Introduction to the use of geophysical datasets for support to geological mapping

High-Resolution (HR) geophysical dataset

- HR geophysical data - magnetics and radiometrics - have been acquired as part of a long-term programme aimed at obtaining complete coverage of Namibia by the year 2008
- Surveys flown with a 200m line spacing and 2500m ties at a terrain clearance of 80 to 100m provide exceptional dataset that enable the regional geology and metallogeny to be reassessed

Input of high-resolution geophysical airborne surveys

- Complementing field geology, high-resolution geophysical airborne surveys provide:
  - An homogeneous and rapid acquisition of physical parameters
  - A good definition of regional scale structures
  - An information about the prolongation of structures and geological units at depth (magnetics)
  - A complete coverage of the survey area, independently of outcrop conditions and vegetation
  - The detection of large hydrothermal alteration zones (pyrrhotite and magnetite for magnetics, potassium and Uranium for radiometrics)

Constraints for interpreting high-resolution geophysical airborne data

- Existing geological maps, displaying lithologies and structures, can not correspond 100% to geophysics without combined interpretation of geological and processing of geophysical data
- There is no fully automatic processing from raw data to interpreted maps. Interpretation requires:
  - A fully-equipped sustainable geophysical interpretation unit, linked with field geologists
  - A knowledge of the relative physical properties of the main geological units of the survey area
  - A reference to the basic principles of structural geology

General methodological framework

- An interpretation project aimed at a better knowledge of the geology of one region, requires a permanent reference to geodynamics
- Interpretation is done in reference to the physical signature of the main geological systems

Earth dynamics and geophysics

- As Earth is a living planet, its dynamics, like core dynamo or plate tectonics, is responsible of phenomenon like magnetic field or earthquakes
- If Earth was homogeneous, made of continuous concentric layers with constant thickness and physical properties, the recording of these phenomenon would be isotrope at the surface
- As Earth is not homogeneous, variation of the measured parameters provides information about its heterogeneity, i.e. about its structure and composition

Main geophysical methods

Method (source)	***"Living Earth"***	***Measured parameters, units***	***Physical properties, units***
Magnetism (natural)	Core dynamo	Magnetic field nT	Magnetic susceptibility: k in SI or CGS
Spectrometry (natural)	Emission spectrum, radioactive decay	Gamma Ray emission Impulse/s	Radioelement contents (% or equivalent ppm)
Gravimetry (natural)	Universal gravitation	Gravity acceleration mGal	Density contrast (d)
Seismics (natural and provoked)	Plate tectonics and stress field	Time, ms	Acoustic impedance = density x velocity Propagation wave velocities in m/s
Geothermy (natural)	Melt and convection	Temperature, degree Gradients, degree/m	Heat conductivity

Global link between Earth dynamics, physical signature and tectonic context

- Variations of the physical properties displayed at the surface of the earth's partly reflects variations in structure and composition of the lithosphere, linked to geodynamics and tectonics
- Geophysical methods evaluate these variations and enable a modelling of their sources

Physical signature and geodynamic context

- Modern concepts for geodynamics and crustal structure relates fundamentally physical properties of rocks and tectonic evolution
- Some examples
  - The magnetic anomalies of the oceanic crust
  - The structure of the lithosphere, rheology and decoupling surfaces
  - The role of gravitational processes in granite ascent processes

An idealistic mountain belt…

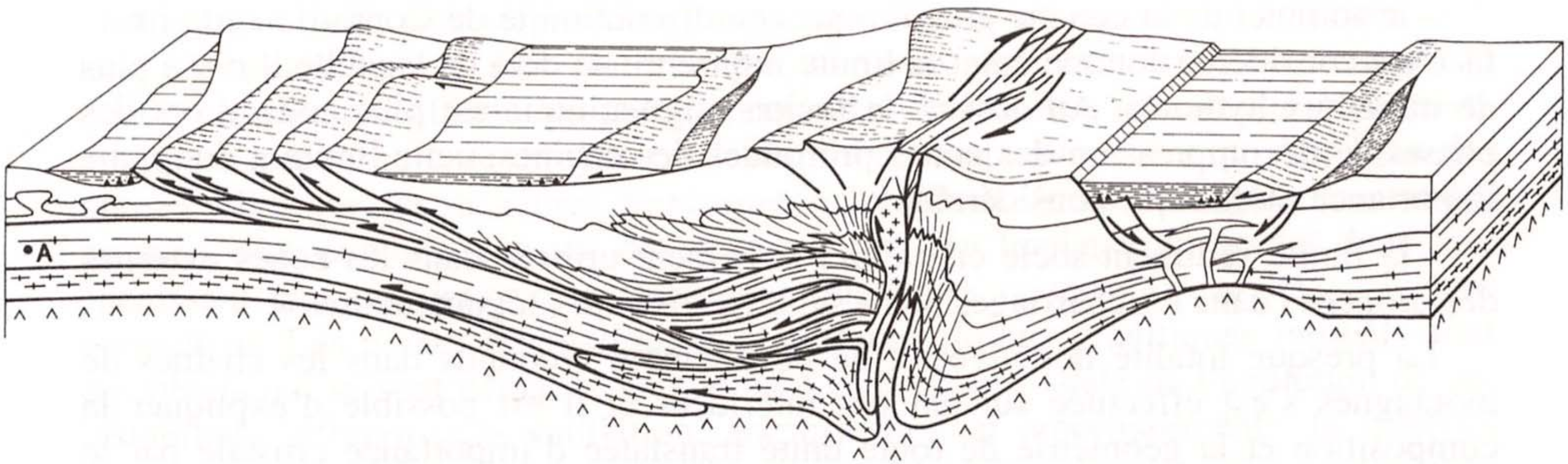
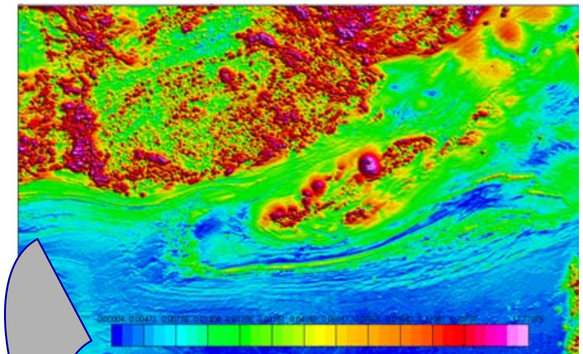
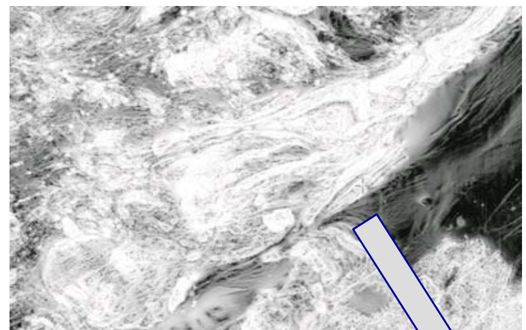


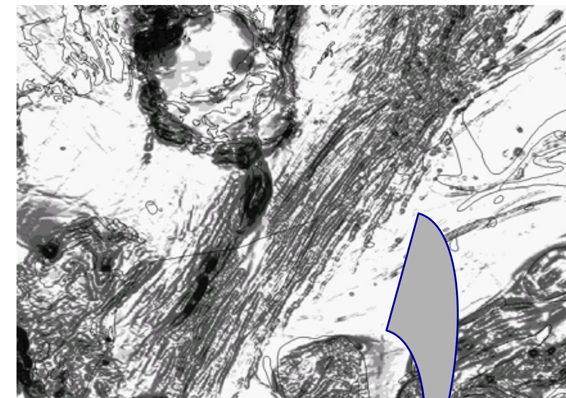
Fig. 18 – Représentation d'une chaîne de montagnes idéalisée où les principales structures d'échelle crustale qui la compose sont représentées ainsi que la répartition des différents domaines de la déformation discontinue et continue. Les nappes de charriages, les décrochements, les corps plutoniques intrusifs et les bassins sont les principaux « objets » structuraux dont la mise en place ou le fonctionnement va entraîner des déplacements relatifs et donc des déformations.

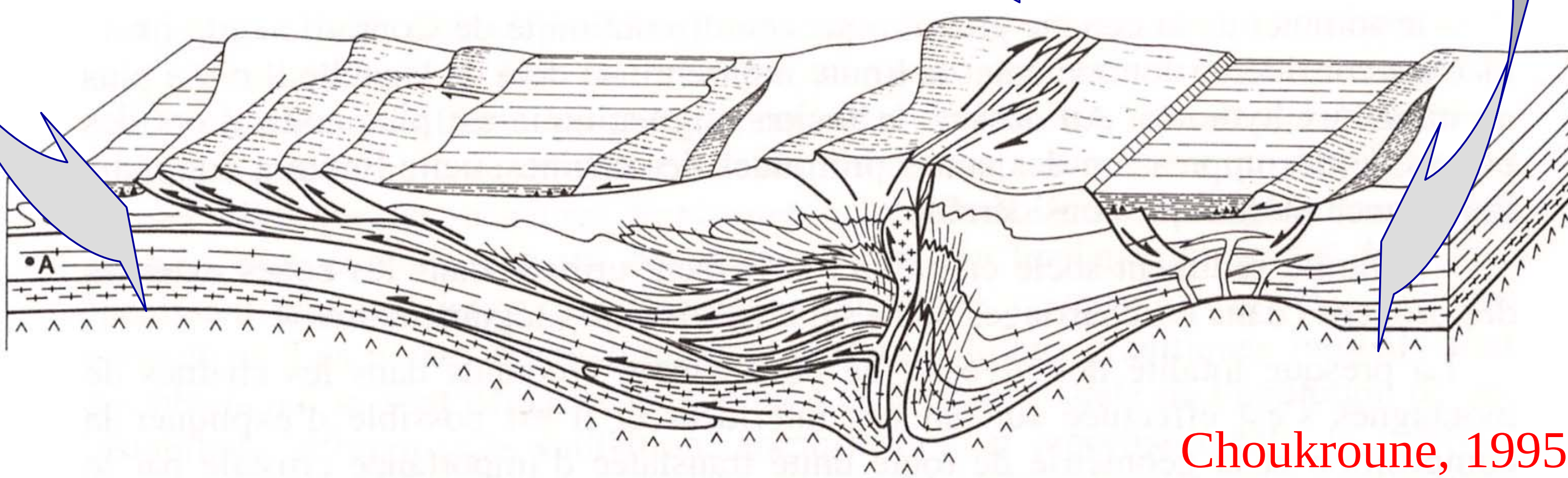
Choukroune, 1995

What geophysical signature for each structural element ?



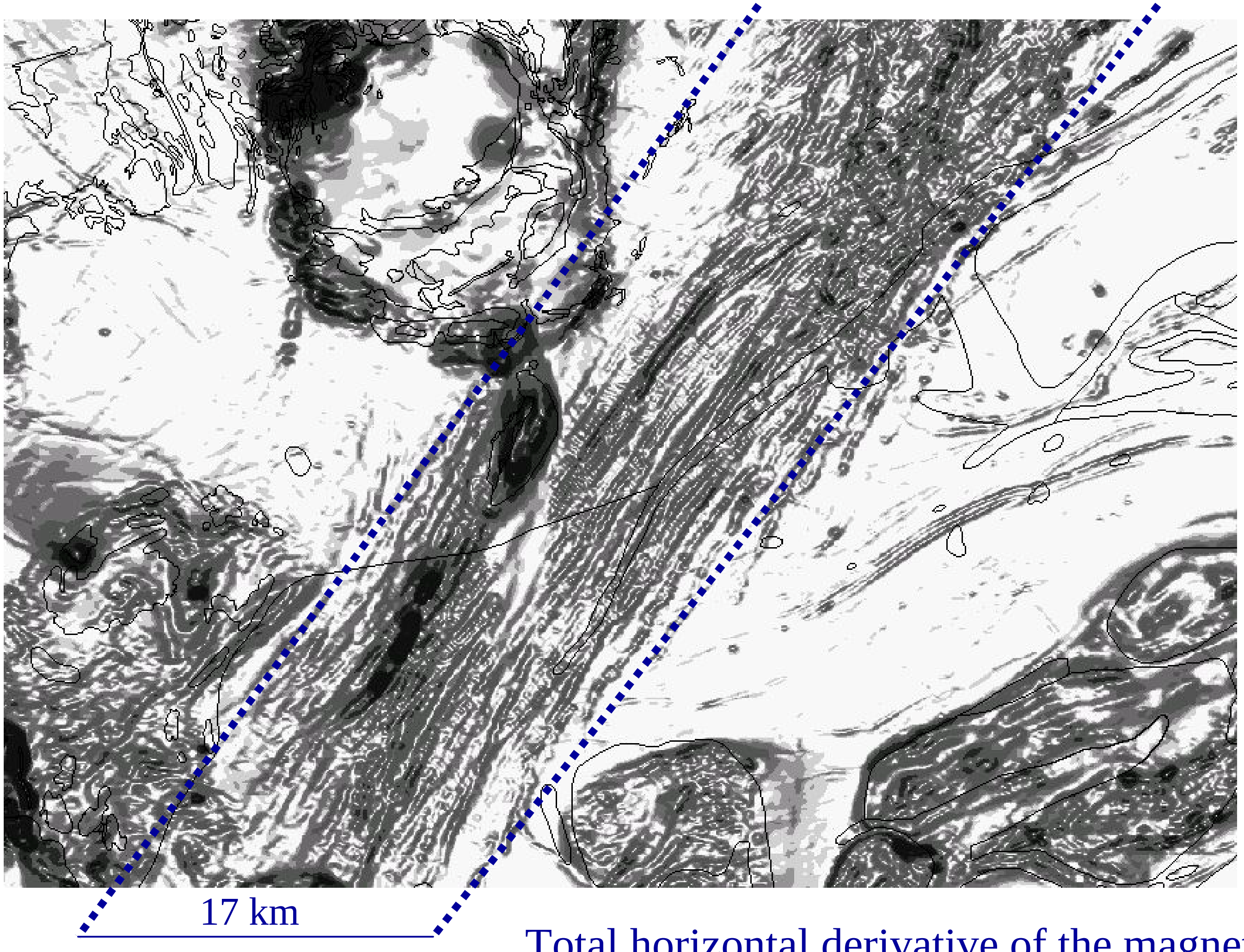






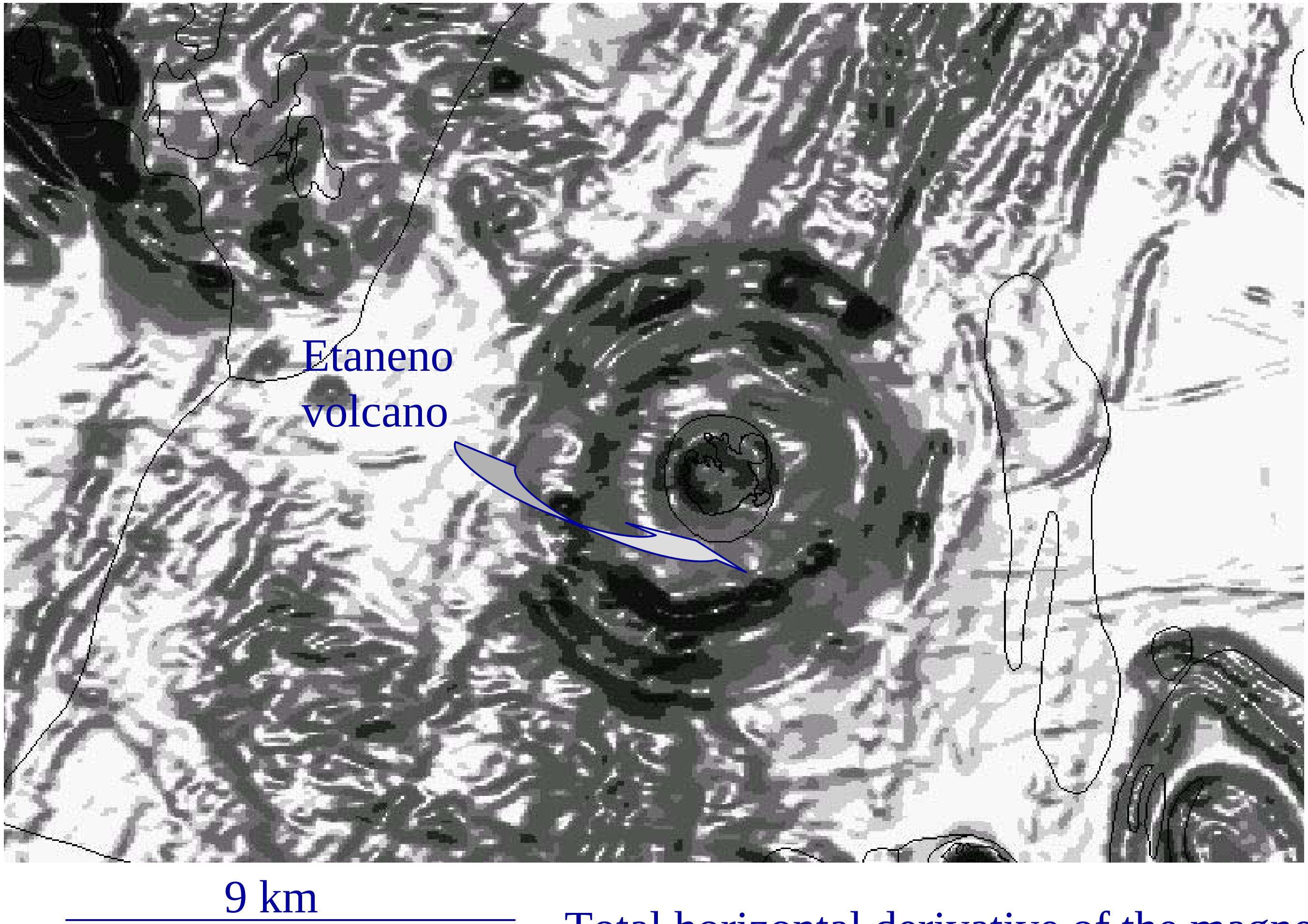
Choukroune, 1995

Rift zone and sheeted dyke complex



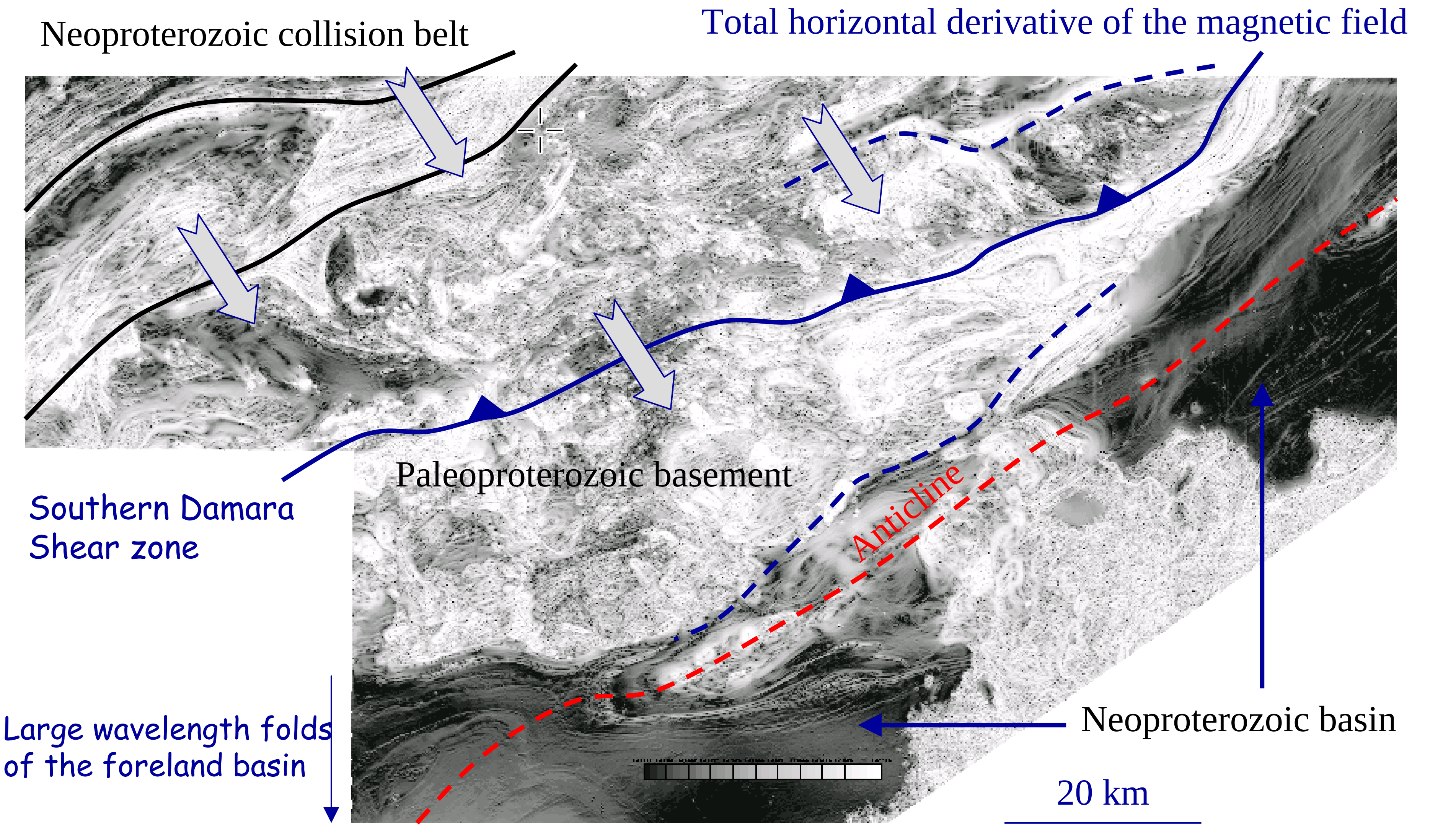
Total horizontal derivative of the magnetic field

Hot spot and ring complexes



Total horizontal derivative of the magnetic field

Collision and shear zone



Introduction to the use of geophysical datasets

MAGNETISM

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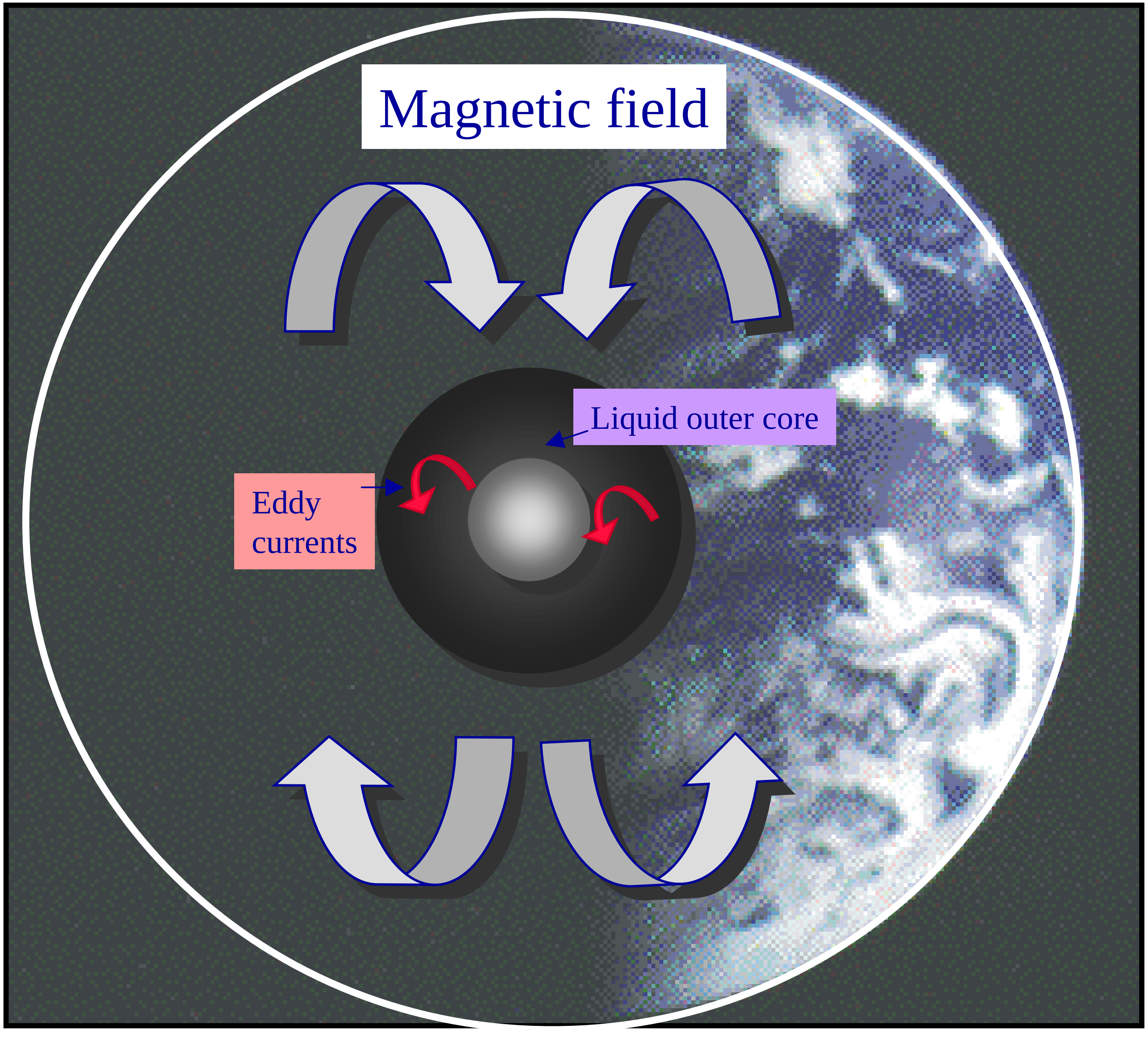
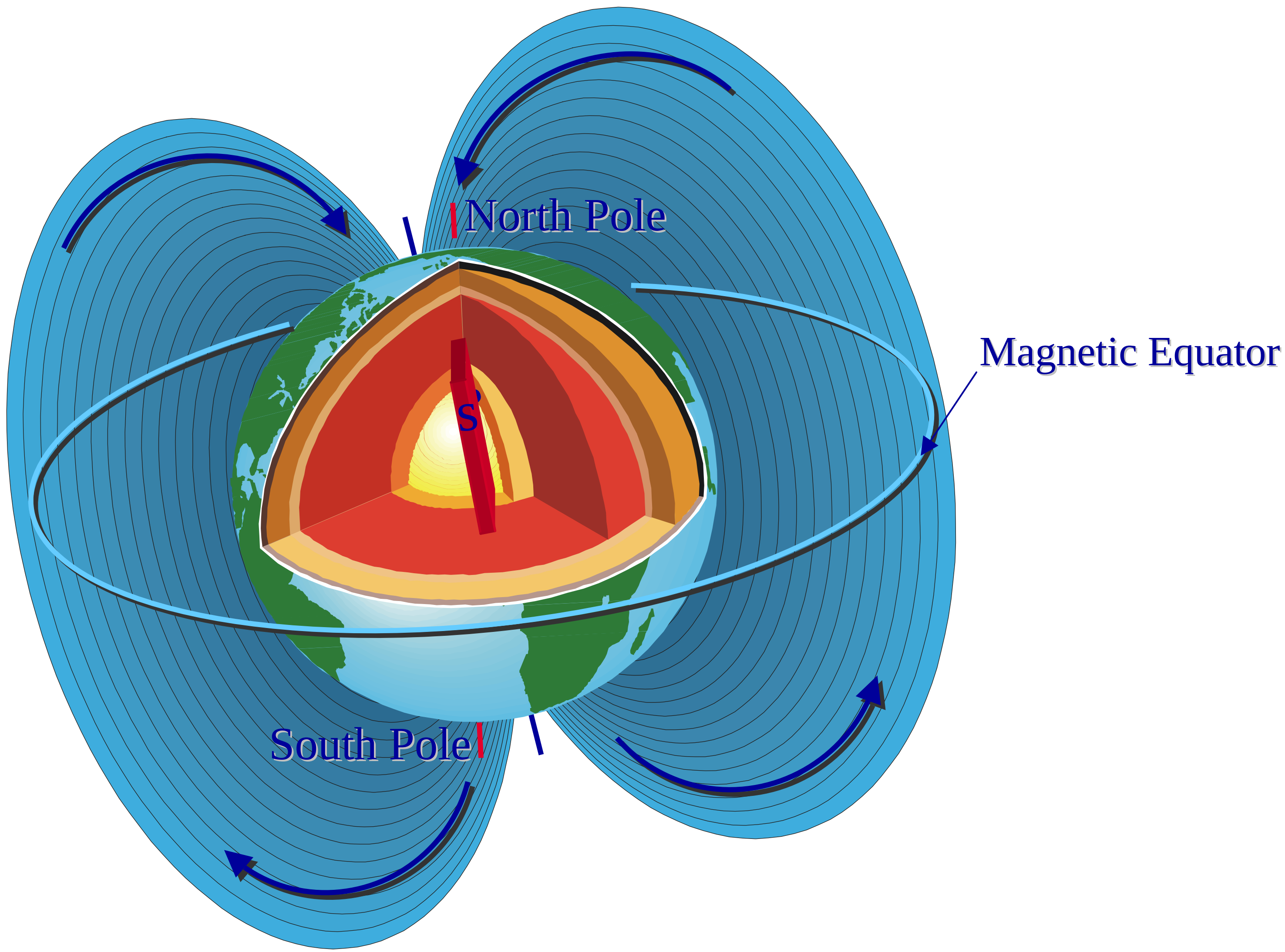
Earth magnetic field

- The main magnetic field
  - produced in the core of the earth and accounts for the very large regional variations in field intensity and direction
- The external magnetic field
  - produced by electric currents in the Earth’s ionosphere
- The anomalous magnetic field
  - produced by ferromagnetic minerals in the Earth’s crust

Earth Magnetic Field



Magnetic Flux Lines



Principles of magnetic surveys

- The physical parameter measured during magnetic surveys is the Total Magnetic Intensity of the earth (TMI)
  - The Total Magnetic Field (no vector or tensor information) is acquired in units of Nano-Tesla [nT] (nano = 10^{-9})
  - The strength of the total magnetic field is dependent on the geographic location and varies with time and distance from the Earth's center (elevation)
  - The dynamic range within a magnetic survey may reach 10000 nT, whilst modern data acquisition and processing allows interpretation of anomalies down to 0.1 nT

What do we measure in magnetism?

- Variations recorded have three sources:
  - The Earth dynamo complexity
  - The external field, including ionosphere currents, diurnal variations corrected by the recording of the base station
  - The structure of the crust and magnetic susceptibility of rocks contributing for less than 10% of the variations

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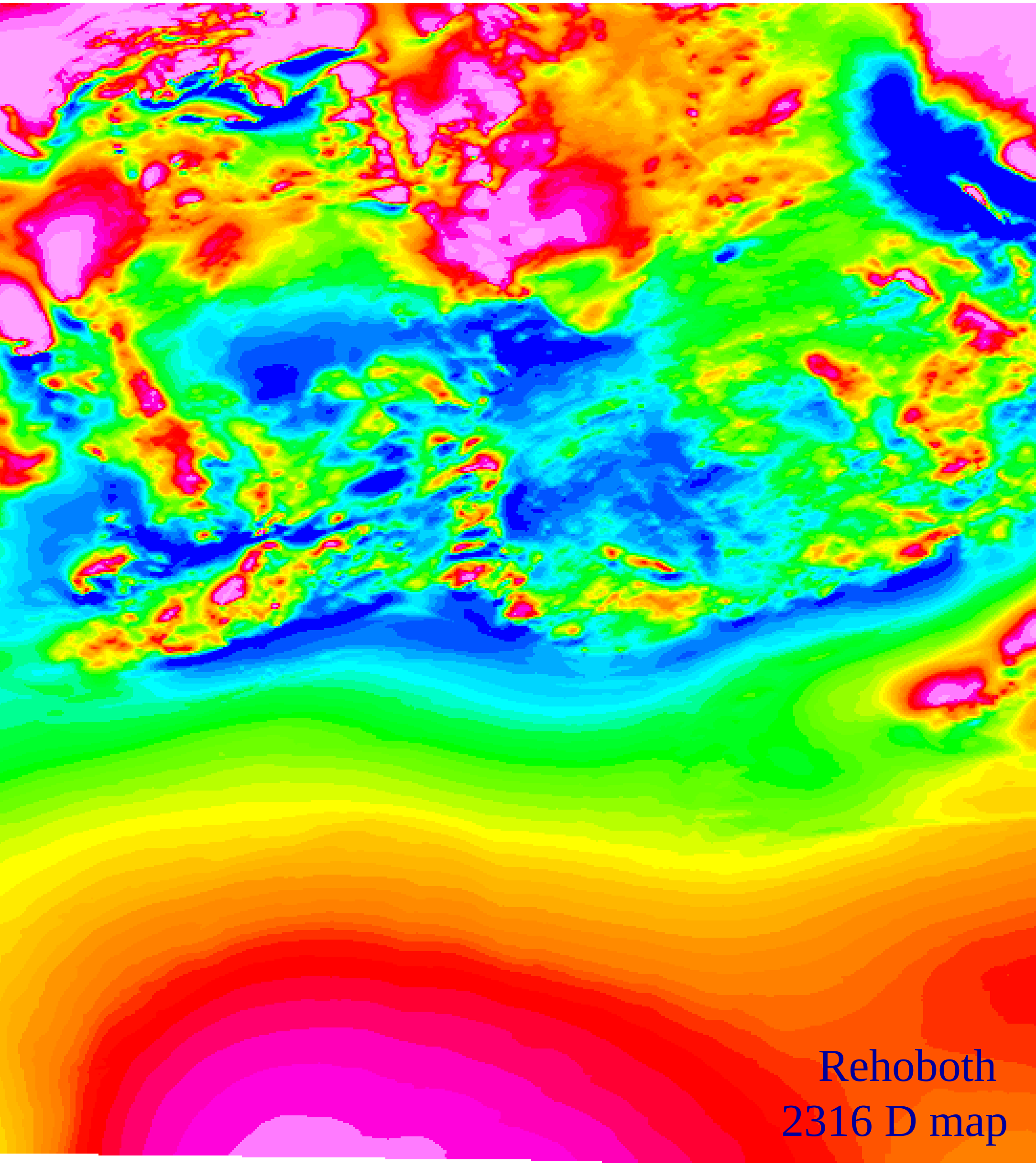
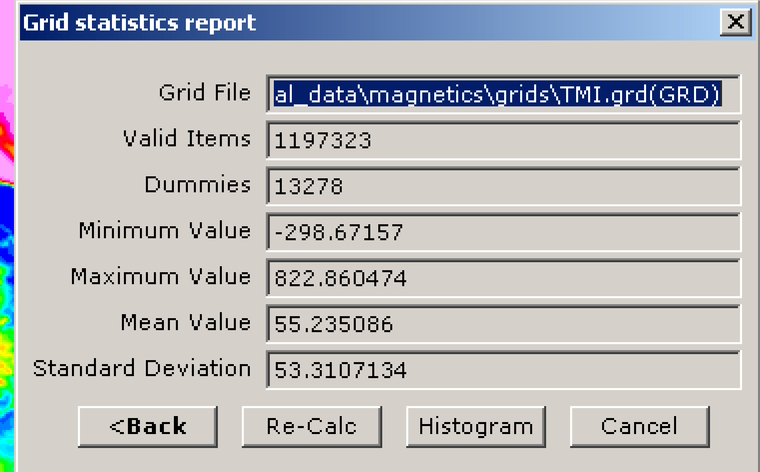
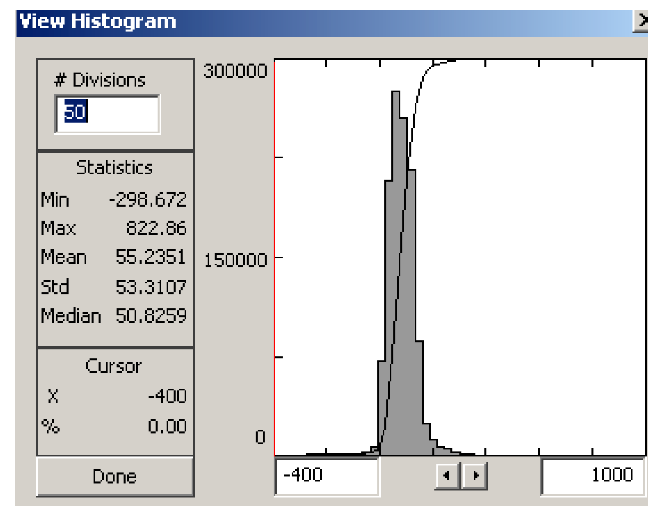




The residual Total Magnetic Intensity of the earth (TMI) measured by airborne geophysical survey



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The magnetic susceptibility of rocks

- The magnetic susceptibility measures the ability of a rock or a mineral to be magnetised, i.e. to produce an induced magnetic field while it is exposed to the magnetic field of the earth
  - Each mineral behaves as a dipole
  - The susceptibility of the mineral or of the rock, k, is the ratio between the induced magnetic field and the Earth magnetic field ($k = I/H$)

- Magnetic susceptibility of a rock depends on:
  - The proportion of magnetic minerals
  - Their nature, i.e. dia (opposite field) vs ferromagnetic (same sense)
- At the scale of anisotropic materials, the magnetic susceptibility vary in intensity according to the orientation of the main fabric of ferro and paramagnetic minerals
  - Anisotropy of magnetic susceptibility is used as a strain marker, especially in granites, where paramagnetic biotite and amphibole are preferentially orientated according to the finite strain ellipsoid

- Most common geological rocks have low magnetic susceptibility
- A high-susceptibility body will produce a stronger induced field than a low-susceptibility one
  - The amplitude of the measured parameter reflects the presence of magnetic or non-magnetic bodies
  - The shape of the measured parameter traduces the shape and the geometry of the body in depth

Magnetic susceptibility of minerals

		Magnetic susceptibility, k x 10^{-6}	
		Range	*Average*
Minerals			
Quartz		-10 - -15	
Feldspar			-12
Calcite		-1 - -10	
Clays		200 - 250	
Graphite			100
Chalcopyrite	CuFeS		400
Pyrite	Fe_2S	50 - 5 000	1 500
Limonite	FeOH		2 500
Arsenopyrite	FeAsS		3 000
Haematite	Fe_2O_3	500 - 35 000	6 500
Chromite		3 000 – 110 000	7 500
Franklinite	Fe-Zn spinelle		430 000
Pyrrhotite	Fe_7S_8	1 - 6 000 000	1 500 000
Ilmenite	$FeTiO_3$	300 000 – 3 500 000	1 800 000
Magnetite	Fe_3O_4	1 200 000 – 19 200 000	6 000 000

Magnetic susceptibility of sediments

	Magnetic susceptibility, k x 10^{-6}	
	Range	*Average*
Sedimentary rocks		**900**
Dolomite	0 - 900	100
Limestone	0 – 3 000	300
Sandstone	0 – 20 000	400
Shale	10 – 15 000	600
Banded Iron Formation	380 000	

- The average values are low to very low. With the remarkable exception of Banded Iron Formation in Proterozoic terrains
- High magnetic susceptibilities in sedimentary basins are mainly related to magnetite-rich layers, either from sedimentary source (heavy minerals in conglomerates and sandstone, iron precipitation), low-temperature hydrothermal alteration or volcanoclastic origin

Magnetic susceptibility of metamorphic rocks

	Magnetic susceptibility, $k \times 10^{-6}$	
	Range	*Average*
Metamorphic		**4 200**
Quartzite		4 000
Amphibolite		700
Schist	30 – 3 000	1 400
Gneiss	10 – 25 000	
Serpentine	3 000 – 17 000	
Granulite	100 – 3 000	

- Average values are low but varies as metamorphism may be responsible of crystallisation or destruction of magnetite and other magnetic species
- For example, high magnetic susceptibilities are related to serpentinisation of ultrabasics or contact metamorphism aureole where haematite in sediment is transformed to magnetite and pyrite to pyrrhotite
- Low-temperature hydrothermal alteration produce reverse reactions

Magnetic susceptibility of plutonic rocks

	Magnetic susceptibility, k x 10^{-6}	
	Range	*Average*
Igneous rocks		**0 – 97 000**
Granite	0 – 50 000	2 500
Porphyry	300 – 200 000	60 000
Rhyolite	200 – 35 000	
Andesite		160 000
Gabbro	1 000 – 90 000	70 000
Basalte/dolerite	200 – 175 000	70 000
Diabase	1000 – 160 000	55 000
Diorite	600 – 120 000	85 000
Pyroxenite		125 000
Peridotite	90 000 – 200 000	150 000

Tables synthesized from Bullock and Isles (1994), Fallon and Backo (1994), Lowrie (1997), World Geosciences

- The values vary very much for each type of rock, depending the type and age of terrains and processes involved in the generation and crystallisation of the igneous rocks
- A basalt or a granite can be magnetised or not depending of many factors

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The interpretation challenge

- A scale problem, from the mineral to the geological unit
- The magnetic susceptibility of the geological units are related to the distribution of magnetic minerals, i.e. to:
  - the lithology and formation of the rock
    - crystallisation in igneous, volcanic and metamorphic rocks
    - sedimentation in sedimentary rocks
  - any alteration related to hydrothermal, metamorphic or deformation process

The objective of interpretation

- Existing geological maps, displaying lithologies and structures, can not correspond 100% to magnetics without combined interpretation of geological and processing of geophysical data
- The key to interpretation of a magnetic survey is understanding the connection between mappable geological units and structures and the distribution of magnetics

But…

- There is no fully automatic processing from raw data to interpreted maps. Interpretation requires:
  - A fully-equipped sustainable geophysical interpretation unit, linked with field geologists
  - A knowledge of the magnetic properties of the main geological units of the survey area
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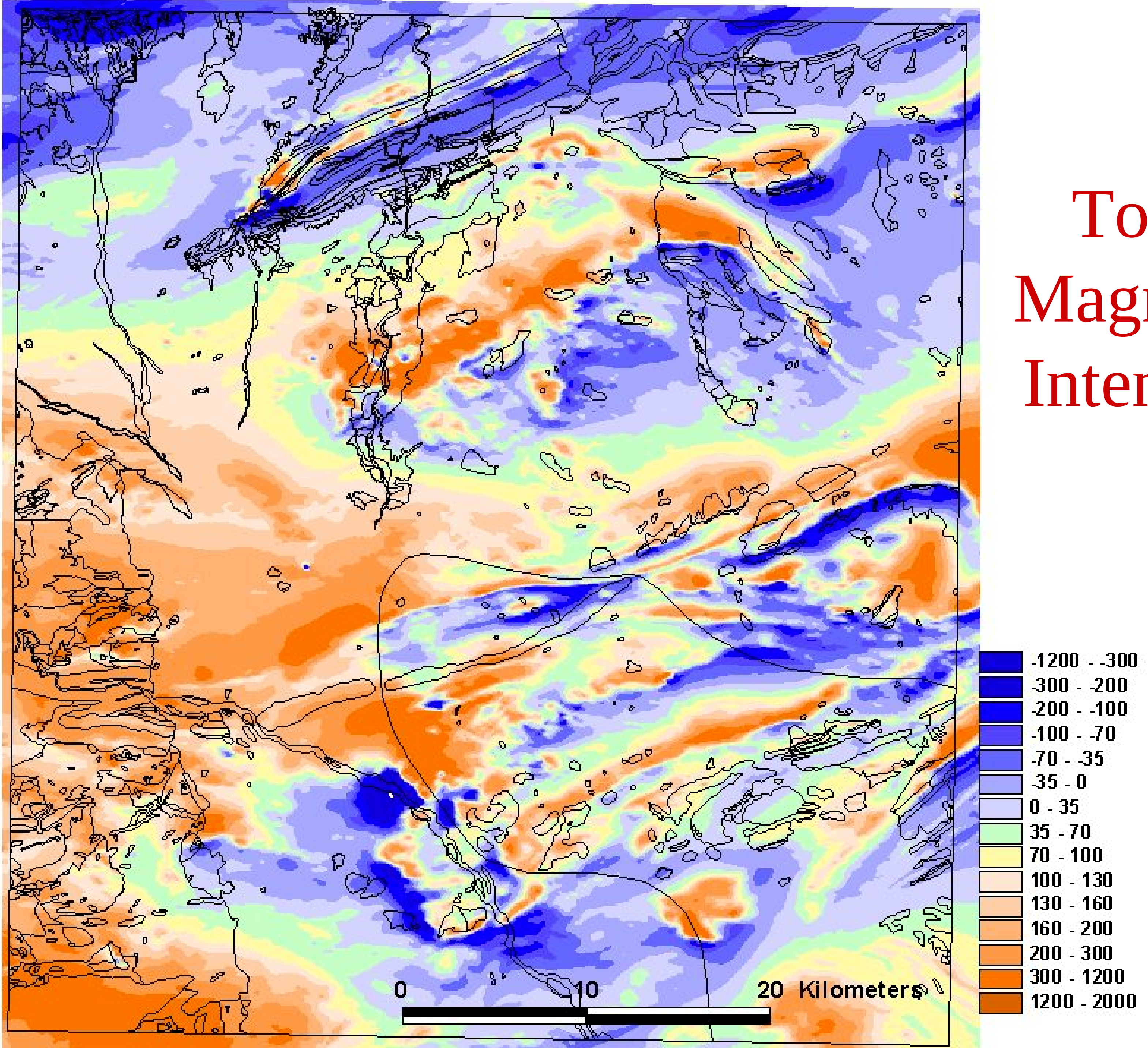
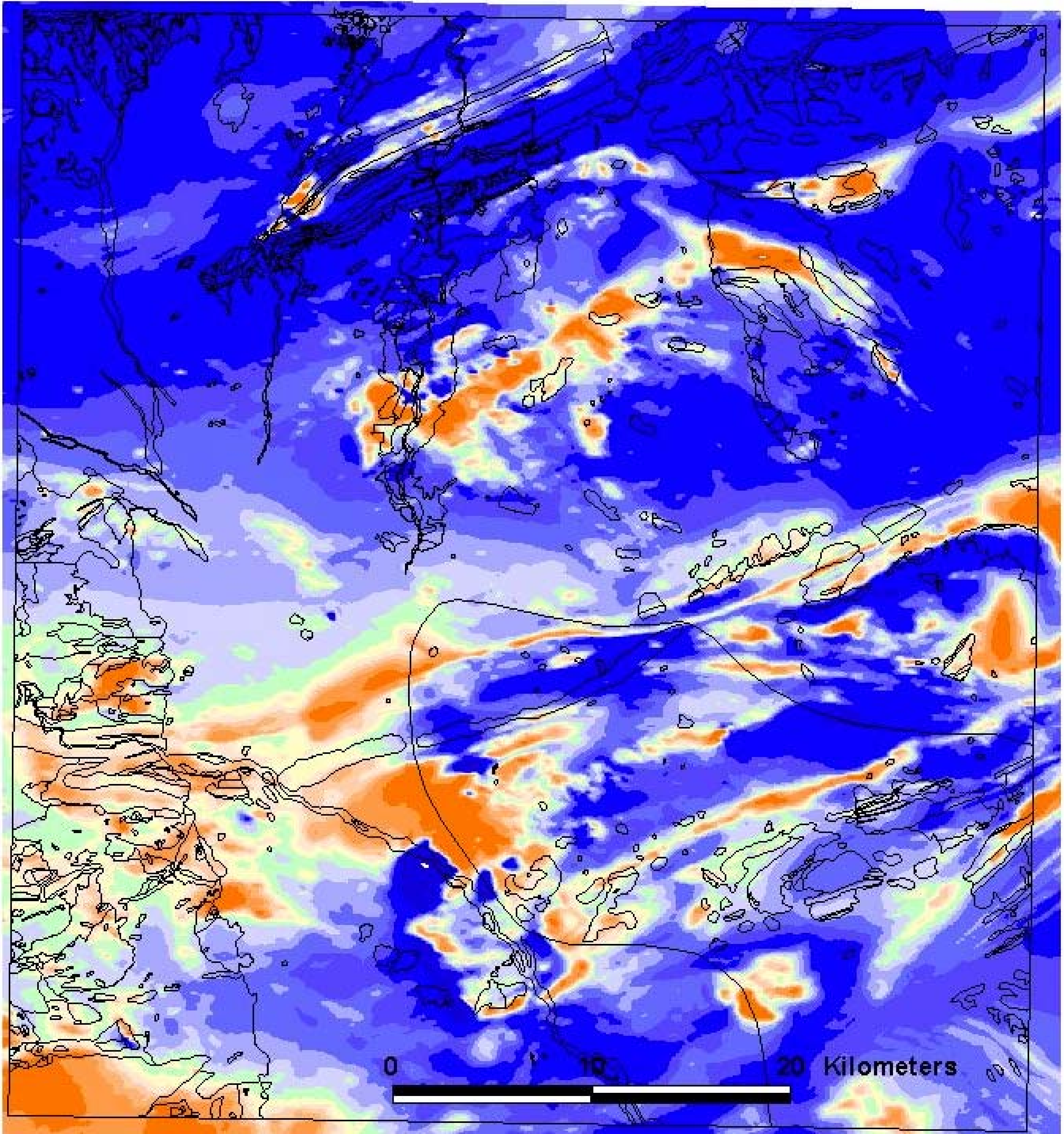
What information can we extract from the analysis of the grid processing ?

- Reduction to pole should eliminate the positive-negative high gradient anomalies
  - If not, the existence of remanence must be envisaged
- Anomalies in the southern hemisphere are southward relocated during reduction to pole
  - If not, the existence of remanence must be envisaged

➢ Compare the following images from the same area



Total Magnetic Intensity



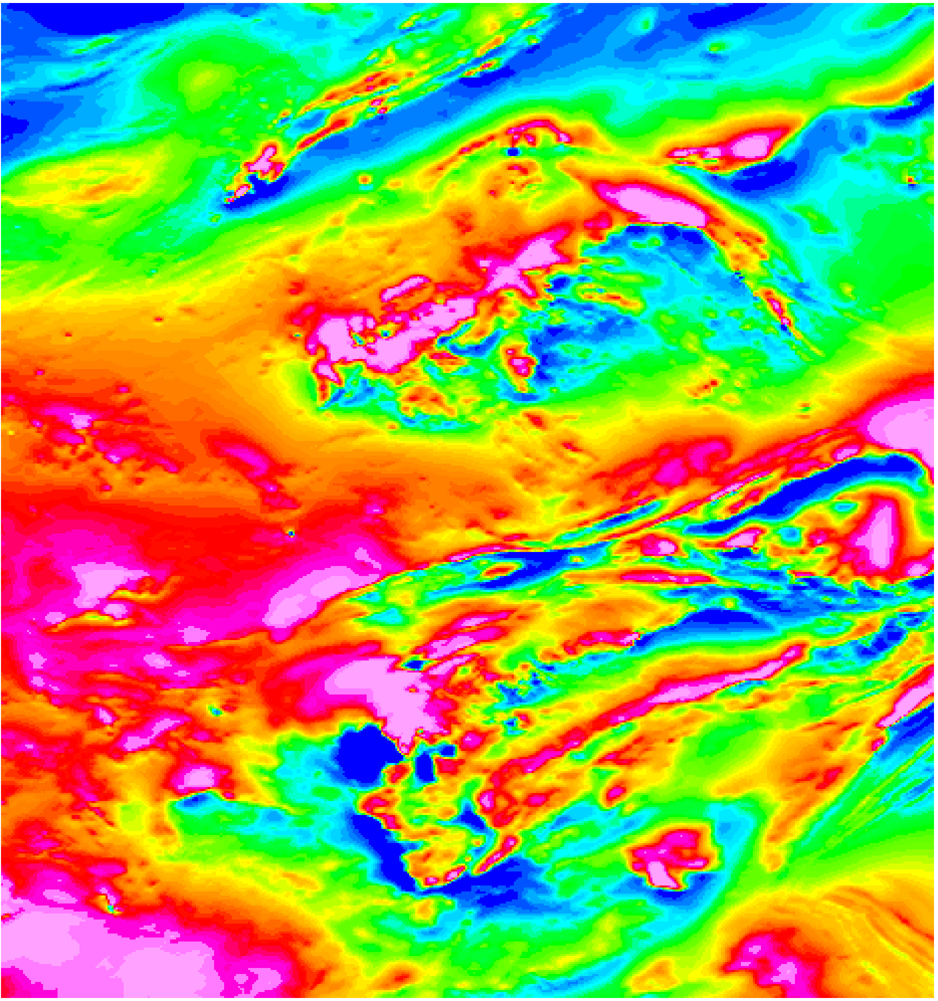
Reduced to Pole

What information can we extract from the analysis of the grid processing ?

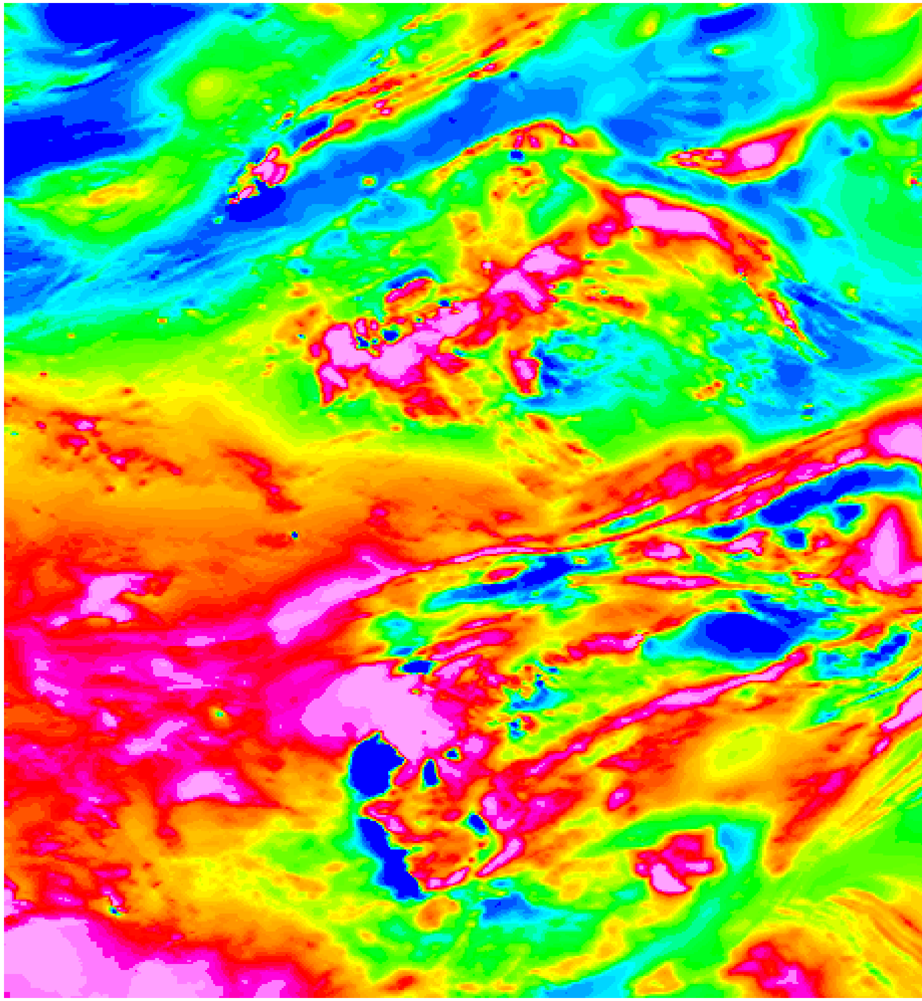
- Total Magnetic Intensity and Reduction to pole illustrates the large and short wavelength
- Analytical signal outlines the « negative-positive » part
- 1st Vertical Derivative underlines short wavelength

➢ Compare the following images from the same area
➢ Identify and underline large and short wavelength

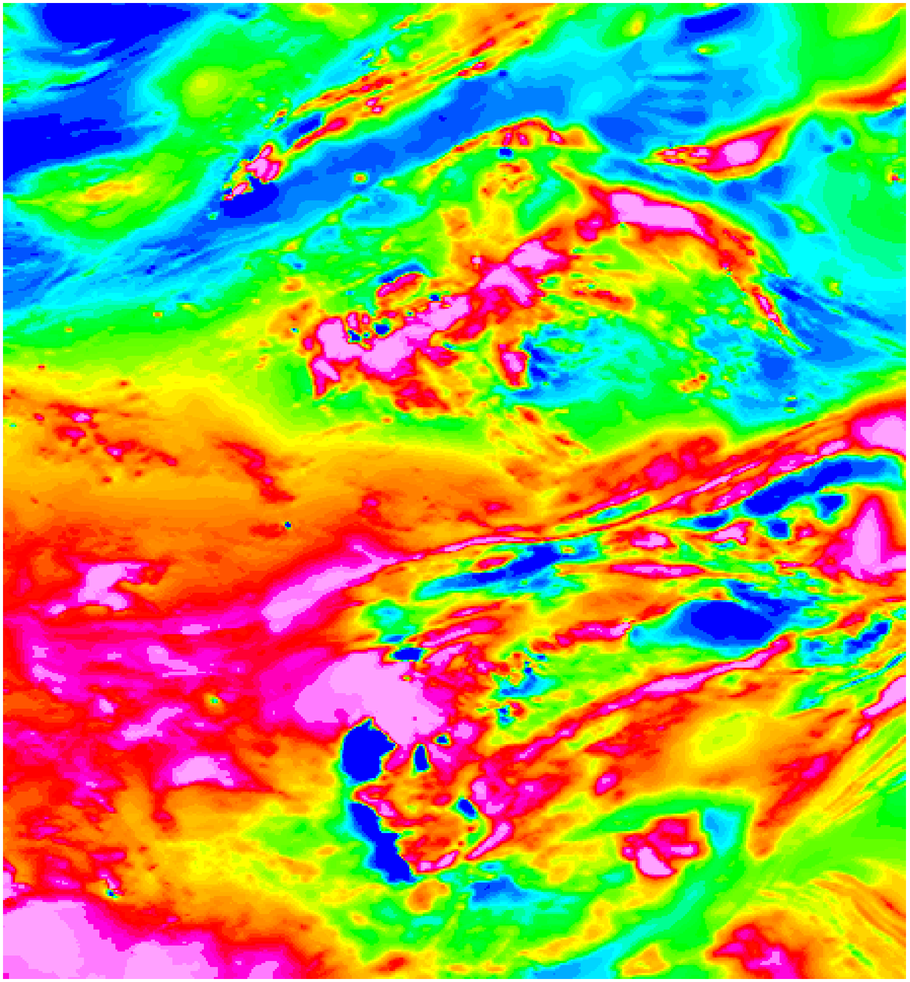
Total Magnetic Intensity



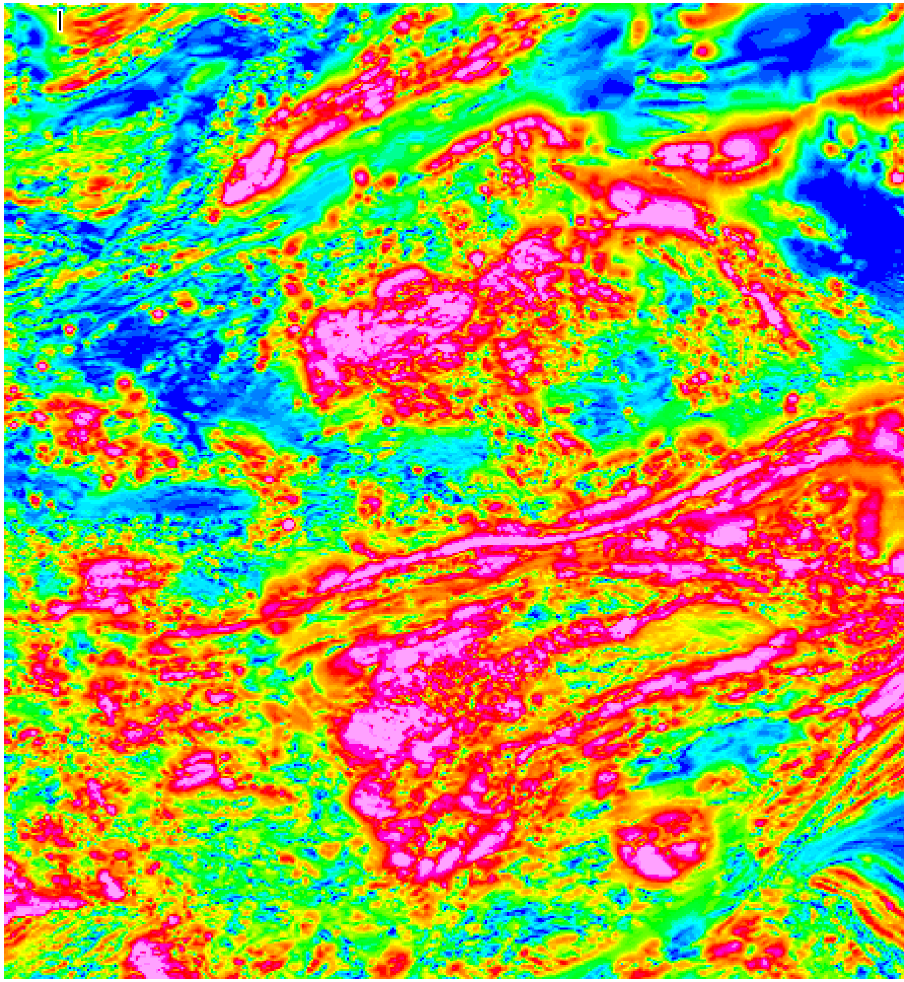
Reduced To Pole



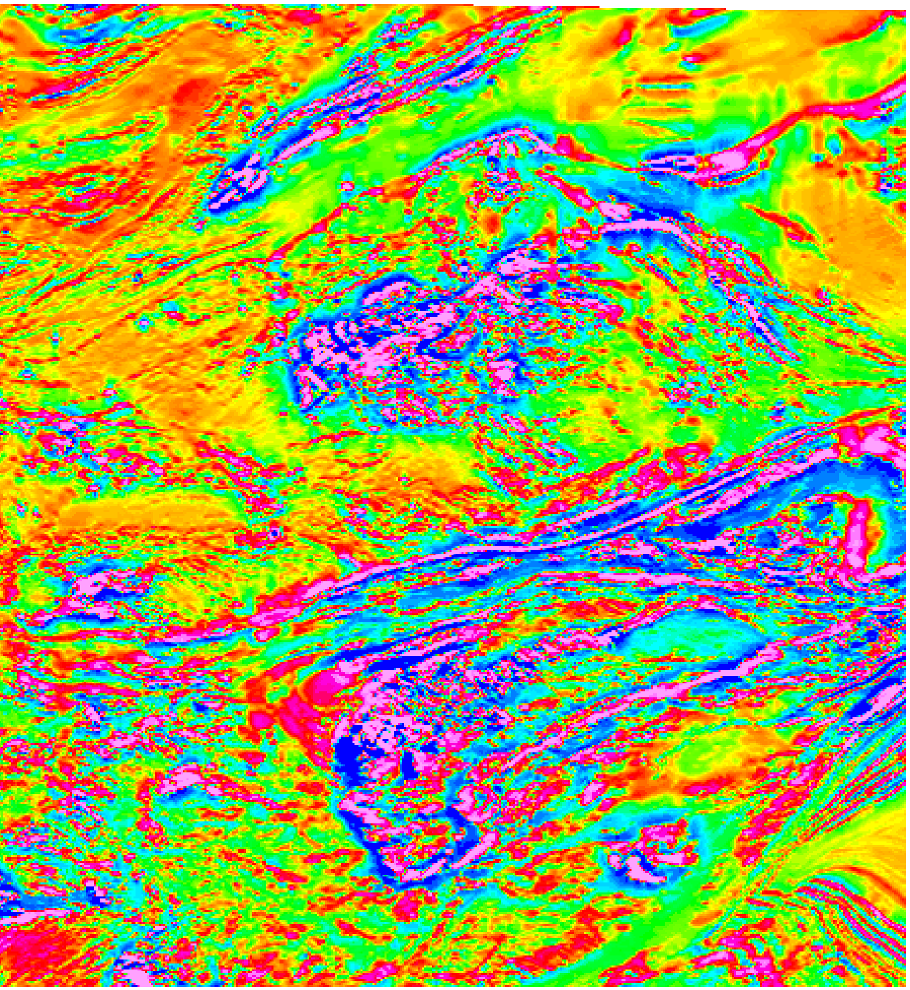
Reduced to pole



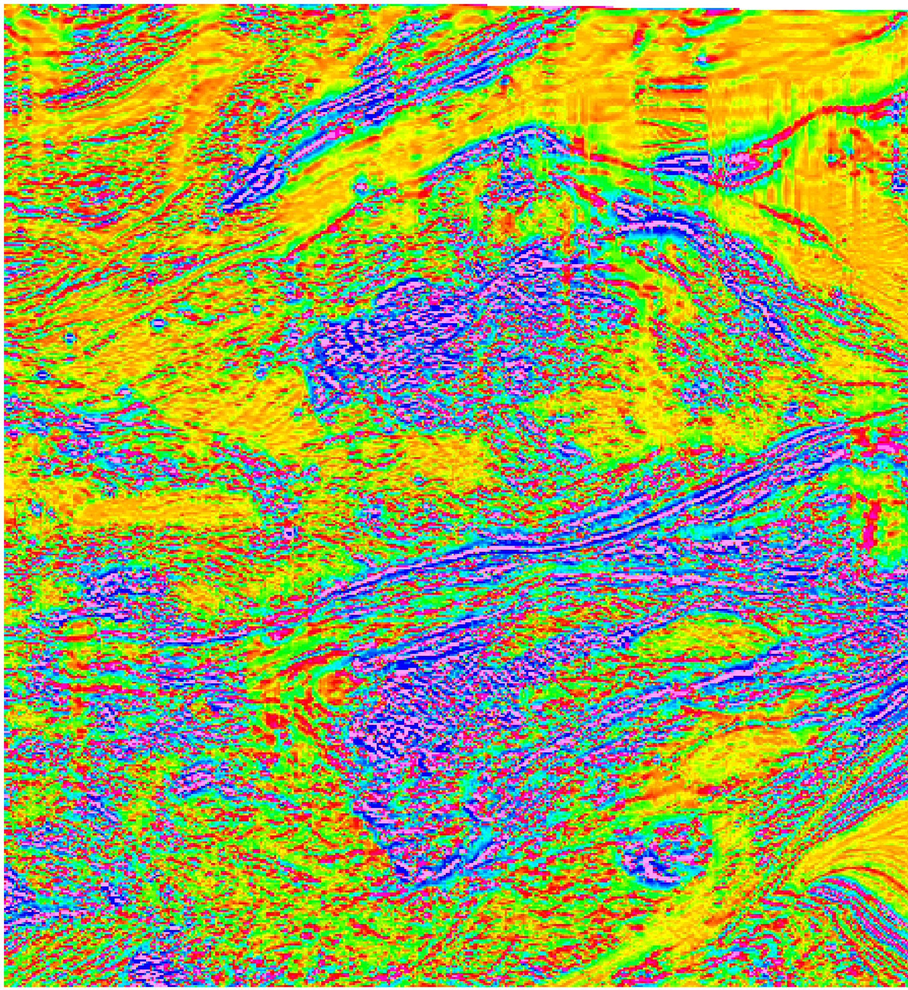
Analytical Signal



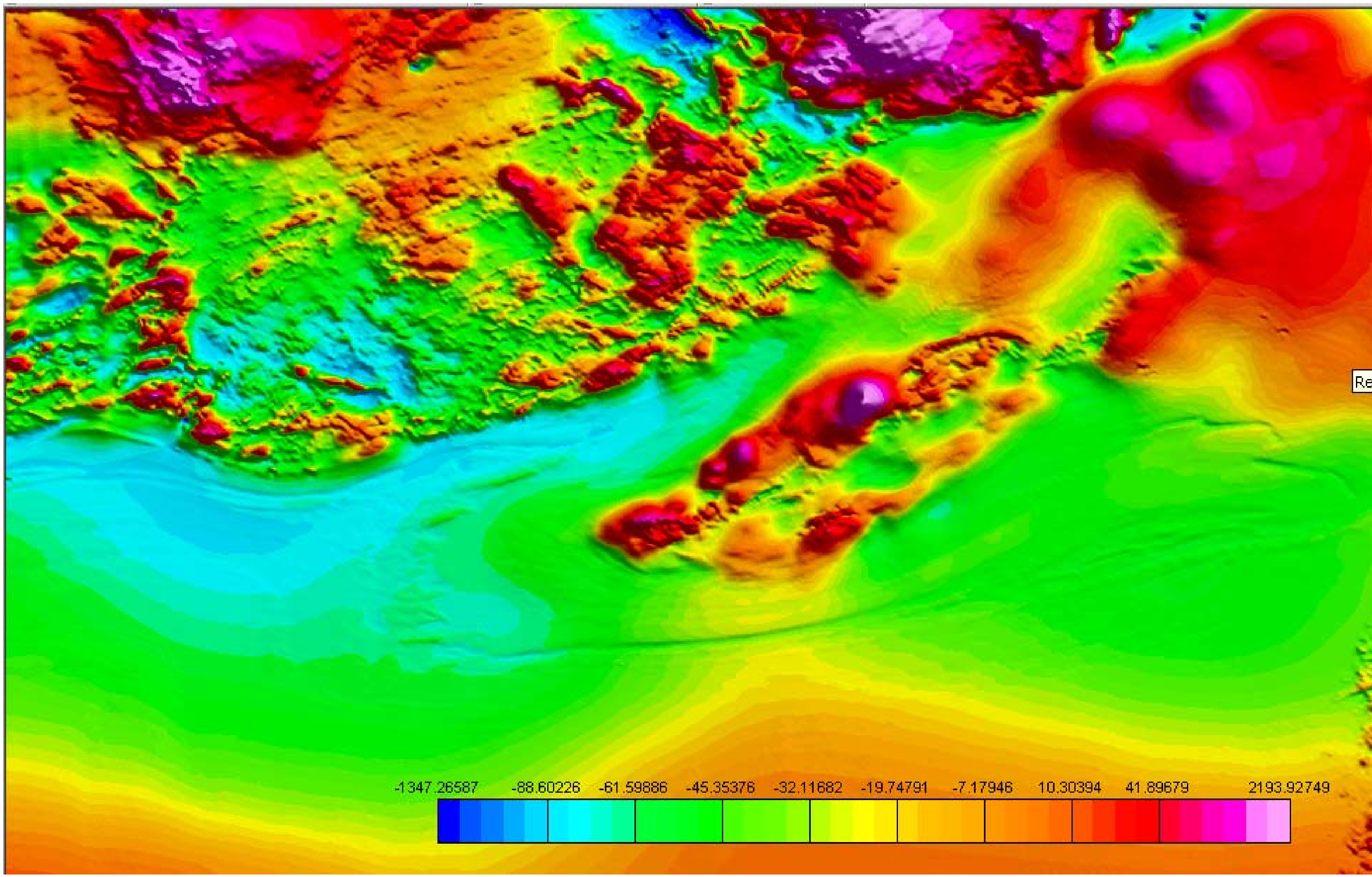
1st Vertical Derivative



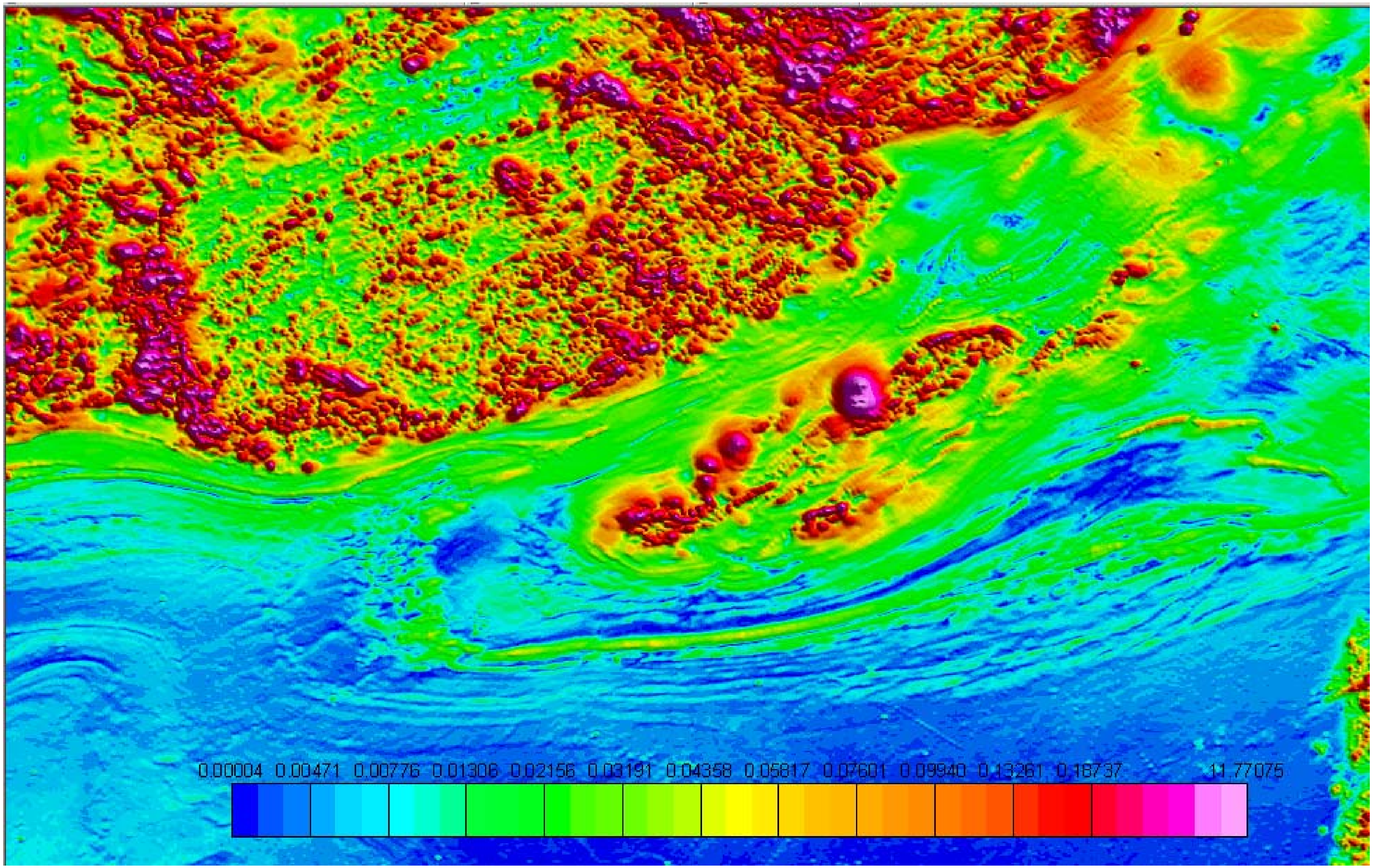
2nd Vertical Derivative



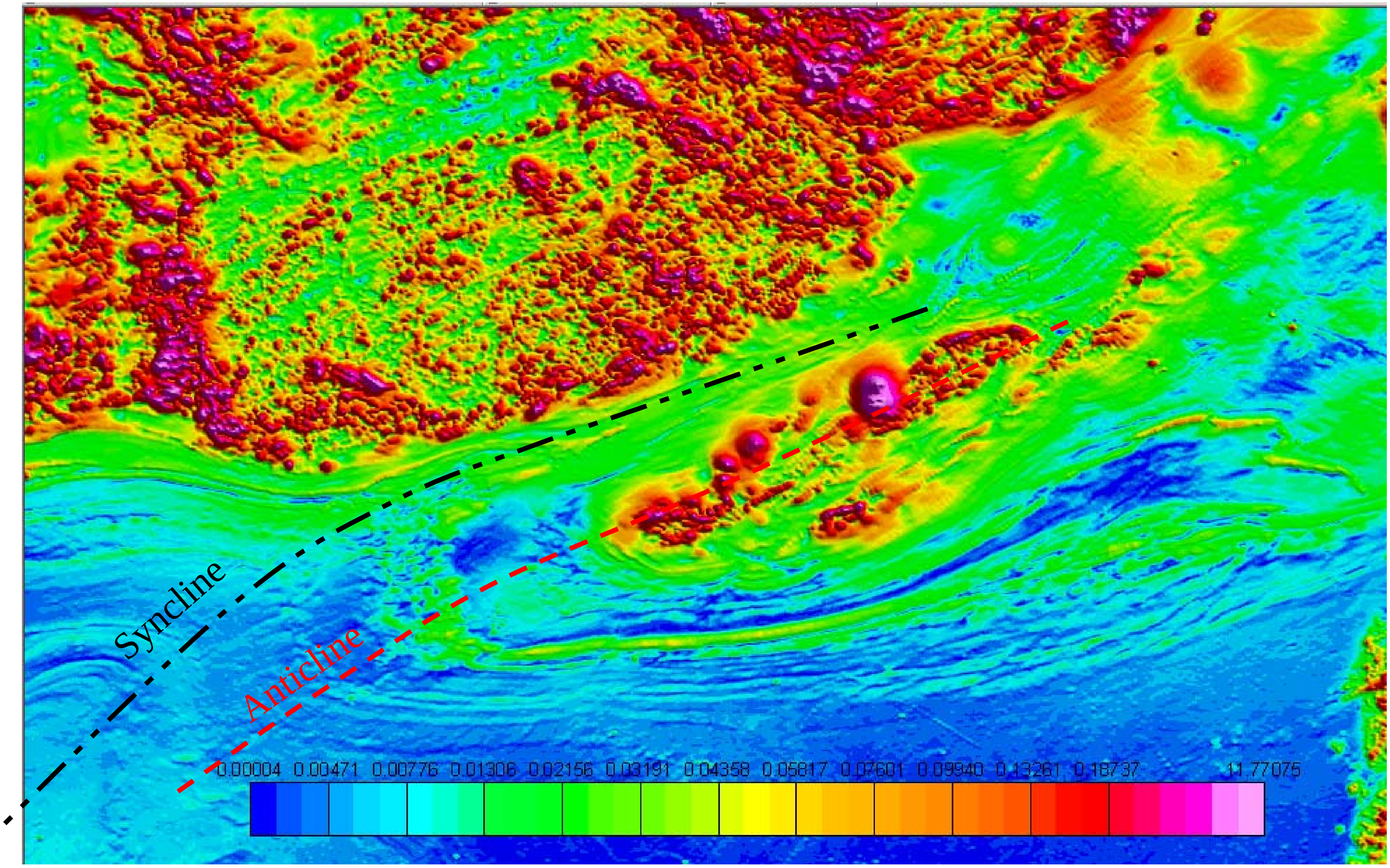
Magnetic field reduced to the pole



Analytical signal of the Magnetic field



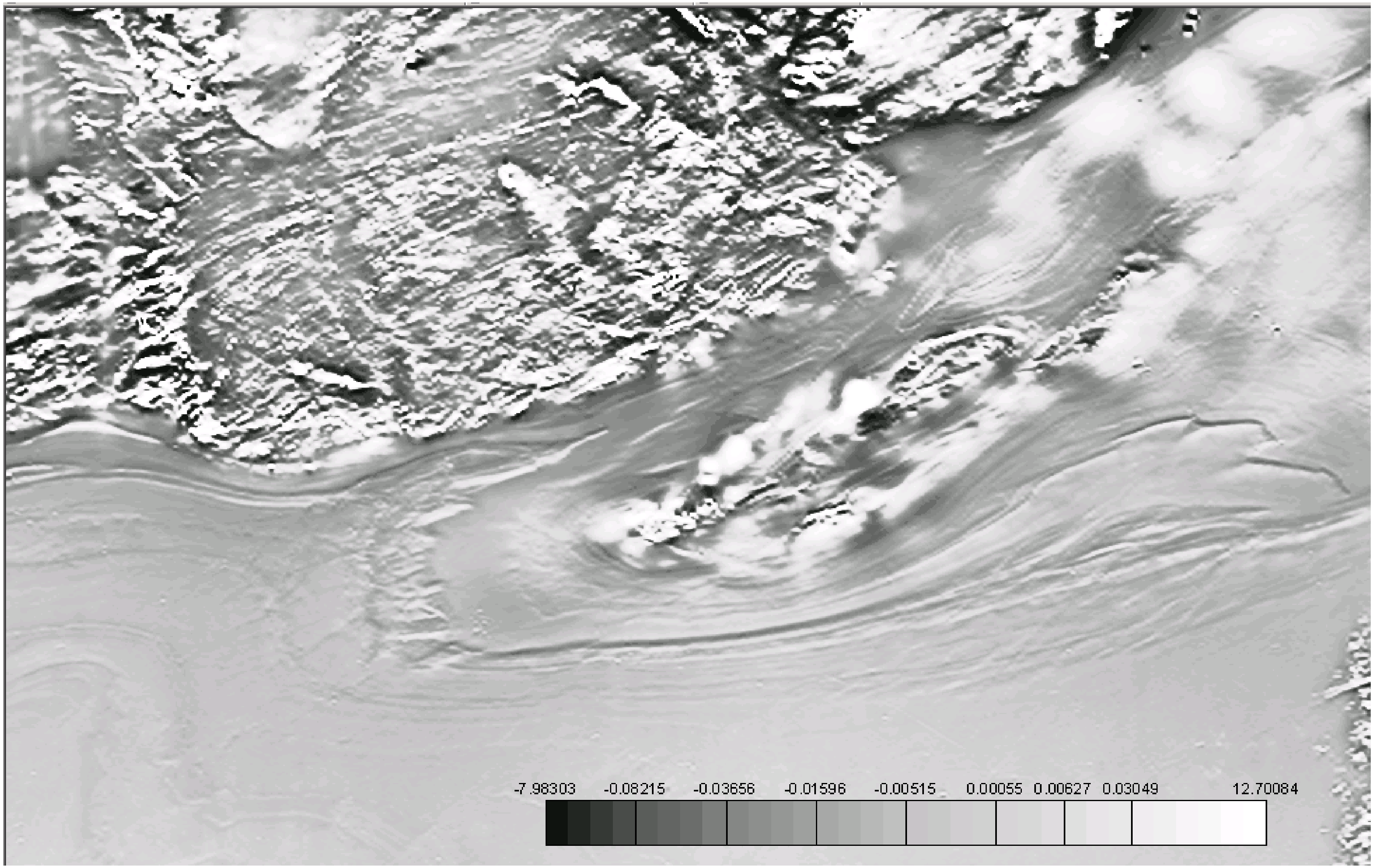
Foreland evolution and folds



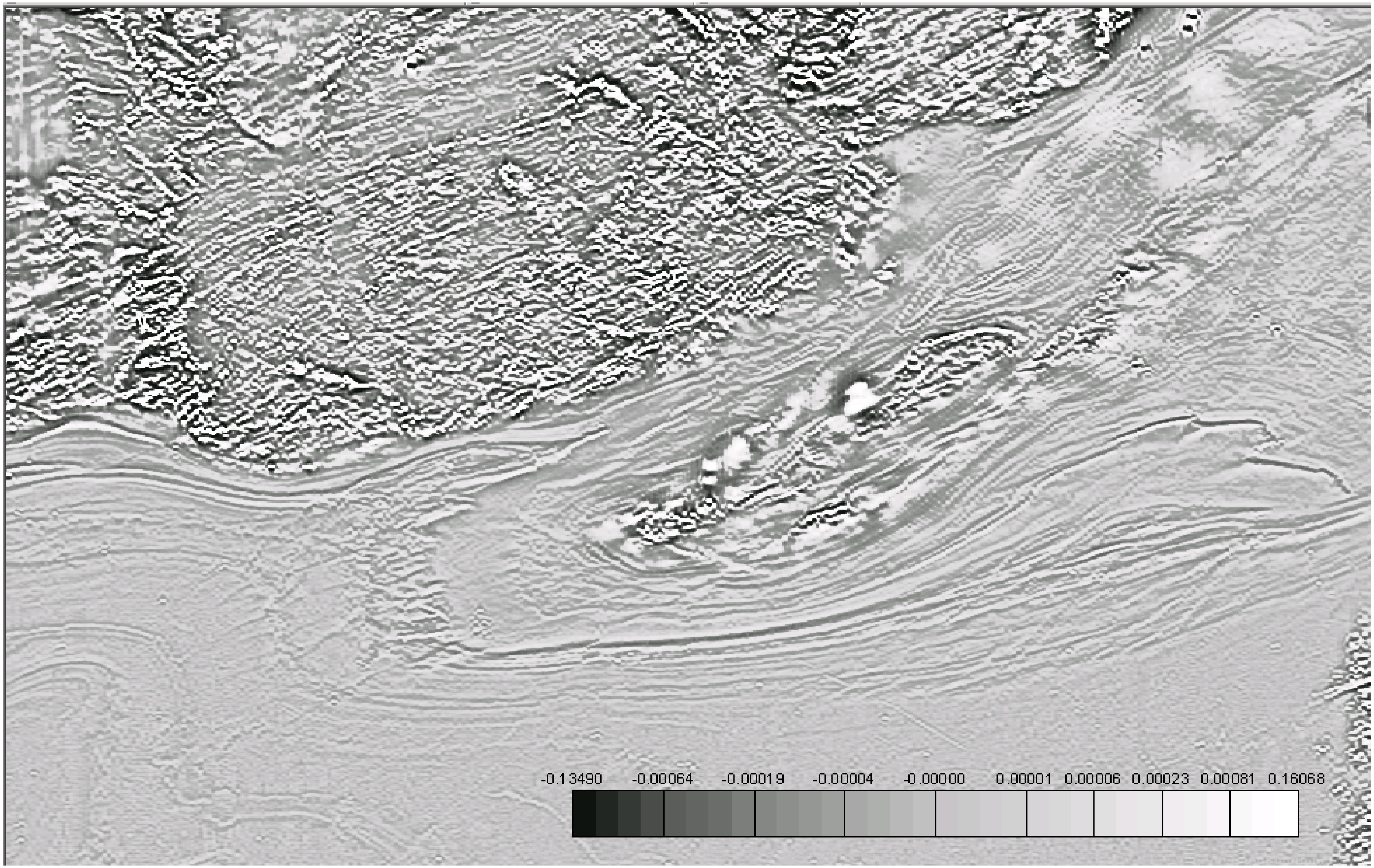
10km

Analytical signal of the magnetic field

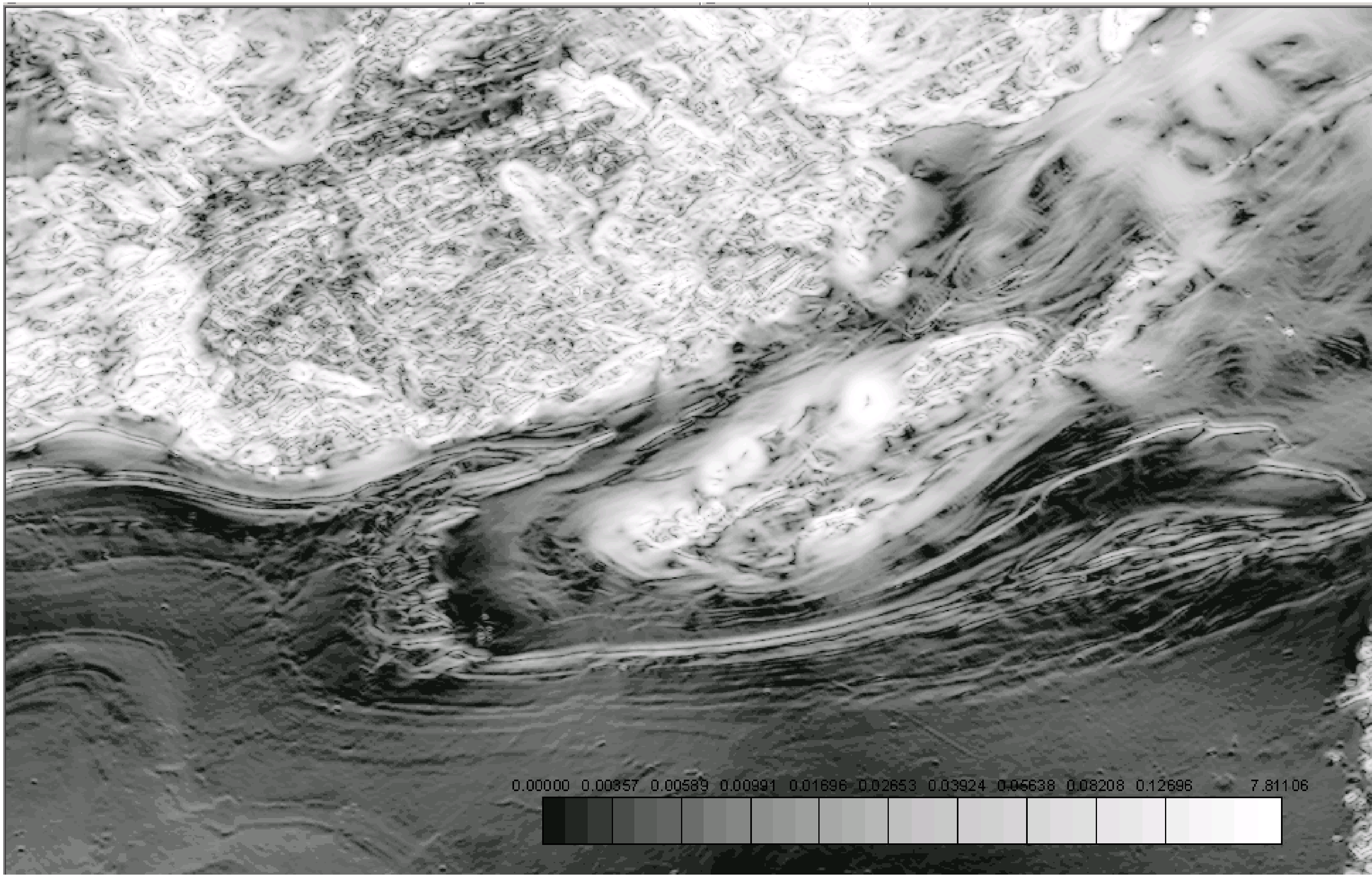
1st vertical derivative of the RTP



2nd vertical derivative of the RTP



Total horizontal derivative of the RTP



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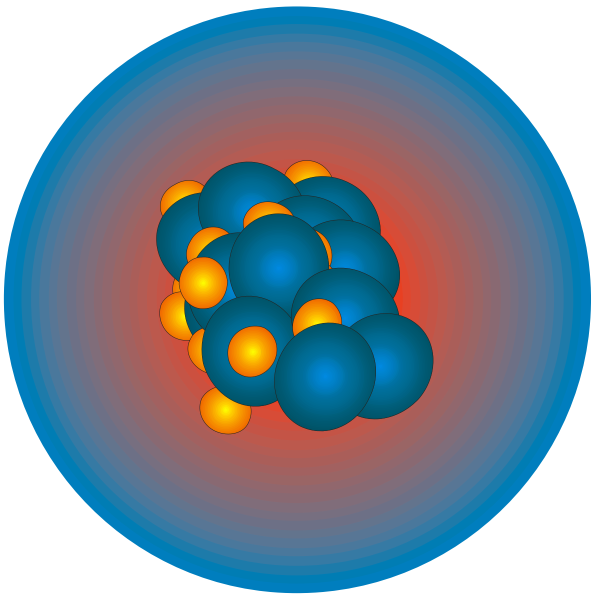
Principles of radiometric surveys

- The physical parameter measured is the gamma-ray activity of radio elements
- The measured gamma radiation is function of the geometry and physical property contrasts of the radioactive sources, on environmental and other effects (soil moisture, rainfall, vegetation, non radioactive overburden, movement of airborne sources of radiation in the Lower atmosphere) and finally size, efficiency and speed of the detector
- Interpolation of recorded value of radioelements enable the production of maps and profiles which locate zones of high and low value and evaluate the amplitude of the signal

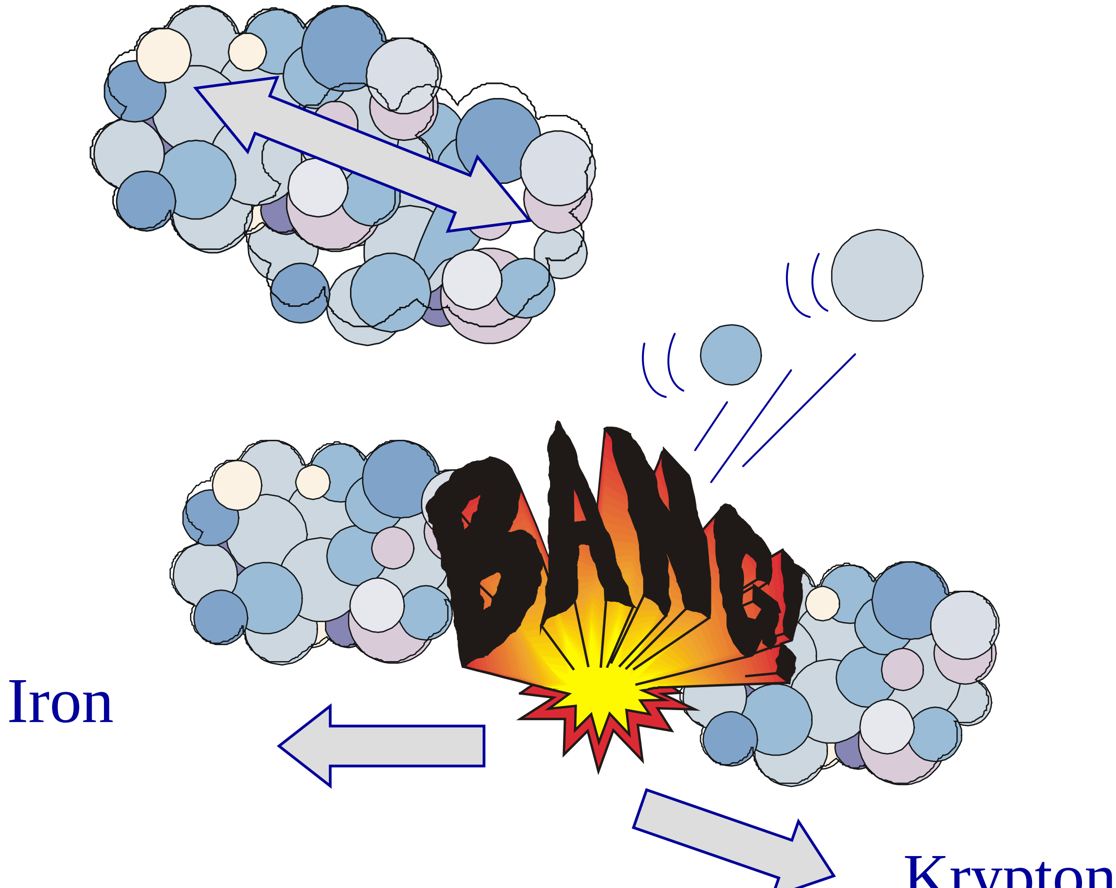
What do we measure?

- The physical parameter detected and measured by radiometric surveys is the gamma-ray activity of radio elements
- Unstable isotopes change to more stable nuclei by the emission of energetic ionising radiation (α, β and γ)
- Each radioisotope has a characteristic probability, the so-called "half-life" of the isotope, the time taken for half the nuclei to decay
- The results are best considered in geochemical terms

Nuclear fission, particles and radiation release



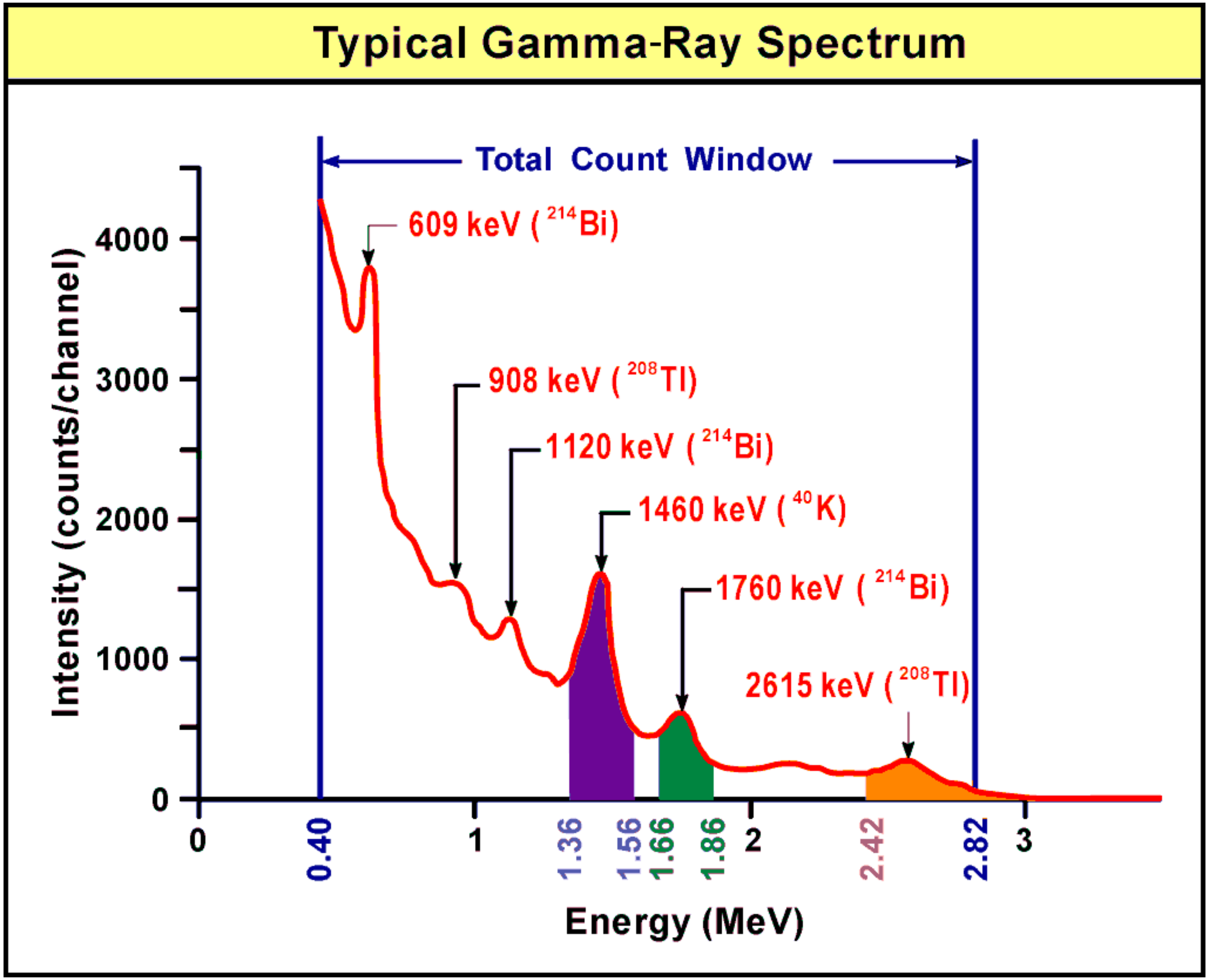
Uranium nucleus splits
into two smaller more stable
elements



Gamma-Ray Emitters

- The 1st group of natural radioactive source is composed of ^{40}K, ^{238}U, ^{235}U, ^{232}Th which have half-lives in the order of $5x10^{9}$ years, i.e., the age of the earth
- ^{238}U and ^{232}Th don't emit γ Ray and we rely on the γ Ray emissions of their radioactive daughter

The Gamma-ray spectrum



Spectrometer

1 cristal
« Up »

4 crystals
« Down »

Iodure Sodium crystals

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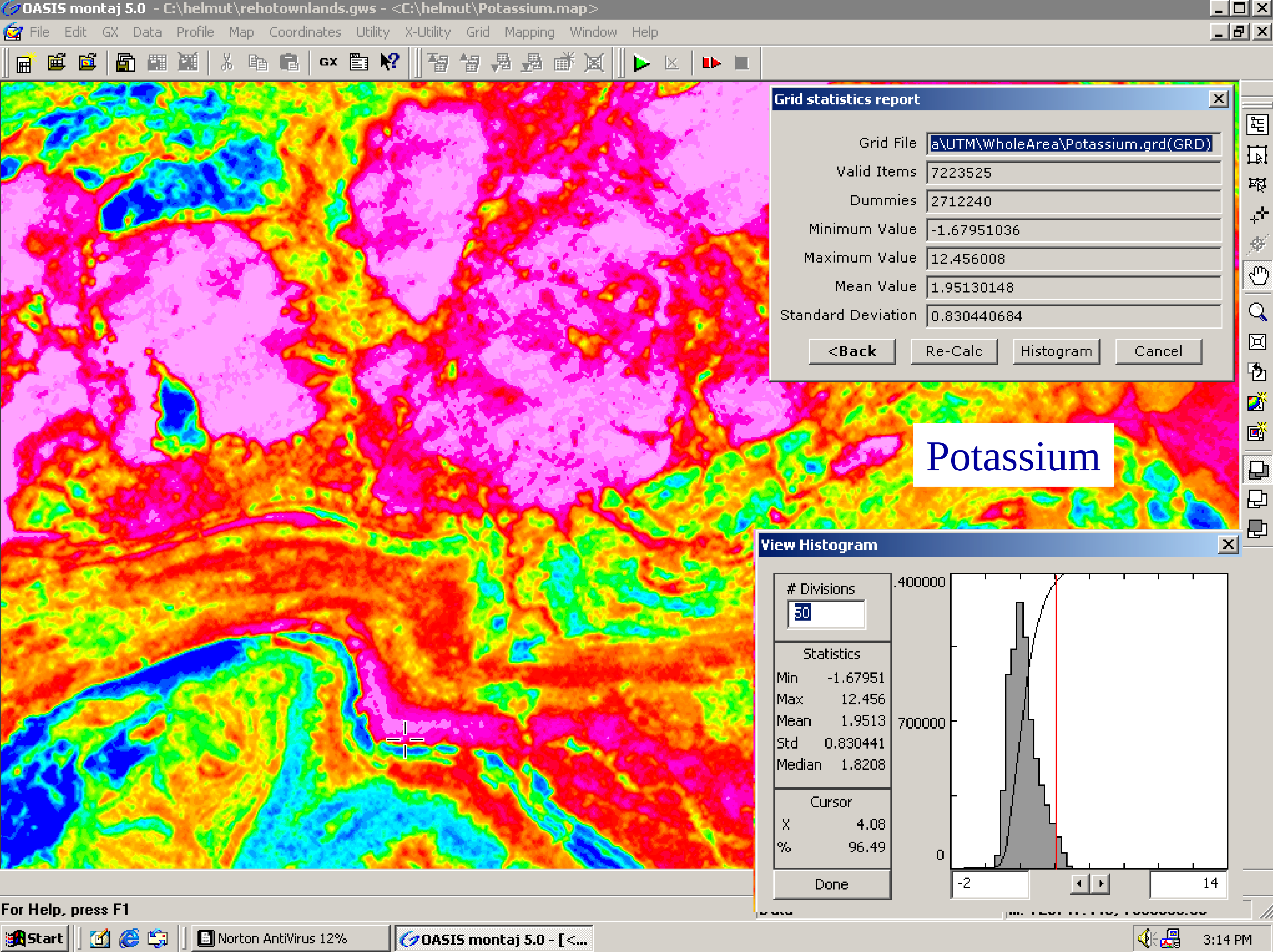
The gamma-ray signature

- Two factors for the usefulness of airborne gamma ray spectrometry
  - the extent to which distribution of the radioelements relates to the differences of lithology of common rocks and alteration processes
  - the extent to which the radioelement content of bedrock is reflected in the composition of superficial materials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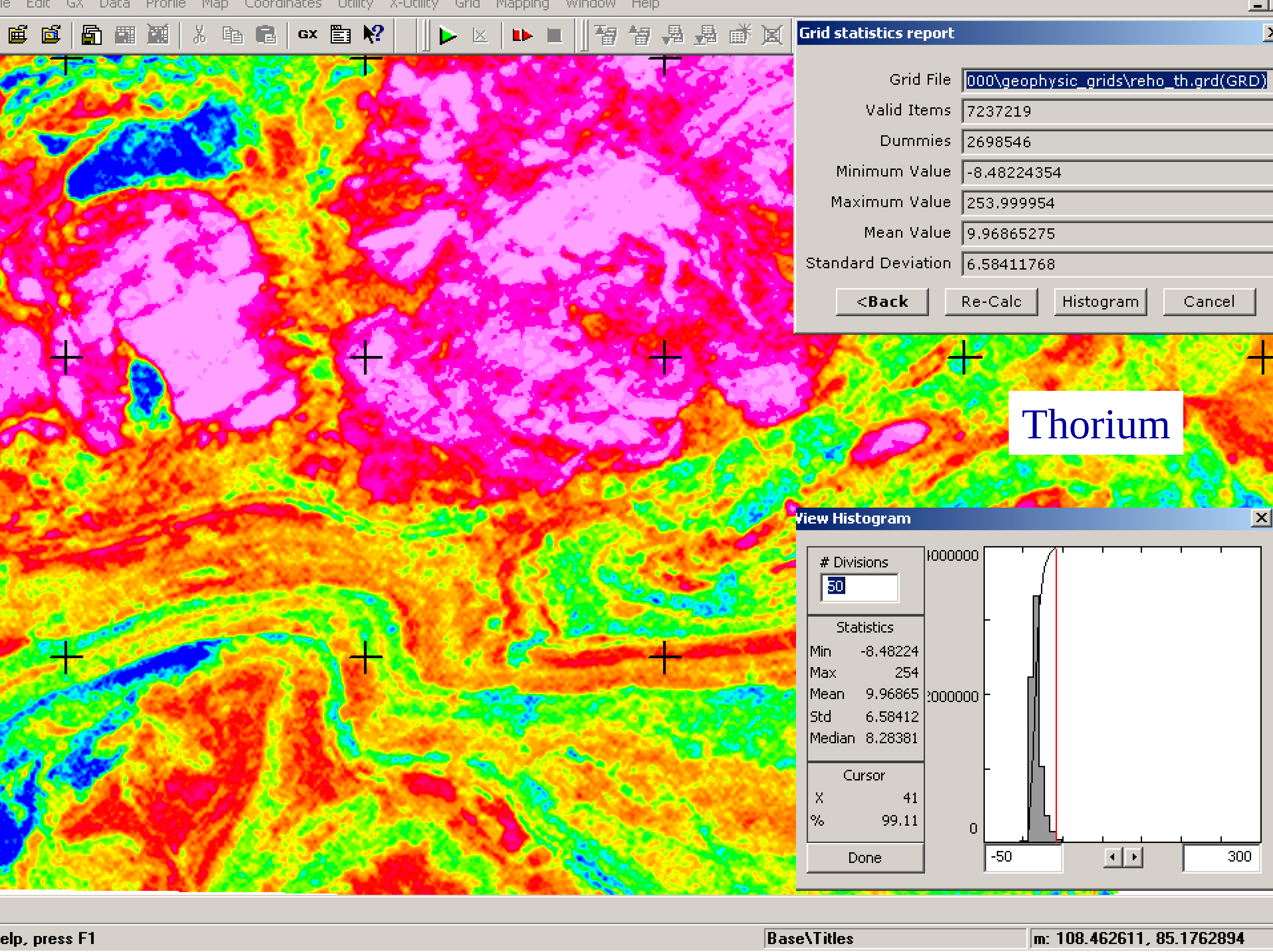
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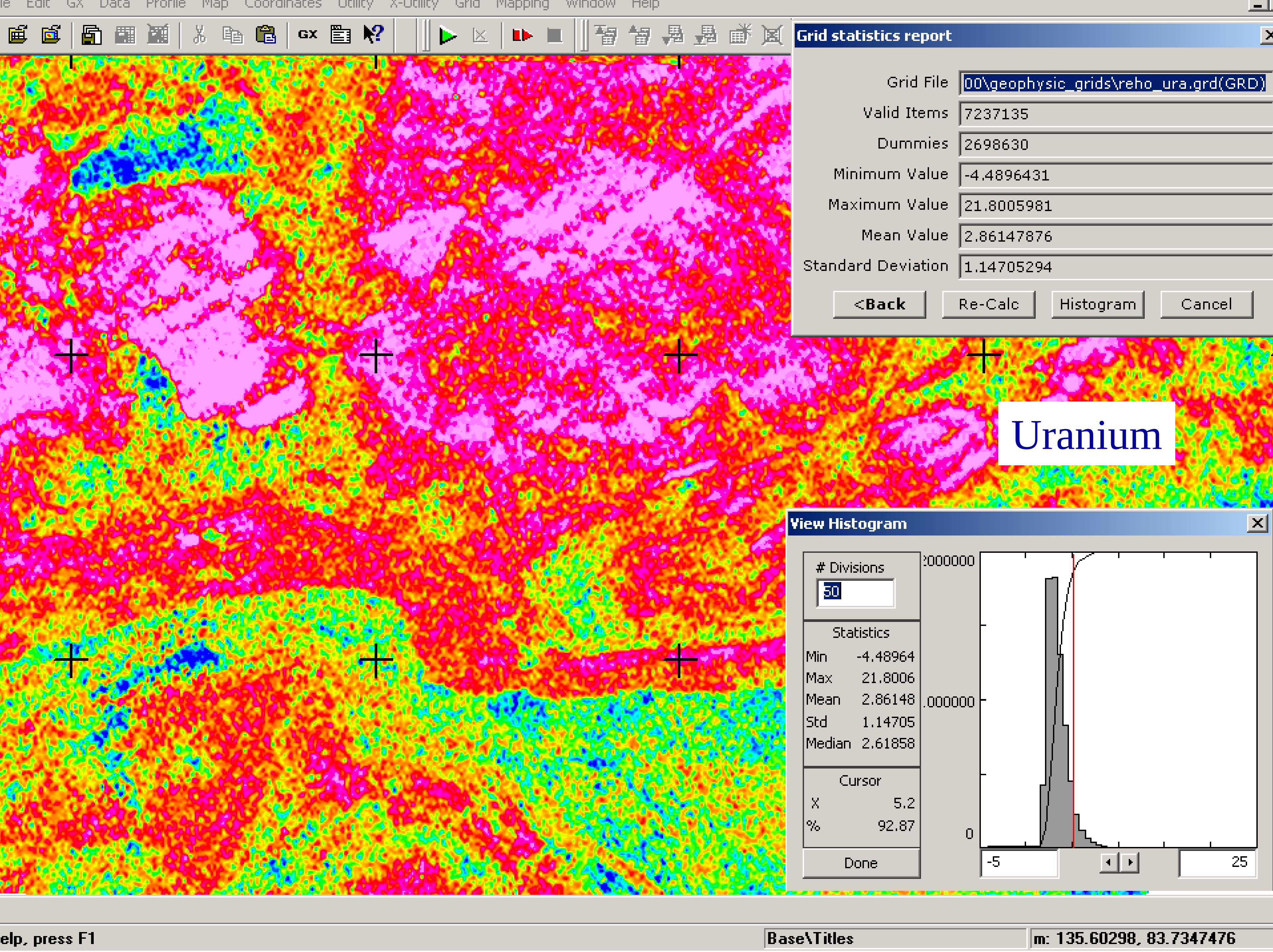
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Median 2.61858
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elp, press F1

Introduction to the use of geophysical datasets

MAGNETISM

- The Earth Magnetic field
- The magnetic susceptibility of rocks
- The use of magnetic data and grid processing for interpretation

RADIOMETRY

- The natural gamma ray activity
- The gamma-ray signature
- Where are radioelements in the (continental) crust ?

Where are radioelements in the (continental) crust ?

- Potassium is the 8^{th} most abundant element in the Earth's crust (1.1 to 2.5 %)
  - most K occurs in potassic feldspars and micas
- Uranium (~2.7 ppm) and Thorium (~8.5 ppm) are trace elements as primary constituents or substituted
  - U in pechblende (UO_2, UO_3), uraninite, Th in thorianite (ThO_2)
  - Constituents of accessory minerals (zircon, monazite 20/15% Th, ± rutile, epidote, ilmenite)
  - Substituted in micas

What are the sources of radioelements in the (continental) crust ?

- Sources of radioactive elements as K, Th and U are found in orogenic or in subduction-related processes:
  - melting and recycling of continental crust
  - large ion lithophile elements as Rb, K, Ba, Th, Sr released and incorporated into rising melts

Radioelements in minerals

	K in %	Th in ppm	U in ppm
Biotite		**0.5 - 50**	**1 - 40**
Amphibole		**5 - 50**	**1 - 30**
K-feldspar		**3 - 7**	**0.2 - 3**
Muscovite			**2 - 8**
Olivine		**trace**	**0.01**
Plagioclase		**0.5 – 0.3**	**0.2 – 0.5**
Pyroxene		**2 - 25**	**0.01 - 40**
Quartz		**0.5 - 6**	**0.1 - 5**

Radioelements in accessory minerals

	K in %	Th in ppm	U in ppm
Allanite		**500 - 5000**	**30 - 700**
In pegmatite		**1000 - 20000**	**7 - 100**
Apatite		**20 - 150**	**5 - 150**
In pegmatite		**50 - 250**	**10 - 50**
Epidote		**50 - 500**	**20 - 50**
Monazite		**25000 - 200000**	**500 - 3000**
Sphene		**100 - 600**	**100 - 700**
Xenotime		**Trace**	**500 - 35000**
Zircon		**100 - 2500**	**300 - 3000**
In pegmatite		**50 - 4000**	**100 - 6000**
Orthite		**5000 - 20000**	**200 - 4000**

Radioelements in rocks

York and Farquhar (1972), Faure (1986)

	Mean K in %	Mean Th in ppm	Mean U in ppm
Acid extrusive	**3.1**	**11.9/21.9**	**4.1/4.1**
Acid intrusive	**3.4/3.5**	**25.7/15**	**4.5/4**
Intermediate extrusive	**1.1**	**2.4**	**1.1**
Intermediate intrusive	**2.1/2.4**	**12.2/9.8**	**3.2/3**
Basic extrusive	**0.7/0.8**	**2.2/1**	**0.8/0.5**
Basic intrusive	**0.8/1**	**2.3/3.4**	**0.8/0.8**
Ultrabasic	**0.3/0.01**	**1.4/0.08/0.02**	**0.3/0.007/0.002**
Alk. interm. extrusive	**6.5**	**133.9**	**29.7**
Alk. interm. intrusive	**4.2**	**132.6**	**55.8**
Alk. Basic extrusive	**1.9**	**8.2**	**2.4**
Alk. Basic intrusive	**1.8**	**8.4**	**2.3**

Radioelements in rocks

Dickson and Scott (1997), average value in brackets

	K in %	Th in ppm	U in ppm
Felsic extrusive	2.0-4.4 (3.7)	13-28 (17)	1.4-13 (2.4)
Felsic intrusive	0.3-4.5 (2.4)	2.3-45 (16)	0.4-7.8 (3.3)
Intermediate extrusive	1.8-4.1 (2.7)	1.5-15 (9)	0.9-5.6 (2.3)
Intermediate intrusive	0.7-5.6 (2.7)	0.8-6.1 (2.4)	0.1-1.2 (0.8)
Mafic volcanics	0.3-1.3 (0.9)	2.2/1	0.3-1.3 (0.7)
Mafic intrusive	0.1-0.8 (0.4)	2.3/3.4	<1.1 (0.3)
Ultramafic volcanics	0.2-0.9(0.4)	<4 (1.2)	0.3-0.9 (0.6)

Radioelements in rocks

York and Farquhar (1972), Faure (1986)

	Mean K in %	Mean Th in ppm	Mean U in ppm
Chemical sediments	0.6	14.9	3.6
Carbonate	0.3/0.3	1.3/1.6	2/1.6
Detrital sediments	1.5/1.2	12.4/5.7	4.8/1.9
Shale	2.7	11.2/12	3.7/4
Orthogneiss	2.5/3.4	14.8/10.6	4/2.3
Amphibolite	0.6	0.9	2
Schist	2.5	10.6	2.3
Paragneiss	2.1	12	3

Dickson and Scott (1997), average value in brackets

Carbonate	<0.5 (0.2)	<2.9 (1.4)	0.4-2.9 (1.4)
Arenite	<5.5 (1.8)	4-22 (12)	0.7-5.1 (2.3)
Shale	0.1-4 (2.6)	10-55 (19)	0.3-1.3 (0.9)

Radioelements in geological provinces

	K in %		Th in ppm		U in ppm		
	Mean/ Modal	Max	Mean/ Modal	Max	Mean/ Modal	Max	
Southern Damara foreland (Rehoboth)	2	4	10	41	2.9	22	Proterozoic greenstone belt
Southern Greenland	1	4	5	40	2	15	Proterozoic metamorphic rocks intruded by alkaline complexes
Rwanda	0.8	2.4	13	30	5	16	Equatorial weathering
Kalgoorlie Goldfield (Fimiston, Australia)	0.8	4.1	0.5	2.3	0.6	4.1	Mineralization
	0.3		0		2.4		Unmineralized host rock