Determinação da forma de corpos 3D via inversão de dados de campos potenciais

Vanderlei C Oliveira Jr

Memorial – parte III

2012

Estrutura

- Problema geofísico
- Parametrização e problema inverso
- Curva v x s
- Testes com dados sintéticos
  - Gadiometria gravimétrica
- Aplicação a dados reais
  - Gradiometria gravimétrica
- Conclusões
- Produção científica
- Considerações pessoais
- Apêndice 1 – Formulação matemática do problema inverso
- Apêndice 2 – Formulação matemática da curva v x s
- Apêndice 3 – Vínculos do problema inverso
- Apêndice 4 – Testes com dados de gradiometria gravimétrica sintéticos
- Apêndice 5 – Teste com dados de gradiometria gravimétrica reais

Estrutura

- Problema geofísico
- Parametrização e problema inverso
- Curva v x s
- Testes com dados sintéticos
  - Gadiometria gravimétrica
- Aplicação a dados reais
  - Gradiometria gravimétrica
- Conclusões
- Produção científica
- Considerações pessoais
- Apêndice 1 – Formulação matemática do problema inverso
- Apêndice 2 – Formulação matemática da curva v x s
- Apêndice 3 – Vínculos do problema inverso
- Apêndice 4 – Testes com dados de gradiometria gravimétrica sintéticos
- Apêndice 5 – Teste com dados de gradiometria gravimétrica reais

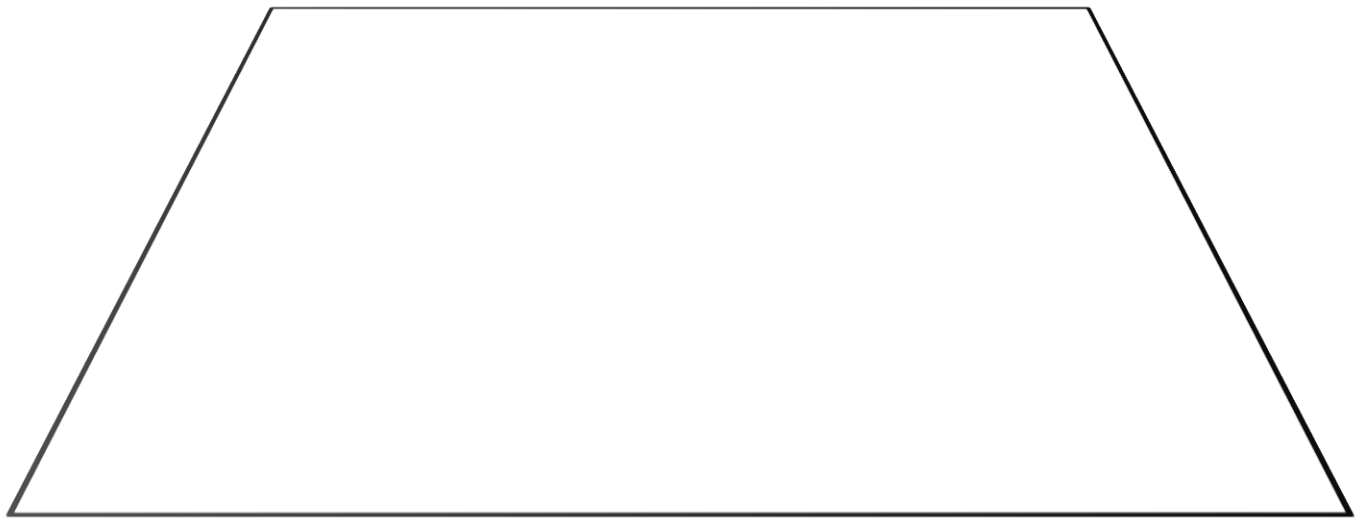
Resultados que compõem a minha tese de doutorado

Problema geofísico

Problema geofísico

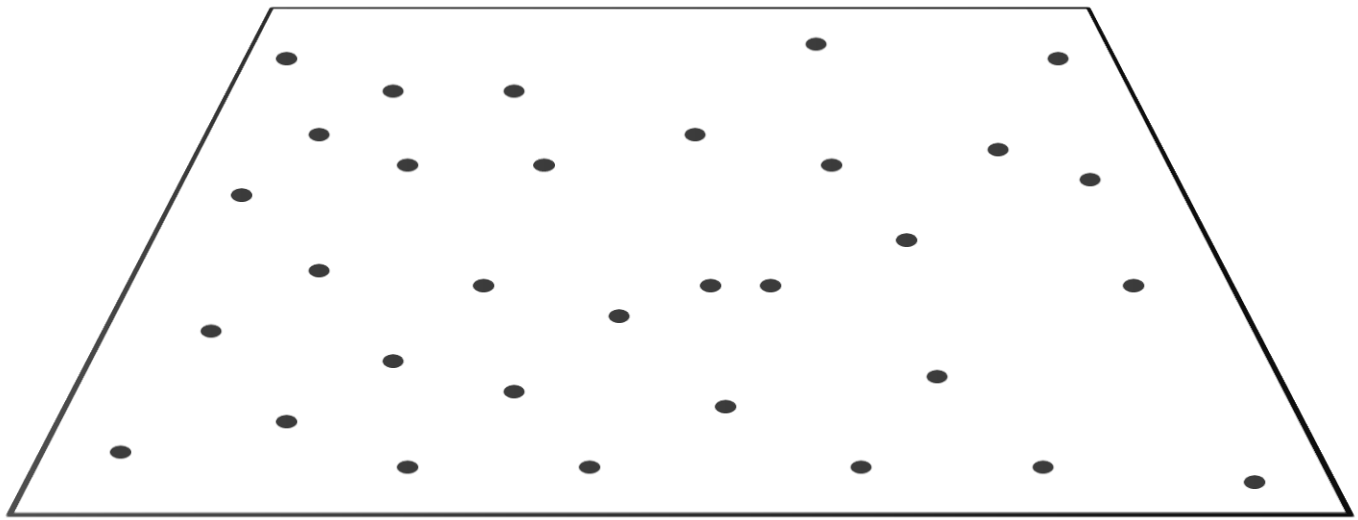
Problema geofísico

Problema geofísico



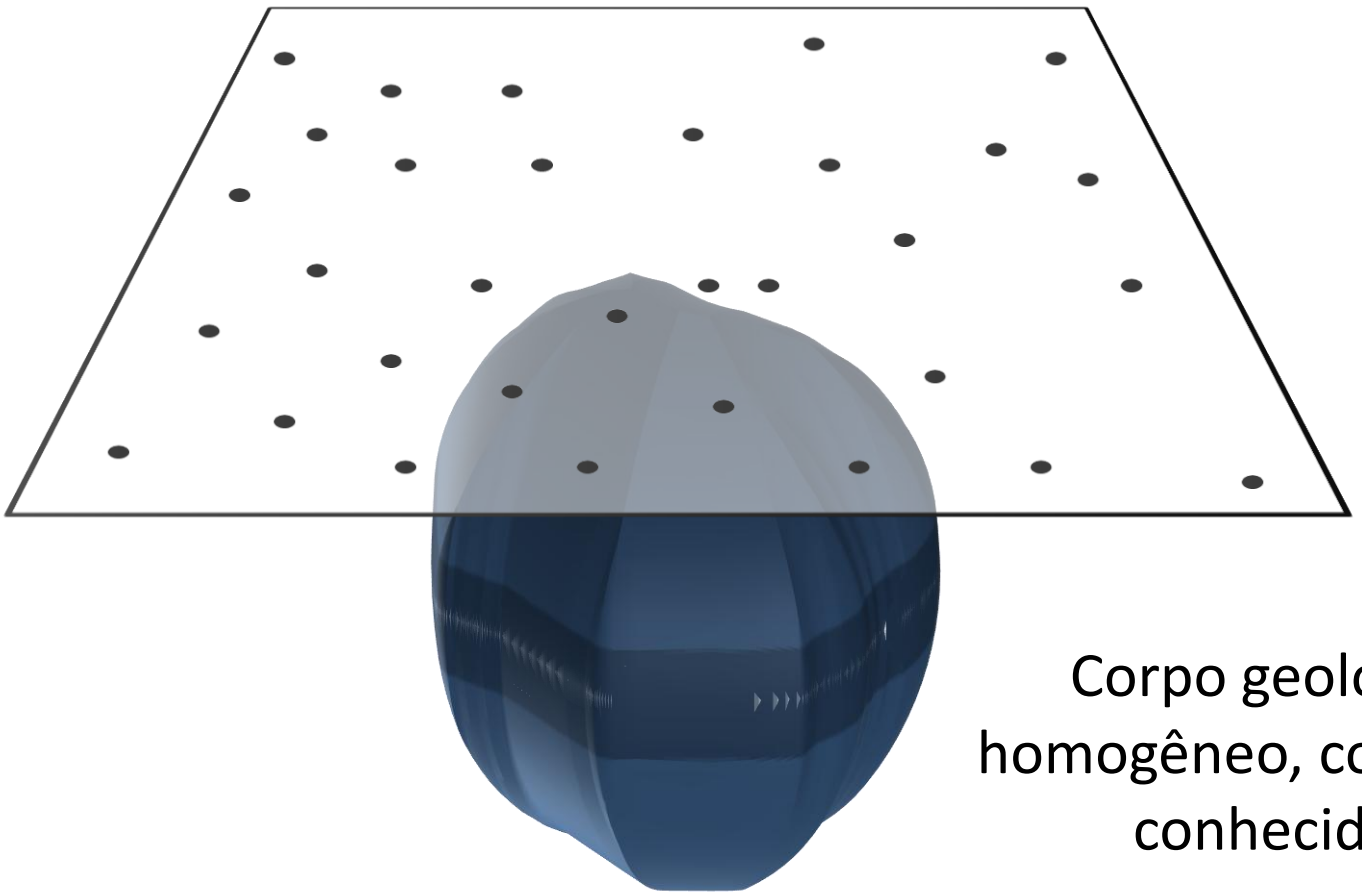
Problema geofísico

Medidas de um campo potencial



Problema geofísico

Medidas de um campo potencial

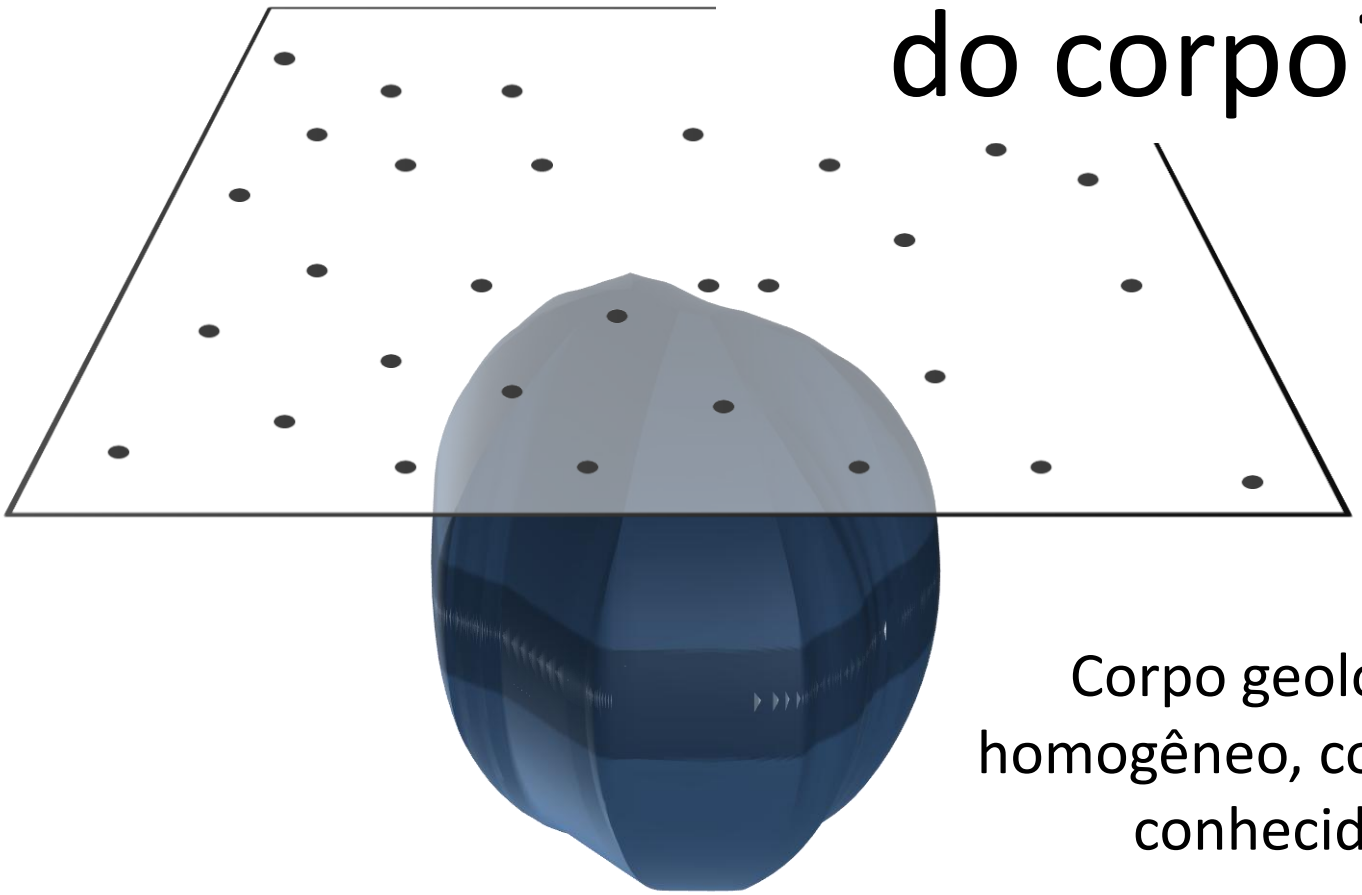


Corpo geológico homogêneo, com η e z_0 conhecidos

Problema geofísico

Medidas de um campo potencial

Qual é a forma do corpo?



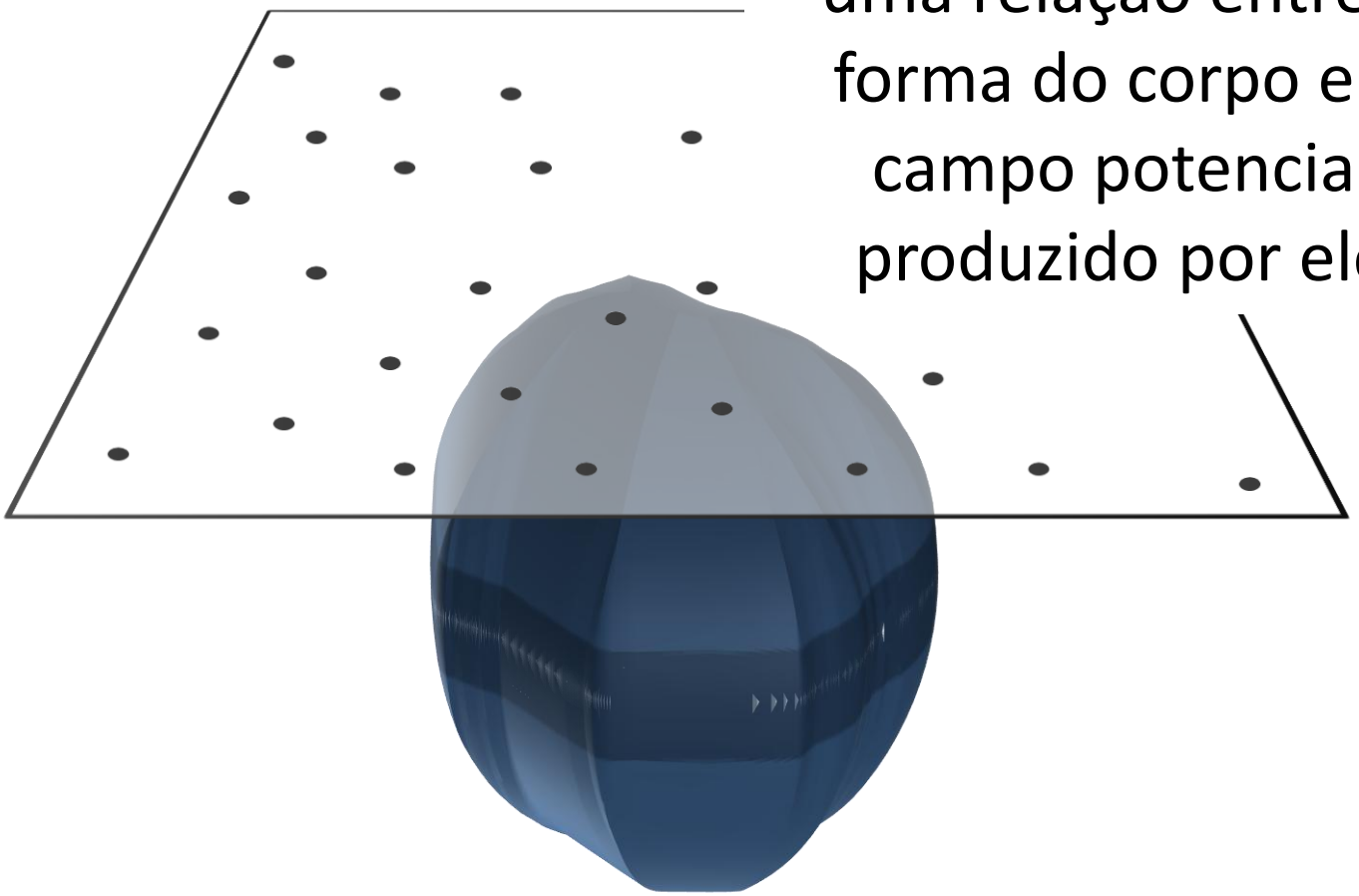
Corpo geológico homogêneo, com η e z_0 conhecidos

Parametrização e problema inverso

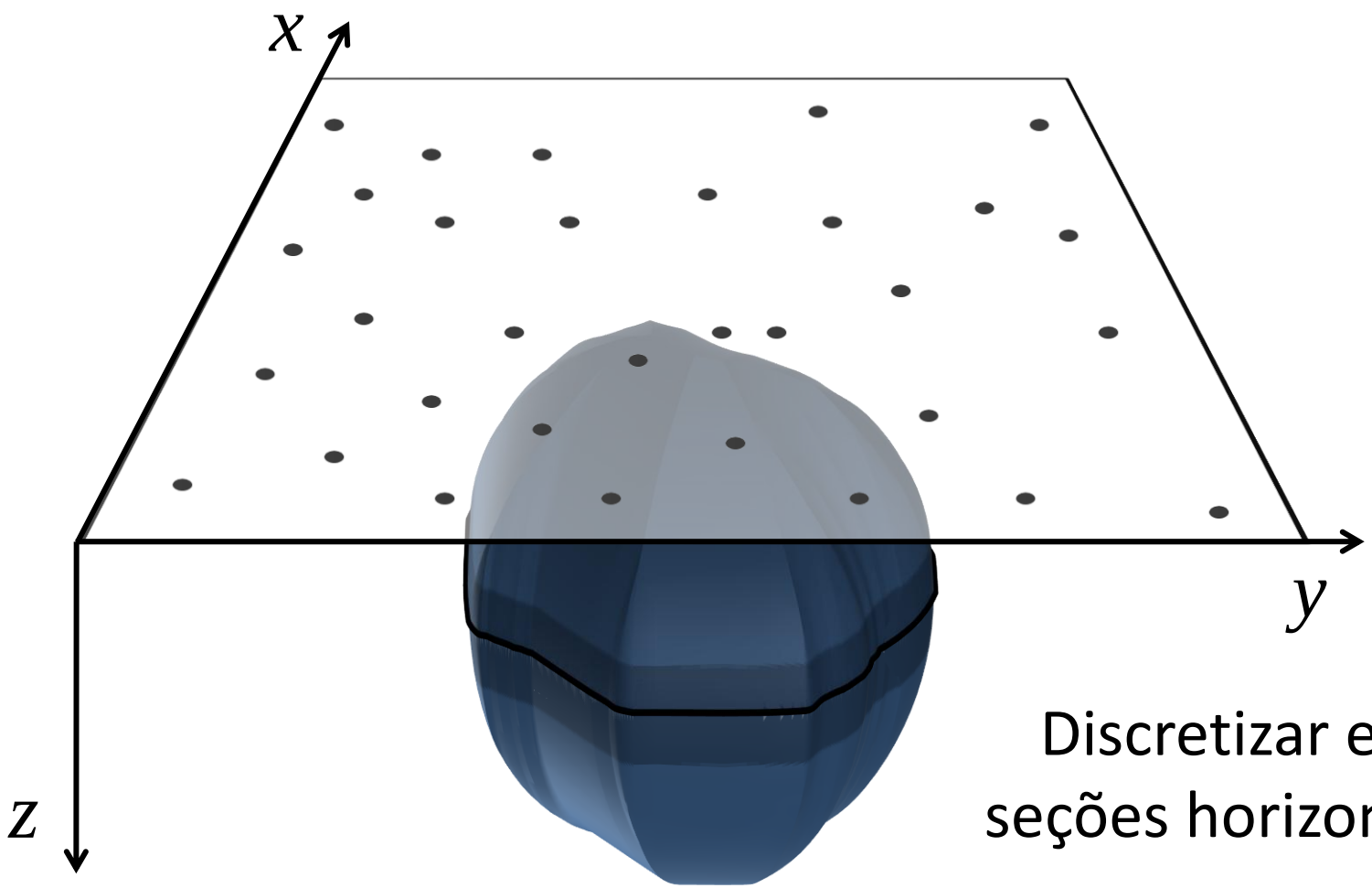
OLIVEIRA JR; BARBOSA; SILVA, 2011
SILVA; BARBOSA, 2004

Parametrização e problema inverso

É preciso estabelecer uma relação entre a forma do corpo e o campo potencial produzido por ele

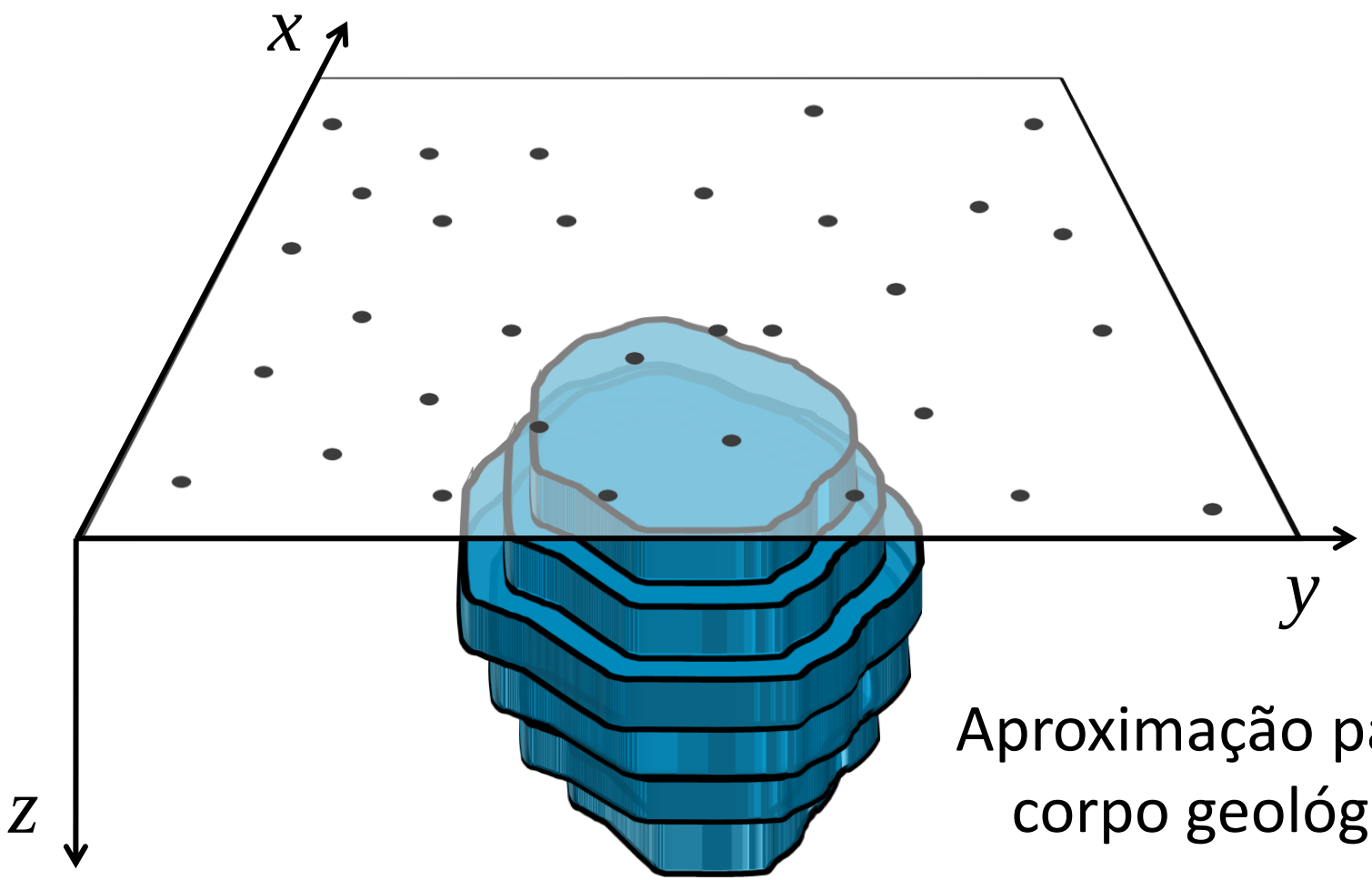


Parametrização e problema inverso



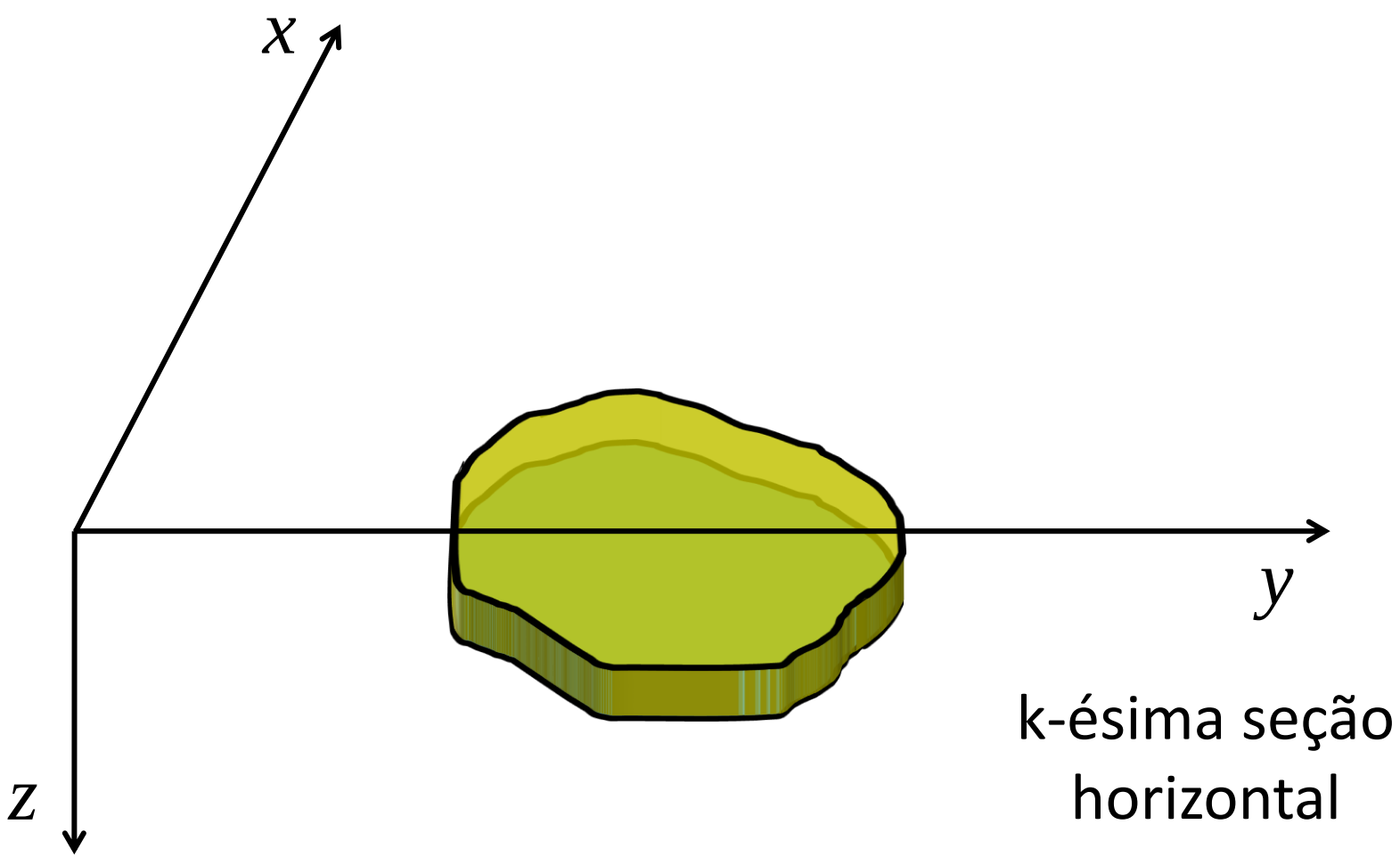
Discretizar em seções horizontais

Parametrização e problema inverso

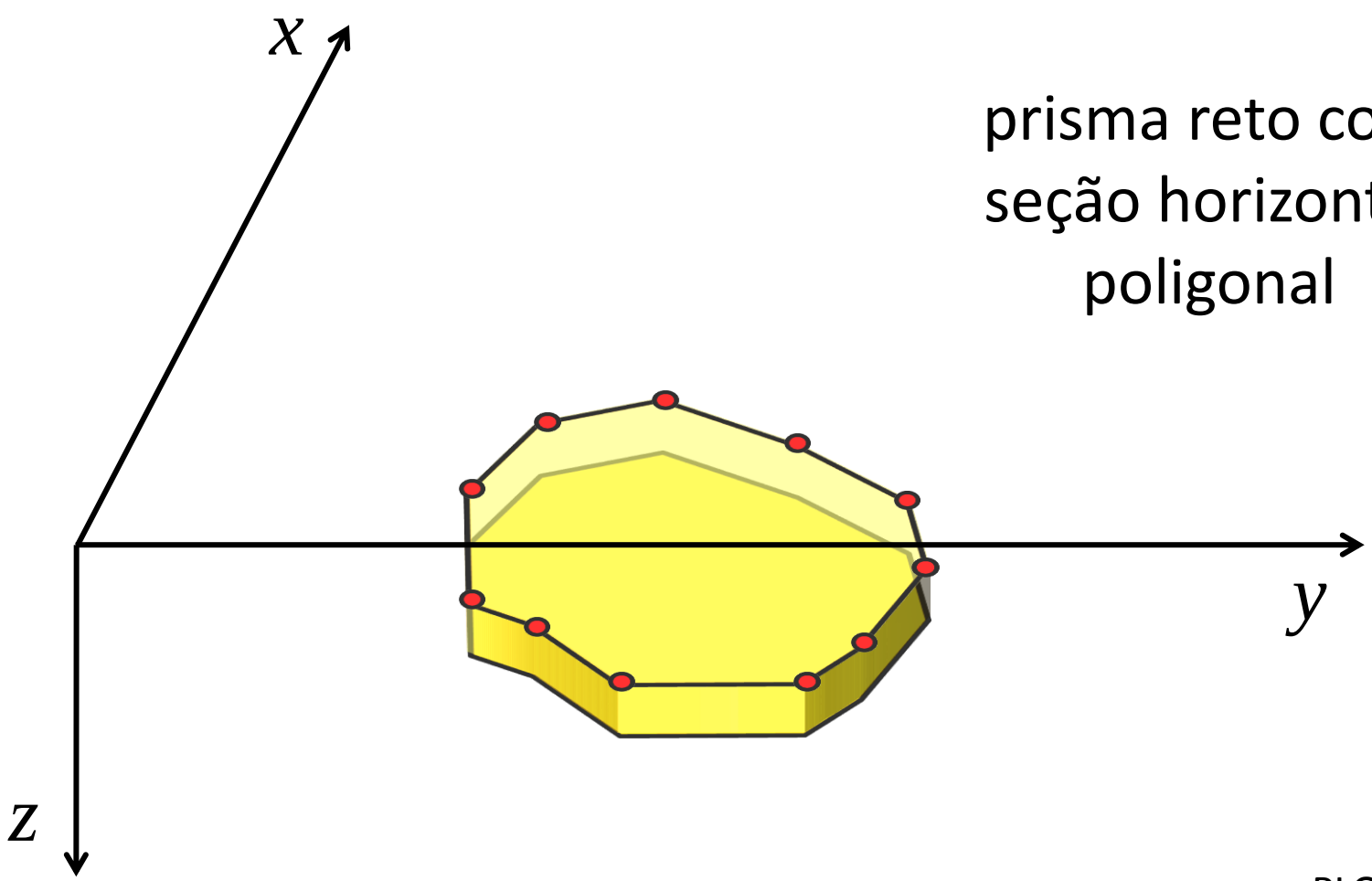


Aproximação para o corpo geológico

Parametrização e problema inverso



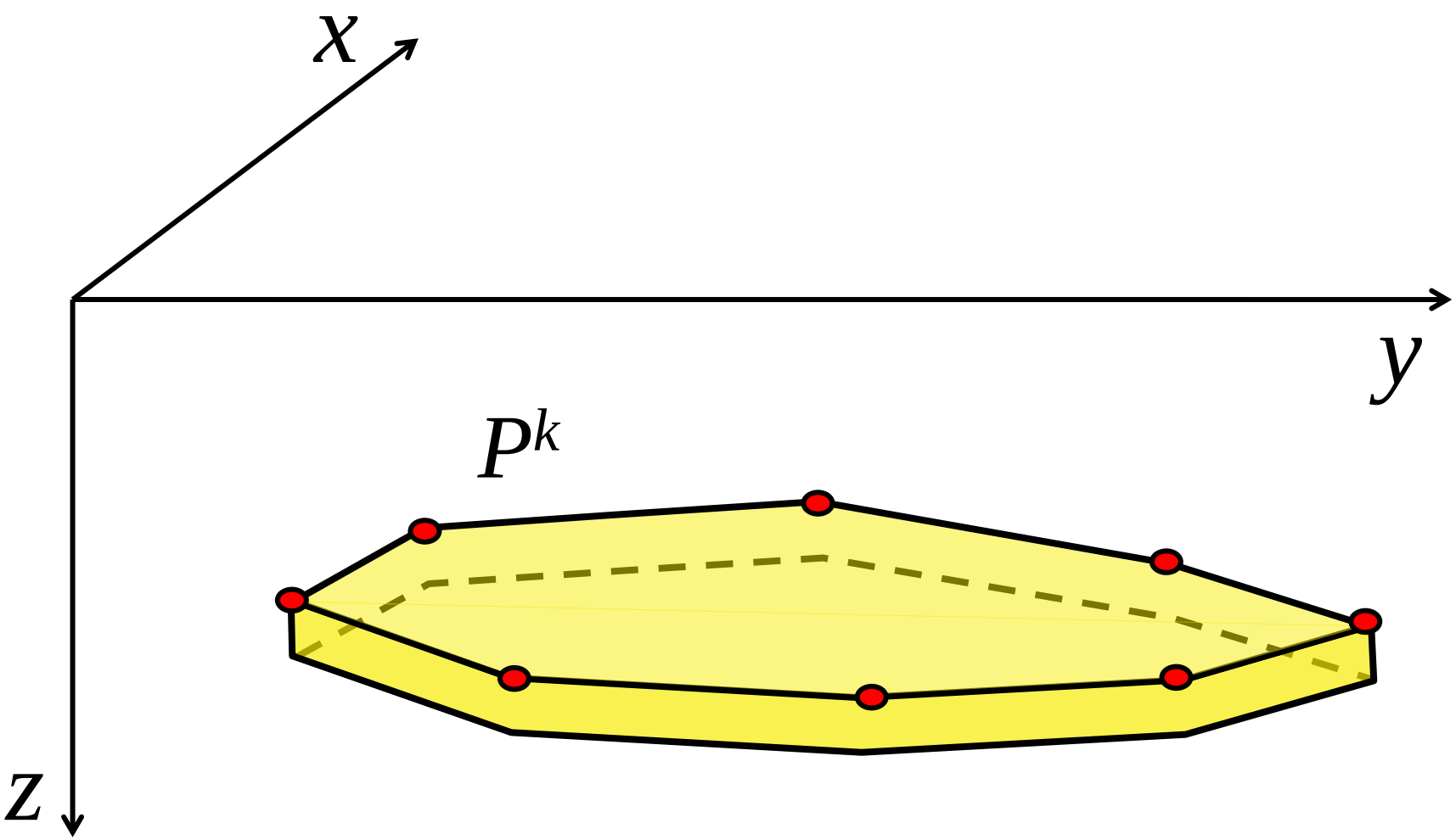
Parametrização e problema inverso



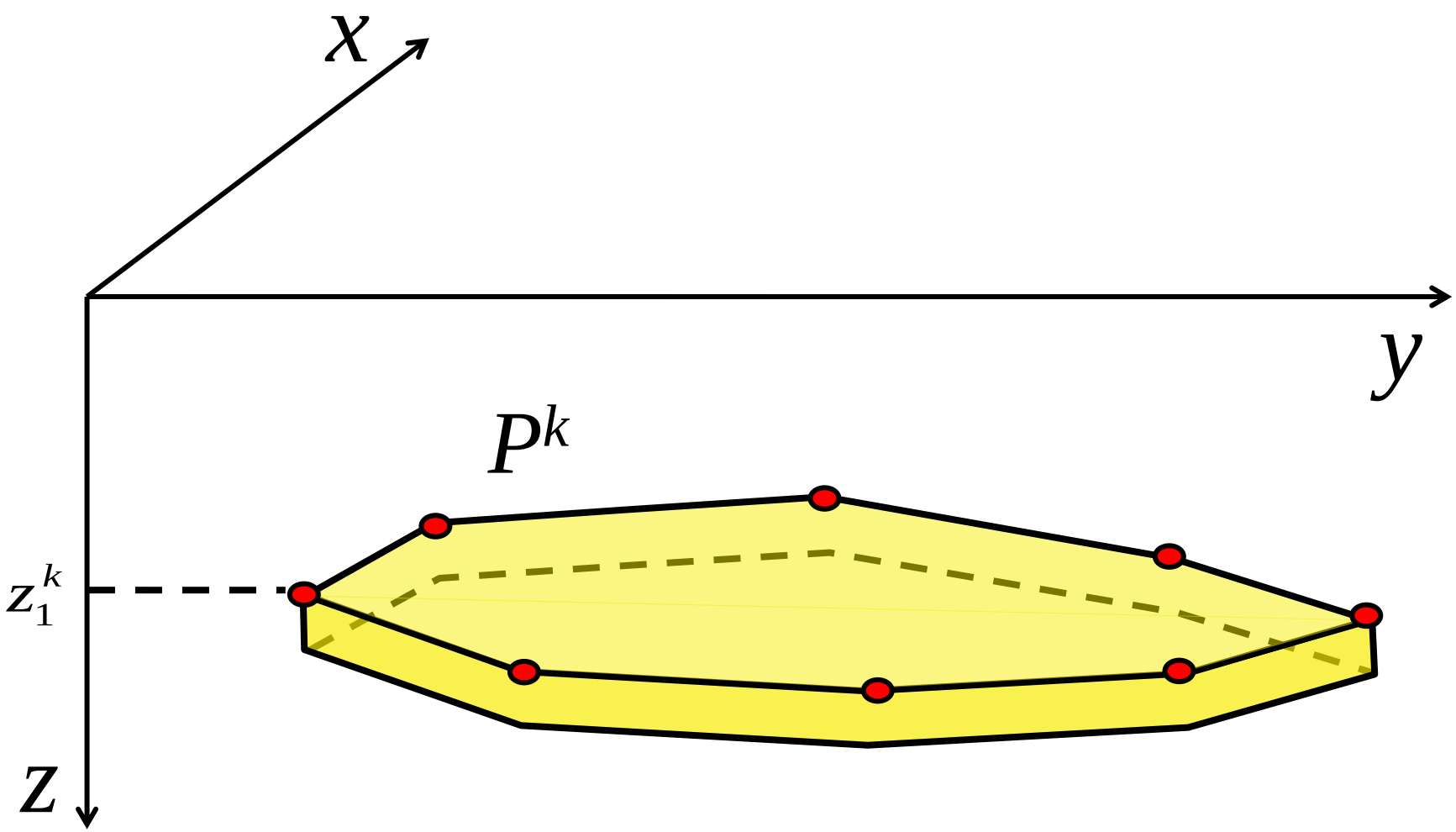
prisma reto com seção horizontal poligonal

PLOUFF, 1976

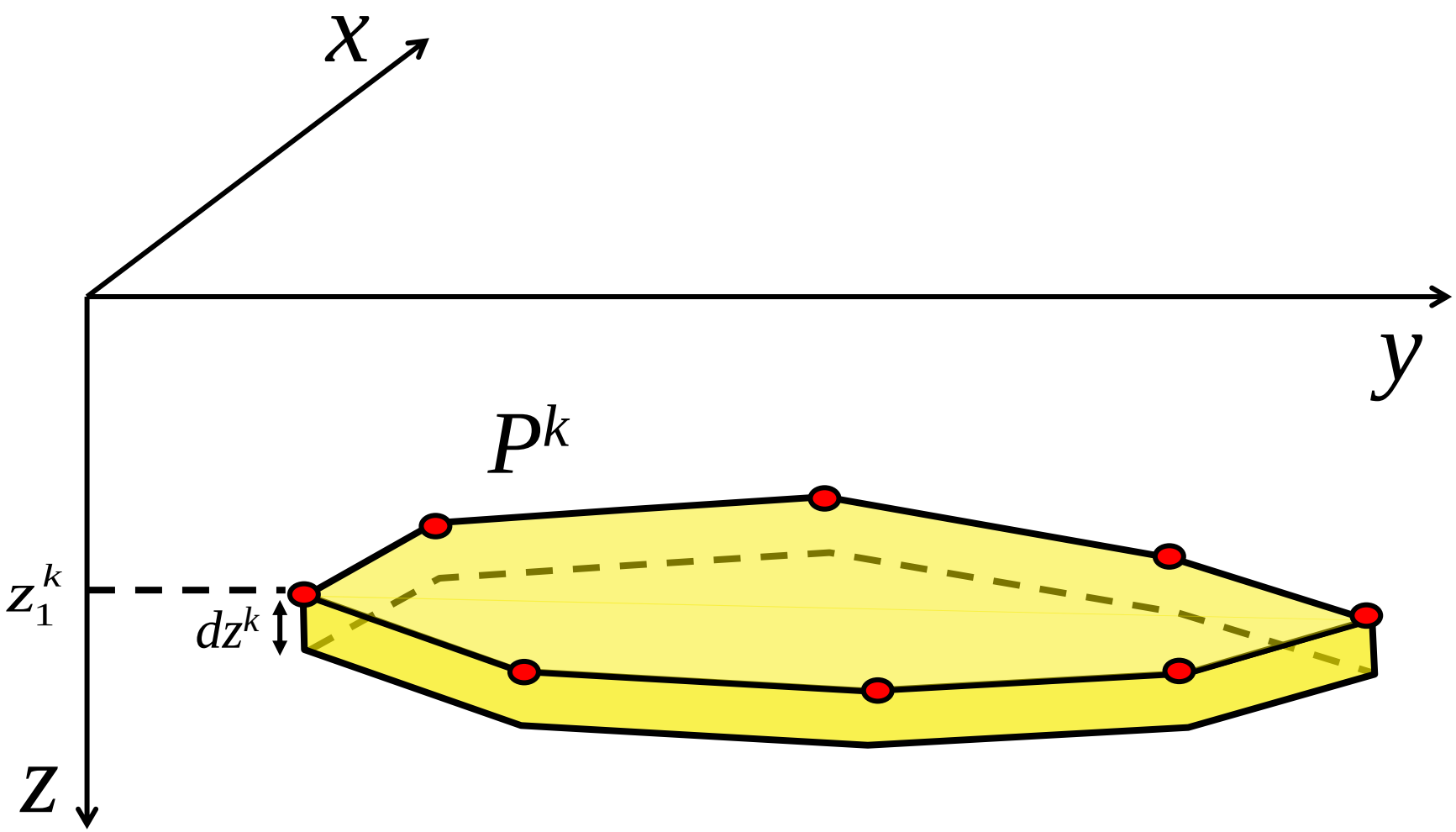
Parametrização e problema inverso



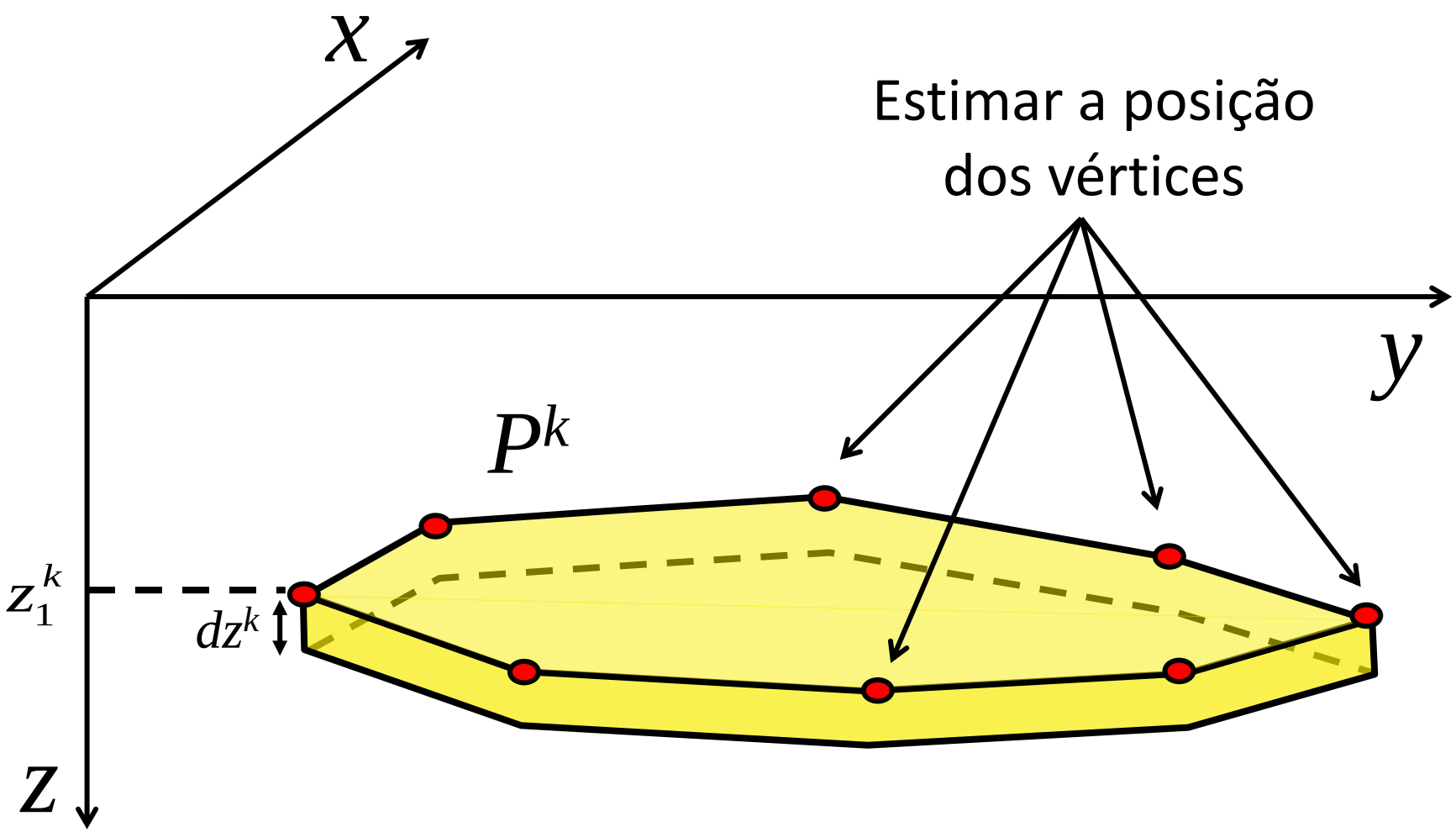
Parametrização e problema inverso



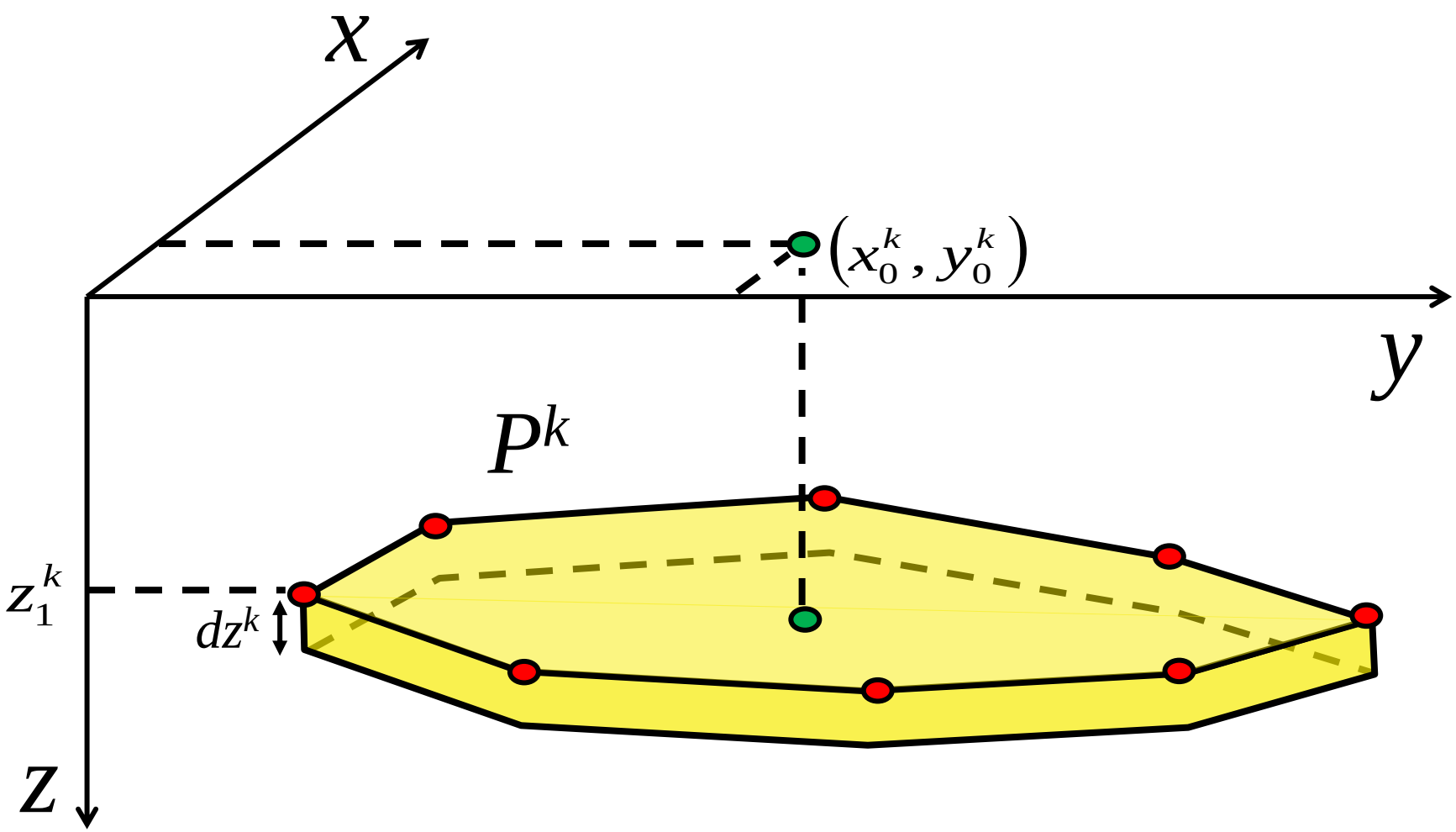
Parametrização e problema inverso



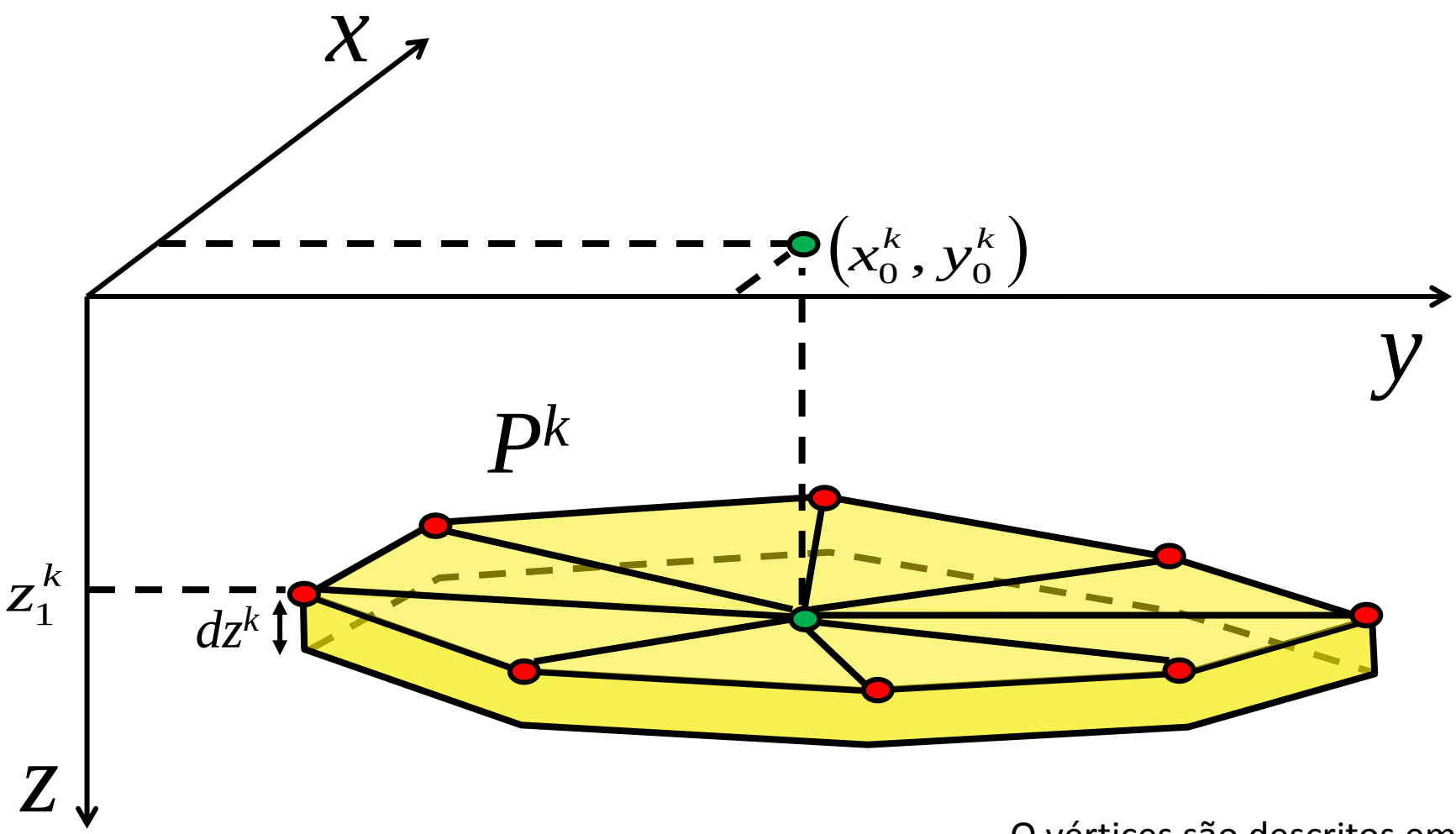
Parametrização e problema inverso



Parametrização e problema inverso

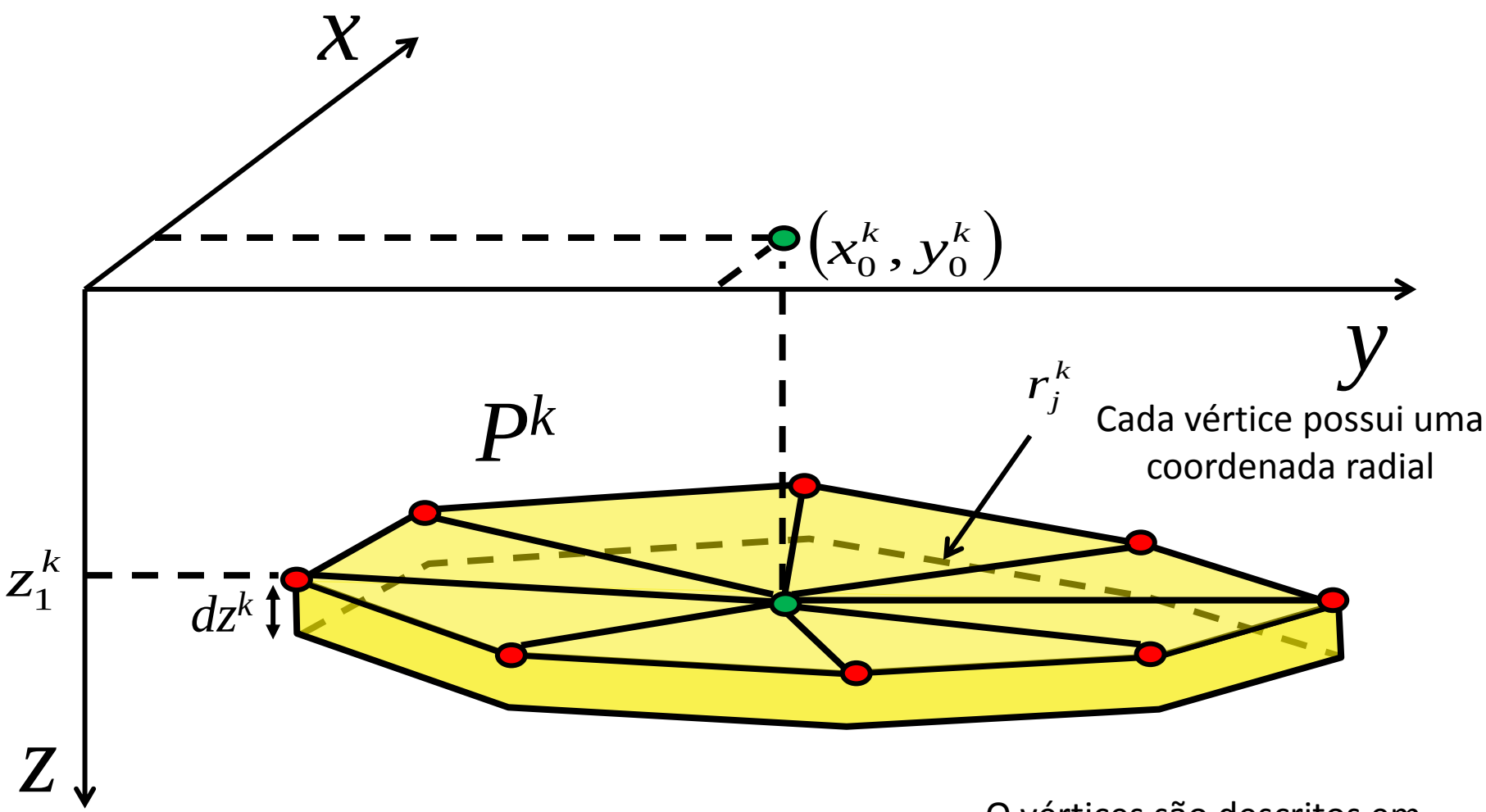


Parametrização e problema inverso



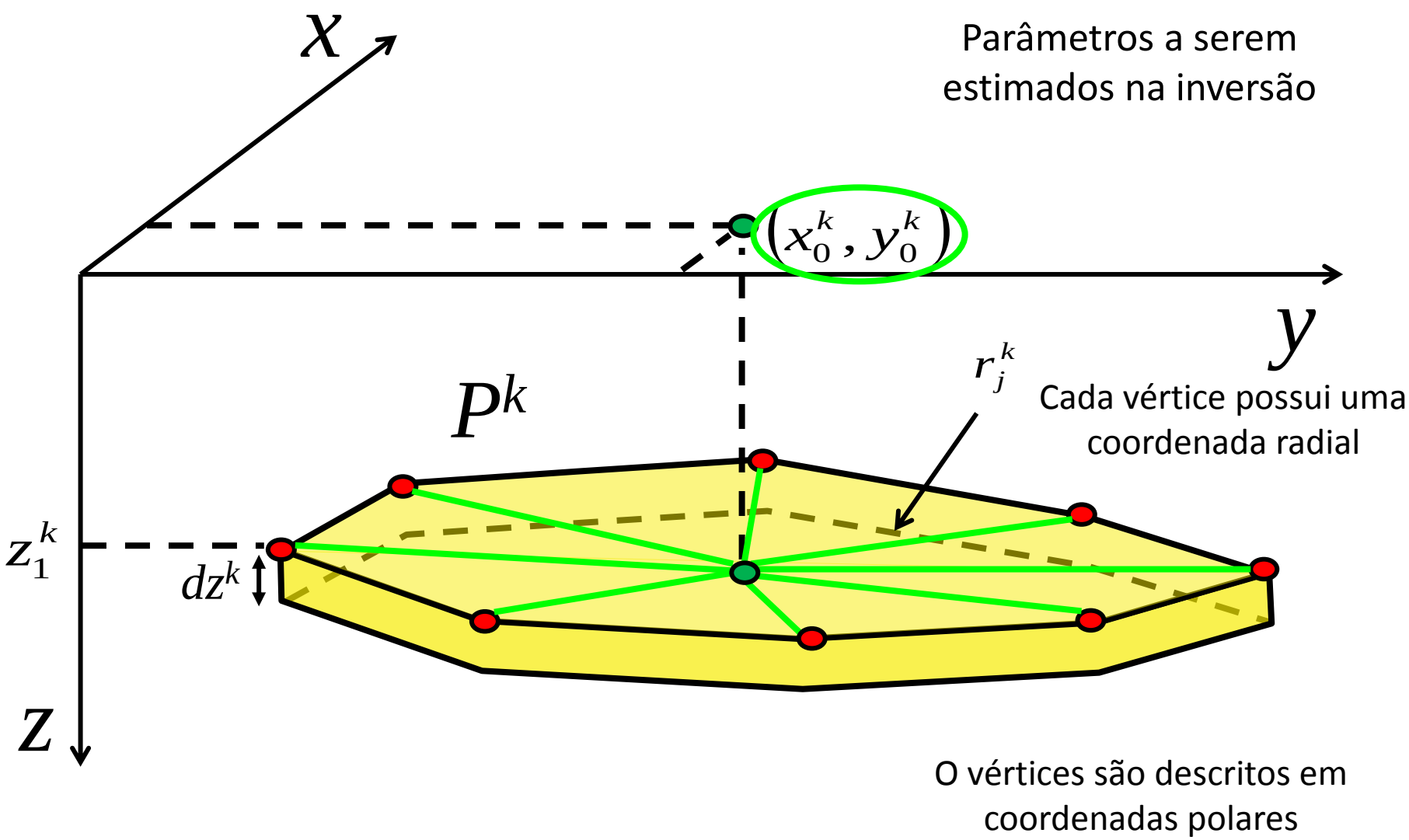
O vértices são descritos em coordenadas polares

Parametrização e problema inverso

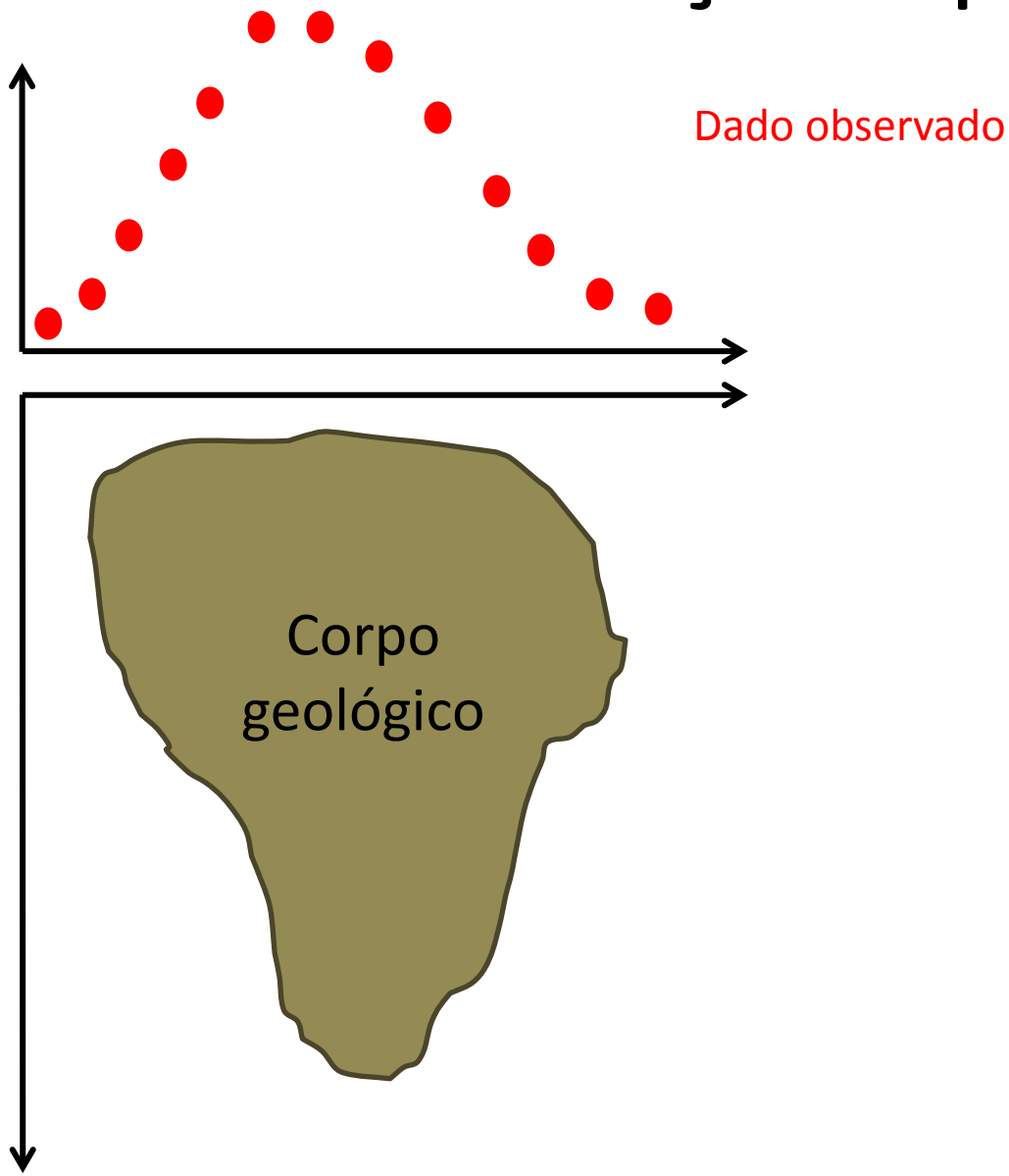


O vértices são descritos em coordenadas polares

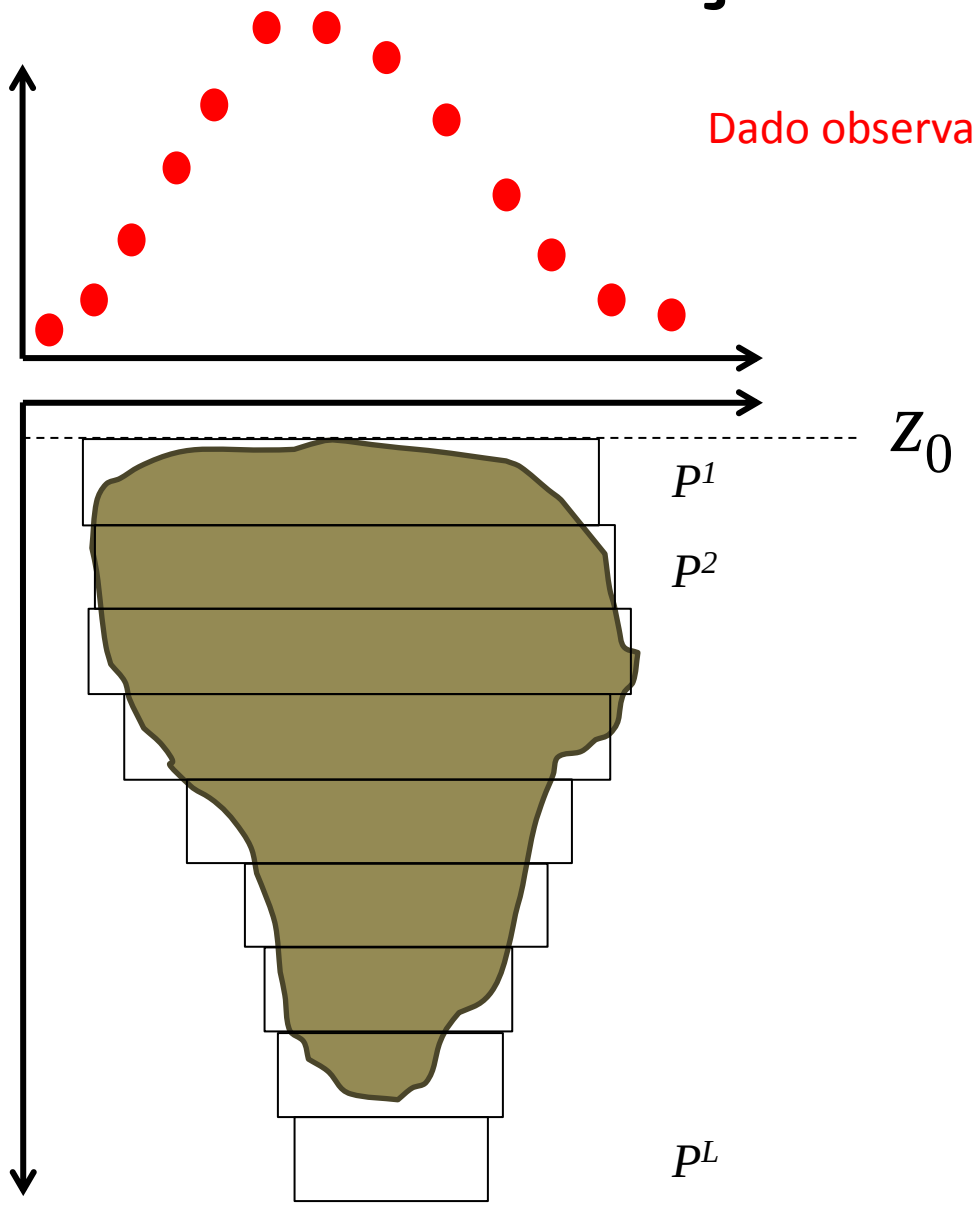
Parametrização e problema inverso



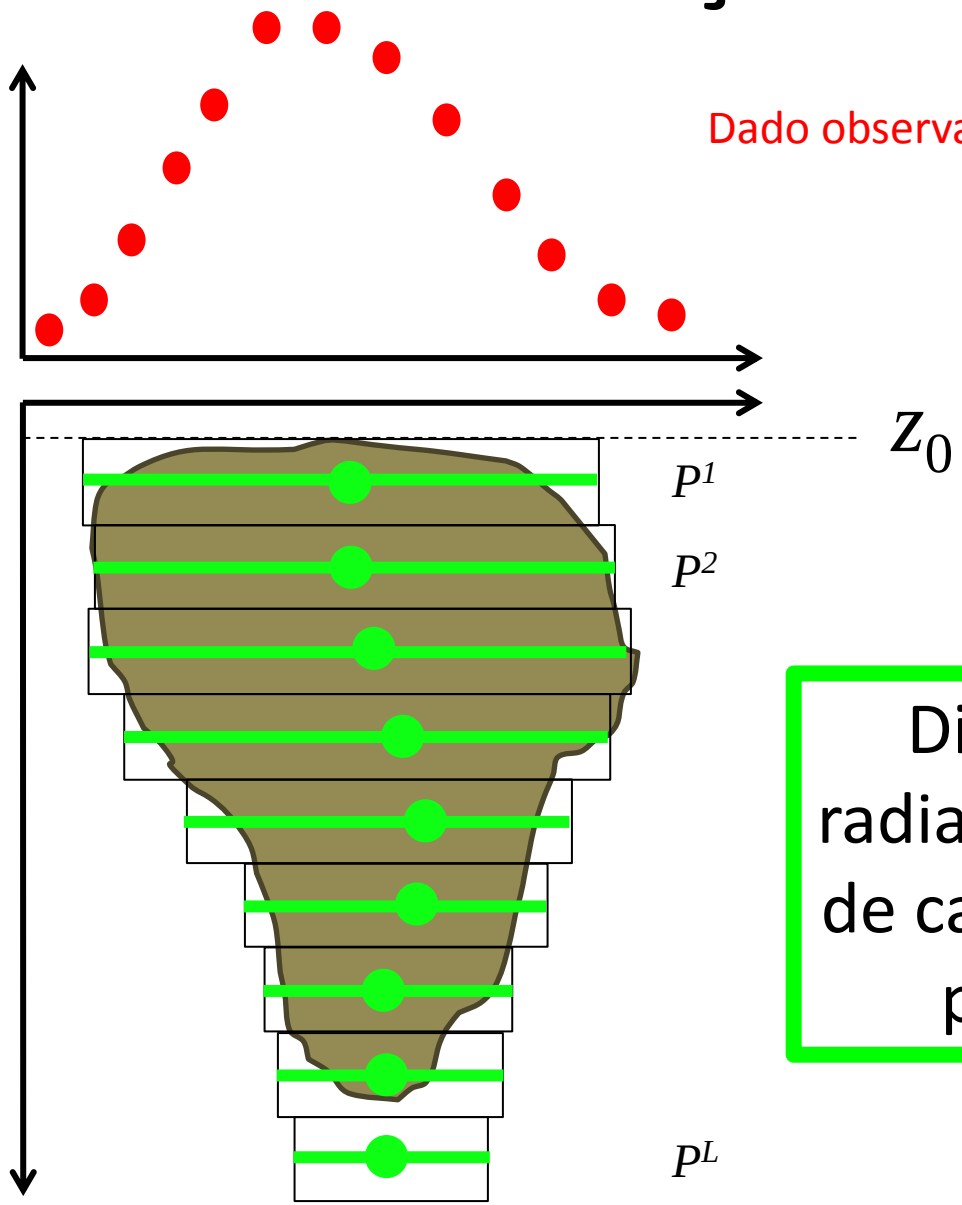
Parametrização e problema inverso



Parametrização e problema inverso

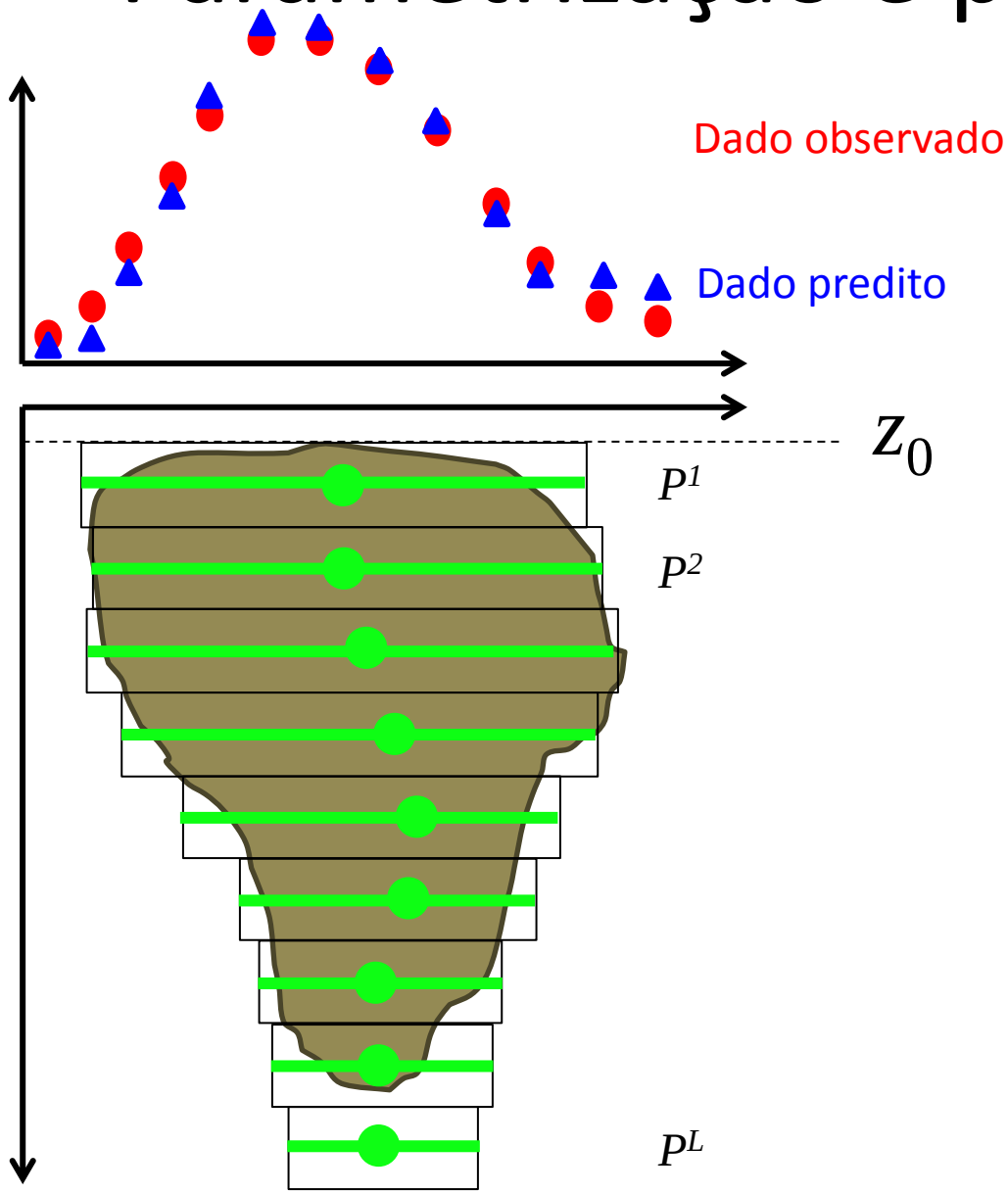


Parametrização e problema inverso

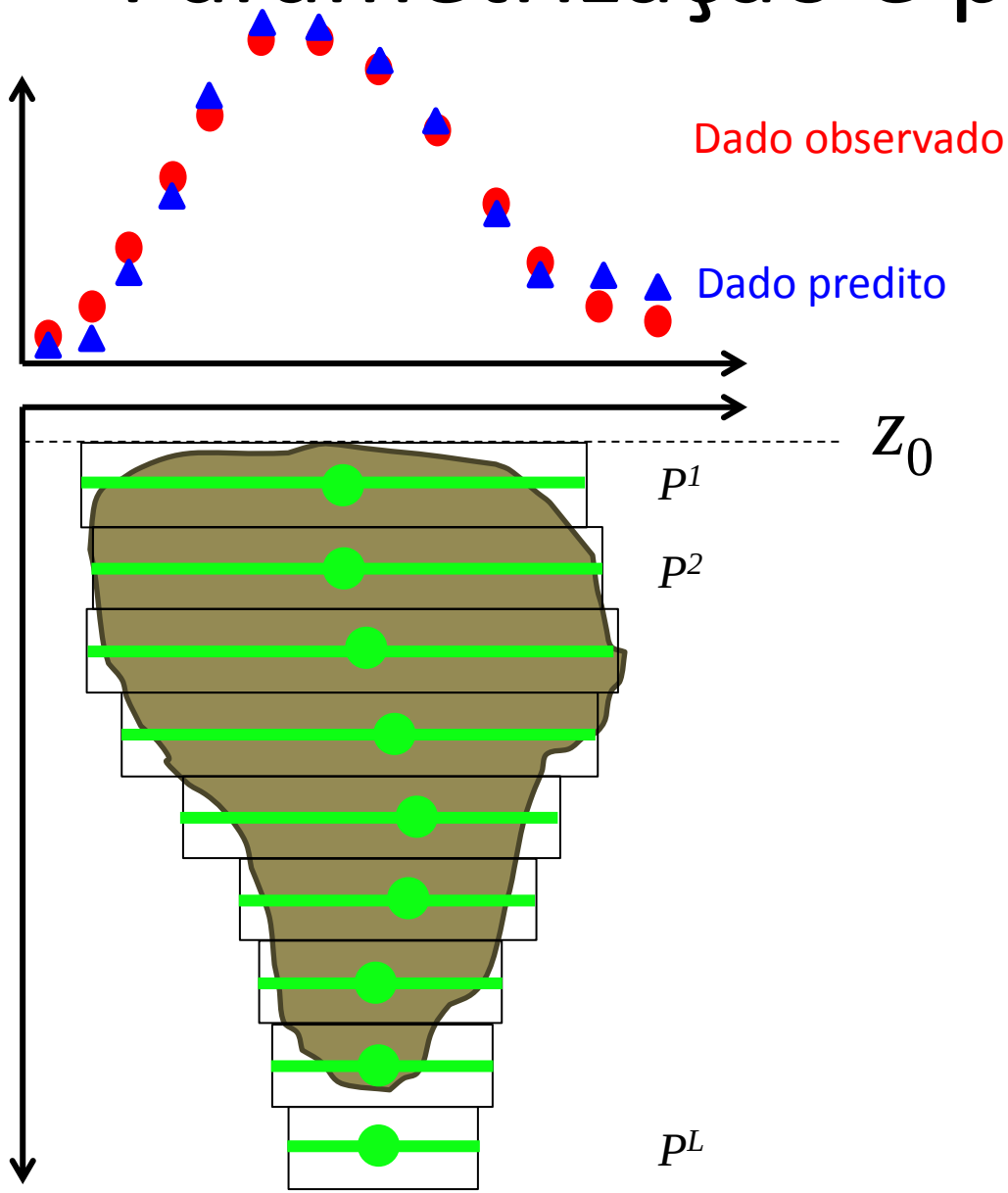


Distâncias radiais e origem de cada um dos prismas

Parametrização e problema inverso

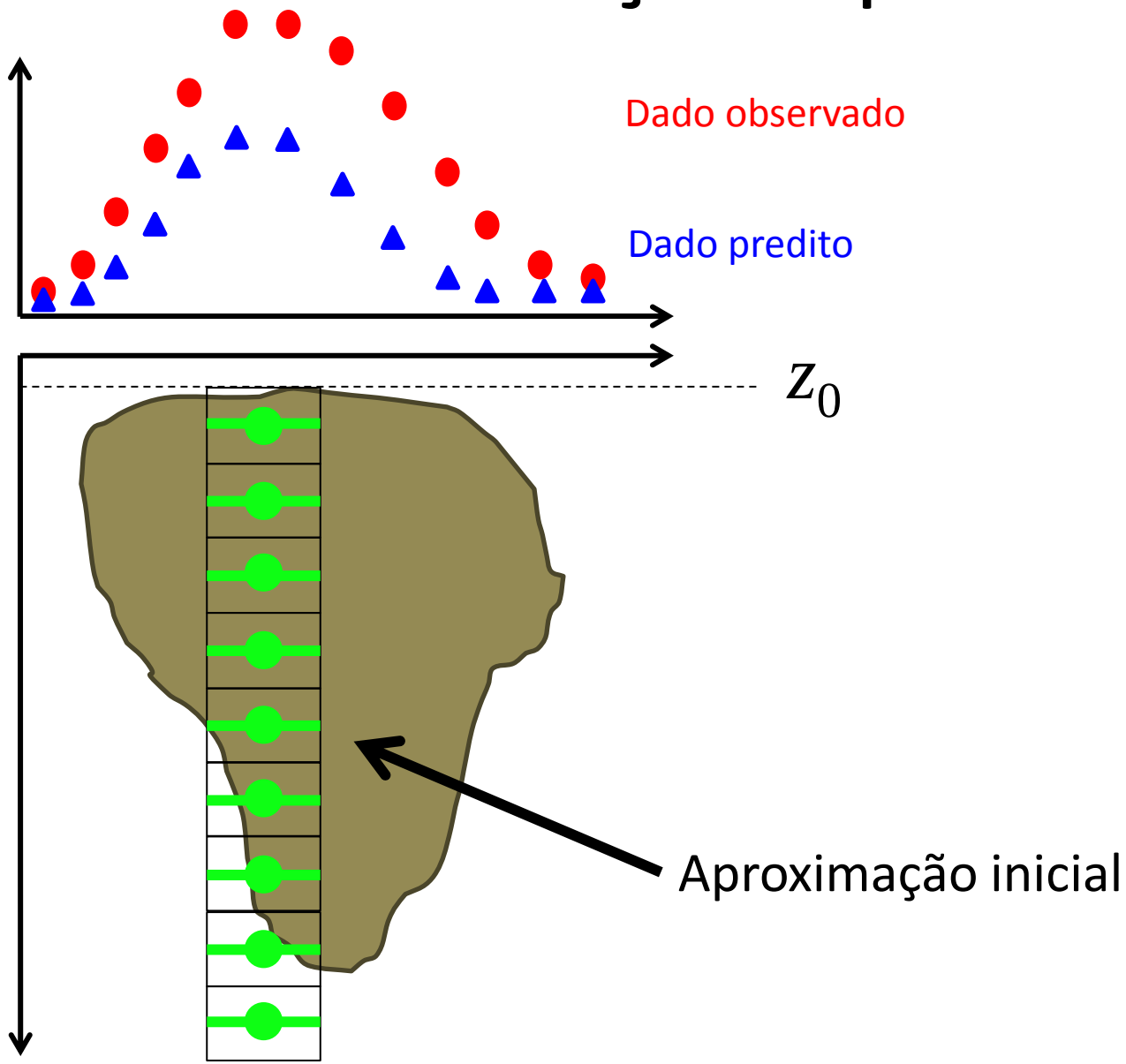


Parametrização e problema inverso



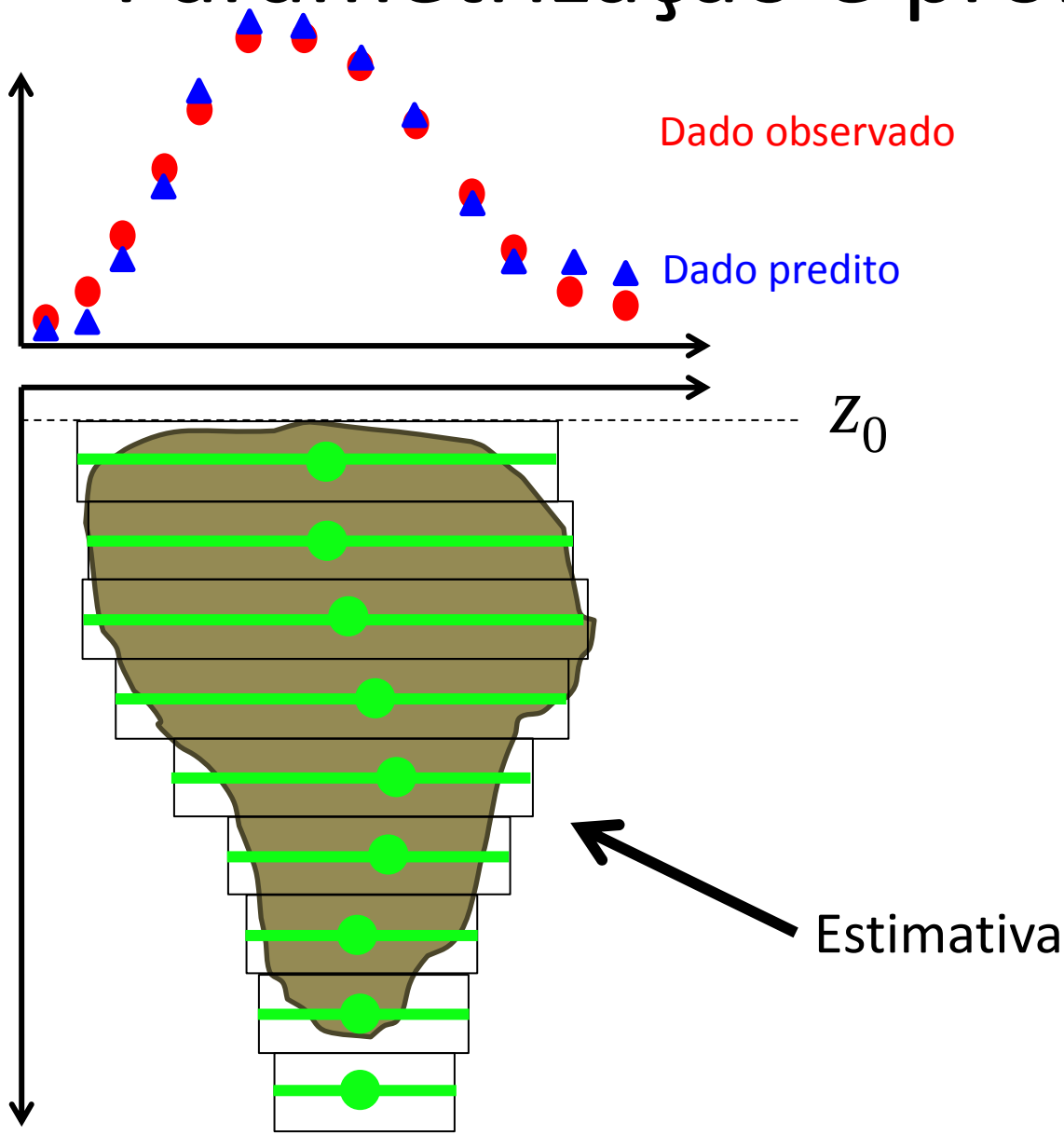
Problema não-linear

Parametrização e problema inverso



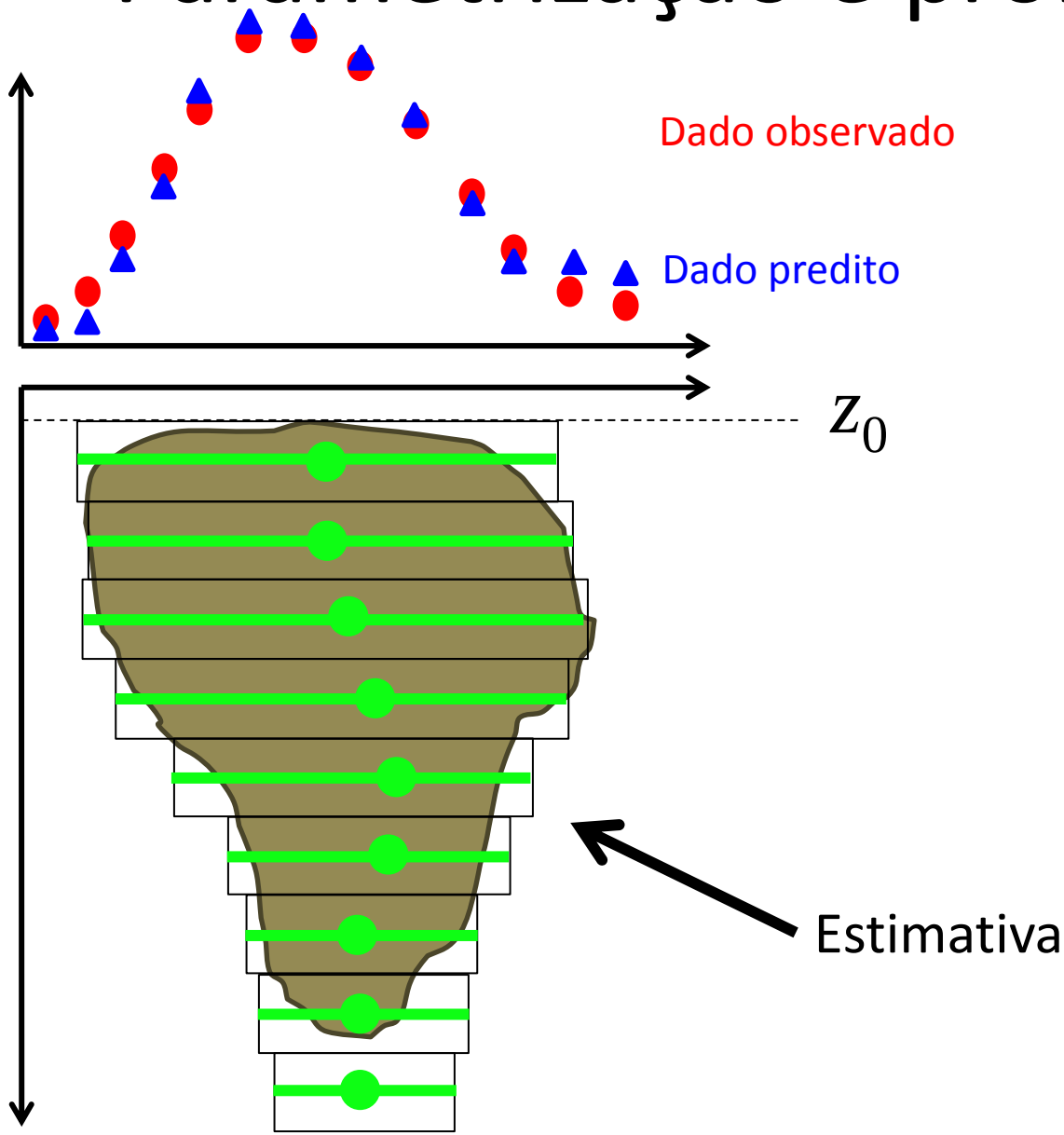
Problema não-linear

Parametrização e problema inverso



Problema não-linear

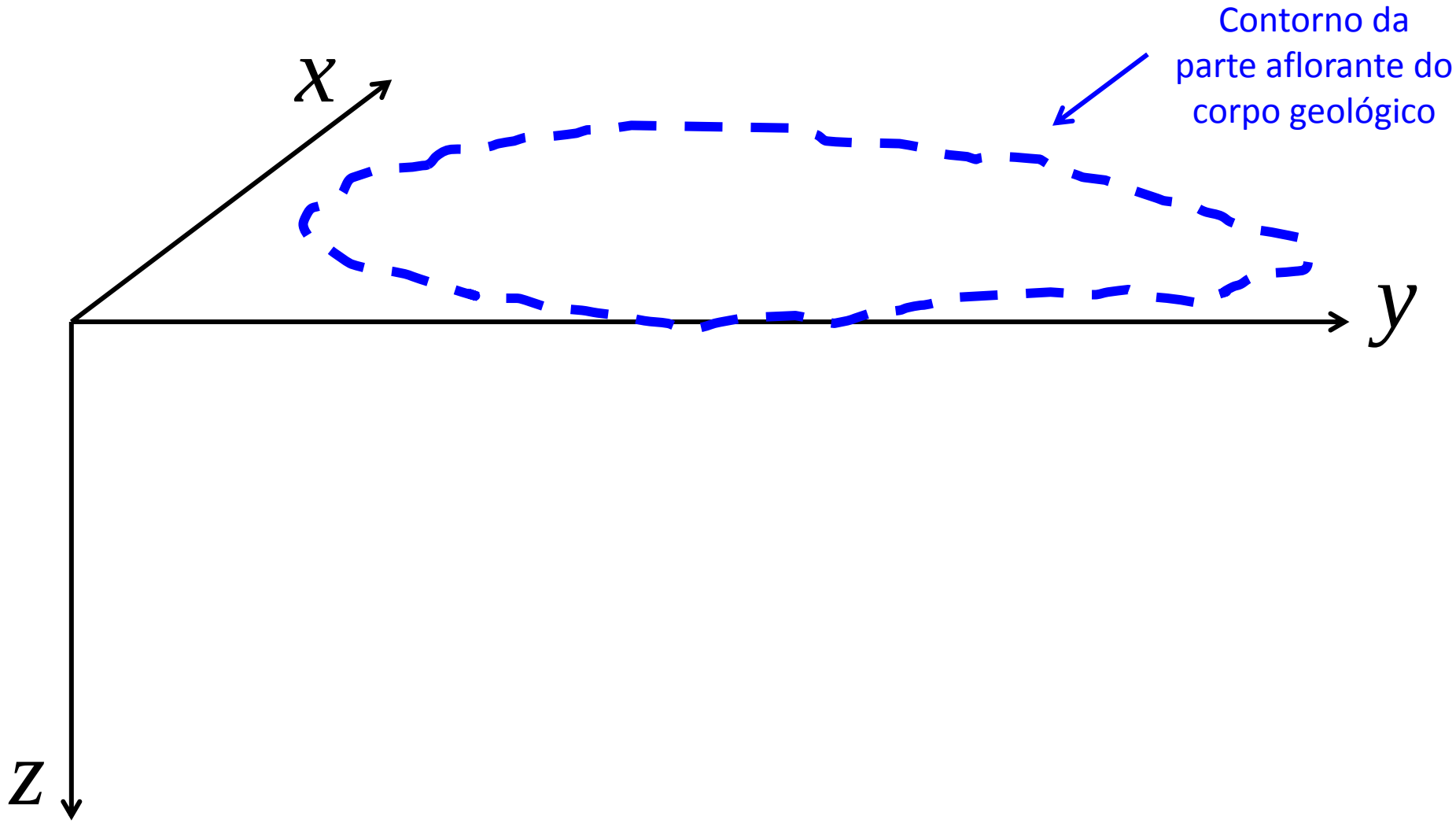
Parametrização e problema inverso



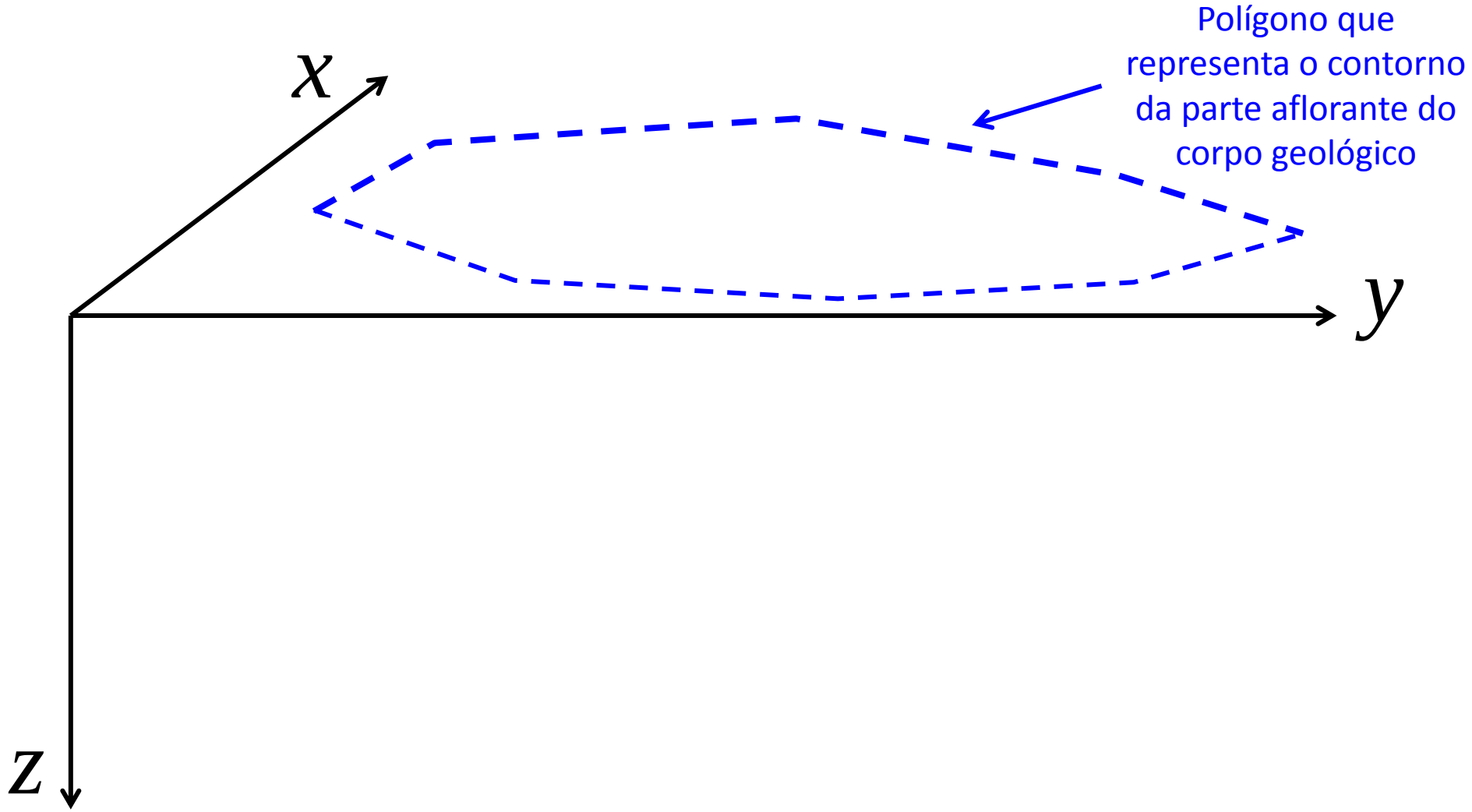
Problema
não-linear
e mal-posto

Regularização
(Vínculos)

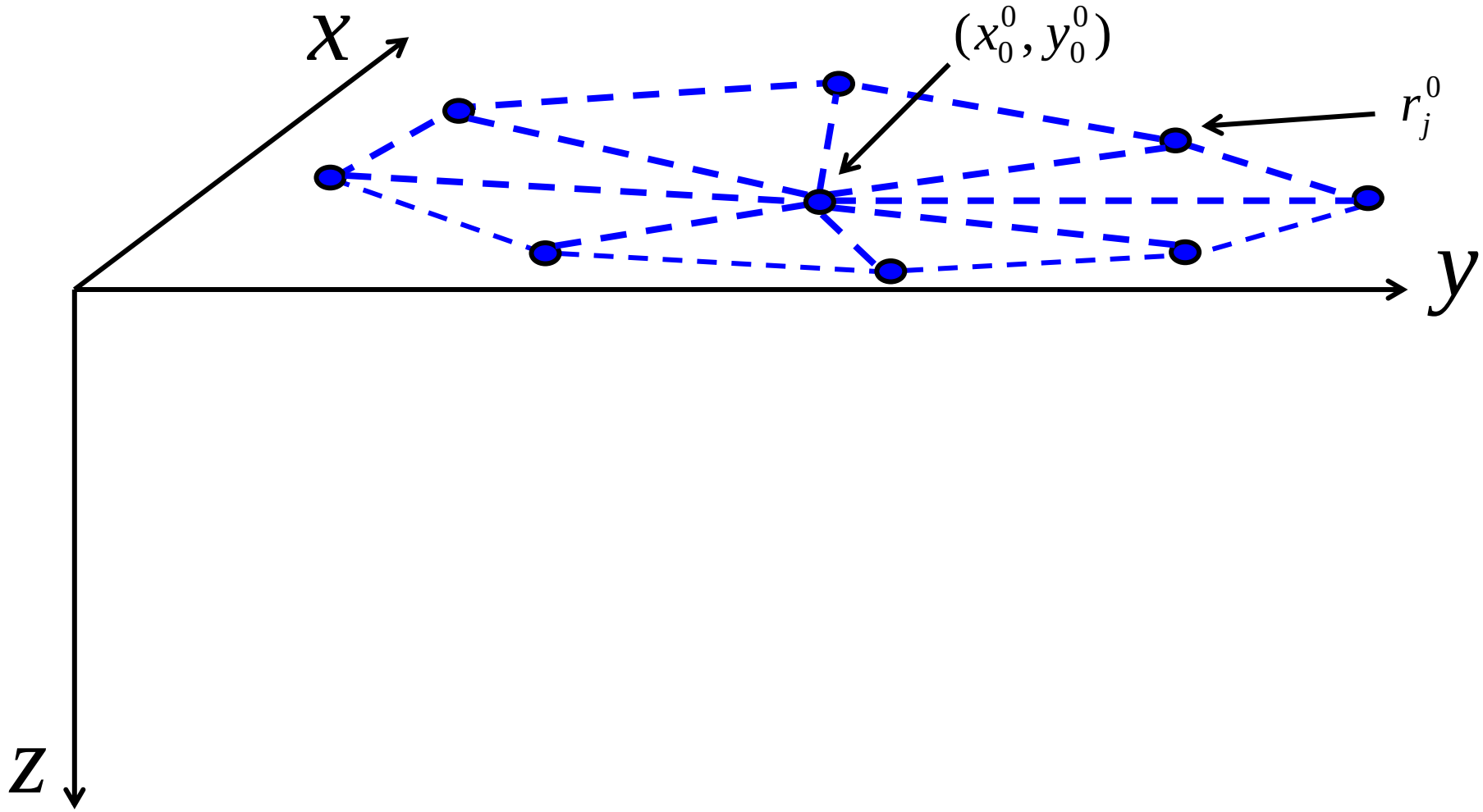
Parametrização e problema inverso



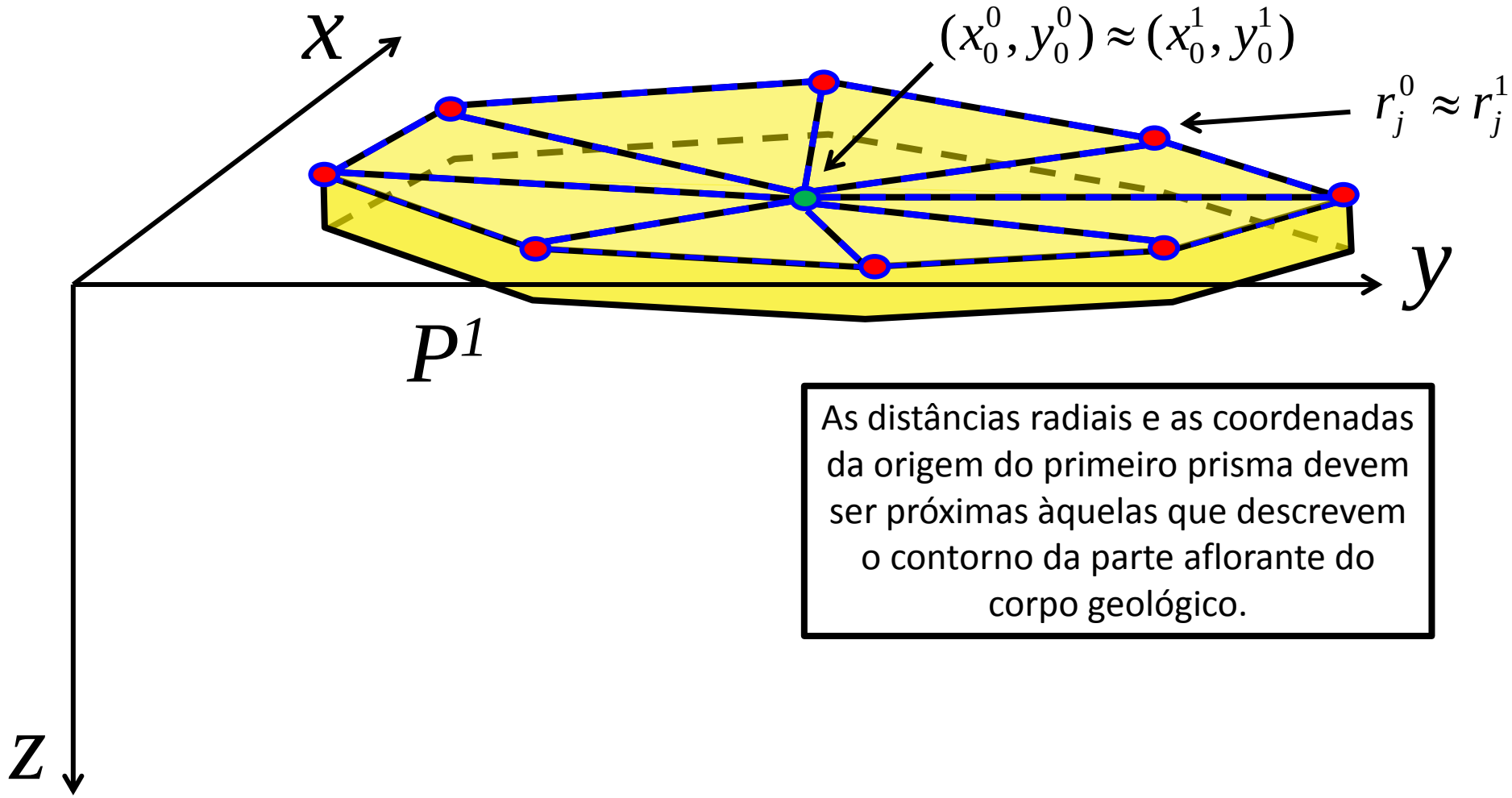
Parametrização e problema inverso



Parametrização e problema inverso

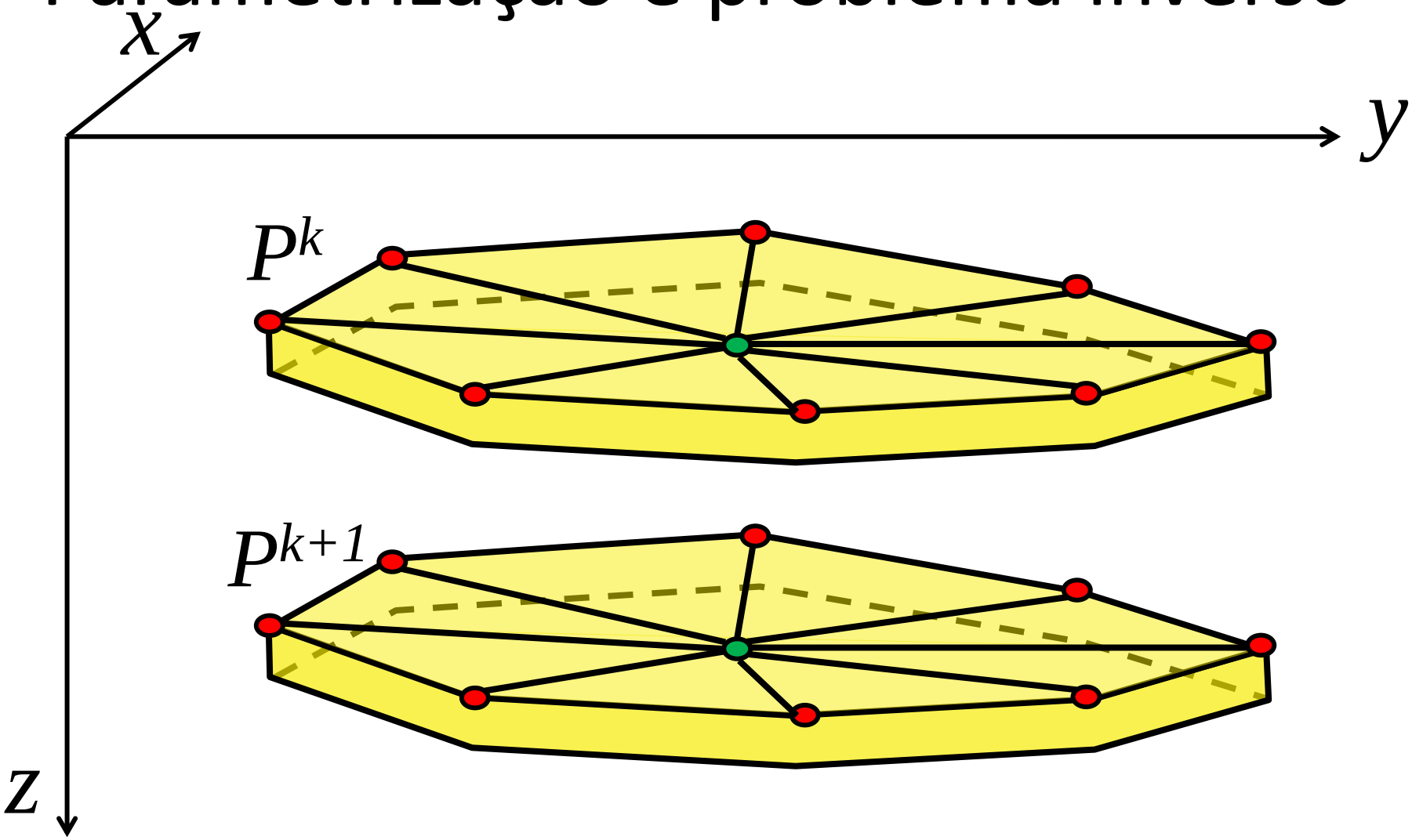


Parametrização e problema inverso

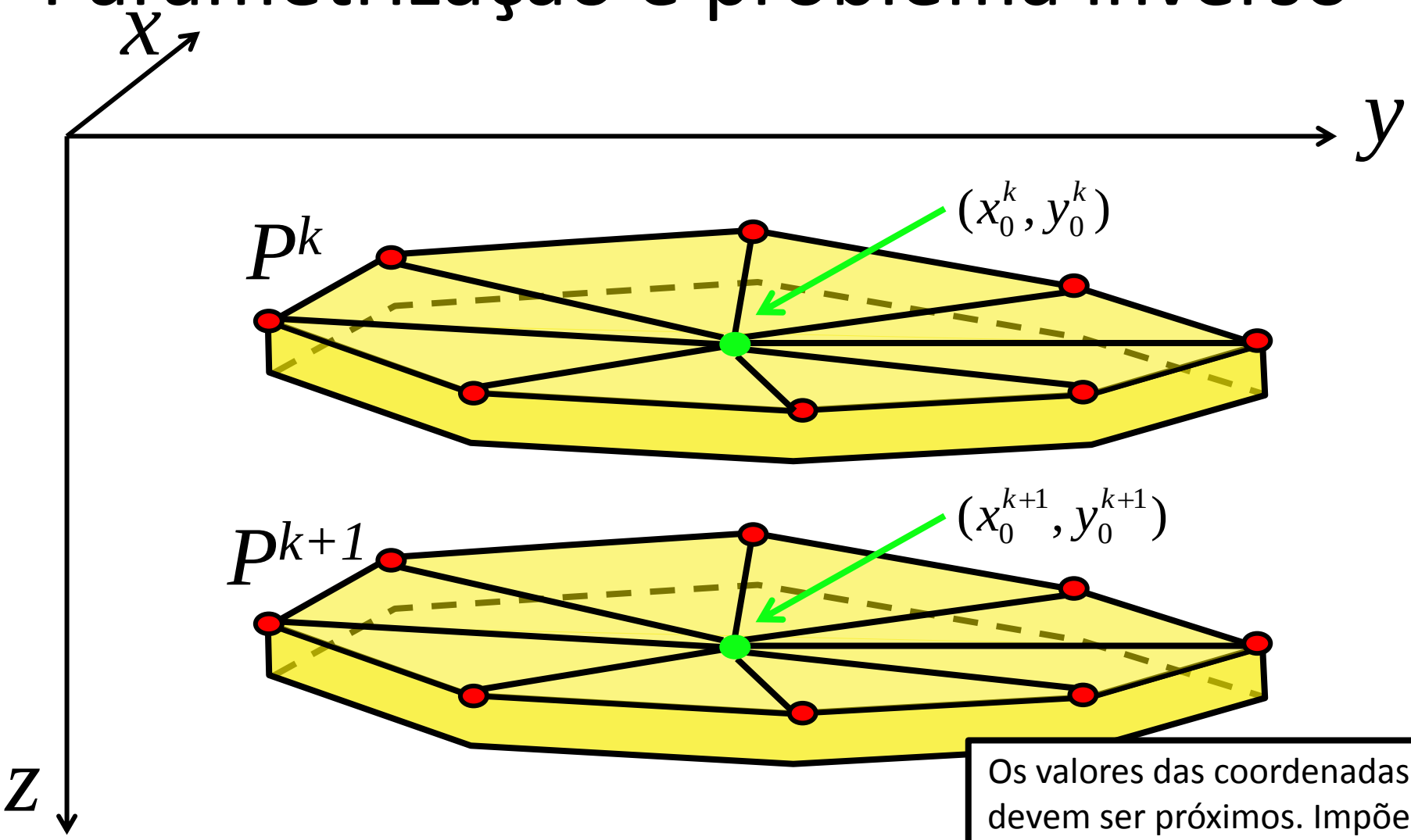


As distâncias radiais e as coordenadas da origem do primeiro prisma devem ser próximas àquelas que descrevem o contorno da parte aflorante do corpo geológico.

Parametrização e problema inverso

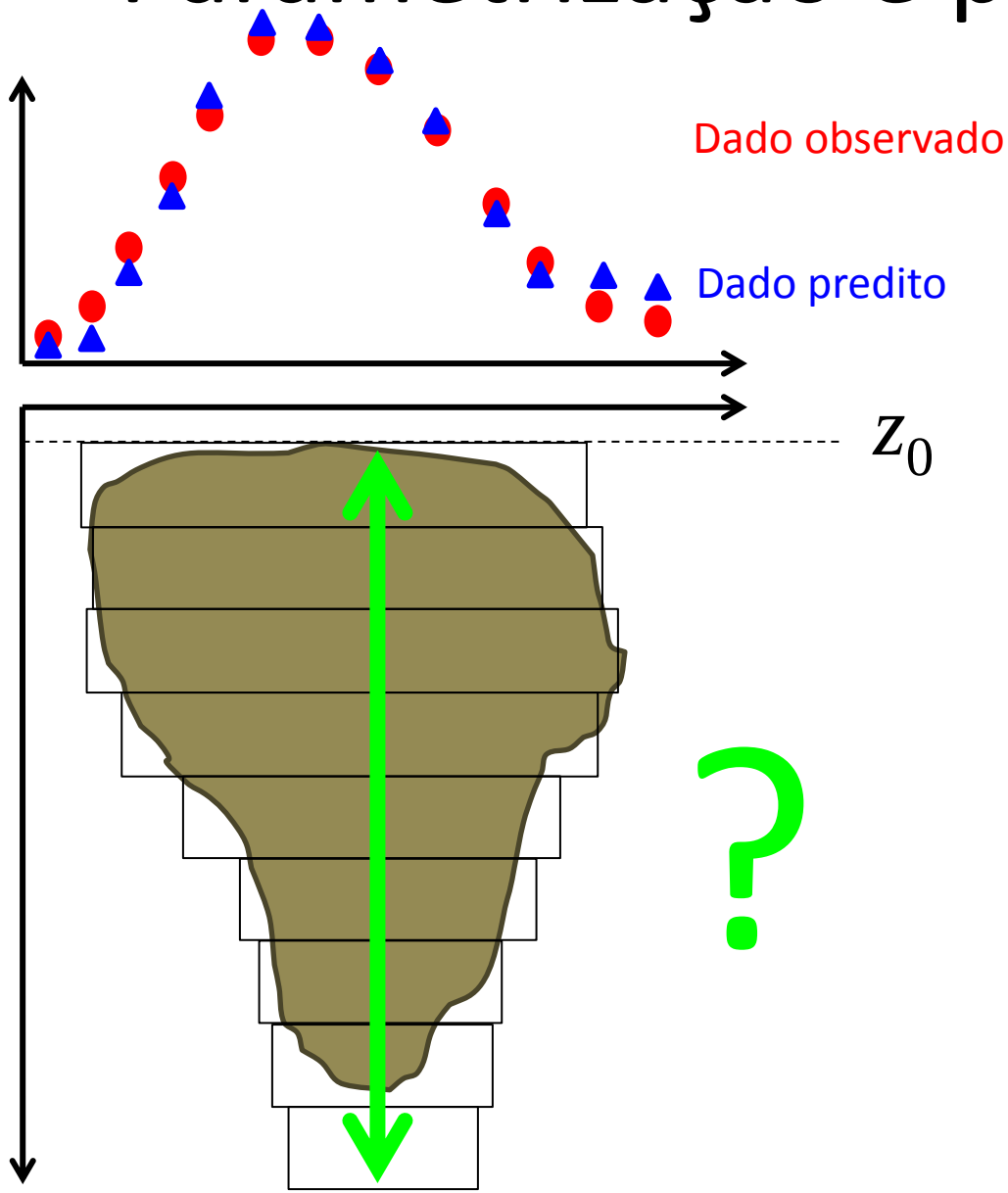


Parametrização e problema inverso



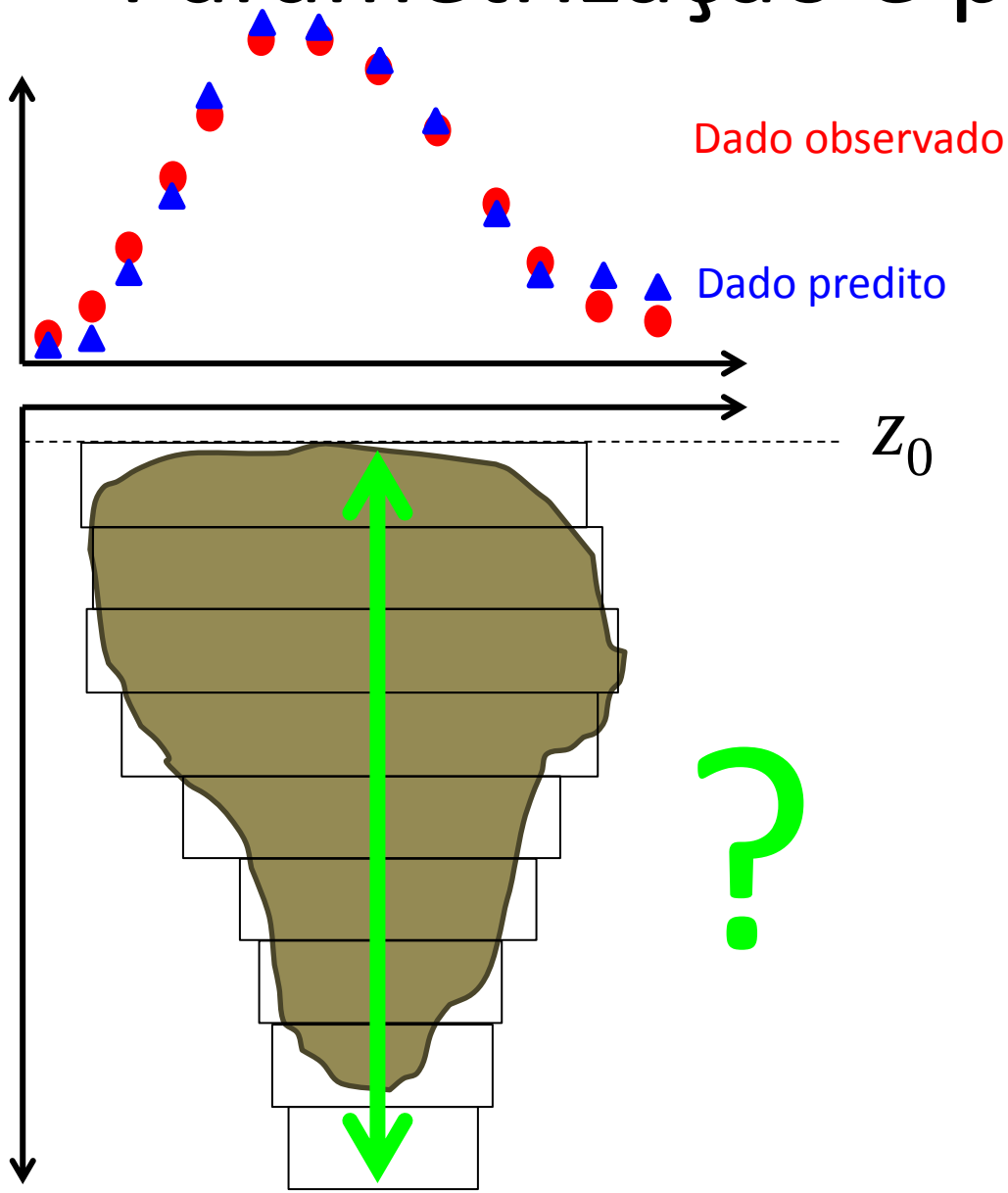
Os valores das coordenadas devem ser próximos. Impõe que a estimativa seja vertical.

Parametrização e problema inverso



Qual a profundidade ótima para o modelo interpretativo?

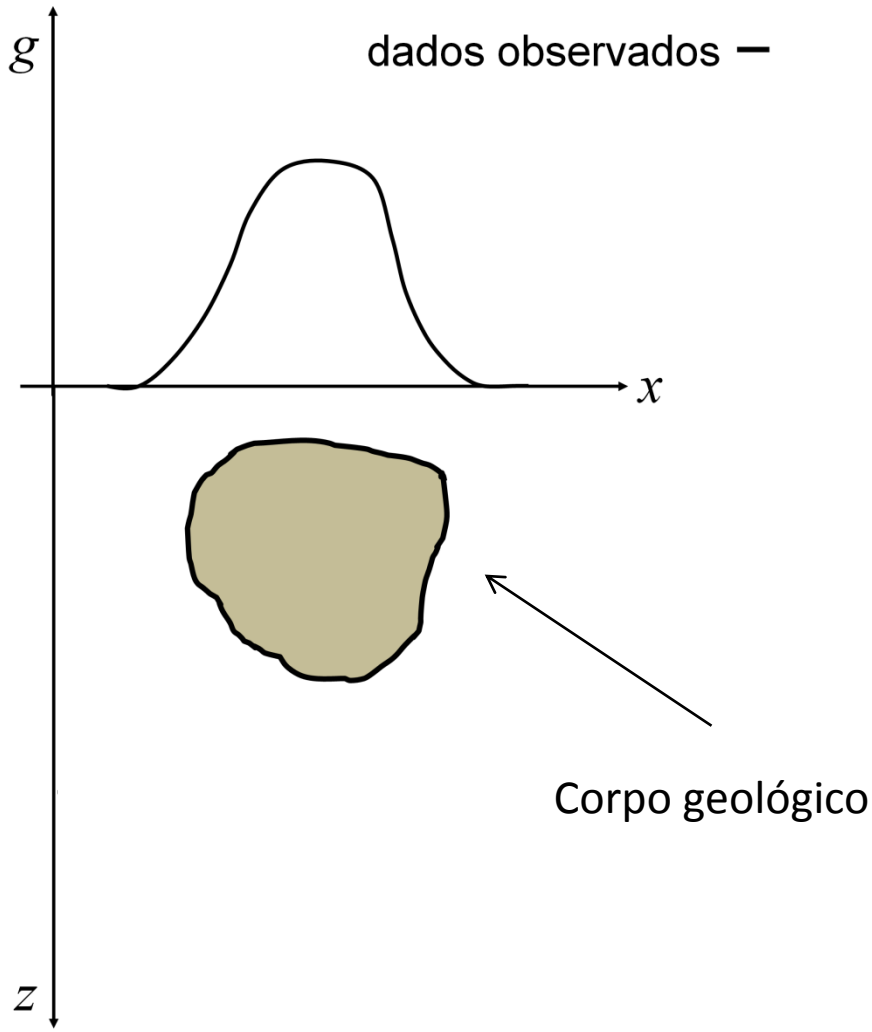
Parametrização e problema inverso



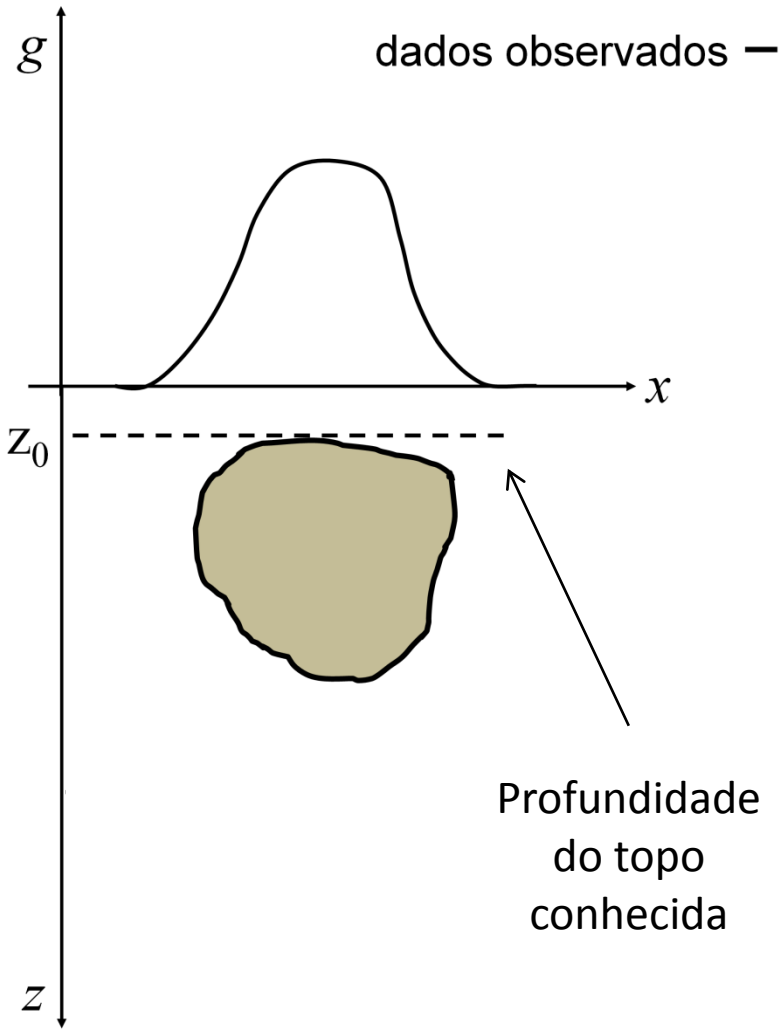
A *profundidade ótima* para o modelo interpretativo pode ser estimada por meio da relação entre o *volume* v *da estimativa* e a *norma L1 dos resíduos* s

Curva v x s

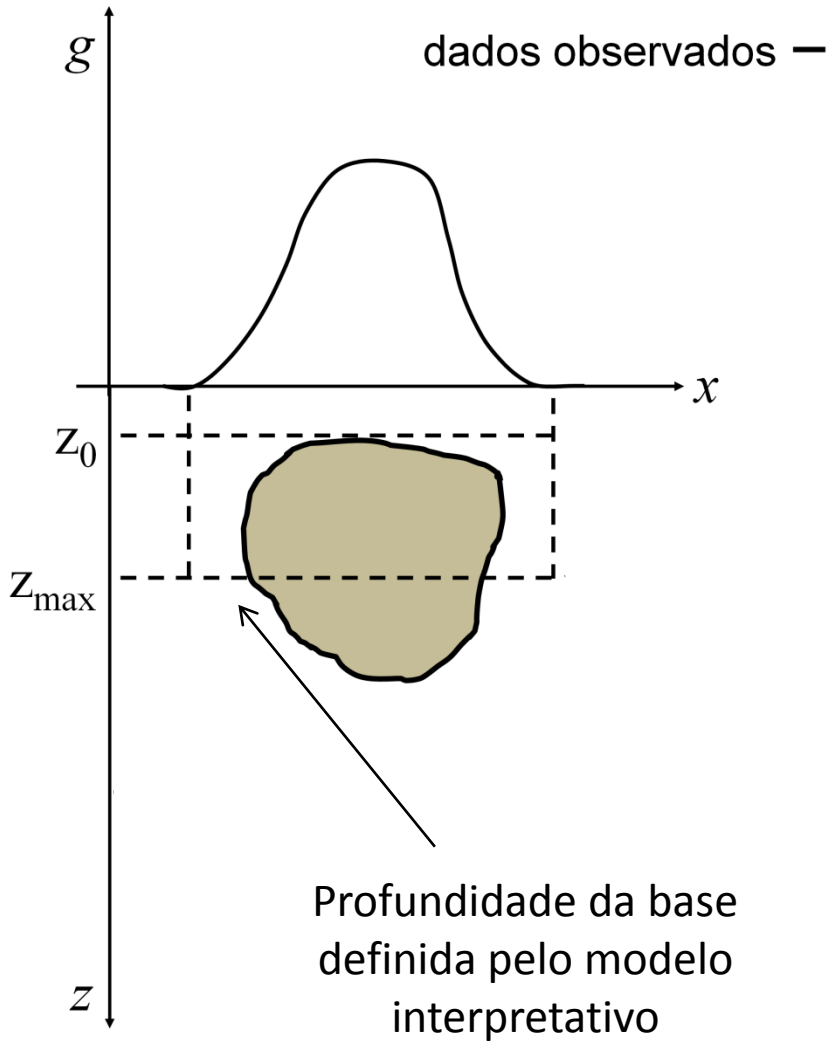
Curva v x s



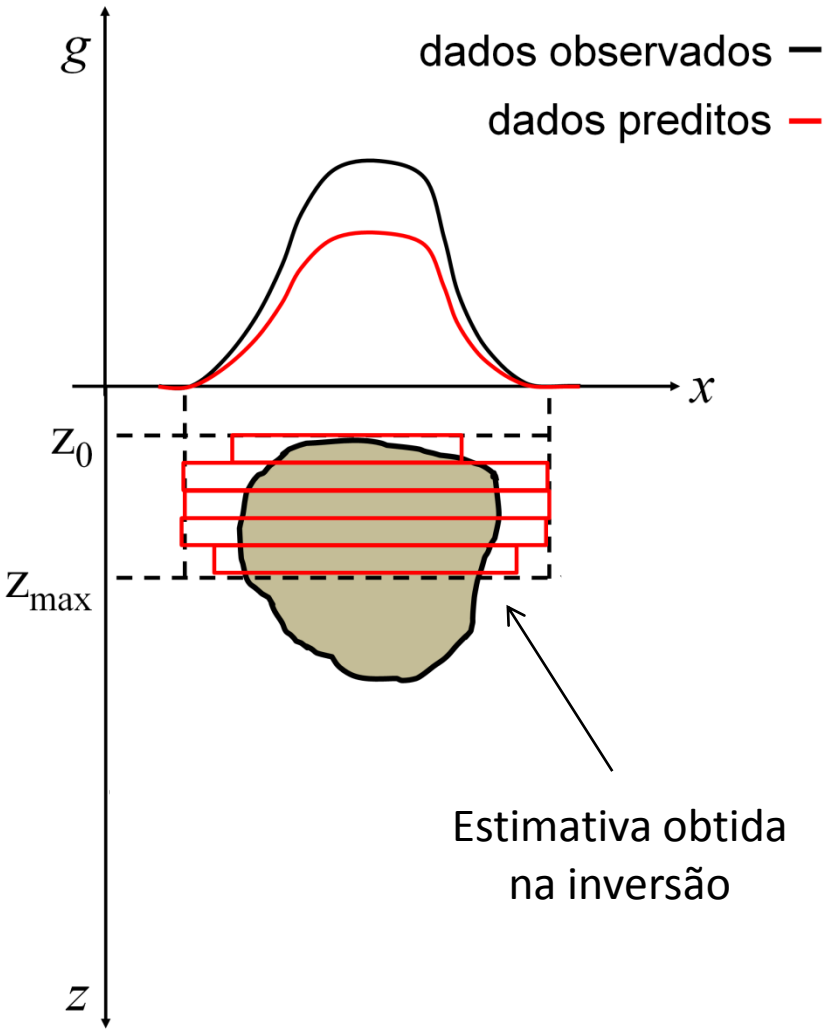
Curva v x s



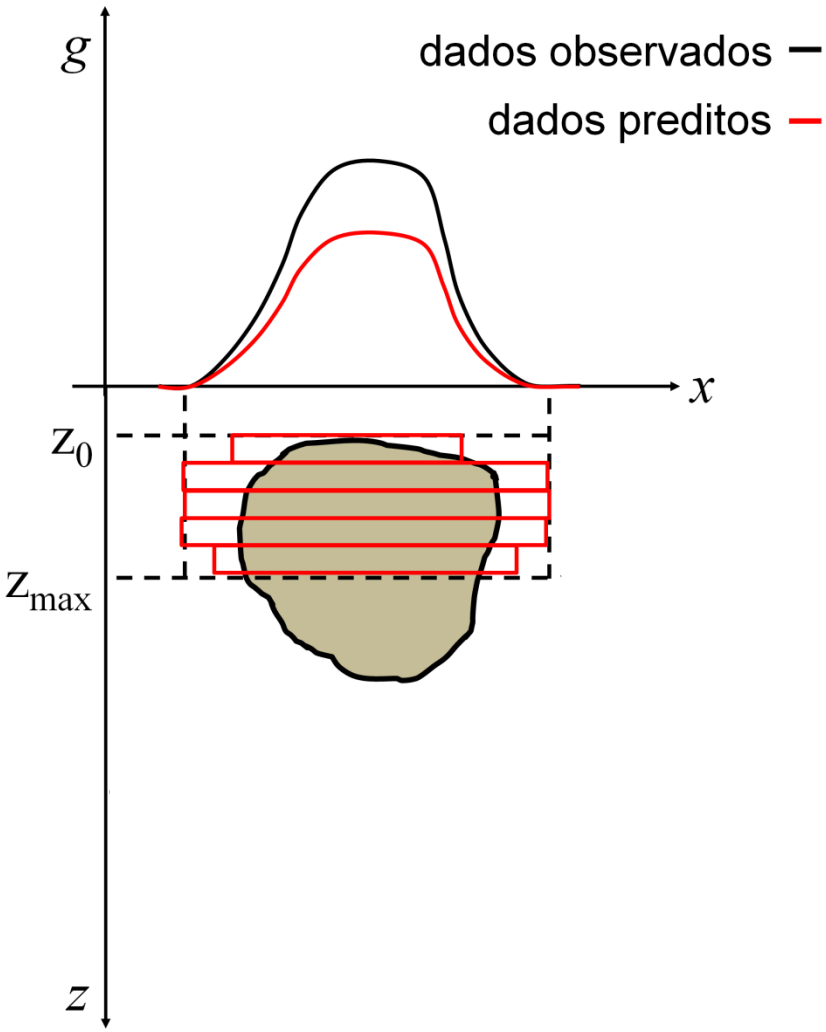
Curva v x s

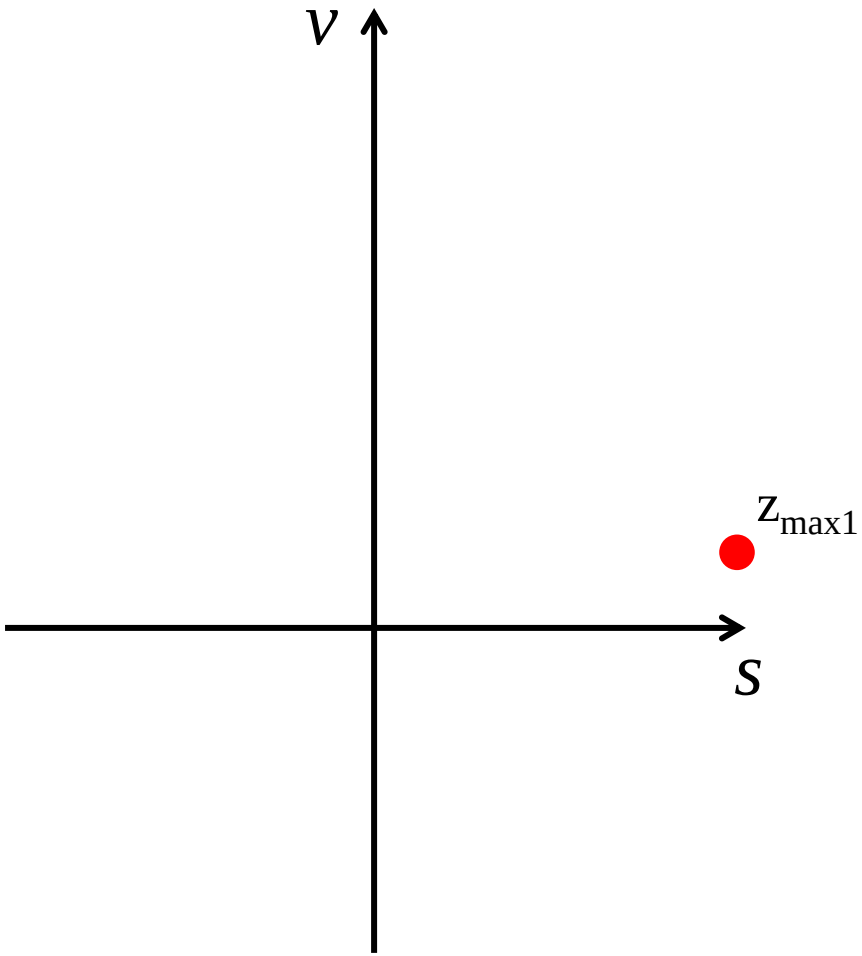

g
dados observados
x
z0
zmax
z
Profundidade da base
definida pelo modelo
interpretativo

Curva v x s

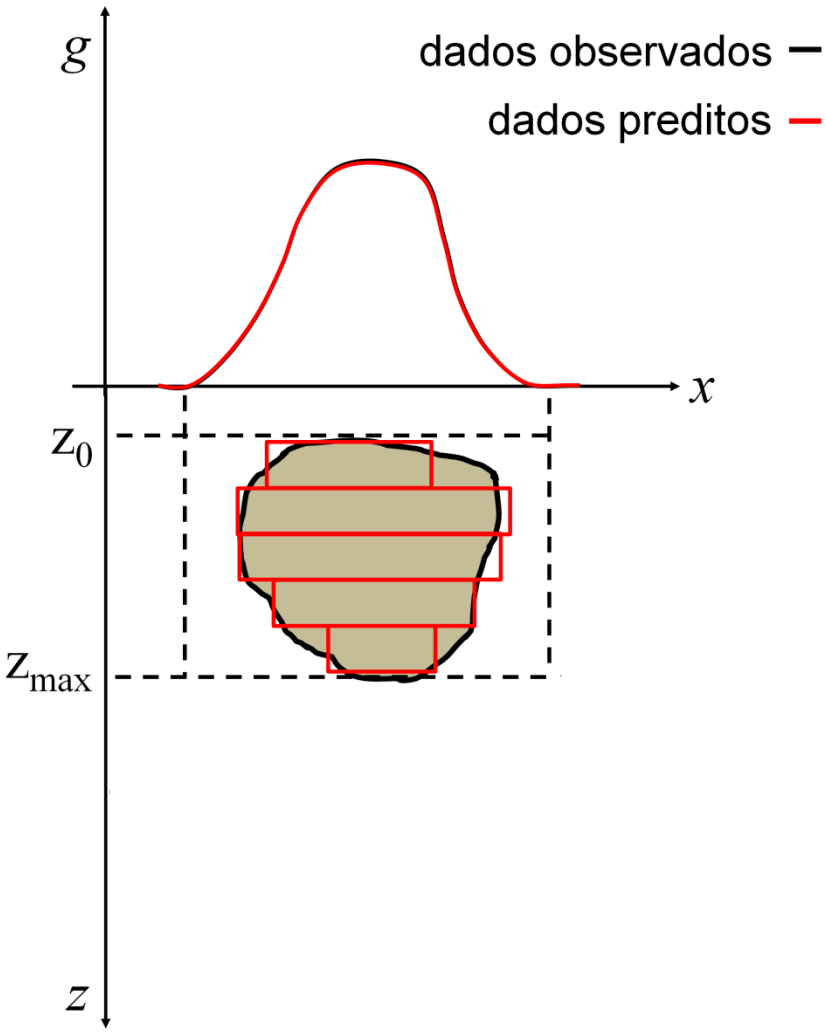

g
dados observados
dados preditos
x
z0
zmax
z
Estimativa obtida
na inversão

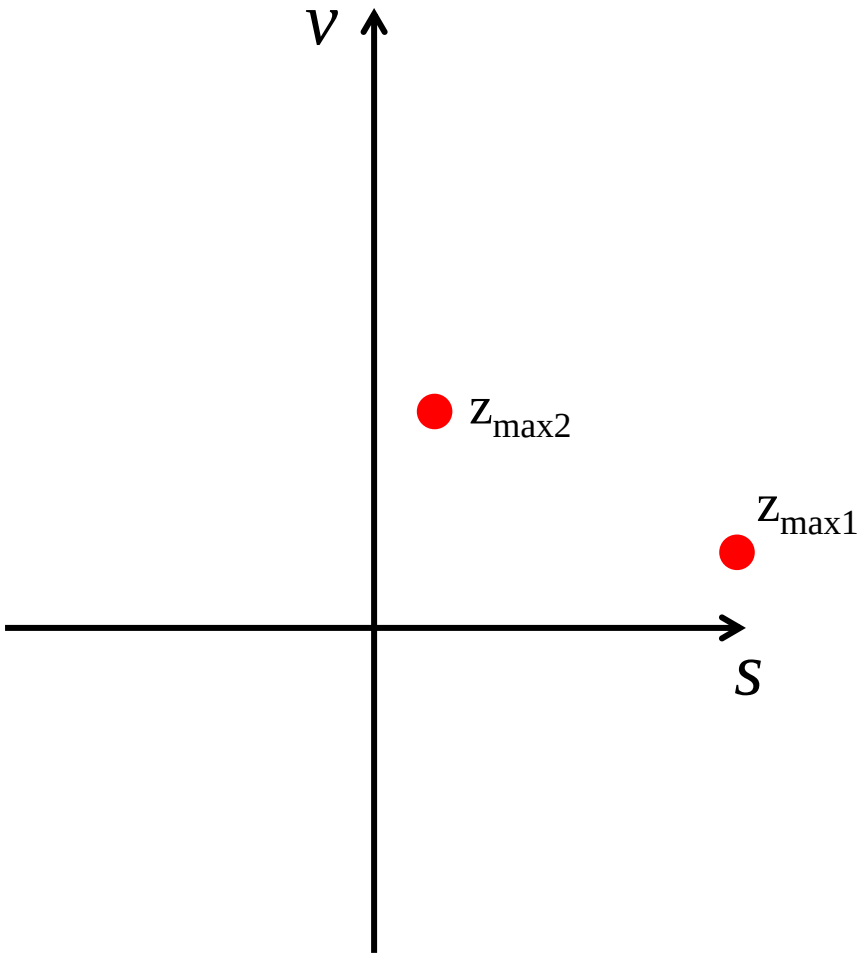
Curva v x s



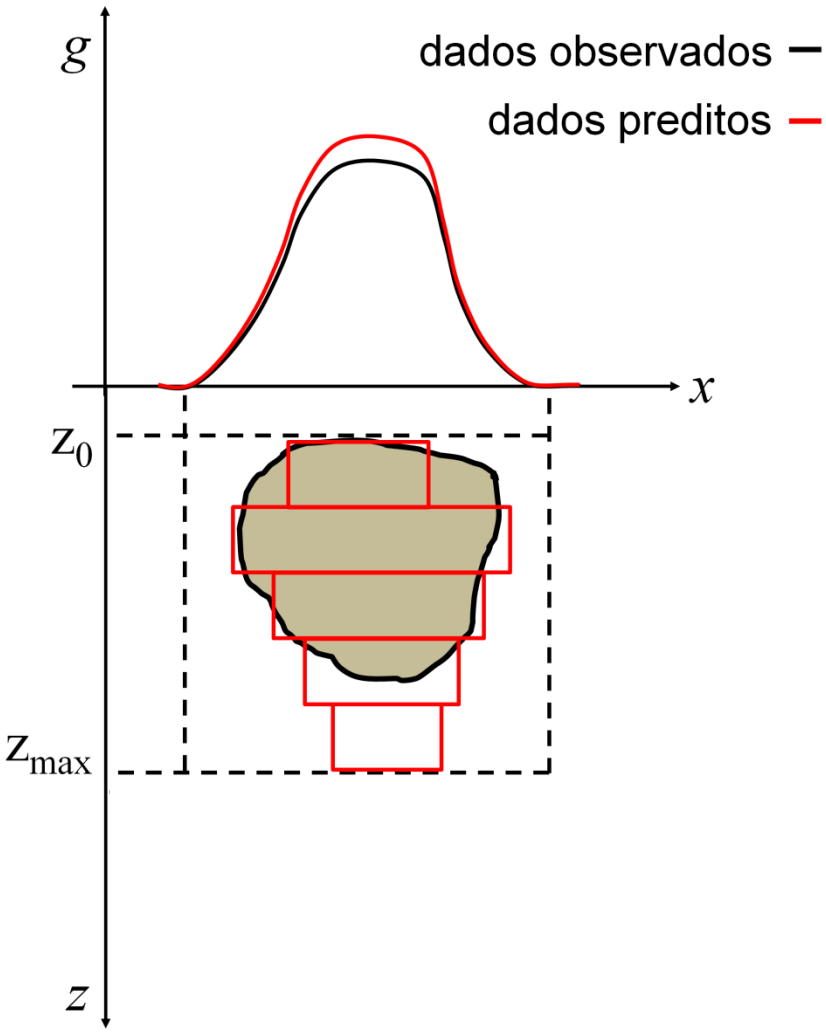


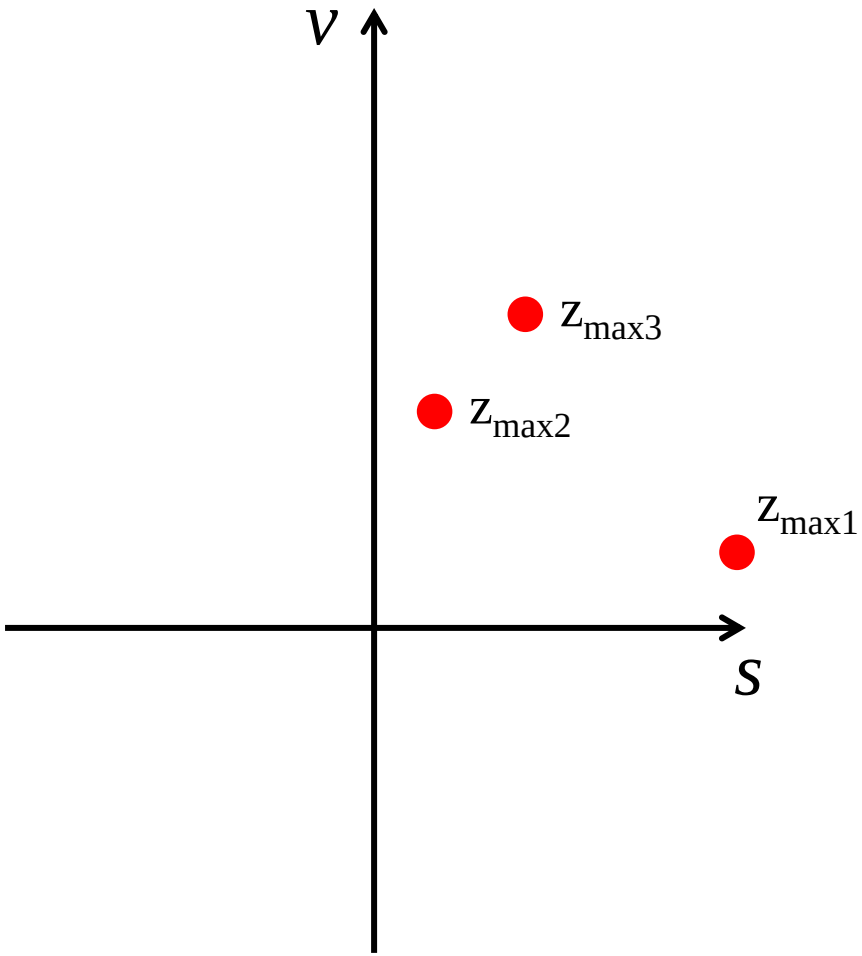
Curva *v* x *s*



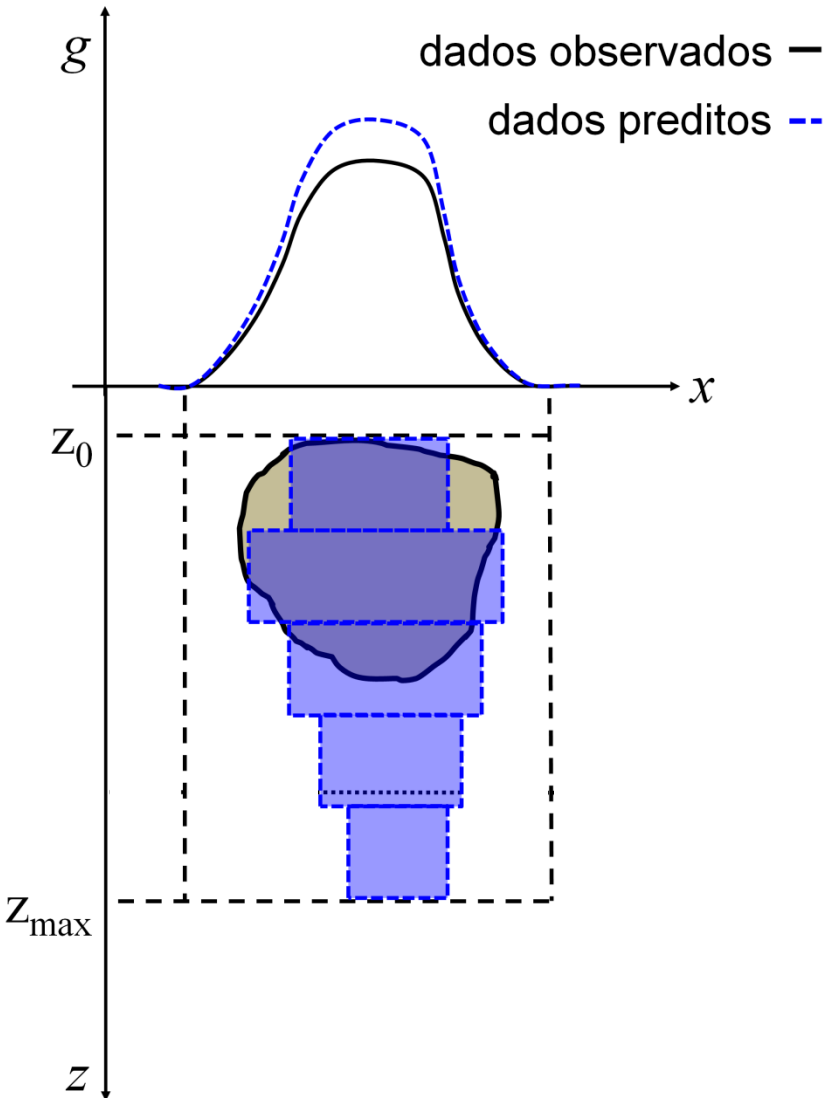


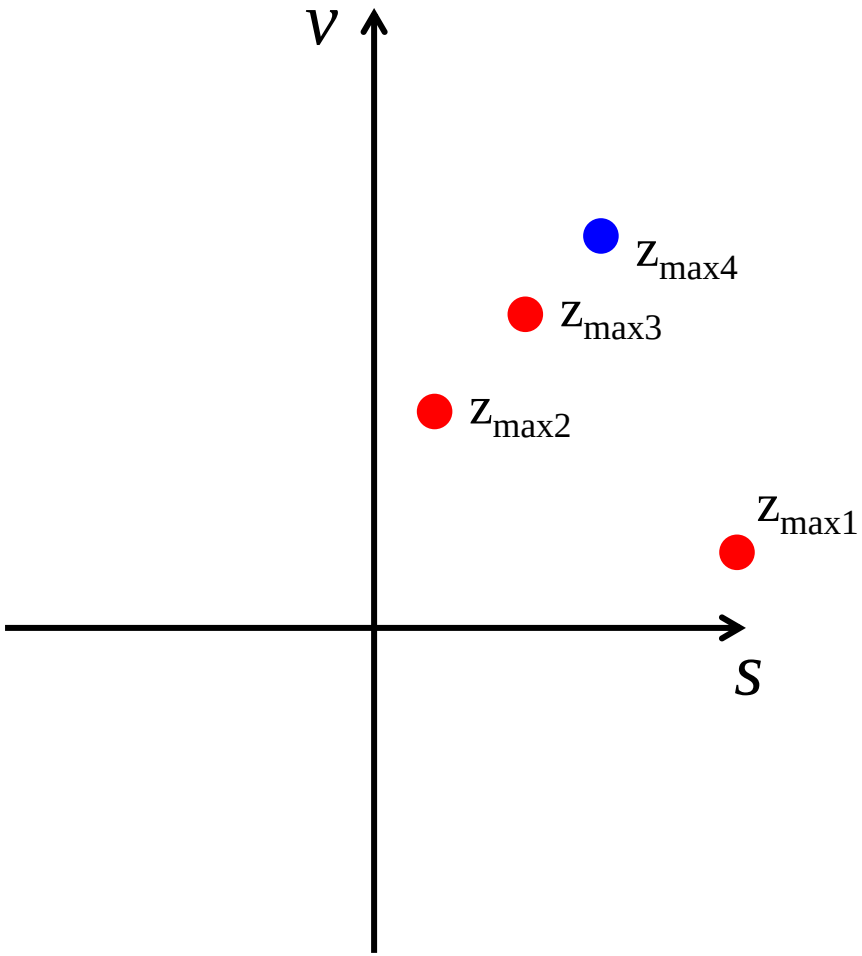
Curva *v* x *s*


g
dados observados
dados preditos
x
z0
zmax
z

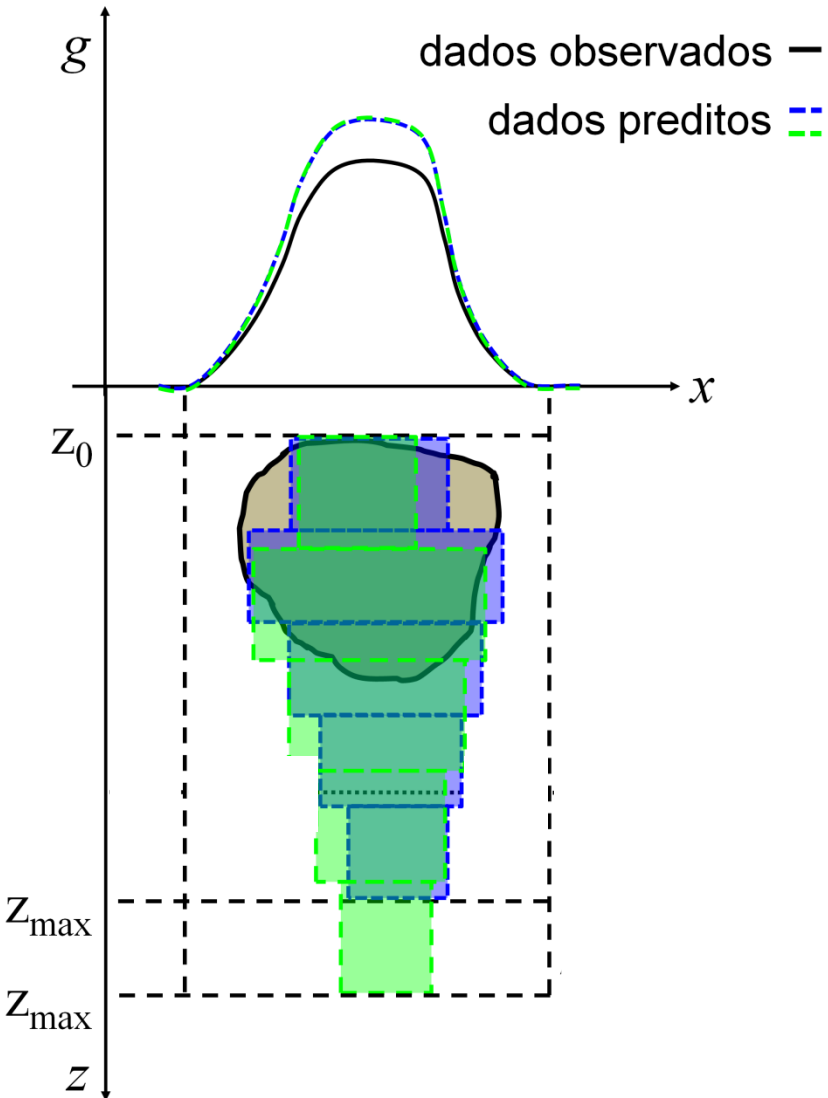

v
zmax3
zmax2
zmax1
s

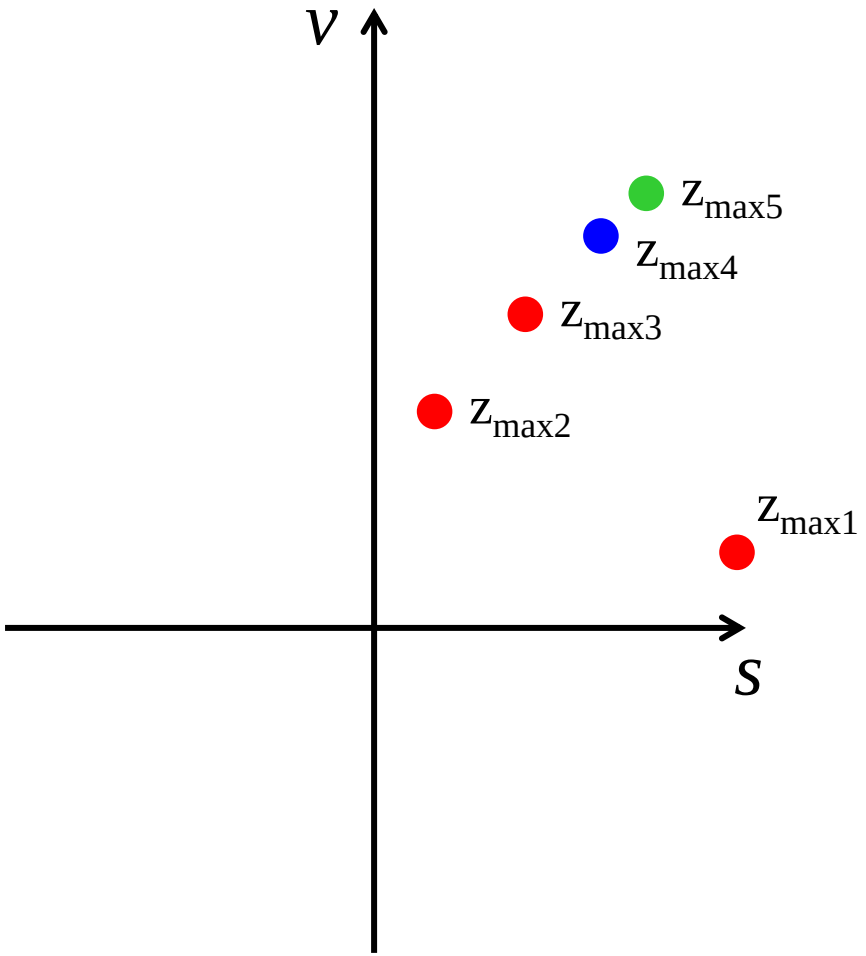
Curva *v* x *s*


g
dados observados
dados preditos
x
z0
zmax
z

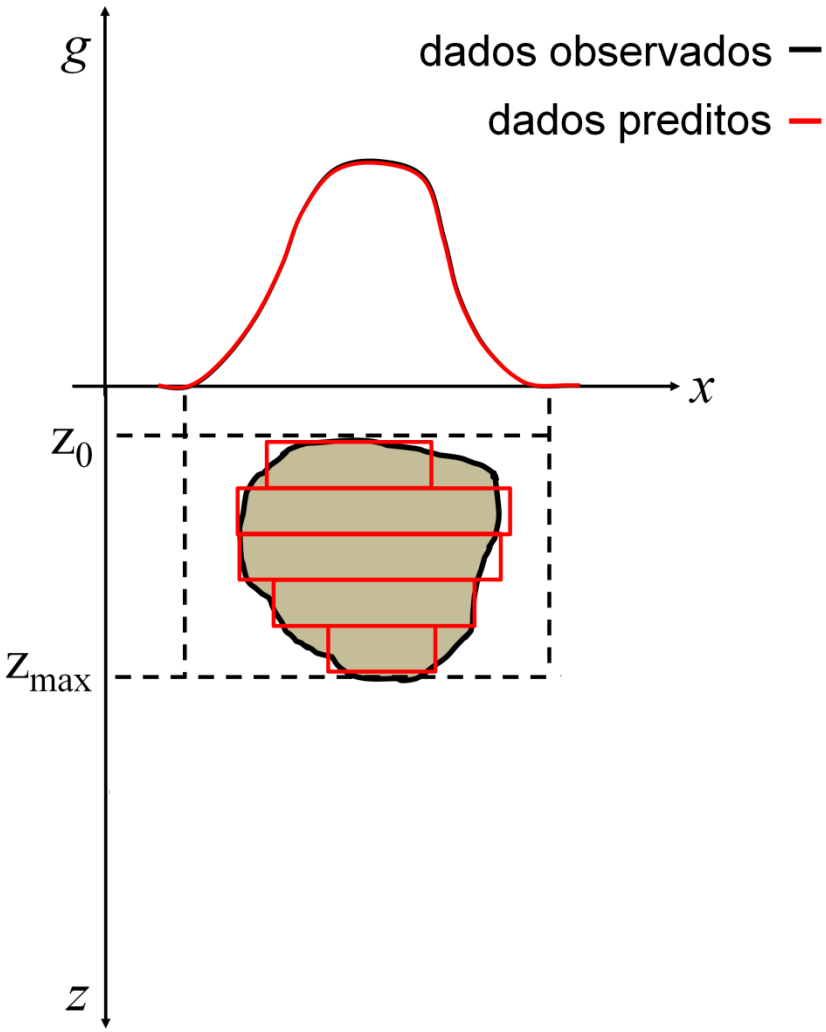

v
zmax4
zmax3
zmax2
zmax1
s

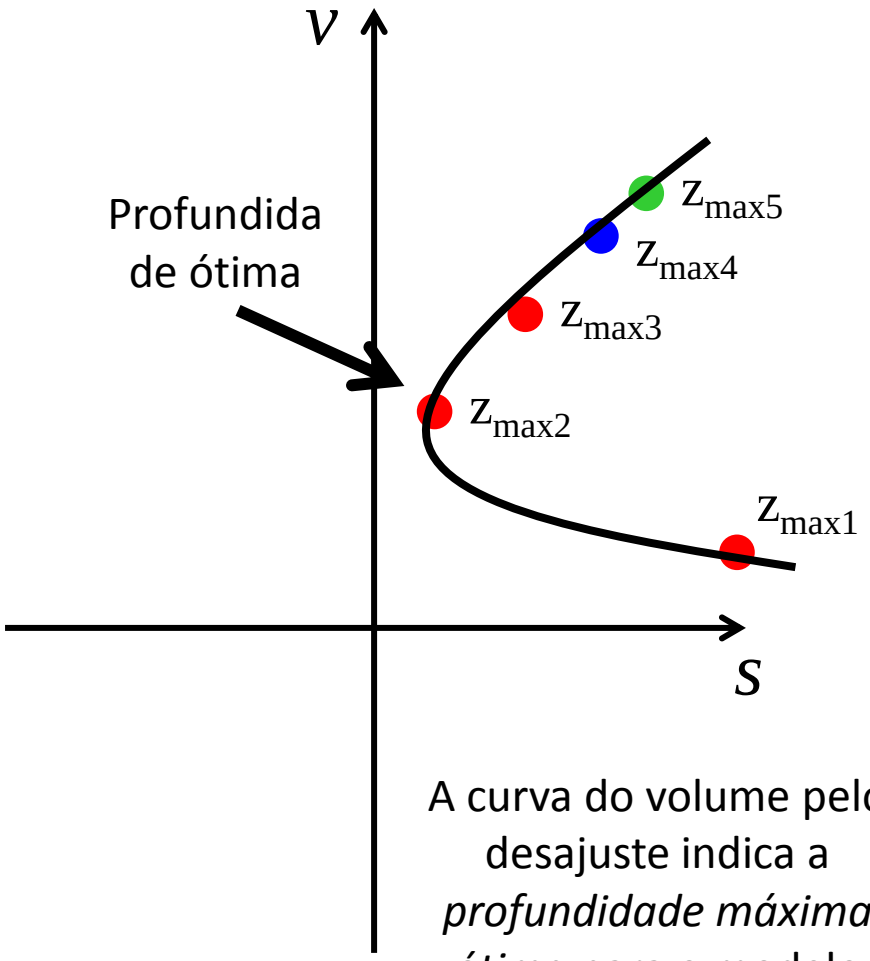
Curva *v* x *s*


g
dados observados
dados preditos
x
z0
zmax
zmax
z


v
zmax5
zmax4
zmax3
zmax2
zmax1
s

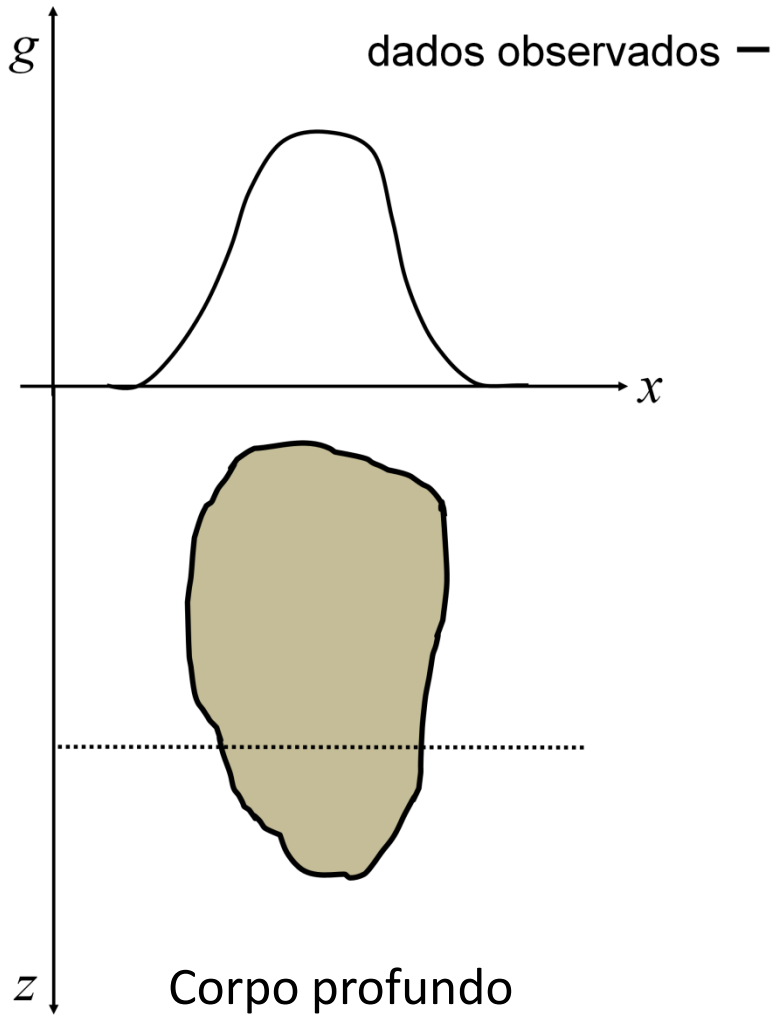
Curva v x s

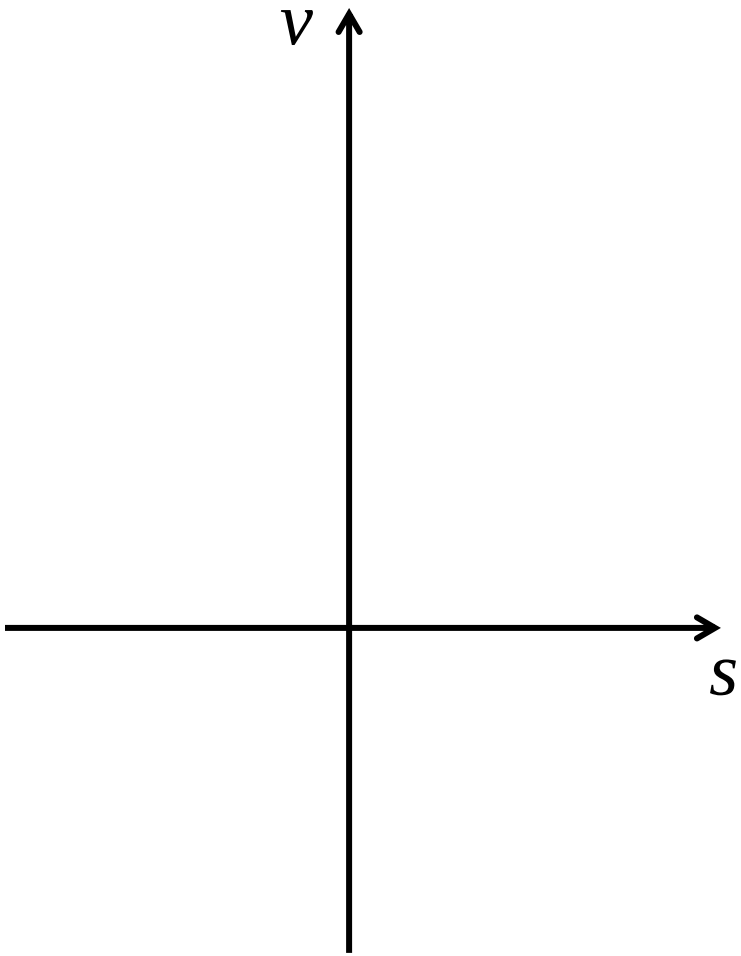




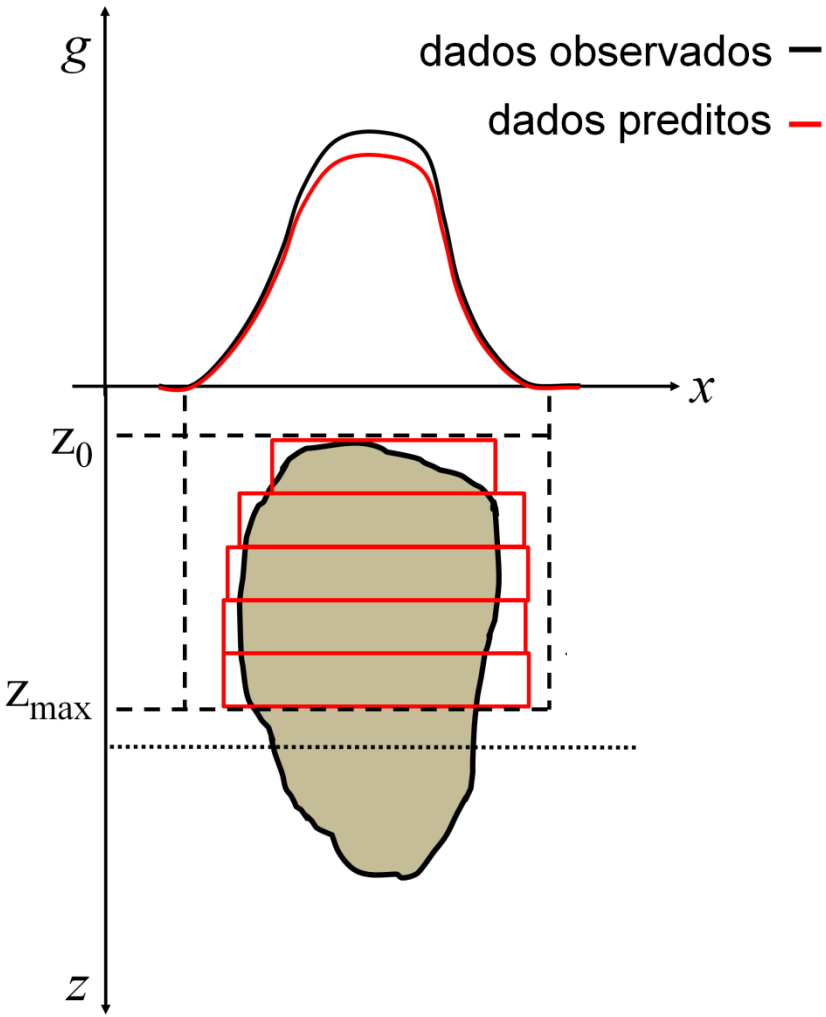
A curva do volume pelo desajuste indica a *profundidade máxima ótima* para o modelo interpretativo

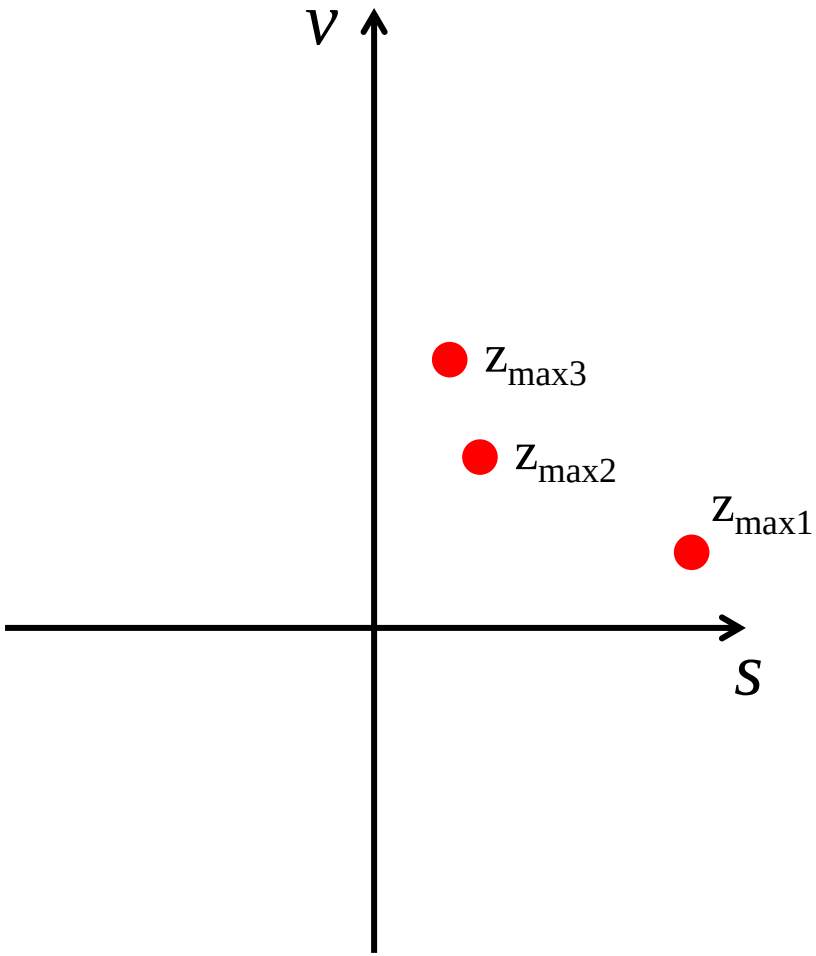
Curva v x s



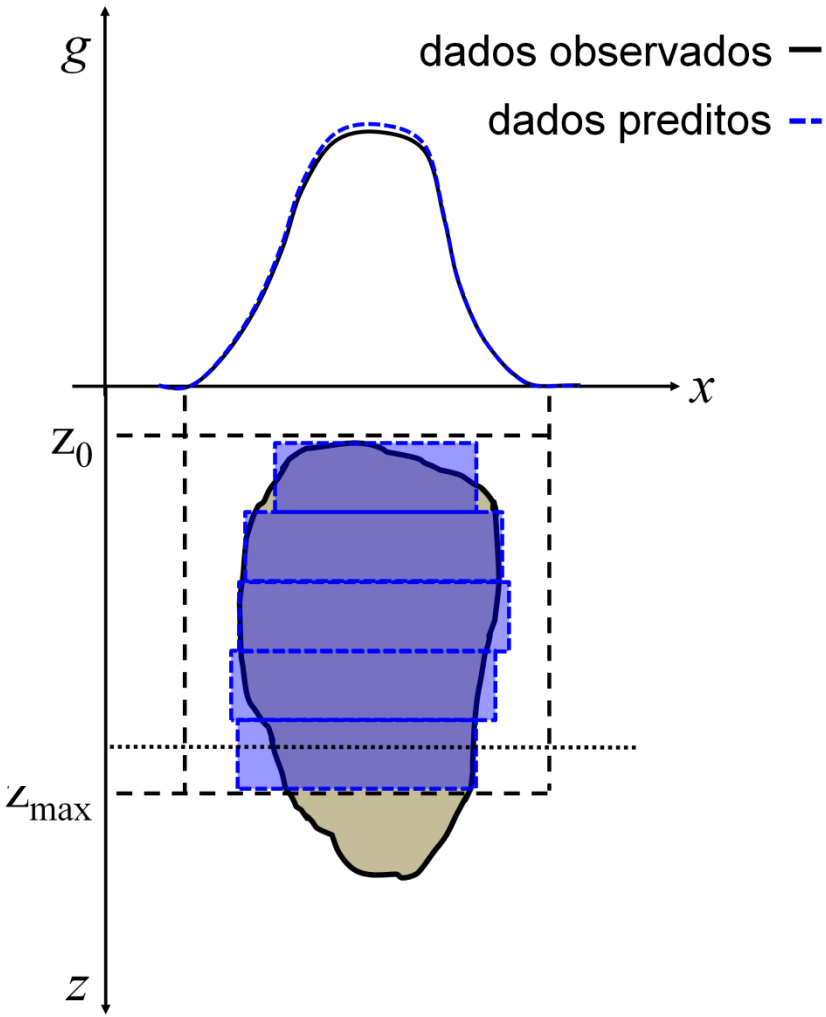


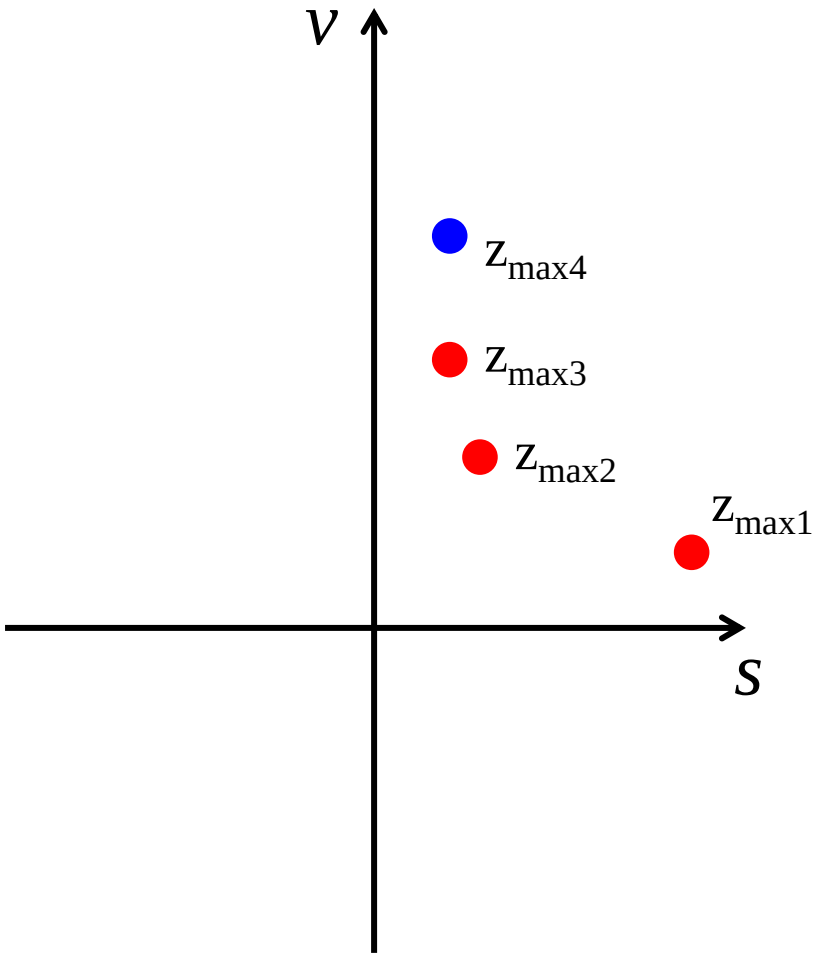
Curva v x s


g
dados observados
dados preditos
x
z0
zmax
z

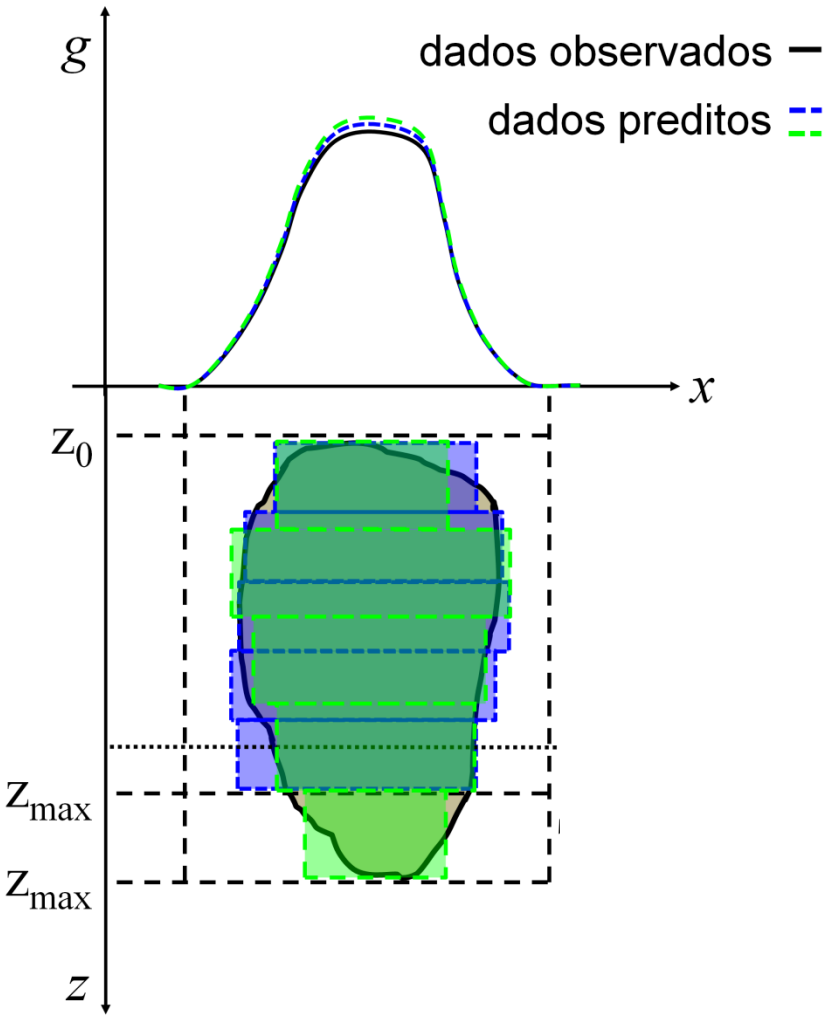

v
zmax3
zmax2
zmax1
s

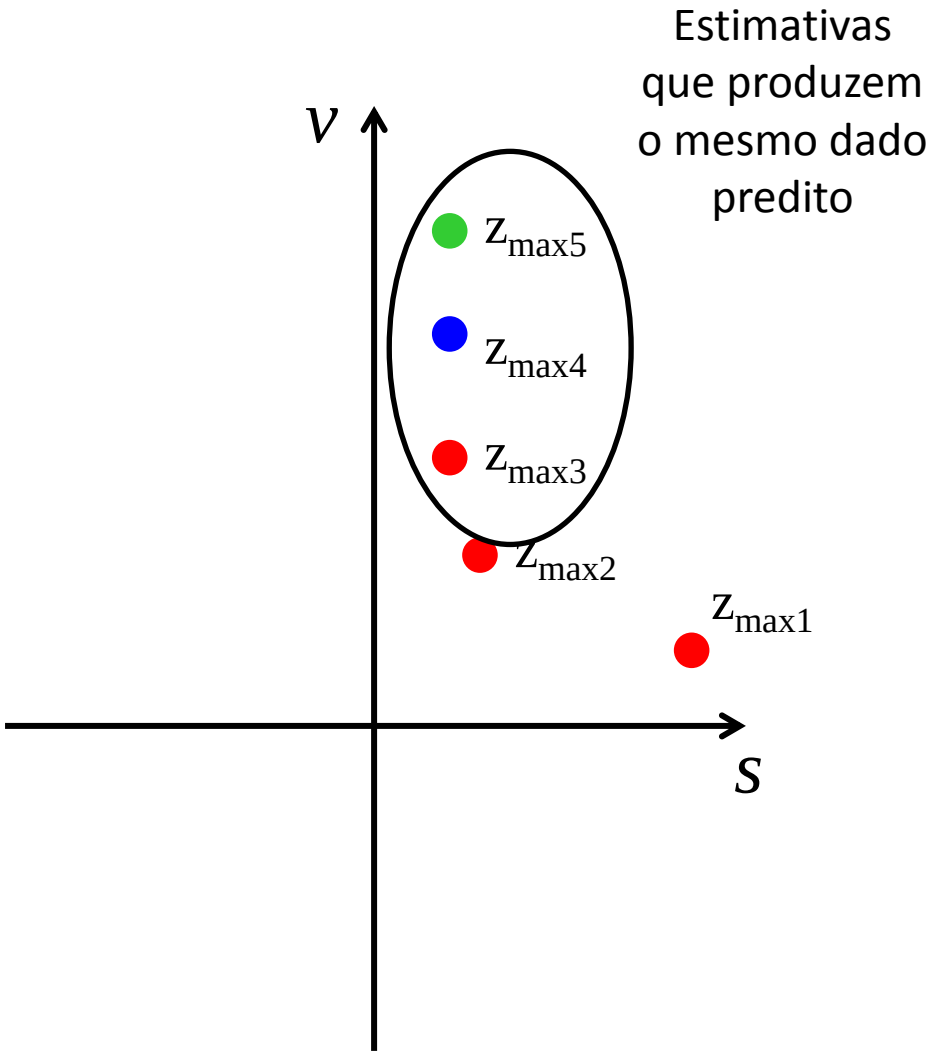
Curva v x s


g
dados observados
dados preditos
x
z0
zmax
z

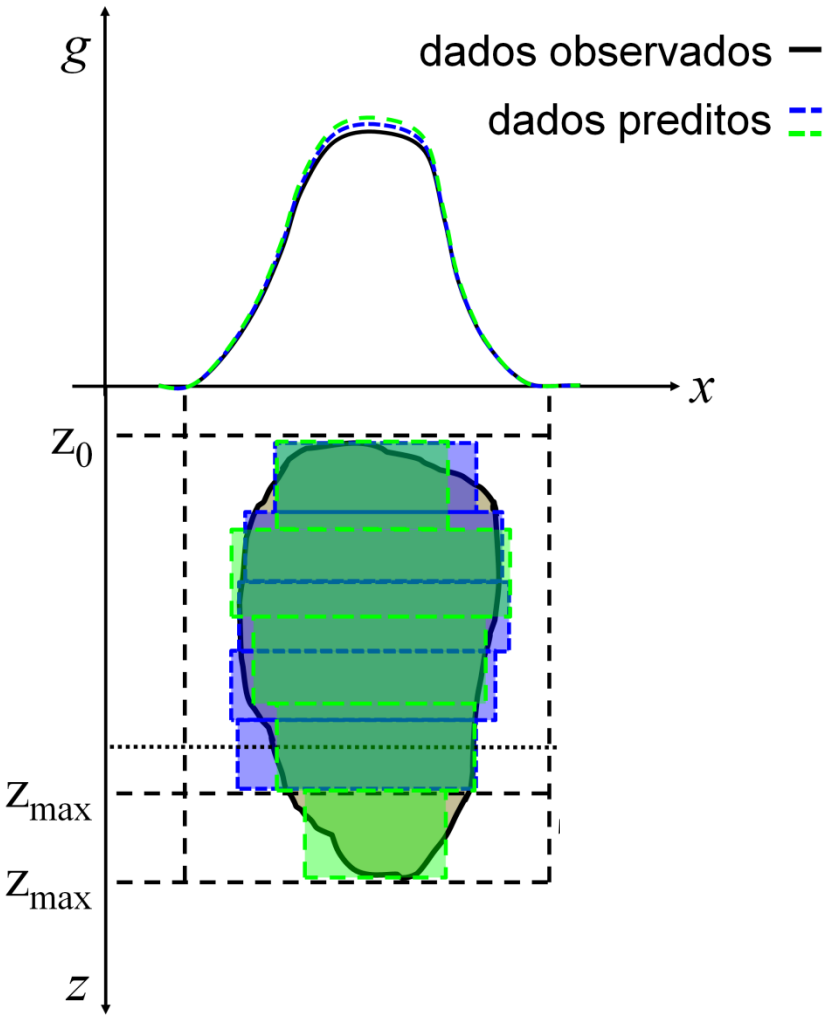

v
zmax4
zmax3
zmax2
zmax1
s

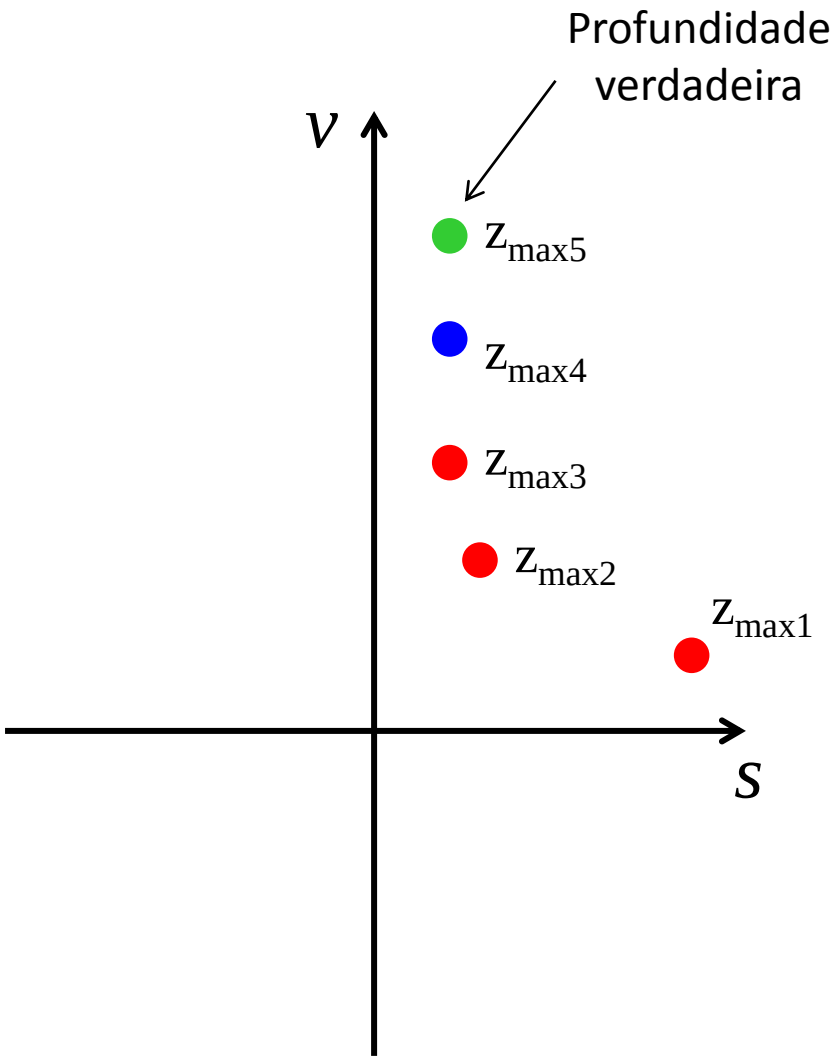
Curva v x s


g
dados observados
dados preditos
x
z0
zmax
zmax
z

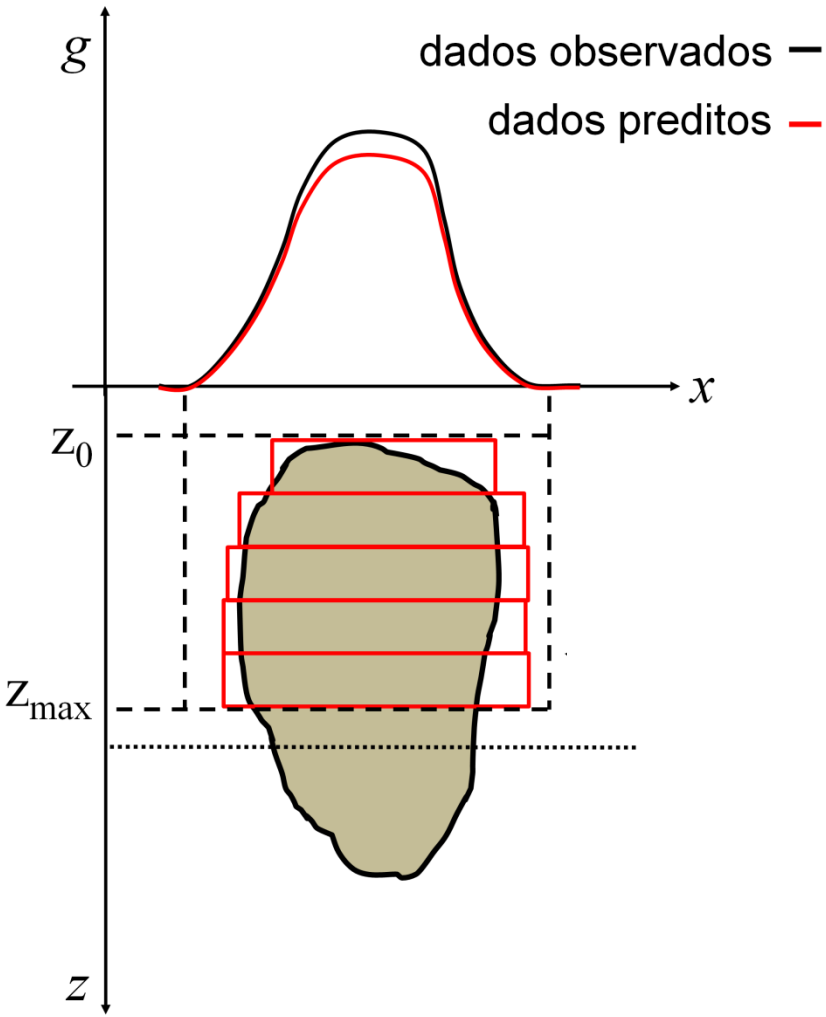

Estimativas que produzem o mesmo dado predito
v
zmax5
zmax4
zmax3
zmax2
zmax1
s

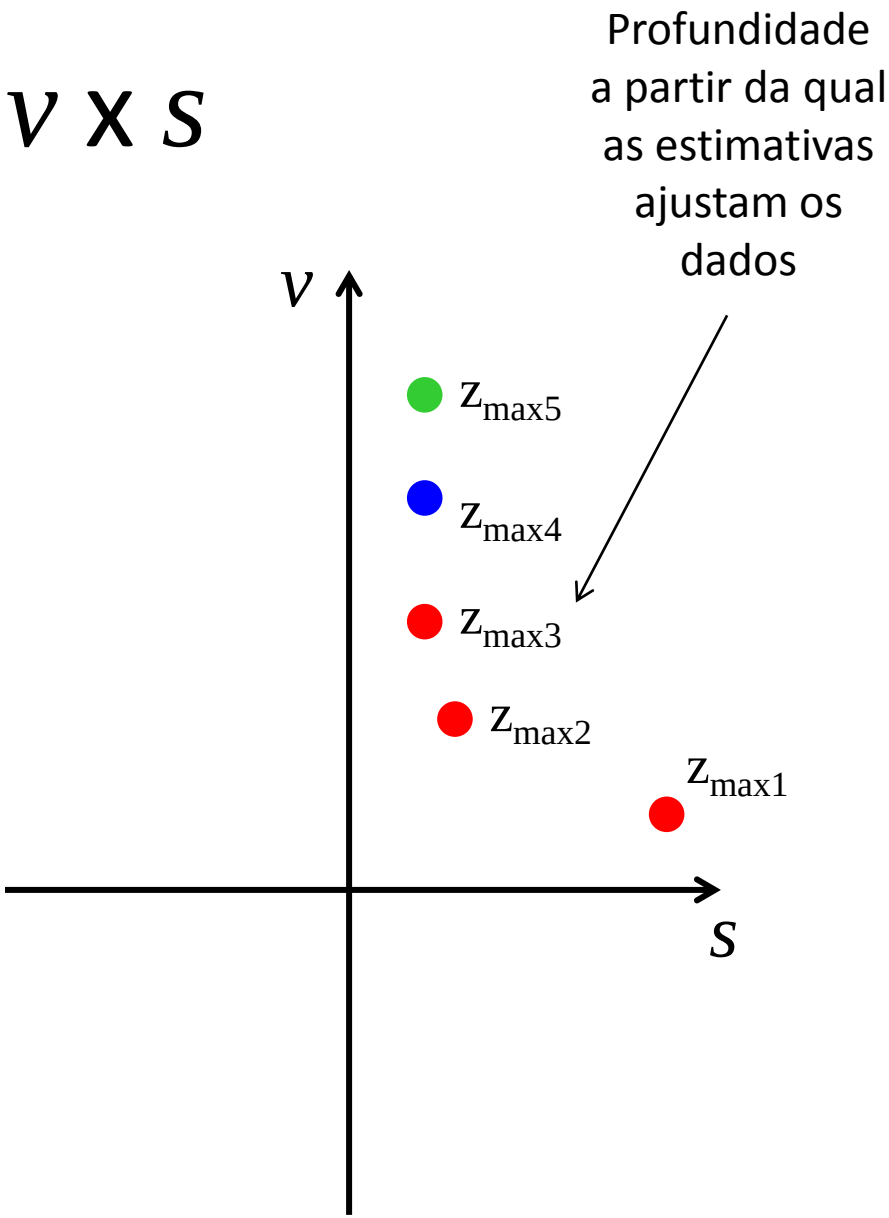
Curva v x s


g
dados observados
dados preditos
x
z0
zmax
zmax
z

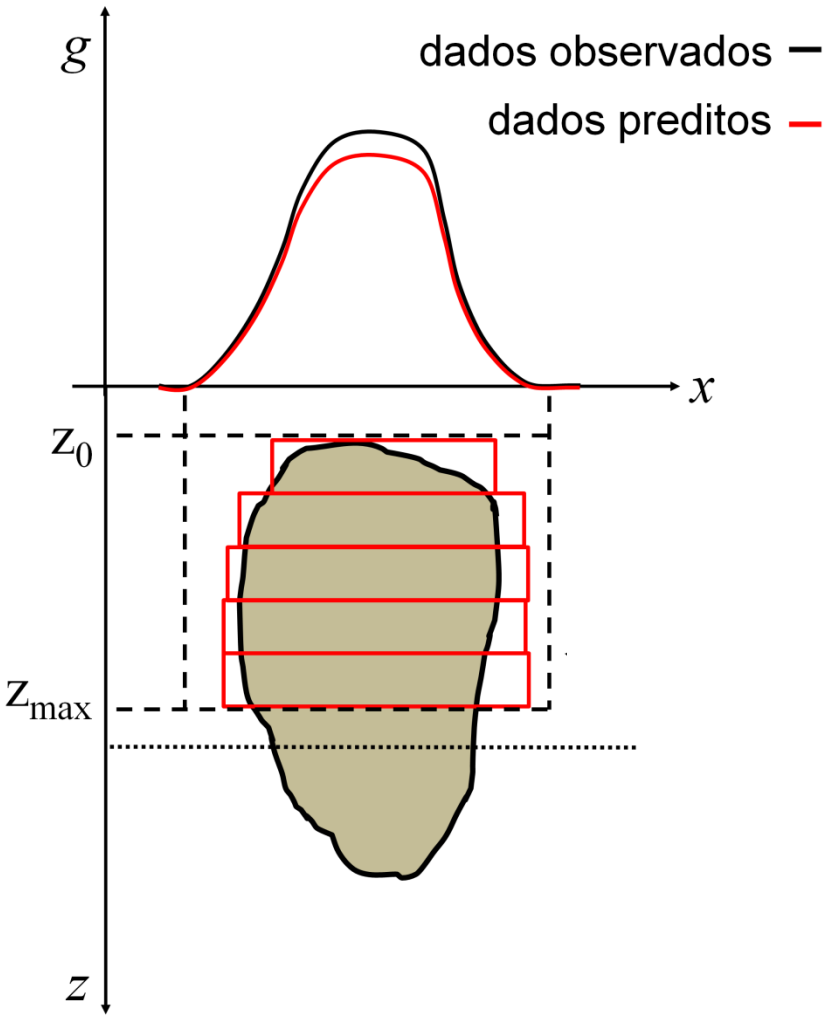

Profundidade verdadeira
v
zmax5
zmax4
zmax3
zmax2
zmax1
s

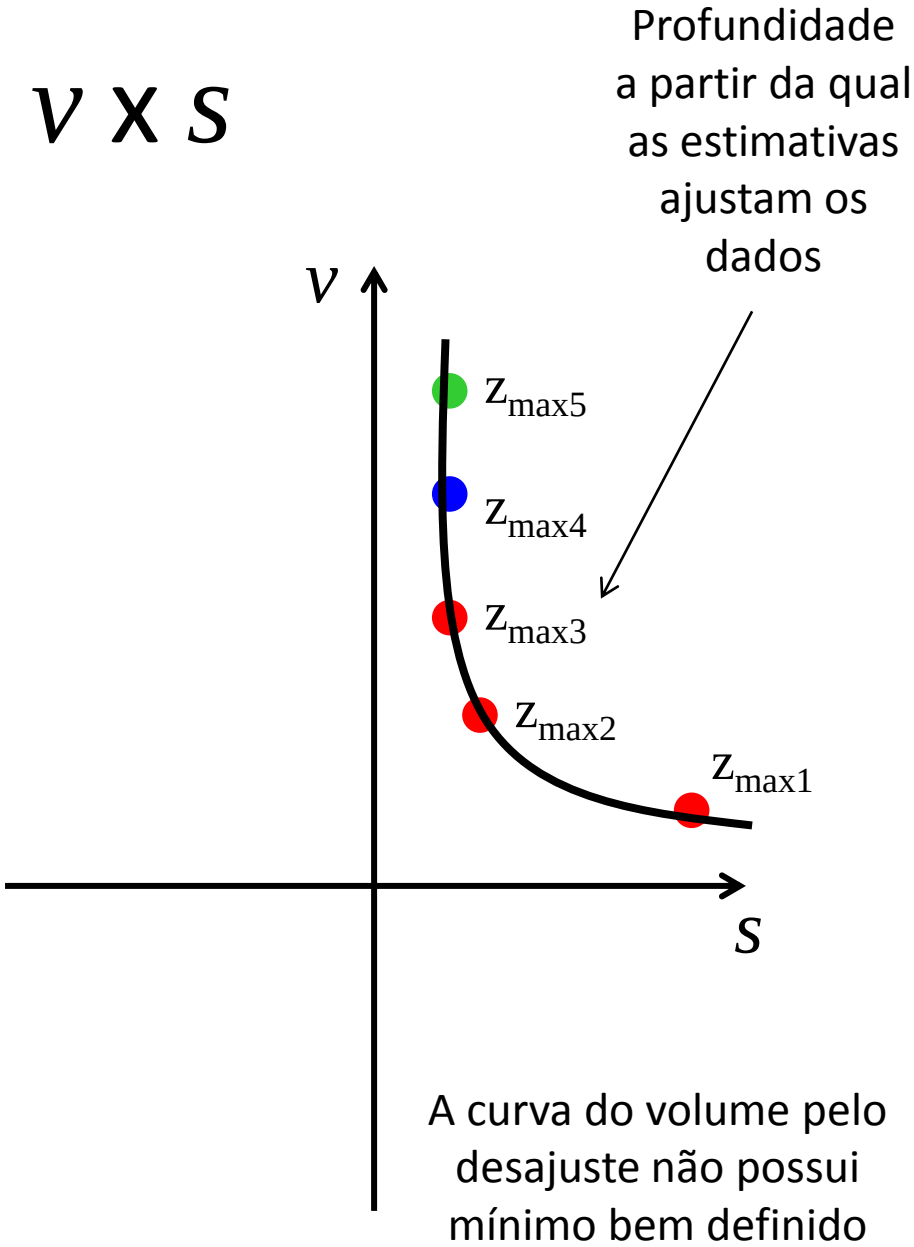
Curva v x s


g
dados observados
dados preditos
x
z0
zmax
z

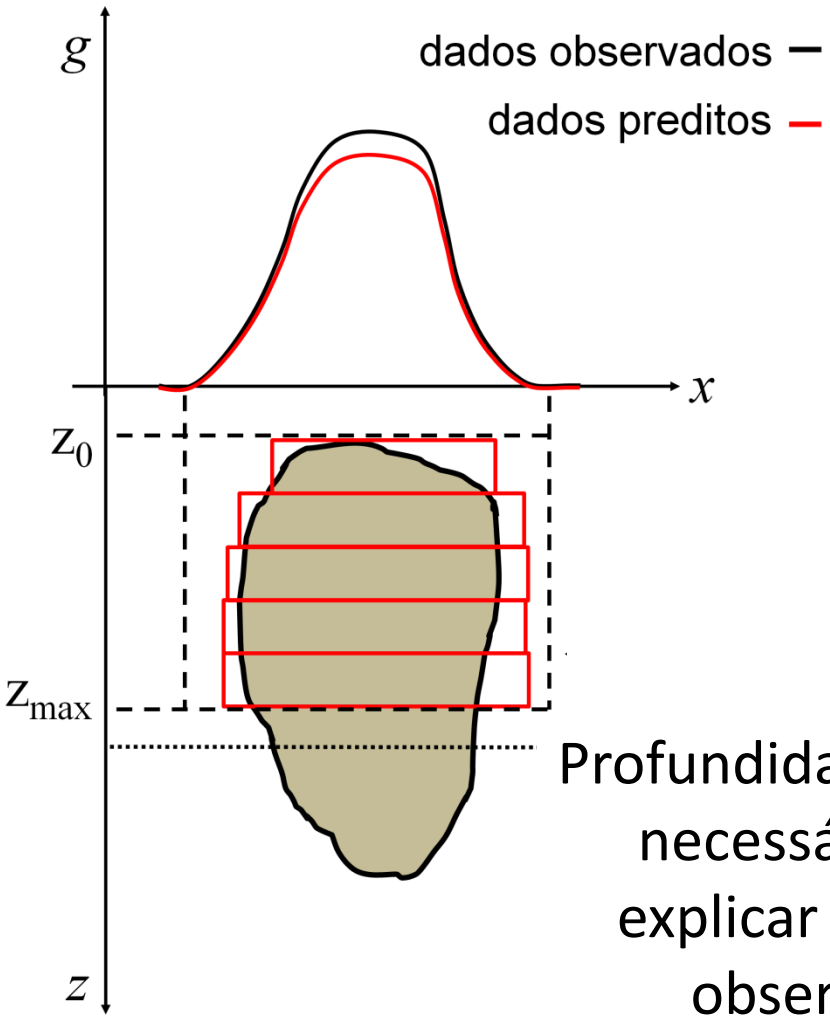

Profundidade a partir da qual as estimativas ajustam os dados
v
zmax5
zmax4
zmax3
zmax2
zmax1
s

Curva v x s

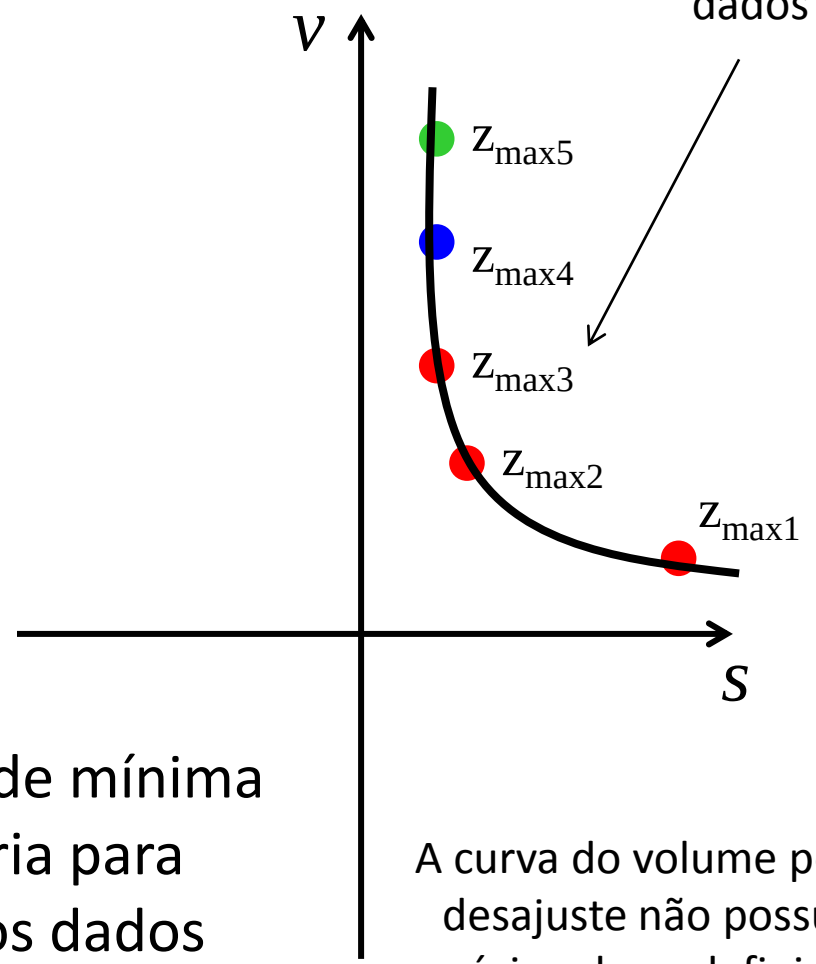

g
dados observados
dados preditos
x
z0
zmax
z


Profundidade a partir da qual as estimativas ajustam os dados
v
zmax5
zmax4
zmax3
zmax2
zmax1
s
A curva do volume pelo desajuste não possui mínimo bem definido

Curva *v* x *s*



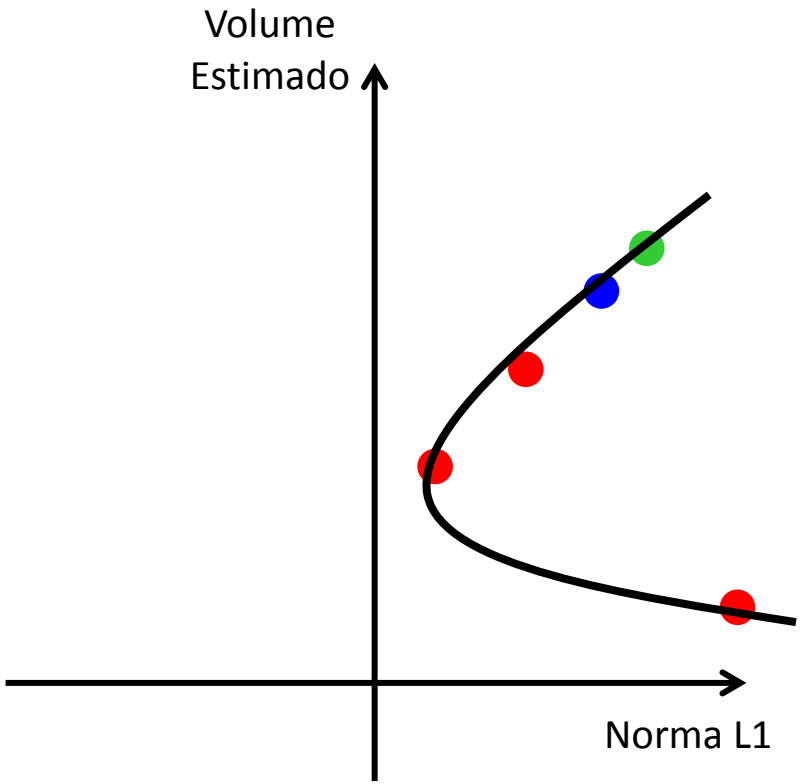
Profundidade mínima necessária para explicar os dados observados



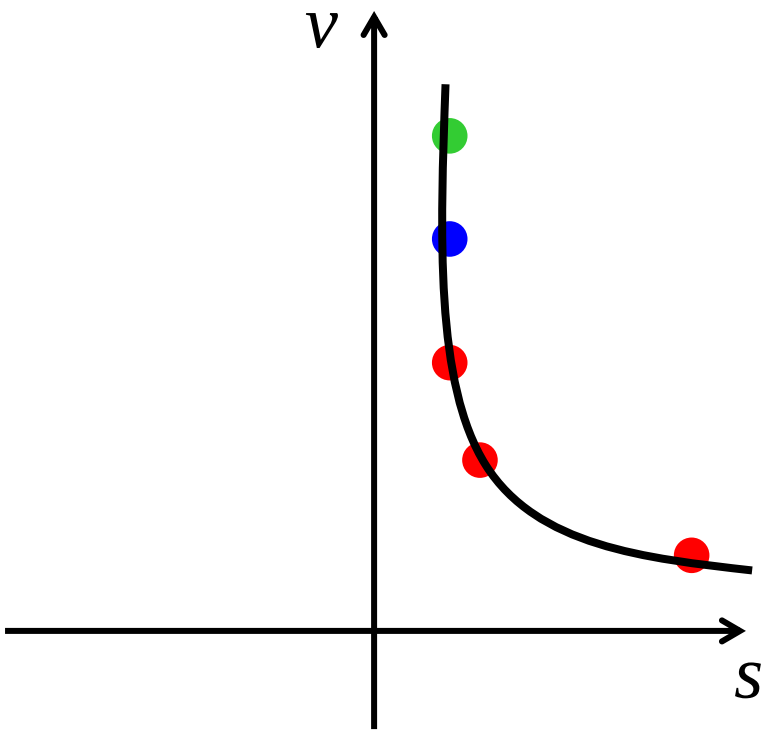
Profundidade a partir da qual as estimativas ajustam os dados

A curva do volume pelo desajuste não possui mínimo bem definido

Curva v x s



Dados COM
resolução



Dados SEM
resolução

Testes com dados sintéticos

Testes com dados sintéticos (Gradiometria gravimétrica)

- Testes 1
  - Validação a curva v x s
  - Influência do ruído

- Testes 2
  - Corpos profundos

- Testes 3
  - Simulação de condições reais

Testes com dados sintéticos (Gradiometria gravimétrica)

- Testes 1
  - Validação a curva v x s
  - Influência do ruído
- Testes 2
  - Corpos profundos
- Testes 3
  - Simulação de condições reais

Não serão mostrados por questão de tempo

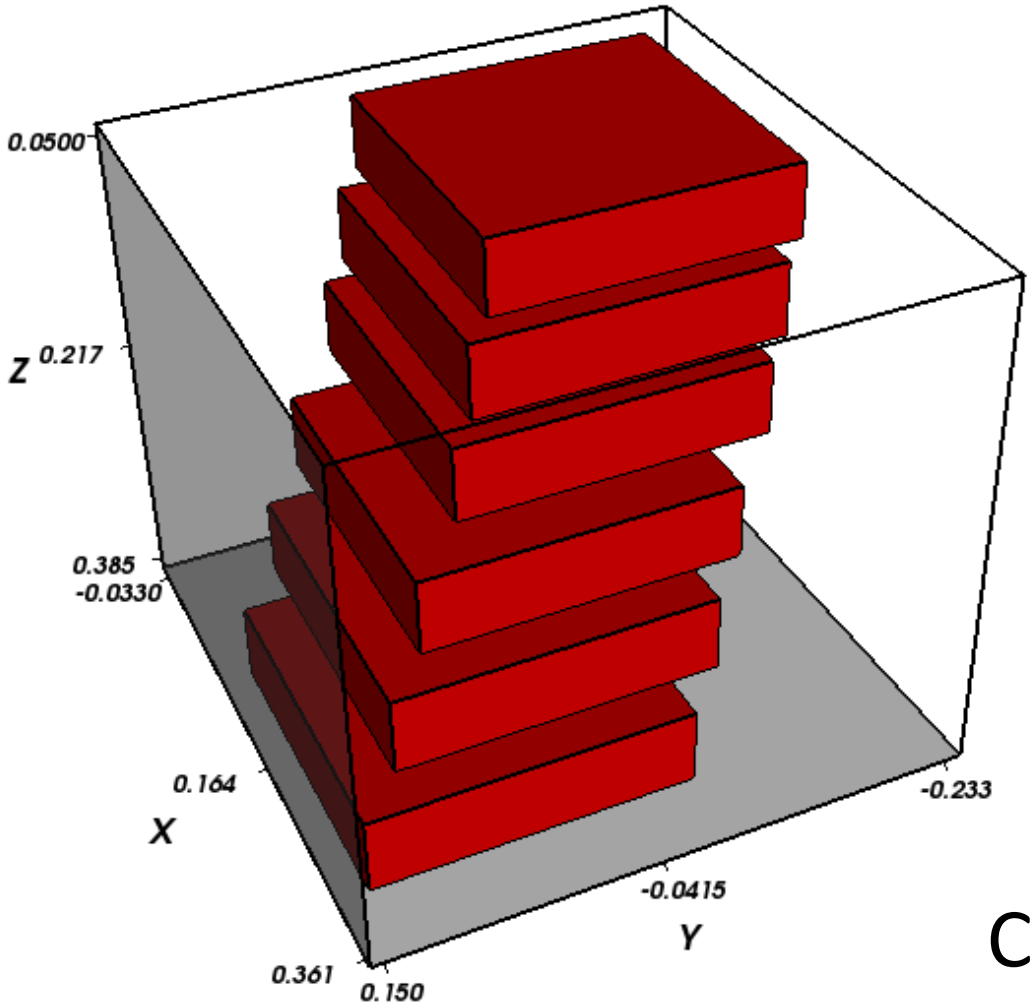
Testes com dados sintéticos (Gradiometria gravimétrica)

- Testes 1
  - Validação a curva v x s
  - Influência do ruído

- Testes 2
  - Corpos profundos

- Testes 3
  - Simulação de condições reais

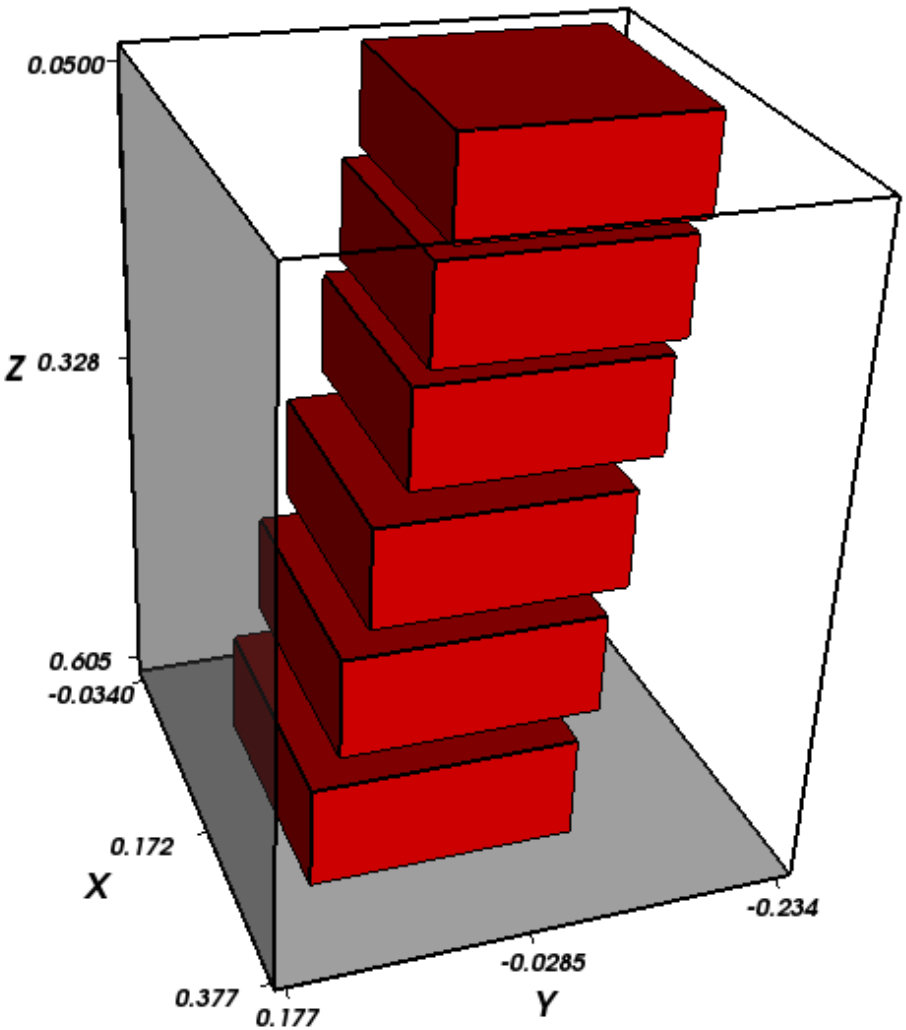
Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



rho: 1,0 g/cm³
topo: 50 m
base: 350m

Corpo raso

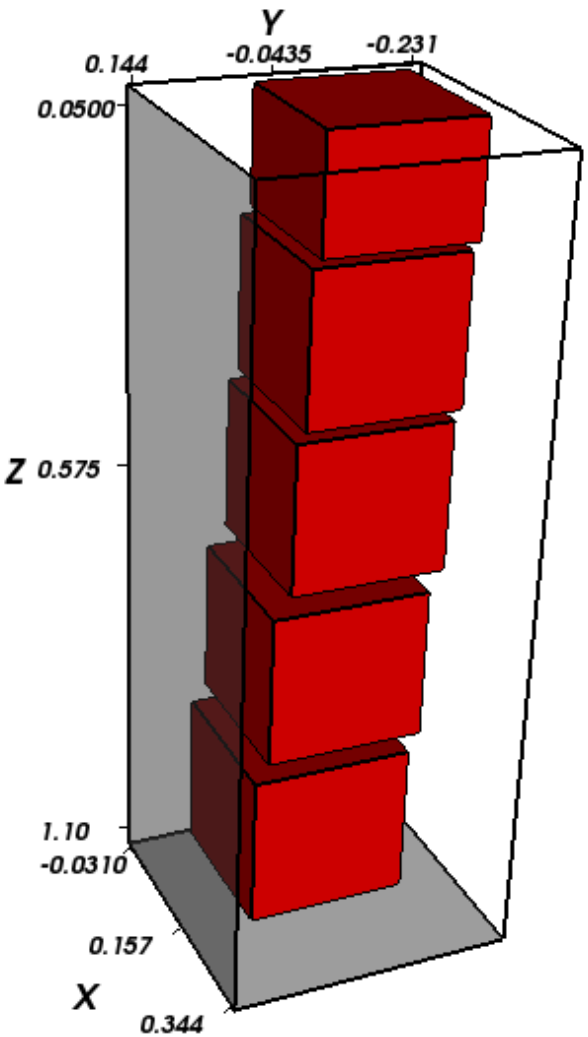
Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



rho: 1,0 g/cm³
topo: 50 m
base: 550m

Corpo intermediário

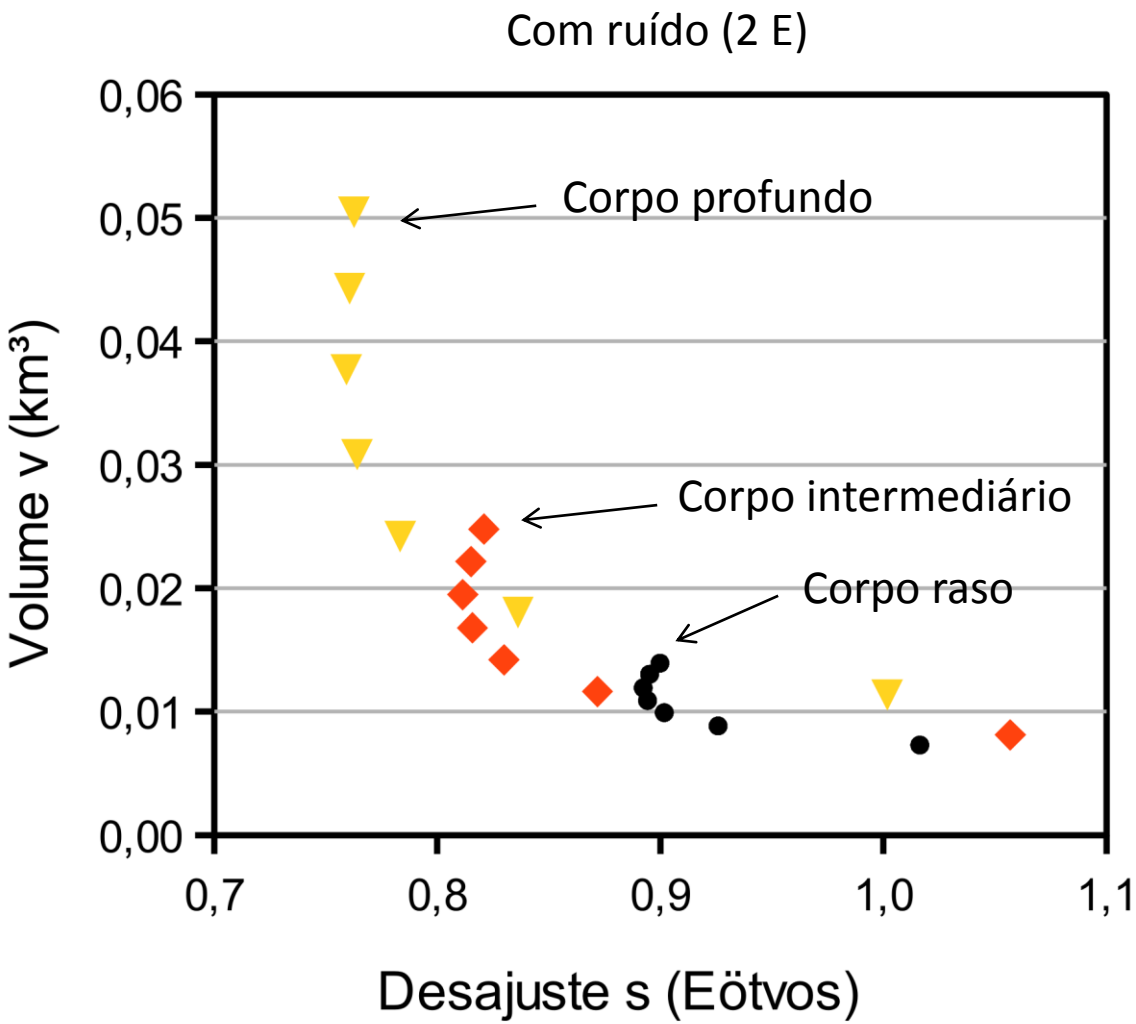
Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



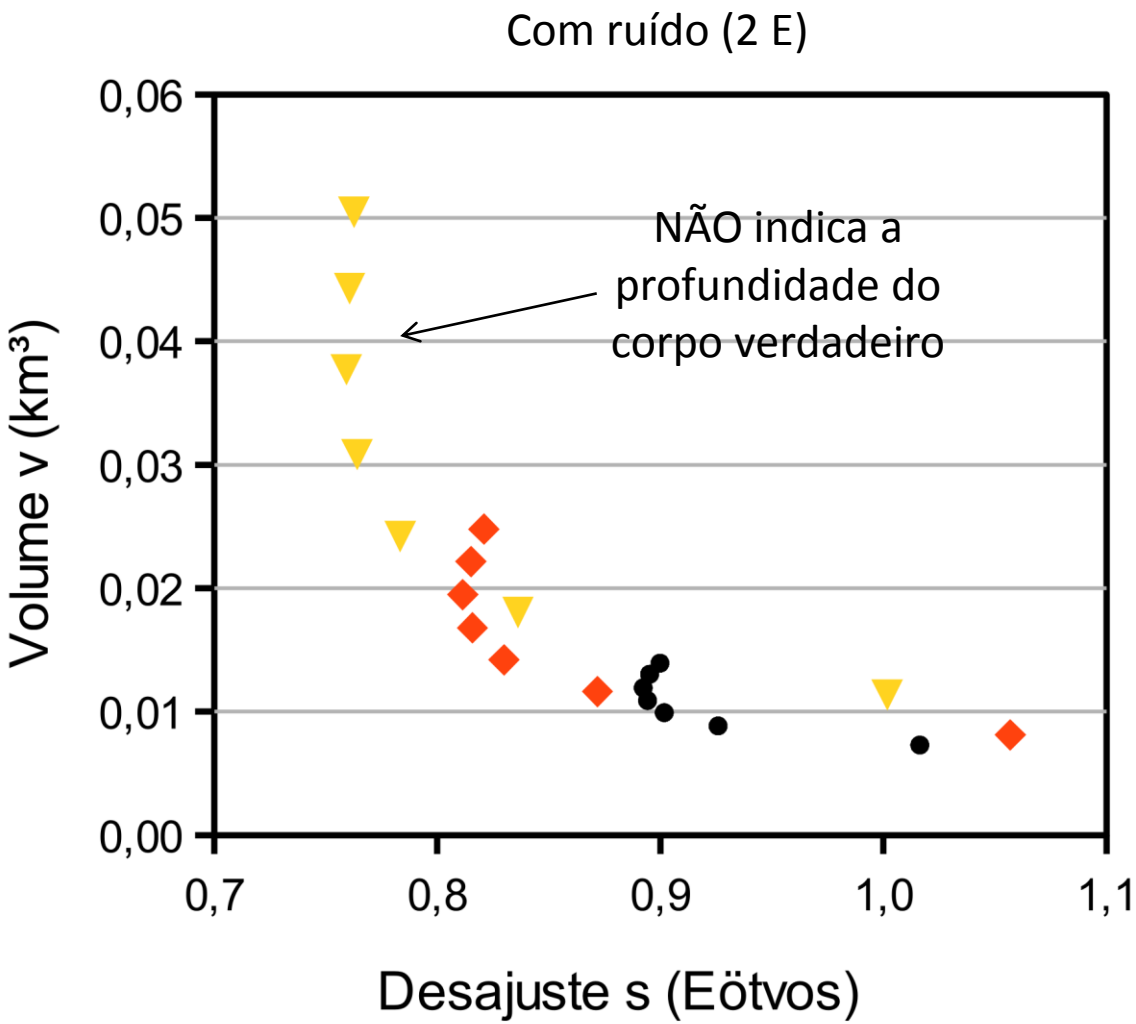
rho: 1,0 g/cm³
topo: 50 m
base: 1000m

Corpo profundo

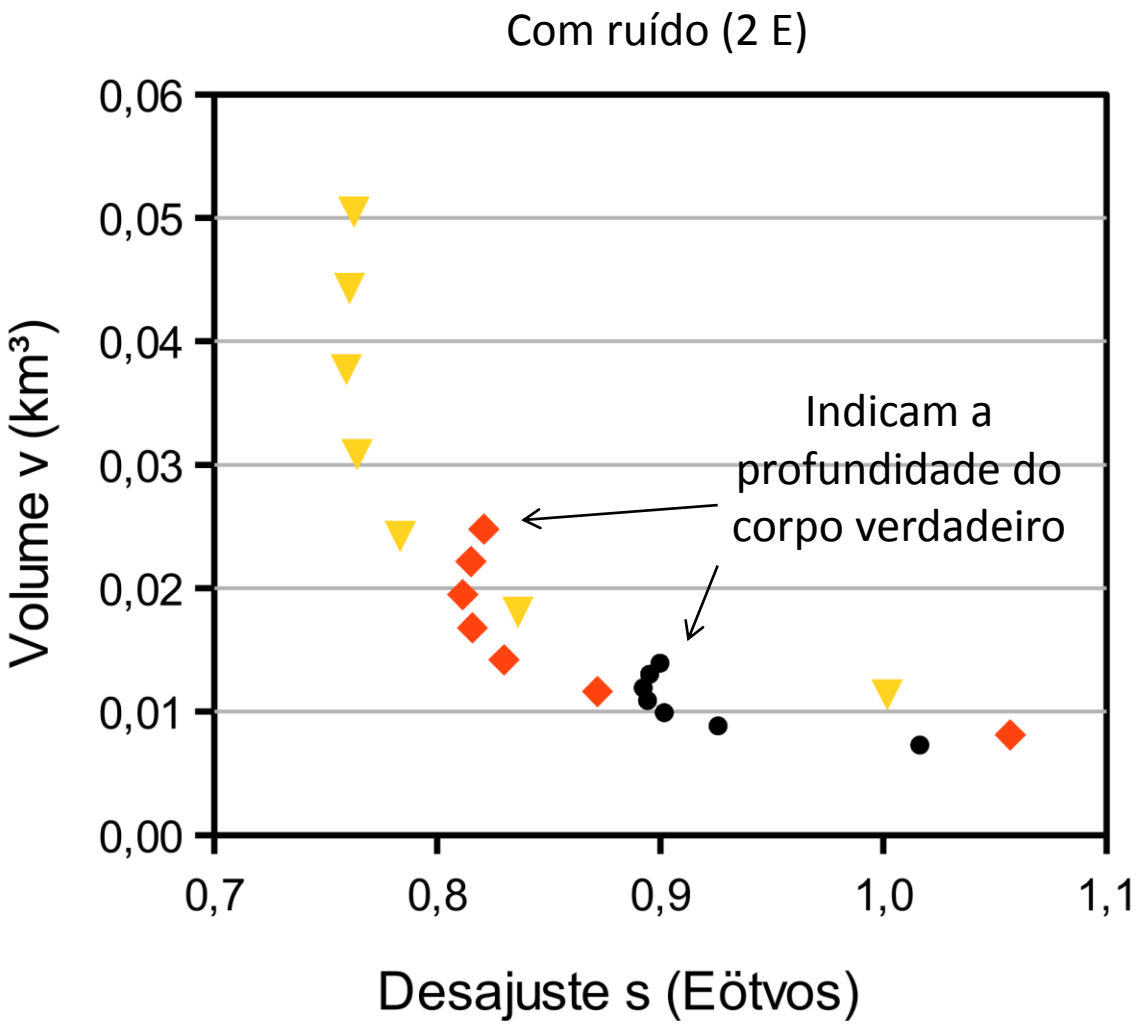
Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



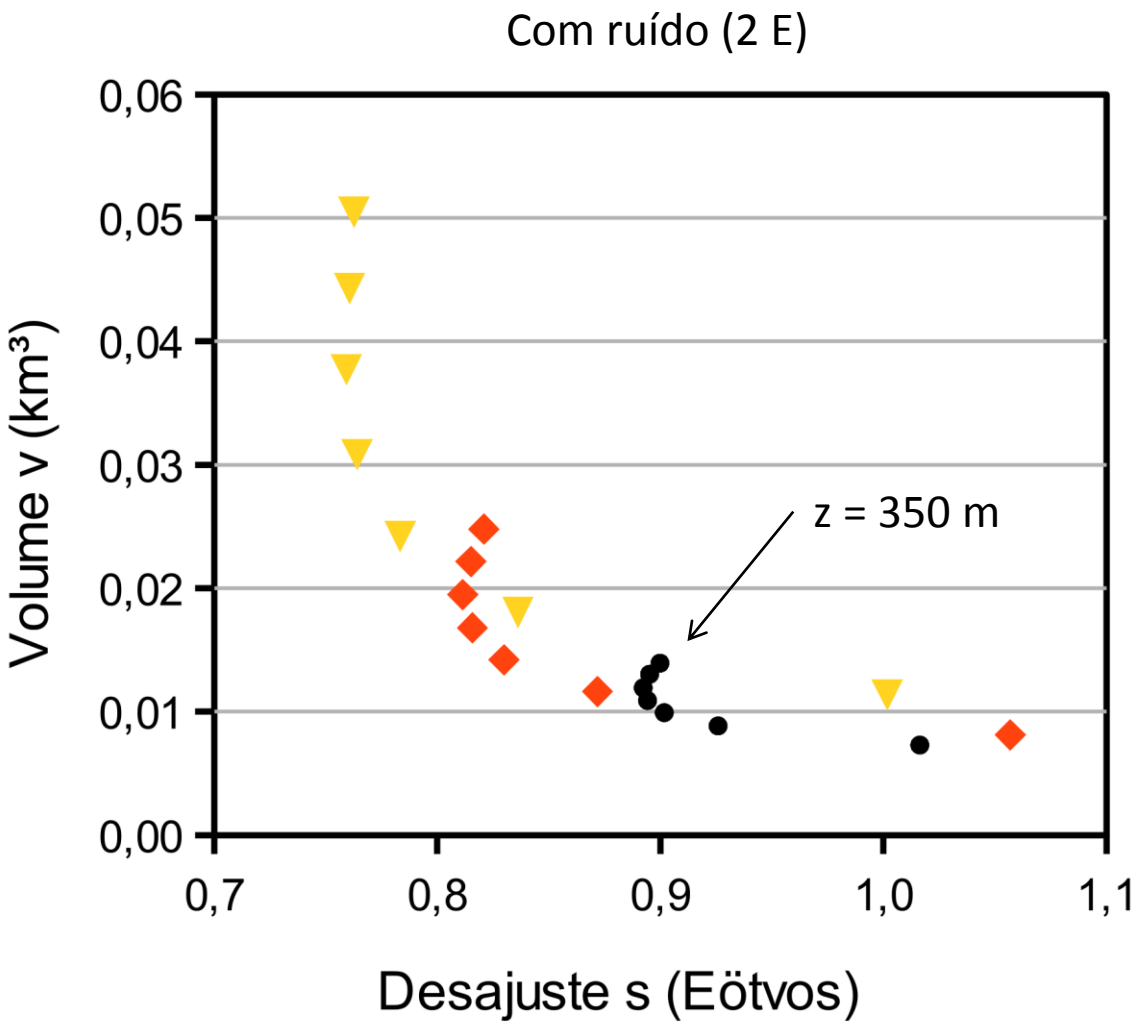
Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)

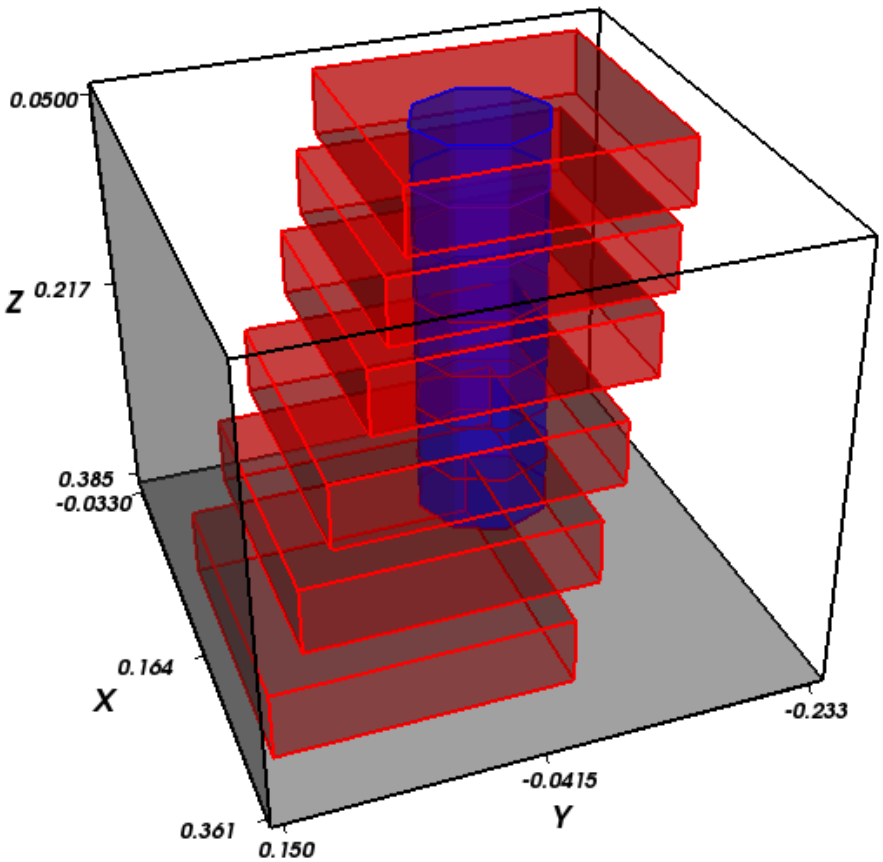


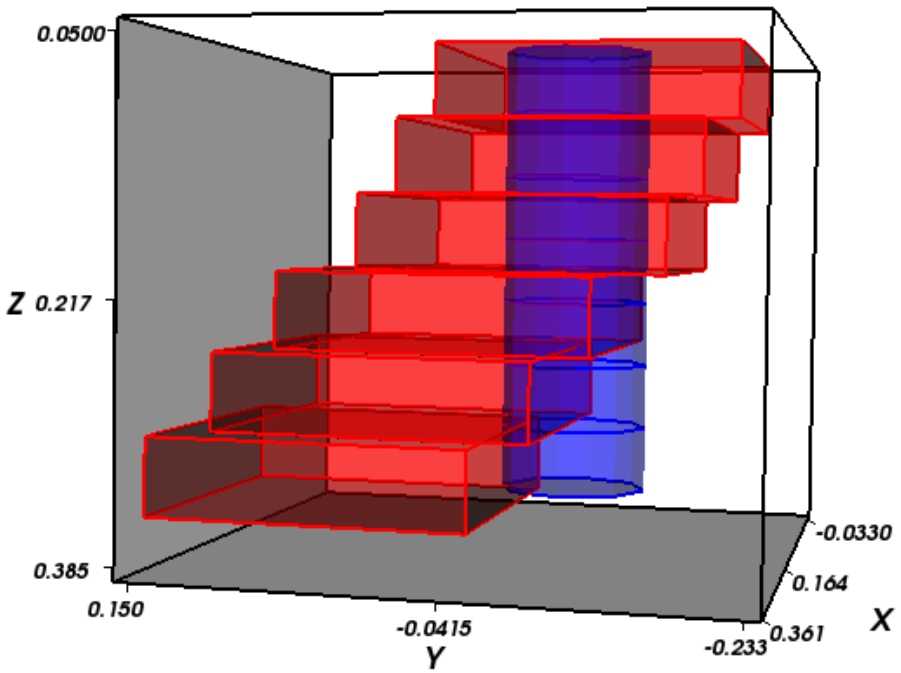
Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)

Corpo raso



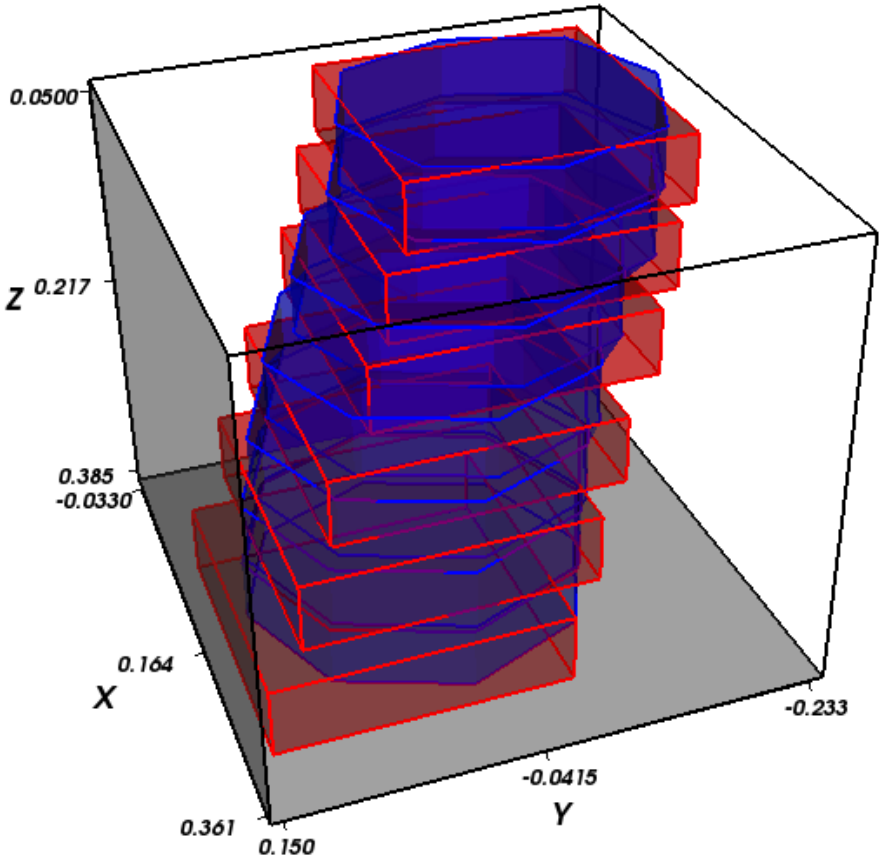


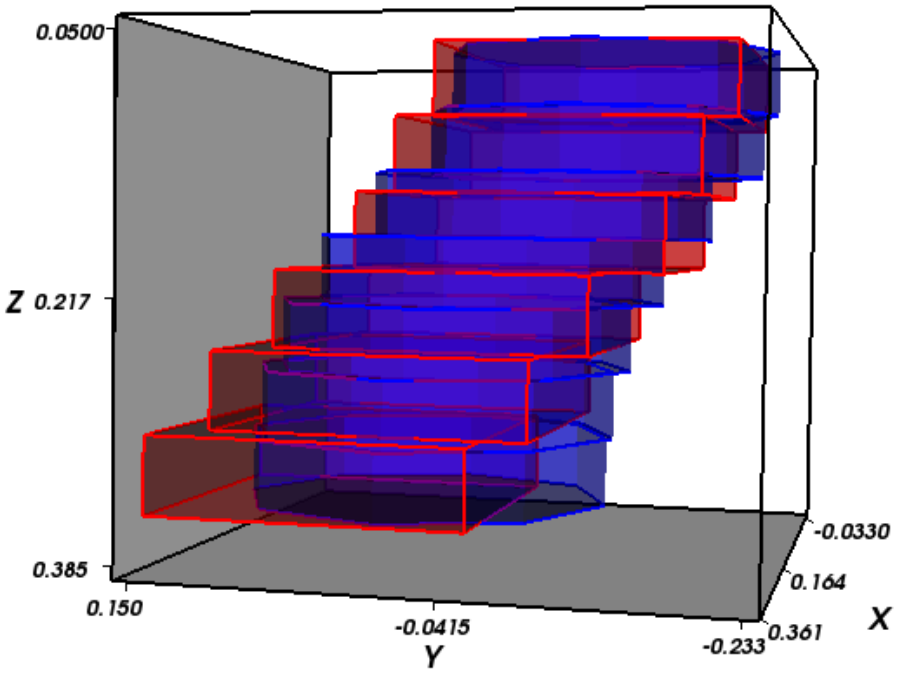
Verdadeiro

Aproximação inicial

Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)

Corpo raso

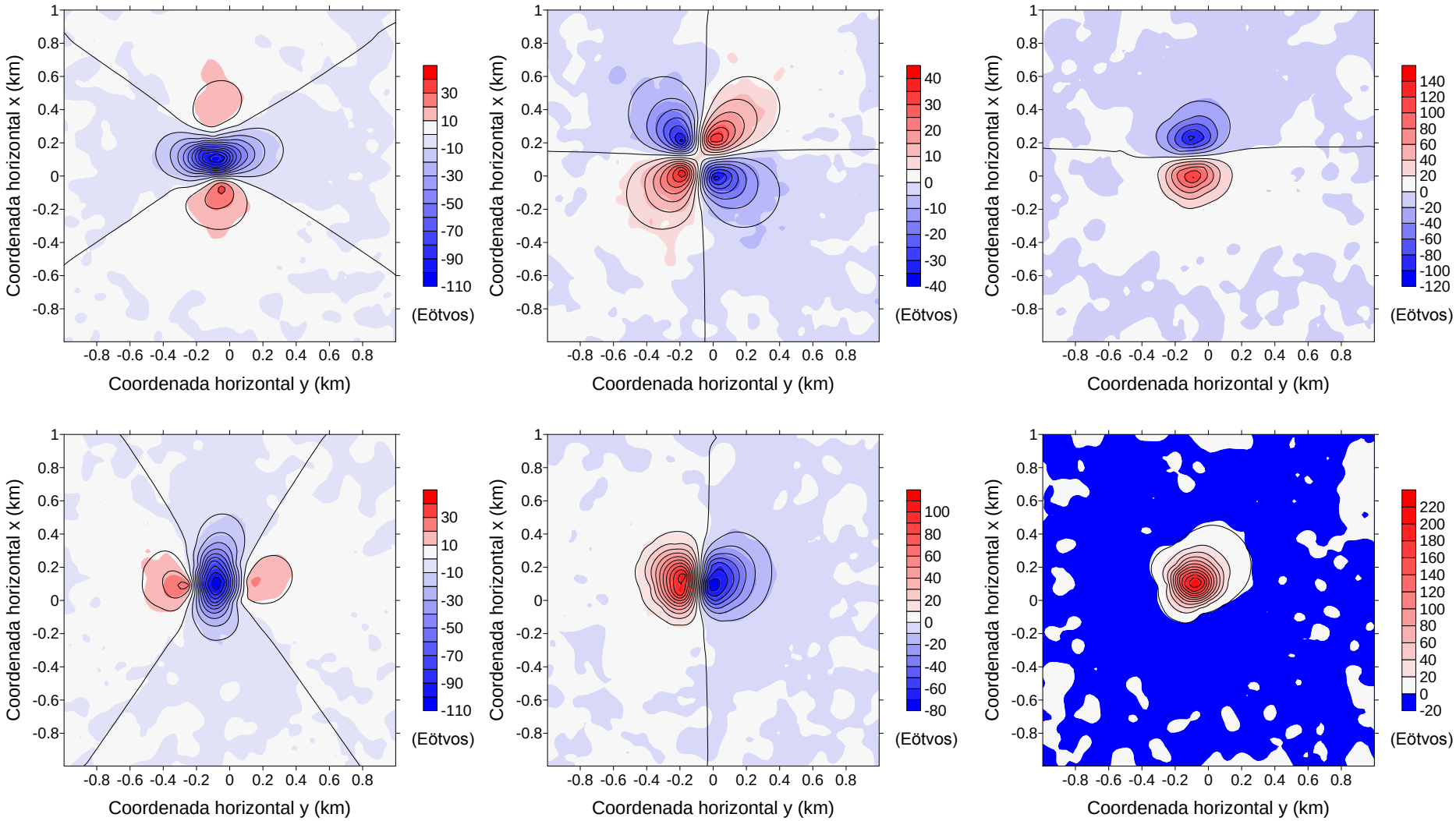




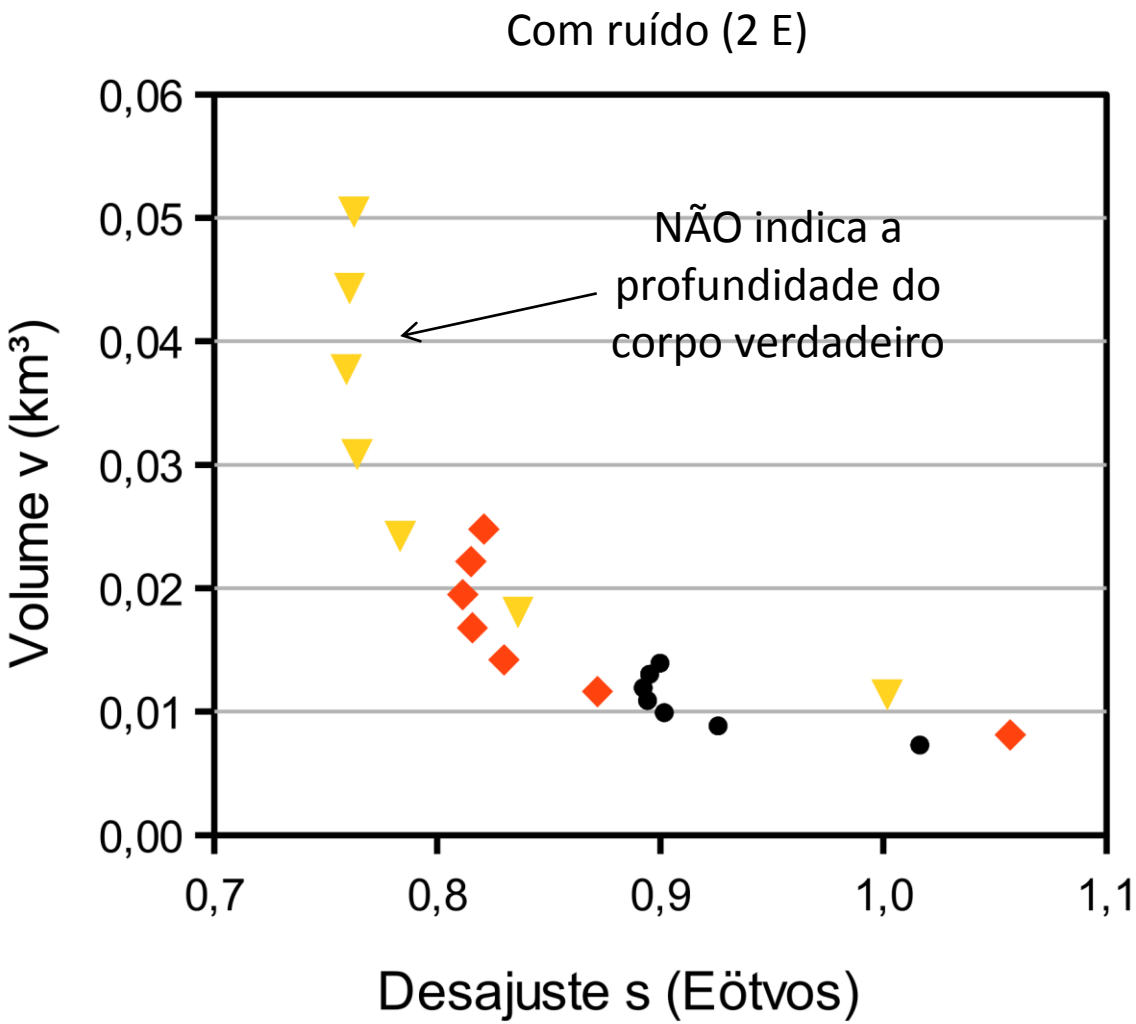
Verdadeiro

Estimativa

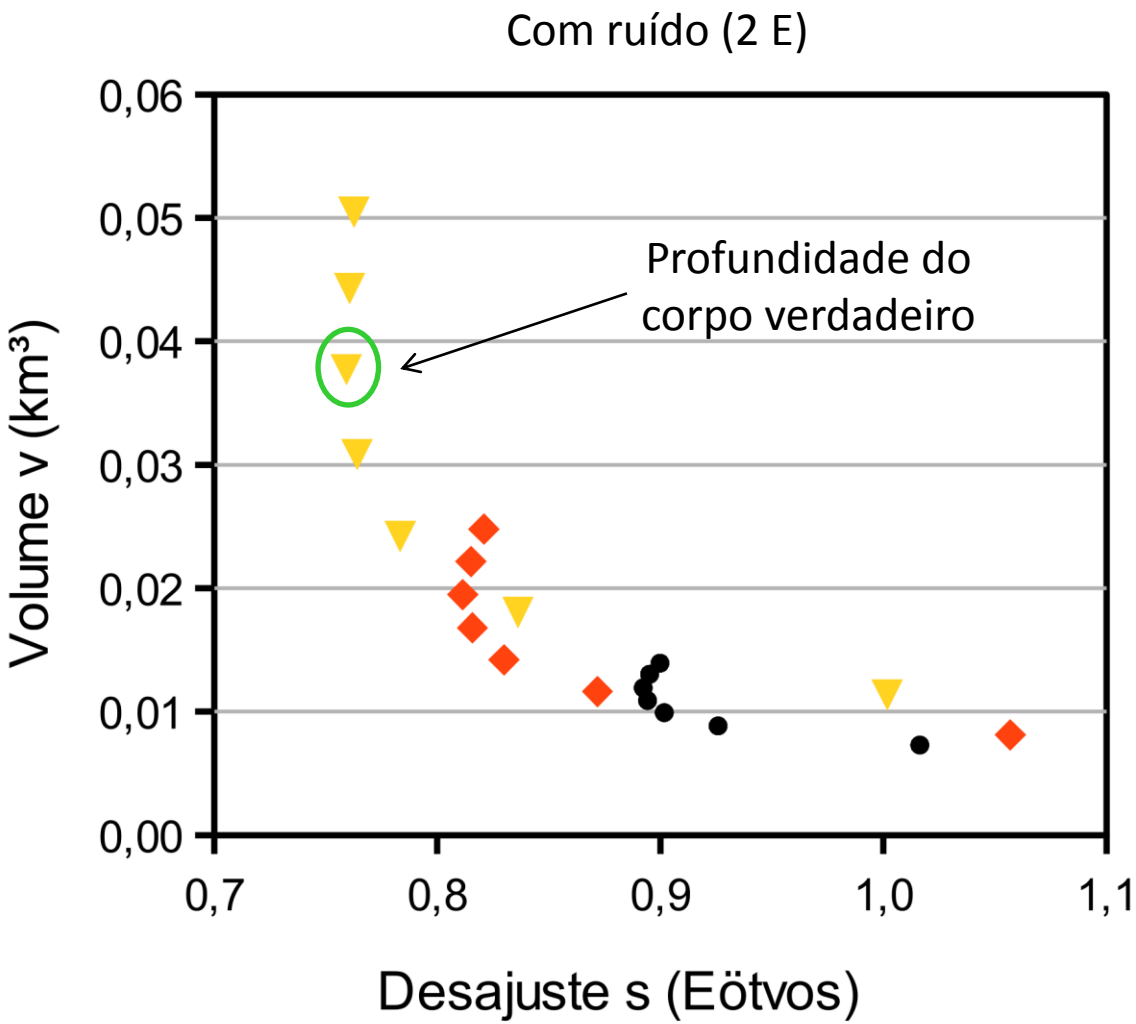
Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



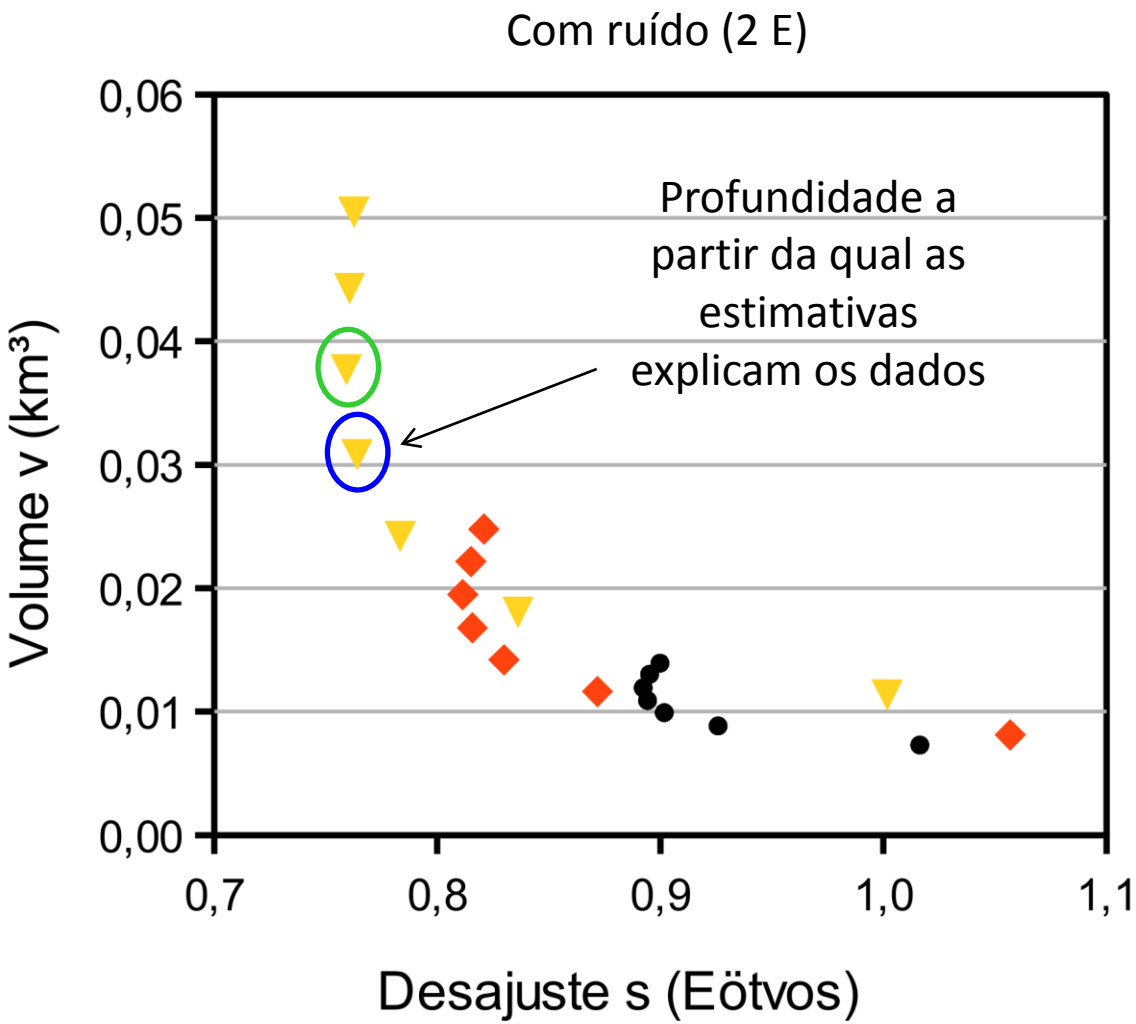
Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



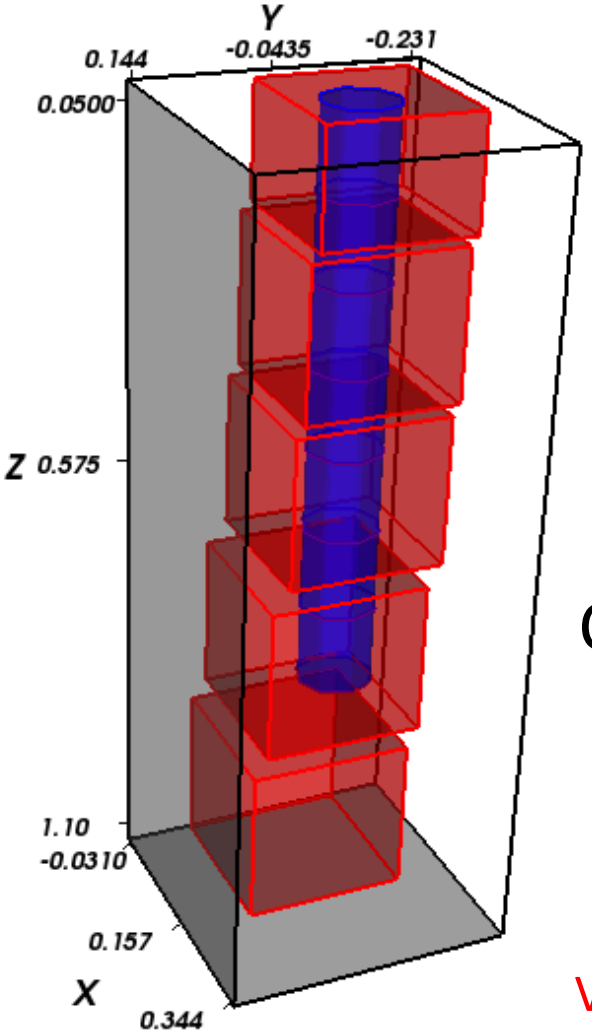
Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



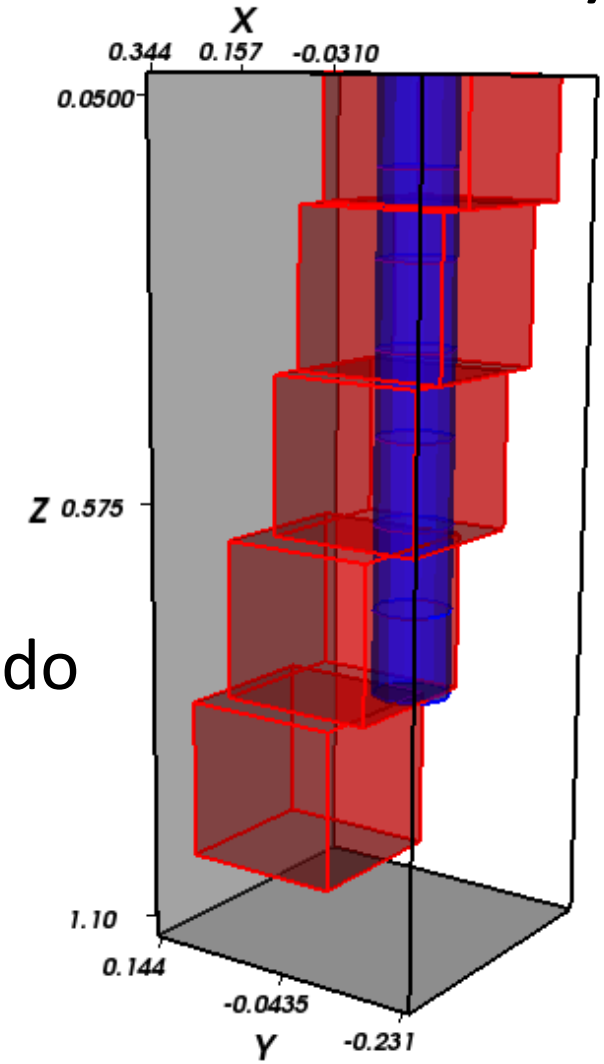
Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



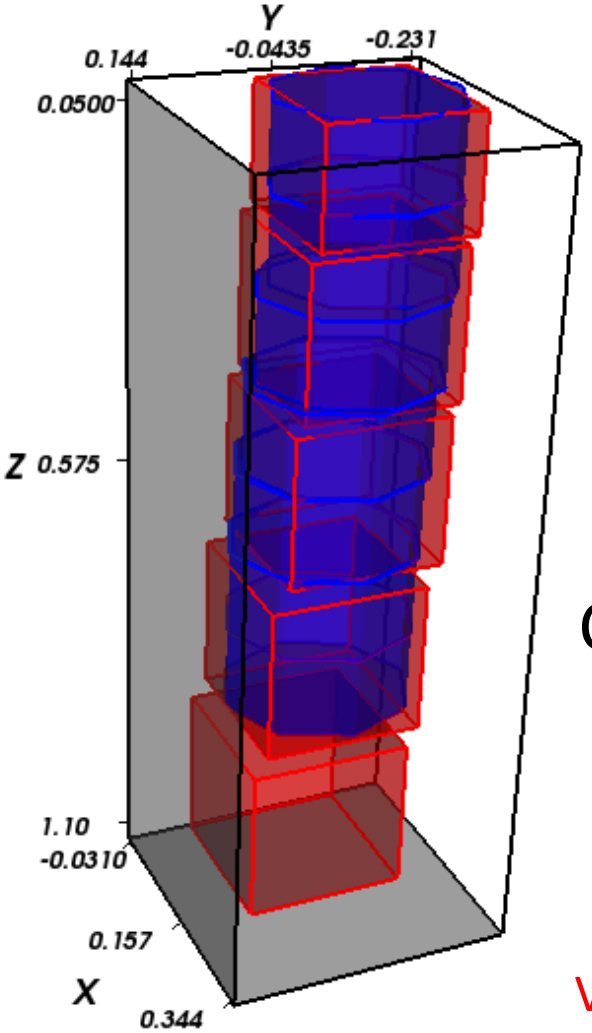
Corpo profundo



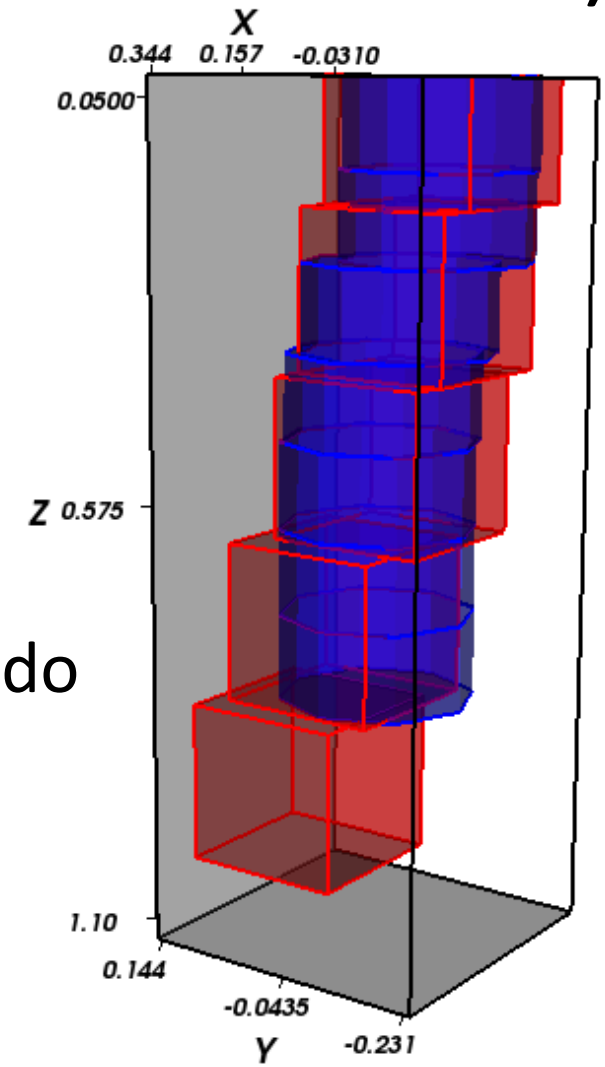
Verdadeiro

Aproximação inicial

Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



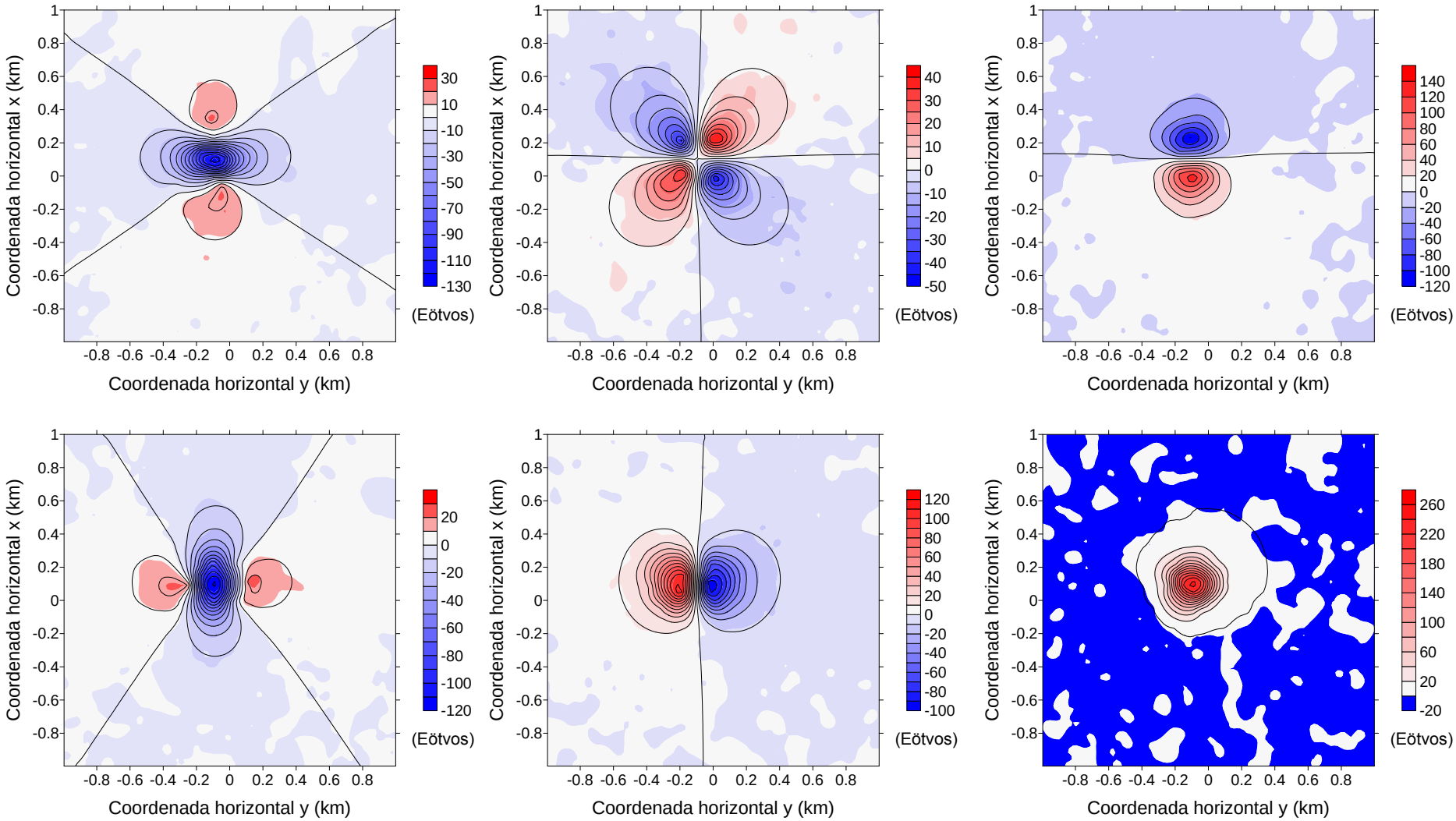
Corpo profundo



Verdadeiro

Estimativa

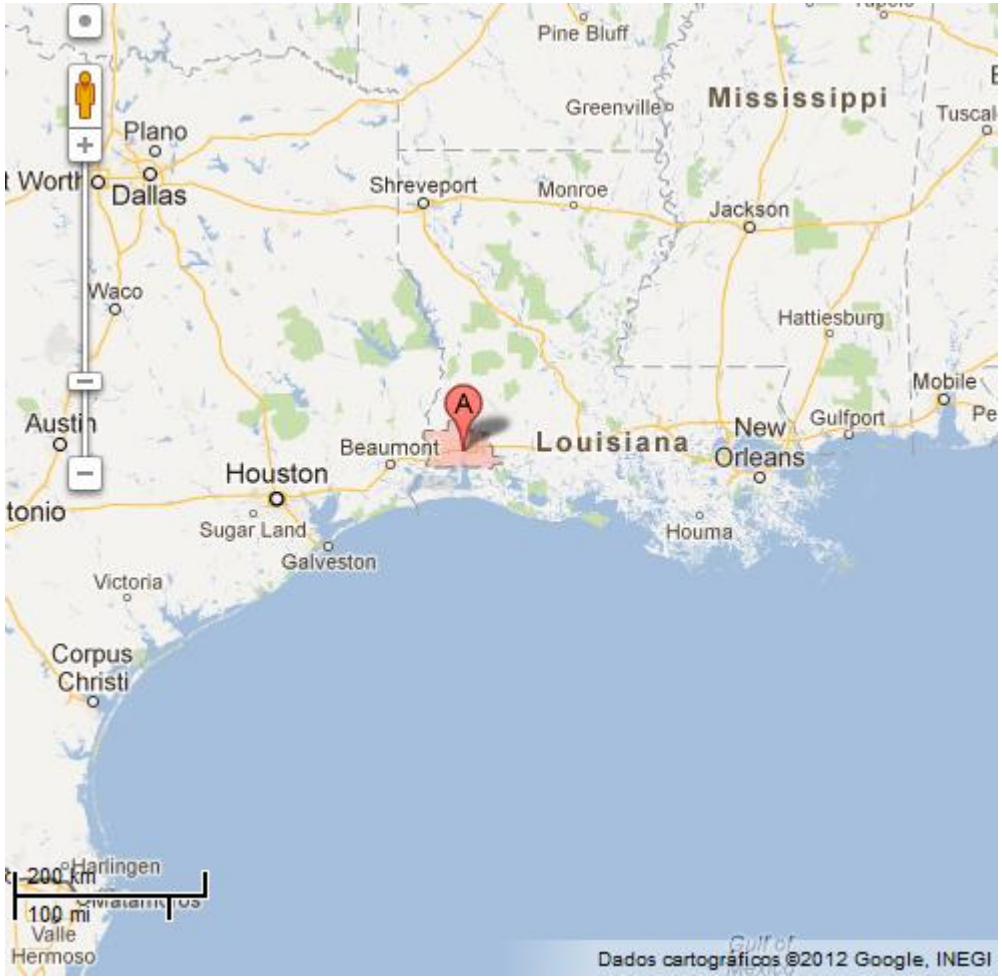
Testes com dados sintéticos (Gradiometria gravimétrica – teste 2)



Aplicação a dados reais (Gradiometria gravimétrica)

Aplicação a dados reais (Gradiometria gravimétrica)

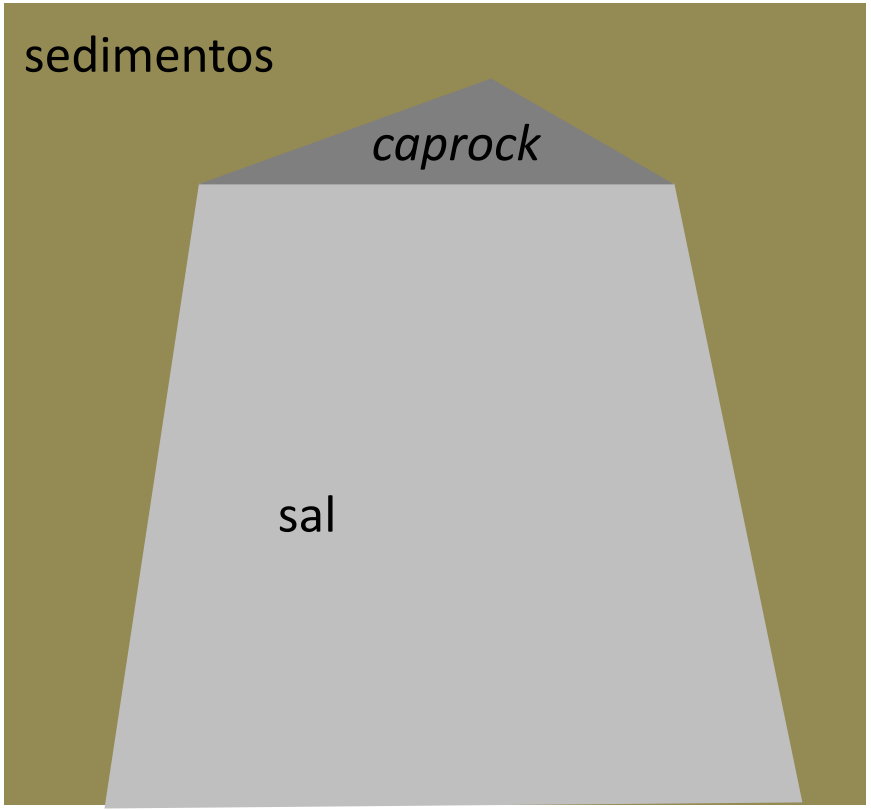
Domo de Sal Vinton, Louisiana - EUA



Aplicação a dados reais (Gradiometria gravimétrica)

Esboço da subsuperfície

Marfurt et. al (2004)
Coker (2006)

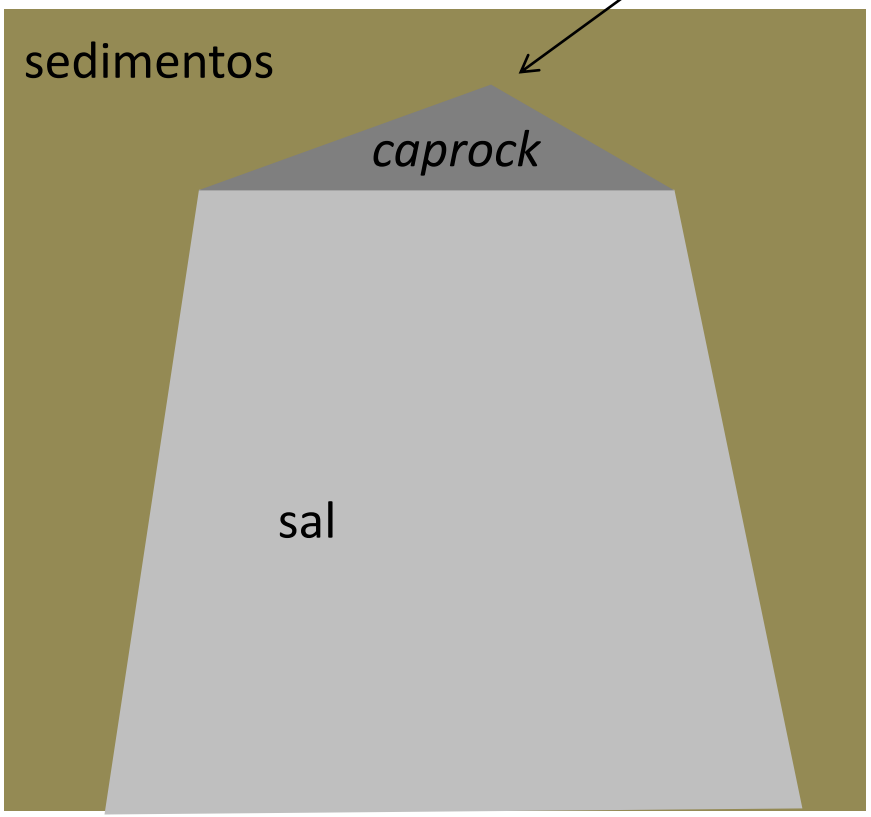


Aplicação a dados reais (Gradiometria gravimétrica)

Esboço da subsuperfície

topo = 160 m (Ennen e Hall, 2011)

Marfurt et. al (2004)
Coker (2006)

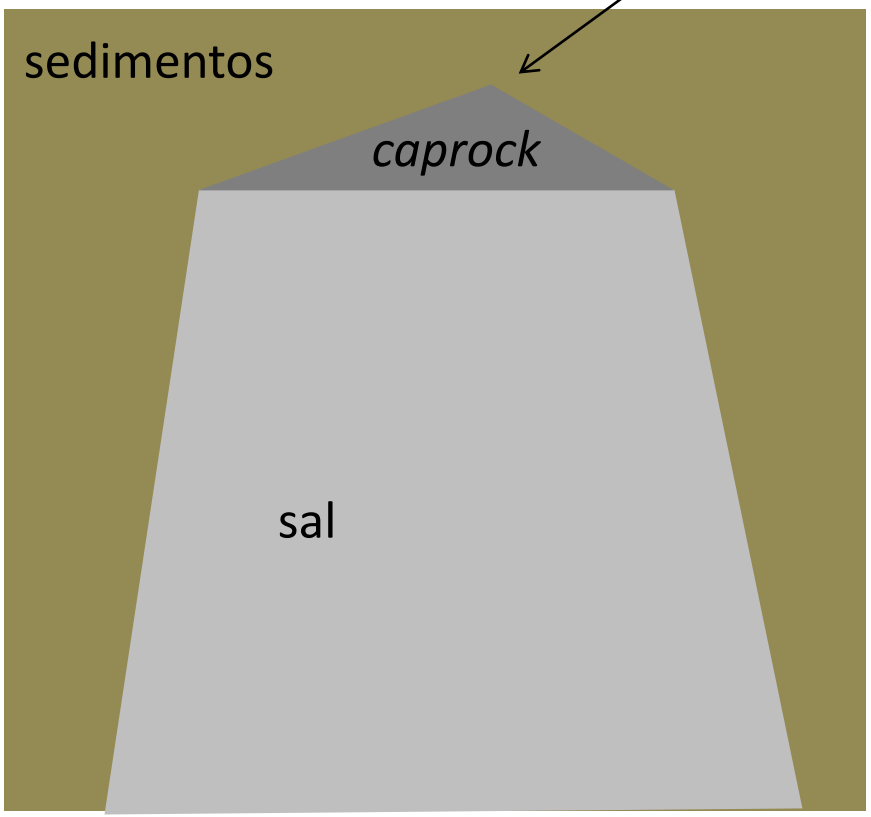


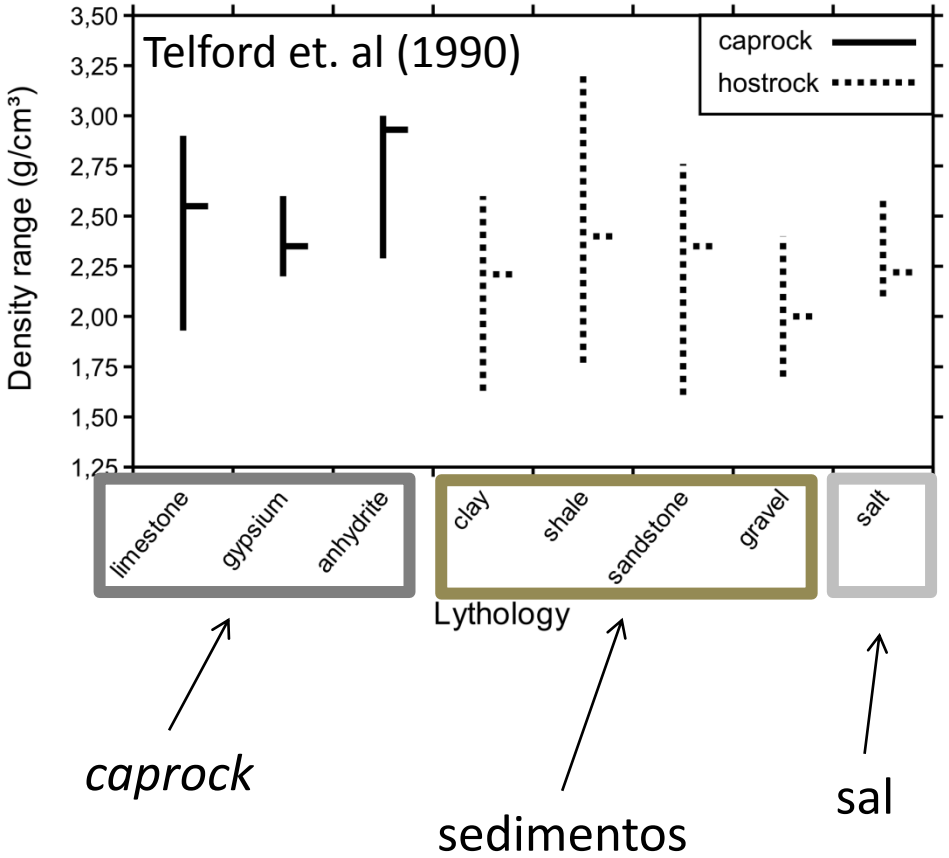
Aplicação a dados reais (Gradiometria gravimétrica)

Esboço da subsuperfície

topo = 160 m (Ennen e Hall, 2011)

Marfurt et. al (2004)
Coker (2006)



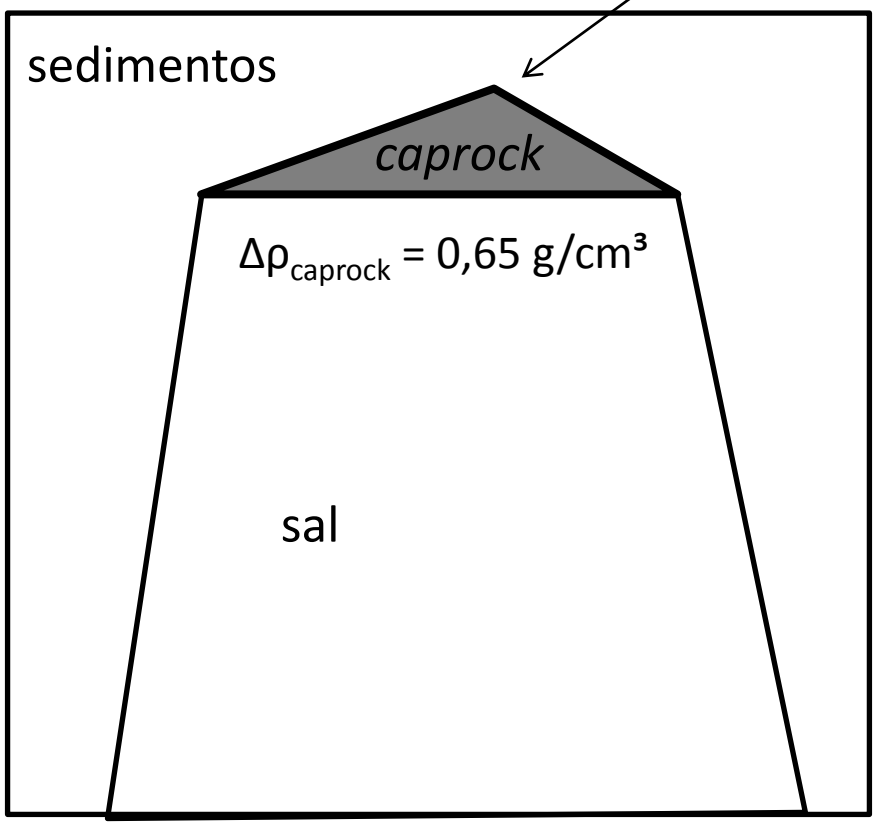


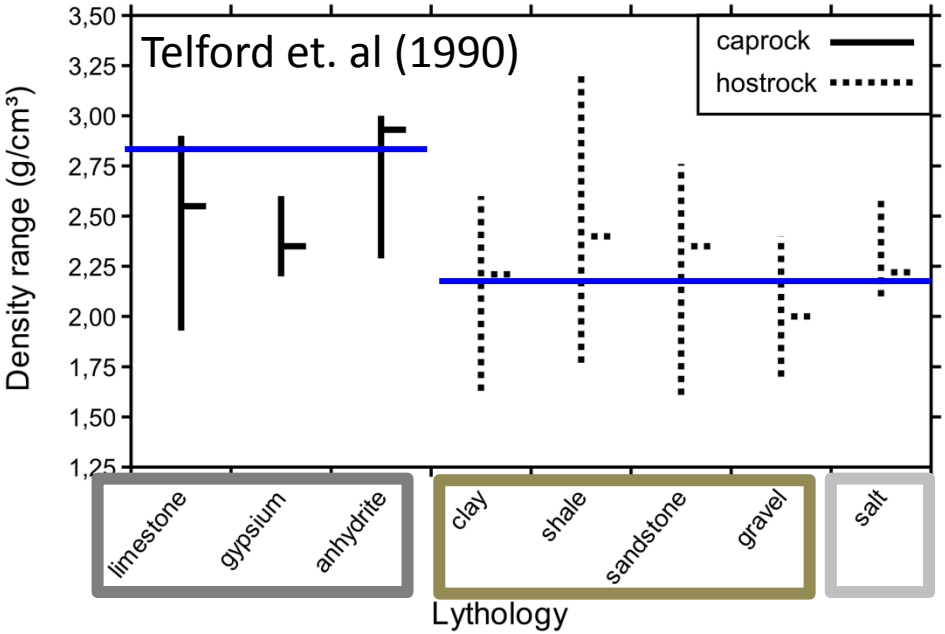
Aplicação a dados reais (Gradiometria gravimétrica)

Esboço da subsuperfície

topo = 160 m (Ennen e Hall, 2011)

Marfurt et. al (2004)
Coker (2006)

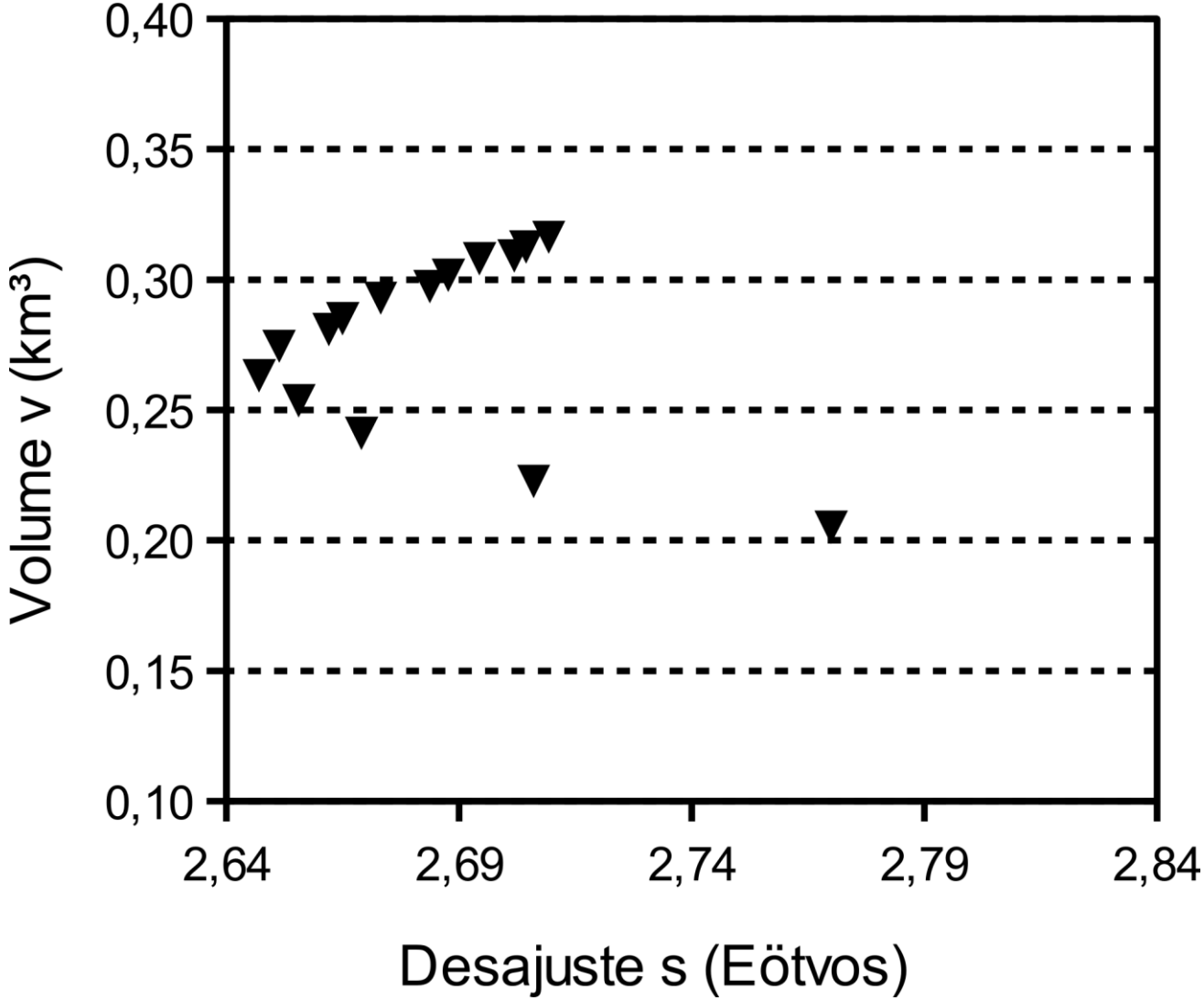




Hipótese 2:

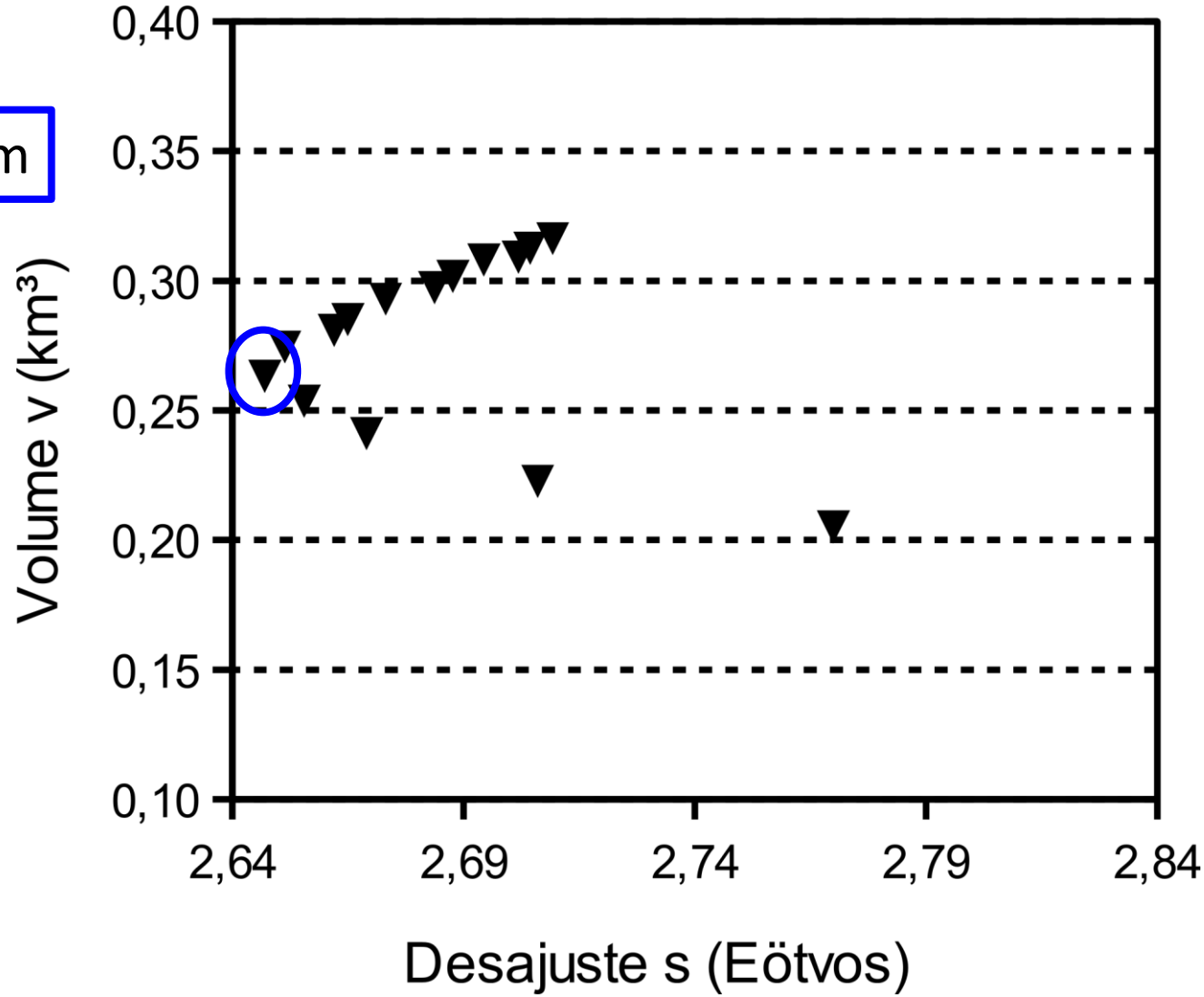
- $\rho_{caprock}$ = 2,85 g/cm³
- $\rho_{sedimentos}$ = 2,20 g/cm³
- ρ_{sal} = 2,20 g/cm³

Aplicação a dados reais (Gradiometria gravimétrica)

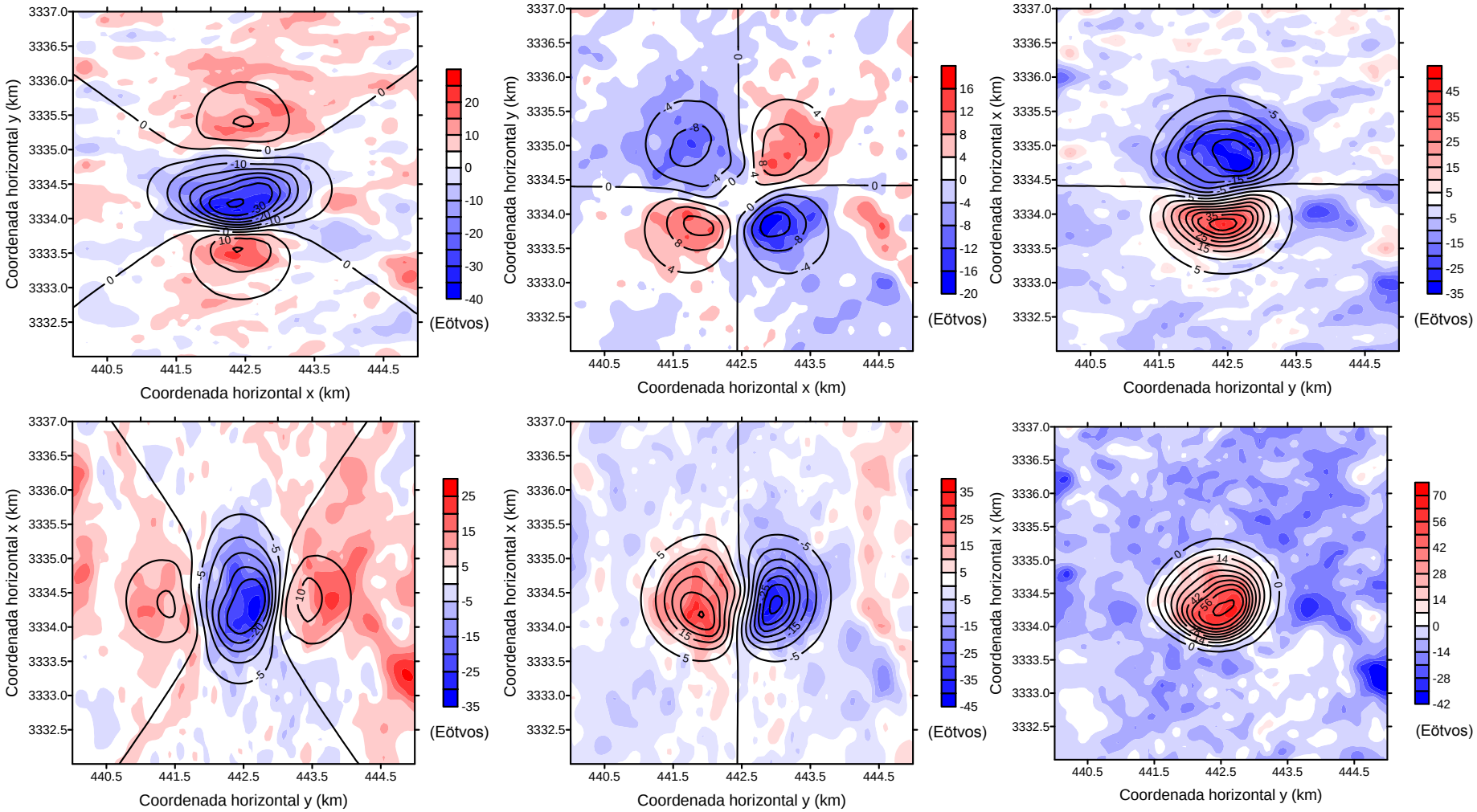


Aplicação a dados reais (Gradiometria gravimétrica)

z = 380 m

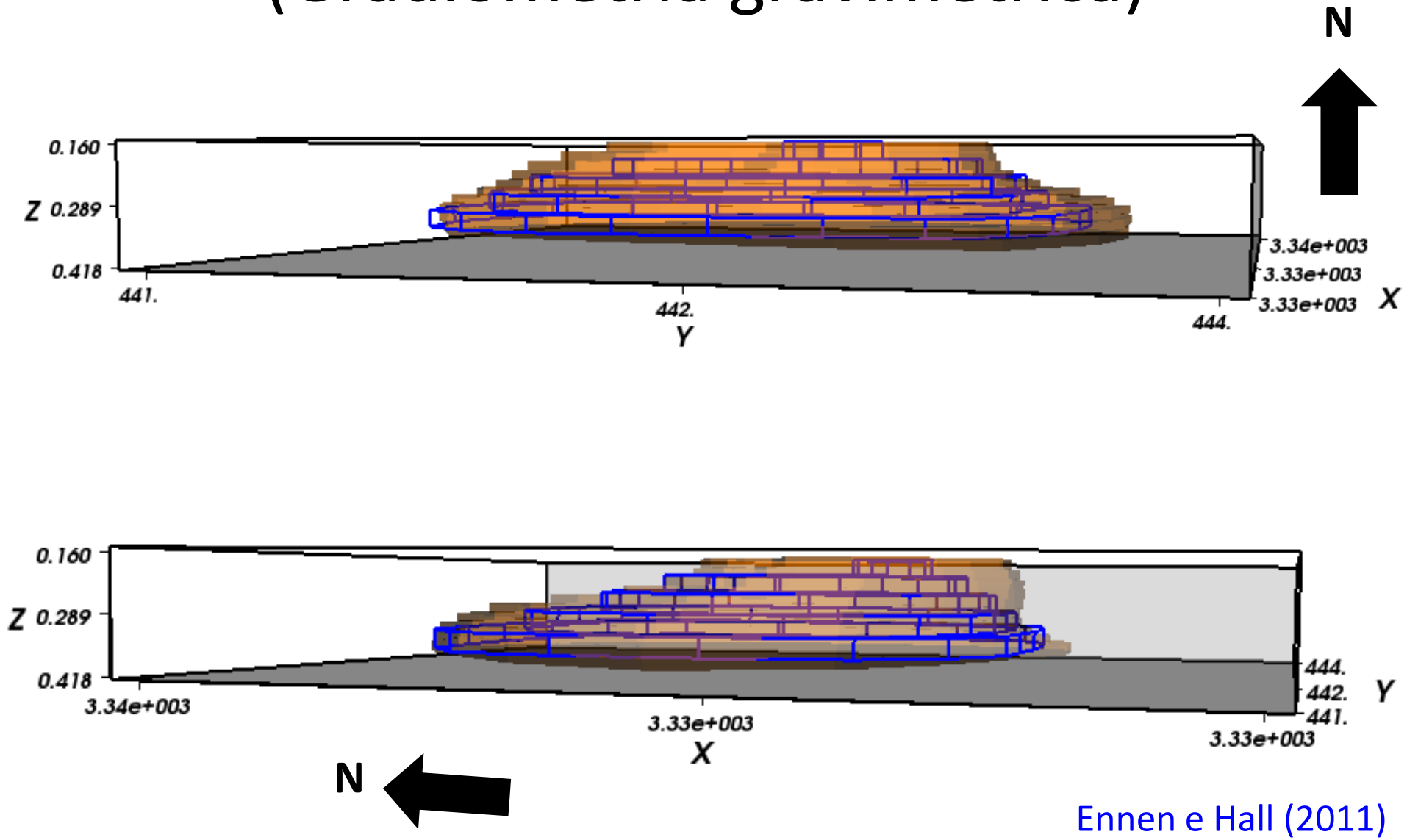


Aplicação a dados reais (Gradiometria gravimétrica)



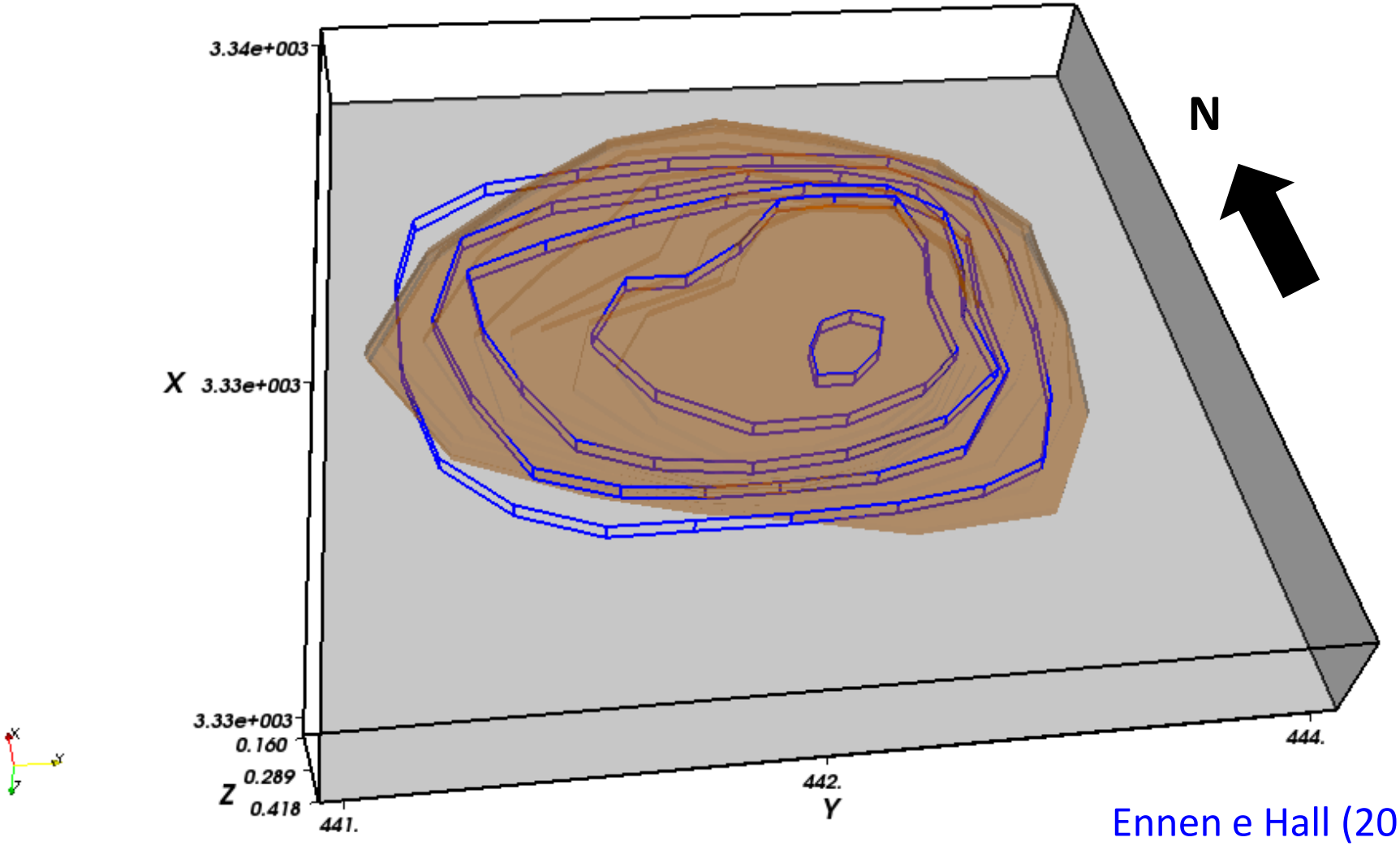
Dados fornecidos pela Bell Geospace

Aplicação a dados reais (Gradiometria gravimétrica)



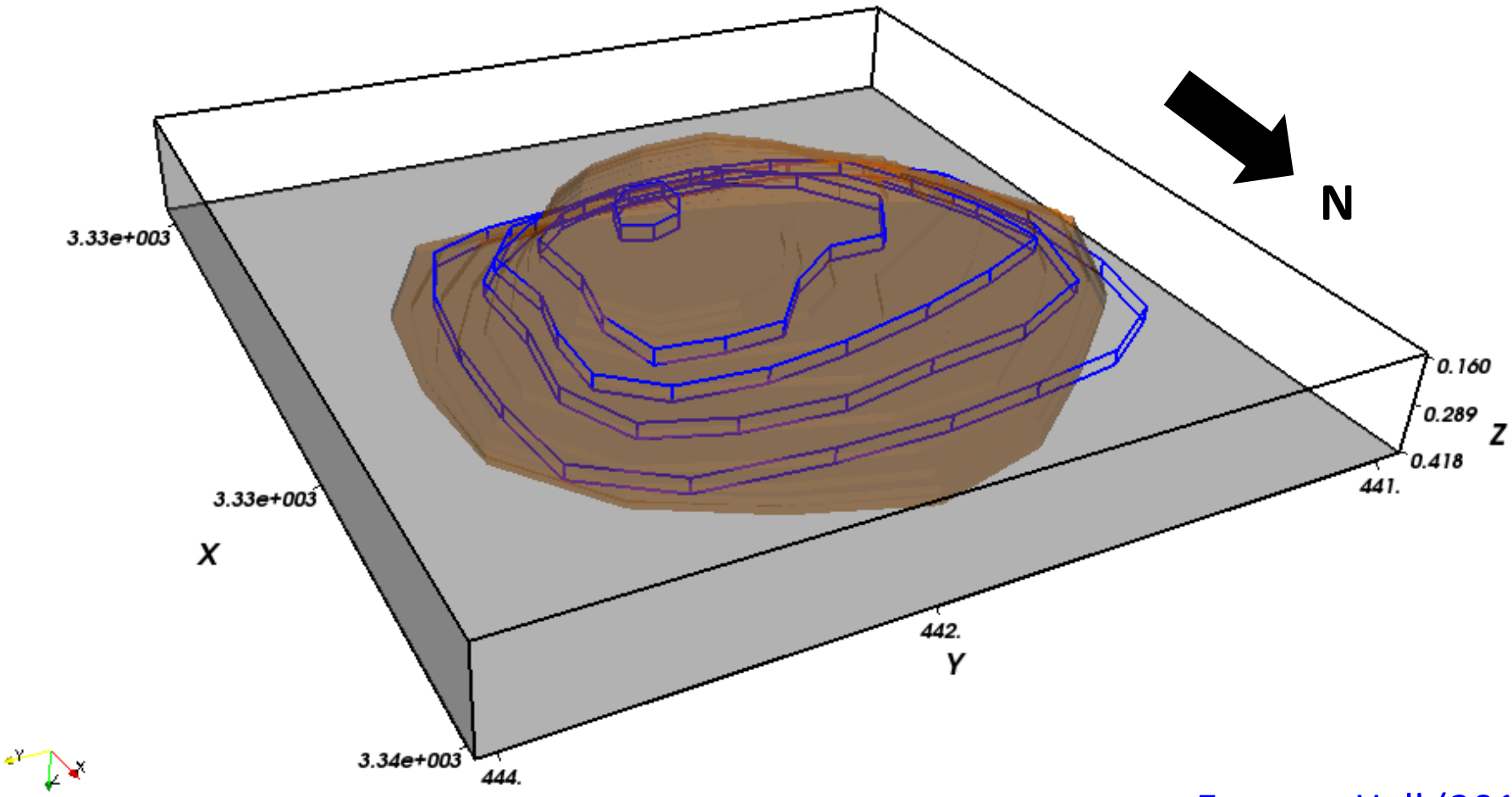
Ennen e Hall (2011)

Aplicação a dados reais (Gradiometria gravimétrica)



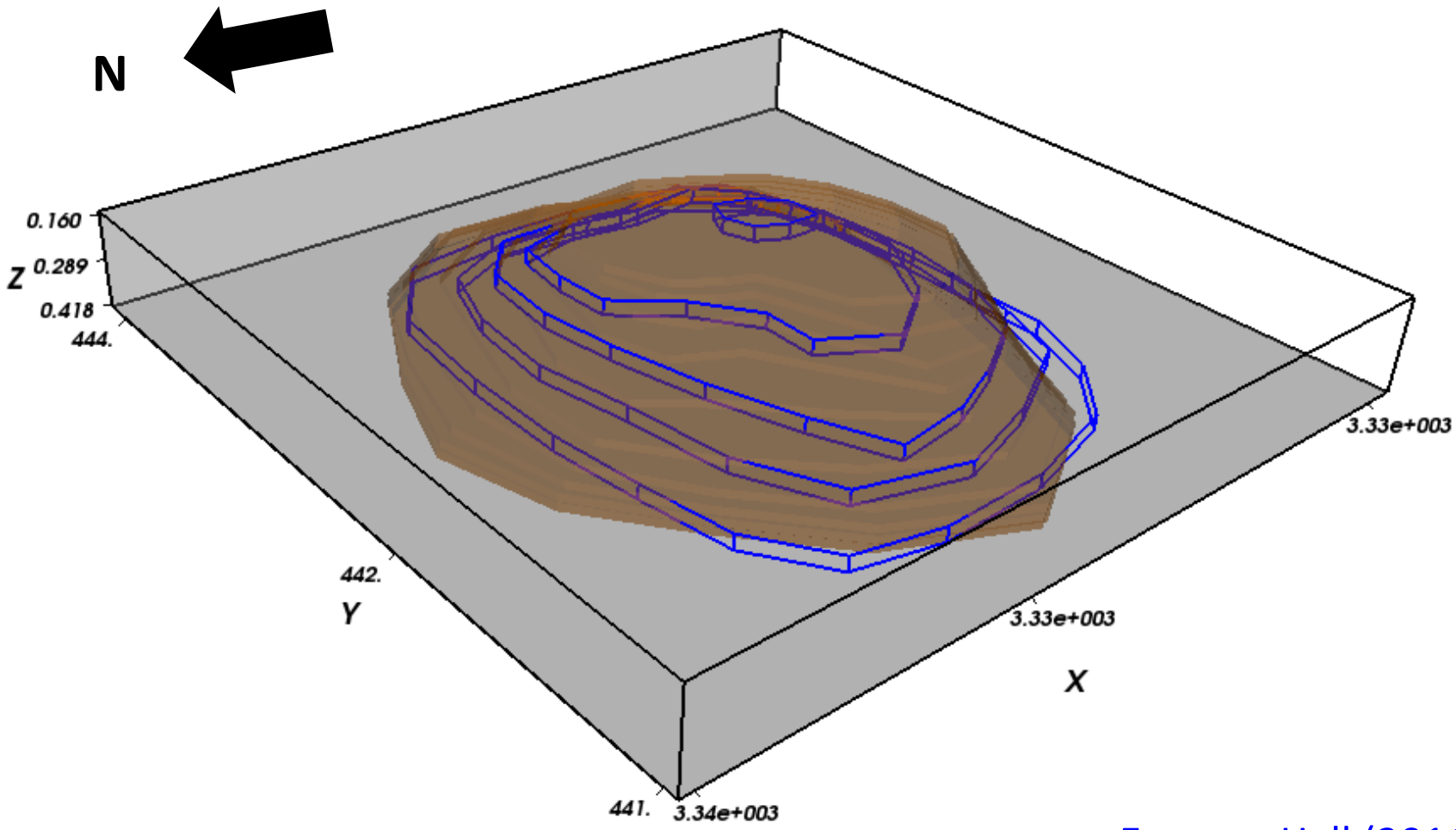
Ennen e Hall (2011)

Aplicação a dados reais (Gradiometria gravimétrica)



Ennen e Hall (2011)

Aplicação a dados reais (Gradiometria gravimétrica)



Ennen e Hall (2011)

Conclusões

- Apresentamos um novo método para a inversão de dados de campos potenciais para a determinação da geometria de corpos homogêneos e isolados
- Testes com dados sintéticos comprovam a eficiência do método
- A curva v x s se mostrou útil na determinação da *profundidade máxima ótima* para o modelo interpretativo
- A interpretação dos dados reais sobre o domo de sal Vinton está consistente com interpretações anteriores
- Uma melhor interpretação dos dados reais sobre o domo de sal Vinton exige mais informação a priori

Conclusões

- Apresentamos um novo método para a inversão de dados de campos potenciais para a determinação da geometria de corpos homogêneos e isolados
- Testes com dados sintéticos comprovam a eficiência do método
- A curva v x s se mostrou útil na determinação da *profundidade máxima ótima* para o modelo interpretativo
- A interpretação dos dados reais sobre o domo de sal Vinton está consistente com interpretações anteriores
- Uma melhor interpretação dos dados reais sobre o domo de sal Vinton exige mais informação a priori

Conclusões

- Apresentamos um novo método para a inversão de dados de campos potenciais para a determinação da geometria de corpos homogêneos e isolados
- Testes com dados sintéticos comprovam a eficiência do método
- A curva v x s se mostrou útil na determinação da *profundidade máxima ótima* para o modelo interpretativo e na análise da resolução dos dados
- A interpretação dos dados reais sobre o domo de sal Vinton está consistente com interpretações anteriores
- Uma melhor interpretação dos dados reais sobre o domo de sal Vinton exige mais informação a priori

Conclusões

- Apresentamos um novo método para a inversão de dados de campos potenciais para a determinação da geometria de corpos homogêneos e isolados
- Testes com dados sintéticos comprovam a eficiência do método
- A curva v x s se mostrou útil na determinação da *profundidade máxima ótima* para o modelo interpretativo e na análise da resolução dos dados
- A interpretação dos dados reais sobre o domo de sal Vinton está consistente com interpretações anteriores
- Uma melhor interpretação dos dados reais sobre o domo de sal Vinton exige mais informação a priori

Conclusões

- Apresentamos um novo método para a inversão de dados de campos potenciais para a determinação da geometria de corpos homogêneos e isolados
- Testes com dados sintéticos comprovam a eficiência do método
- A curva v x s se mostrou útil na determinação da *profundidade máxima ótima* para o modelo interpretativo e na análise da resolução dos dados
- A interpretação dos dados reais sobre o domo de sal Vinton está consistente com interpretações anteriores
- Uma melhor interpretação dos dados reais sobre o domo de sal Vinton exige mais informação a priori

Referências

ENNEN, C.; HALL, S. Structural mapping of the Vinton Salt dome, Louisiana, using gravity gradiometry data. In.: SEG San Antonio 2011 Annual Meeting, 2011, San Antonio. **SEG San Antonio 2011 Annual Meeting**, SEG, p. 830-835.

OLIVEIRA JR, V. C.; BARBOSA, V. C. F.; SILVA, J. B. C. Source geometry estimation using the mass excess criterion to constraint 3-D radial inversion of gravity data. **Geophysical Journal International**. v. 187, p. 754-772, 2011.

PLOUFF, D. Gravity and magnetic fields of polygonal prisms and application to magnetic terrain correction. **Geophysics**. v. 41, p. 727-741, 1976.

SILVA, J. B. C.; BARBOSA, V. C. F. Generalized radial inversion of 2D potential field data. **Geophysics**. v. 69, p. 1405-1413, 2004.

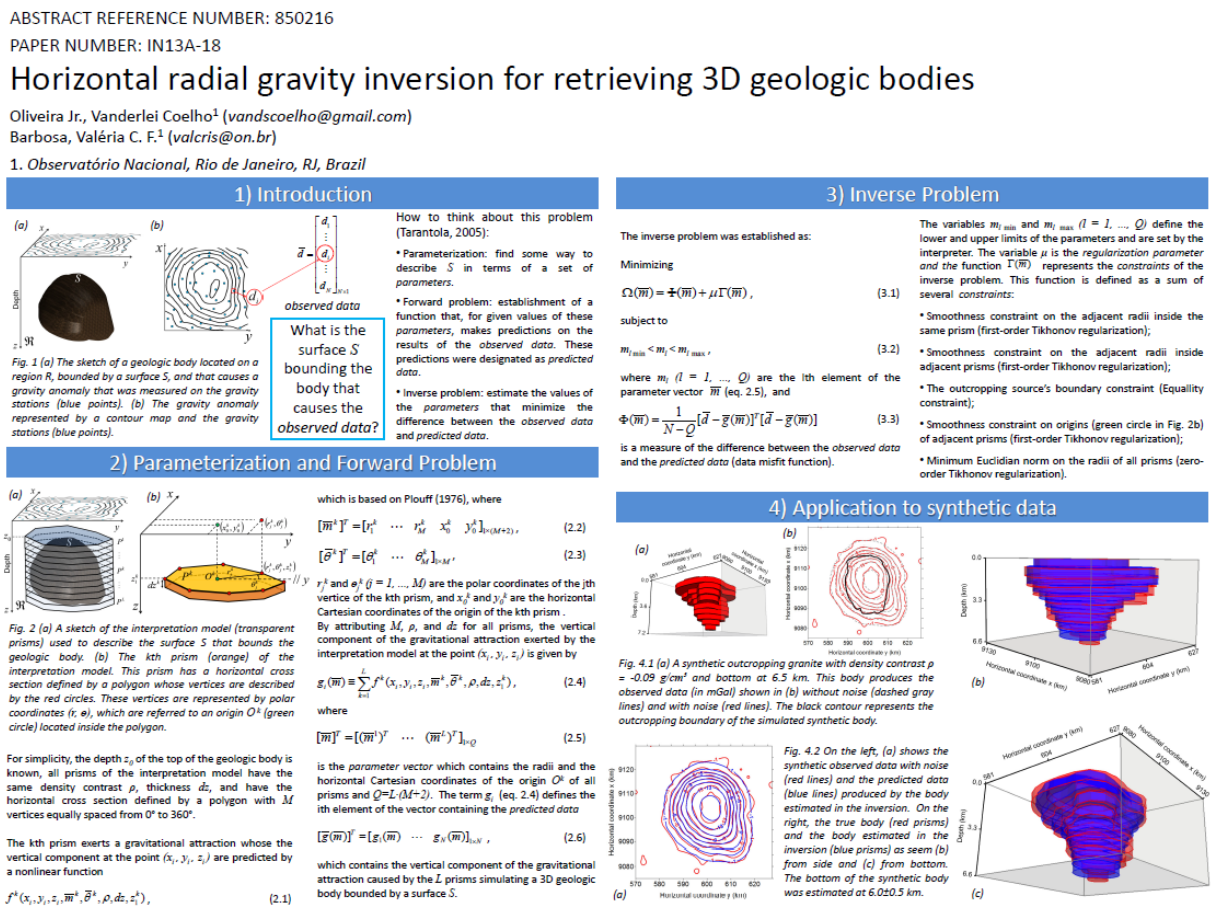
TELFORD, W. M.; GELDART, L. P.; SHERIFF, R. E. **Applied Geophysics**. 2ª ed. New York: Cambridge University Press, 1990. 750 p.

Produção científica

- AGU – Meeting of the Americas (2010)
- 12th International Congress of the SBGf (2011)
- SEG International Exposition and 81st Annual Meeting (2011)
- 73rd EAGE Conference & Exhibition incorporating SPE EUROPEC (2011)
- Artigo publicado na Geophysical Journal International (2011)

Produção científica

- AGU – Meeting of the Americas (2010)
- 12th International Co the SBGf (2011)
- SEG International Exp and 81st Annual Mee (2011)
- 73rd EAGE Conferenc Exhibition incorporat EUROPEC (2011)
- Artigo publicado na Geophysical Journal International (2011)



ABSTRACT REFERENCE NUMBER: 850216

PAPER NUMBER: IN13A-18

Horizontal radial gravity inversion for retrieving 3D geologic bodies

Oliveira Jr., Vanderlei Coelho[1] (*vandscoelho@gmail.com*)
Barbosa, Valéria C. F.[1] (*valcris@on.br*)

1. *Observatório Nacional, Rio de Janeiro, RJ, Brazil*

1) Introduction

observed data

What is the surface S bounding the body that causes the *observed data*?

Fig. 1 (a) The sketch of a geologic body located on a region R, bounded by a surface S, and that causes a gravity anomaly that was measured on the gravity stations (blue points). (b) The gravity anomaly represented by a contour map and the gravity stations (blue points).

How to think about this problem (Tarantola, 2005):

- Parameterization: find some way to describe S in terms of a set of *parameters*.
- Forward problem: establishment of a function that, for given values of these *parameters*, makes predictions on the results of the *observed data*. These predictions were designated as *predicted data*.
- Inverse problem: estimate the values of the *parameters* that minimize the difference between the *observed data* and *predicted data*.

2) Parameterization and Forward Problem

Fig. 2 (a) A sketch of the interpretation model (transparent prisms) used to describe the surface S that bounds the geologic body. (b) The kth prism (orange) of the interpretation model. This prism has a horizontal cross section defined by a polygon whose vertices are described by the red circles. These vertices are represented by polar coordinates (r, θ), which are referred to an origin O k (green circle) located inside the polygon.

For simplicity, the depth z_0 of the top of the geologic body is known, all prisms of the interpretation model have the same density contrast ρ, thickness dz, and have the horizontal cross section defined by a polygon with M vertices equally spaced from 0° to 360°.

The kth prism exerts a gravitational attraction whose the vertical component at the point (x_i, y_i, z_i) are predicted by a nonlinear function

$$f^k(x_i, y_i, z_i, \overline{m}^k, \overline{\theta}^k, \rho, dz, z_i^k), \quad (2.1)$$

which is based on Plouff (1976), where

$$[\overline{m}^k]^T = [r_1^k \ \cdots \ r_M^k \ \ x_0^k \ \ y_0^k]_{1\times(M+2)}, \quad (2.2)$$

$$[\overline{\theta}^k]^T = [\theta_1^k \ \cdots \ \theta_M^k]_{1\times M}, \quad (2.3)$$

r_j^k and θ_j^k ($j = 1, \ldots, M$) are the polar coordinates of the jth vertice of the kth prism, and x_0^k and y_0^k are the horizontal Cartesian coordinates of the origin of the kth prism .

By attributing M, ρ, and dz for all prisms, the vertical component of the gravitational attraction exerted by the interpretation model at the point (x_i, y_i, z_i) is given by

$$g_i(\overline{m}) \equiv \sum_{k=1}^{L} f^k(x_i, y_i, z_i, \overline{m}^k, \overline{\theta}^k, \rho, dz, z_i^k), \quad (2.4)$$

where

$$[\overline{m}]^T = [(\overline{m}^1)^T \ \cdots \ (\overline{m}^L)^T]_{1\times Q} \quad (2.5)$$

is the *parameter vector* which contains the radii and the horizontal Cartesian coordinates of the origin O^k of all prisms and $Q=L\cdot(M+2)$. The term g_i (eq. 2.4) defines the ith element of the vector containing the *predicted data*

$$[\overline{g}(\overline{m})]^T = [g_1(\overline{m}) \ \cdots \ g_N(\overline{m})]_{1\times N}, \quad (2.6)$$

which contains the vertical component of the gravitational attraction caused by the L prisms simulating a 3D geologic body bounded by a surface S.

3) Inverse Problem

The inverse problem was established as:

Minimizing

$$\Omega(\overline{m}) = \Phi(\overline{m}) + \mu\Gamma(\overline{m}), \quad (3.1)$$

subject to

$$m_{l\,\min} < m_l < m_{l\,\max}, \quad (3.2)$$

where m_l ($l = 1, \ldots, Q$) are the lth element of the parameter vector $\overline{m}$ (eq. 2.5), and

$$\Phi(\overline{m}) = \frac{1}{N-Q}[\overline{d} - \overline{g}(\overline{m})]^T[\overline{d} - \overline{g}(\overline{m})] \quad (3.3)$$

is a measure of the difference between the *observed data* and the *predicted data* (data misfit function).

The variables $m_{l\,\min}$ and $m_{l\,\max}$ ($l = 1, \ldots, Q$) define the lower and upper limits of the parameters and are set by the interpreter. The variable μ is the *regularization parameter and the* function $\Gamma(\overline{m})$ represents the *constraints* of the inverse problem. This function is defined as a sum of several *constraints*:

- Smoothness constraint on the adjacent radii inside the same prism (first-order Tikhonov regularization);
- Smoothness constraint on the adjacent radii inside adjacent prisms (first-order Tikhonov regularization);
- The outcropping source's boundary constraint (Equality constraint);
- Smoothness constraint on origins (green circle in Fig. 2b) of adjacent prisms (first-order Tikhonov regularization);
- Minimum Euclidian norm on the radii of all prisms (zero-order Tikhonov regularization).

4) Application to synthetic data

Fig. 4.1 (a) A synthetic outcropping granite with density contrast ρ = -0.09 g/cm³ and bottom at 6.5 km. This body produces the observed data (in mGal) shown in (b) without noise (dashed gray lines) and with noise (red lines). The black contour represents the outcropping boundary of the simulated synthetic body.

Fig. 4.2 On the left, (a) shows the synthetic observed data with noise (red lines) and the predicted data (blue lines) produced by the body estimated in the inversion. On the right, the true body (red prisms) and the body estimated in the inversion (blue prisms) as seem (b) from side and (c) from bottom. The bottom of the synthetic body was estimated at 6.0±0.5 km.

Produção científica

- AGU – Meeting of the Americas (2010)
- 12th International Congress of the SBGf (2011)
- SEG International Exposition and 81st Annual Meeting (2011)
- 73rd EAGE Conference & Exhibition incorporating SPE EUROPEC (2011)
- Artigo publicado na Geophysical Journal International (2011)

Estimação da geometria de corpos 3D via inversão gravimétrica radial e massa anômala

Vanderlei C. Oliveira Jr. e Valéria C. F. Barbosa (ON/MCT)

Copyright 2011, SBGf - Sociedade Brasileira de Geofísica

This paper was prepared for presentation during the 12th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 15-19, 2011.

Contents of this paper were reviewed by the Technical Committee of the 12th International Congress of the Brazilian Geophysical Society and do not necessarily represent any position of the SBGf, its officers or members. Electronic reproduction or storage of any part of this paper for commercial purposes without the written consent of the Brazilian Geophysical Society is prohibited.

Abstract

We present a new 3D gravity-inversion approach that retrieves the geometry of an isolated geologic source with known density contrast and depth of the top. We approximate the source by an interpretation model formed by an ensemble of vertically juxtaposed right prisms whose horizontal cross-sections are described by polygons. The horizontal coordinates defining the vertices of the polygon of each prism are the parameters to be estimated by inversion and the depth of the bottom of the interpretation model is estimated by a new criterion based on the curve of the estimated total-anomalous mass versus the data-misfit measure. Applications to both synthetic and field data sets show that our method obtains stable solutions that recover the geometry of the 3D source and fit the data, even in the case of a complex simulated body with variable dips and strikes. Our method has the advantage of requiring no constraints favoring homogeneity and compactness, which makes it operationally simple.

Introdução

Poucos autores propuseram métodos de inversão gravimétrica para recuperar a geometria de corpos geológicos 3D (ou 2D) sem estimar uma distribuição 3D (ou 2D) de densidade Nestes poucos métodos, o modelo interpretativo é formado por um prisma horizontalmente infinito e com seção transversal poligonal, no caso de um corpo 2D (Silva e Barbosa, 2004), ou por um corpo poliédrico, no caso de um corpo 3D (Moraes e Hansen, 2001). Nestes casos, a propriedade física (contraste de densidade) do corpo é considerada conhecida e os parâmetros a serem estimados são os contornos do polígono (no caso 2D) ou do poliedro (no caso 3D), que definem o modelo interpretativo.

Neste trabalho, apresentamos um novo método de inversão gravimétrica 3D que é uma generalização do método desenvolvido por Silva e Barbosa (2004) e usa um modelo interpretativo formado por um conjunto de prismas 3D e justapostos verticalmente. Para obter estimativas únicas e estáveis, impusemos vínculos sobre a forma da fonte. Embora o método proposto produza estimativas estáveis e que ajustam os dados dentro da precisão experimental, estas dependem da profundidade máxima estabelecida para o modelo interpretativo. Para reduzir esta ambiguidade, propusemos um novo critério baseado na curva da estimativa da massa anômala total versus uma medida de desajuste dos dados. Testes com dados sintéticos mostram que o método pode ser útil na estimação da geometria de corpos 3D complexos e isolados. O método também foi aplicado aos dados reais sobre o greenstone belt Matsitama, Botsuana. A estimativa ajusta os dados de forma aceitável e mostra uma intrusão inclinada com mergulhos e strikes variáveis e profundidade máxima de 8,0 km.

Metodologia

Problema direto

Seja g_i^{obs} a i-ésima observação, no ponto (x_i, y_i, z_i), da anomalia de gravidade produzida por uma fonte localizada em subsuperfície e com profundidade z_0 do topo conhecida. Consideramos que o contraste de densidade entre a fonte geológica e as rochas encaixantes seja constante ou variável com a profundidade. Para delinear o contorno 3D da fonte, aproximamos o seu volume por um conjunto de L prismas retos e justapostos verticalmente. O contraste de densidade de cada prisma, ρ^k, $k = 1, \ldots, L$, é considerado constante e conhecido. Cada prisma tem a espessura dz constante e conhecida e a seção horizontal descrita por um polígono com um número M fixo de vértices igualmente espaçados entre 0° e 360°. Os vértices do polígono são descritos em coordenadas polares referidas a uma origem arbitrária O^k dentro do polígono (Figura 1).

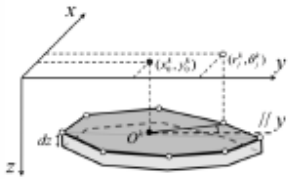


Figura 1: Representação esquemática do k-ésimo prisma do modelo interpretativo. Os círculos brancos representam os vértices e o círculo preto O^k representa a origem arbitrária do polígono que define a seção horizontal do k-ésimo prisma.

As distâncias radiais dos vértices (r_j^k, $j = 1, \ldots, M$, $k = 1, \ldots, L$) e as coordenadas Cartesianas horizontais (x_0^k and y_0^k, $k = 1, \ldots, L$) da origem arbitrária O^k, $k = 1, \ldots, L$, do conjunto de L prismas verticalmente justapostos são os elementos do vetor P-dimensional de parâmetros $\mathbf{m}$, em

Produção científica

- AGU – Meeting of the Americas (2010)
- 12th International Congress of the SBGf (2011)
- SEG International Exposition and 81st Annual Meeting (2011)
- 73rd EAGE Conference & Exhibition incorporating SPE EUROPEC (2011)
- Artigo publicado na Geophysical Journal International (2011)

Radial gravity inversion constrained by total anomalous mass excess for retrieving 3D bodies

Vanderlei C. Oliveira Jr. and Valéria C. F. Barbosa, Observatório Nacional*

Summary

We present a new 3D gravity-inversion approach that retrieves the geometry of an isolated geologic source with known density contrast and depth of the top. We approximate the source by an interpretation model formed by an ensemble of vertically juxtaposed right prisms whose horizontal cross-sections are described by unknown polygons. The vertices of the polygon of each prism are described by polar coordinates with an unknown origin within the prism. Our method estimates the radii associated with the vertices of each polygon and the horizontal Cartesian coordinates of the unknown origin. The depth of the bottom of the interpretation model is estimated by a new criterion based on the curve of the estimated total-anomalous mass versus the data-misfit measure. Applications to both synthetic and field data sets show that our method obtains stable solutions that recover the geometry of the 3D source and fit the data, even in the case of a complex simulated body with variable dips and strikes. Our method has the advantage of requiring no constraints favoring homogeneity and compactness, which makes it operationally simple.

Introduction

A few authors have proposed gravity-inversion methods to retrieve the geometry of 3D (or 2D) geologic sources that do not estimate a 3D density-contrast distribution. In these methods, the interpretation model consists either of a horizontally infinite prism with polygonal cross section (Silva and Barbosa, 2004) or of a polyhedral body (Moraes and Hansen, 2001) that delineates the contour of, respectively, 2D or 3D sources. Hence, the physical property (density contrast) of the body is assumed to be known and the parameters to be estimated are the vertices of the polygonal cross section (in the 2D case) or of the polyhedral body (in the 3D case) that define the interpretation model. Here, we present a new 3D gravity-inversion method that is a generalization of the Silva and Barbosa's (2004) method and uses an interpretation model formed by a set of vertically juxtaposed 3D prisms. To obtain unique and stable estimates, we impose constraints on the source shape. Although the proposed method estimates a stable solution that fits the observed gravity anomaly within the measurement errors, it will depend on the maximum depth assumed for the interpretation model. To reduce this ambiguity, we propose a new criterion based on the curve of the estimated total-anomalous mass versus the data-misfit measure. Tests conducted with synthetic data shows that the method can be of utility in estimating the geometry of complex 3D isolated source. The method has also been applied to a real gravity-data set over greenstone rocks in Matsitama (Botswana). The estimated source fits acceptably the gravity anomaly and retrieves a dipping intrusion with variable dips and strikes and with maximum bottom depth of 8.0 km.

Methodology

Forward problem

Let g_i^{obs} be the ith observation of the gravity anomaly at the point (x_i, y_i, z_i) produced by a 3D outcropping source (or a buried source, but with a known depth to the top at z_0) confined beneath the earth's surface. We assume that the density contrast between the geologic source and the host rocks is either constant or variable with depth. To delineate the contour of the 3D source we approximate its volume by a set of L vertical, juxtaposed 3D prisms in the vertical direction. The density contrast of each prism, ρ^k, $k = 1, \ldots, L$, is assumed constant and known. Each prism has a constant and known thickness dz and a horizontal cross-section described by a polygon with a fixed number M of vertices equally spaced from 0° to 360°. The vertices of the polygon are described in polar coordinates referred to an arbitrary origin O^k within the polygon (Figure 1).

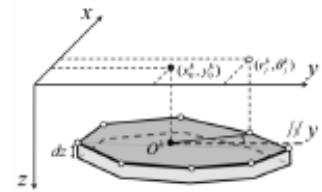


Figure 1: Schematic representation of the kth prism of the interpretation model. The white circles represent the vertices and the black circle O^k represents the arbitrary origin of the polygon defining the horizontal cross-section of the kth prism.

The radii of the vertices (r_j^k, $j = 1, \ldots, M$, $k = 1, \ldots, L$) and the horizontal Cartesian coordinates (x_0^k and y_0^k, $k = 1, \ldots, L$) of the arbitrary origins O^k, $k = 1, \ldots, L$, of the ensemble of L vertically stacked prisms are the elements of the P-dimensional parameter vector $\mathbf{m}$ where $P = L(M + 2)$. So, the theoretical vertical component of the gravity field, at the ith observation point (x_i, y_i, z_i), caused by the set of L 3D prisms is given by

© 2011 SEG
SEG San Antonio 2011 Annual Meeting
Downloaded 09 Sep 2012 to 200.20.187.15. Redistribution subject to SEG license or copyright; see Terms of Use at http://segdl.org/

Produção científica

- AGU – Meeting of the Americas (2010)
- 12th International Congress of the SBGf (2011)
- SEG International Exposition and 81st Annual Meeting (2011)
- 73rd EAGE Conference & Exhibition incorporating SPE EUROPEC (2011)
- Artigo publicado na Geophysical Journal International (2011)

Vienna '11

P285

3D Radial Inversion of Gravity Data for Estimating the Source's Geometry

V.C. Oliveira Jr* (Observatorio National) & V.C.F. Barbosa (Observatorio National)

SUMMARY

We present a new 3D gravity-inversion approach that retrieves the geometry of an isolated geologic source with density contrast and depth of the top known. We approximate the source by an ensemble of vertically juxtaposed 3D right prisms whose horizontal cross-sections are described by polygons and thicknesses are fixed. The polygon vertices of each prism are described by polar coordinates with an unknown origin within the prism. Our method estimates the horizontal Cartesian coordinates of the unknown origin and the radii of the vertices of each polygon. To obtain stable estimates we impose constraints on the source shape. The estimated solution, despite being stable and fitting the data, will depend on the maximum depth assumed for the set of 3D prisms. We also propose a new criterion to determine the optimum depth-to-bottom estimate of the source based on the curve of the estimated total-anomalous mass versus estimated data-misfit measure for the range of different tentative maximum depths considered. Applications to both synthetic and field data show that our method obtains stable solutions that recover the geometry of the 3D source and fit the data, even in the case of a complex simulated body with variable dips and strikes.

Produção científica

- AGU – Meeting of the Americas (2010)
- 12th International Congress of the SBGf (2011)
- SEG International Exposition and 81st Annual Meeting (2011)
- 73rd EAGE Conference & Exhibition incorporating SPE EUROPEC (2011)
- Artigo publicado na Geophysical Journal International (2011)

Geophysical Journal International

Geophys. J. Int. (2011) 187, 754–772 doi: 10.1111/j.1365-246X.2011.05172.x

Source geometry estimation using the mass excess criterion to constrain 3-D radial inversion of gravity data

Vanderlei C. Oliveira, Jr,[1] Valéria C. F. Barbosa[1] and João B. C. Silva[2]

[1]*Observatório Nacional, Gal. José Cristino, 77, São Cristóvão, Rio de Janeiro, 20921-400, Brazil. E-mail: vandrcoelho@gmail.com*
[2] *Universidade Federal do Pará, Dep. Geofísica CG, Caixa Postal 1611, 66017-900, Belém, Pará, Brazil*

Accepted 2011 July 26. Received 2011 July 26; in original form 2010 October 13

GJI Gravity, geodesy and tides

SUMMARY

We present a gravity-inversion method for estimating the geometry of an isolated 3-D source, assuming prior knowledge about its top and density contrast. The subsurface region containing the geological sources is discretized into an ensemble of 3-D vertical prisms juxtaposed in the vertical direction of a right-handed coordinate system. The prisms' thicknesses and density contrasts are known, but their horizontal cross-sections are described by unknown polygons. The horizontal coordinates of the polygon vertices approximately represent the edges of horizontal depth slices of the 3-D geological source. The polygon vertices of each prism are described by polar coordinates with an unknown origin within the prism. Our method estimates the horizontal Cartesian coordinates of the unknown origin and the radii associated with the vertices of each polygon for a fixed number of equally spaced central angles from 0° to 360°. By estimating these parameters from gravity data, we retrieve a set of vertically stacked prisms with polygonal horizontal sections that represents a set of juxtaposed horizontal depth slices of the estimated source. This set, therefore, approximates the 3-D source's geometry. To obtain stable estimates we impose constraints on the source shape. The judicious use of first-order Tikhonov regularization on either all or a few parameters allows estimating both vertical and inclined sources whose shapes can be isometric or anisometric. The estimated solution, despite being stable and fitting the data, will depend on the maximum depth assumed for the set of juxtaposed 3-D prisms. To reduce the class of possible solutions compatible with the gravity anomaly and the constraints, we use a criterion based on the relationship between the data-misfit measure and the estimated total-anomalous mass computed along successive inversions, using different tentative maximum depths for the set of assumed juxtaposed 3-D prisms. In applying this criterion, we plotted the curve of the estimated total-anomalous mass m_t versus data-misfit measure s for the range of different tentative maximum depths. The tentative value for the maximum depth producing the smallest value of data-misfit measure in the $m_t \times s$ curve is the best estimate of the true (or minimum) depth to the bottom of the source, depending on whether the true source produces a gravity anomaly that is able (or not) to resolve the depth to the source bottom. This criterion was theoretically deduced from Gauss' theorem. Tests with synthetic data shows that the correct depth-to-bottom estimate of the source is obtained if the minimum of s on the $m_t \times s$ curve is well defined; otherwise this criterion provides just a lower bound estimate of the source's depth to the bottom. These synthetic results show that the method efficiently recovers source geometries dipping at different angles. Test on real data from the Matsitama intrusive complex (Botswana) retrieved a dipping intrusion with variable dips and strikes and with bottom depth of 8.0 ± 0.5 km.

Key words: Numerical solutions; Inverse theory; Gravity anomalies and Earth structure.

1 INTRODUCTION

The reconstruction of 3-D (or 2-D) geological sources from a discrete set of gravity data measured at the Earth's surface usually follows two strategies. The first one is the interactive gravity forward modelling and the second strategy comprises the gravity-inversion methods.

The interactive gravity forward modelling consists in inferring a representation of the 3-D (or 2-D) geometry of geological sources in the subsurface that fits the observed gravity data. Hence, the

754

© 2011 Observatório Nacional
Geophysical Journal International © 2011 RAS

Considerações pessoais

- Este trabalho me ajudou a vislumbrar o estado da arte em minha área de pesquisa

- Tema de pesquisa pouco desenvolvido, sobretudo para dados magnéticos e de gradiometria gravimétrica (meu tema de tese)

- Possíveis desdobramentos da pesquisa:
  - Corpos alongados
  - Inversão conjunta
  - Múltiplos corpos

Considerações pessoais

- Este trabalho me ajudou a vislumbrar o estado da arte em minha área de pesquisa

- Tema de pesquisa pouco desenvolvido, sobretudo para dados magnéticos e de gradiometria gravimétrica (meu tema de tese)

- Possíveis desdobramentos da pesquisa:
  - Corpos alongados
  - Inversão conjunta
  - Múltiplos corpos

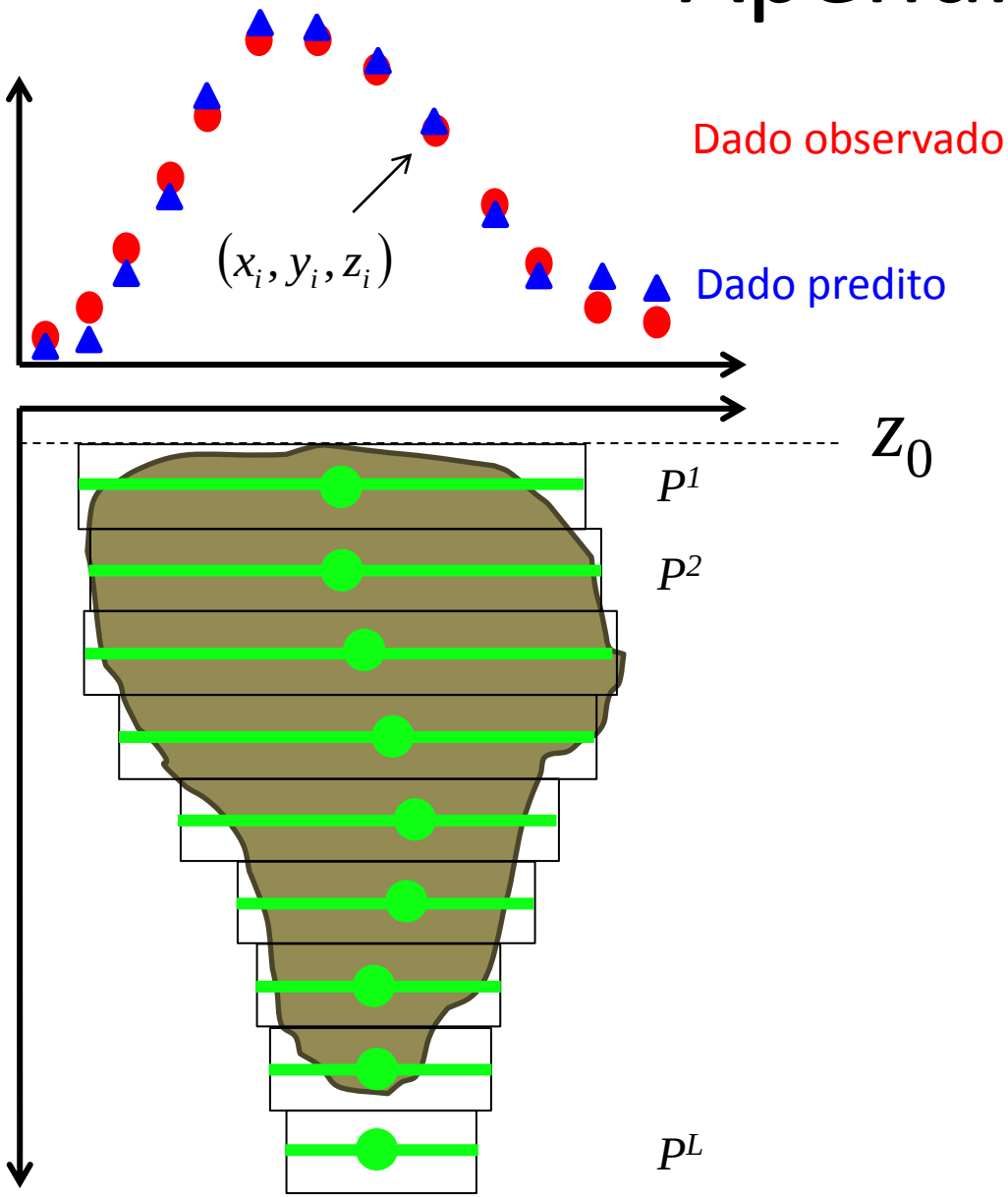
Considerações pessoais

- Este trabalho me ajudou a vislumbrar o estado da arte em minha área de pesquisa

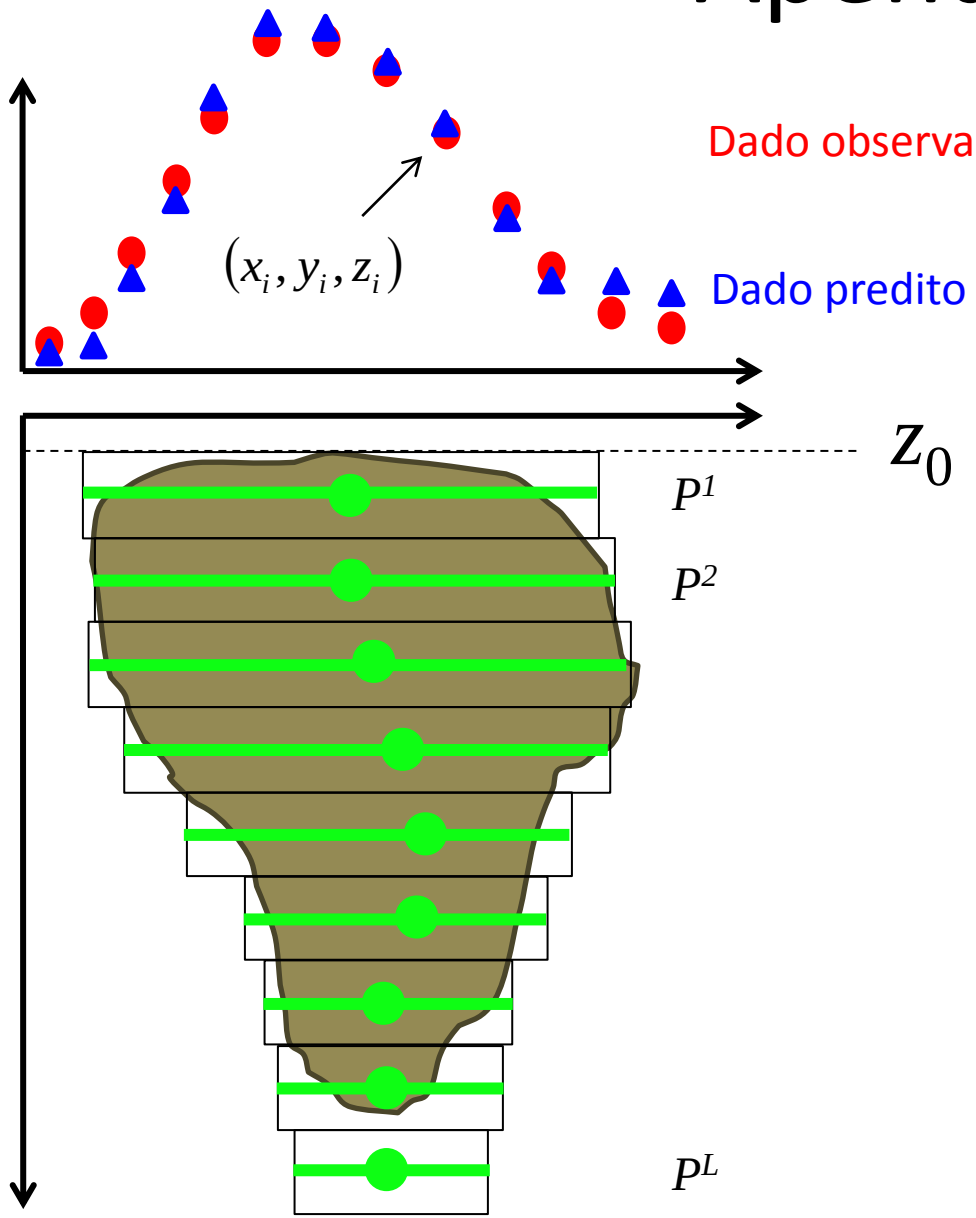
- Tema de pesquisa pouco desenvolvido, sobretudo para dados magnéticos e de gradiometria gravimétrica (meu tema de tese)

- Possíveis desdobramentos da pesquisa:
  - Corpos alongados
  - Inversão conjunta
  - Múltiplos corpos

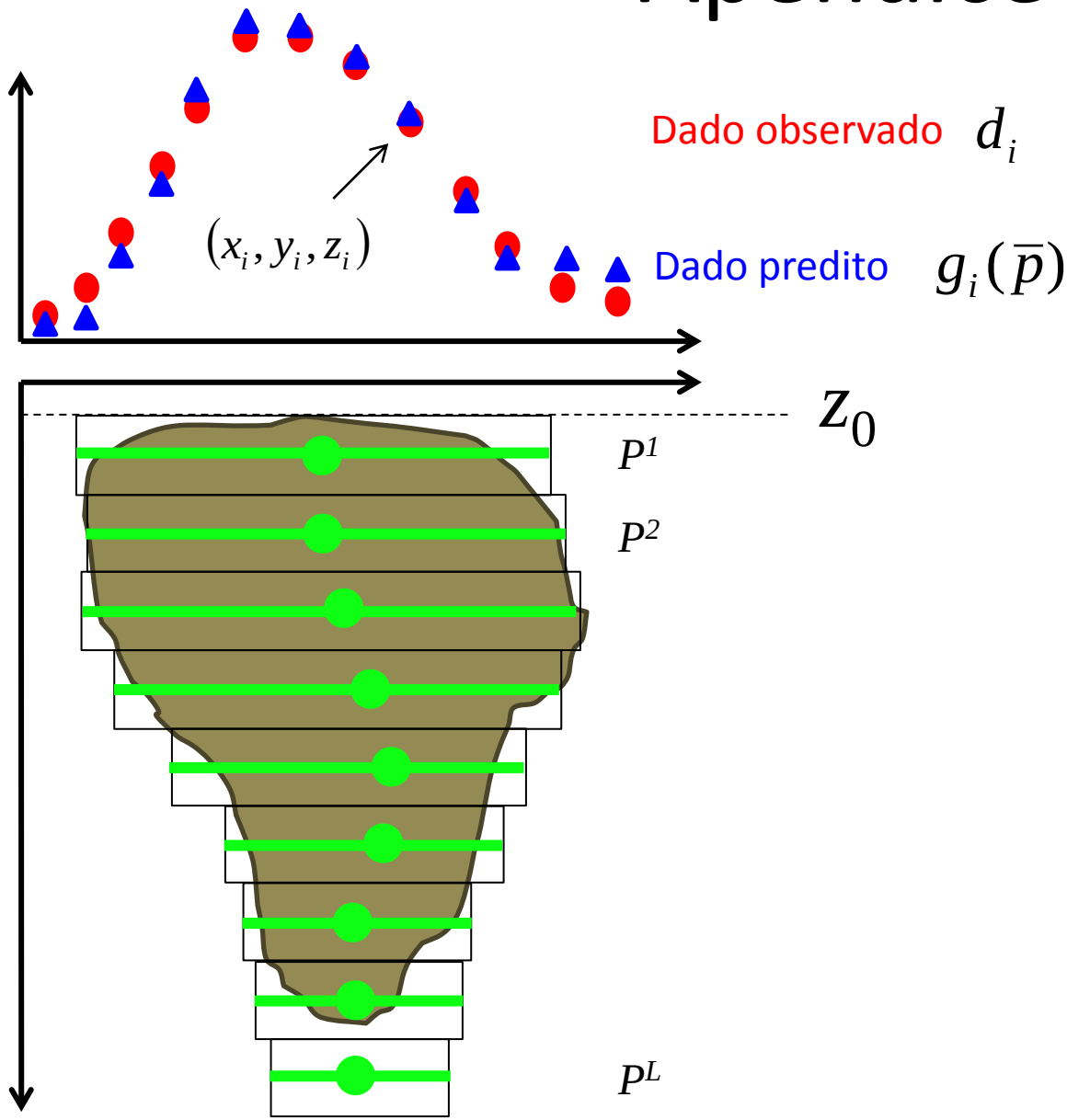
Apêndice 1



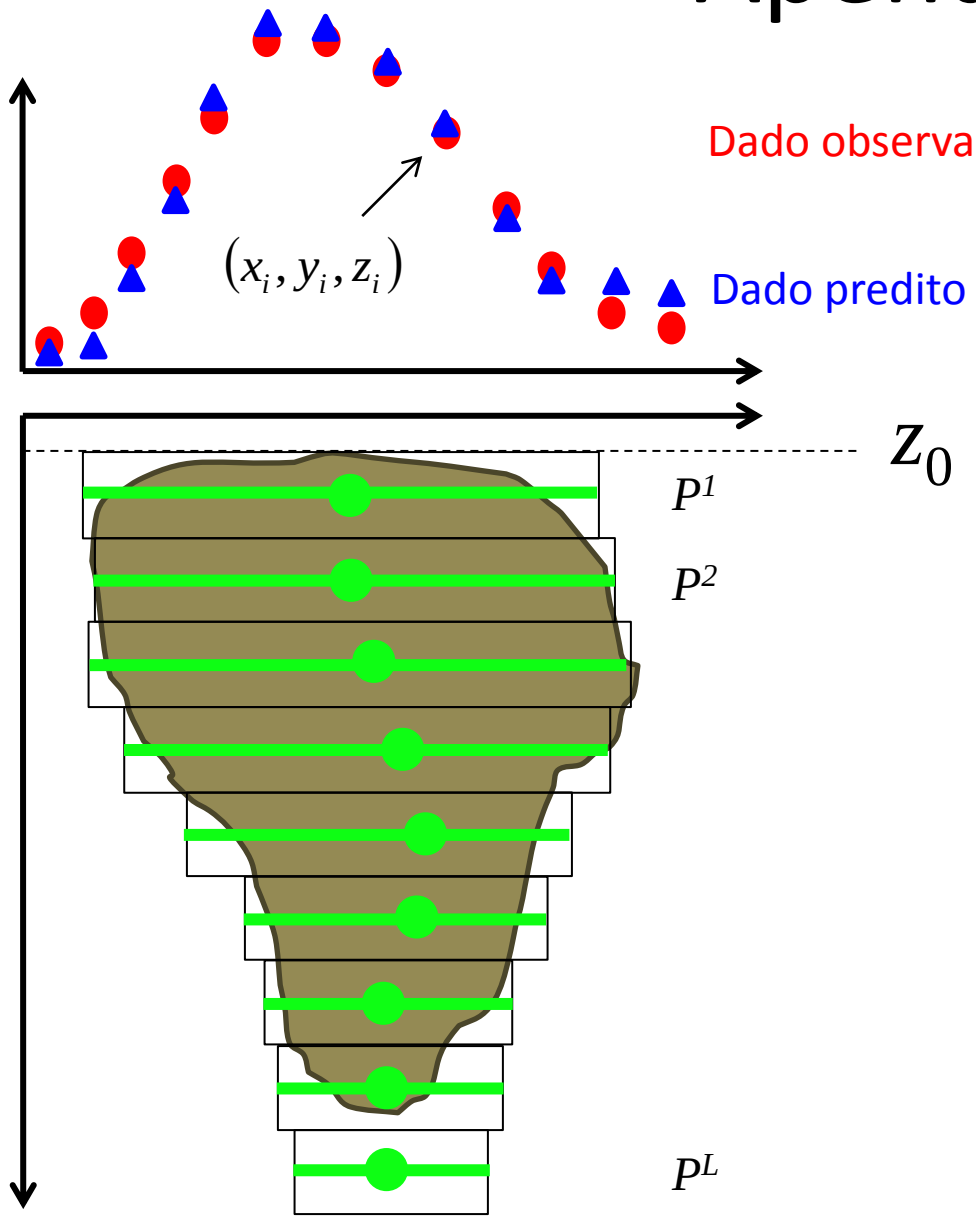
Apêndice 1



Apêndice 1


Dado observado d_i
Dado predito $g_i(\overline{p})$
(x_i, y_i, z_i)
z_0
P^1
P^2
P^L

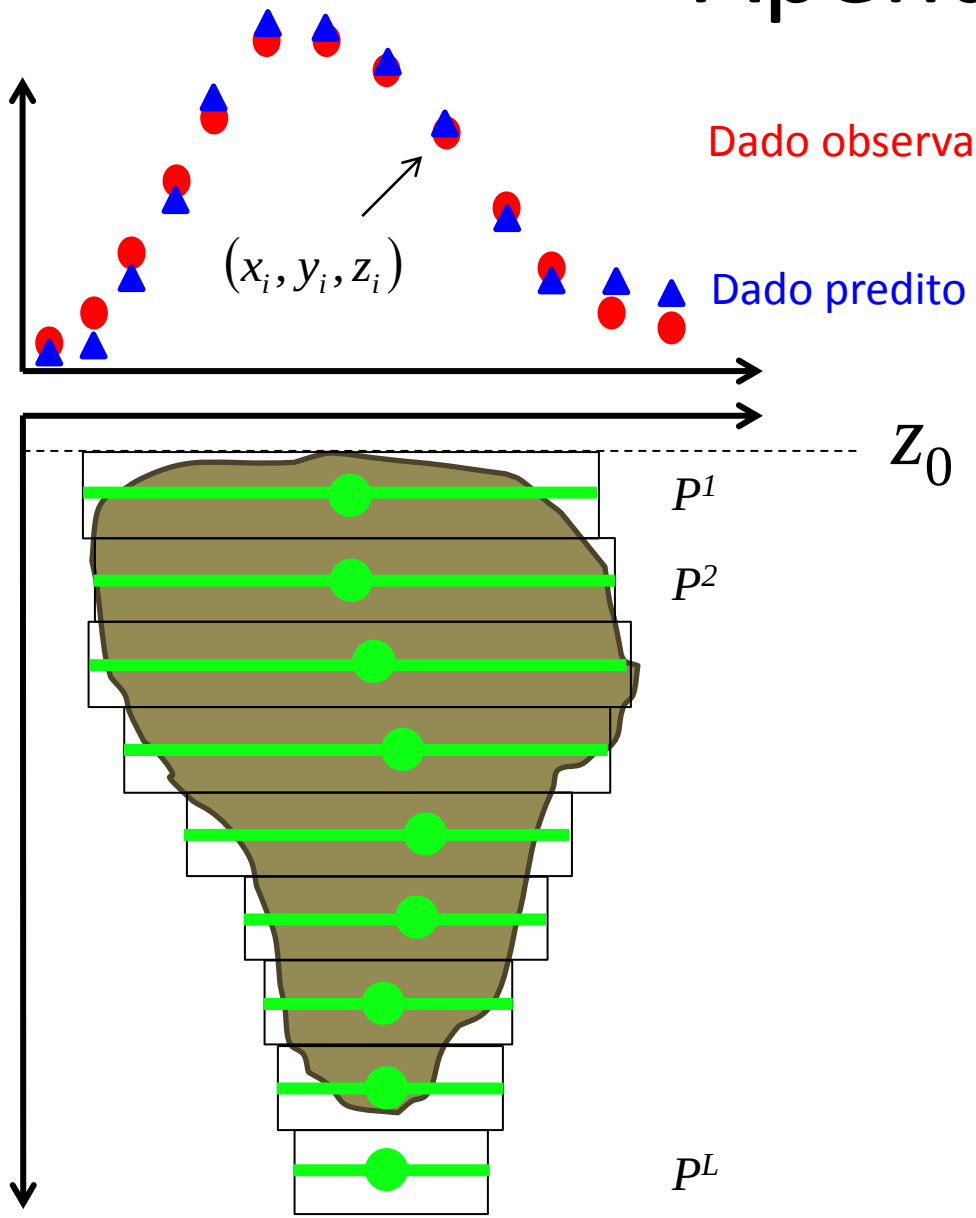
Apêndice 1



Dado observado d_i

Dado predito $g_i(\overline{p})$ $\quad \overline{p} = \begin{bmatrix} \overline{p}^1 \\ \vdots \\ \overline{p}^L \end{bmatrix}_{M \times 1}$

Apêndice 1

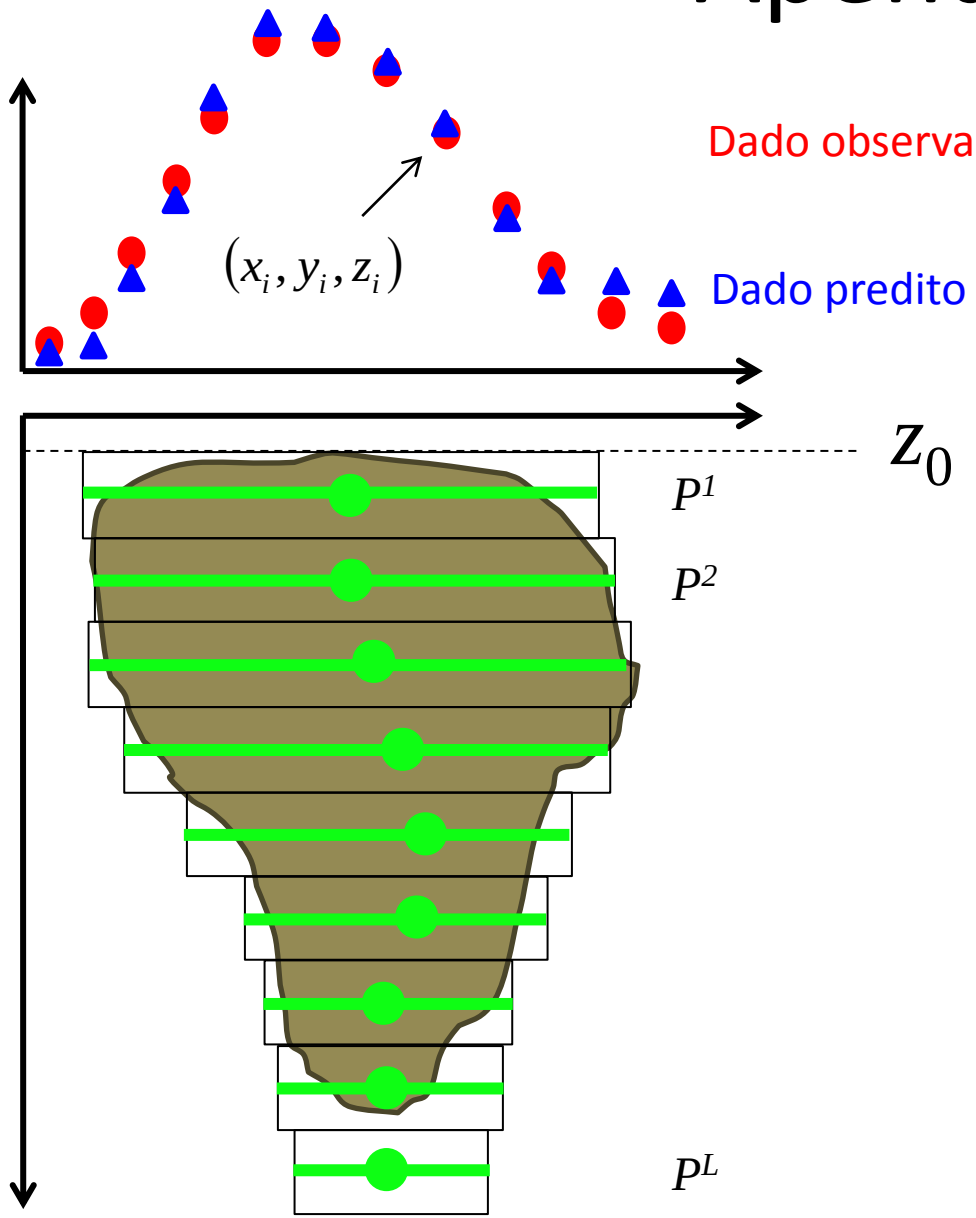


Dado observado d_i

Dado predito $g_i(\overline{p})$

$$\overline{p} = \begin{bmatrix} \overline{p}^1 \\ \vdots \\ \overline{p}^L \end{bmatrix}_{M\times 1} \quad \overline{p}^k = \begin{bmatrix} r_1^k \\ \vdots \\ r_{M^k}^k \\ x_0^k \\ y_0^k \end{bmatrix}_{(M^k+2)\times 1}$$

Apêndice 1



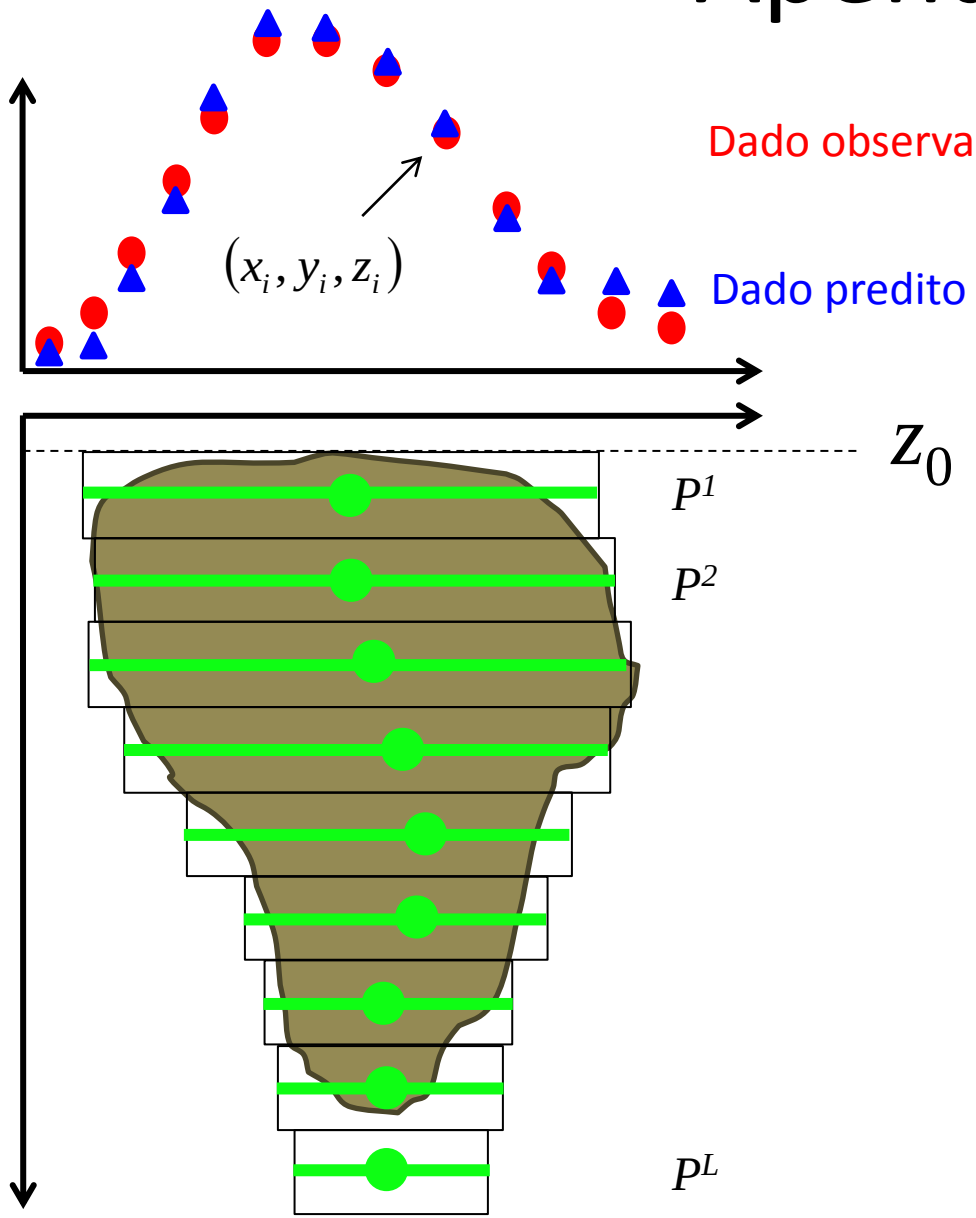
Dado observado d_i

Dado predito $g_i(\bar{p})$

$$\bar{p} = \begin{bmatrix} \bar{p}^1 \\ \vdots \\ \bar{p}^L \end{bmatrix}_{M\times 1} \quad \bar{p}^k = \begin{bmatrix} r_1^k \\ \vdots \\ r_{M^k}^k \\ x_0^k \\ y_0^k \end{bmatrix}_{(M^k+2)\times 1}$$

$$\bar{d} = \begin{bmatrix} d_1 \\ \vdots \\ d_N \end{bmatrix}_{N\times 1} \qquad \bar{g}(\bar{p}) = \begin{bmatrix} g_1(\bar{p}) \\ \vdots \\ g_N(\bar{p}) \end{bmatrix}_{N\times 1}$$

Apêndice 1



Dado observado d_i

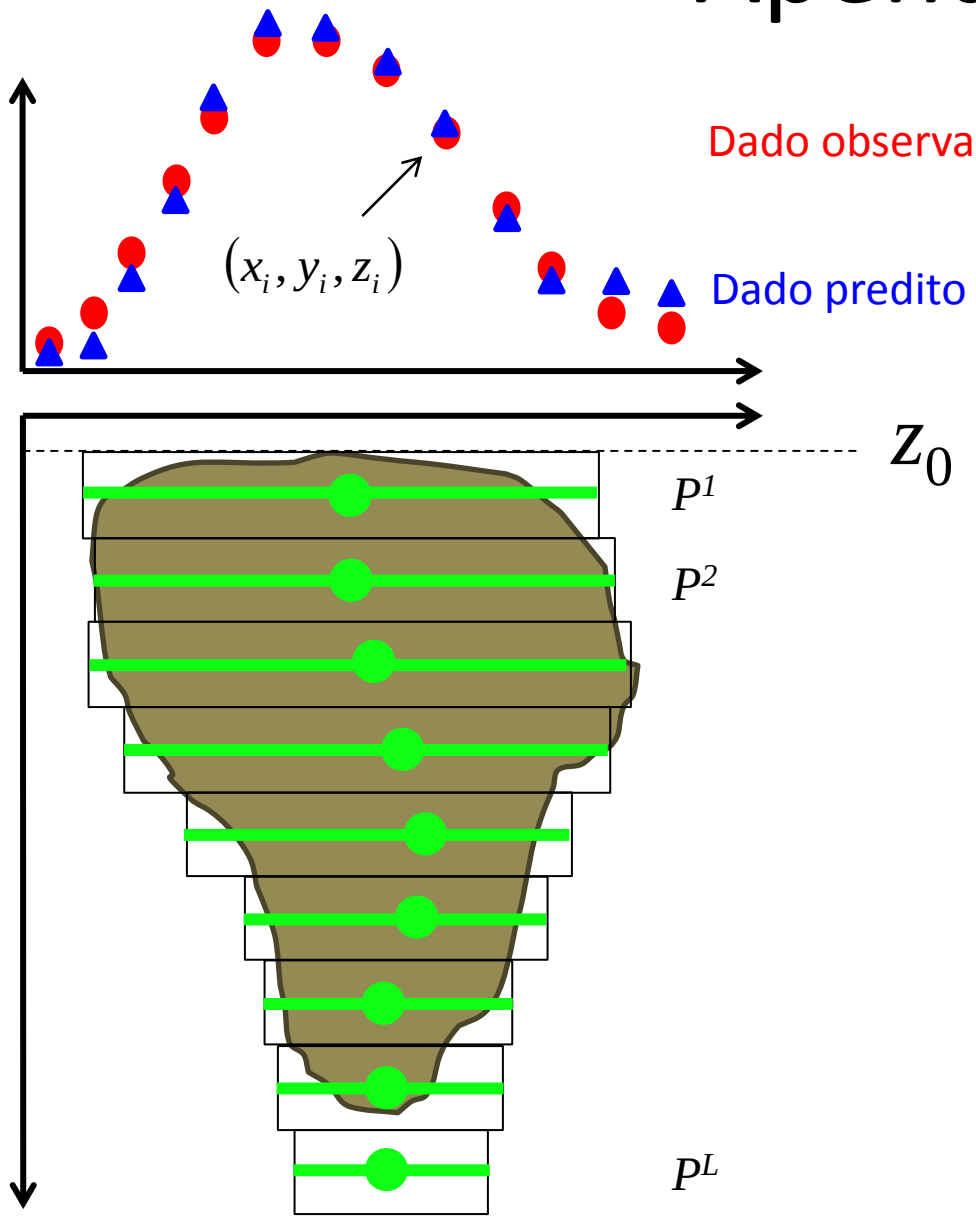
Dado predito $g_i(\bar{p})$

$$\bar{p} = \begin{bmatrix} \bar{p}^1 \\ \vdots \\ \bar{p}^L \end{bmatrix}_{M\times 1} \quad \bar{p}^k = \begin{bmatrix} r_1^k \\ \vdots \\ r_{M^k}^k \\ x_0^k \\ y_0^k \end{bmatrix}_{(M^k+2)\times 1}$$

$$\bar{d} = \begin{bmatrix} d_1 \\ \vdots \\ d_N \end{bmatrix}_{N\times 1} \qquad \bar{g}(\bar{p}) = \begin{bmatrix} g_1(\bar{p}) \\ \vdots \\ g_N(\bar{p}) \end{bmatrix}_{N\times 1}$$

$$\phi(\bar{p}) = [\bar{d} - \bar{g}(\bar{p})]^T [\bar{d} - \bar{g}(\bar{p})]$$

Apêndice 1



Dado observado d_i

Dado predito $g_i(\bar{p})$

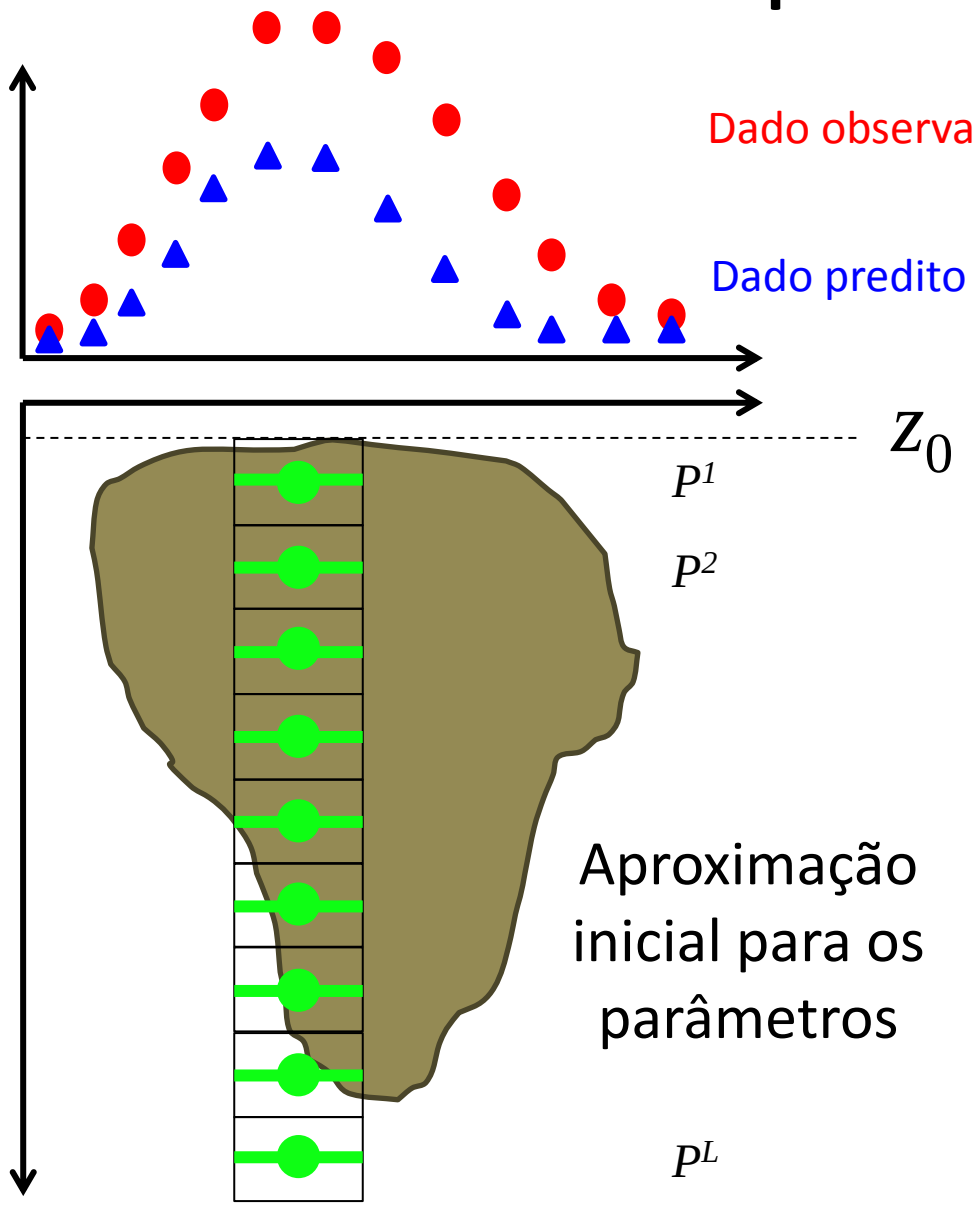
$$\bar{p} = \begin{bmatrix} \bar{p}^1 \\ \vdots \\ \bar{p}^L \end{bmatrix}_{M\times 1} \quad \bar{p}^k = \begin{bmatrix} r_1^k \\ \vdots \\ r_{M^k}^k \\ x_0^k \\ y_0^k \end{bmatrix}_{(M^k+2)\times 1}$$

$$\bar{d} = \begin{bmatrix} d_1 \\ \vdots \\ d_N \end{bmatrix}_{N\times 1} \qquad \bar{g}(\bar{p}) = \begin{bmatrix} g_1(\bar{p}) \\ \vdots \\ g_N(\bar{p}) \end{bmatrix}_{N\times 1}$$

$$\phi(\bar{p}) = [\bar{d} - \bar{g}(\bar{p})]^T [\bar{d} - \bar{g}(\bar{p})]$$

Problema não-linear

Apêndice 1



Dado observado d_i

Dado predito $g_i(\bar{p})$

$$\bar{p} = \begin{bmatrix} \bar{p}^1 \\ \vdots \\ \bar{p}^L \end{bmatrix}_{M\times 1} \quad \bar{p}^k = \begin{bmatrix} r_1^k \\ \vdots \\ r_{M^k}^k \\ x_0^k \\ y_0^k \end{bmatrix}_{(M^k+2)\times 1}$$

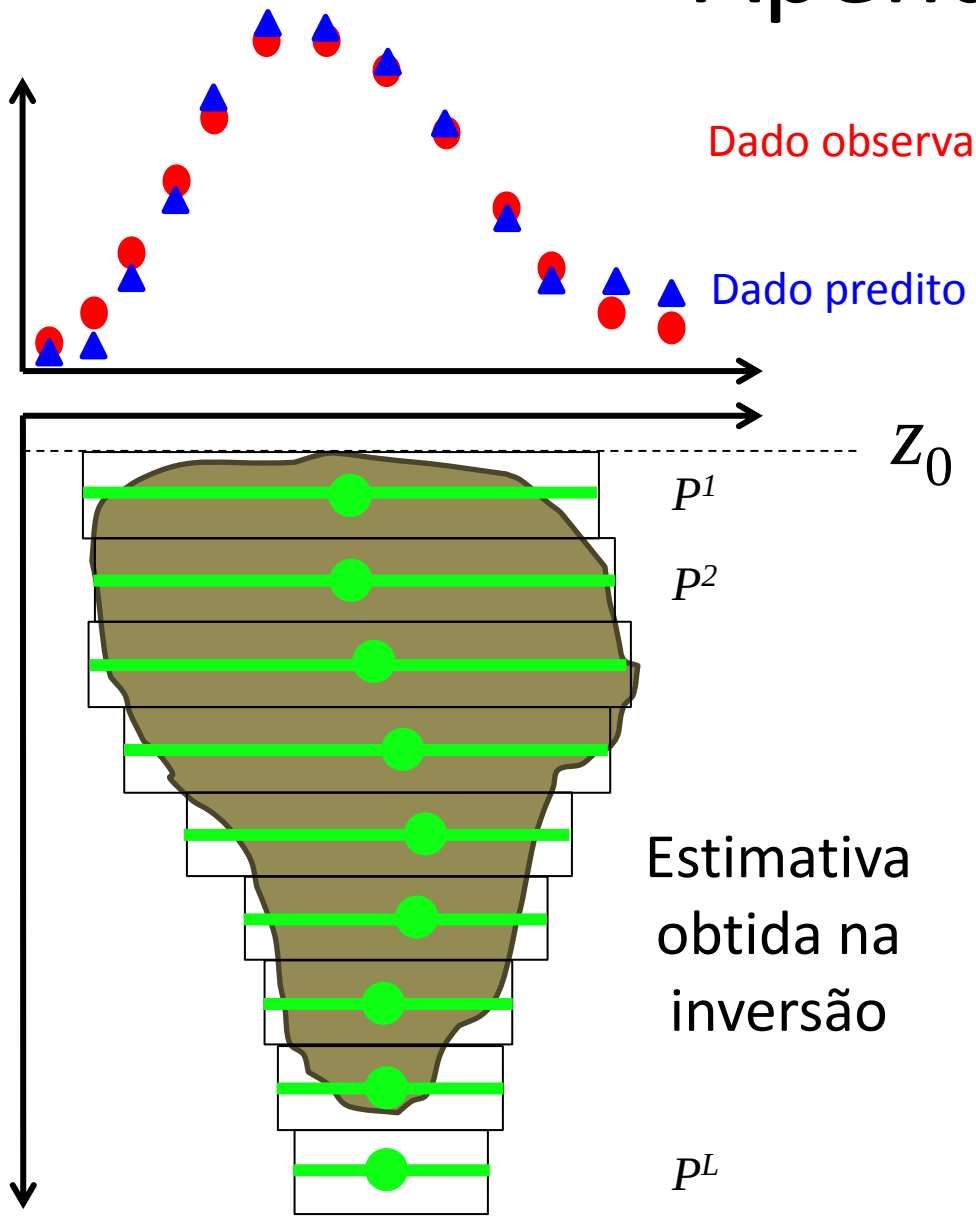
$$\bar{d} = \begin{bmatrix} d_1 \\ \vdots \\ d_N \end{bmatrix}_{N\times 1} \qquad \bar{g}(\bar{p}) = \begin{bmatrix} g_1(\bar{p}) \\ \vdots \\ g_N(\bar{p}) \end{bmatrix}_{N\times 1}$$

Aproximação inicial para os parâmetros

$$\phi(\bar{p}) = [\bar{d} - \bar{g}(\bar{p})]^T [\bar{d} - \bar{g}(\bar{p})]$$

Problema não-linear

Apêndice 1



Dado observado d_i

Dado predito $g_i(\bar{p})$

$$\bar{p} = \begin{bmatrix} \bar{p}^1 \\ \vdots \\ \bar{p}^L \end{bmatrix}_{M\times 1} \quad \bar{p}^k = \begin{bmatrix} r_1^k \\ \vdots \\ r_{M^k}^k \\ x_0^k \\ y_0^k \end{bmatrix}_{(M^k+2)\times 1}$$

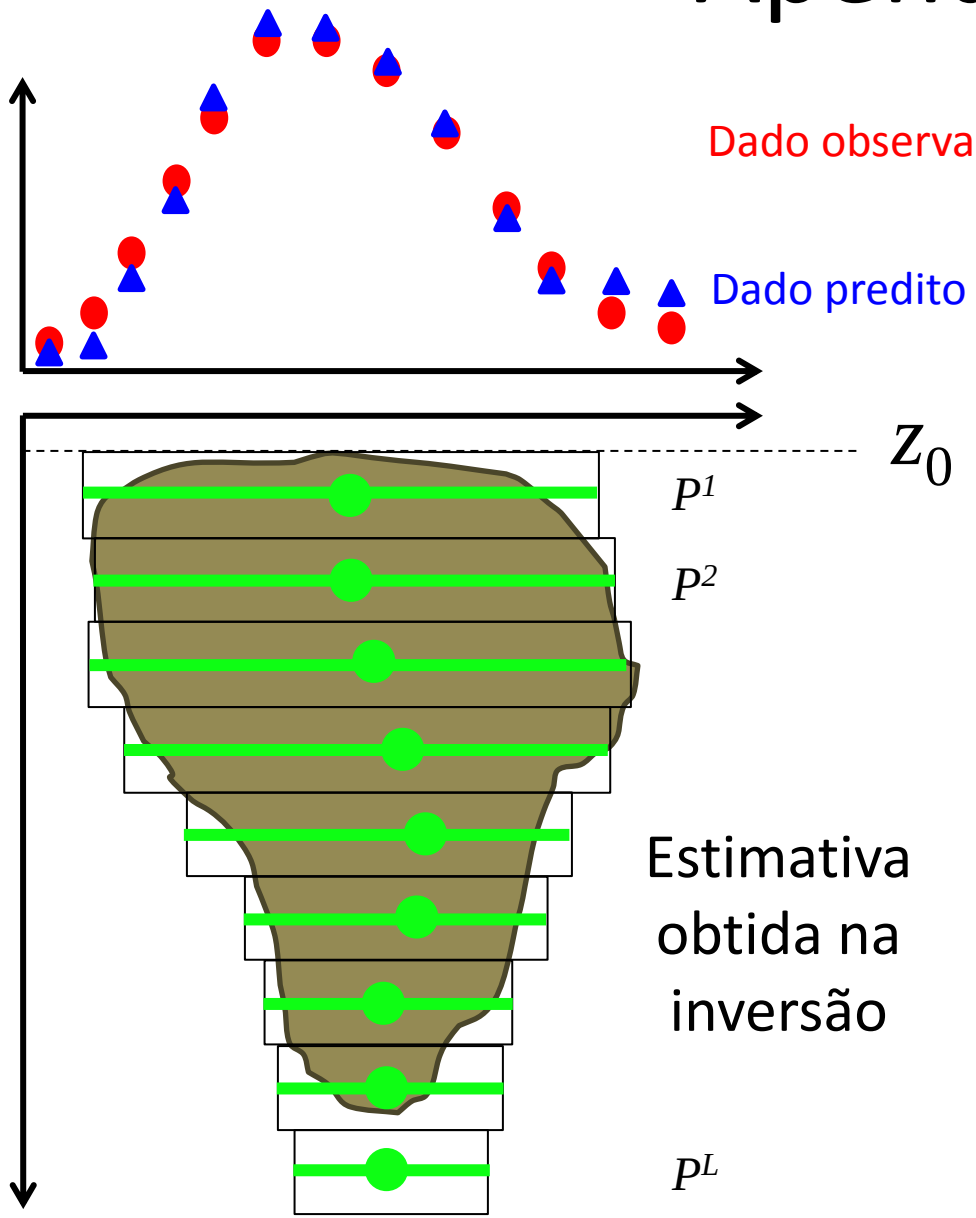
Estimativa obtida na inversão

$$\bar{d} = \begin{bmatrix} d_1 \\ \vdots \\ d_N \end{bmatrix}_{N\times 1} \qquad \bar{g}(\bar{p}) = \begin{bmatrix} g_1(\bar{p}) \\ \vdots \\ g_N(\bar{p}) \end{bmatrix}_{N\times 1}$$

$$\phi(\bar{p}) = [\bar{d} - \bar{g}(\bar{p})]^T [\bar{d} - \bar{g}(\bar{p})]$$

Problema não-linear

Apêndice 1



Dado observado d_i

Dado predito $g_i(\bar{p})$

$$\bar{p} = \begin{bmatrix} \bar{p}^1 \\ \vdots \\ \bar{p}^L \end{bmatrix}_{M\times 1} \quad \bar{p}^k = \begin{bmatrix} r_1^k \\ \vdots \\ r_{M^k}^k \\ x_0^k \\ y_0^k \end{bmatrix}_{(M^k+2)\times 1}$$

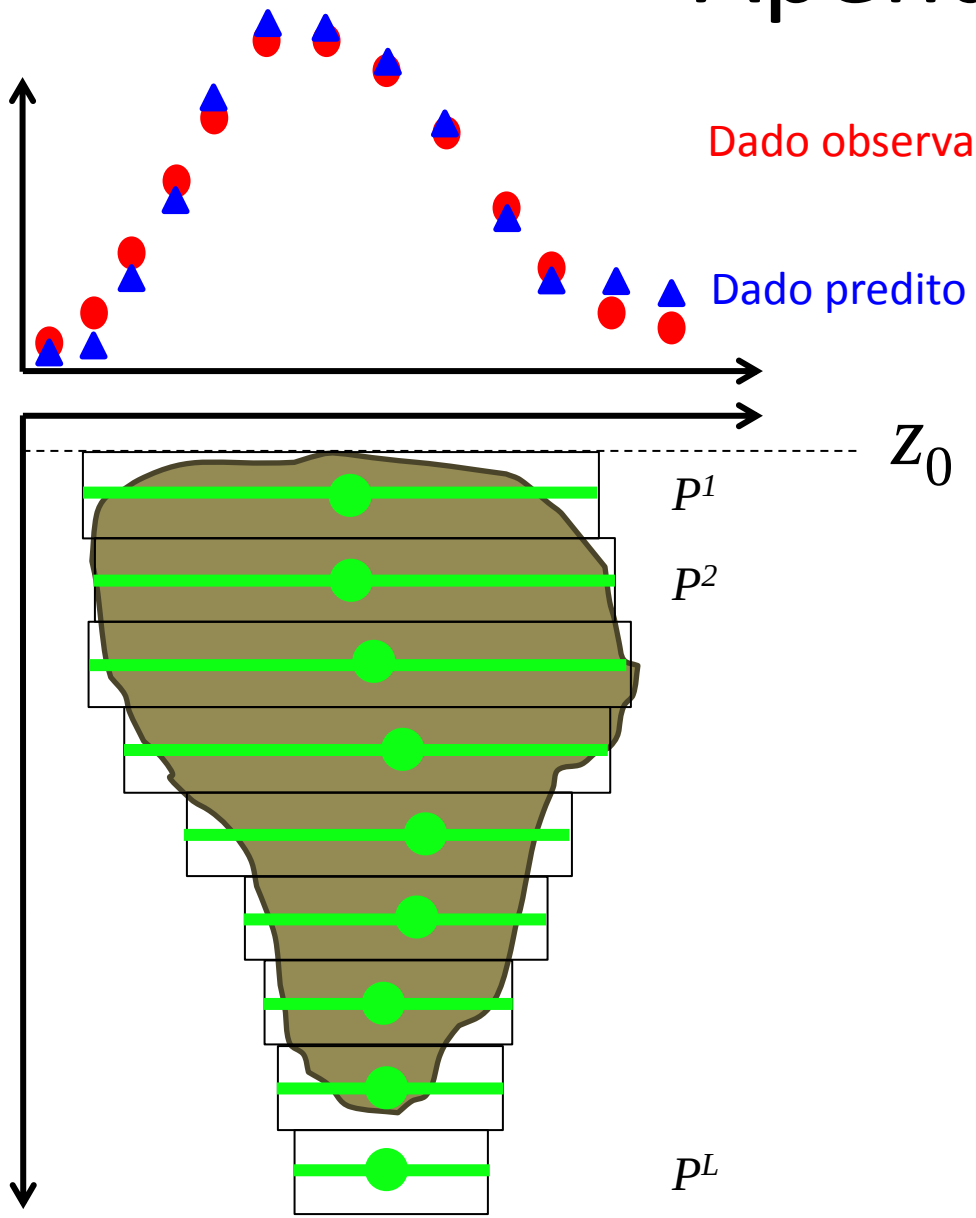
Estimativa obtida na inversão

$$\bar{d} = \begin{bmatrix} d_1 \\ \vdots \\ d_N \end{bmatrix}_{N\times 1} \qquad \bar{g}(\bar{p}) = \begin{bmatrix} g_1(\bar{p}) \\ \vdots \\ g_N(\bar{p}) \end{bmatrix}_{N\times 1}$$

$$\phi(\bar{p}) = [\bar{d} - \bar{g}(\bar{p})]^T [\bar{d} - \bar{g}(\bar{p})]$$

Problema não-linear e MAL-POSTO

Apêndice 1



Dado observado d_i

Dado predito $g_i(\bar{p})$

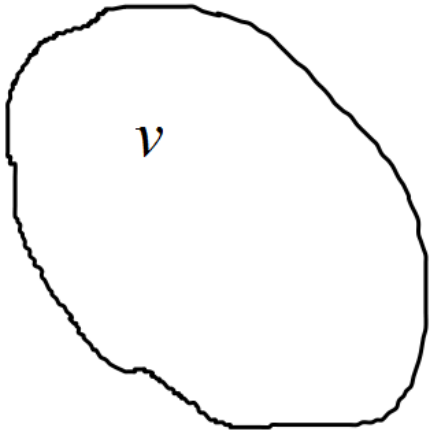
$$\bar{p} = \begin{bmatrix} \bar{p}^1 \\ \vdots \\ \bar{p}^L \end{bmatrix}_{M\times 1} \quad \bar{p}^k = \begin{bmatrix} r_1^k \\ \vdots \\ r_{M^k}^k \\ x_0^k \\ y_0^k \end{bmatrix}_{(M^k+2)\times 1}$$

$$\bar{d} = \begin{bmatrix} d_1 \\ \vdots \\ d_N \end{bmatrix}_{N\times 1} \qquad \bar{g}(\bar{p}) = \begin{bmatrix} g_1(\bar{p}) \\ \vdots \\ g_N(\bar{p}) \end{bmatrix}_{N\times 1}$$

$$\psi(\bar{p}) = \phi(\bar{p}) + \mu\theta(\bar{p})$$

Regularização

Apêndice 2



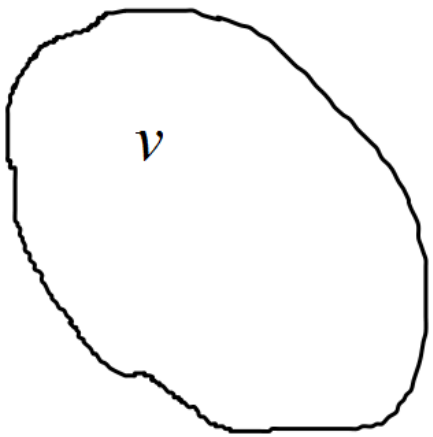
Distribuição anômala de propriedade física η com volume v e que produz um campo potencial anômalo

Apêndice 2

Ponto onde é medido o campo potencial anômalo

(gravimetria, gradiometria gravimétrica, magnetometria)

$(x_i\,,\,y_i\,,\,z_i\,)$



Distribuição anômala de propriedade física η com volume v e que produz um campo potencial anômalo

Apêndice 2

Ponto onde é medido o campo potencial anômalo

(gravimetria, gradiometria gravimétrica, magnetometria)

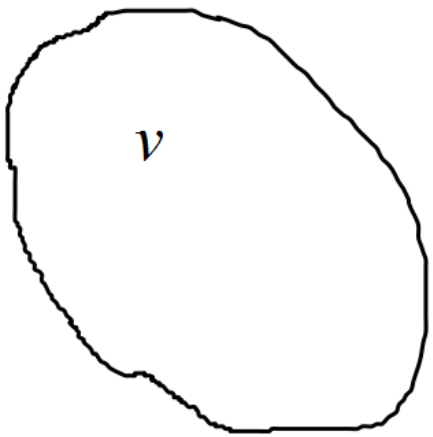
$(x_i\,,\,y_i\,,\,z_i\,)$

$$g_i(v) = \eta \iiint_v G(\bar{x}', \bar{x})\,dv$$

ponto dentro da fonte

campo potencial anômalo no ponto (x_i, y_i, z_i)

ponto (x_i, y_i, z_i)



Distribuição anômala de propriedade física η com volume v e que produz um campo potencial anômalo

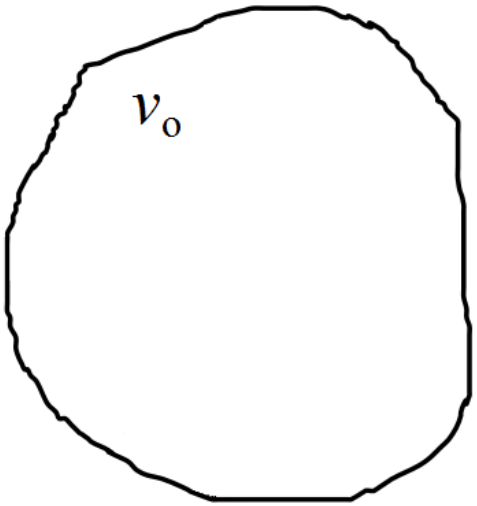
Apêndice 2

Dado observado

$(x_i\,,\,y_i\,,\,z_i\,)$

$$g_i(v_0)$$

Volume verdadeiro



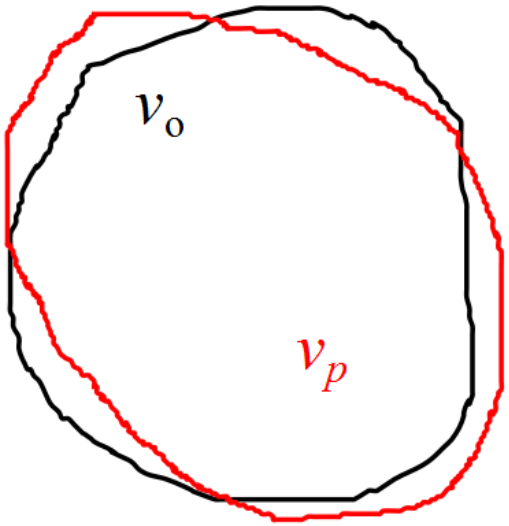
Apêndice 2

(x_i, y_i, z_i)

Dado observado $g_i(v_0)$

Dado predito $g_i(v_p)$

Volume verdadeiro



Volume estimado

Apêndice 2

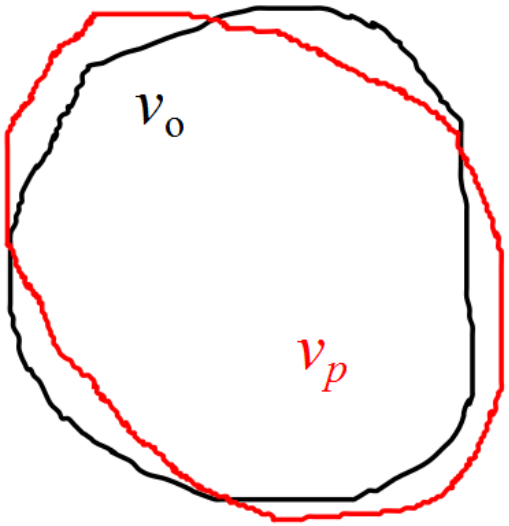
(x_i, y_i, z_i)

Dado observado $g_i(v_0)$

Dado predito $g_i(v_p)$

$$v_p = v_0 + \Delta v$$

Volume verdadeiro



Volume estimado

Apêndice 2

(x_i, y_i, z_i)

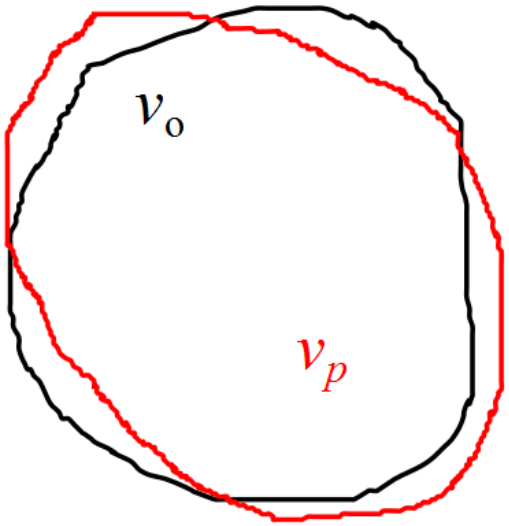
Dado observado $g_i(v_0)$

Dado predito $g_i(v_p)$

$$v_p = v_0 + \Delta v$$

$$g_i(\underbrace{v_0 + \Delta v}_{v_p}) \approx g_i(v_0) + \frac{dg_i(v_0)}{dv}\Delta v$$

Volume verdadeiro



Volume estimado

Apêndice 2

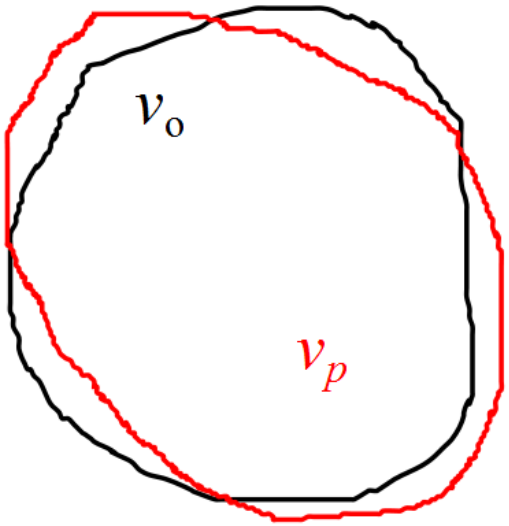
(x_i, y_i, z_i)

Dado observado $g_i(v_0)$

Dado predito $g_i(v_p)$

$$v_p = v_0 + \Delta v$$

Volume verdadeiro



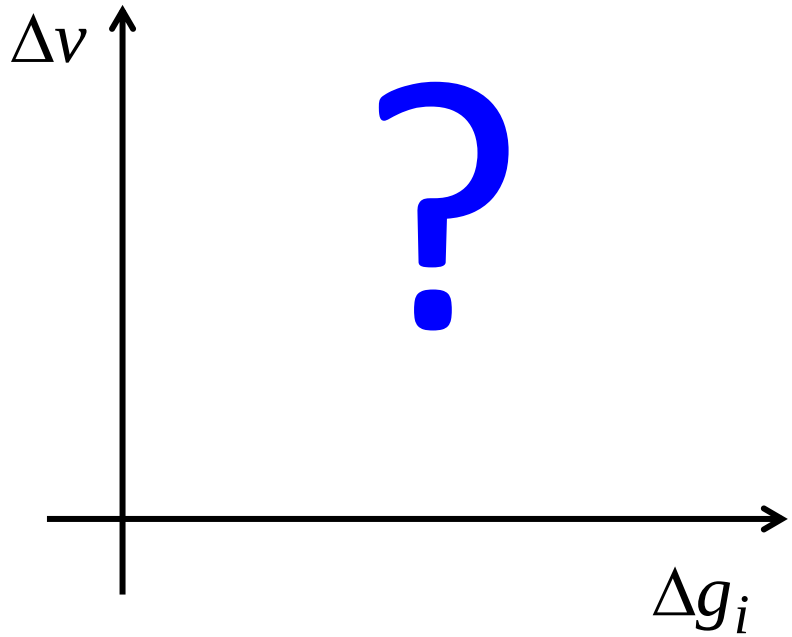
Volume estimado

$$g_i(\underbrace{v_0 + \Delta v}_{v_p}) \approx g_i(v_0) + \frac{dg_i(v_0)}{dv}\Delta v$$

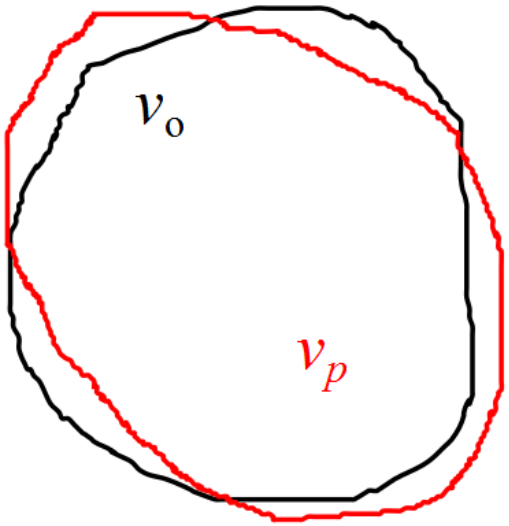
$$\underbrace{g_i(v_p) - g_i(v_0)}_{\Delta g_i} \approx \frac{dg_i(v_0)}{dv}\Delta v$$

Apêndice 2

(x_i, y_i, z_i)



Volume verdadeiro

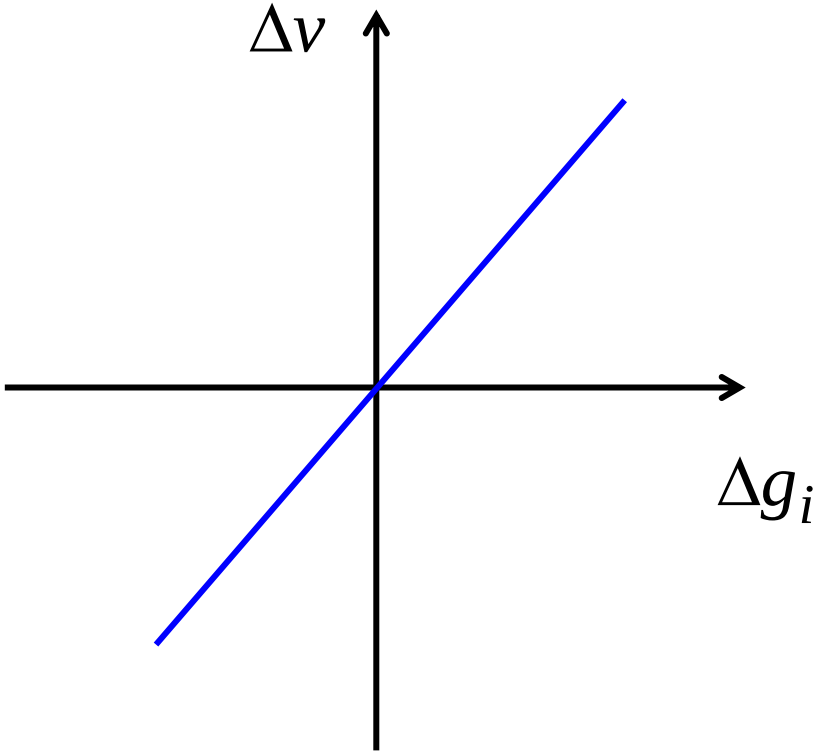


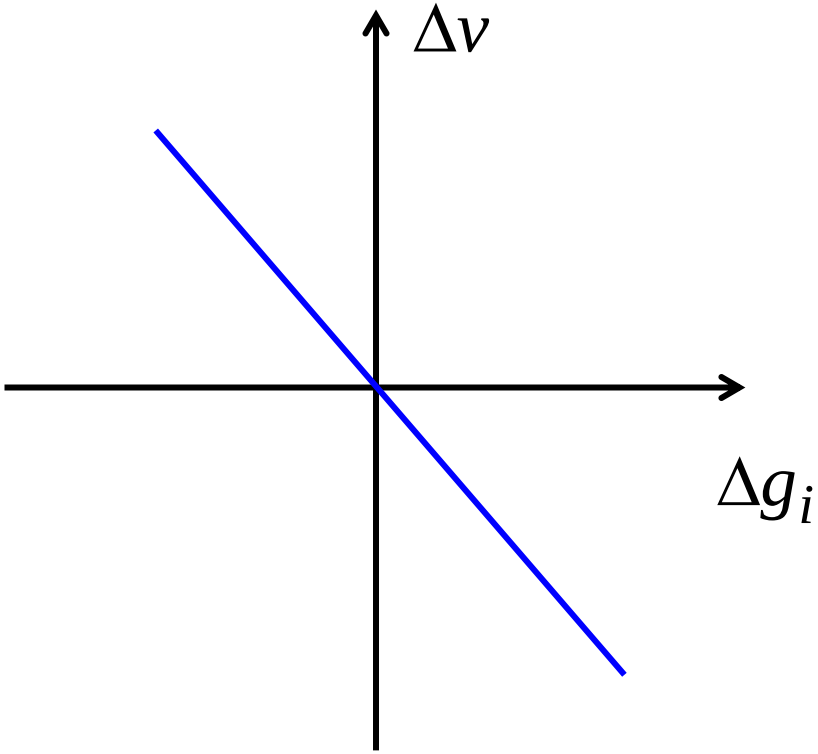
Volume estimado

$$\underbrace{g_i(v_p) - g_i(v_0)}_{\Delta g_i} \approx \boxed{\frac{dg_i(v_0)}{dv}} \Delta v$$

Apêndice 2

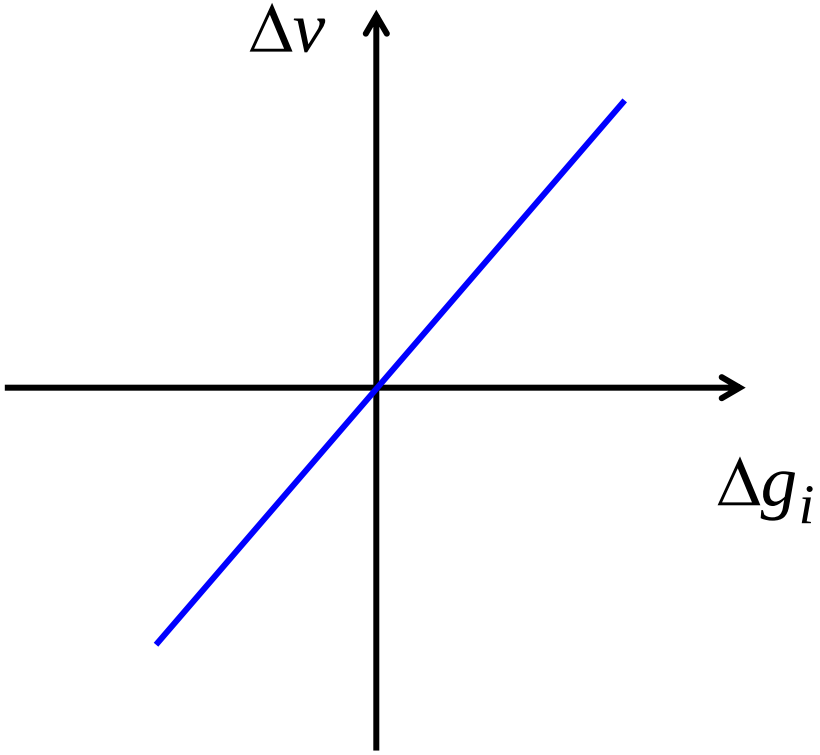
$$\frac{dg_i(v_0)}{dv} > 0 \qquad \boxed{\underbrace{g_i(v_p) - g_i(v_0)}_{\Delta g_i} \approx \frac{dg_i(v_0)}{dv}\underbrace{(v_p - v_0)}_{\Delta v}} \qquad \frac{dg_i(v_0)}{dv} < 0$$





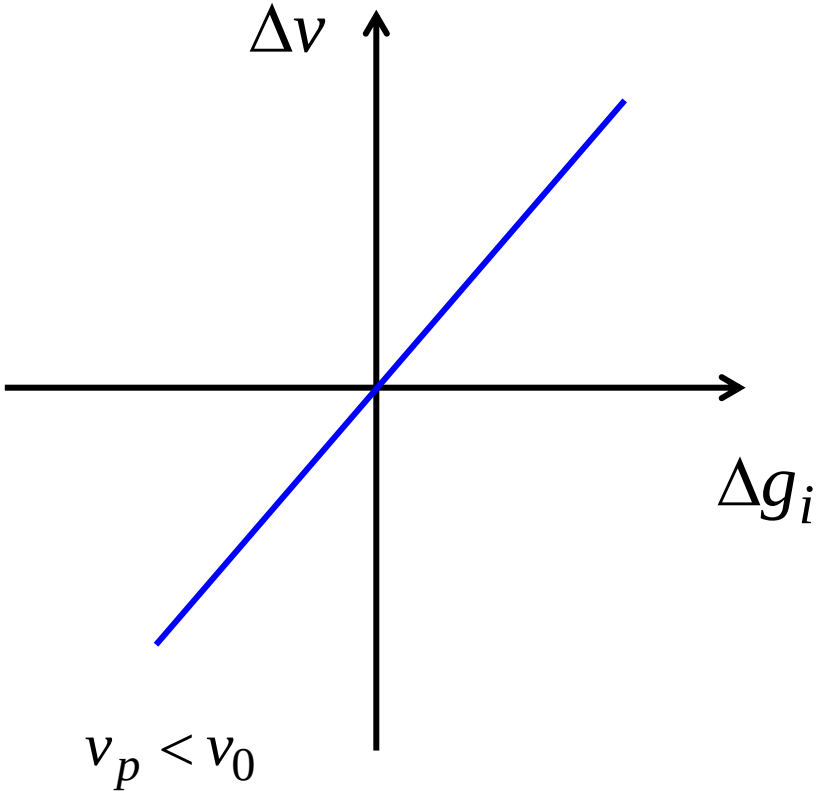
Apêndice 2

$$\frac{dg_i(v_0)}{dv} > 0$$



Apêndice 2

$$\frac{dg_i(v_0)}{dv} > 0$$



$$v_p < v_0$$

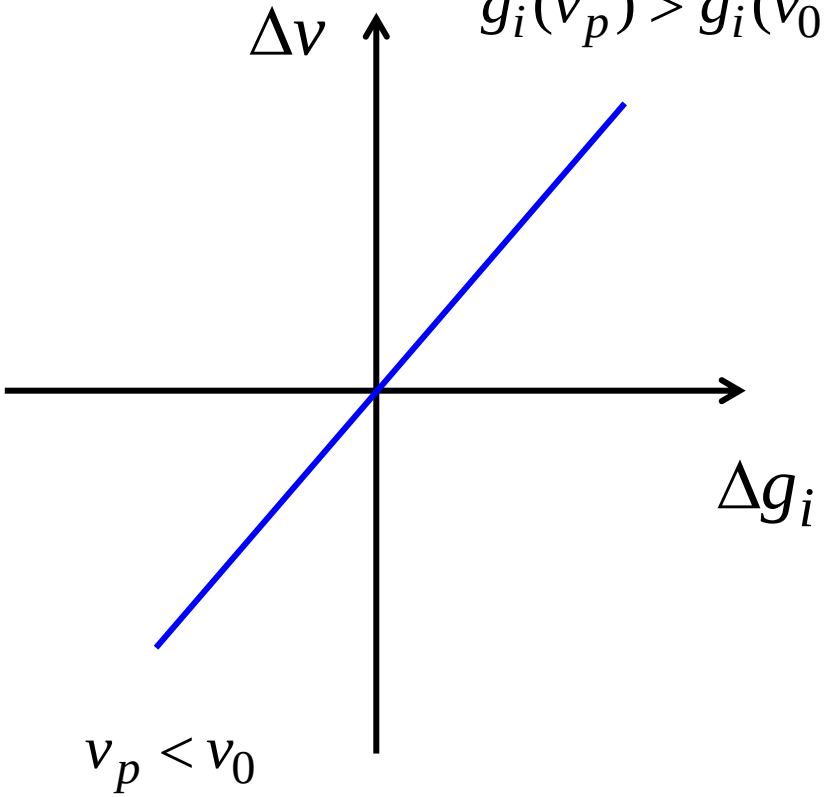
$$g_i(v_p) < g_i(v_0)$$

Apêndice 2

$$\frac{dg_i(v_0)}{dv} > 0$$

$$v_p > v_0$$

$$g_i(v_p) > g_i(v_0)$$



$$v_p < v_0$$

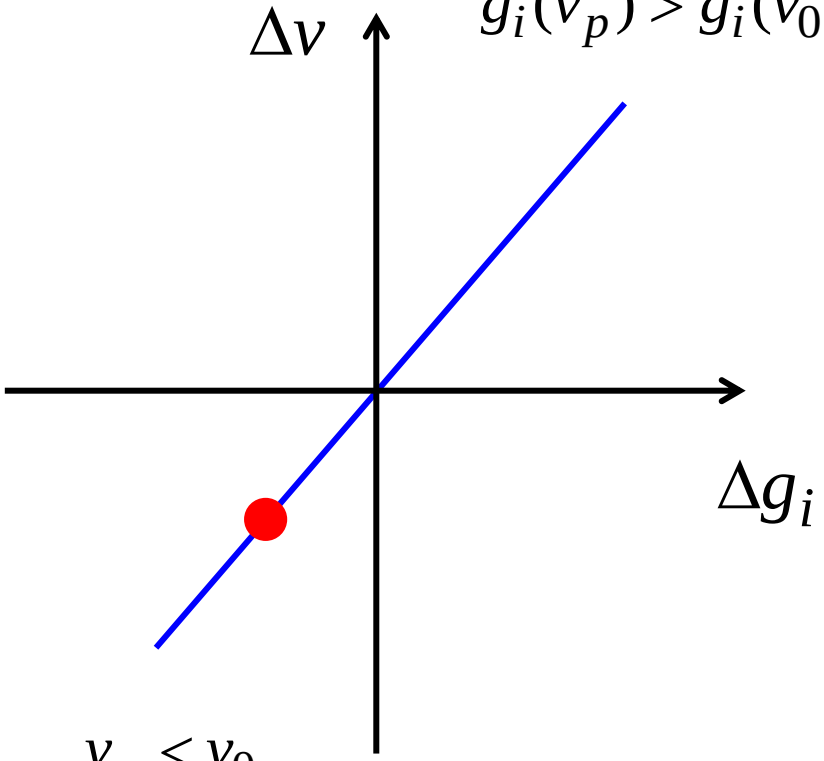
$$g_i(v_p) < g_i(v_0)$$

Apêndice 2

$$\frac{dg_i(v_0)}{dv} > 0$$

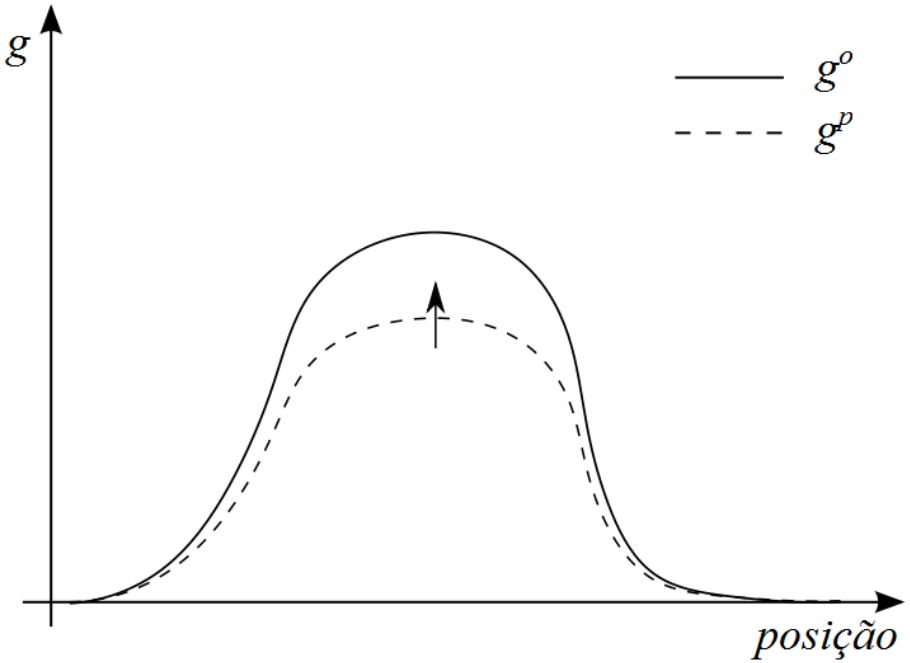
$$v_p > v_0$$

$$g_i(v_p) > g_i(v_0)$$



$$v_p < v_0$$

$$g_i(v_p) < g_i(v_0)$$

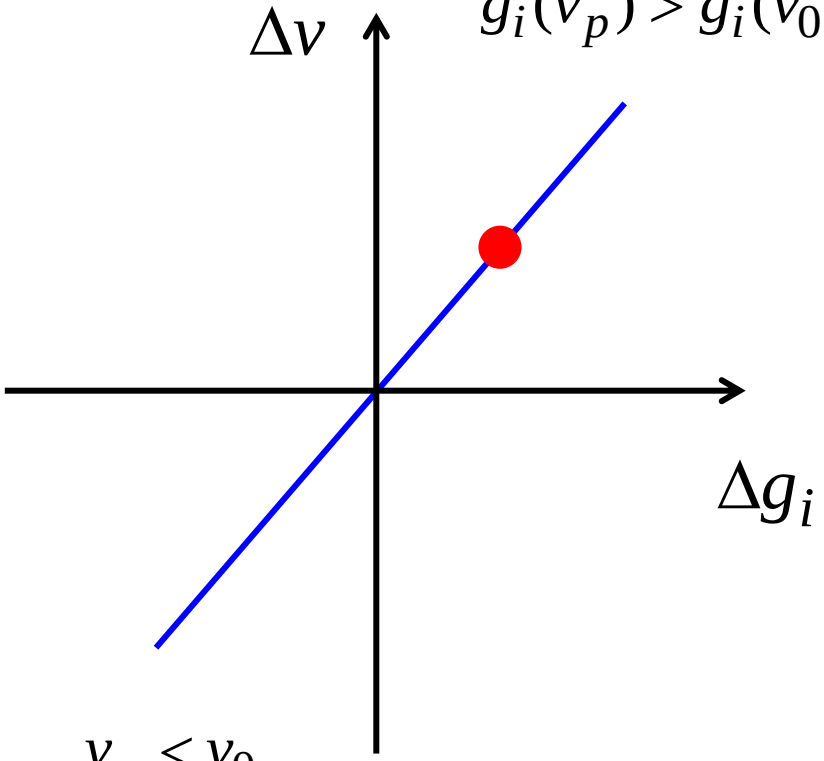


Apêndice 2

$$\frac{dg_i(v_0)}{dv} > 0$$

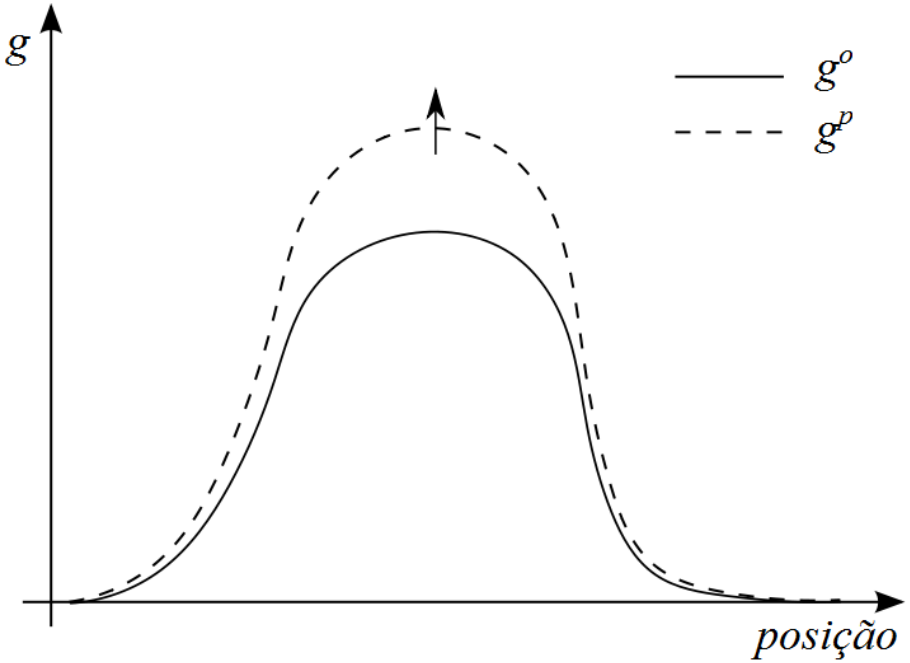
$$v_p > v_0$$

$$g_i(v_p) > g_i(v_0)$$



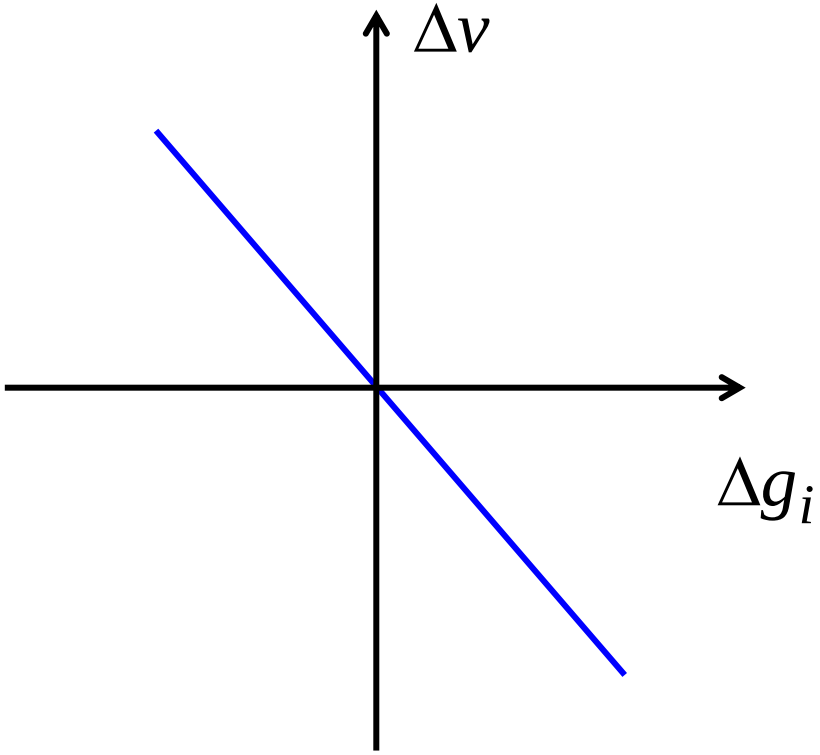
$$v_p < v_0$$

$$g_i(v_p) < g_i(v_0)$$



Apêndice 2

$$\frac{dg_i(v_0)}{dv} < 0$$

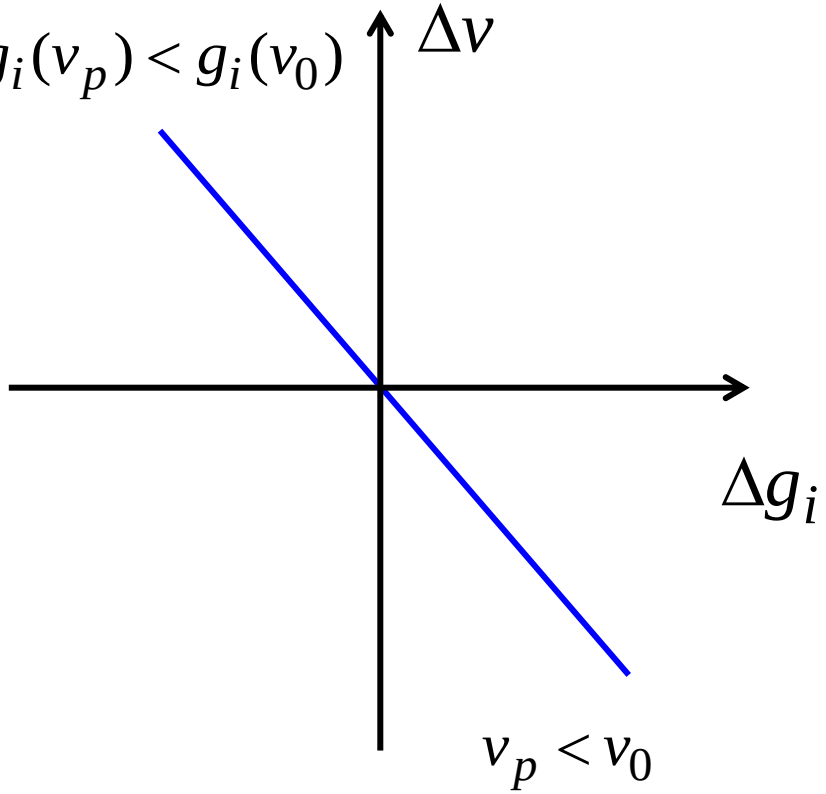


Apêndice 2

$$\frac{dg_i(v_0)}{dv} < 0$$

$v_p > v_0$

$g_i(v_p) < g_i(v_0)$



$v_p < v_0$

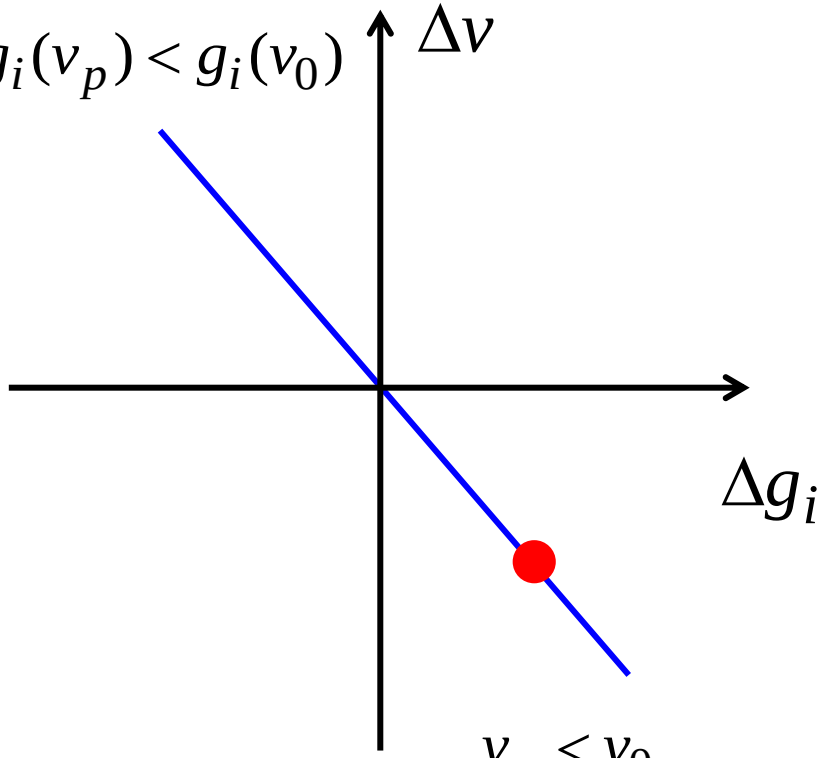
$g_i(v_p) > g_i(v_0)$

Apêndice 2

$$\frac{dg_i(v_0)}{dv} < 0$$

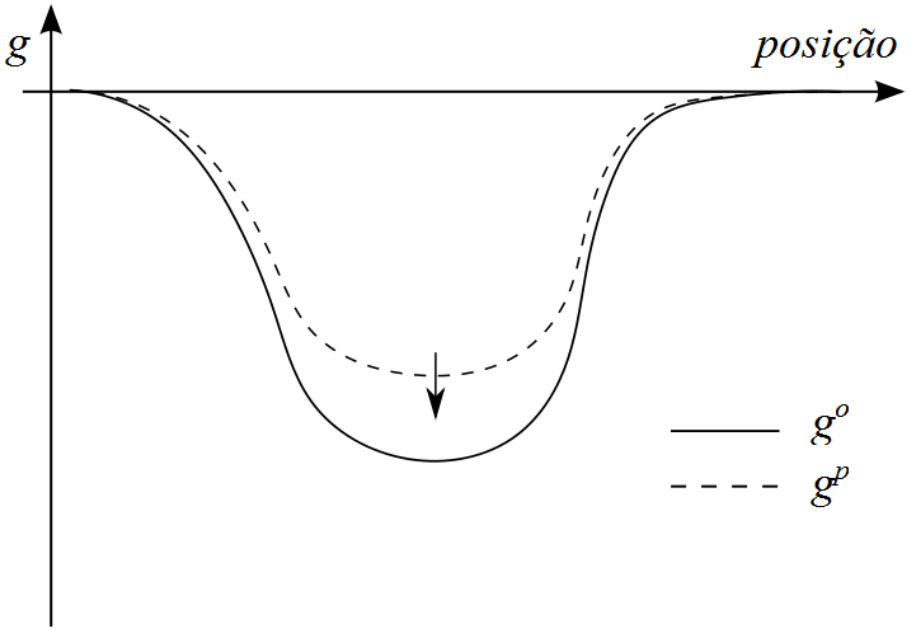
$$v_p > v_0$$

$$g_i(v_p) < g_i(v_0)$$



$$v_p < v_0$$

$$g_i(v_p) > g_i(v_0)$$

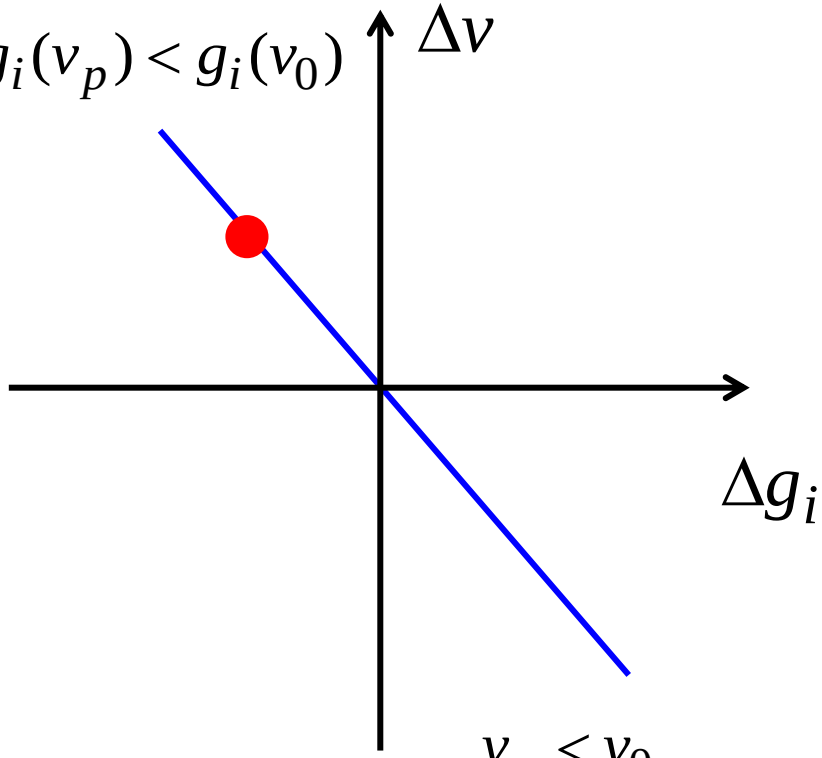


Apêndice 2

$$\frac{dg_i(v_0)}{dv} < 0$$

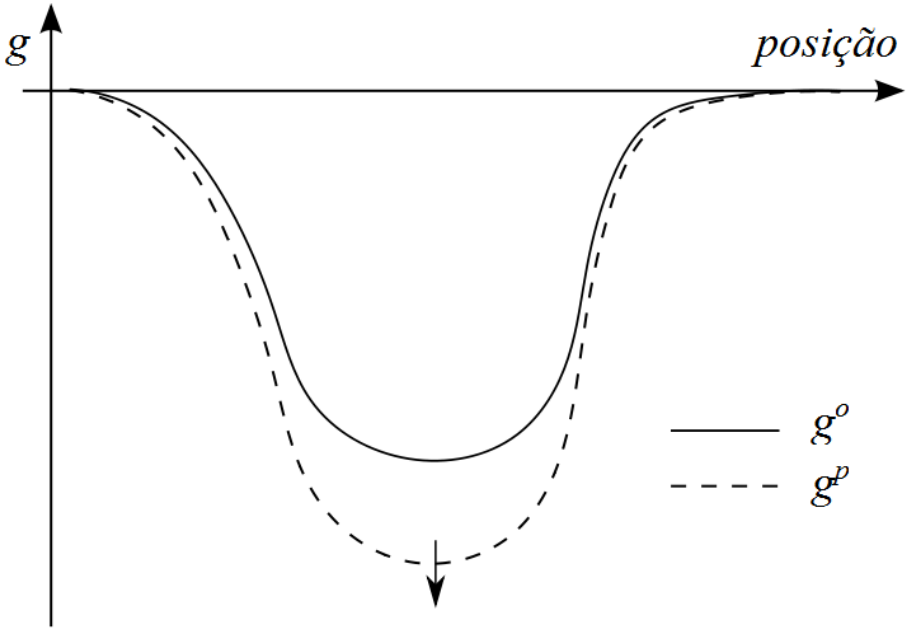
$$v_p > v_0$$

$$g_i(v_p) < g_i(v_0)$$



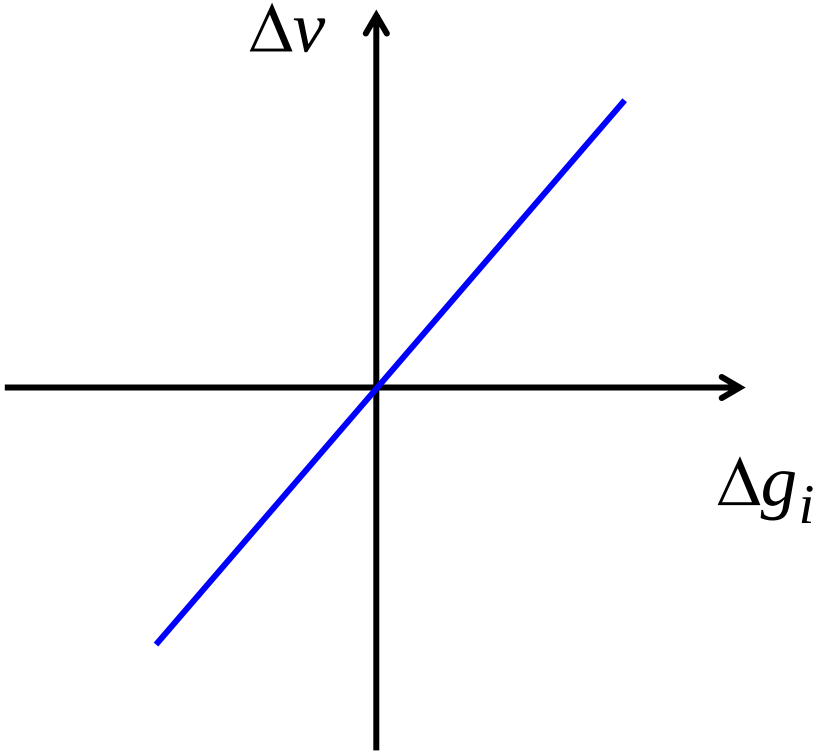
$$v_p < v_0$$

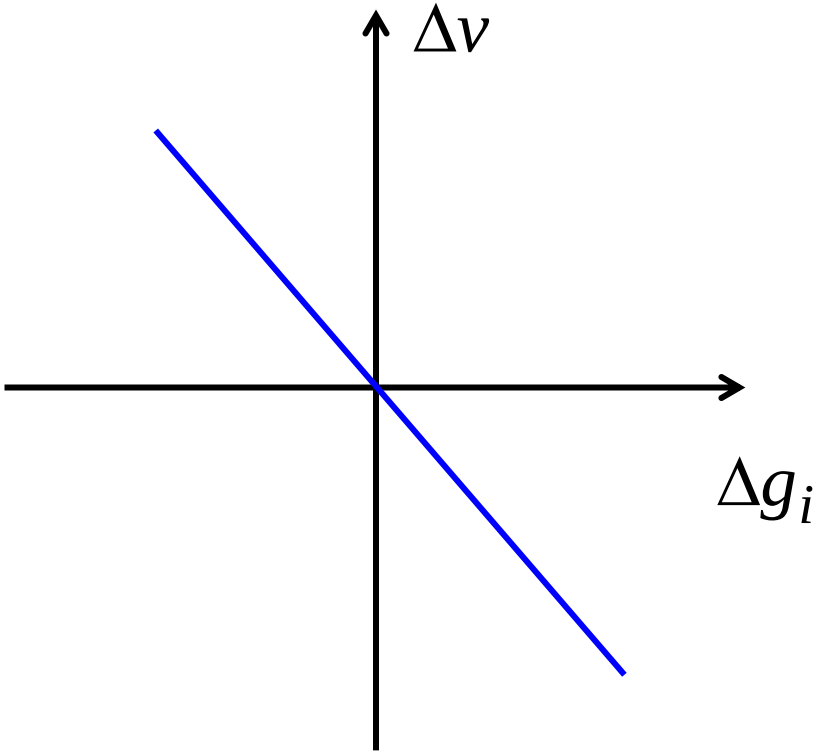
$$g_i(v_p) > g_i(v_0)$$



Apêndice 2

$$\frac{dg_i(v_0)}{dv} > 0 \qquad \boxed{\underbrace{g_i(v_p) - g_i(v_0)}_{\Delta g_i} \approx \frac{dg_i(v_0)}{dv}\underbrace{(v_p - v_0)}_{\Delta v}} \qquad \frac{dg_i(v_0)}{dv} < 0$$



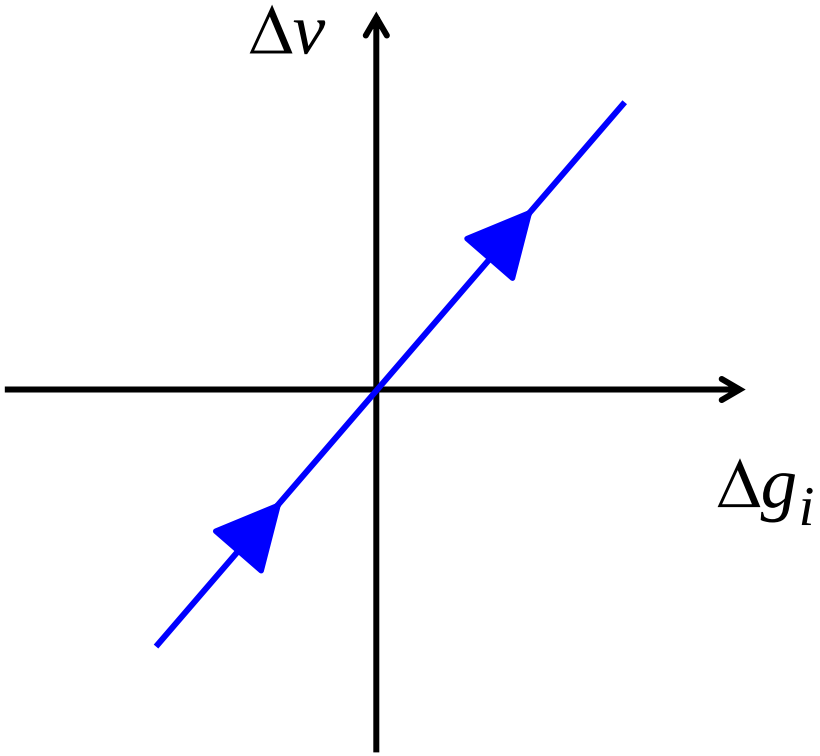


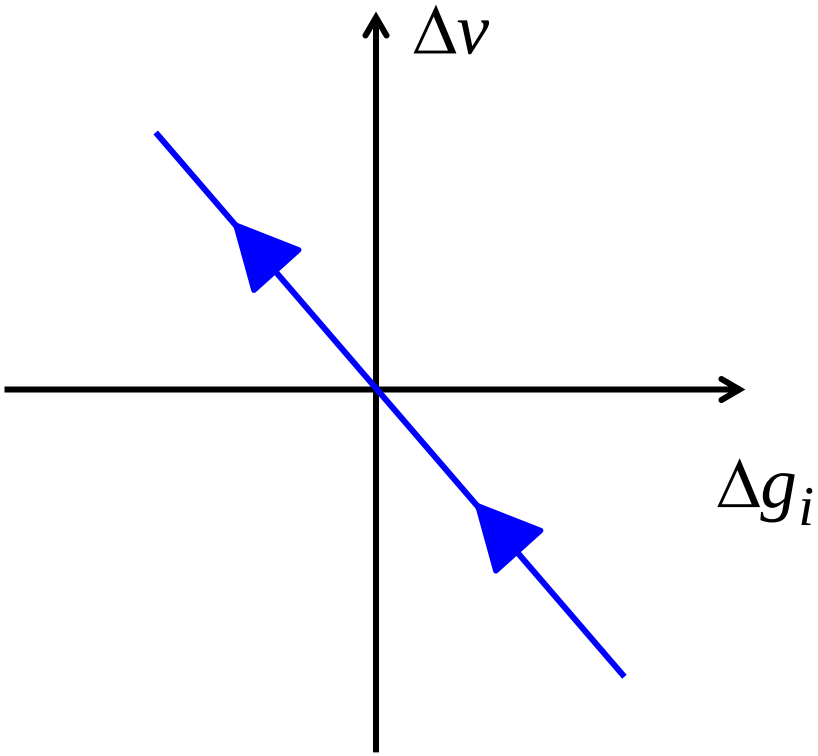
Apêndice 2

$$\frac{dg_i(v_0)}{dv} > 0$$

Sentido, sobre as retas, associado ao crescimento de v_p

$$\frac{dg_i(v_0)}{dv} < 0$$



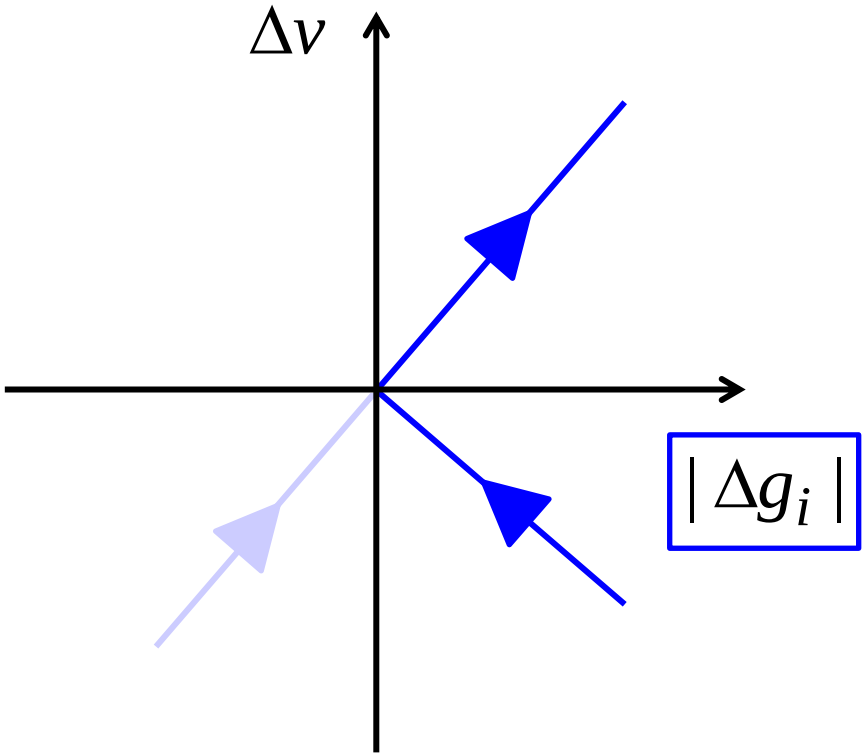


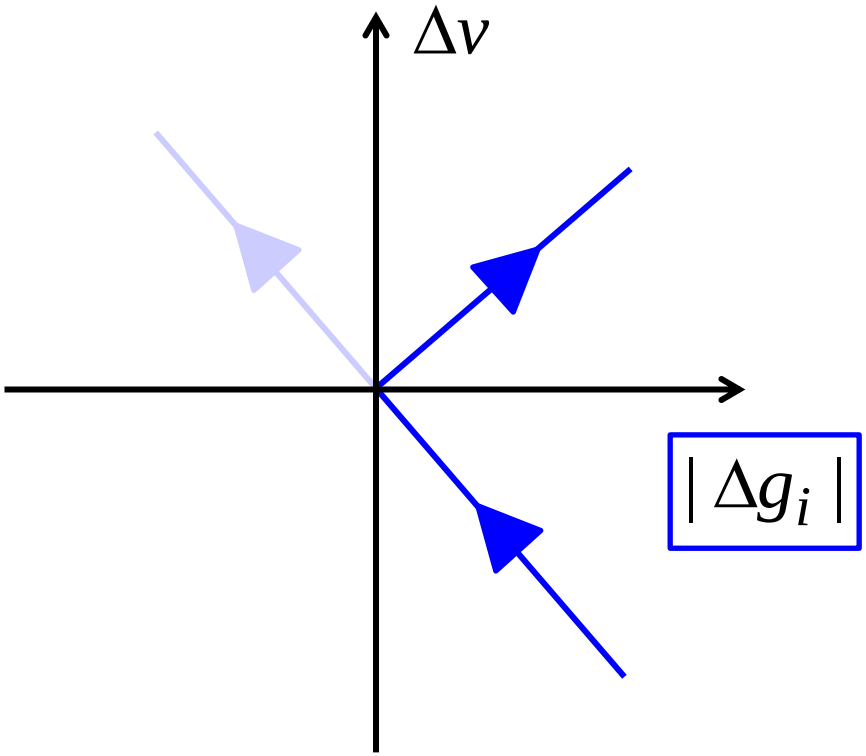
Apêndice 2

$$\frac{dg_i(v_0)}{dv} > 0$$

As curvas ficam iguais se substituirmos Δg por $|\Delta g|$

$$\frac{dg_i(v_0)}{dv} < 0$$

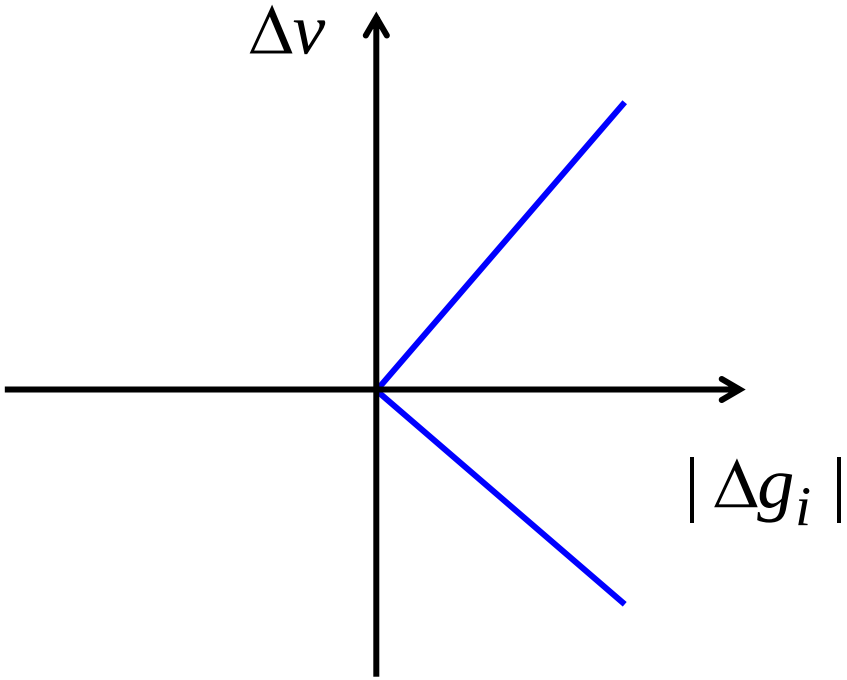




Apêndice 2

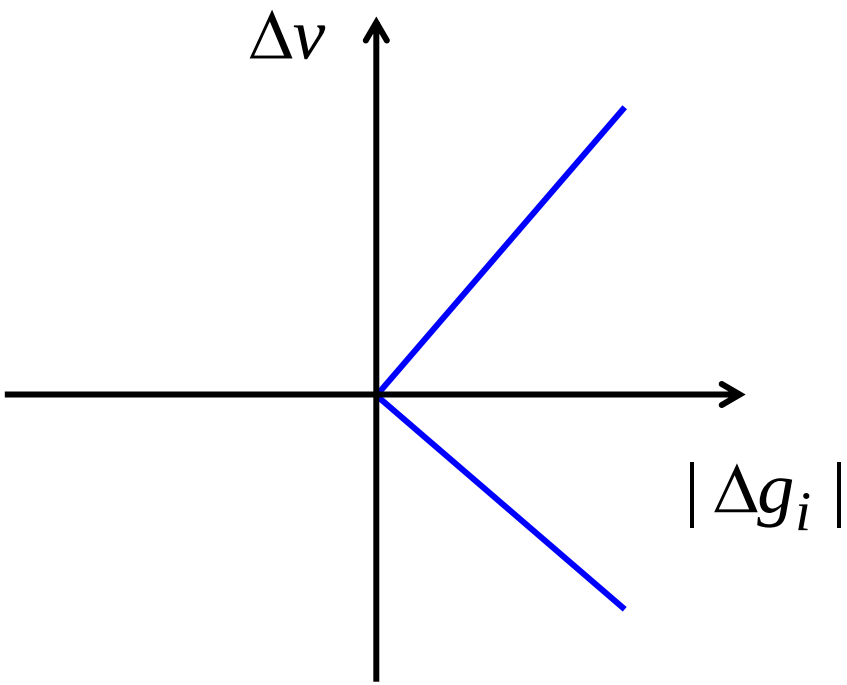
Curva calculada no ponto

$(x_i\,,\,y_i\,,\,z_i)$

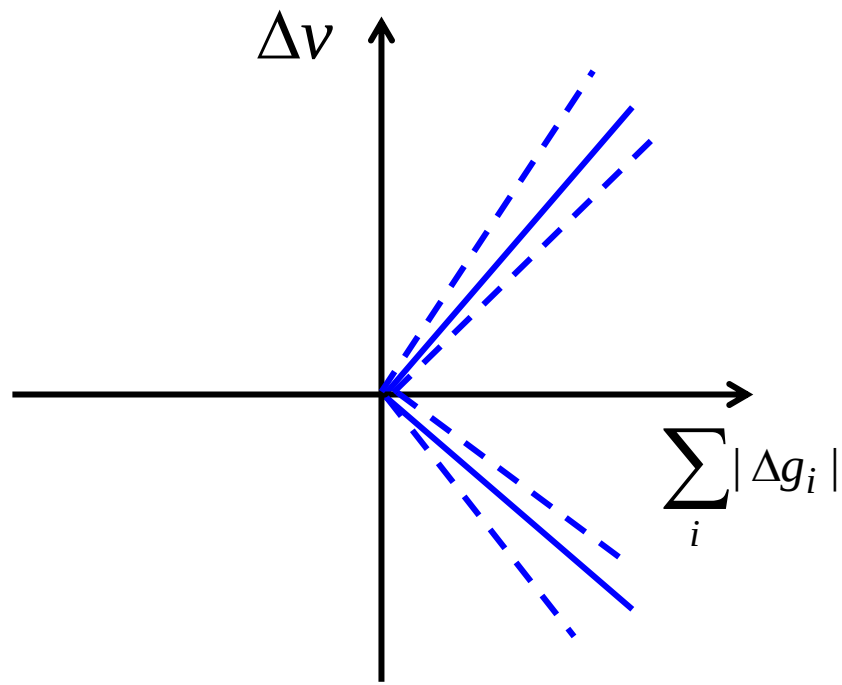


Apêndice 2

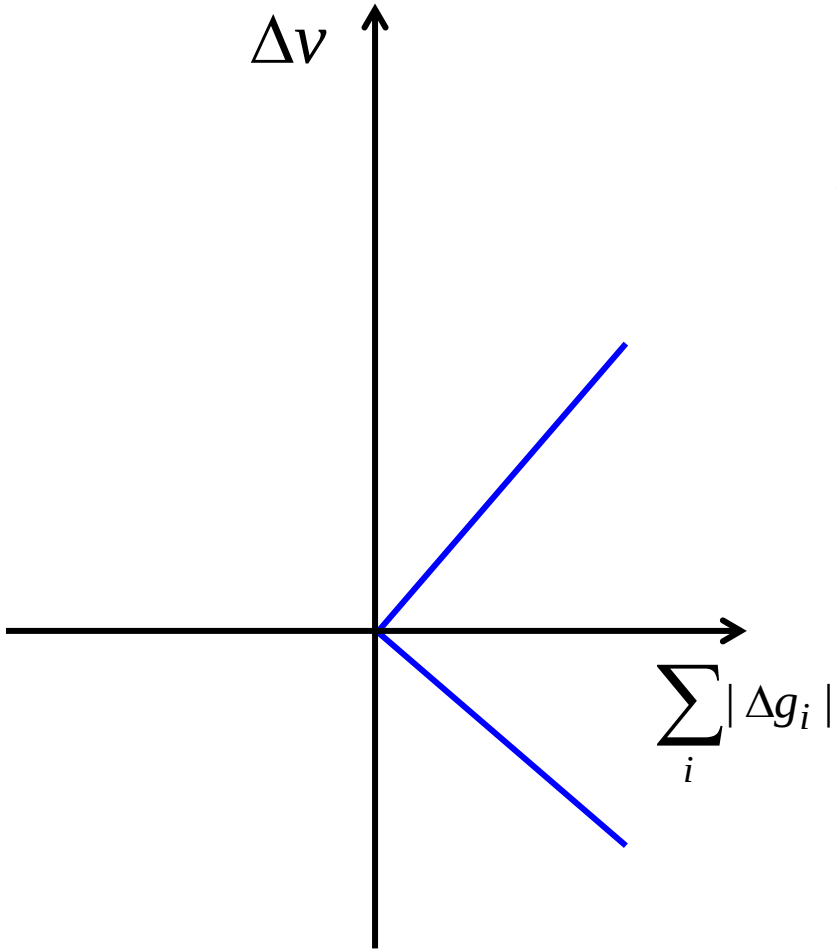
Curva calculada no ponto $(x_i\,,\,y_i\,,\,z_i)$

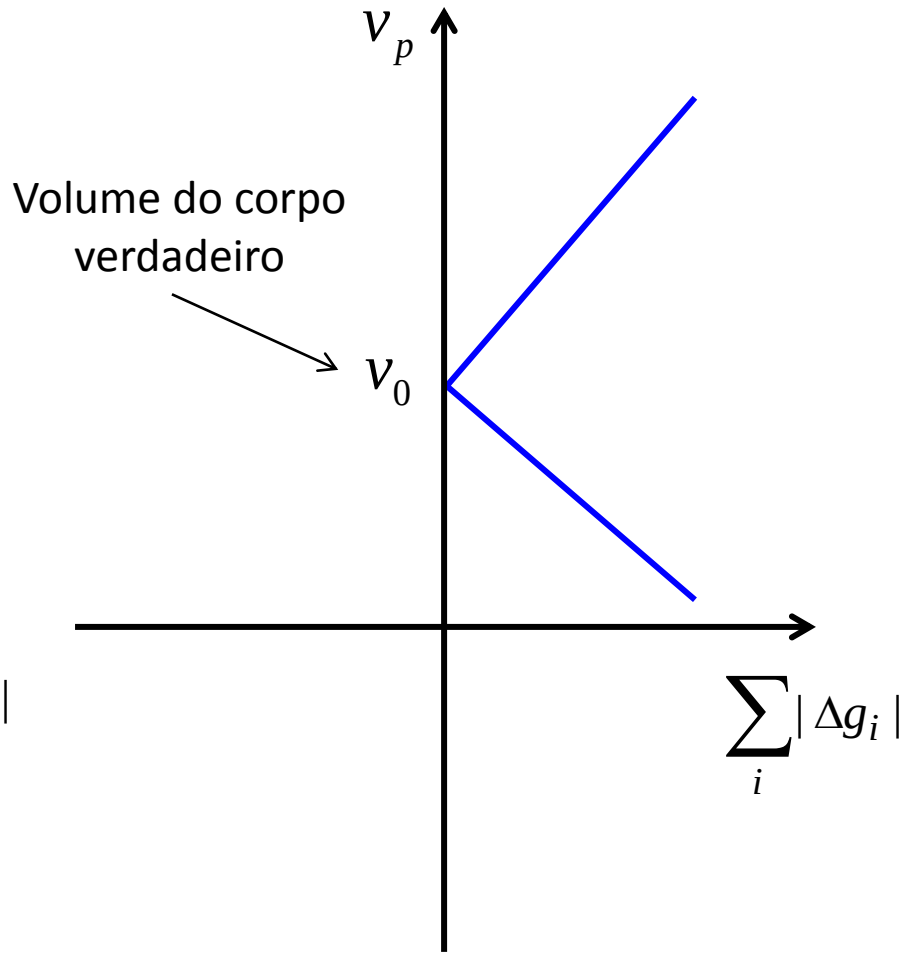


Empilhamento das curvas calculadas para um conjunto de pontos $(x_i\,,\,y_i\,,\,z_i)$



Apêndice 2


Δv
$\sum_i |\Delta g_i|$


v_p
Volume do corpo verdadeiro
v_0
$\sum_i |\Delta g_i|$

Apêndice 2

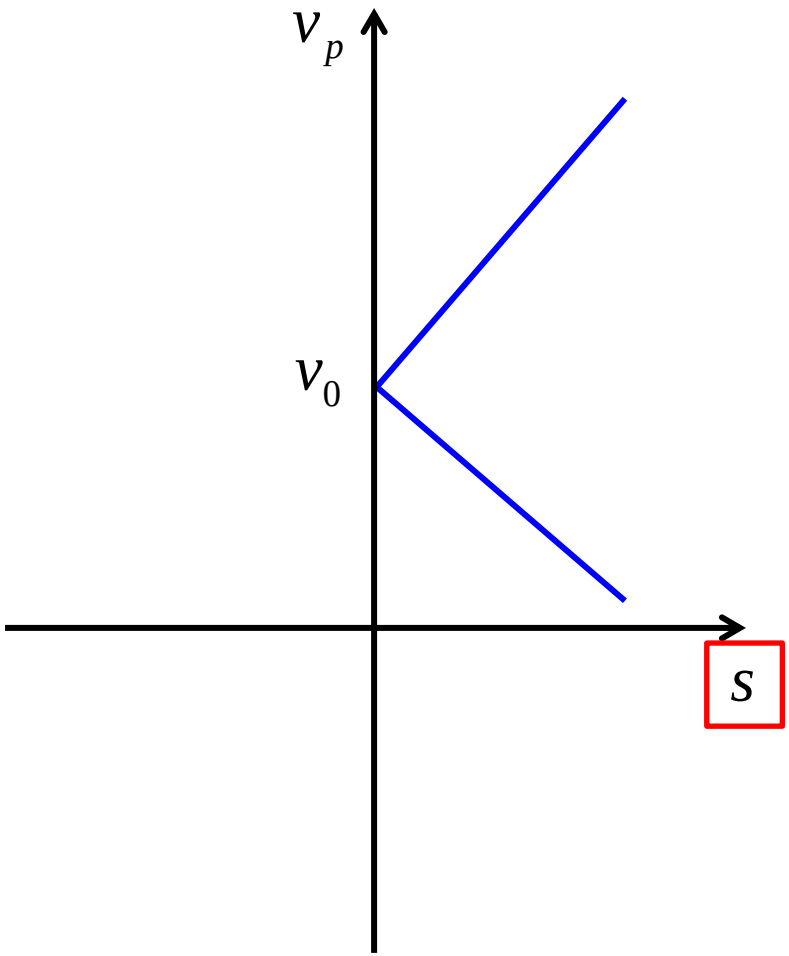
escalar positivo (fator de escala)

dado predito

dado observado

$$s = f \sum_{i=1}^{N} | g_i^p - g_i^o |$$

Norma L1 dos resíduos



Apêndice 2

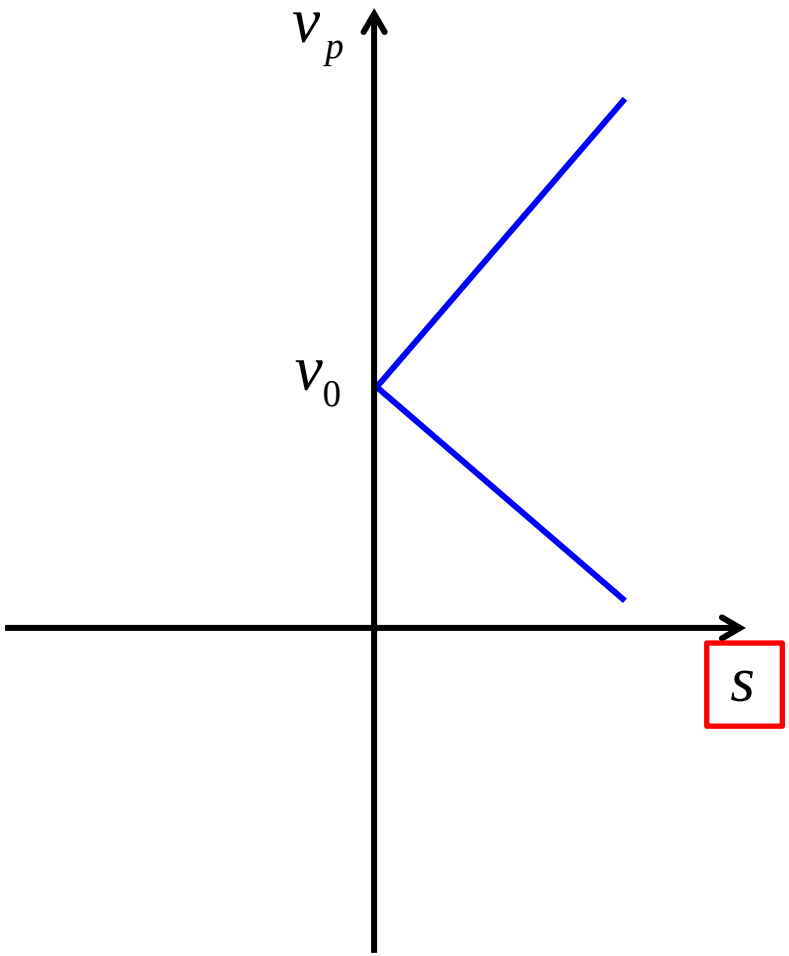
escalar positivo (fator de escala) — dado predito — dado observado

$$s = f \sum_{i=1}^{N} | g_i^p - g_i^o |$$

Norma L1 dos resíduos

$$f = \sqrt{\frac{N}{\sum_{i=1}^{N} (g_i^o)^2}}$$

O fator de escala pode ser definido como o inverso da norma L2 dos dados observados



Apêndice 2

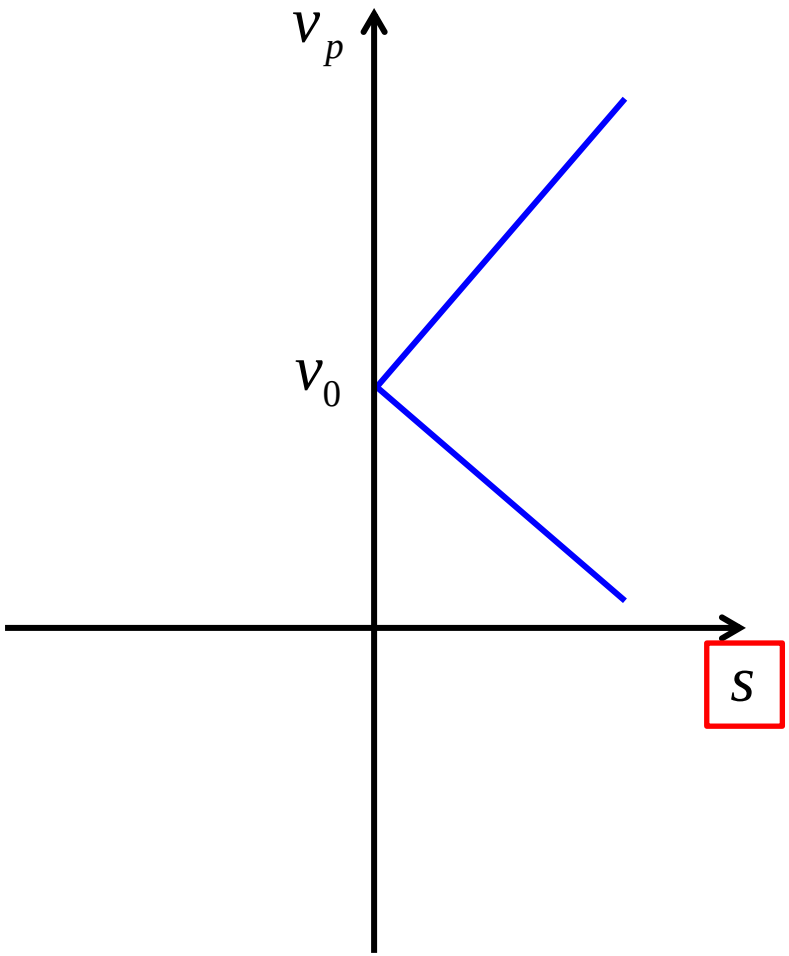
escalar positivo (fator de escala) — dado predito — dado observado

$$s = f \sum_{i=1}^{N} | g_i^p - g_i^o |$$

Norma L1 dos resíduos

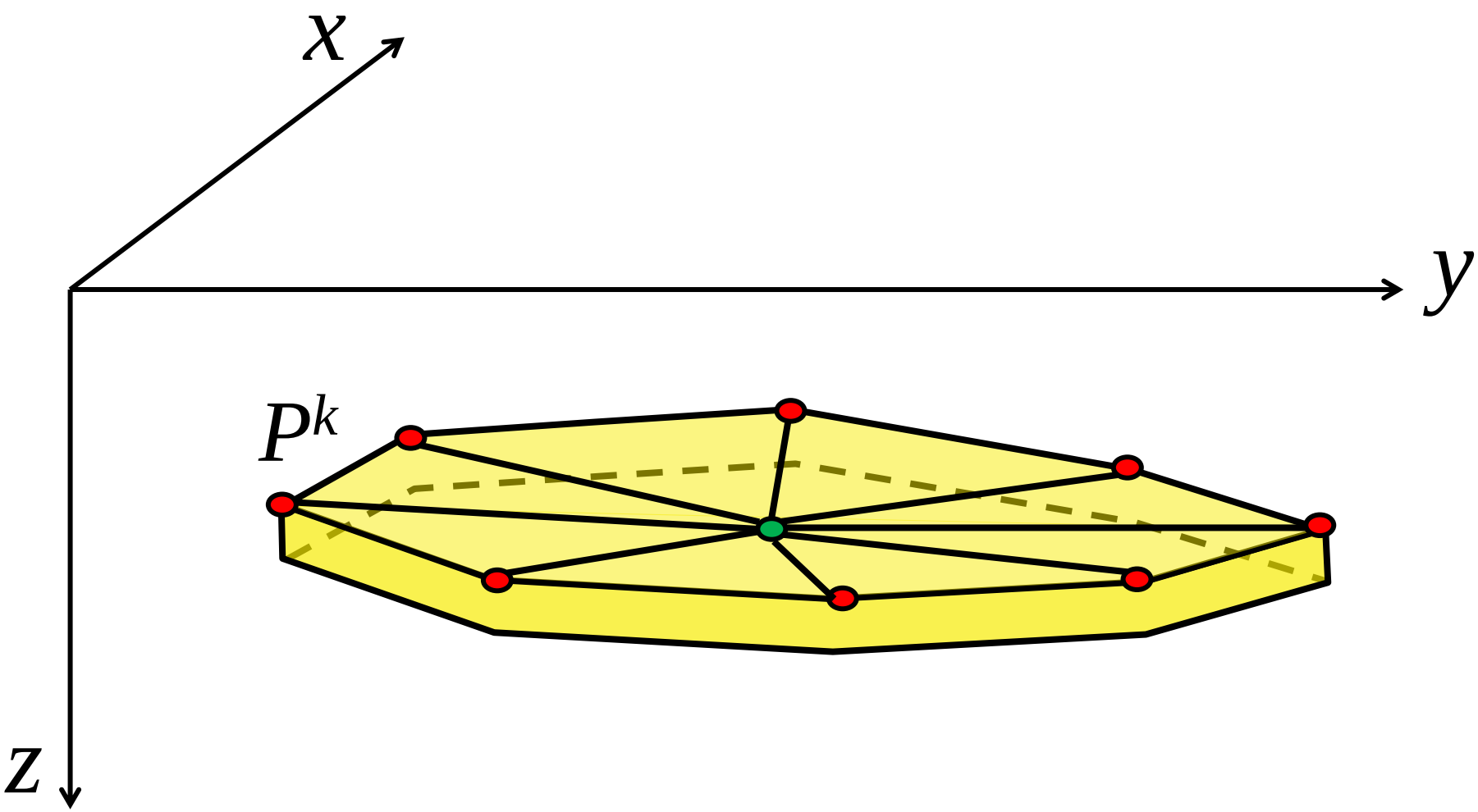
$$f = \sqrt{\frac{N}{\sum_{i=1}^{N} (g_i^o)^2}}$$

O fator de escala pode ser definido como o inverso da norma L2 dos dados observados



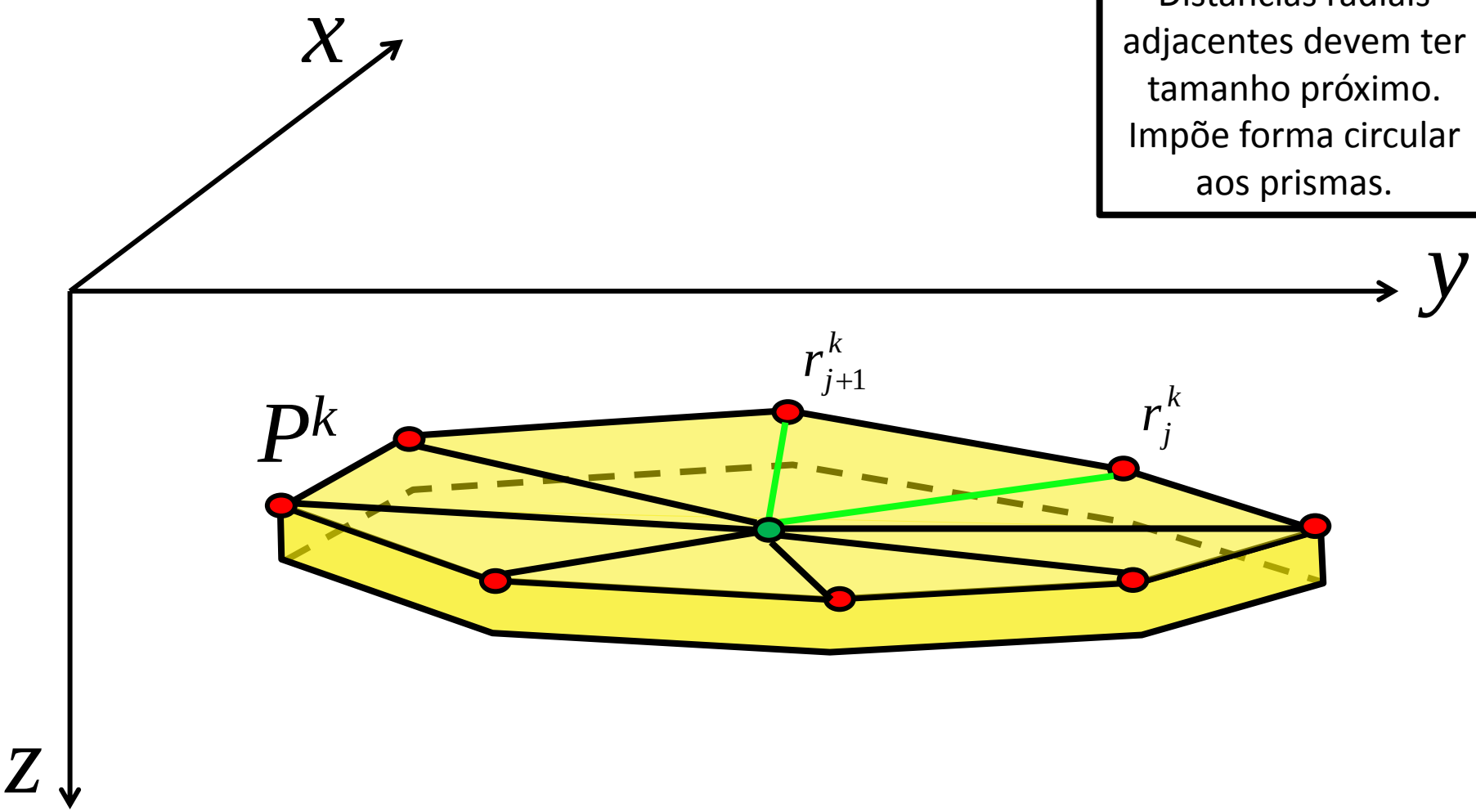
Inversão conjunta

Apêndice 3

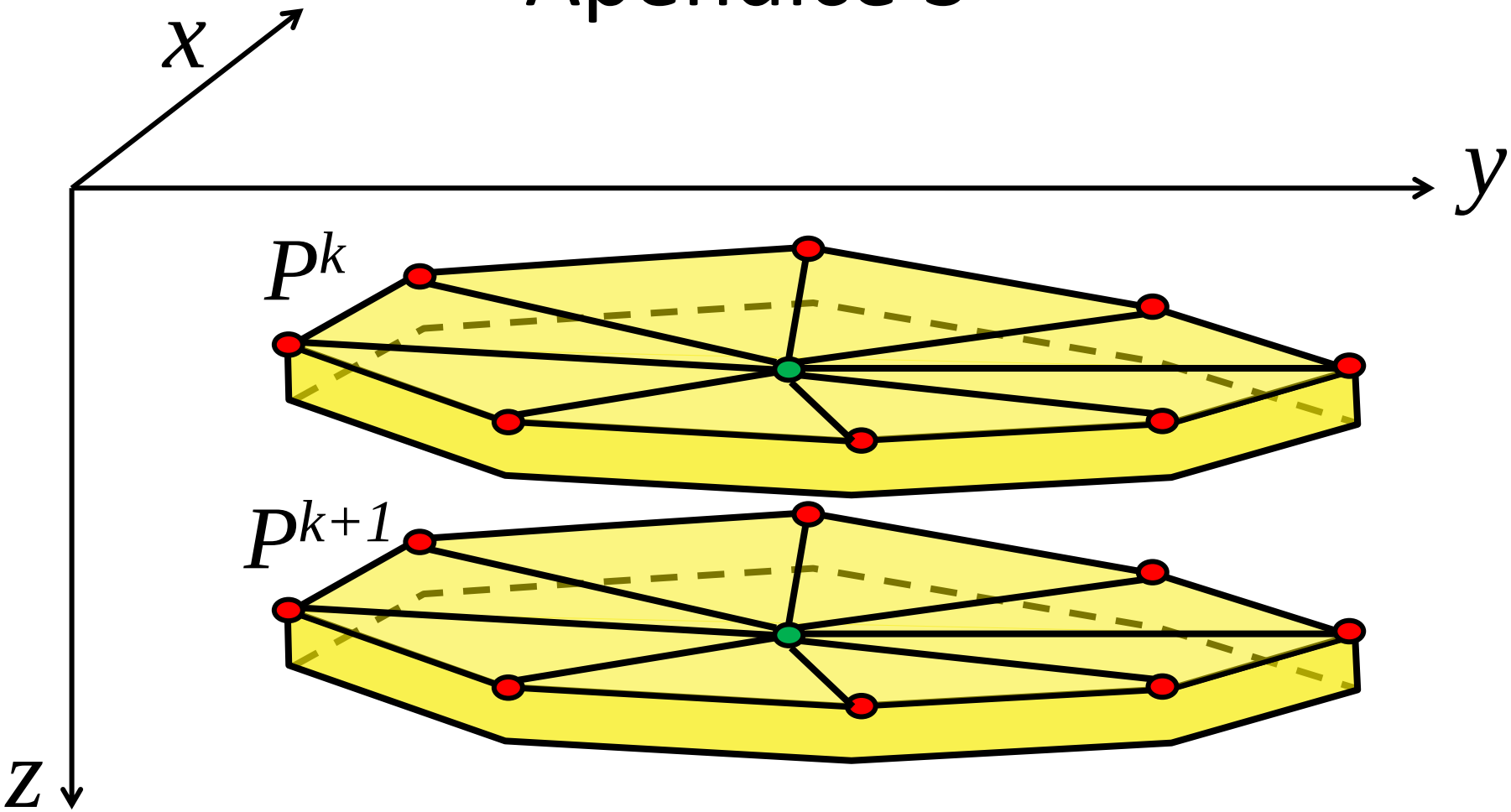


Apêndice 3

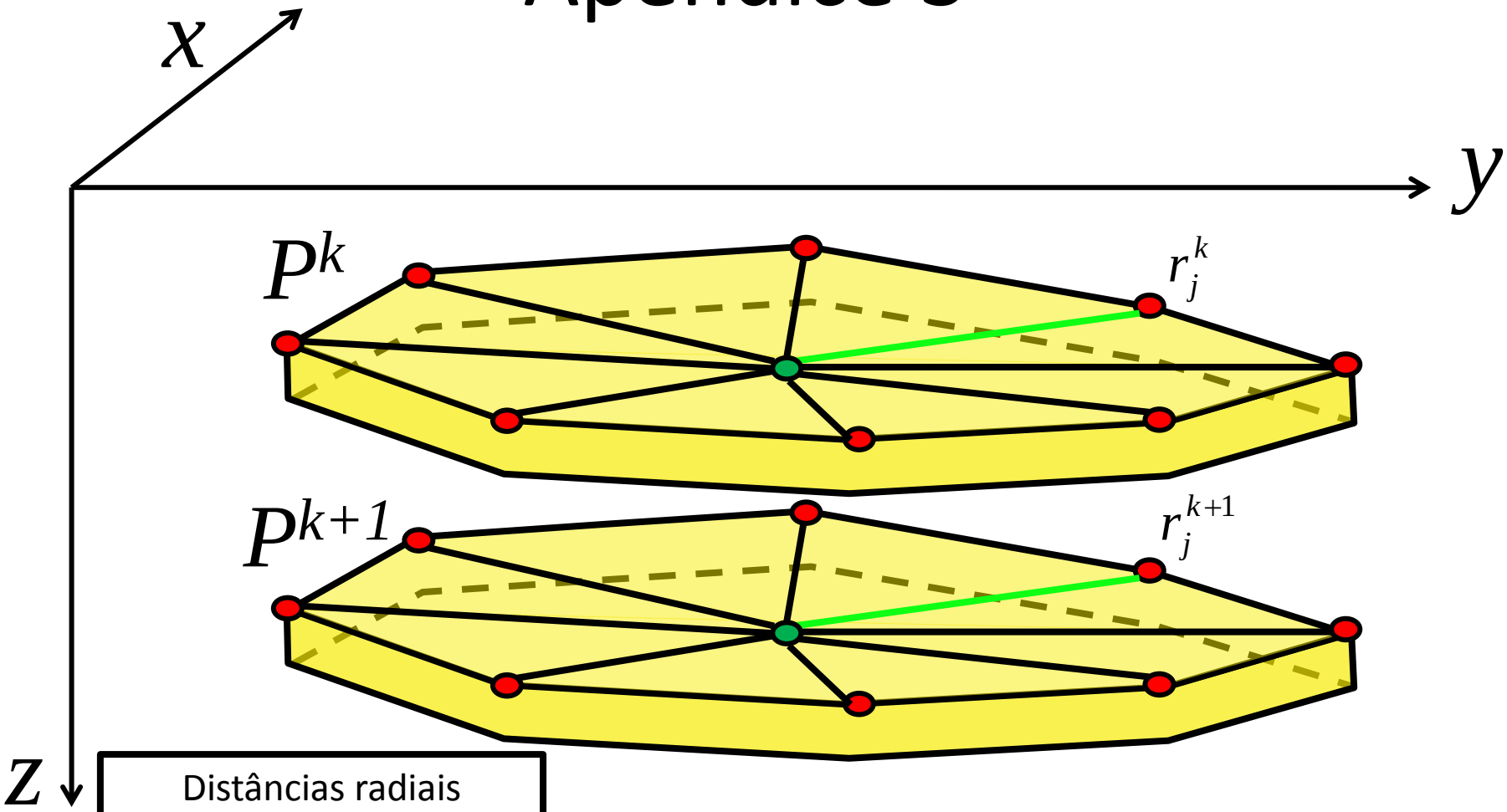
Distâncias radiais adjacentes devem ter tamanho próximo. Impõe forma circular aos prismas.



Apêndice 3

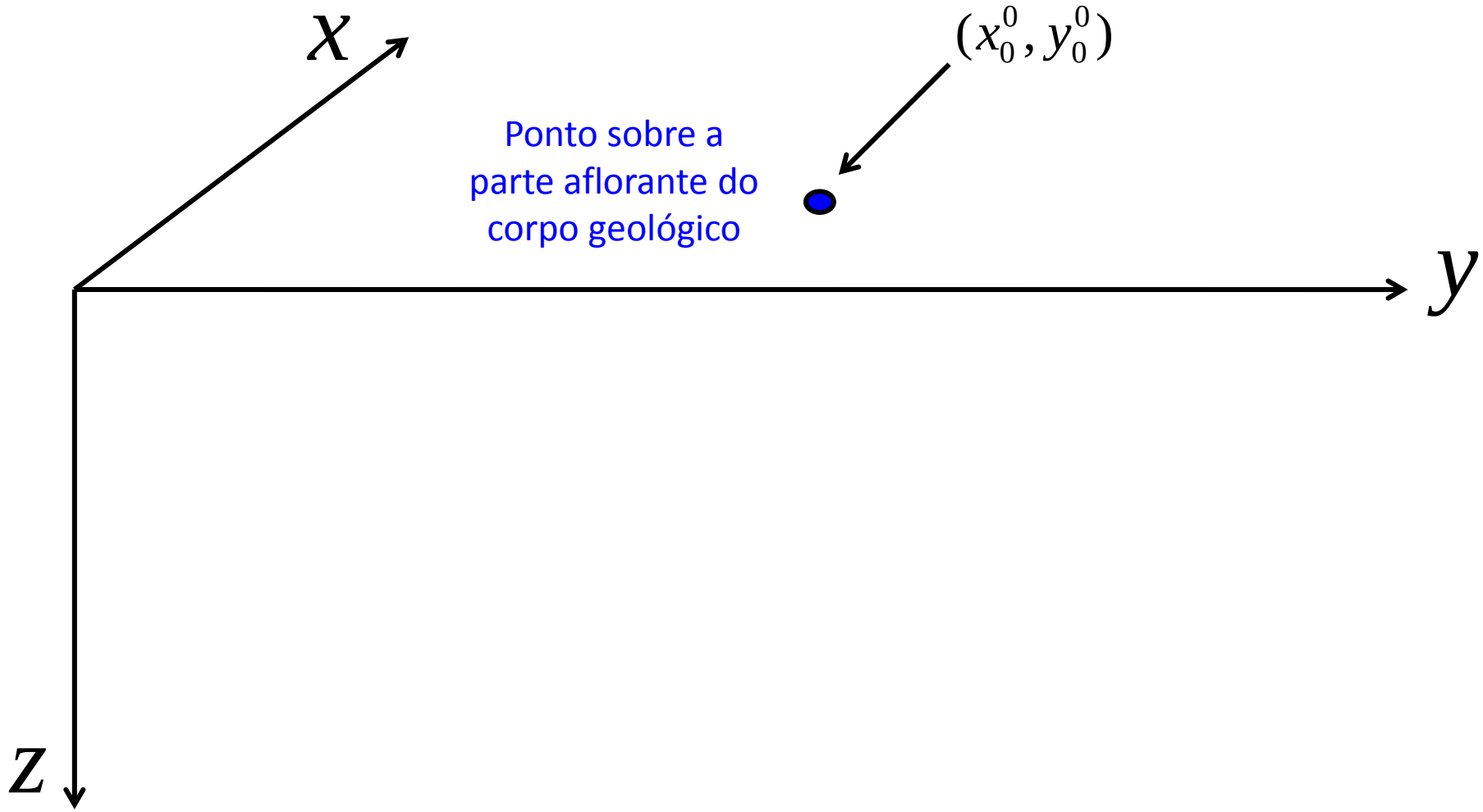


Apêndice 3

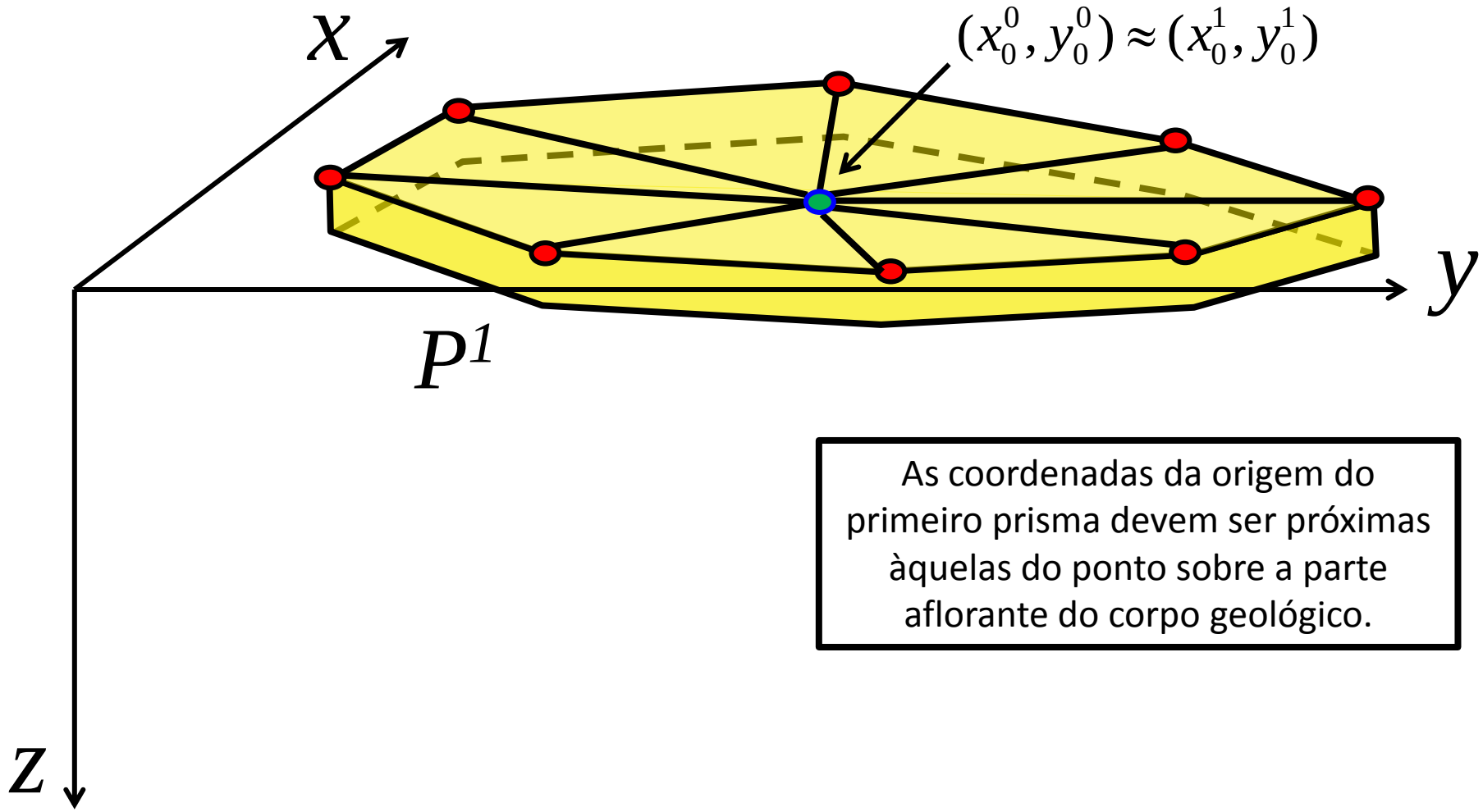


Distâncias radiais adjacentes devem ter tamanho próximo. Impõe a mesma forma a todos os prismas.

Apêndice 3

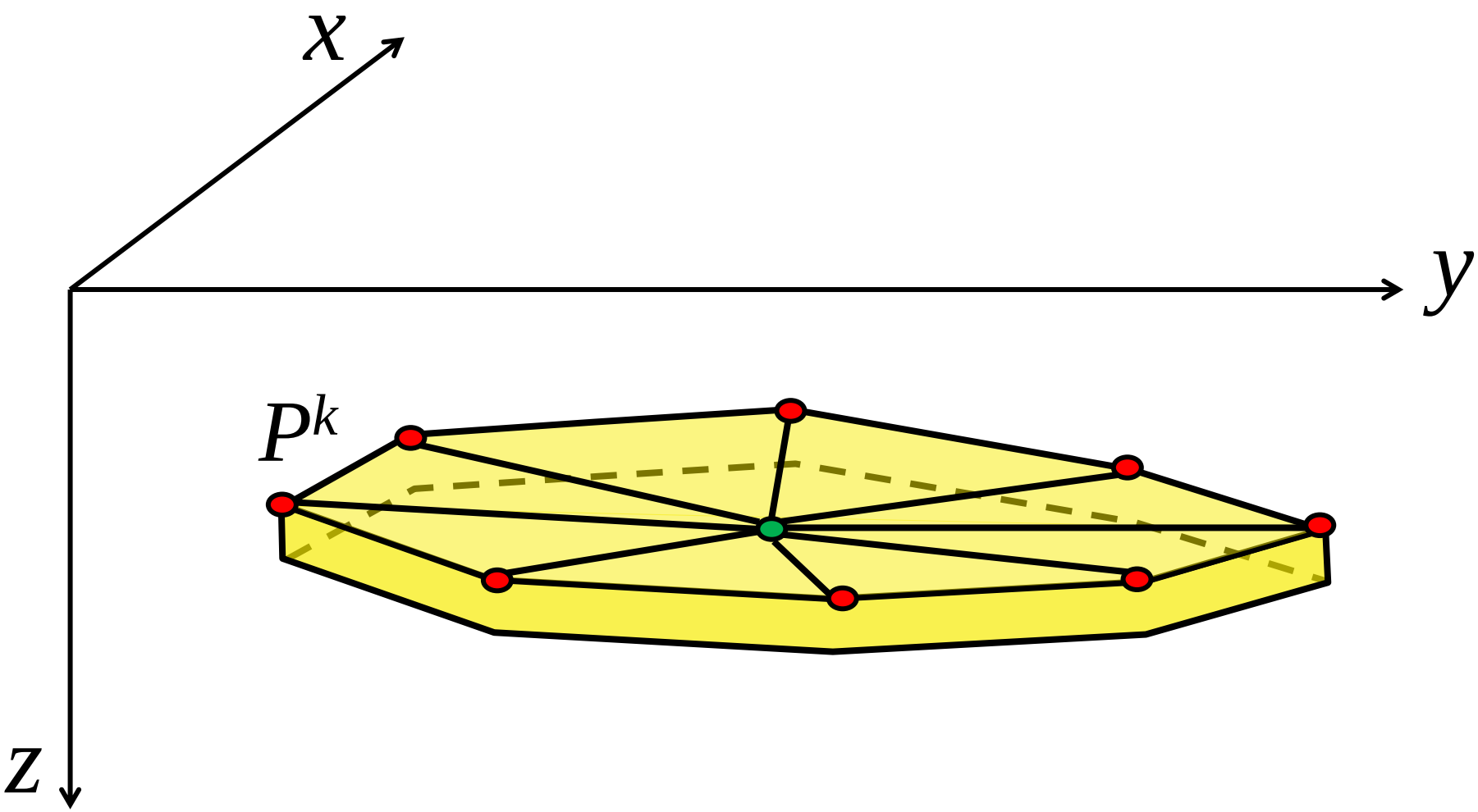

x
(x_0^0, y_0^0)
Ponto sobre a
parte aflorante do
corpo geológico
y
z

Apêndice 3

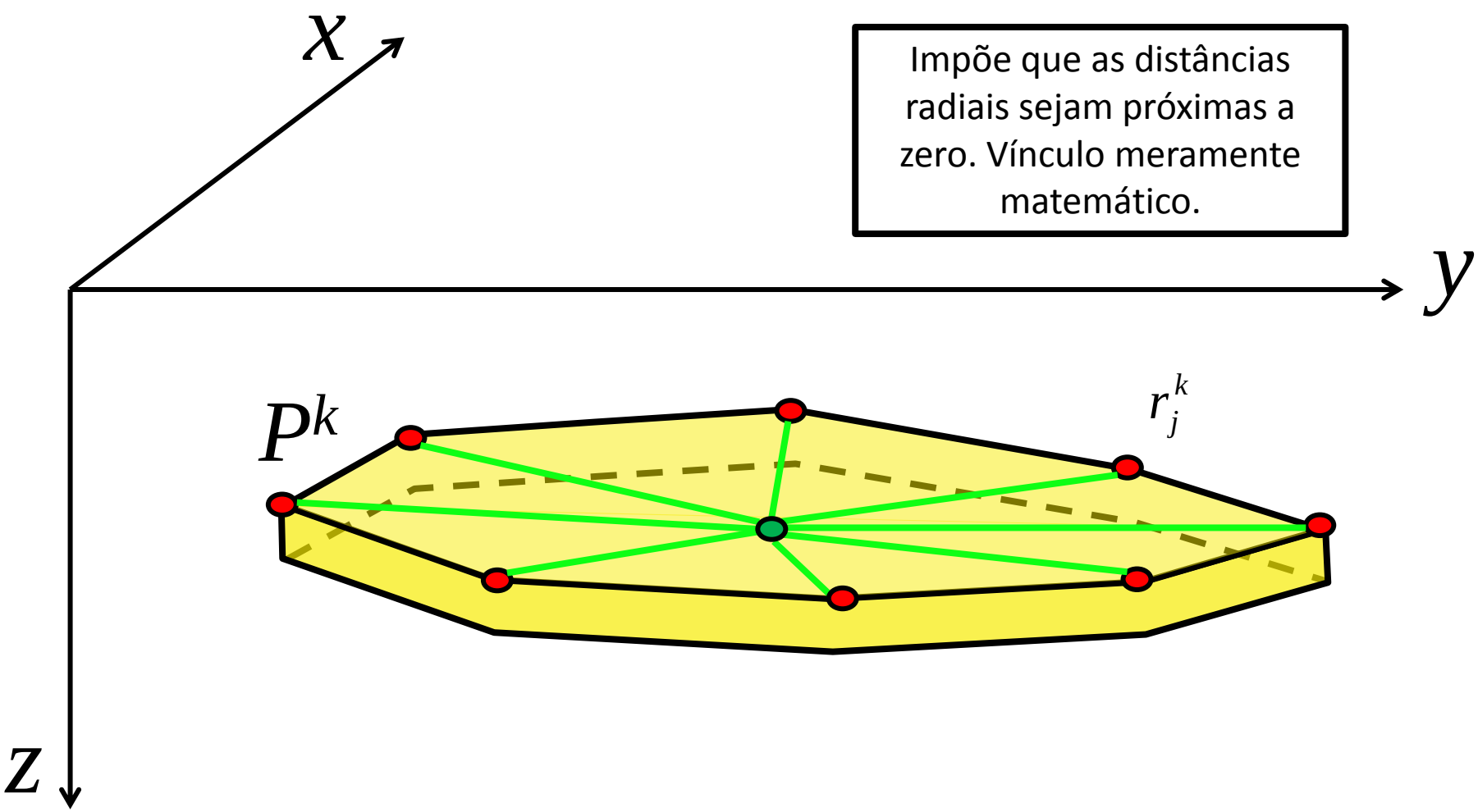


As coordenadas da origem do primeiro prisma devem ser próximas àquelas do ponto sobre a parte aflorante do corpo geológico.

Apêndice 3

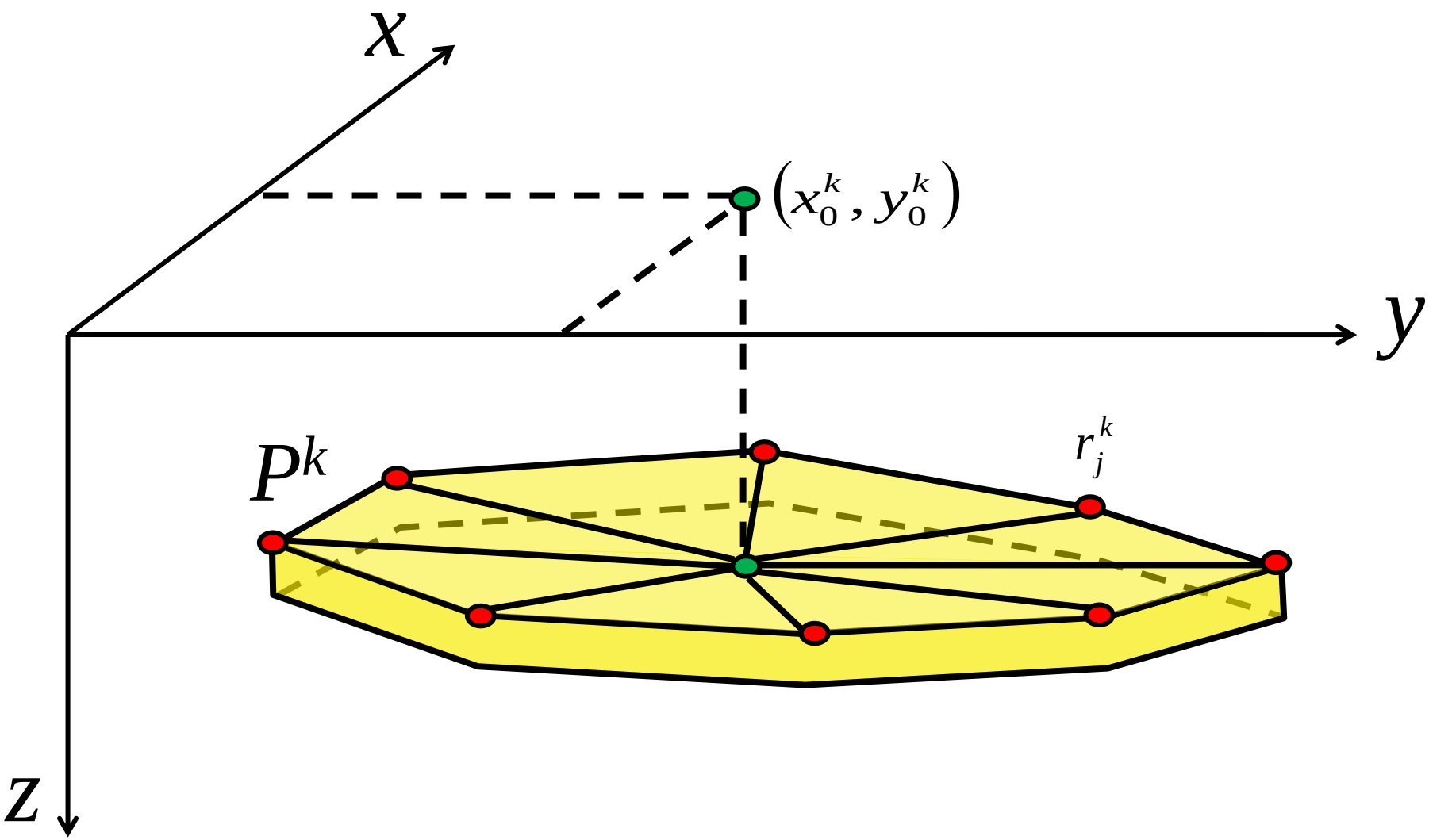


Apêndice 3

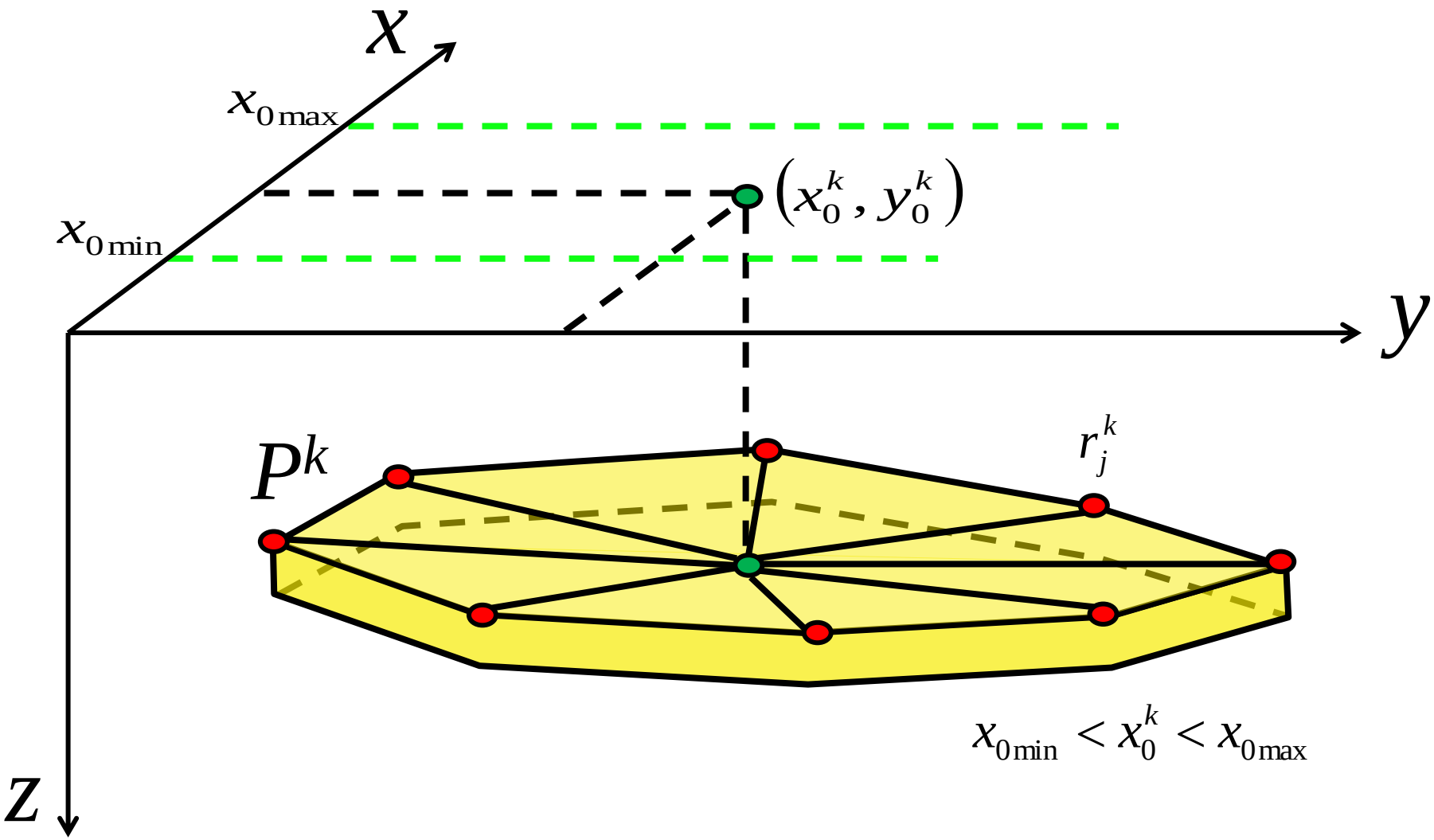


Impõe que as distâncias radiais sejam próximas a zero. Vínculo meramente matemático.

Apêndice 3

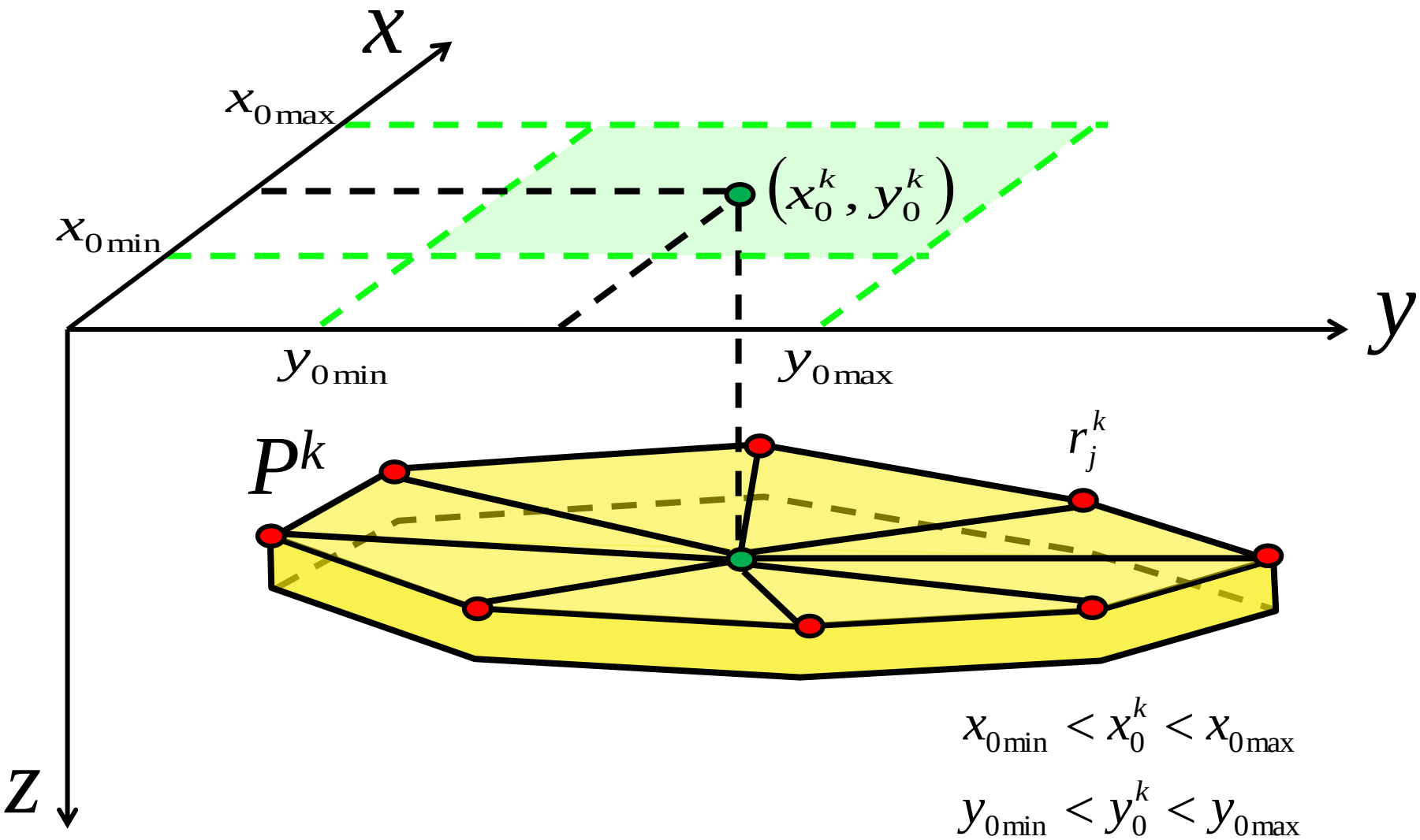


Apêndice 3



$$x_{0\min} < x_0^k < x_{0\max}$$

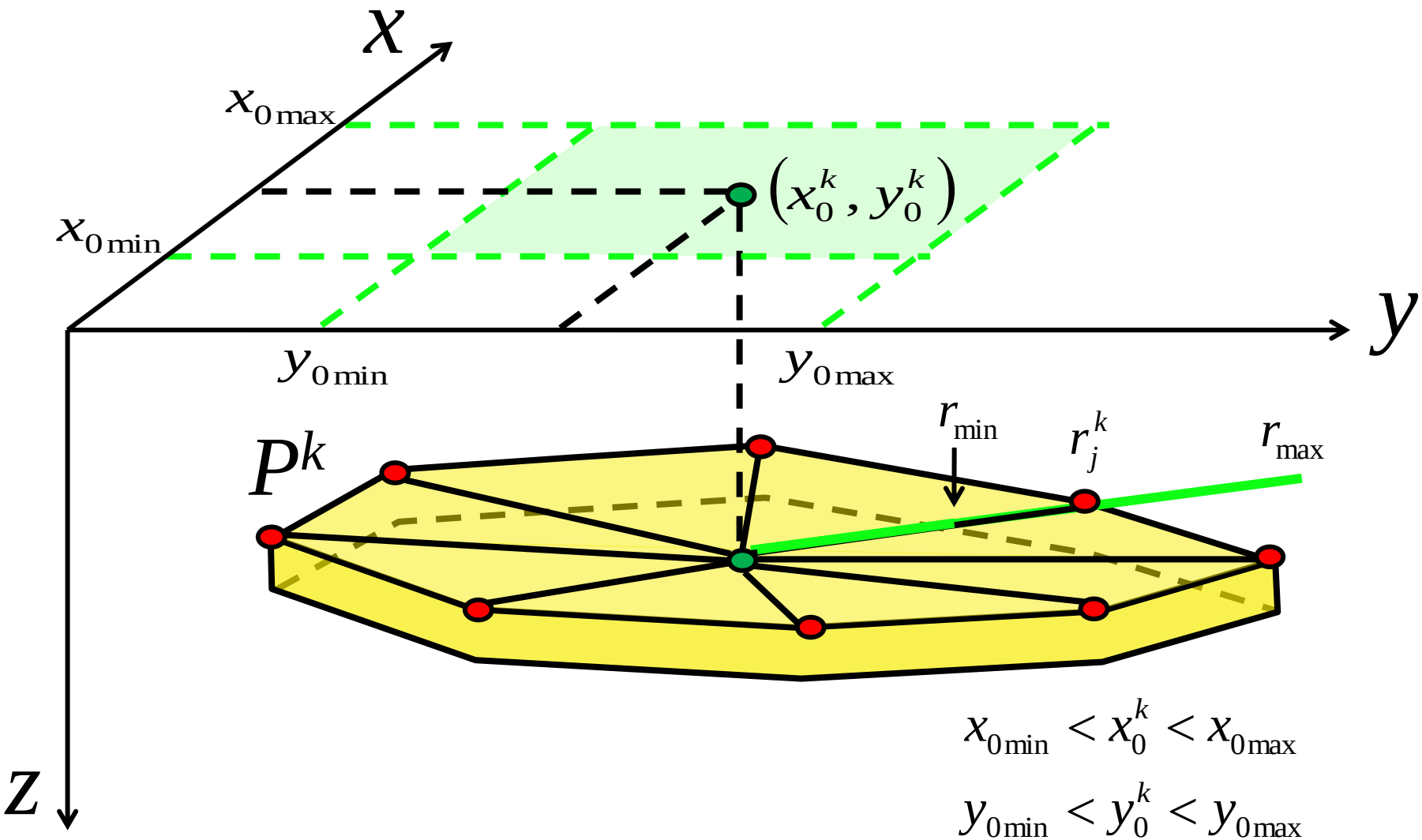
Apêndice 3



$$x_{0\min} < x_0^k < x_{0\max}$$

$$y_{0\min} < y_0^k < y_{0\max}$$

Apêndice 3

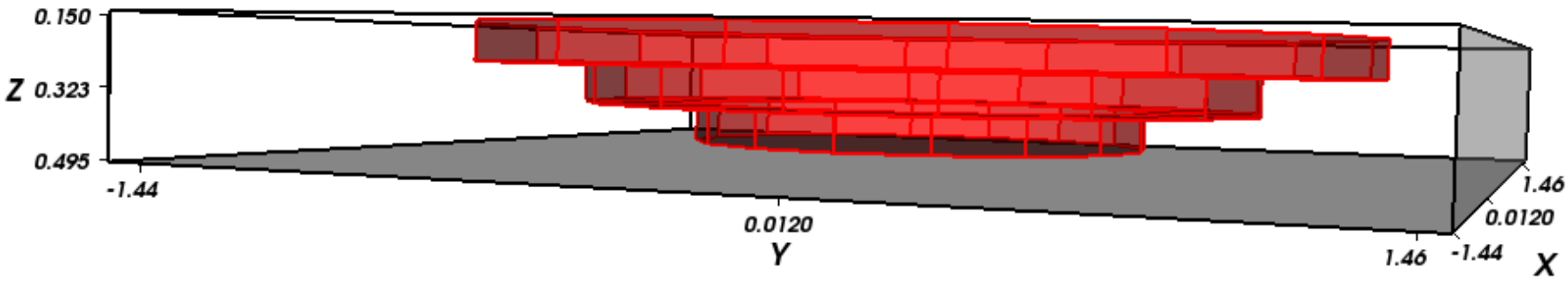


$$x_{0\min} < x_0^k < x_{0\max}$$

$$y_{0\min} < y_0^k < y_{0\max}$$

$$r_{\min} < r_j^k < r_{\max}$$

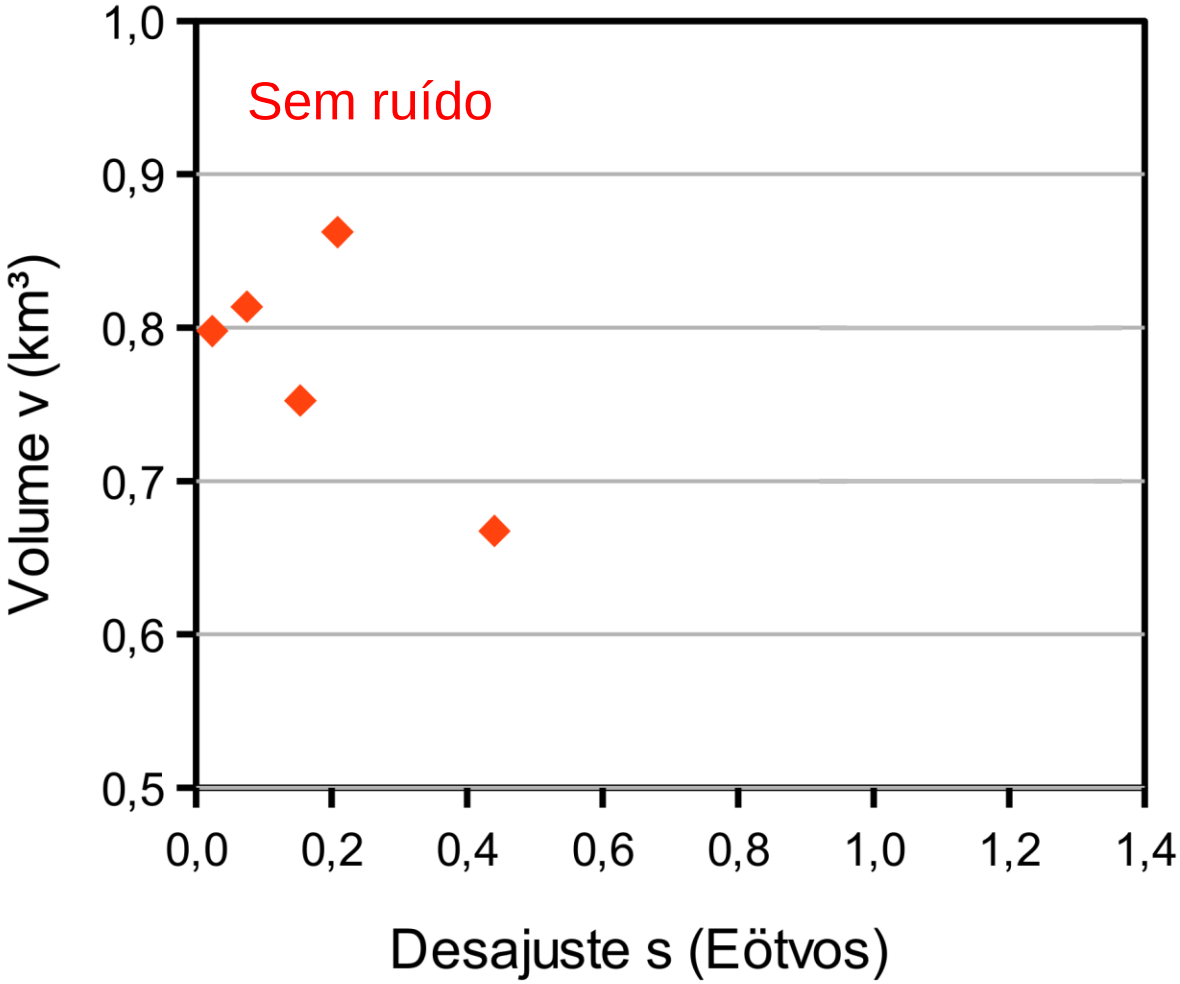
Apêndice 4



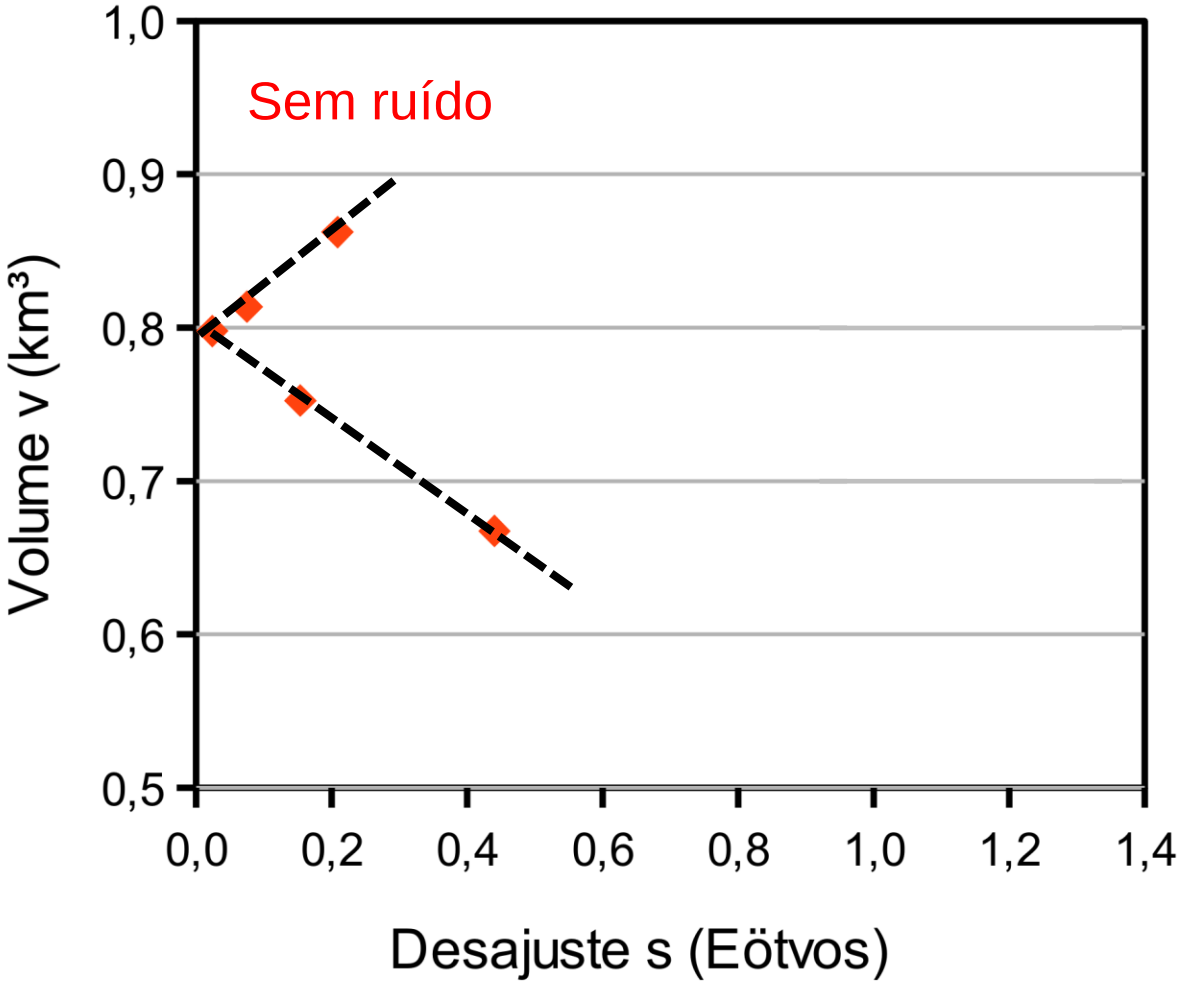
- topo: 150 m
- base: 450 m
- rho: 1,0 g/cm³
- volume: 0,8 km³
- dimensão horizontal máxima: 2400 m

Corpo verdadeiro

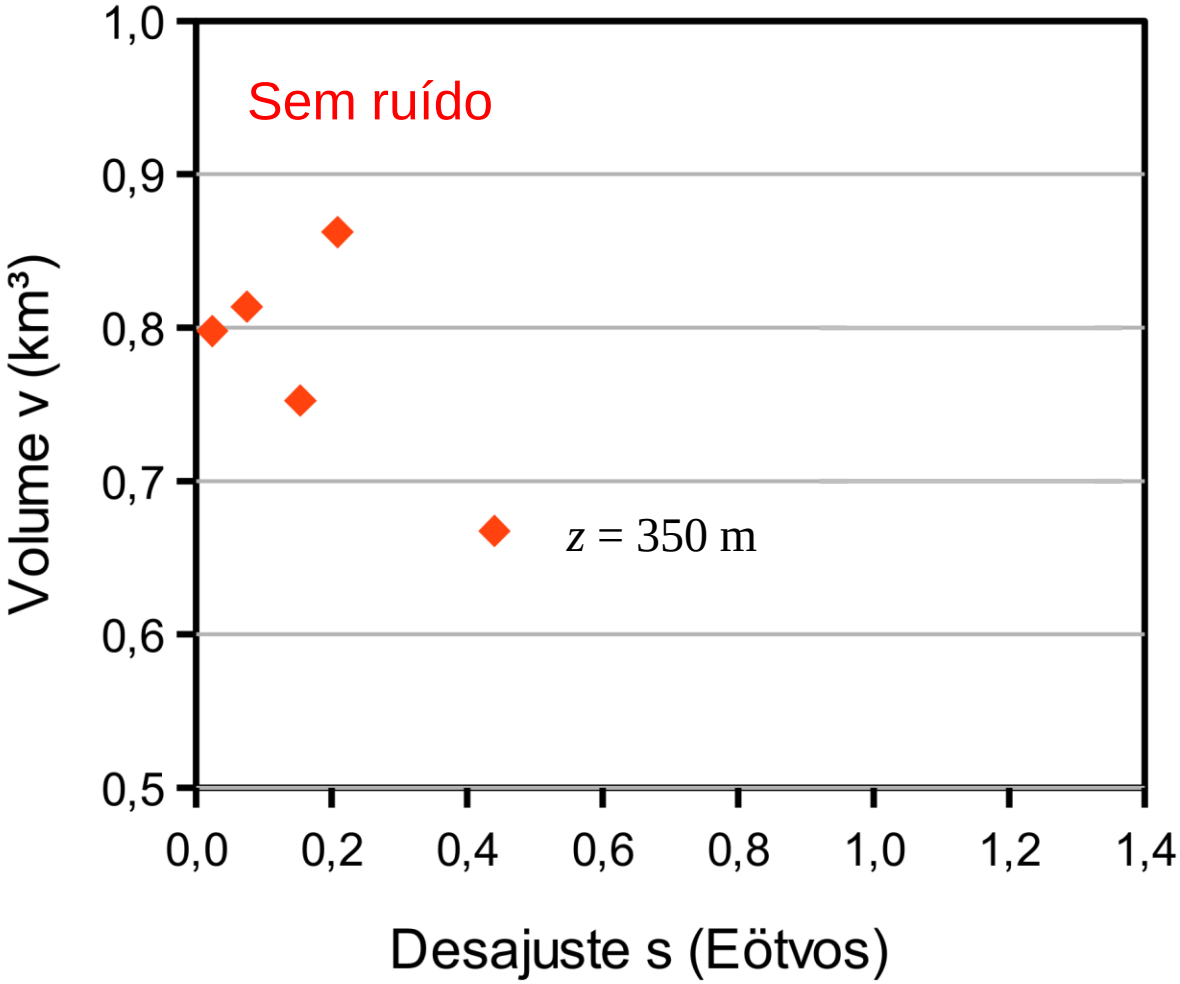
Apêndice 4


Sem ruído
1,0
0,9
0,8
0,7
0,6
0,5
Volume v (km³)
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
Desajuste s (Eötvos)

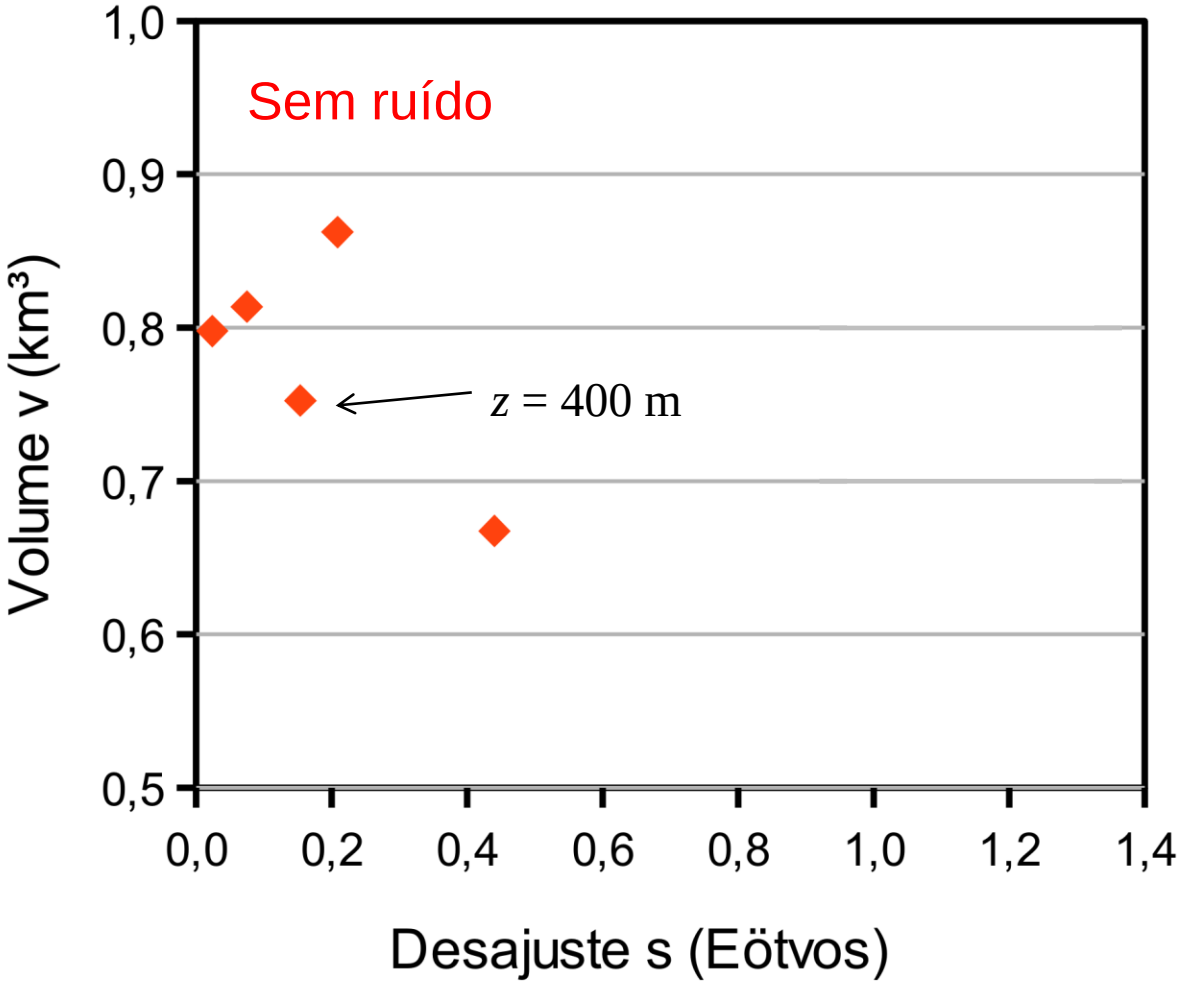
Apêndice 4


Sem ruído
1,0
0,9
0,8
0,7
0,6
0,5
Volume v (km³)
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
Desajuste s (Eötvos)

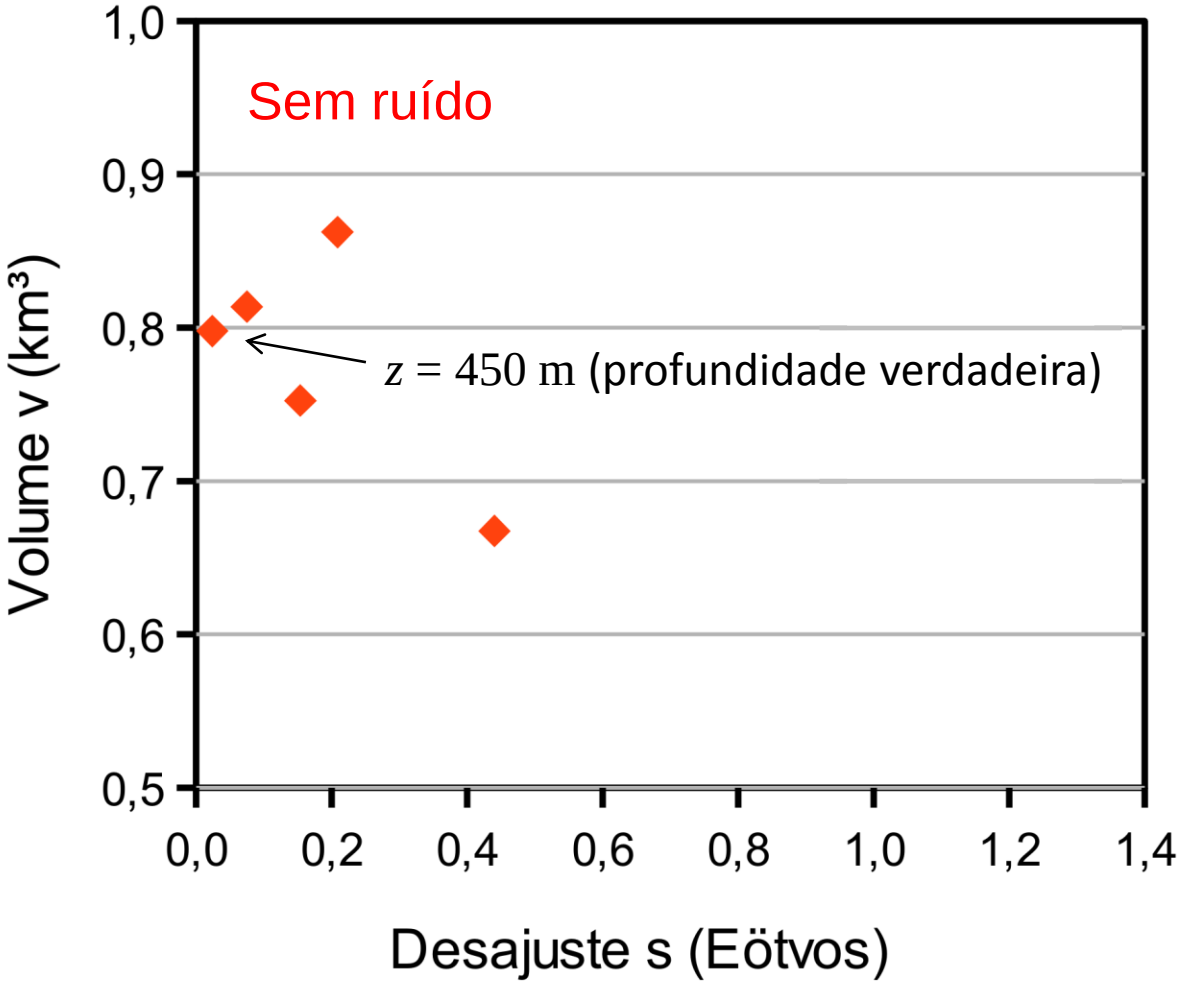
Apêndice 4


Sem ruído
z = 350 m
Volume v (km³)
1,0
0,9
0,8
0,7
0,6
0,5
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
Desajuste s (Eötvos)

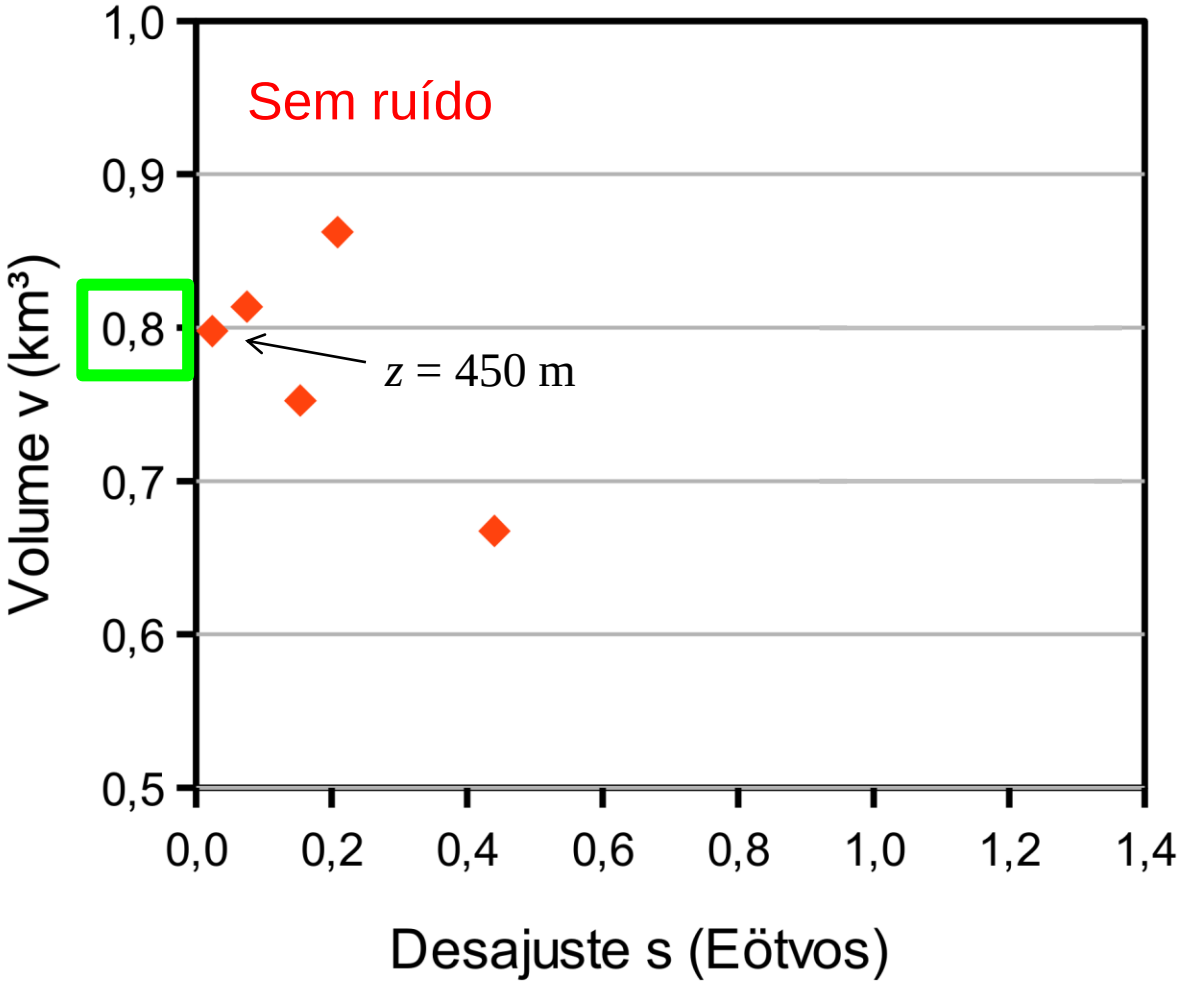
Apêndice 4


Sem ruído
z = 400 m
Volume v (km³)
Desajuste s (Eötvos)
1,0
0,9
0,8
0,7
0,6
0,5
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4

Apêndice 4

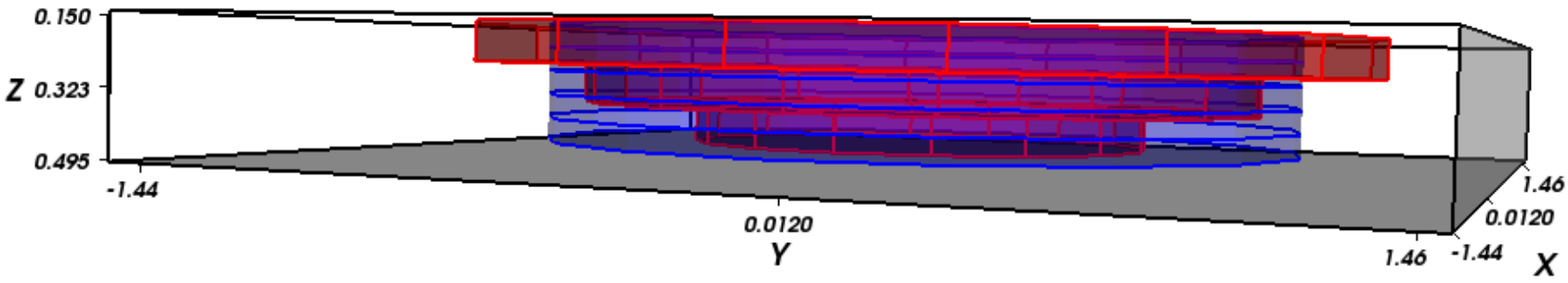

Sem ruído
z = 450 m (profundidade verdadeira)
Volume v (km³)
1,0
0,9
0,8
0,7
0,6
0,5
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
Desajuste s (Eötvos)

Apêndice 4



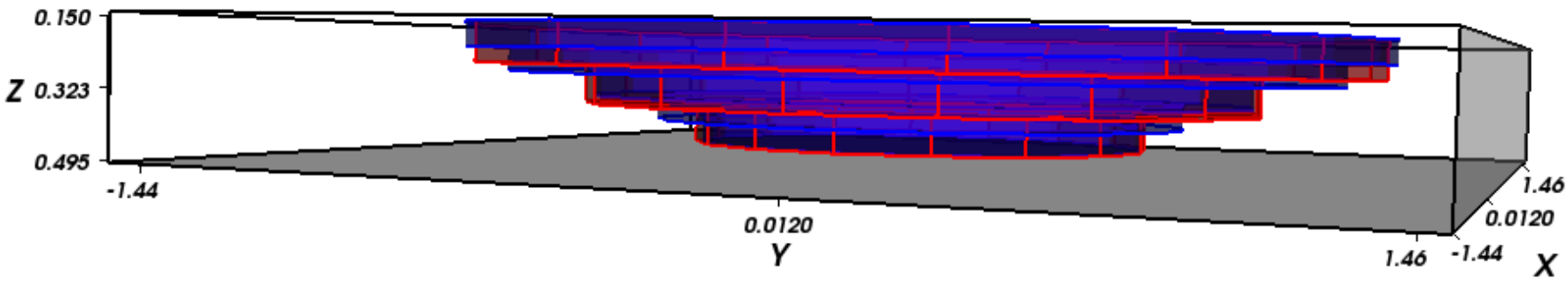
A estimativa possui o mesmo volume do corpo verdadeiro (0,8 km³)

Apêndice 4



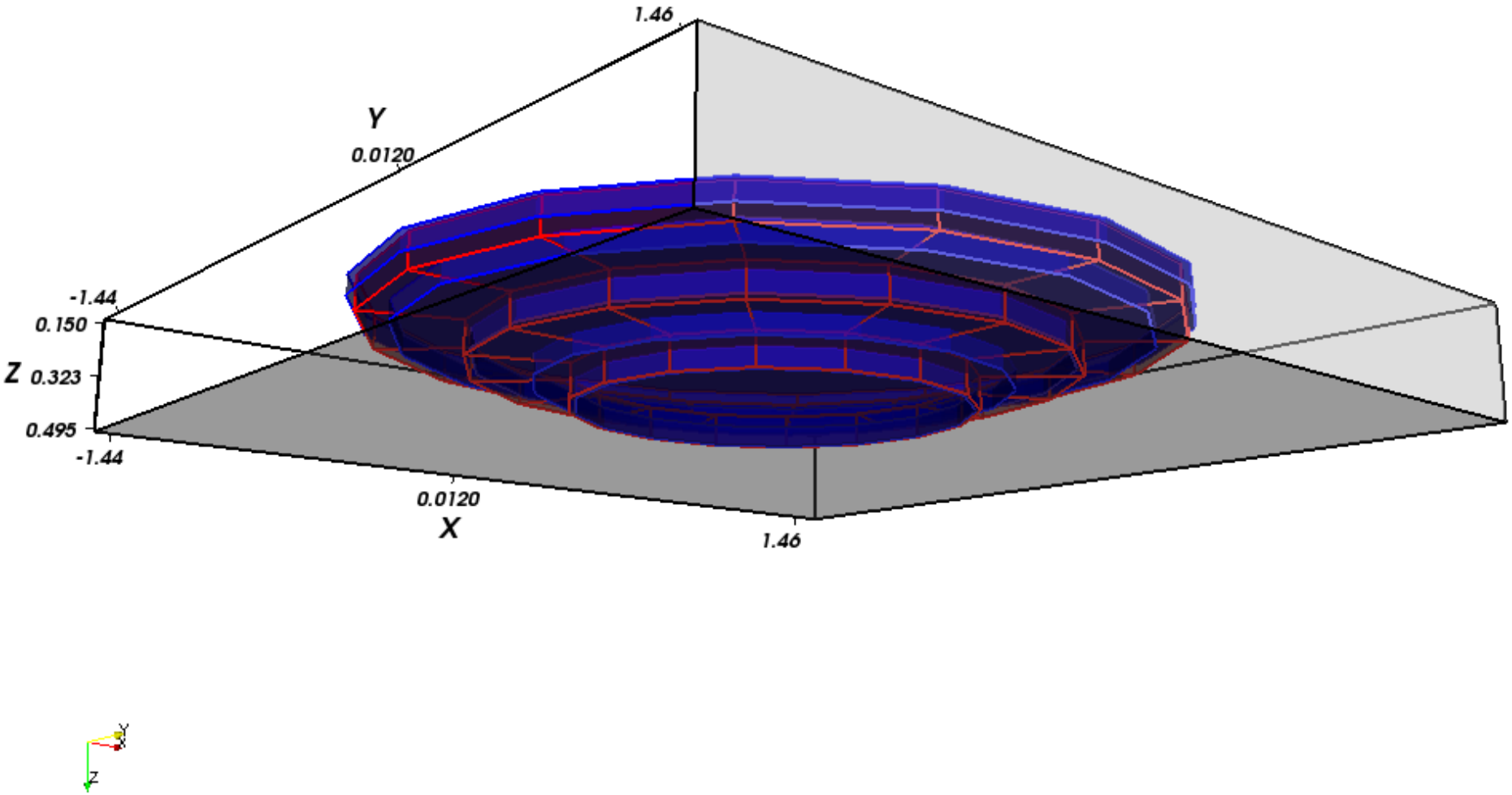
Corpo verdadeiro
Aproximação inicial

Apêndice 4

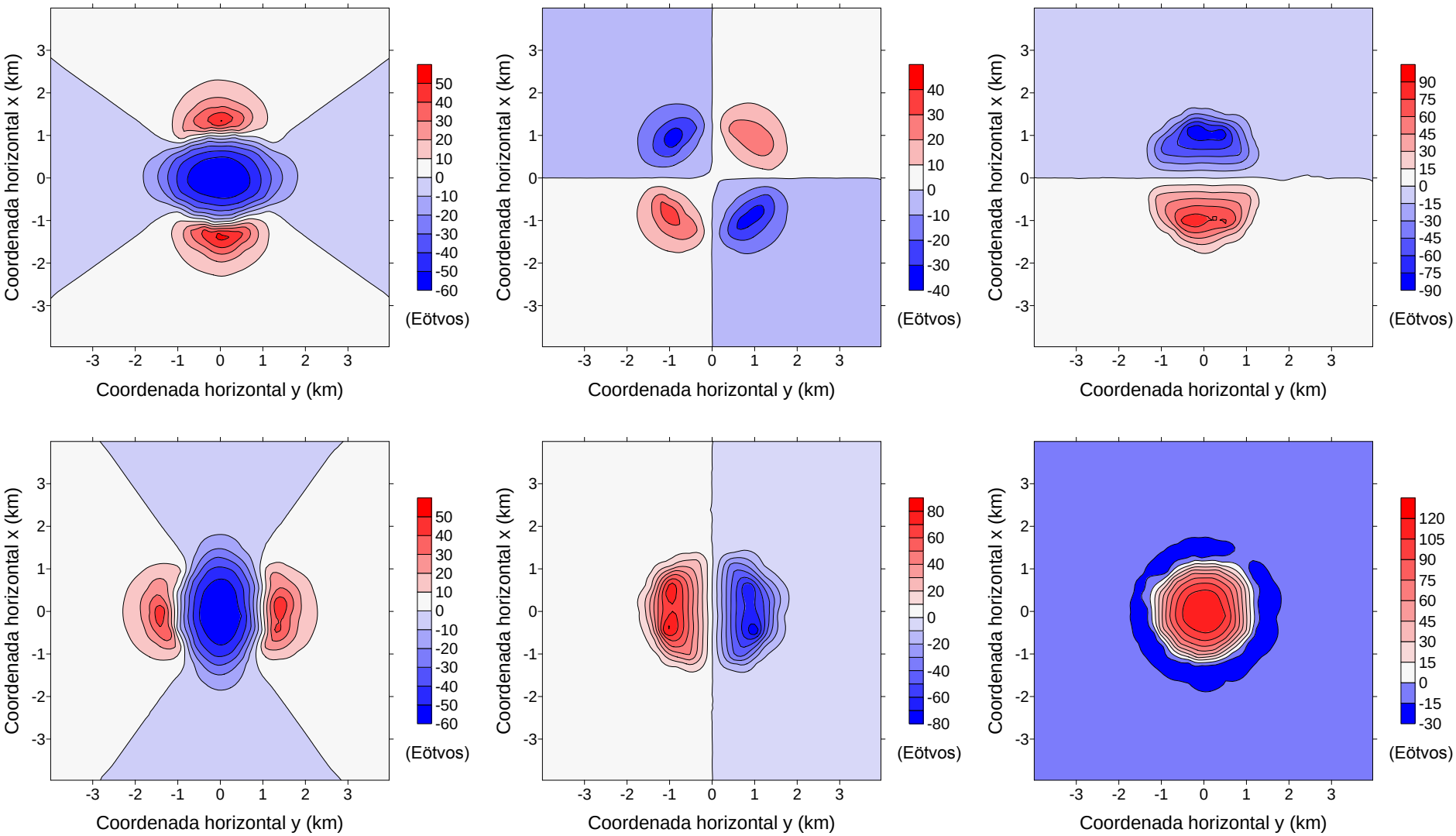


Corpo verdadeiro
Corpo estimado

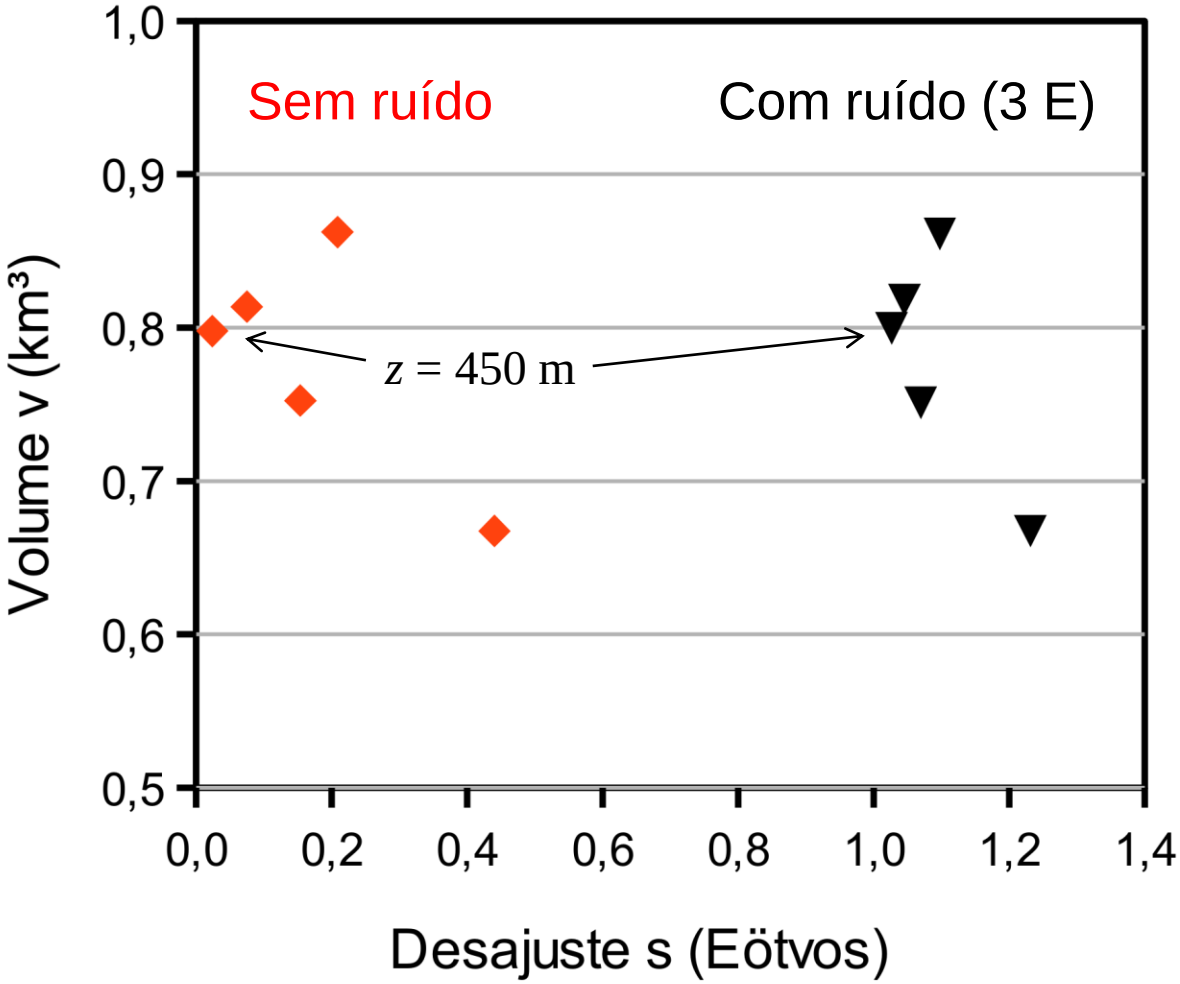
Apêndice 4



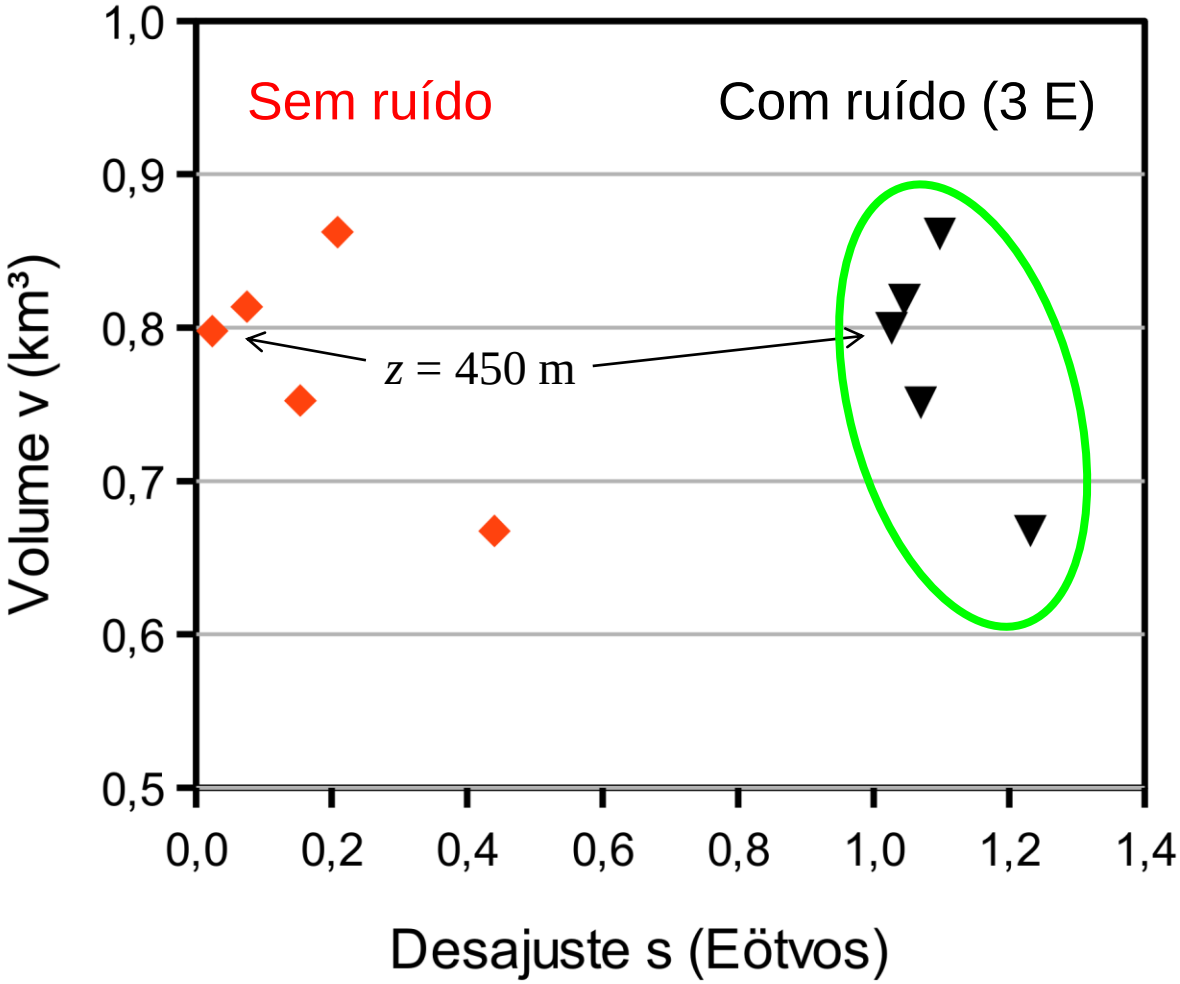
Apêndice 4


Coordenada horizontal x (km)
Coordenada horizontal y (km)
(Eötvos)
50 40 30 20 10 0 -10 -20 -30 -40 -50 -60
40 30 20 10 0 -10 -20 -30 -40
90 75 60 45 30 15 0 -15 -30 -45 -60 -75 -90
50 40 30 20 10 0 -10 -20 -30 -40 -50 -60
80 60 40 20 0 -20 -40 -60 -80
120 105 90 75 60 45 30 15 0 -15 -30

Apêndice 4

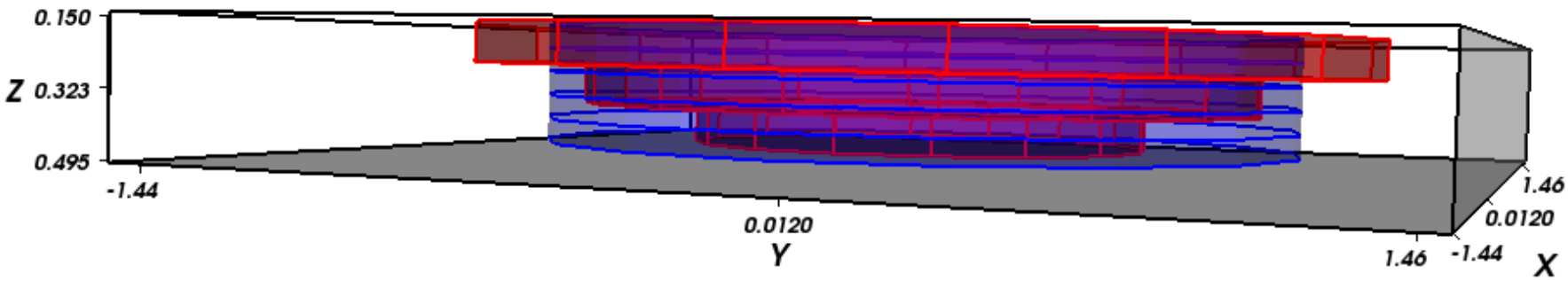

Sem ruído
Com ruído (3 E)
z = 450 m
Volume v (km³)
Desajuste s (Eötvos)
1,0
0,9
0,8
0,7
0,6
0,5
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4

Apêndice 4

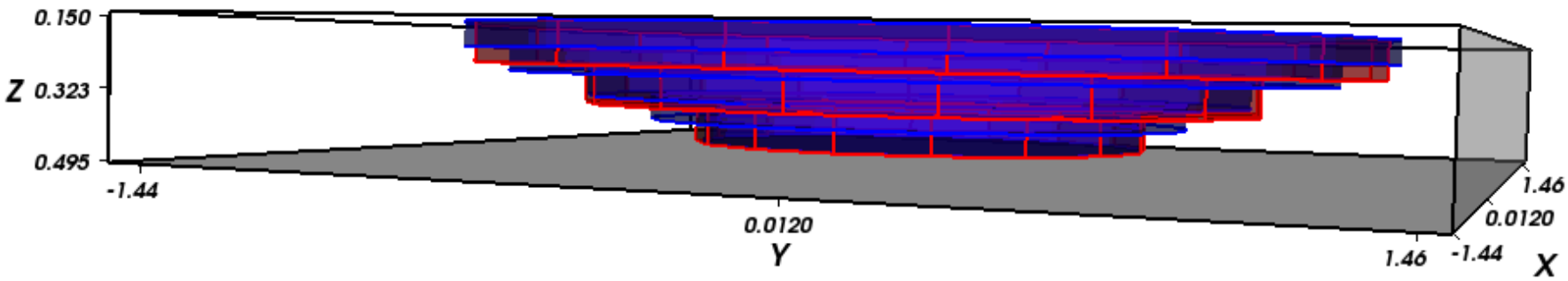


O ruído degrada o mínimo da curva *v* x *s*

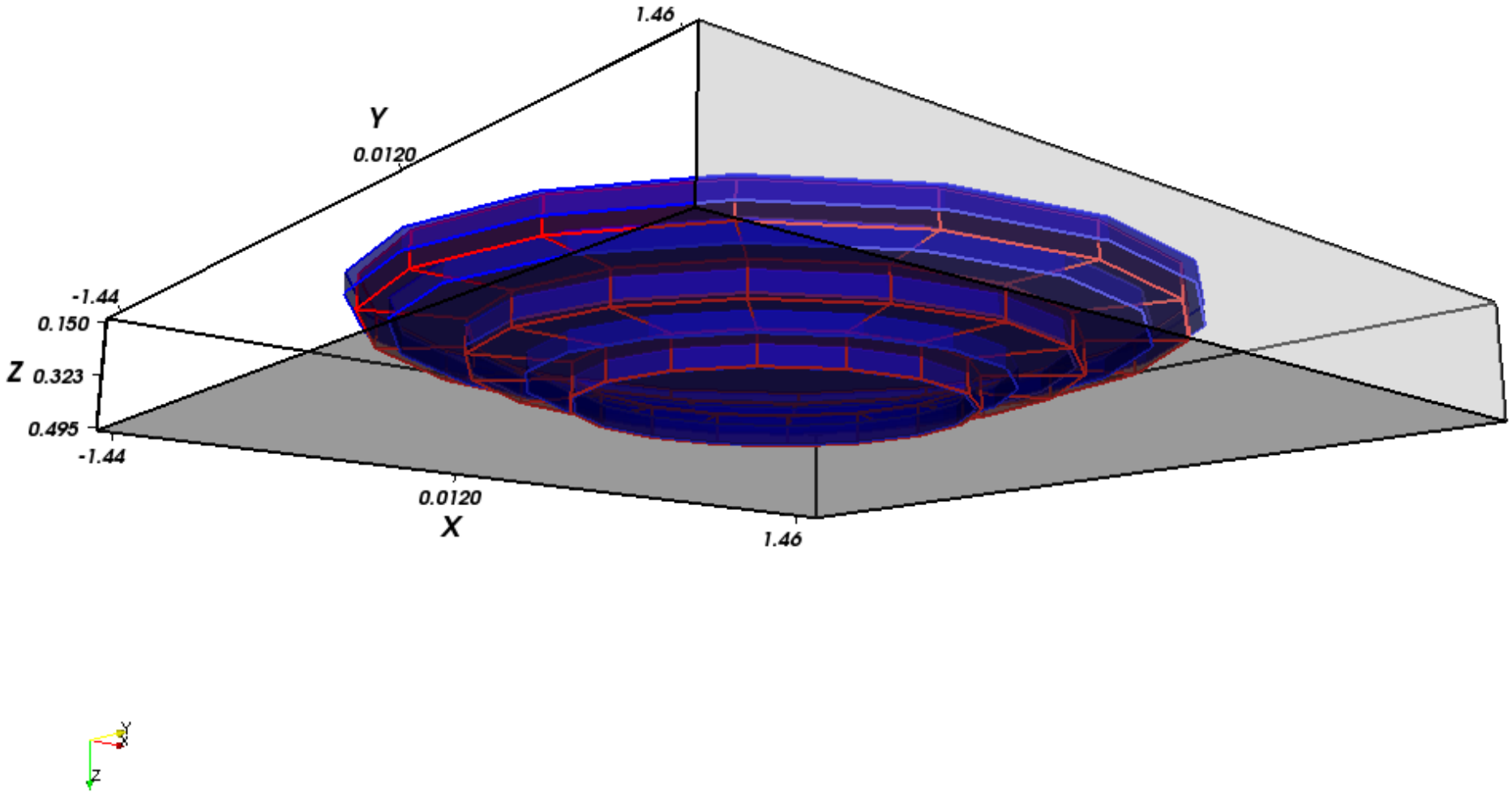
Apêndice 4



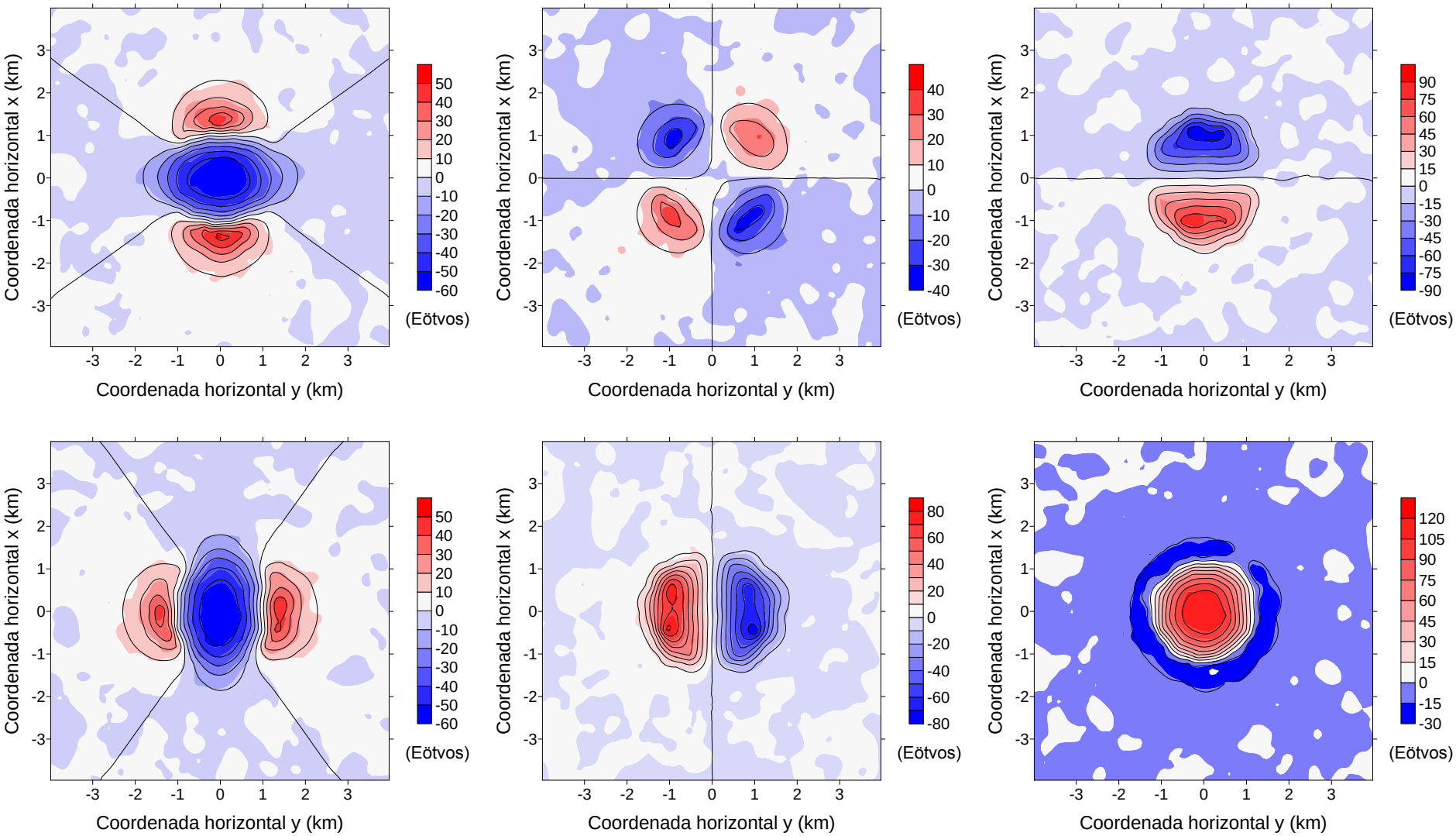
Apêndice 4



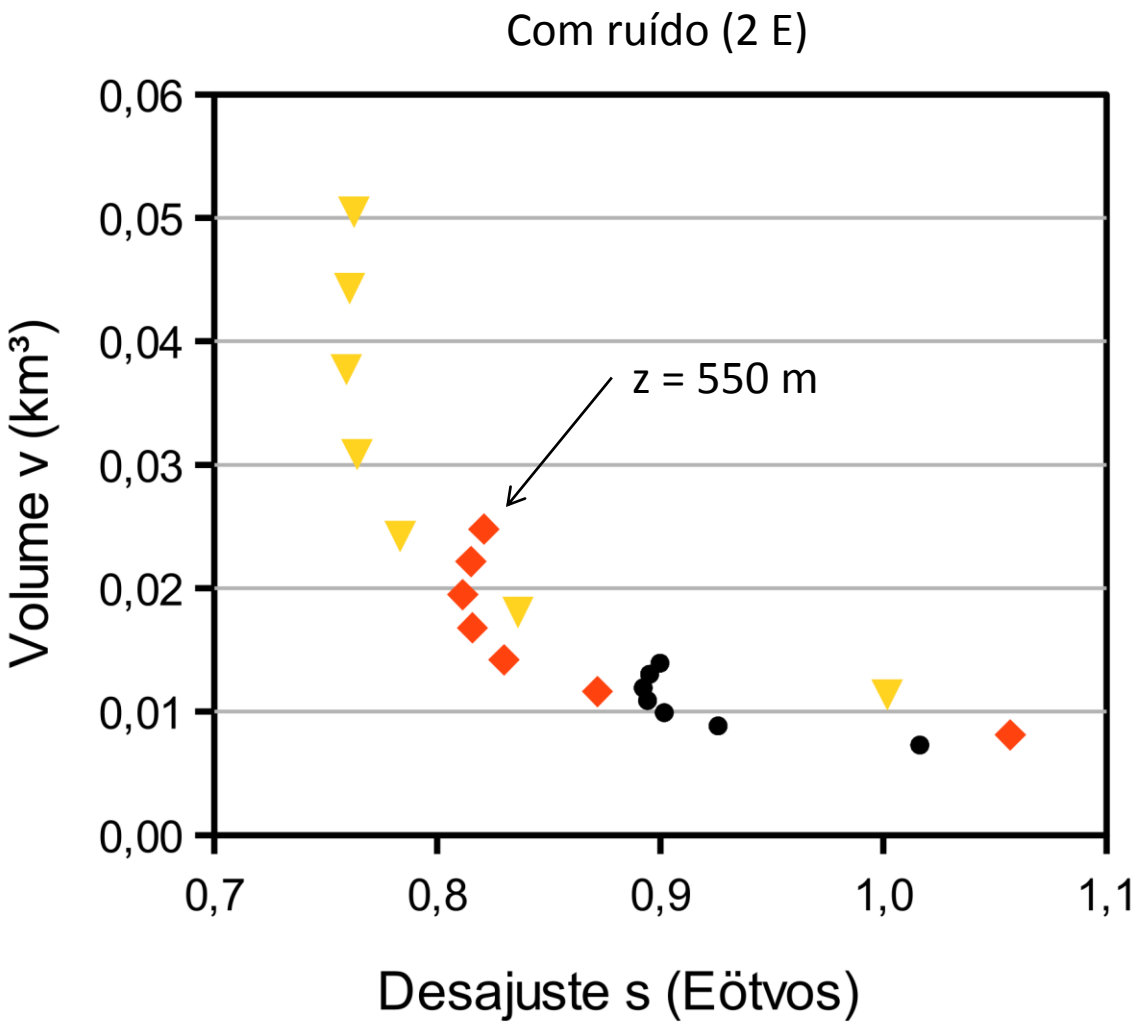
Apêndice 4



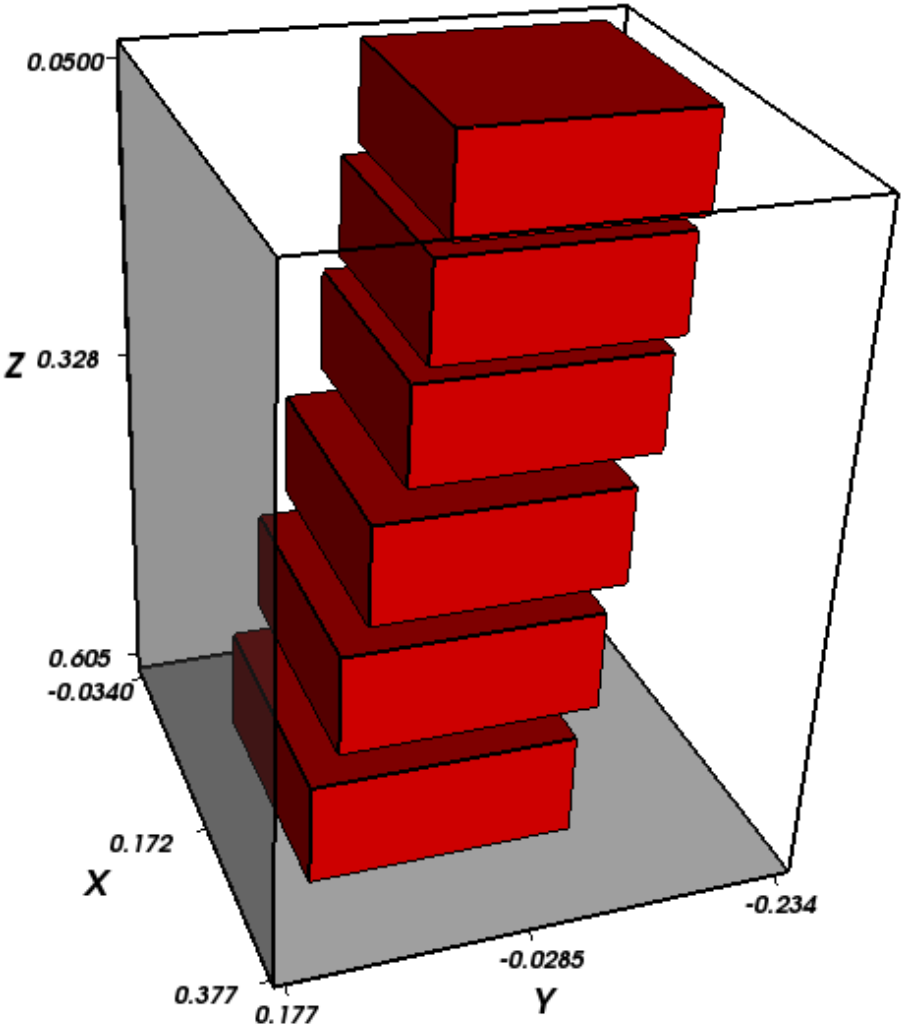
Apêndice 4


Coordenada horizontal x (km)
Coordenada horizontal y (km)
(Eötvos)
50 40 30 20 10 0 -10 -20 -30 -40 -50 -60
40 30 20 10 0 -10 -20 -30 -40
90 75 60 45 30 15 0 -15 -30 -45 -60 -75 -90
50 40 30 20 10 0 -10 -20 -30 -40 -50 -60
80 60 40 20 0 -20 -40 -60 -80
120 105 90 75 60 45 30 15 0 -15 -30
-3 -2 -1 0 1 2 3

Apêndice 4

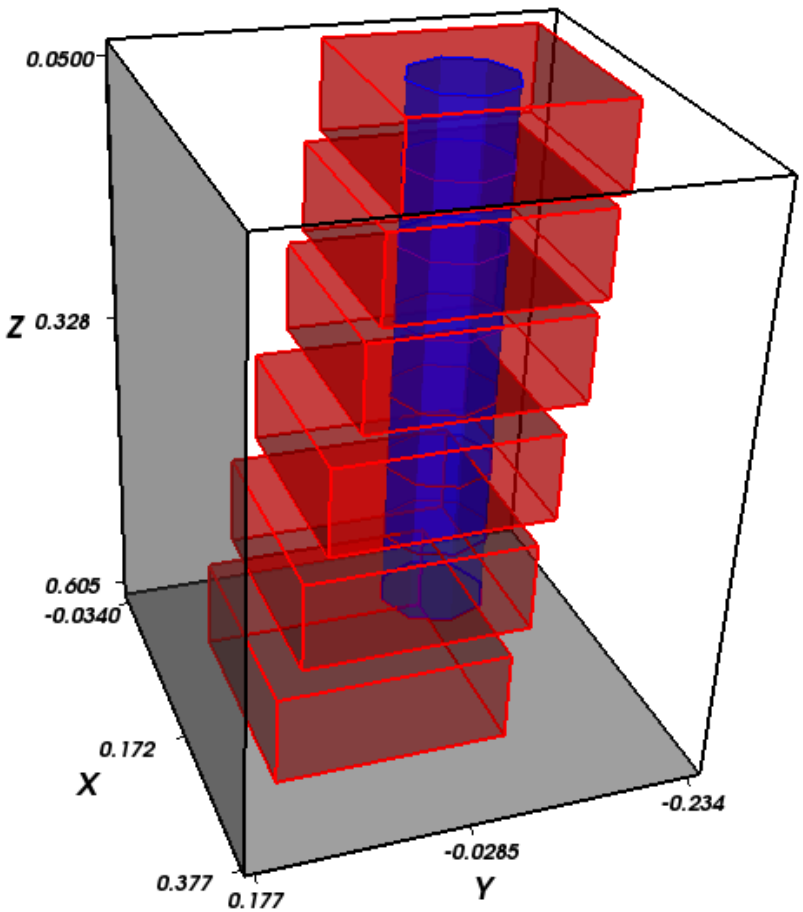

Com ruído (2 E)
0,06
0,05
0,04
0,03
0,02
0,01
0,00
Volume v (km³)
z = 550 m
0,7
0,8
0,9
1,0
1,1
Desajuste s (Eötvos)

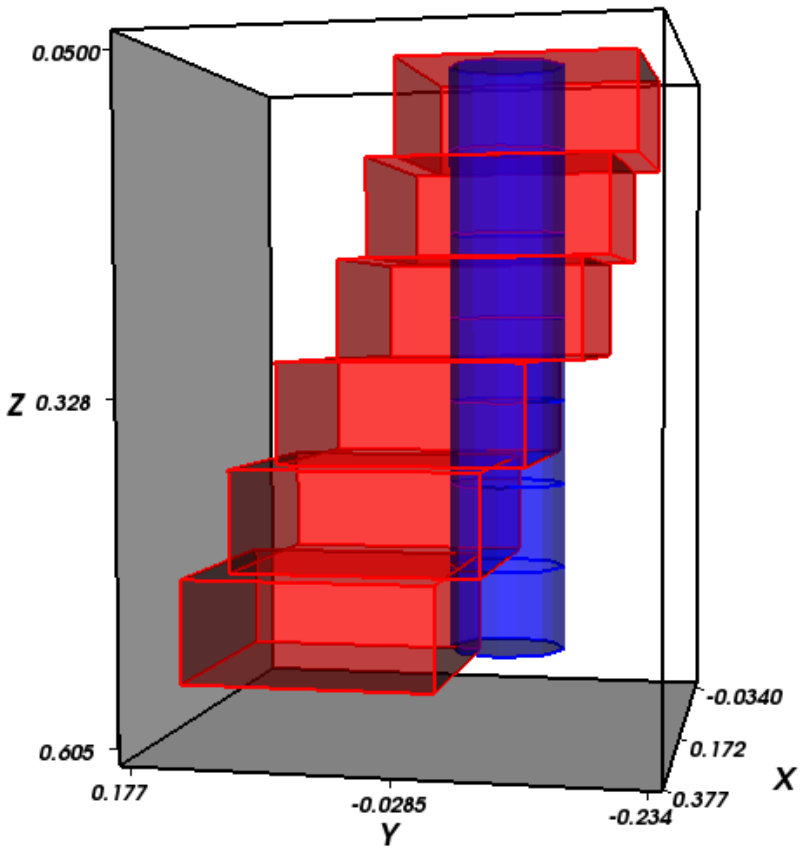
Apêndice 4



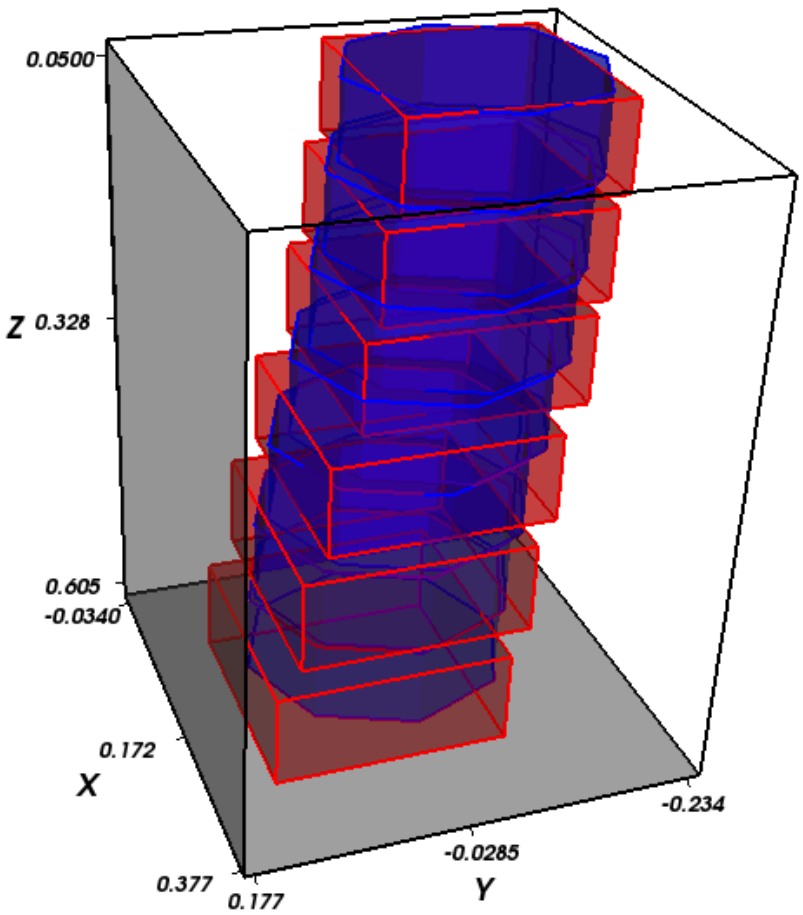
rho: 1,0 g/cm³
topo: 50 m
base: 550m

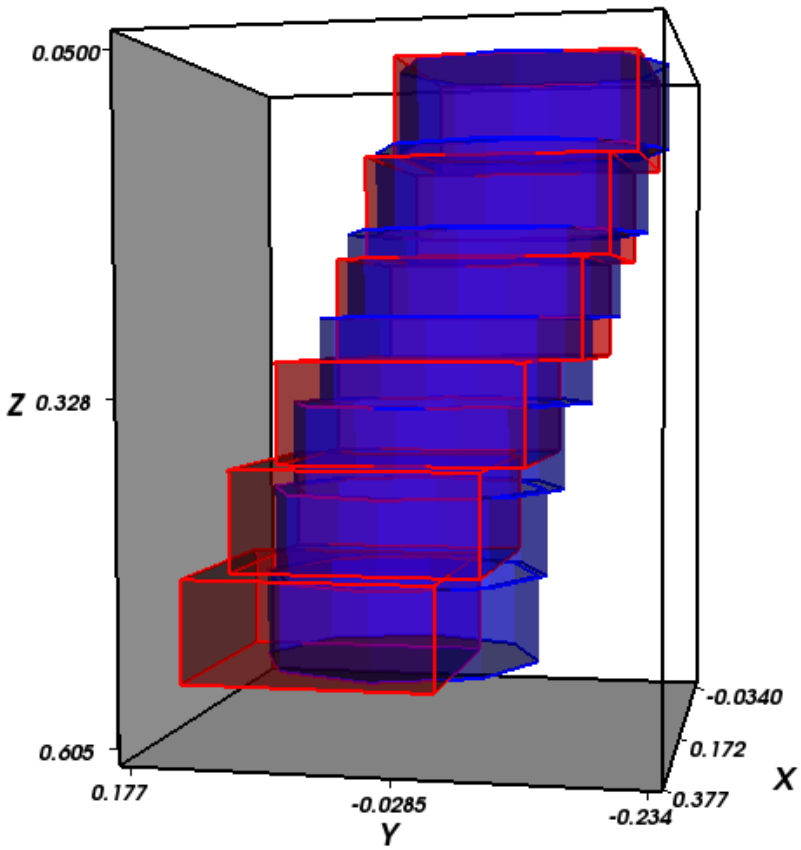
Apêndice 4


0.0500
Z 0.328
0.605
-0.0340
0.172
X
0.377
0.177
-0.0285
Y
-0.234

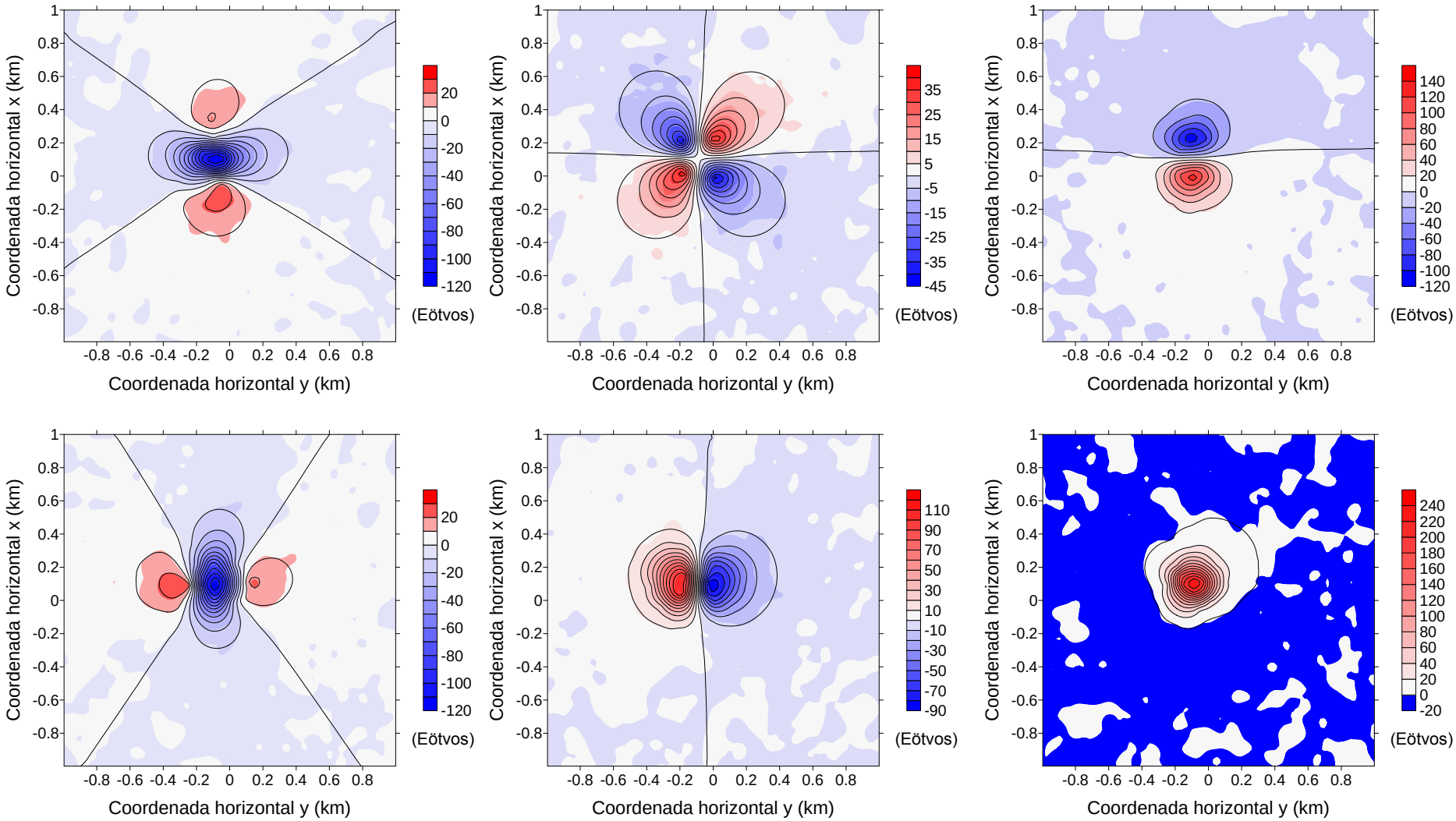

0.0500
Z 0.328
0.605
0.177
-0.0285
Y
-0.234
-0.0340
0.172
0.377
X

Apêndice 4

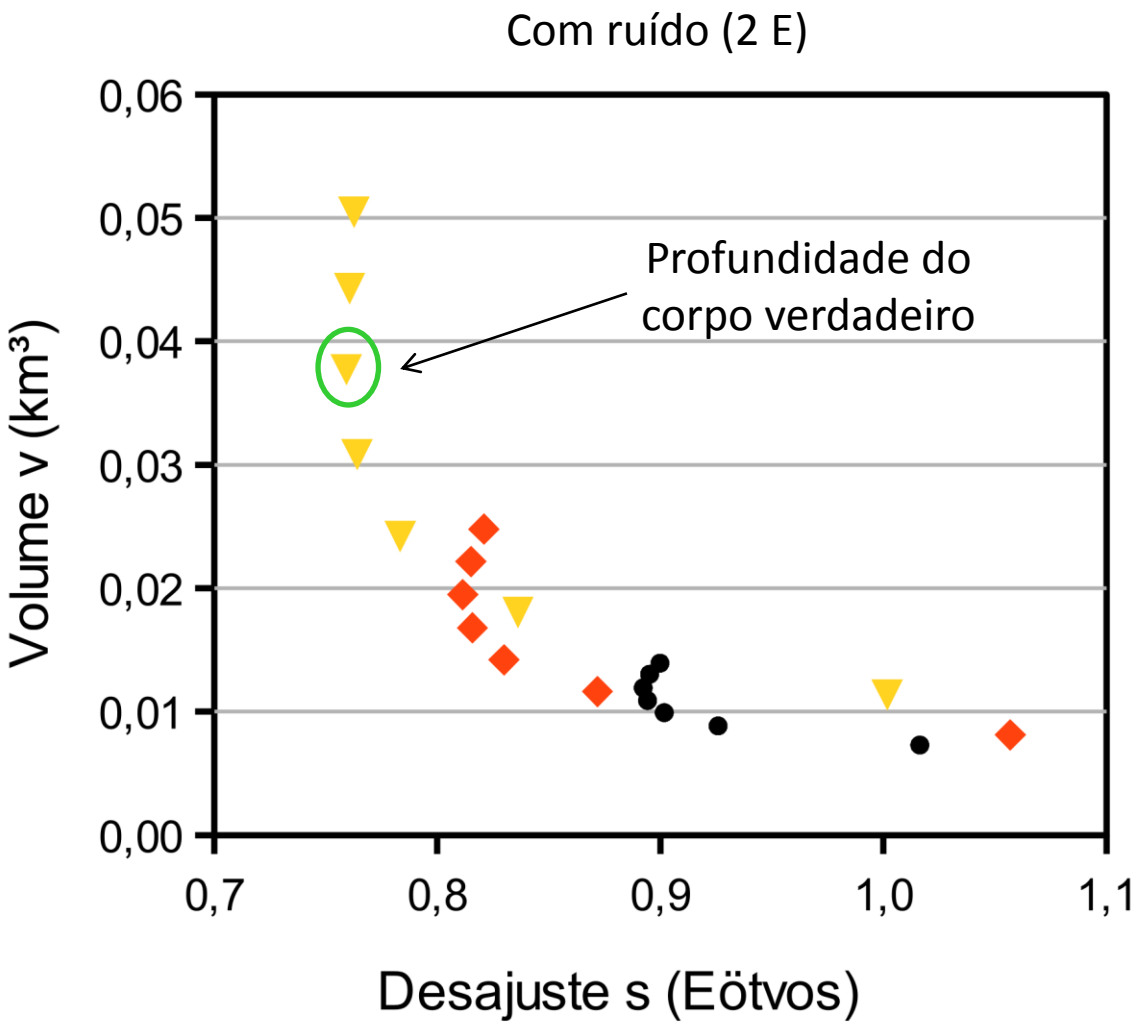

0.0500
Z 0.328
0.605
-0.0340
0.172
X
0.377
0.177
-0.0285
Y
-0.234


0.0500
Z 0.328
0.605
0.177
-0.0285
Y
-0.234
-0.0340
0.172
0.377
X

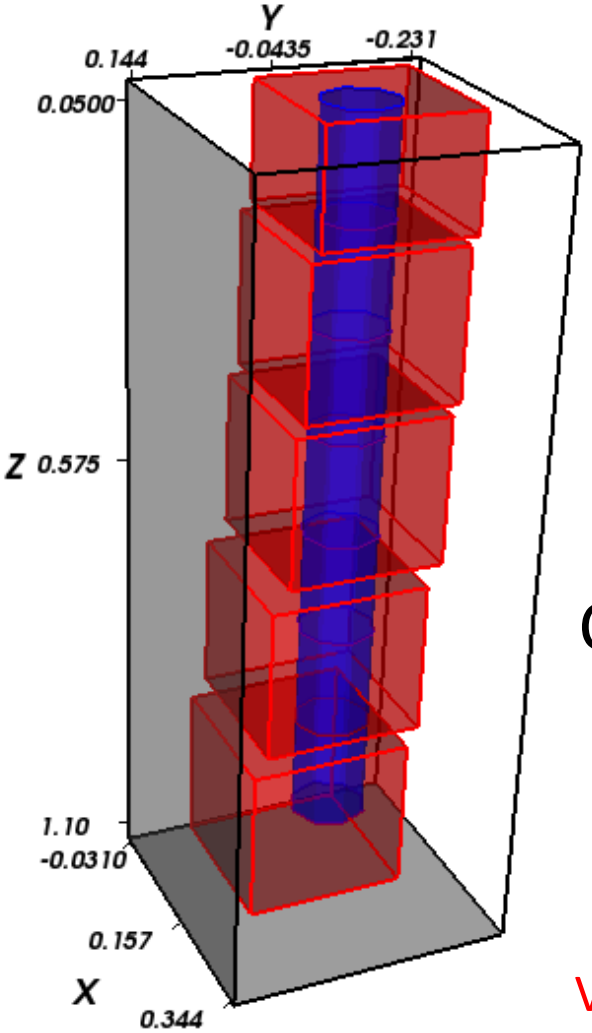
Apêndice 4


Coordenada horizontal x (km)
Coordenada horizontal y (km)
(Eötvos)
20 0 -20 -40 -60 -80 -100 -120
35 25 15 5 -5 -15 -25 -35 -45
140 120 100 80 60 40 20 0 -20 -40 -60 -80 -100 -120
20 0 -20 -40 -60 -80 -100 -120
110 90 70 50 30 10 -10 -30 -50 -70 -90
240 220 200 180 160 140 120 100 80 60 40 20 0 -20

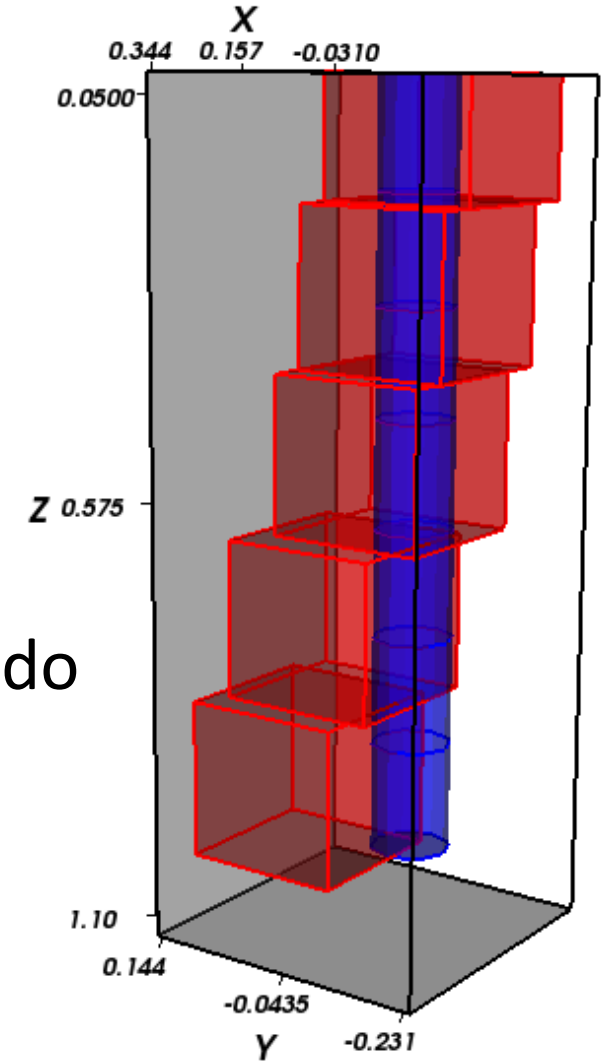
Apêndice 4


Com ruído (2 E)
Profundidade do corpo verdadeiro
Volume v (km³)
0,06
0,05
0,04
0,03
0,02
0,01
0,00
0,7
0,8
0,9
1,0
1,1
Desajuste s (Eötvos)

Apêndice 4



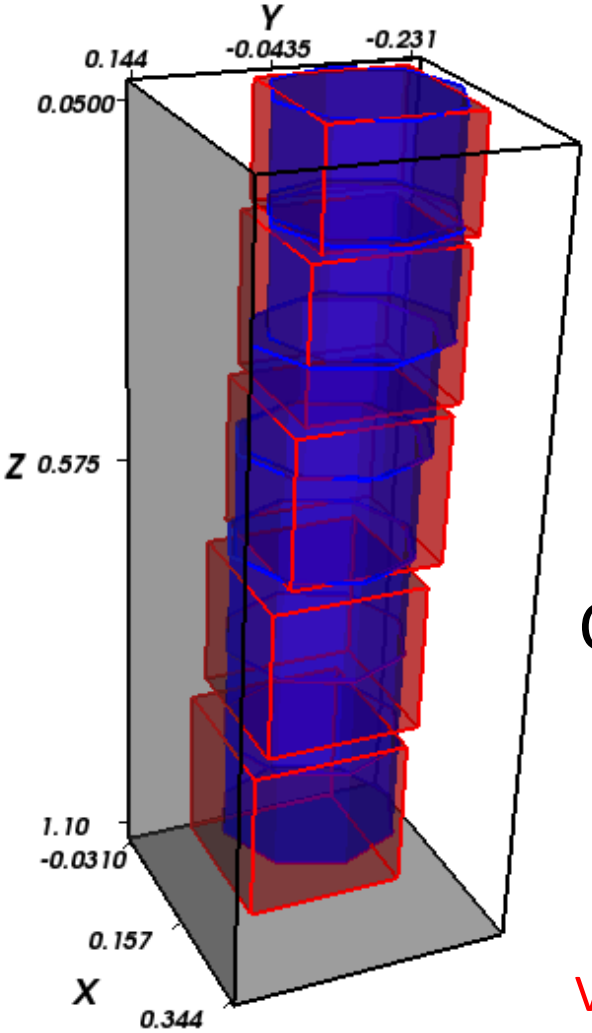
Corpo profundo



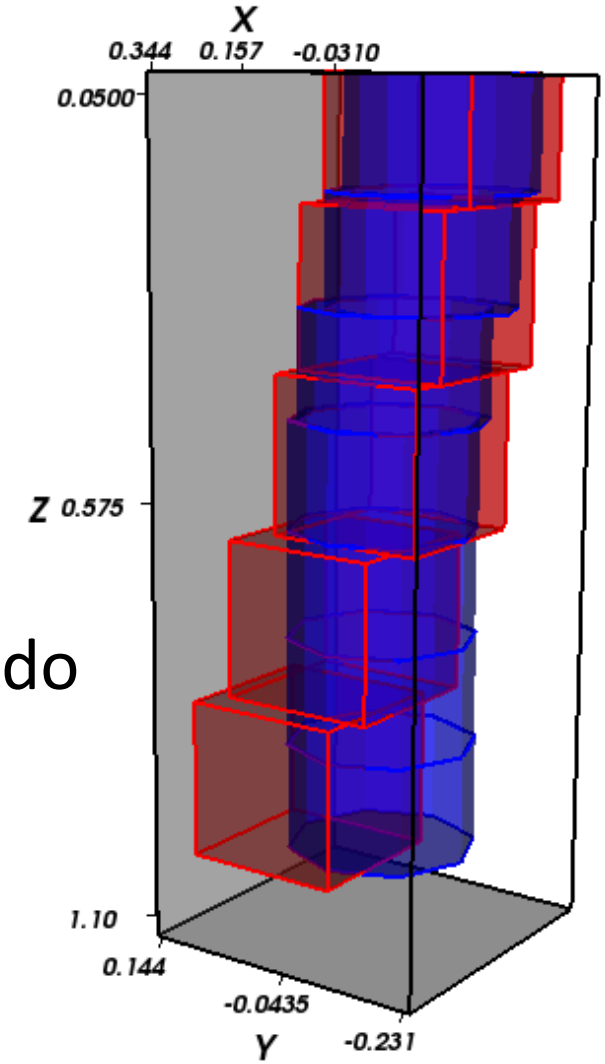
Verdadeiro

Aproximação inicial

Apêndice 4



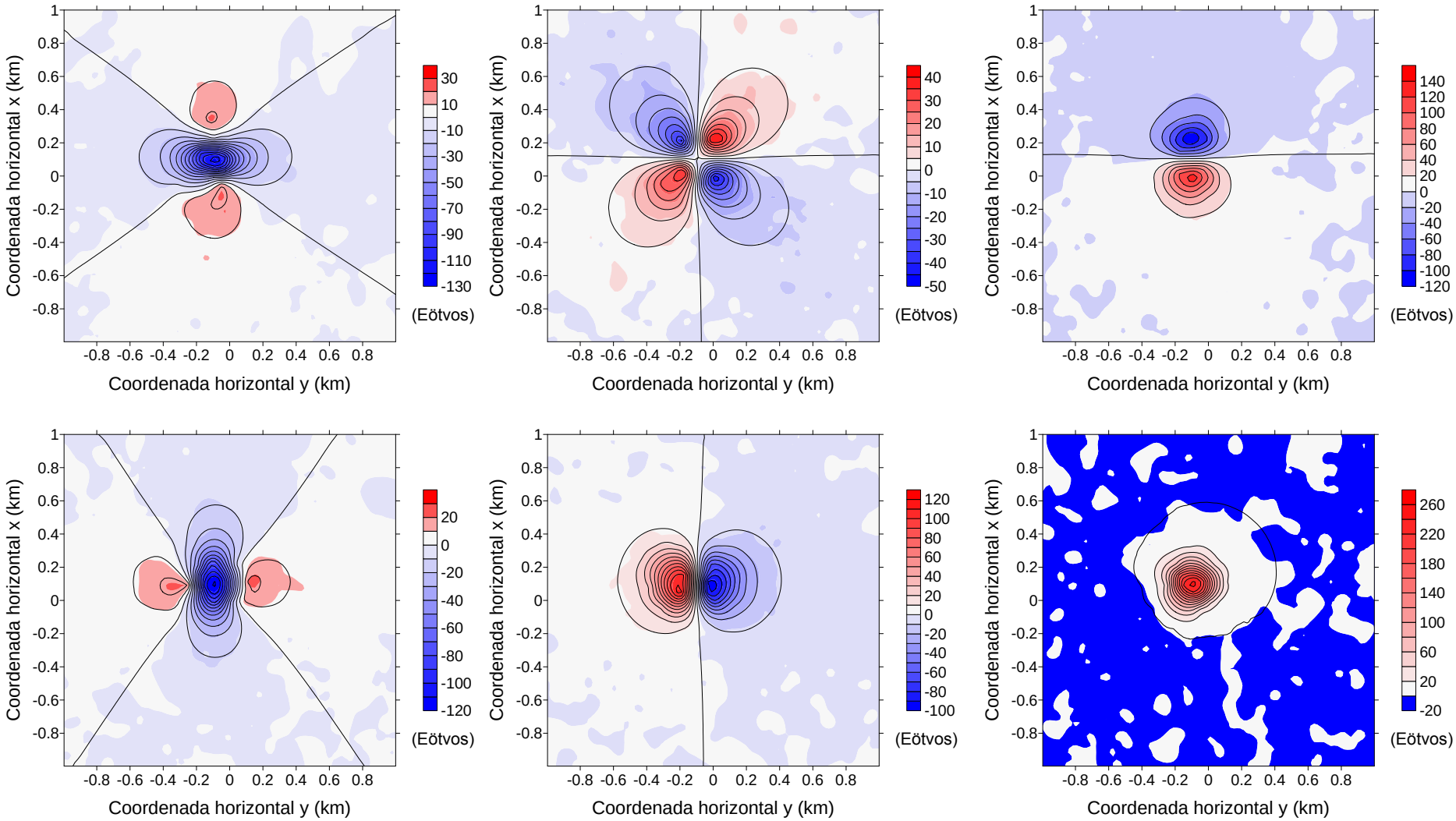
Corpo profundo



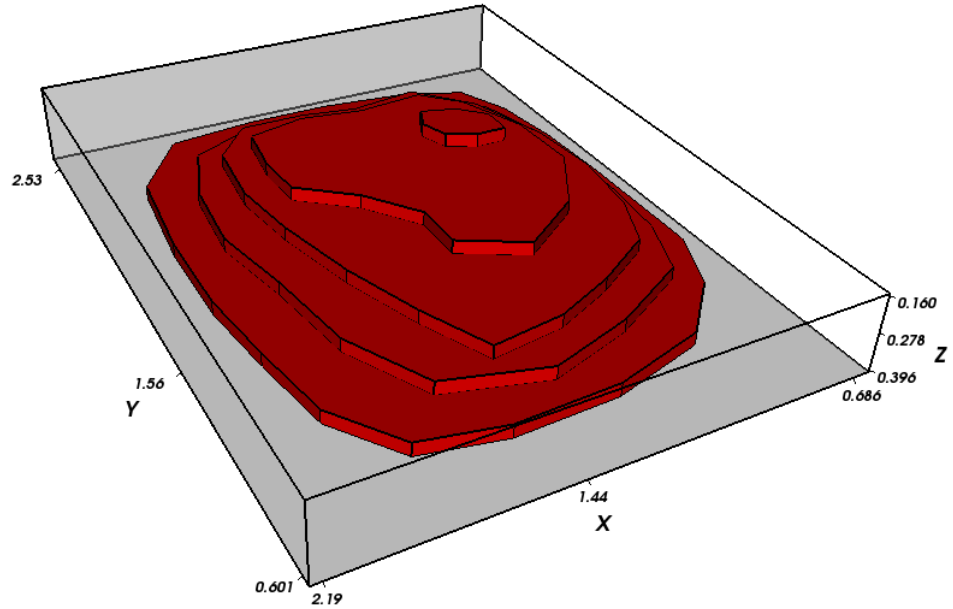
Verdadeiro

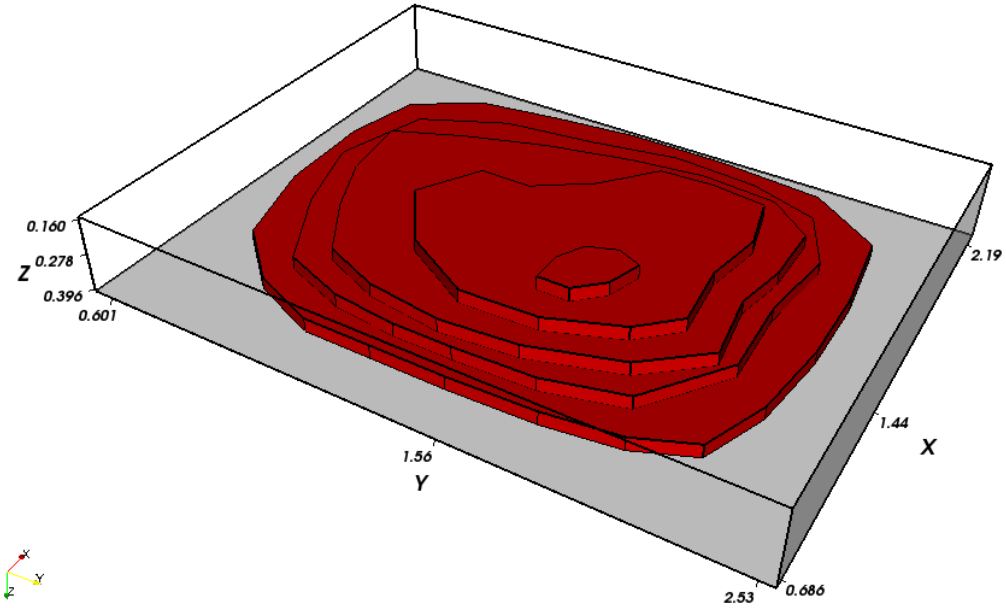
Estimativa

Apêndice 4


Coordenada horizontal x (km)
Coordenada horizontal y (km)
(Eötvos)
30 10 -10 -30 -50 -70 -90 -110 -130
40 30 20 10 0 -10 -20 -30 -40 -50
140 120 100 80 60 40 20 0 -20 -40 -60 -80 -100 -120
20 0 -20 -40 -60 -80 -100 -120
120 100 80 60 40 20 0 -20 -40 -60 -80 -100
260 220 180 140 100 60 20 -20

Apêndice 4



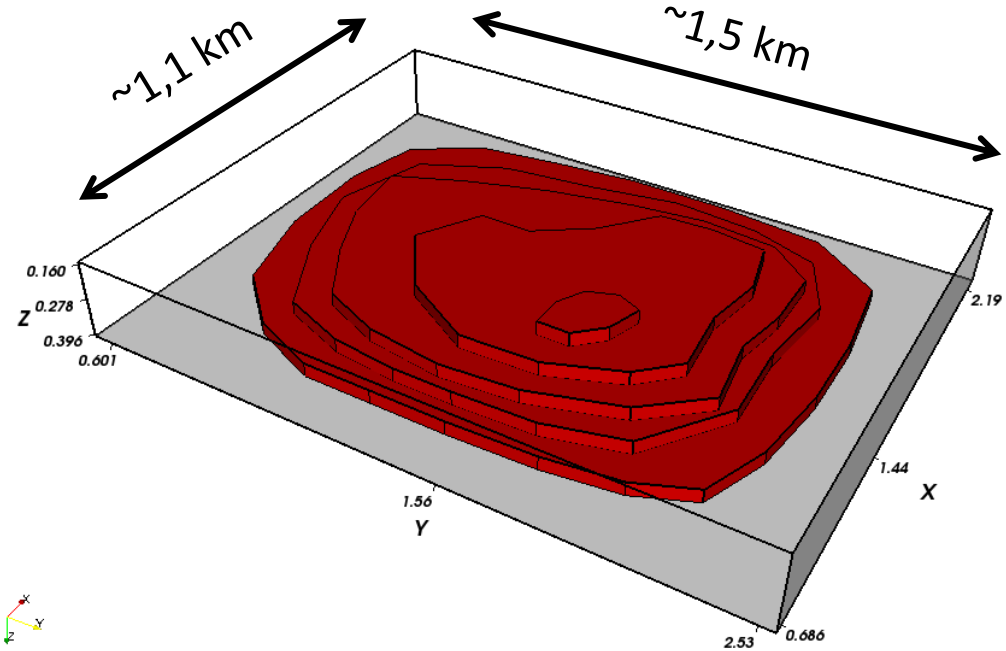


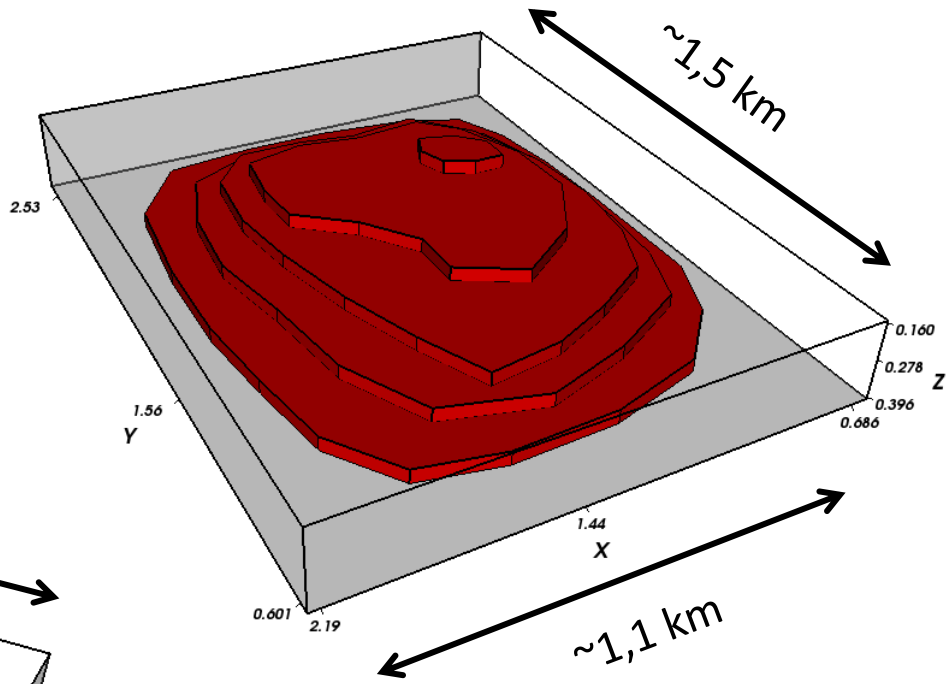
Modelo obtido via modelagem direta das componentes do tensor gravimétrico sobre o domo de sal Vinton, EUA (Ennen e Hall, 2011)

Este modelo visa explicar a "*caprock*"

Apêndice 4

rho: 1,23 g/cm³
topo: 160 m
base: 360 m





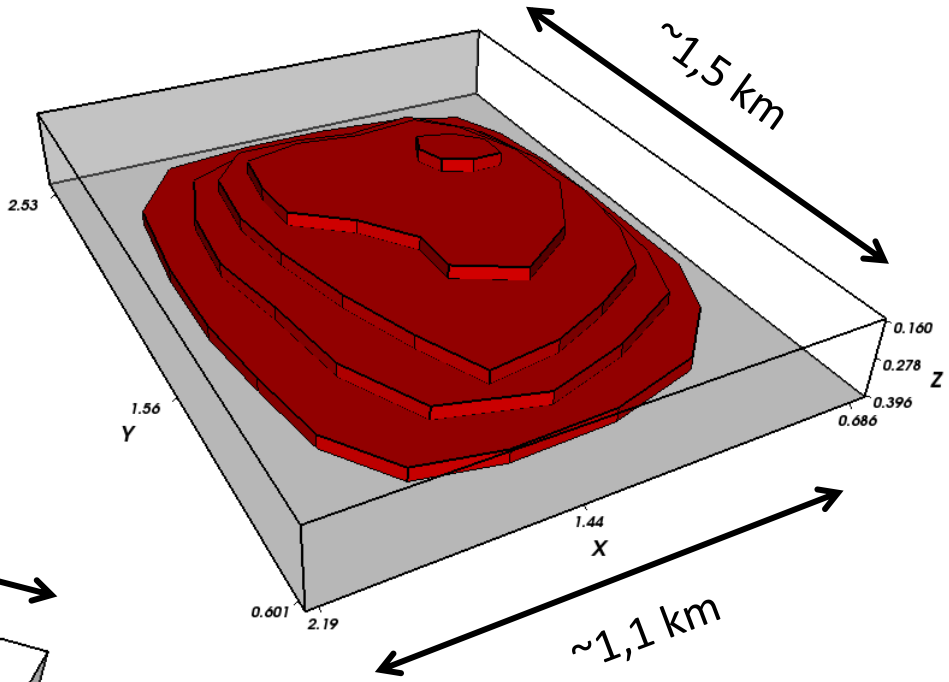
Modelo obtido via modelagem direta das componentes do tensor gravimétrico sobre o domo de sal Vinton, EUA (Ennen e Hall, 2011)

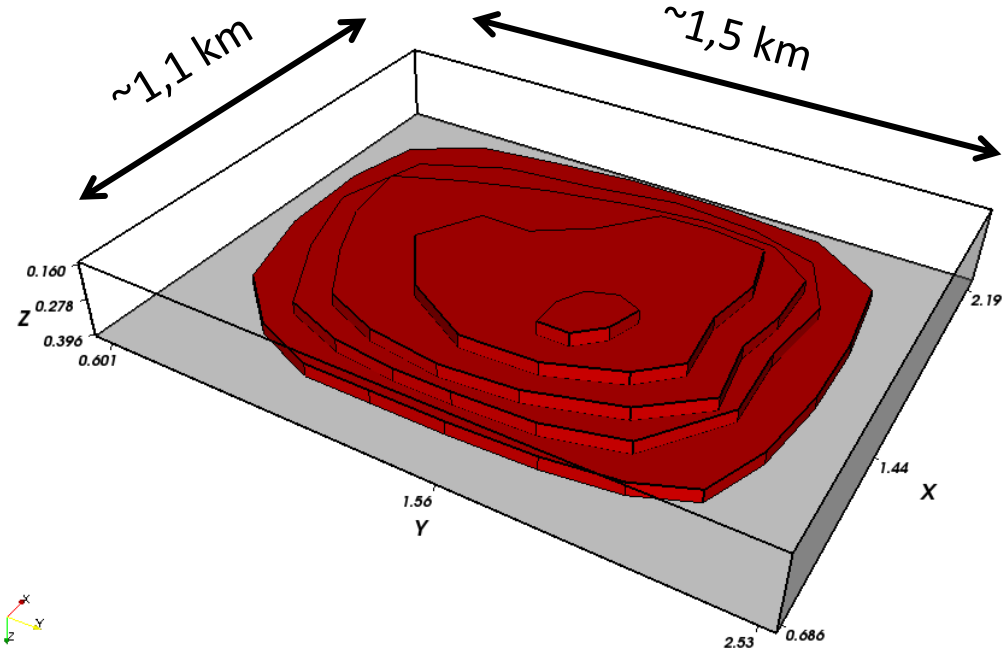
Este modelo visa explicar a "*caprock*"

Apêndice 4

rho: 1,23 g/cm³
topo: 160 m
base: 360 m

Os dados produzidos por este modelo foram contaminados com 5 E e utilizados na inversão

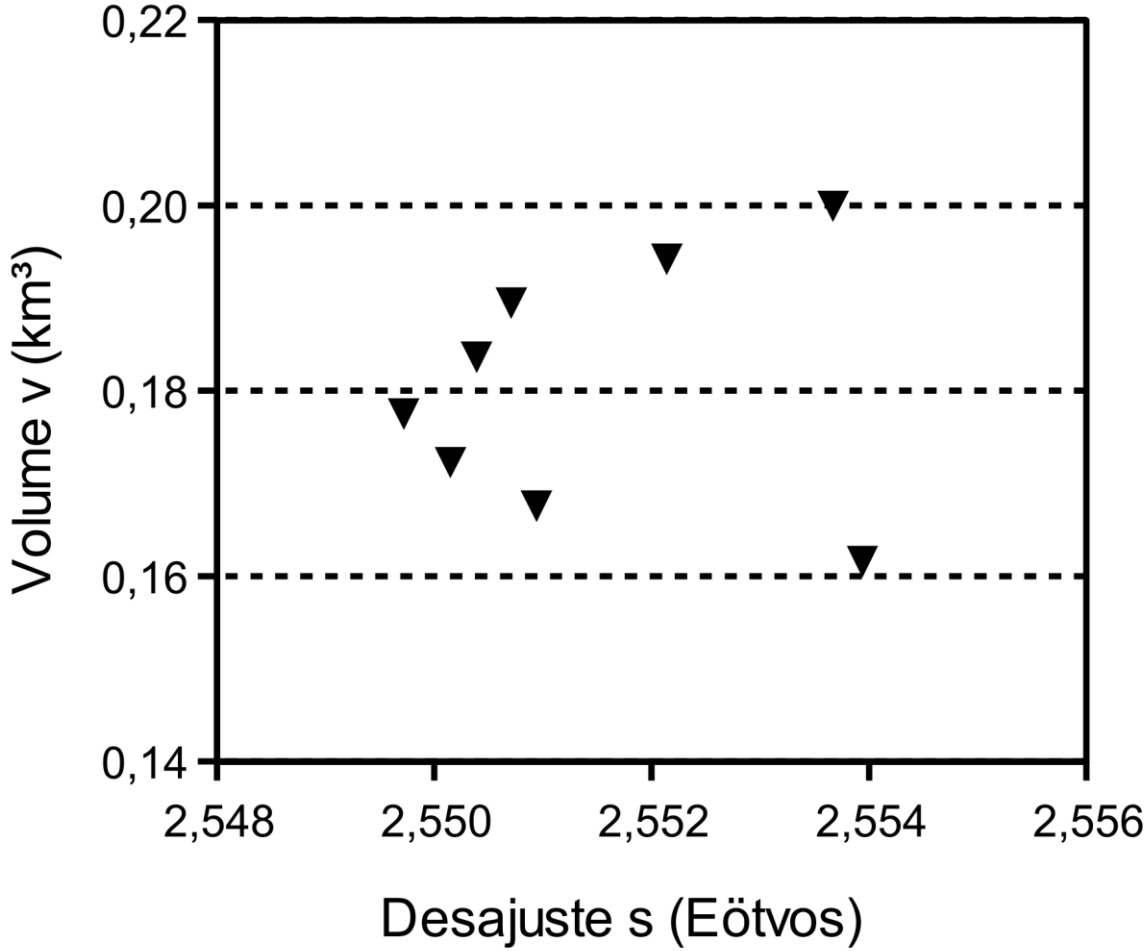




Modelo obtido via modelagem direta das componentes do tensor gravimétrico sobre o domo de sal Vinton, EUA (Ennen e Hall, 2011)

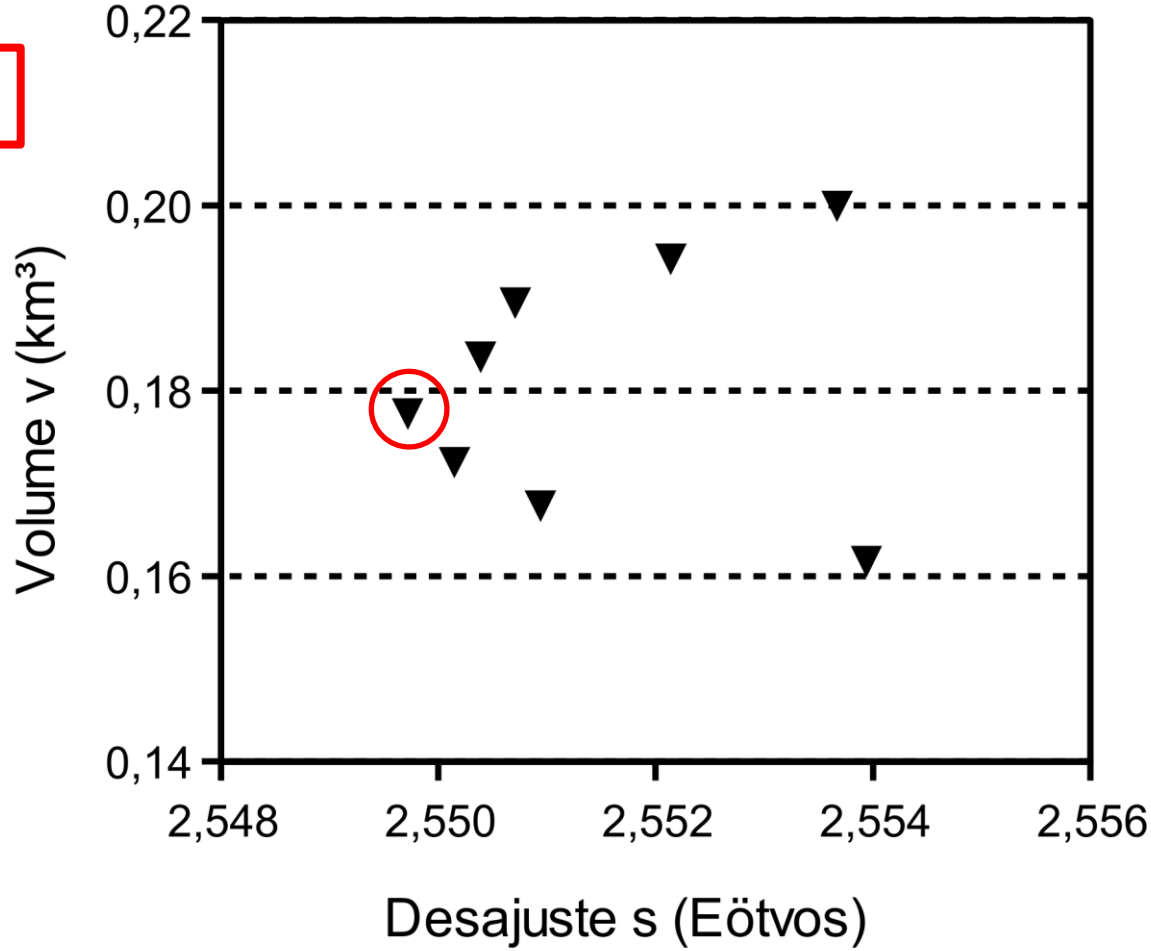
Este modelo visa explicar a "*caprock*"

Apêndice 4

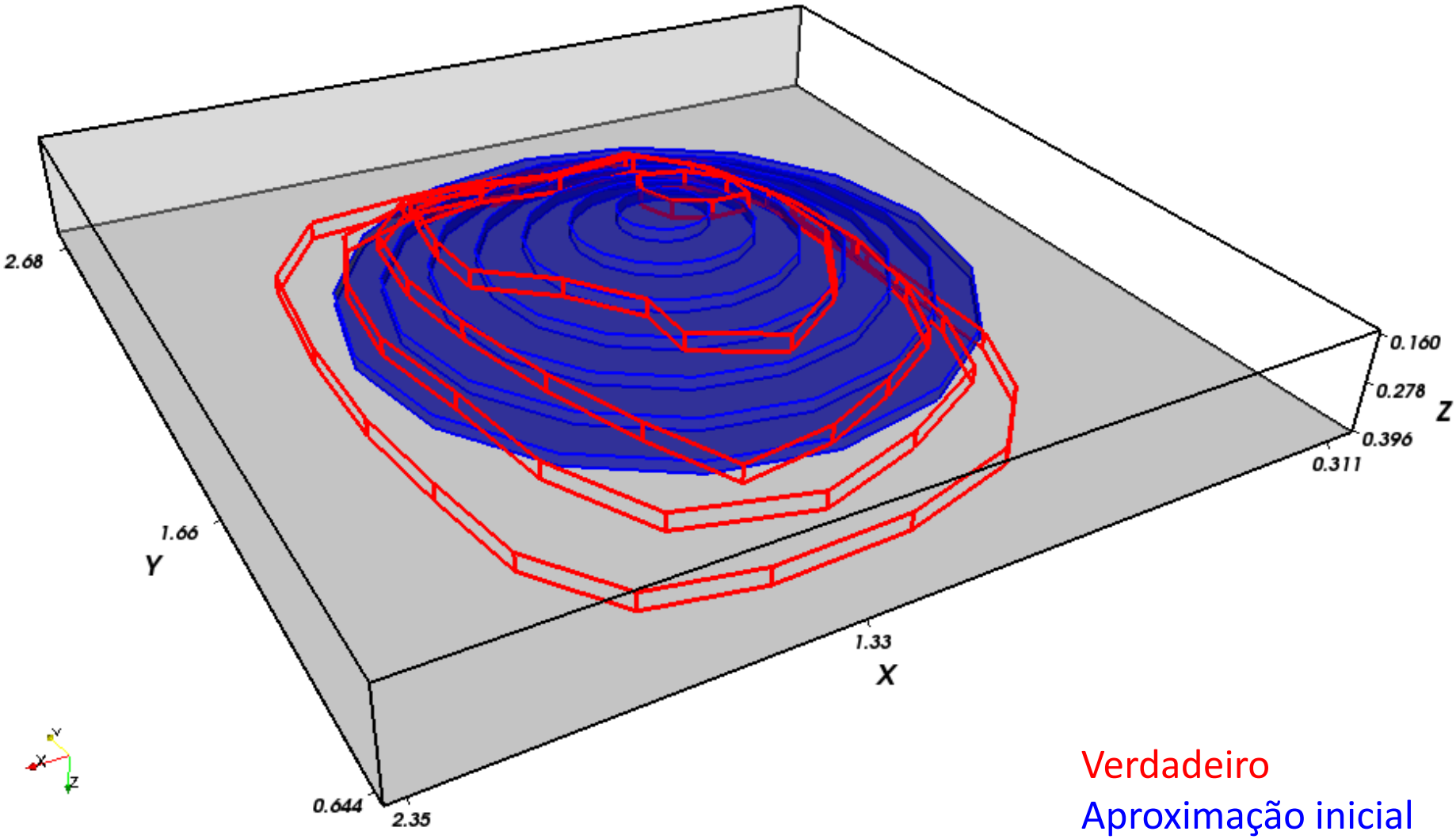

0,22
0,20
0,18
0,16
0,14
Volume v (km³)
2,548
2,550
2,552
2,554
2,556
Desajuste s (Eötvos)

Apêndice 4

$z = 360$ m



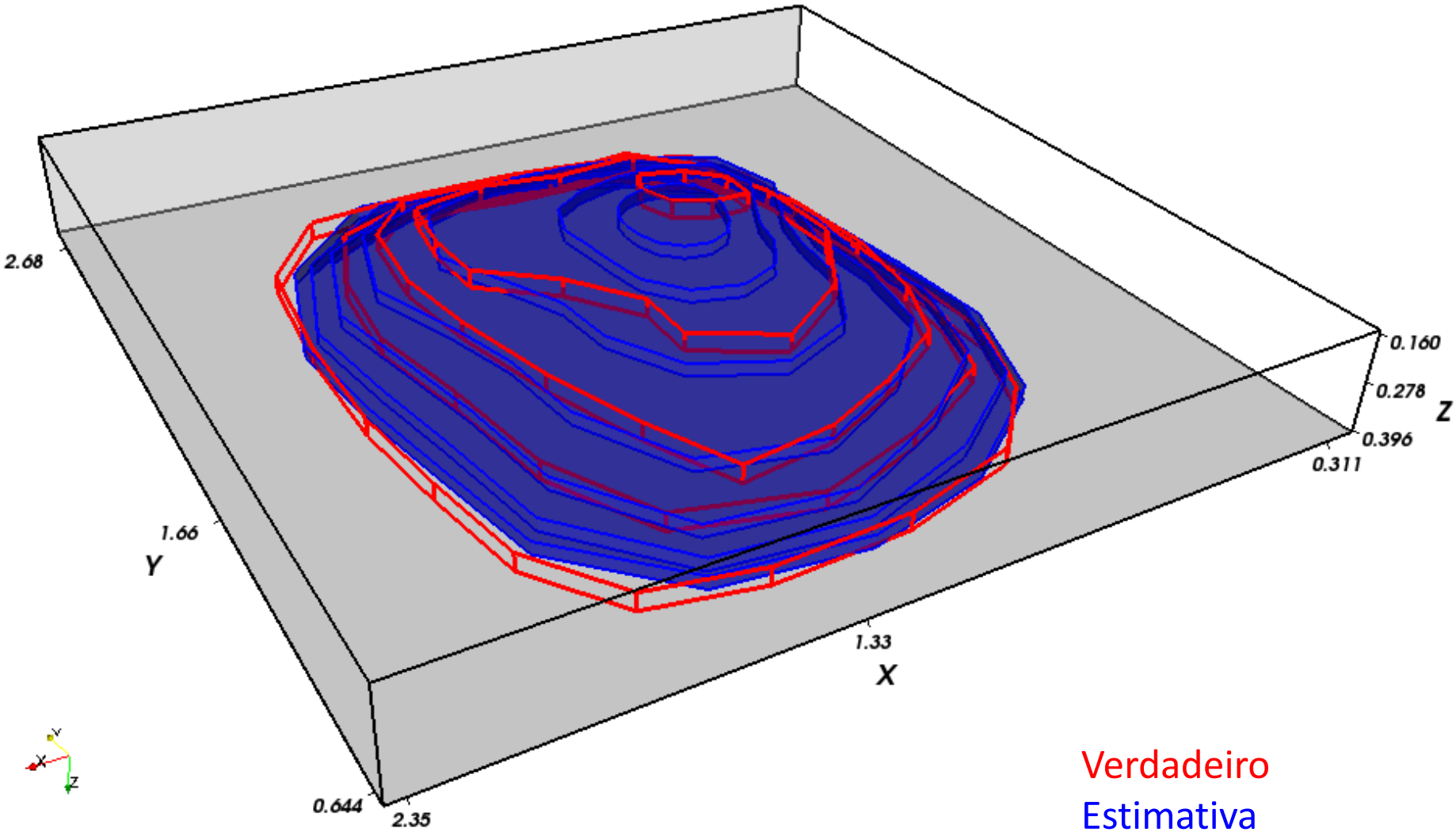
Apêndice 4



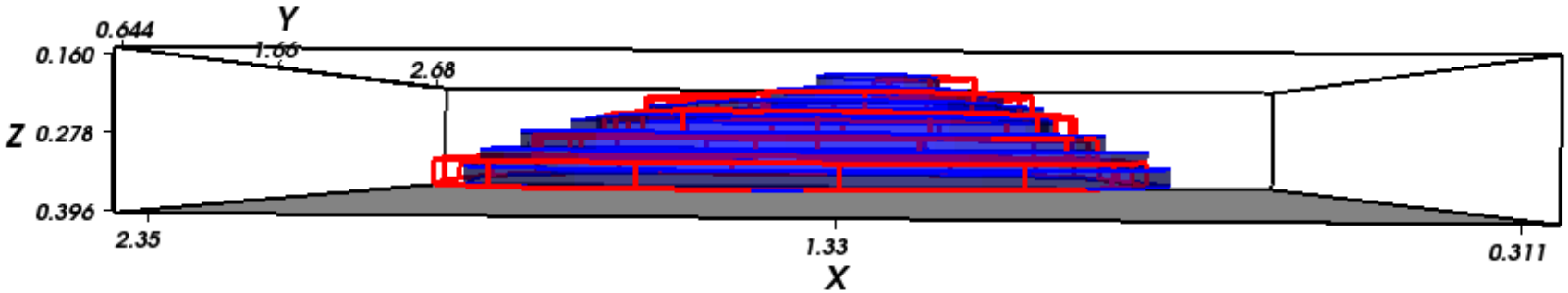
Verdadeiro

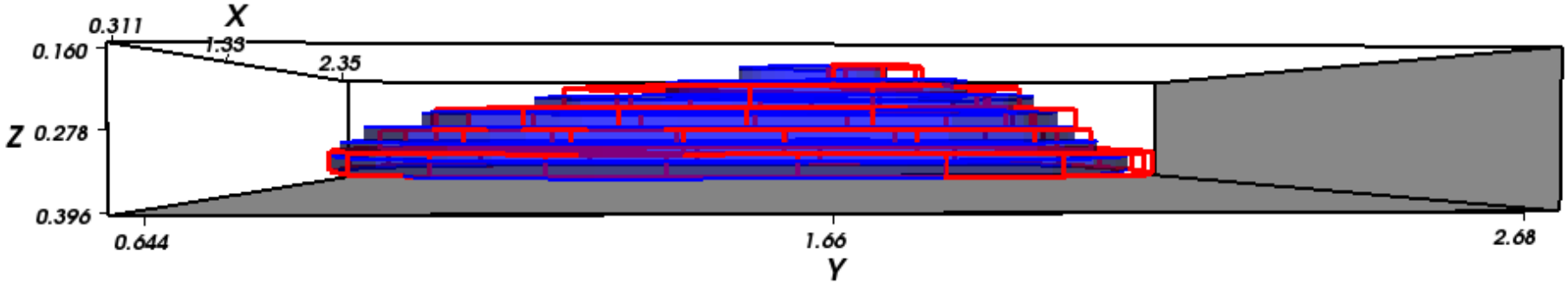
Aproximação inicial

Apêndice 4


2.68
1.66
Y
0.644
2.35
1.33
X
0.160
0.278
0.396
0.311
Z
Verdadeiro
Estimativa

Apêndice 4

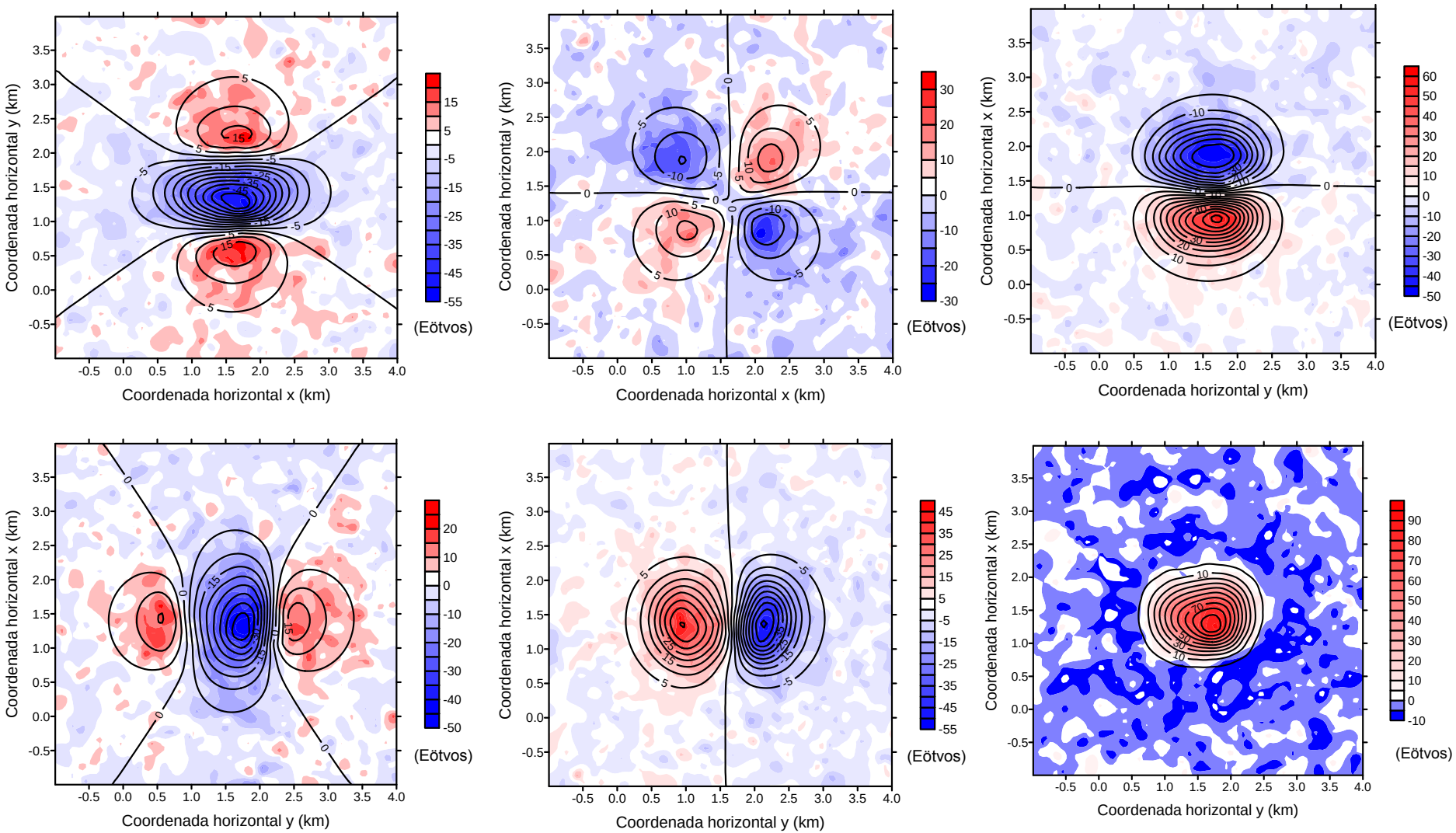




Verdadeiro

Estimativa

Apêndice 4

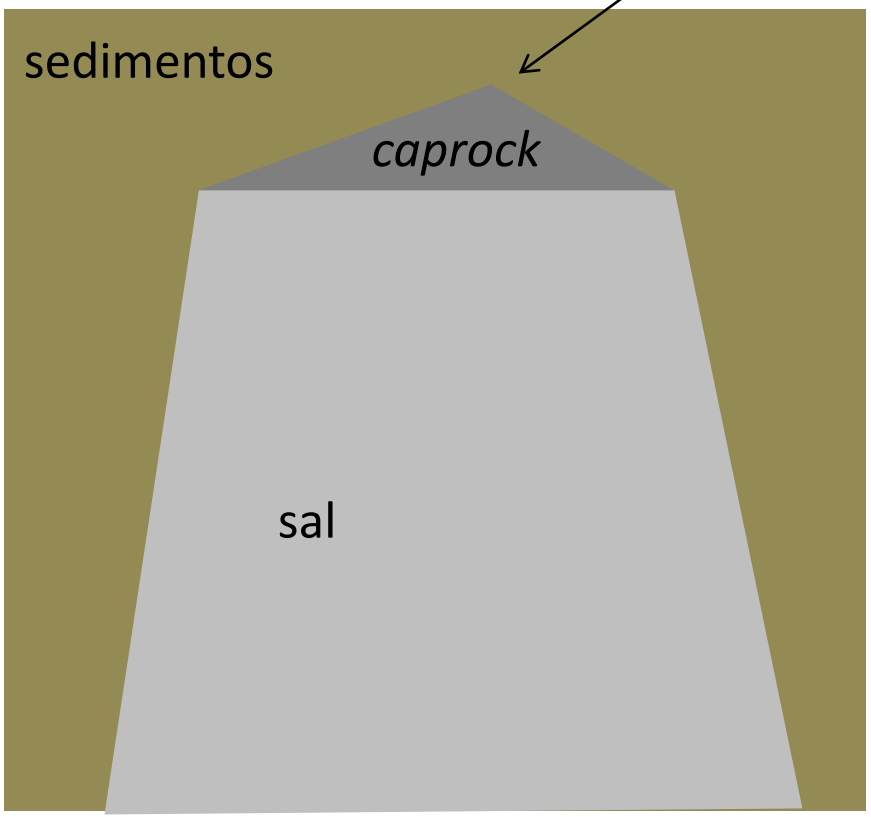

Coordenada horizontal y (km)
Coordenada horizontal x (km)
(Eötvos)
Coordenada horizontal x (km)
Coordenada horizontal y (km)
(Eötvos)
Coordenada horizontal y (km)
Coordenada horizontal x (km)
(Eötvos)
Coordenada horizontal x (km)
Coordenada horizontal y (km)
(Eötvos)
Coordenada horizontal y (km)
Coordenada horizontal x (km)
(Eötvos)

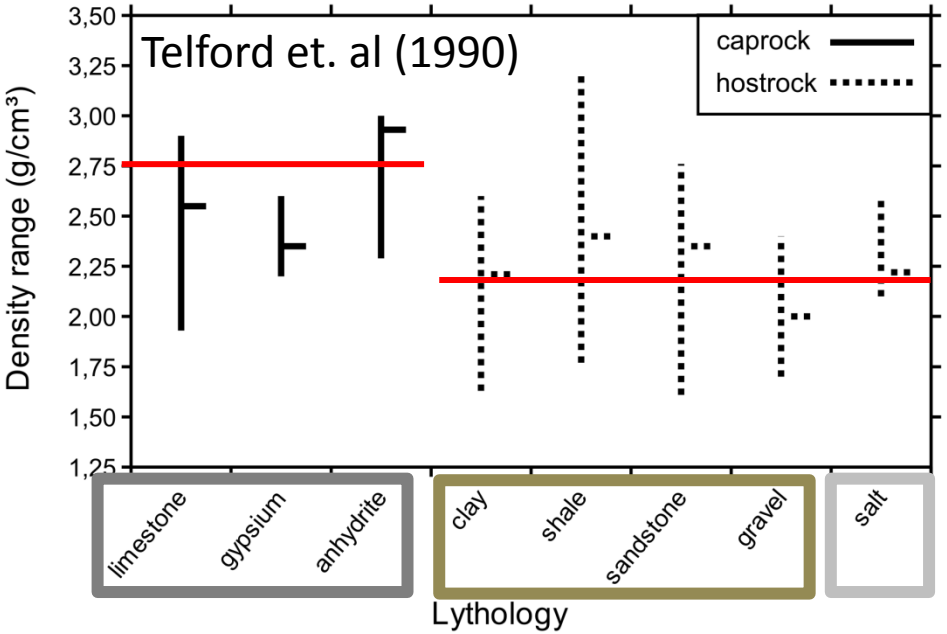
Apêndice 5

Esboço da subsuperfície

topo = 160 m (Ennen e Hall, 2011)

Marfurt et. al (2004)
Coker (2006)





Hipótese 1:

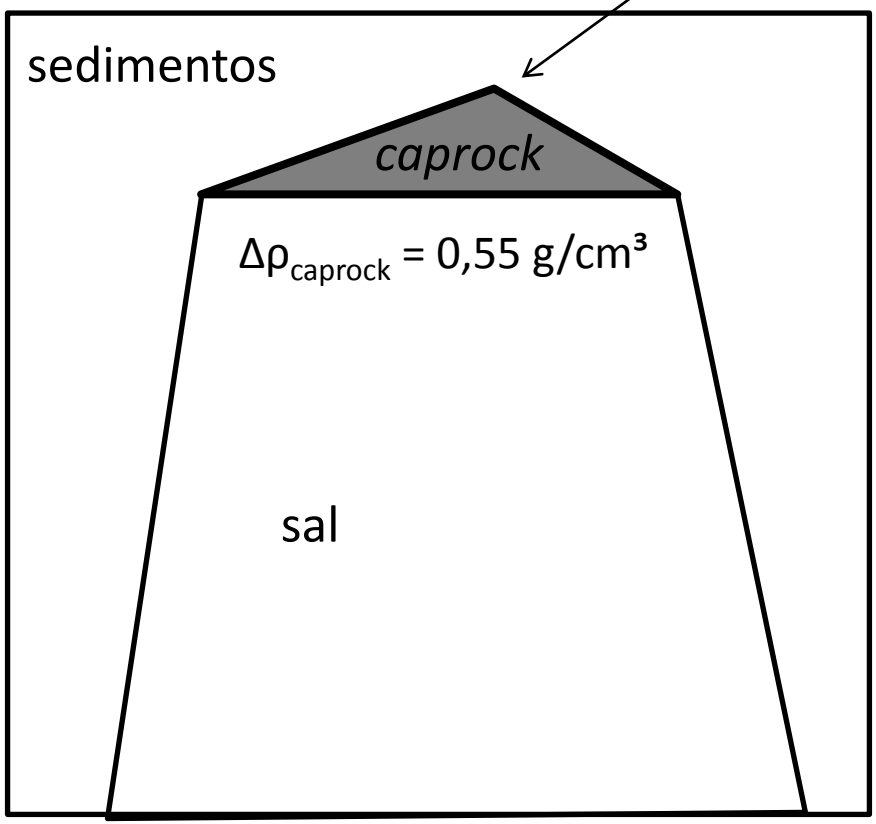
- $\rho_{caprock}$ = 2,75 g/cm³ (Ennen e Hall, 2011)
- $\rho_{sedimentos}$ = 2,20 g/cm³
- ρ_{sal} = 2,20 g/cm³

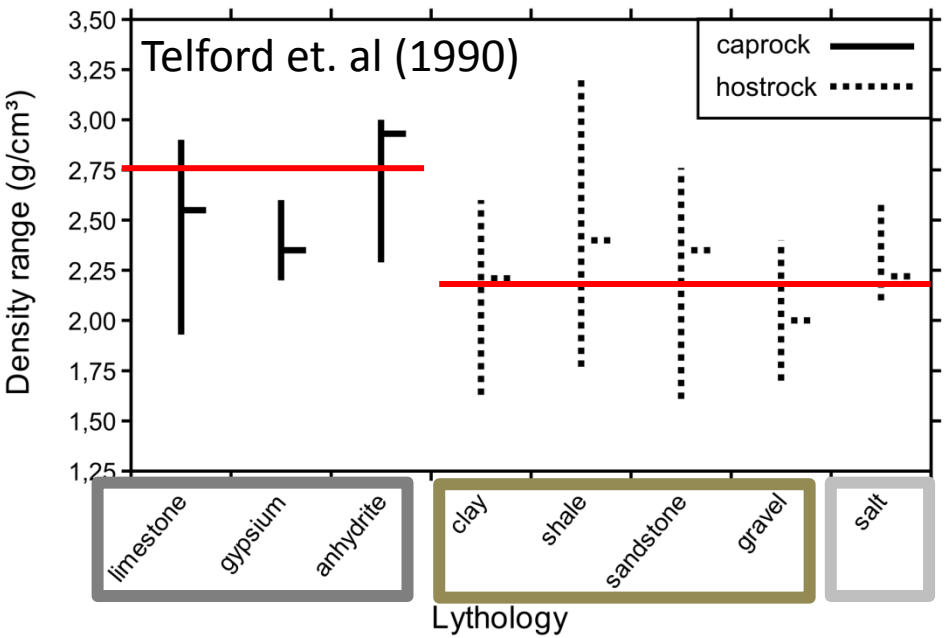
Apêndice 5

Esboço da subsuperfície

topo = 160 m (Ennen e Hall, 2011)

Marfurt et. al (2004)
Coker (2006)

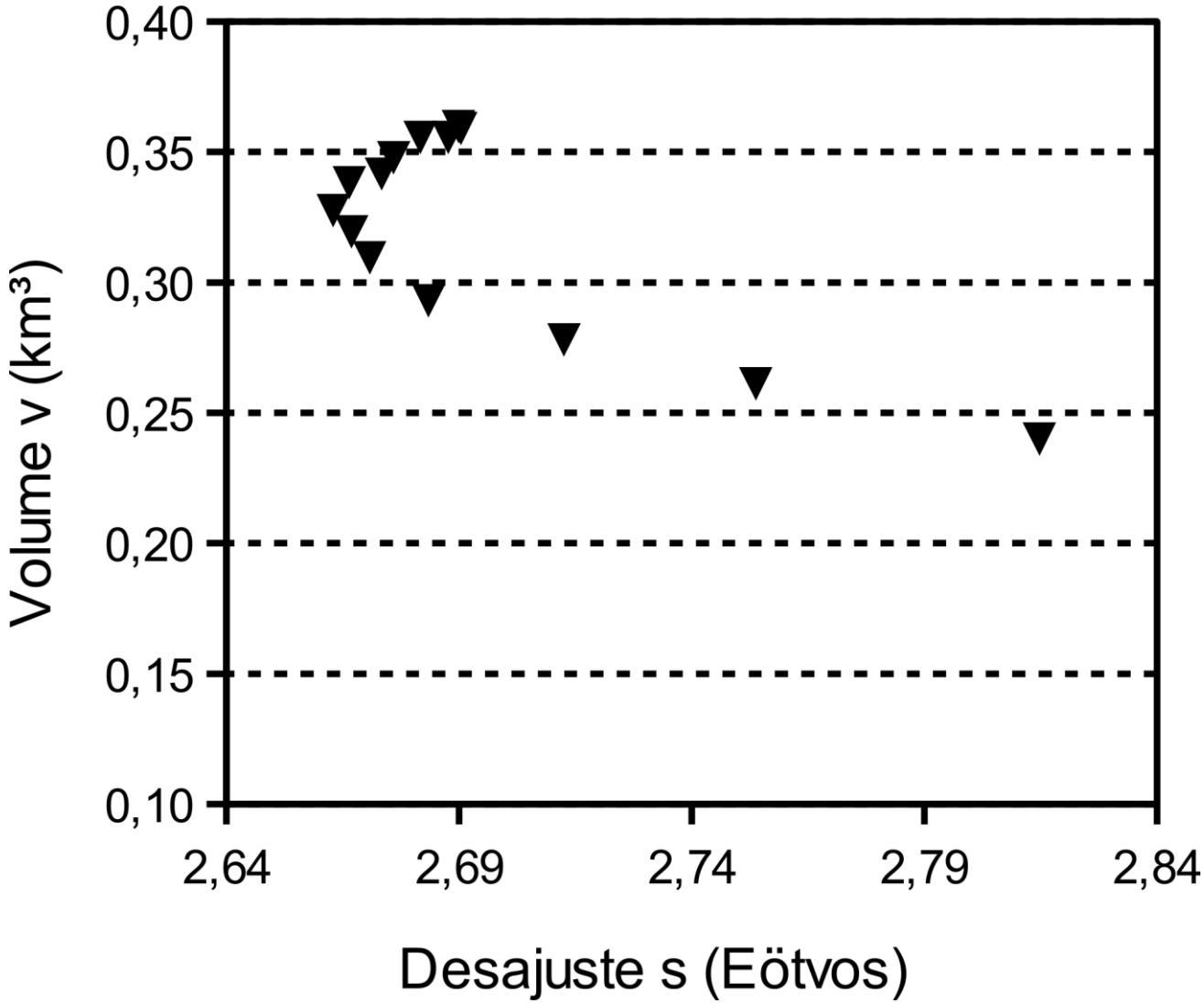




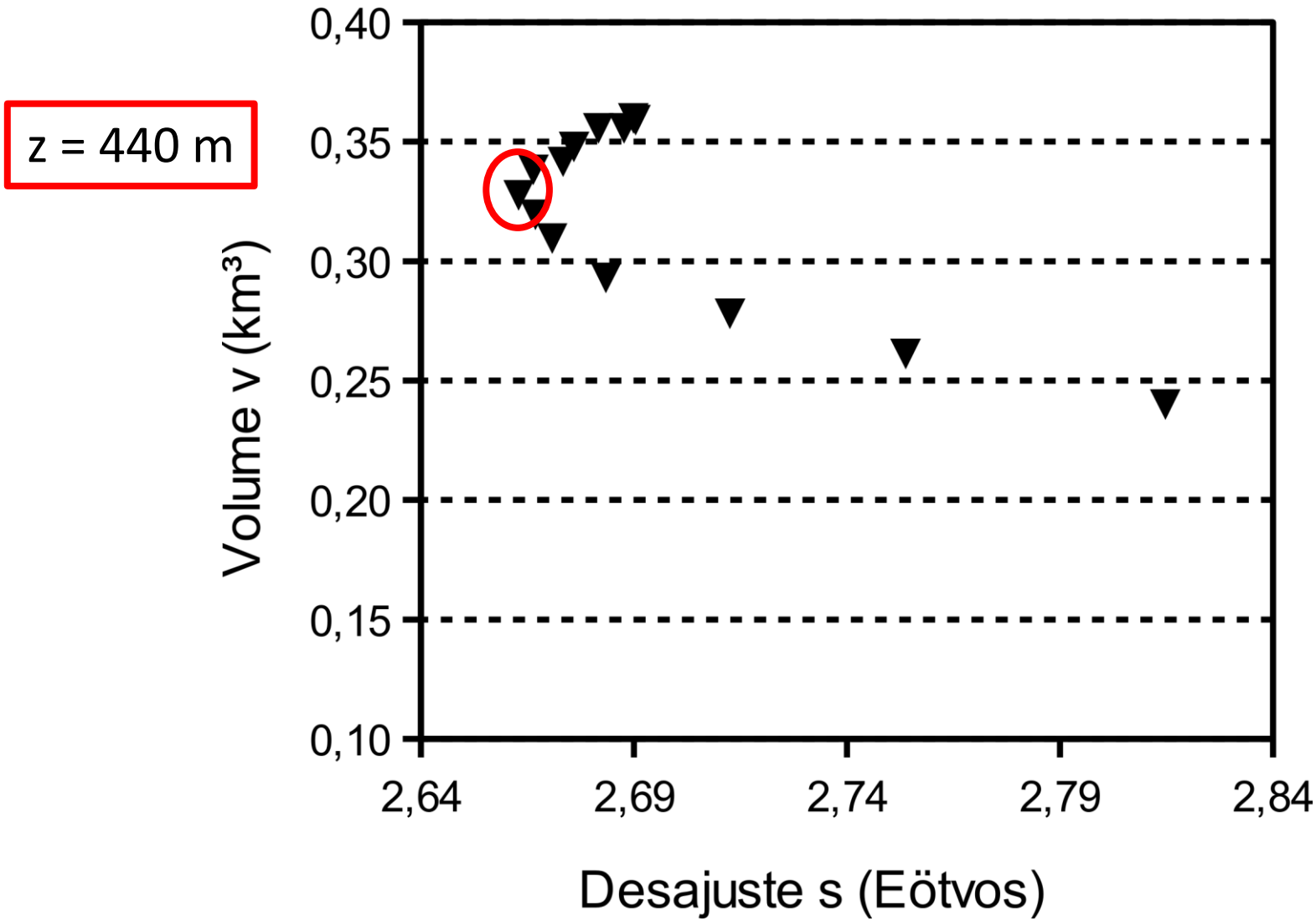
Hipótese 1:

- $\rho_{caprock}$ = 2,75 g/cm³ (Ennen e Hall, 2011)
- $\rho_{sedimentos}$ = 2,20 g/cm³
- ρ_{sal} = 2,20 g/cm³

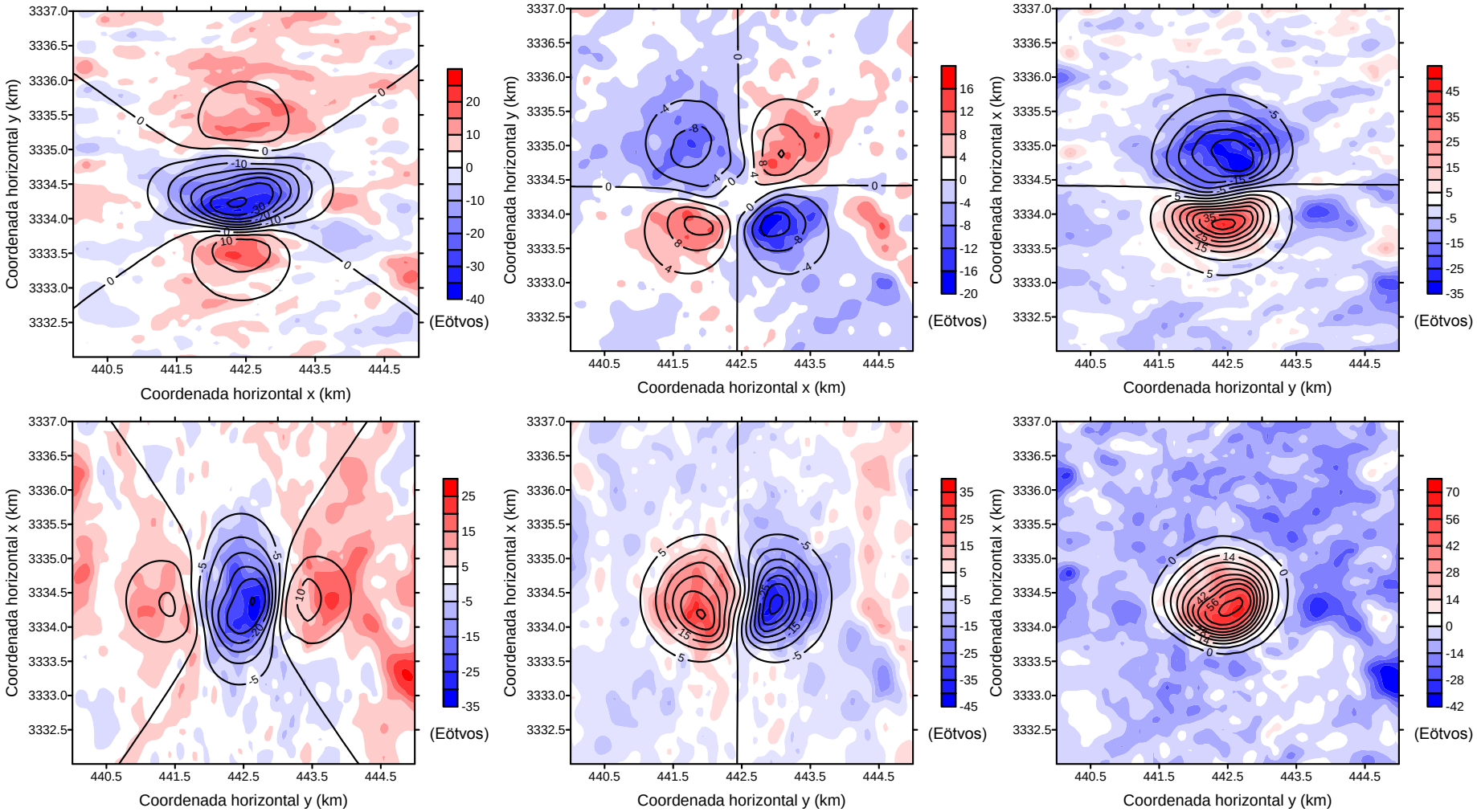
Apêndice 5


0,40
0,35
0,30
0,25
0,20
0,15
0,10
Volume v (km³)
2,64
2,69
2,74
2,79
2,84
Desajuste s (Eötvos)

Apêndice 5

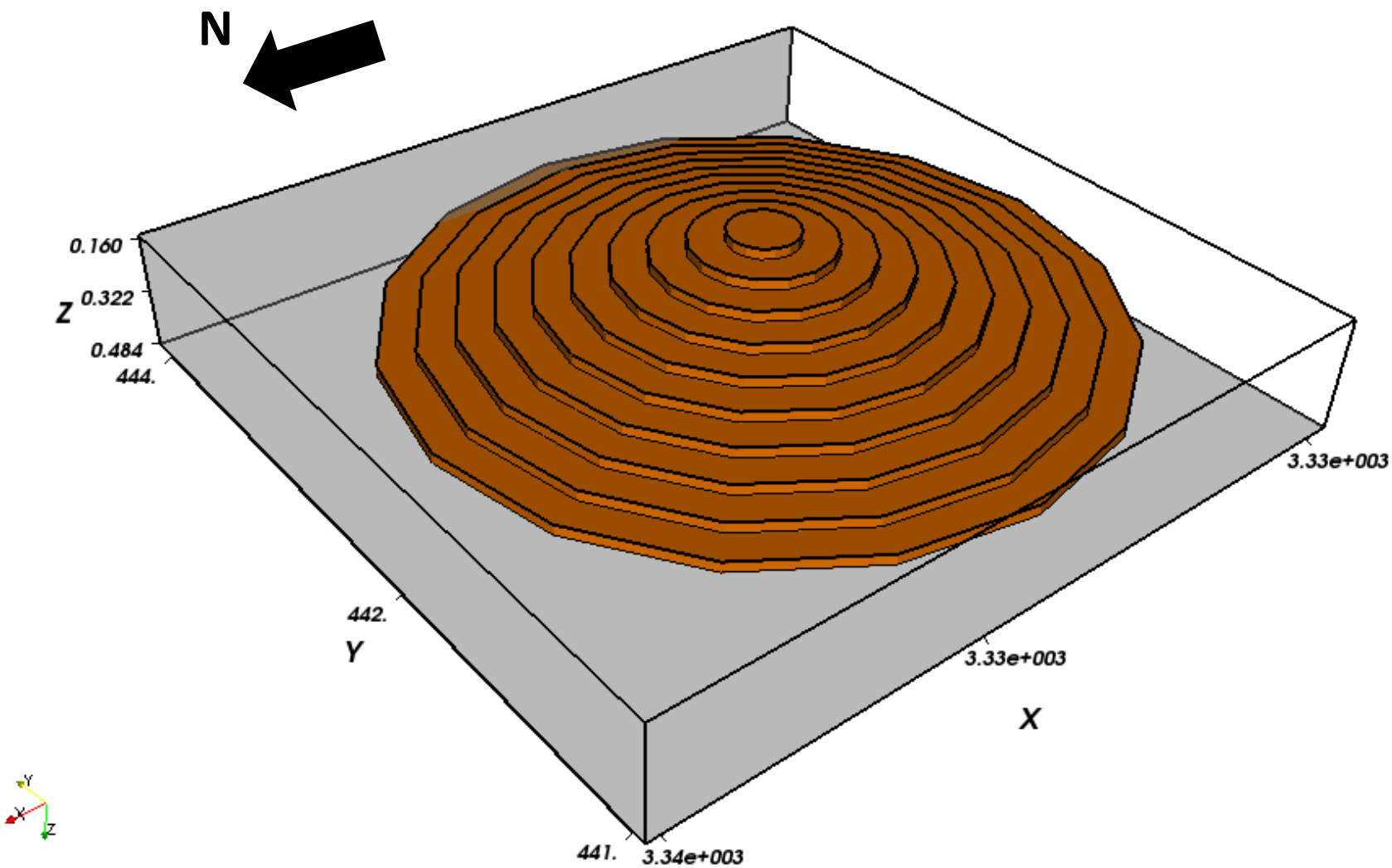

z = 440 m
0,40
0,35
0,30
0,25
0,20
0,15
0,10
Volume v (km³)
2,64
2,69
2,74
2,79
2,84
Desajuste s (Eötvos)

Apêndice 5

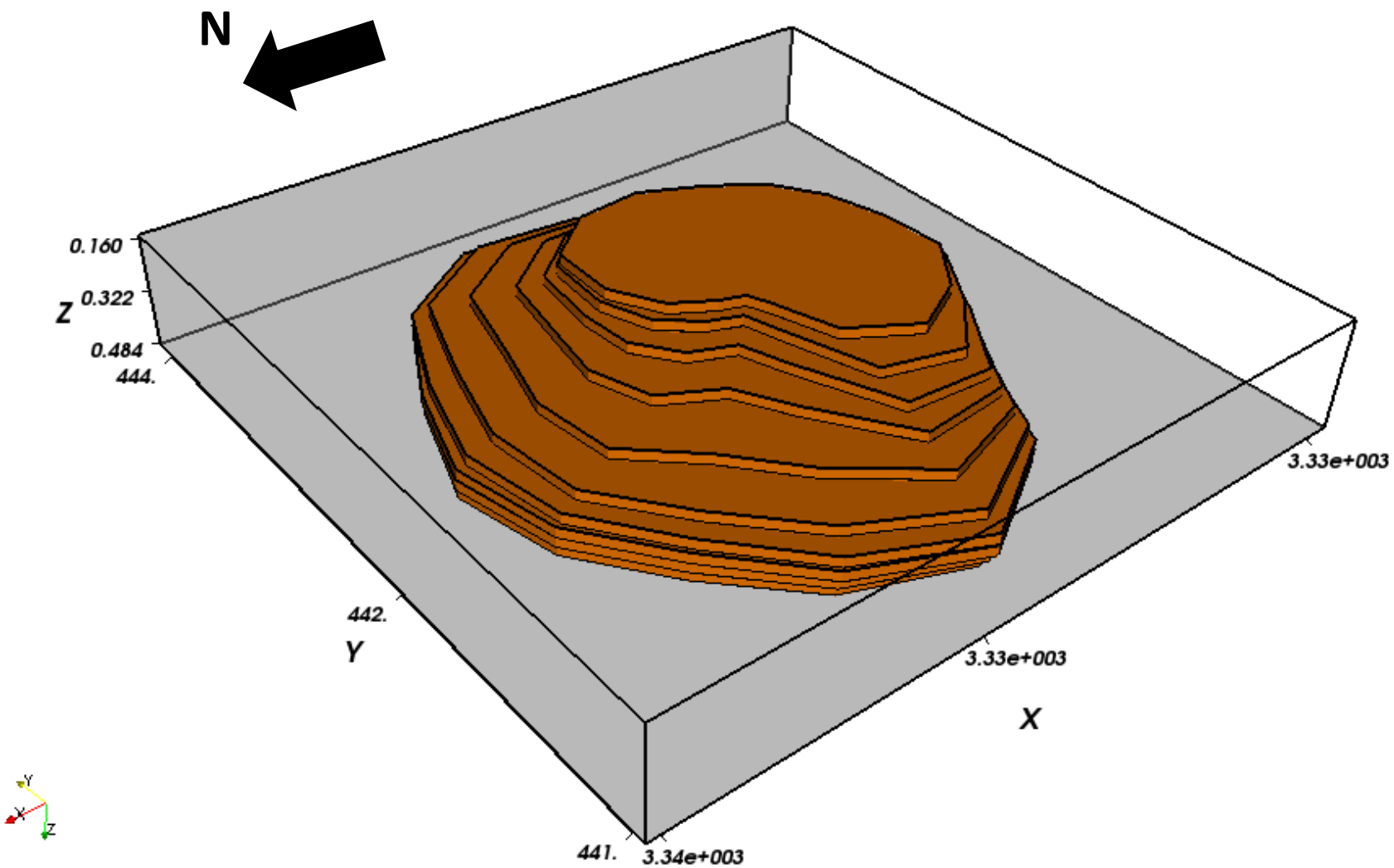


Dados fornecidos pela Bell Geospace

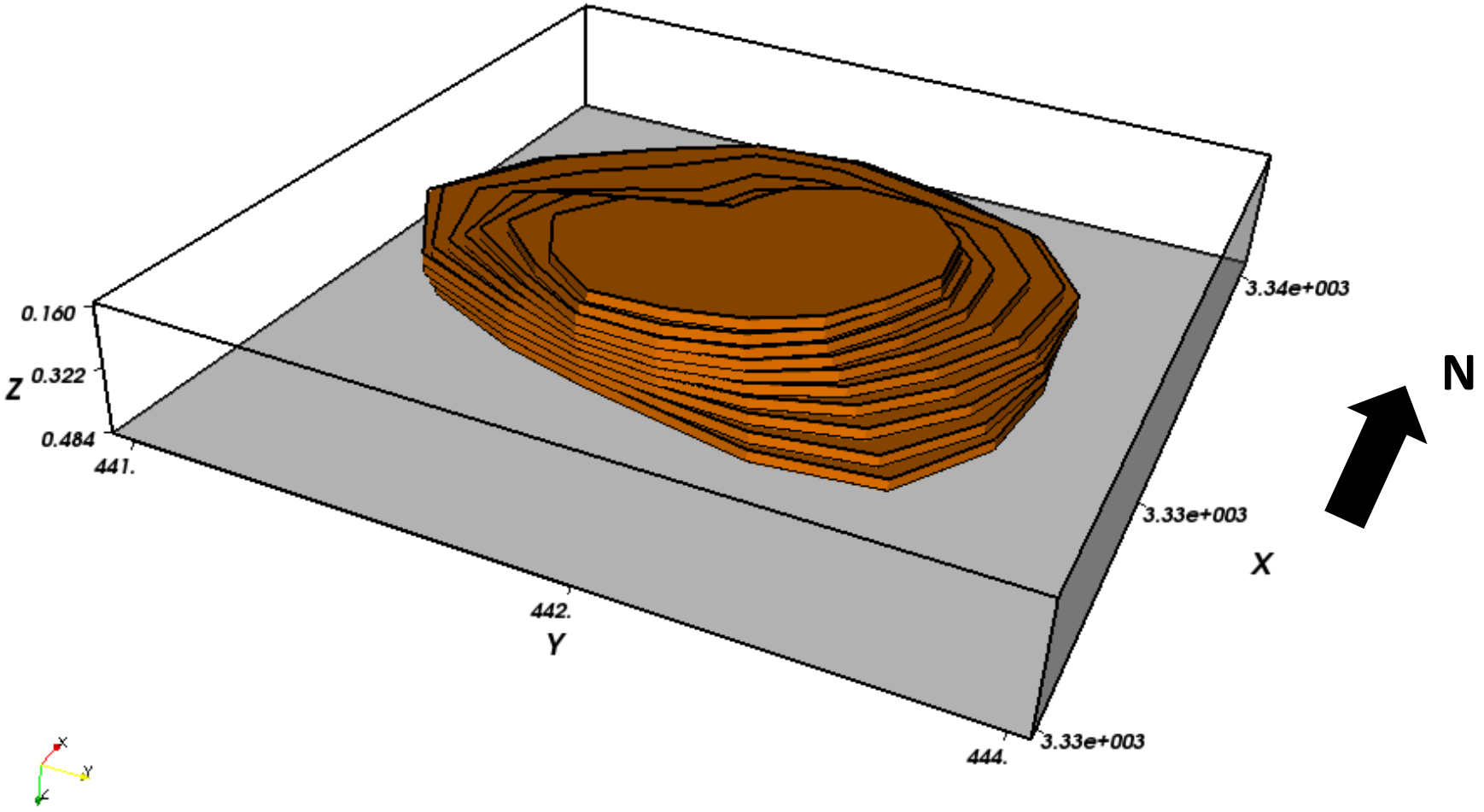
Apêndice 5



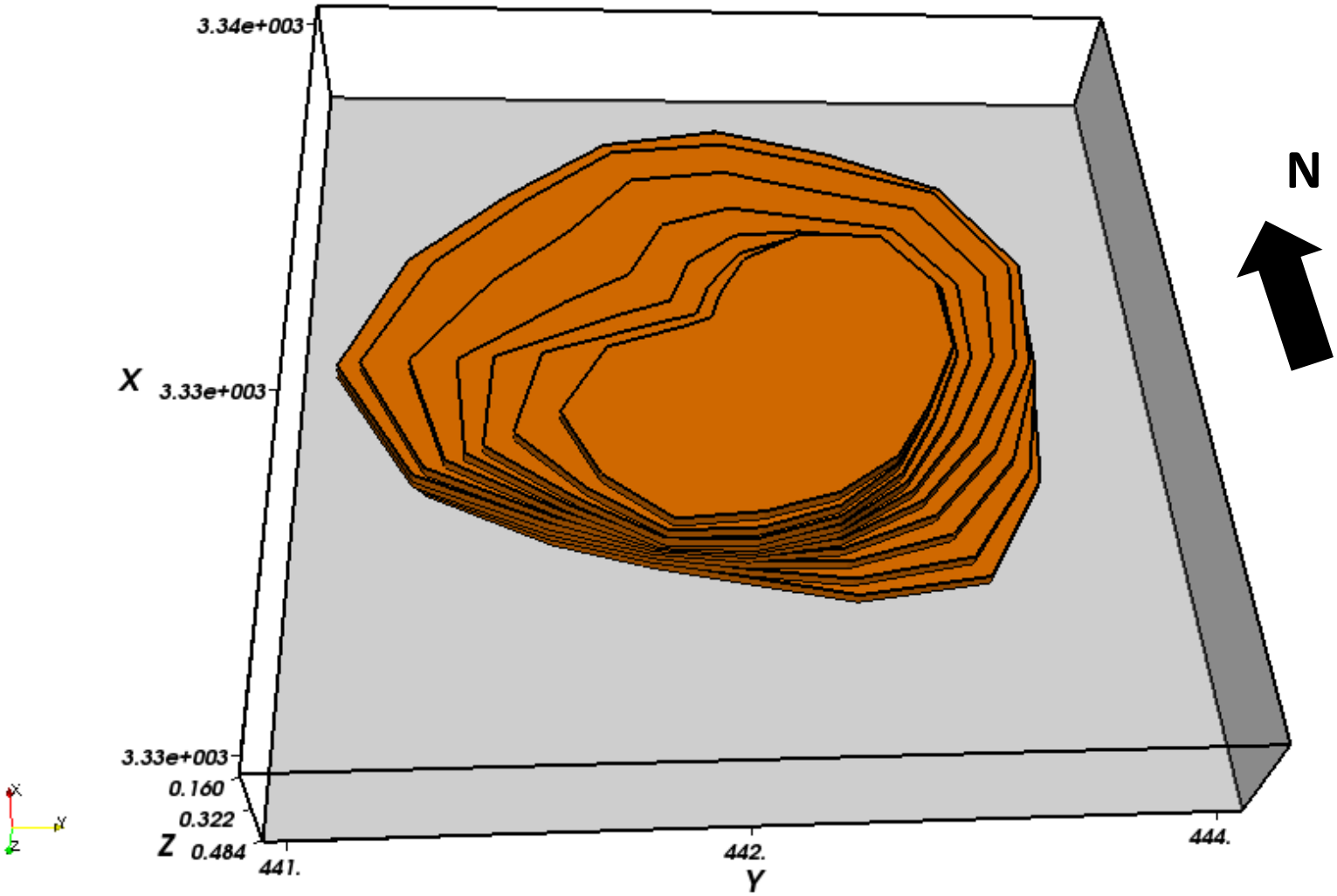
Apêndice 5



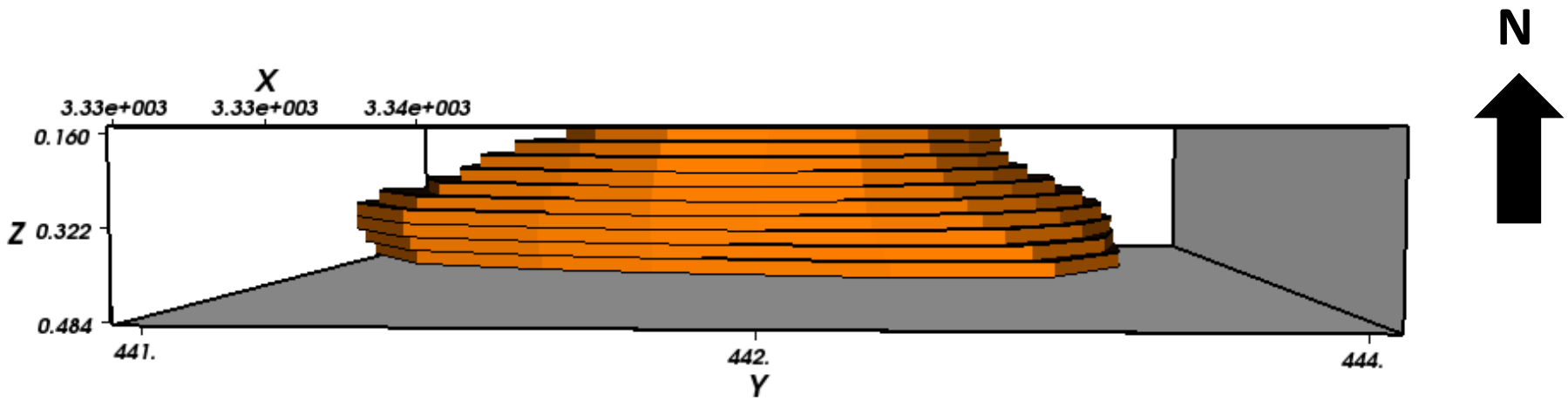
Apêndice 5

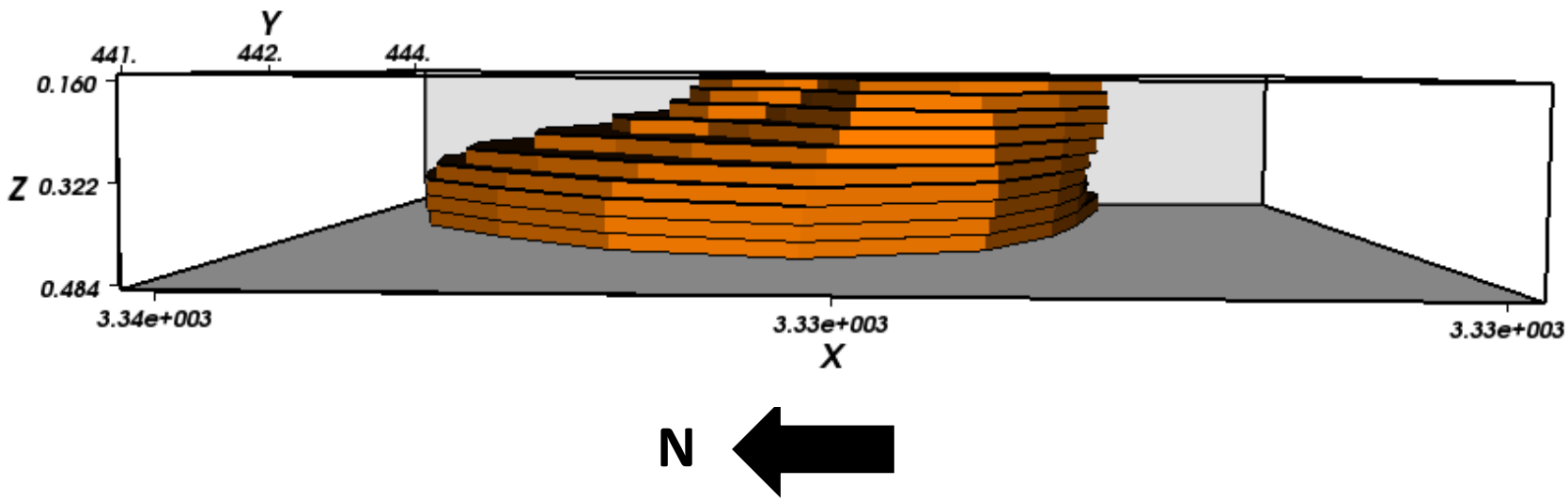


Apêndice 5

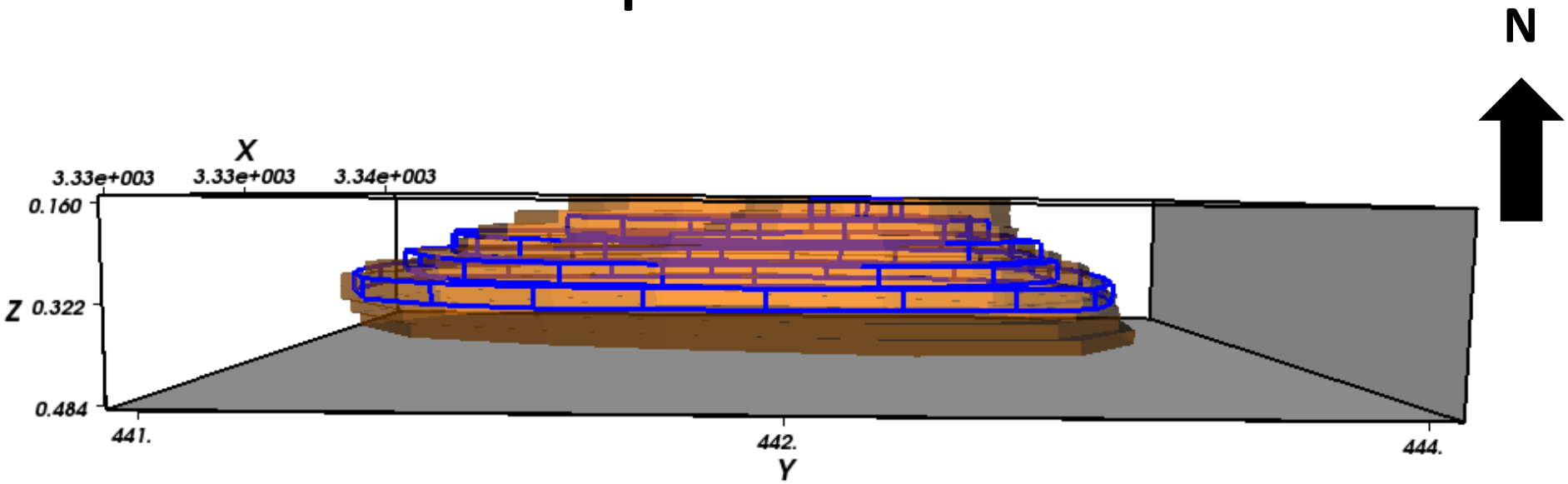


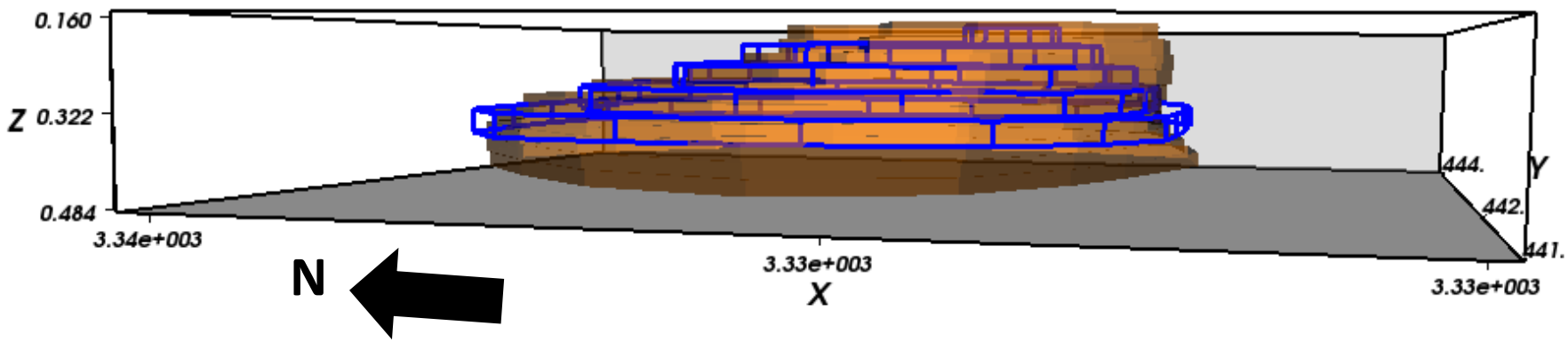
Apêndice 5


N
X
3.33e+003
3.33e+003
3.34e+003
0.160
Z 0.322
0.484
441.
442.
444.
Y

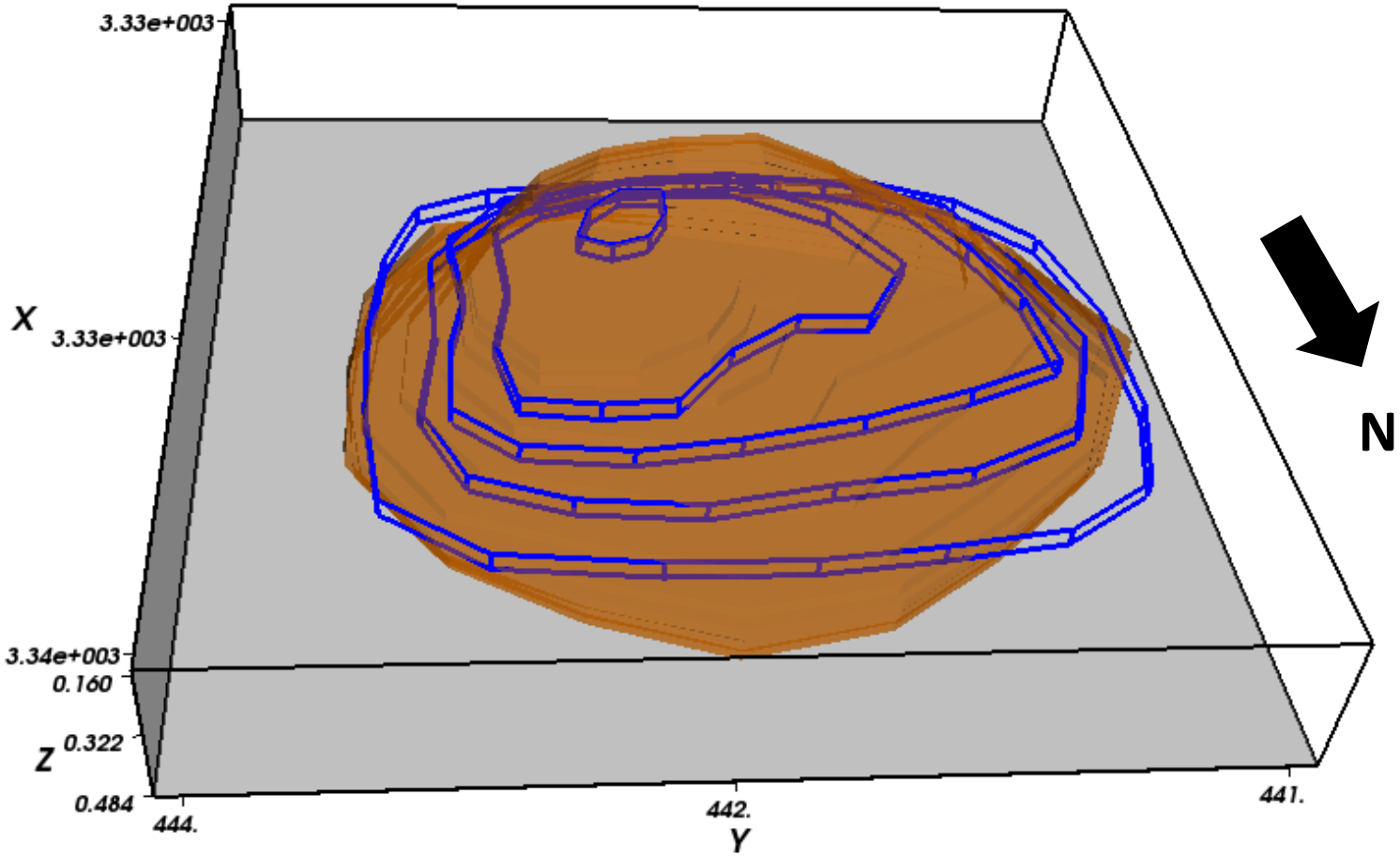

Y
441.
442.
444.
0.160
Z 0.322
0.484
3.34e+003
3.33e+003
3.33e+003
X
N

Apêndice 5

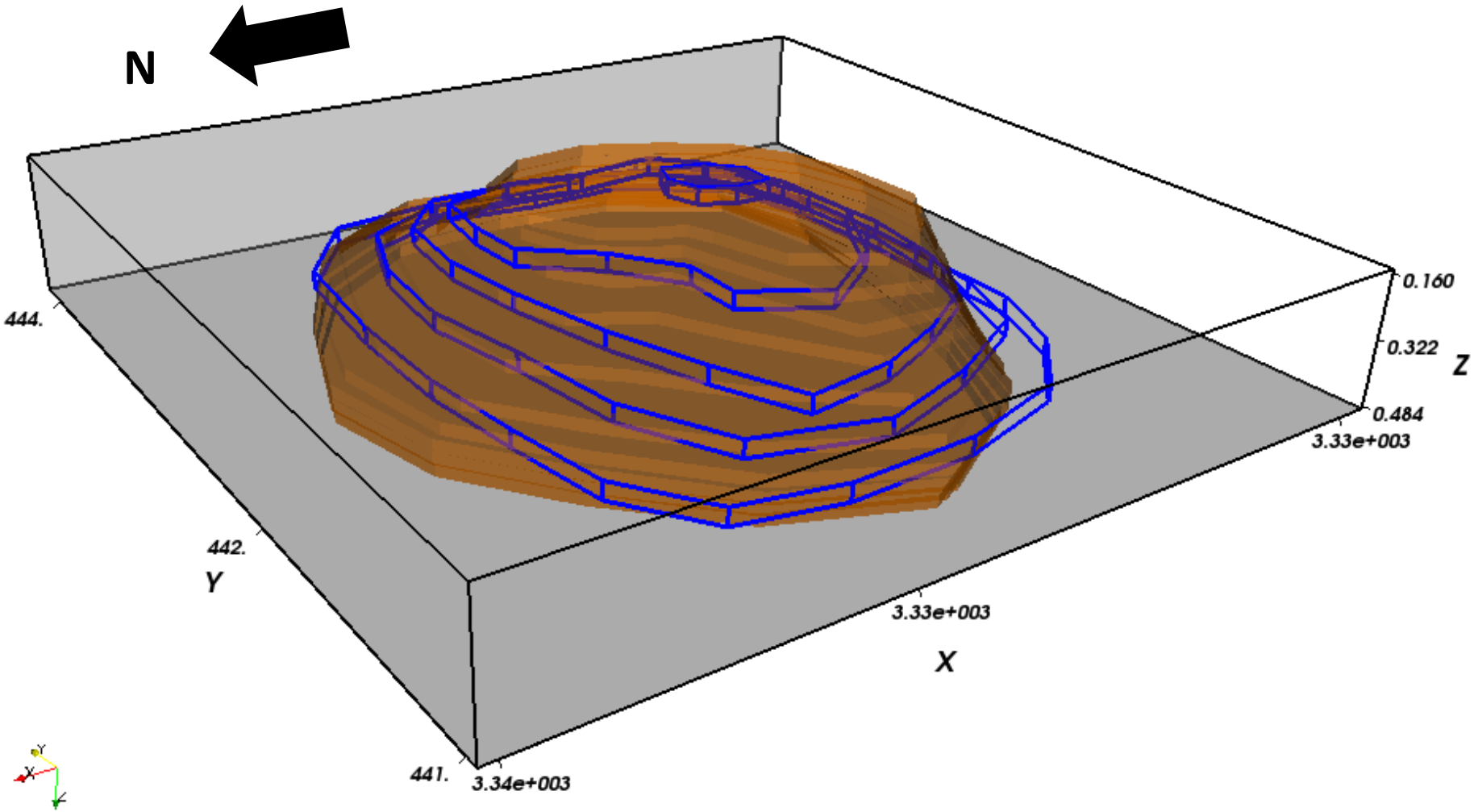
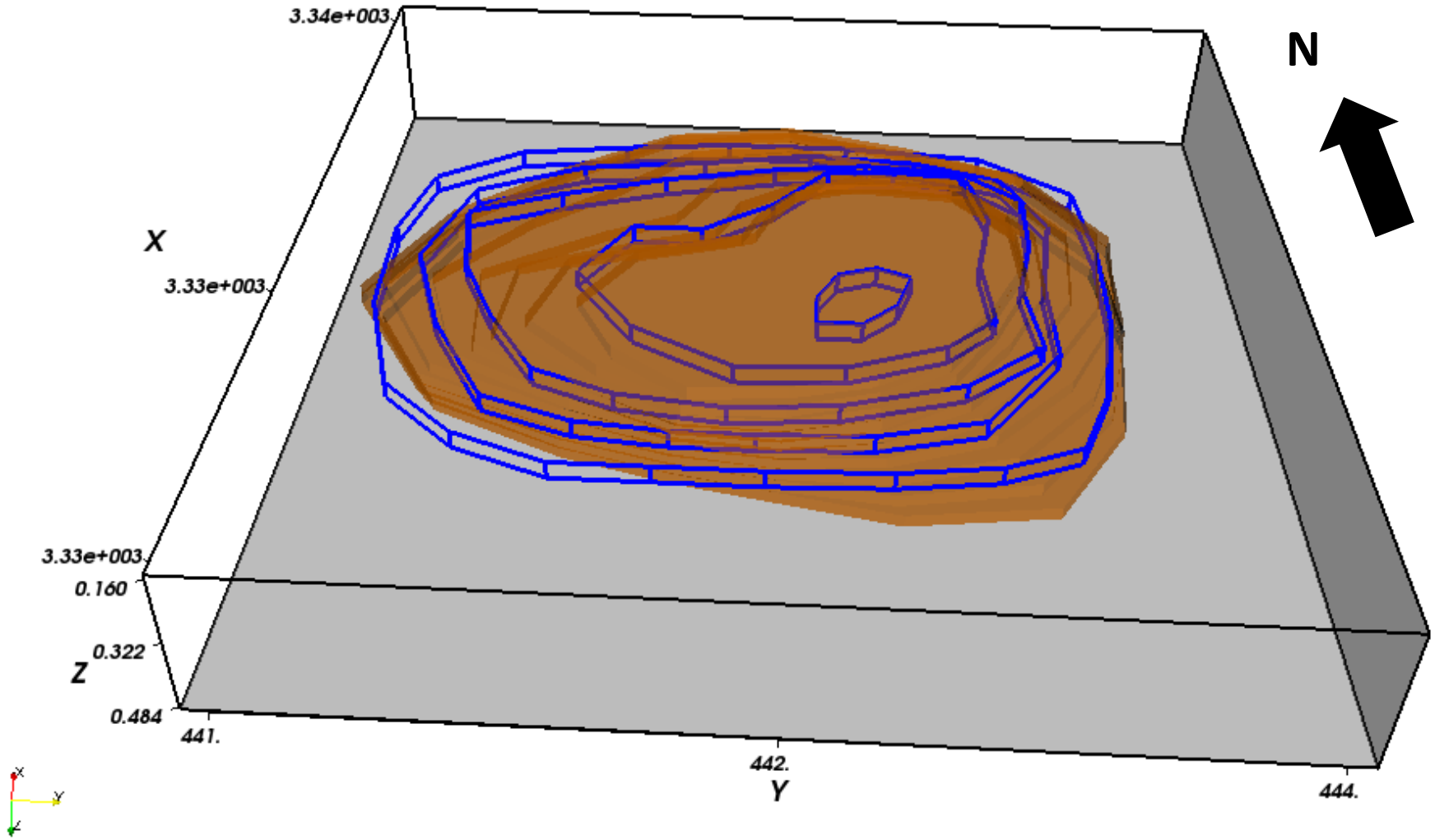

N
X
3.33e+003
3.33e+003
3.34e+003
0.160
Z 0.322
0.484
441.
442.
Y
444.


0.160
Z 0.322
0.484
3.34e+003
N
3.33e+003
X
444.
Y
442.
441.
3.33e+003

Apêndice 5



Apêndice 5



Apêndice 5