



INSTITUTO GEOFISICO DO INFANTE DOM LUIZ  
CENTRO DE GEOFISICA DA UNIVERSIDADE DE LISBOA

## Cap 2. Campo Magnético Crustal

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**IDL-FCUL**

# Campo Magnético Total



**Campo Magnético Principal**

→ Originado no núcleo externo



**Campo Magnético Externo**

→ Ionosfera e exterior da  
Terra



**Campo Magnético Crustal**

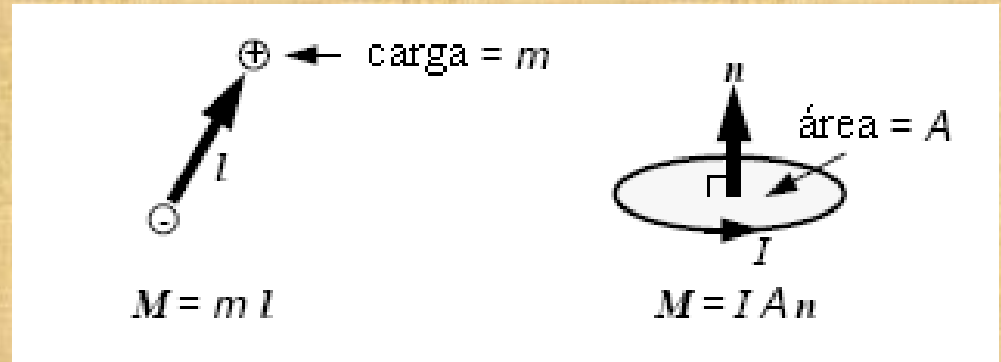
→ Litosfera

# Campo Magnético Crustal

1. Principiais propriedades magnéticas
2. Comportamentos magnéticos
3. Domínios magnéticos
4. Óxidos de ferro e titânio
5. Magnetização das rochas
6. Anisotropia de Susceptibilidade Magnética (ASM)
7. Mineralogia magnética

# 1. Magnetismo de Rocha – Principiais propriedades magnéticas

## Momento magnético



## Magnetização

$$J = \frac{\sum M_i}{\text{volume}}$$

## Susceptibilidade magnética

$$J = k.H$$

$k$ : a suscetibilidade por unidade de volume (SI/cm<sup>3</sup>)

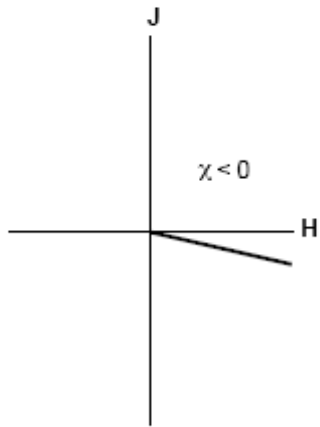
$\chi$ : a suscetibilidade por unidade de massa (SI/g).

# Principiais propriedades magnéticas - Unidades

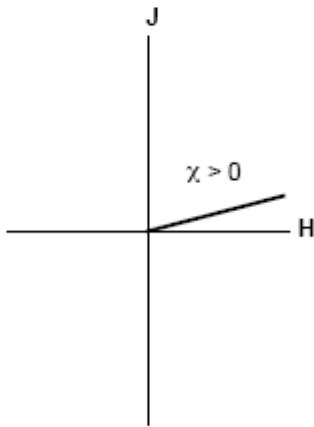
Quantity	Symbol	SI	cgs	Relationship
Magnetic moment	$m$	$\text{Am}^2$	emu	$1 \text{ Am}^2 = 10^3 \text{ emu}$
Magnetization	$M$	$\text{Am}^{-1}$	$\text{emu cm}^{-3}$	$1 \text{ Am}^{-1} = 10^{-3} \text{ emu cm}^{-3}$
Magnetic field	$H$	$\text{Am}^{-1}$	Oersted (oe)	$1 \text{ Am}^{-1} = 4\pi \times 10^{-3} \text{ oe}$
Magnetic induction	$B$	T	Gauss (G)	$1 \text{ T} = 10^4 \text{ G}$
Permeability of free space	$\mu_0$	$\text{Hm}^{-1}$	1	$4\pi \cdot 10^7 \text{ Hm}^{-1} = 1$
Magnetic susceptibility				
Volumetric	$\kappa$	Dimensionless	$\text{emu cm}^{-3} \text{ oe}$	$1 \text{ SI} = 1/4\pi \text{ emu cm}^{-3} \text{ oe}^{-1}$
Mass	$\chi$	$\text{m}^3 \text{ kg}^{-1}$	$\text{emu g}^{-1} \text{ oe}$	$1 \text{ m}^3 \text{ kg}^{-1} = 10^3/4\pi \text{ emu g}^{-1} \text{ oe}^{-1}$

# 2. Comportamentos magnéticos

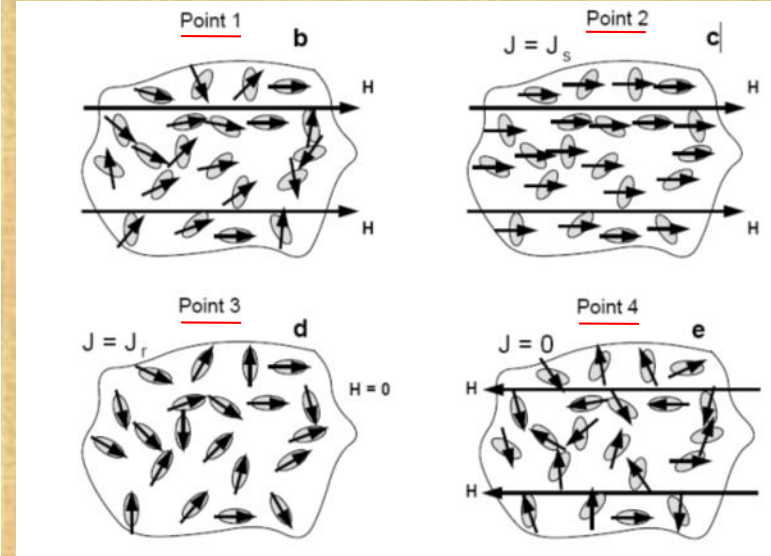
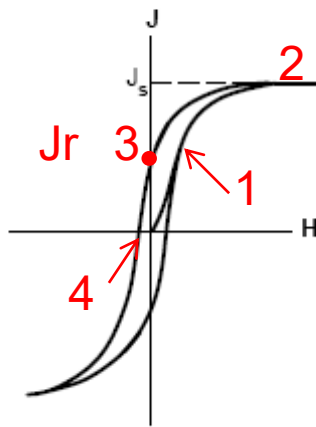
Diamagnético



Paramagnético



Ferromagnético

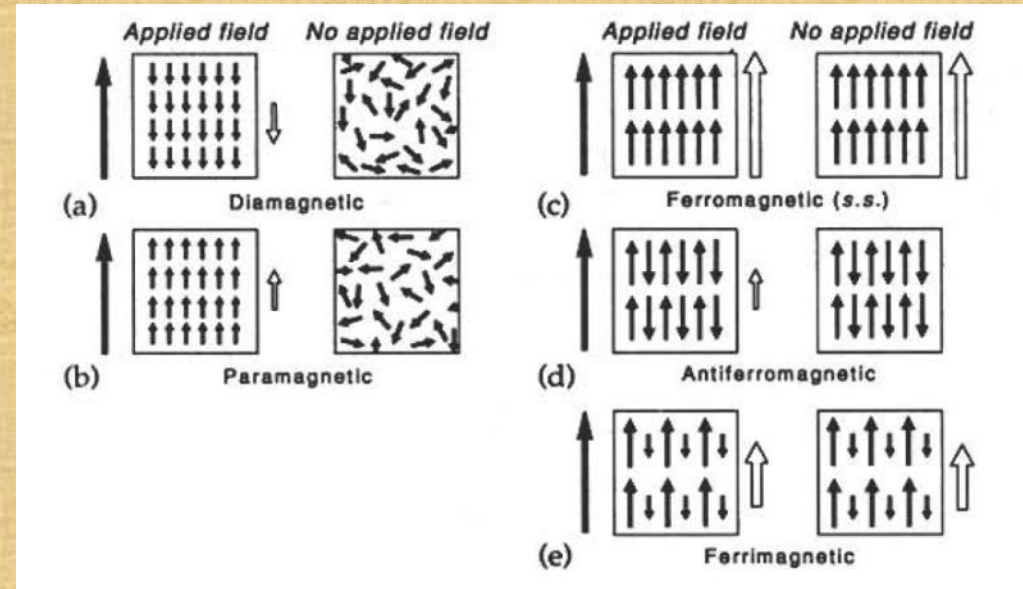
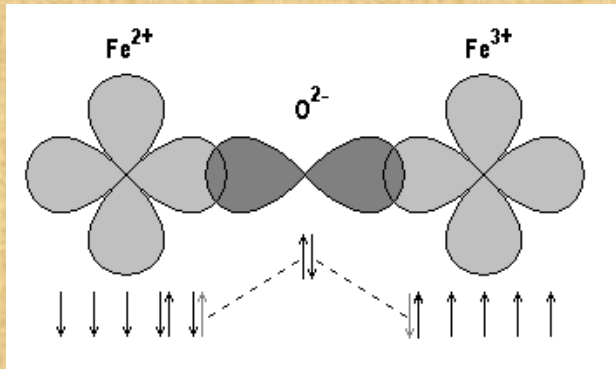


Quartzo  
 $\text{SiO}_2$

Biotite  
 $\text{K}(\text{Mg}, \text{Fe})_3\text{AlSi}_3\text{O}_{10}(\text{F}, \text{OH})_2$

Magnetite  
 $\text{Fe}_3\text{O}_4$

# Ferromagnetismo



## Exchange coupling:

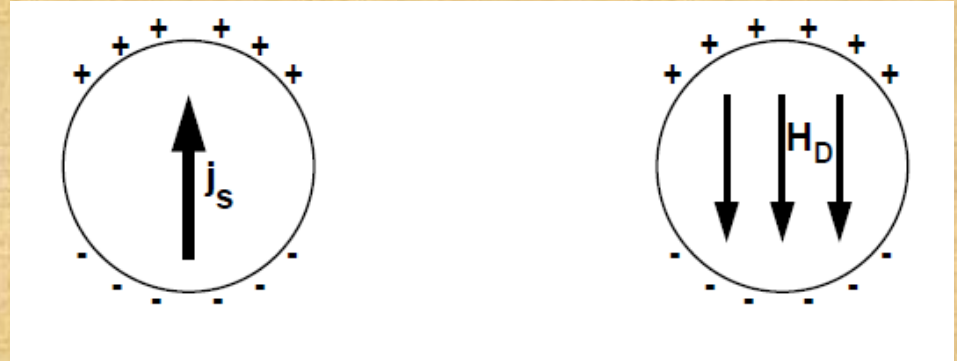
- Princípio de Pauli
- Paramagnéticos: sem overlap das órbitas e sem “exchange coupling”
- Ferromagnéticos: overlap orbitais e “exchange coupling”
- $T^{\circ}_{\text{Curie}}$ : interação interatômicas fraca e sem “exchange coupling”

Para electrões de um mesmo átomo, o princípio de Pauli implica que dois electrões não podem ter os mesmos quatro números quânticos. Por exemplo, se os números quânticos  $n$ ,  $l$ , e  $m_l$  são iguais nos dois electrões, estes deverão necessariamente ter os números  $m_s$  diferentes, e portanto os dois electrões têm spins opostos.

# Energia Magnetostática & factor auto-desmagnetizante

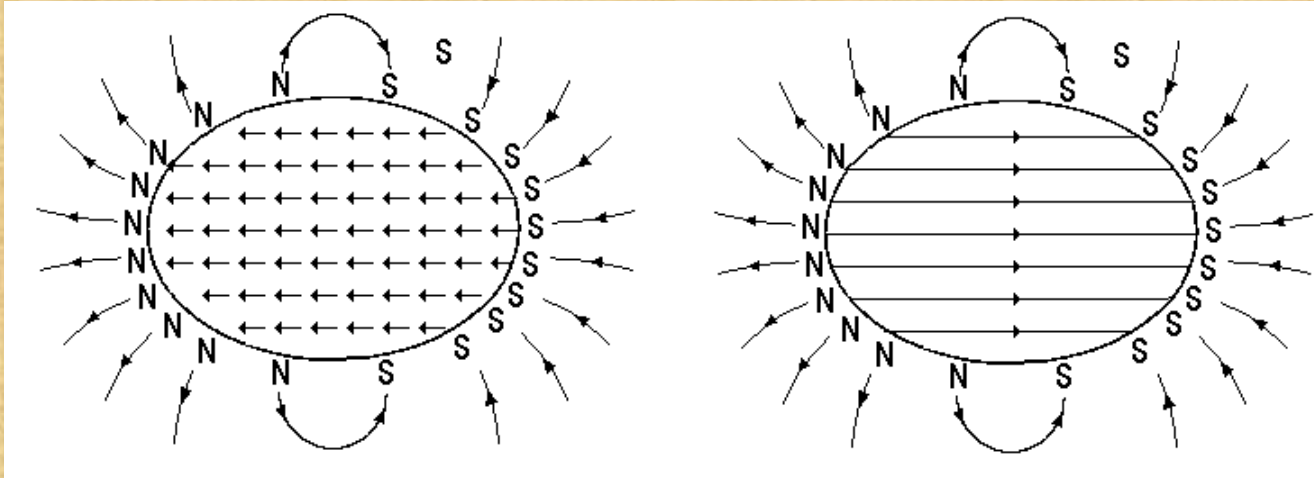
A distribuição das cargas magneticas cria um campo desmagnetizante interno:

$$H_D = -N_D j$$



A interacção deste campo com a magnetização do grão gera a energia magnetostática:

$$e_m = -\frac{\mathbf{j} \cdot \mathbf{H}}{2} = -\frac{\mathbf{j} \cdot \mathbf{H}_D}{2} = -\frac{(\mathbf{j}_s) \cdot (-N_D \mathbf{j}_s)}{2} = \frac{N_D j_s^2}{2}$$

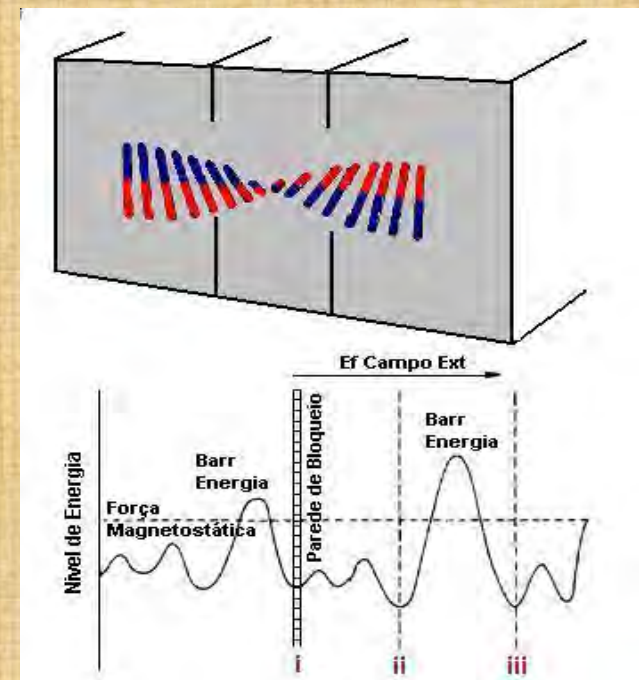
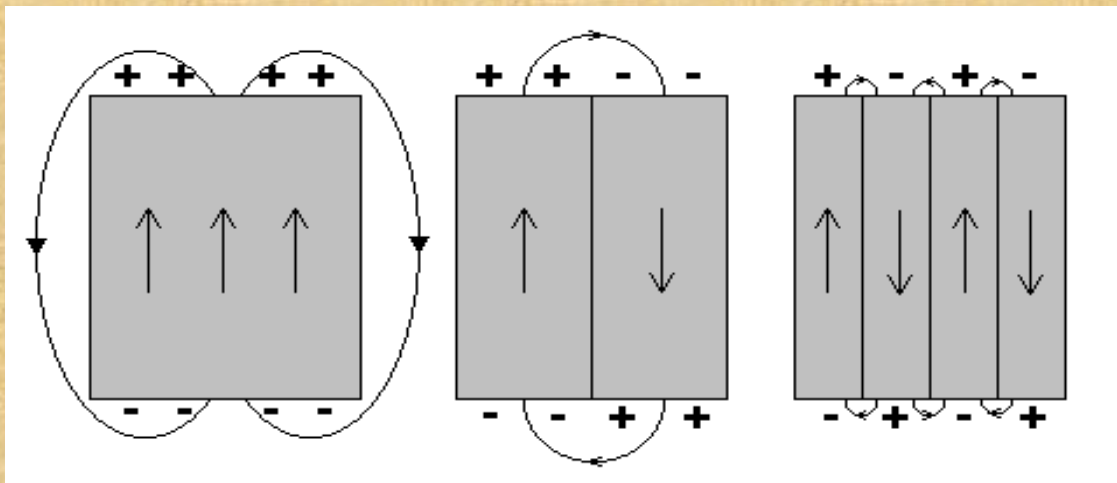
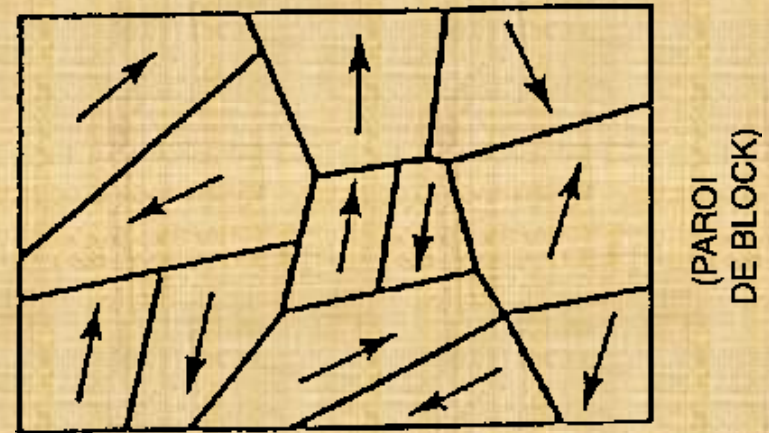




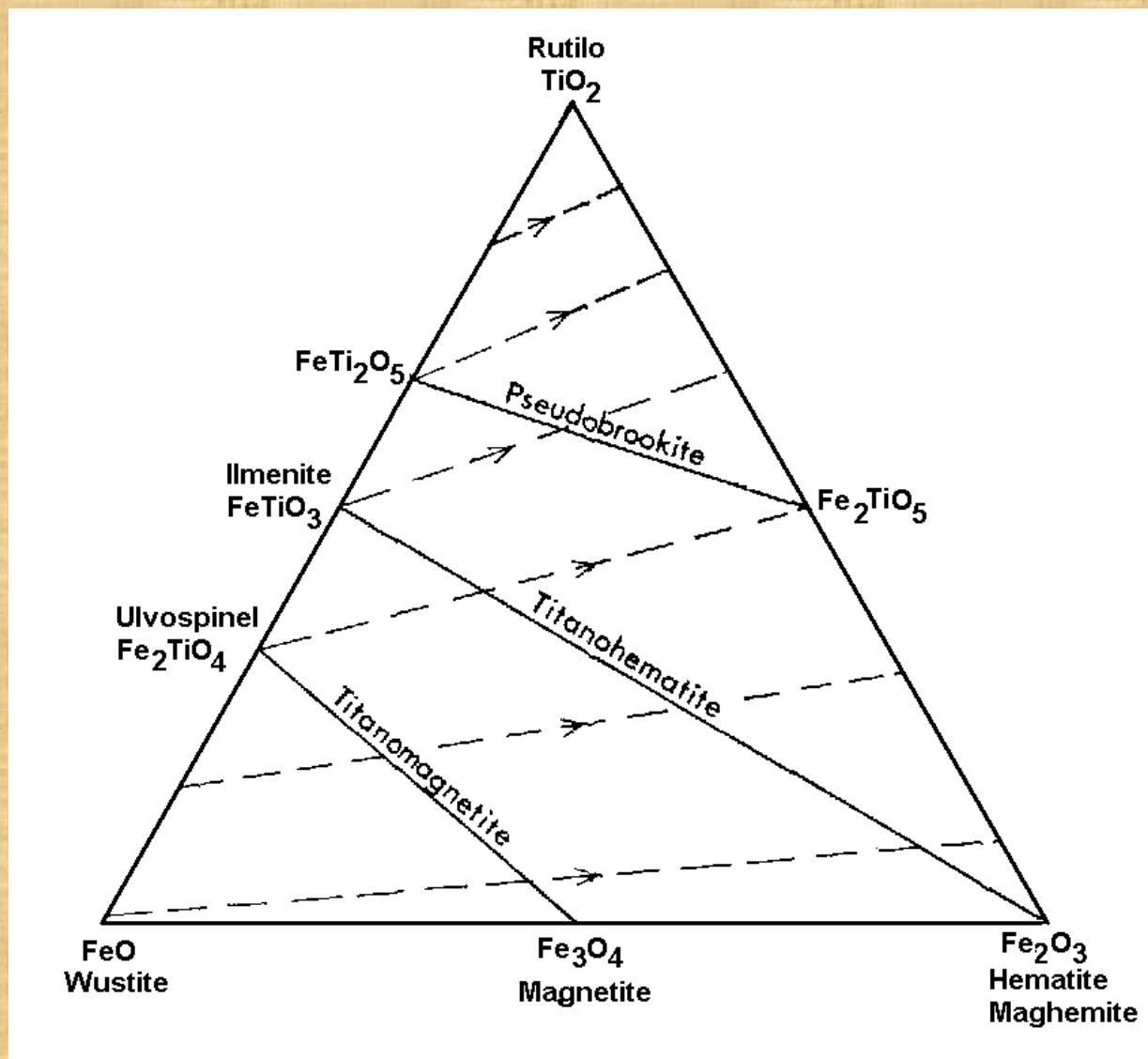
# 3. Domínios magnéticos

A região do espaço em qual todos os momentos magnéticos são orientados numa mesma direção é chamada de **domínio de Weiss** e os limites entre estes domínios são chamados de **paredes de Bloch**.

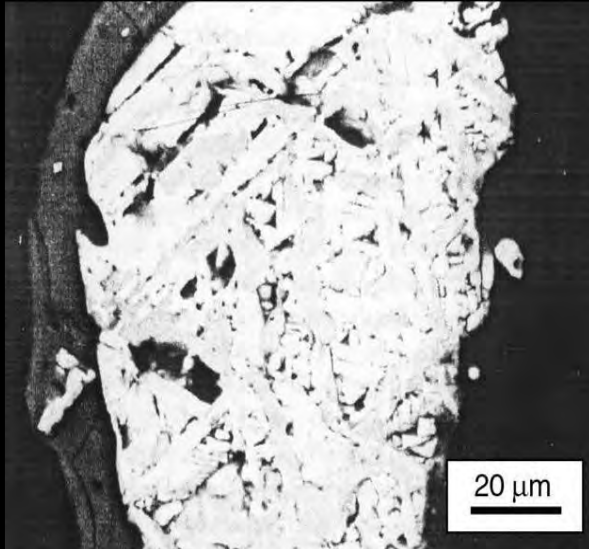
A dimensão dos domínios é da ordem de 0.1-0.05 m e a das paredes é de 0.1m.



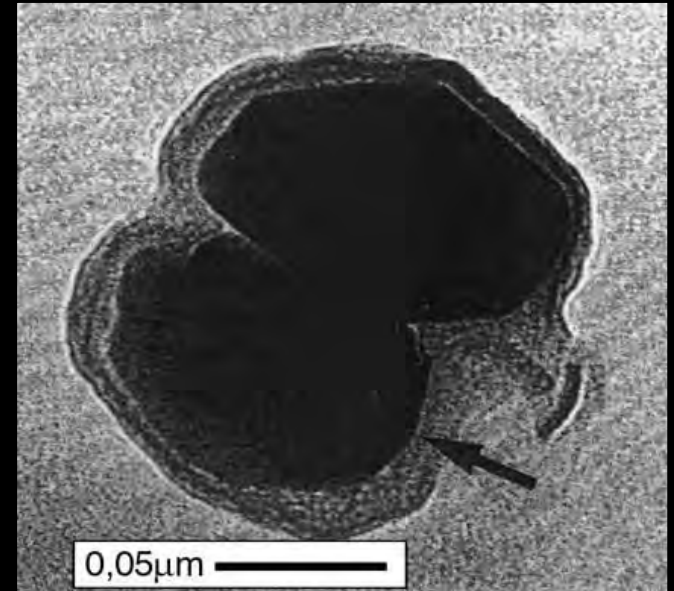
## 4. Óxidos de ferro e titânio



# Imagens SEM: óxidos de ferro “primários”



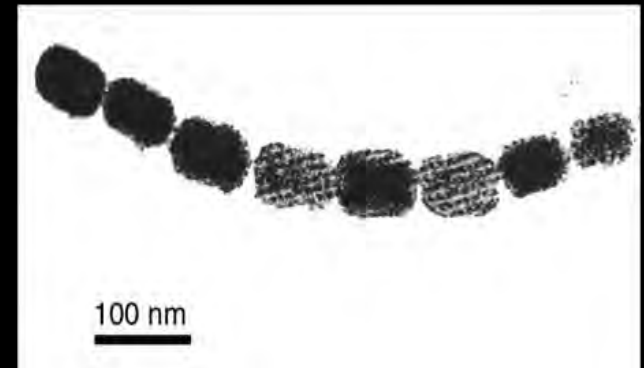
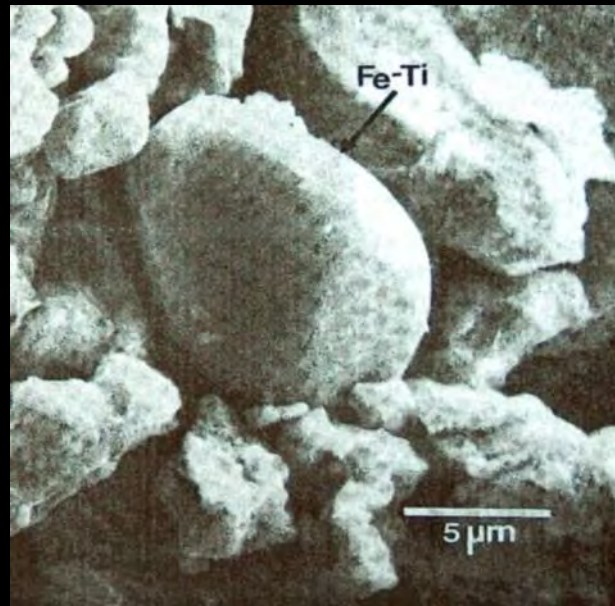
Magnetita detrítica com texturas de oxidação de alta temperatura, carbonatos  
Mississipian, USA  
McCabe *et al.* (1989). *JGR*, 94(8), 10.429-10.443.



Magnetita SD de bactérias magnetosomes, carbonatos de Mururoa  
Aïssaoui *et al.* (1990). *EPSL*, 97, 102-112.

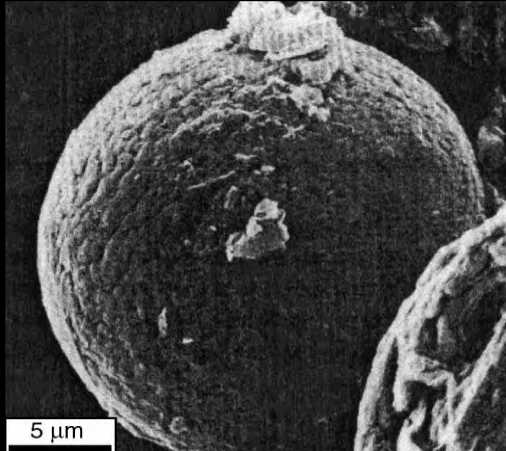
Ti-magnetita detrítica da Fm. Wabash (Indiana, USA)

Suk *et al.* (1992). *Tectonophys.*, 215, 255-272.



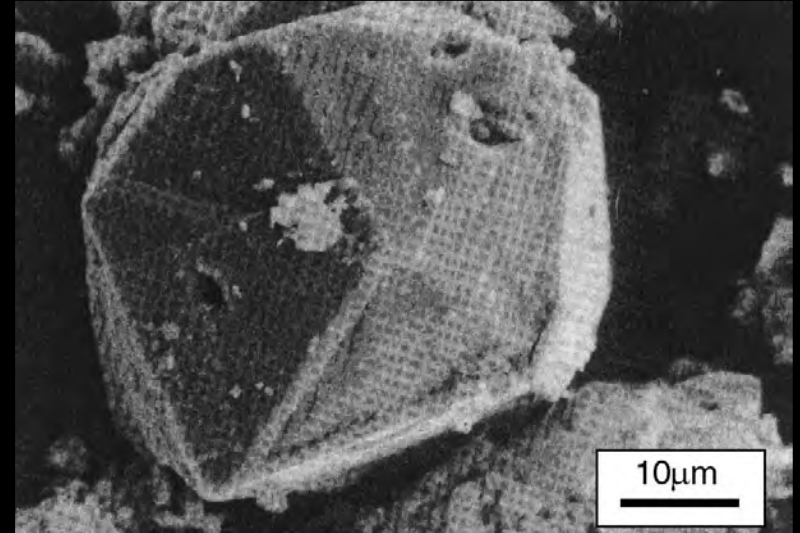
Cadeia de magnetita biogênicas de um magnetosome  
Stolz *et al.* (1986). *Nature*, 321, 26.

# Imagens SEM: óxidos de ferro “secundários”



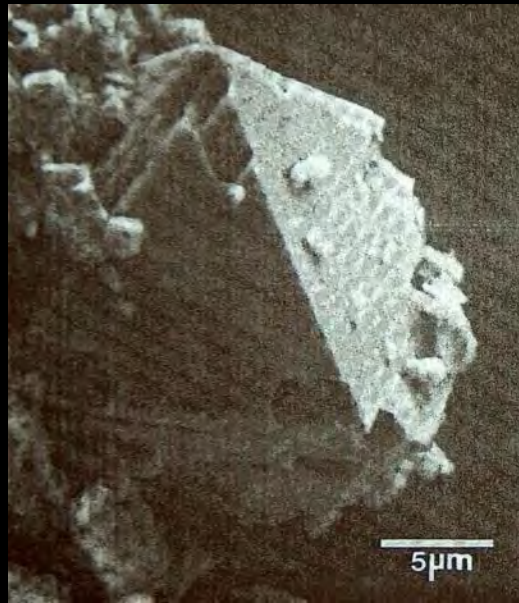
Magnetita autigênica esférica

Elmore & Leach (1990). *Geology*, 18, 124-127.



Magnetita euhedral, carbonatos paleozóicos (Missouri, USA)

Sun & Jackson (1994). *JGR*, 99(B2), 2935-2942.



Óxido de ferro octohedral

autigênico, da Formação Pride

Mountain (Alabama, USA)

Suk et al. (1992). *Tectonophys.*, 215,

255-272.

Magnetita autigênico

substituindo a pirita

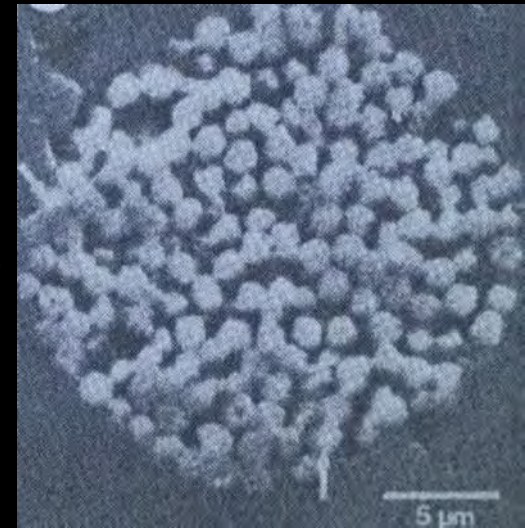
framboidal

Fm. Onondaga (New

York, USA)

Suk et al. (1992). *Nature*,

345, 611-613.



# Principais propriedades magnéticas dos ferromagnéticos

**Table 2.1** Some generalized properties of ferromagnetic (s.l.) minerals

Mineral	Composition	Curie/Néel temperature (°C)	Saturation magnetization ( $A\ m^2/kg$ )	Mass susceptibility ( $\times 10^{-8}\ SI/kg$ )	$P_J$	$T$	'Easy' direction	Density ( $kg/m^3$ )
Magnetite	$\alpha\text{-Fe}_3\text{O}_4$	575	90–93	578	1.18	–0.30	$\langle 111 \rangle^*$	5200
Maghaemite	$\gamma\text{-Fe}_2\text{O}_3$	(350)	80–85	500	†	†	$\langle 111 \rangle$	4800
Haematite	$\alpha\text{-Fe}_2\text{O}_3$	680	0.2–0.5	25	>100	1.0	Basal	5300
Goethite	$\gamma\text{-FeOOH}$	120–130	0.001–1	0.5–1.5	†	†		4300
Pyrrhotite	$\text{FeS}_{1.14}$	320	1–2	0.1–20	3–400	0.8	Basal	4600
Franklinite	$\text{ZnFe}_2\text{O}_4$	60	0.006–3	†	†	†		5340
Jacobsite	$\text{MnFe}_2\text{O}_4$	300	0.7–3	†	†	†		4870
Chromite	$\text{FeCr}_2\text{O}_4$	–84	0.003–0.007	†	†	†		5090
Cobaltite	$\text{CoAsS}$	†	0.0005–0.2	†	†	†		6300

The values for saturation magnetization and, especially, mass susceptibility are only indicative of the order of magnitude and are strongly dependent on grain size and shape in particular (see text and Figure 2.6). Published values of these parameters show considerable variation, the mass susceptibility of pyrrhotite, for example, varying from 3.2 to  $>2000 \times 10^{-8}\ SI/kg$ .  $P_J$  and  $T$  are the parameters for the degree of anisotropy and shape of the susceptibility ellipsoid (Jelinek, 1981; section 1.5).

\*The 'easy' direction in magnetite is  $\langle 100 \rangle$  at temperatures  $< 130\text{K}$ .

† Undefined or variable parameter.

## 5. Magnetização das rochas

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**Magnetização total**

$$J = J_i + J_r$$

**Magnetização induzida**

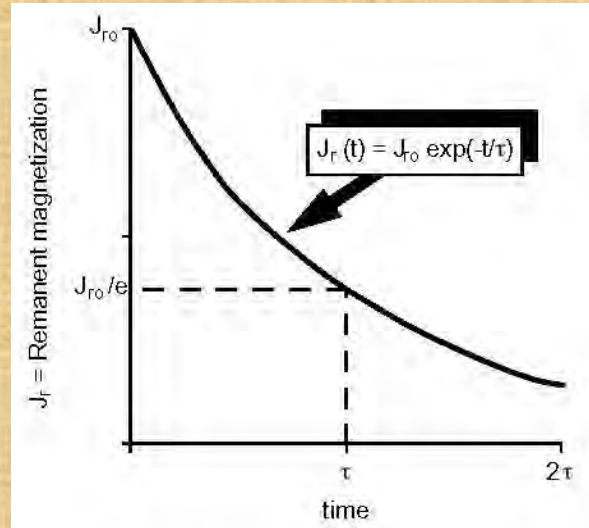
$$J = \chi \cdot H$$

**Magnetização remanescente**  
**(SD)**

$$J_r(t) = J_{ro} \exp(-t/\tau)$$

# Magnetização das rochas

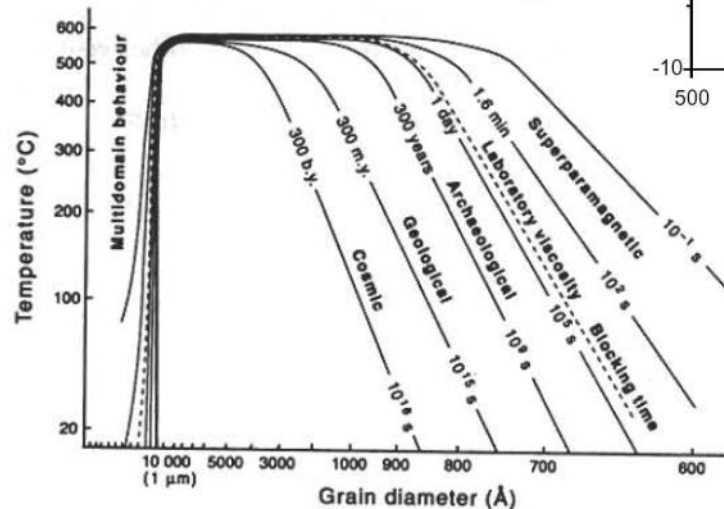
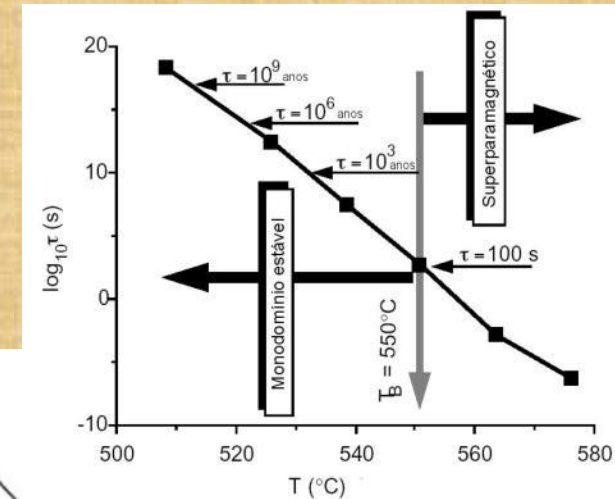
## Magnetização remanescente (SD)



$$J_r(t) = J_{r0} \exp(-t/\tau)$$

$$\tau = 1/C \cdot \exp [ v h_c j_s / 2kT ]$$

- C : fator de freqüência = 10<sup>8</sup> s<sup>-1</sup>
- v : volume dos grãos SD
- h<sub>c</sub> : coercividade dos grãos SD
- j<sub>s</sub> : magnetização de saturação
- kT : energia térmica



**Superparamagnetismo:** a magnetização de uma partícula muito pequena (nanopartículas) pode “virar” com a influencia da temperatura. O tempo entre as duas direcções é chamada de tempo de relaxação de Néel.

Na ausência de um campo externo, quando o tempo de medida é muito mas comprido que o tempo de relaxação, a magnetização se aproxima de 0 → SP

Neste estado, um campo externo é capaz de magnetizar as nanopartículas como se fossem paramagnéticos. Porem, a susceptibilidade magnética dos SP é muito mais alto que os paramagnéticos.

# Tipos de magnetização das rochas

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**Magnetização Remanescente Térmica**  
(TRM)

Primárias

**Magnetização Remanescente Detrítica**  
(DRM)

**Magnetização Remanescente Química**  
(CRM)

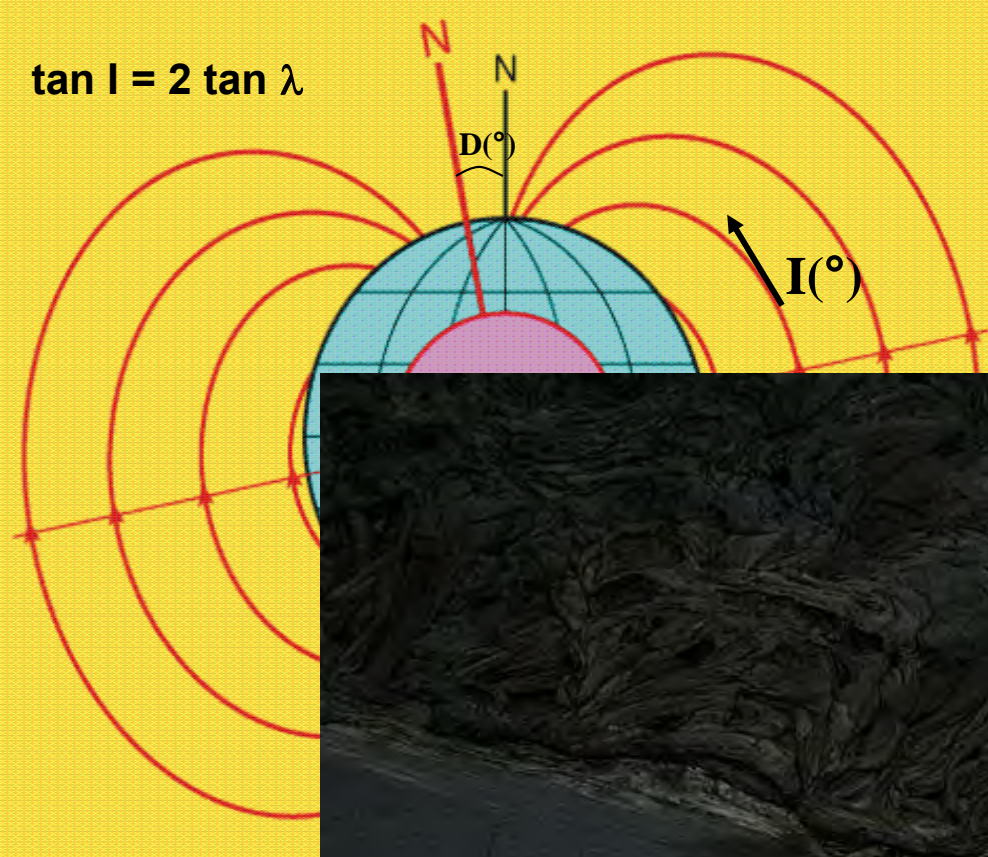
**Magnetização Remanescente Viscosa**  
(VRM)

Razão de  
Koenigsberger:

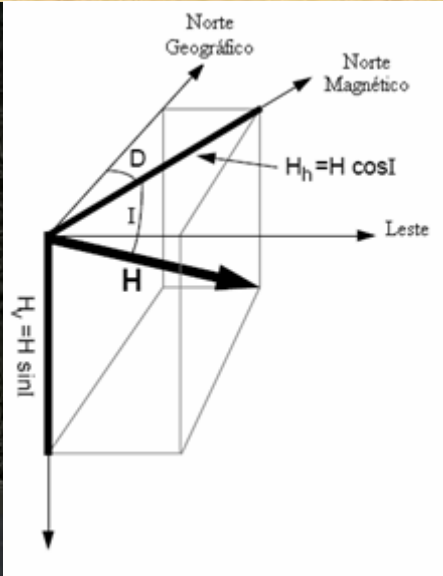
$$Q = \frac{\vec{M}_{\text{remanescente}}}{\vec{M}_{\text{induzida}}}$$



$$\tan I = 2 \tan \lambda$$



TRM

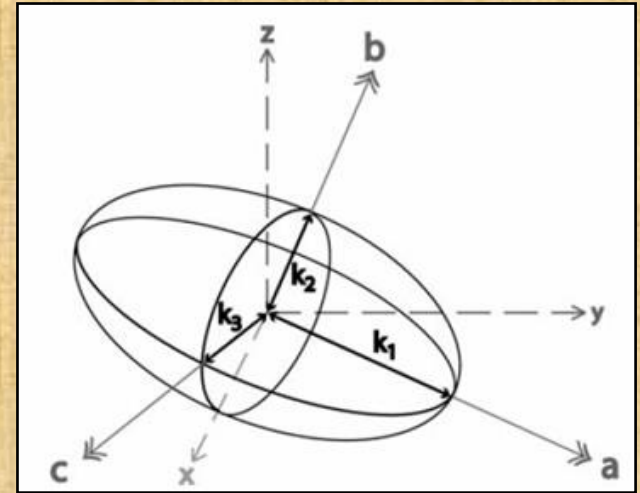


# 6. Anisotropia de Susceptibilidade Magnética (ASM)

## Princípios:

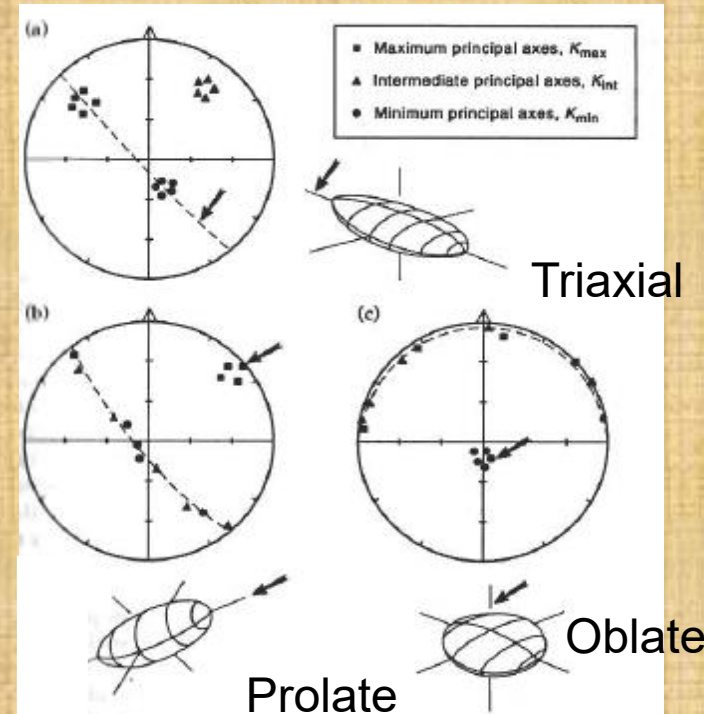
- Estudo da anisotropia magnética dos minerais (para- e ferromagnéticos):

Rochas nas quais a intensidade de magnetização depende da direção do campo aplicado são magneticamente **anisotrópicas** (a direção de magnetização pode ser desviada daquela do campo magnetizante).



## Aplicações:

- Determinação de paleocorrentes (sedimentos) e fluxos (magmas)
- Mecanismos pós-deposicionais: migração de fluidos, compactação (diagenesis)
- Tectónica: intrusão, deformação, metamorfismo
- Petrofísica: porosidade e permeabilidade



# Anisotropia de Susceptibilidade Magnética (ASM)

$$K_{mean} = \frac{K_1 + K_2 + K_3}{3}$$

**Grau de Anisotropia :**

$$P = \frac{K_1}{K_3}$$

(Nagata, 1961)

$$H = \frac{K_1 - K_3}{K_{mean}}$$

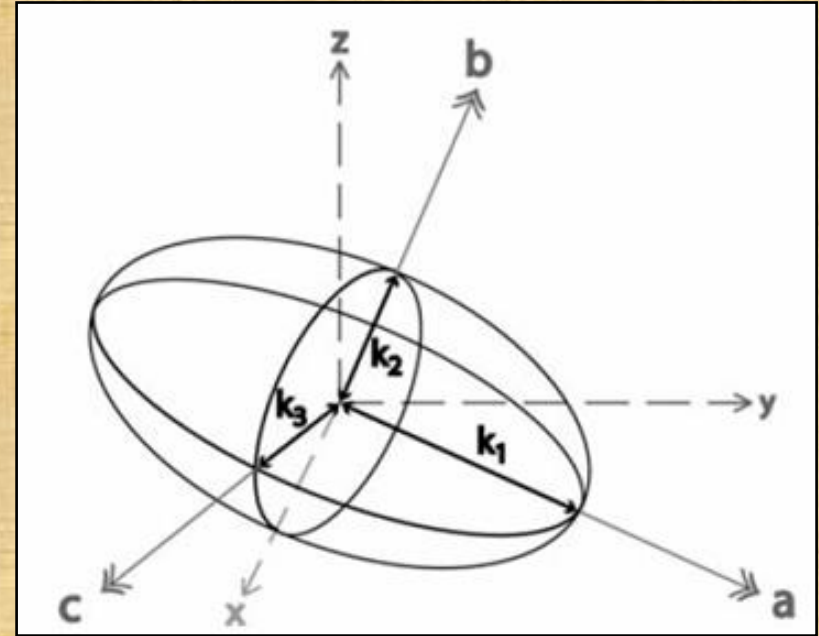
(Owens, 1974)

$$P_J = \exp \sqrt{\left\{ 2 \left[ (\eta_1 - \eta_m)^2 + (\eta_2 - \eta_m)^2 + (\eta_3 - \eta_m)^2 \right] \right\}}$$

(Jelinek, 1981)

$$\eta_i = \ln K_i$$

$$\eta_m = \frac{\eta_1 + \eta_2 + \eta_3}{3}$$



# Anisotropia de Susceptibilidade Magnética (ASM)

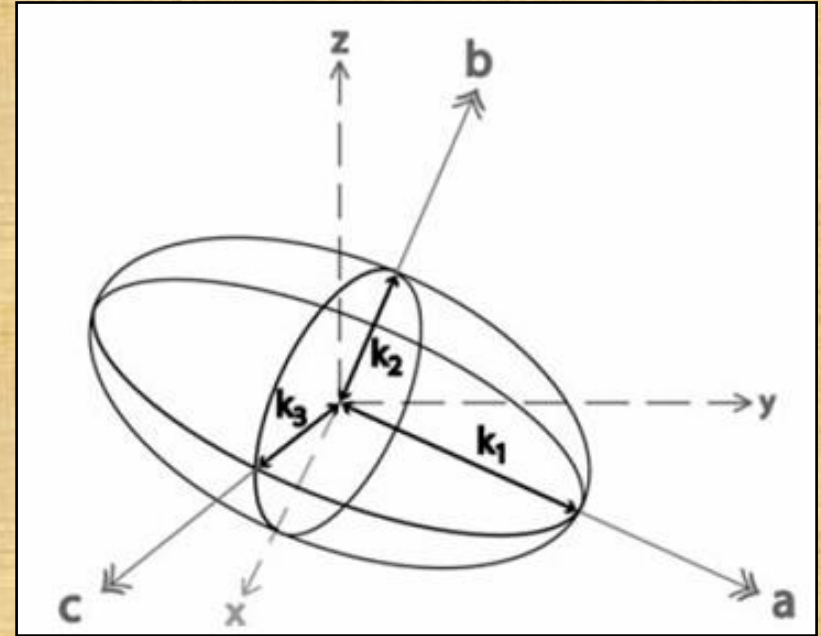
## Parâmetro de forma:

Lineação:

$$L = \frac{K_1}{K_2} \quad (\text{Balsey \& Buddington, 1960})$$

Foliação:

$$F = \frac{K_2}{K_3} \quad (\text{Stacey et al., 1962})$$



Lineação normalizada:

$$L = \frac{K_1 - K_2}{K_{mean}}$$

(Khan, 1962)

Foliação normalizada:

$$F = \frac{K_2 - K_3}{K_{mean}}$$

(Jelinek, 1981)

$$T = \left[ \frac{2 \ln(K_2 / K_3)}{\ln(K_1 / K_3)} \right] - 1$$





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# Anisotropia de Susceptibilidade Magnética (ASM)

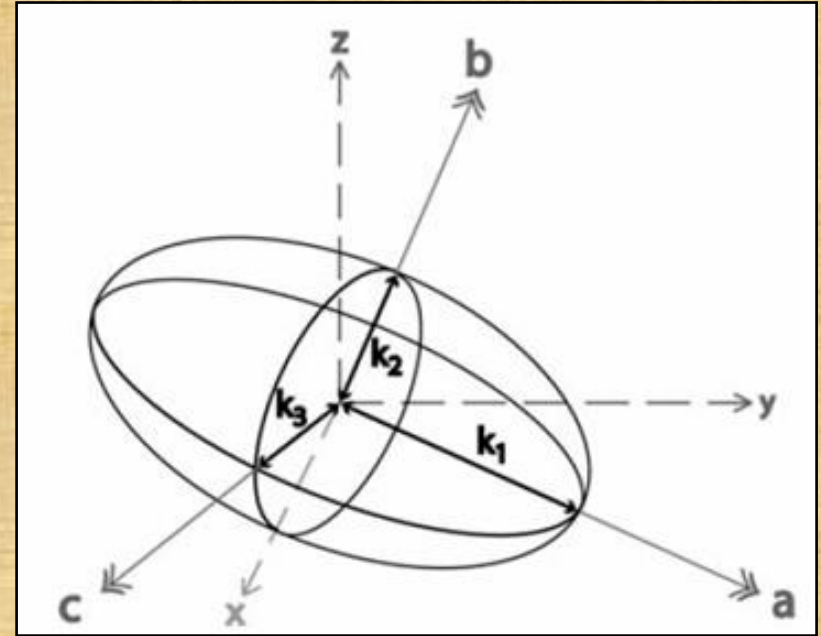
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Lineação normalizada:

$$L = \frac{K_1 - K_2}{K_{mean}}$$

(Khan, 1962)

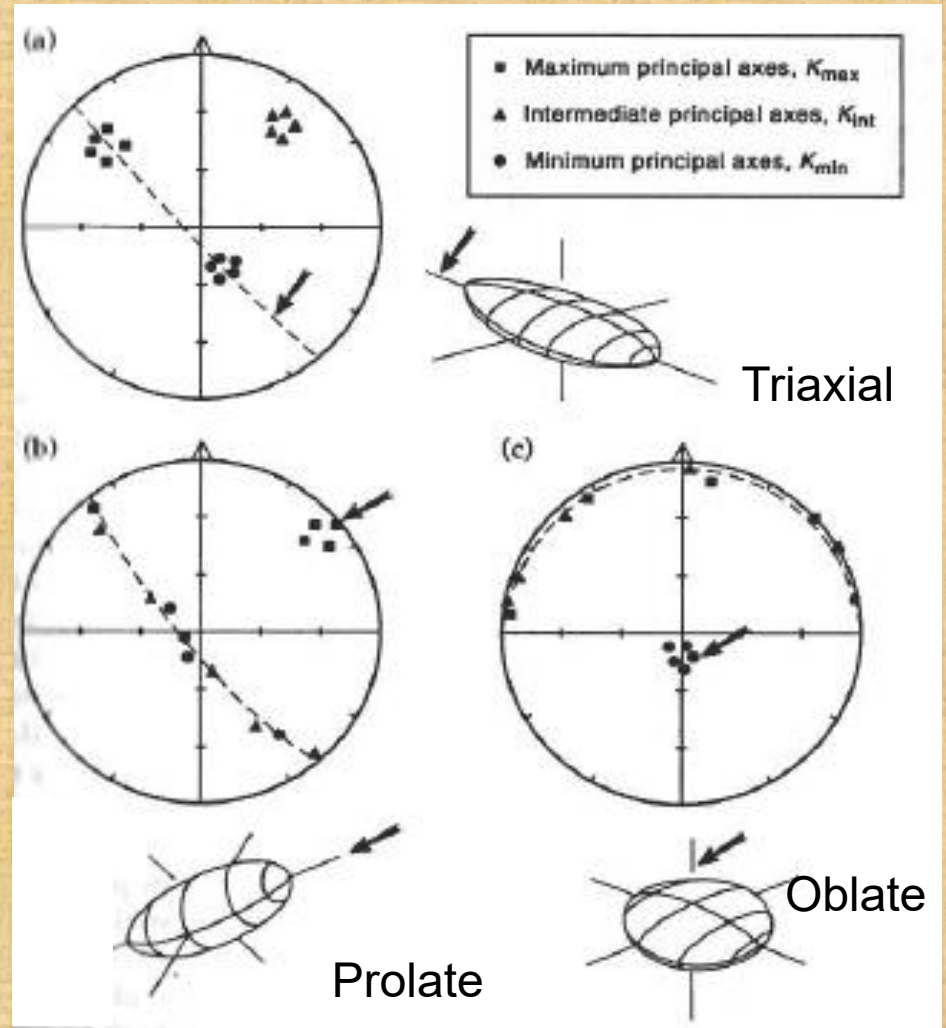
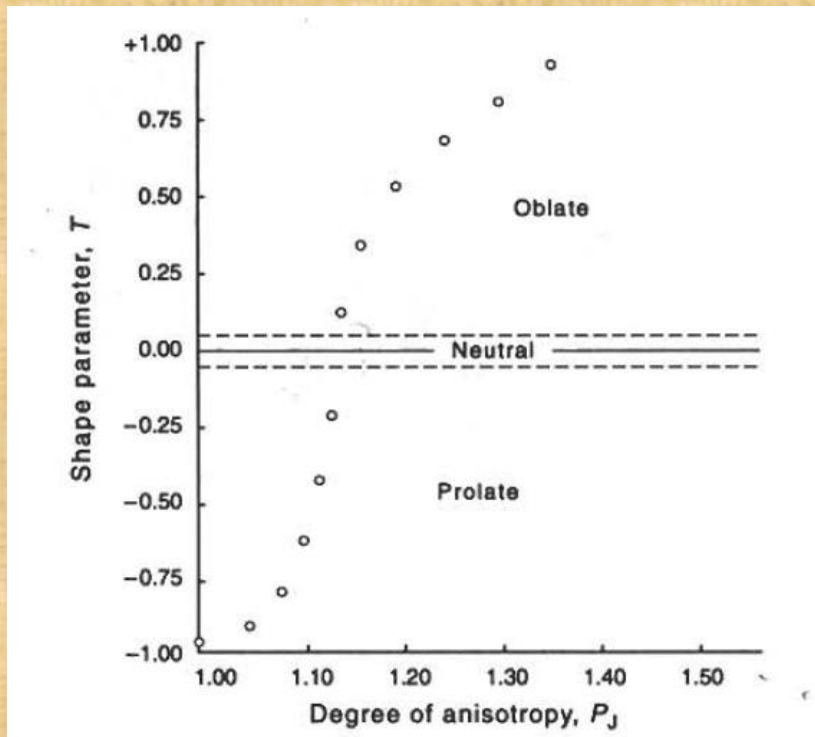
Foliação normalizada:

$$F = \frac{K_2 - K_3}{K_{mean}}$$

(Jelinek, 1981)

$$T = \left[ \frac{2 \ln(K_2 / K_3)}{\ln(K_1 / K_3)} \right] - 1$$

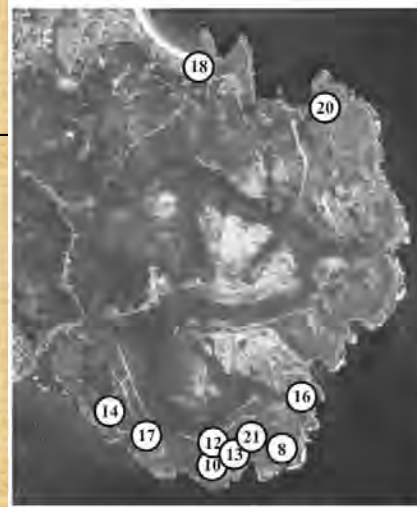
# Anisotropia de Susceptibilidade Magnética (ASM)



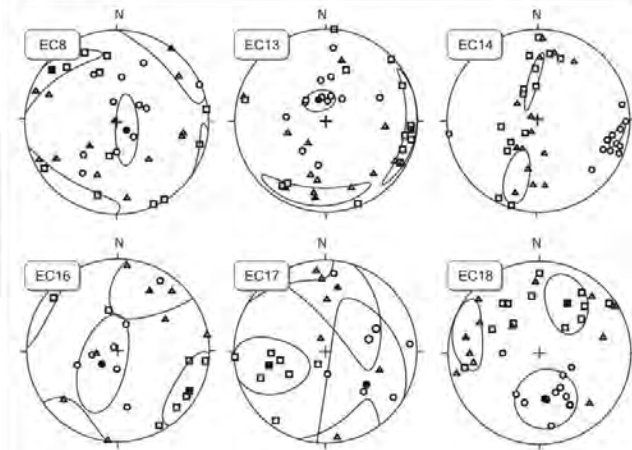


# ASM em rochas vulcânicas

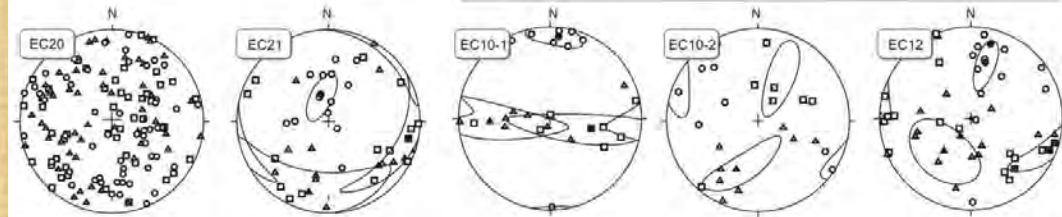
**Província Magmática do Cabo Recife, Brasil**  
(Font et al., 2009)



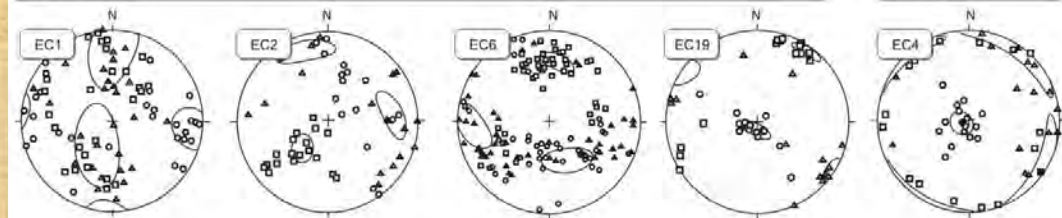
Granites



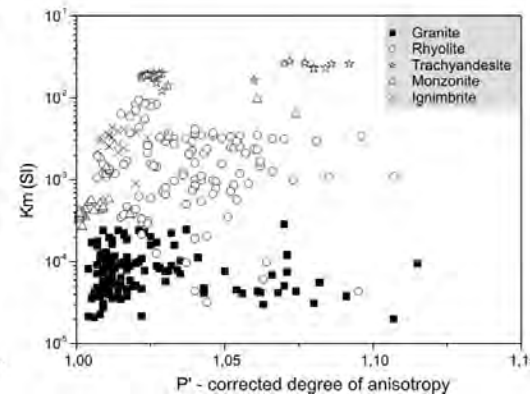
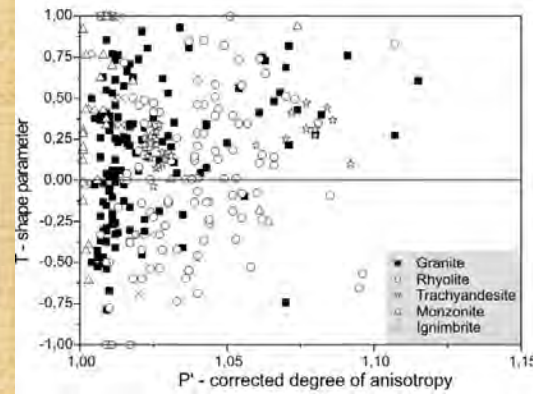
Monzonites



Rhyolites



Ignimbrite



# ASM em sedimentos

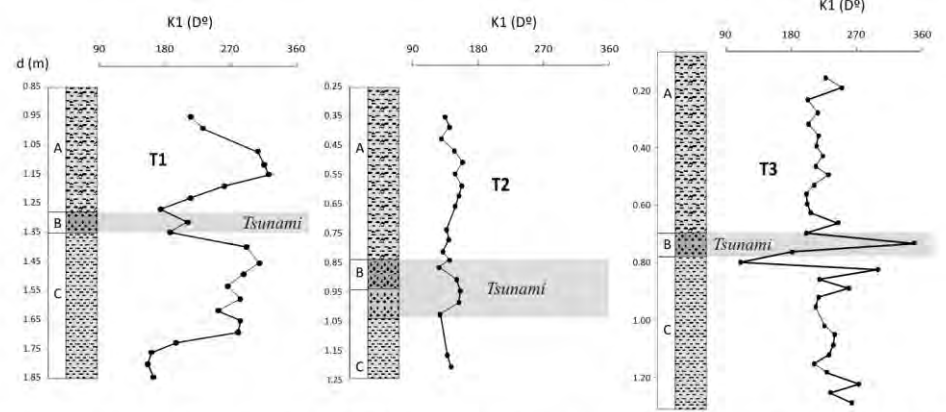


Fig. B. Distribution of  $k_1$  in T1, T2 and T3. The tsunami deposit presents a scattered distribution of the  $k_1$  in T3 that could be due to the unconsolidate aspect of our cubic samples.

## Estuário da Boca do Rio, Algarve (Font et al., in review)

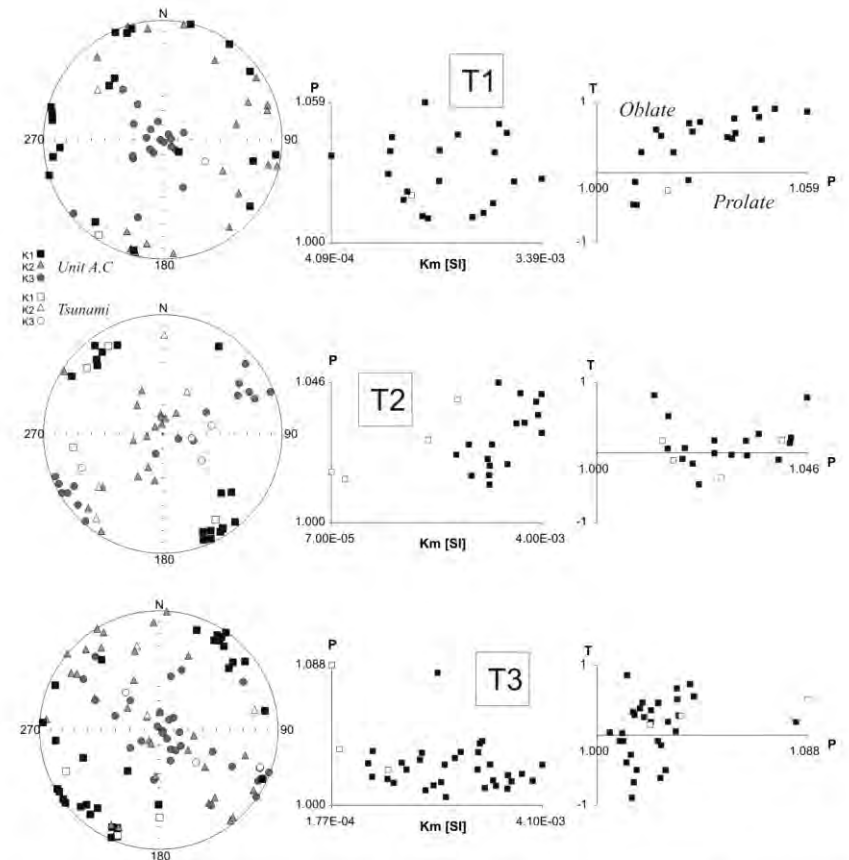


Fig. C. Stereographic representation of AMS data of T1, T2 and T3. The anisotropy parameter (P) is represented versus mean MS (Km) and the shape parameter (T).

# 7. Mineralogia magnética

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## → Caracterizar os portadores magnéticos:

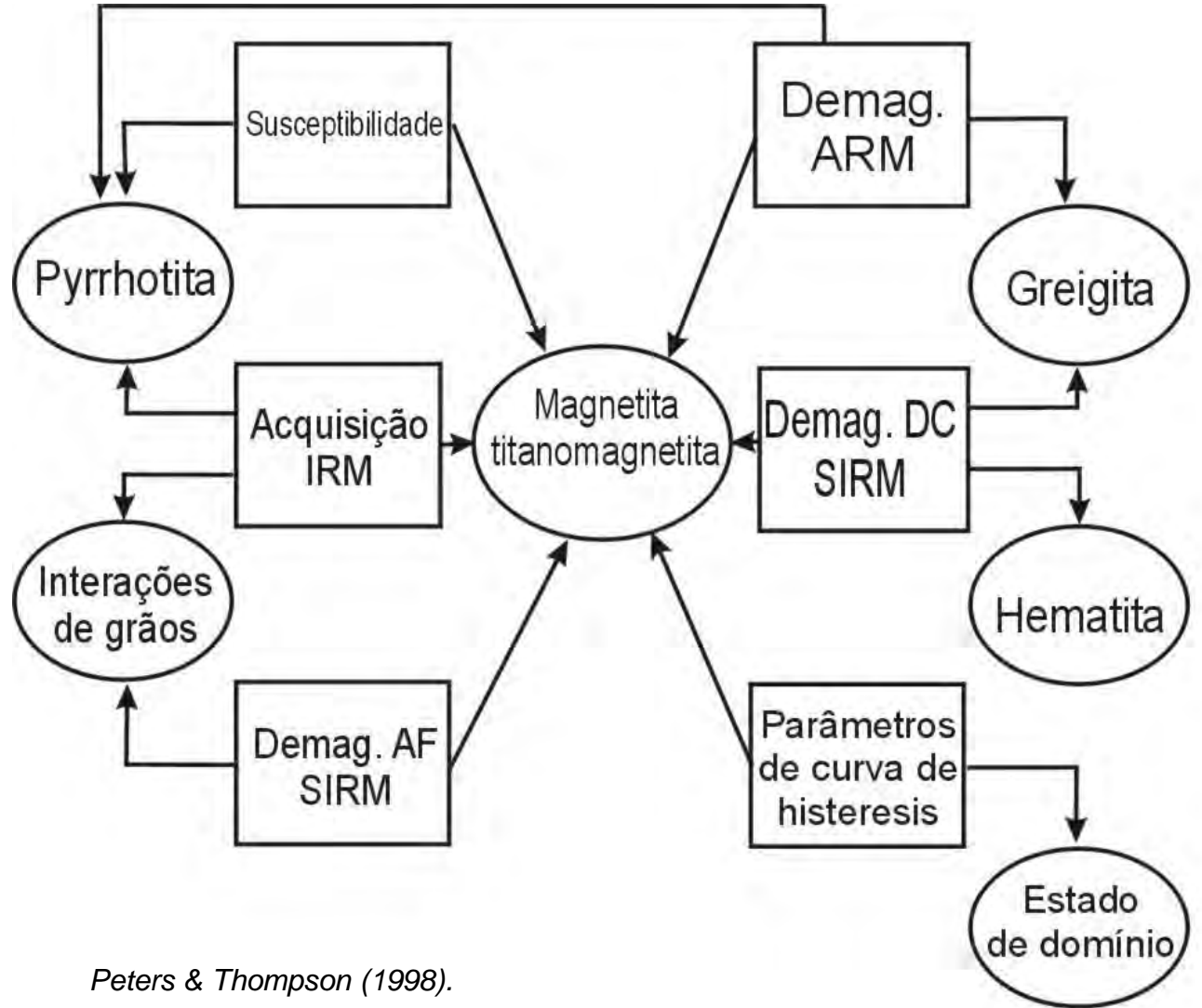
- Natureza (óxidos ou sulfatos de ferro)
- Tamanho (SD, MD ou SP)
- Origem (primária ou secundária)

## → Usando as propriedades magnéticas:

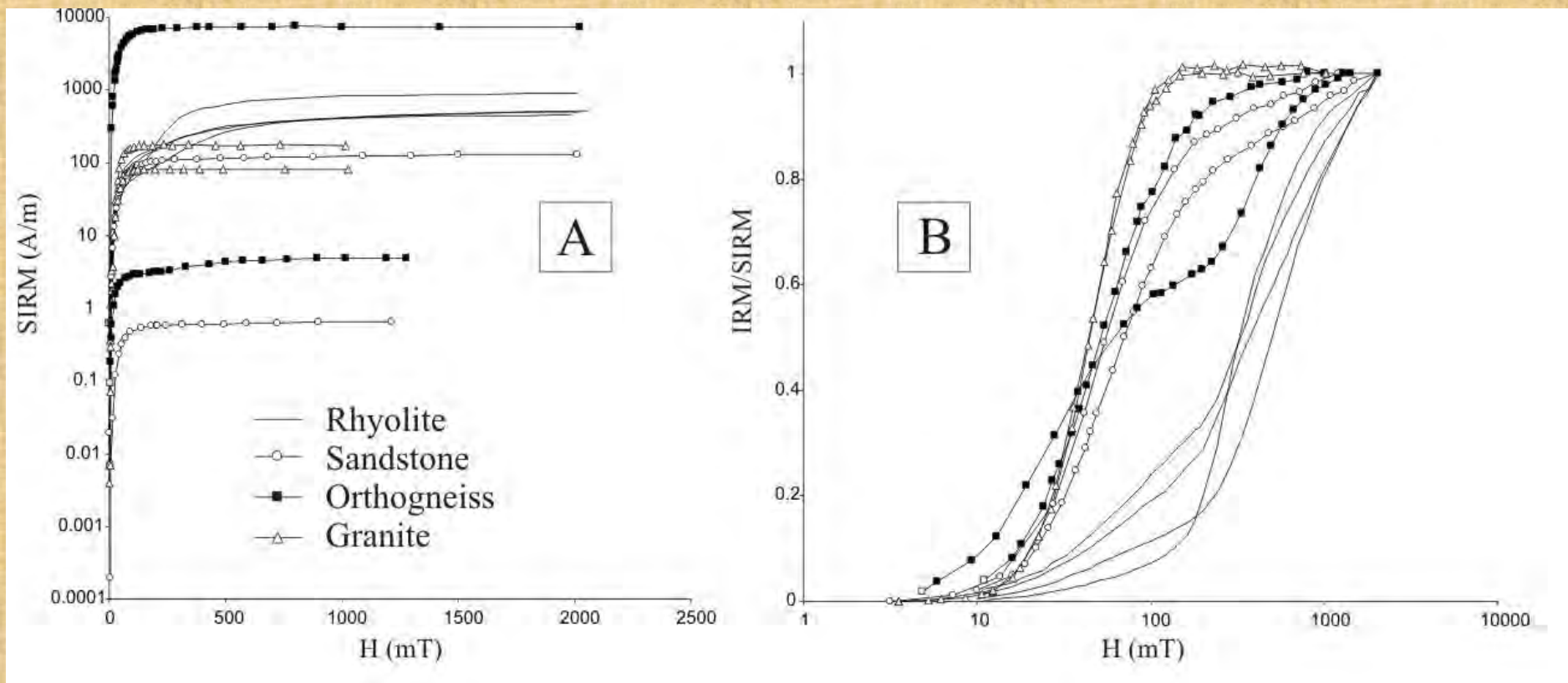
- Susceptibilidade magnética ( $k$ )
- Temperatura de Curie ( $T^{\circ}_c$ )
- Coercividade ( $H_c$ )
- SIRM (IRM a saturação)
- ARM (Anhysteretic Remanent Magnetization)

# Mineralogia magnética

→ T° ambiente

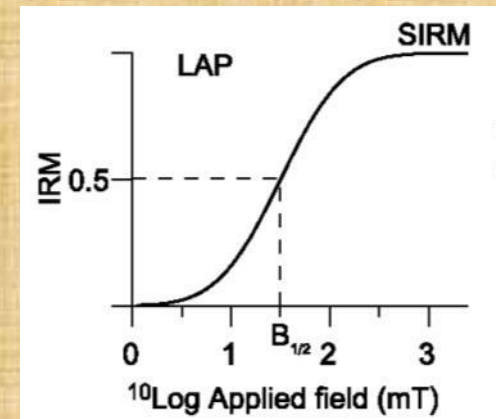


# IRM (Isothermal Remanent Magnetization)

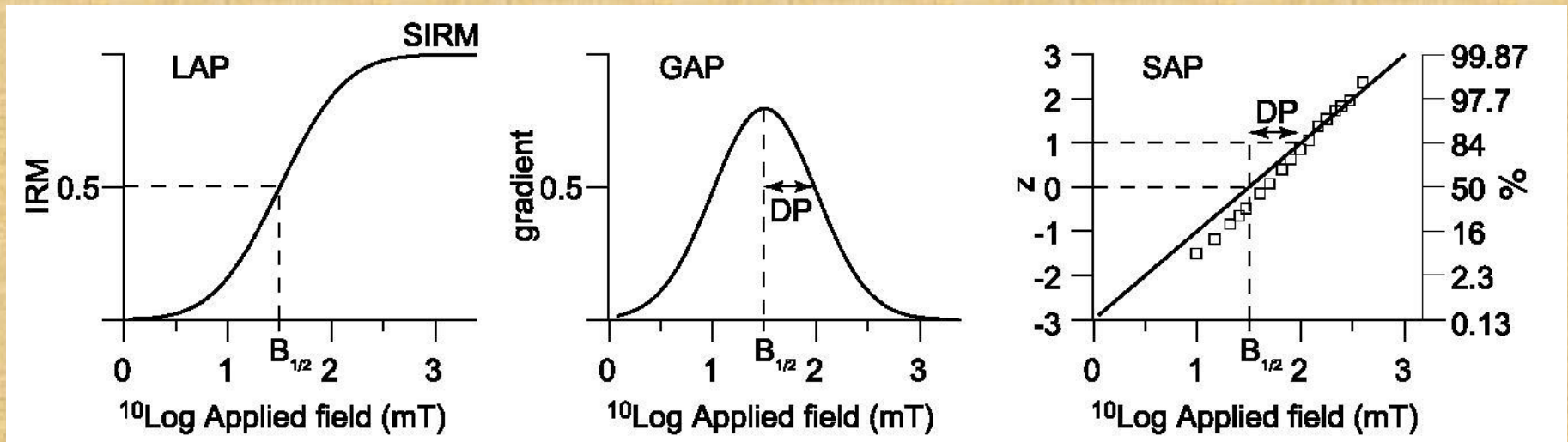


→ Concentração dos ferromagnéticos

→ Natureza (magnetite ou hematite por exemplo) a partir da **coercividade** ( $H_c \sim B_{1/2}$ )



# IRM (Isothermal Remanent Magnetization)



→ Terceiro parâmetros: DP

→ Permite caracterizar os minerais de alta coercividade mesmo sem atingir a saturação

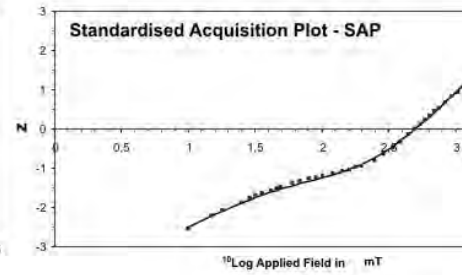
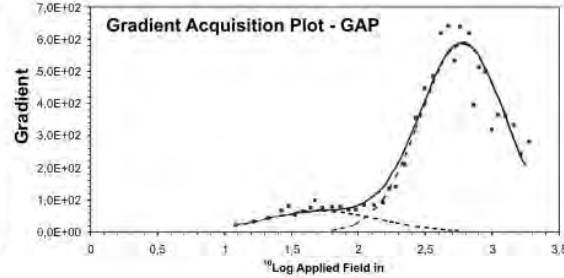
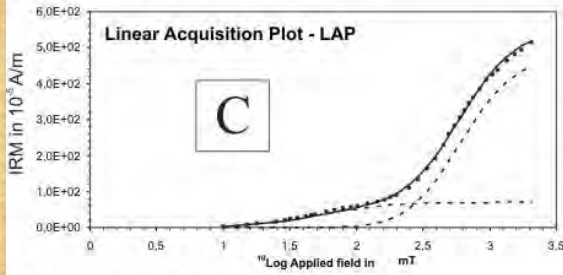
Robertson & France (1994). *Phys. Earth Planet. Int.*, 82, 223-234.

Stockhausen (1998). *Geophys. Res. Lett.*, 25, 2217-2220.

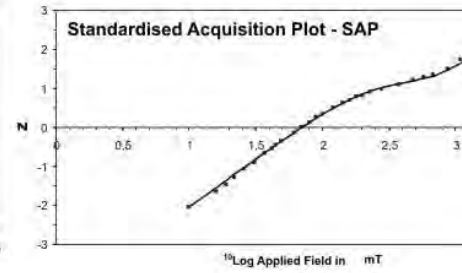
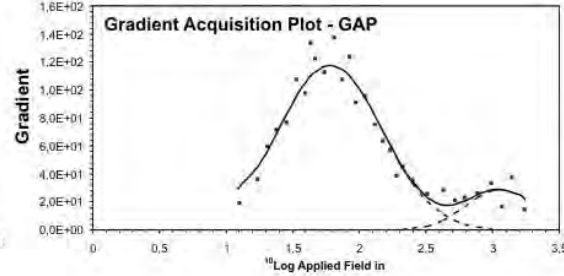
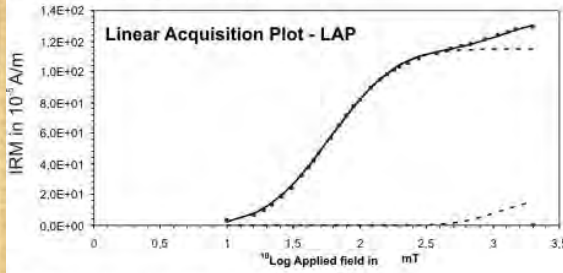
Kruiver et al. (2003). *Geophys. J. Int.*, 153, 317-332.

# IRM (Isothermal Remanent Magnetization)

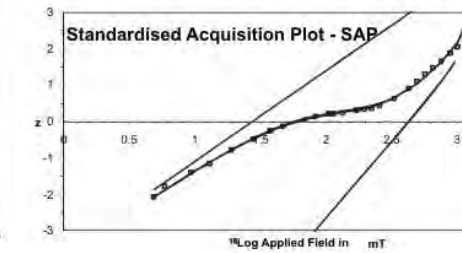
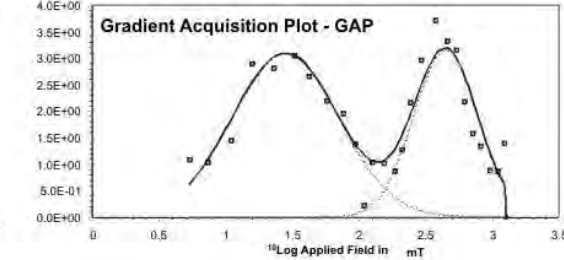
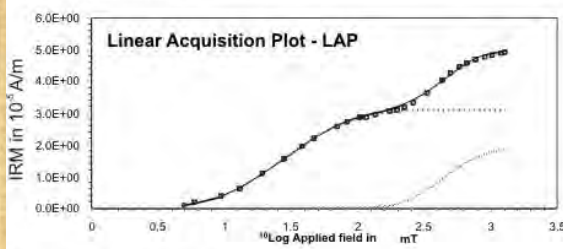
## *Rhyolites* (CP2-A1)



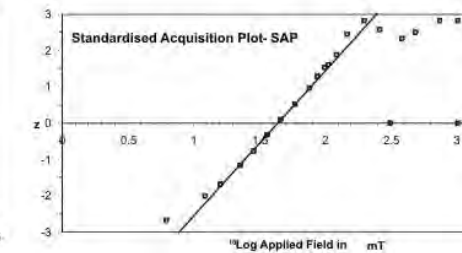
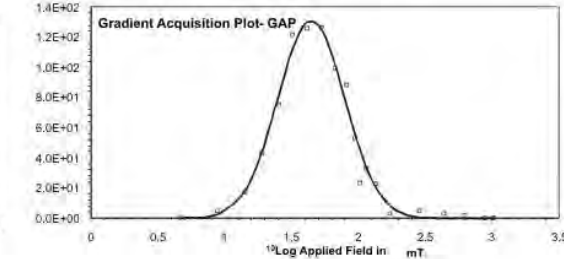
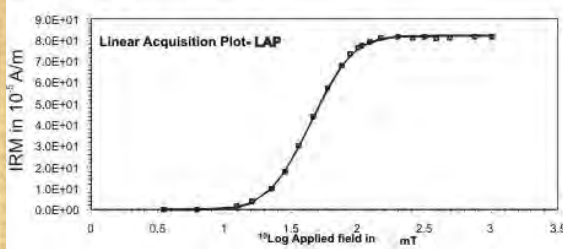
## *Sandstones* (CP9-C1)



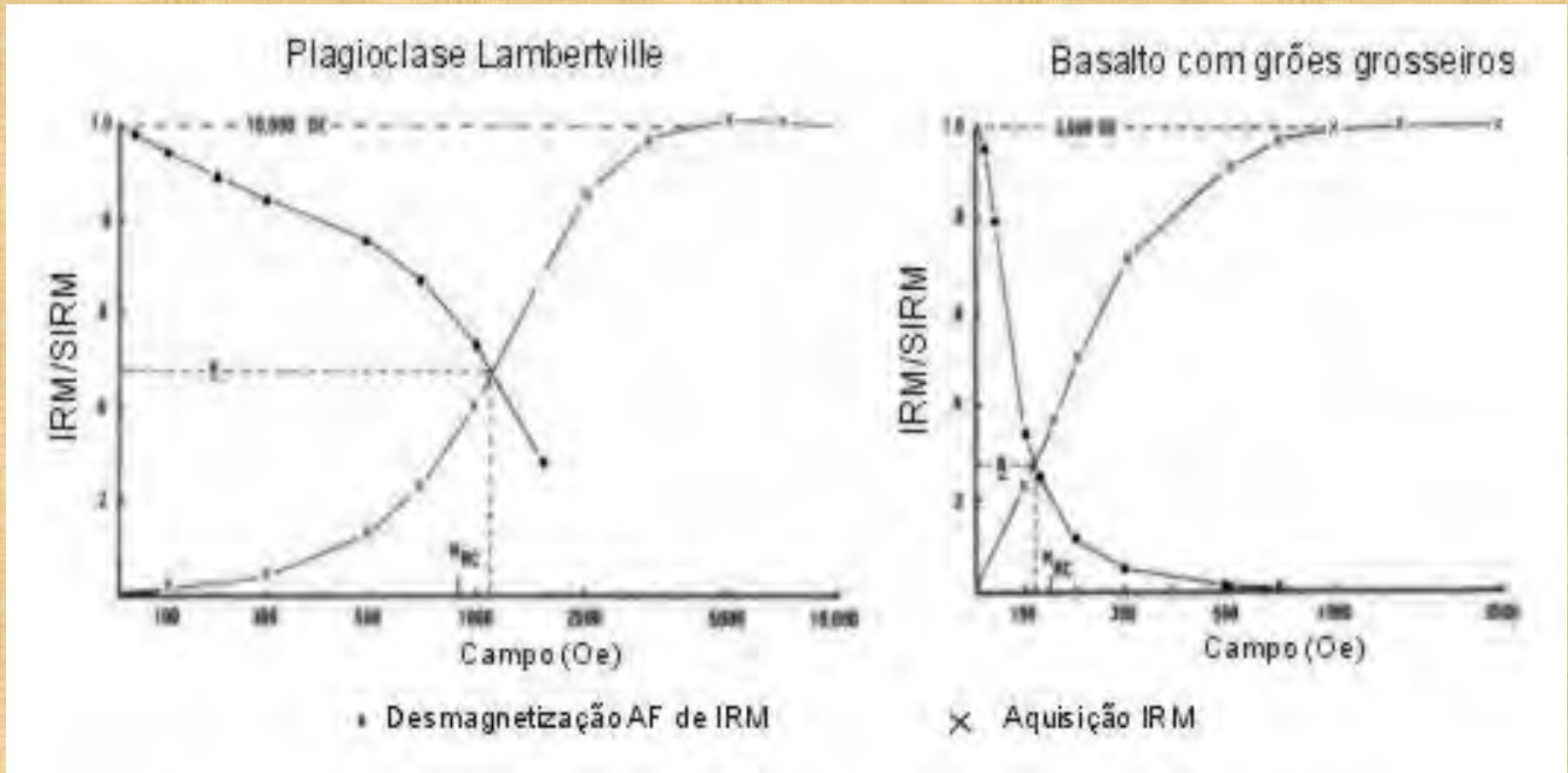
## *Orthogneiss* (CP18-A1)



## *Granites* (CP60-E2)



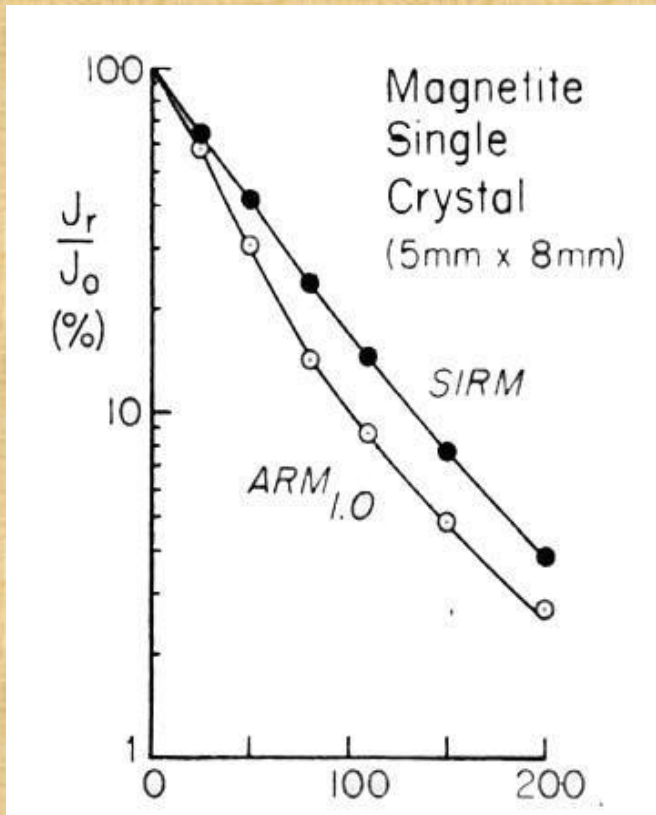
# IRM (Isothermal Remanent Magnetization)



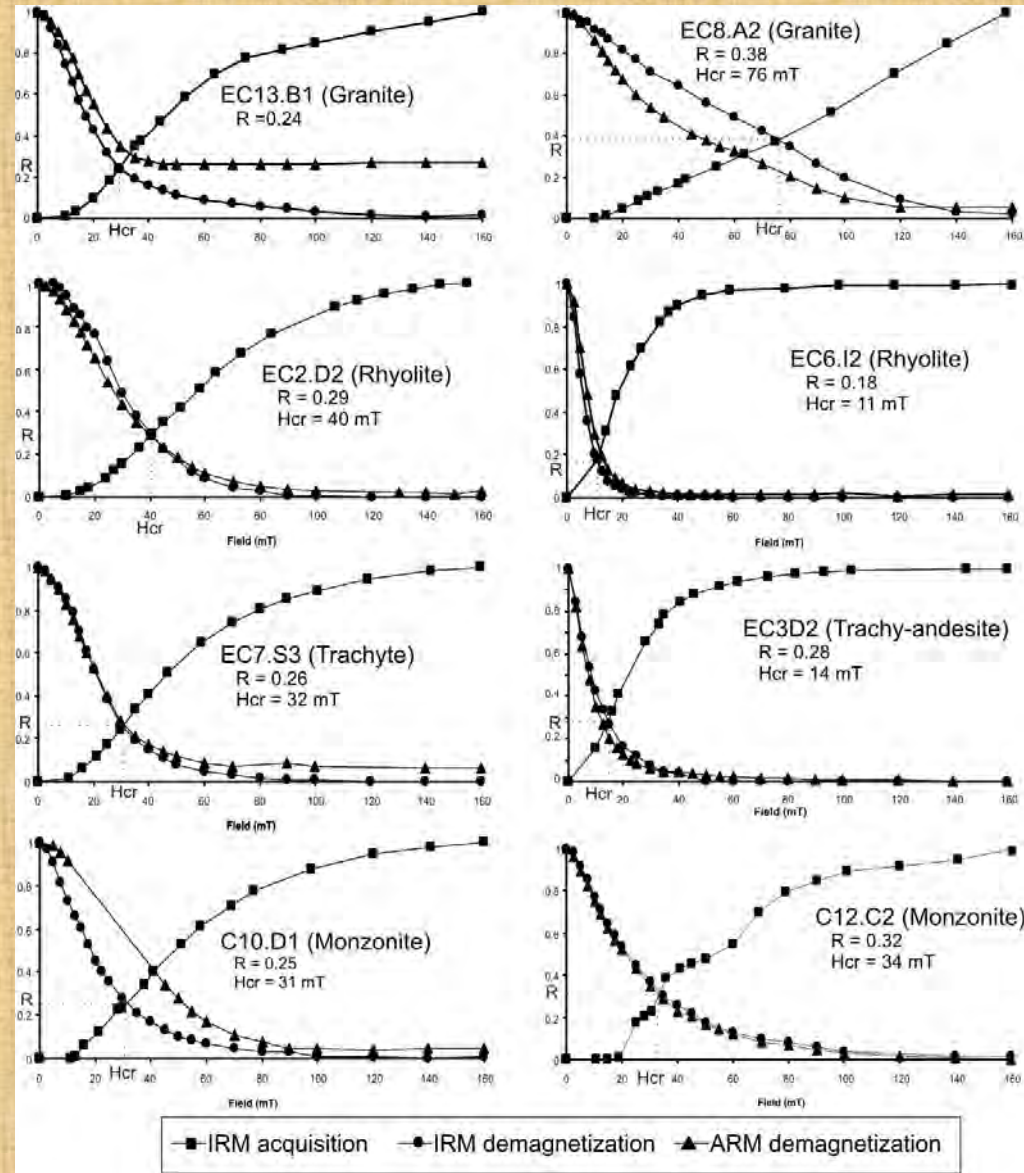
Teste de Cisowski (1981)



# ARM (Anhysteretic Remanent Magnetization)



Teste modificado de Lowrie-Fuller (1971)

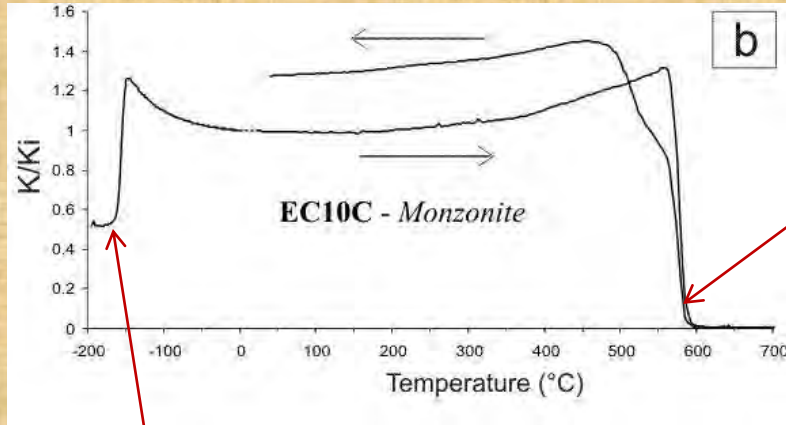


IRM = Magnetização de campo forte

ARM = Magnetização de campo fraco

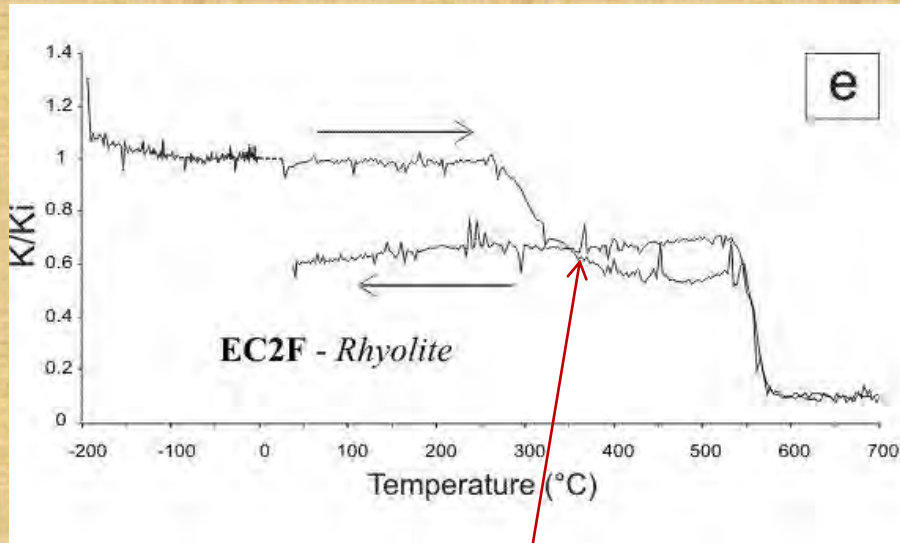
→ SD

# Curvas termomagnéticas

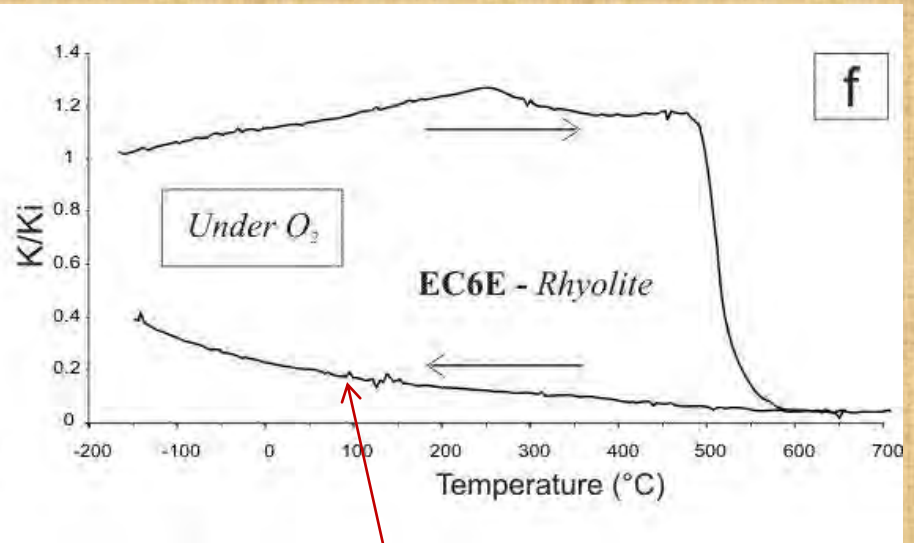


T° Curie magnetite ~580 °C

T° Verwey



T° maghemite  
destruction ~350 °C



Hematite??