Universidade de São Paulo

INSTITUTO DE ASTRONOMIA, GEOFÍSICA E CIÊNCIAS ATMOSFÉRICAS

Geofísica da América do Sul

Método magnetotelúrico

Novembro 2022

Gabriel N. Dragone (gabriel.dragone@usp.br)

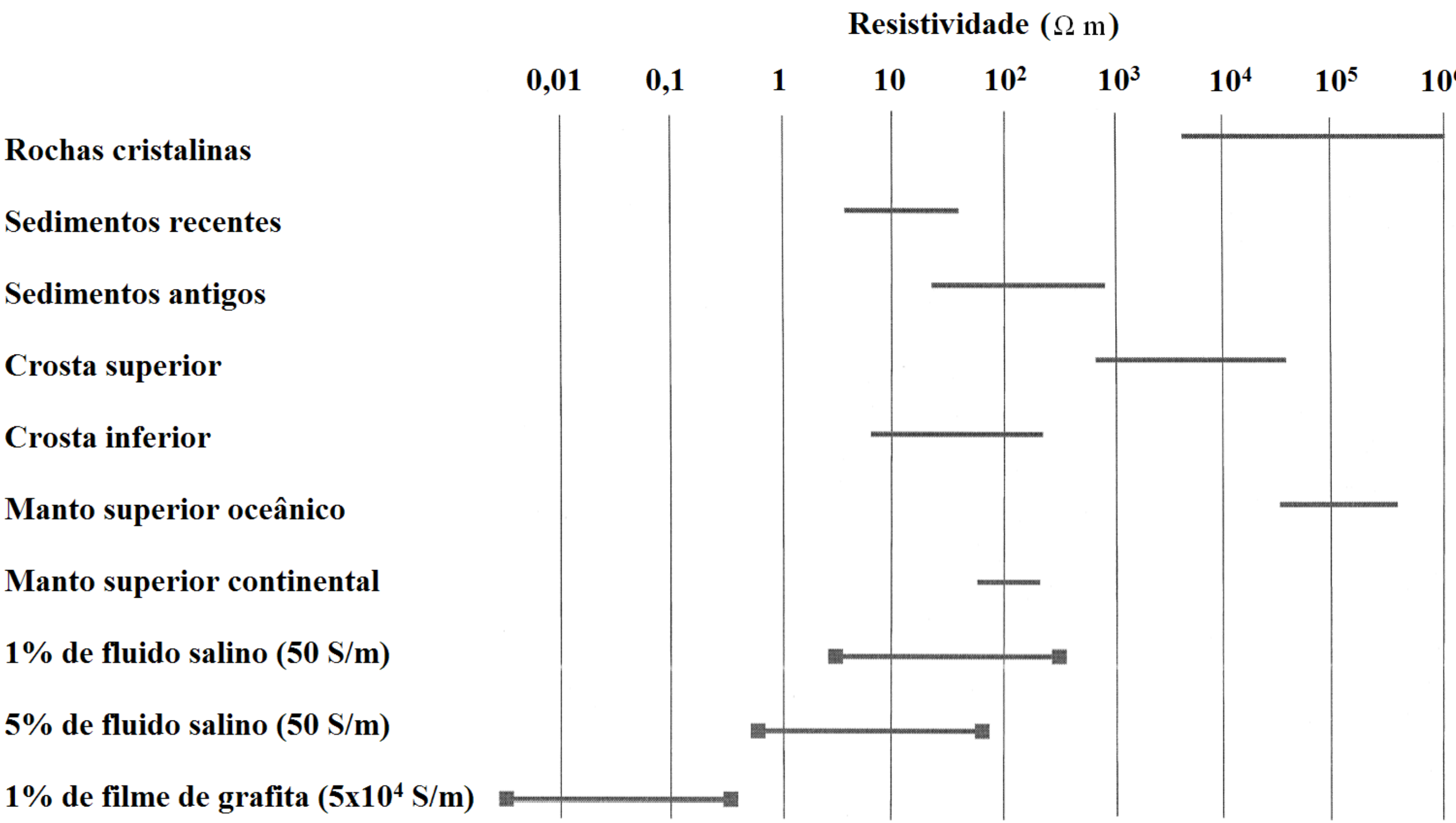
Introdução

- 1) Princípios básicos do método magnetotelúrico (MT)
  - O que é?
  - Por que fazer?
  - Como fazer?
- 2) Exemplos de aplicação na América do Sul

O que é o método MT?

- Método eletromagnético passivo, usa fontes naturais;
- Distribuição da condutividade elétrica em subsuperfície;

$$\begin{cases} \sigma & \text{(condutividade)} \\ \rho = \dfrac{1}{\sigma} & \text{(resistividade)} \end{cases}$$



Adaptado de Jones (1999)

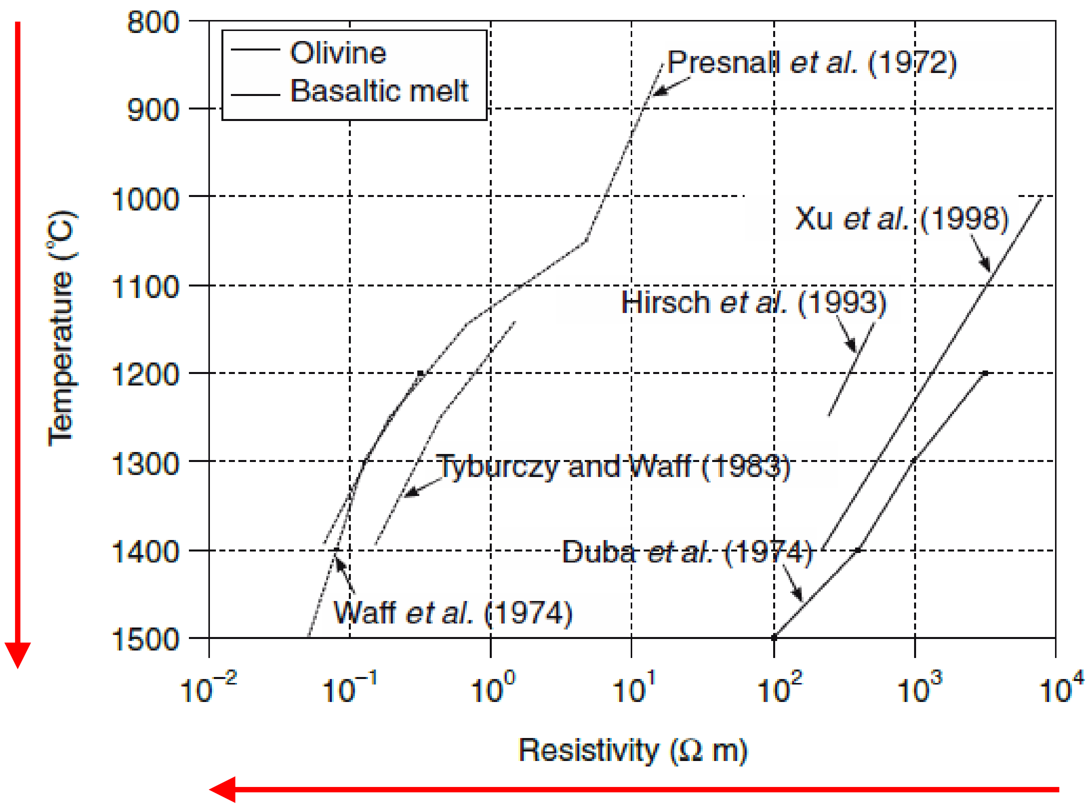
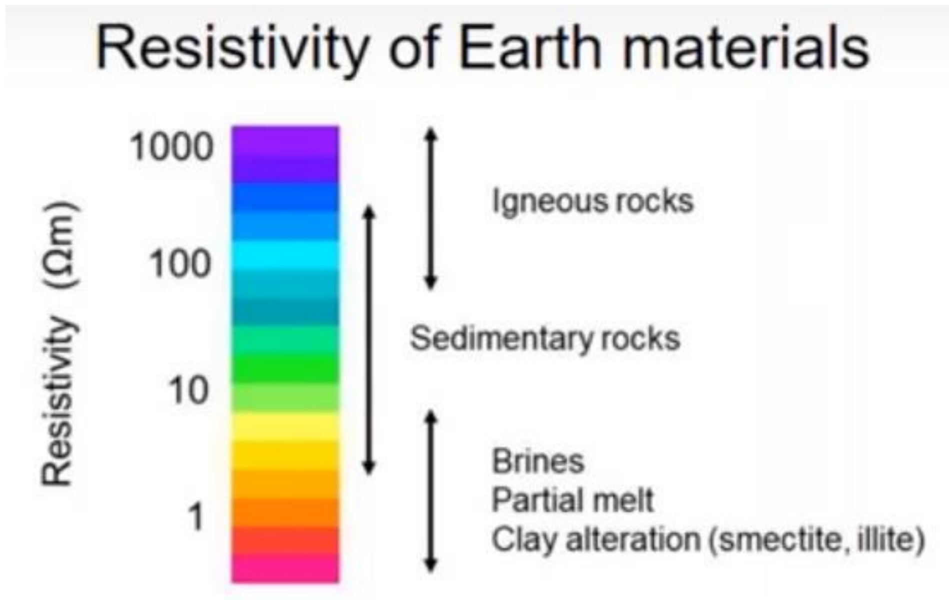


Figure 1.4 Electrical resistivities of dry olivine and basaltic melt as a function of temperature. Basaltic melt is approximately three orders of magnitude less resistive than dry olivine.

(Simpson and Bahr, 2005)



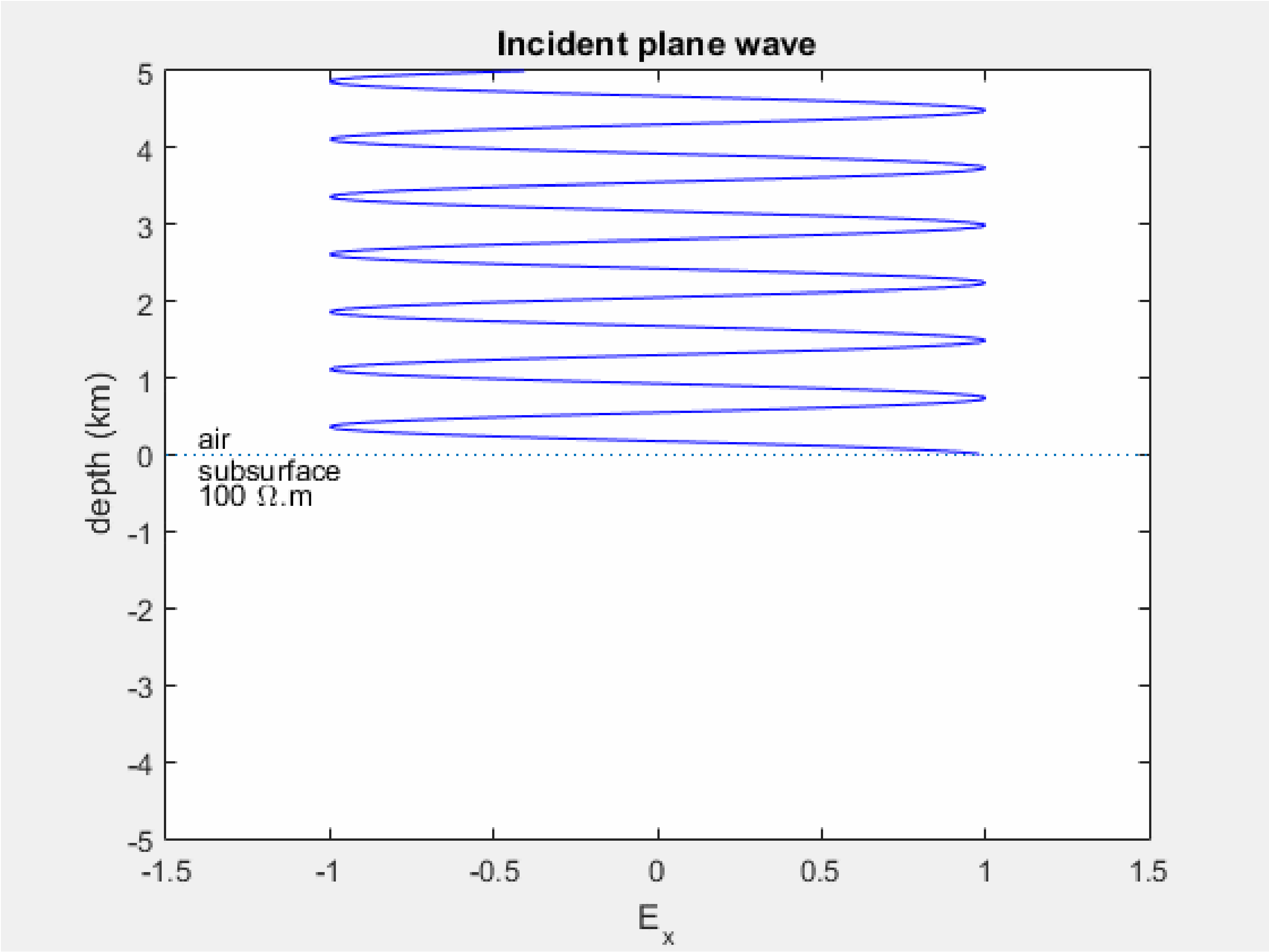
M. Unsworth (https://www.youtube.com/watch?v=ce4ATvbCwAw)

Por que fazer MT?

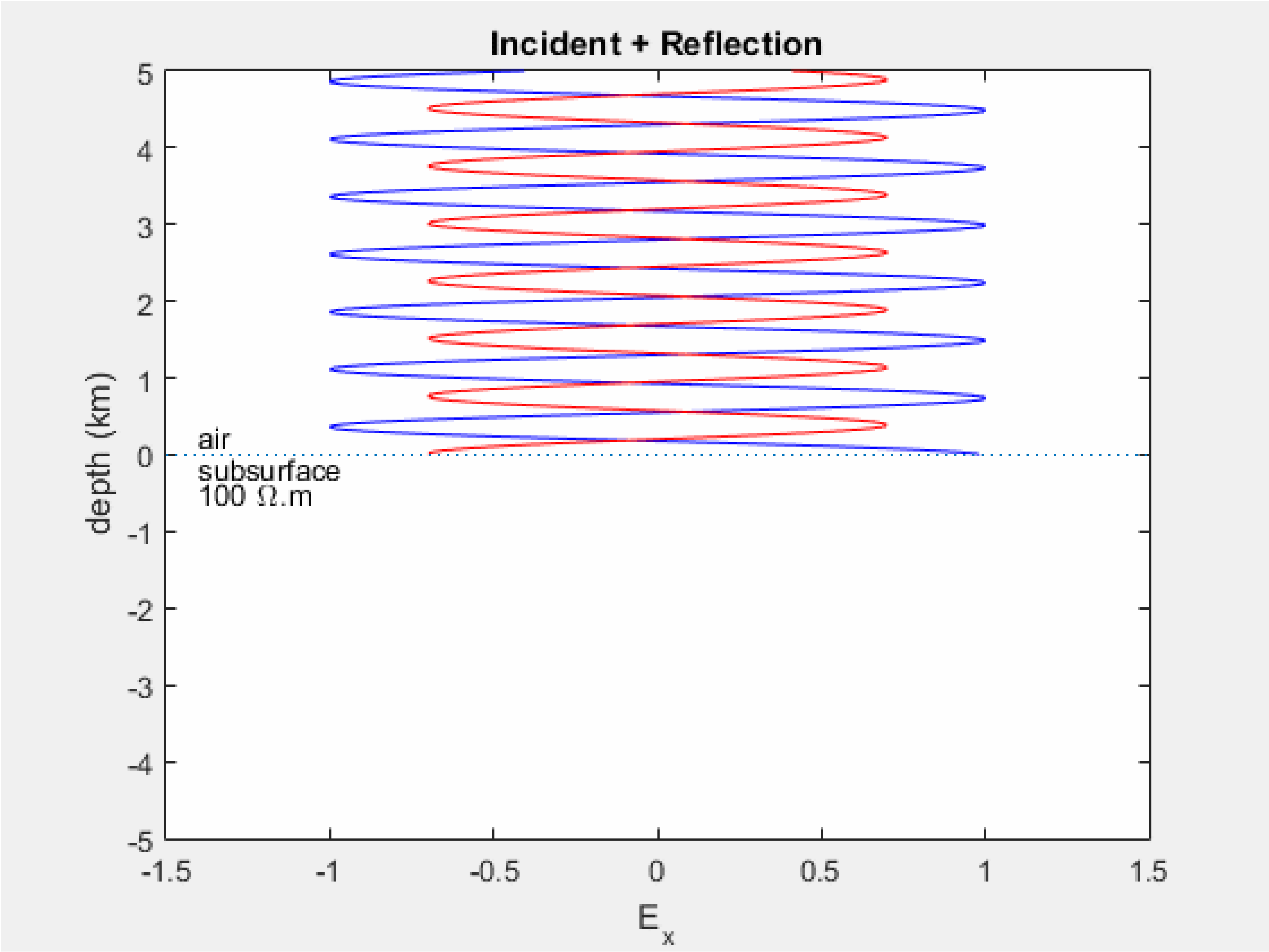
- Único método que permite obter a resistividade a grandes profundidades;
  - Perfilagem;
  - DC;
  - Outros métodos EM.

- Profundidade de investigação controlada pela frequência/período do sinal:

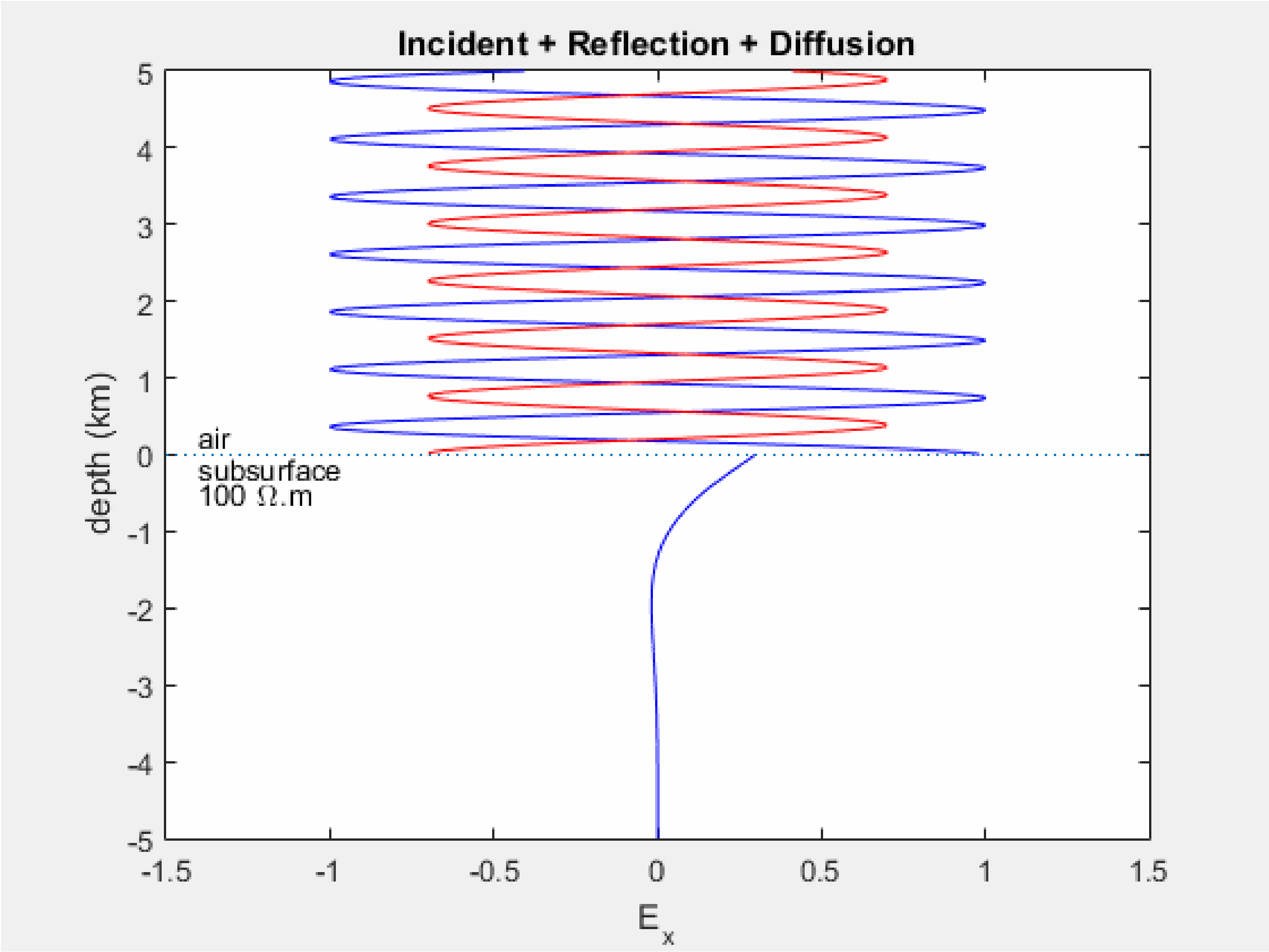
Profundidade pelicular (*skin depth*)



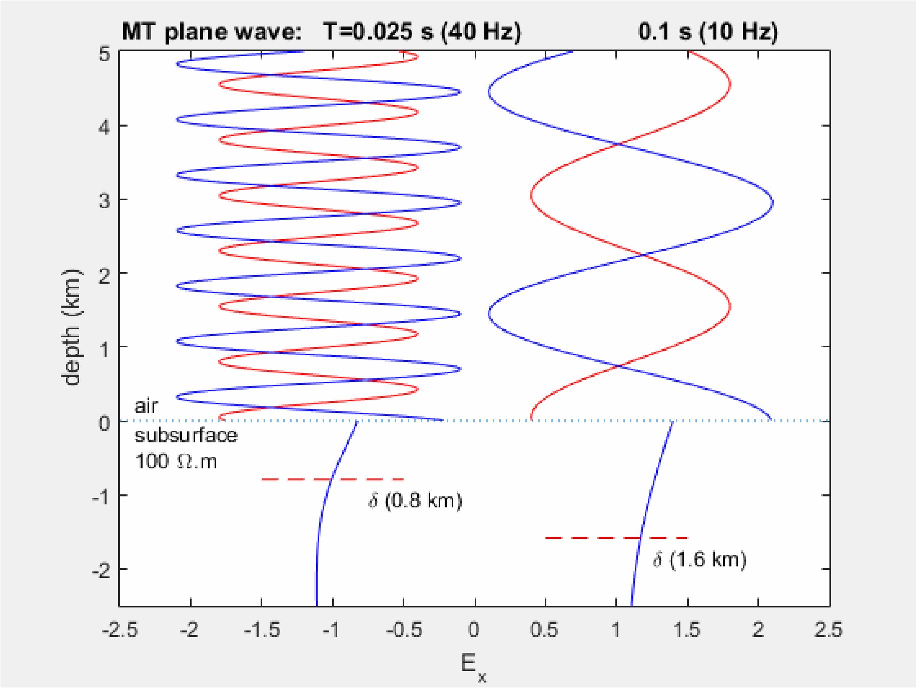
Animation adapted from the original by M. Unsworth (https://sites.ualberta.ca/~unsworth/MT/MT.html)



Animation adapted from the original by M. Unsworth (https://sites.ualberta.ca/~unsworth/MT/MT.html)



Animation adapted from the original by M. Unsworth (https://sites.ualberta.ca/~unsworth/MT/MT.html)



- Propagação do sinal é difusiva, ocorre atunação com a profundidade.
- *Skin depth*:
- Profundidade na qual o campo terá decaído com uma proporção de 1/e;
- Profundidade que o sinal alcança depende do período (T) e resistividade (ρ) do meio:

$$\delta \cong 500\sqrt{\rho T}$$

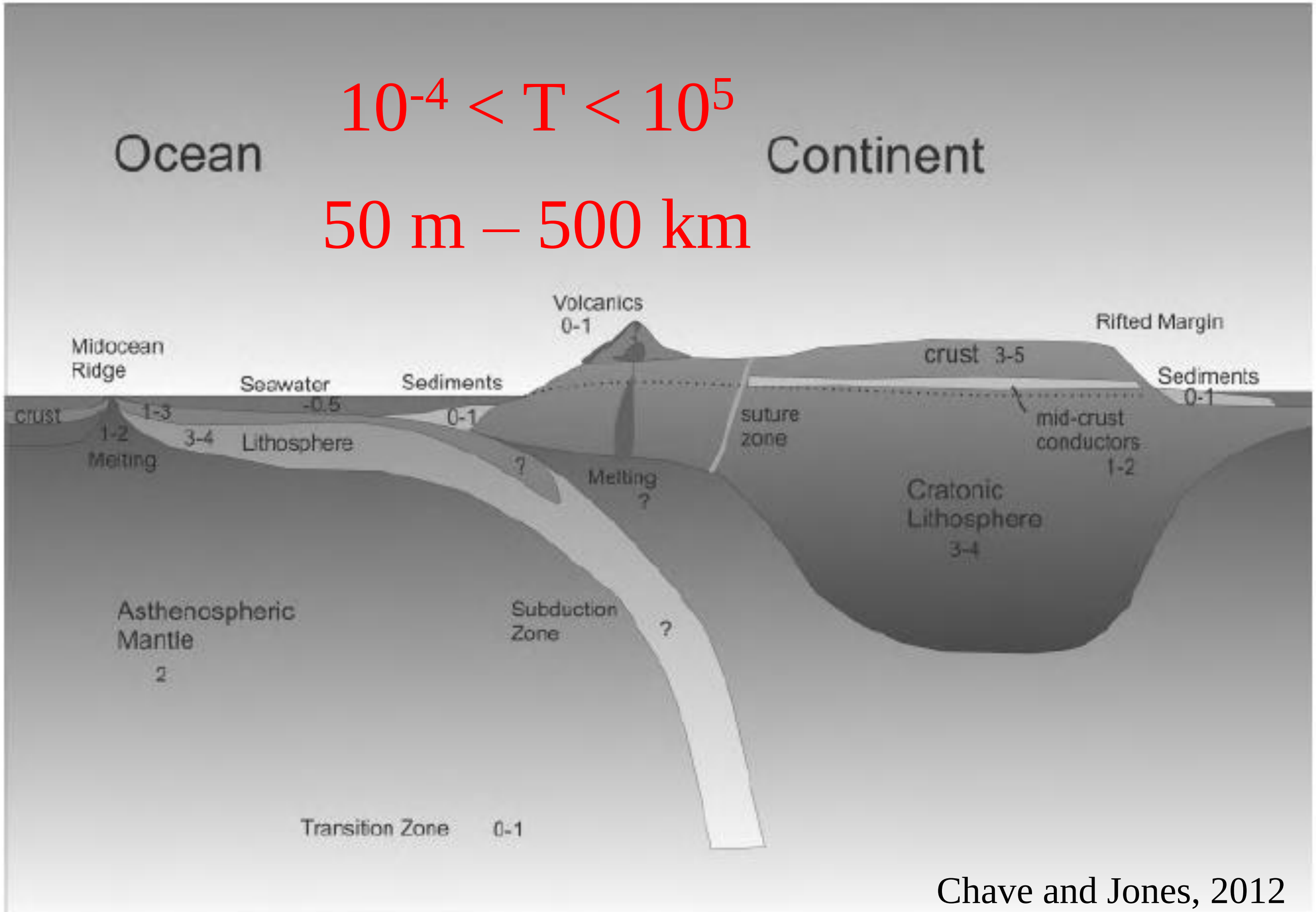
Animation adapted from the original by M. Unsworth (https://sites.ualberta.ca/~unsworth/MT/MT.html)

Considere os seguintes cenários:

1) Uma sondagem MT realizada em uma bacia sedimentar, com resistividade média de 10 Ωm. Qual a profundidade de investigação (*skin depth*) para um período de 0,1 s? E para um período de 10 s?

2) Uma sondagem MT realizada fora da bacia sedimentar, sobre rocha cristalina com resistividade média de 1000 Ωm. Qual a profundidade de investigação para um período de 10 s?

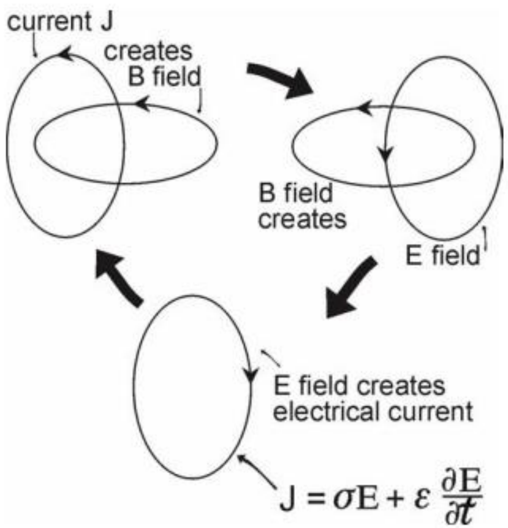
$$\delta \cong 500\sqrt{\rho T}$$



A cartoon of the continents and oceans showing key features and typical ranges of resistivity in each; numbers shown are $\log_{10}(\text{resistivity}/\Omega\ \text{m})$.

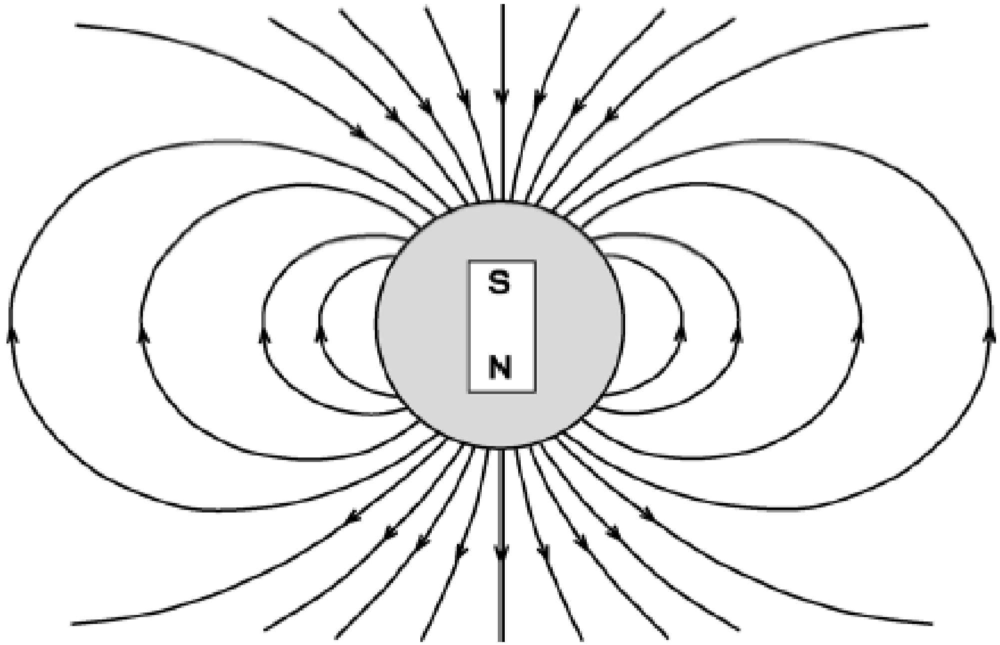
Princípio

- Oscilações naturais do campo geomagnético → fonte para a indução eletromagnética
- Variações no campo magnético induzem correntes elétricas (Lei de Faraday);
- As correntes, por suas vezes, induzem um campo magnético secundário (Lei de Ampère).

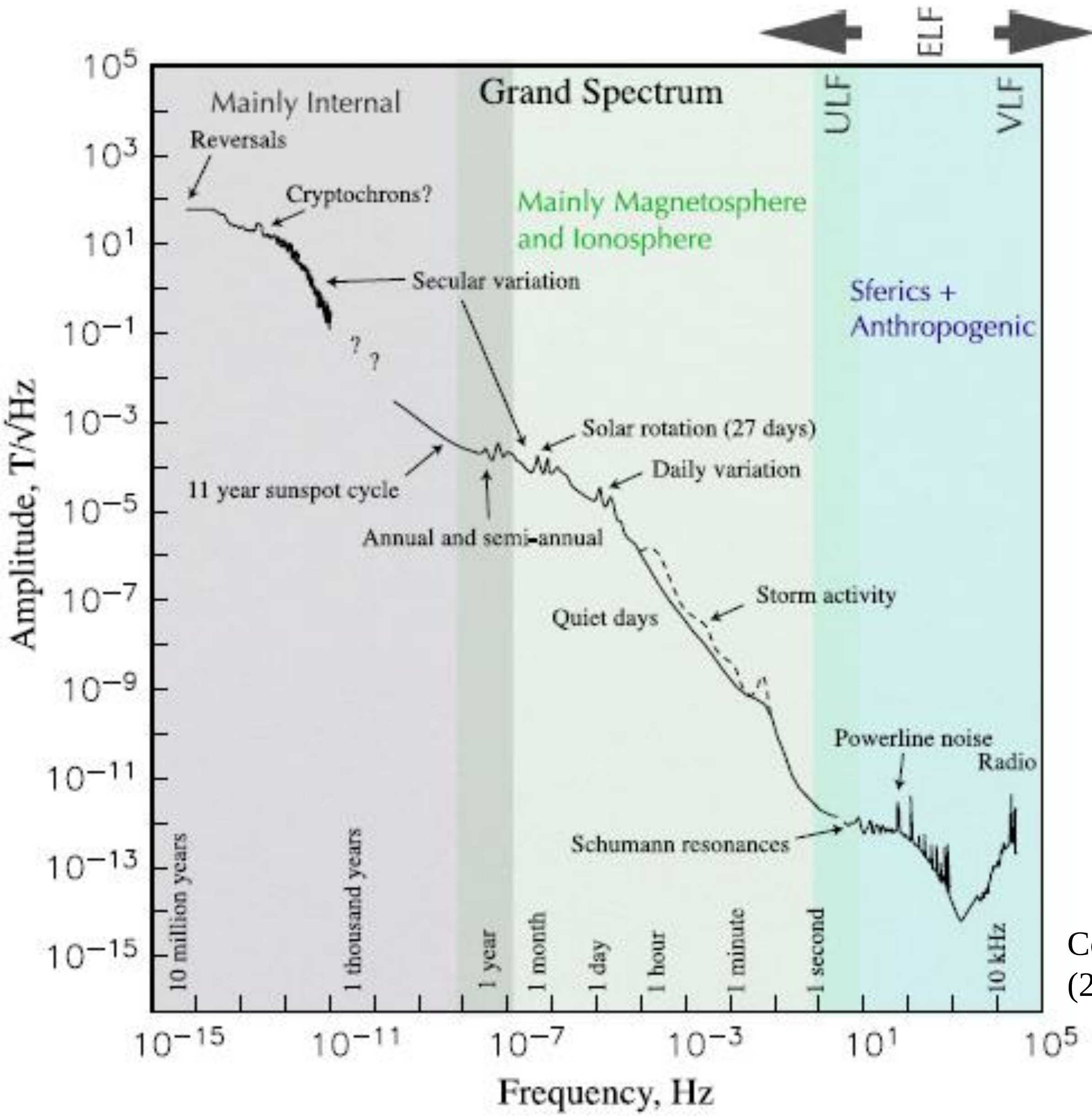


(Annan, 2003)

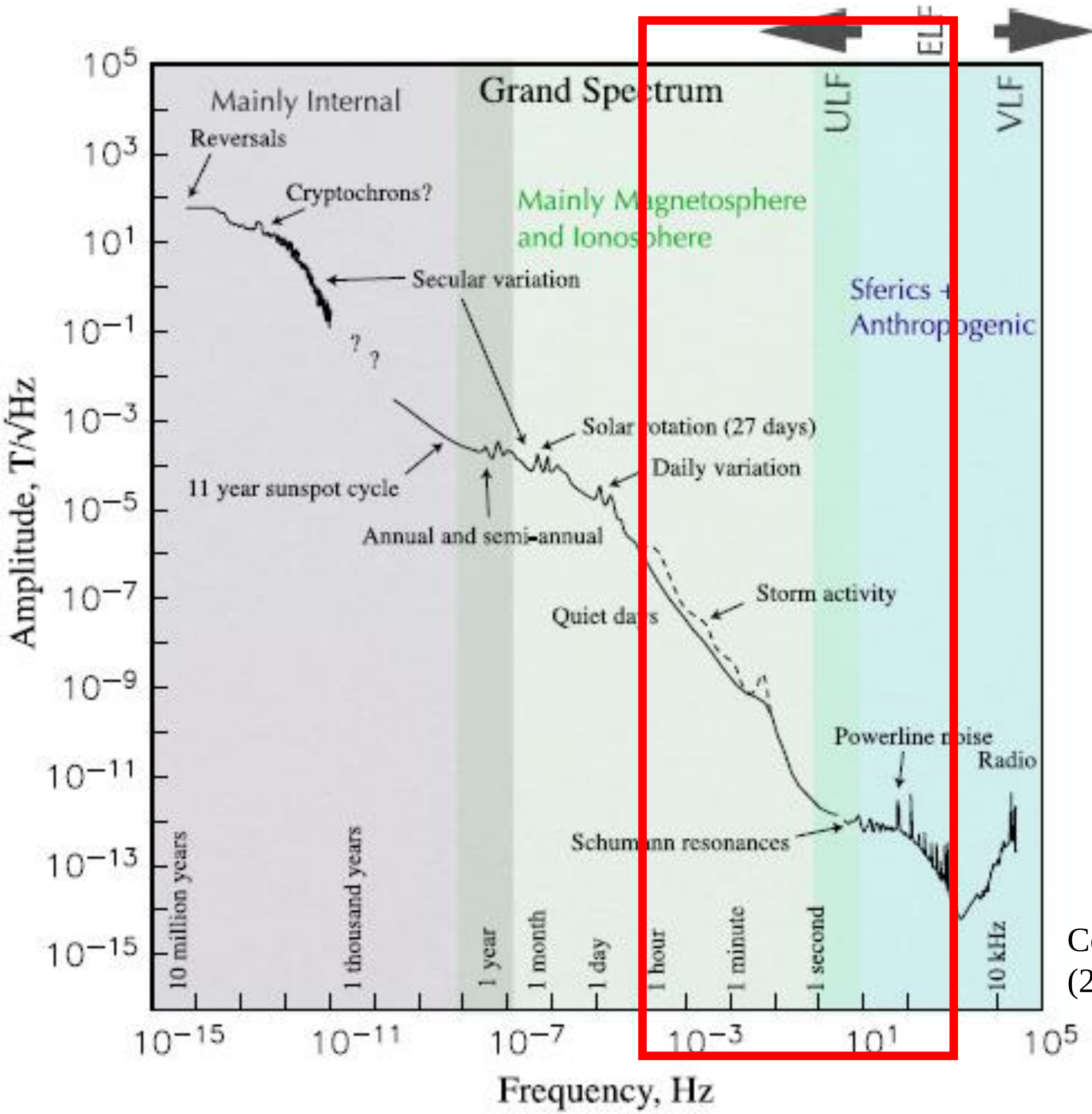
A fonte do sinal



Fowler (2005)

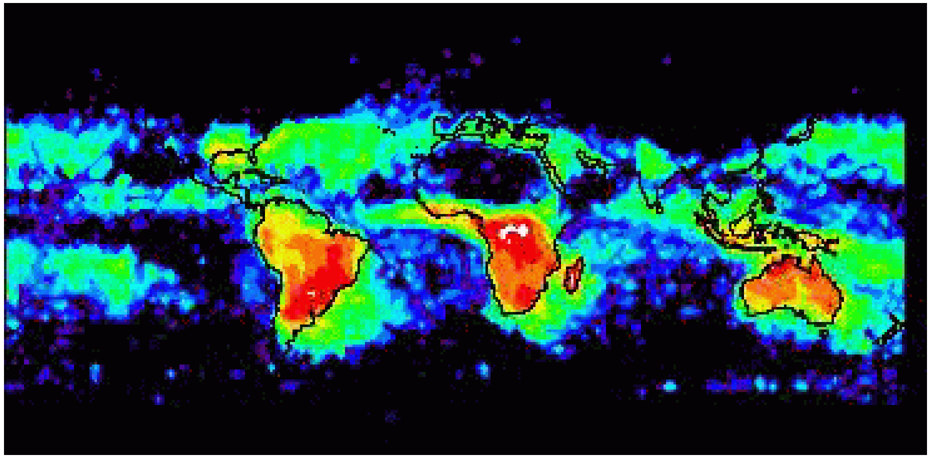


Constable (2016)

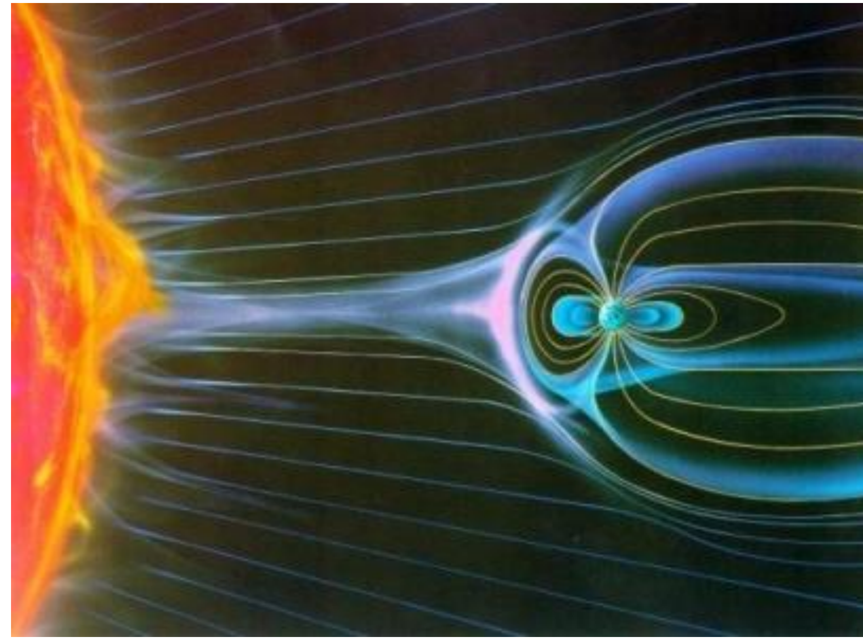


Constable (2016)

T < 1s	T > 1s



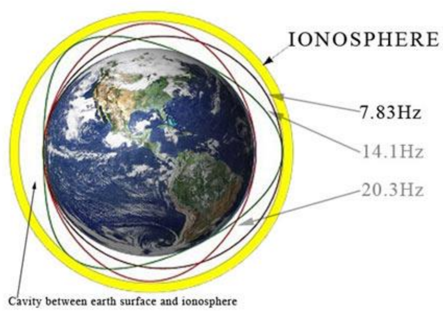
Number of lightning strikes/km² - yearly variation (NSSTC)



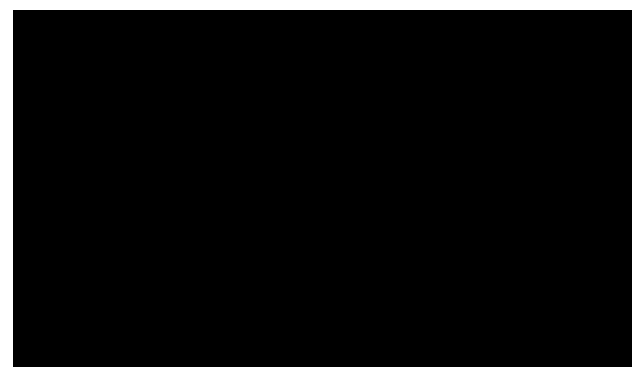
NASA (sci.esa.int)

Foto: Felipe Ribeiro

(www.inpe.br/webelat)



(www.shumann.ie)



(https://solarsystem.nasa.gov/resources/2286/modeling-earths-magnetism/)

Como fazer MT?

- Resistividade obtida pela razão entre os campos EM:

$$\rho = \frac{T}{2\pi\mu_0}\left|\frac{E_x}{H_y}\right|^2$$

- Japão: Kato e Kikuchi (1950) e Rikitake (1950)

1. *Notes on the Electromagnetic Induction within the Earth.*

By Tsuneji RIKITAKE,

Earthquake Research Institute.

(Read Feb. 19 and June 18, 1946.—Received June 30, 1946.)

- União Soviética: Tikhonov (1950)

ON DETERMINING ELECTRICAL CHARACTERISTICS OF THE DEEP LAYERS OF THE EARTH'S CRUST

A. N. Tikhonov

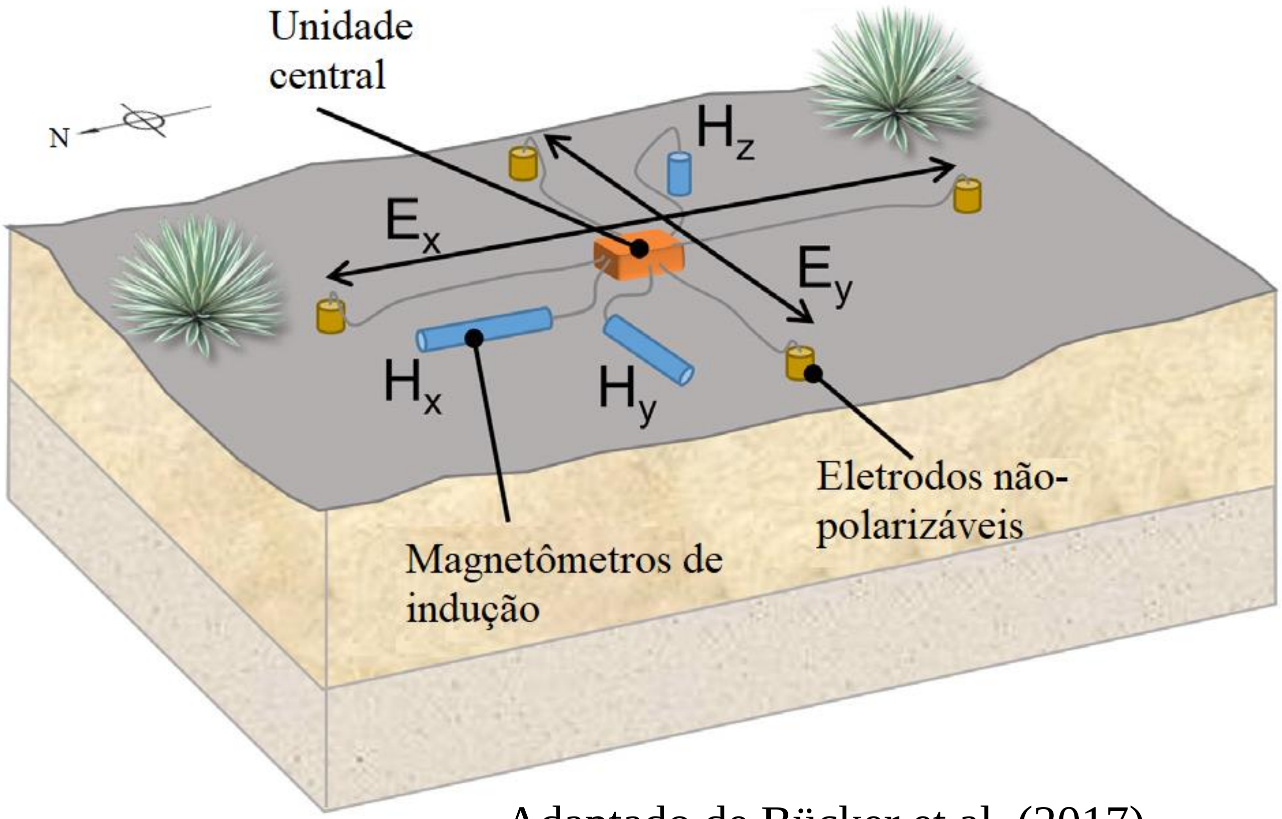
Geophysical Institute Academy of Science, USSR
Institute of Scientific Investigations of the Earth Magnetism
Translated by L. Perlovsky and C. Tarlowski

- França: Cagniard (1952)

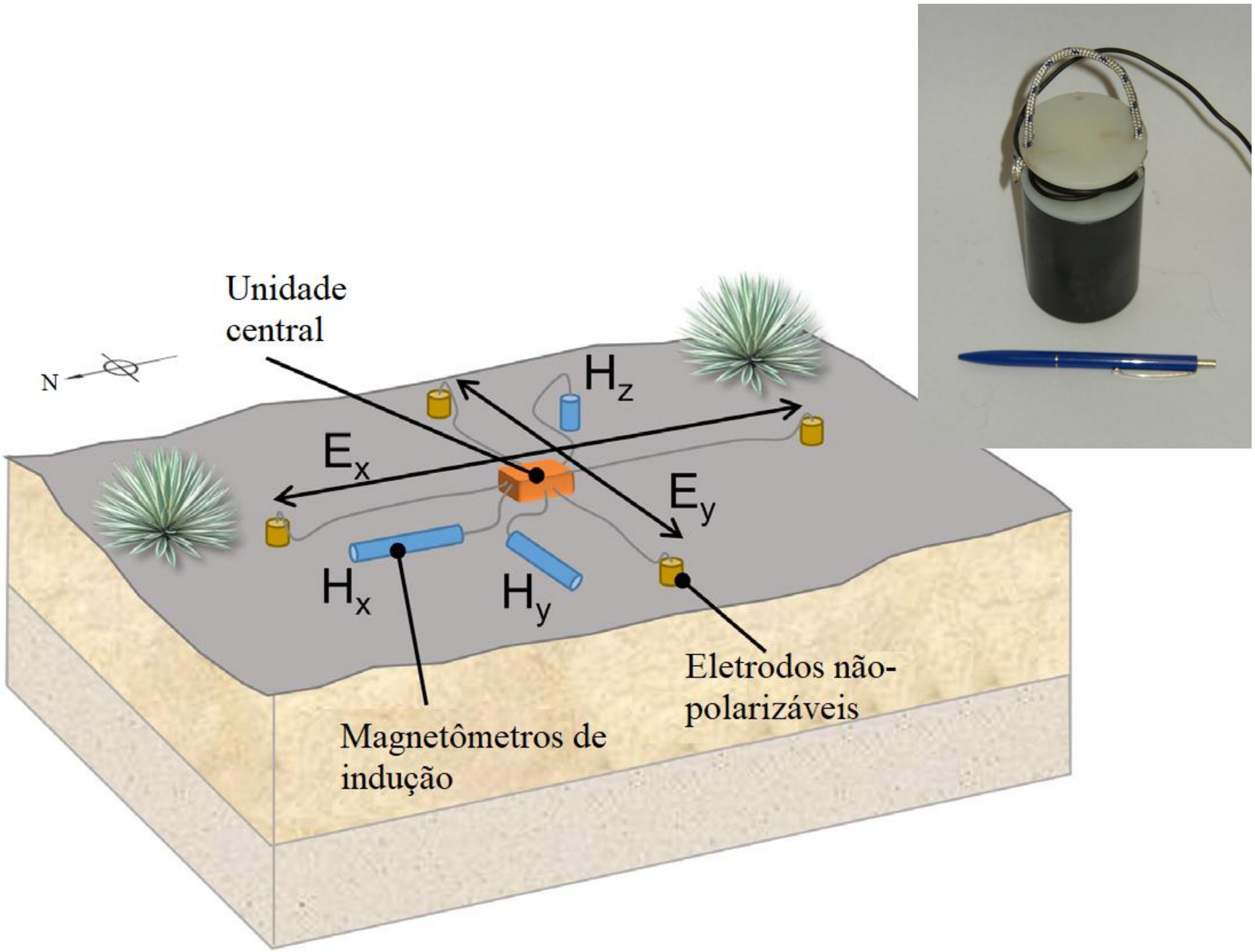
BASIC THEORY OF THE MAGNETO-TELLURIC METHOD OF GEOPHYSICAL PROSPECTING*†‡

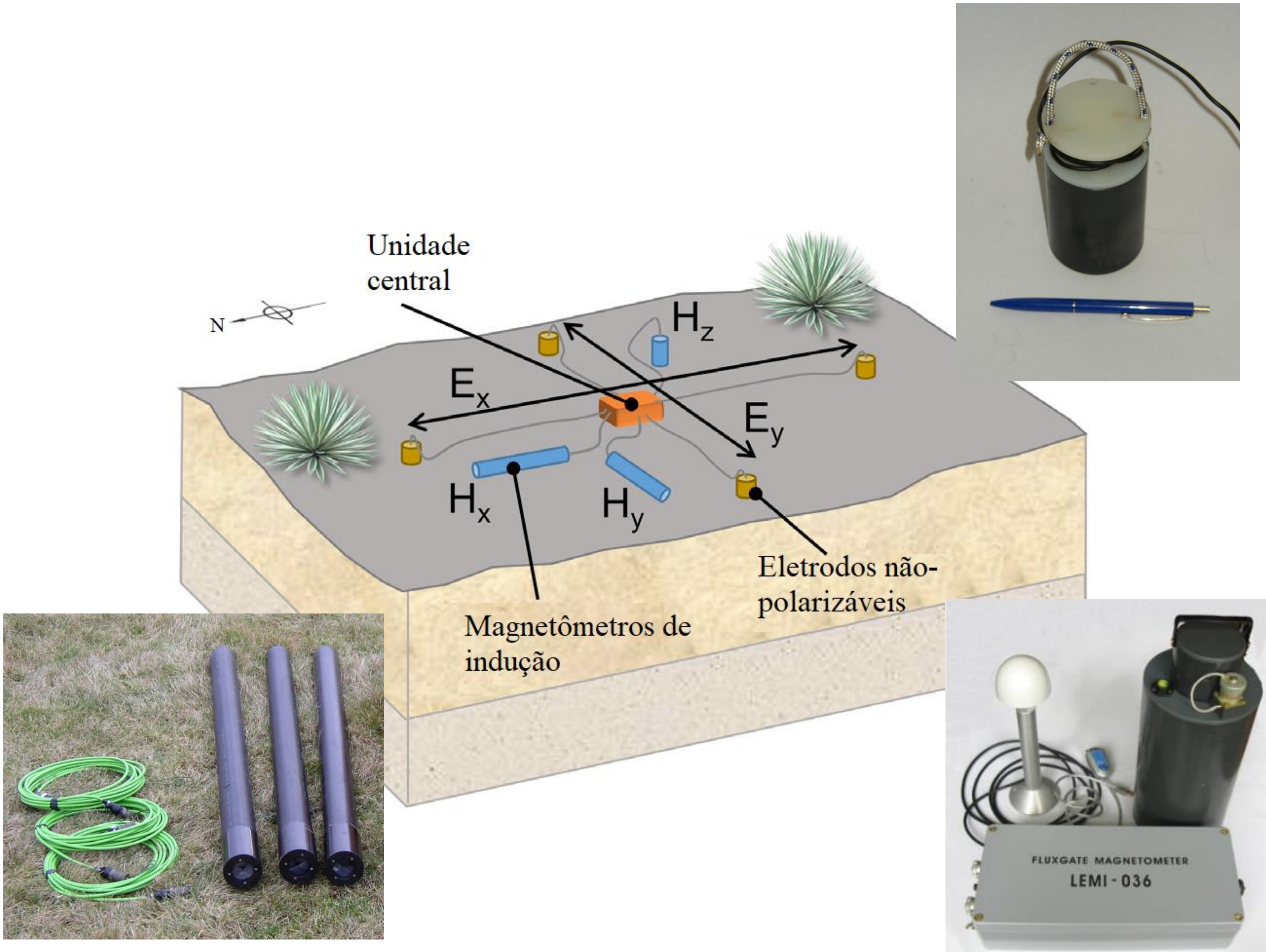
LOUIS CAGNIARD§

Aquisição de dados

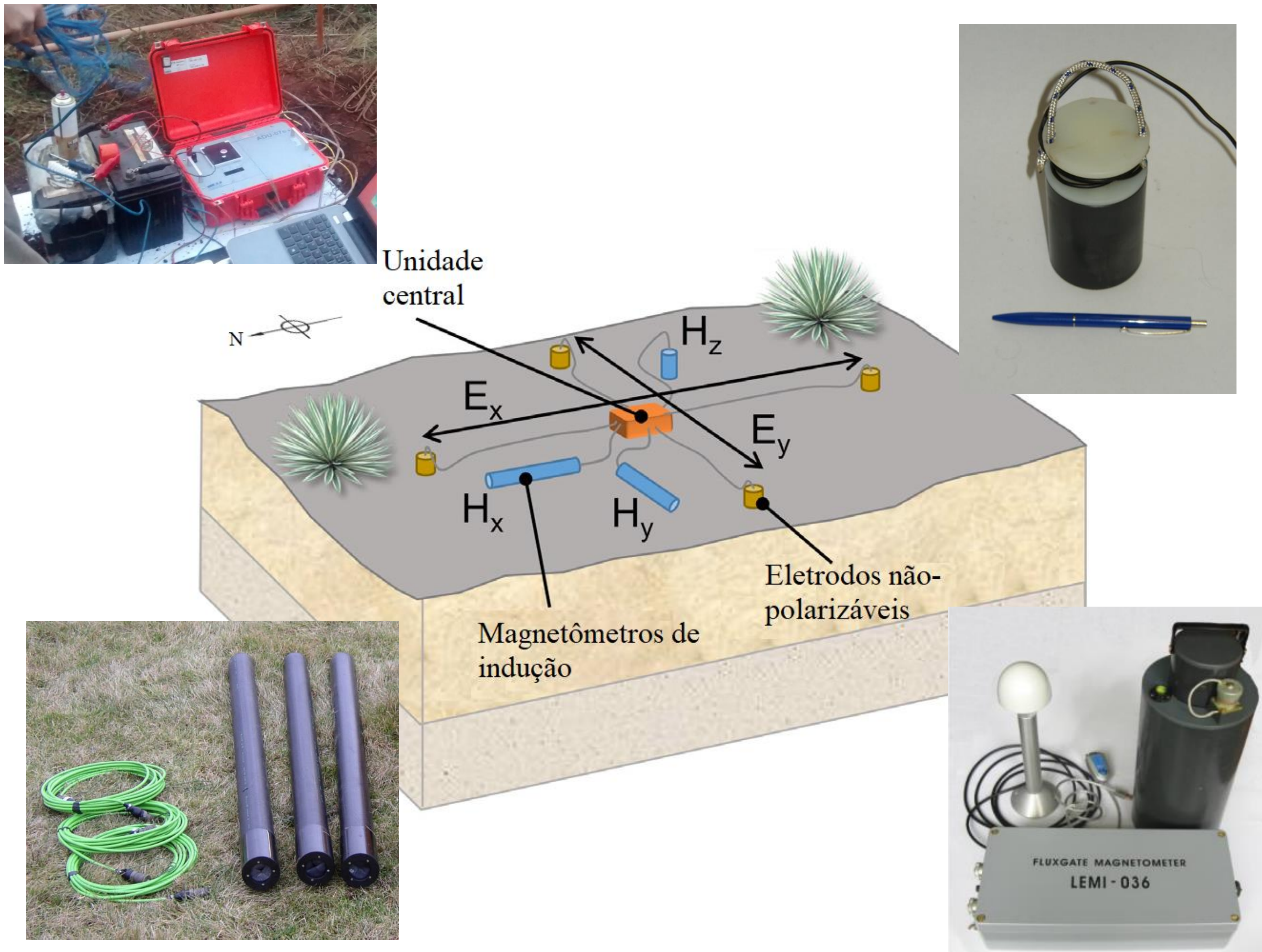


Adaptado de Bücker et al. (2017)


Unidade
central
N
H_z
E_x
E_y
H_x
H_y
Eletrodos não-
polarizáveis
Magnetômetros de
indução

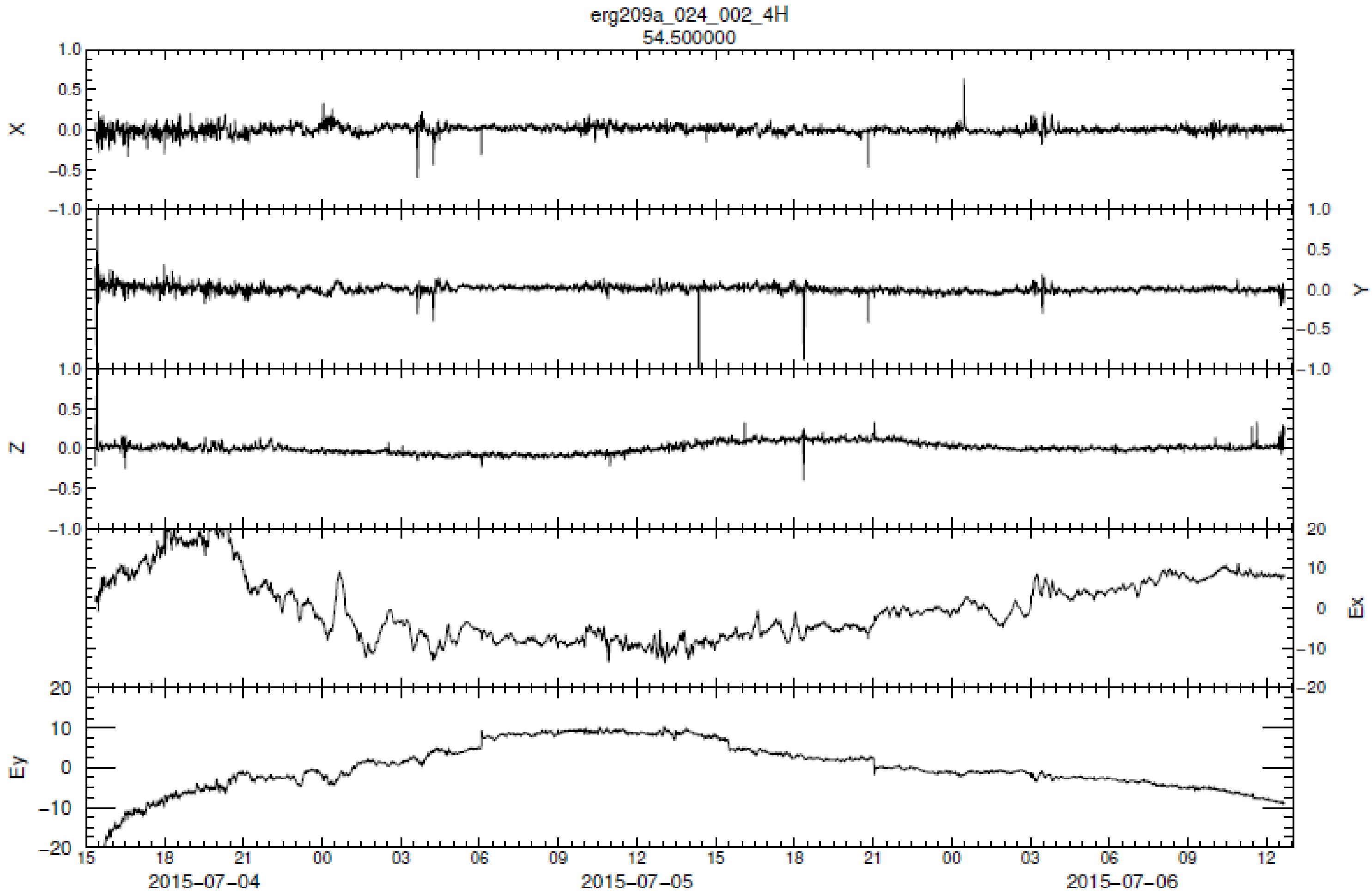


Unidade central
N
H_z
E_x
E_y
H_x
H_y
Eletrodos não-polarizáveis
Magnetômetros de indução
FLUXGATE MAGNETOMETER
LEMI - 036



Unidade central
N
H_z
E_x
E_y
H_x
H_y
Eletrodos não-polarizáveis
Magnetômetros de indução
FLUXGATE MAGNETOMETER
LEMI - 036

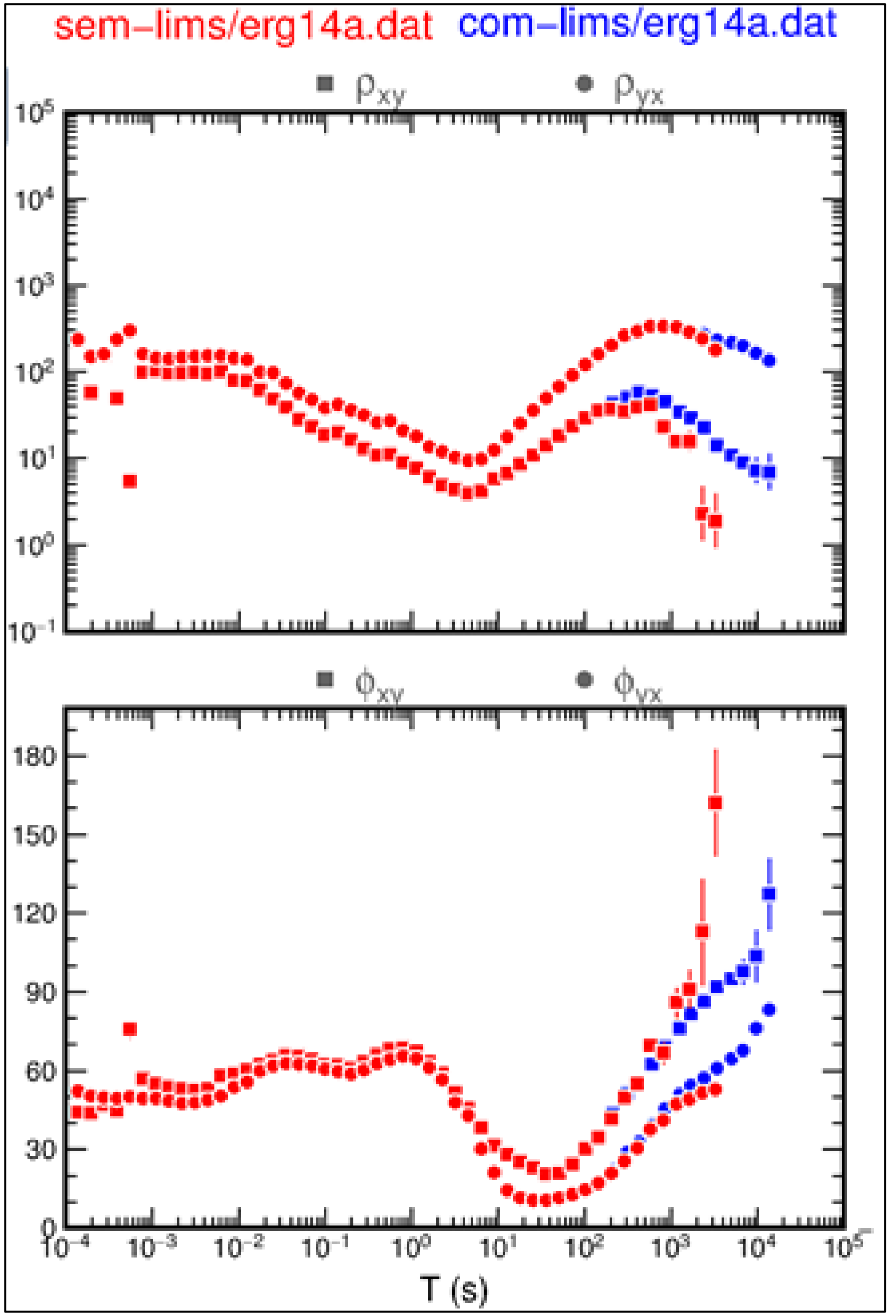


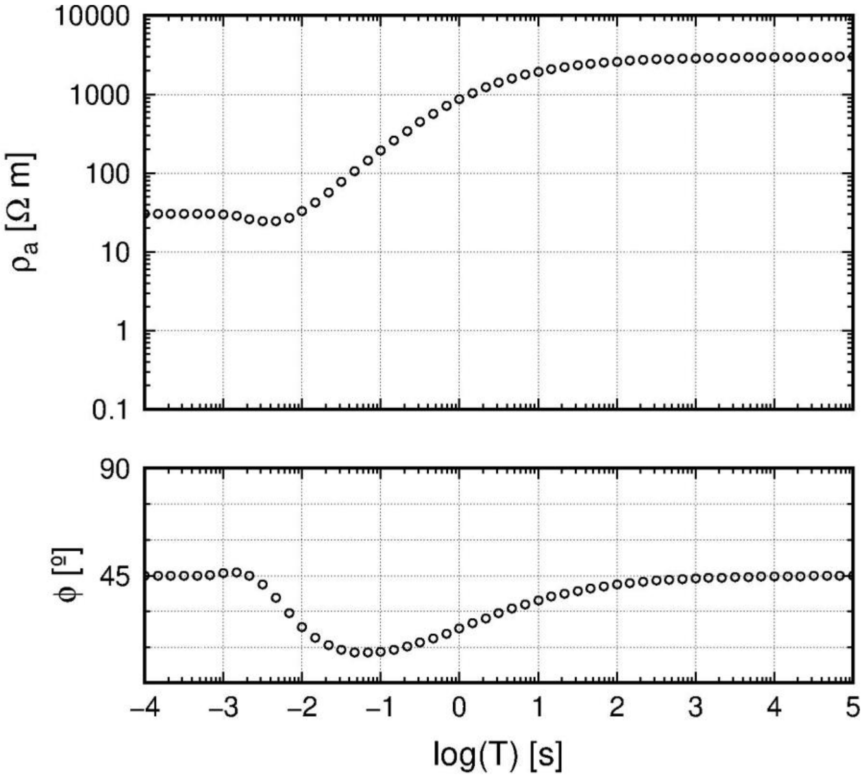
erg209a_024_002_4H
54.500000
X
Y
Z
Ex
Ey
2015-07-04
2015-07-05
2015-07-06

- Série temporal
- FFT (T $\longrightarrow$ f)
- E/H – obtenção das curvas de resistividade e fase
- H/Hz – vetores de indução

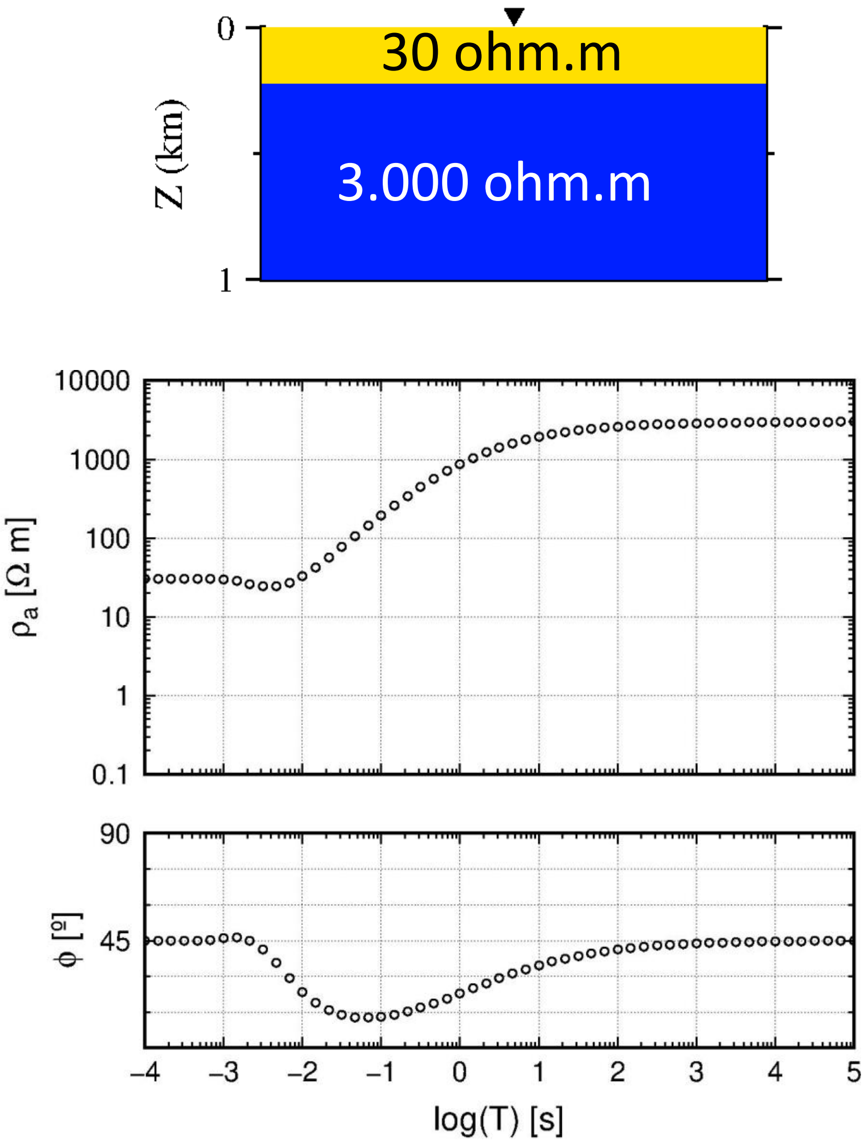
- Banda-larga: normalmente de 24 a 48h;
  - Bobinas de indução;
  - Períodos de 10^{-4} a ~3,600 s.
- Período longo: três a quatro semanas;
  - Magnetômetro *fluxgate*;
  - Períodos de 1 s a >10,000 s.

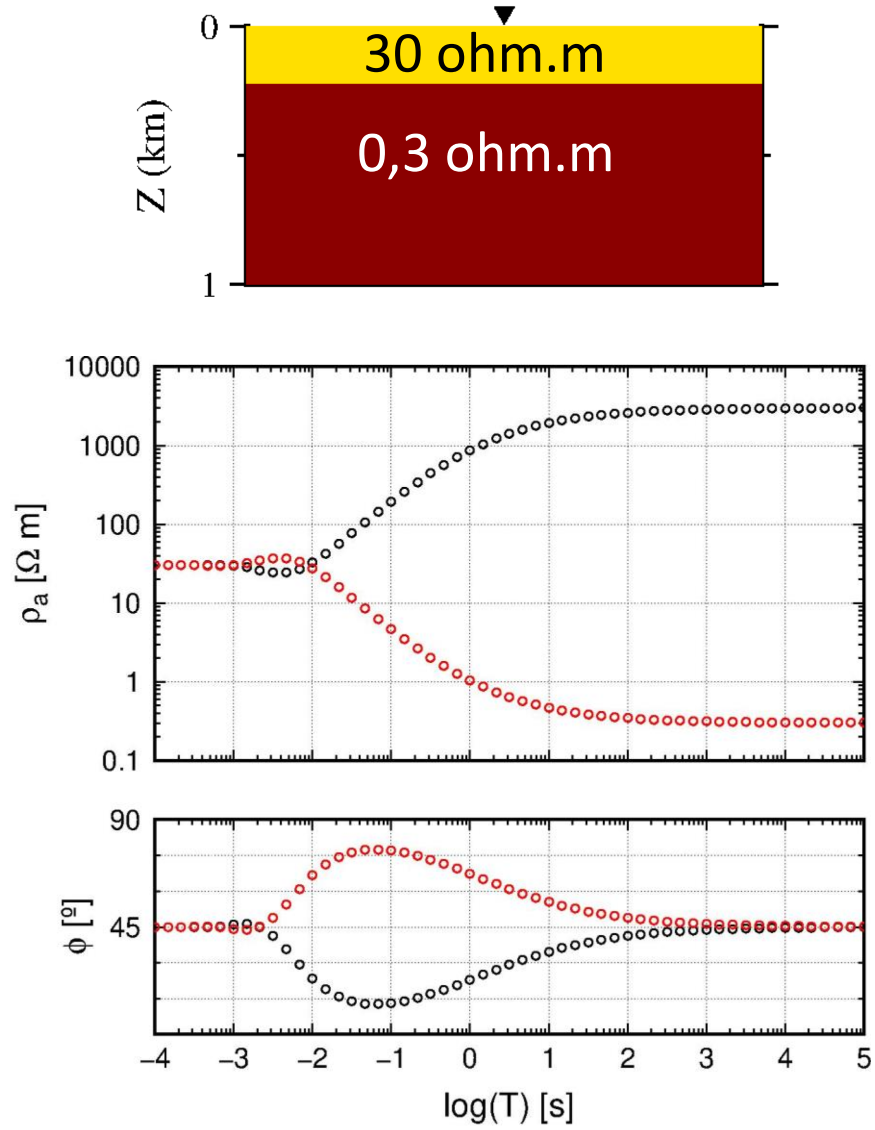


- E/H – obtenção das curvas de resistividade e fase

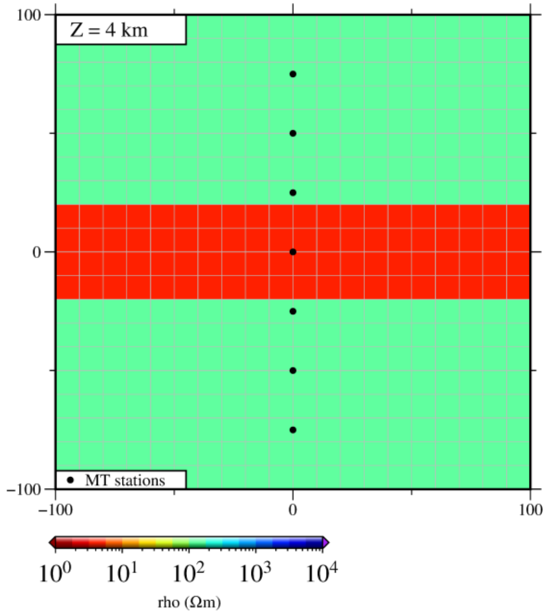


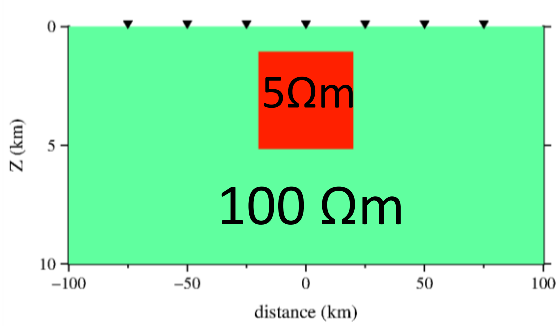
- E/H – obtenção das curvas de resistividade e fase

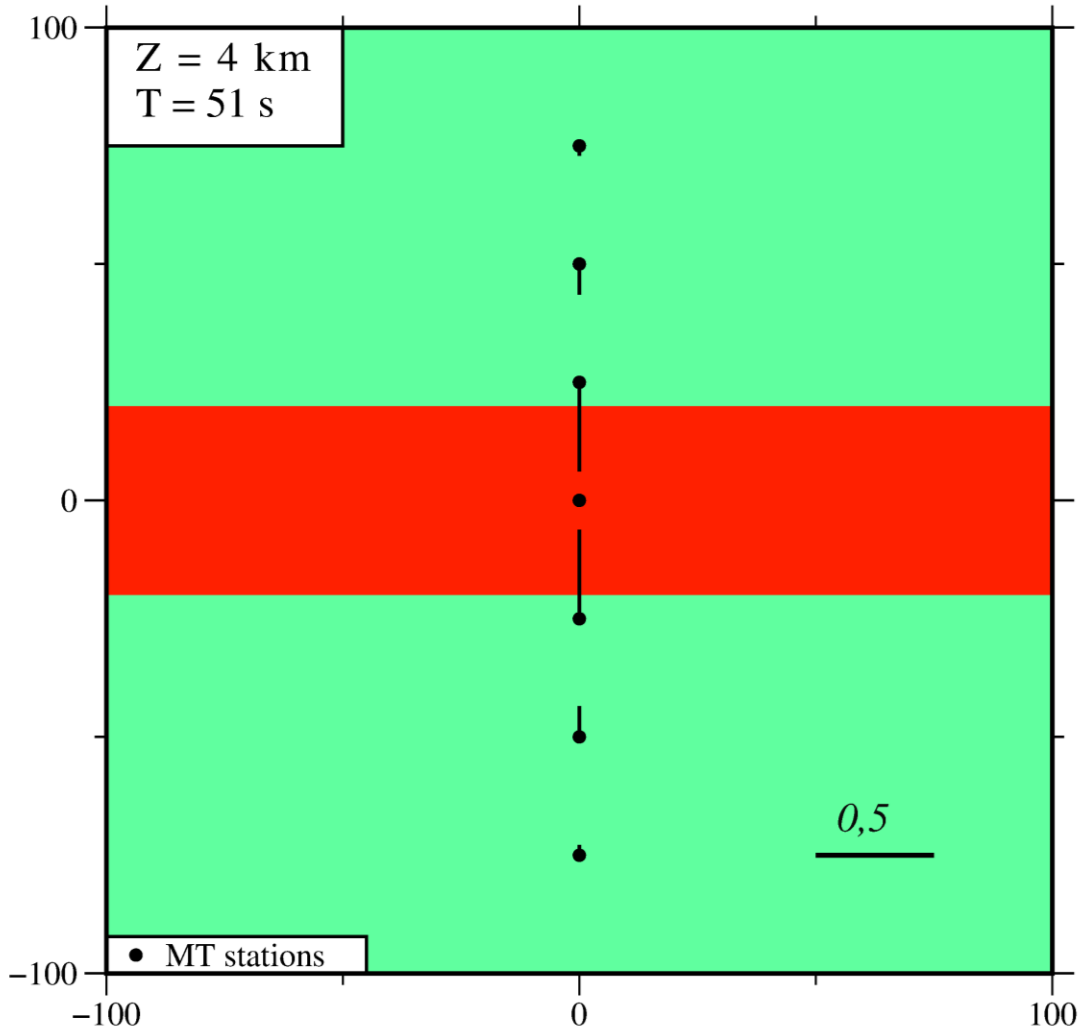




- H/Hz – vetores de indução

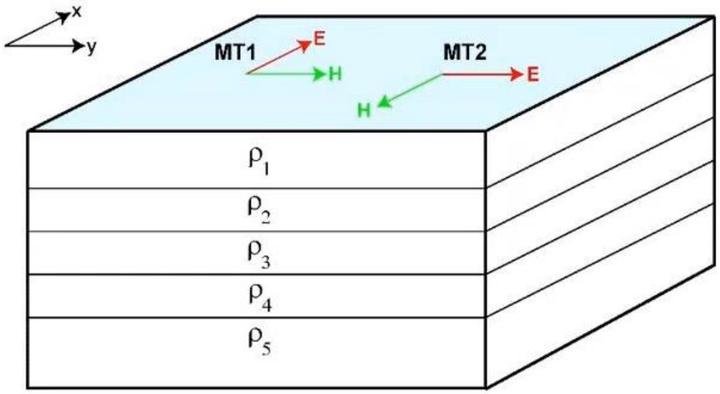


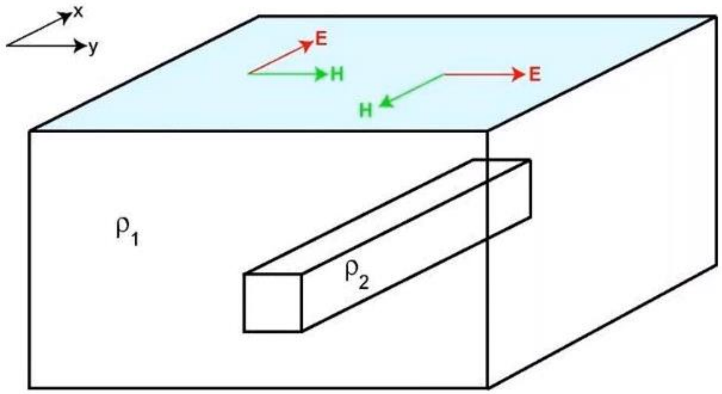




Obtenção de modelos elétricos que expliquem os dados.

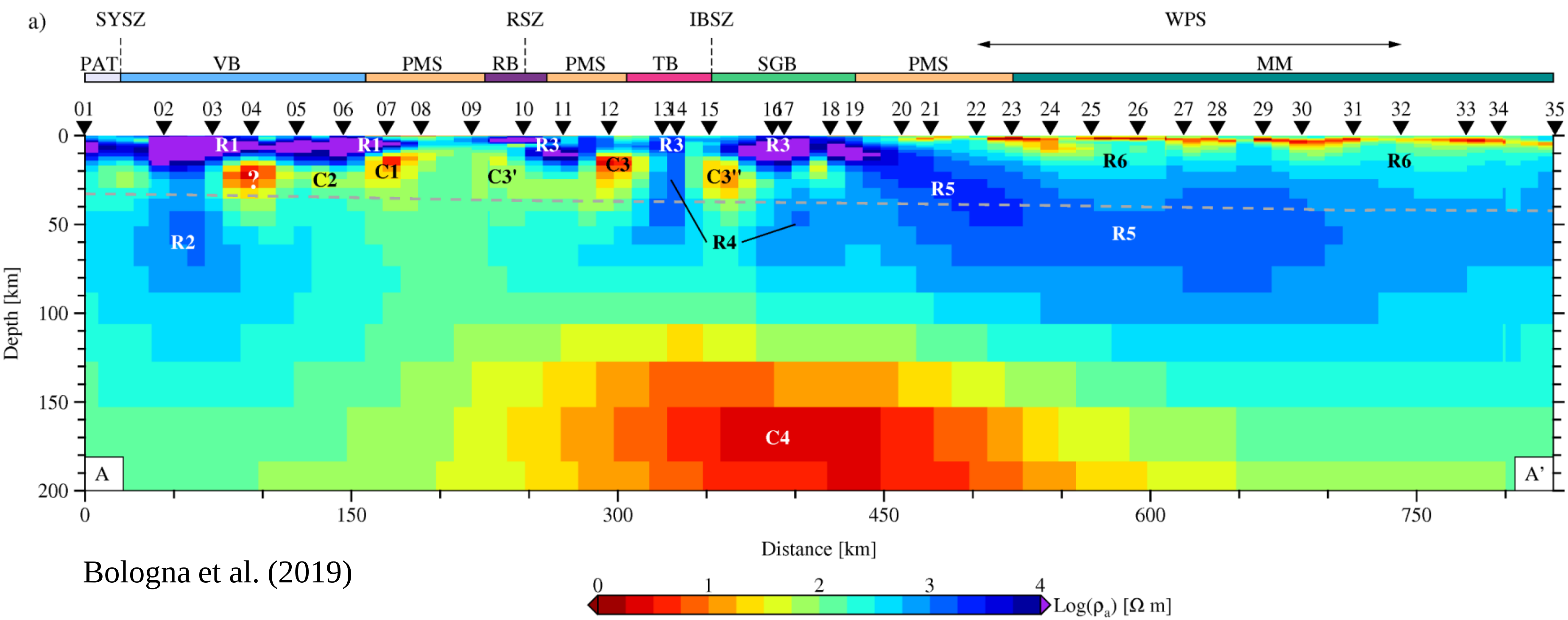
Modelos podem ser 1-D, 2-D ou 3-D





Inversão: dados medidos → modelo elétrico

1-D, 2-D, 3-D

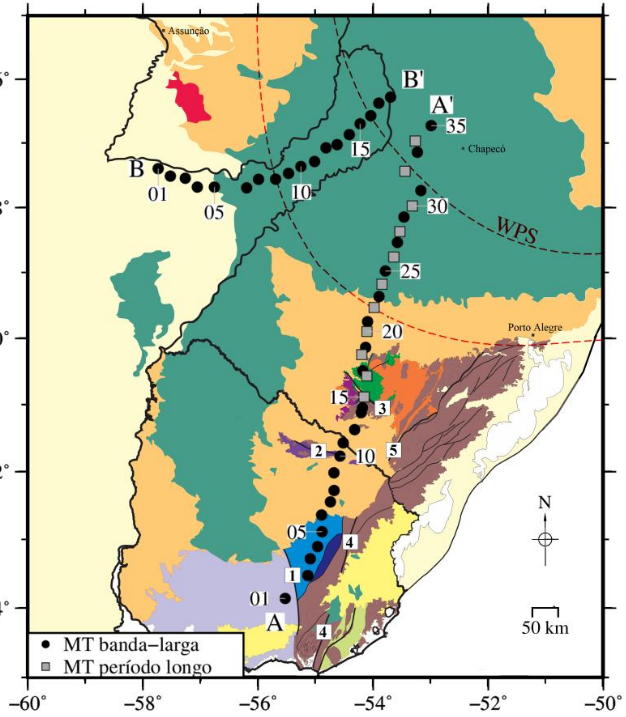


Bologna et al. (2019)

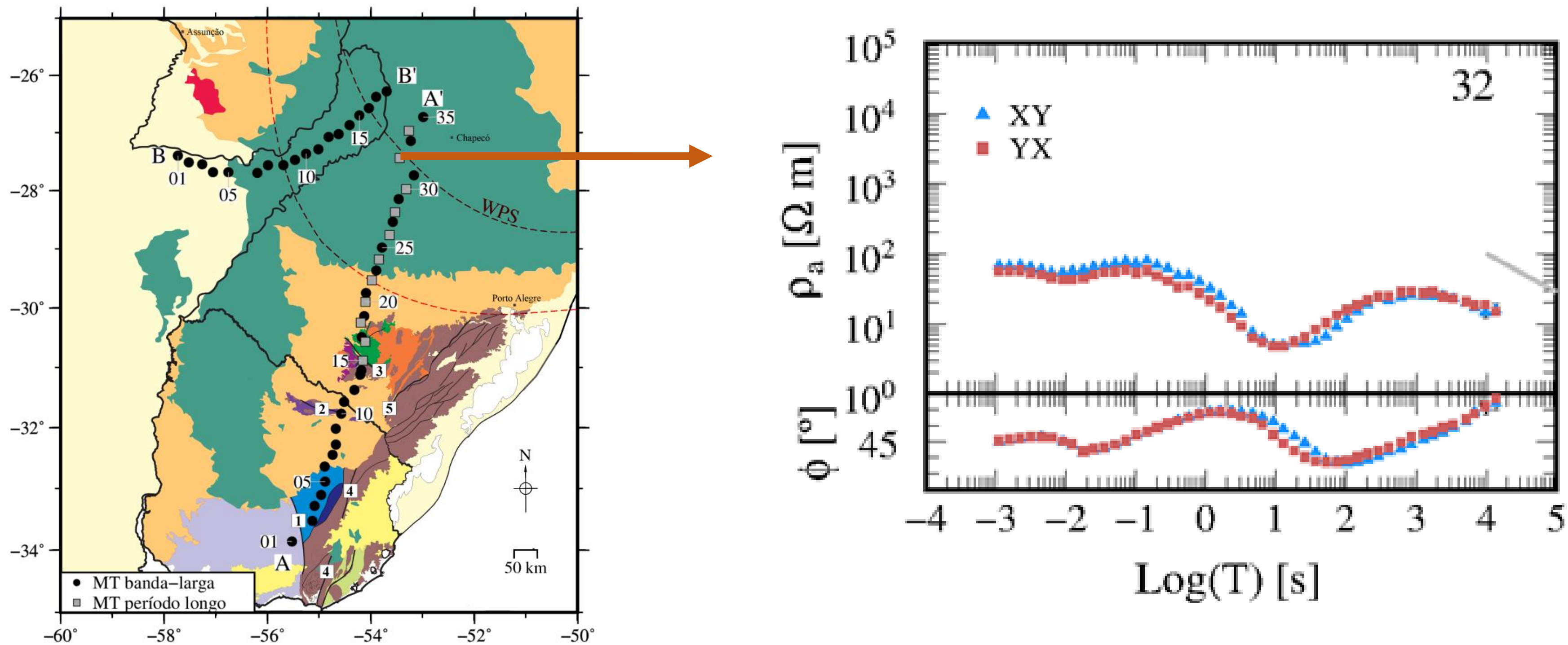
Parte 2

MT na América do Sul

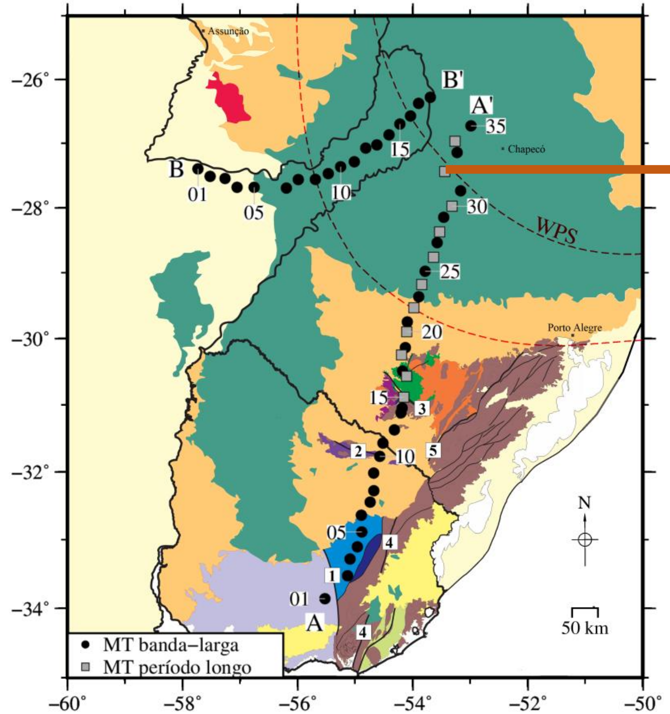
Bacia do Paraná



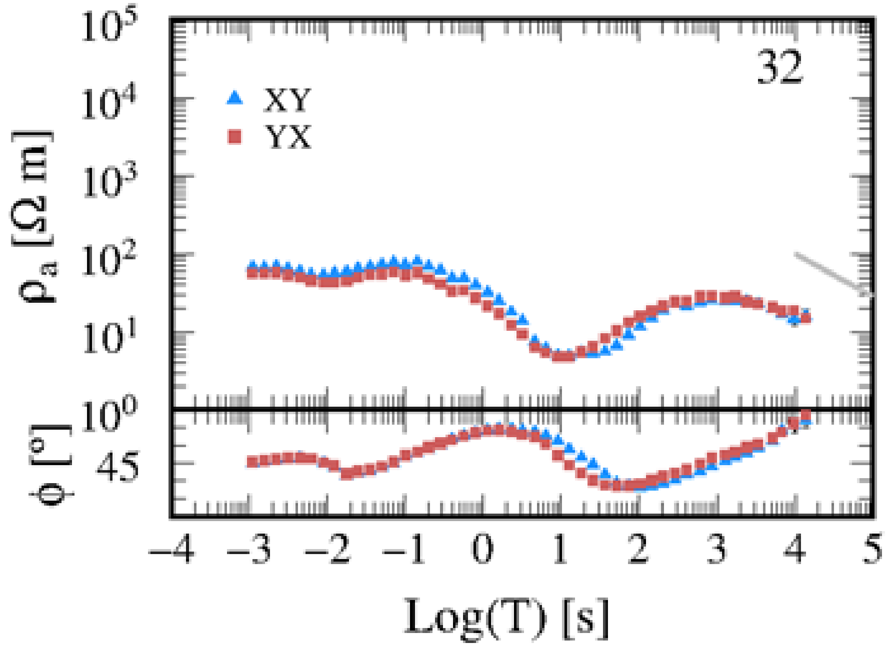
Assunção
Chapecó
Porto Alegre
WPS
B
B'
A
A'
N
50 km
MT banda–larga
MT período longo
−26°
−28°
−30°
−32°
−34°
−60°
−58°
−56°
−54°
−52°
−50°



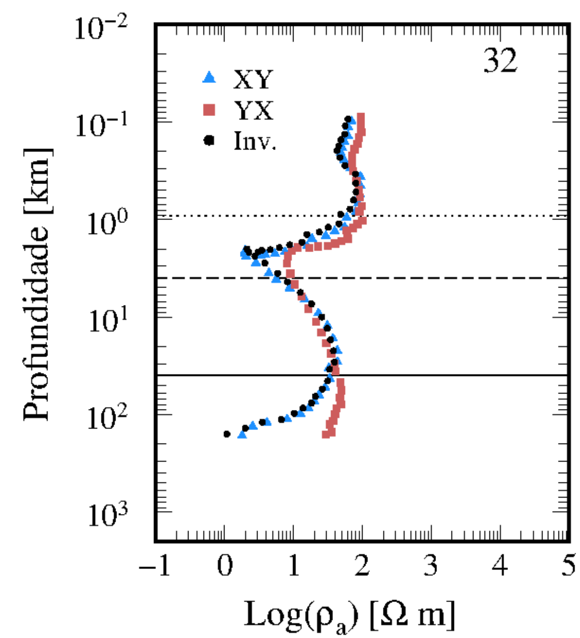
Assunção
Chapecó
Porto Alegre
WPS
B
B'
A
A'
01
05
10
15
20
25
30
35
1
2
3
4
5
N
50 km
MT banda–larga
MT período longo
−26°
−28°
−30°
−32°
−34°
−60°
−58°
−56°
−54°
−52°
−50°
32
XY
YX
ρ_a [Ω m]
ϕ [°]
10^5
10^4
10^3
10^2
10^1
10^0
45
−4
−3
−2
−1
0
1
2
3
4
5
Log(T) [s]



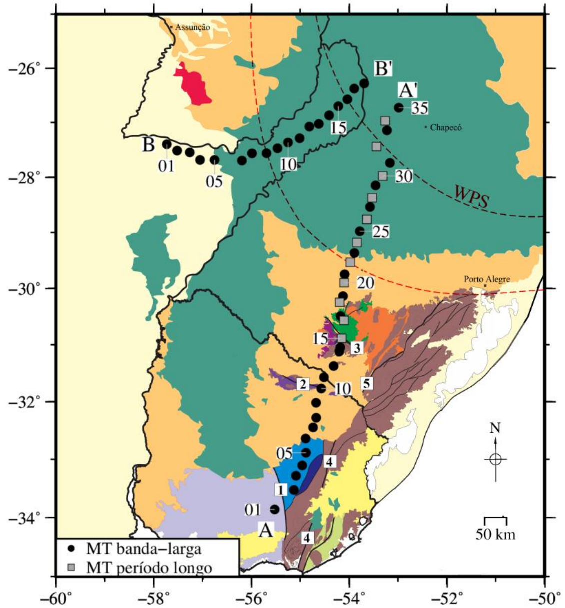
Assunção
Chapecó
Porto Alegre
B
B'
A
A'
WPS
N
50 km
MT banda–larga
MT período longo
−26°
−28°
−30°
−32°
−34°
−60°
−58°
−56°
−54°
−52°
−50°



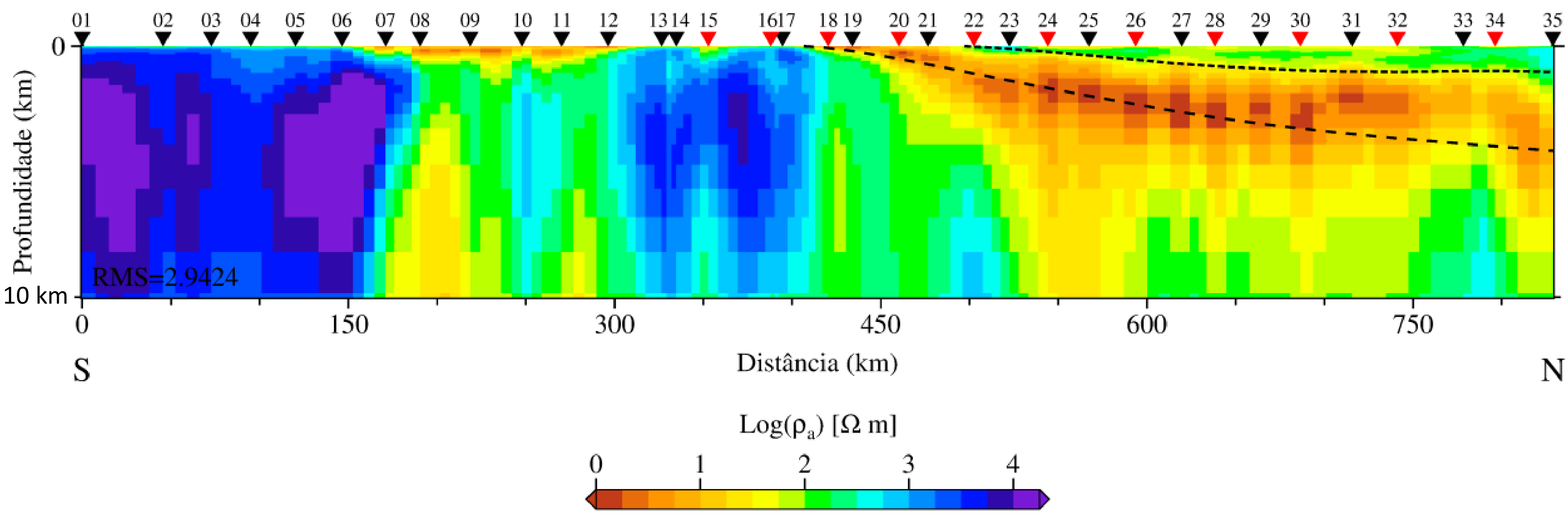
32
XY
YX
ρ_a [Ω m]
φ [°]
45
Log(T) [s]

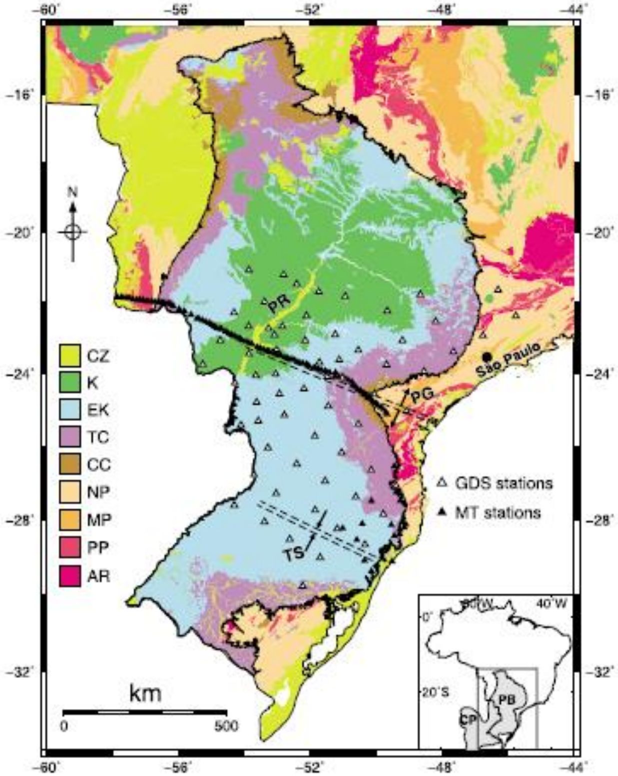


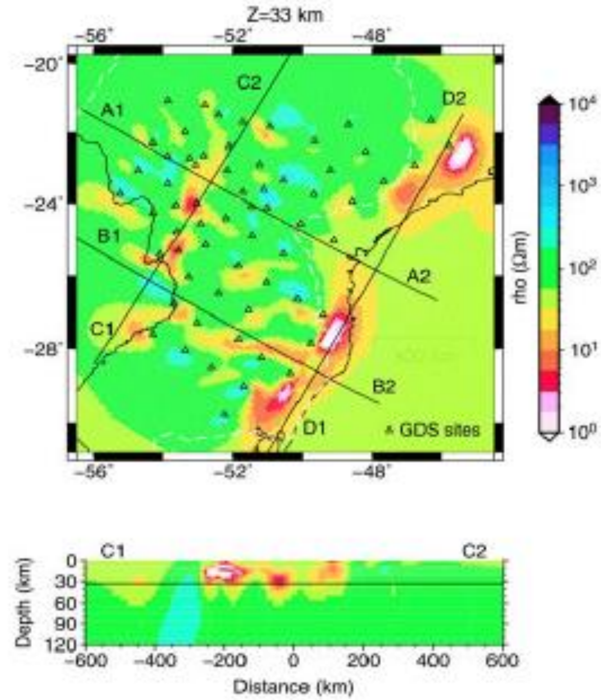
32
XY
YX
Inv.
Profundidade [km]
Log(ρ_a) [Ω m]

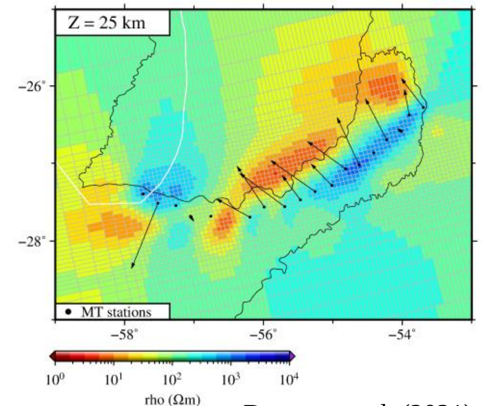


Bacia do Paraná



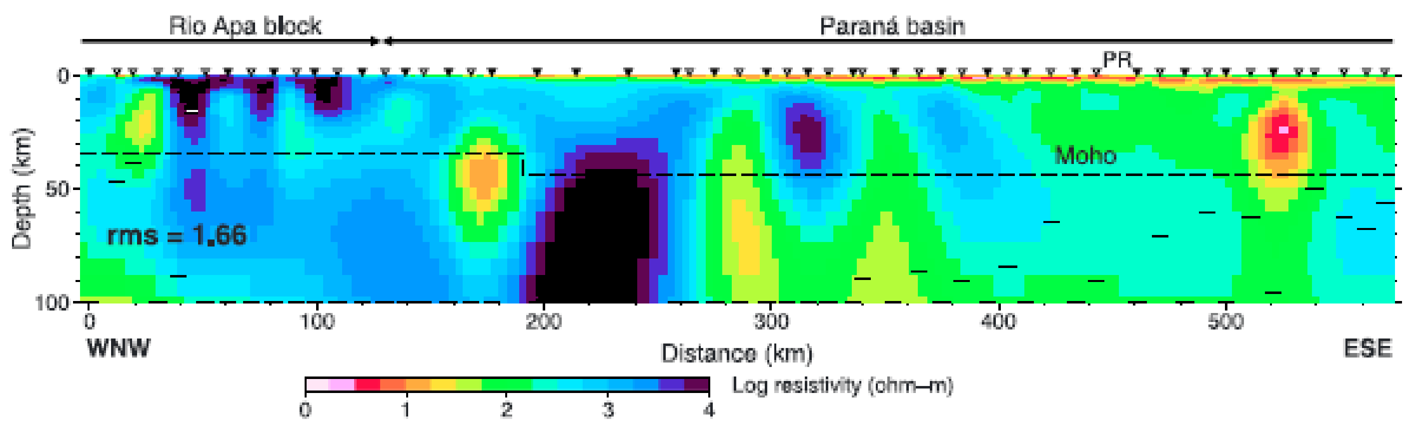






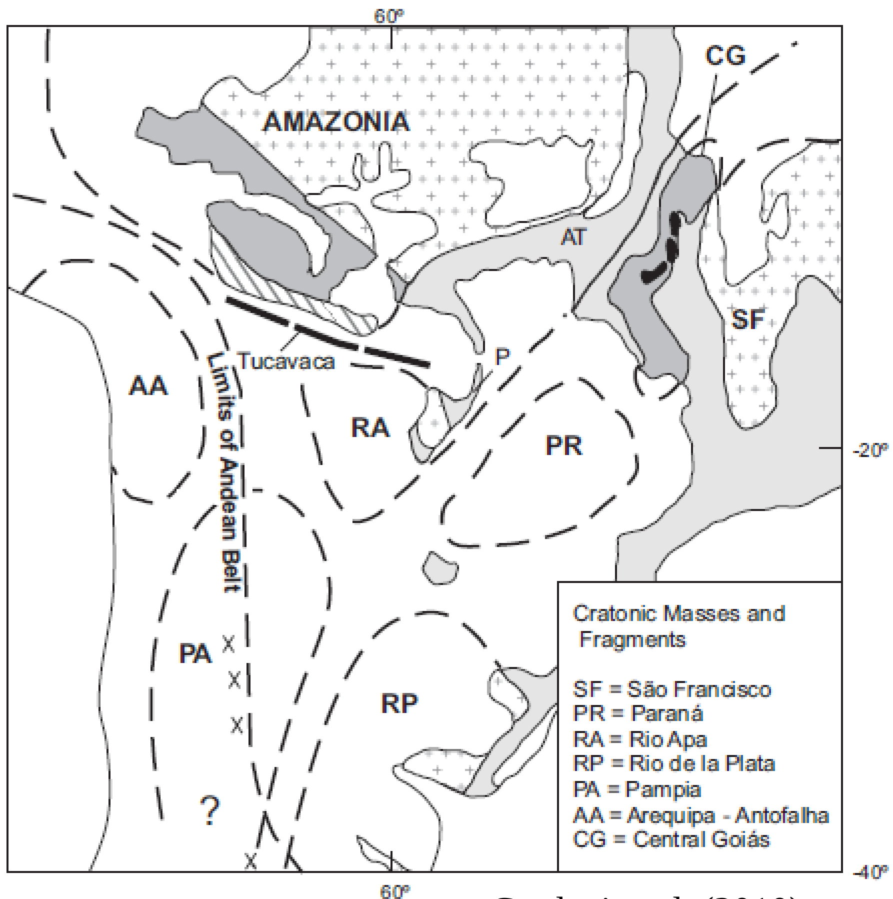
Dragone et al. (2021)

Padilha et al. (2015)



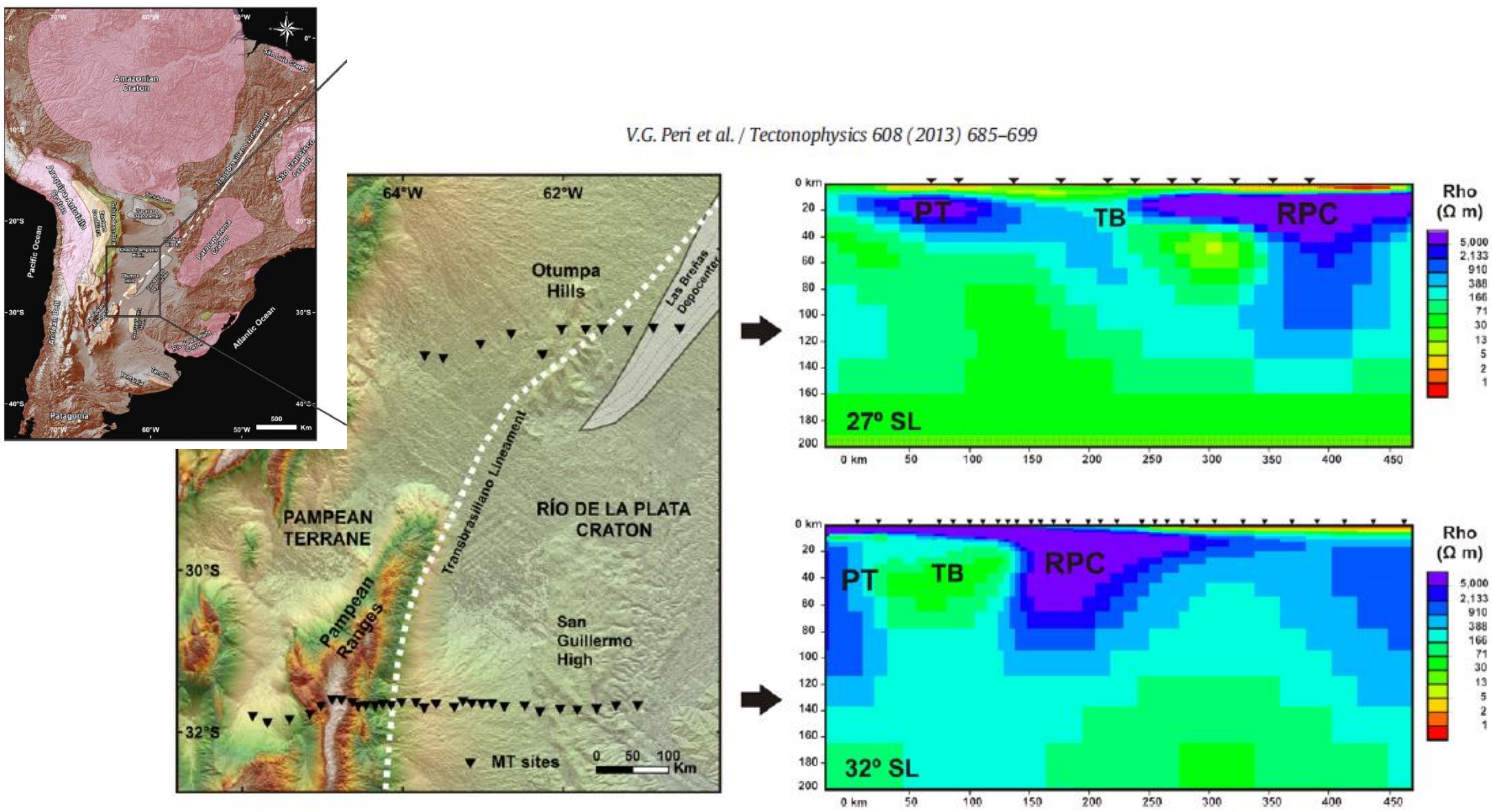
Pampia / Rio de la Plata

- Borda oeste do cráton Rio de la Plata: Terreno Pampia (Ramos, 2010)
- Região coberta por sedimentos.

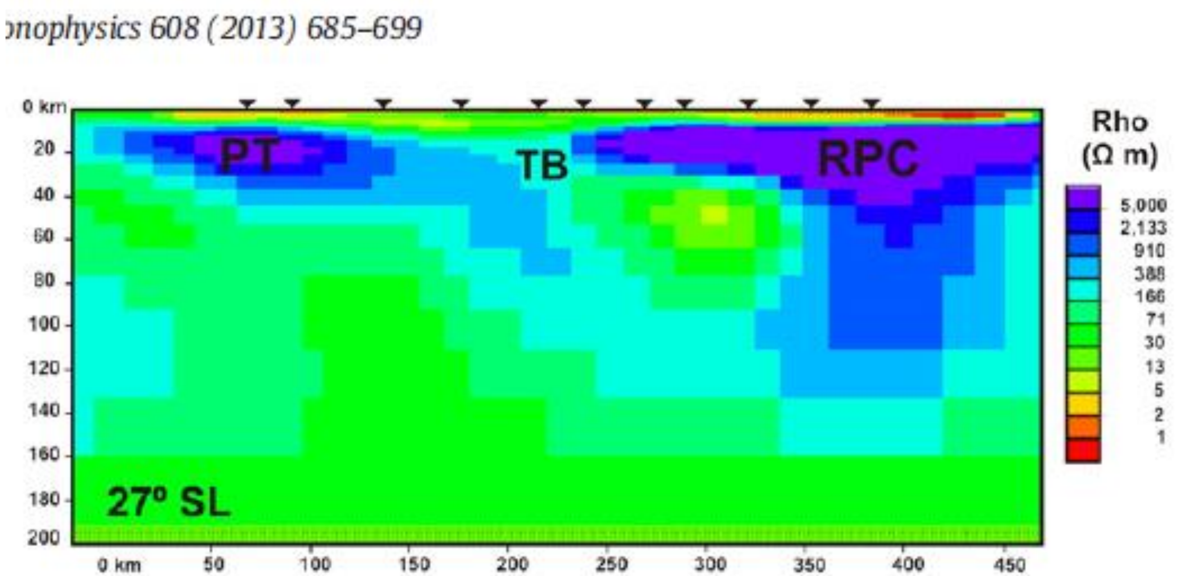


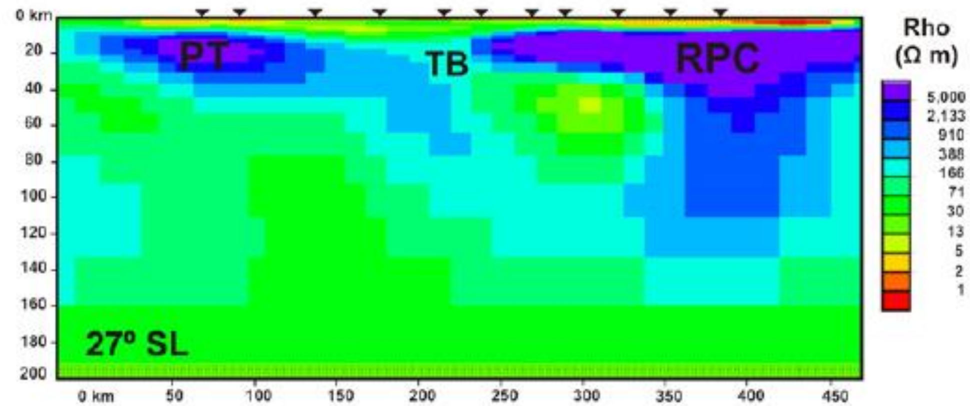
Cordani et al. (2010)

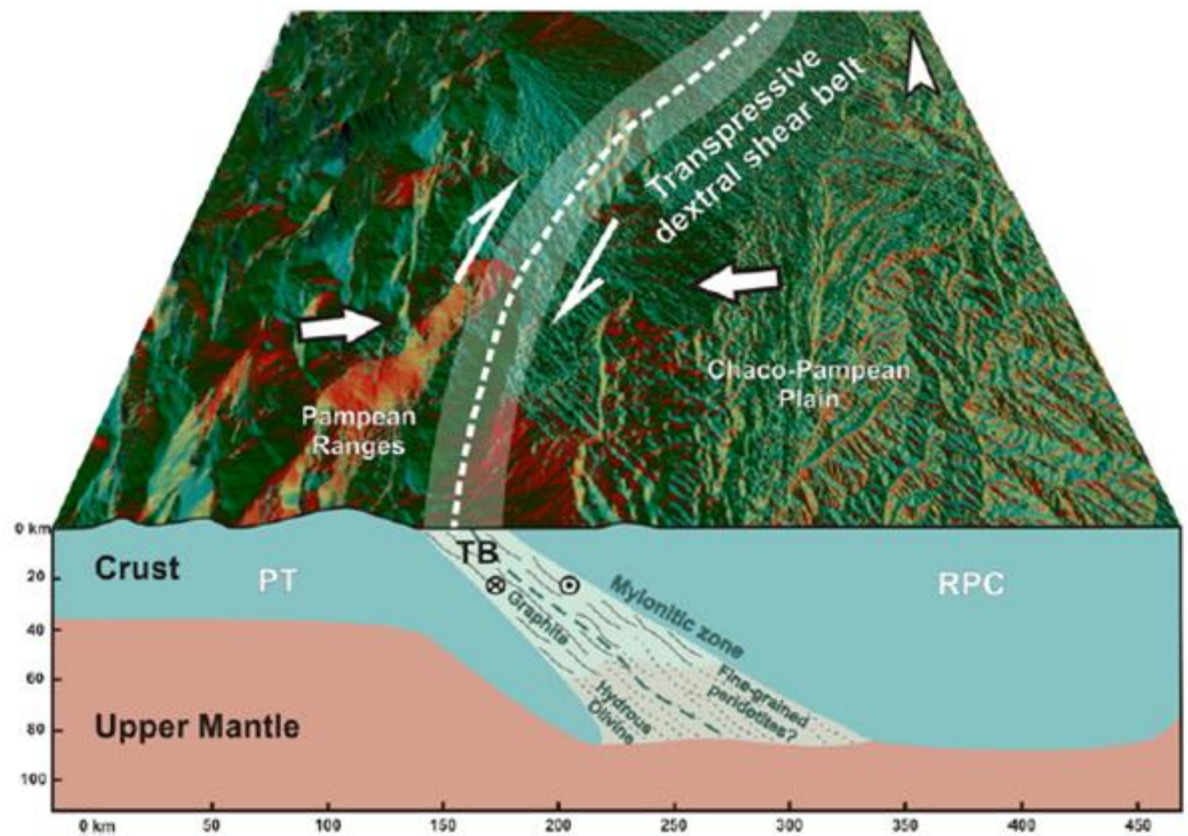
- Perfil MT W-E na BCP (Peri et al., 2013)
- Crosta média/inferior usualmente mais condutiva; não é o caso aqui;



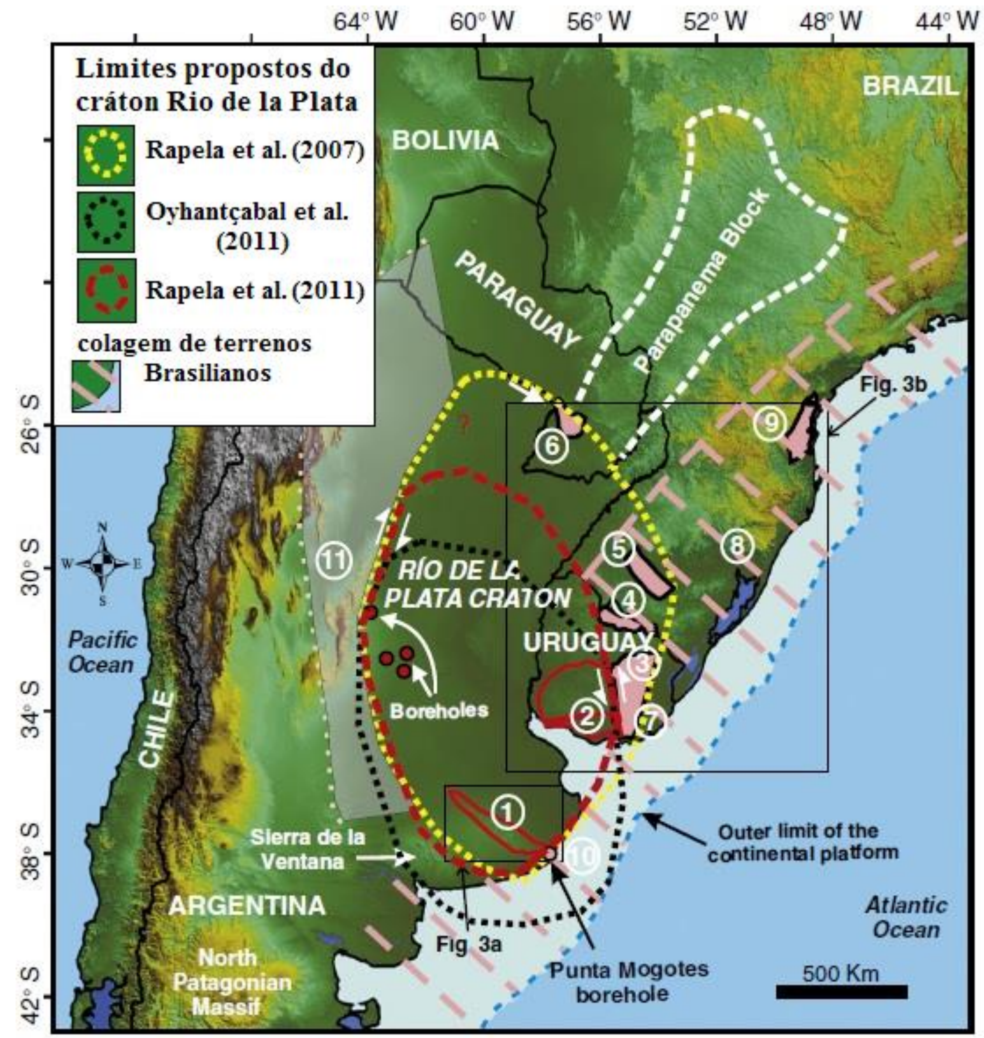
- Região estável;
- Condutor: descartam ideias de fluidos (consumidos ou volatilizados), sulfetos e óxidos (não há dados); carbonatitos (instáveis <130 km); fundidos parciais (não há basaltos na região);
- Alinhamento de filmes de grafita (orgânica em sedimentos; inorgânica a partir de CO_2 do manto);
- Compatível com zonas de colisão: convergência Neoproterozoica entre Pampia e RdP.



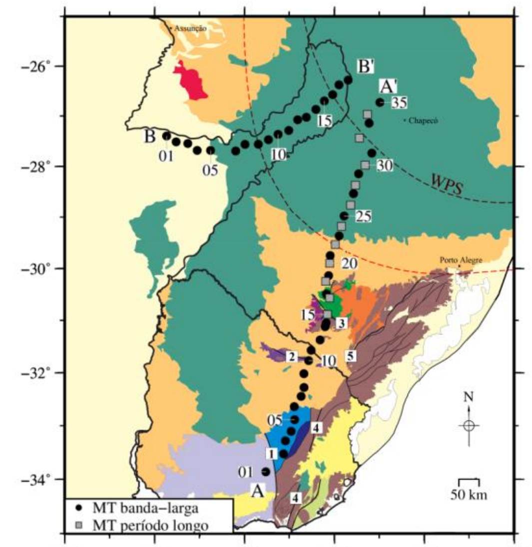

0 km
20
40
60
80
100
120
140
160
180
200
PT
TB
RPC
27º SL
0 km 50 100 150 200 250 300 350 400 450
Rho
(Ω m)
5,000
2,133
910
388
166
71
30
13
5
2
1


Transpressive
dextral shear belt
Pampean
Ranges
Chaco-Pampean
Plain
0 km
20
40
60
80
100
Crust
PT
TB
RPC
Graphite
Mylonitic zone
Hydrous
Olivine
Fine-grained
peridotites?
Upper Mantle
0 km 50 100 150 200 250 300 350 400 450

Rio de la Plata



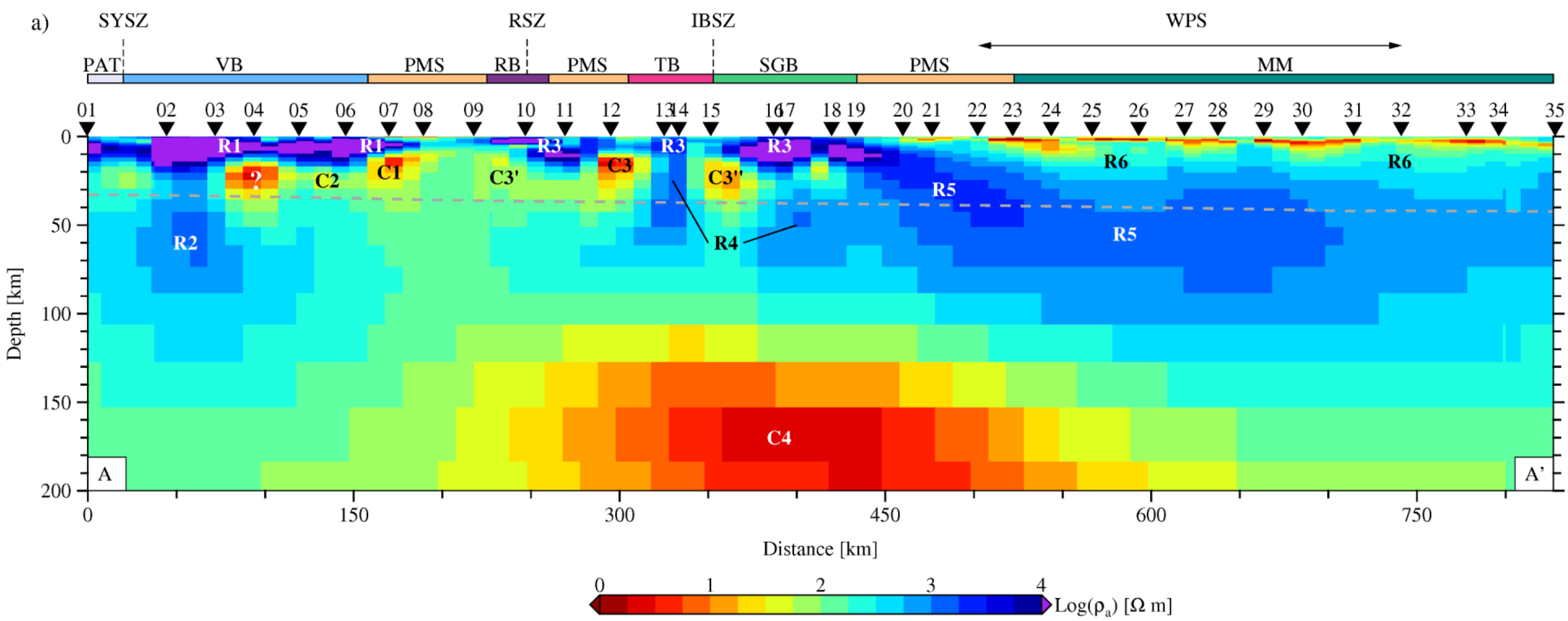
Adaptado de Rapela et al. (2011)

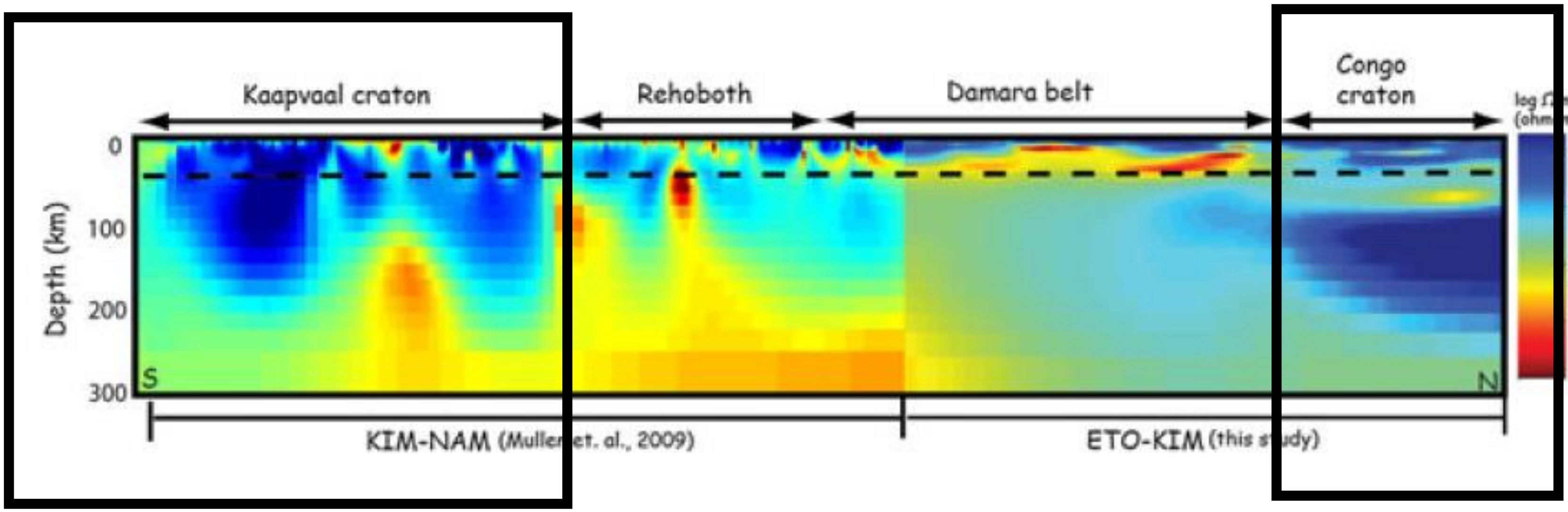


RdP – Rapela et al. (2007)

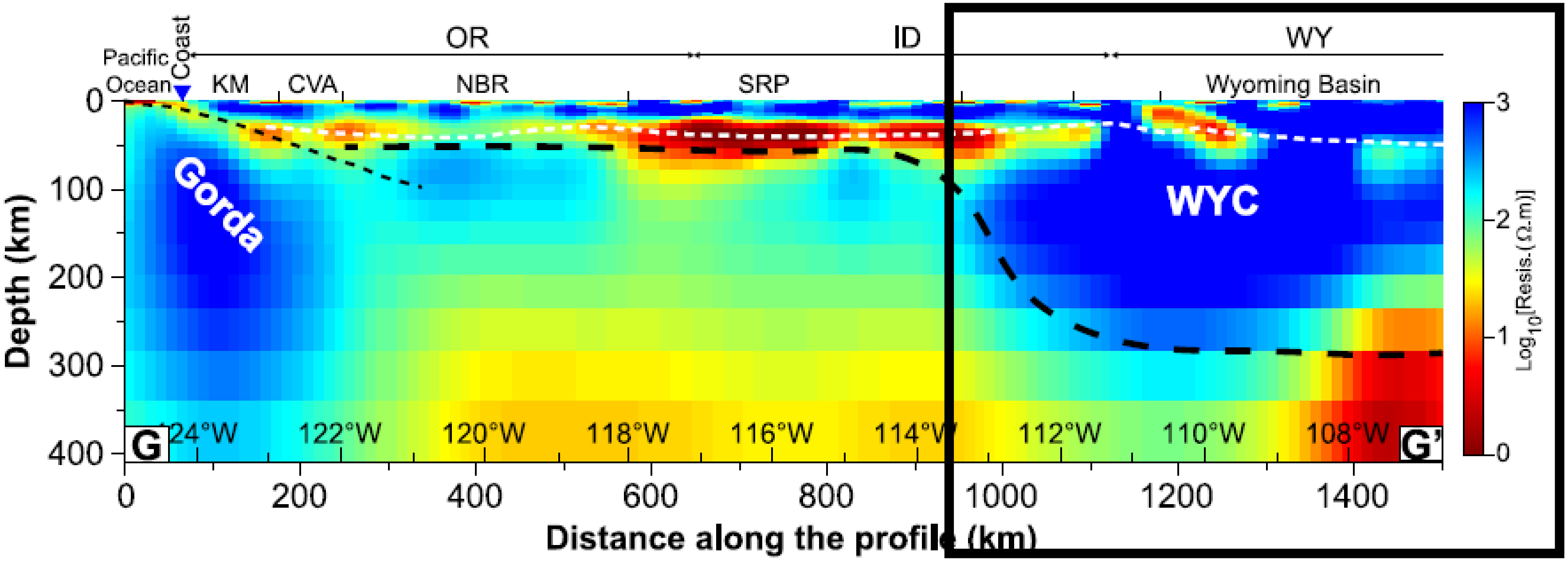
RdP – Rapela et al. (2011); Oyhantçabal et al. (2011)

RdP – Bologna et al. (2019)



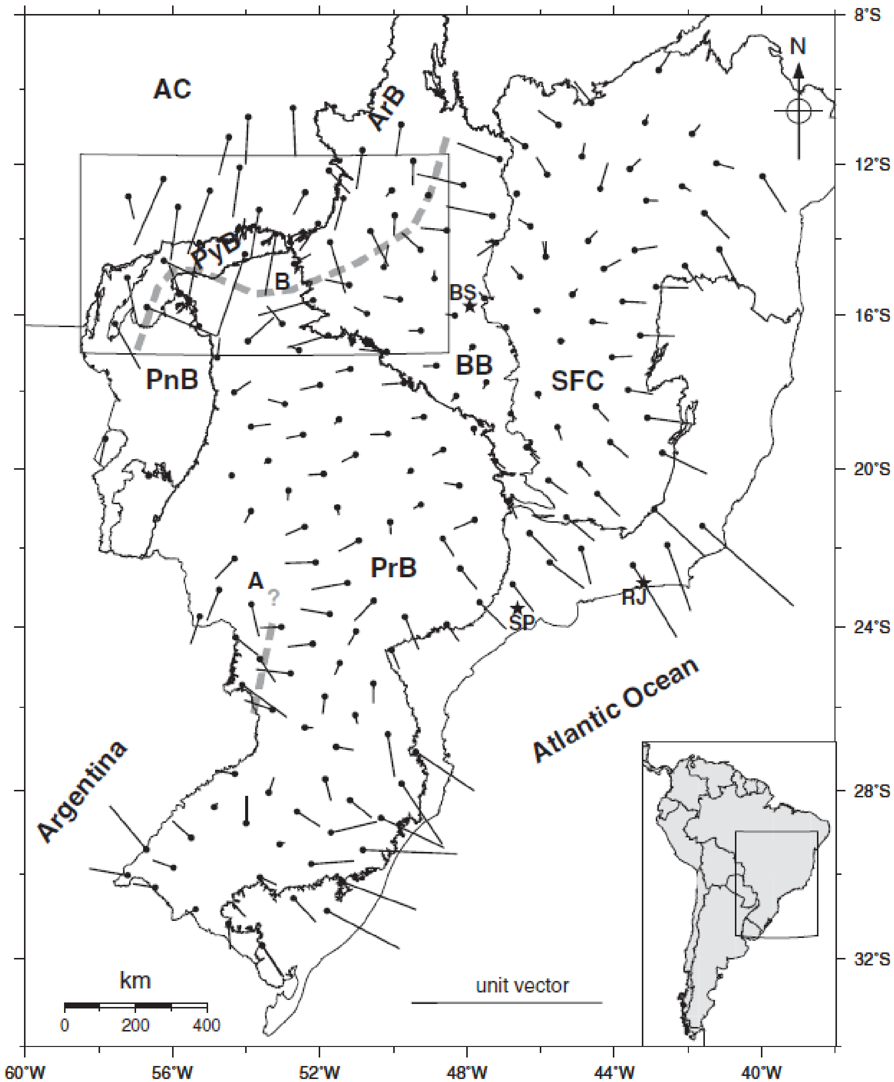


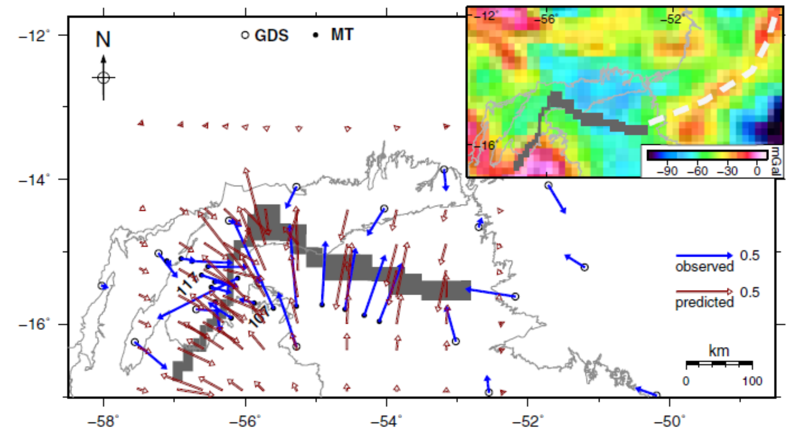
(Khoza et al., 2013)



(Meqbel et al., 2014)

Província Tocantins





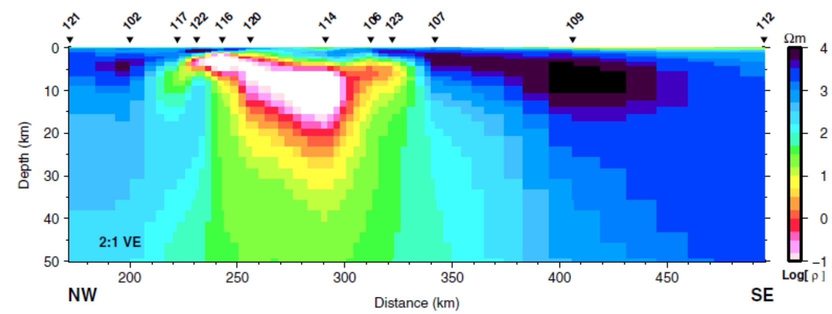
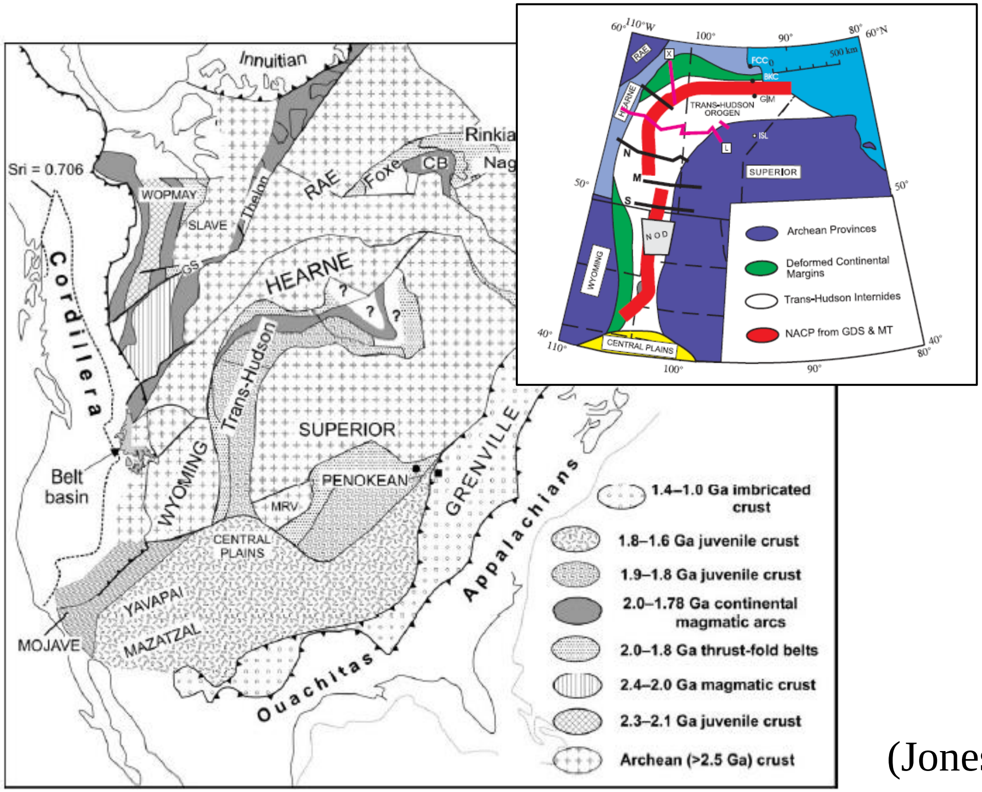
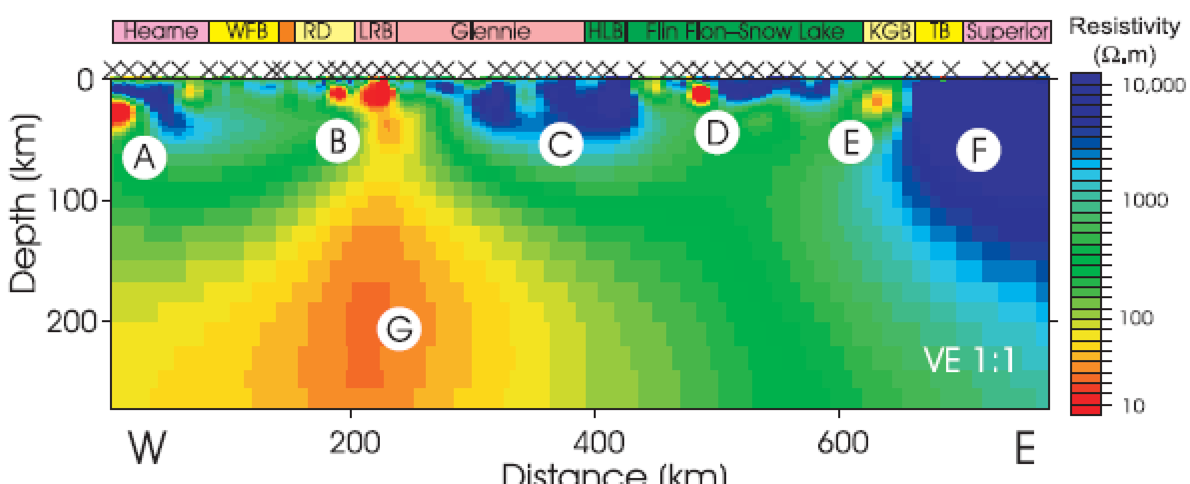


Figure 4. 2-D resistivity model obtained by inversion of TM mode across the Paraguay Belt.

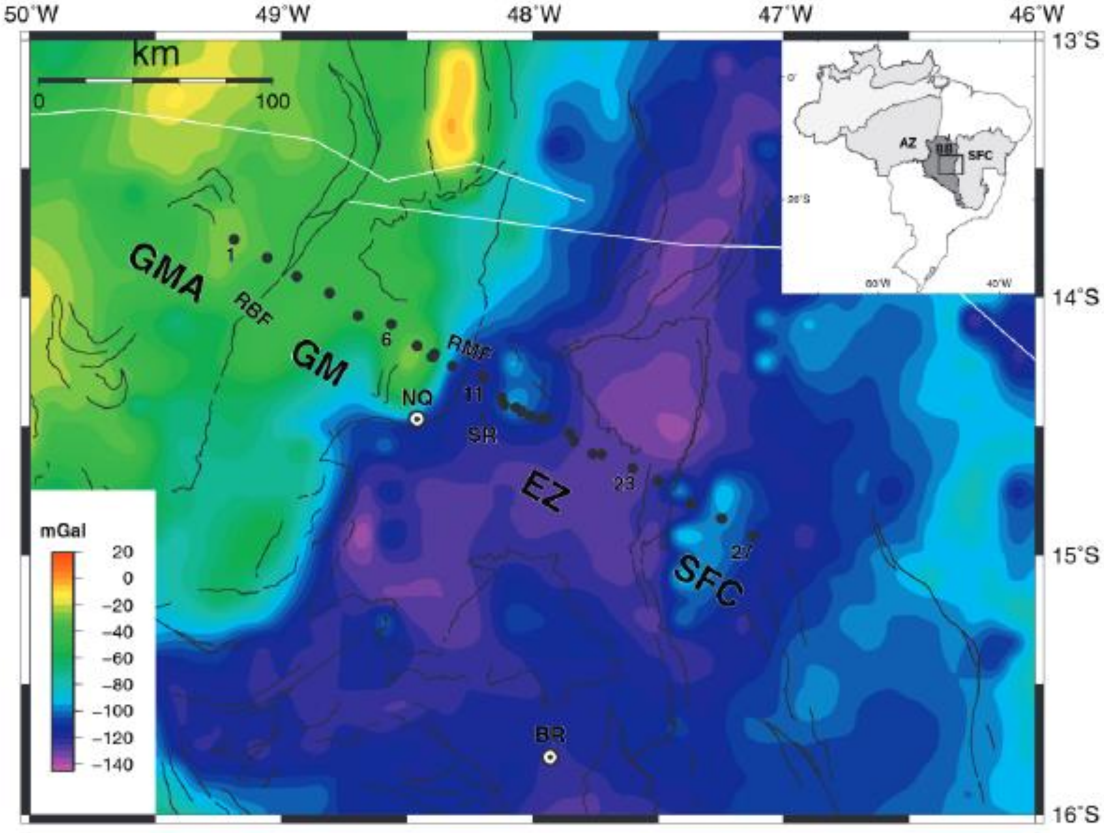
Bologna et al. (2014)

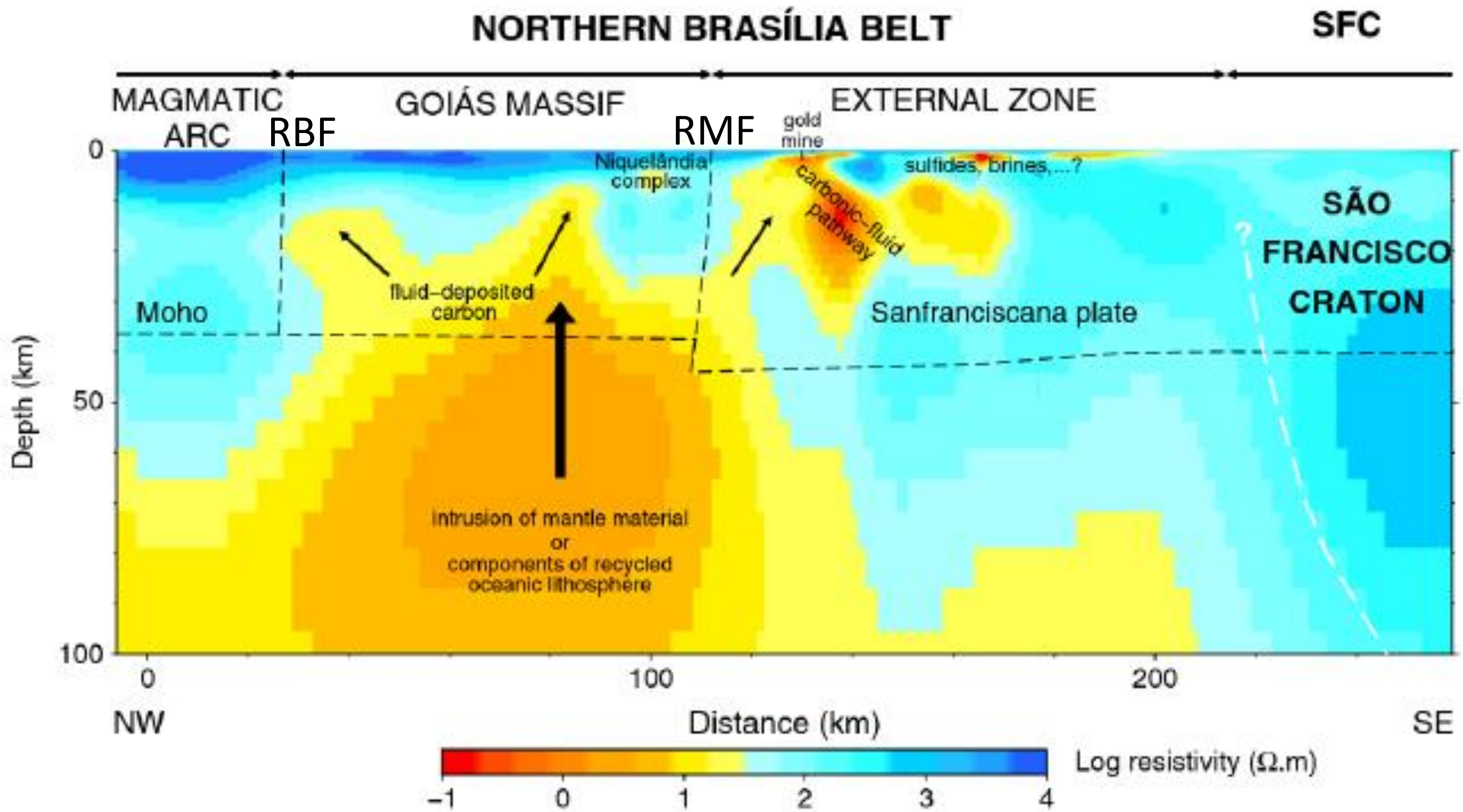


(Jones et al., 2005)



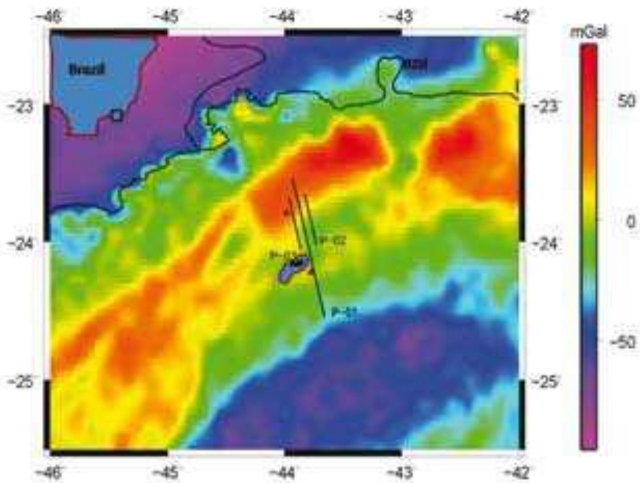
- Padilha et al. (2012)





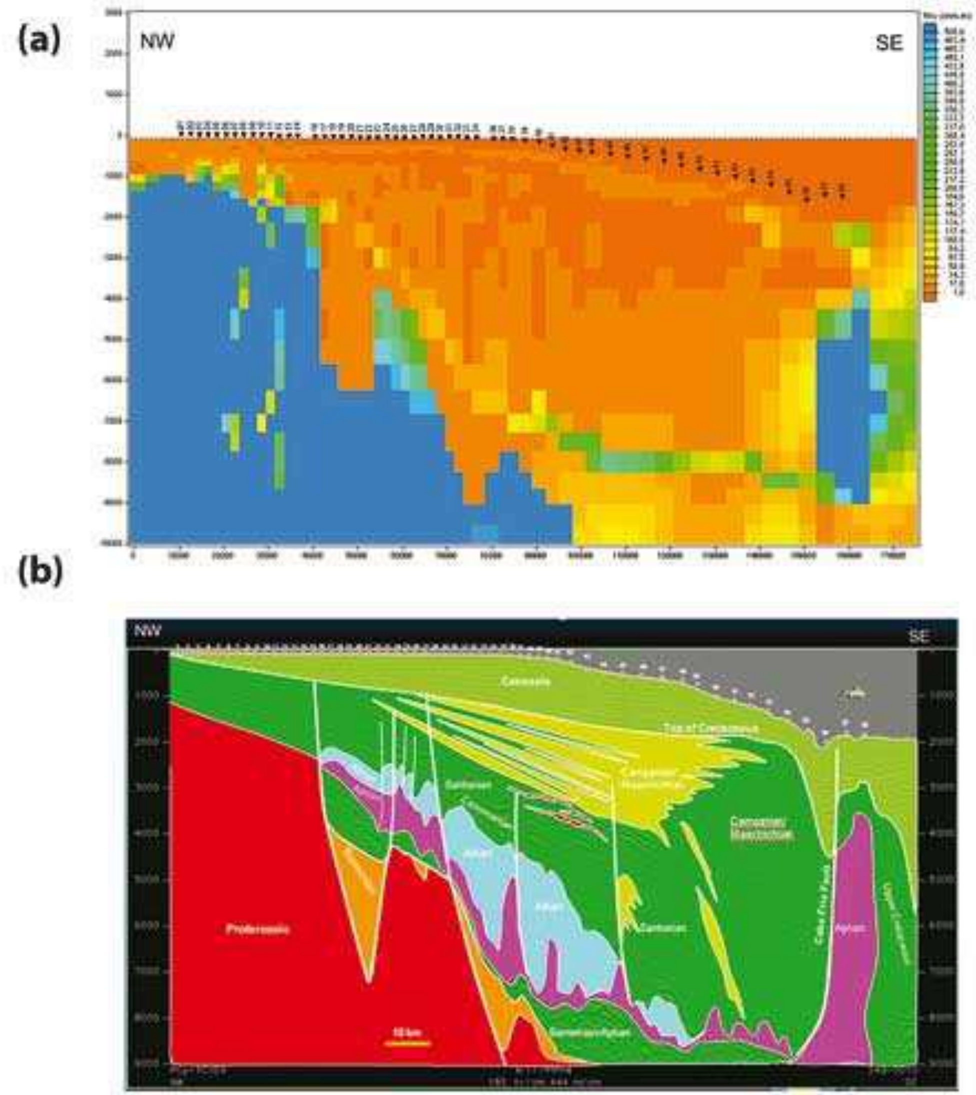
NORTHERN BRASÍLIA BELT
SFC
MAGMATIC ARC
GOIÁS MASSIF
EXTERNAL ZONE
RBF
RMF
gold mine
Niquelândia complex
sulfides, brines,...?
carbonic-fluid pathway
SÃO FRANCISCO CRATON
fluid-deposited carbon
Moho
Sanfranciscana plate
intrusion of mantle material or components of recycled oceanic lithosphere
Depth (km)
0
50
100
Distance (km)
0
100
200
NW
SE
Log resistivity (Ω.m)
−1
0
1
2
3
4

Bacia de Santos

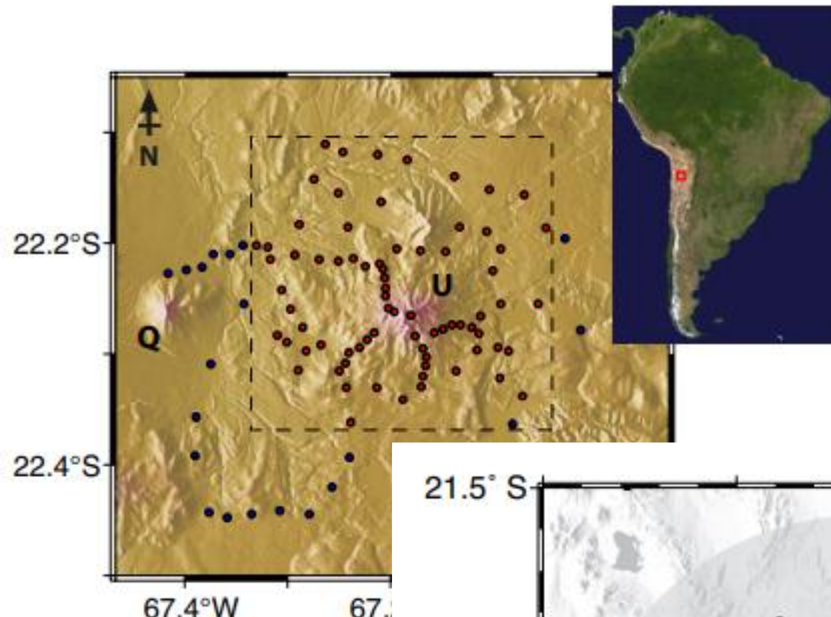


(Fontes et al., 2009)

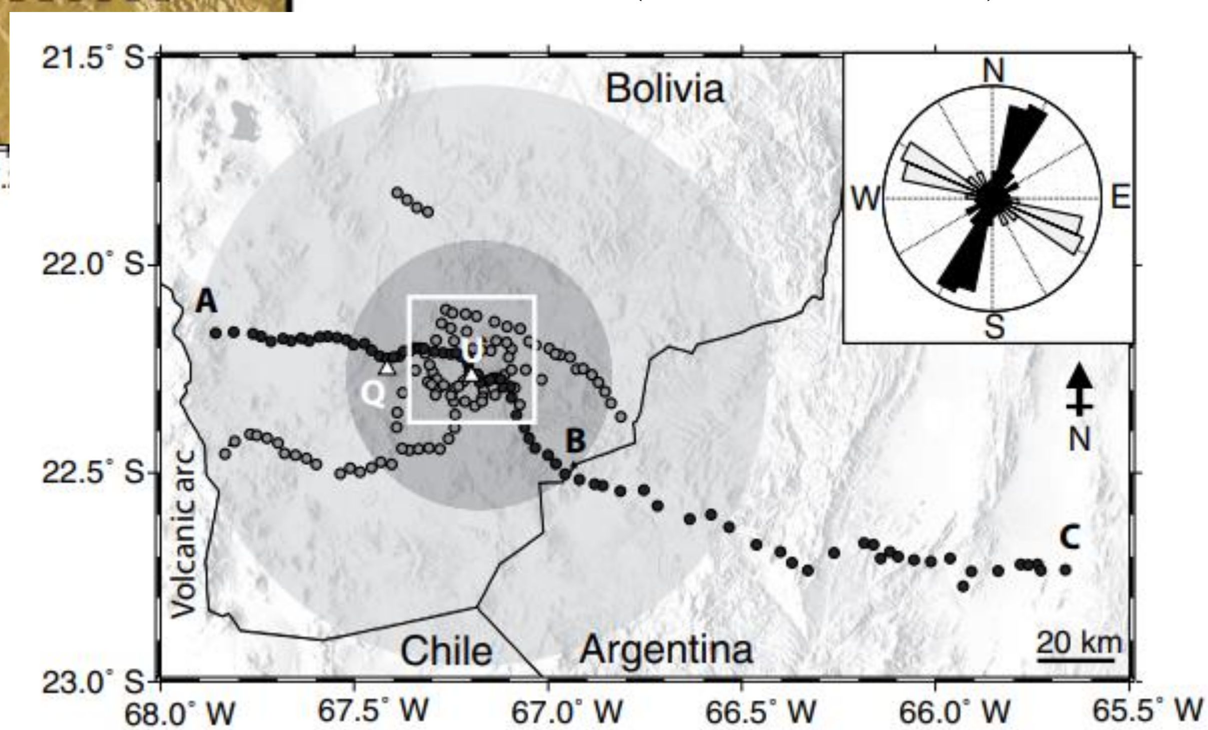
(a)

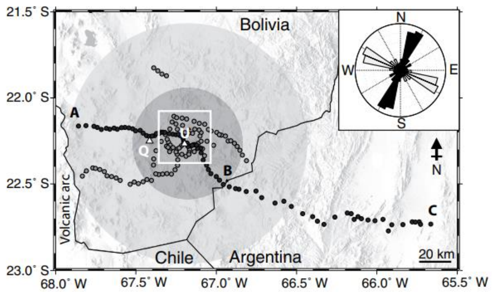


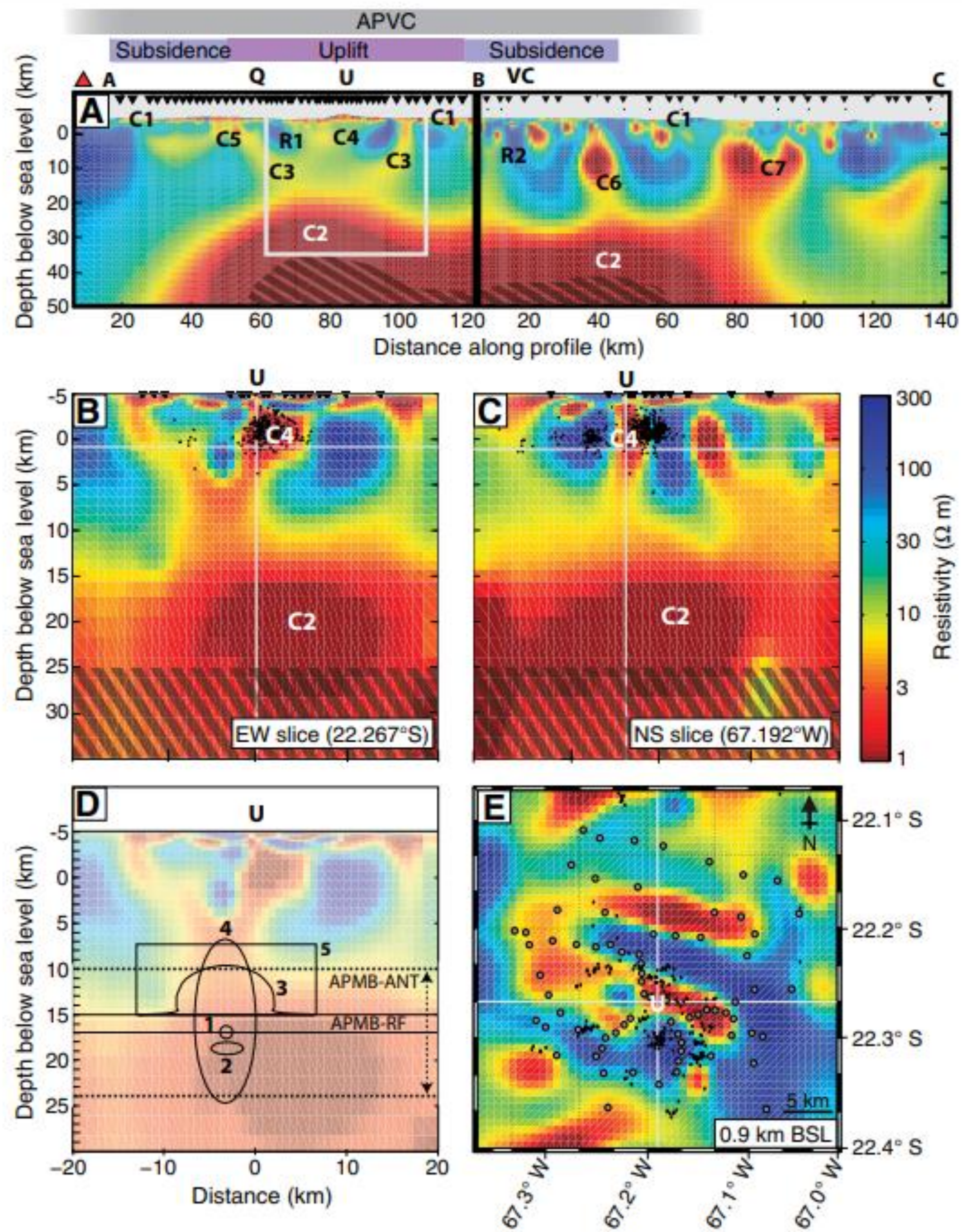
Regiões vulcânicas – Bolívia



(Comeau et al., 2015)







- U—Volcán Uturuncu;
- Q—Volcán Quetena;
- VC—Vilama Caldera;
- APVC—Altiplano-Puna Volcanic Complex.

Obrigado!

Bibliografia básica método MT

- Chave, A. D.; Jones, A. G. (Eds.). *The Magnetotelluric method: theory and practice*. Cambridge: Cambridge University Press, 2012.
- Simpson, F.; Bahr, K. *Practical Magnetotellurics*. Cambridge University Press, Cambridge, 2005. 270 p.
- Vozoff, K. The Magnetotelluric Method. In: Nabighian, M. N. (ed.) *Electromagnetic Methods in Applied Geophysics*, vol. 2, Cap. 8, p. 641-711, 1991.