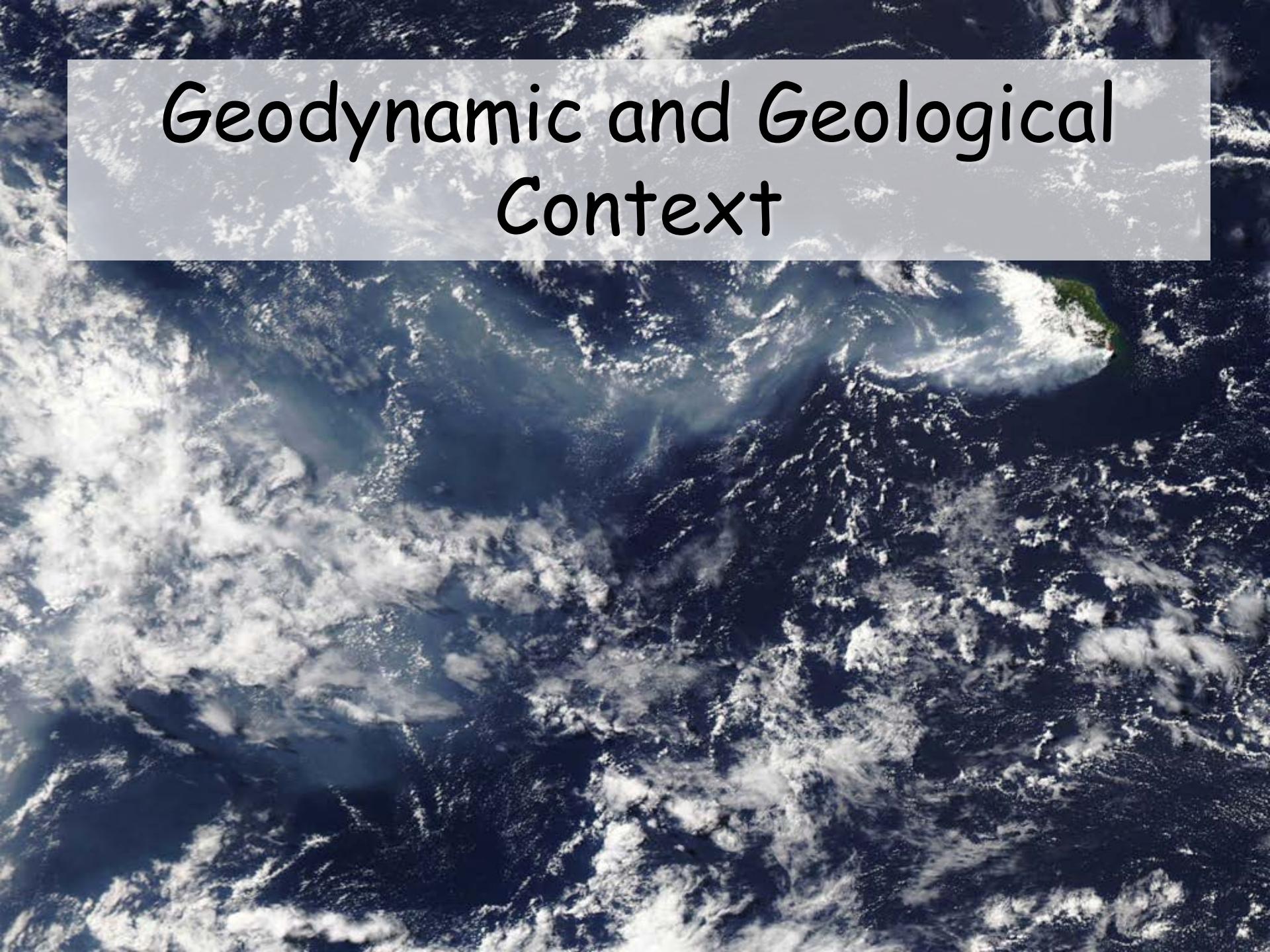


# Internal Structure of a hot spot oceanic volcanic system :

## La Réunion

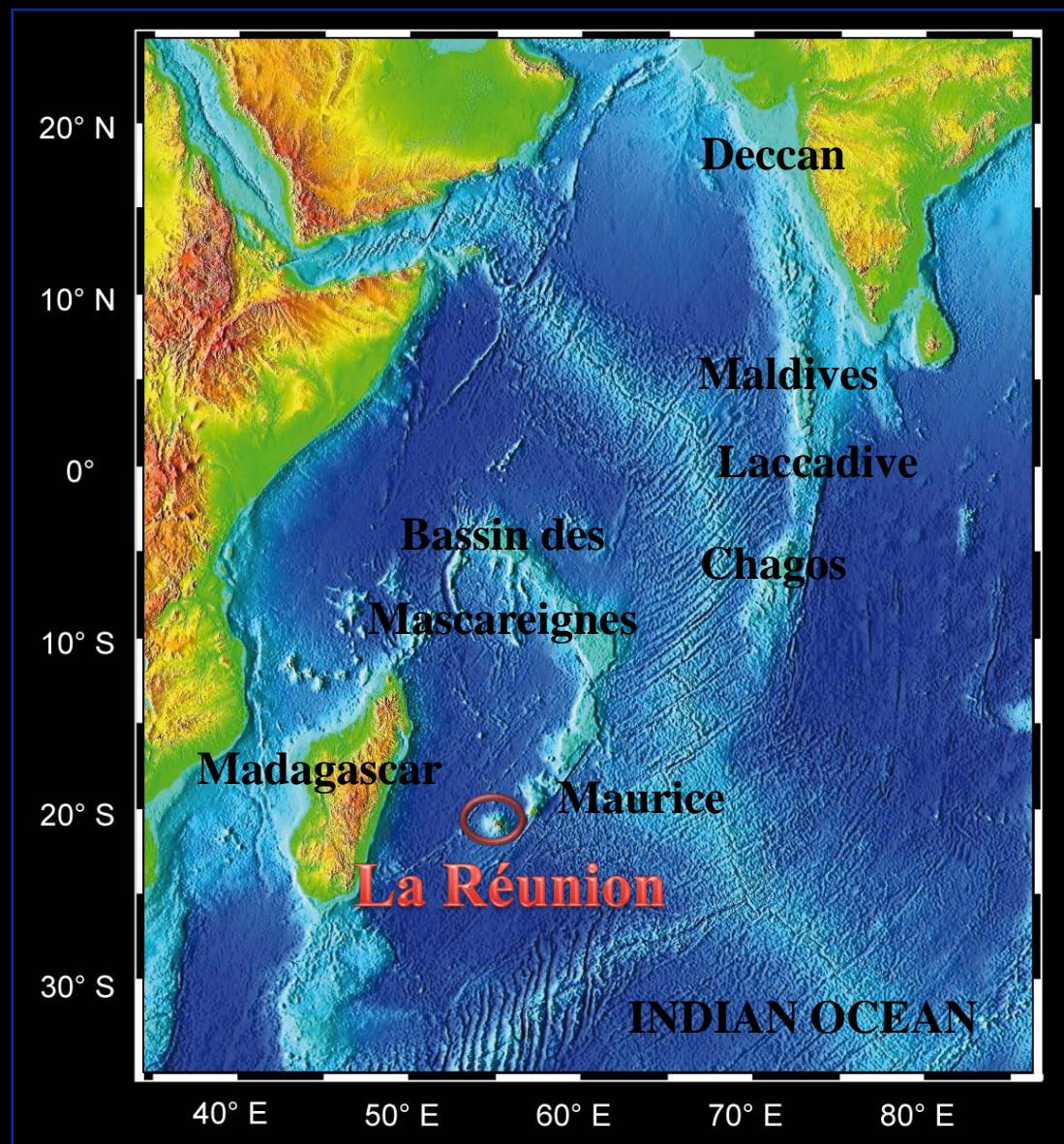
### Geophysical approaches

# Geodynamic and Geological Context

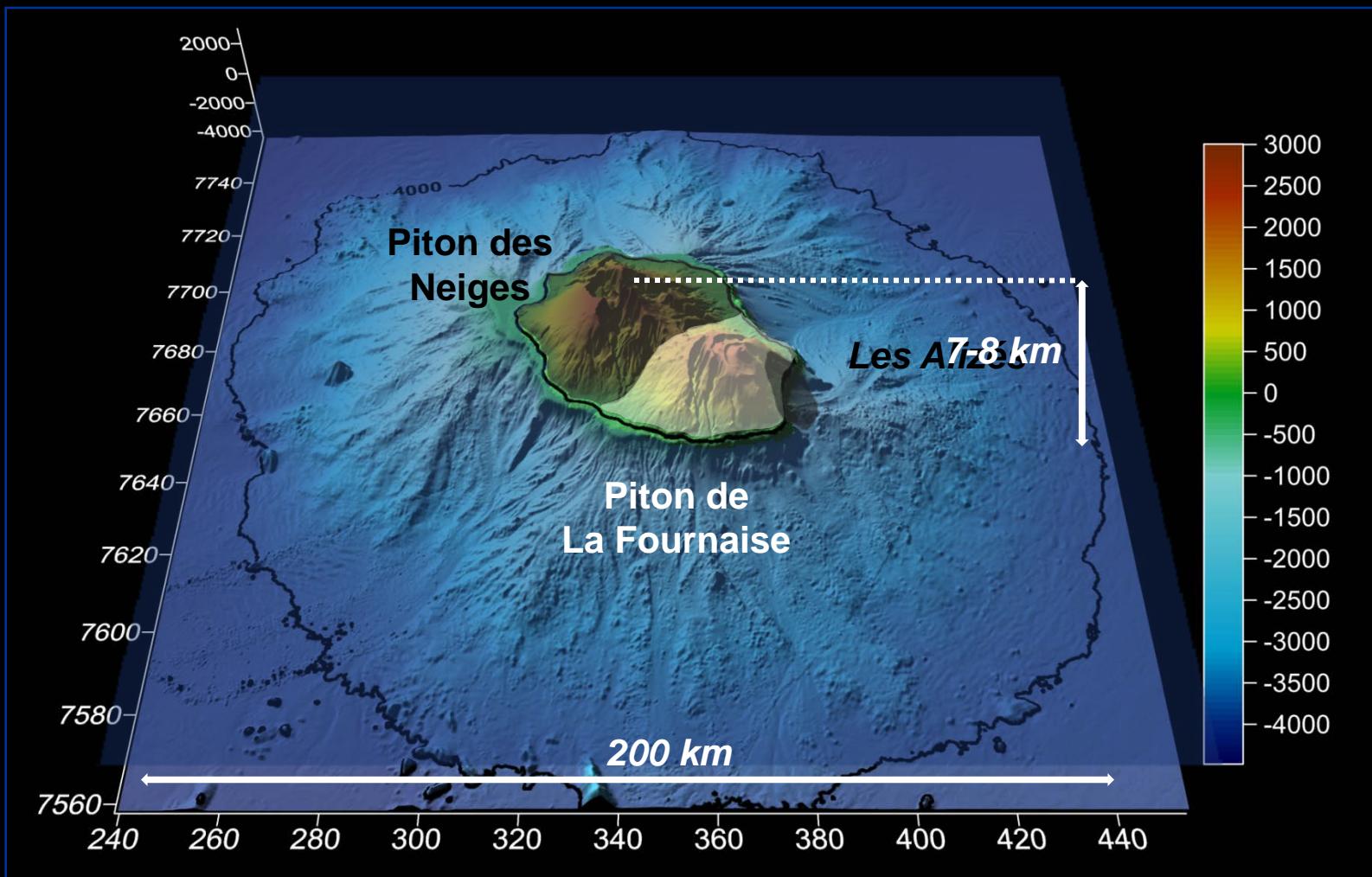


# Geodynamic Context

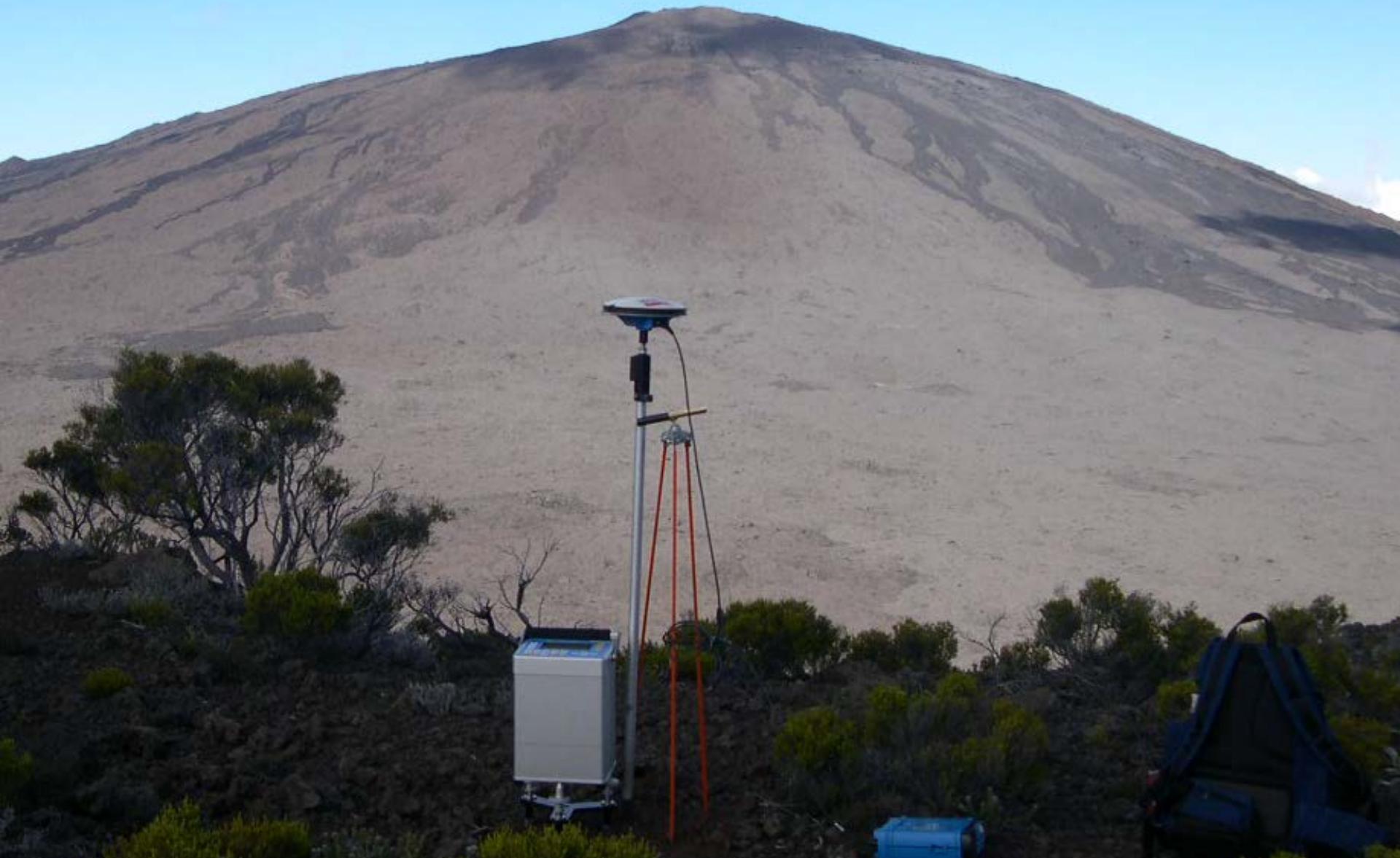
- La Réunion (Indian Ocean)  
 $21^{\circ}10'S; 55^{\circ}44'E$
- Intraplate volcanic system of Bassin des Mascareignes
- Last expression in surface of an asthenospheric hotspot



# Geological Context

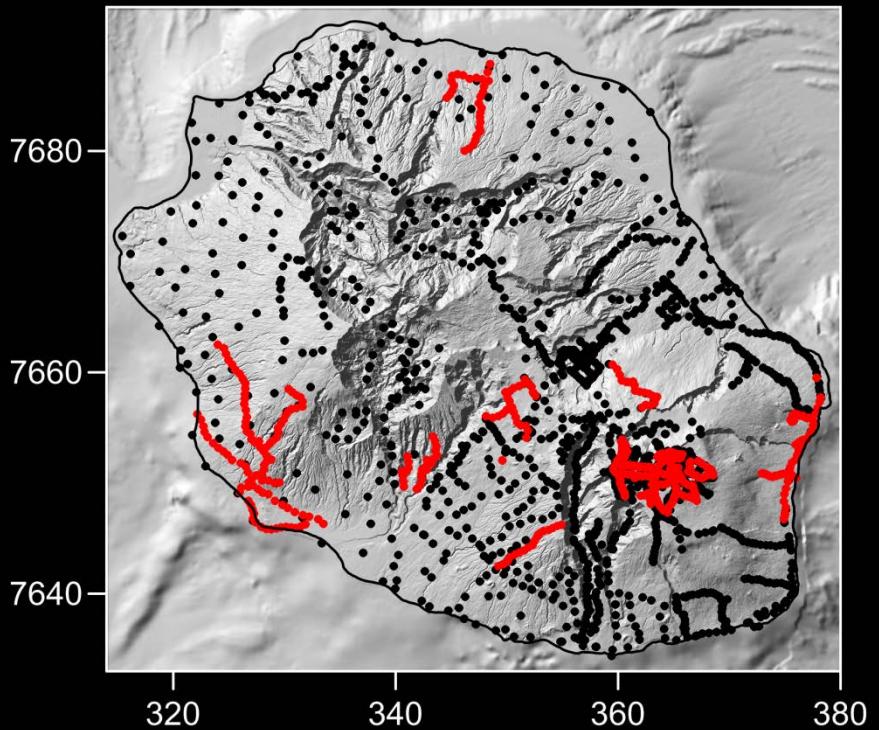


# Methods and Data



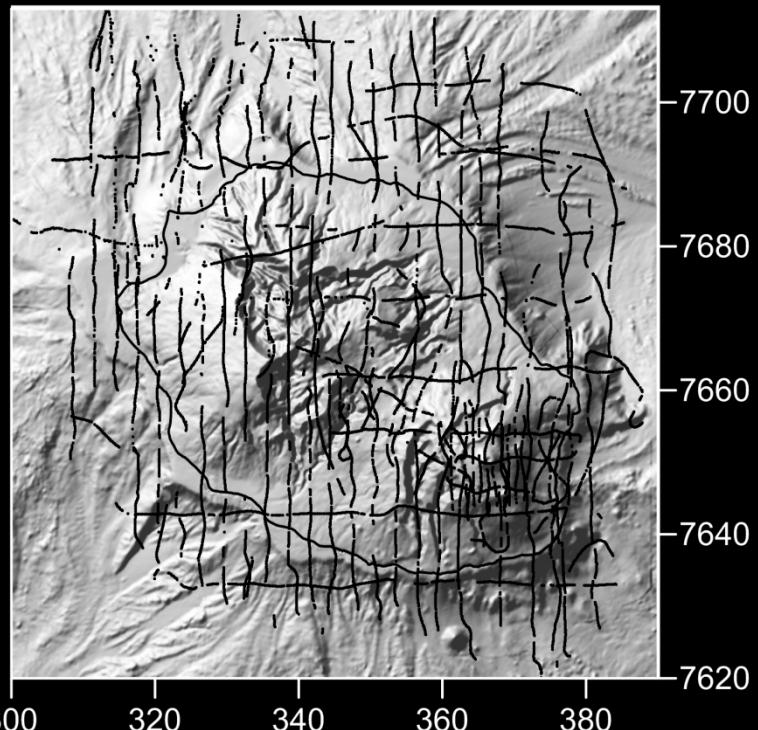
# Methods and Data

## Gravity



*Old surveys*  
(1979, 1999, 2003, 2004)  
**2007 survey**

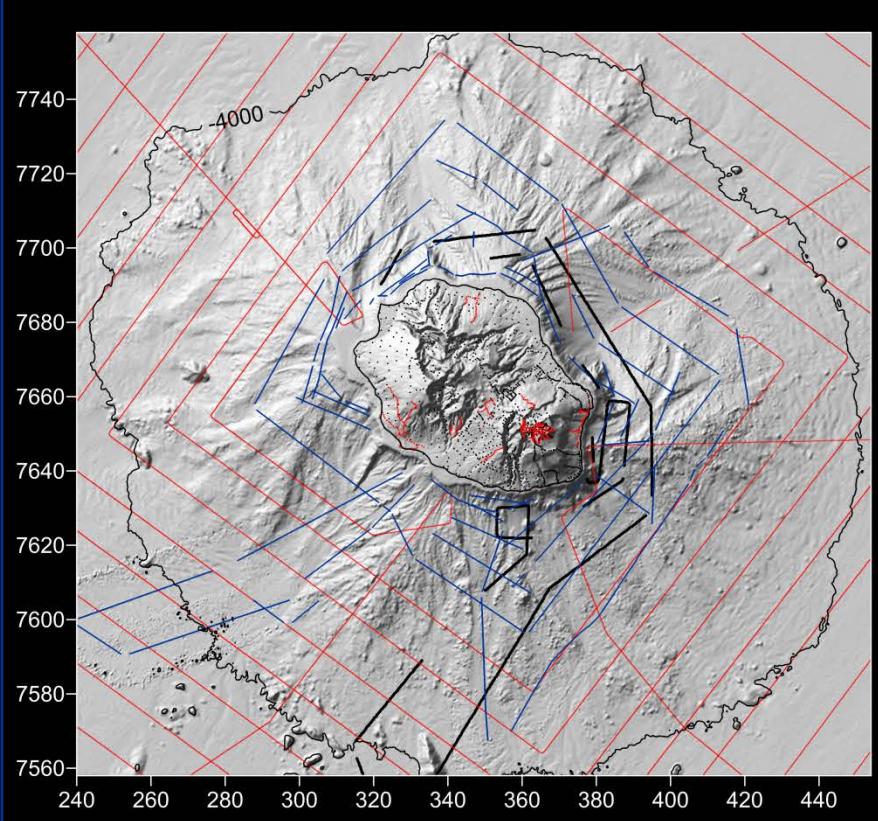
## Magnetism



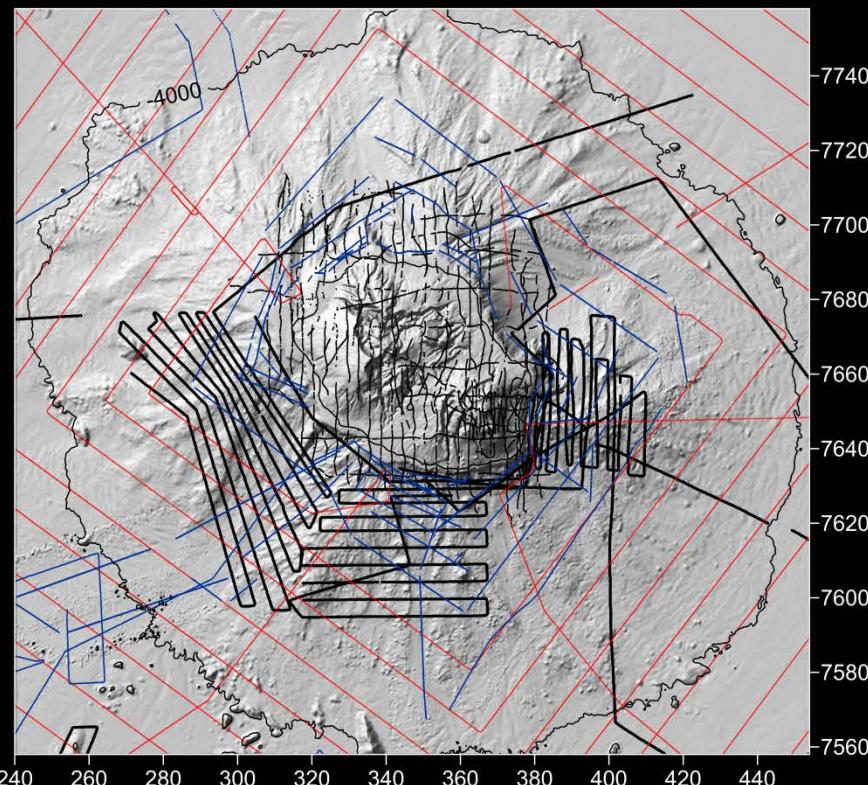
*Aeromagnetic survey (1986)*

# Methods and Data

## Gravity



## Magnetism



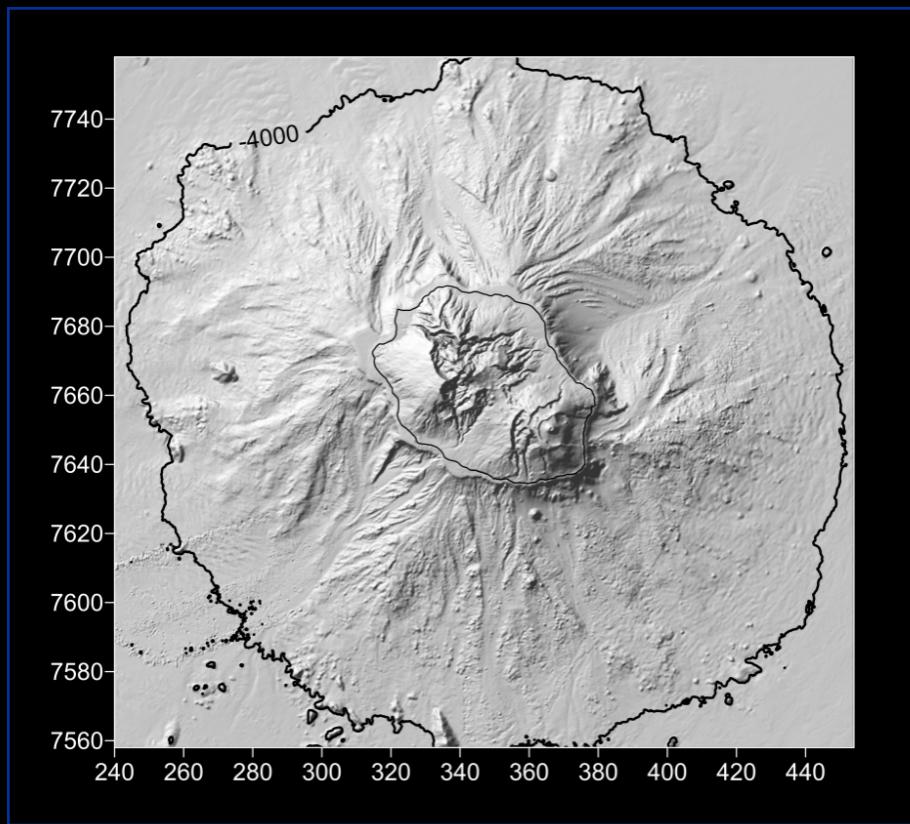
*Forever (2006)  
Eroder 1 (2006) & 2 (2007)  
Old surveys*

# Modelling

- 3D Inversions (*Gmsys 3D, GRAV3D & MAG3D*)
  - ⇒ Smooth models of the density and magnetization distribution
  
- 2D, 2D 1/2 , 2D ¾ gravity and magnetic modelling (*GMSYS*)
  - ⇒ More detailed models with more geological and geophysical constraints

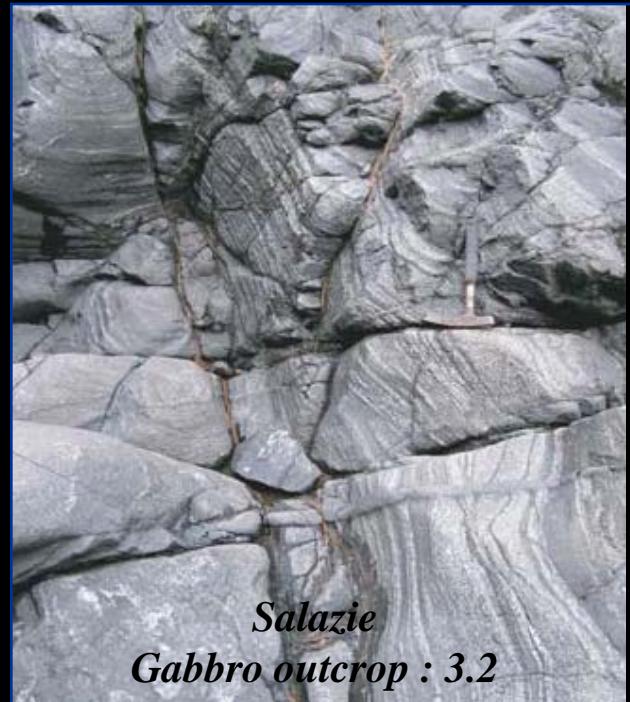
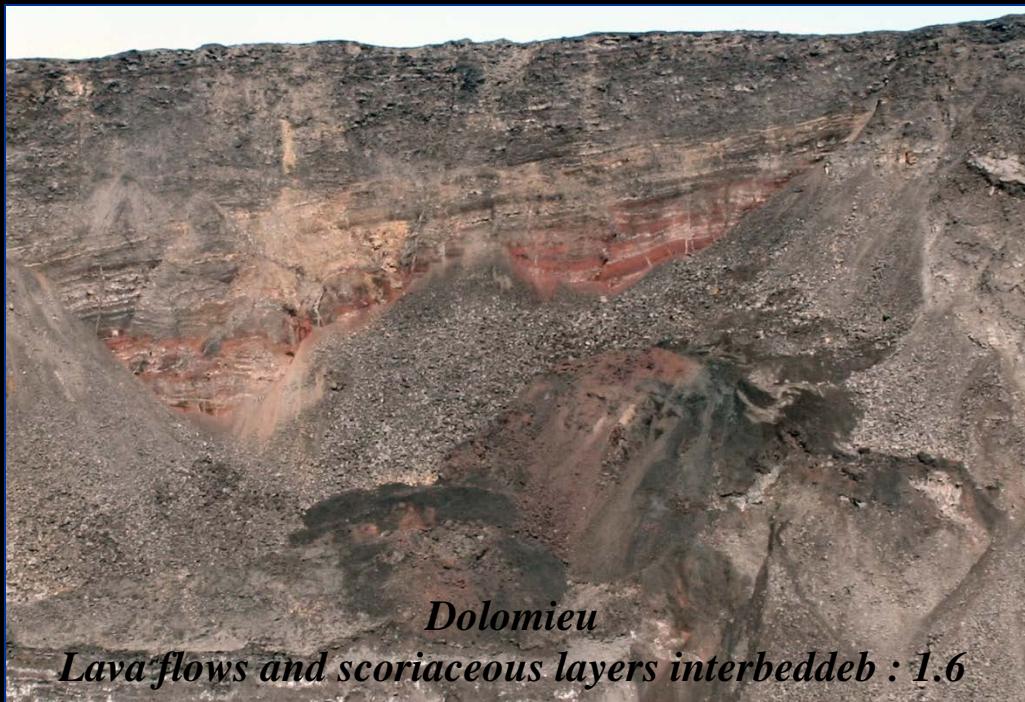
# Modelling constraints

- Bathymetric and seismic data  $\Leftrightarrow$  base of the volcanic edifice – 4000 m



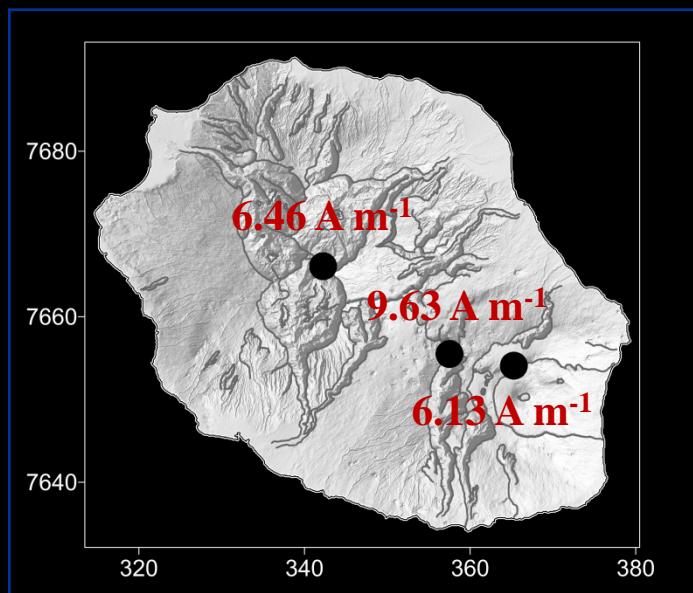
# Modelling constraints

- Bathymetric and seismic data  $\Leftrightarrow$  base of the volcanic edifice – 4000 m
- Geological and geophysical observations  $\Leftrightarrow$   $1.6 < \rho < 3.2 \text{ } 10^3 \text{ kg m}^{-3}$



# Modelling constraints

- Bathymetric and seismic data  $\Leftrightarrow$  base of the volcanic edifice – 4000 m
- Geological and geophysical observations  $\Leftrightarrow 1.6 < \rho < 3.2 \text{ } 10^3 \text{ kg m}^{-3}$
- Paleomagnetic studies  $\Leftrightarrow \pm 8 \text{ A m}^{-1}$



# Gravity of La Réunion



# Gravity of Piton de la Fournaise

## Qualitative interpretation

### ➤ Positive anomalies

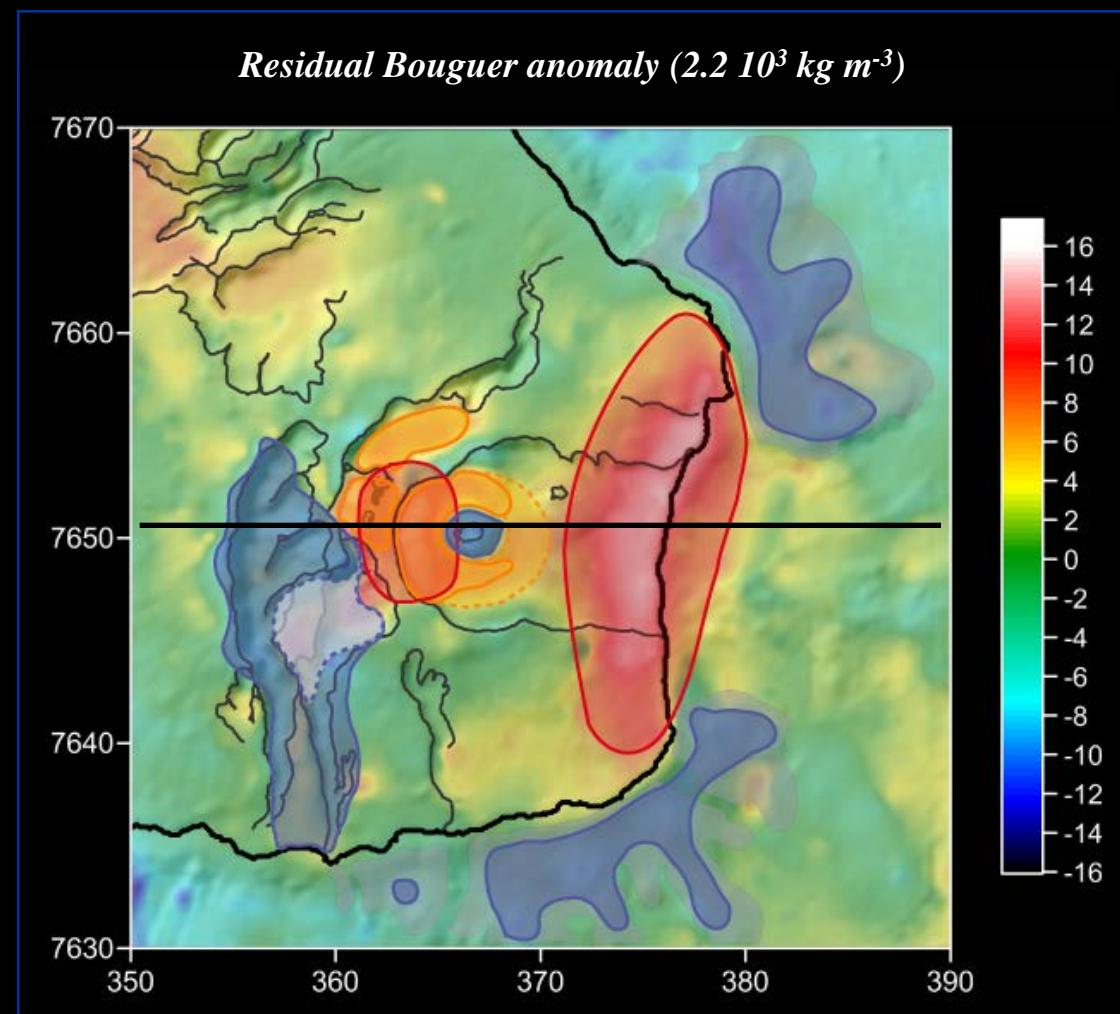
- ⇒ Long  $\lambda$
- Grand Brûlé
- Ancient Shield

### ⇒ Medium $\lambda$

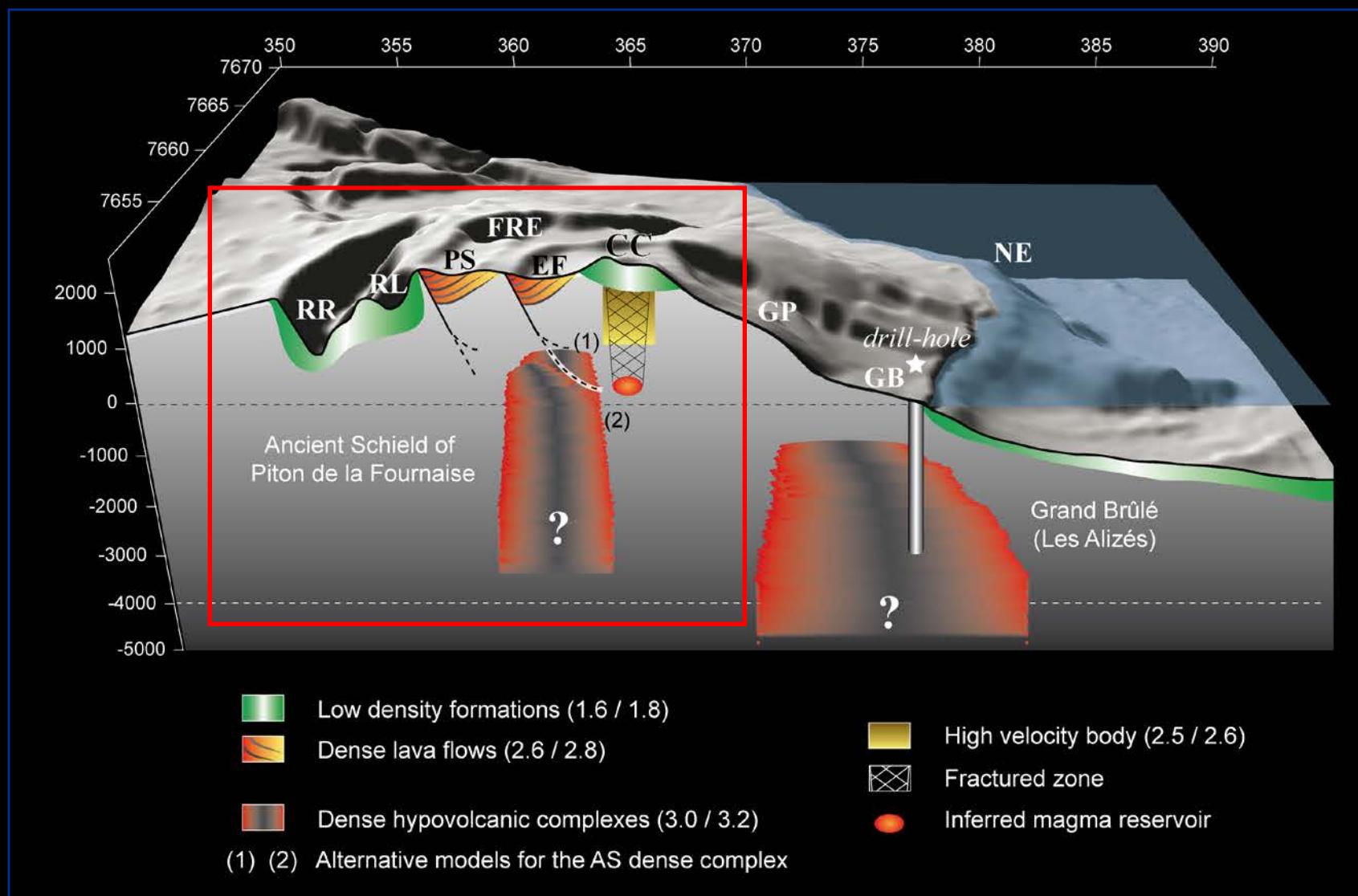
- Plaine des Sables
- Fond de la Rivière de l'Est
- Enclos Fouqué

### ➤ Negative anomalies

- Central Cone
- Rivière de l'Est – Rivière des Remparts
- NE & SE rift zones

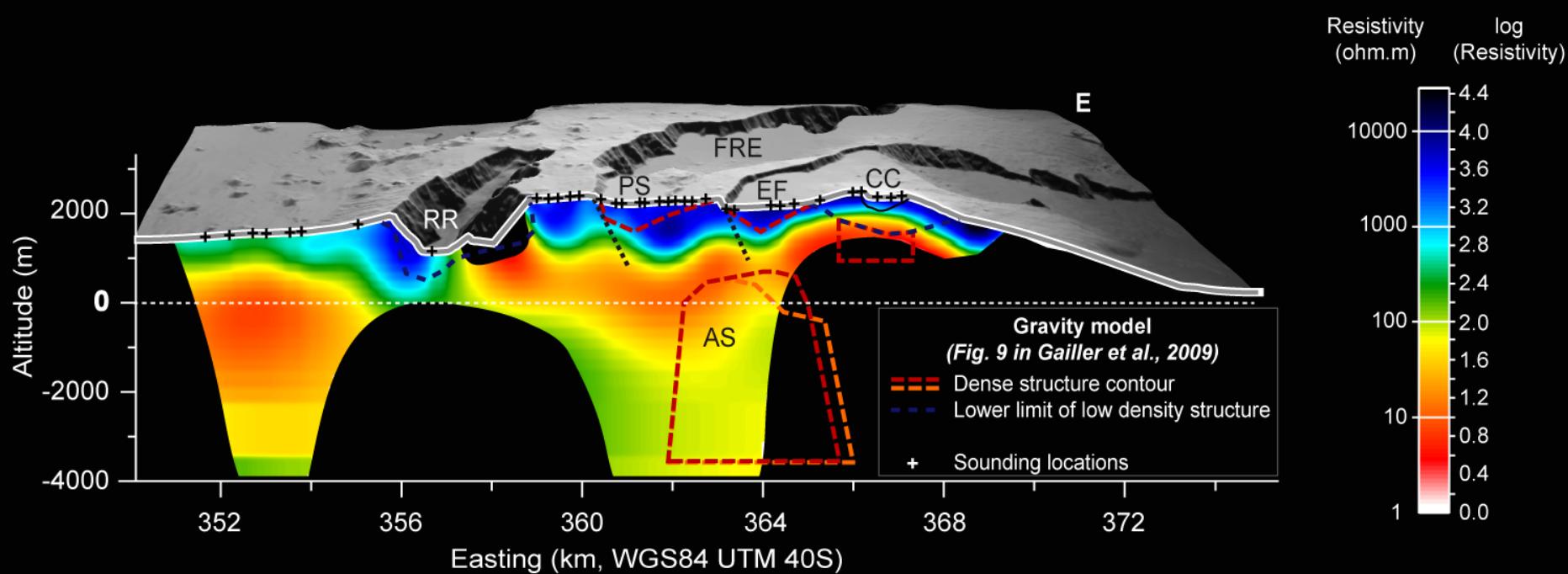


# Gravity of Piton de la Fournaise



# Coherency Gravity – Resistivity

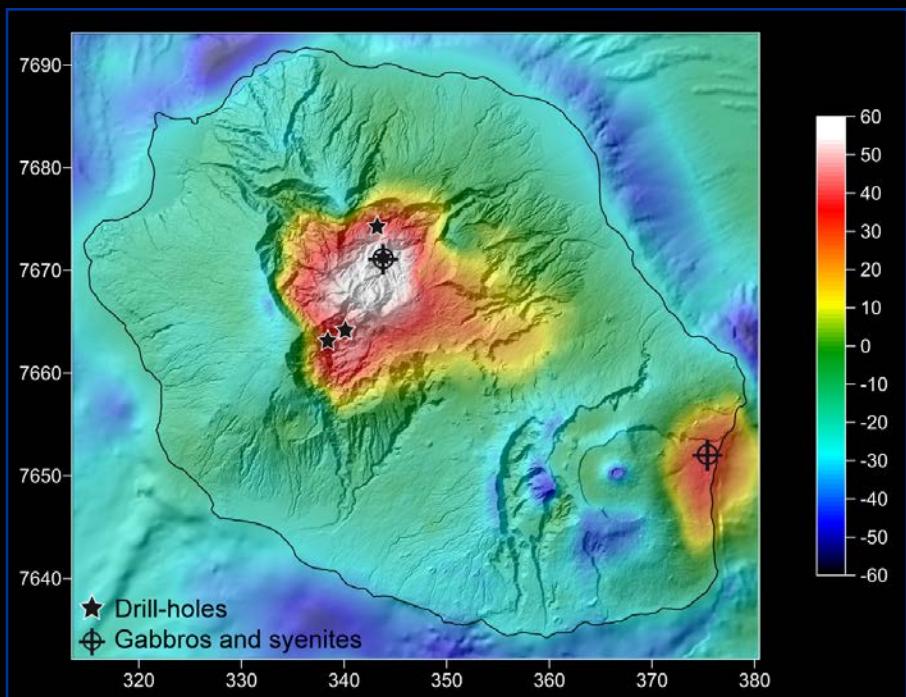
## 2D model of the resistivity data



➤ Doming of the intermediate conductor below the Central Cone associated with PdF hydrothermal system

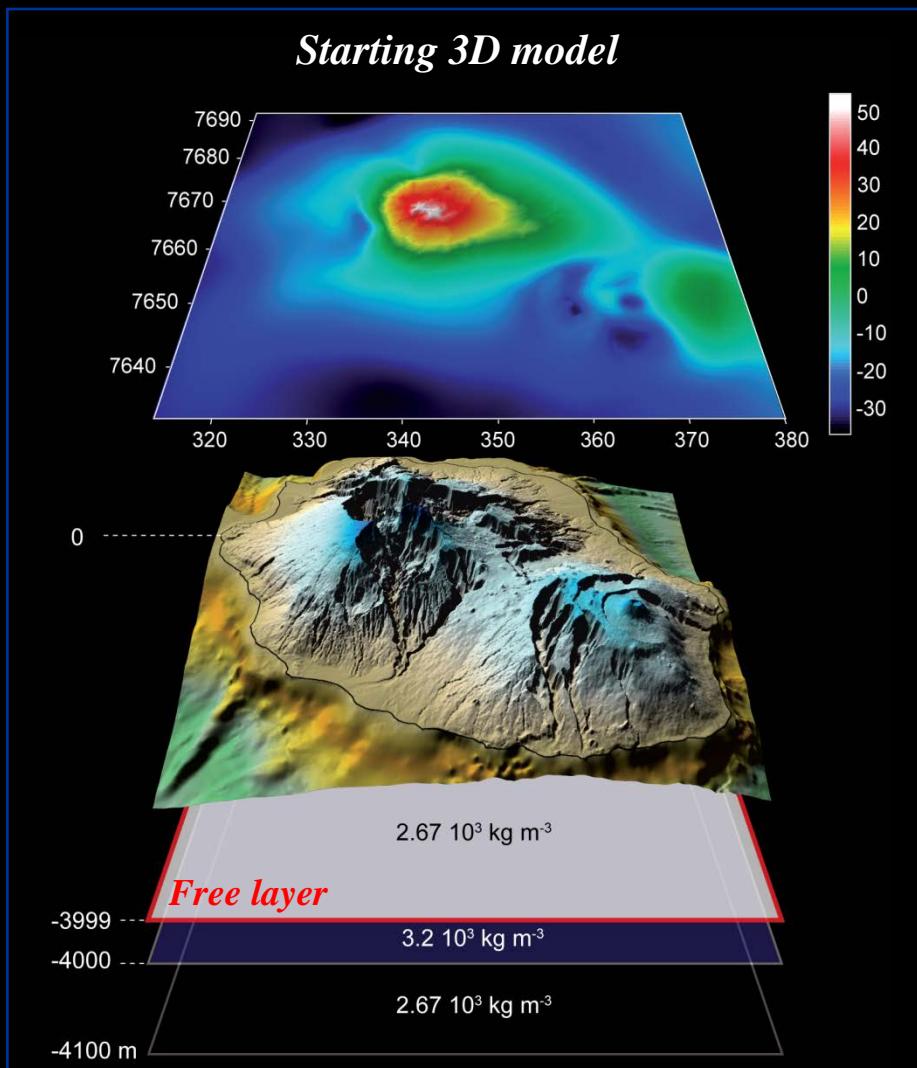
# Gravity of Piton des Neiges

## 3D Modelling



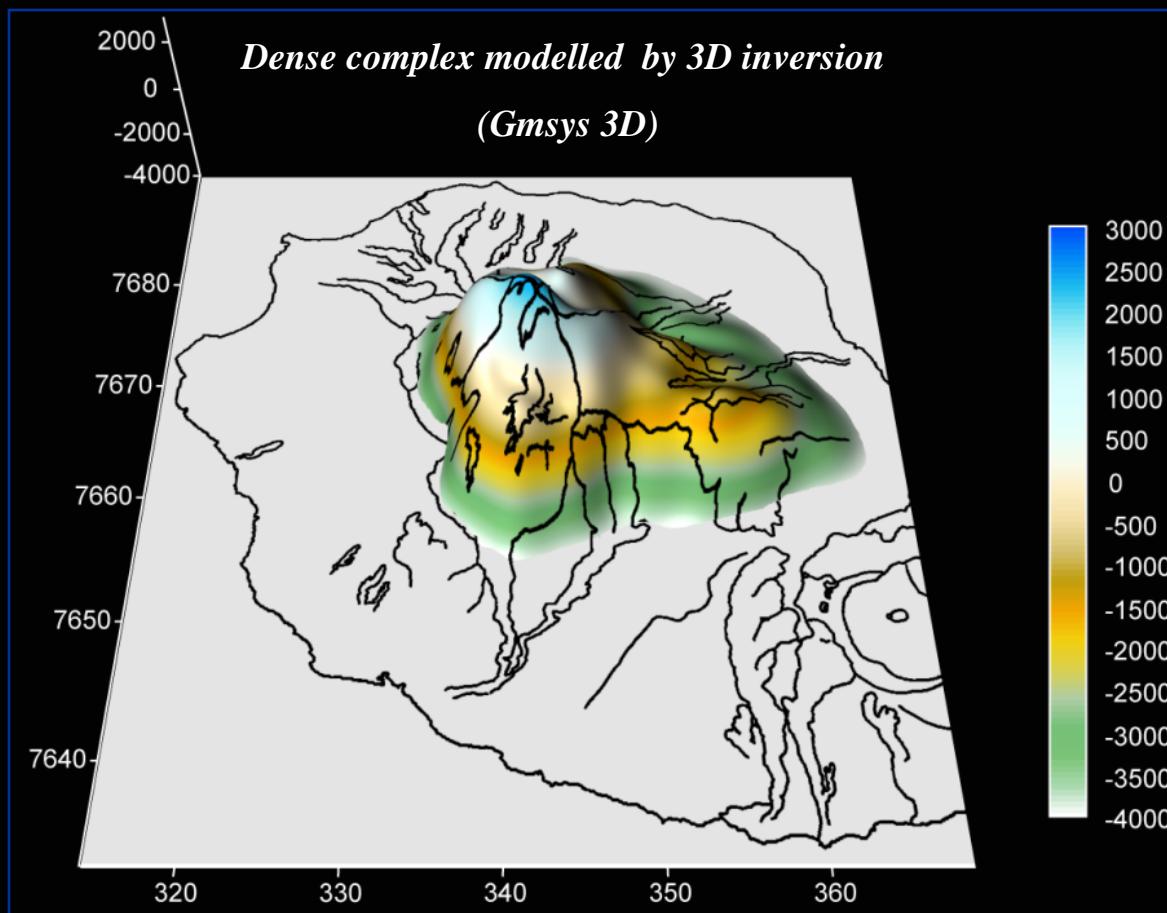
### ➤ Main positive anomaly

- Gabbros, syenites and cumulates  
(Cilaos et Salazie)
- $\rho > 3.0$



# Gravity of Piton des Neiges

## 3D Modelling

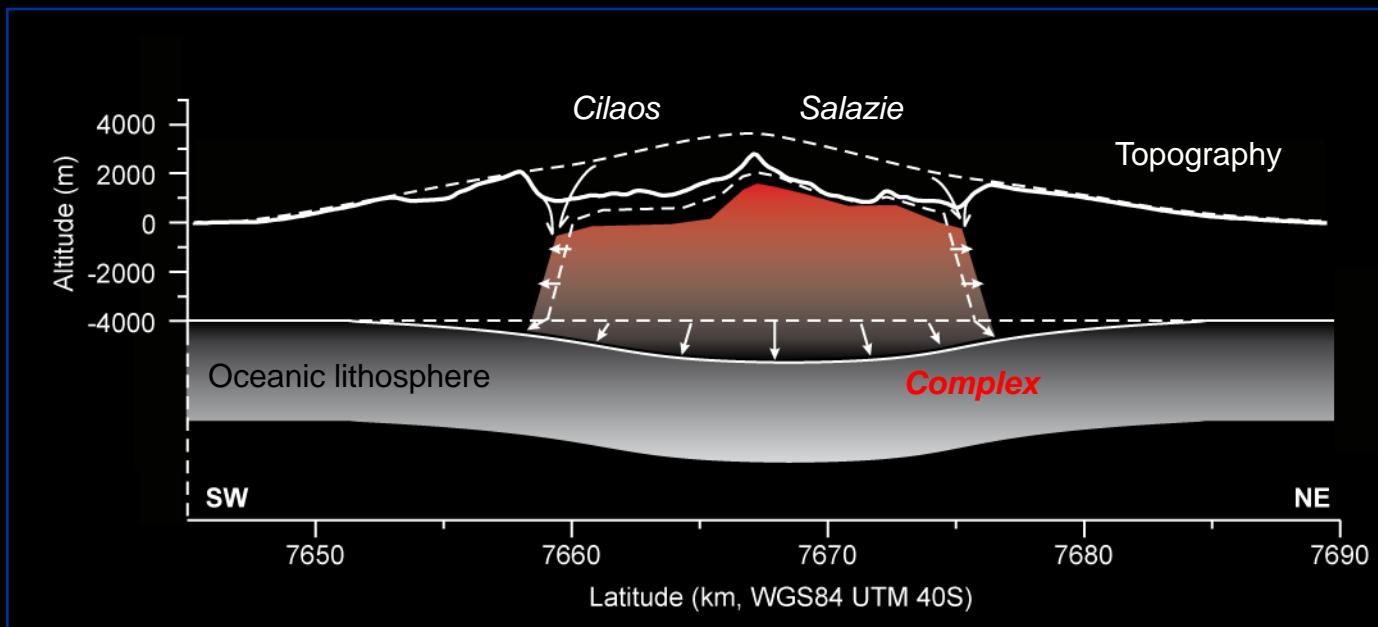


- Close correlation between the modelled body and the main depressions (Cirques, Bébour-Bélouve, Plaine des Palmistes) + equivalent solution in 2D

# Gravity of Piton des Neiges

## The hypovolcanic complex : synthesis and interpretation

- Endogenous construction by magmatic intrusions + shallow intrusive system



- Subsidence of the intrusive complex + normal faults

↳ Relation between the complex subsidence and the depressions

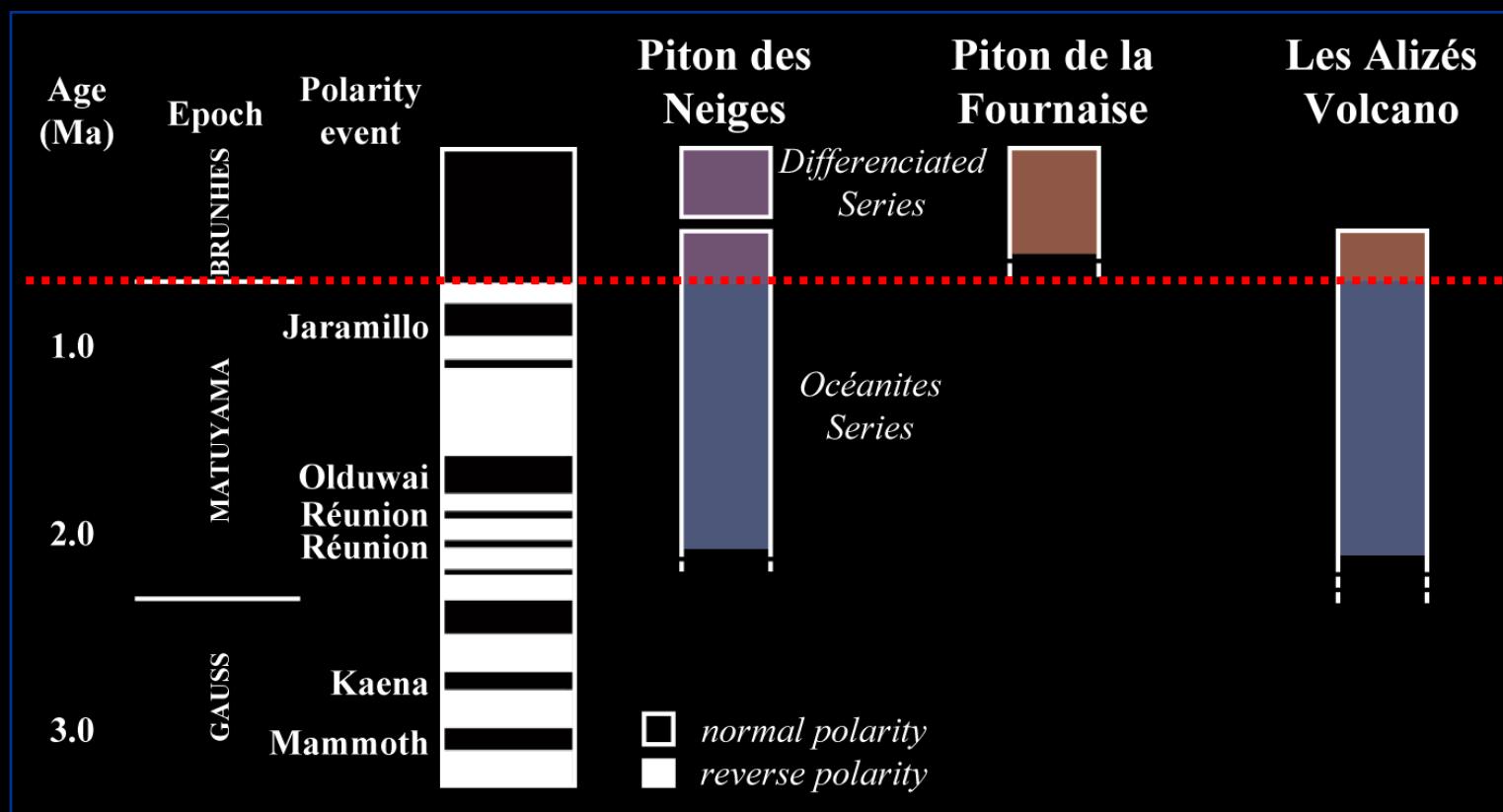
# Magnetism of La Réunion



Aeromagnetic survey (1986)

# Magnetism of La Réunion

## The magnetic anomalies in La Réunion



➤ 0.78 Ma : Geomagnetic reversal *Matuyama - Brunhes*

# Magnetism of La Réunion

## Qualitative interpretation

➤ Juxtaposition normally and reversely magnetized series

### ➤ Positive anomalies

- PdN :

Central zone, W and NE flanks

- PdF :

Central zone, S flank

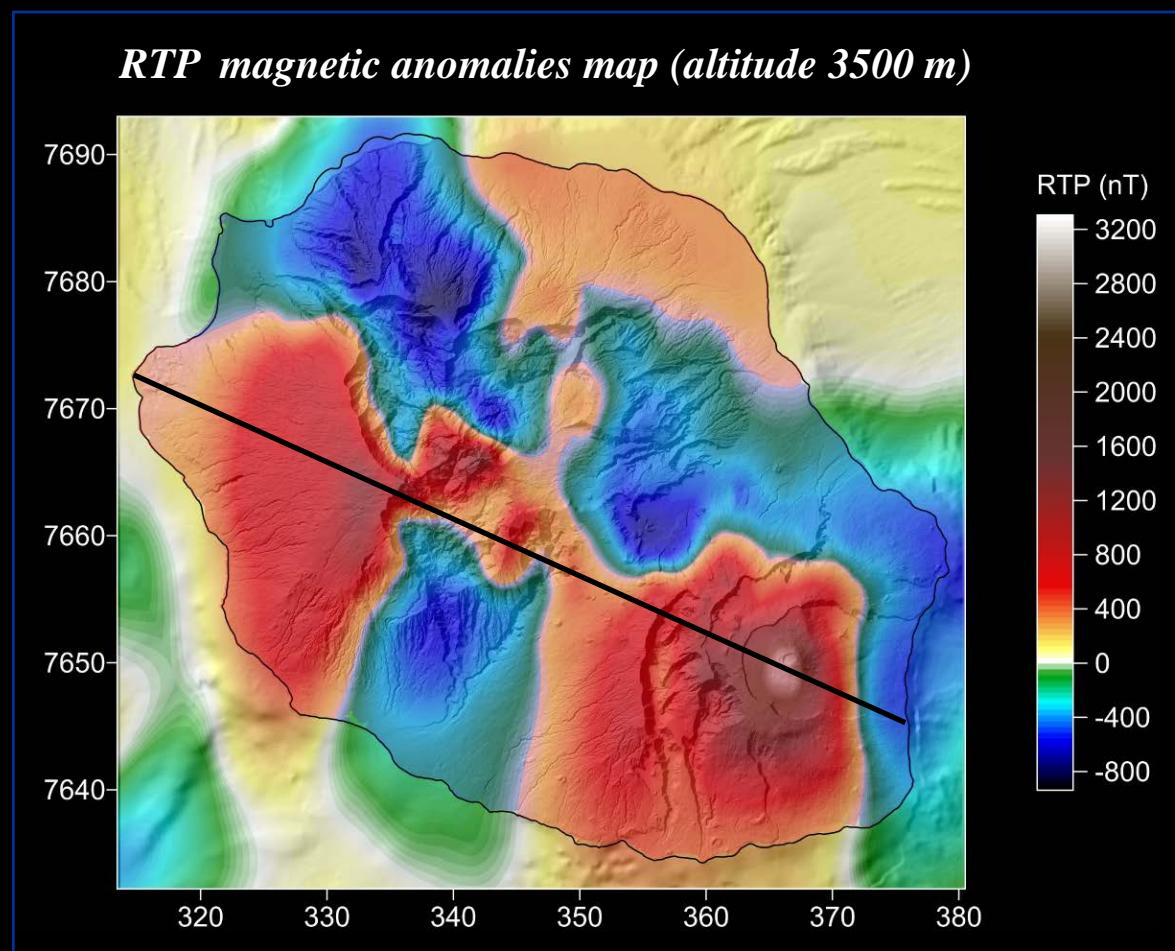
### ➤ Negative anomalies

- PdN :

N and S flanks

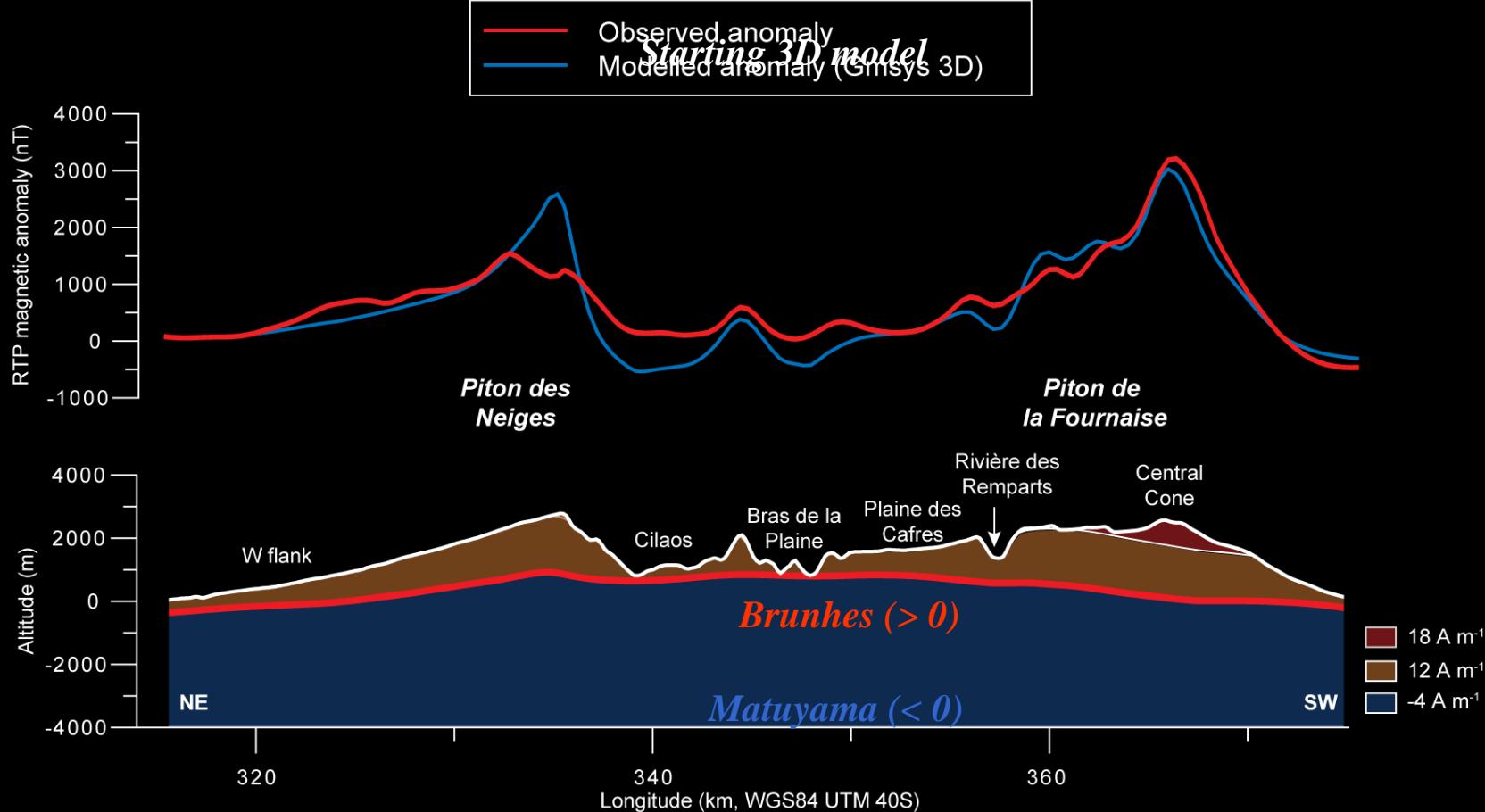
- PdF :

NE transition, N and E flanks



# Magnetism of La Réunion

## 3D modelling

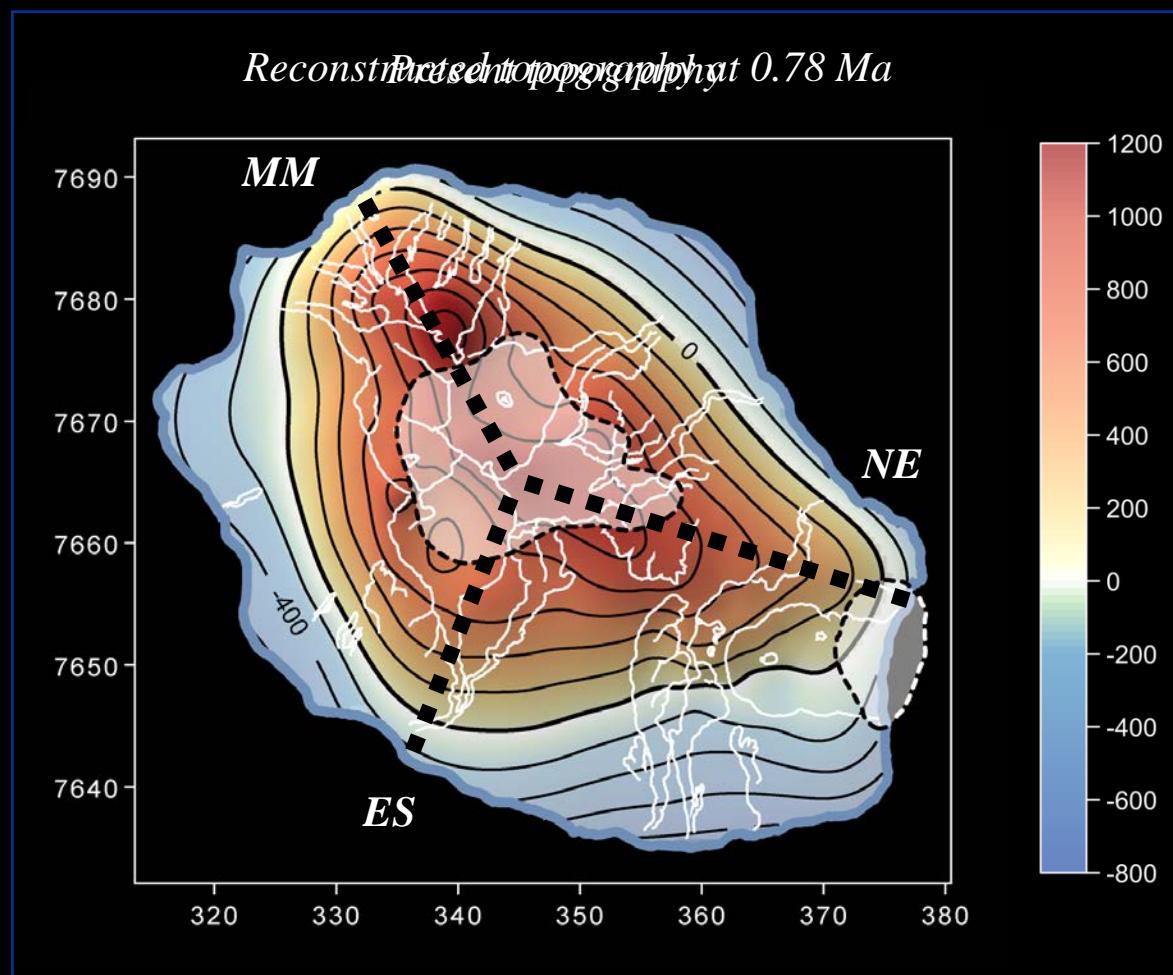


# The Island pre-Brunhes morphology

↳ 3 branches system diverging from the PdN center

- NW arm ~ La Montagne Massif (MM)
- SE arm ~ NE continuation of PdF
- SW arm ~ Etang Salé (ES) rift zone

➤ Similar morphology of the PdN dense body



# The Submarine Flanks



# Gravity of the Submarine Bulges

## Qualitative interpretation

➤ Three main submarine features associated with particular gravity signal

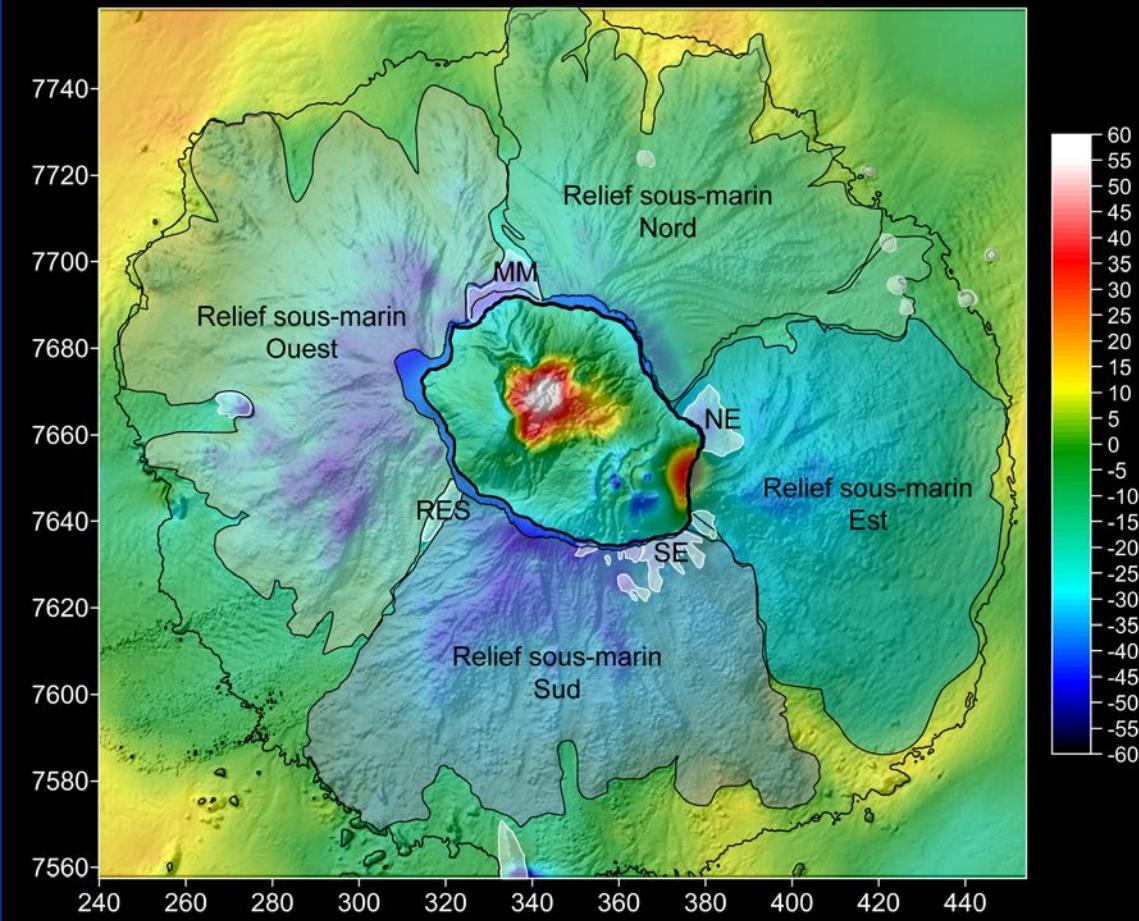
■ Relief in continuation of rift zones, seamounts and oceanic plate constructions

■ Coastal shelf

■ Submarine bulges

*Residual Bouguer anomaly*

Density correction :  $2.67 \cdot 10^3 \text{ kg m}^{-3}$

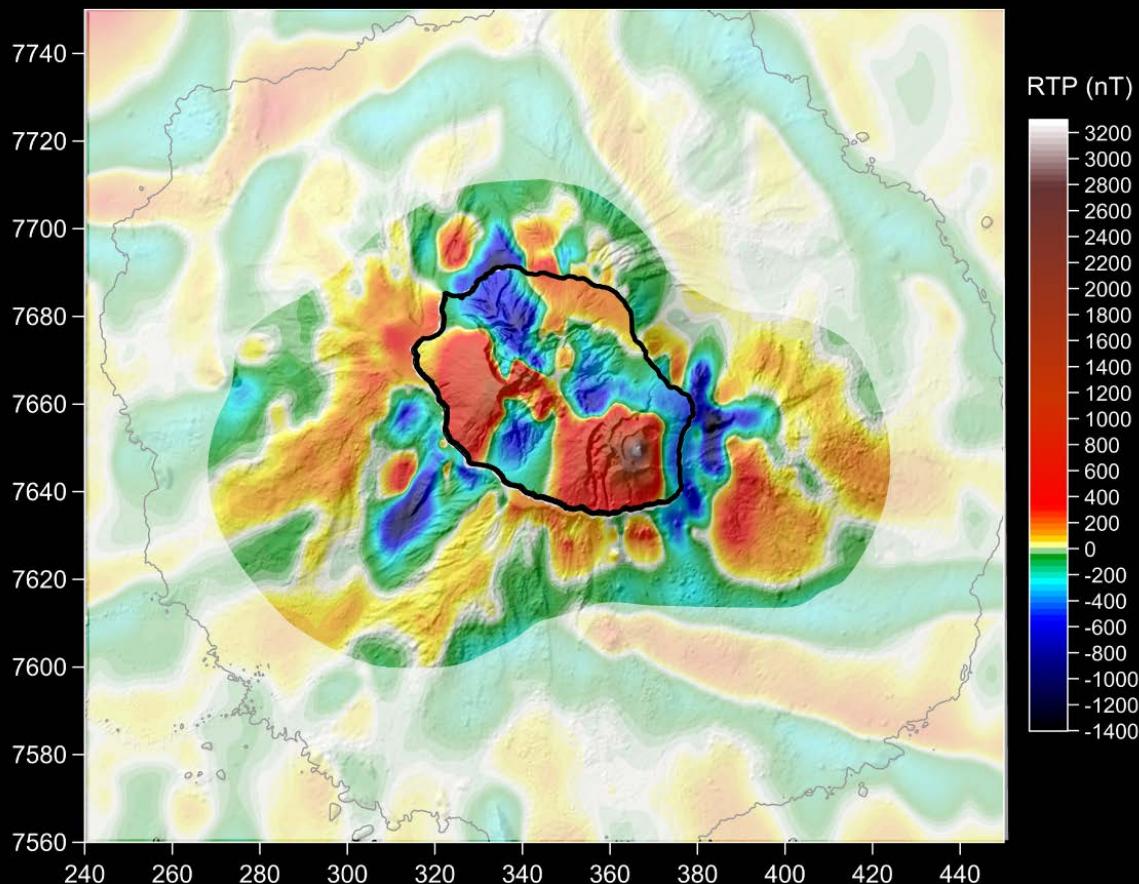


# Magnetism of the Submarine Bulges

## Qualitative interpretation

- Negative and positive high amplitude anomalies
  - ⇒ sources which have kept their coherent thermoremanent component
- Submarine bulges composed of breccias
  - ⇒ virtually ‘transparent’ from a magnetic point of view

*Composite RTP magnetic anomalies  
(declination : 0° ; inclination : -36°) :*



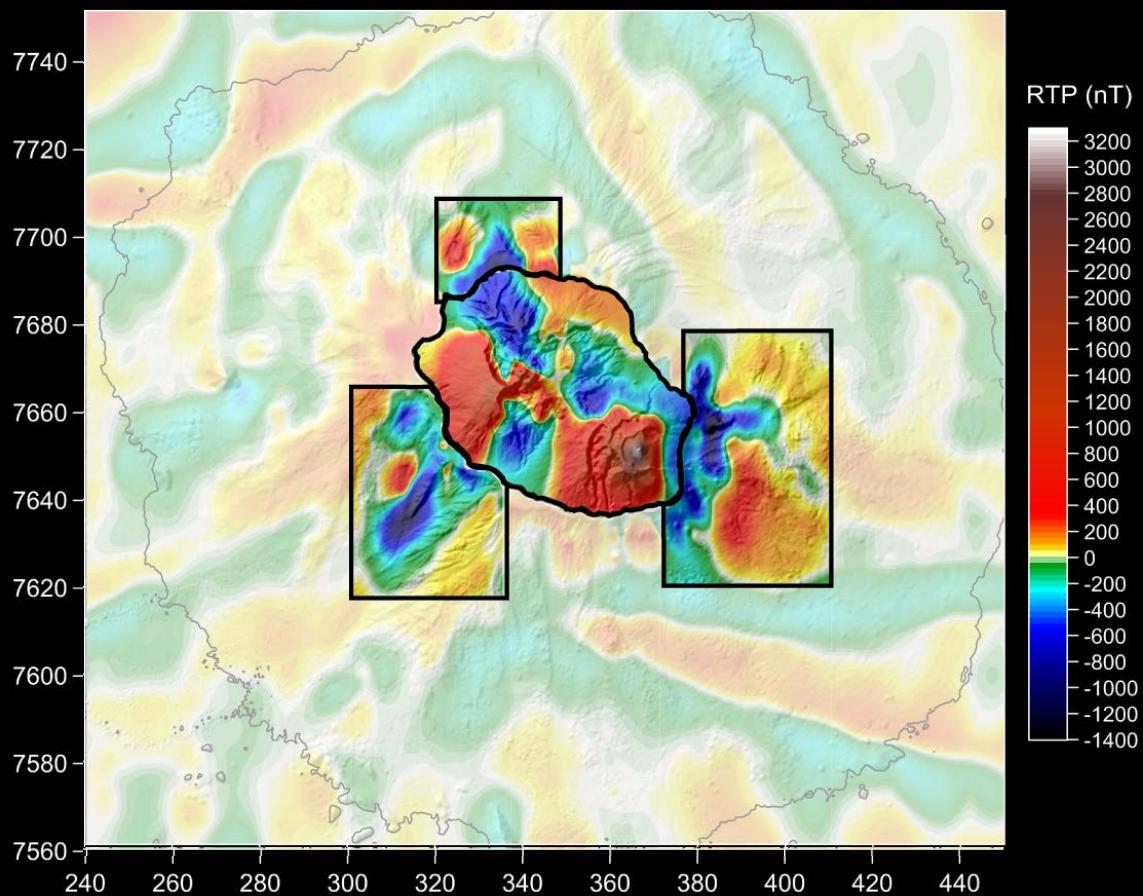
- Marine data compiled at sealevel
- Aeromagnetic data compiled at 3500 m asl

# Magnetism of the Submarine Bulges

## Qualitative interpretation

- Volcanic constructions related to La Réunion volcanism
  - ⇒ Les Alizés zone (E)
  - ⇒ Etang Salé zone (SW)
  - ⇒ La Montagne Massif (N)

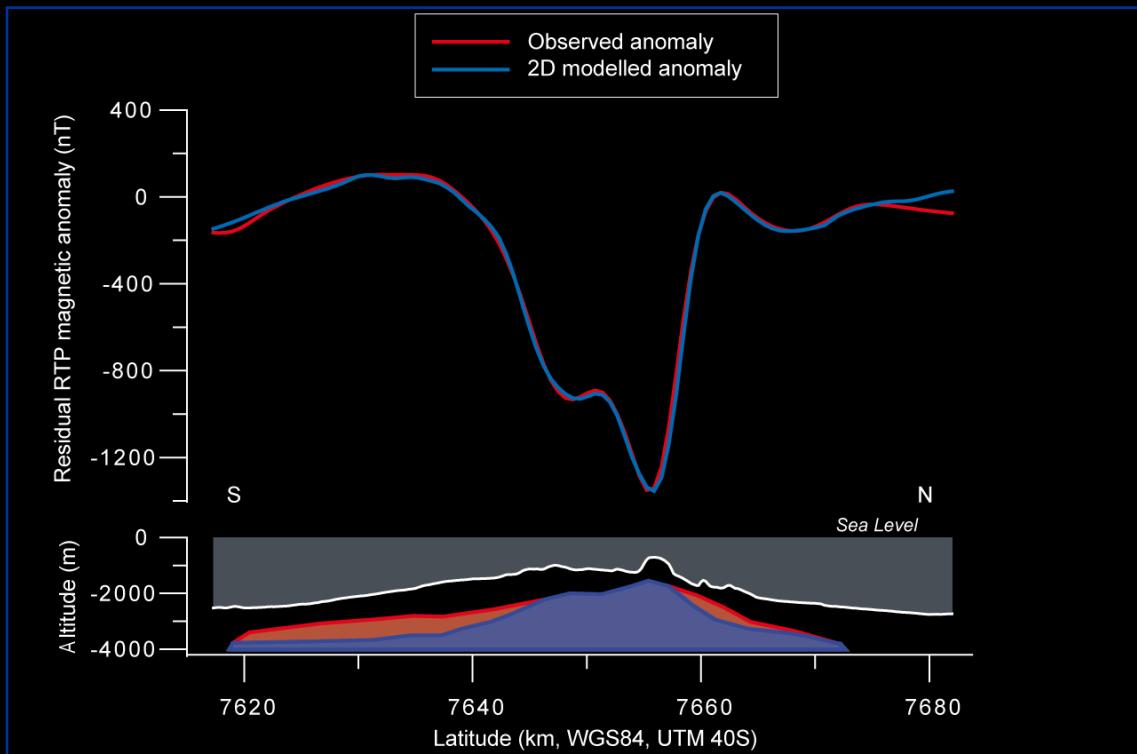
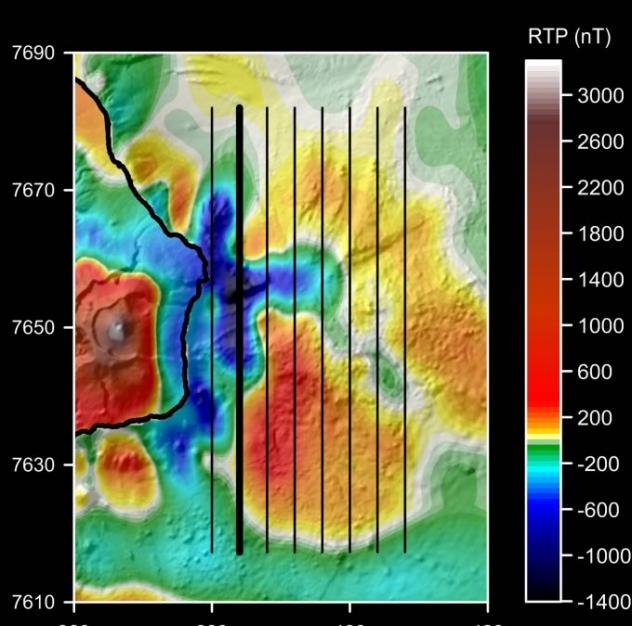
*Composite RTP magnetic anomalies  
(declination : 0° ; inclination : -36°) :*



# The E area : Les Alizés Volcano

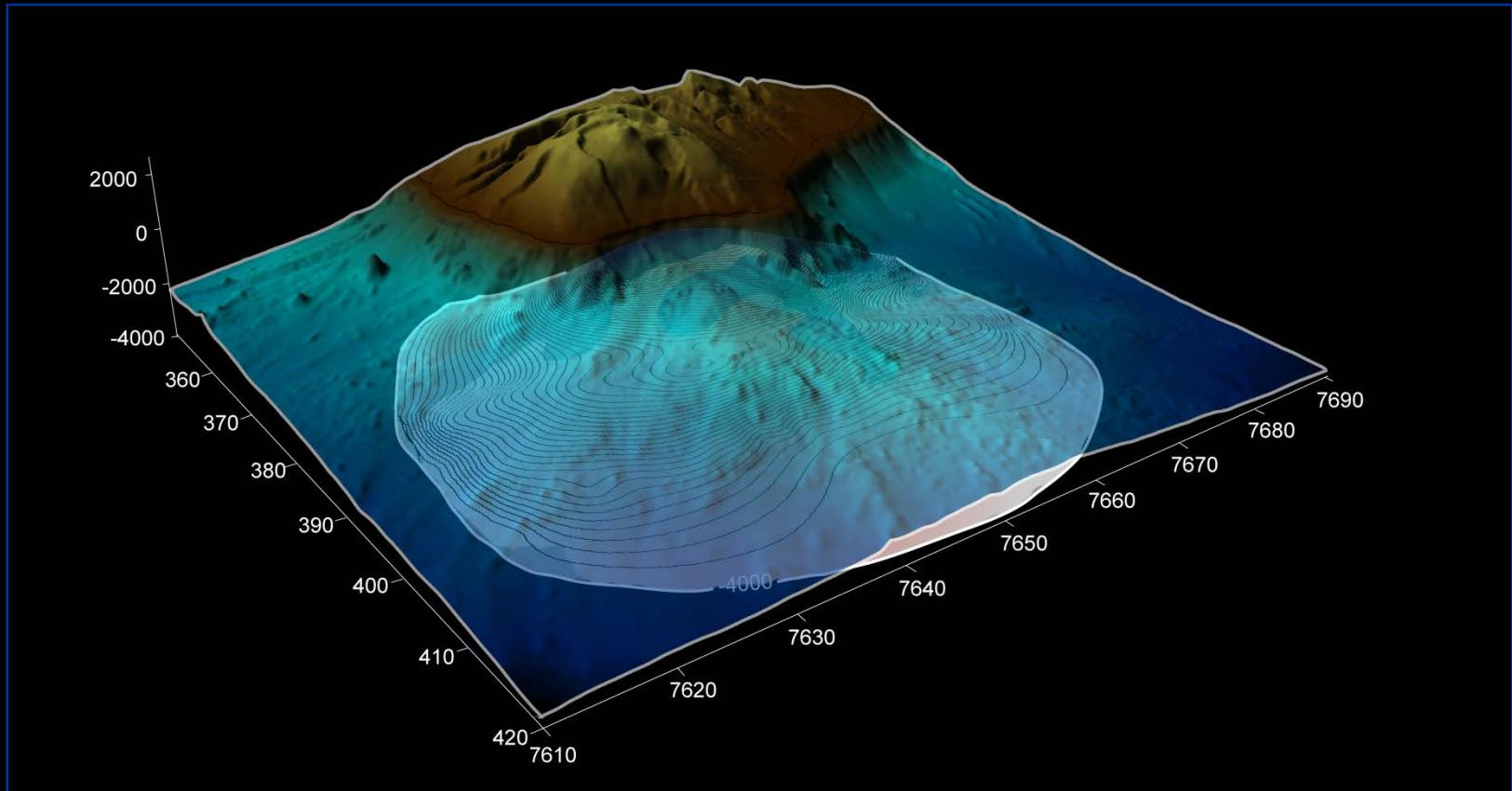
## Magnetic interpretation

- Both normal and reversely magnetized bodies
  - ⇒ Reversely magnetized Matuyama (< 0.780 Ma) construction
  - ⇒ Covered by normally magnetized Brunhes (> 0.780 Ma) formations



# The E area : Les Alizés Volcano

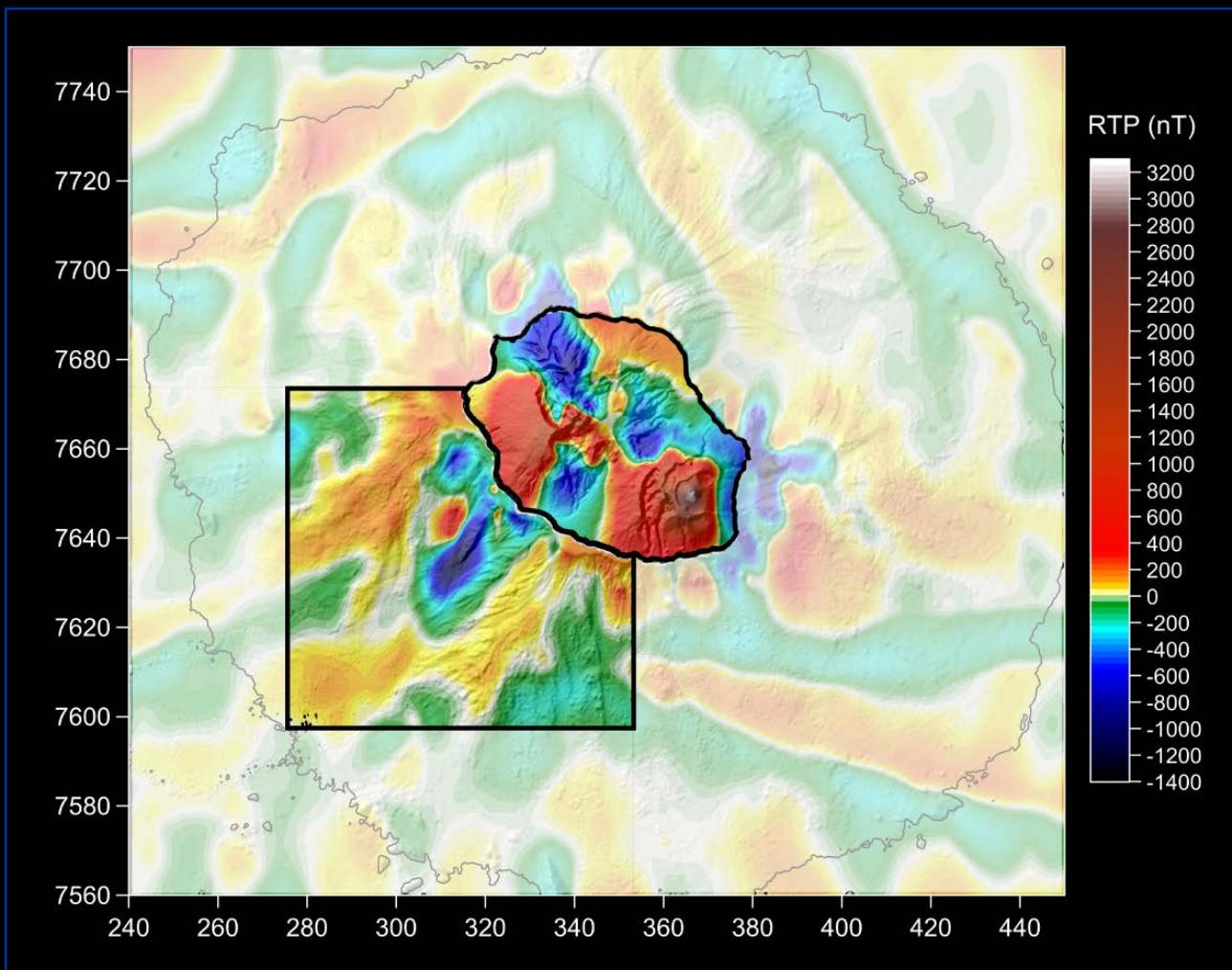
3D reconstruction of the submarine part



↳ General morphology of a volcano flank ( $\sim 60 * 50$  km) organized around the Grand Brûlé hypovolcanic complex

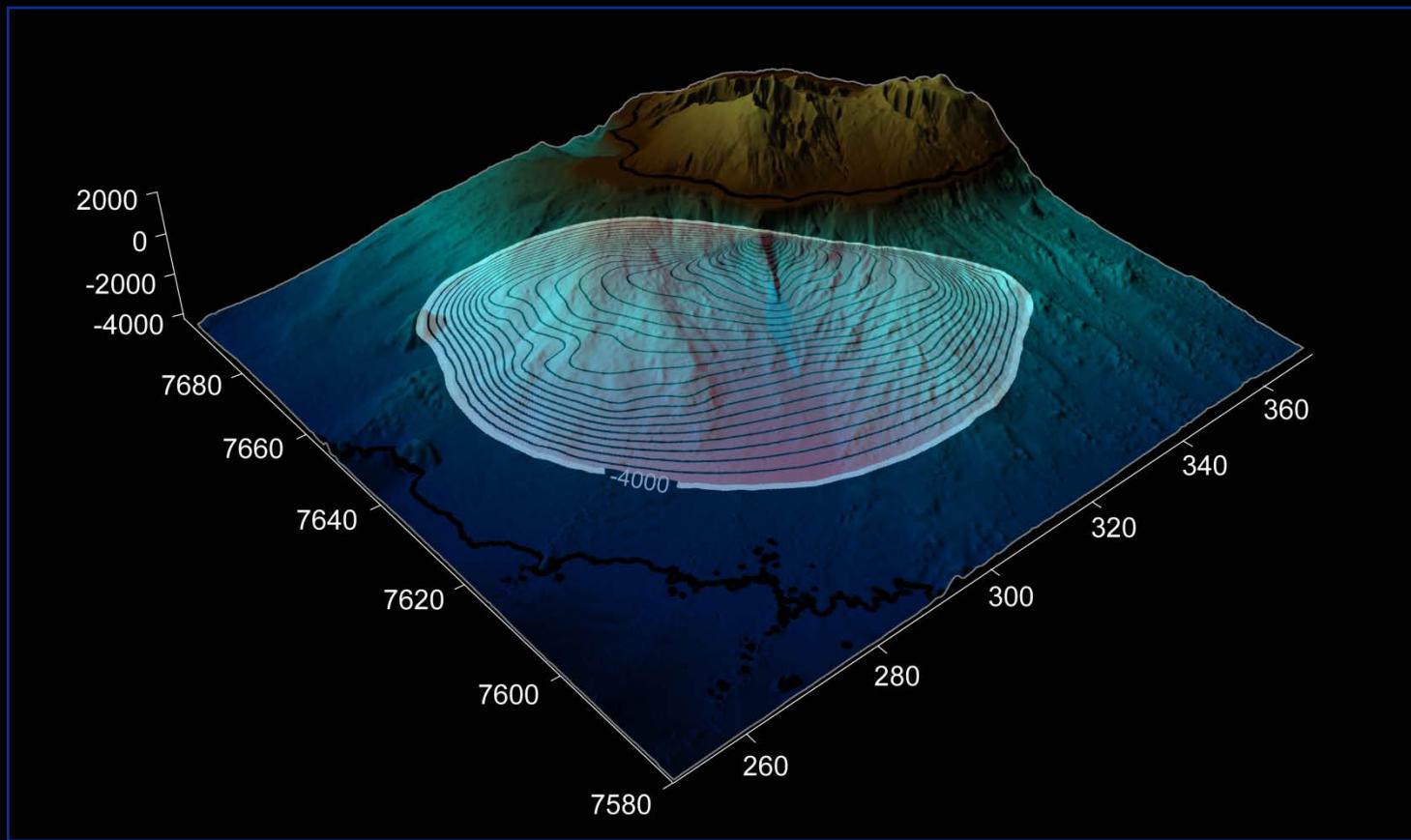
# The SW area : Etang Salé Ridge

3D reconstruction of the submarine part



# The SW area : Etang Salé Ridge

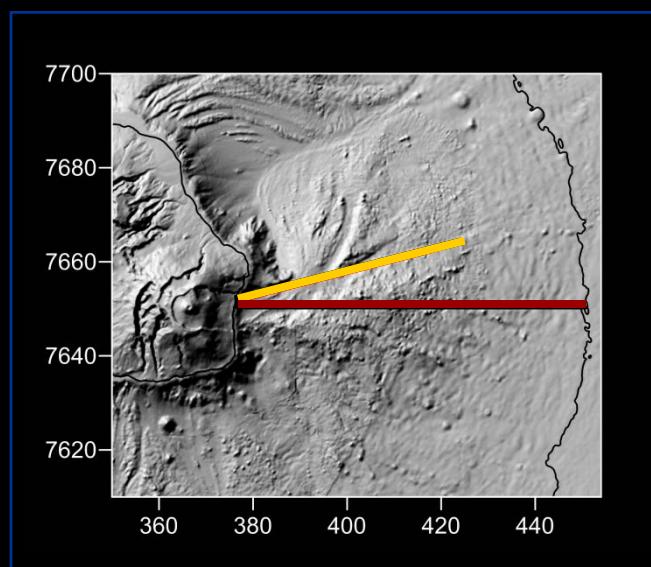
3D reconstruction of the submarine part



↳ Huge 3D ellipsoidal morphology ~ 80\*90 km organized around the rift zone

# Magnetism versus Seismic reflexion

- High correlation between seismic interfaces and volcanic construction inferred from magnetic data
- Similar scheme to the E and to the SW



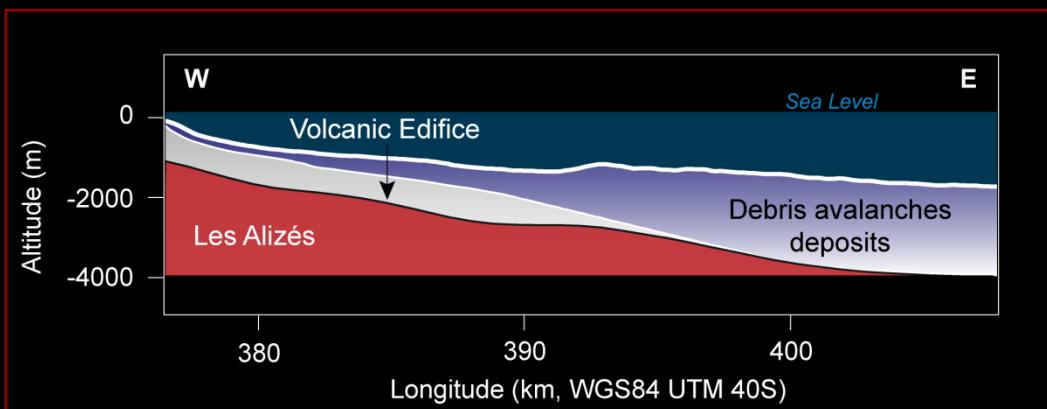
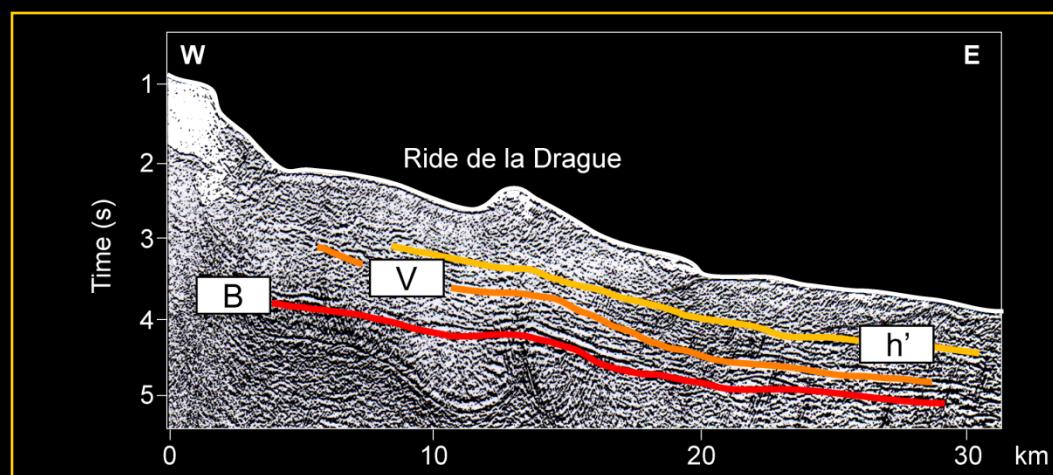
## Seismic horizons

(*de Voogd et al., 1999; Pou Palomé, 1997*)

**B** top of the oceanic basement

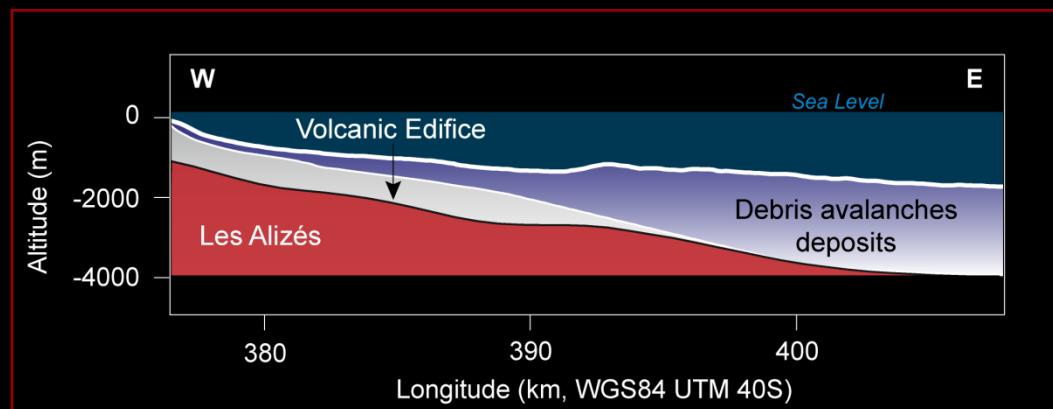
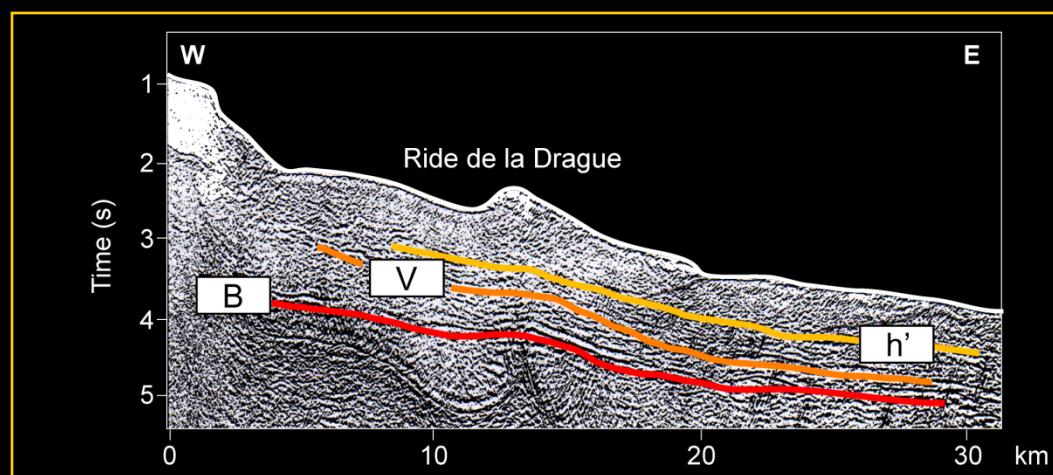
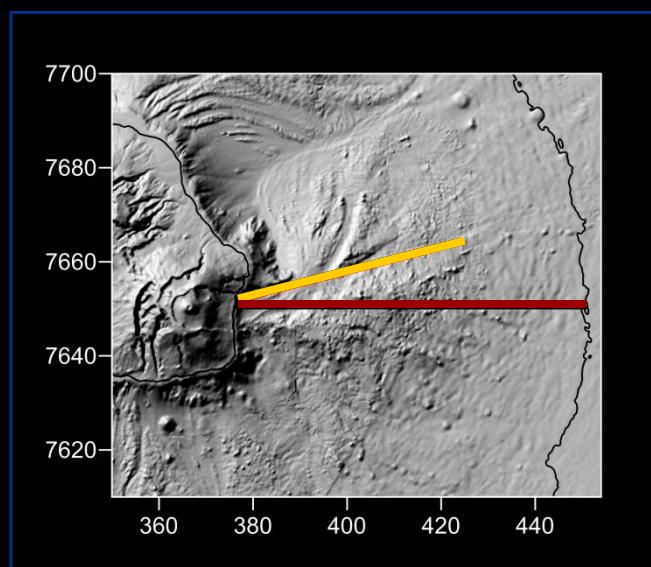
**V** base of the edifice (of the sediments)

**h'** of Les Alizés?



# Magnetism versus Seismic reflexion

- High correlation between seismic interfaces and volcanic construction inferred from magnetic data
- Similar scheme to the E and to the SW

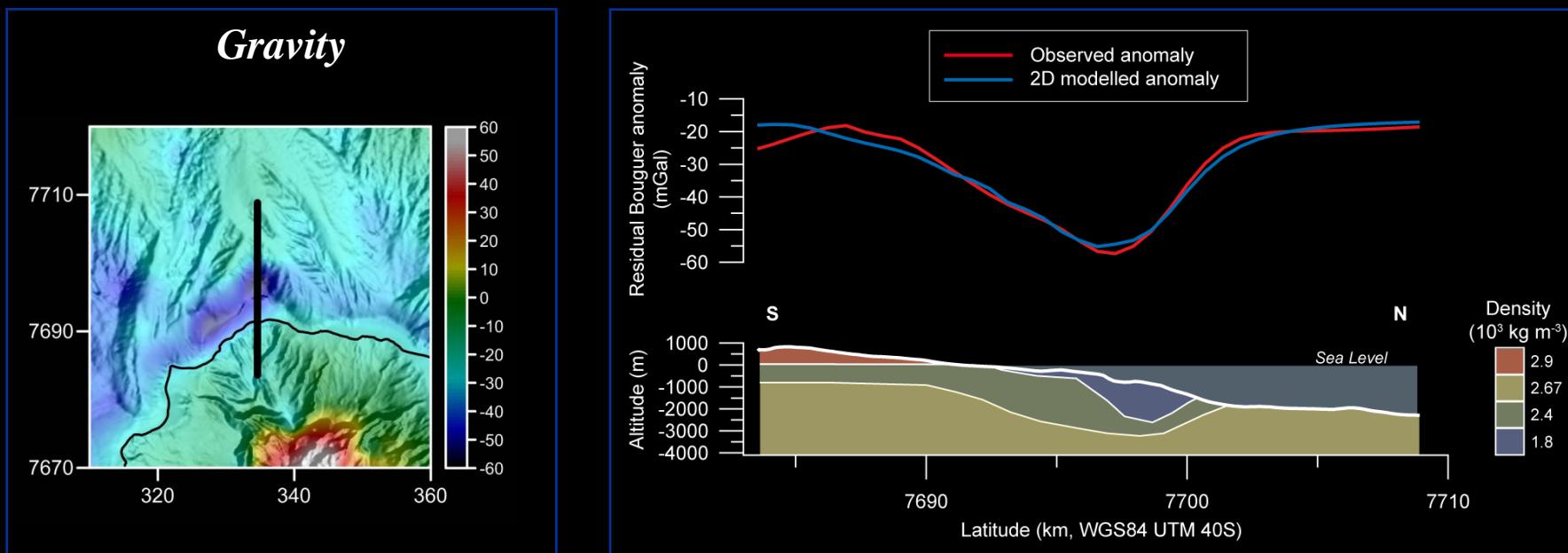


☛ No bulging of the oceanic crust

# The Coastal Shelf

## Gravity Interpretation

- Belt of negative Bouguer anomalies
- Large magnetic **anomalies both on land and offshore**

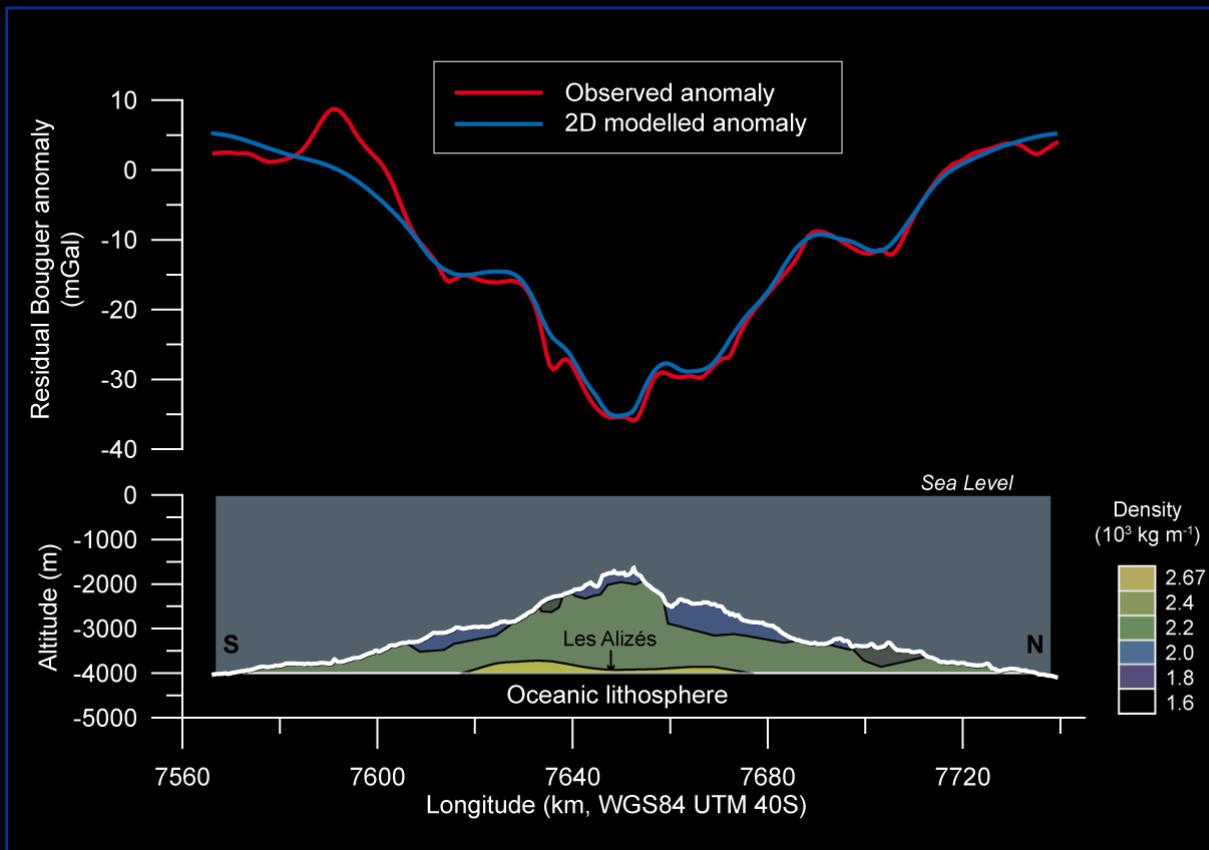
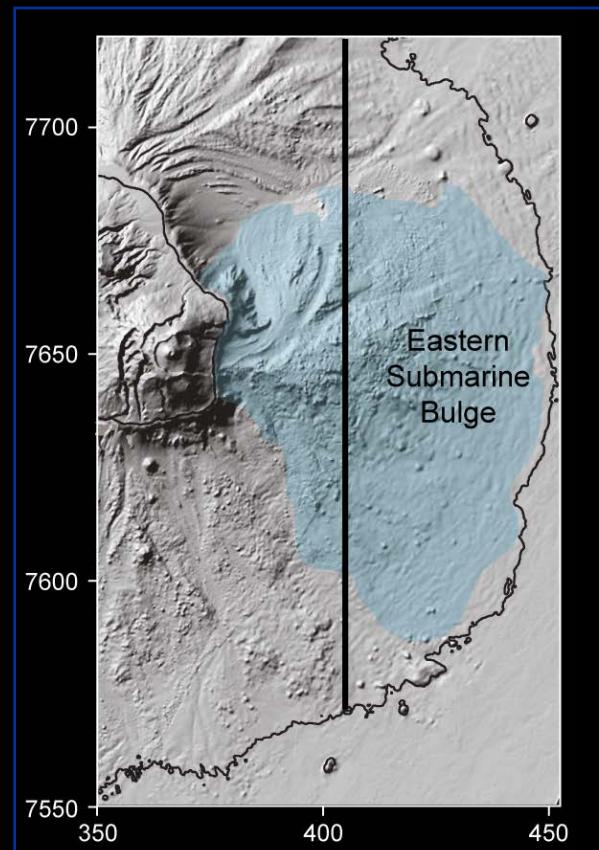


➡ Association **hyaloclastites & pillow lavas** :  
*Lower density but have kept their thermoremanent component*

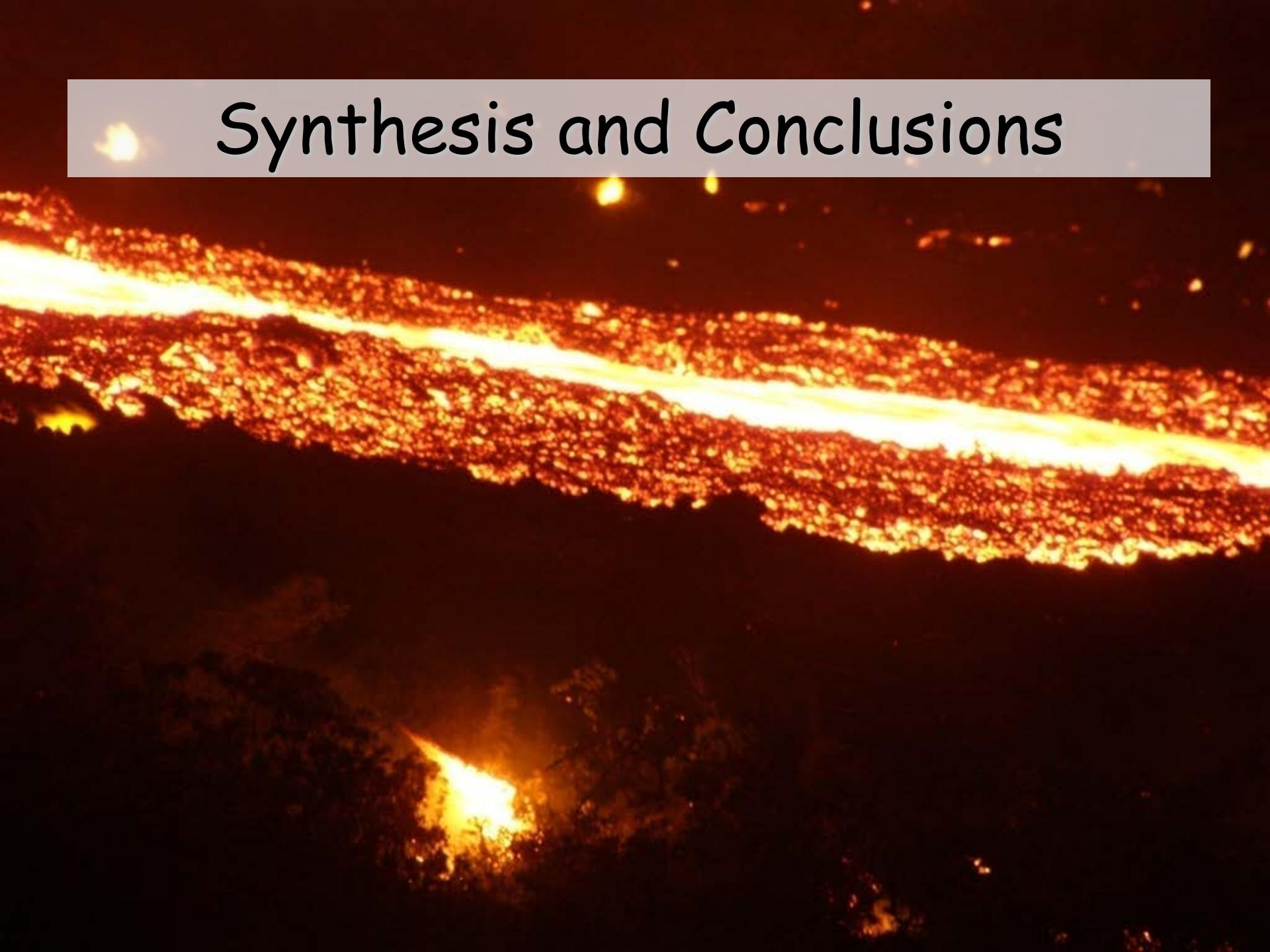
# The Submarine Bulges

## Gravity interpretation

- Submarine bulges mainly composed of breccias
  - ↳ Lower magnetization and density / volcanic constructions

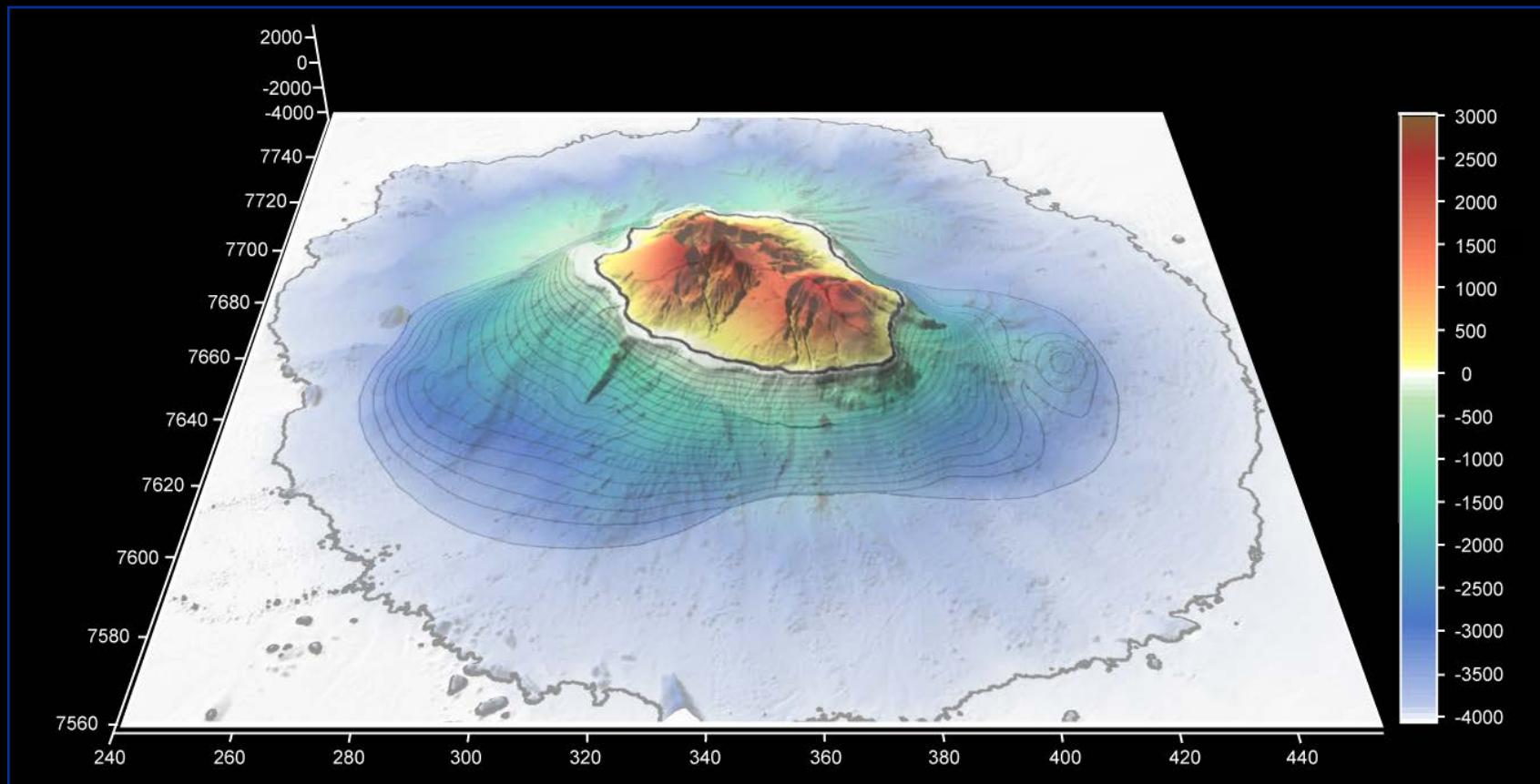


# Synthesis and Conclusions

A photograph of a massive forest fire at night. The scene is dominated by intense orange and yellow flames that have consumed a wide area of trees. The fire's edge curves across the frame, with brighter, more turbulent flames on the right and a darker, smoldering area on the left. In the foreground, dark silhouettes of unburned trees are visible against the bright fire. The overall atmosphere is one of a major, uncontrollable wildfire.

# Synthesis and Conclusions

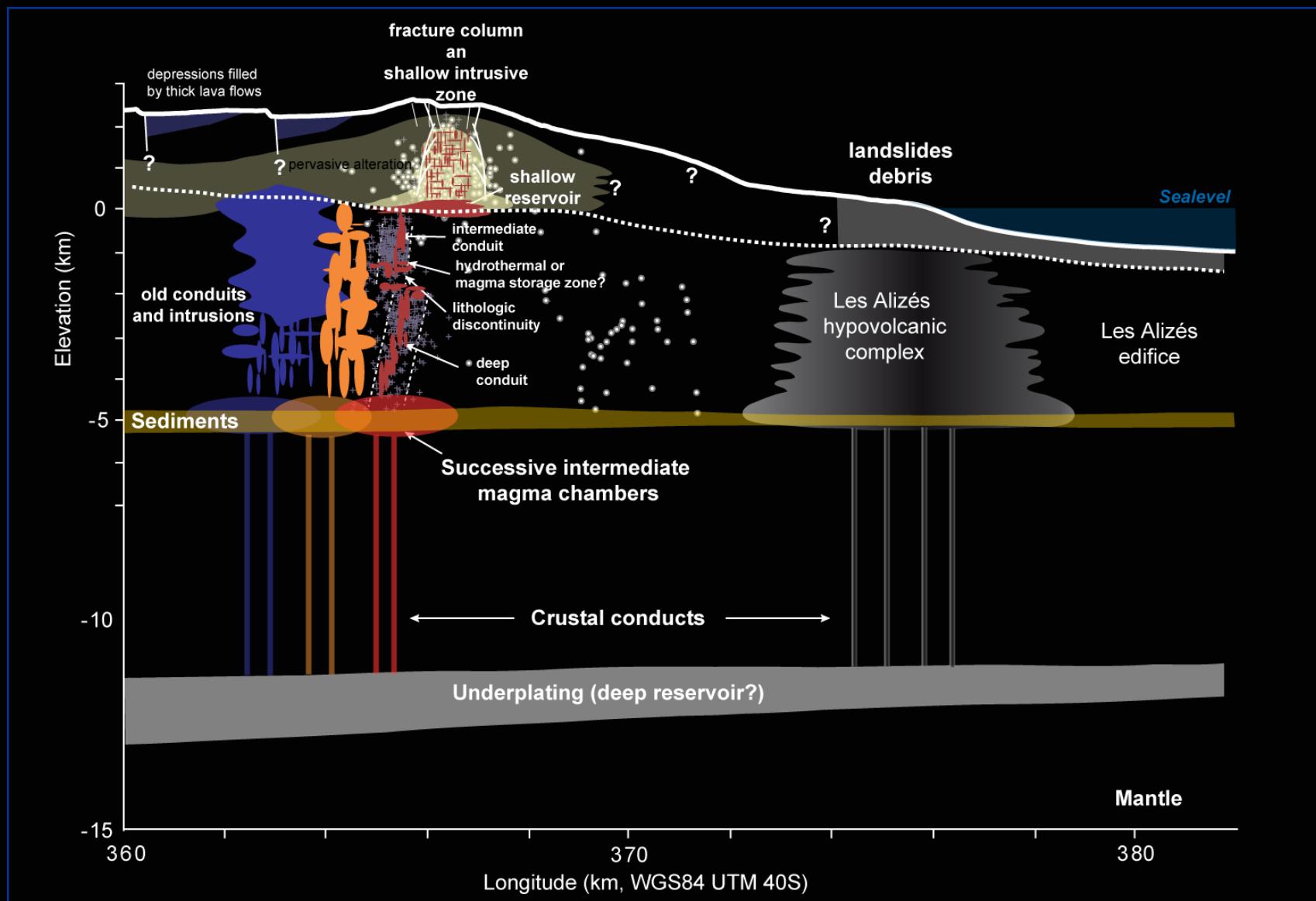
*Hypothetical map showing the distribution of old rifts in the area*



- Relationship between the distribution of old rift morphology and:
  - ⇒ Bulges composed of debris avalanches deposits accumulation

# Synthesis and Conclusions

## *Piton de la Fournaise internal structure (Lénat et al., accepted)*



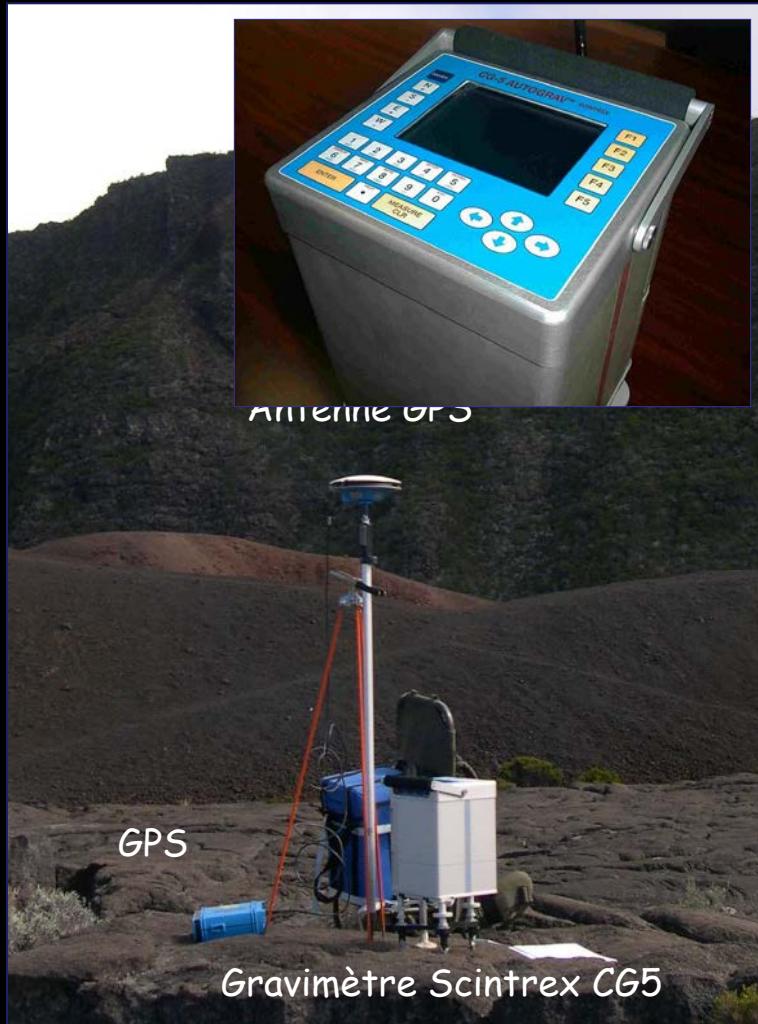
A circular porthole view from a ship looking out over the ocean towards a green, hilly coastline under a blue sky with clouds.

Thank you  
for your attention

# Data acquisition

## Gravity

On land

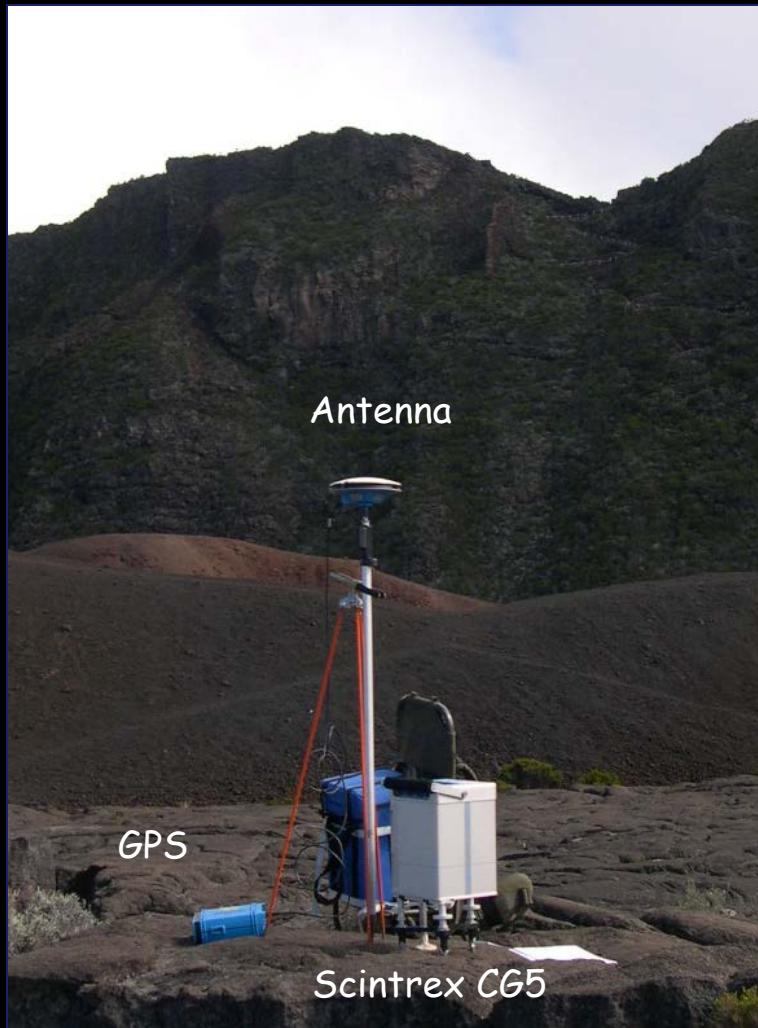


- **SCINTREX CG-5** gravimeter
  - Automatic, manual levelling
  - Altitude and positionning by differential GPS
- ⚡ *More precise measurement*

# Data acquisition

## Gravity

On land



Offshore



➤ Relative gravimeter

# Data acquisition

## Magnetism

### Aeromagnetic survey



### Offshore



*ERODER survey, july 2006*



#### ➤ Magnetometer :

- ⇒ Launched behind the aircraft or the ship
- ⇒ Immersion < 300 m

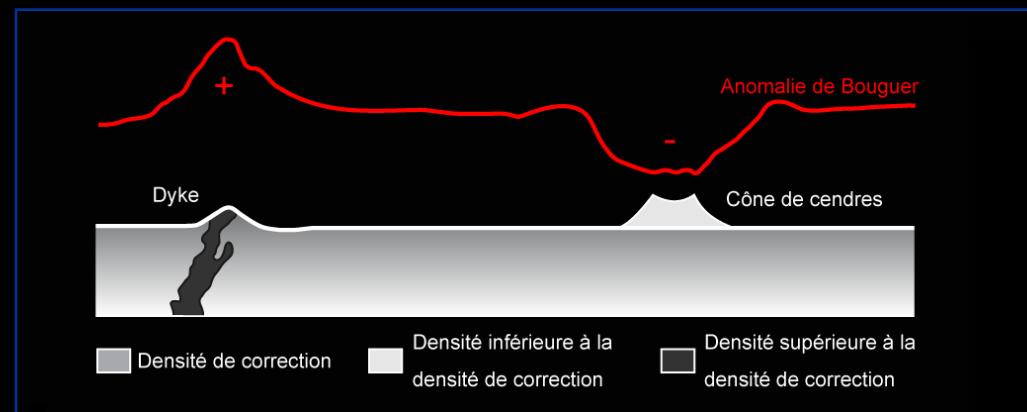
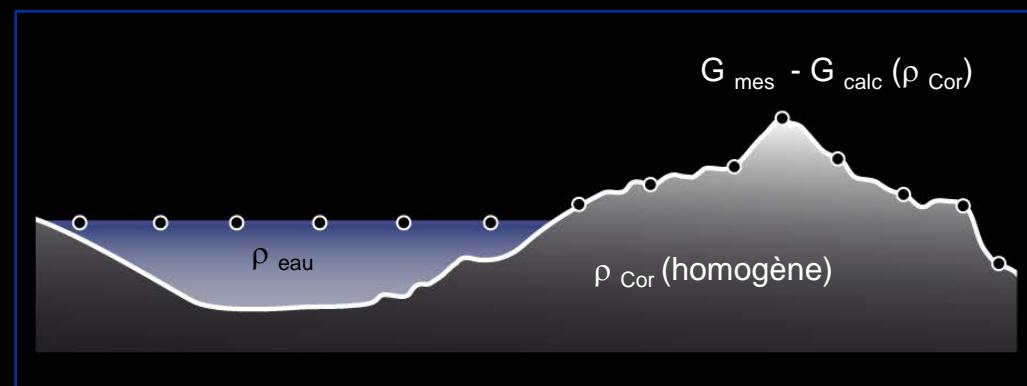
# Gravity : Theory

## Etude de la pesanteur terrestre

- Heterogeneous distribution of the densities in the Earth  
⇒ *Gravity anomalies*

↳ Information on the internal structure

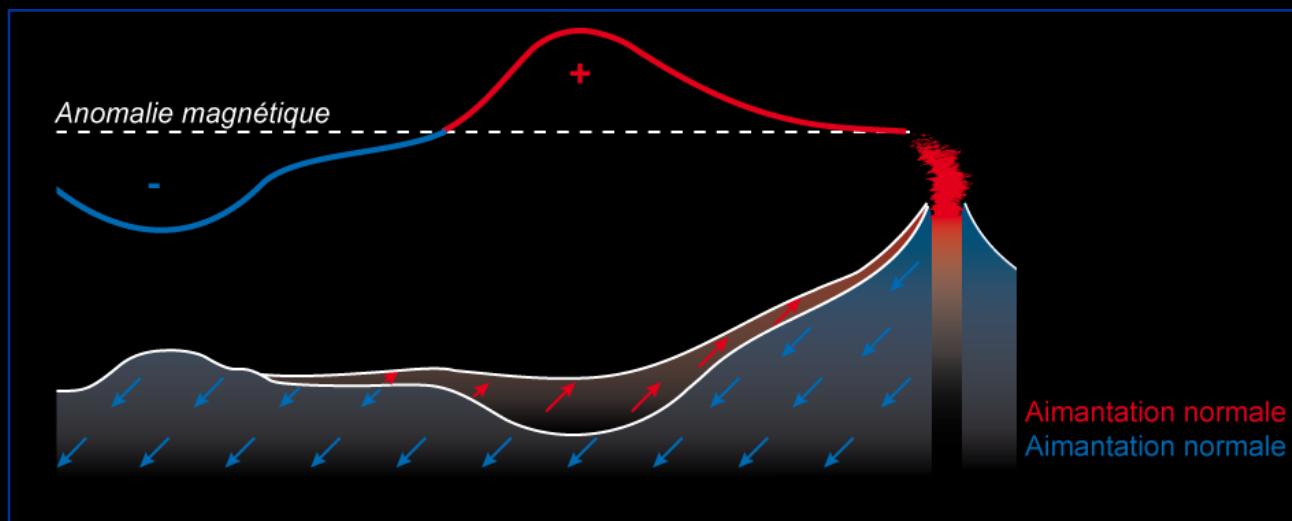
- Gravity effect of structures with  $\rho \neq \rho_{cor}$



# Magnetism : Theory

## Origin of magnetic anomalies

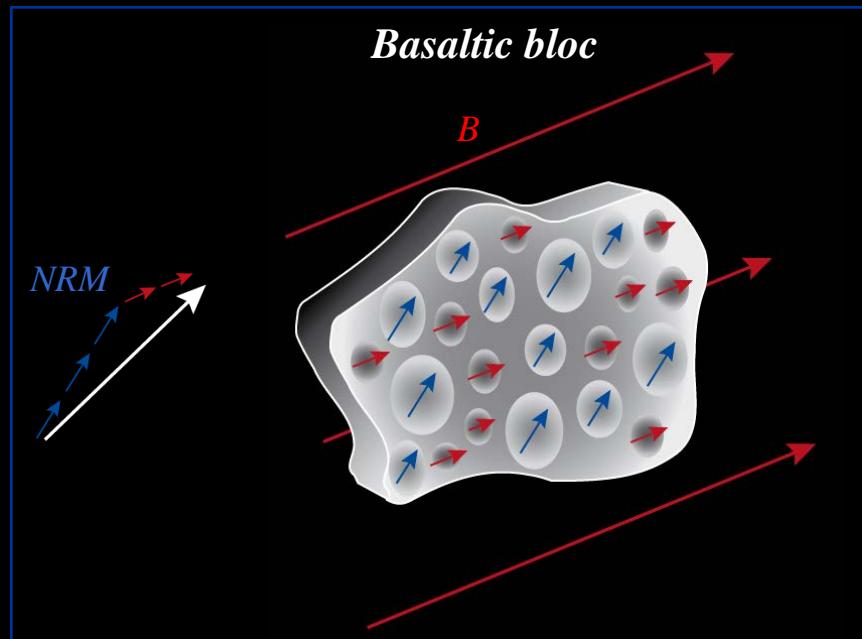
- Magnetic anomalies = local anomalies / field of deep origin (~ IGRF, *International Geomagnetism Reference Field*)
- ⇒ Magnetization contrasts (intensity and/or direction) between ≠ formations of the crust



# Magnetism : Theory

## Rocks magnetizations

- Total apparent magnetization of a rock = **Natural Remanent Magnetization (NRM)** + **Induced Magnetization**

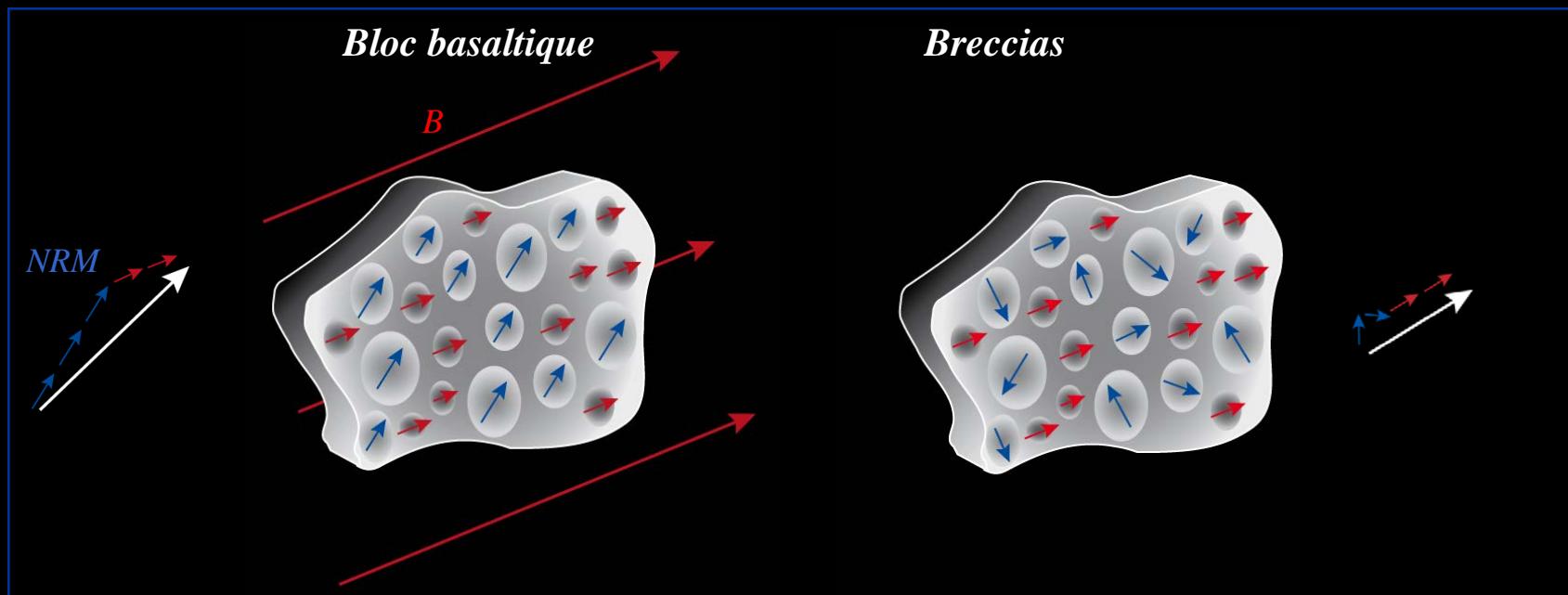


- NRM = sum of different magnetization
- Principal component in volcanic rocks = Thermo Remanent Magnetization (*TRM*)

# Magnetism : Theory

## Rocks magnetizations

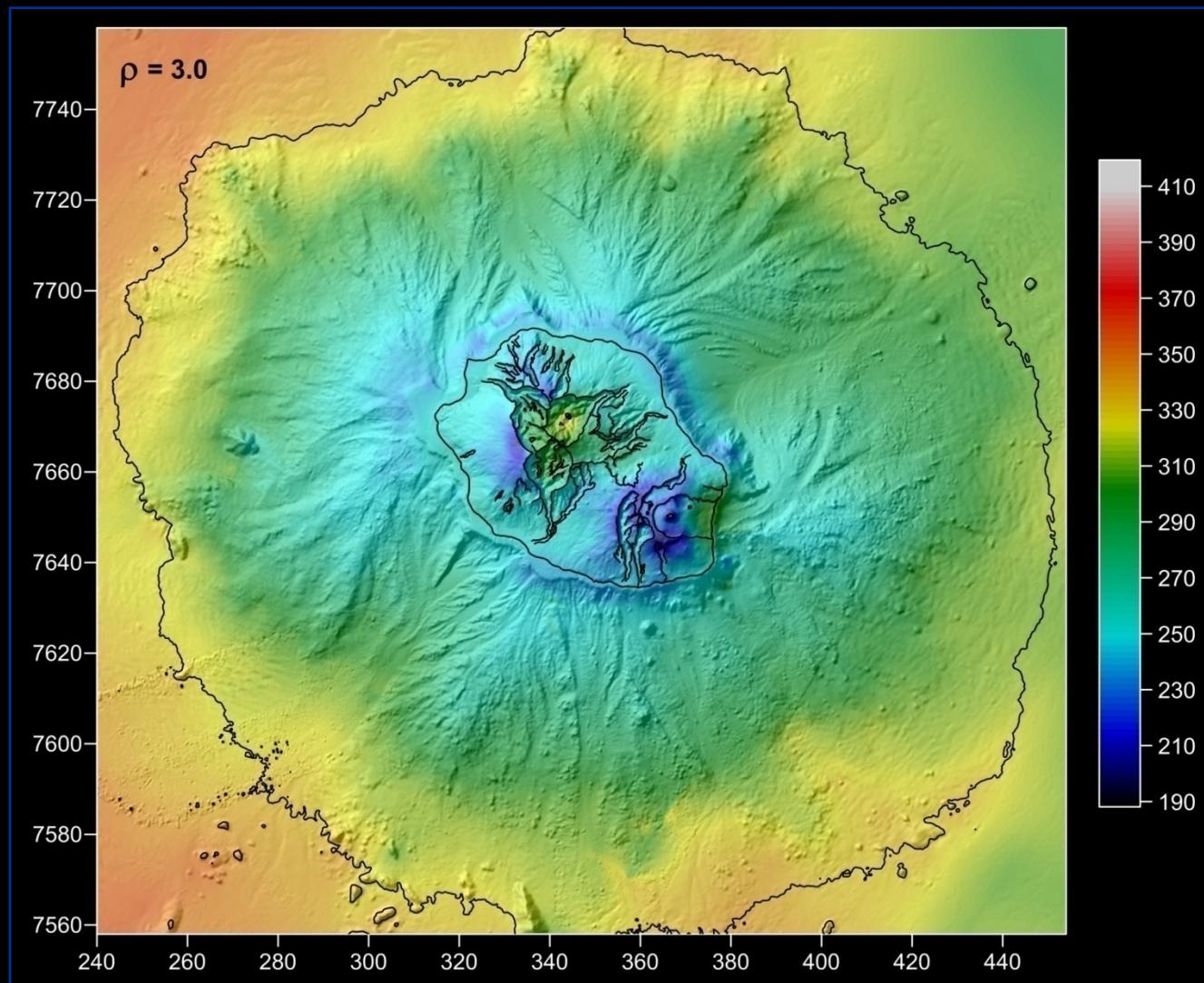
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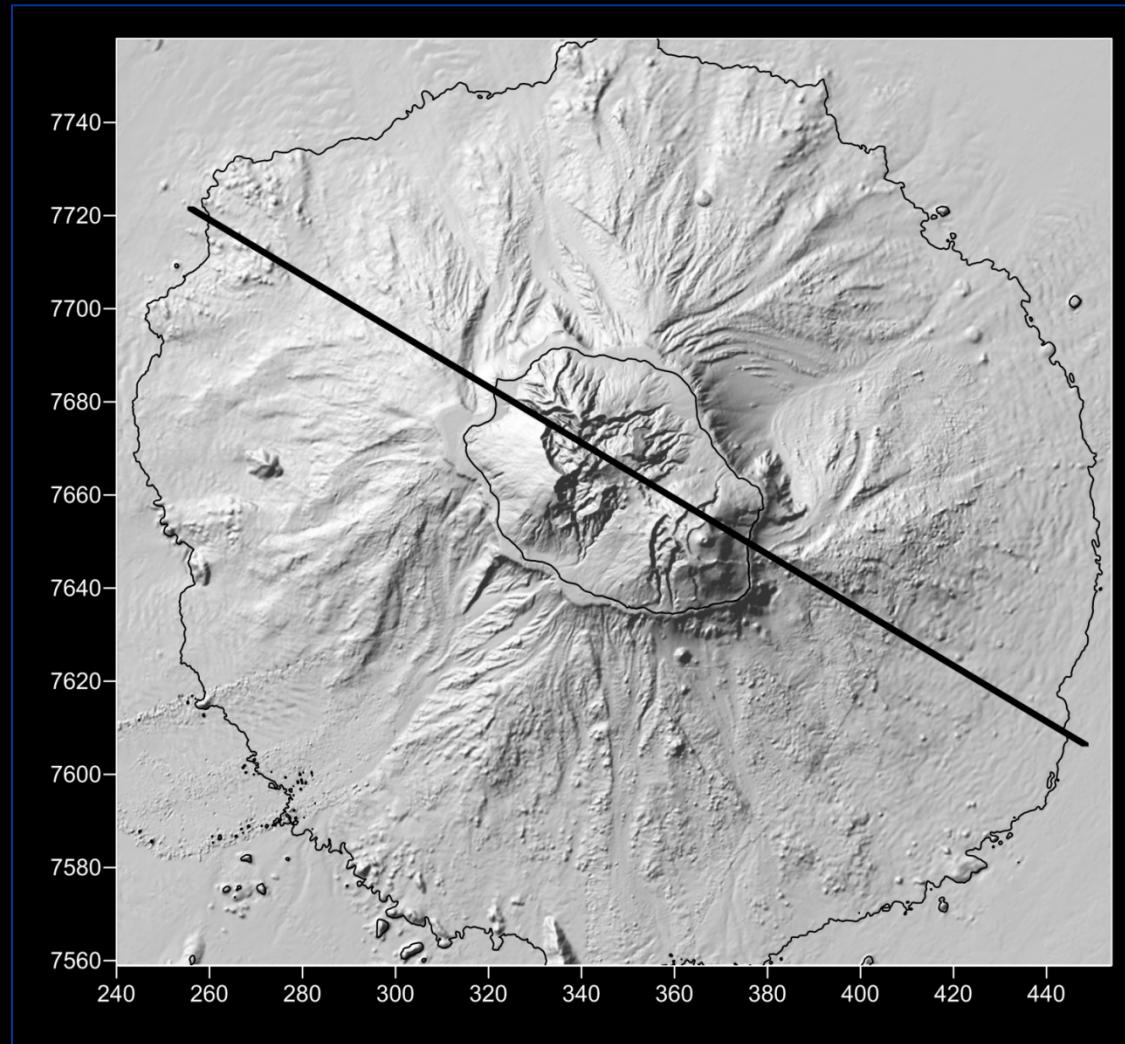
# Gravity

Density correction (*Nettleton, 1939*)



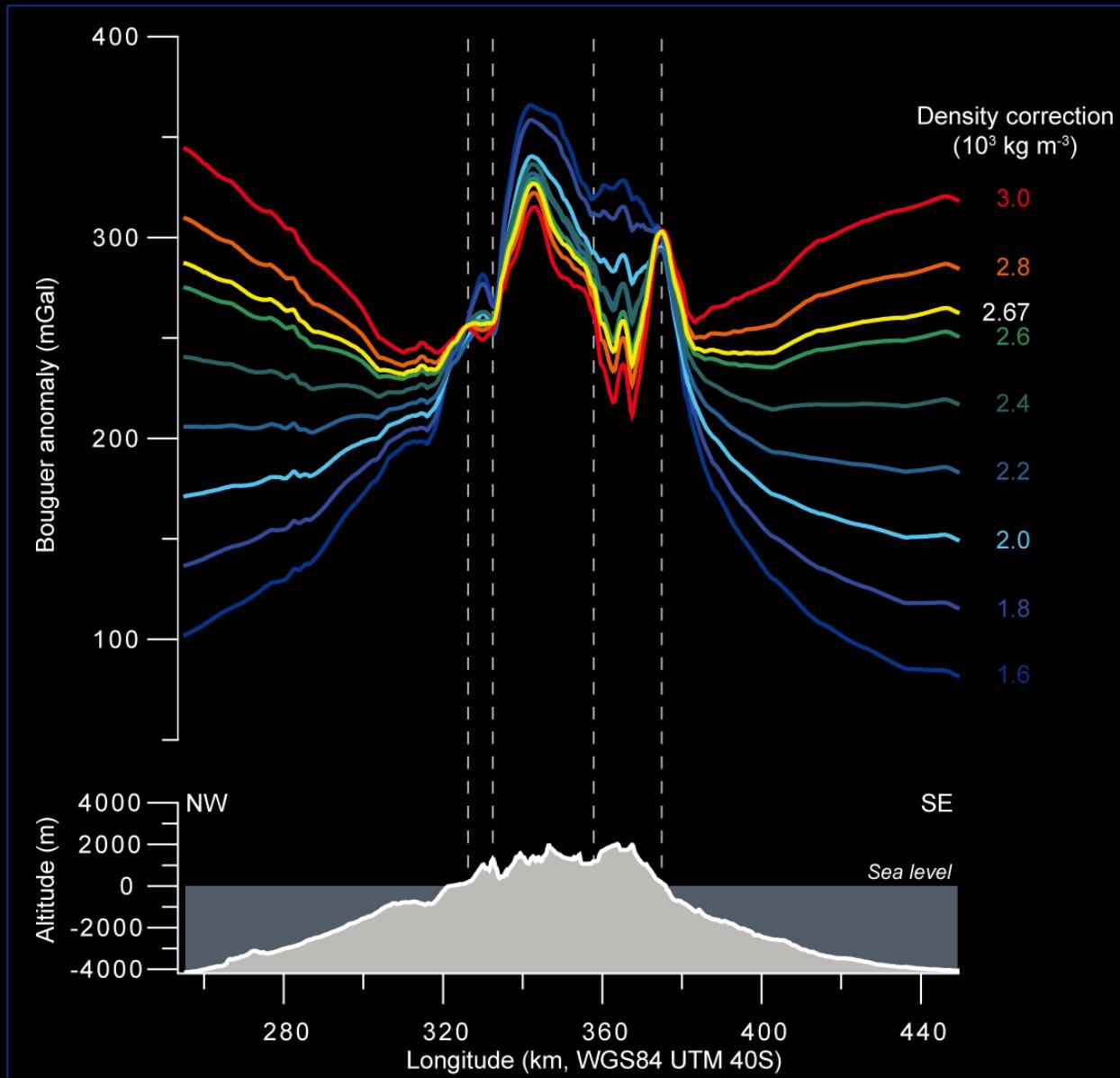
# Gravity

**Regional density correction** (*Nettleton, 1939*)



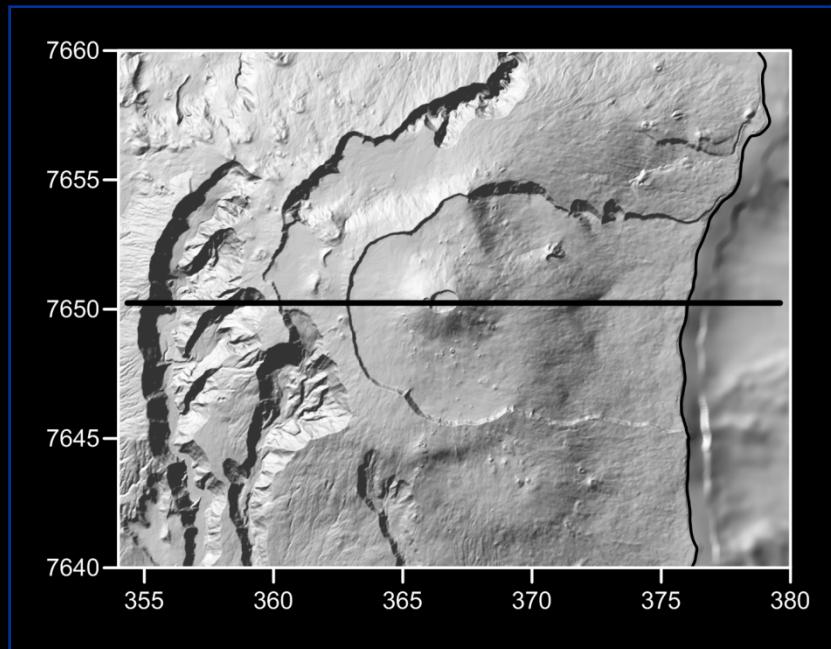
# Gravity

## Regional density correction (*Nettleton, 1939*)



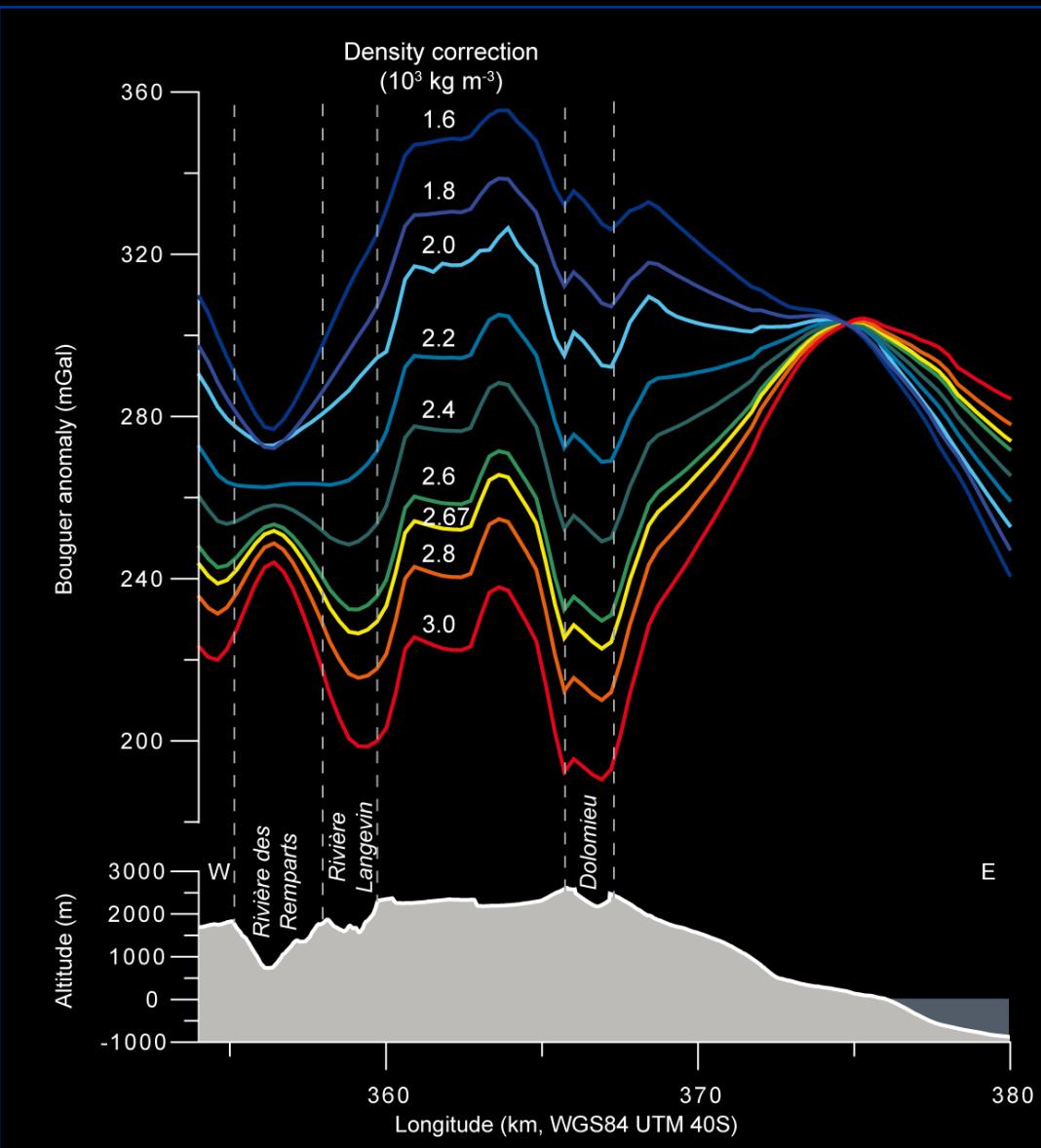
# Gravity

**Local density correction** (*Nettleton, 1939*)



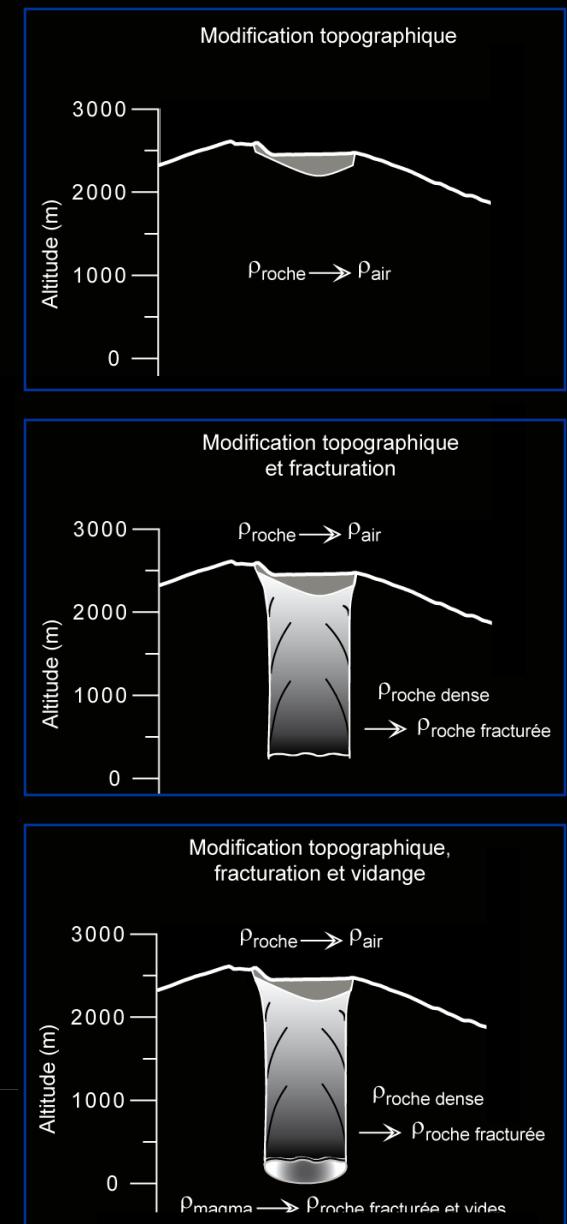
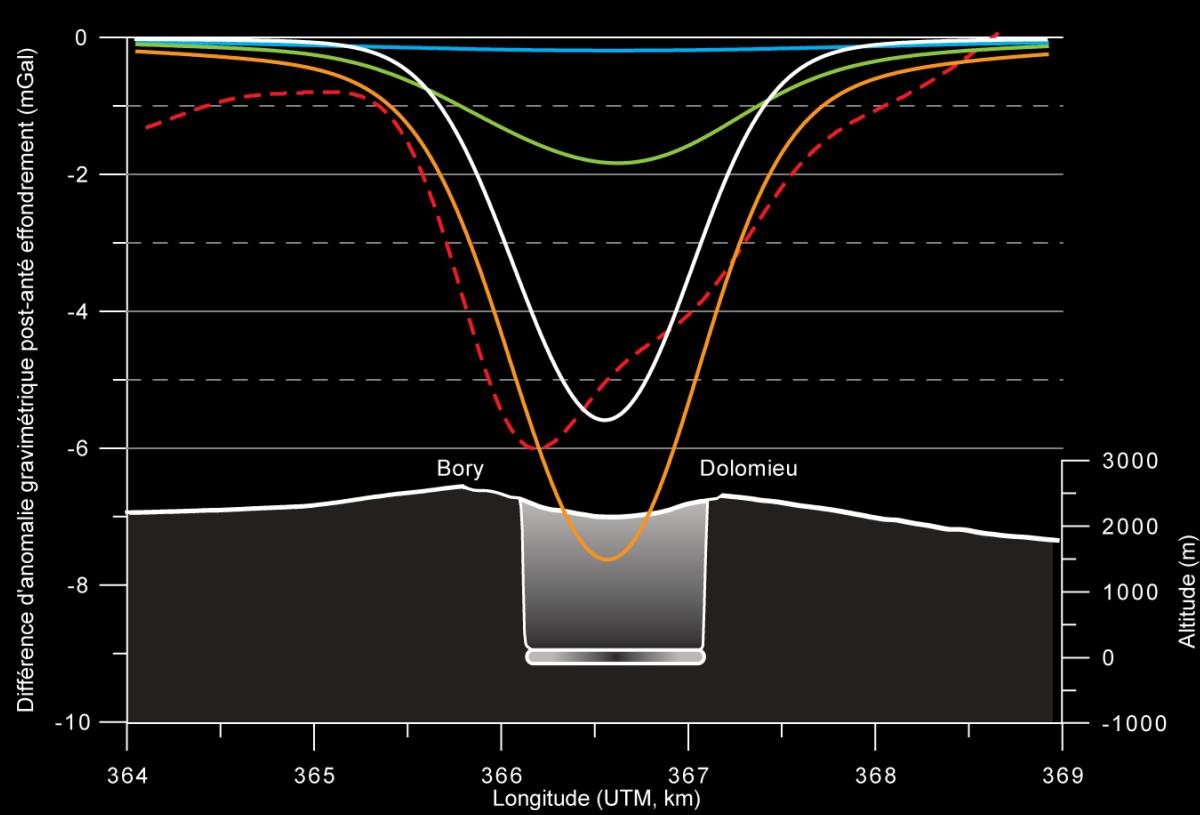
# Gravity

Local density correction (*Nettleton, 1939*)

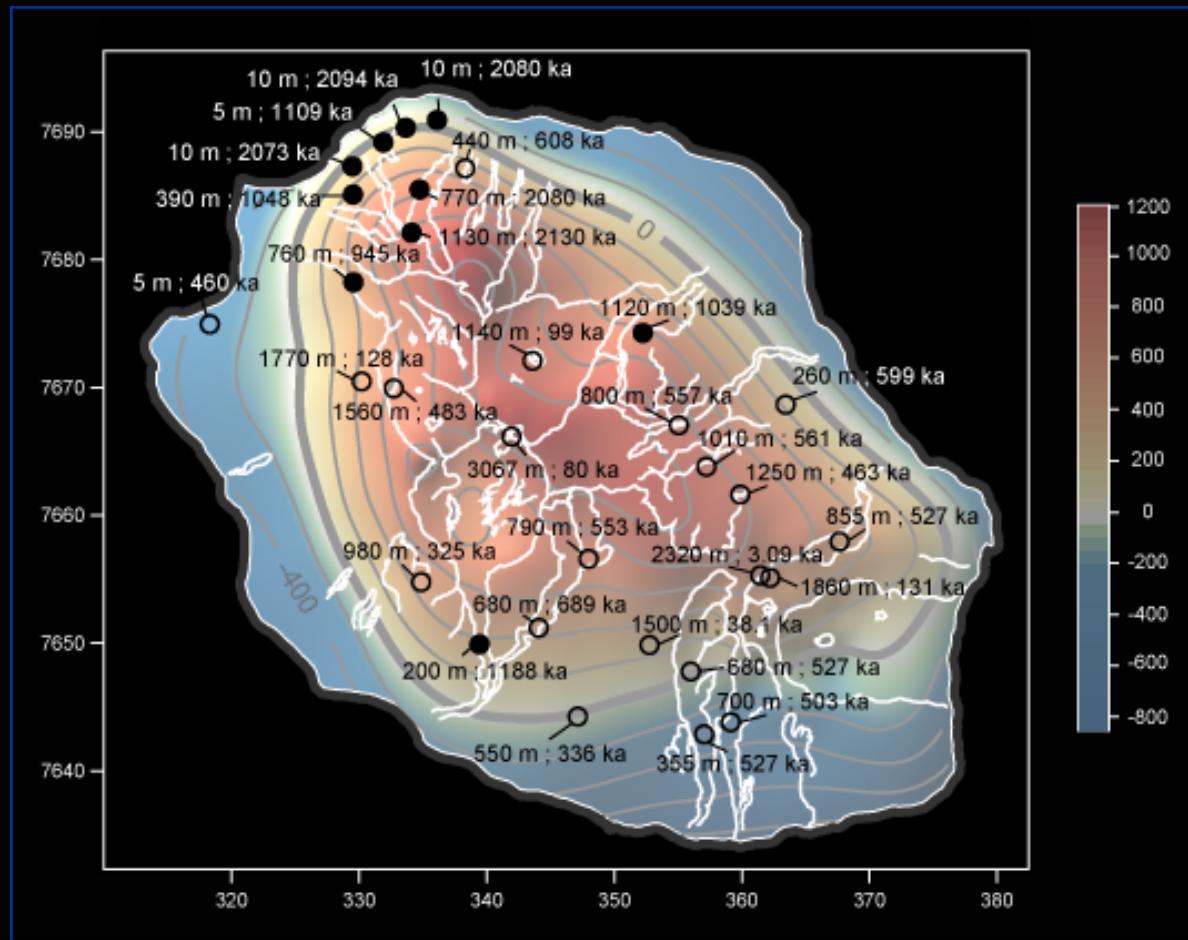


# Mass Transfer

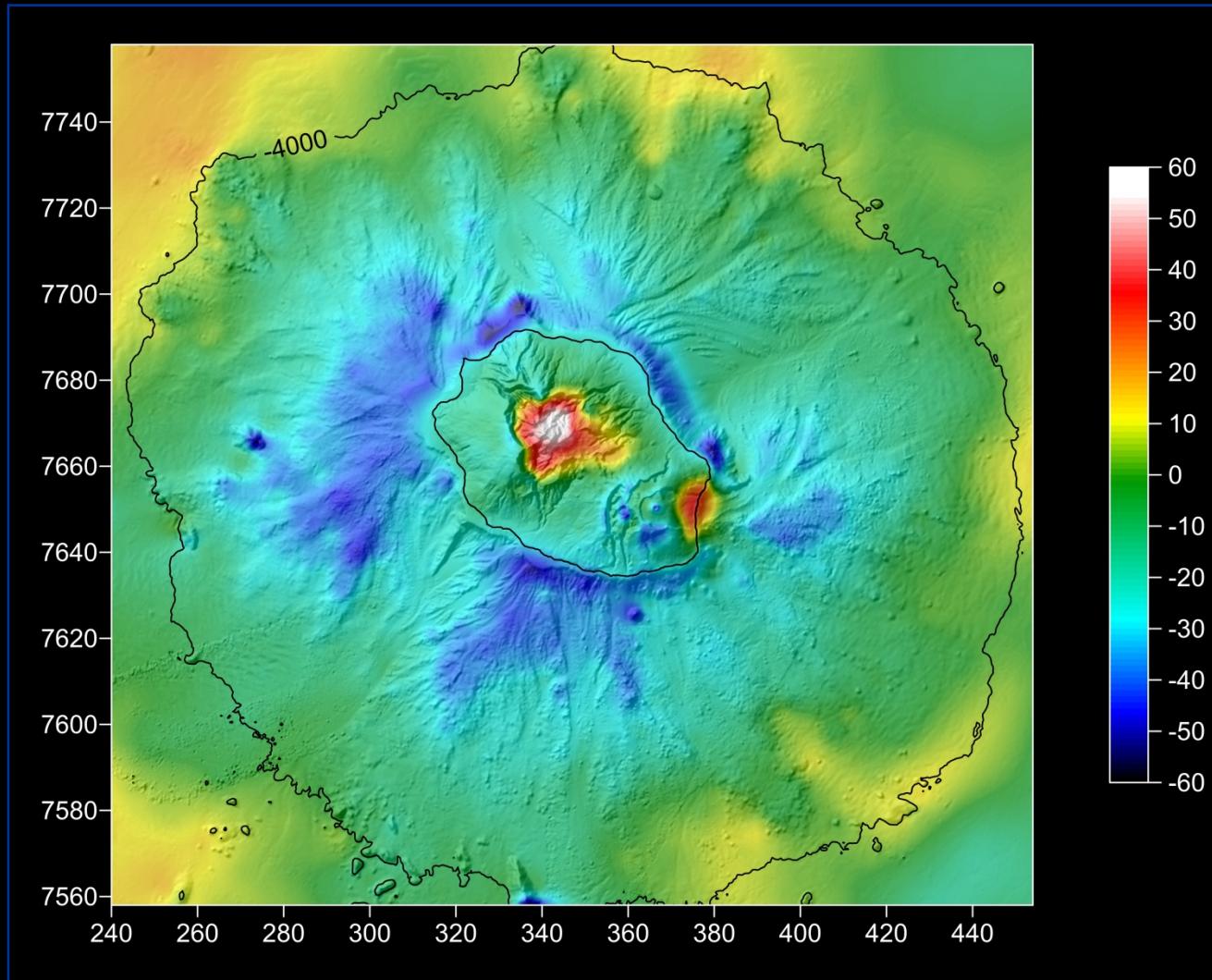
## 3D Modeling



# Pre-Brunhes morphology



# Gravity of the Submarine flanks

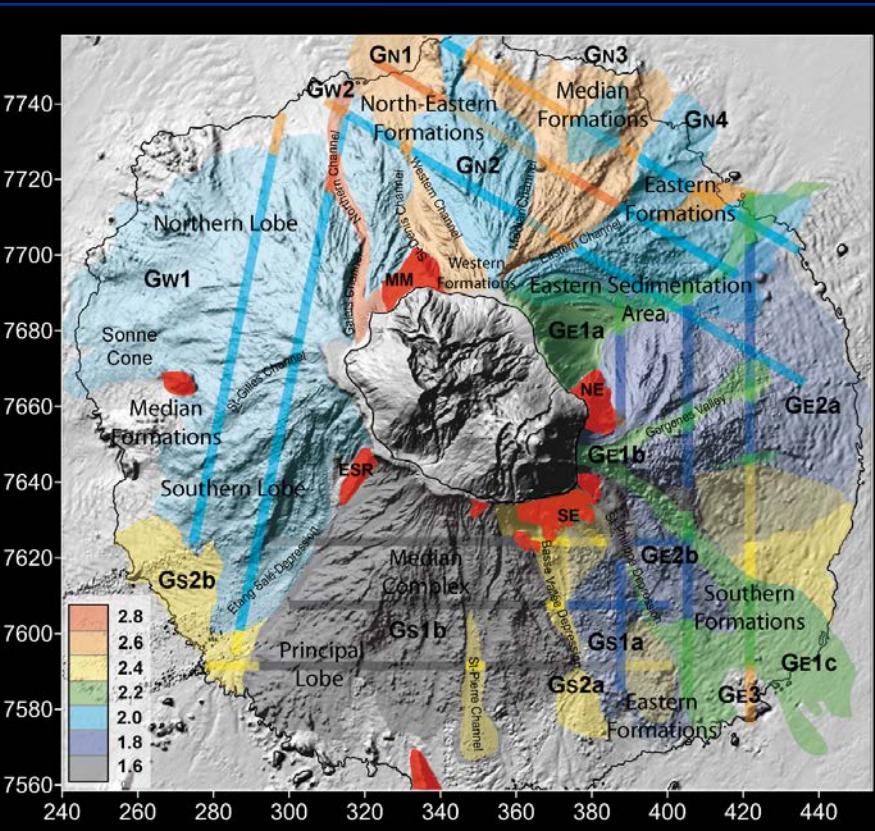
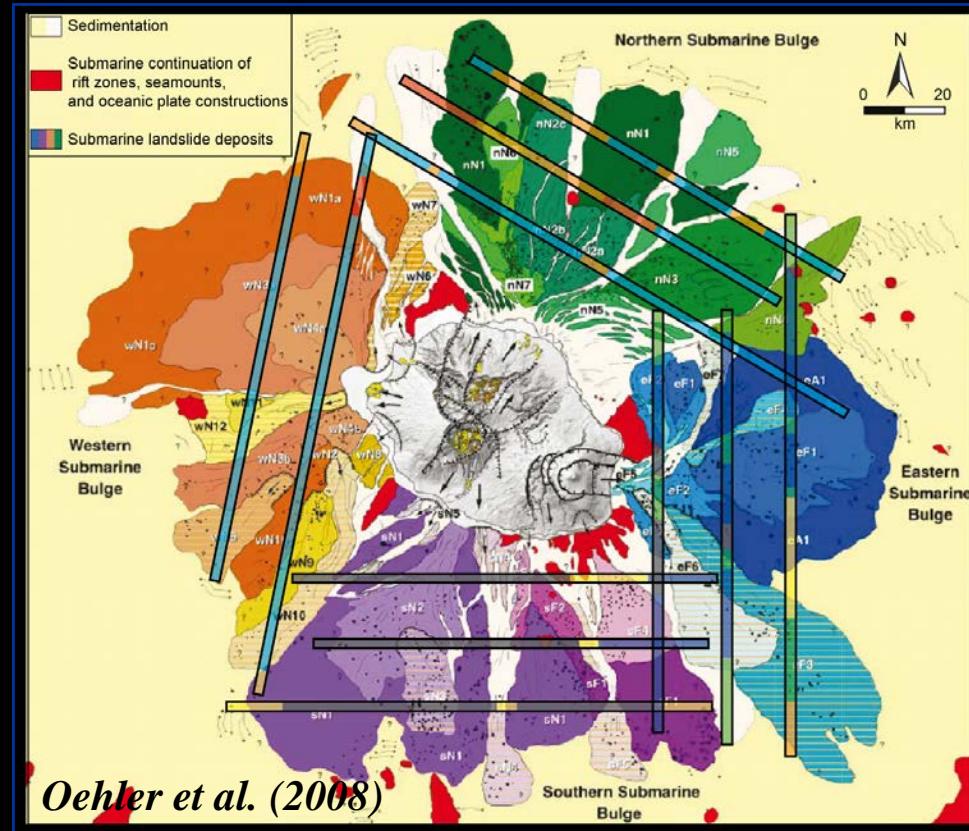


*Regional Bouguer anomaly  
Original Bouguer anomaly  
Density :  $2.67 \cdot 10^3 \text{ kg m}^{-3}$*

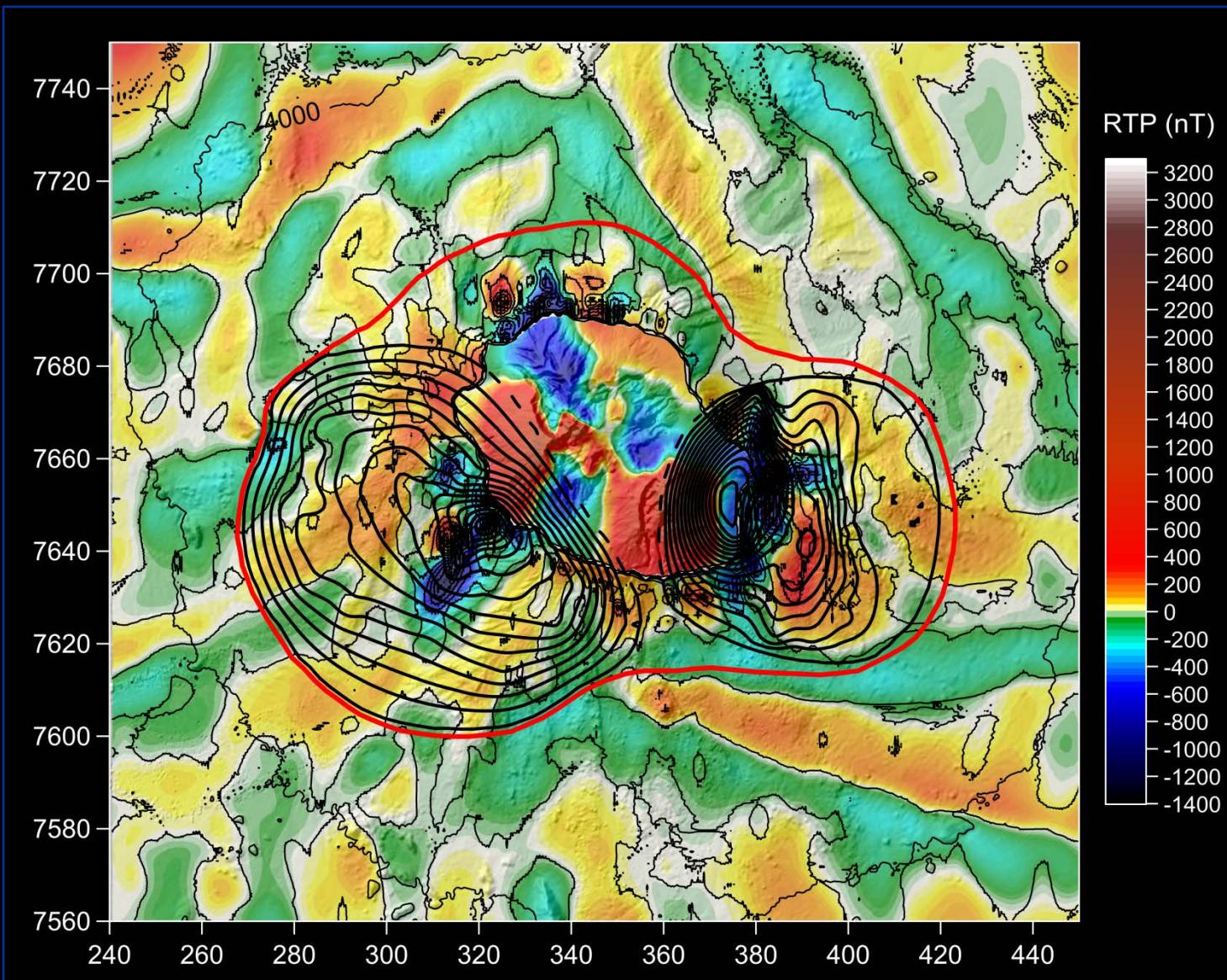
# The Submarine Bulges

## Geological correlation

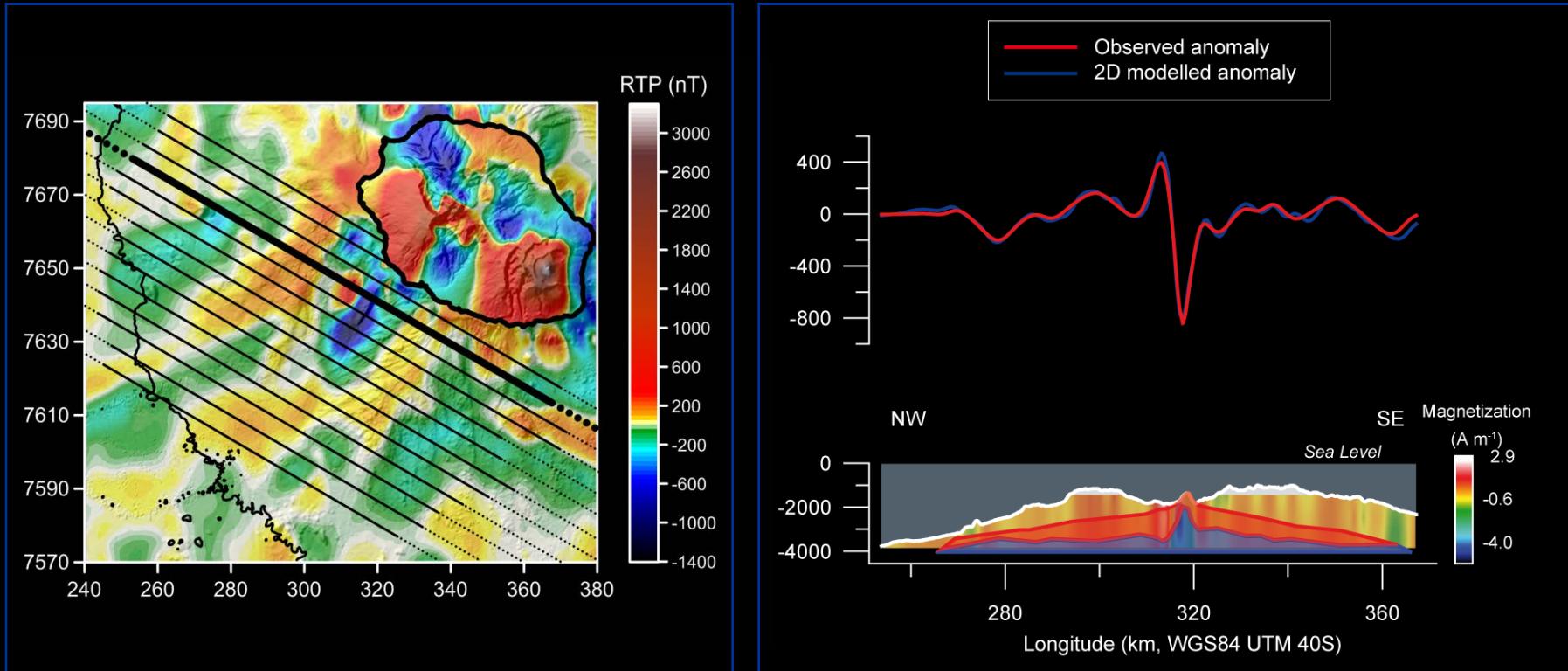
- Lateral variations of density
  - Correlations with units of the geological map (*Oehler et al. 2008*) and surface facies



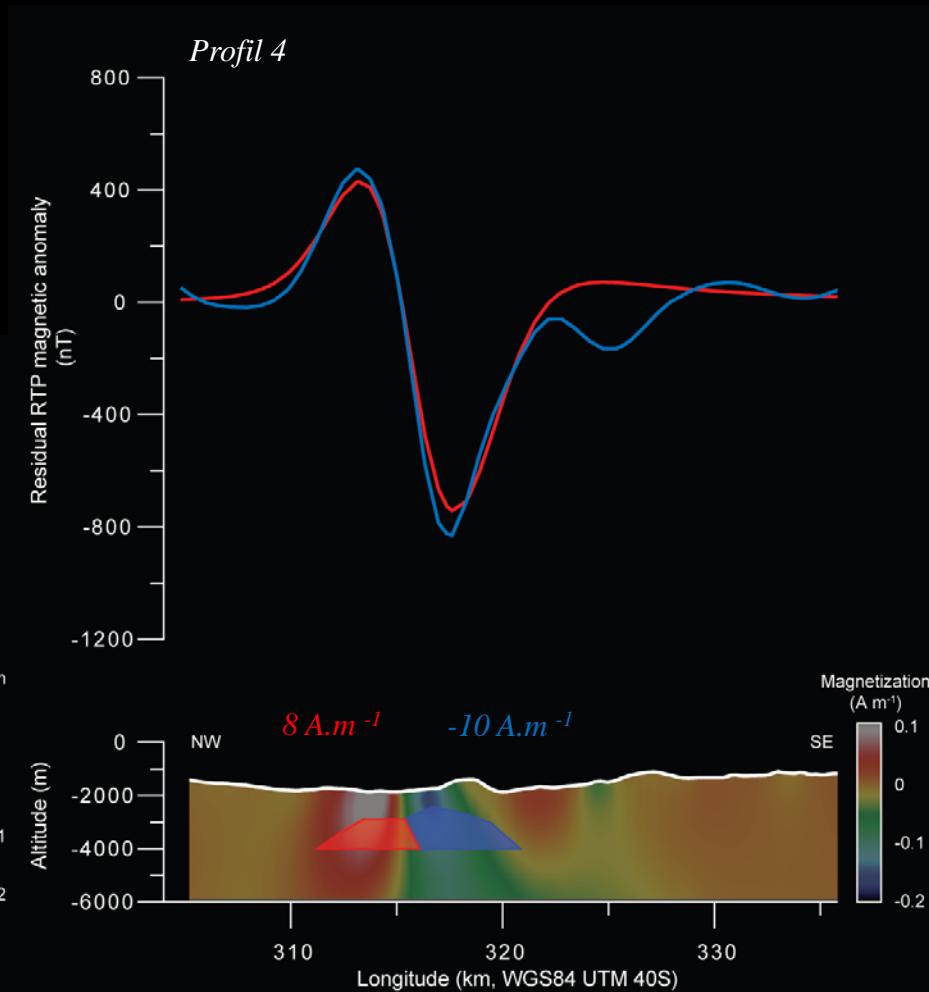
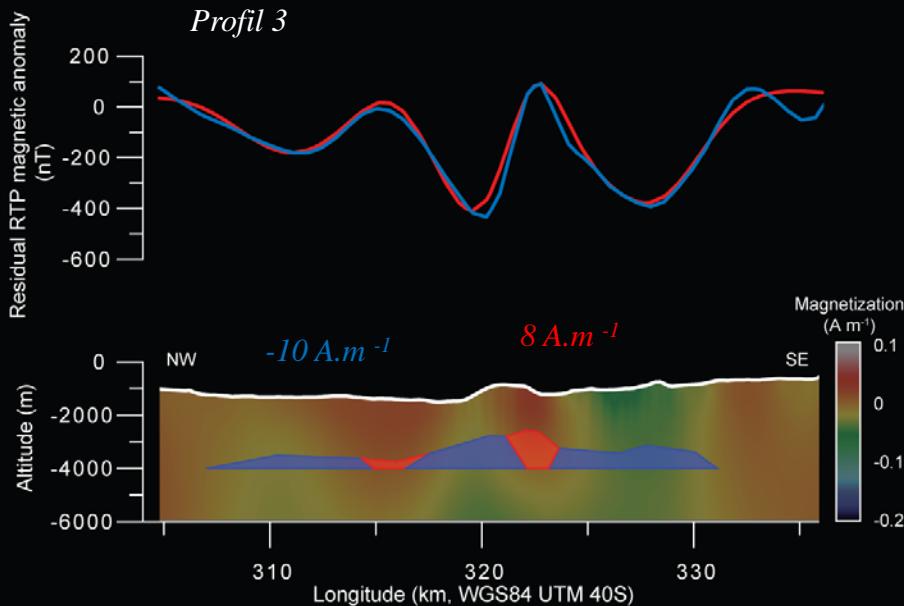
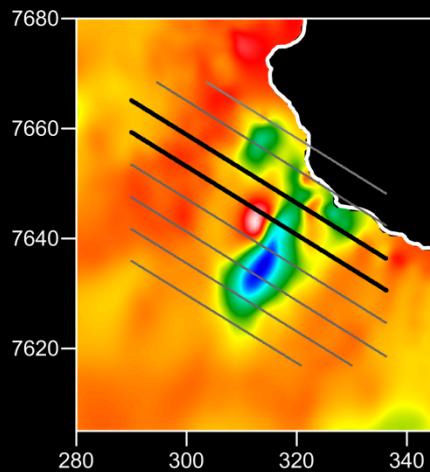
# Magnetic interpretation



# Etang Salé Ridge : Magnetic models



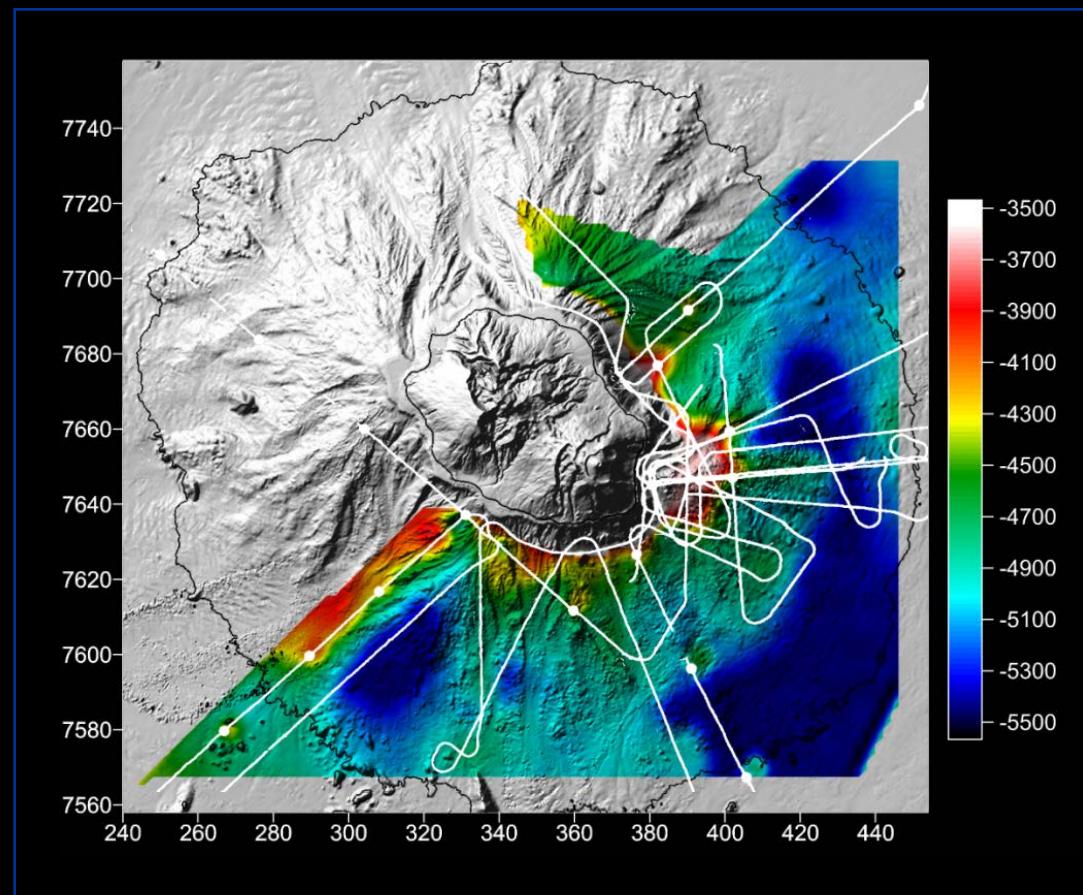
# Etang Salé Ridge : Alternative magnetic models



# Comparison with seismic data

## Seismic interpretation

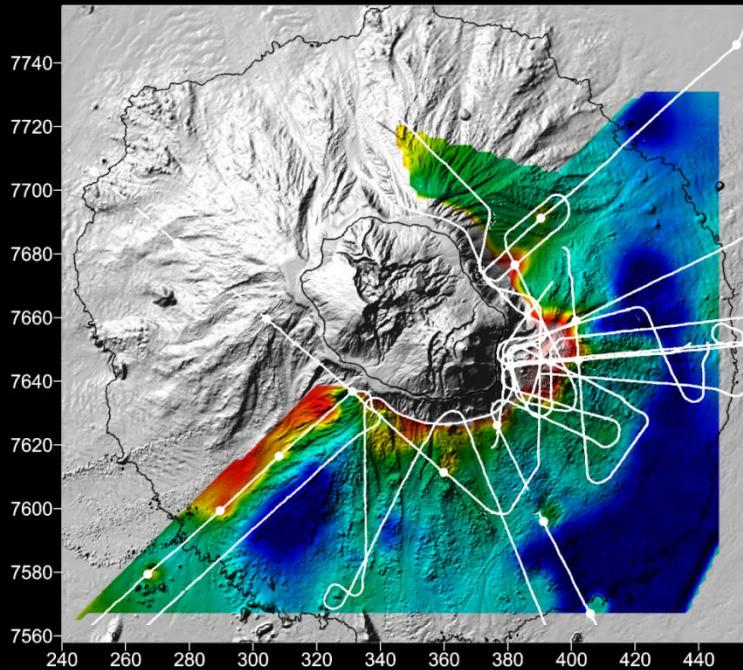
- Seismic interfaces :
  - ⇒ Top of the oceanic basement
  - (B)
  - ⇒ Base of the volcaniclastic edifice (V)
  - ⇒ Top of Les Alizés Volcano (H)
  
- V systematically bulged toward the island
  - ⇒ crust upwardly bended



# Seismic Data

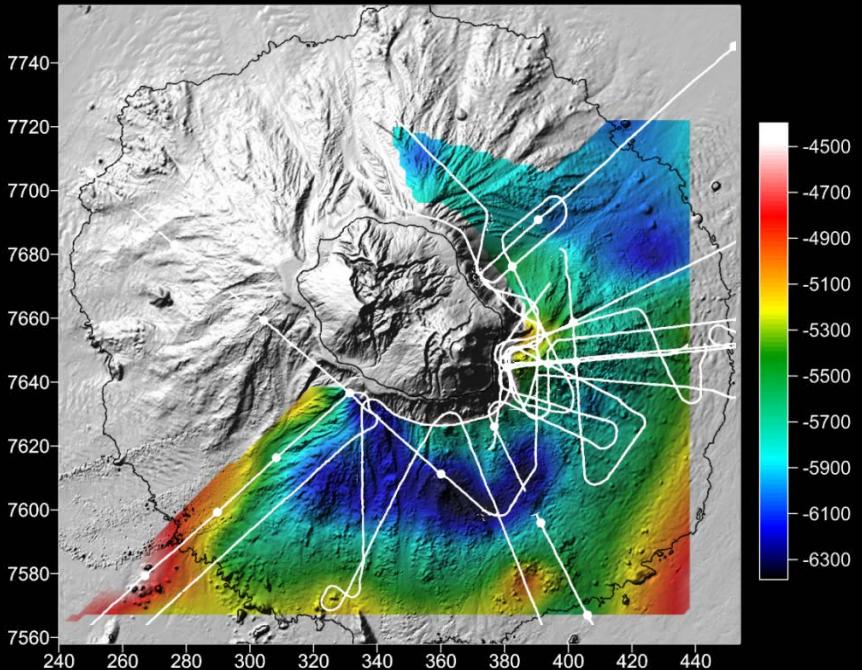
## Horizon V

Base of the volcanic edifice

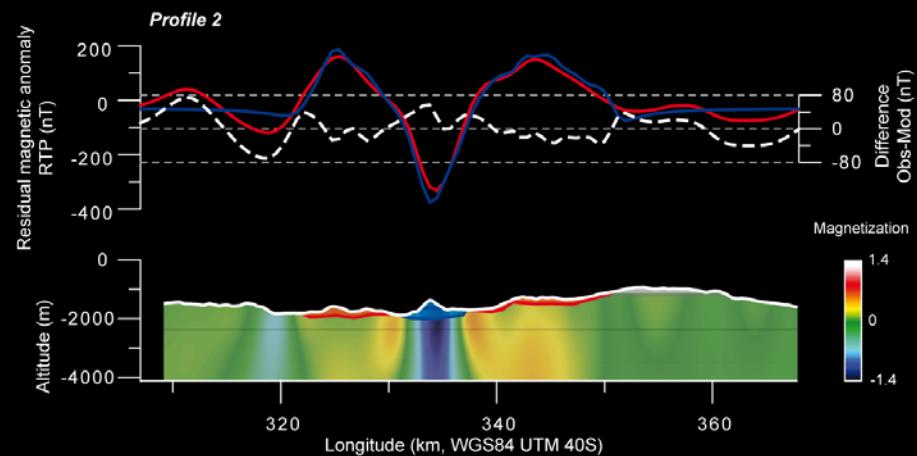
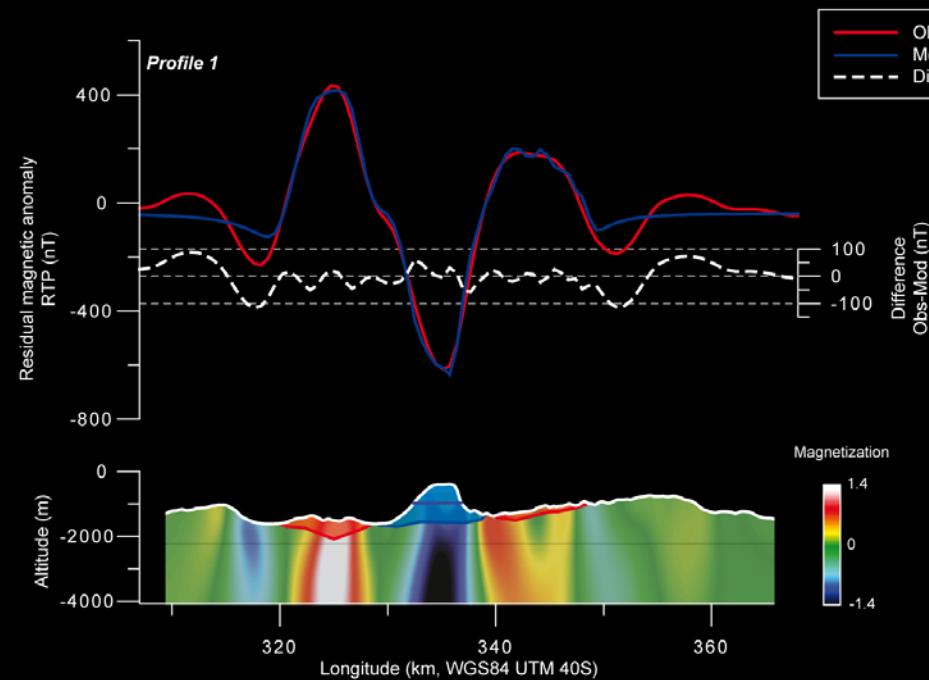
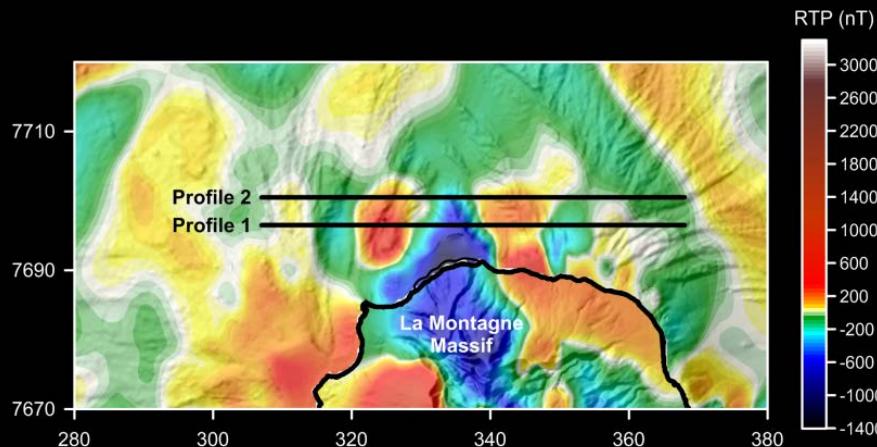


## Horizon B

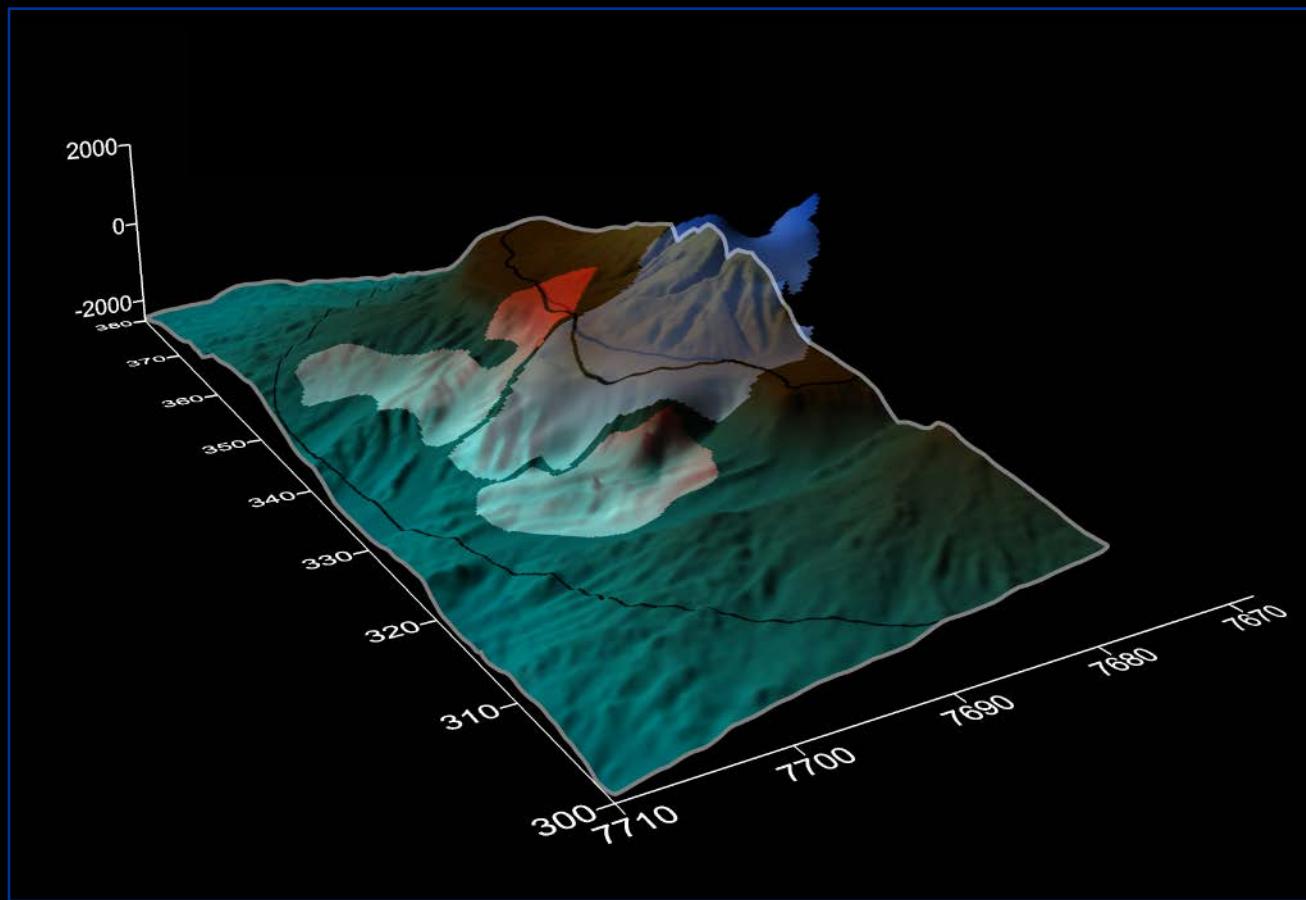
Preexisting oceanic plate



# La Montagne Massif : Magnetic Data

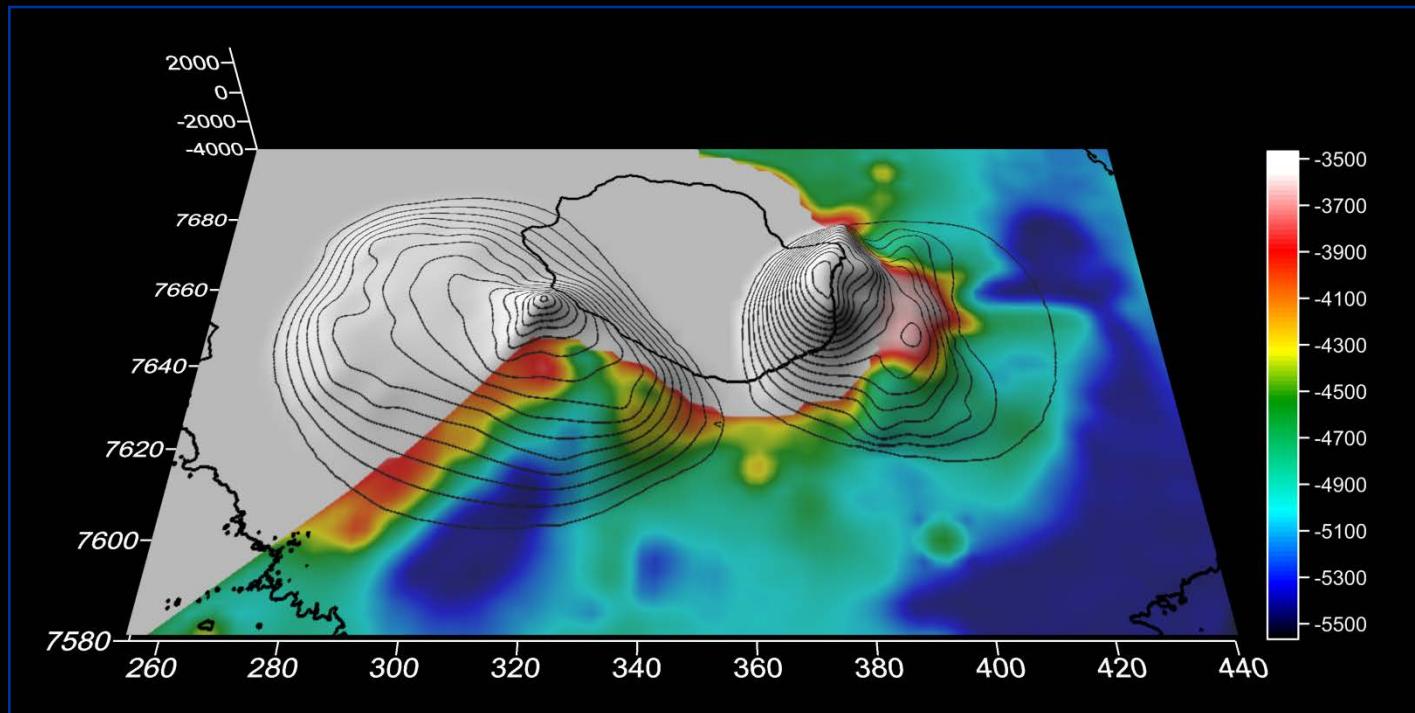


# La Montagne Massif : Magnetic data



# Magnetism vs Seismic reflection

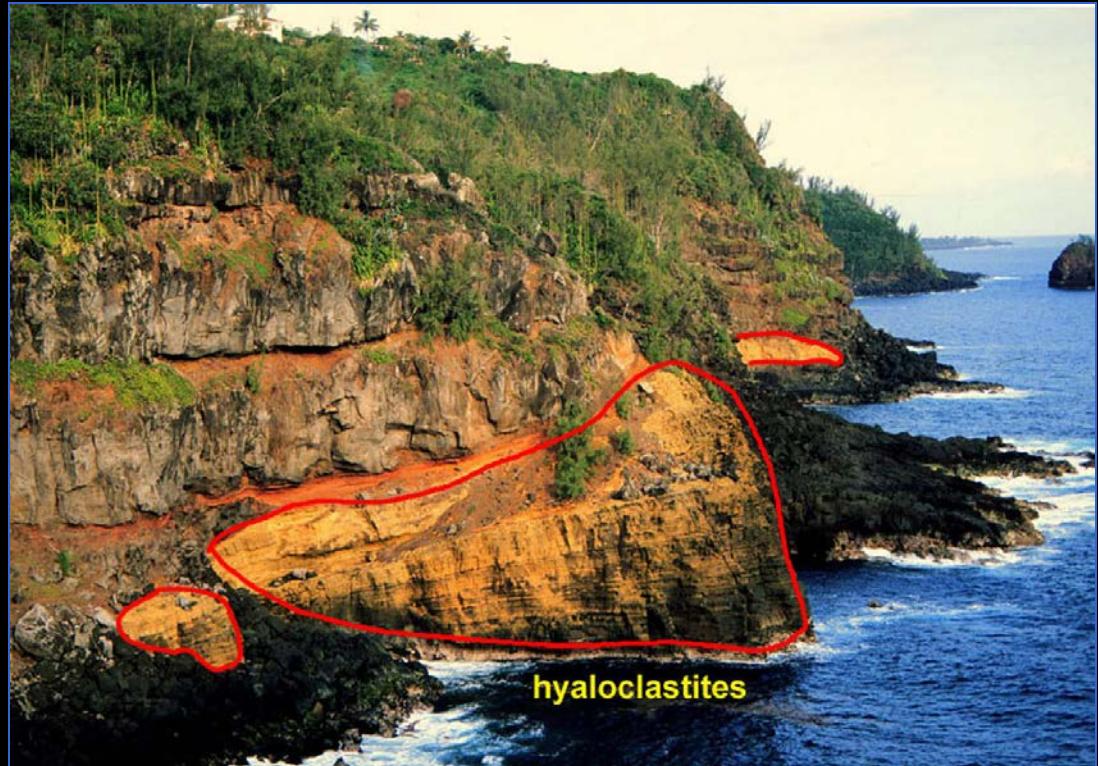
- Seismic horizons: top of the volcanic constructions beneath débris avalanches deposits and sediments



↳ No bulging of the oceanic crust

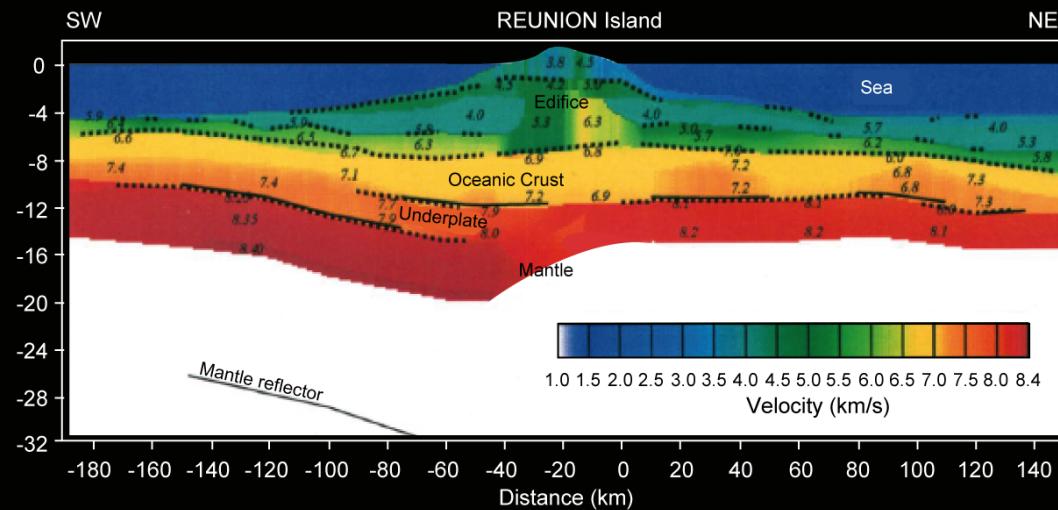
# Hyaloclastites

*Hyaloclastites cliff of Grand-Anse*

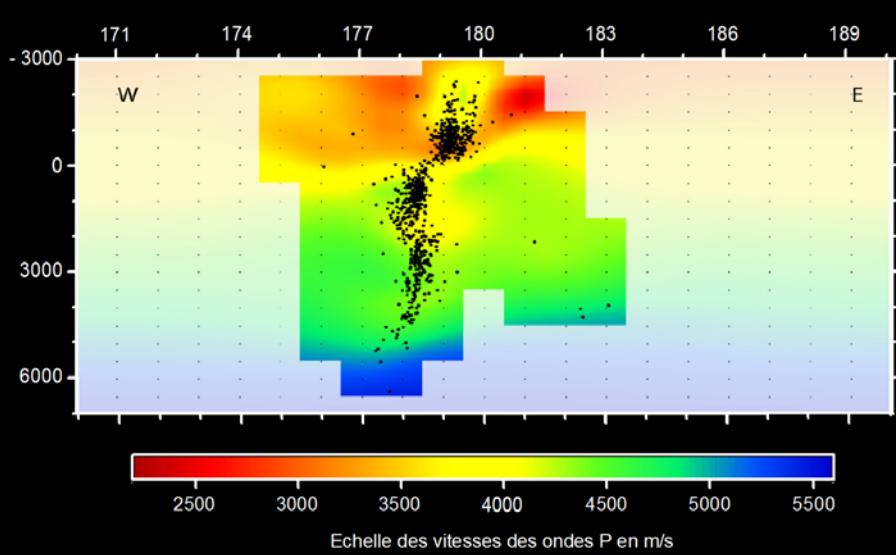


# Hyaloclastites

Gallart et al. (1999) 2007



Pronot, 2007



Hirn et al., 1998

