precision: 1 ft Sample Rate: 10.0 Hz
Aircraft Navigation:	NovAtel OEM4 Card with an Aero antenna mounted on the tail of the helicopter; Operating Limit: -40°C to 85°C Real-Time Accuracy: 1.2m CEP (L1 WAAS) Real-Time Measurement Precision: 6 cm RMS Sample Rate: 2.0 Hz
Transmitter Loop Positional Data:	NovAtel OEM4 with Aero Antenna mounted on the generator platform. Operating Limit: -40°C to 85°C Real-Time Accuracy: 1.8m CEP (L1) Real-Time Measurement Precision: 6 cm RMS Sample Rate: 2.0 Hz
Barometric Altimeter:	Motorola MPX4115AP analog pressure sensor mounted in the helicopter Operating Range: 55 kPa to 108 kPa Operating Limit: -40°C to 125°C Accuracy: ± 1.5 kPa (0°C to 85°C) ± 3.0 kPa (-20°C to 0°C, 85°C to 105°C) ± 4.5 kPa (-40°C to -20°C, 105°C to 125°C) Measurement Precision: 0.01 kPa Sampling Rate = 10.0 Hz
Temperature:	Analog Devices 592 sensor mounted on the camera box Operating Range: -40°C to + 75°C Operating Limit: -40°C to + 75°C Accuracy: ± 1.5°C Measurement Precision: 0.03°C Sampling Rate = 10.0 Hz

Base Station Equipment

Primary Magnetometer:	CGG CF1 using Scintrex cesium vapour sensor with Marconi GPS card and antenna for measurement synchronization to GPS. The base station also collects barometric pressure and outside temperature. Magnetometer Operating Range: 15,000 to 100,000 nT Barometric Operating Range: 55kPa to 108 kPa Temperature Operating Range: -40°C to 75°C Sample Rate: 1.0 Hz

GPS Receiver: NovAtel OEM4 Card with an Aero antenna

Real-Time Accuracy: 1.8m CEP (L1)
Sample Rate: 1.0 Hz

Secondary Magnetometer: GEM Systems GSM-19

Operating Range: 20,000 to 120,000 nT
Operating Limit: -40°C to 60°C
Accuracy: ± 0.2 nT
Measurement Precision: 0.01 nT
Sample Rate: 0.33 Hz

Quality Control and Preliminary Data Processing

Digital data for each flight were uploaded to CGG's secure file transfer regularly in order to verify data quality and completeness in the office. A database was created and updated using Geosoft Oasis Montaj and proprietary CGG Atlas software. This allowed the field personnel to calculate, display and verify both the positional (flight path) and geophysical data. The initial database was examined as a preliminary assessment of the data acquired for each flight.

Initial processing of CGG survey data consists of differential corrections to the airborne GPS data, verification of EM calibrations, drift correction of the raw airborne EM data, spike rejection and filtering of all geophysical and ancillary data, verification of the digital video, calculation of preliminary resistivity data, and diurnal correction of magnetic data.

All data, including base station records, were checked on a daily basis to ensure compliance with the survey contract specifications. Re-flights were required if any of the following specifications were not met.

Navigation

A specialized GPS system provided in-flight navigation control. The system determined the absolute position of the helicopter by monitoring the range information of twelve channels (satellites). The Novatel OEM4 receiver was used for this application. In North America, the OEM4 receiver is WAAS-enabled (Wide Area Augmentation System) providing better real-time positioning.

A Novatel OEM4 GPS base station was used to record pseudo-range, carrier phase, ephemeris, and timing information of all available GPS satellites in view at a one second interval. These data are used to improve the conversion of aircraft raw ranges to differentially corrected aircraft position. The GPS antenna was set-up in a location that allowed for clear sight of the satellites above. The set-up of the antenna also considered surfaces that could cause signal reflection around the antenna that could be a source of error to the received data measurements.

Flight Path

Flight lines did not deviate from the intended flight path by more than 25% of the planned flight path over a distance of more than 1 kilometre. Flight specifications were based on GPS positional data recorded at the helicopter.

Clearance

The survey elevation is defined as the measurement of the helicopter radar altimeter to the tallest obstacle in the helicopter path. An obstacle is any structure or object which will impede the path of the helicopter to the ground and is not limited to and includes tree canopy, towers and power lines.

Survey elevations may vary based on the pilot's judgement of safe flying conditions around man-made structures or in rugged terrain.

The nominal survey elevation achieved for the helicopter and instrumentation during data collection was:

Helicopter	83 metres
Magnetometer	35 metres
HELITEM Receiver	62 metres
HELITEM Transmitter	35 metres

Survey elevations did not deviate by more than 20% over a distance of 2 km from the contracted elevation except for a few lines that were re-flown where they exceeded this specification.

Flying Speed

The average calculated ground speed was 86.5 km/h ranging between 49 to 122 km/h. This resulted in a ground sample interval of approximately 1.4 to 3.4 metres at a 10 Hz sampling rate.

Airborne High Sensitivity Magnetometer

To assess the noise quality of the collected airborne magnetic data, CGG monitors the 4th difference results during flight which is verified post flight by the processor. The contracted specification for the collected airborne magnetic data was that the non-normalized 4th difference would not exceed 1.0 nT over a continuous distance of 1 kilometre excluding areas where this specification was exceeded due to natural anomalies.

Magnetic Base Station

Ground magnetic base stations were set-up to measure the total intensity of the earth's magnetic field. The base stations were placed in a magnetically quiet area, away from power lines and moving metallic objects. The contracted specification for the collected ground magnetic data was the non-linear variations in the magnetic data were not to exceed 10 nT per minute. Throughout the period of the survey the earth's magnetic activity was calm. Magnetic diurnal activity never exceed 1.7 nT except on October 7th (Flight 35038) where the non-linear variation on tie line 190400 reached 10.4 nT for two seconds and tie lines 190200 and 190300 had non-linear variation up to 7 nT.

CGG's standard of setting up the base station within 50 km from the centre of the survey block allowed for successful removal of the active magnetic events on the collected airborne magnetic data.

Electromagnetic Data

The noise envelopes of the EM data, as indicated on the raw traces of dB/dT channel 30 (or calculated last off-time channel), shall not exceed the following tolerances continuously over a horizontal distance of 1,000 metres under normal survey conditions:

- 30 Hz configuration: dB/dt X and Z < 2.5 nT/s and B-Field X and Z < 6.5 pT

Noise level is specified as being plus or minus two standard deviations of the high-pass filtered channel data.

Spheric pulses may occur having strong peaks but narrow widths. If the frequency of spheric events significantly degrades the data quality with respect to survey objectives in the judgment of the CGG geophysical data processor, the data will be flagged for discussion.

The HELITEM EM system includes two power line channel for noise monitoring.

In-Flight EM System Calibration

Calibration consists of measuring the system characteristics out of ground effect and compensation of the electromagnetic data for these measured effects. The reference waveforms recorded during the pre-flight calibration form an important part of the delivered data and are critical to accurate inversion of the data. During the pre-flight calibration, a minimum of 30 seconds of data is collected out-of-ground-effect to monitor the effectiveness of the calibration and the accuracy to the base levels. During any post-flight calibration, a minimum of 30 seconds of data is collected out-of-ground-effect; these data are compared with the pre-flight calibration data to quantify drift.

Measurements of in-flight noise levels, out of ground effect, are made at the high altitude portions of each flight. Static or Hover noise levels are not directly related to those seen in flight due to geometry and compensation considerations that are only addressed in a dynamic situation.

Data Processing

Flight Path Recovery

To check the quality of the positional data the speed of the helicopter is calculated using the differentially corrected x, y and z data. Any sharp changes in the speed are used to flag possible problems with the positional data. Where speed jumps occur, the data are inspected to determine the source of the error. The erroneous data are deleted and splined if less than two seconds in length. If the error is greater than two seconds the raw data are examined and if acceptable, may be shifted and used to replace the bad data. The GPS-Z component is the most common source of error. When it shows problems that cannot be corrected by recalculating the differential correction, the barometric altimeter is used as a guide to assist in making the appropriate correction. The corrected WGS84 longitude and latitude coordinates were transformed to NAD83 using the following parameters.

Datum:	NAD83
Ellipsoid:	GRS80
Projection:	UTM Zone 17N
Central meridian:	81° West
False Easting:	500000 metres
False Northing:	0 metres
Scale factor:	0.9996
WGS84 to Local Conversion:	Molodensky
Dx,Dy,Dz:	0, 0, 0

Recorded video flight path may also be linked to the data and used for verification of the flight path. Fiducial numbers are recorded continuously and are displayed on the margin of each digital image. This procedure ensures accurate correlation of data with respect to visible features on the ground. The fiducials appearing on the video frames and the corresponding fiducials in the digital profile database originate from the data acquisition system and are based on incremental time from start-up. Along with the acquisition system time, UTC time is also recorded in parallel and displayed (Figure 4).

Altitude Data

Radar altimeter data are despiked by applying a 1.5 second median and smoothed using a 1.5 second Hanning filter. The radar altimeter data are then subtracted from the GPS elevation to create a digital elevation model that is gridded and used in conjunction with profiles of the radar altimeter and flight path video to detect any spurious values.

Figure 4 Flight path video

Magnetics

Magnetic Base Station Diurnal

The raw diurnal data are sampled at 1 Hz and imported into a database. The data are filtered with a 51 second median filter and then a 51 second Hanning filter to remove spikes and smooth short wavelength variations. A non-linear variation is then calculated and a flag channel is created to indicate where the variation exceeds the survey tolerance. Acceptable diurnal data are interpolated to a 10 Hz sample rate and the local regional field value of 55553 nT, calculated from the average of the whole days diurnal data of the project, was removed to leave the diurnal variation. This diurnal variation is then ready to be used in the processing of the airborne magnetic data.

Residual Magnetic Intensity

The Total Magnetic Field (TMF) data collected in flight were profiled on screen along with a fourth difference channel calculated from the TMF. Spikes were removed manually where indicated by the fourth difference. The despiked data were then corrected for lag by 2.8 seconds. The diurnal variation that was extracted from the filtered ground station data was then removed from the despiked and lagged TMF. The IGRF was calculated using the 2015 IGRF model for the specific survey location, date and altitude of the sensor and removed from the TMF to obtain the Residual Magnetic Intensity (RMI). The results were then levelled using tie and traverse line intercepts. Manual adjustments were applied to any lines that required levelling, as indicated by shadowed images of the gridded magnetic data. The manually levelled data were then subjected to a microlevelling filter.

Calculated Vertical Magnetic Gradient

The levelled, Residual Magnetic Intensity grid was subjected to a processing algorithm that enhances the response of magnetic bodies in the upper 500 metres and attenuates the response of deeper bodies. The resulting calculated vertical gradient grid provides better definition and resolution of near-surface magnetic units. It also identifies weak magnetic features that may not be quite as evident in the RMI data. Regional magnetic variations and changes in lithology, however, may be better defined on the Residual Magnetic Intensity.

Electromagnetics

dB/dt Data

Lag correction: 0 samples

Data correction: The X, Y and Z component data are re-processed from the raw stream to produce the 30 raw channels at 10 samples per second.

The following processing steps are applied to the dB/dt data from all coil sets:

- The raw stream data is re-processed post-flight using start-of-flight and end-of-flight calibrations to remove spheric spikes, coil oscillation, system drift, and to filter VLF noise;
- Noise filtering is done using an adaptive filter technique based on time domain triangular operators. Using a second difference value to identify changes in gradient along each channel, minimal filtering (21 points) is applied over the peaks of the anomalies, ranging in set increments up to a maximum amount of filtering in the resistive background areas (35 points for both the X and the Z component data);
- The filtered X, Y and Z component data are then levelled in flight form for any residual and non-linear drift that was not adequately corrected during the drift correction;
- Finally, line-based levelling and microlevelling are applied as required.

B-field Data

The data acquisition system produces 30 B-field channels each for X, Y and Z component in real-time during flight, however these channels are only used for field QC. For delivery and generation of derived products, the final B-field channels are derived from the final levelled dB/dt data.

Coil Oscillation Correction

The electromagnetic receiver sensor of the HELITEM is housed in a platform container which is slung below the helicopter using a cable and attached to the transmitter loop through a network of cables. The platform design reduces the rotation of the receiver coils in flight as well as improves the stability of the receiver-transmitter geometry. However sudden changes in airspeed of the aircraft, strong variable crosswinds, or other turbulence can still result in sudden moves of the platform. This can cause the induction sensors inside the platform to rotate about their mean orientation. The effect of coil oscillation on the data increases as the signal from the ground (conductivity) increases and may not be noticeable when flying over areas which are generally resistive.

Using the changes in the coupling of the primary field, it is possible to estimate the pitch, roll and yaw of the receiver sensors. Only the pitch, which affects mainly the X and Z components, was considered for correction. The pitch angles during flight are estimated and corrected to the local average pitch value, removing the effects caused by the deviation of the receiver sensor from its nominal position. Using the GPS mounted on the transmitter loop centre, attitude of the receiver sensor platform is calculated and used for correction.

dB/dt Z Data

Except for extremely conductive areas, the amplitude of the dB/dt Z component increases with the conductivities of the earth. Due to the geometry of the HELITEM system, the Z component response from a near vertical discrete conductor peaks at either side but nulls where the transmitter is on top of the conductor. This results an “M” shaped Z component anomaly over a vertical conductor. The amplitudes of, and the distance between the two peaks can be used to indicate the dip angle and dip direction of the conductor.

Apparent Resistivity from Z data

CGG has developed an algorithm that converts the response in any measurement window (on-time or off-time) into an apparent resistivity. This is performed using a look-up table that contains the response at a range of half-space resistivities and altimeter heights. The apparent resistivity is calculated by fitting all 30 channels of the either the X-coil and Z-coil response of the dB/dt or B-Field component to the homogeneous-half-space model (or the thin sheet model). The apparent resistivity provides the maximum information on the near-surface resistivity of the ground which, when combined with the magnetic signature, provides good geological mapping.

For the present dataset, apparent resistivities were calculated for all 30 channels using the dB/dt Z-component data. Grids were generated for

Time Constant (TAU)

The time constant values are obtained by fitting the channel data from either the complete off-time signal of the decay transient or only a selected portion of it (as defined by specific channels) to a single exponential of the form:

$$Y = Ae^{-t/\tau}$$

where A is amplitude at time zero, t is time in microseconds and τ is the time constant, expressed in microseconds. A semi-log plot of this exponential function will be displayed as a straight line, the slope of which will reflect the rate of decay and therefore the strength of the conductivity. A slow rate of decay, reflecting a high conductivity, will be represented by a high time constant.

As a single parameter, the time constant provides more useful information than the amplitude data of any given single channel, as it indicates not only the peak position of the response but also the relative strength of the conductor. It also allows better discrimination of conductive axes within a broad formational group of conductors.

For the present dataset, three time constant channels and grids were generated for early, middle and late delay times to provide an approximation of conductor response strength and position at varying depth (where early time is the shallowest, late time the deepest). These time constant channels were calculated by fitting the response of the dB/dt Z-component to the exponential function over the following windows:

- Channels 6 - 9 (window centres 0.1261 - 0.2238 ms after turnoff)
- Channels 12– 15 (window centres 0.3866 – 0.6836 ms after turnoff)
- Channels 19 - 22 (window centres 1.4567 – 2.5675 ms after turnoff)

Note that blank spaces in the grid products (and null values in the profile data) represent areas (generally of very high resistivity) where the algorithm is unable to fit an exponential function to the channels selected.

Apparent Chargeability

The transmitted magnetic field induces electric fields in the ground and these fields can build up electrical charge on polarizable minerals. After the time-domain EM transmitter is turned off electric currents continue to flow in the ground, decaying in strength, creating the signal normally measured as “EM” data and used to calculate the ground conductivity. In chargeable ground, the electric charge continues to build until the field due to the charge is greater than the field remaining from the EM pulse. At this time the polarization starts to drive current in the opposite direction, creating a reverse anomaly that also decays away as the built-up charges dissipate. In many cases the chargeability/conductivity effect may be more subtle, appearing in the data as a reduction in the EM amplitude and distortion of the EM decay curve.

The apparent chargeability estimation from the airborne time domain EM data is carried out by first decomposing the measured EM response into an inductive and a polarization component, if the earth is polarizable and the IP effect is detected by the EM survey. This algorithm extracts the subtle as well as more prominent polarizable response from the measured EM data. The apparent chargeability is then estimated by the integration of the extracted polarization response. The apparent chargeability thus derived serves as a measure of the distribution of the polarizable zones in the survey area as detected by the EM survey. This estimated chargeability is not the intrinsic chargeability (m) as in the Cole-Cole relaxation model. Correlation of possible IP effects should be cross referenced to power lines and man-made structures as cultural features may interfere with the EM response and give spurious IP signatures. The data are provided in pT.

Digital Elevation

The radar altimeter values are subtracted from the differentially corrected and de-spiked GPS-Z values to produce profiles of the height above mean sea level along the survey lines. These values are gridded to produce a surface showing approximate elevations within the survey area. Any subtle line-to-line discrepancies are manually removed. After the manual corrections are applied, the digital terrain data are filtered with a microlevelling algorithm.

The accuracy of the elevation calculation is directly dependent on the accuracy of the two input parameters, radar altimeter and GPS-Z. The GPS-Z value is primarily dependent on the number of available satellites. Although post-processing of GPS data will yield X and Y accuracies in the order of 1-2 metres, the accuracy of the Z value is usually much less, sometimes in the ±5 metre range. Further inaccuracies may be introduced during the interpolation and gridding process.

Because of the inherent inaccuracies of this method, no guarantee is made or implied that the information displayed is a true representation of the height above sea level. Although this product may be of some use as a general reference, THIS PRODUCT MUST NOT BE USED FOR NAVIGATION PURPOSES.

Final Products

This section lists the products that have been provided under the terms of the survey agreement. Other products can be prepared from the existing dataset, if requested. Most parameters can be displayed as contours, profiles, or in colour.

Digital Archives

Line and grid data in the form of a Geosoft database (*.gdb) and Geosoft grids (*.grd) have been created. The formats and layouts of these archives are further described in Appendix B (Data Archive Description).

Report

A digital copy of this Geophysical Survey Report in PDF format.

Flight Path Videos

All survey flights in BIN/BDX format with a viewer.

CONCLUSIONS AND RECOMMENDATIONS

This report provides a very brief description of the survey results and describes the equipment, data processing procedures and logistics of the airborne survey over the Sudbury Area, near Sudbury, Ontario. The various grids included with this report display the magnetic and conductive properties of the survey area.

It is recommended that the survey results be assessed and fully evaluated in conjunction with all other available geophysical, geological and geochemical information. In particular, structural analysis of the data should be undertaken and areas of interest should be selected. It is important that careful examination of these areas be carried out on the ground in order to eliminate possible man-made sources of the EM anomalies. An attempt should be made to determine the geophysical “signatures” over any known zones of mineralization in the survey areas or their vicinity.

It is also recommended that image processing of existing geophysical data be considered, in order to extract the maximum amount of information from the survey results. Current software and imaging techniques often provide valuable information on structure and lithology, which may not be clearly evident on the contour and colour maps. These techniques can yield images that define subtle, but significant, structural details.

Respectfully submitted,

CGG

R509527

Appendix A List of Personnel

List of Personnel:

The following personnel were involved in the acquisition, processing, interpretation and presentation of data, relating to a HELITEM airborne geophysical survey carried out for North American Palladium over the Sudbury Area near Sudbury, Ontario.

Doug Garrie	Manager, Geophysical Services
Brett Robinson	Project Manager
Chris Sawyer	Flight Planner
Davon Watson	Electronics Technician
Jorje Naranjo	Electronics Technician
Mihai Szentesy	Field Data Processor
David Mimim	Pilot (Canadian Helicopters)
Matthew Rutty	AME (Canadian Helicopters)
Simon Robitaille	AME (Canadian Helicopters)
Elizabeth Bowslaugh	Geophysicist
Amar Neku	Data Processor

All personnel were employees of CGG, except where indicated.

Appendix B Data Archive Description

Data Archive Description:

Survey Details:

Survey Area Name:	Sudbury Area
Project number:	509527
Client:	North American Palladium
Survey Company Name:	CGG
Flown Dates:	September 19, 2015 to October 11, 2015
Archive Creation Date:	November 6, 2015

Geodetic Information for map products:

Datum:	NAD83
Ellipsoid:	GRS80
Projection:	UTM Zone 17N
Central meridian:	81° West
False Easting:	500000 metres
False Northing:	0 metres
Scale factor:	0.9996
WGS84 to Local Conversion:	Molodensky
Dx,Dy,Dz:	0, 0, 0

Flight Logs:

A PDF file of all the survey flights:

509527 Flight logs.pdf

Grid Archive:

Geosoft Grids:

File	Description	Units
mag	Residual Magnetic Intensity	nT
cvg	Calculated Vertical Magnetic Gradient	nT/m
decay_dbz_6to9	Time Constant at 0.1261 - 0.2238 ms from the end of pulse	µs
decay_dbz_12to15	Time Constant at 0.3866 – 0.6836 ms from the end of pulse	µs
decay_dbz_19to22	Time Constant at 1.4567 – 2.5675 ms from the end of pulse	µs
res_dbz_ch8	Apparent Resistivity – channel 8	ohm·m
res_dbz_ch13	Apparent Resistivity – channel 13	ohm·m
res_dbz_ch21	Apparent Resistivity – channel 21	ohm·m
dbz_ip	Apparent Chargeability	pT

Linedata Archive:

Geosoft Database Layout:

Field	Variable	Description	Units
1	x_heli	Helicopter Easting NAD83	m
2	y_heli	Helicopter Northing NAD83	m

3	fid	fiducial	-
4	longitude_heli	Helicopter Longitude WGS84	degrees
5	latitude_heli	Helicopter Latitude WGS84	degrees
6	x_tx	Transmitter loop Easting NAD83	m
7	y_tx	Transmitter loop Northing NAD83	m
8	longitude_tx	Transmitter loop Longitude WGS84	degrees
9	latitude_tx	Transmitter loop Latitude WGS84	degrees
10	flight	Flight number	-
11	date	Flight date	ddmmyy
12	altrad_heli	Height above surface from radar altimeter	m
13	altrad_tx	Height above surface from transmitter	m
14	gpsz_heli	Helicopter height above geoid	m
15	gpsz_tx	Transmitter height above geoid	m
16	dem	Digital elevation model (above geoid)	m
17	diurnal	Measured ground magnetic intensity	nT
18	diurnal_cor	Diurnal correction – base removed	nT
19	mag_raw	Total magnetic field – spike rejected	nT
20	mag_lag	Total magnetic field - corrected for lag	nT
21	mag_diu	Total magnetic field – diurnal variation removed	nT
22	igrf	international geomagnetic reference field	nT
23	mag_rmi	Residual magnetic intensity	nT
24-53	emx_db_post[0] – [29]	dB/dt X component channels 1 – 30 – compensated	nT/s
54-83	emy_db_post[0] – [29]	dB/dt Y component channels 1 – 30 – compensated	nT/s
84-113	emz_db_ post[0] – [29]	dB/dt Z component channels 1 – 30 – compensated	nT/s
114-143	emx_bf_ post[0] – [29]	B field X component channels 1 – 30 – compensated	pT
144-173	emy_bf_post[0] – [29]	B field Y component channels 1 – 30 – compensated	pT
174-203	emz_bf_post[0] – [29]	B field Z component channels 1 – 30 – compensated	pT
204-233	emx_db[0] – [29]	dB/dt X component channels 1 – 30 - levelled	nT/s
234-263	emy_db[0] – [29]	dB/dt Y component channels 1 – 30 - levelled	nT/s
264-293	emz_dbl[0] – [29]	dB/dt Z component channels 1 – 30 - levelled	nT/s
294-323	emx_bf[0] – [29]	B field X component channels 1 – 30 - levelled	pT
324-353	emy_bf[0] – [29]	B field Y component channels 1 – 30 - levelled	pT
354-383	emz_bf[0] – [29]	B field Z component channels 1 – 30 - levelled	pT
384	decay_dbz_6to9	Time Constant at 0.1261 - 0.2238 ms from the end of pulse	µs
385	decay_dbz_12to15	Time Constant at 0.3866 – 0.6836 ms from the end of pulse	µs
386	decay_dbz_19to22	Time Constant at 1.4567 – 2.5675 ms from the end of pulse	µs
387	res_dbz	Apparent Resistivity channels 1 - 30	ohm·m
388	dbz_ip	Apparent Chargeability	pT
389	x_powerline	Power line monitor X-channel	µV
390	z_powerline	Power line monitor Z-channel	µV
391	Tx_current	Transmitter peak current	amp

Note – Null values are displayed as *.

Report:

A logistics and processing report for Project #509527 in PDF format:

R509527.pdf

Video:

Digital video in BIN/BDX format for all survey flights including a viewer.

CGGSurveyReplay

Reference Waveform Description:

The information shown below is a sample.

```
/Calibration Data [FLT 99041 Cal# 1 Start FID 50172 End Fid 50293]
/Base Frequency : 30 Hz
/Sample Interval: 8.1380208 µs

/ -------------------------------------------------------------------------------
/ XYZ REF WAVEFORM EXPORT
/SAMPLE  T_Current[A] dB/dt_X[nT/s] dB/dt_Y[nT/s] dB/dt_Z[nT/s] BF_X[pT] BF_Y[pT] BF_Z[pT]
   0            0.512         1.570         1.439        -0.803   -2.479   13.000    0.877
   1            0.512        -1.756         3.954        -3.239   -2.496   12.984    0.886
   2            0.512        -3.027        -2.154        -1.877   -2.477   12.94     0.921
   |              |             |             |             |        |        |        |
   |              |             |             |             |        |        |        |
   |              |             |             |             |        |        |        |
   |              |             |             |             |        |        |        |
 509           -0.513         3.593         2.359         4.060    0.141   -0.002    0.031
 510           -0.513         9.231        -3.096         0.690    0.102   -0.028   -0.013
 511           -0.512         0.194         0.533        -1.855    0.002    0.006   -0.020
```

The first column is the sample number. There are a total of 2048 samples representing a half-wave cycle or one pulse. The subsequent columns are: transmitter current, measured X primary field, measured Y primary field, and measured Z primary field for dB/dt and B-Field.

Appendix C Map Product Grids

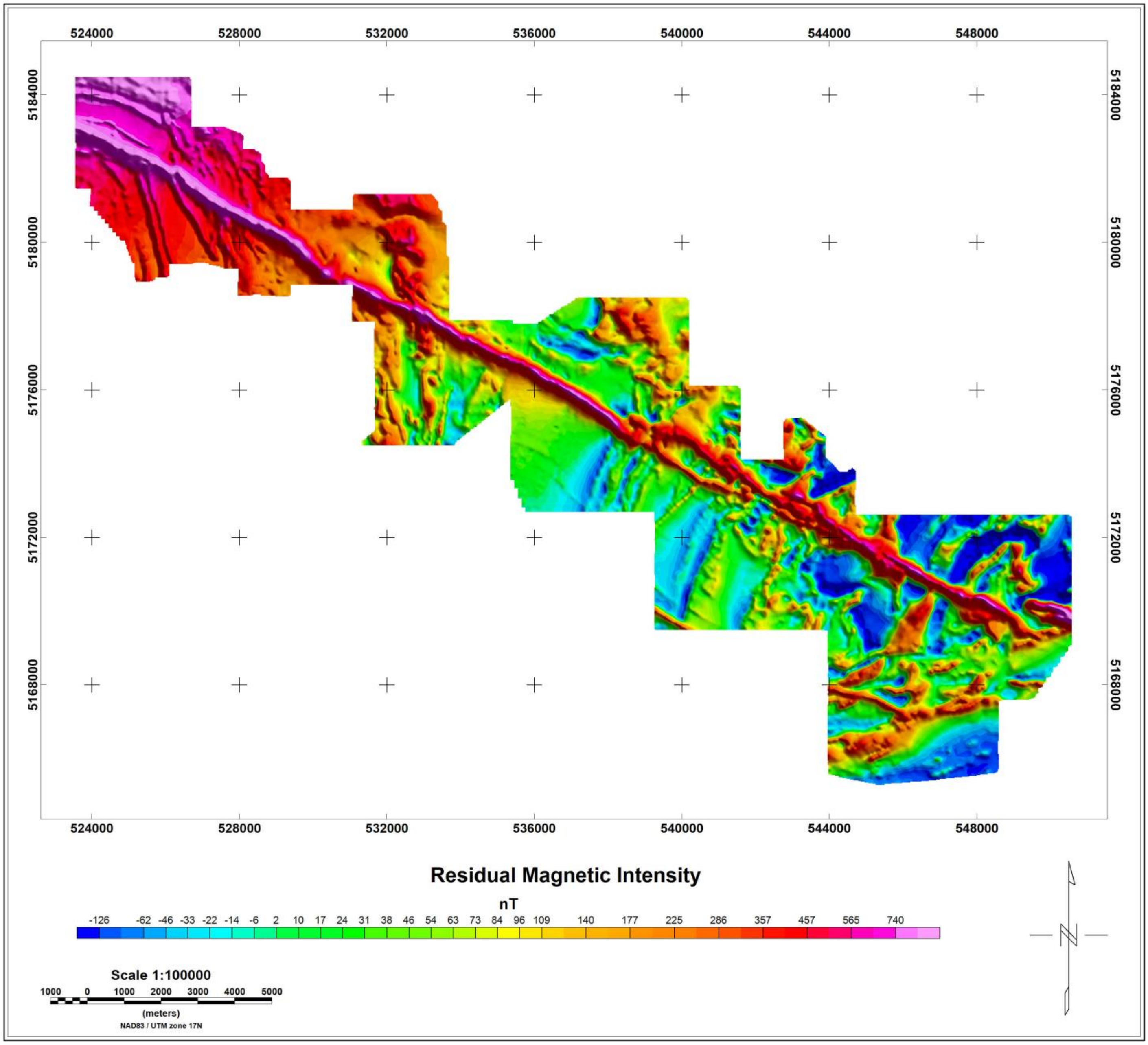


Figure 5 Residual Magnetic Intensity

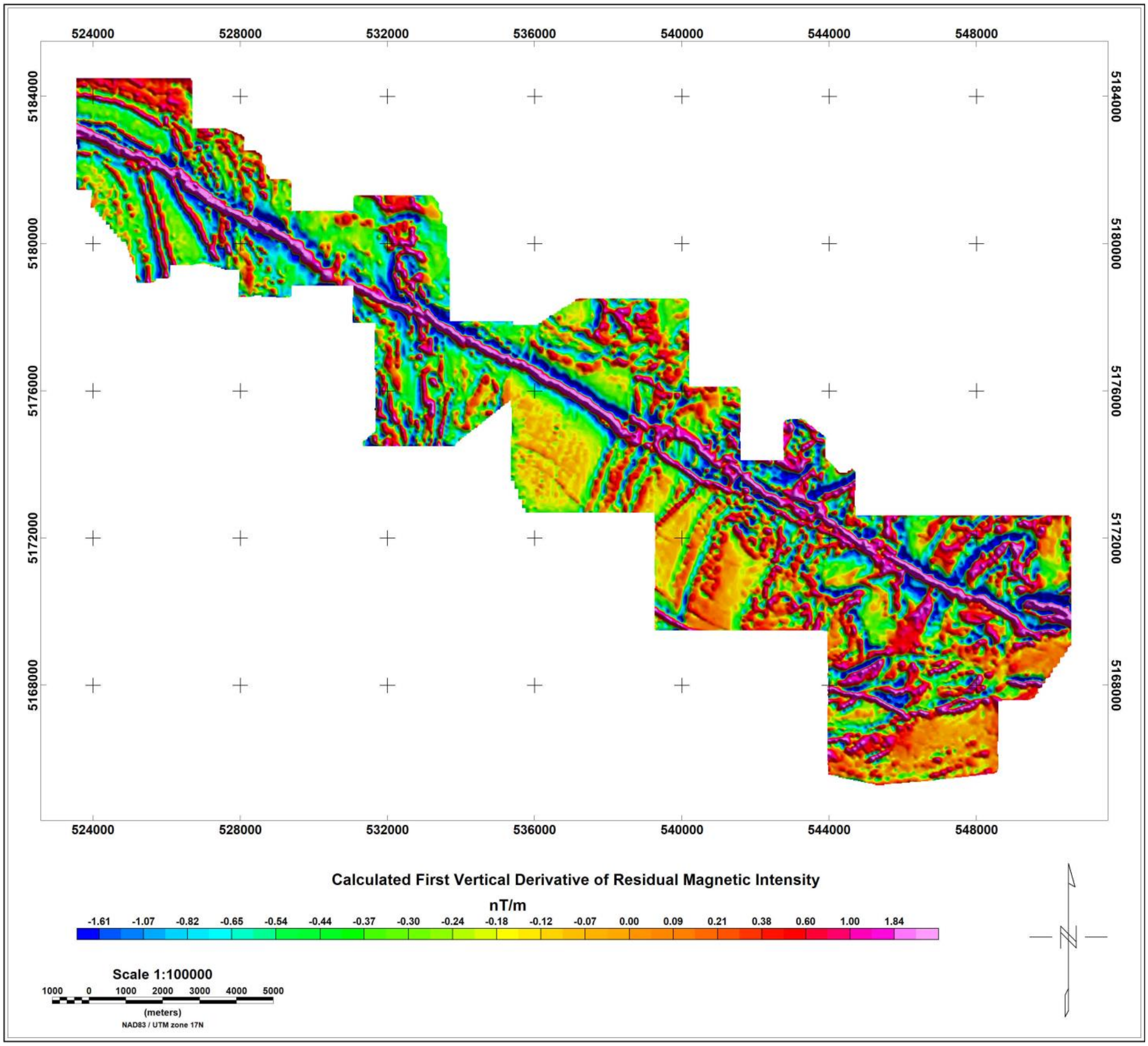


Figure 6 Calculated Vertical Magnetic Gradient

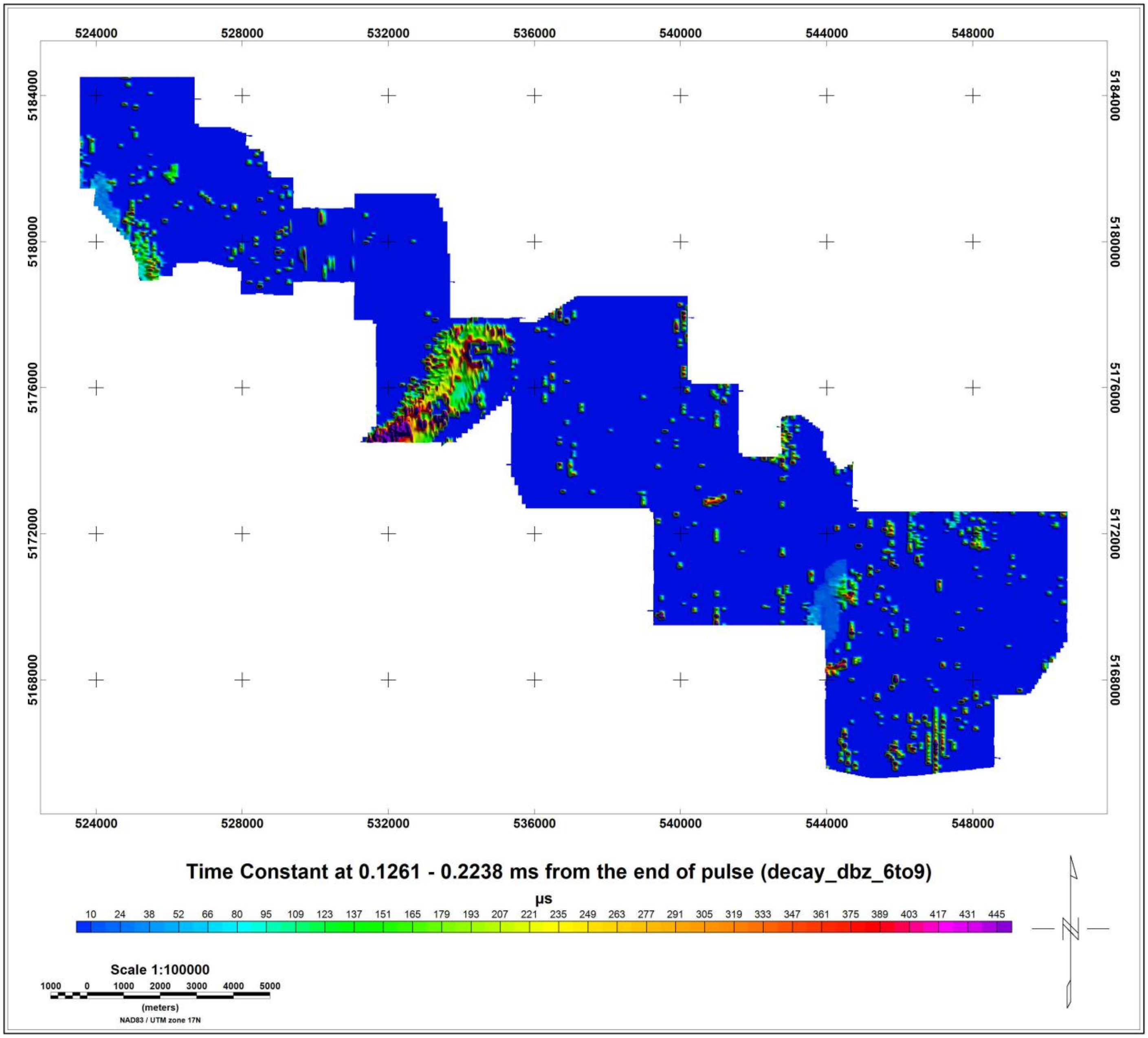


Figure 7 Time Constant at 0.1261 - 0.2238 ms from the end of pulse

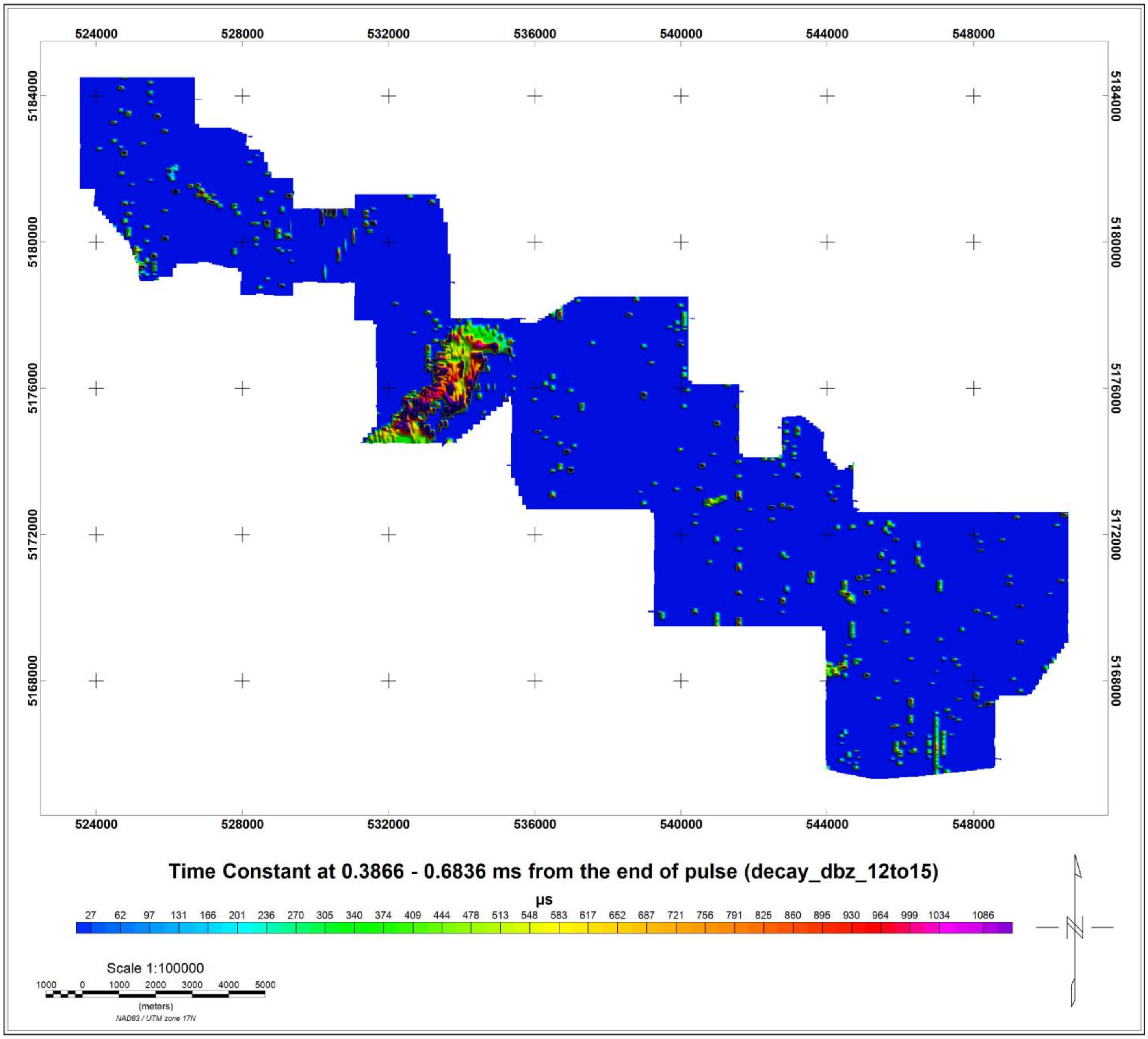


Figure 8 Time Constant at 0.3866 - 0.6836 ms from the end of pulse

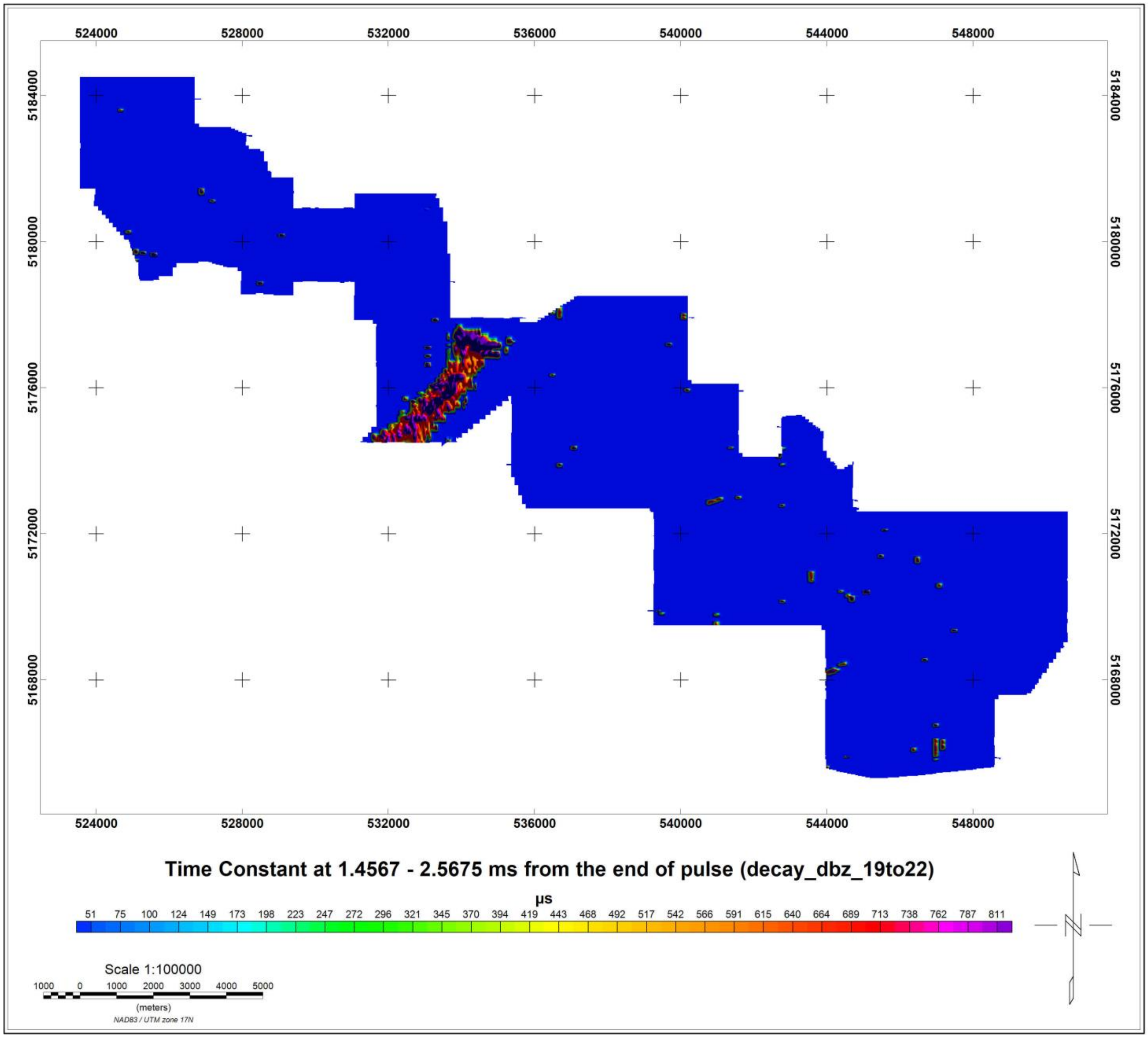


Figure 9 Time Constant at 1.4567 - 2.5675 ms from the end of pulse

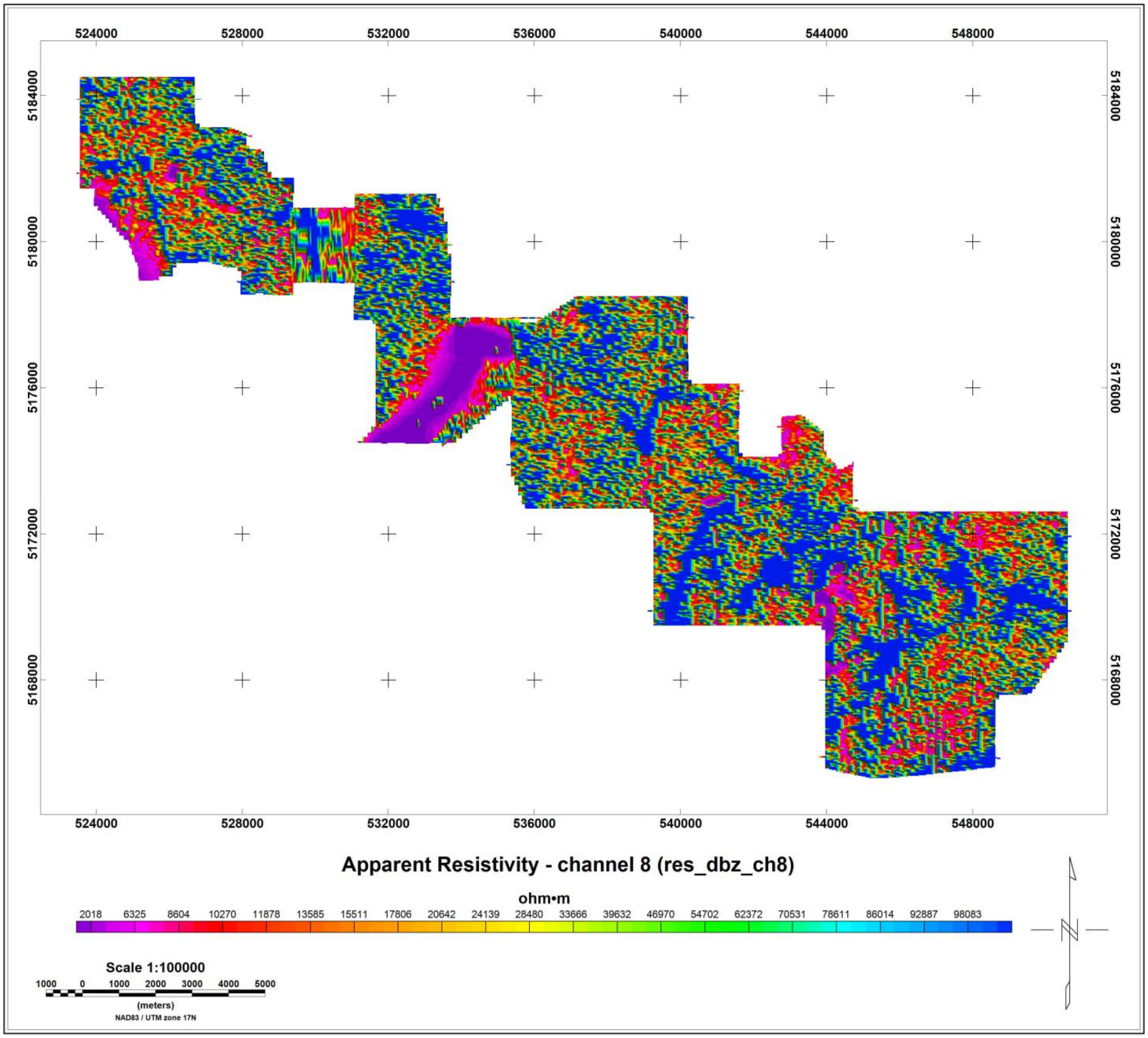


Figure 10 Apparent Resistivity - channel 8

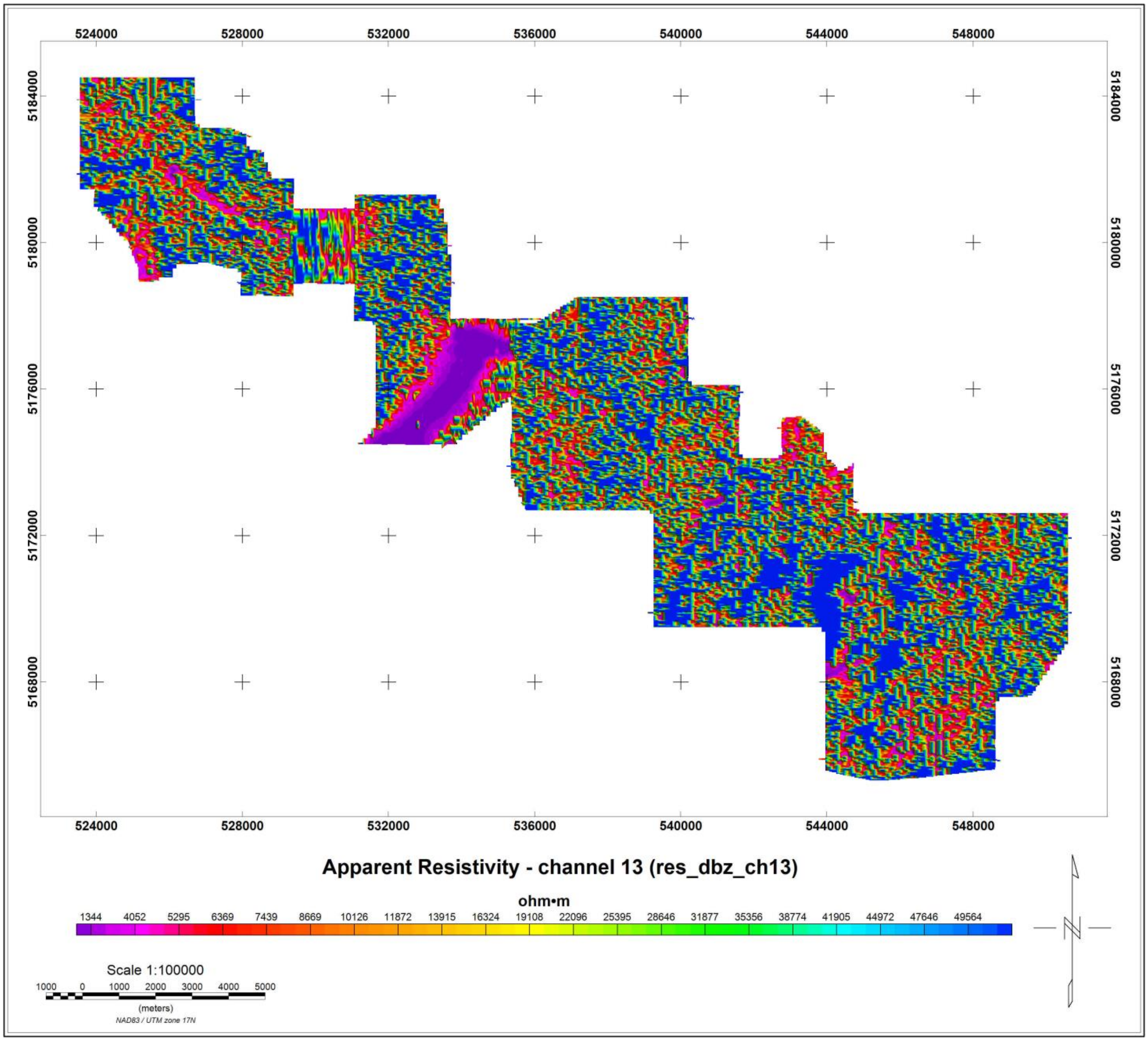


Figure 11 Apparent Resistivity - channel 13

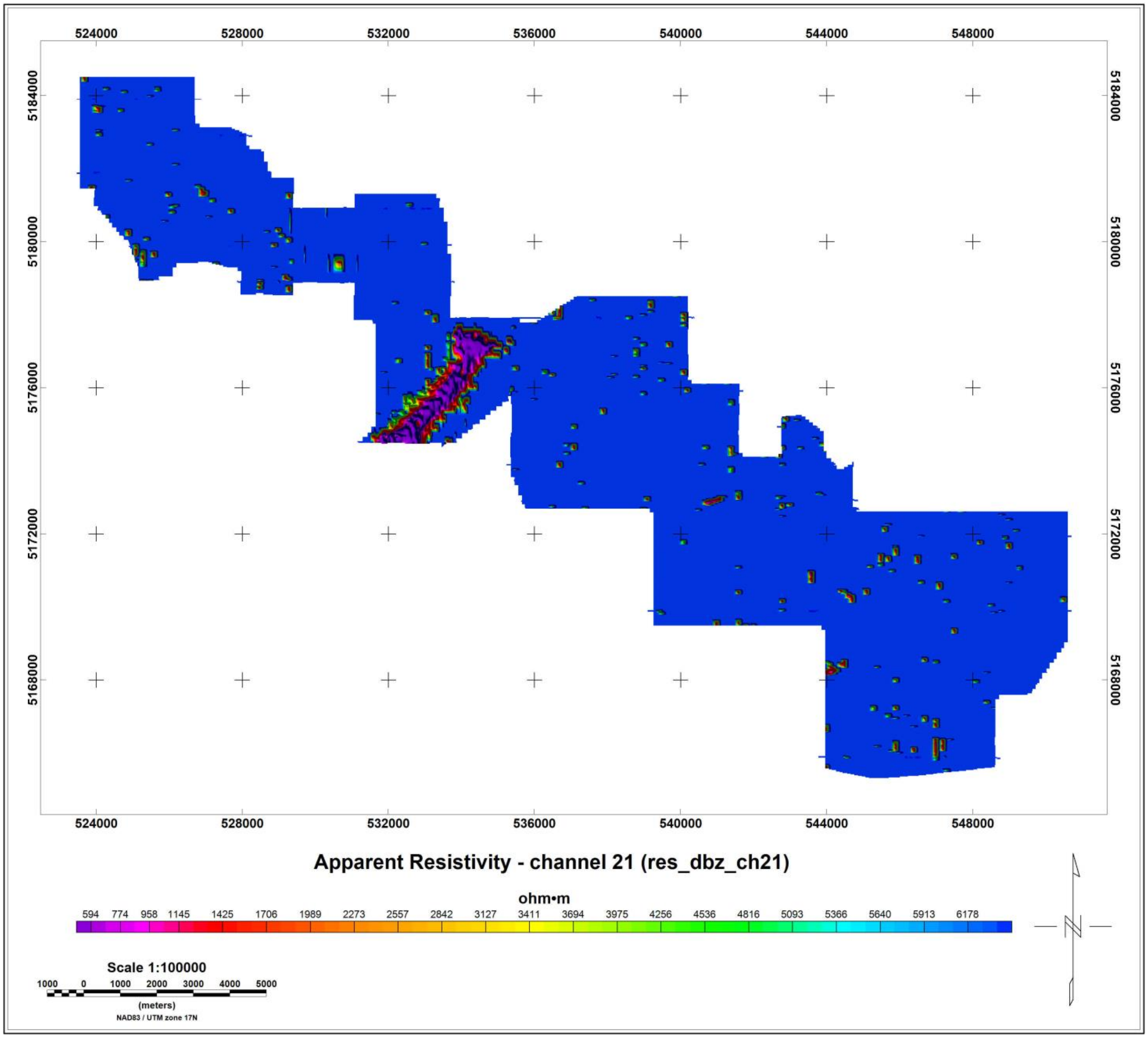


Figure 12 Apparent Resistivity - channel 21

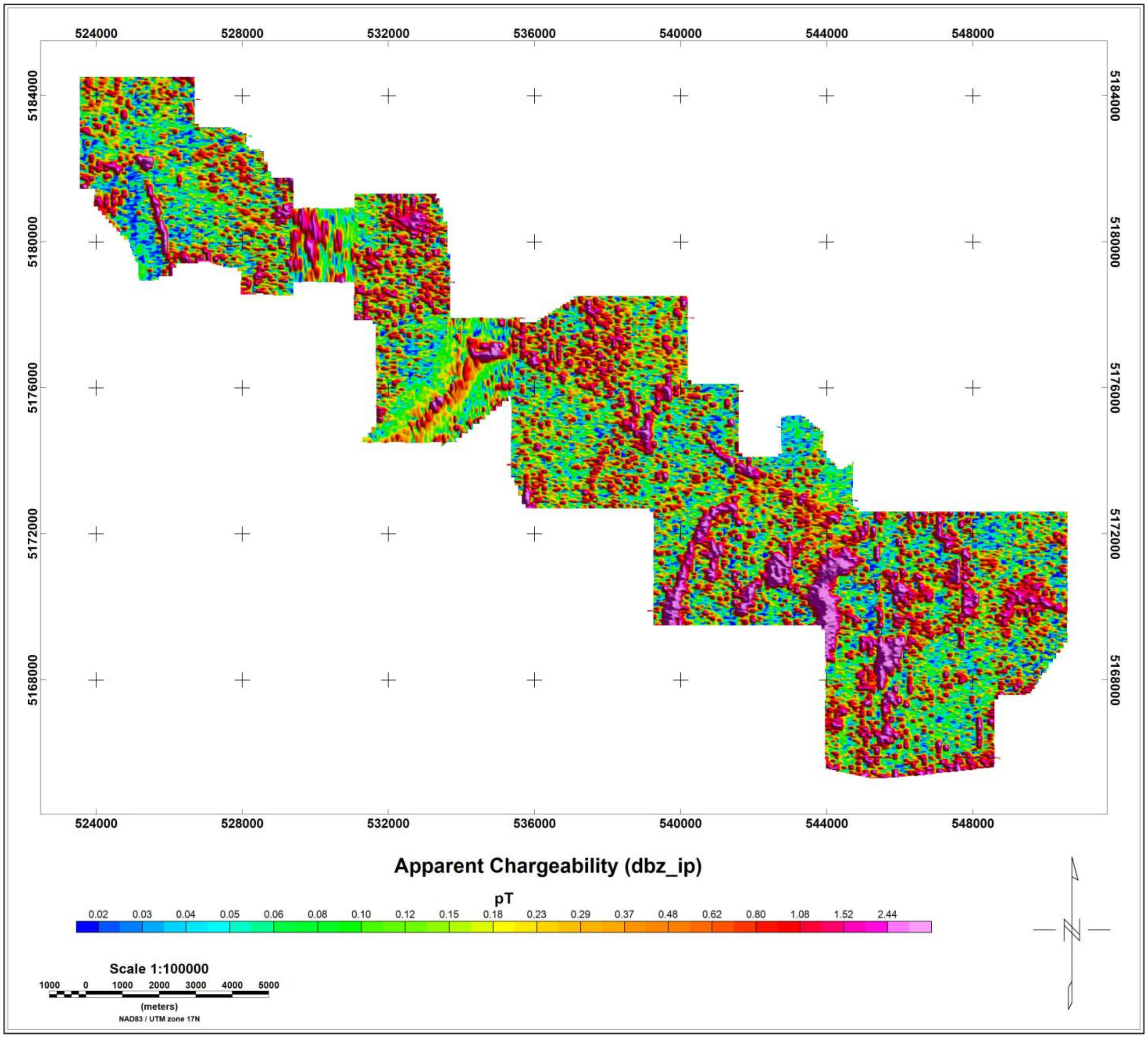


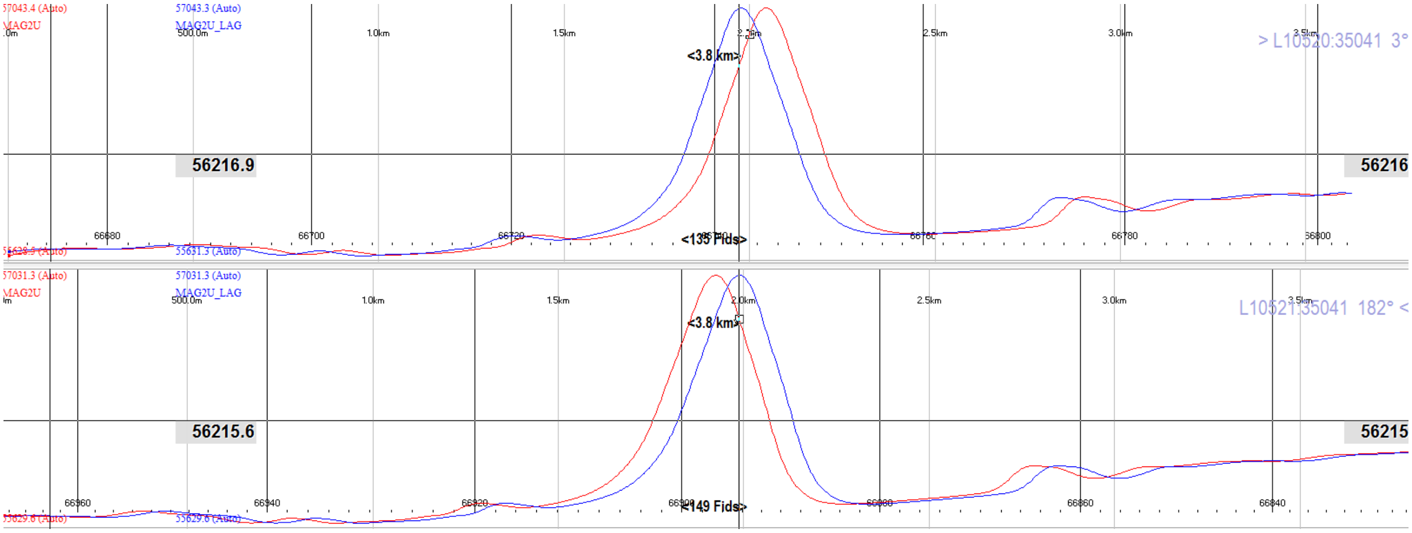
Figure 13 Apparent Chargeability

Appendix D Calibration and Tests

Magnetics Lag Test

Project Number:509527	**Survey Type:HTEM/MAGNETICS**
Date Flown:8 October, 2015	**Aircraft Registration:C-GZIK**
Flight Number:35041	**Location:Sudbury, Ontario**

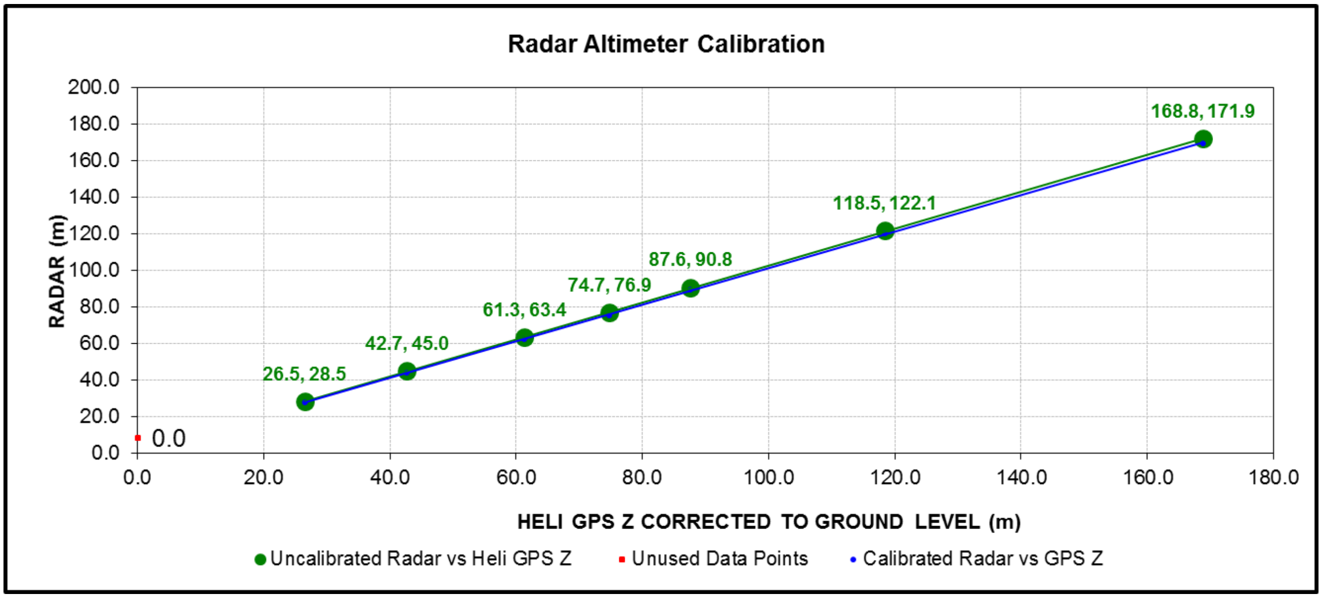
Correction Lag Applied: 2.4 (Test) and 2.8 (Processing) seconds

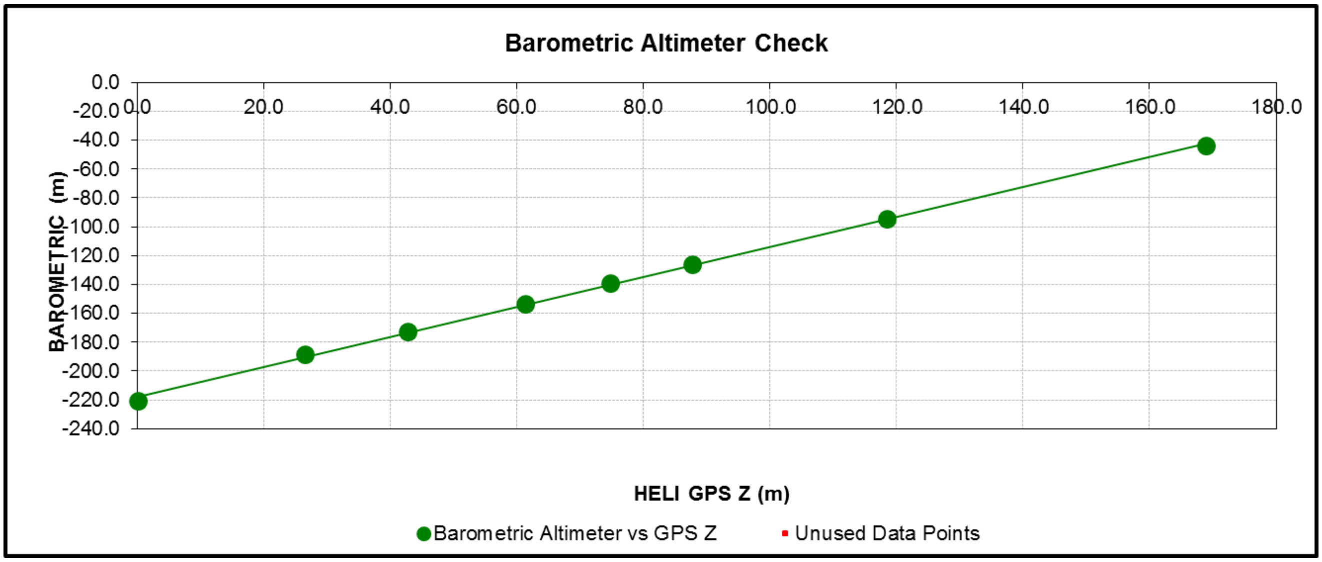


Project Number: 509527
Date Flown: 26 September
Flight Number: 35005

Survey Type: HTEM/MAGNETICS
Aircraft Registration: C-GZIK
Location: Sudbury, Ontario

LINE	TARGET RADAR (ft)	ZHG_HELI	ZHG_BIRD	ALTRAD_FT	ALTBAR_M
1	0	298.2		27.0	77.6
100	100	324.7		93.4	109.7
150	150	340.9		147.5	125.6
200	200	359.6		208.1	144.8
250	250	373.0		252.4	158.9
300	300	385.9		297.8	172.1
400	400	416.7		400.5	203.5
500	500	467.1		564.1	254.8




Barometric Altimeter Check
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
-120.0
-140.0
-160.0
-180.0
-200.0
-220.0
-240.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
BAROMETRIC (m)
HELI GPS Z (m)
● Barometric Altimeter vs GPS Z
▪ Unused Data Points

Appendix E Helicopter Airborne Electromagnetic Systems

HELICOPTER AIRBORNE ELECTROMAGNETIC SYSTEMS

General

The operation of a helicopter time-domain electromagnetic system (EM) involves the measurement of decaying secondary electromagnetic fields induced in the ground by a series of short current pulses generated from a towed transmitter. Variations in the decay characteristics of the secondary field (sampled and displayed as windows) are analyzed and interpreted to provide information about the subsurface geology.

A number of factors combine to give the helicopter platforms good signal-to-noise ratio, depth of penetration and excellent resolution: 1) the principle of sampling the induced secondary field in the absence of the primary field (during the “off-time”), 2) the large dipole moment 3) the low flying height of the system and spatial proximity of the transmitter and receiver. Such a system is also relatively insensitive to noise due to air turbulence. However, sampling in the “on-time” can also result in excellent sensitivity for mapping very resistive features and very conductive geologic features (Annan et al, 1991, Geophysics v.61, p. 93-99).

Methodology

The CGG time-domain helicopter electromagnetic system (HELITEM) uses a high-speed digital EM receiver. The primary electromagnetic pulses are created by a series of discontinuous sinusoidal current pulses fed into a two-turn transmitting loop towed below the helicopter. The base frequency rate is selectable, with 25, 30, 75 and 90 currently being available. The length of the pulse can be tailored to suit the targets. Standard pulse widths available are 2.0 and 4.0 ms. The available off-time can be selected to be as great as 16 ms. The dipole moment depends on the pulse width and base frequency used on the survey. The specific dipole moment, waveform and gate settings for this survey are given in the main body of the report.

The receiver sensor is a three-axis (x, y & z) induction coil set housed in a platform suspended on the tow cable below the helicopter and above the transmitter. The tow cable is non-magnetic to reduce noise levels. The tow cable is 51.9 m long. The receiver is 26.7 m above and 12.9 m ahead of the transmitter in flight.

For each primary pulse a secondary magnetic field is produced by decaying eddy currents in the ground. These in turn induce a voltage in the receiver coils, which is the electromagnetic response. Good conductors decay slowly, poorer conductors more rapidly.

Operations, which are carried out in the receiver, are:

1. *Primary-field removal:* In addition to measuring the secondary response from the ground, the receiver sensor coils also measure the primary response from the transmitter. During flight, the receiver sensor position and orientation changes slightly, and this has a very strong effect on the magnitude of the total response (primary plus secondary) measured at the receiver coils. The variable primary field response is distracting because it is unrelated to the ground response. The primary field is measured by flying at an altitude such that no ground response is measurable. These calibration signals are used to define the shape of the primary waveform. By definition this primary field includes the response of the current in the transmitter loop plus the response of any slowly decaying eddy currents induced in the helicopter. We assume that the shape of the primary will not change as the receiver sensor position changes, but that the amplitude will vary. The primary-field-removal procedure involves solving for the amplitude of the primary field in the measured response and removing this from the total response to leave a secondary response. Note that this procedure removes any “in-phase” response from the ground which has the same shape as the primary field.

2. *Digital Stacking:* Stacking is carried out to reduce the effect of broadband noise in the data.

3. *Windowing of data*: The digital receiver samples the secondary and primary electromagnetic field at 2048 points per EM pulse and windows the signal in up to 30 time gates whose centres and widths are software selectable and which may be placed anywhere within or outside the transmitter pulse. This flexibility offers the advantage of arranging the gates to suit the goals of a particular survey, ensuring that the signal is appropriately sampled through its entire dynamic range.

4. *Primary Field:* The primary field at the receiver sensor is measured for each stack and recorded as a separate data channel to assess the variation in coupling between the transmitter and the receiver sensor induced by changes in system geometry.

One of the major roles of the digital receiver is to provide diagnostic information on system functions and to allow for identification of noise events, such as sferics, which may be selectively removed from the EM signal. The high digital sampling rate yields maximum resolution of the secondary field.

System Hardware

The airborne EM system consists of the helicopter, the on-board hardware, and the software packages controlling the hardware.

Transmitter System

The transmitter system drives high-current pulses of an appropriate shape and duration through the coils towed below the helicopter.

System Timing Clock

This subsystem provides appropriate timing signals to the transmitter, and also to the analog-to-digital converter, in order to produce output pulses and capture the ground response. All systems are synchronized to GPS time.

Platform Systems

A three-axis induction coil sensor is mounted inside a platform on the tow cable. The platform is connected to the transmitter loop through a network of cables to ensure a more robust and better stability of the transmitter-receiver geometry. A magnetometer sensor is attached to the transmitter loop near its centre.

Power Line Monitor

The power line monitor gives the amplitude of the received signal at the power line frequency (50 or 60 Hz). Appropriate selection of the base frequency (such that the power line frequency is an even harmonic of the base frequency) and tapered stacking combine to strongly attenuate power line signals. When passing directly over a power line, the rapid lateral variations in the strength and direction of the magnetic fields associated with the power line can result in imperfect cancellation of the power line response during stacking. Some power line related interference can manifest itself in a form that is similar to the response of a discrete conductor. The exact form of the monitor profile over a power line depends on the flight line direction, power line direction, power line current, and receiver component, but the monitor will show a general increase in amplitude approaching the power line.

Grids (or images) of the power line monitor reveal the location of the transmission lines. Note that the X component (horizontal receiver coil axis parallel with the flight line direction) does not register any response from power lines parallel to the flight line direction since the magnetic fields associated with power lines only vary in a direction perpendicular to the power line. Note also that the Y component (horizontal receiver coil axis perpendicular to the flight line direction) is sensitive to power lines parallel to the flight direction.

Appendix F Airborne Transient EM Interpretation

Interpretation of transient electromagnetic data

Introduction

The basis of the transient electromagnetic (EM) geophysical surveying technique relies on the premise that changes in the primary EM field produced in the transmitting loop will result in eddy currents being generated in any conductors in the ground. The eddy currents then decay to produce a secondary EM field which may be sensed in the receiver coil.

The HELITEM airborne transient (or time-domain) EM system incorporates a high-speed digital receiver which records the secondary field response with a high degree of accuracy. Most often the earth's total magnetic field is recorded concurrently.

Although the approach to interpretation varies from one survey to another depending on the type of data presentation, objectives and local conditions, the following generalizations may provide the reader with some helpful background information.

The main purpose of the interpretation is to determine the probable origin of the responses detected during the survey and to suggest recommendations for further exploration. This is possible through an objective analysis of all characteristics of the different types of responses and associated magnetic anomalies, if any. If possible the airborne results are compared to other available data. Certitude is seldom reached, but a high probability is achieved in identifying the causes in most cases. One of the most difficult problems is usually the differentiation between surface conductor responses and bedrock conductor responses.

Types of Conductors

Bedrock Conductors

The different types of bedrock conductors normally encountered are the following:

1. *Graphites*. Graphitic horizons (including a large variety of carbonaceous rocks) occur in sedimentary formations of the Precambrian as well as in volcanic tuffs, often concentrated in shear zones. They correspond generally to long, multiple conductors lying in parallel bands. They have no magnetic expression unless associated with pyrrhotite or magnetite. Their conductivity is variable but generally high.

2. *Massive sulphides*. Massive sulphide deposits usually manifest themselves as short conductors of high conductivity, often with a coincident magnetic anomaly. Some massive sulphides, however, are not magnetic, others are not very conductive (discontinuous mineralization or sphalerite), and some may be located among formational conductors so that one must not be too rigid in applying the selection criteria.

   In addition, there are syngenetic sulphides whose conductive pattern may be similar to that of graphitic horizons but these are generally not as prevalent as graphites.

3. *Magnetite and some serpentinized ultrabasics*. These rocks are conductive and very magnetic.

4. *Manganese oxides*. This mineralization may give rise to a weak EM response.

Surficial Conductors

1. Beds of clay and alluvium, some swamps, and brackish ground water are usually poorly conductive to moderately conductive.

2. Lateritic formations, residual soils and the weathered layer of the bedrock may cause surface anomalous zones, the conductivity of which is generally low to medium but can occasionally be high. Their presence is often related to the underlying bedrock.

Cultural Conductors (Man-Made)

3. *Power lines*. These frequently, but not always, produce a conductive type of response. In the case when the radiated field is not removed by the power line comb filter, the anomalous response can exhibit phase changes between different windows. In the case of current induced by the EM system in a grounded wire, or steel pylon, the anomaly may look very much like a bedrock conductor.

4. *Grounded fences or pipelines*. These will invariably produce responses much like a bedrock conductor. Whenever they cannot be identified positively, a ground check is recommended.

5. *General culture*. Other localized sources such as certain buildings, bridges, irrigation systems, tailings ponds etc., may produce EM anomalies. Their instances, however, are rare and often they can be identified on the visual path recovery system.

Analysis of the Conductors

The rate of decay of a conductor is generally indicative of the conductivity of the anomalous material. However, the decay rate alone is not generally a decisive criterion in the analysis of a conductor. In particular, one should note:

- its shape and size,
- all local variations of characteristics within a conductive zone,
- any associated geophysical parameter (e.g. magnetism),
- the geological environment,
- the structural context, and
- the pattern of surrounding conductors.

The first objective of the interpretation is to classify each conductive zone according to one of the three categories which best defines its probable origin. The categories are cultural, surficial and bedrock. A second objective is to assign to each zone a priority rating as to its potential as an economic prospect.

Bedrock Conductors

This category comprises those anomalies which cannot be classified according to the criteria established for cultural and surficial responses. It is difficult to assign a universal set of values which typify bedrock conductivity because any individual zone or anomaly might exhibit some, but not all, of these values and still be a bedrock conductor. The following criteria are considered indicative of a bedrock conductor:

1. An intermediate to high conductivity identified by a response with slow decay, with an anomalous response present in the later windows.

2. For vertical conductors, the anomaly should be narrow, relatively symmetrical, with two well-defined z-component peaks and a null between the peaks.

3. If the conductor is thin, the response characteristics varies as a function of depth and dips. If the conductor is wider, the responses might look more similar to the sphere responses.

4. A small to intermediate amplitude. Large amplitudes are normally associated with surficial conductors. The amplitude varies according to the depth of the source.

5. A degree of continuity of the EM characteristics across several lines.

6. An associated magnetic response of similar dimensions. One should note, however, that those magnetic rocks which weather to produce a conductive upper layer will possess this magnetic association. In the absence of one or more of the characteristics defined in 1, 2, 3, 4 and 5, the related magnetic response cannot be considered significant.

Most obvious bedrock conductors occur in long, relatively monotonous, sometimes multiple zones following formational strike. Graphitic material is usually the most probable source. Massive syngenetic sulphides extending for many kilometres are known in nature but, in general, they are not common. Long formational structures associated with a strong magnetic expression may be indicative of banded iron formations.

In summary, a bedrock conductor reflecting the presence of a massive sulphide would normally exhibit the following characteristics:

- a high conductivity,
- an appropriate anomaly shape,
- a small to intermediate amplitude,
- an isolated setting,
- a short strike length (in general, not exceeding one kilometre), and
- preferably, with a localized magnetic anomaly of matching dimensions.

Surficial Conductors

This term is used for geological conductors in the overburden, either glacial or residual in origin, and in the weathered layer of the bedrock. Most surficial conductors are probably caused by clay minerals. In some environments the presence of salts will contribute to the conductivity. Other possible electrolytic conductors are residual soils, swamps, brackish ground water and alluvium such as lake or river-bottom deposits, flood plains and estuaries.

Normally, most surficial materials have low to intermediate conductivity so they are not easily mistaken for highly conductive bedrock features. Also, many of them are wide and their anomaly shapes are typical of broad horizontal sheets.

When surficial conductivity is high it is usually still possible to distinguish between a horizontal plate (more likely to be surficial material) and a vertical body (more likely to be a bedrock source) thanks to the characteristic shapes of the two anomalies and the differences in the x-component responses.

One of the more ambiguous situations as to the true source of the response is when surface conductivity is related to bedrock lithology as for example, surface alteration of an underlying bedrock unit. At times, it is also difficult to distinguish between a weak conductor within the bedrock (e.g. near-massive sulphides) and a surficial source.

In the search for massive sulphides or other bedrock targets, surficial conductivity is generally considered as interference but there are situations where the interpretation of surficial-type conductors is the primary goal. When soils, weathered or altered products are conductive, and in-situ, the responses are a very useful aid to geologic mapping. Shears and faults are often identified by weak, usually narrow, anomalies.

Analysis of surficial conductivity can be used in the exploration for such features as lignite deposits, kimberlites, paleochannels and ground water. In coastal or arid areas, surficial responses may serve to define the limits of fresh, brackish and salty water.

Cultural Conductors

The majority of cultural anomalies occur along roads and are accompanied by a response on the power line monitor. This monitor is set to 50 or 60 Hz, depending on the local power grid. In some cases, the current induced in the power line results in anomalies which could be mistaken for bedrock responses. There are also some power lines which have no response whatsoever.

The power line monitor, of course, is of great assistance in identifying cultural anomalies of this type. It is important to note, however, that geological conductors in the vicinity of power lines may exhibit a weak response on the monitor because of current induction via the earth.

Fences, pipelines, communication lines, railways and other man-made conductors can give rise to responses, the strength of which will depend on the grounding of these objects.

Another facet of this analysis is the line-to-line comparison of anomaly character along suspected man-made conductors. In general, the amplitude, the rate of decay, and the anomaly width should not vary a great deal along any one conductor, except for the change in amplitude related to terrain clearance variation. A marked departure from the average response character along any given feature gives rise to the possibility of a second conductor.

In most cases a visual examination of the site will suffice to verify the presence of a man-made conductor. If a second conductor is suspected the ground check is more difficult to accomplish. The object would be to determine if there is (i) a change in the man-made construction, (ii) a difference in the grounding conditions, (iii) a second cultural source, or (iv) if there is, indeed, a geological conductor in addition to the known man-made source.

The selection of targets from within extensive (formational) belts is much more difficult than in the case of isolated conductors. Local variations in the EM characteristics, such as in the amplitude, decay, shape etc., can be used as evidence for a relatively localized occurrence. Changes in the character of the EM responses, however, may be simply reflecting differences in the conductive formations themselves rather than indicating the presence of massive sulphides and, for this reason, the degree of confidence is reduced.

Another useful guide for identifying localized variations within formational conductors is to examine the magnetic data in map or image form. Further study of the magnetic data can reveal the presence of faults, contacts, and other features which, in turn, help define areas of potential economic interest.

Finally, once ground investigations begin, it must be remembered that the continual comparison of ground knowledge to the airborne information is an essential step in maximizing the usefulness of the airborne EM data.

Appendix G Multicomponent Modeling

Multicomponent helicopter airborne EM modelling

PLATE MODELING

The PLATE program has been used to generate synthetic responses over a number of plate models with 75 m of burial depth and varying dips (0, 45, 90 and 135 degrees). The geometry assumed for the HELITEM system is shown in Figure 14. In all cases the plate has a strike length of 200m, with a strike direction into the page. The width of the plate is 200m. As the flight path traverses the center of the plate, the Y component is zero and has not been plotted.

GPS position in the data archive is referenced to the helicopter tail, above the receiver. Modelling programs using the transmitter must be adjusted using the system geometry shown in Figure 14.

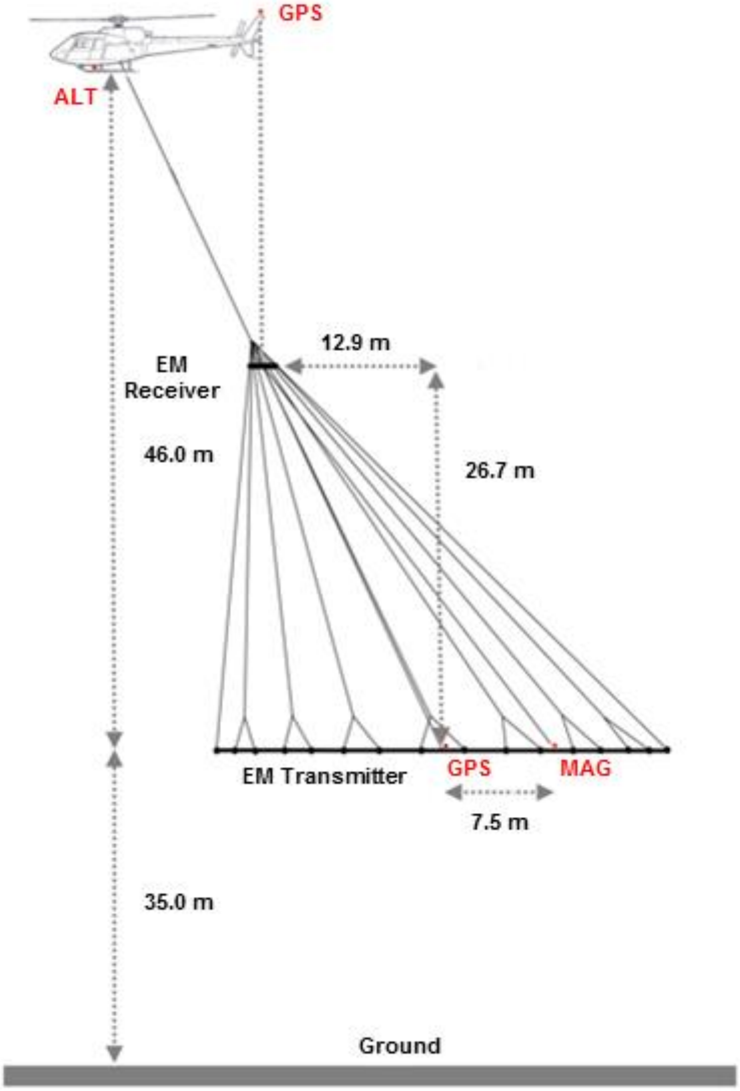


Figure 14 Geometry of the HELITEM System

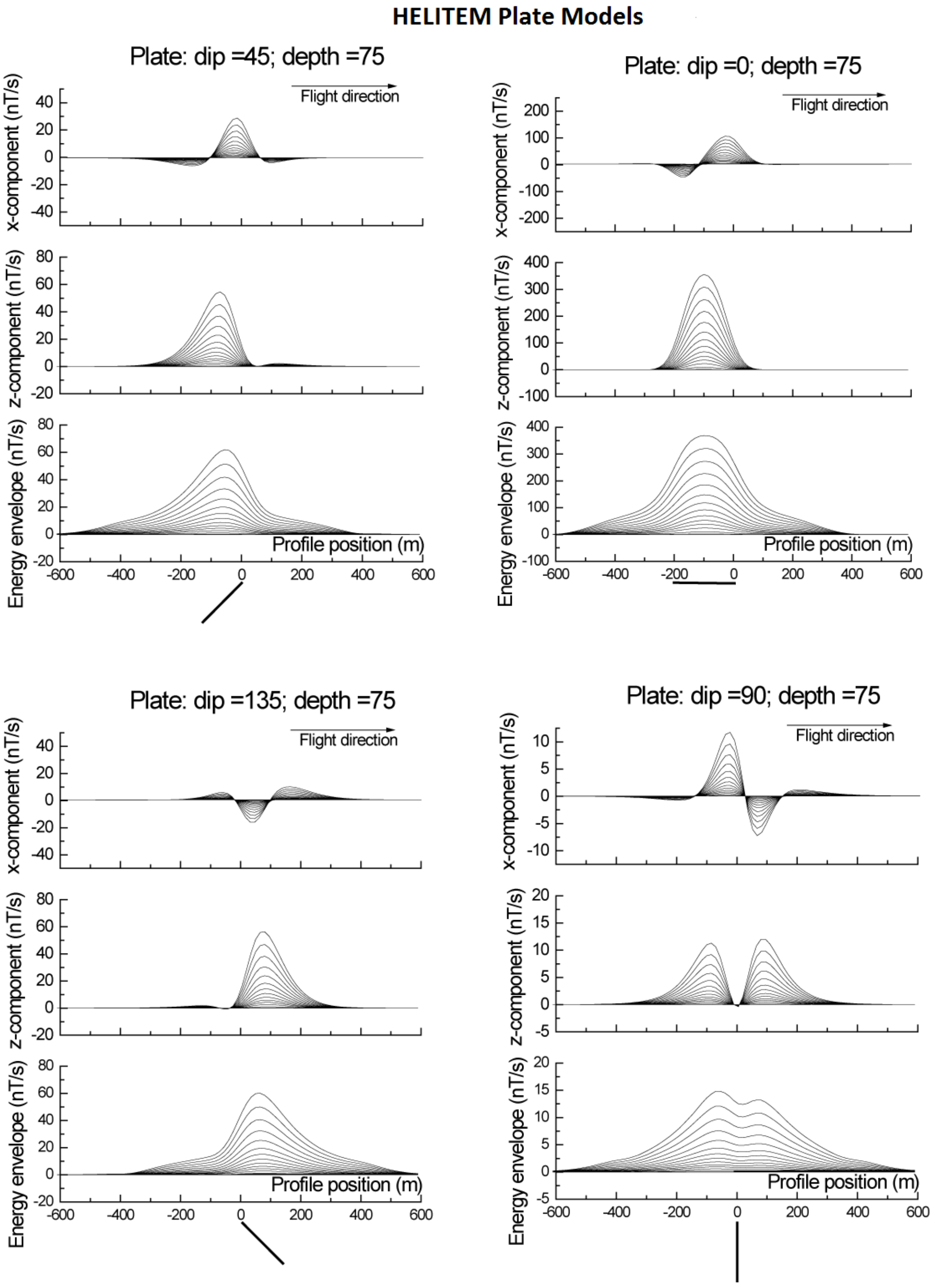


Figure 15 Plate model with a flying direction of left to right

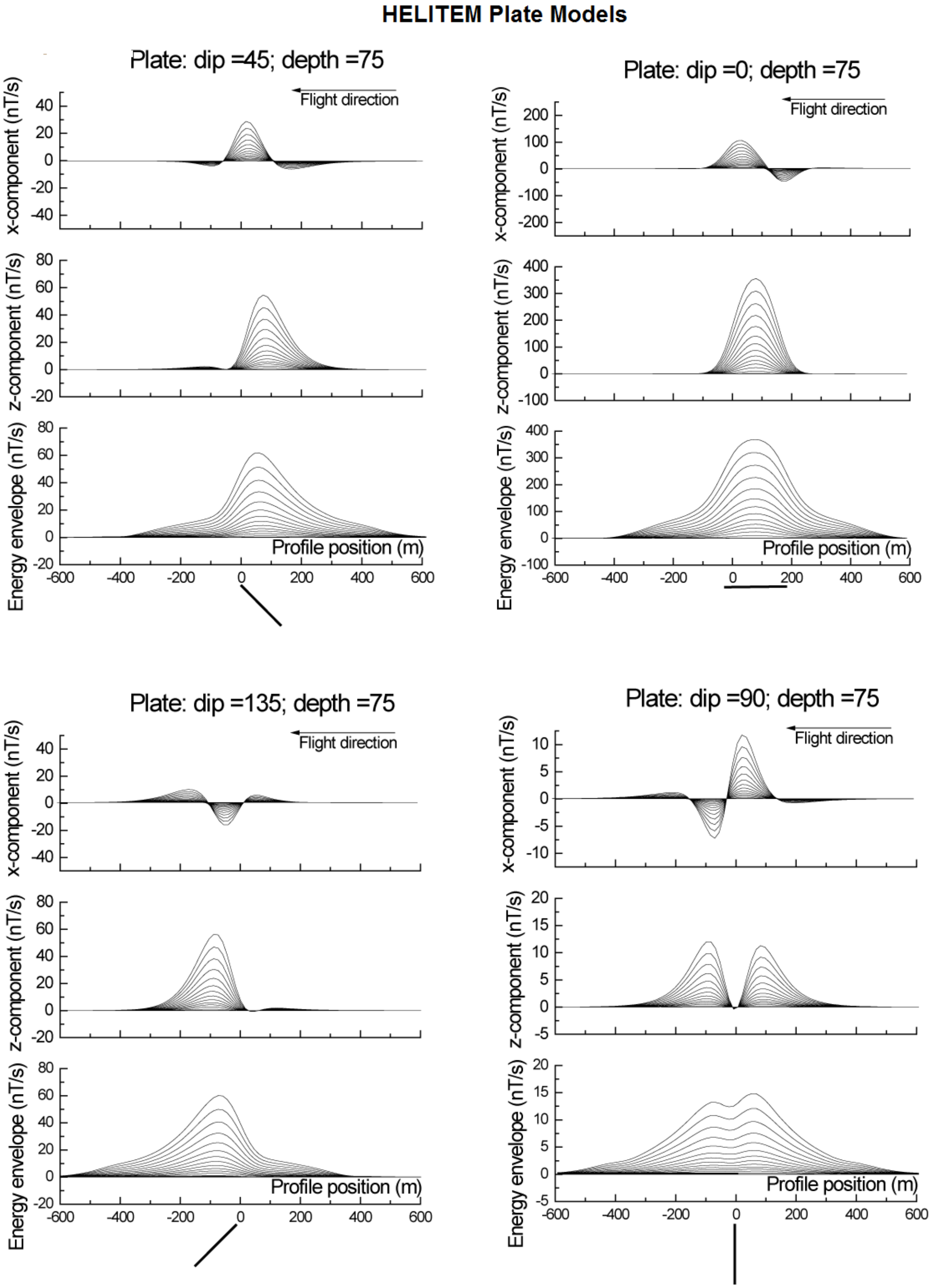


Figure 16 Plate model with flying direction from right to left

Appendix H Glossary

CGG GLOSSARY OF AIRBORNE GEOPHYSICAL TERMS

accelerometer: an instrument that measures both acceleration (due to motion) and acceleration due to ***gravity***.

altitude attenuation: the absorption of gamma rays by the atmosphere between the earth and the detector. The number of gamma rays detected by a system decreases as the altitude increases.

AGG: Airborne ***gravity gradiometer.***

AGS: Airborne ***gamma-ray spectrometry***.

amplitude: The strength of the total electromagnetic field. In ***frequency domain*** it is most often the sum of the squares of ***in-phase*** and ***quadrature*** components. In multi-component electromagnetic surveys it is generally the sum of the squares of all three directional components.

analytic signal: The total amplitude of all the directions of magnetic ***gradient***. Calculated as the sum of the squares.

anisotropy: Having different ***physical parameters*** in different directions. This can be caused by layering or fabric in the geology. Note that a unit can be anisotropic, but still **homogeneous**.

anomaly: A localized change in the geophysical data characteristic of a discrete source, such as a conductive or magnetic body: something locally different from the **background**.

apparent- : the ***physical parameters*** of the earth measured by a geophysical system are normally expressed as apparent, as in "apparent ***resistivity"***. This means that the measurement is limited by assumptions made about the geology in calculating the response measured by the geophysical system. Apparent resistivity calculated with ***HEM***, for example, generally assumes that the earth is a ***homogeneous half-space*** – not layered.

attitude: the orientation of a geophysical system relative to the earth. Some surveys assume the instrument attitudes are constant, and other surveys measure the attitude and correct the data for the changes in response because of attitude.

B-field: In time-domain **electromagnetic** surveys, the magnetic field component of the (electromagnetic) **field**. This can be measured directly, although more commonly it is calculated by integrating the time rate of change of the magnetic field **dB/dt**, as measured with a receiver coil.

background: The "normal" response in the geophysical data – that response observed over most of the survey area. **Anomalies** are usually measured relative to the background. In airborne gamma-ray spectrometric surveys the term defines the **cosmic**, radon, and aircraft responses in the absence of a signal from the ground.

base-level: The measured values in a geophysical system in the absence of any outside signal. All geophysical data are measured relative to the system base level.

base frequency: The frequency of the pulse repetition for a ***time-domain electromagnetic*** system. Measured between subsequent positive pulses.

base magnetometer: A stationary magnetometer used to record the ***diurnal*** variations in the earth's magnetic field; to be used to correct the survey magnetic data.

bird: A common name for the pod towed beneath or behind an aircraft, carrying the geophysical sensor array.

bucking: The process of removing the strong ***signal*** from the ***primary field*** at the ***receiver*** from the data, to measure the ***secondary field***. It can be done electronically or mathematically. This is done in ***frequency-domain EM***, and to measure ***on-time*** in ***time-domain EM***.

calibration: a procedure to ensure a geophysical instrument is measuring accurately and repeatably. Most often applied in ***EM*** and ***gamma-ray spectrometry***.

calibration coil: A wire coil of known size and dipole moment, which is used to generate a field of known ***amplitude*** and ***phase*** or ***decay constant*** in the receiver, for system calibration. Calibration coils can be external, or internal to the system. Internal coils may be called Q-coils.

coaxial coils: **[CX]** Coaxial coils in an HEM system are in the vertical plane, with their axes horizontal and collinear in the flight direction. These are most sensitive to vertical conductive objects in the ground, such as thin, steeply dipping conductors perpendicular to the flight direction. Coaxial coils generally give the sharpest anomalies over localized conductors. (See also ***coplanar coils***)

coil: A multi-turn wire loop used to transmit or detect electromagnetic fields. Time varying ***electromagnetic*** fields through a coil induce a voltage proportional to the strength of the field and the rate of change over time.

compensation: Correction of airborne geophysical data for the changing effect of the aircraft. This process is generally used to correct data in ***fixed-wing time-domain electromagnetic*** surveys (where the transmitter is on the aircraft and the receiver is moving), and magnetic surveys (where the sensor is on the aircraft, turning in the earth's magnetic field.

component: In ***frequency domain electromagnetic*** surveys this is one of the two **phase** measurements – ***in-phase or quadrature***. In "multi-component" electromagnetic surveys it is also used to define the measurement in one geometric direction (vertical, horizontal in-line and horizontal transverse – the Z, X and Y components).

Compton scattering: gamma ray photons will bounce off electrons as they pass through the earth and atmosphere, reducing their energy and then being detected by ***radiometric*** sensors at lower energy levels. See also ***stripping***.

conductance: See ***conductivity thickness***

conductivity: [σ] The facility with which the earth or a geological formation conducts electricity. Conductivity is usually measured in milli-Siemens per metre (mS/m). It is the reciprocal of ***resistivity***.

conductivity-depth imaging: see ***conductivity-depth transform***.

conductivity-depth transform: A process for converting electromagnetic measurements to an approximation of the conductivity distribution vertically in the earth, assuming a ***layered earth***. (Macnae and Lamontagne, 1987; Wolfgram and Karlik, 1995)

conductivity thickness: [σt] The product of the ***conductivity***, and thickness of a large, tabular body. (It is also called the "conductivity-thickness product") In electromagnetic geophysics, the response of a thin plate-like conductor is proportional to the conductivity multiplied by thickness. For example a 10 metre thickness of 20 Siemens/m mineralization will be equivalent to 5 metres of 40 S/m; both have 200 S conductivity thickness. Sometimes referred to as conductance.

conductor: Used to describe anything in the ground more conductive than the surrounding geology. Conductors are most often clays or graphite, or hopefully some type of mineralization, but may also be man-made objects, such as fences or pipelines.

continuation: mathematical procedure applied to ***potential field*** geophysical data to approximate data collected at a different altitude. Data can be continued upward to a higher altitude or downward to a lower altitude.

coplanar coils: **[CP]** In HEM, the coplanar coils lie in the horizontal plane with their axes vertical, and parallel. These coils are most sensitive to massive conductive bodies, horizontal layers, and the ***halfspace***.

cosmic ray: High energy sub-atomic particles from outer space that collide with the earth's atmosphere to produce a shower of gamma rays (and other particles) at high energies.

counts (per second): The number of ***gamma-rays*** detected by a gamma-ray ***spectrometer*.** The rate depends on the geology, but also on the size and sensitivity of the detector.

culture: A term commonly used to denote any man-made object that creates a geophysical anomaly. Includes, but not limited to, power lines, pipelines, fences, and buildings.

current channelling: See current gathering.

current gathering: The tendency of electrical currents in the ground to channel into a conductive formation. This is particularly noticeable at higher frequencies or early time channels when the formation is long and parallel to the direction of current flow. This tends to enhance anomalies relative to inductive currents (see also ***induction***). Also known as current channelling.

daughter products: The radioactive natural sources of gamma-rays decay from the original "parent" element (commonly potassium, uranium, and thorium) to one or more lower-energy "daughter" elements. Some of these lower energy elements are also radioactive and decay further. ***Gamma-ray spectrometry*** surveys may measure the gamma rays given off by the original element or by the decay of the daughter products.

dB/dt: As the ***secondary electromagnetic field*** changes with time, the magnetic field [**B**] component induces a voltage in the receiving ***coil***, which is proportional to the rate of change of the magnetic field over time.

decay: In ***time-domain electromagnetic*** theory, the weakening over time of the ***eddy currents*** in the ground, and hence the ***secondary field*** after the ***primary field*** electromagnetic pulse is turned off. In ***gamma-ray spectrometry***, the radioactive breakdown of an element, generally potassium, uranium, thorium, into their ***daughter*** products.

decay constant: see time constant.

decay series: In ***gamma-ray spectrometry***, a series of progressively lower energy ***daughter products*** produced by the radioactive breakdown of uranium or thorium.

depth of exploration: The maximum depth at which the geophysical system can detect the target. The depth of exploration depends very strongly on the type and size of the target, the contrast of the target with the surrounding geology, the homogeneity of the surrounding geology, and the type of geophysical system. One measure of the maximum depth of exploration for an electromagnetic system is the depth at which it can detect the strongest conductive target – generally a highly conductive horizontal layer.

differential resistivity: A process of transforming ***apparent resistivity*** to an approximation of layer resistivity at each depth. The method uses multi-frequency HEM data and approximates the effect of shallow layer ***conductance*** determined from higher frequencies to estimate the deeper conductivities (Huang and Fraser, 1996)

dipole moment: [NIA] For a transmitter, the product of the area of a ***coil***, the number of turns of wire, and the current flowing in the coil. At a distance significantly larger than the size of the coil, the magnetic field from a coil will be the same if the dipole moment product is the same. For a receiver coil, this is the product of the area and the number of turns. The sensitivity to a magnetic field (assuming the source is far away) will be the same if the dipole moment is the same.

diurnal: The daily variation in a natural field, normally used to describe the natural fluctuations (over hours and days) of the earth's magnetic field.

dielectric permittivity: **[ε]** The capacity of a material to store electrical charge, this is most often measured as the relative permittivity [ε_r], or ratio of the material dielectric to that of free space. The effect of high permittivity may be seen in HEM data at high frequencies over highly resistive geology as a reduced or negative ***in-phase***, and higher ***quadrature*** data.

dose rate: see **exposure rate**.

drape: To fly a survey following the terrain contours, maintaining a constant altitude above the local ground surface. Also applied to re-processing data collected at varying altitudes above ground to simulate a survey flown at constant altitude.

drift: Long-time variations in the base-level or calibration of an instrument.

eddy currents: The electrical currents induced in the ground, or other conductors, by a time-varying ***electromagnetic field*** (usually the ***primary field***). Eddy currents are also induced in the aircraft's metal frame and skin; a source of ***noise*** in EM surveys.

electromagnetic: **[EM]** Comprised of a time-varying electrical and magnetic field. Radio waves are common electromagnetic fields. In geophysics, an electromagnetic system is one which transmits a time-varying ***primary field*** to induce ***eddy currents*** in the ground, and then measures the ***secondary field*** emitted by those eddy currents.

energy window: A broad spectrum of ***gamma-ray*** energies measured by a spectrometric survey. The energy of each gamma-ray is measured and divided up into numerous discrete energy levels, called windows.

equivalent (thorium or uranium): The amount of radioelement calculated to be present, based on the gamma-rays measured from a **daughter** element. This assumes that the ***decay series*** is in equilibrium – progressing normally.

exposure rate: in radiometric surveys, a calculation of the total exposure rate due to gamma rays at the ground surface. It is used as a measurement of the concentration of all the **radioelements** at the surface. Sometimes called "dose rate".See also: **natural exposure rate**.

fiducial, or fid: Timing mark on a survey record. Originally these were timing marks on a profile or film; now the term is generally used to describe 1-second interval timing records in digital data, and on maps or profiles.

Figure of Merit: **(FOM)** A sum of the 12 distinct magnetic noise variations measured by each of four flight directions, and executing three aircraft attitude variations (yaw, pitch, and roll) for each direction. The flight directions are generally parallel and perpendicular to planned survey flight directions. The FOM is used as a measure of the **manoeuvre noise** before and after **compensation.**

fixed-wing: Aircraft with wings, as opposed to "rotary wing" helicopters.

flight: a continuous interval of survey data collection, generally between stops at base to refuel.

flight-line: a single line of data across the survey area. Surveys are generally comprised of many parallel flight lines to cover the survey area, with wider-spaced ***tie lines*** perpendicular. Flight lines are generally separated by ***turn-arounds*** when the aircraft is outside the survey area.

footprint: This is a measure of the area of sensitivity under the aircraft of an airborne geophysical system. The footprint of an ***electromagnetic*** system is dependent on the altitude of the system, the orientation of the transmitter and receiver and the separation between the receiver and transmitter, and the conductivity of the ground. The footprint of a ***gamma-ray spectrometer*** depends mostly on the altitude. For all geophysical systems, the footprint also depends on the strength of the contrasting ***anomaly***.

frequency domain: An ***electromagnetic*** system which transmits a harmonic ***primary field*** that oscillates over time (e.g. sinusoidal), inducing a similarly varying electrical current in the ground. These systems generally measure the changes in the ***amplitude*** and ***phase*** of the ***secondary field*** from the ground at different frequencies by measuring the **in-phase** and **quadrature** phase components. See also ***time-domain***.

full-stream data: Data collected and recorded continuously at the highest possible sampling rate. Normal data are stacked (see ***stacking***) over some time interval before recording.

gamma-ray: A very high-energy photon, emitted from the nucleus of an atom as it undergoes a change in energy levels.

gamma-ray spectrometry: Measurement of the number and energy of natural (and sometimes man-made) gamma-rays across a range of photon energies.

GGI: gravity gradiometer instrument. An airborne gravity gradiometer (AGG) consists of a GGI mounted in an inertial platform together with a temperature control system.

gradient: In magnetic surveys, the gradient is the change of the magnetic field over a distance, either vertically or horizontally in either of two directions. Gradient data can be measured, or calculated from the total magnetic field data because it changes more quickly over distance than the ***total magnetic field***, and so may provide a more precise measure of the location of a source. See also ***analytic signal***.

gradiometer, gradiometry: instrument and measurement of the gradient, or change in a field with location usually for ***gravity*** or ***magnetic*** surveys. Used to provide higher resolution of ***targets***, better ***interpretation*** of ***target*** geometry, independence from drift and absolute field and, for ***gravity***, accelerations of the aircraft.

gravity: Survey collecting measurements of the earth's gravitational field strength. Denser objects in the earth create stronger gravitational pull above them.

ground effect: The response from the earth. A common ***calibration*** procedure in many geophysical surveys is to fly to altitude high enough to be beyond any measurable response from the ground, and there establish ***base levels*** or ***backgrounds***.

half-space: A mathematical model used to describe the earth – as infinite in width, length, and depth below the surface. The most common halfspace models are ***homogeneous*** and ***layered earth***.

heading error: A slight change in the magnetic field measured when flying in opposite directions.

HEM: Helicopter ElectroMagnetic, This designation is most commonly used for helicopter-borne, ***frequency-domain*** electromagnetic systems. At present, the transmitter and receivers are normally mounted in a ***bird*** carried on a sling line beneath the helicopter.

herringbone pattern: A pattern created in geophysical data by an asymmetric system, where the **anomaly** may be extended to either side of the source, in the direction of flight. Appears like fish bones, or like the teeth of a comb, extending either side of centre, each tooth an alternate flight line.

homogeneous: This is a geological unit that has the same ***physical parameters*** throughout its volume. This unit will create the same response to an HEM system anywhere, and the HEM system will measure the same apparent ***resistivity*** anywhere. The response may change with system direction (see ***anisotropy***).

HFEM: Helicopter Frequency-domain ElectroMagnetic, This designation is used for helicopter-borne, **frequency-*domain*** electromagnetic systems. Formerly most often called HEM.

HTEM: Helicopter Time-domain ElectroMagnetic, This designation is used for the new generation of helicopter-borne, ***time-domain*** electromagnetic systems.

in-phase: the component of the measured ***secondary field*** that has the same phase as the transmitter and the ***primary field***. The in-phase component is stronger than the ***quadrature*** phase over relatively higher ***conductivity***.

induction: Any time-varying electromagnetic field will induce (cause) electrical currents to flow in any object with non-zero ***conductivity***. (see ***eddy currents***)

induction number: also called the "response parameter", this number combines many of the most significant parameters affecting the ***EM*** response into one parameter against which to compare responses. For a ***layered earth*** the response parameter is $\mu\omega\sigma h^2$ and for a large, flat, ***conductor*** it is $\mu\omega\sigma th$, where μ is the ***magnetic permeability***, ω is the angular ***frequency***, σ is the **conductivity**, t is the thickness (for the flat conductor) and h is the height of the system above the conductor.

inductive limit: When the frequency of an EM system is very high, or the **conductivity** of the target is very high, the response measured will be entirely **in-phase** with no **quadrature** (**phase** angle =0). The in-phase response will remain constant with further increase in conductivity or frequency. The system can no longer detect changes in conductivity of the target.

infinite: In geophysical terms, an "infinite' dimension is one much greater than the ***footprint*** of the system, so that the system does not detect changes at the edges of the object.

International Geomagnetic Reference Field: **[IGRF]** An approximation of the smooth magnetic field of the earth, in the absence of variations due to local geology. Once the IGRF is subtracted from the measured magnetic total field data, any remaining variations are assumed to be due to local geology. The IGRF also predicts the slow changes of the field up to five years in the future.

inversion, or **inverse modeling**: A process of converting geophysical data to an earth model, which compares theoretical models of the response of the earth to the data measured, and refines the model until the response closely fits the measured data (Huang and Palacky, 1991)

layered earth: A common geophysical model which assumes that the earth is horizontally layered – the ***physical parameters*** are constant to ***infinite*** distance horizontally, but change vertically.

lead-in: approach to a ***flight line*** outside of survey area to establish proper track and stabilize instrumentations. The lead-in for a helicopter survey is generally shorter than required for fixed-wing.

line source, or line current: a long narrow object that creates an ***anomaly*** on an ***EM*** survey. Generally man-made objects like fences, power lines, and pipelines (***culture***).

mag: common abbreviation for ***magnetic.***

magnetic: ("**mag**") a survey measuring the strength of the earth's magnetic field, to identify geology and targets by their effect on the field.

magnetic permeability: **[μ]** This is defined as the ratio of magnetic induction to the inducing magnetic field. The relative magnetic permeability [μ_r] is often quoted, which is the ratio of the rock permeability to the permeability of free space. In geology and geophysics, the ***magnetic susceptibility*** is more commonly used to describe rocks.

magnetic susceptibility: **[k]** A measure of the degree to which a body is magnetized. In SI units this is related to relative ***magnetic permeability*** by $k=\mu_r-1$, and is a dimensionless unit. For most geological material, susceptibility is influenced primarily by the percentage of magnetite. It is most often quoted in units of 10^{-6}. In HEM data this is most often apparent as a negative ***in-phase*** component over high susceptibility, high ***resistivity*** geology such as diabase dikes.

manoeuvre noise: variations in the magnetic field measured caused by changes in the relative positions of the magnetic sensor and magnetic objects or electrical currents in the aircraft. This type of noise is generally corrected by magnetic **compensation**.

model: Geophysical theory and applications generally have to assume that the geology of the earth has a form that can be easily defined mathematically, called the model. For example steeply dipping **conductor**s are generally modeled as being **infinite** in horizontal and depth extent, and very thin. The earth is generally modeled as horizontally layered, each layer infinite in extent and uniform in characteristic. These models make the mathematics to describe the response of the (normally very complex) earth practical. As theory advances, and computers become more powerful, the useful models can become more complex.

natural exposure rate: in radiometric surveys, a calculation of the total exposure rate due to natural-source gamma rays at the ground surface. It is used as a measurement of the concentration of all the natural **radioelements** at the surface. See also: **exposure rate**.

natural source: any geophysical technique for which the source of the energy is from nature, not from a man-made object. Most commonly applied to natural source ***electromagnetic*** surveys.

noise: That part of a geophysical measurement that the user does not want. Typically this includes electronic interference from the system, the atmosphere (***sferics***), and man-made sources. This can be a subjective judgment, as it may include the response from geology other than the target of interest. Commonly the term is used to refer to high frequency (short period) interference. See also ***drift***.

Occam's inversion: an ***inversion*** process that matches the measured ***electromagnetic*** data to a theoretical model of many, thin layers with constant thickness and varying resistivity (Constable et al, 1987).

off-time: In a ***time-domain electromagnetic*** survey, the time after the end of the ***primary field pulse***, and before the start of the next pulse.

on-time: In a ***time-domain electromagnetic*** survey, the time during the ***primary field pulse***.

overburden: In engineering and mineral exploration terms, this most often means the soil on top of the unweathered bedrock. It may be sand, glacial till, or weathered rock.

Phase, phase angle: The angular difference in time between a measured sinusoidal electromagnetic field and a reference – normally the primary field. The phase is calculated from tan^{-1}(***in-phase / quadrature***).

physical parameters: These are the characteristics of a geological unit. For electromagnetic surveys, the important parameters are ***conductivity, magnetic permeability*** (or ***susceptibility***) and ***dielectric permittivity***; for magnetic surveys the parameter is magnetic susceptibility, and for gamma ray spectrometric surveys it is the concentration of the major radioactive elements: potassium, uranium, and thorium.

permittivity: see ***dielectric permittivity***.

permeability: see ***magnetic permeability***.

potential field: A field that obeys Laplace's Equation. Most commonly used to describe ***gravity*** and ***magnetic*** measurements.

primary field: the EM field emitted by a transmitter. This field induces ***eddy currents*** in (energizes) the conductors in the ground, which then create their own ***secondary*** **fields**.

pulse: In time-domain EM surveys, the short period of intense ***primary*** field transmission. Most measurements (the ***off-time***) are measured after the pulse. **On-time** measurements may be made during the pulse.

quadrature: that component of the measured ***secondary field*** that is phase-shifted 90° from the ***primary field***. The quadrature component tends to be stronger than the ***in-phase*** over relatively weaker ***conductivity***.

Q-coils: see ***calibration coil***.

radioelements: This normally refers to the common, naturally-occurring radioactive elements: potassium (K), uranium (U), and thorium (Th). It can also refer to man-made radioelements, most often cobalt (Co) and cesium (Cs)

radiometric: Commonly used to refer to ***gamma ray*** spectrometry.

radon: A radioactive daughter product of uranium and thorium, radon is a gas which can leak into the atmosphere, adding to the non-geological background of a gamma-ray spectrometric survey.

receiver: the ***signal*** detector of a geophysical system. This term is most often used in active geophysical systems – systems that transmit some kind of signal. In airborne ***electromagnetic*** surveys it is most often a ***coil***. (see also, ***transmitter***)

resistivity: **[ρ]** The strength with which the earth or a geological formation resists the flow of electricity, typically the flow induced by the ***primary field*** of the electromagnetic transmitter. Normally expressed in ohm-metres, it is the reciprocal of ***conductivity***.

resistivity-depth transforms: similar to ***conductivity depth transforms***, but the calculated ***conductivity*** has been converted to ***resistivity***.

resistivity section: an approximate vertical section of the resistivity of the layers in the earth. The resistivities can be derived from the ***apparent resistivity***, the ***differential resistivities***, ***resistivity-depth transforms***, or ***inversions***.

response parameter: another name for the **induction number**.

secondary field: The field created by conductors in the ground, as a result of electrical currents induced by the ***primary field*** from the ***electromagnetic*** transmitter. Airborne ***electromagnetic*** systems are designed to create and measure a secondary field.

Sengpiel section: a ***resistivity section*** derived using the ***apparent resistivity*** and an approximation of the depth of maximum sensitivity for each frequency.

sferic: Lightning, or the ***electromagnetic*** signal from lightning, it is an abbreviation of "atmospheric discharge". These appear to magnetic and electromagnetic sensors as sharp "spikes" in the data. Under some conditions lightning storms can be detected from hundreds of kilometres away. (see ***noise***)

signal: That component of a measurement that the user wants to see – the response from the targets, from the earth, etc. (See also ***noise***)

skin depth: A measure of the depth of penetration of an electromagnetic field into a material. It is defined as the depth at which the primary field decreases to 1/e of the field at the surface. It is calculated by approximately 503 x √(resistivity/frequency). Note that depth of penetration is greater at higher ***resistivity*** and/or lower ***frequency***.

spec: common abbreviation for *gamma-ray spectrometry*.

spectrometry: Measurement across a range of energies, where ***amplitude*** and energy are defined for each measurement. In gamma-ray spectrometry, the number of gamma rays are measured for each energy ***window***, to define the ***spectrum***.

spectrum: In ***gamma ray spectrometry***, the continuous range of energy over which gamma rays are measured. In ***time-domain electromagnetic*** surveys, the spectrum is the energy of the **pulse** distributed across an equivalent, continuous range of frequencies.

spheric: see ***sferic***.

stacking: Summing repeat measurements over time to enhance the repeating ***signal***, and minimize the random ***noise***.

stinger: A boom mounted on an aircraft to carry a geophysical sensor (usually ***magnetic***). The boom moves the sensor farther from the aircraft, which might otherwise be a source of ***noise*** in the survey data.

stripping: Estimation and correction for the gamma ray photons of higher and lower energy that are observed in a particular ***energy window***. See also ***Compton scattering***.

susceptibility: See ***magnetic susceptibility***.
tau: [τ] Often used as a name for the ***decay time constant***.

TDEM: ***time domain electromagnetic***.

thin sheet: A standard model for electromagnetic geophysical theory. It is usually defined as a thin, flat-lying conductive sheet, ***infinite*** in both horizontal directions. (see also ***vertical plate***)

tie-line: A survey line flown across most of the ***traverse lines***, generally perpendicular to them, to assist in measuring ***drift*** and ***diurnal*** variation. In the short time required to fly a tie-line it is assumed that the drift and/or diurnal will be minimal, or at least changing at a constant rate.

time constant: The time required for an ***electromagnetic*** field to decay to a value of 1/e of the original value. In ***time-domain*** electromagnetic data, the time constant is proportional to the size and ***conductance*** of a tabular conductive body. Also called the decay constant.

Time channel: In ***time-domain electromagnetic*** surveys the decaying ***secondary field*** is measured over a period of time, and the divided up into a series of consecutive discrete measurements over that time.

time-domain: ***Electromagnetic*** system which transmits a pulsed, or stepped ***electromagnetic*** field. These systems induce an electrical current (***eddy current***) in the ground that persists after the ***primary field*** is turned off, and measure the change over time of the ***secondary field*** created as the currents ***decay***. See also ***frequency-domain***.

total energy envelope: The sum of the squares of the three ***components*** of the ***time-domain electromagnetic secondary field***. Equivalent to the ***amplitude*** of the secondary field.

transient: Time-varying. Usually used to describe a very short period pulse of ***electromagnetic*** field.

transmitter: The source of the ***signa***l to be measured in a geophysical survey. In airborne ***EM*** it is most often a **coil** carrying a time-varying electrical current, transmitting the ***primary field***. (see also ***receiver***)

traverse line: A normal geophysical survey line. Normally parallel traverse lines are flown across the property in spacing of 50 m to 500 m, and generally perpendicular to the target geology. Also called a **flight line**.

turn-arounds: The time the aircraft is turning between one ***traverse*** or ***tie line*** and the next. Turn-arounds are generally outside the survey area, and the data collected during this time generally are not useable, because of aircraft ***manoeuvre noise***.

vertical plate: A standard model for electromagnetic geophysical theory. It is usually defined as thin conductive sheet, ***infinite*** in horizontal dimension and depth extent. (see also ***thin shee***t)

waveform: The shape of the ***electromagnetic pulse*** from a ***time-domain*** electromagnetic transmitter.

window: A discrete portion of a ***gamma-ray spectrum*** or ***time-domain electromagnetic decay***. The continuous energy spectrum or ***full-stream*** data are grouped into windows to reduce the number of samples, and reduce ***noise***.

zero, or zero level: The ***base level*** of an instrument, with no ***ground effect*** or ***drift***. Also, the act of measuring and setting the zero level.
can detect the strongest conductive target – generally a highly conductive horizontal layer.

Common Symbols and Acronyms

k	Magnetic susceptibility
ε	Dielectric permittivity
μ, μ_r	Magnetic permeability, relative permeability
ρ, ρ_a	Resistivity, apparent resistivity
σ,σ_a	Conductivity, apparent conductivity
σt	Conductivity thickness
τ	Tau, or time constant
Ωm	ohm-metres, units of resistivity
AGS	Airborne gamma ray spectrometry.
CDT	Conductivity-depth transform, conductivity-depth imaging (Macnae and Lamontagne, 1987; Wolfgram and Karlik, 1995)
CPI, CPQ	Coplanar in-phase, quadrature
CPS	Counts per second
CTP	Conductivity thickness product
CXI, CXQ	Coaxial, in-phase, quadrature
FOM	Figure of Merit
fT	femtoteslas, common unit for measurement of B-Field in time-domain EM
EM	Electromagnetic
keV	kilo electron volts – a measure of gamma-ray energy
MeV	mega electron volts – a measure of gamma-ray energy 1MeV = 1000keV
NIA	dipole moment: turns x current x Area
nT	nanotesla, a measure of the strength of a magnetic field
nT/s	nanoteslas/second; standard unit of measurement of secondary field dB/dt in time domain EM.
nG/h	nanoGreys/hour – gamma ray dose rate at ground level
ppm	parts per million – a measure of secondary field or noise relative to the primary or radioelement concentration.
pT	picoteslas: standard unit of measurement of B-Field in time-domain EM
pT/s	picoteslas per second: Units of decay of secondary field, dB/dt
S	siemens – a unit of conductance
x:	the horizontal component of an EM field parallel to the direction of flight.
y:	the horizontal component of an EM field perpendicular to the direction of flight.
z:	the vertical component of an EM field.

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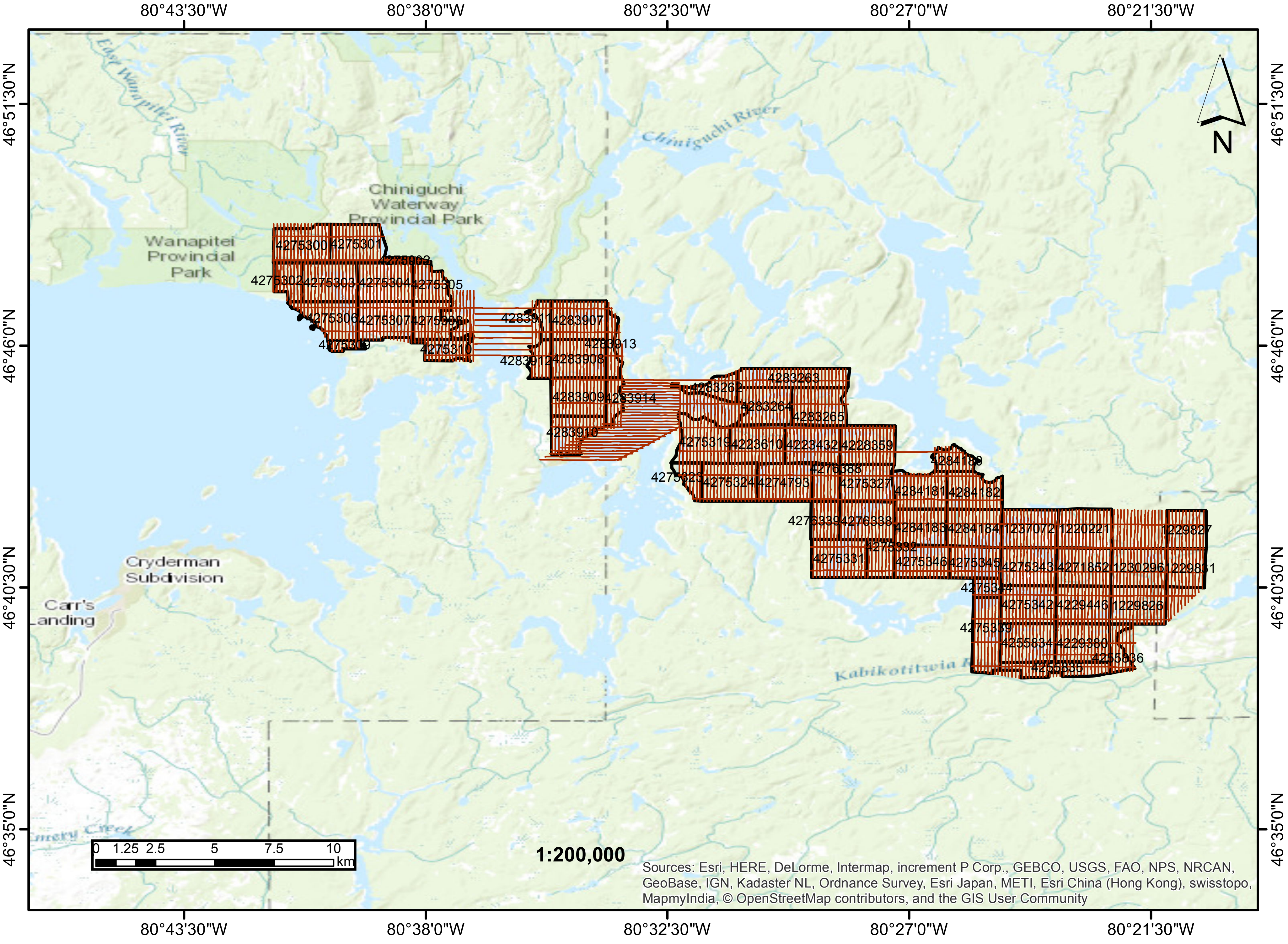
EMERALD LAKE HELITEM SURVEY
FLIGHT PATH - CLAIM NUMBERS



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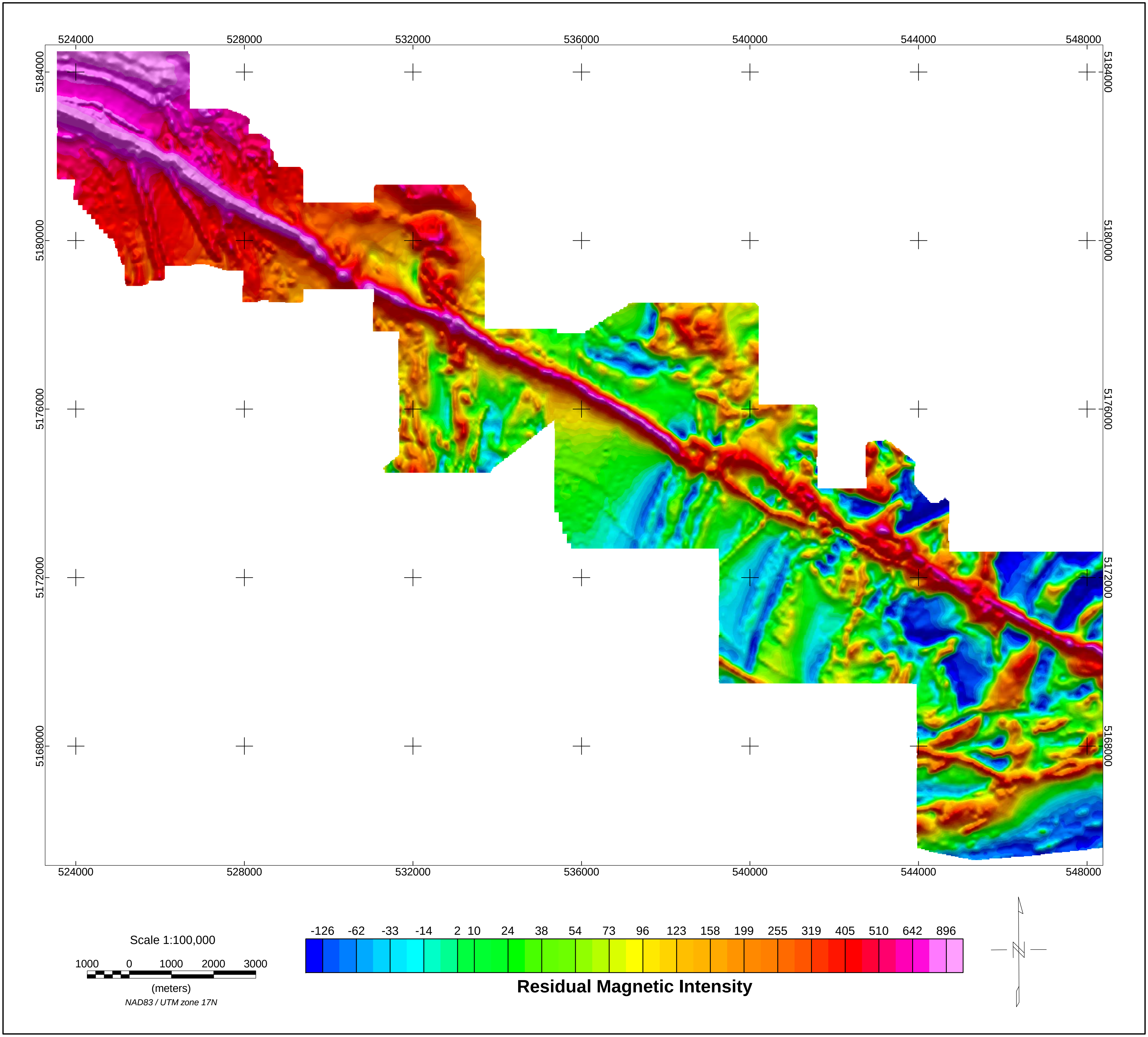
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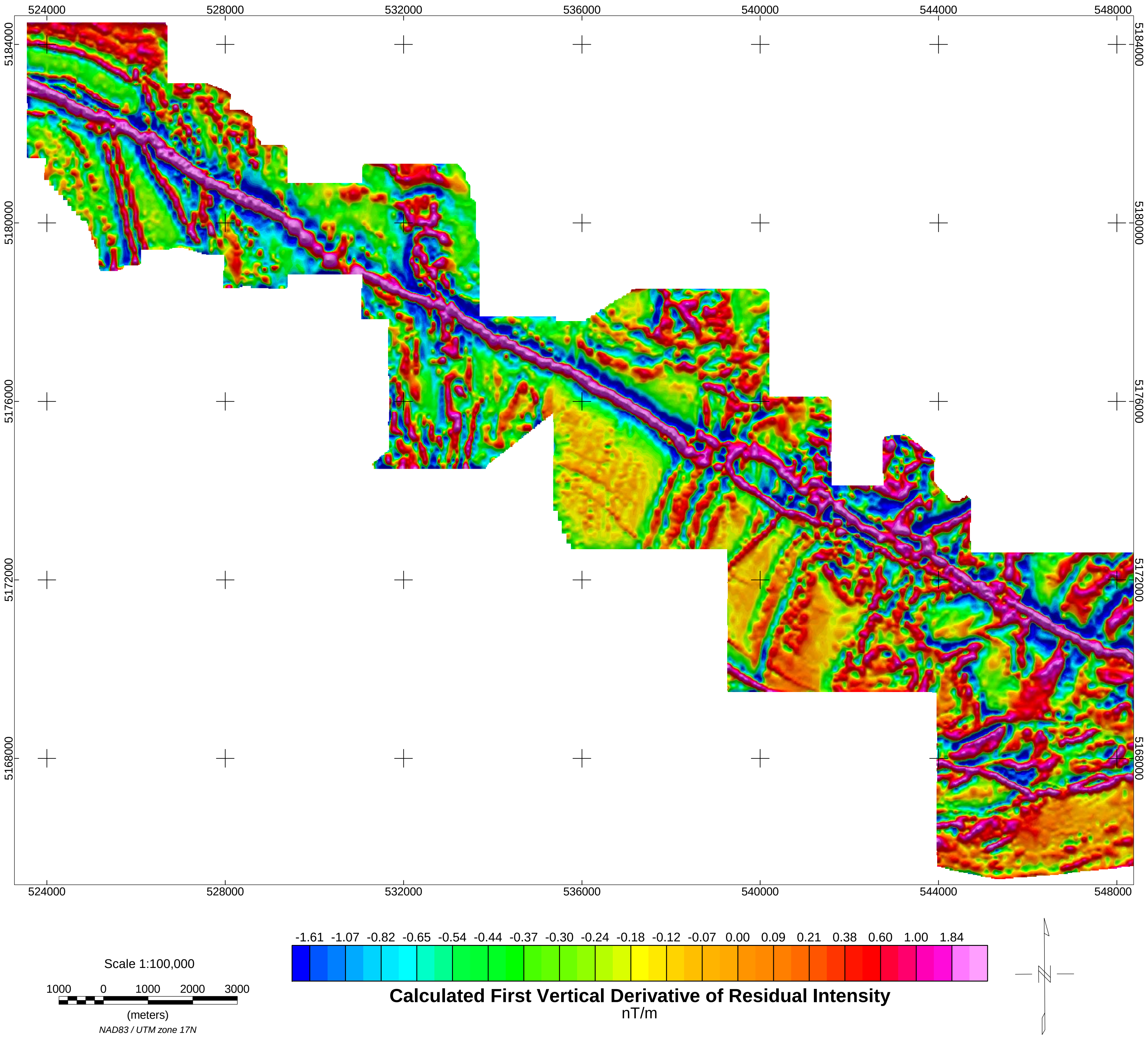
Residual Magnetic Intensity



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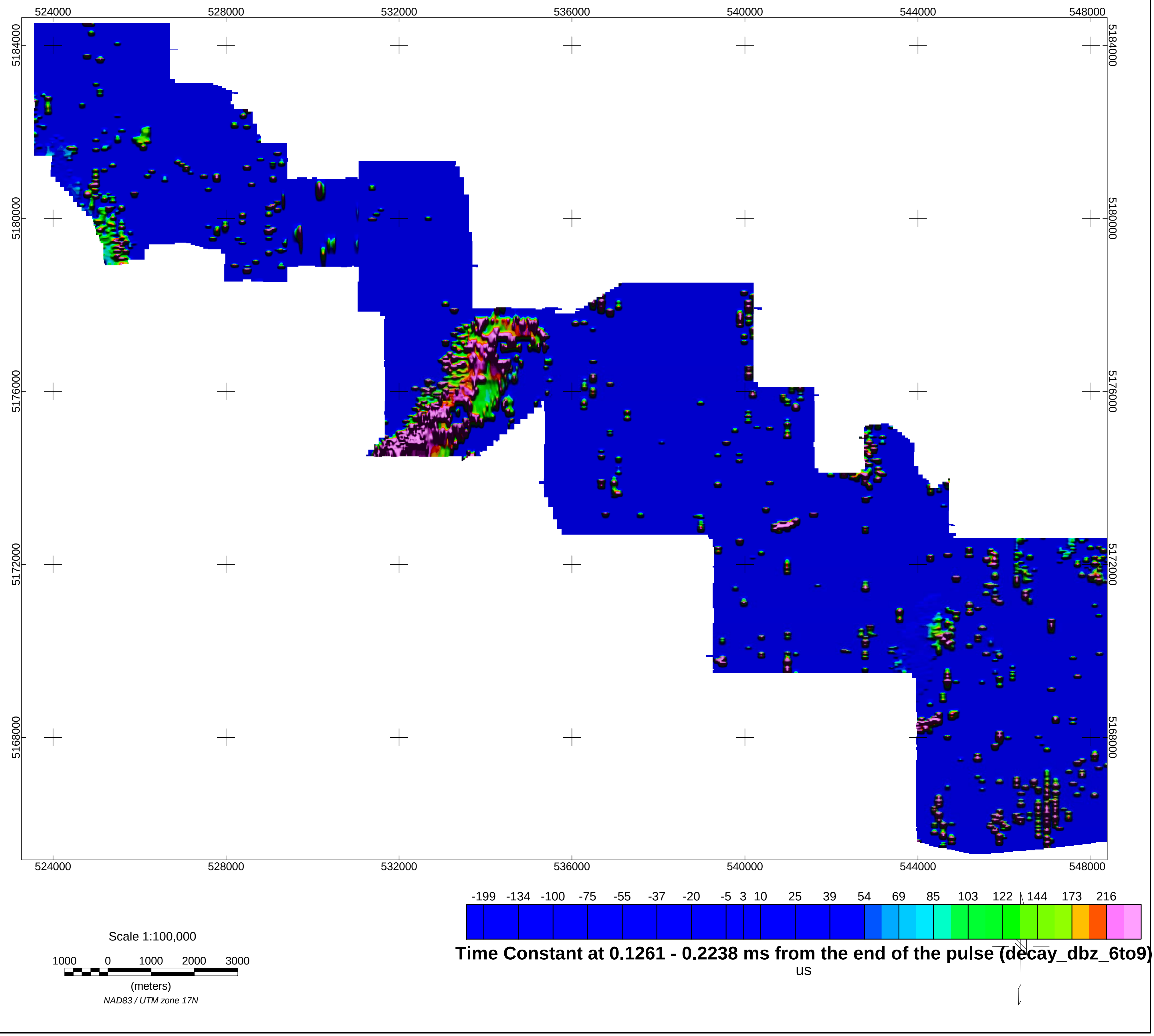
nT/m



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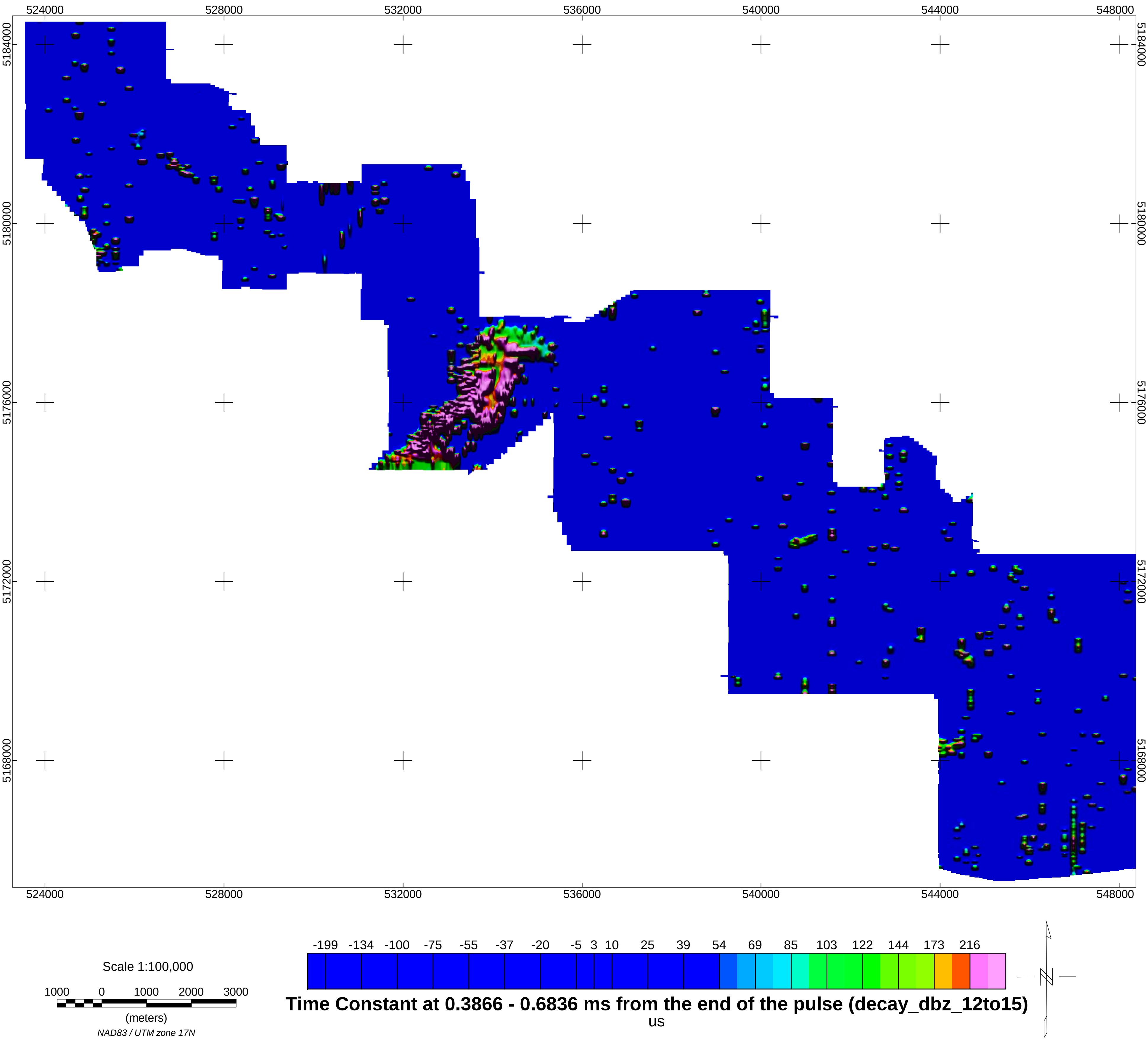
us



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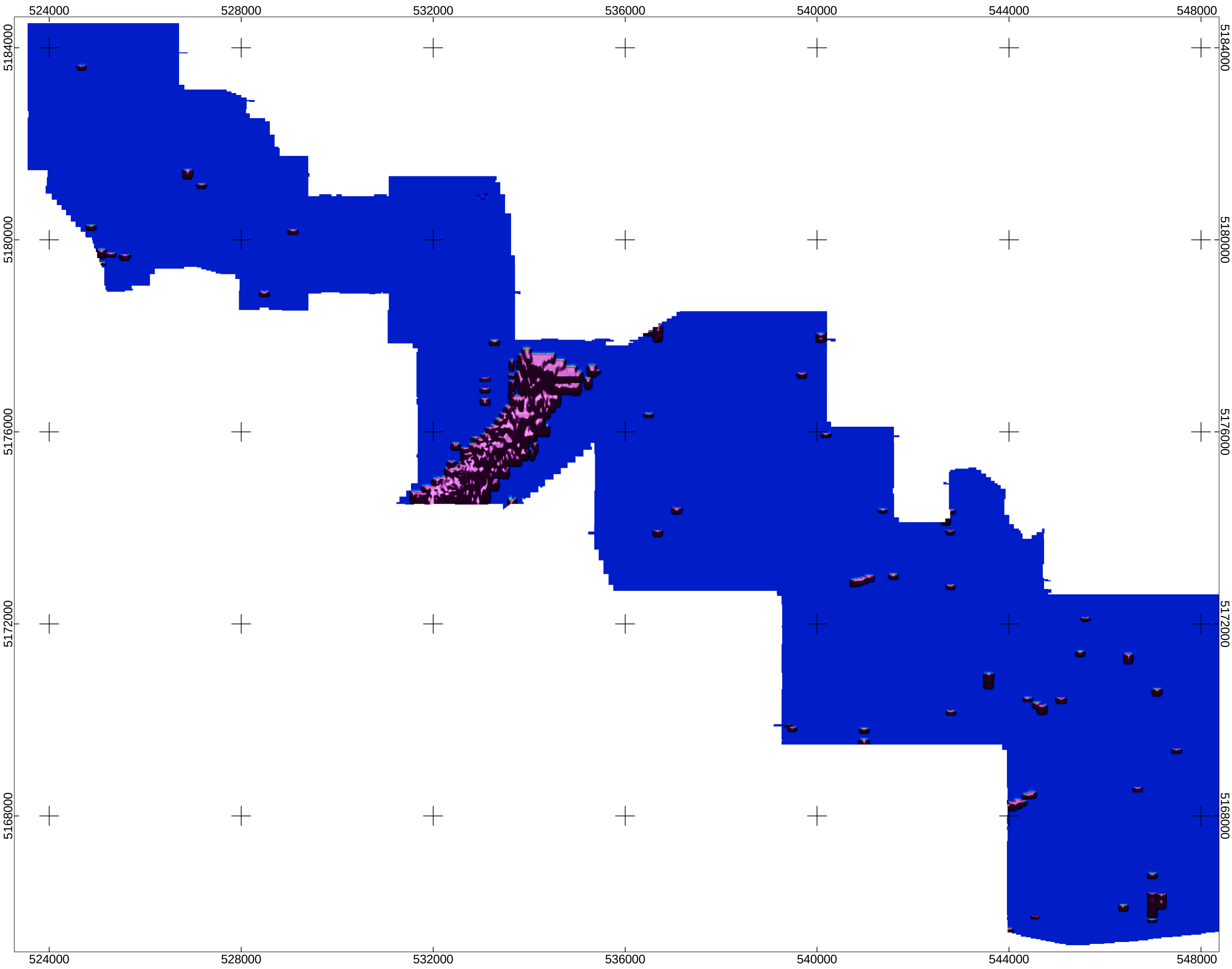

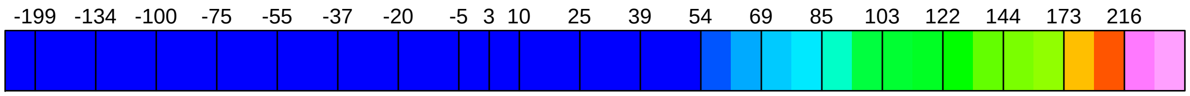

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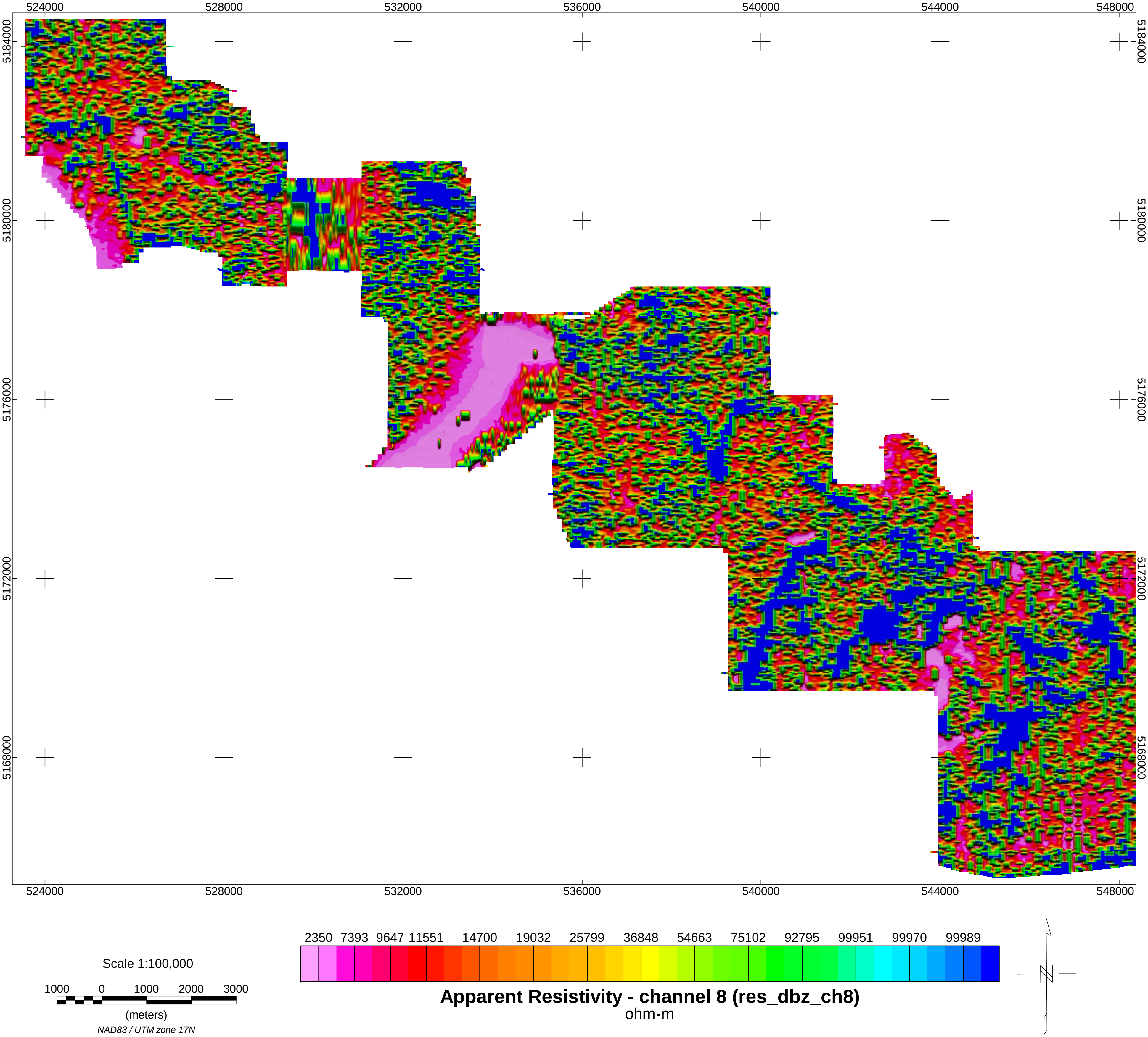
(meters)

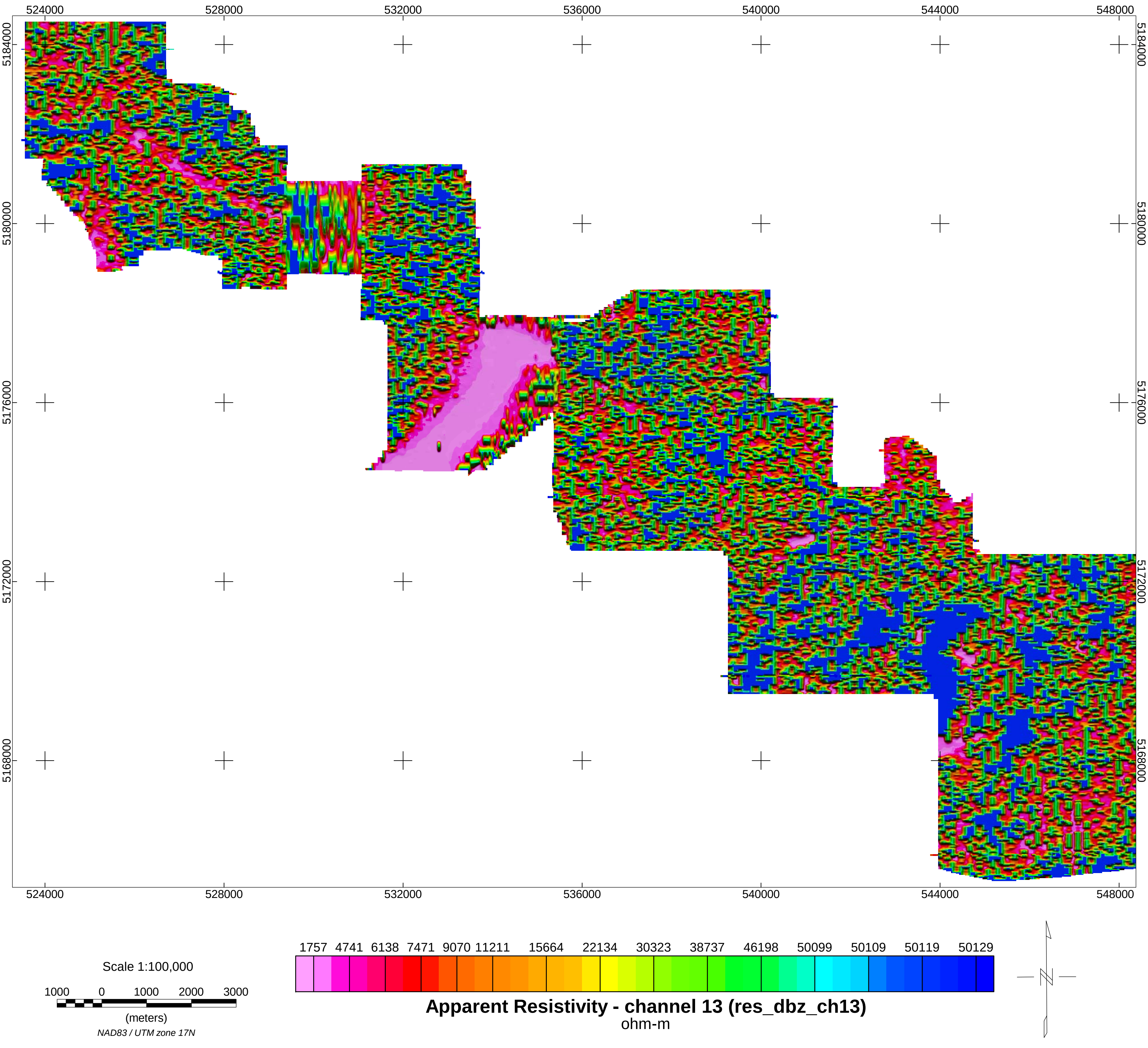
NAD83 / UTM zone 17N

Time Constant at 1.4567 -2.5675 ms from the end of the pulse (decay_dbz_19to22)

us

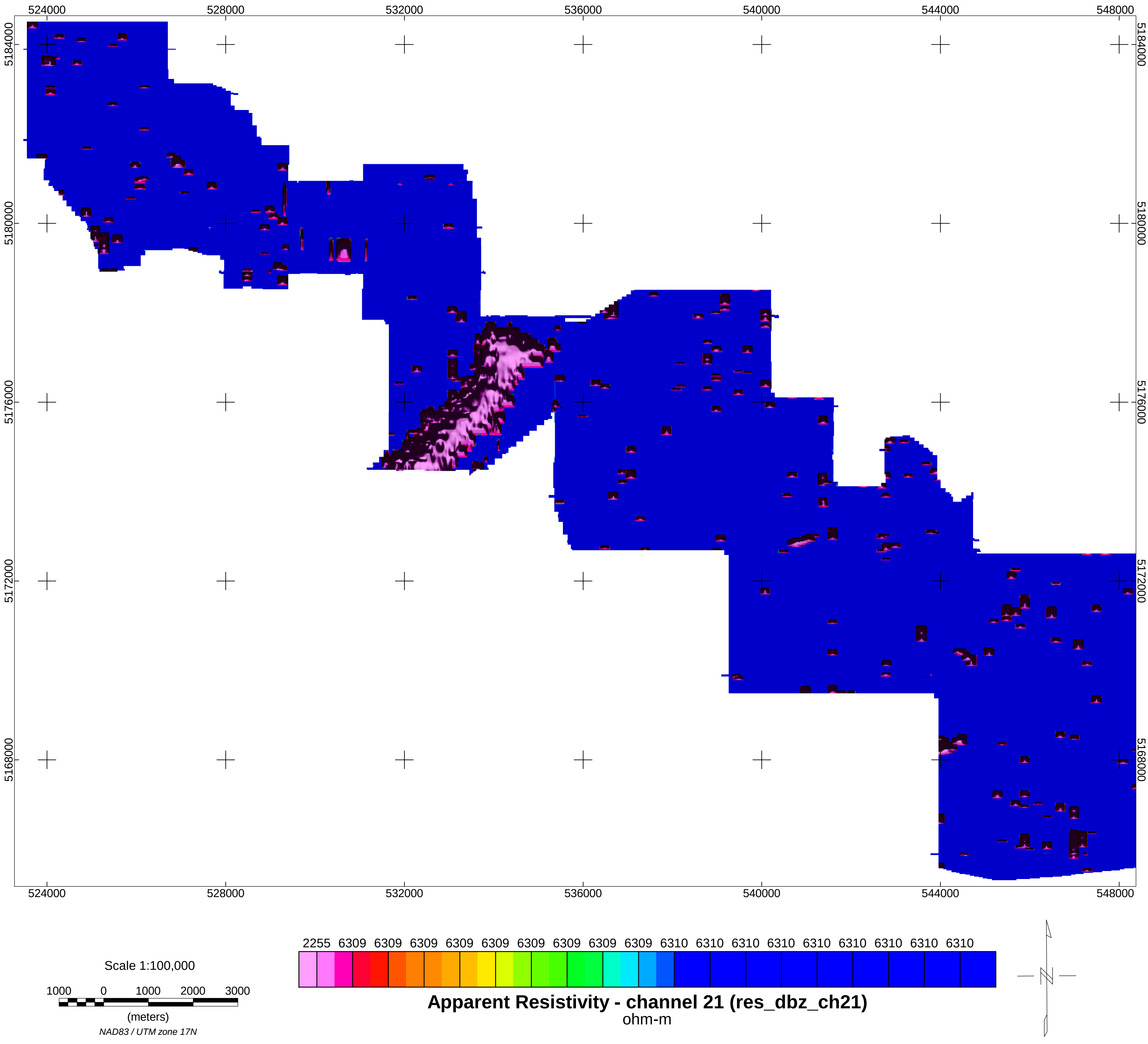


Apparent Resistivity - channel 8 (res_dbz_ch8)
ohm-m

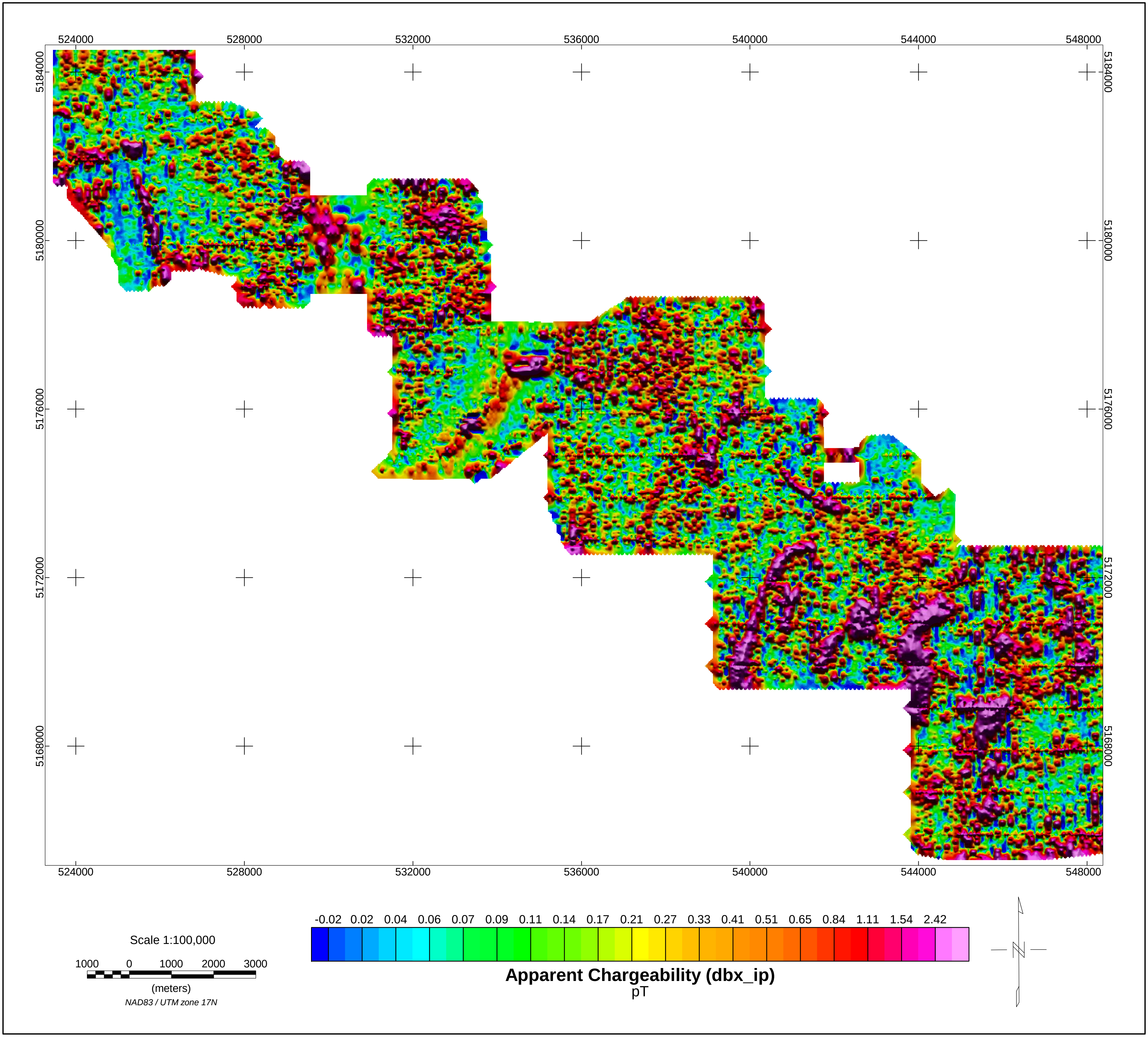


Apparent Resistivity - channel 13 (res_dbz_ch13)

ohm-m



Apparent Resistivity - channel 21 (res_dbz_ch21)
ohm-m



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NAD83 / UTM zone 17N
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Apparent Chargeability (dbx_ip)
pT