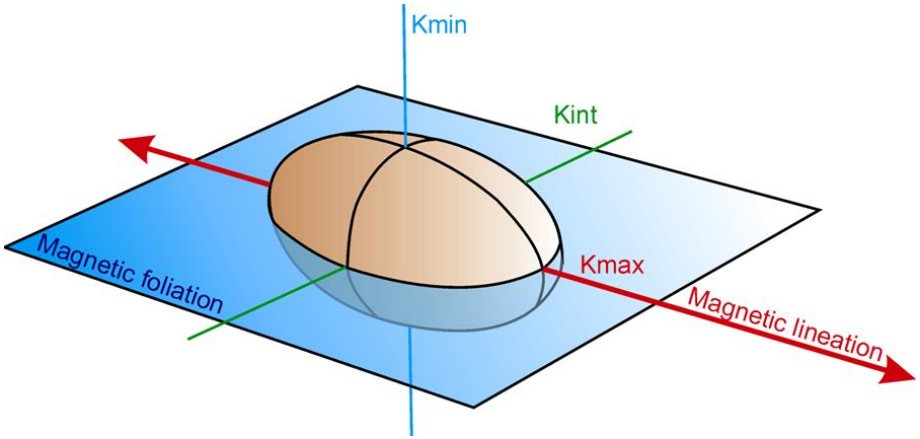
Magnetic Anisotropy of Rocks



Martin Chadima

AGICO Inc., Brno, Czech Republic (chadima@agico.cz)

Institute of Geology of the Czech Academy of Sciences, Prague, Czech Republic

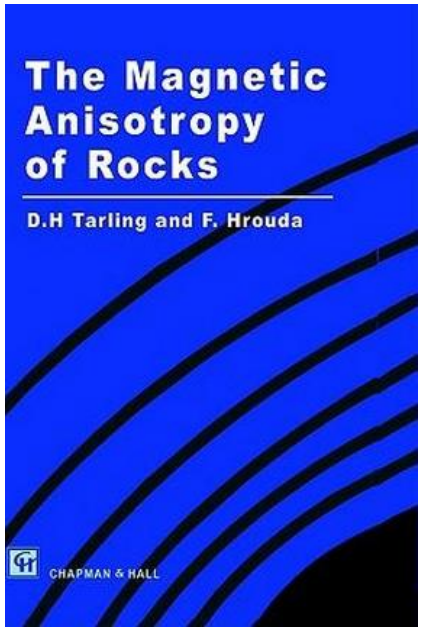
AGICO

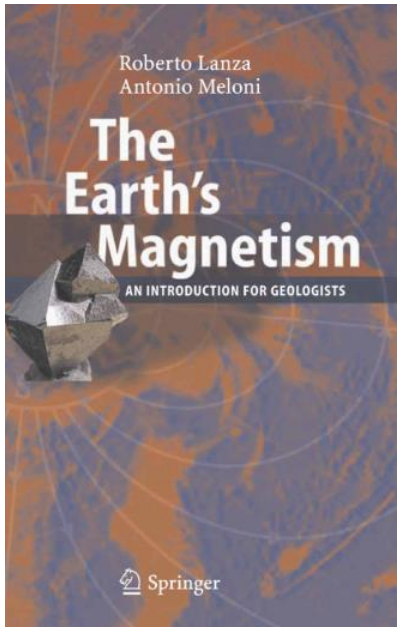
ADVANCED
GEOSCIENCE
INSTRUMENTS
COMPANY

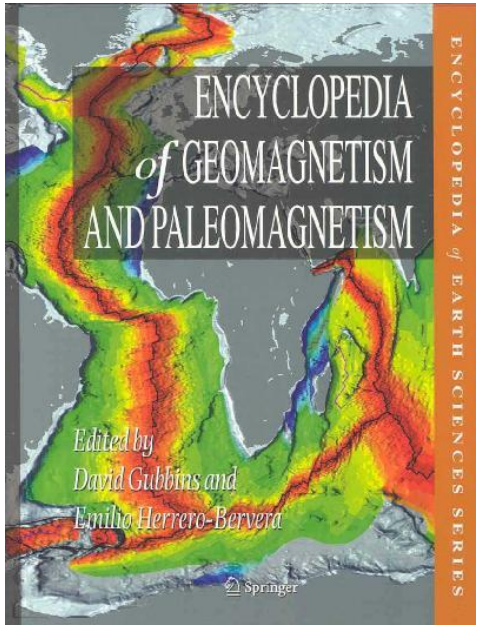
Institute of Geology of the CAS, v. v. i.

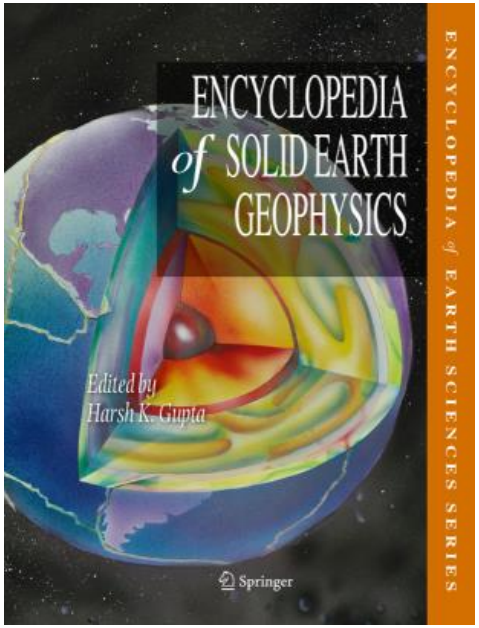
Literature

- Tarling, D.H. & Hrouda, F. 1993. The Magnetic Anisotropy of Rock. *Chapman & Hall*, 217 pp.
- Lanza, R. & Meloni, A. 2006. The Earth's Magnetism: An Introduction for Geologist. *Springer*, 278 pp. (Chapter 5).
- Hrouda, F. 2007. Magnetic Susceptibility, Anisotropy. Encyclopedia of Geomagnetism and Paleomagnetism. *Springer*. 546-560.
- Sagnotti, L. 2009. Magnetic anisotropy. Encyclopedia of Solid Earth Geophysics. *Springer*. 717-729.
- Tauxe, L. 2013. Lectures in paleomagnetism. http://magician.ucsd.edu/Essentials_2/WebBook2ch13.html#x15-15500013.
- Hrouda, F., 1982. Magnetic anisotropy of rocks and its application in geology and geophysics. *Geophysical Surveys*, 5, 37–82.
- Borradaile, G. J. & Henry, B. 1997. Tectonic applications of magnetic susceptibility and its anisotropy. *Earth Science Reviews*, 42, 49–93.
- Jackson,M.J. & Tauxe, L. 1991. Anisotropy of magnetic susceptibility and remanence: developments in the characterization of tectonic, sedimentary, and igneous fabric. *Reviews of Geophysics*, 29, 371–376.
- Rochette, P., Jackson, M. J. & Aubourg, C. 1992. Rock magnetism and the interpretation of anisotropy of magnetic susceptibility. *Reviews of Geophysics*, 30, 209–226.









Agenda

1. Definition and application in geology
2. Magnetic anisotropy of minerals
3. Magnetic fabric vs. texture of rocks
4. Magnetic fabric of sedimentary, deformed, and metamorphosed rocks
5. Magnetic fabric of igneous rocks
6. Sampling, measurement and data processing

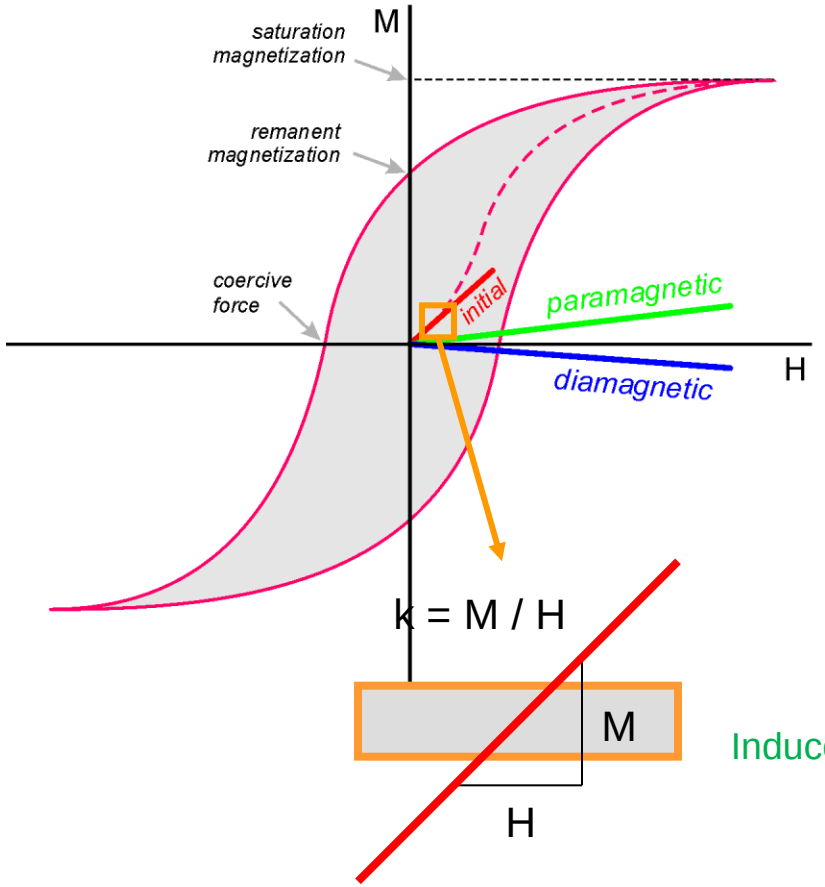
Agenda

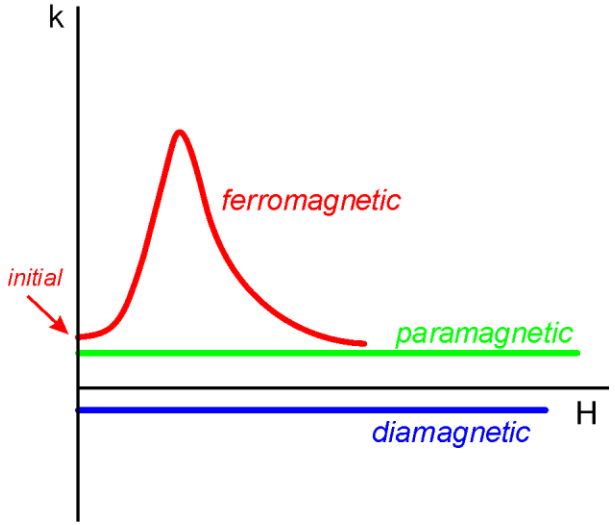
1. Definition and application in geology
2. Magnetic anisotropy of minerals
3. Magnetic fabric vs. texture of rocks
4. Magnetic fabric of sedimentary, deformed, and metamorphosed rocks
5. Magnetic fabric of igneous rocks
6. Sampling, measurement and data processing

Definition

- Magnetic anisotropy is a directional variability of a certain magnetic property, usually **A**nisotropy of **M**agnetic **S**usceptibility (AMS)
- Tool to study rock texture (Petrofabric)
- Compared to the other methods of fabric analysis (U-stage, X-ray texture goniometry, neutron texture goniometry, EBSD), AMS is fast, cheap, high-resolution, non-destructive.
- It can be applied to many samples covering whole outcrops, drill cores, or geological units.
- Application in structural geology and tectonics, volcanology, sedimentology, and paleomagnetism.

- Magnetic susceptibility is the ability to acquire induced magnetization, i.e. ability to get magnetized





$$\mathbf{M} = \mathbf{Mi} + \mathbf{Mr}$$

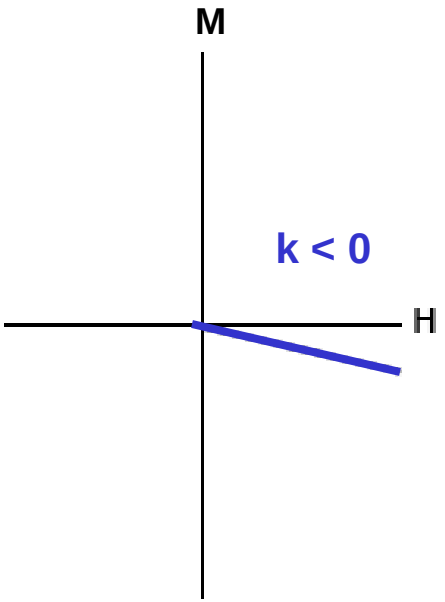
Induced magnetization — Remanent magnetization

$$\mathbf{Mi} = k \times \mathbf{H}$$

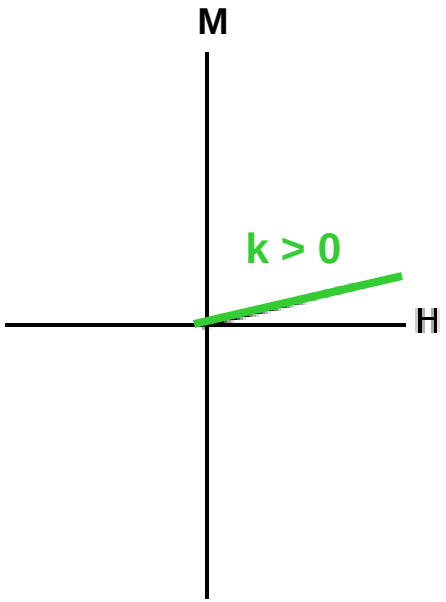
Magnetic susceptibility

$$k = \mathbf{Mi} / \mathbf{H}$$

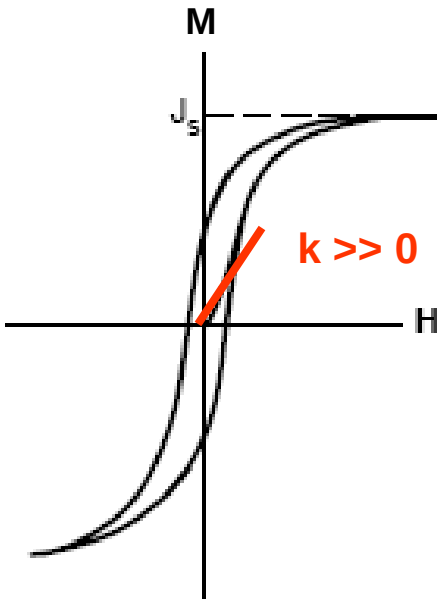
Diamagnetism



Paramagnetism



Ferromagnetism (s.l.)

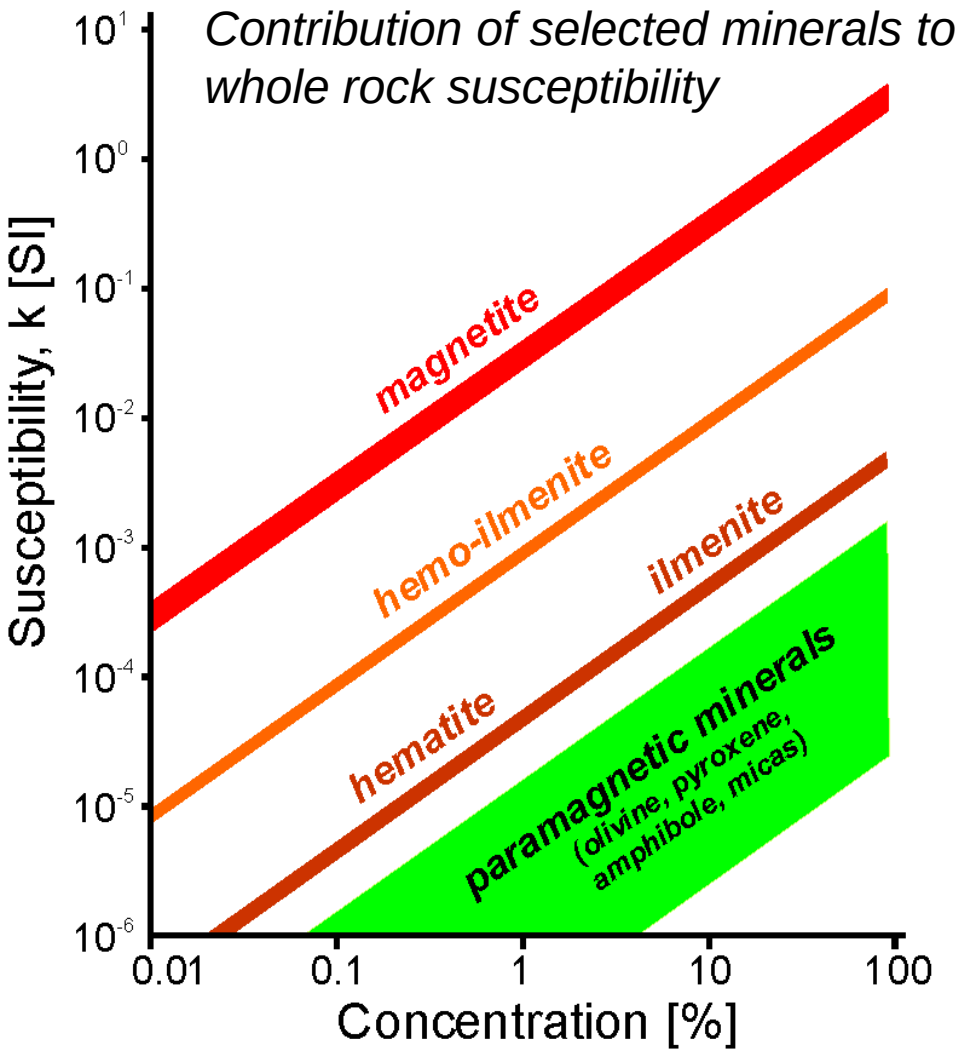


Induced magnetization antiparallel to the external field	Induced magnetization parallel to the external field	Complex relationship between external field and induced magnetization: hysteresis curve
Magnetic susceptibility relatively **low** and **negative**	Magnetic susceptibility relatively **low** and **positive**	Magnetic susceptibiliy relatively **high**
No remanence	**No remanence**	**Remanent magnetization**
quartz *calcite* *aragonite*	*pyroxene* *hornblende* *olivine* *micas*	*iron* *magnetite* *hematite* *pyrrhotite*

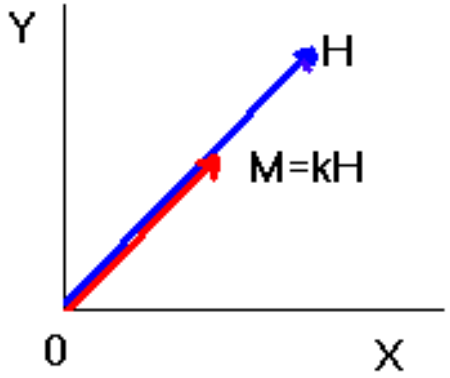
- Magnetic susceptibility is the ability to acquire induced magnetization, i.e. ability to get magnetized

$$\mathbf{M} = k \times \mathbf{H}$$

$$k = M / \mathbf{H}$$



Anisotropy magnetic susceptibility (AMS)



Magnetically isotropic material

$M_1 = k\ H_1$

$M_2 = k\ H_2$

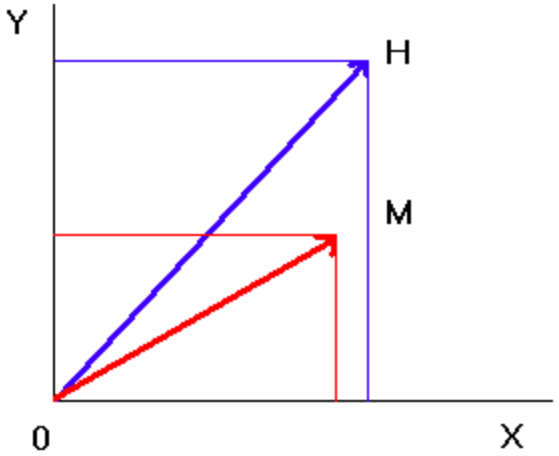
$M_3 = k\ H_3$

Magnetization of anisotropic materials

$M_1 = k_{11}\ H_1 + k_{12}\ H_2 + k_{13}\ H_3$

$M_2 = k_{21}\ H_1 + k_{22}\ H_2 + k_{23}\ H_3$

$M_3 = k_{31}\ H_1 + k_{32}\ H_2 + k_{33}\ H_3$



Matrix notation

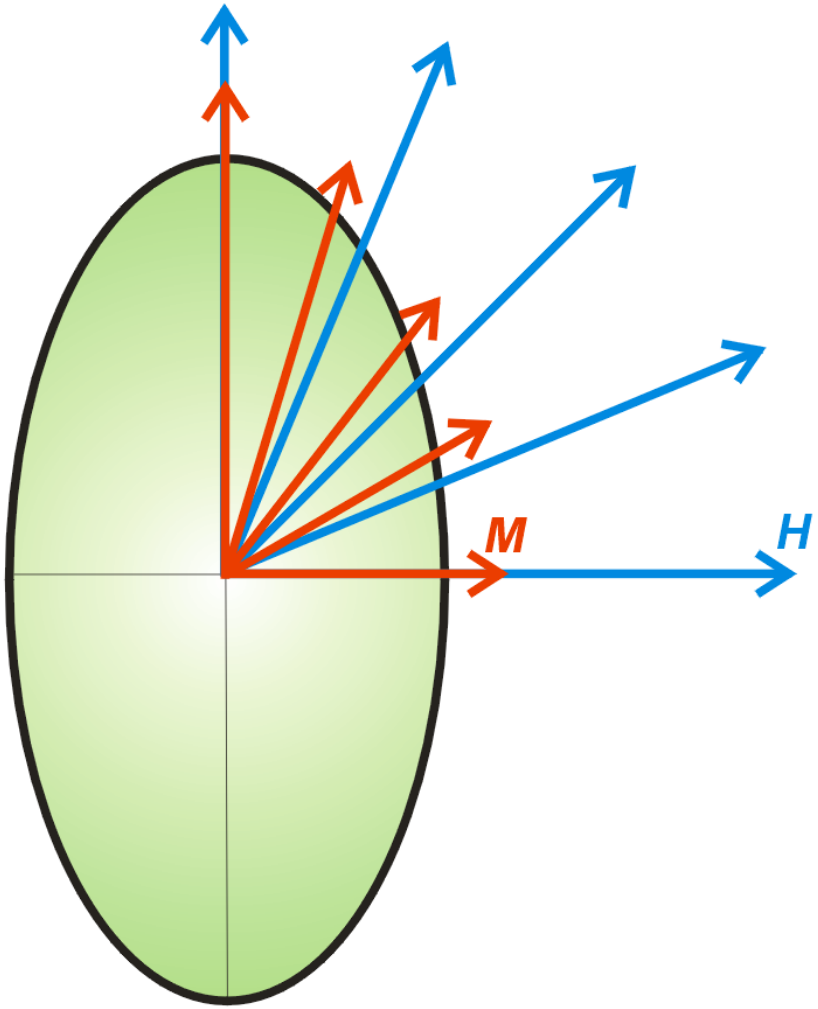
Vector of field intensity

$$\begin{vmatrix} M_1 \\ M_2 \\ M_3 \end{vmatrix} = \begin{vmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{vmatrix} \begin{vmatrix} H_1 \\ H_2 \\ H_3 \end{vmatrix}$$

Vector of magnetization

Susceptibility tensor

Anisotropic magnetizing ellipsoidal grain

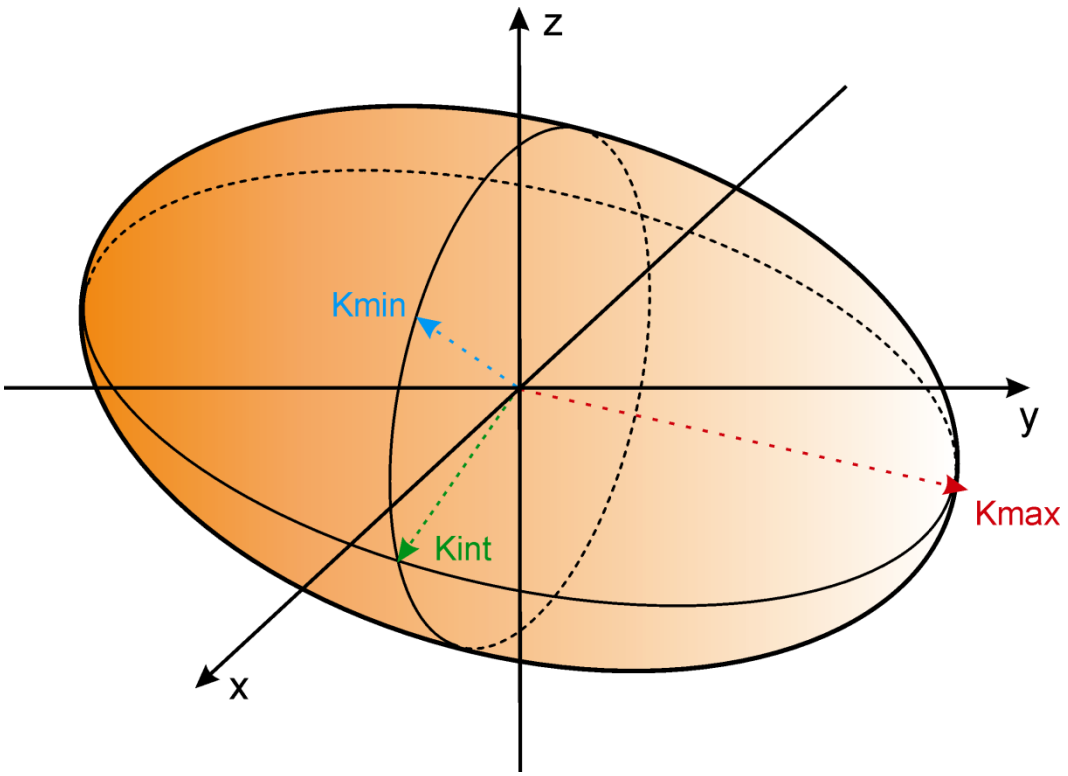


- If one magnetizes an ellipsoidal grain of magnetite and the magnetizing field is parallel to ellipsoid axes, the magnetization is parallel to the field.
- Otherwise, the magnetization deflects from the field.
- The relationship between field and magnetization is described by the susceptibility tensor.

$$\mathbf{M} = k \times \mathbf{H}$$

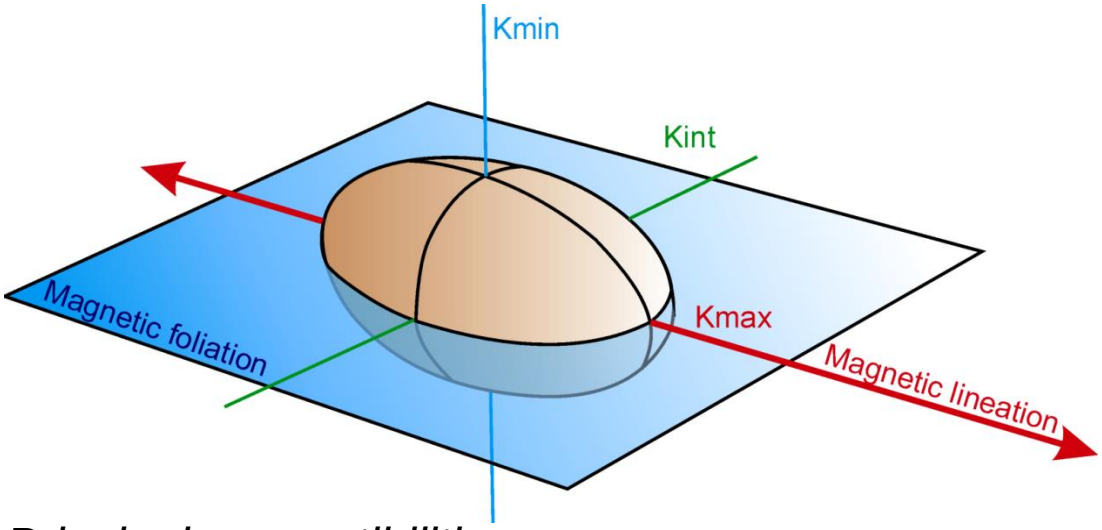
Ellipsoid as geometrical visualization of tensor

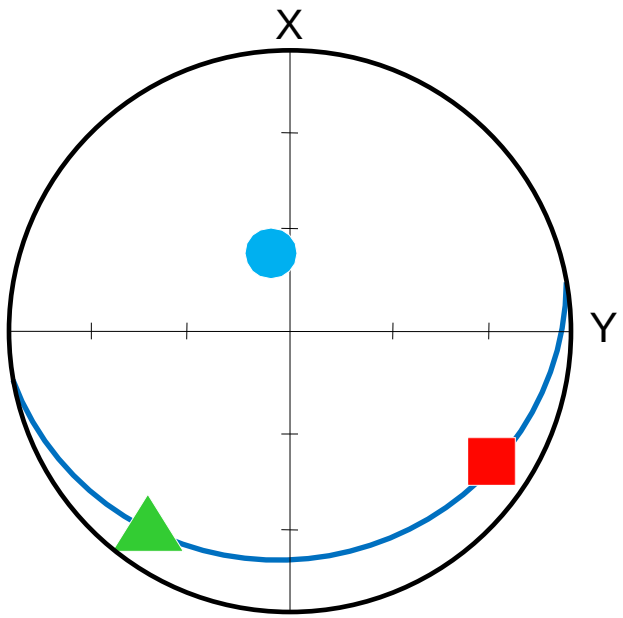
$$\begin{vmatrix} M_1 \\ M_2 \\ M_3 \end{vmatrix} = \begin{vmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{vmatrix} \begin{vmatrix} H_1 \\ H_2 \\ H_3 \end{vmatrix}$$



Magnetic fabric

Rock fabric defined from magnetic anisotropy





Principal susceptibilities

$k_1 \geq k_2 \geq k_3$

Mean susceptibility

$k_m = (k_1 + k_2 + k_3) / 3$

Degree of anisotropy

$P = k_1 / k_3$

Shape parameter

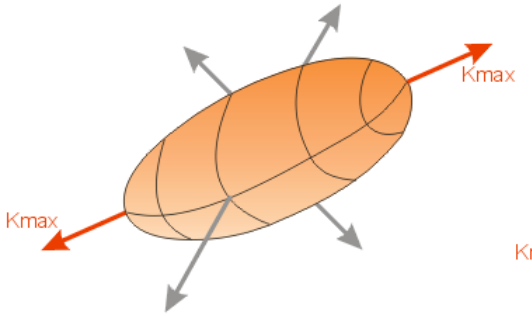
$T = (2\eta_2 - \eta_1 - \eta_3) / (\eta_1 - \eta_3)$

where $\eta_1 = \ln k_1$, $\eta_2 = \ln k_2$, $\eta_3 = \ln k_3$

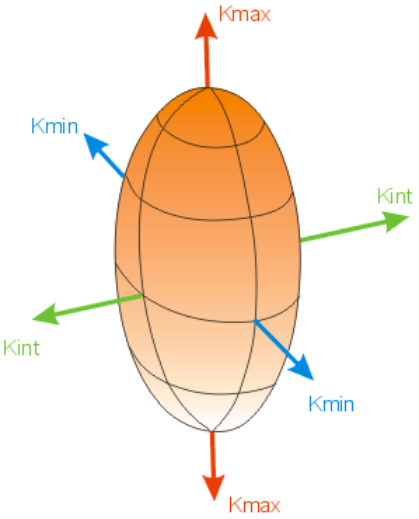
$+1 > T > 0$	oblate (planar) fabric
$-1 < T < 0$	prolate (linear) fabric

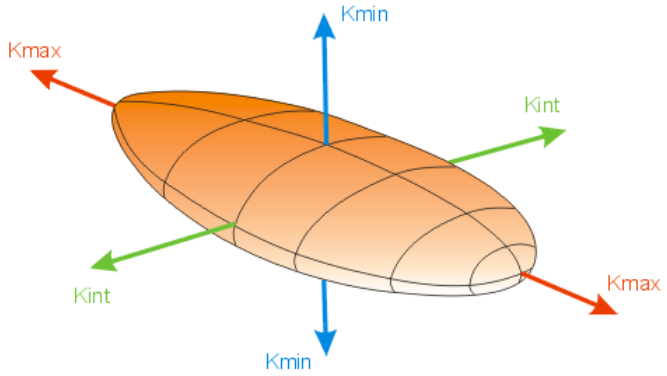
Shapes of anisotropy ellipsoids

Rotational prolate

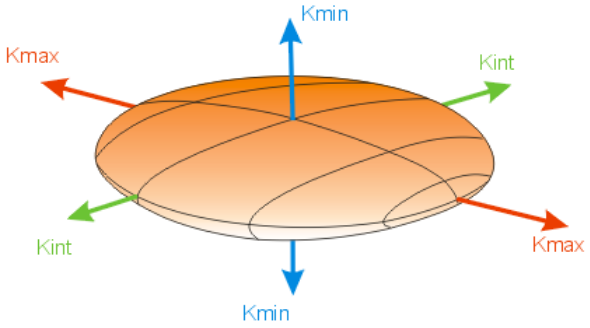


Triaxial prolate

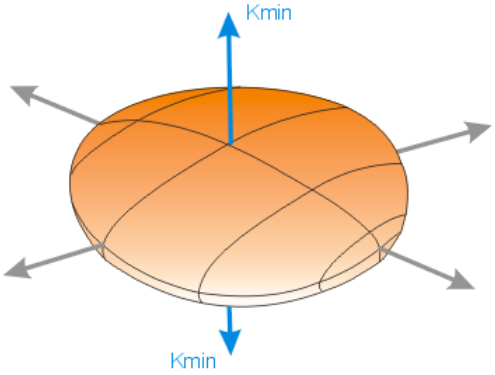




Neutral



Triaxial oblate



Rotational oblate

Quantitative parametrs of anisotropy

$k_1 \geq k_2 \geq k_3$ ← *principal susceptibilities*

$k_m = (k_1 + k_2 + k_3) / 3$ ← *mean susceptibility*

$P = k_1 / k_3$ ← *degree of anisotropy*

$L = k_1 / k_2$ ← *degree of magnetic lineation*

$F = k_2 / k_3$ ← *degree of magnetic foliation*

$T = (2\eta_2 - \eta_1 - \eta_3) / (\eta_1 - \eta_3)$ ← *shape parameter*

where $\eta_1 = \ln k_1$, $\eta_2 = \ln k_2$, $\eta_3 = \ln k_3$

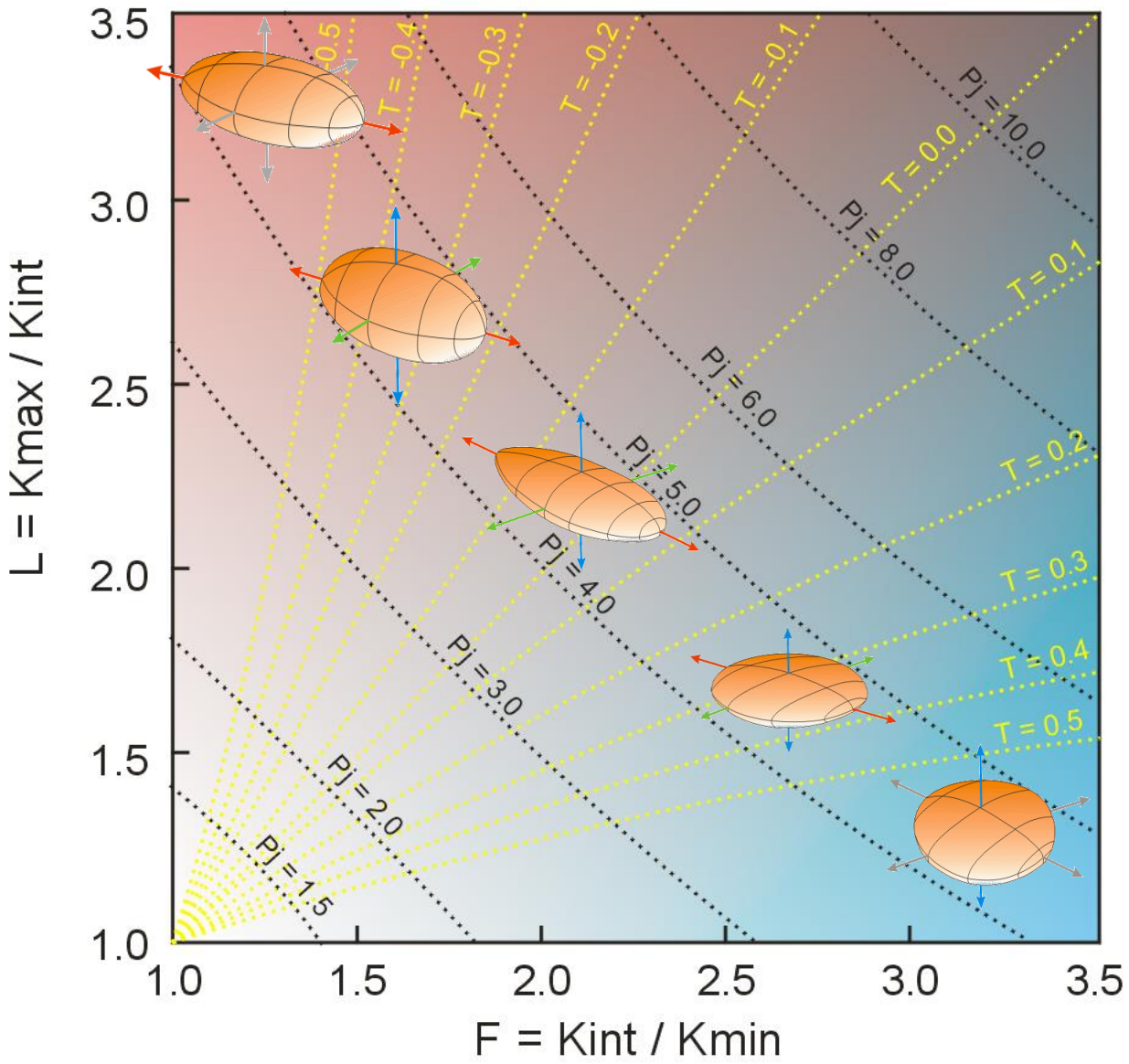
$+1 > T > 0$ *oblate (planar) ellipsoid*

$-1 < T < 0$ *prolate (linear) ellipsoid*

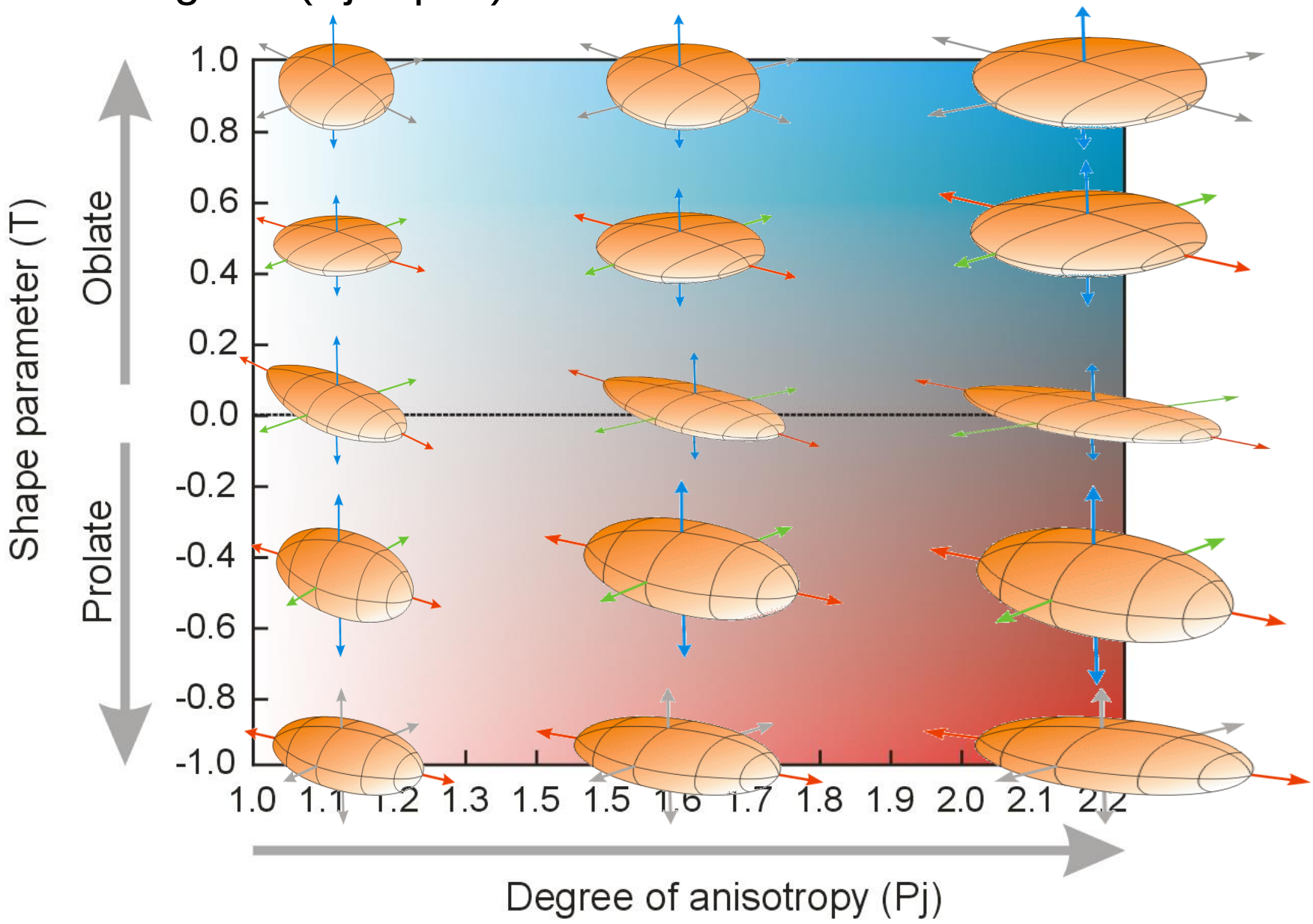
$Pj = P^a$ ← *corrected degree of anisotropy*

$a = \sqrt{(1+T^2 / 3)}$

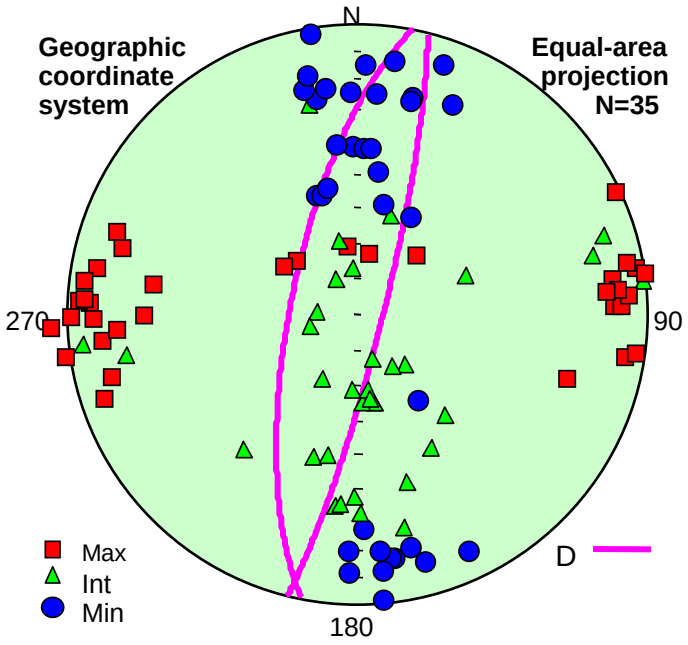
Flinn diagram (L-F plot)



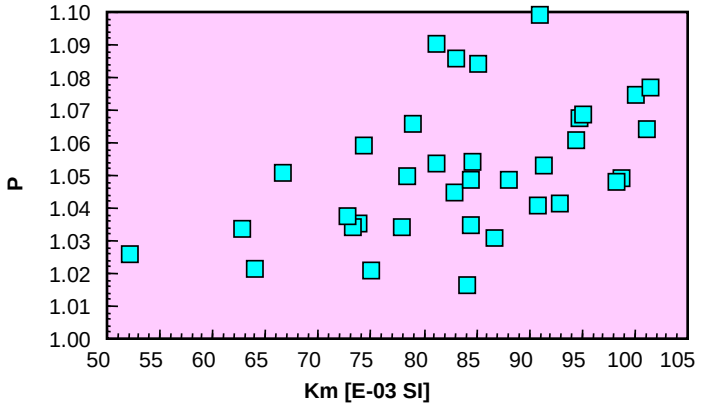
Jelinek diagram (Pj-T plot)



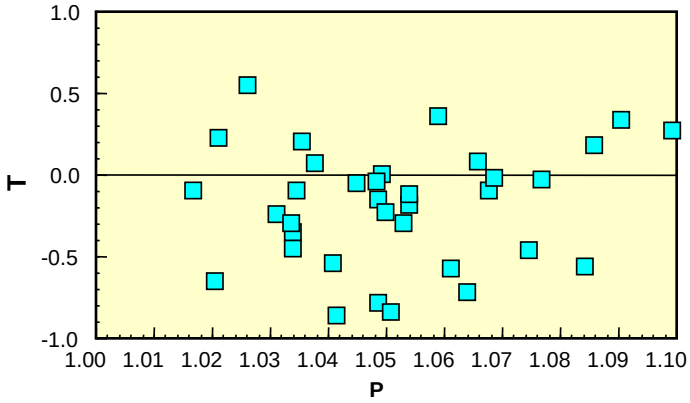
Lambert projection, Lower hemisphere



Degree of anisotropy vs. Mean susceptibility



P-T plot (Jelinek plot)



Agenda

1. Definition and application in geology
2. Magnetic anisotropy of minerals
3. Magnetic fabric vs. texture of rocks
4. Magnetic fabric of sedimentary, deformed, and metamorphosed rocks
5. Magnetic fabric of igneous rocks
6. Sampling, measurement and data processing

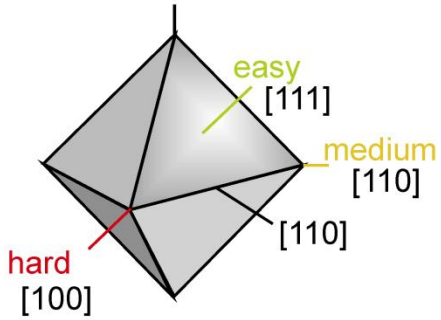
Shape anisotropy

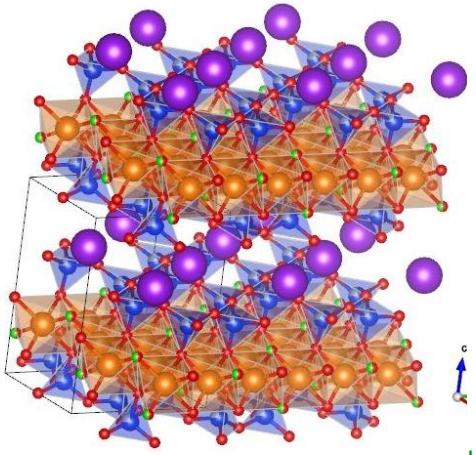
Magnetocrystalline anisotropy

Magnetite

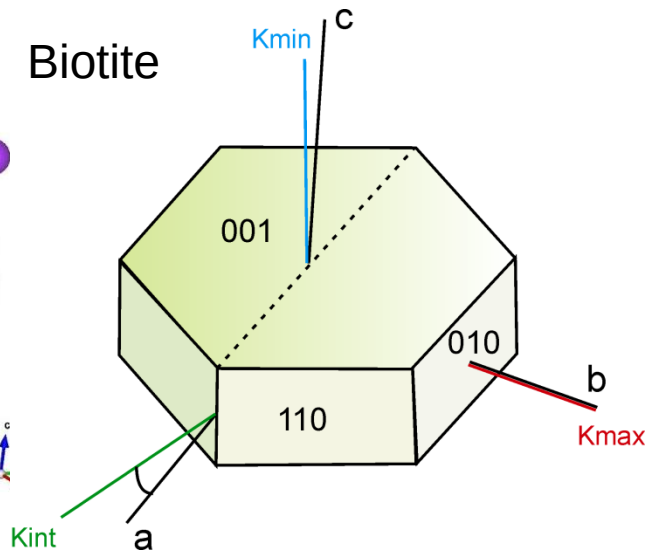
All other minerals

Magnetite crystal

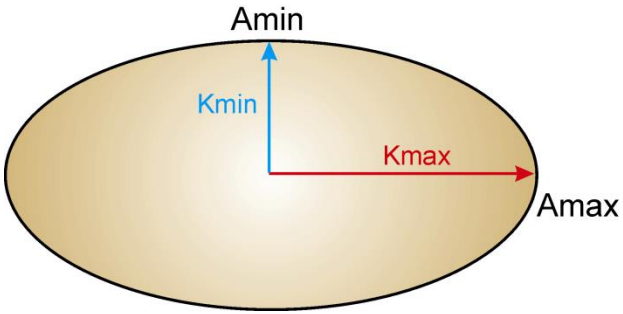




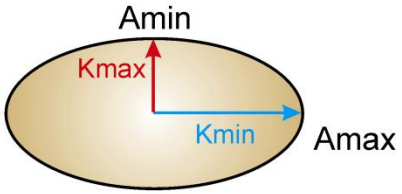
Biotite

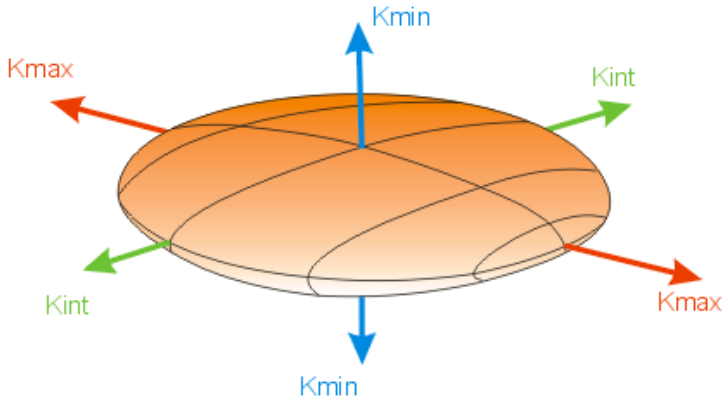


Multi-domain magnetite

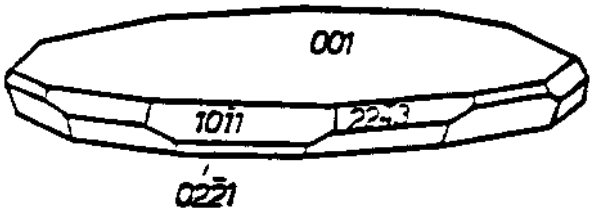


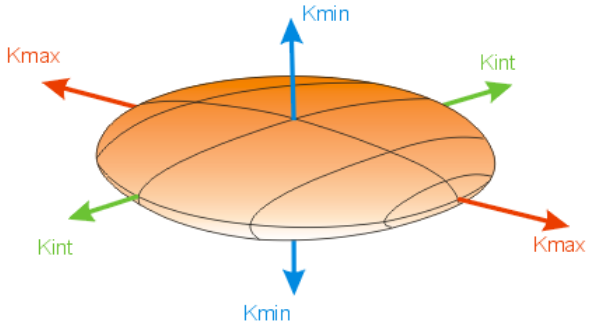
Single-domain magnetite





Magnetocrystalline anisotropy

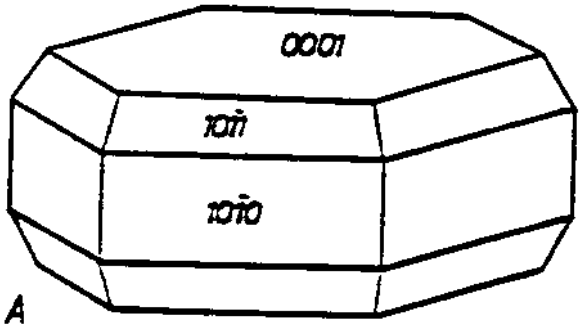


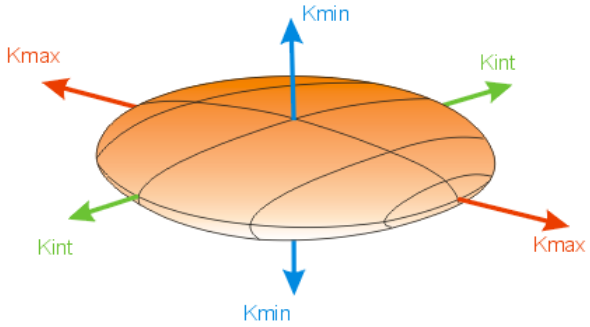


Hematite

$k_1 = k_2 >> k_3$

$P > 100$



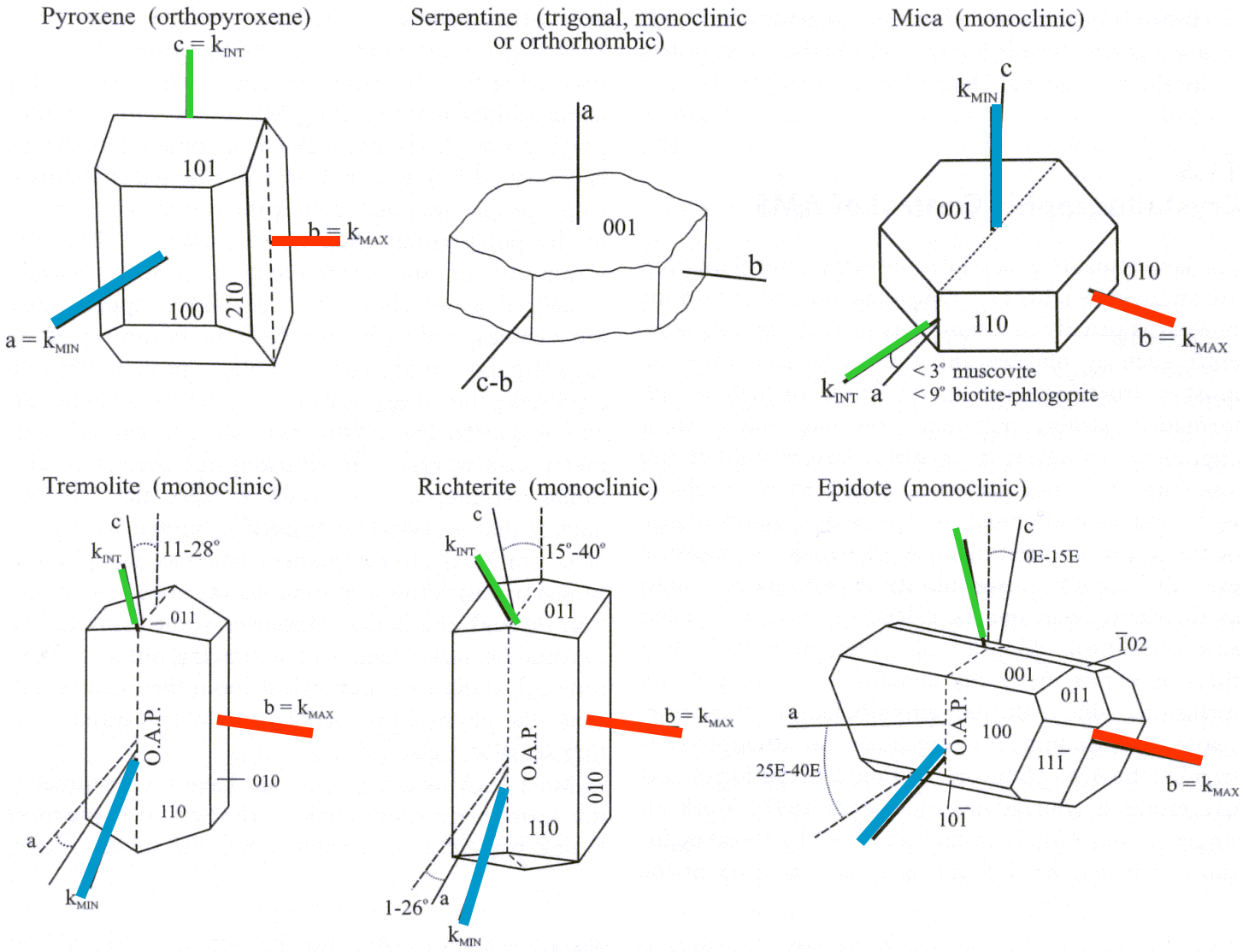


Pyrrhotite

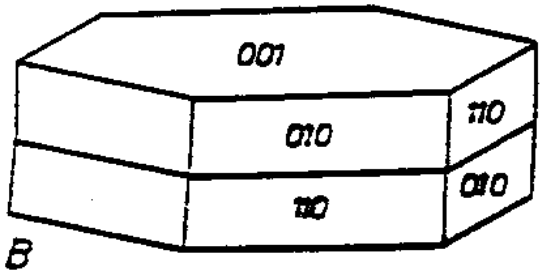
$k_1 = k_2 >> k_3$

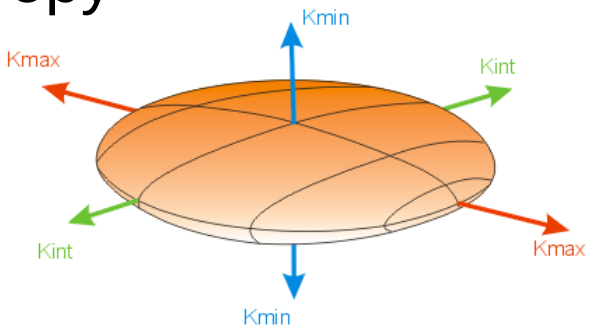
$P > 300$

Magnetocrystalline anisotropy



Magnetocrystalline anisotropy

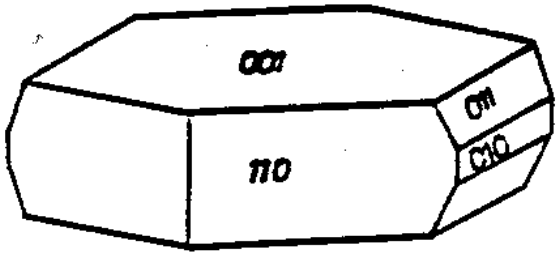


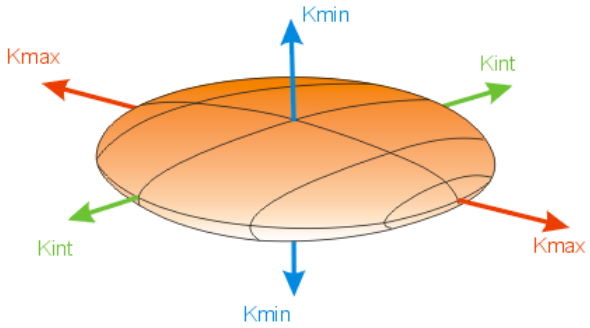


Biotite

$k_1 = k_2 > k_3$

P = 1.2-1.6

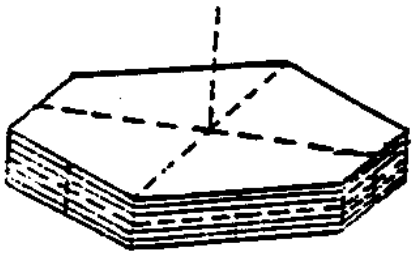


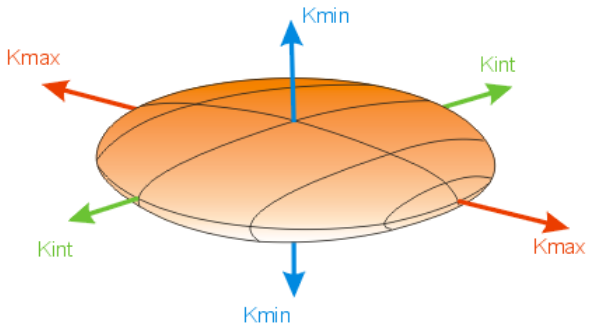


Muscovite

$k_1 = k_2 > k_3$

P = 1.3-1.4





Chlorite

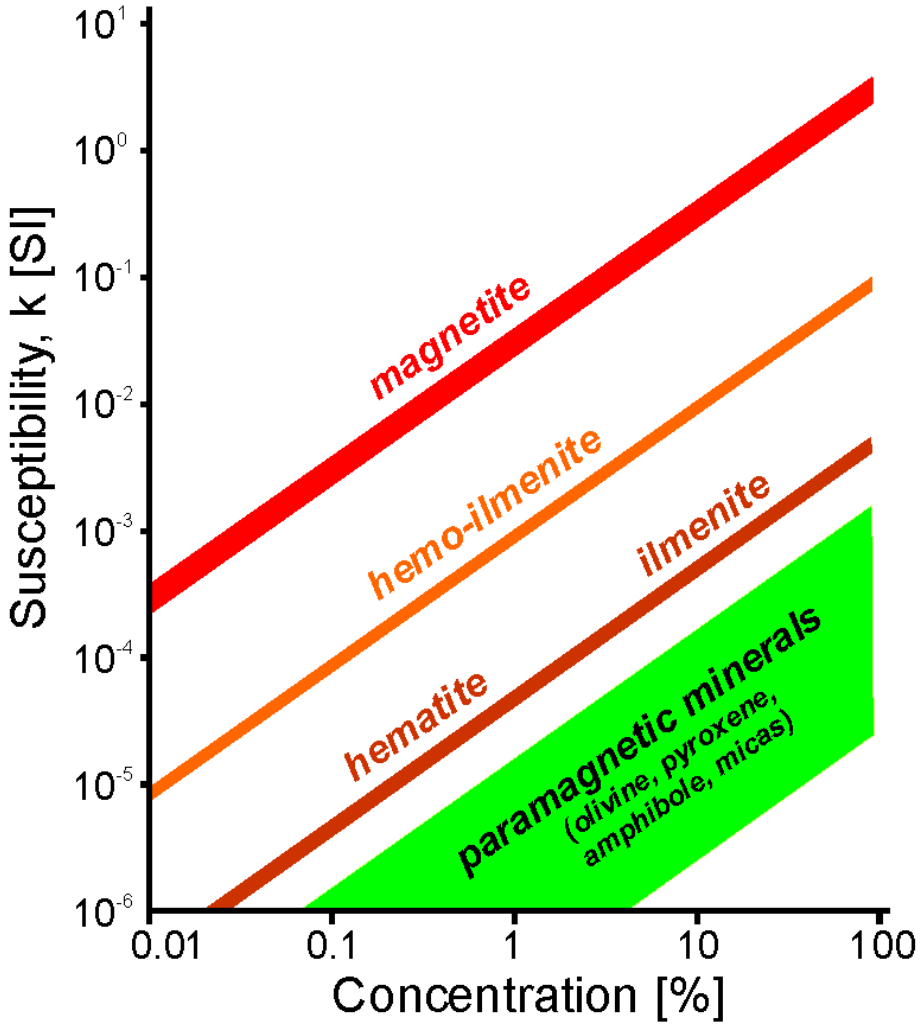
$k_1 = k_2 > k_3$

P = 1.2-1.8

Magnetic properties of selected minerals

Mineral	Susceptibility [10^{-6}]	Degree of anisotropy	Shape of anisotropy	Anisotropy type
Magnetite	3000000	1.1 to 3.0	Variable	Shape
Hematite	1300 to 7000	>100	~1.00	Magnetocrystalline
Pyrrhotite		100 to 10000	~1.00	Magnetocrystalline
Actinolite	490	1.2 to 1.2	-0.40 to 0.40	Magnetocrystalline
Hornblende	746 to 1368	1.665	-0.51	Magnetocrystalline
Glaucophane	787	1.205	0.10	Magnetocrystalline
Chlorite	70 to 1550	1.2 to 1.7	~1.00	Magnetocrystalline
Biotite	998 to 1290	1.2 to 1.6	~1.00	Magnetocrystalline
Phlogopite	1178	1.3	0.95	Magnetocrystalline
Muscovite	122 to 165	1.4	0.44	Magnetocrystalline
Quartz	-13.4 to -15.4	1.01	1.00	Magnetocrystalline
Calcite	-13.8	1.11	1.00	Magnetocrystalline
Aragonite	-15.0	1.15	0.80	Magnetocrystalline

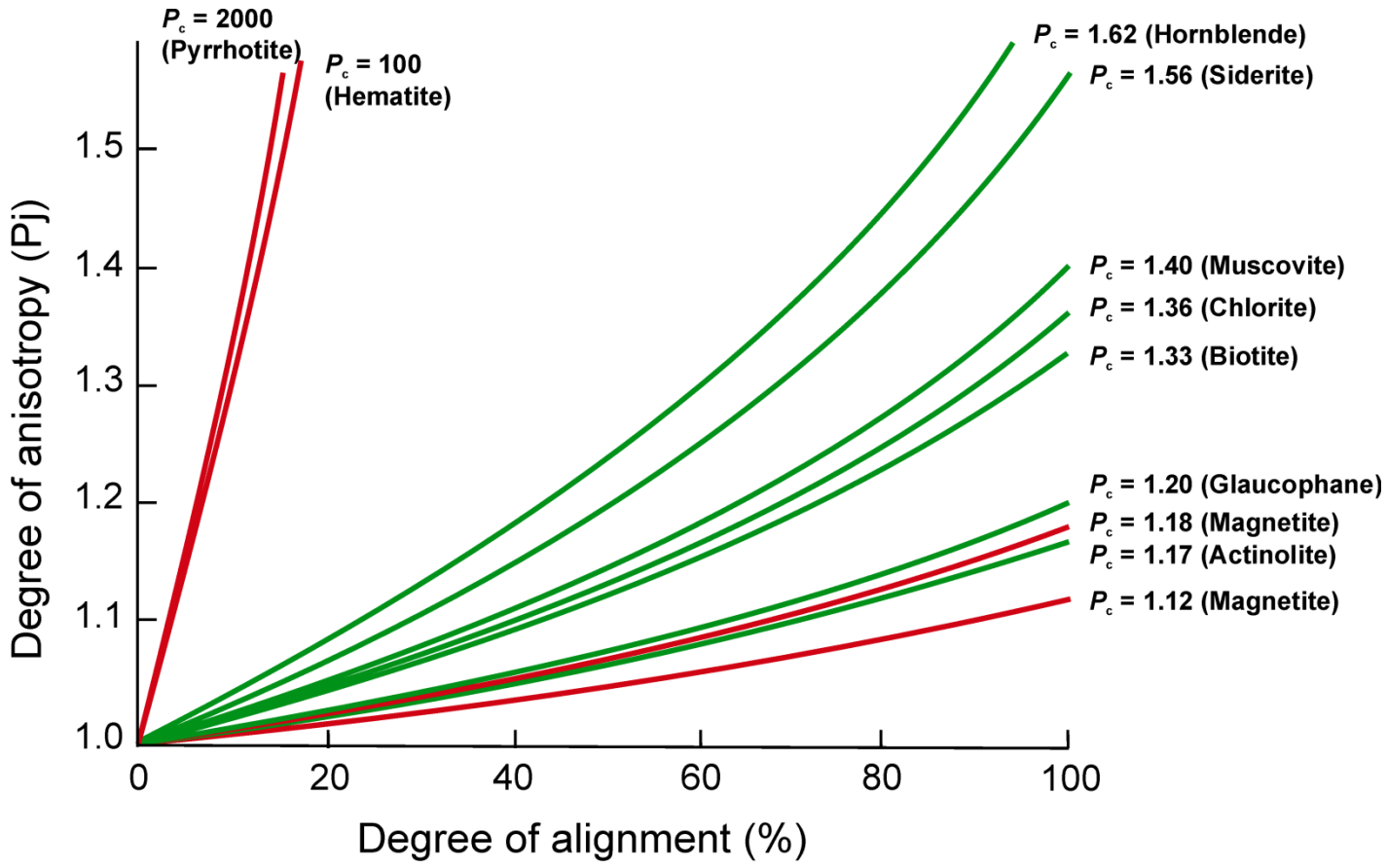
Contribution of selected minerals to whole rock susceptibility

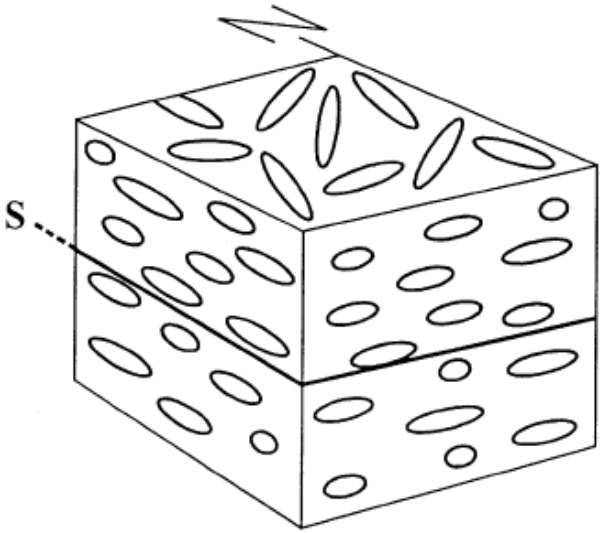


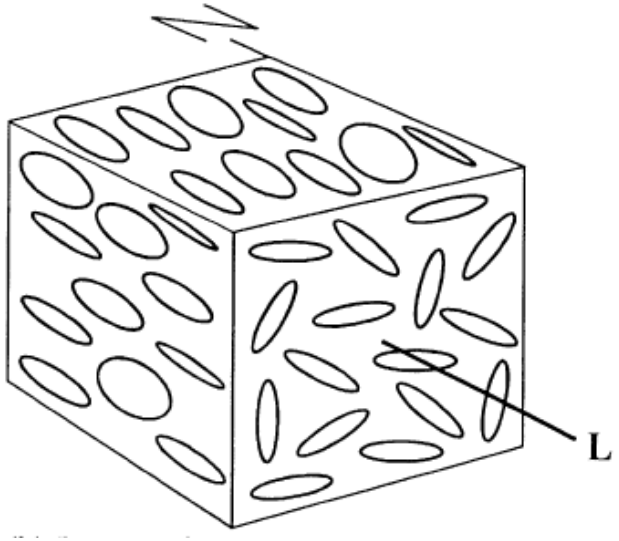
Agenda

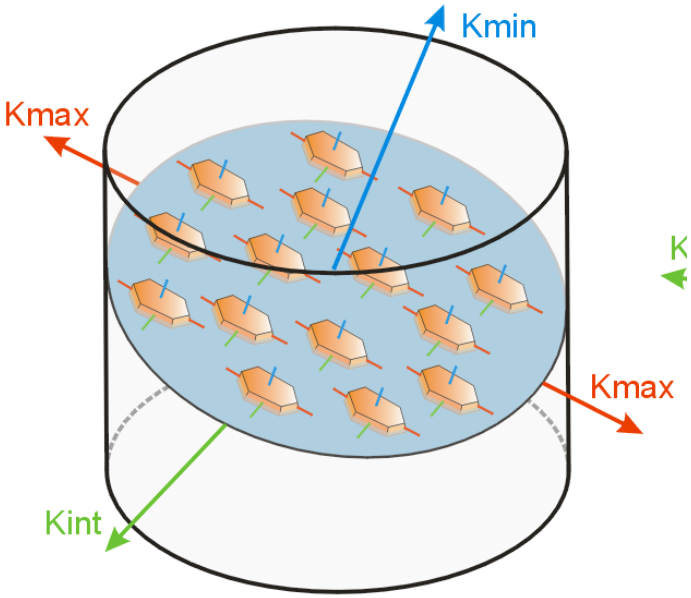
1. Definition and application in geology
2. Magnetic anisotropy of minerals
3. Magnetic fabric vs. texture of rocks
4. Magnetic fabric of sedimentary, deformed, and metamorphosed rocks
5. Magnetic fabric of igneous rocks
6. Sampling, measurement and data processing

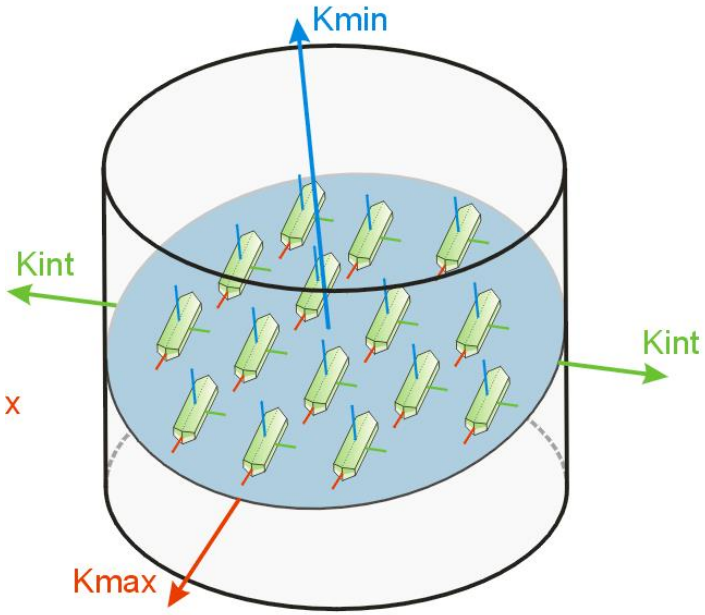
Rock anisotropy degree as a function of preferred orientation of its minerals



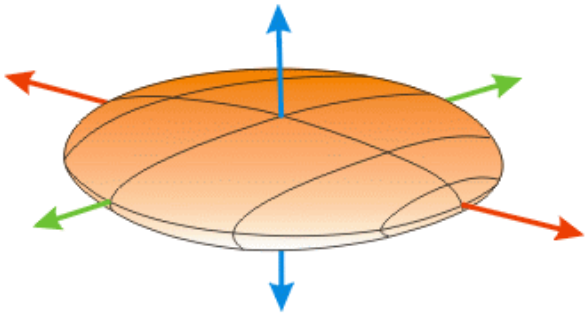

N
S

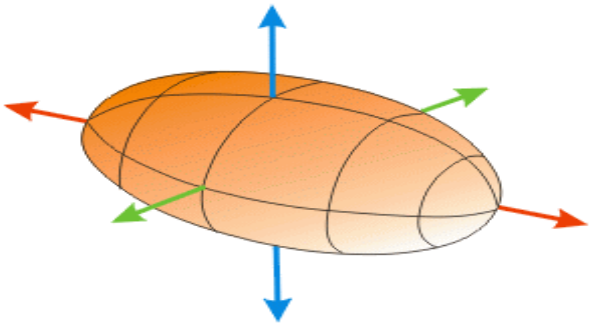

N
L

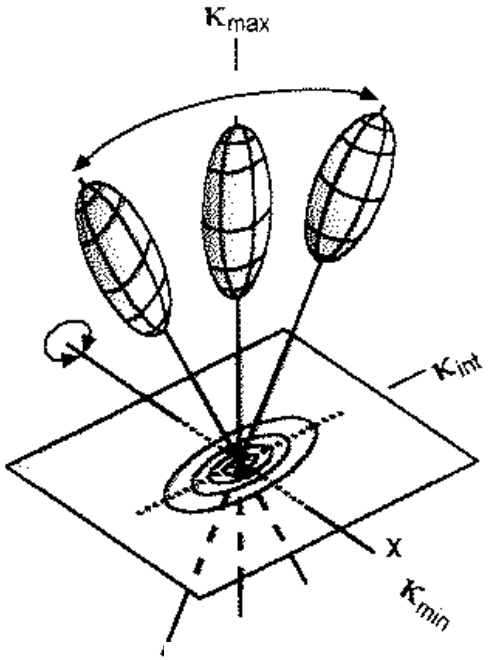

Kmin
Kmax
K
Kmax
Kint


Kmin
Kint
Kint
x
Kmax

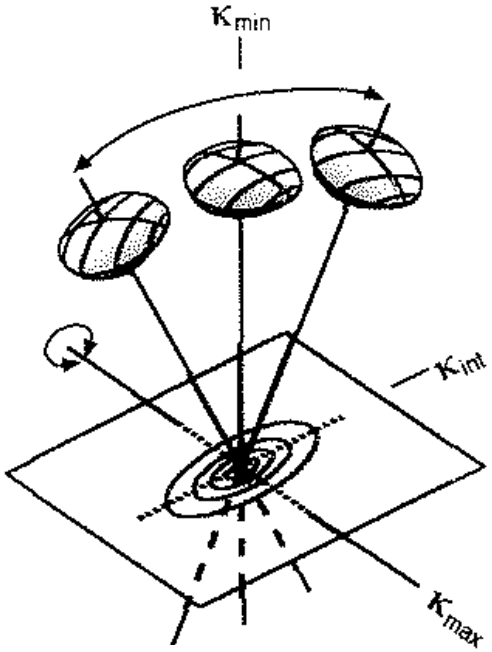
Magnetic fabrics of higher order





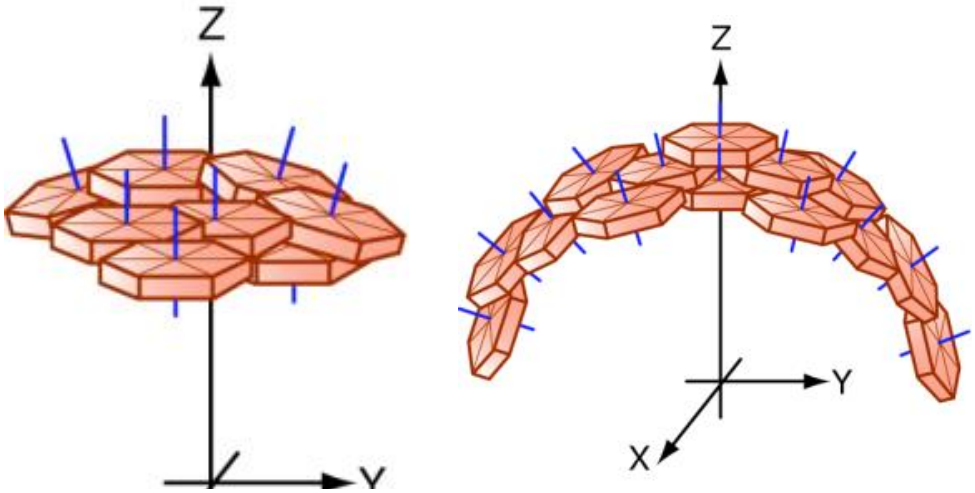


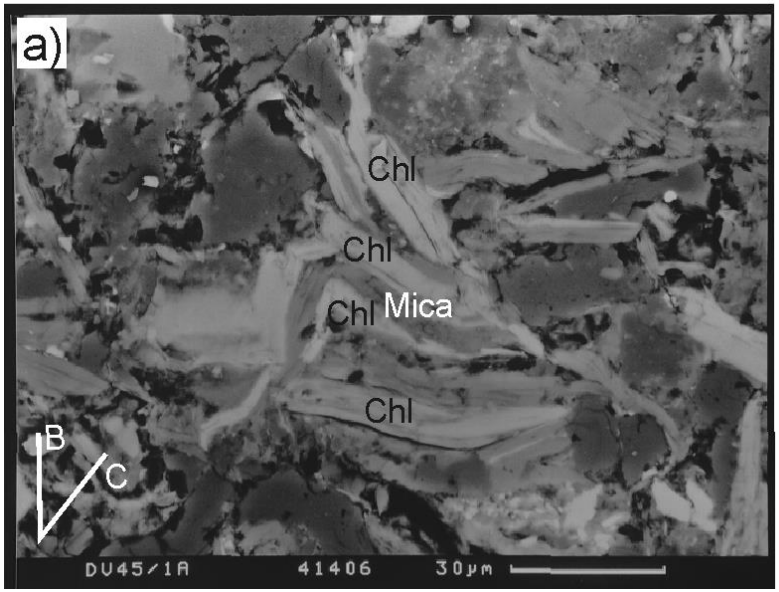
oblate fabric

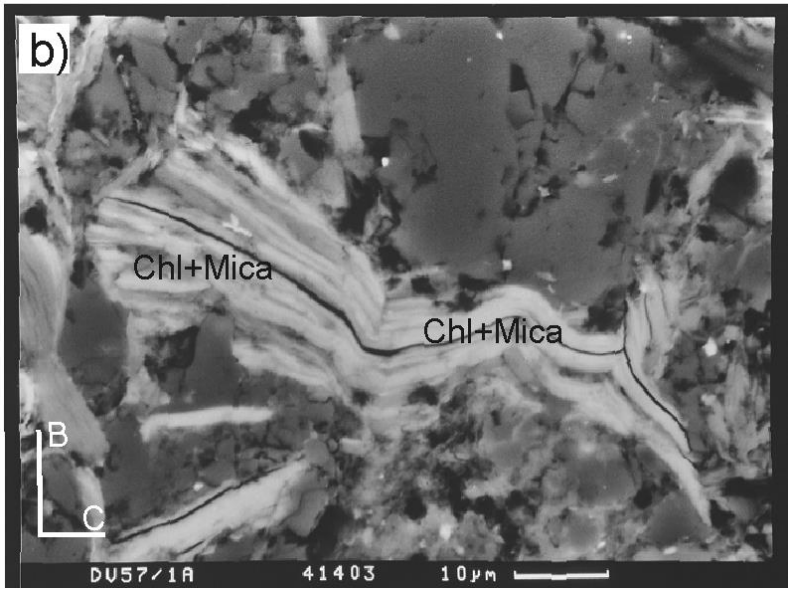


prolate fabric

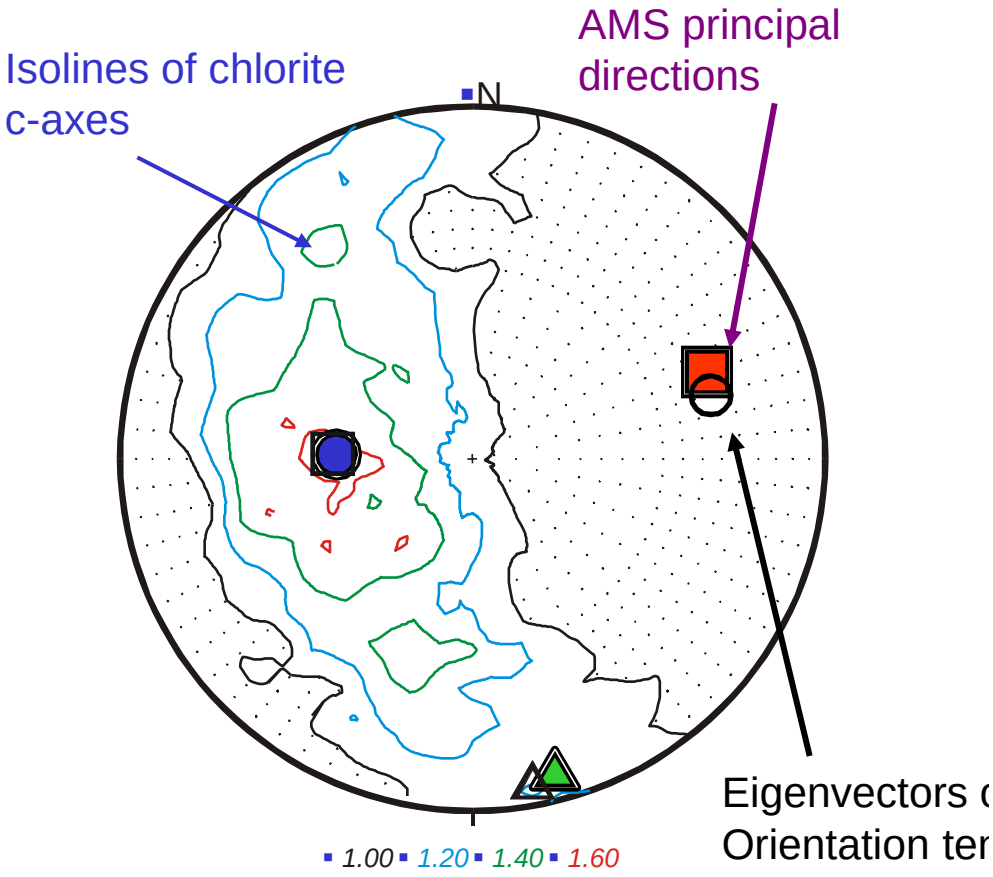
Comparison of magnetic fabric and neutron texture goniometry

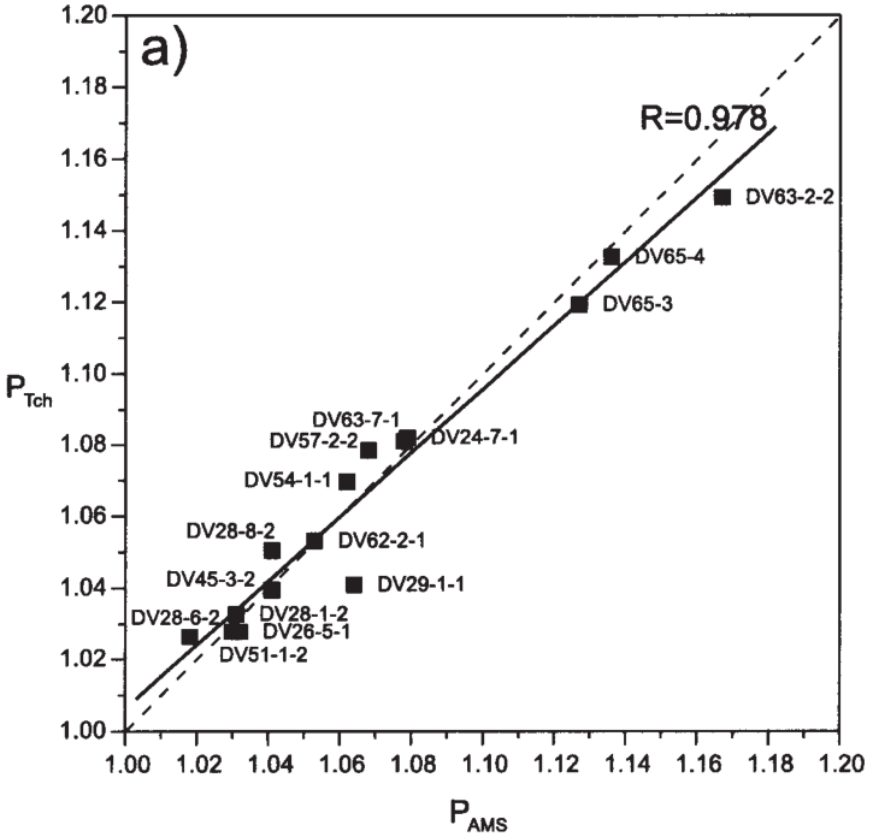






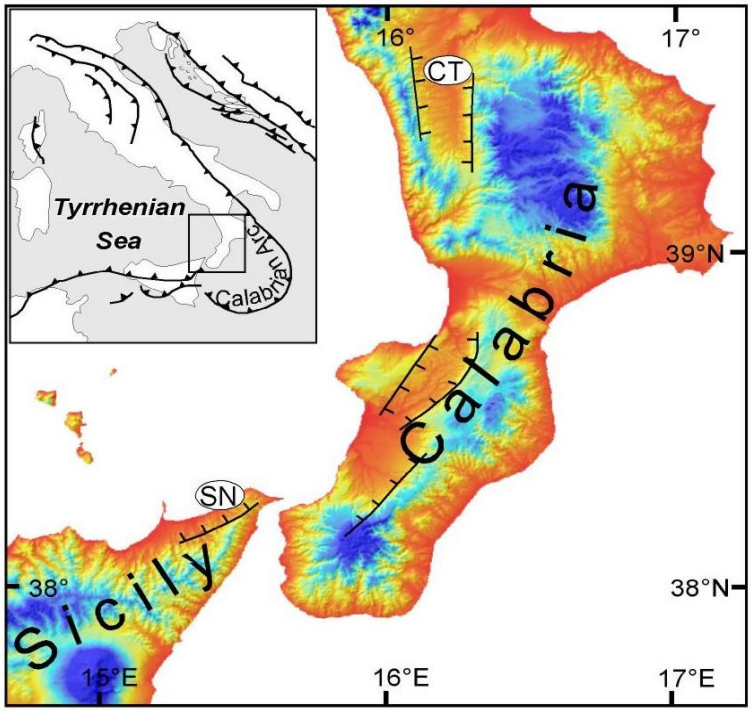
Comparison of magnetic fabric and neutron texture goniometry

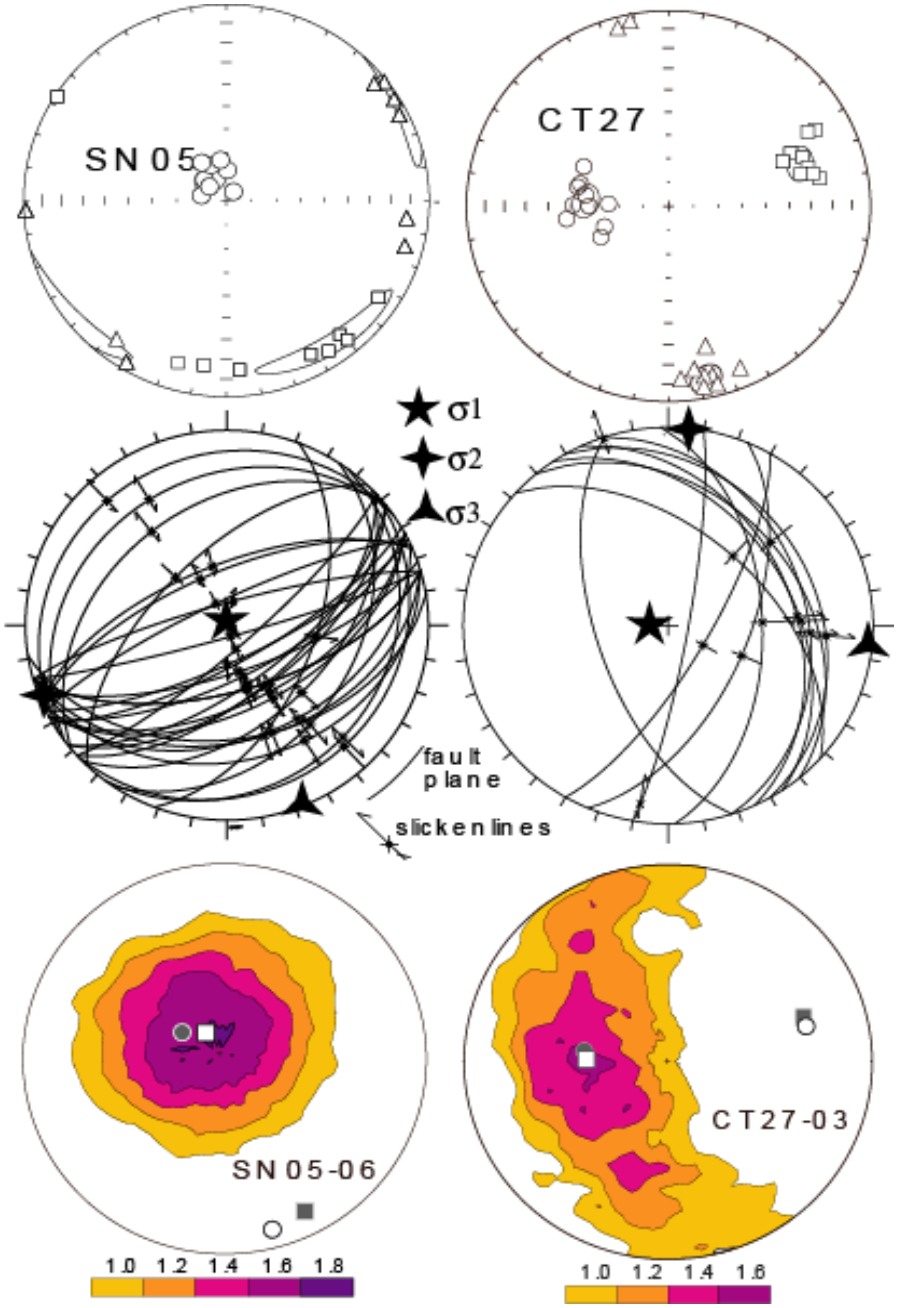




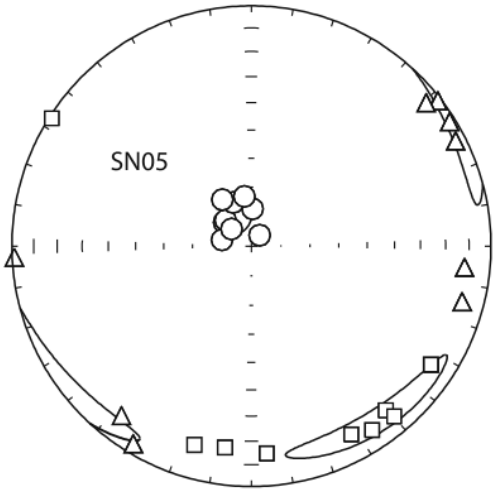
Neutron texture goniometer TEX2
GKSS Forschungszentrum Geesthacht GmbH, Germany

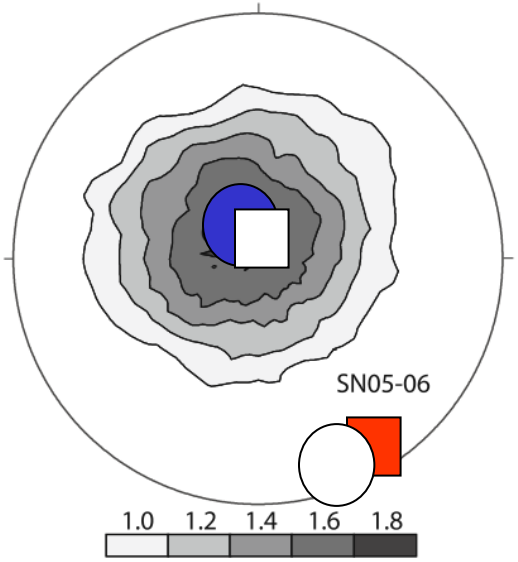
Shale, Rhenohercynian Belt, Czech Republic

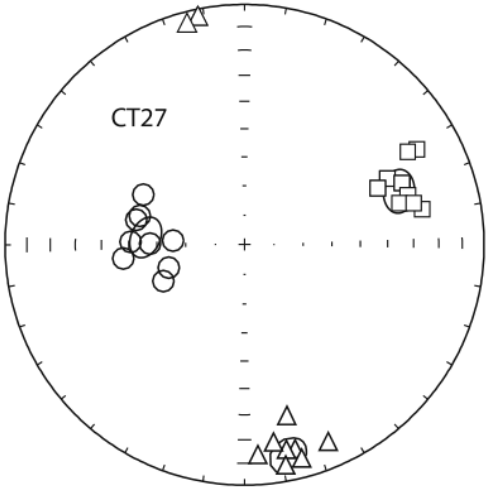

Tyrrhenian
Sea
Calabrian Arc
16°
17°
CT
39°N
Calabria
SN
38°
Sicily
38°N
15°E
16°E
17°E

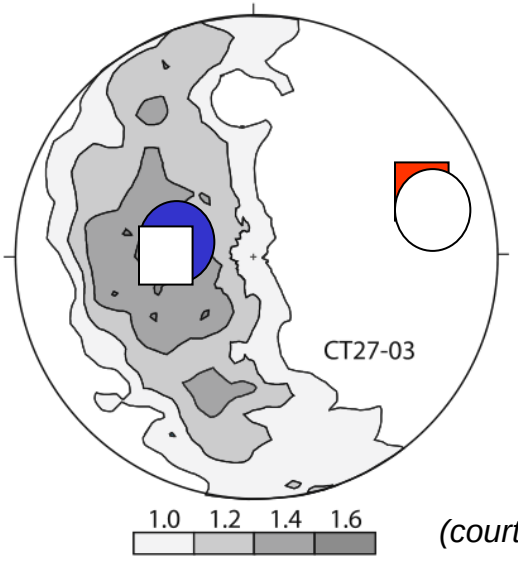

SN 05
CT27
σ1
σ2
σ3
fault plane
slickenlines
SN 05-06
1.0 1.2 1.4 1.6 1.8
CT27-03
1.0 1.2 1.4 1.6

Comparison of magnetic fabric and neutron texture goniometry









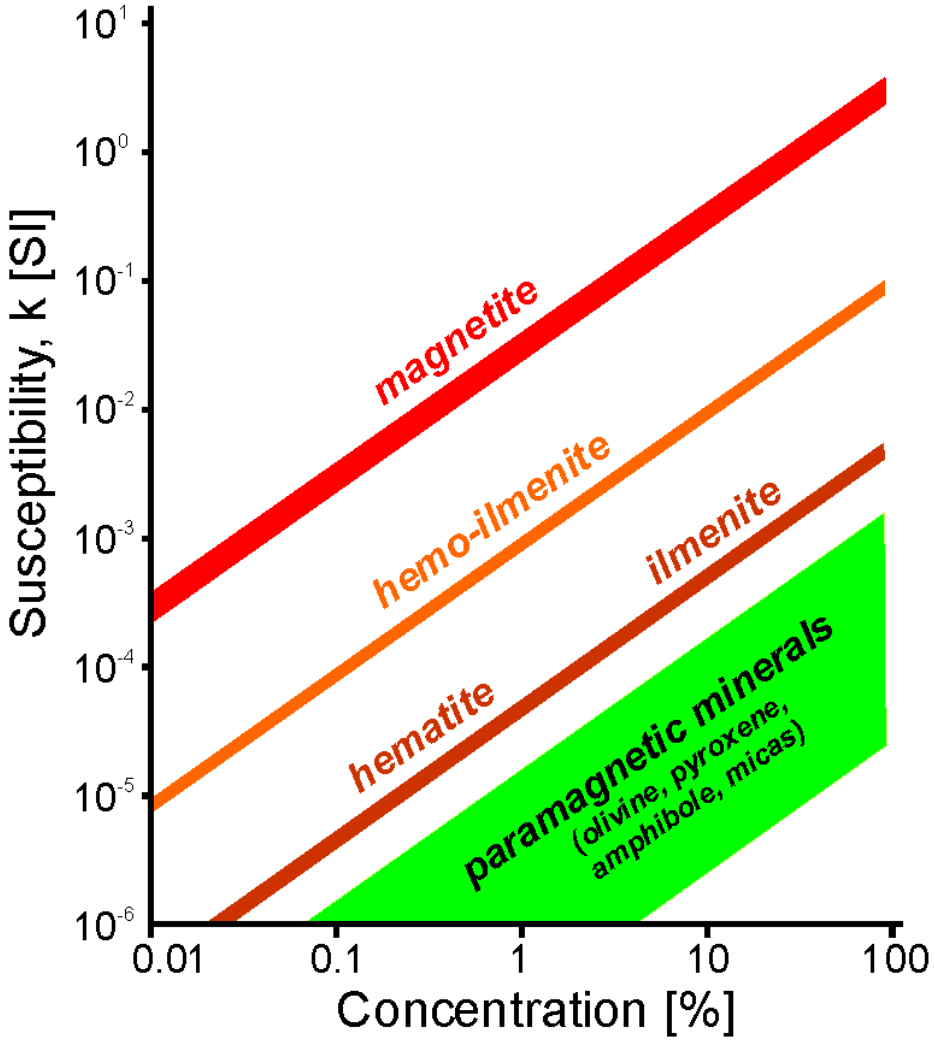
Neogene basin, Southern Italy

(courtesy F. Cifelli)

Agenda

1. Definition and application in geology
2. Magnetic anisotropy of minerals
3. Magnetic fabric vs. texture of rocks
4. Magnetic fabric of sedimentary, deformed, and metamorphosed rocks
5. Magnetic fabric of igneous rocks
6. Sampling, measurement and data processing

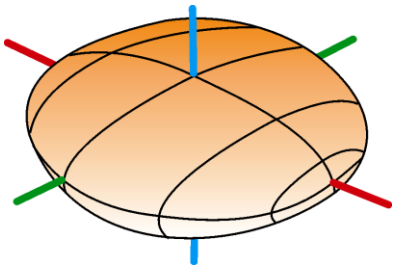
Magnetic susceptibility usually carried by paramagnetic minerals



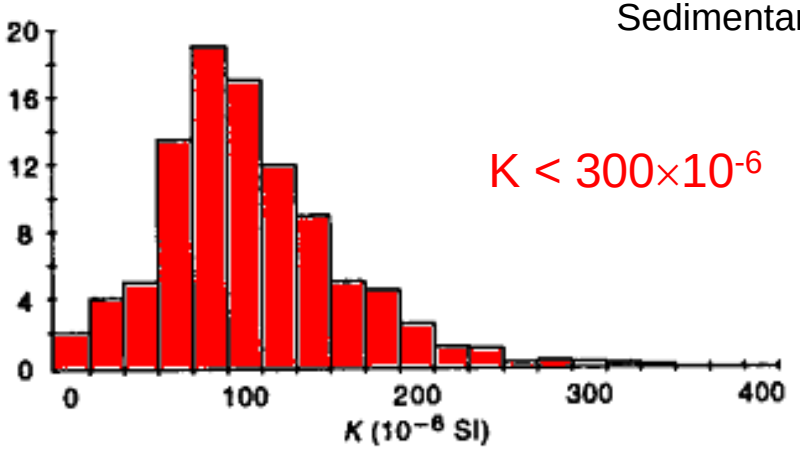
•Relatively low magnetic susceptibility

•Anisotropy degree < 5%

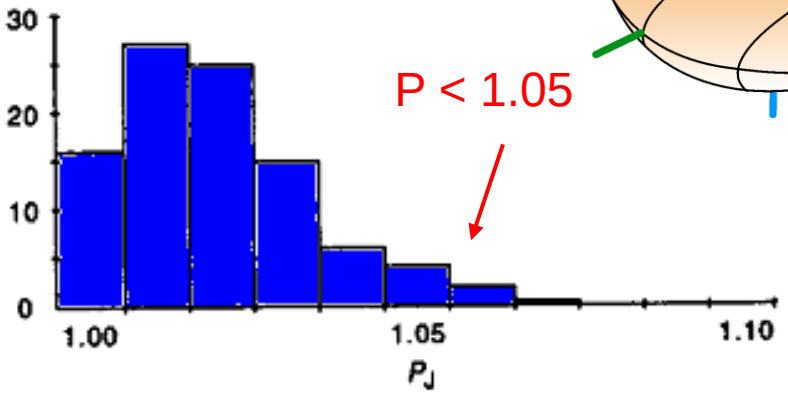
•Oblate fabric



Sedimentary rocks

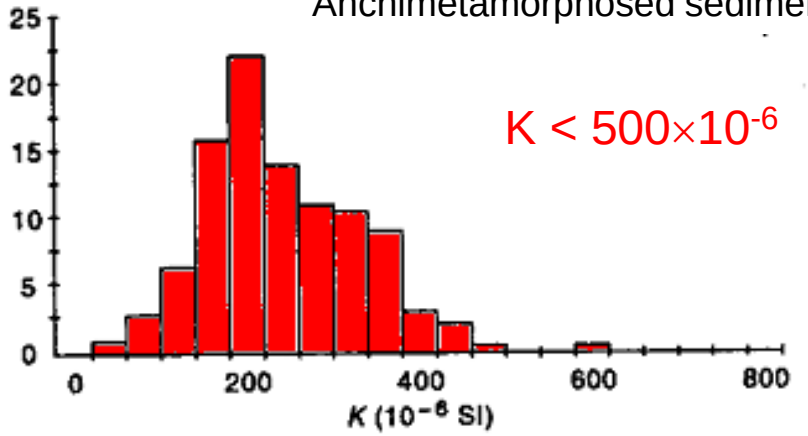


$K < 300 \times 10^{-6}$

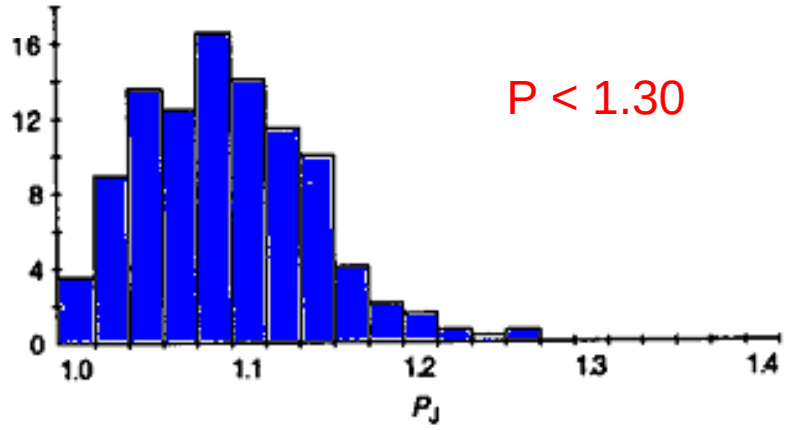


$P < 1.05$

Anchimetamorphosed sediments



$K < 500 \times 10^{-6}$

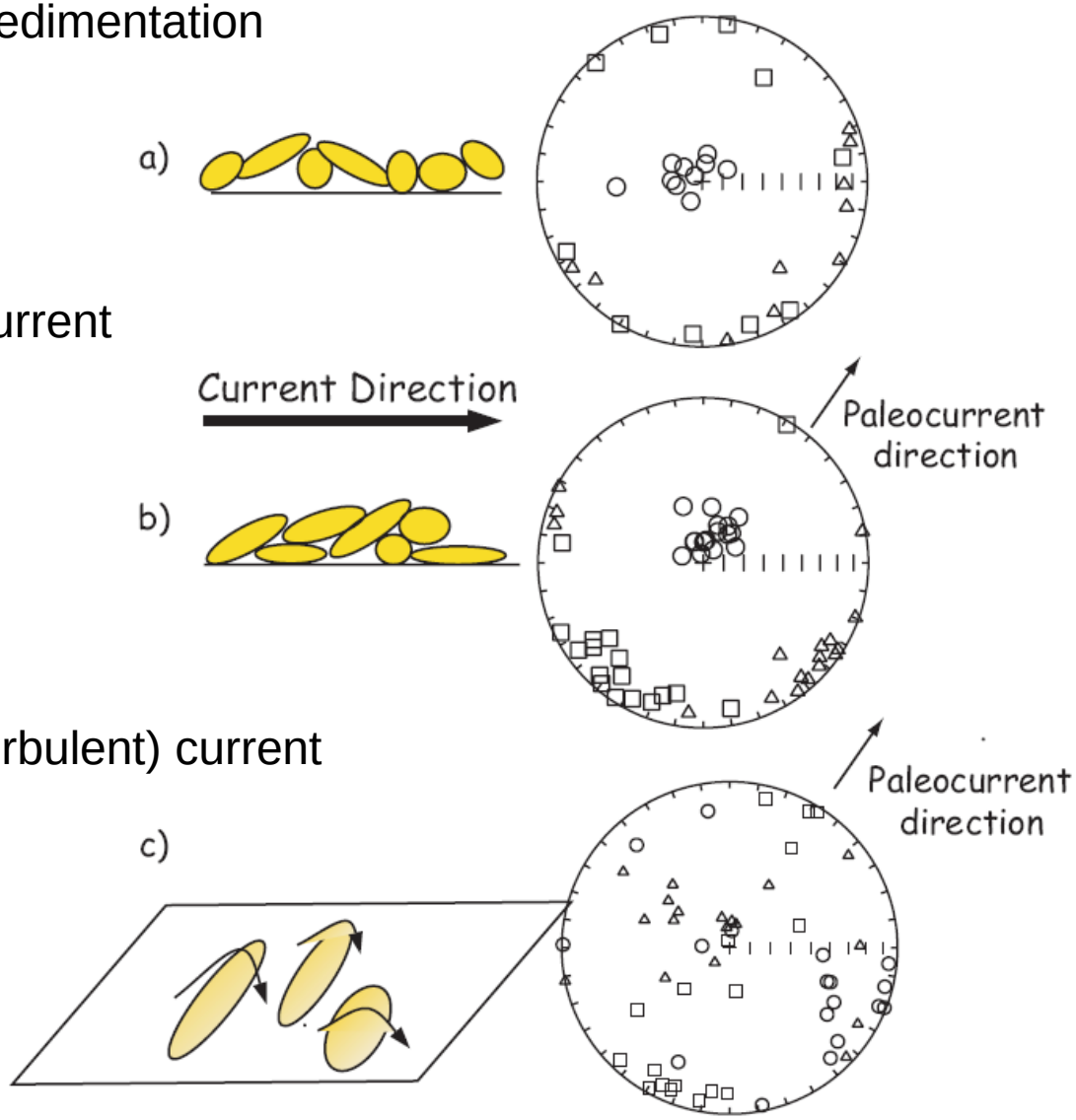


$P < 1.30$

•calm sedimentation

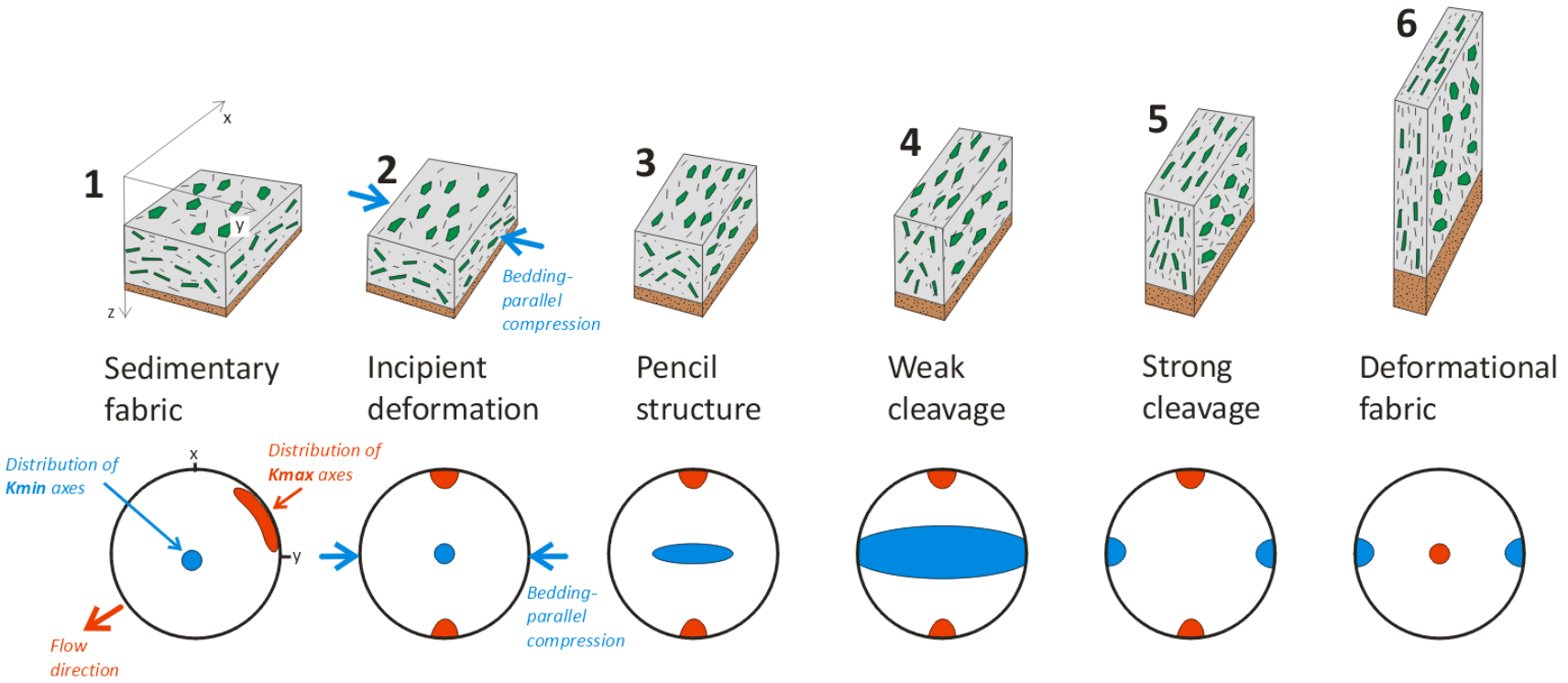
•slow current

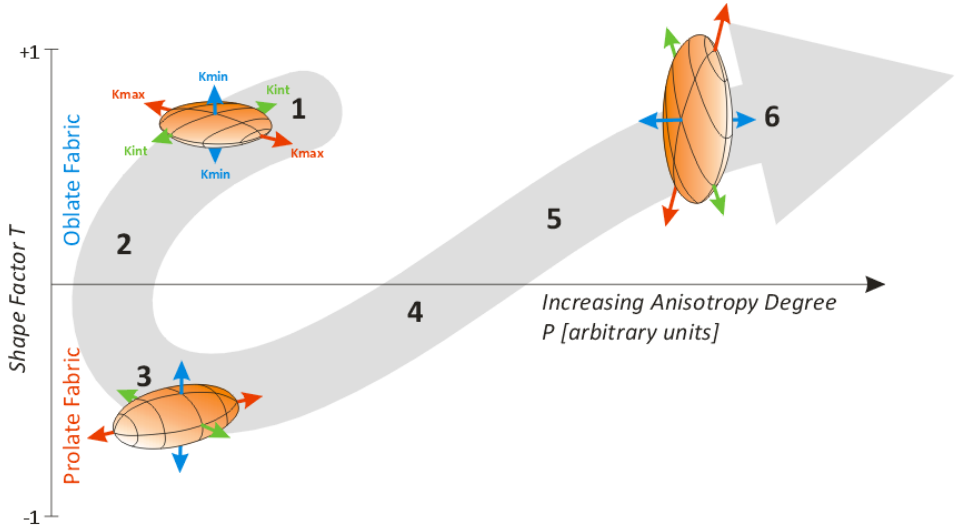
•fast (turbulent) current



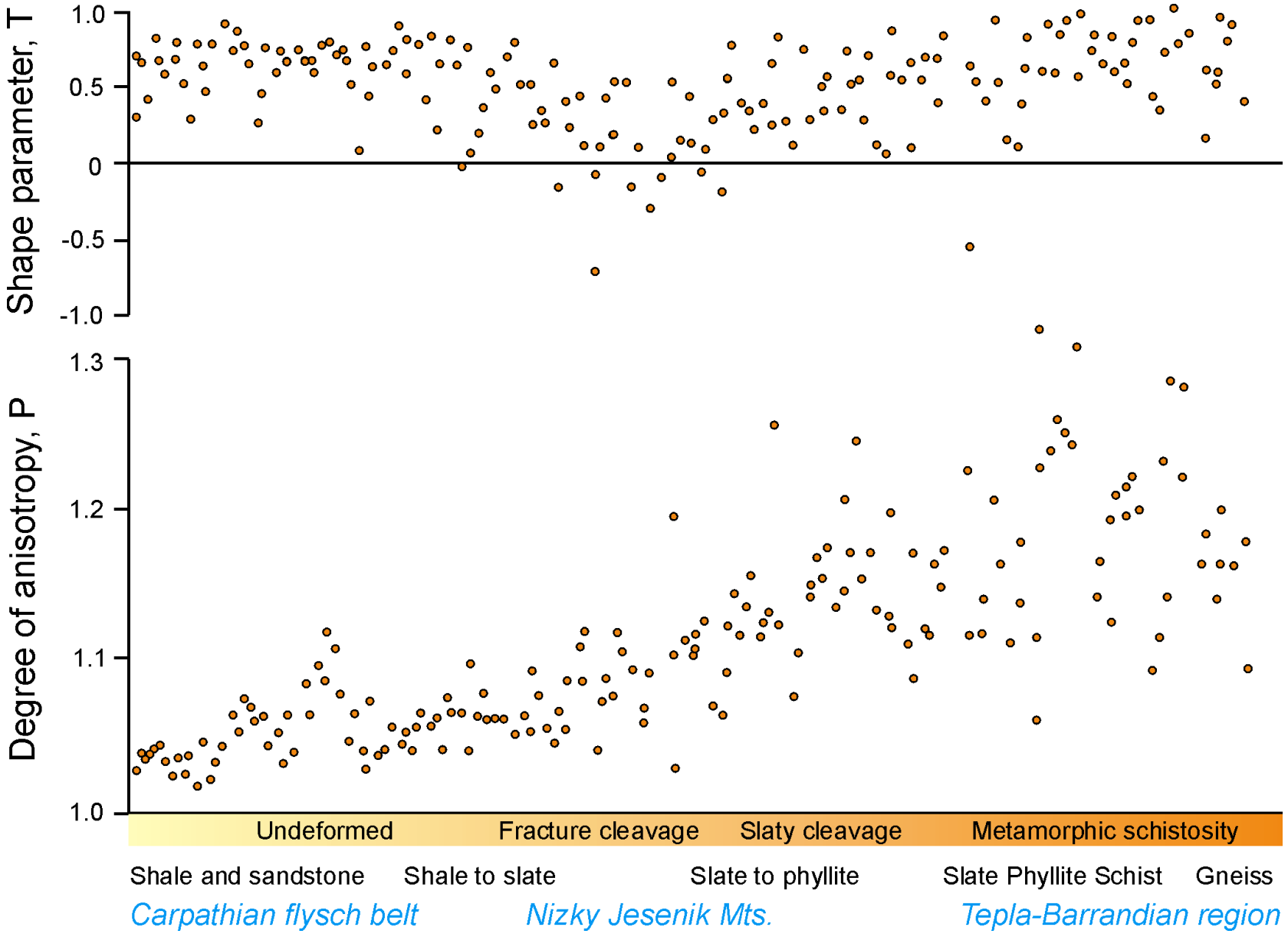
(after Tauxe 2013)

4. Magnetic fabric of sedimentary, deformed, and metamorphosed rocks

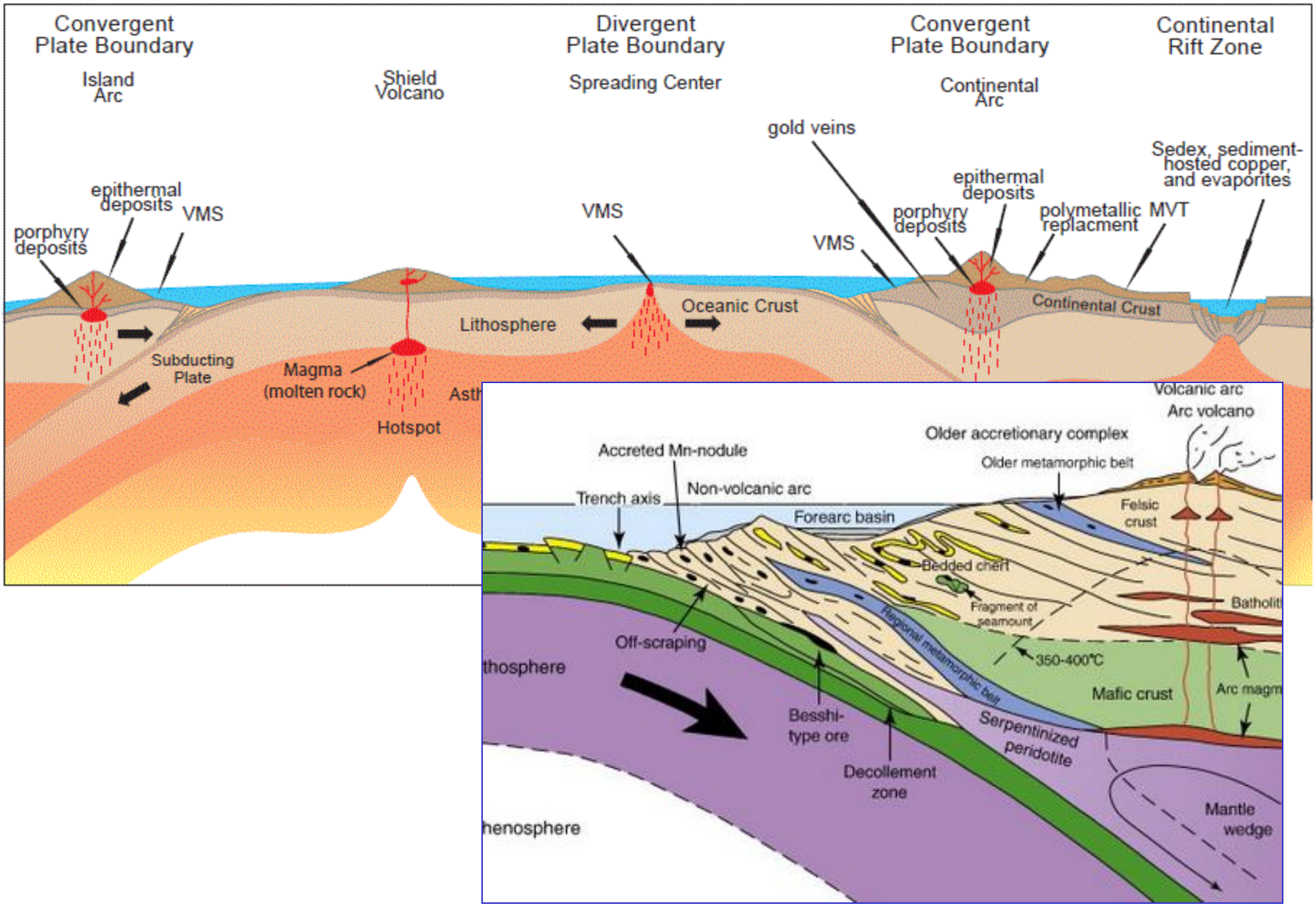




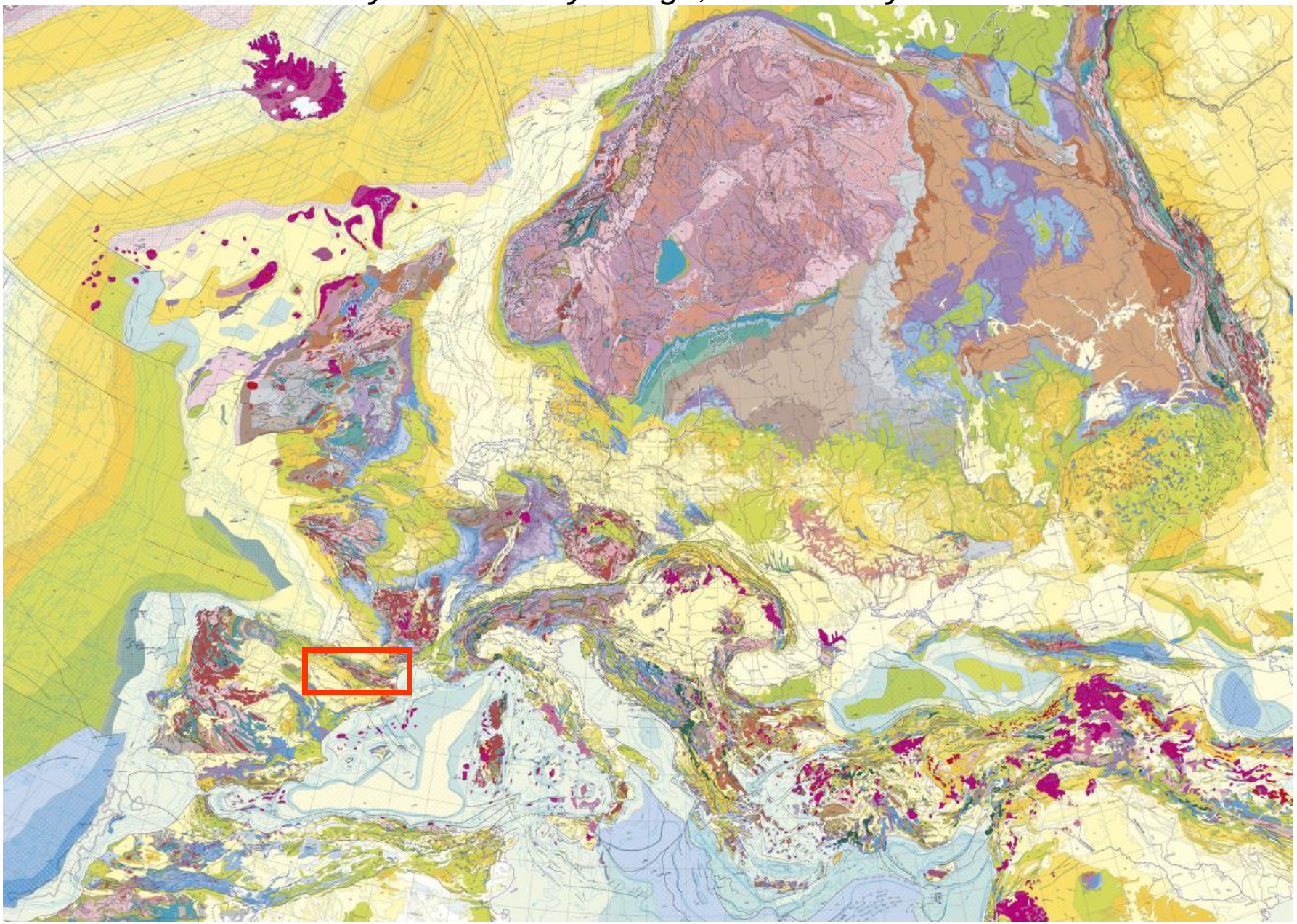
Pencil structure
(southern Pyrenees, Spain)


Shape parameter, T
1.0
0.5
0
-0.5
-1.0
Degree of anisotropy, P
1.3
1.2
1.1
1.0
Undeformed
Fracture cleavage
Slaty cleavage
Metamorphic schistosity
Shale and sandstone
Shale to slate
Slate to phyllite
Slate Phyllite Schist
Gneiss
Carpathian flysch belt
Nizky Jesenik Mts.
Tepla-Barrandian region

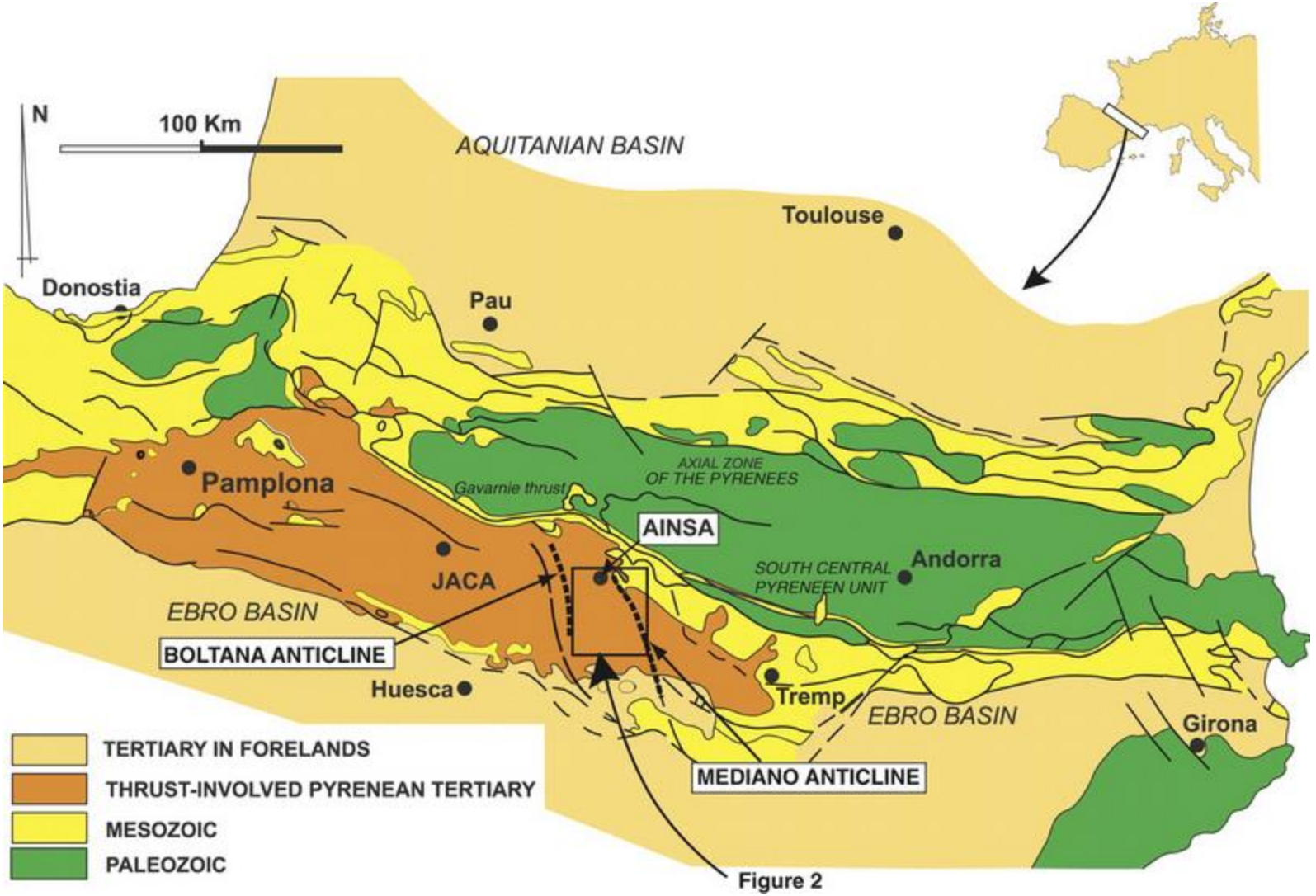
Accretionary wedge



Tertiary accretionary wedge, southern Pyrenees

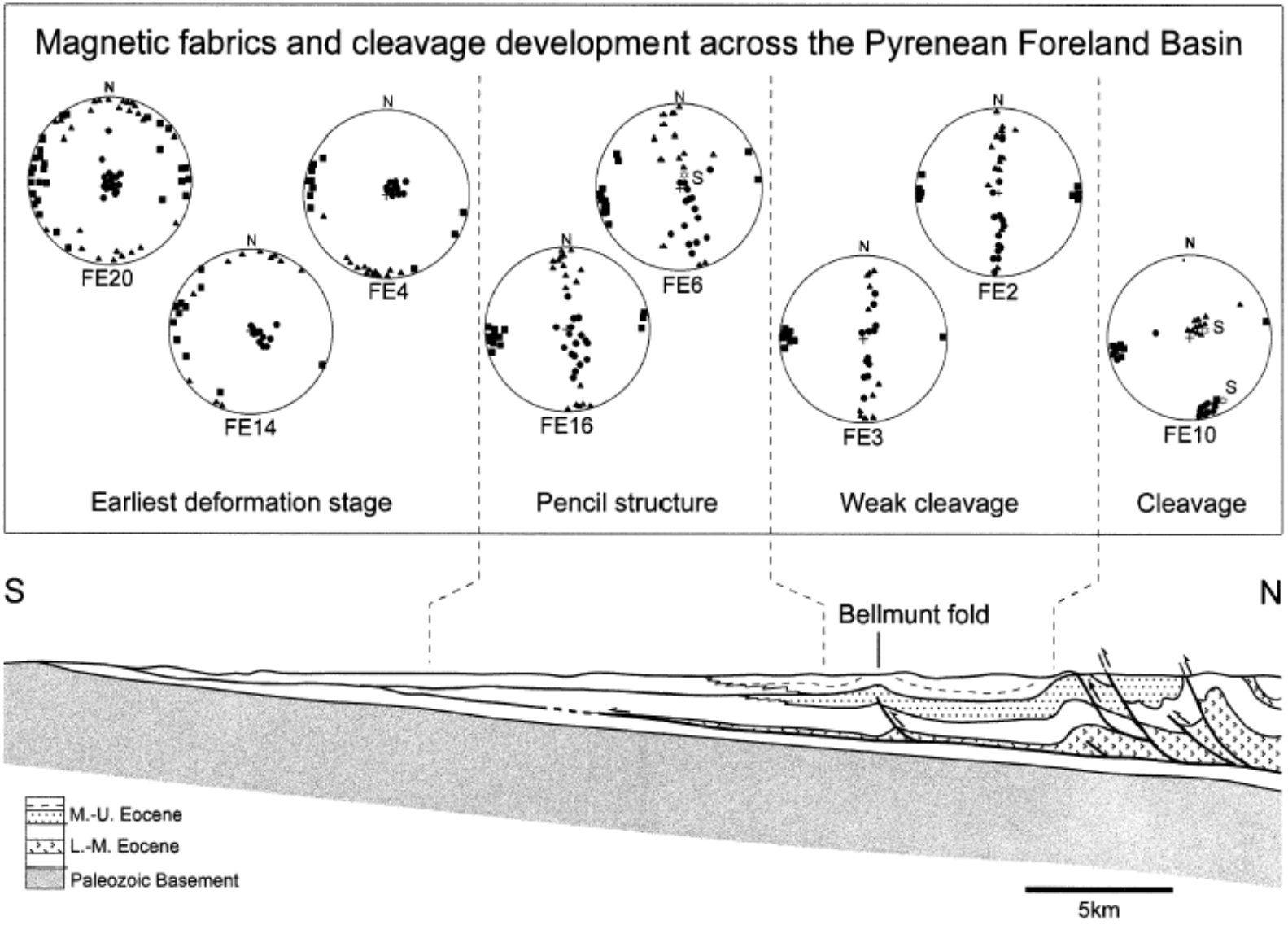


Tertiary accretionary wedge, southern Pyrenees



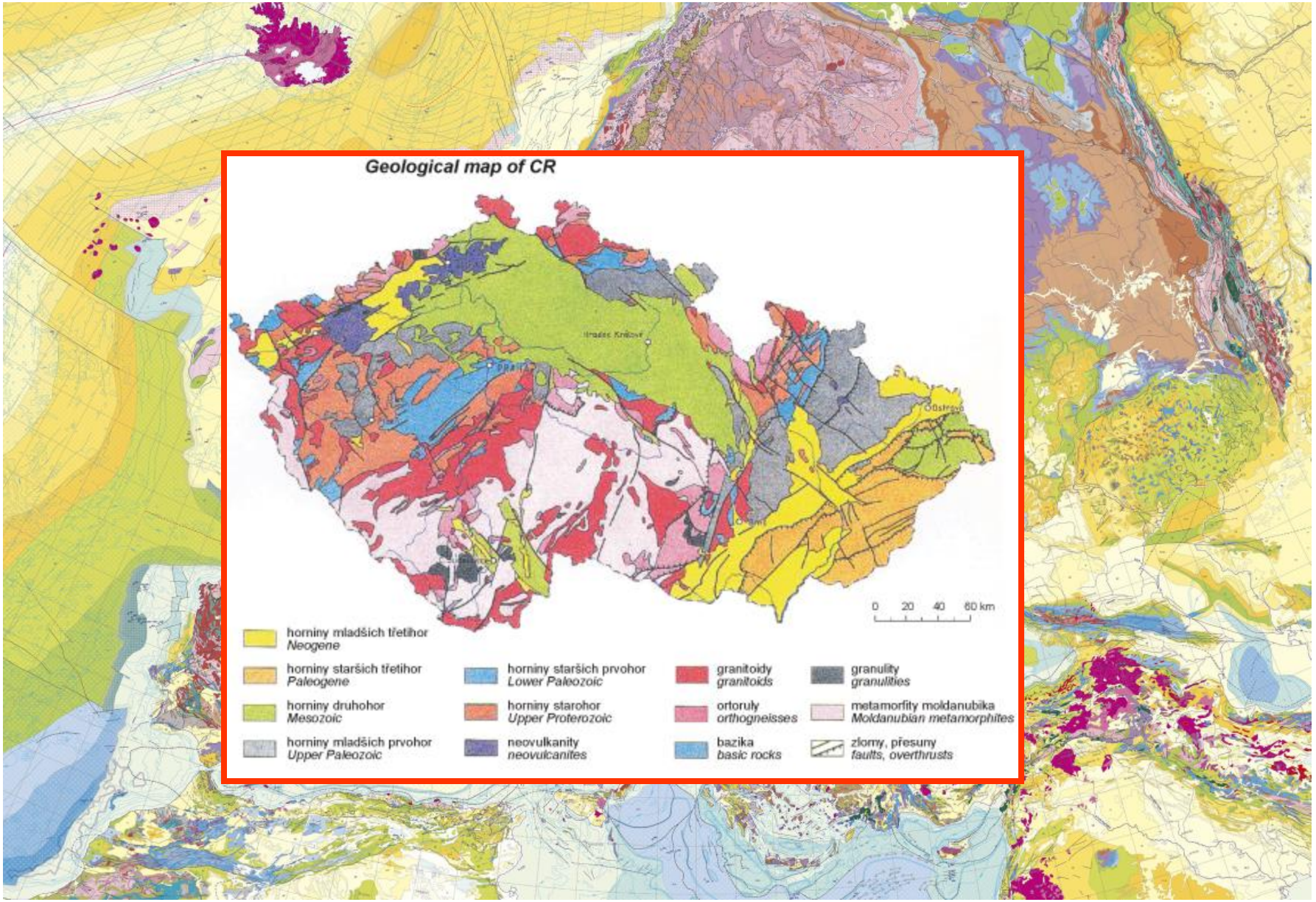
(Parés & van der Pluijm 1999)

Tertiary accretionary wedge, southern Pyrenees

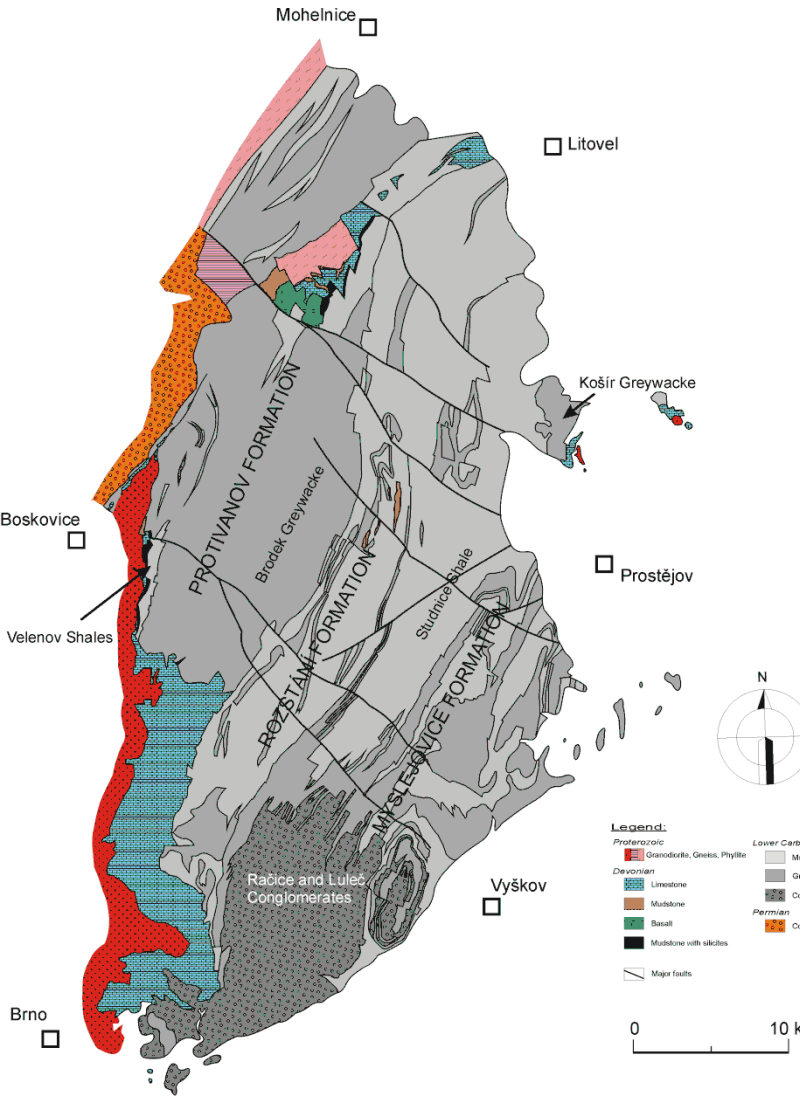


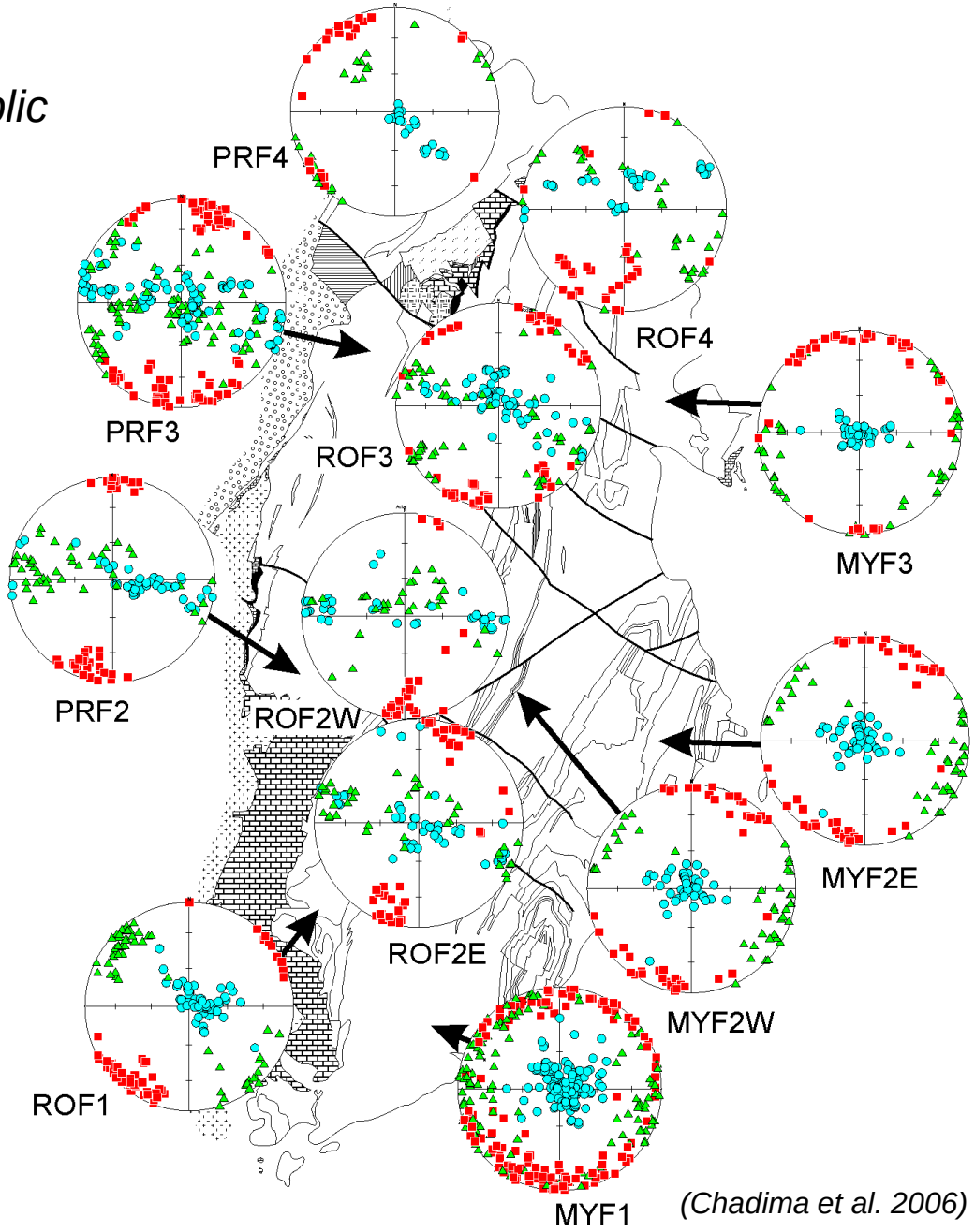
(Parés & van der Pluijm 1999)

Paleozoic accretionary wedge Rhenohercynian Belt, Czech Republic



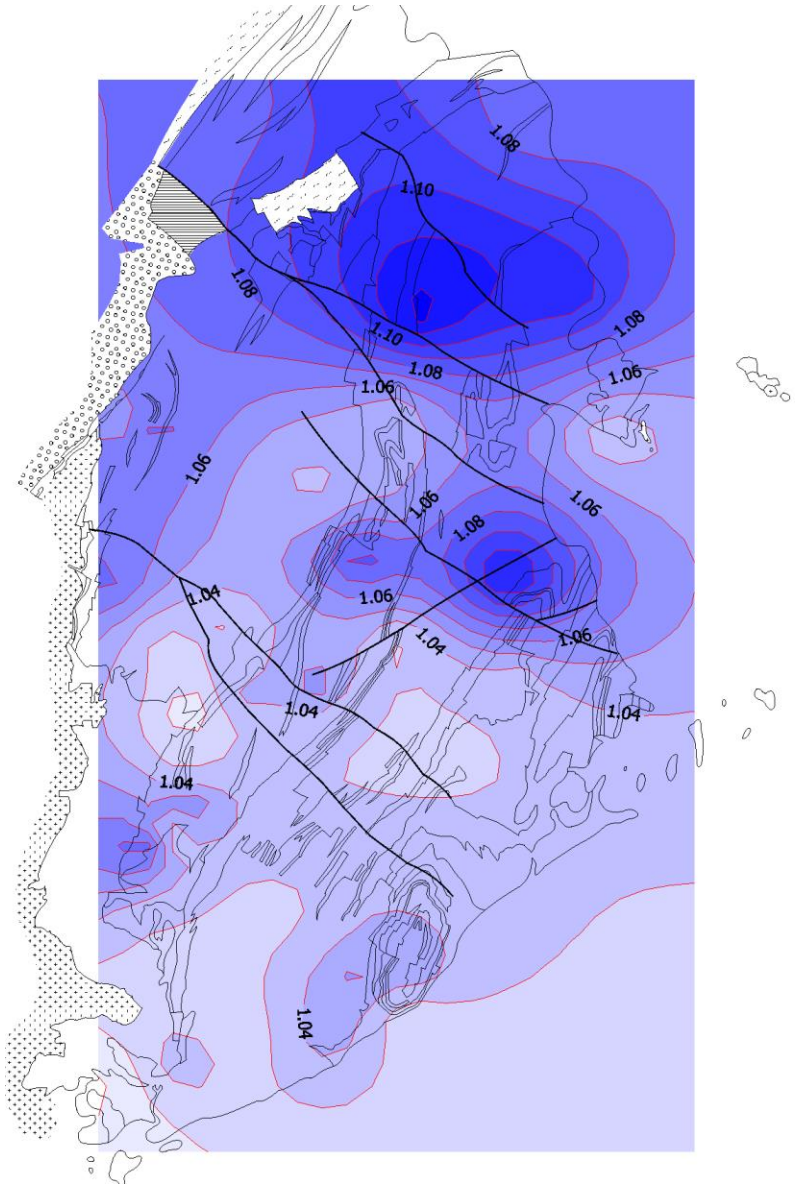
Paleozoic accretionary wedge
Rhenohercynian Belt, Czech Republic



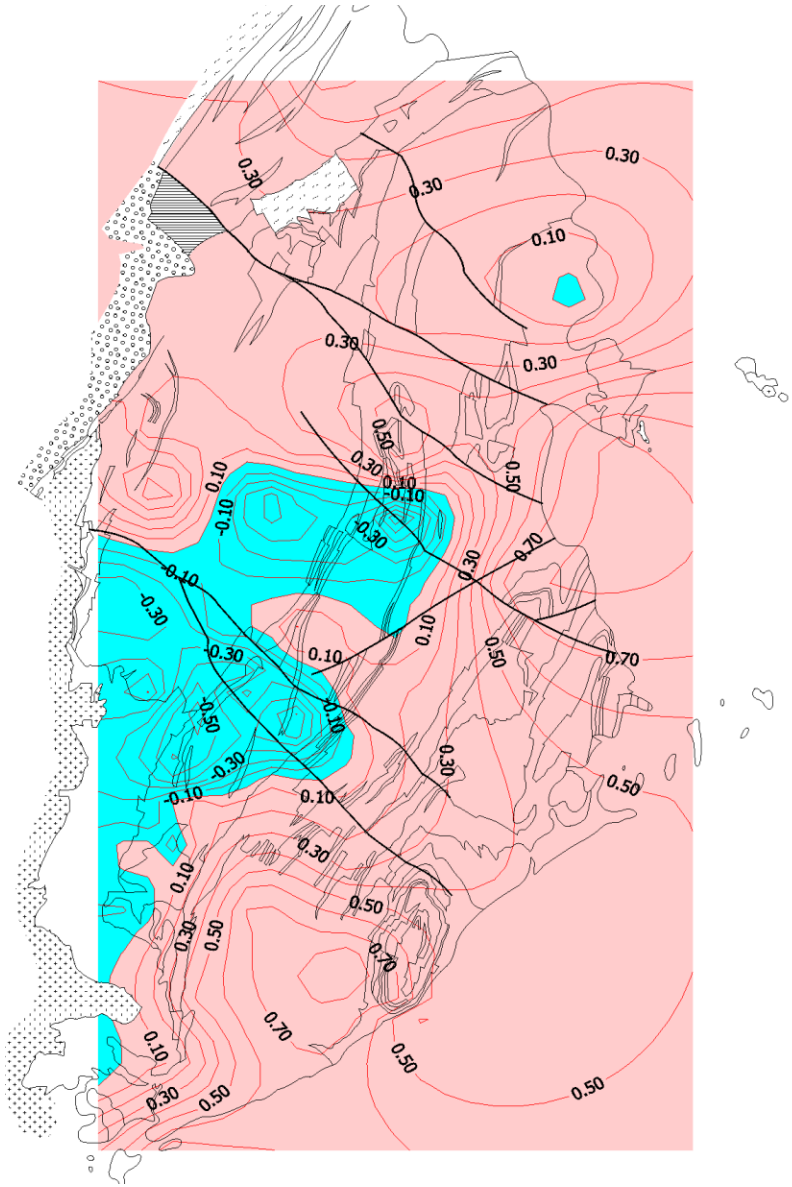


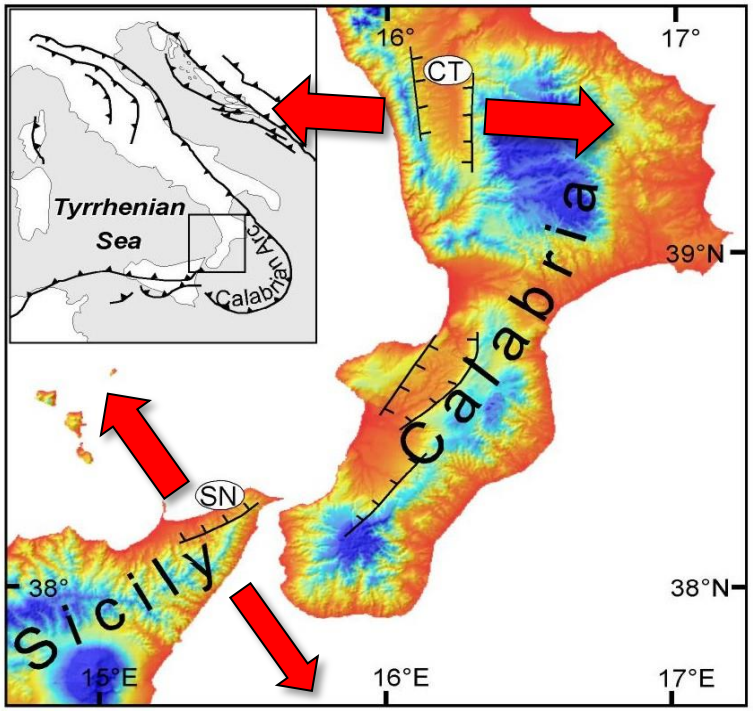
(Chadima et al. 2006)

Anisotropy degree (P)



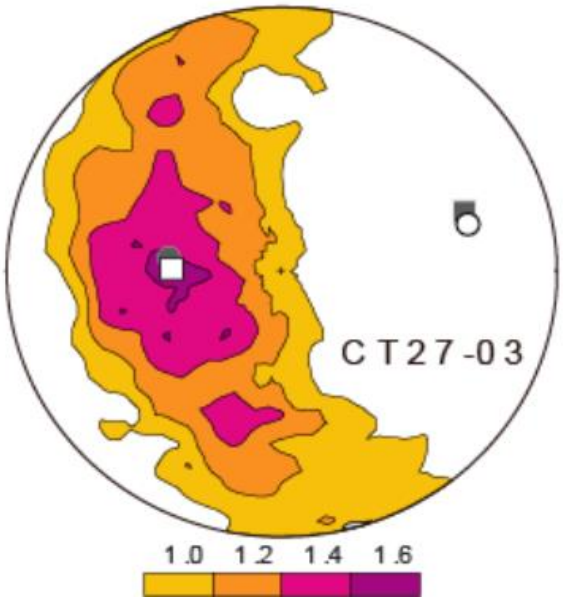
Shape parameter (T)

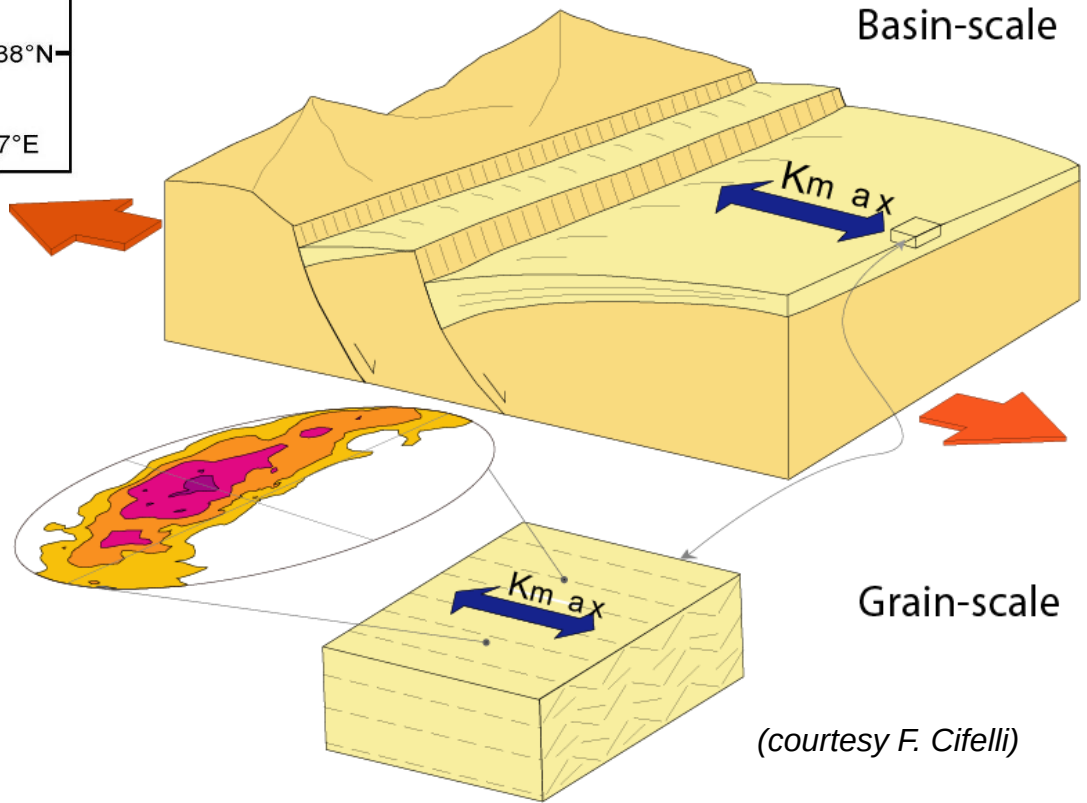




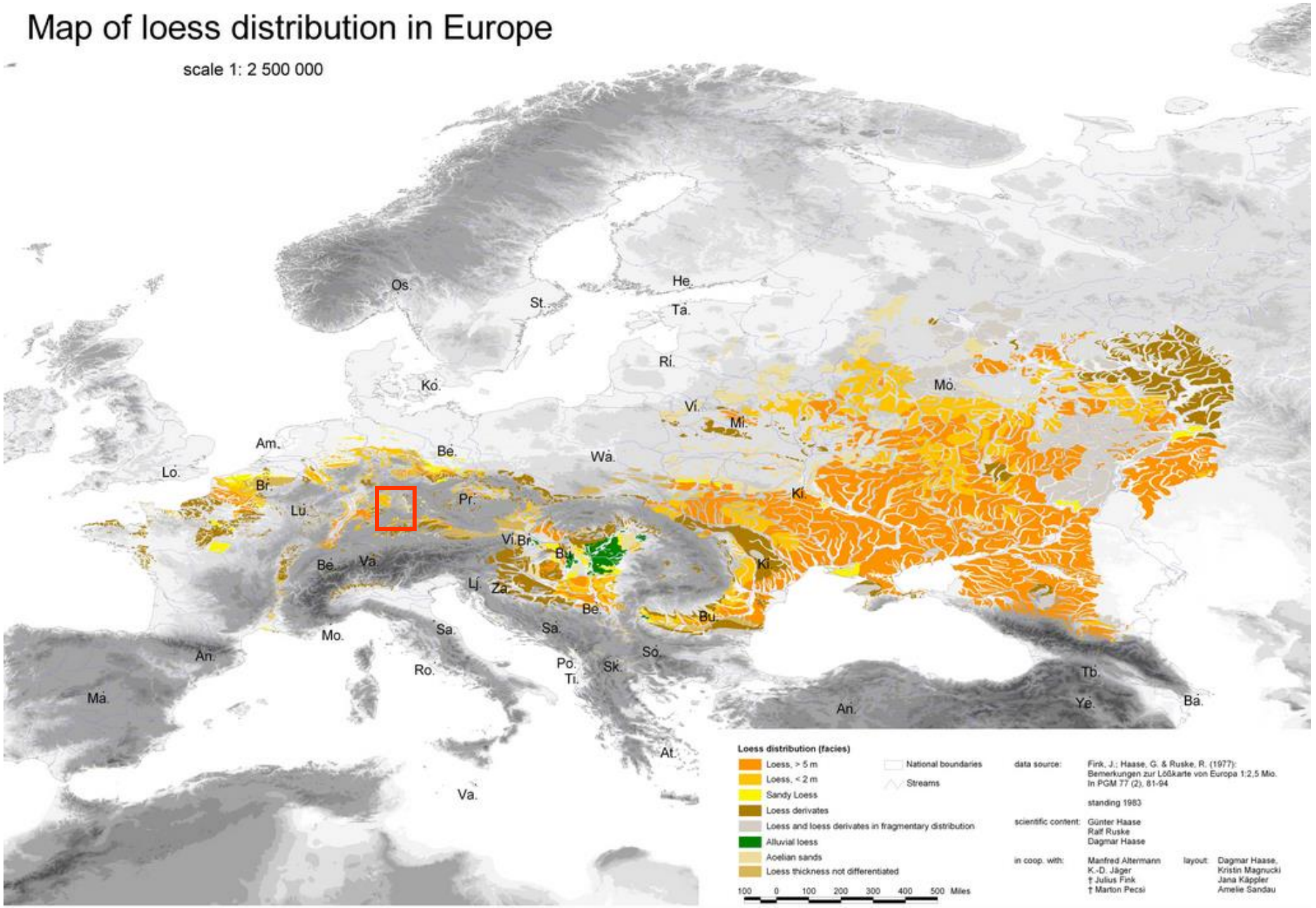
Extentional tectonic setting

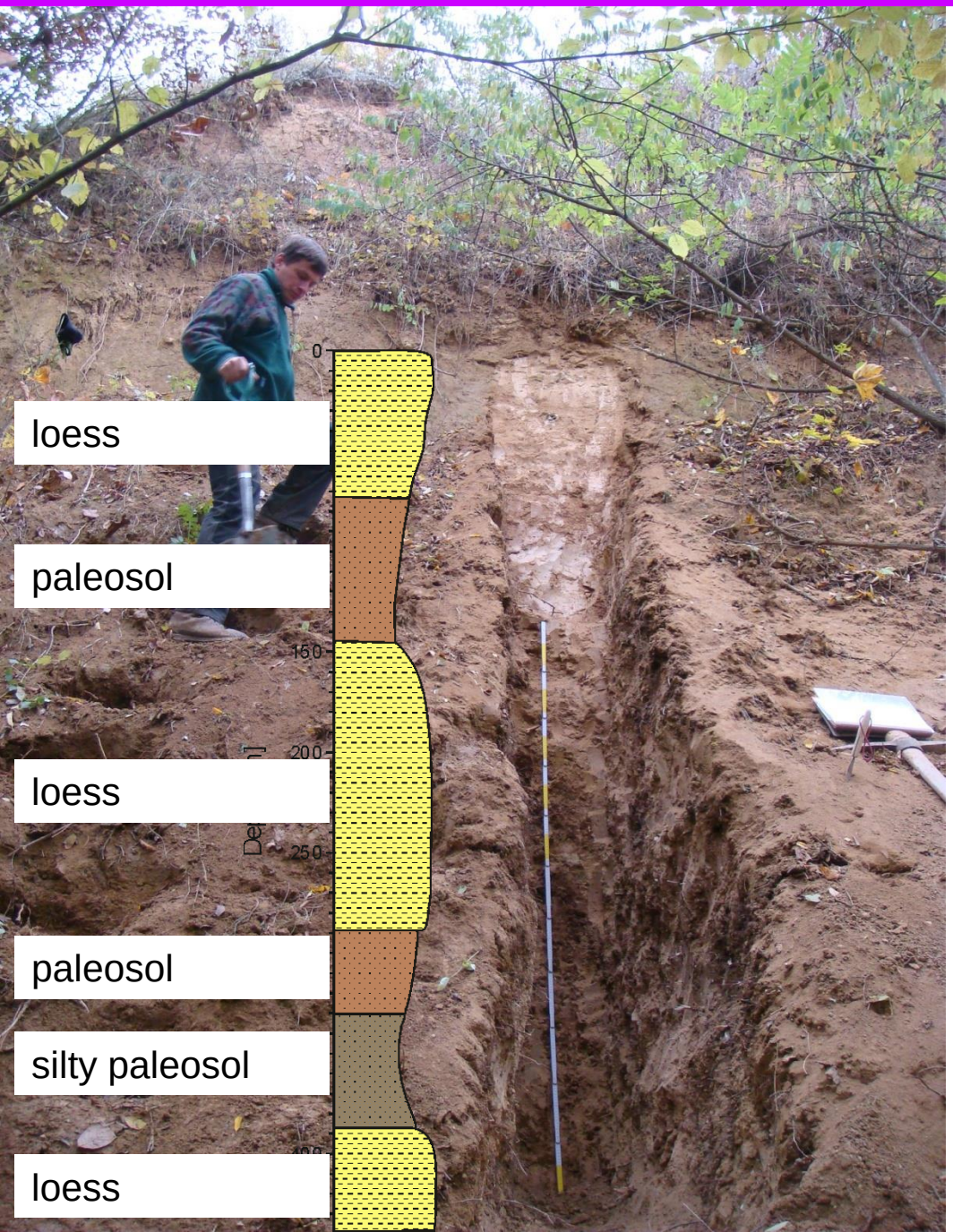
- *Extentional setting*
- *Neogene basin, southern Italy*

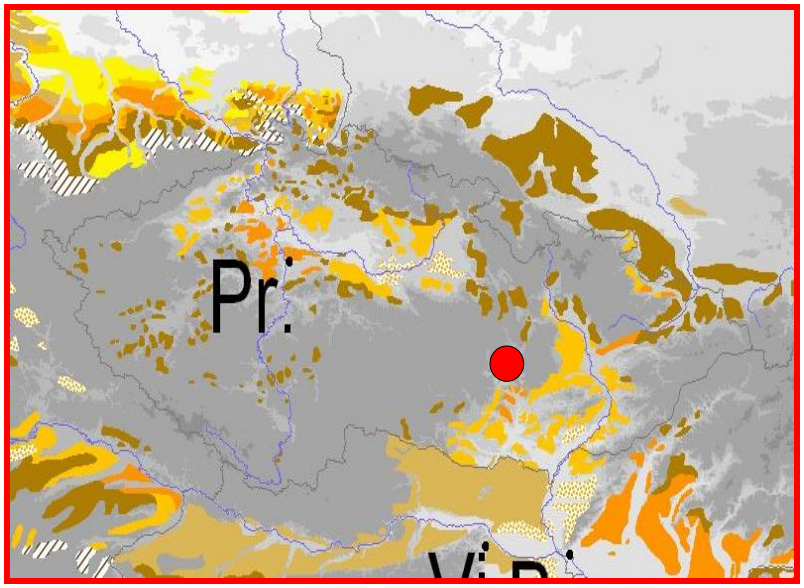


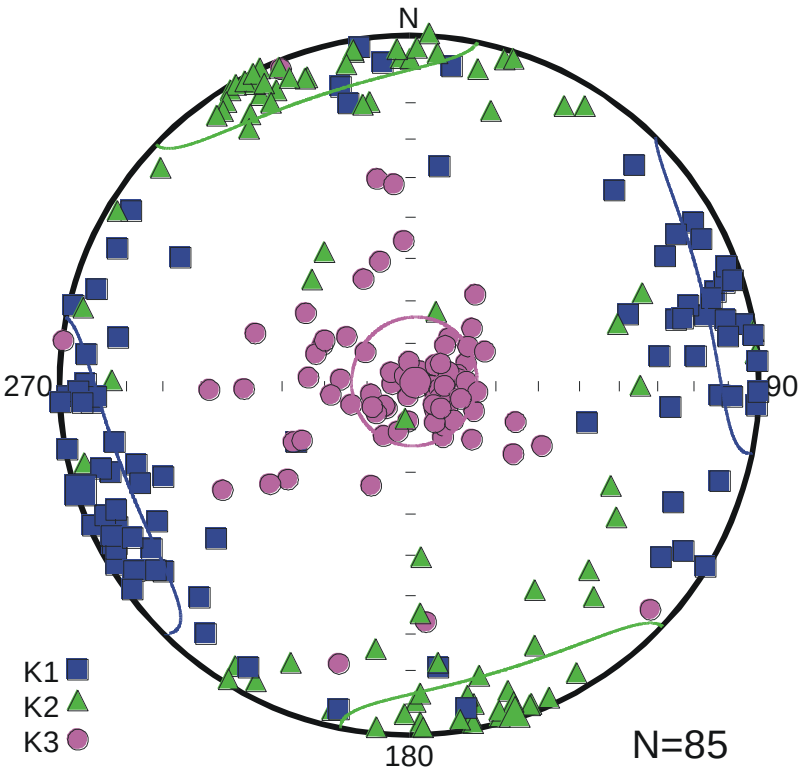


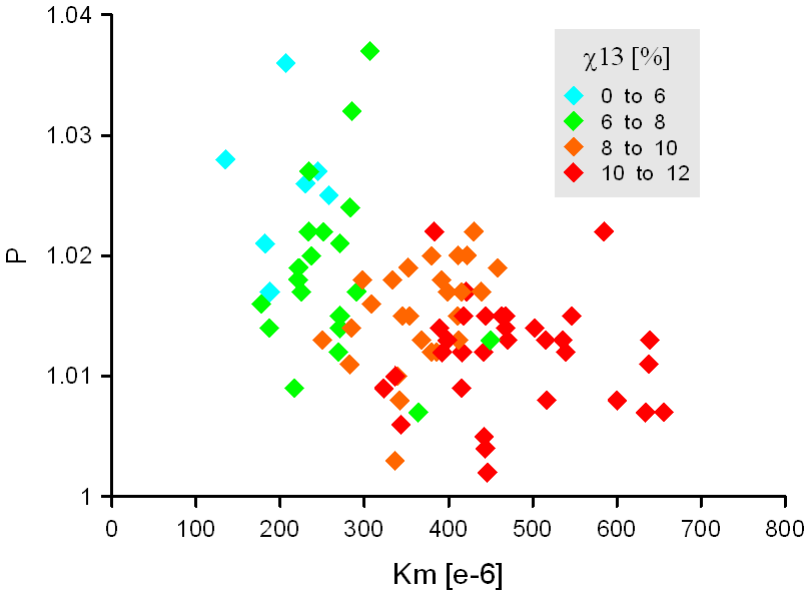
(courtesy F. Cifelli)

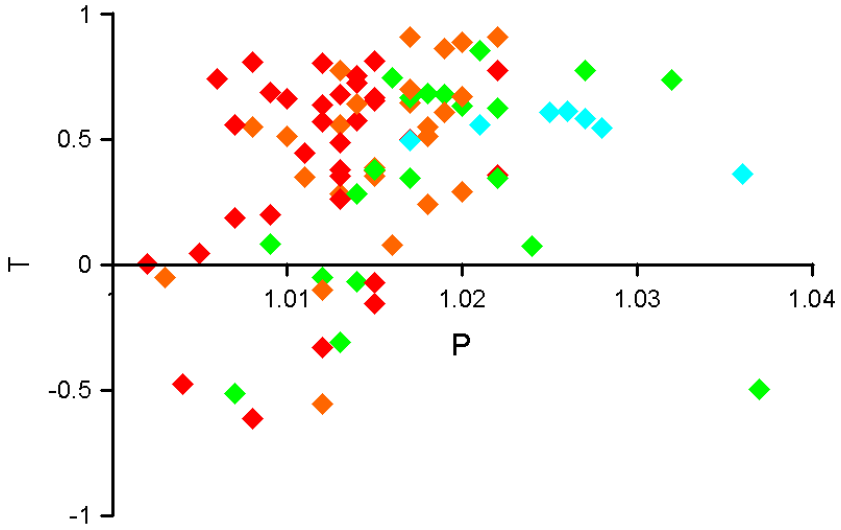

Map of loess distribution in Europe
scale 1: 2 500 000
Os.
St.
He.
Ta.
Ri.
Ko.
Mo.
Vi.
Mi.
Am.
Be.
Wa.
Lo.
Br.
Lu.
Pr.
Ki.
Vi.
Br.
Bu.
Be.
Va.
Li.
Za.
Ki.
Be.
Bu.
Mo.
Sa.
Sa.
An.
So.
Ro.
Po.
Ti.
Sk.
Tb.
Ma.
An.
Ye.
Ba.
At.
Va.
Loess distribution (facies)
Loess, > 5 m
Loess, < 2 m
Sandy Loess
Loess derivates
Loess and loess derivates in fragmentary distribution
Alluvial loess
Aeolian sands
Loess thickness not differentiated
National boundaries
Streams
100 0 100 200 300 400 500 Miles
data source:
Fink, J.; Haase, G. & Ruske, R. (1977): Bemerkungen zur Lößkarte von Europa 1:2,5 Mio. In PGM 77 (2), 81-94
standing 1983
scientific content:
Günter Haase
Ralf Ruske
Dagmar Haase
in coop. with:
Manfred Altermann
K.-D. Jäger
† Julius Fink
† Marton Pecsi
layout:
Dagmar Haase,
Kristin Magnucki
Jana Käppler
Amelie Sandau


loess
paleosol
loess
paleosol
silty paleosol
loess

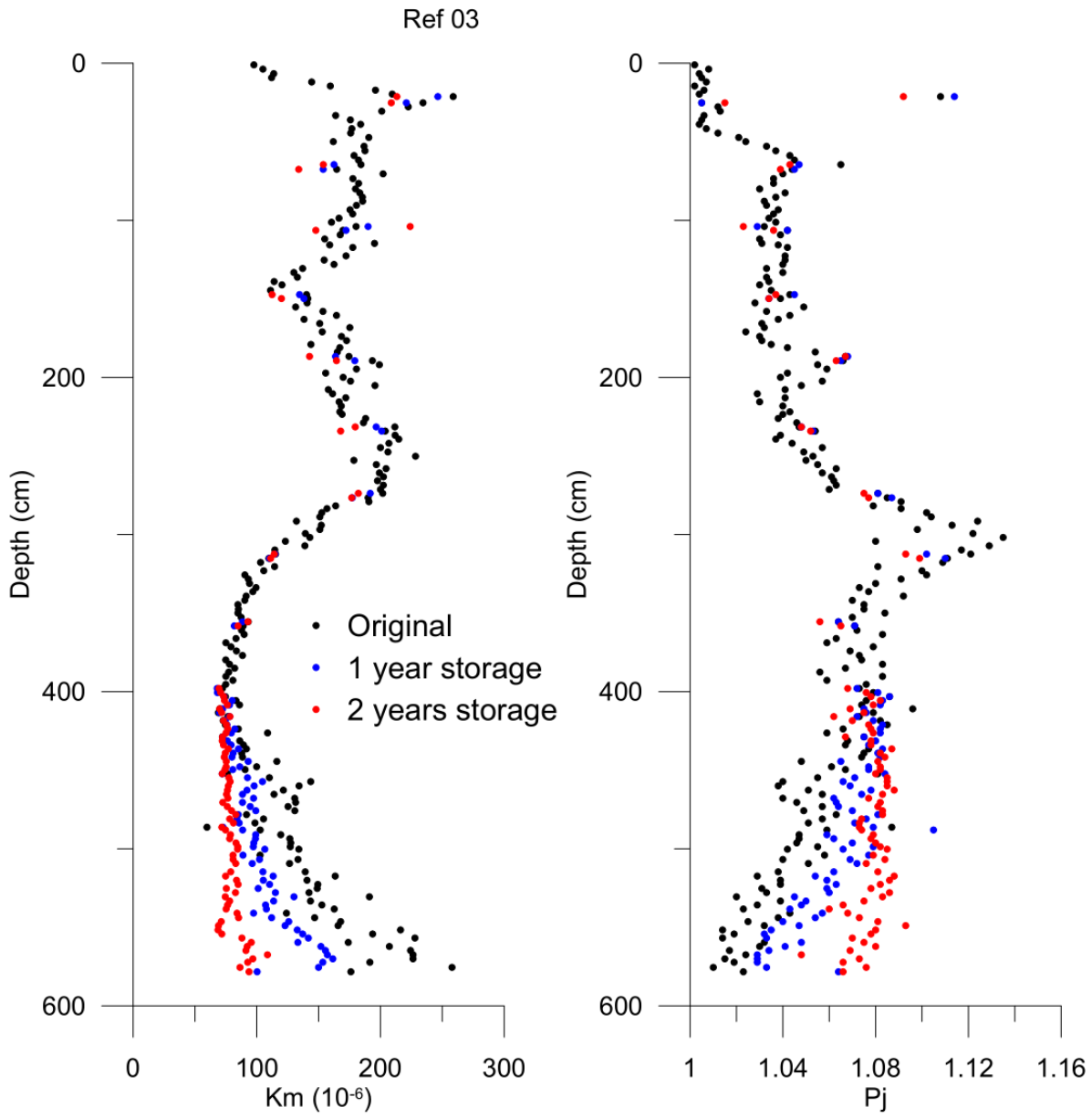

Pr.

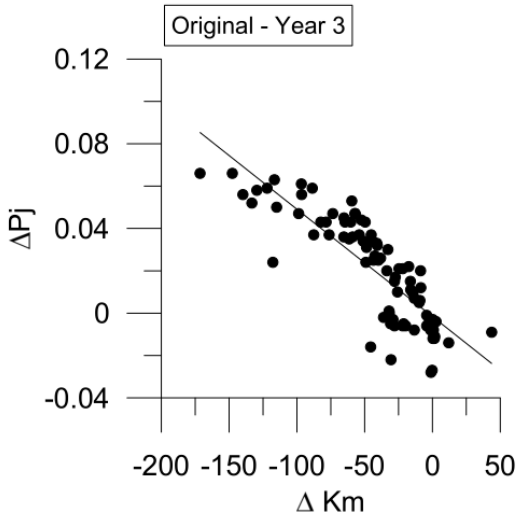

N
270
90
180
K1
K2
K3
N=85

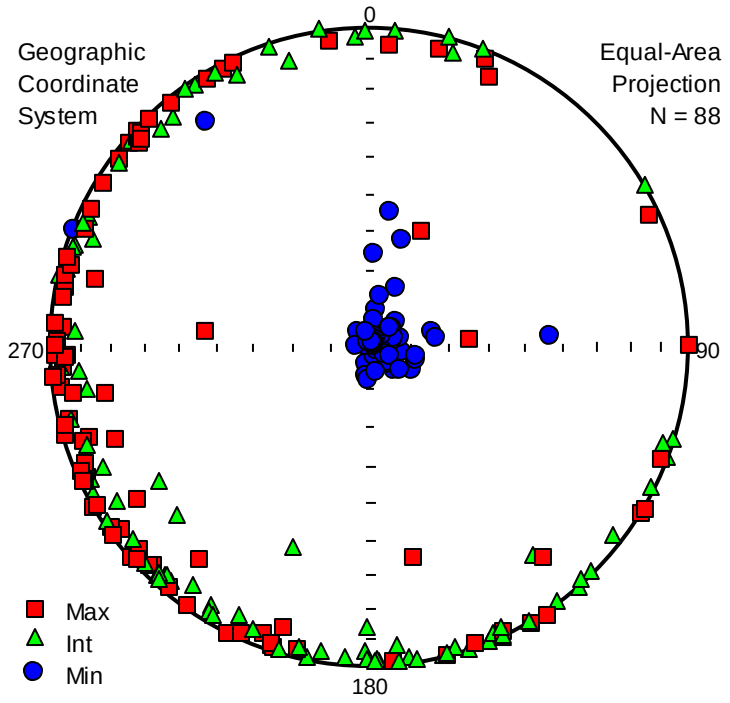

χ13 [%]
0 to 6
6 to 8
8 to 10
10 to 12
P
Km [e-6]
1.04
1.03
1.02
1.01
1
0
100
200
300
400
500
600
700
800

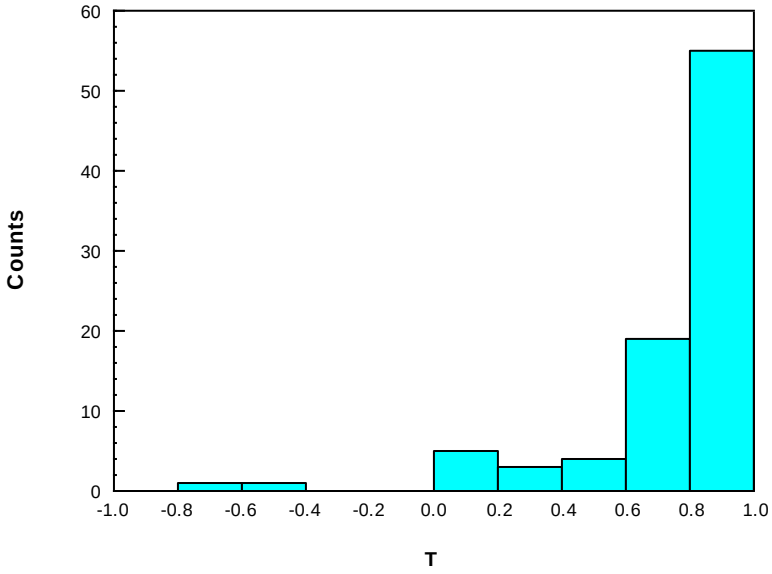

T
P
1
0.5
0
-0.5
-1
1.01
1.02
1.03
1.04

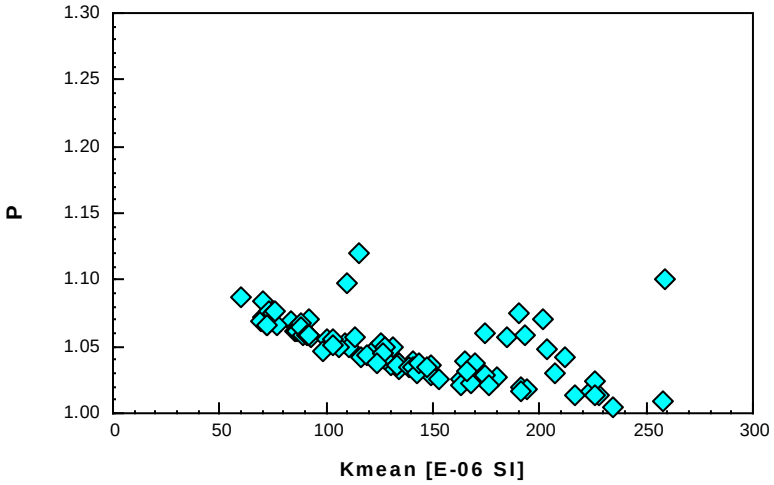
Cross-section of unconsolidated sediment from Baltic Sea

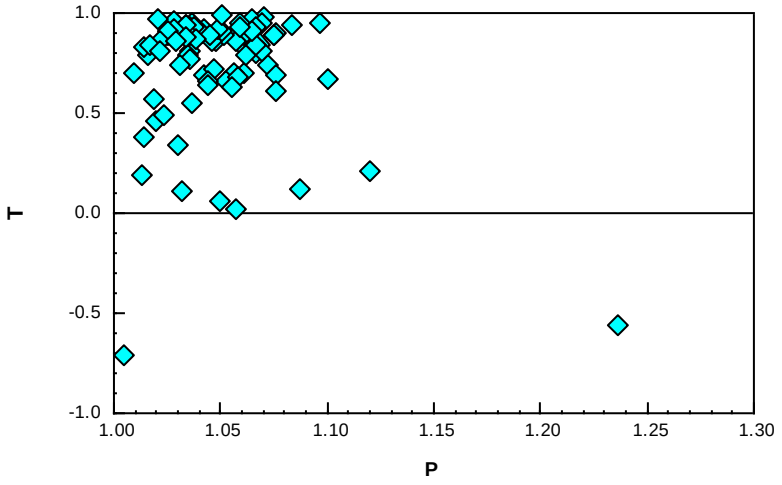


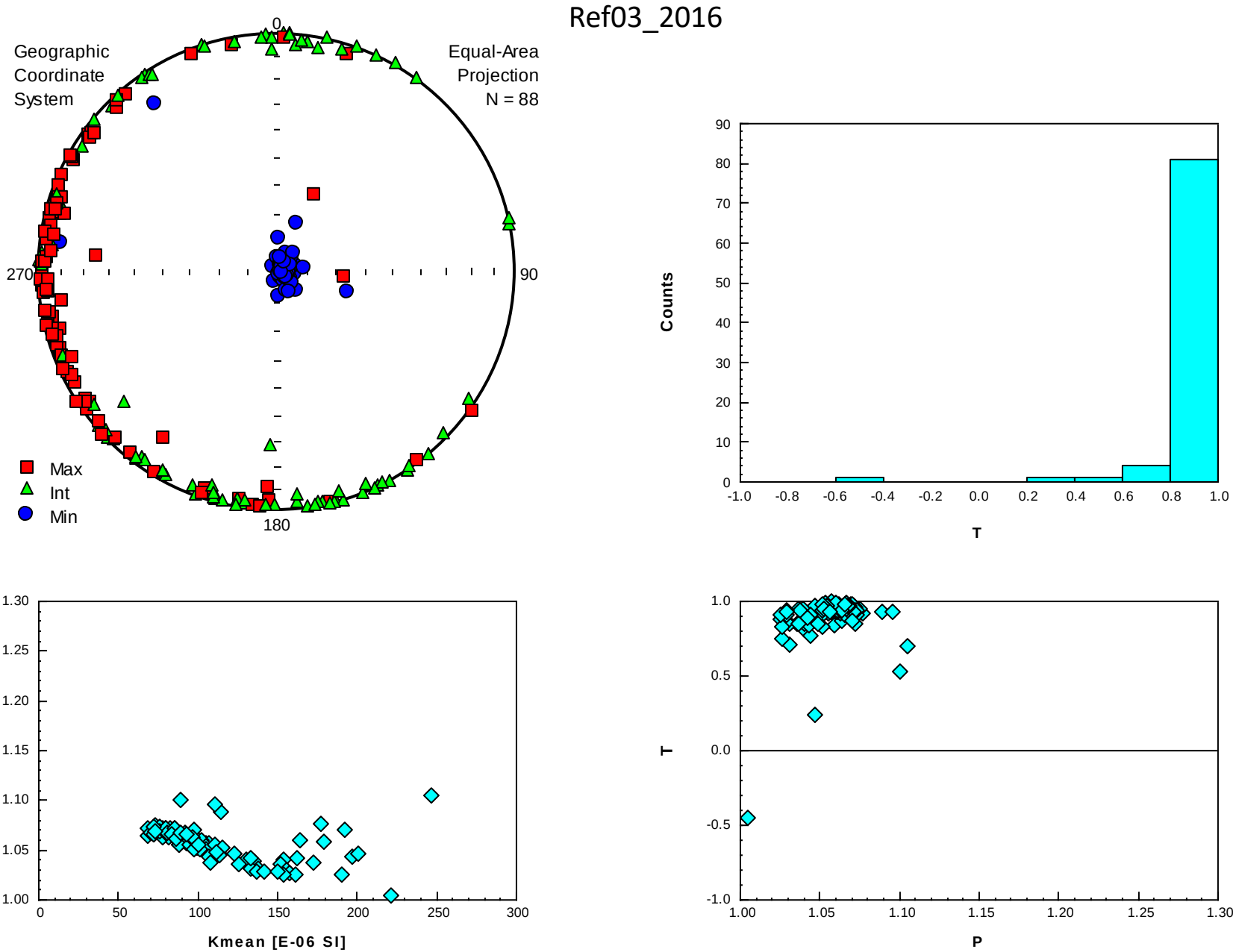



Ref03_2015
Geographic
Coordinate
System
Equal-Area
Projection
N = 88
0
90
180
270
Max
Int
Min

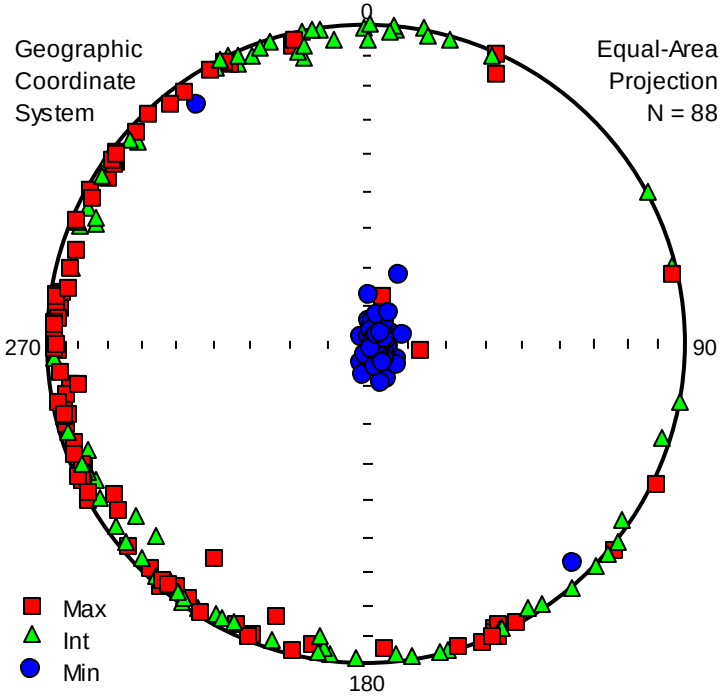

Counts
T
60
50
40
30
20
10
0
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

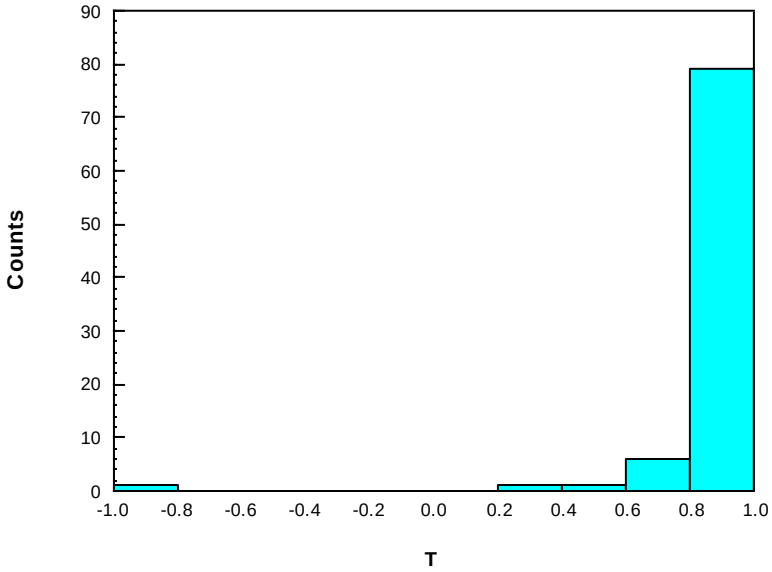

P
Kmean [E-06 SI]
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0
50
100
150
200
250
300

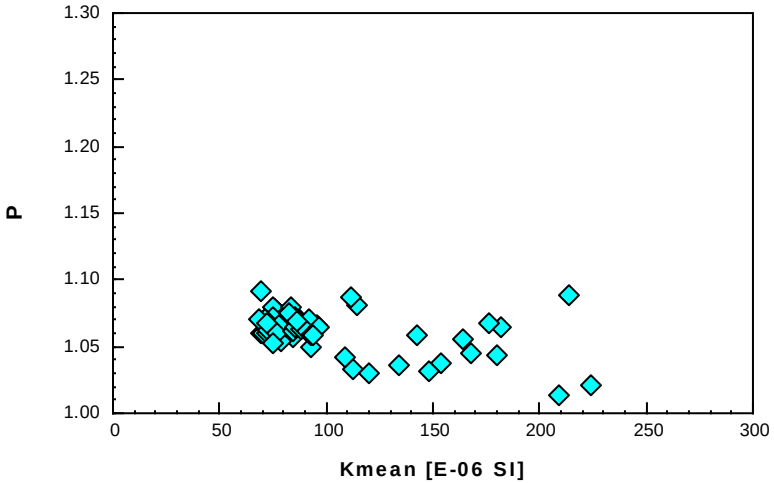

T
P
1.0
0.5
0.0
-0.5
-1.0
1.00
1.05
1.10
1.15
1.20
1.25
1.30

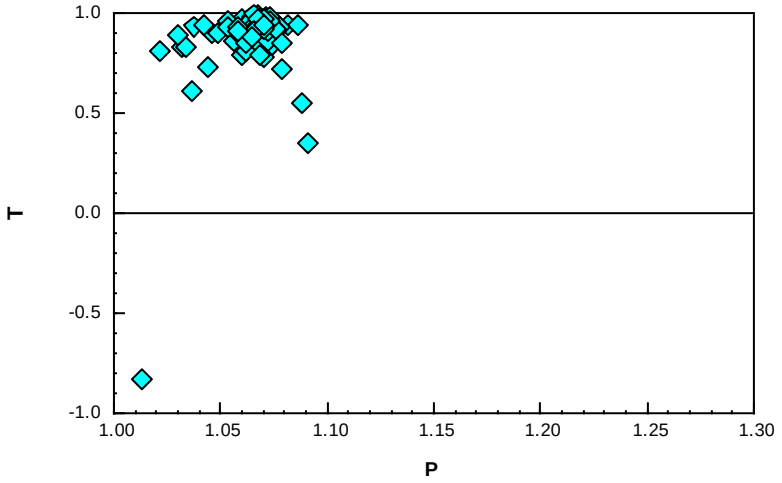

Ref03_2016
Geographic
Coordinate
System
Equal-Area
Projection
N = 88
0
90
180
270
Max
Int
Min
Counts
T
P
Kmean [E-06 SI]
T
P

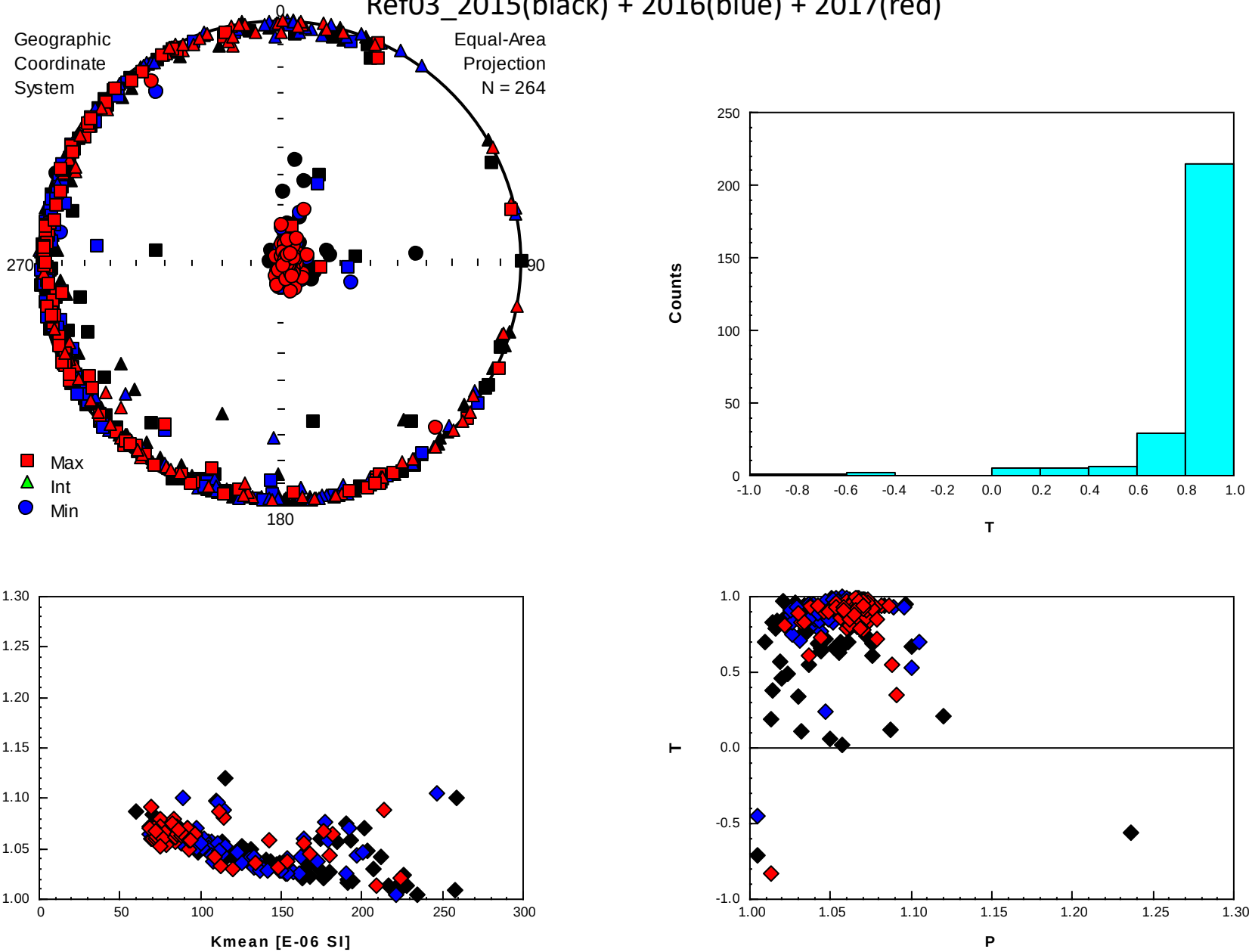
Ref03_2017

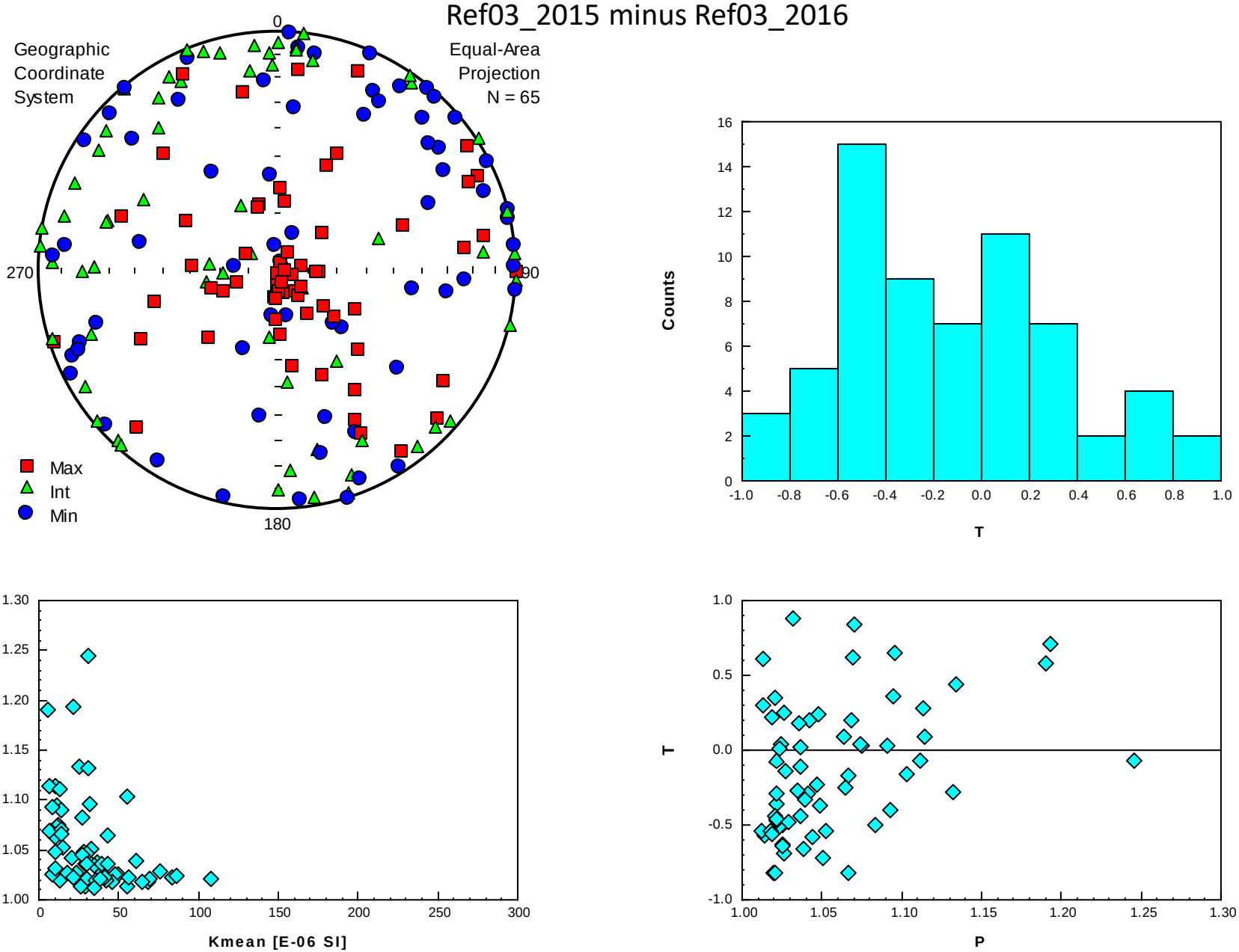

Geographic
Coordinate
System
Equal-Area
Projection
N = 88
0
90
180
270
Max
Int
Min

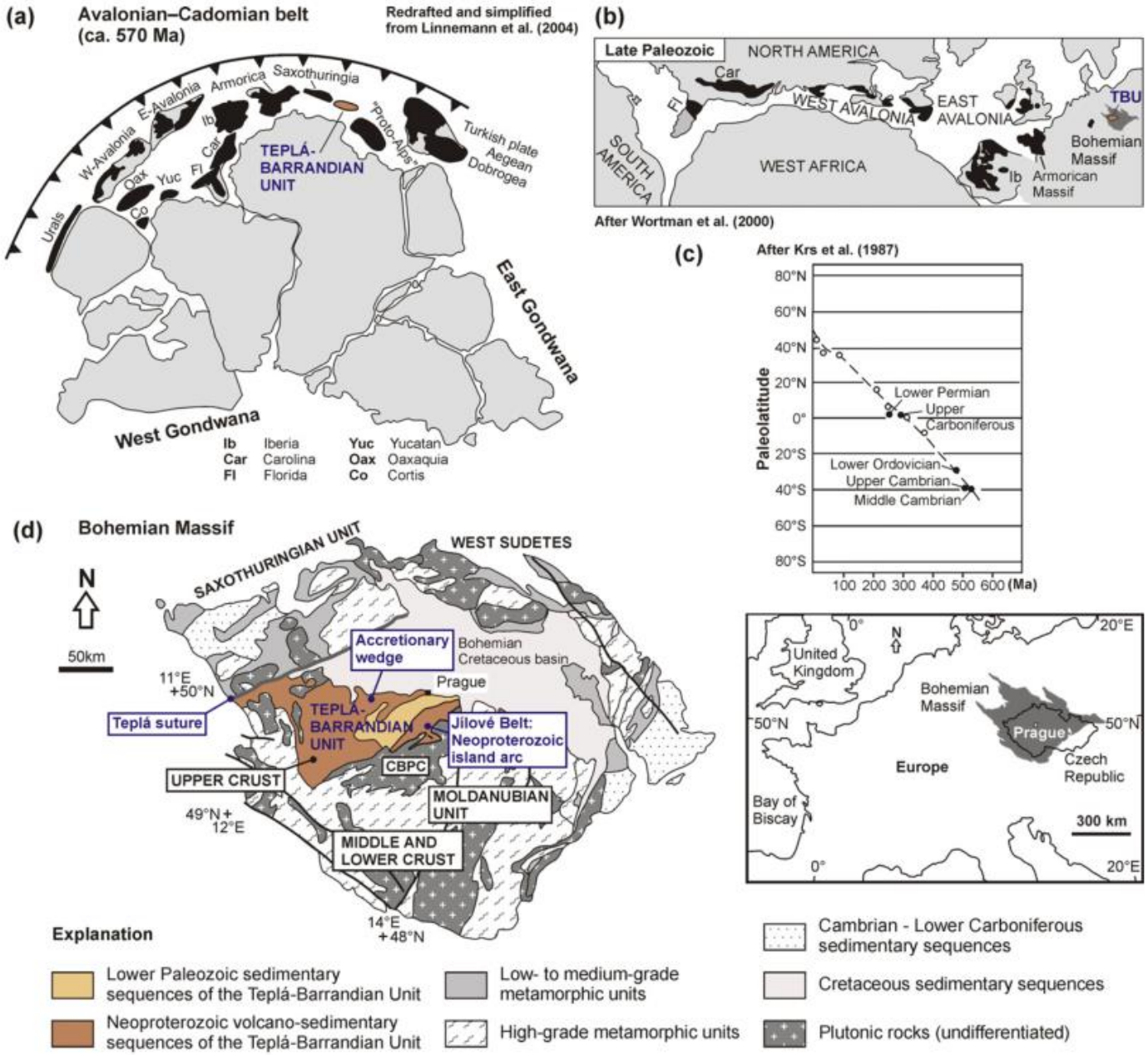

Counts
T
90
80
70
60
50
40
30
20
10
0
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0


P
Kmean [E-06 SI]
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0
50
100
150
200
250
300

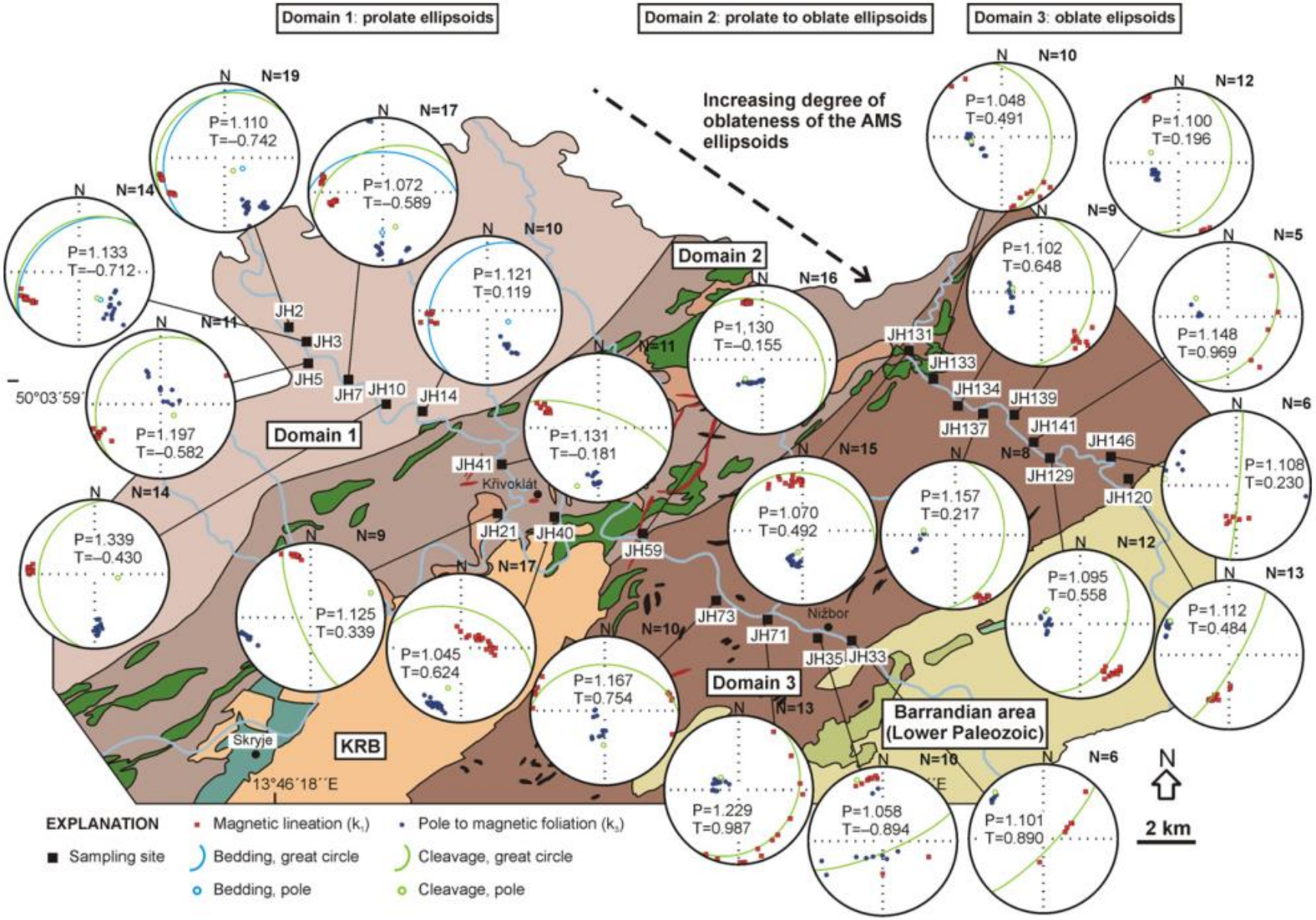

T
P
1.0
0.5
0.0
-0.5
-1.0
1.00
1.05
1.10
1.15
1.20
1.25
1.30


Ref03_2015(black) + 2016(blue) + 2017(red)
Geographic
Coordinate
System
Equal-Area
Projection
N = 264
0
90
180
270
Max
Int
Min
Counts
T
P
Kmean [E-06 SI]

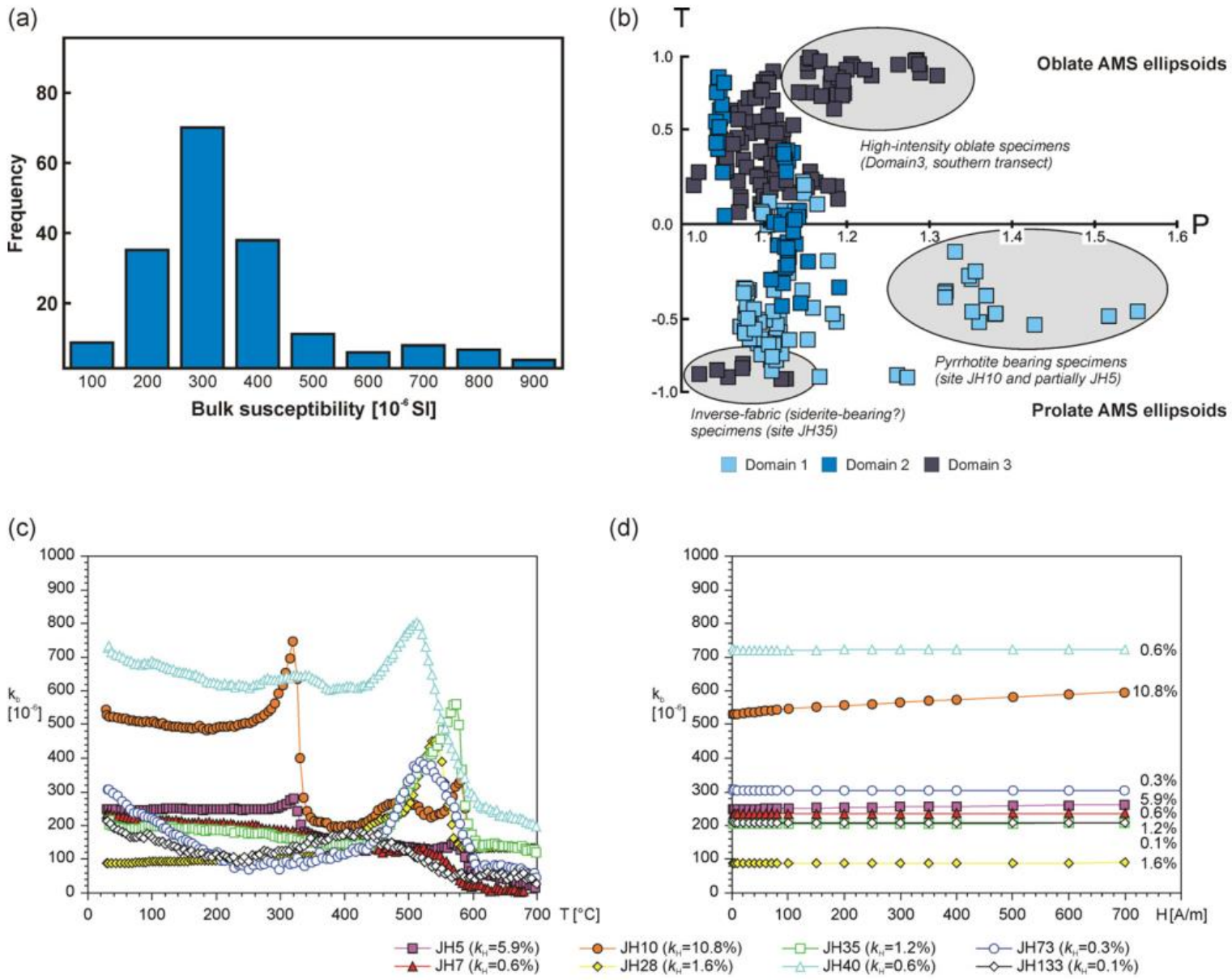

Ref03_2015 minus Ref03_2016
Geographic
Coordinate
System
Equal-Area
Projection
N = 65
0
90
180
270
Max
Int
Min
Counts
T
P
Kmean [E-06 SI]
T
P



(Hajná et al. 2010)



(Hajná et al. 2010)



(Hajná et al. 2010)

Agenda

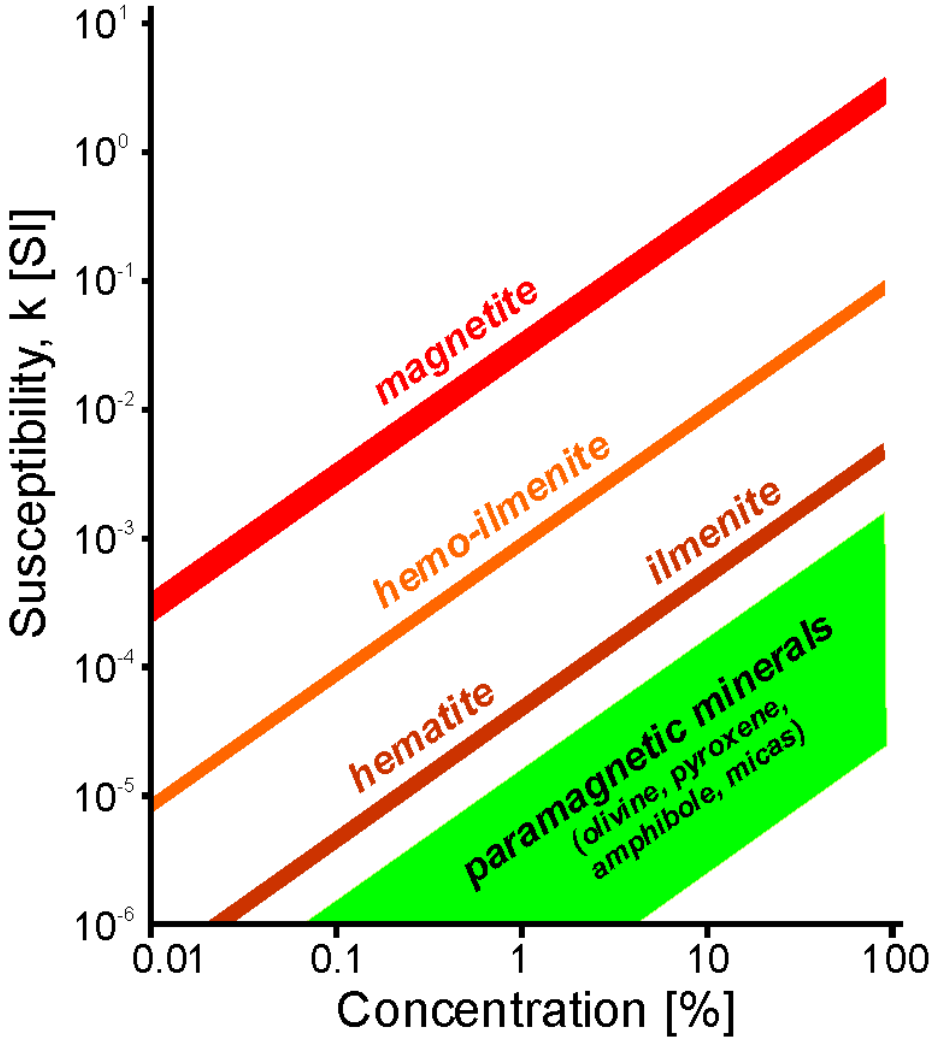
1. Definition and application in geology
2. Magnetic anisotropy of minerals
3. Magnetic fabric vs. texture of rocks
4. Magnetic fabric of sedimentary, deformed, and metamorphosed rocks
5. Magnetic fabric of igneous rocks
6. Sampling, measurement and data processing

1. **Volcanic rocks**

2. **Dikes**

3. **Plutonic rocks**

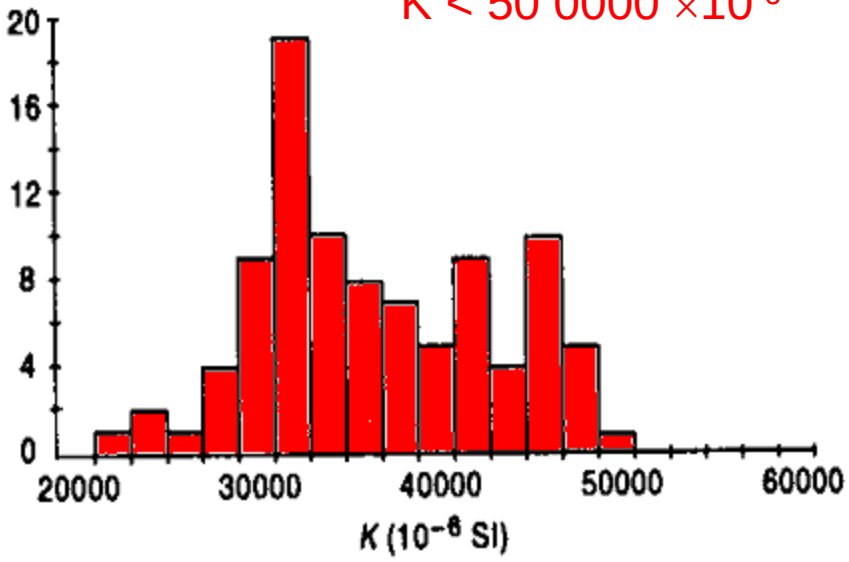
Magnetic susceptibility dominantly carried by magnetite



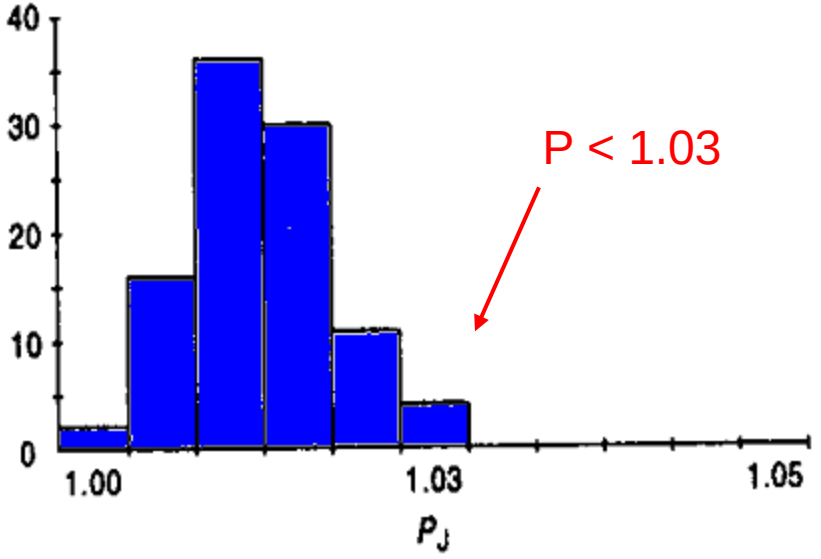
Igneous rocks

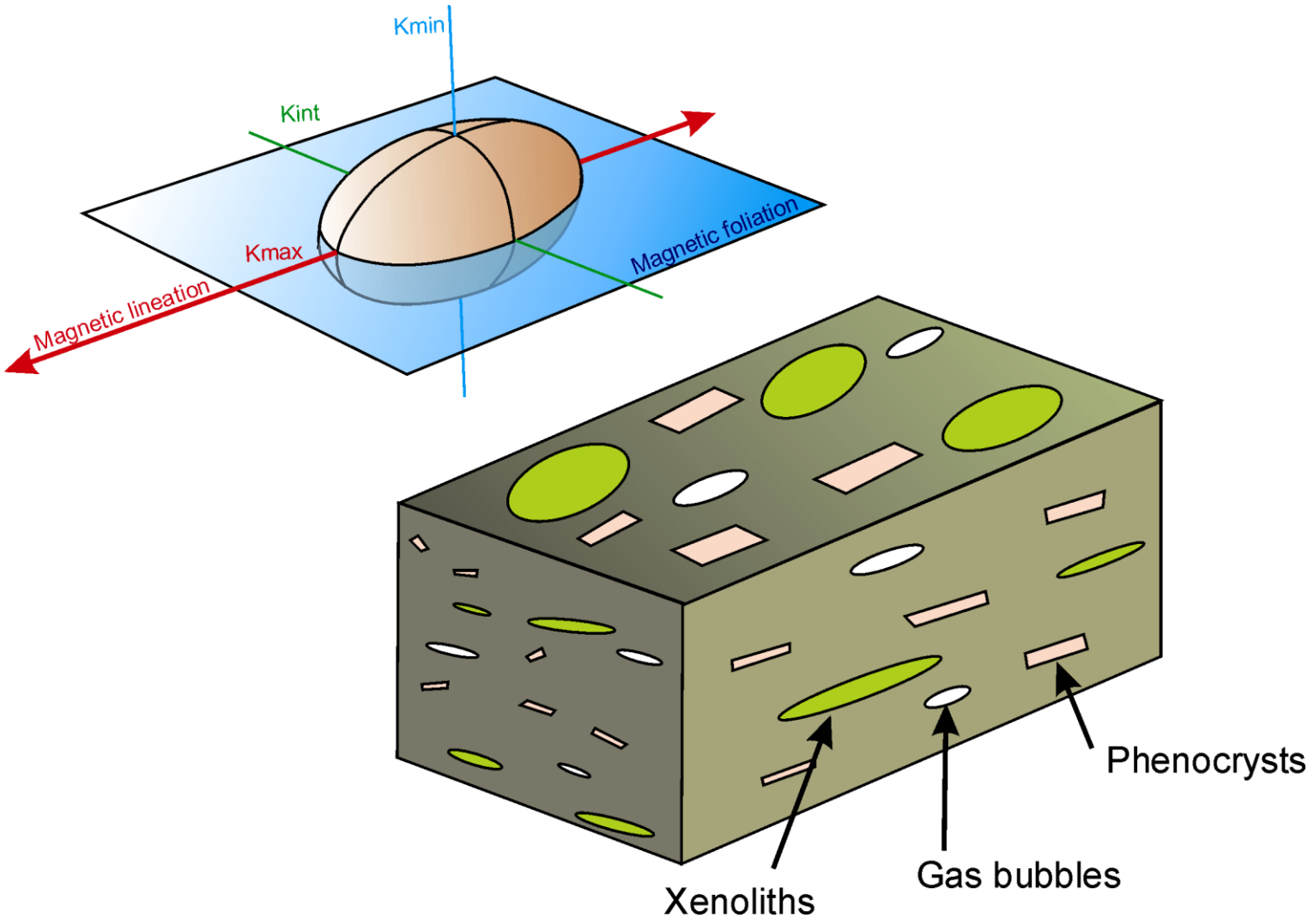
Very high magnetic susceptibility

$K < 50\ 0000 \times 10^{-6}$

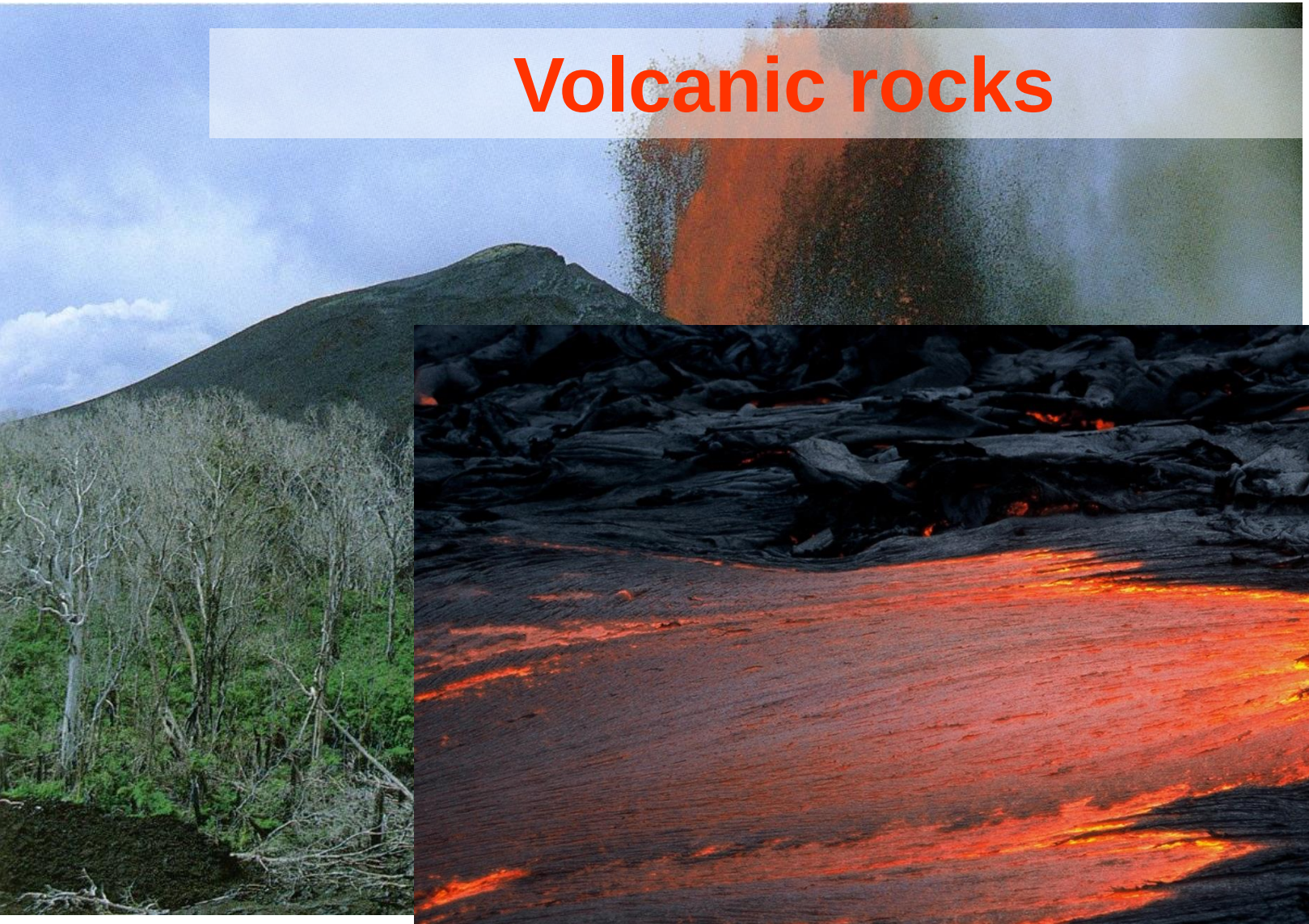


Relatively low anisotropy degree



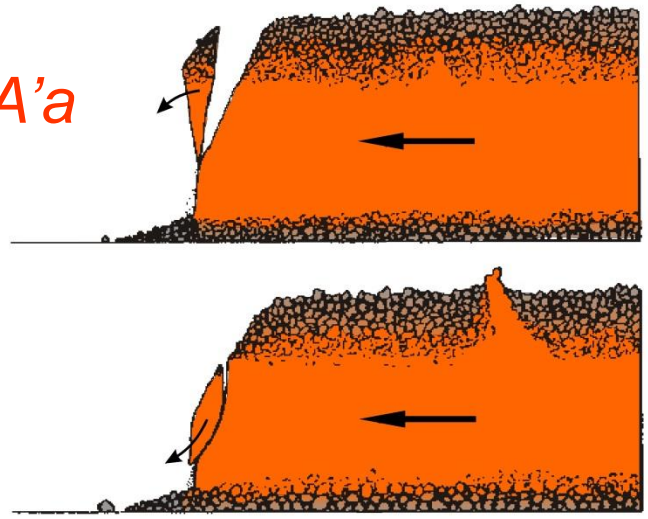

Kmin
Kint
Kmax
Magnetic lineation
Magnetic foliation
Phenocrysts
Gas bubbles
Xenoliths

Volcanic rocks

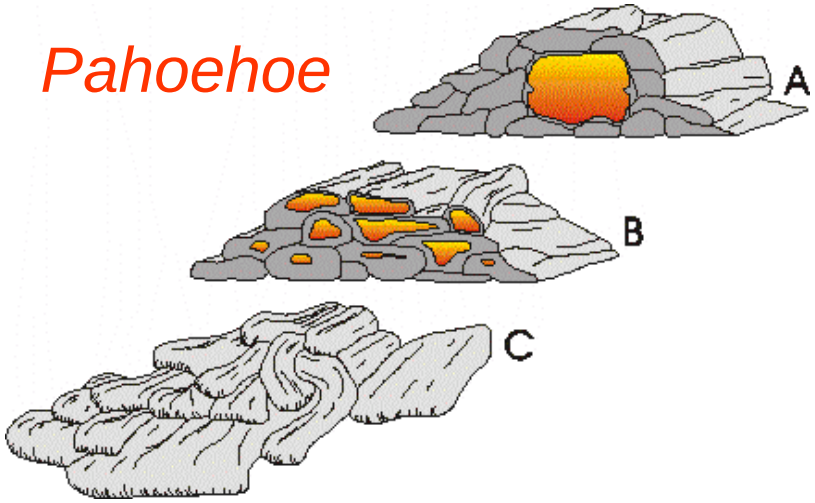


Lava flows

A'a

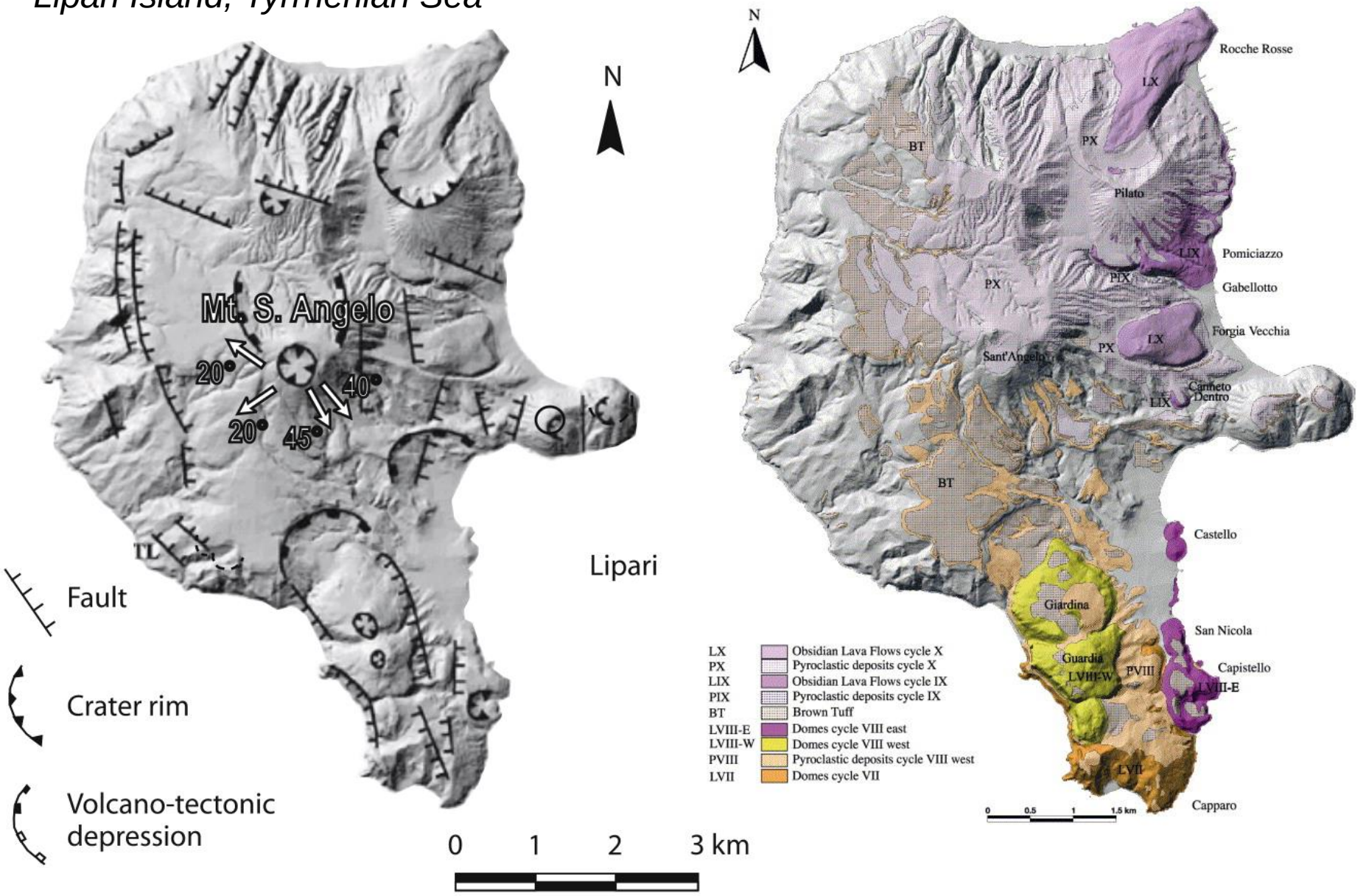


Pahoehoe

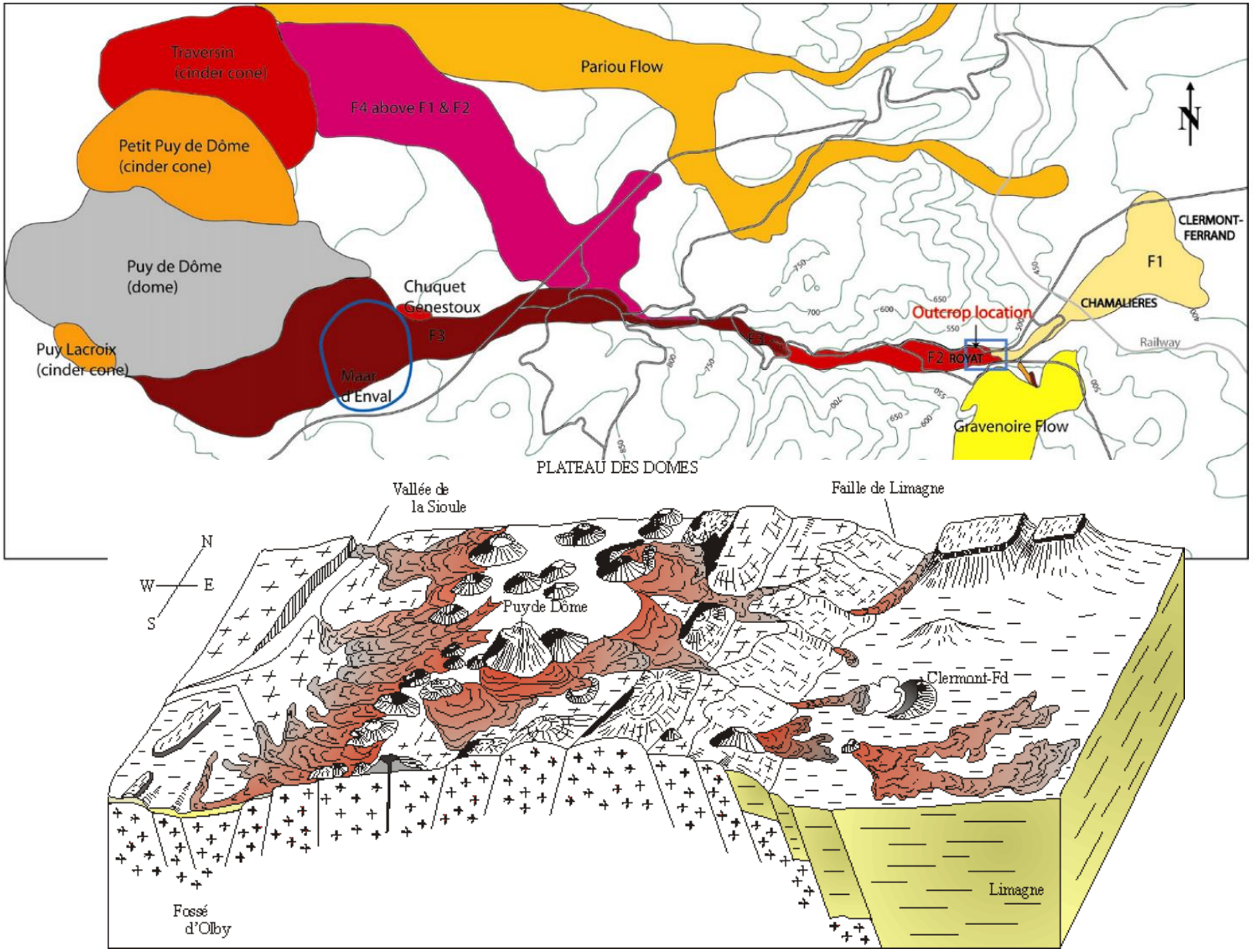


Lipari Island, Tyrrhenian Sea, Italy

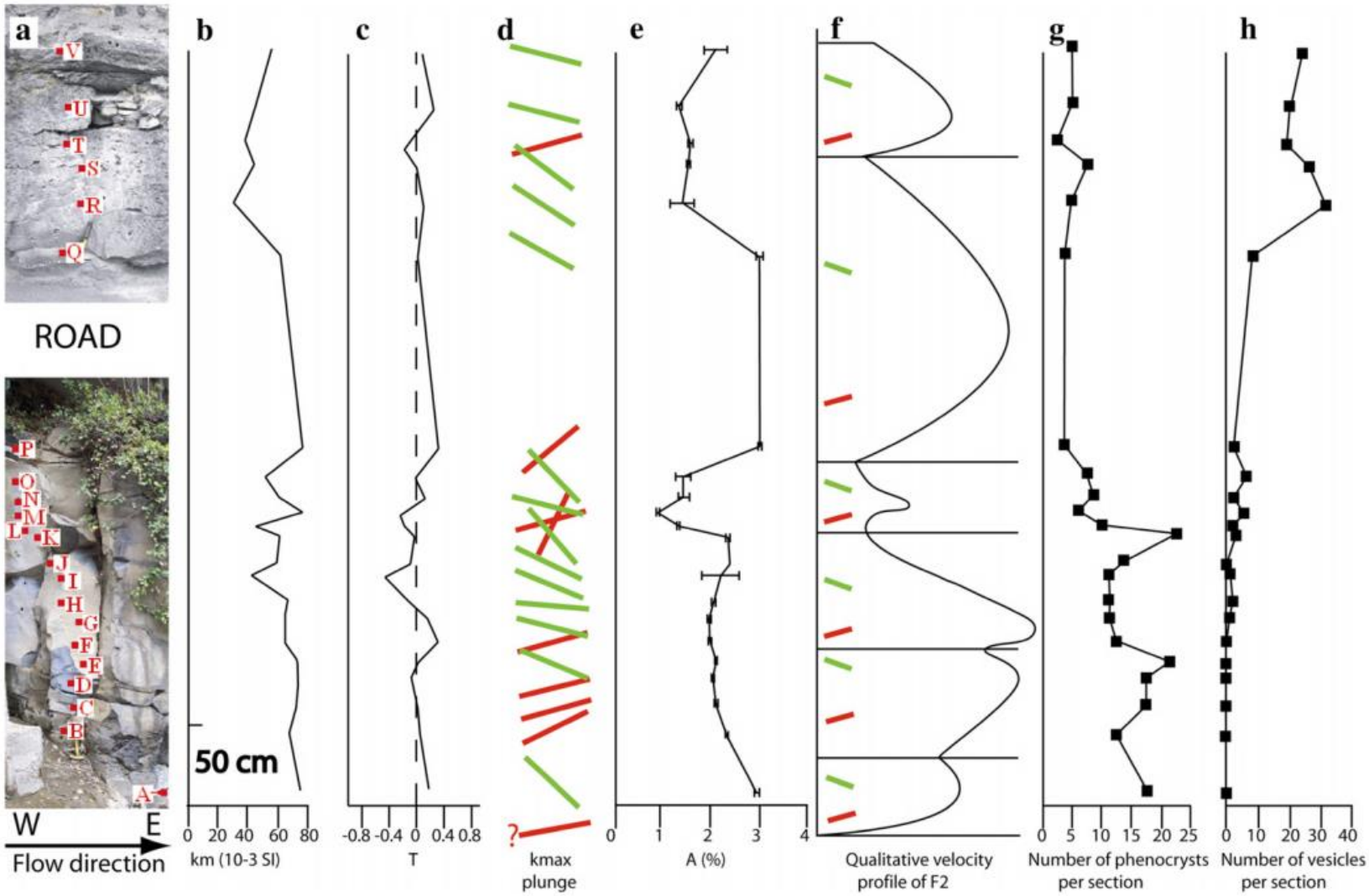
Lipari Island, Tyrrhenian Sea



Chaîne des Puys, Massif Central, France



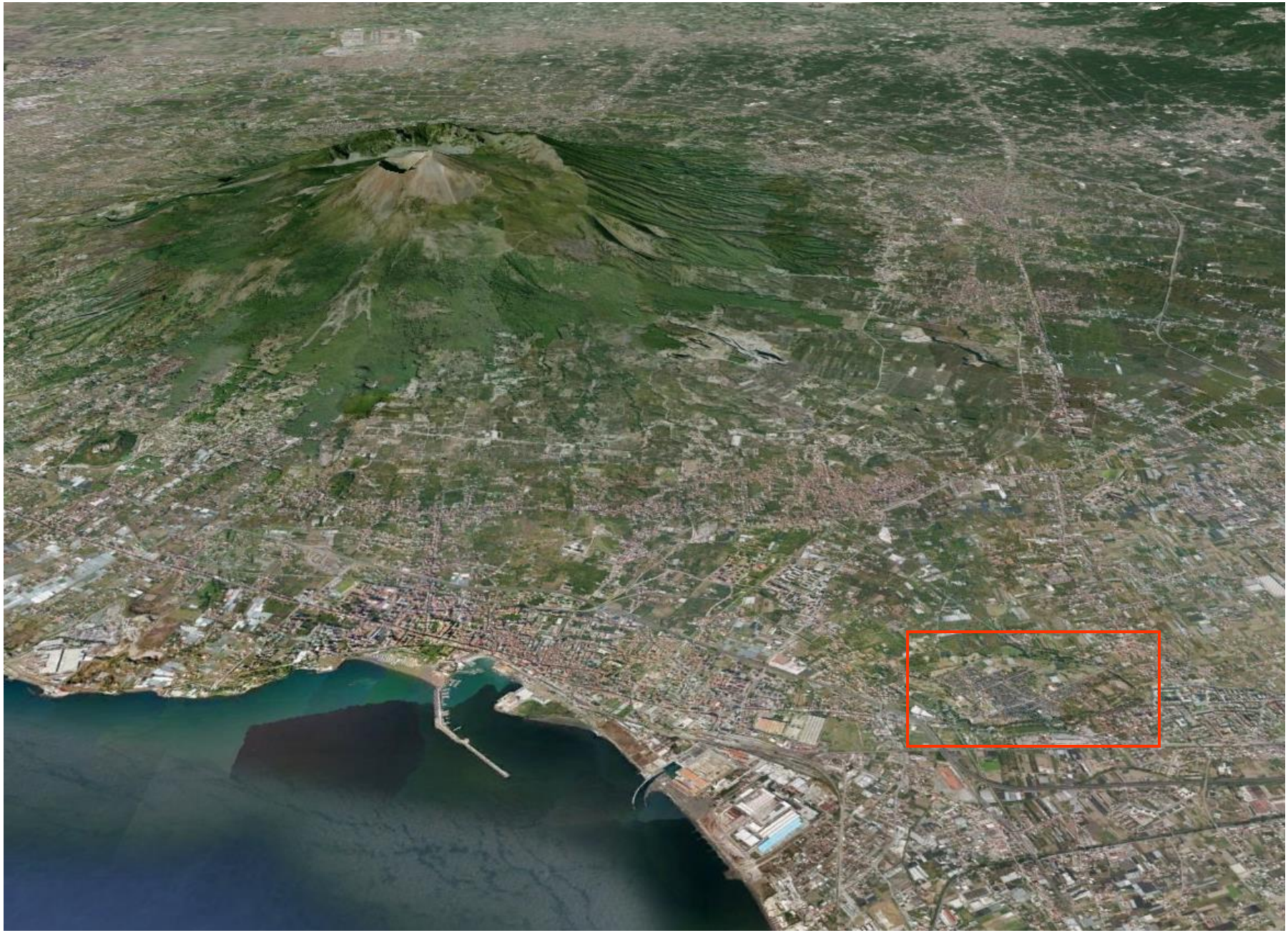
Section across lava flow

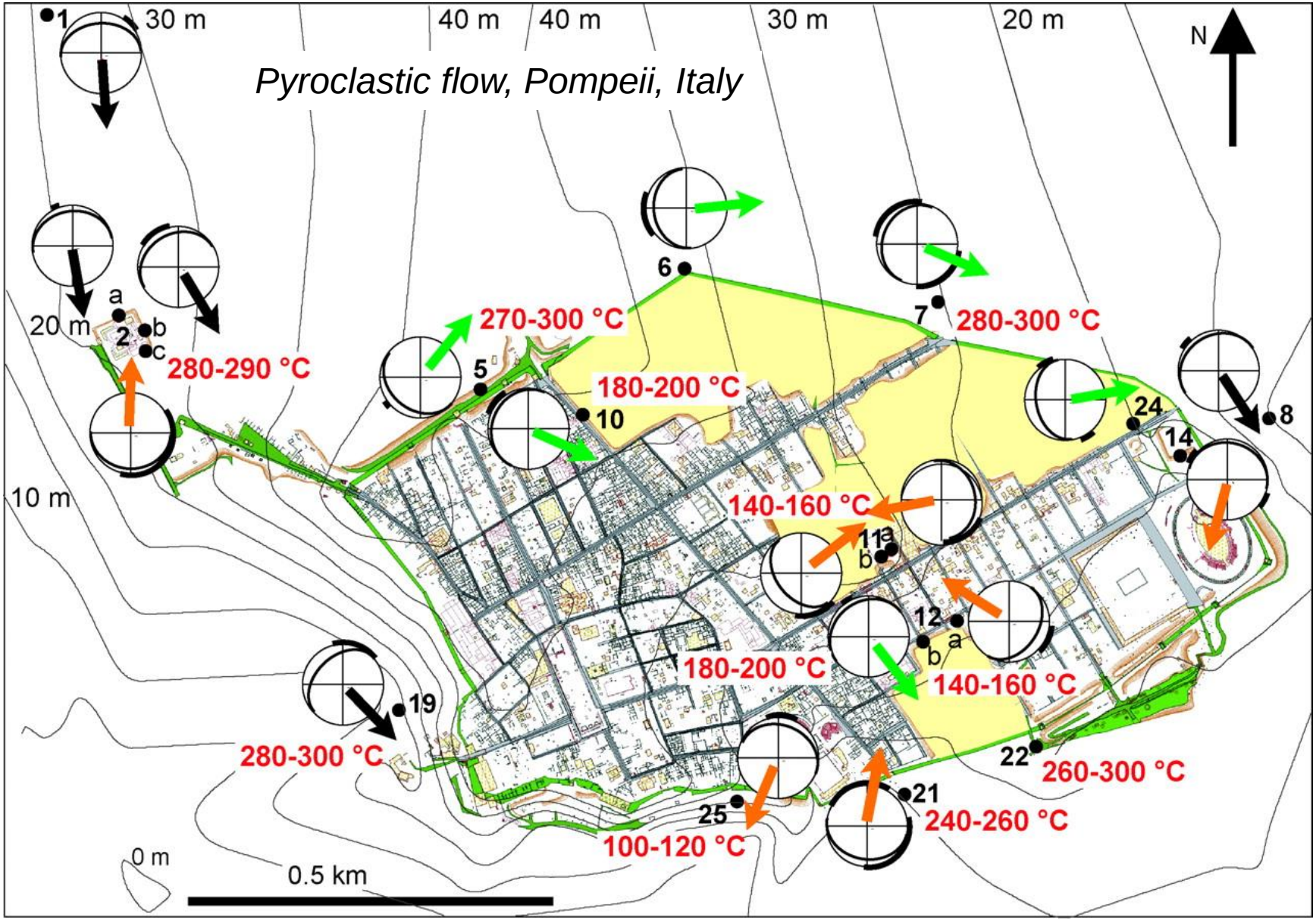


(Loock et al. 2008)

Pyroclastic flow, Pompeii, Italy

(Gurioli et al. 2005)

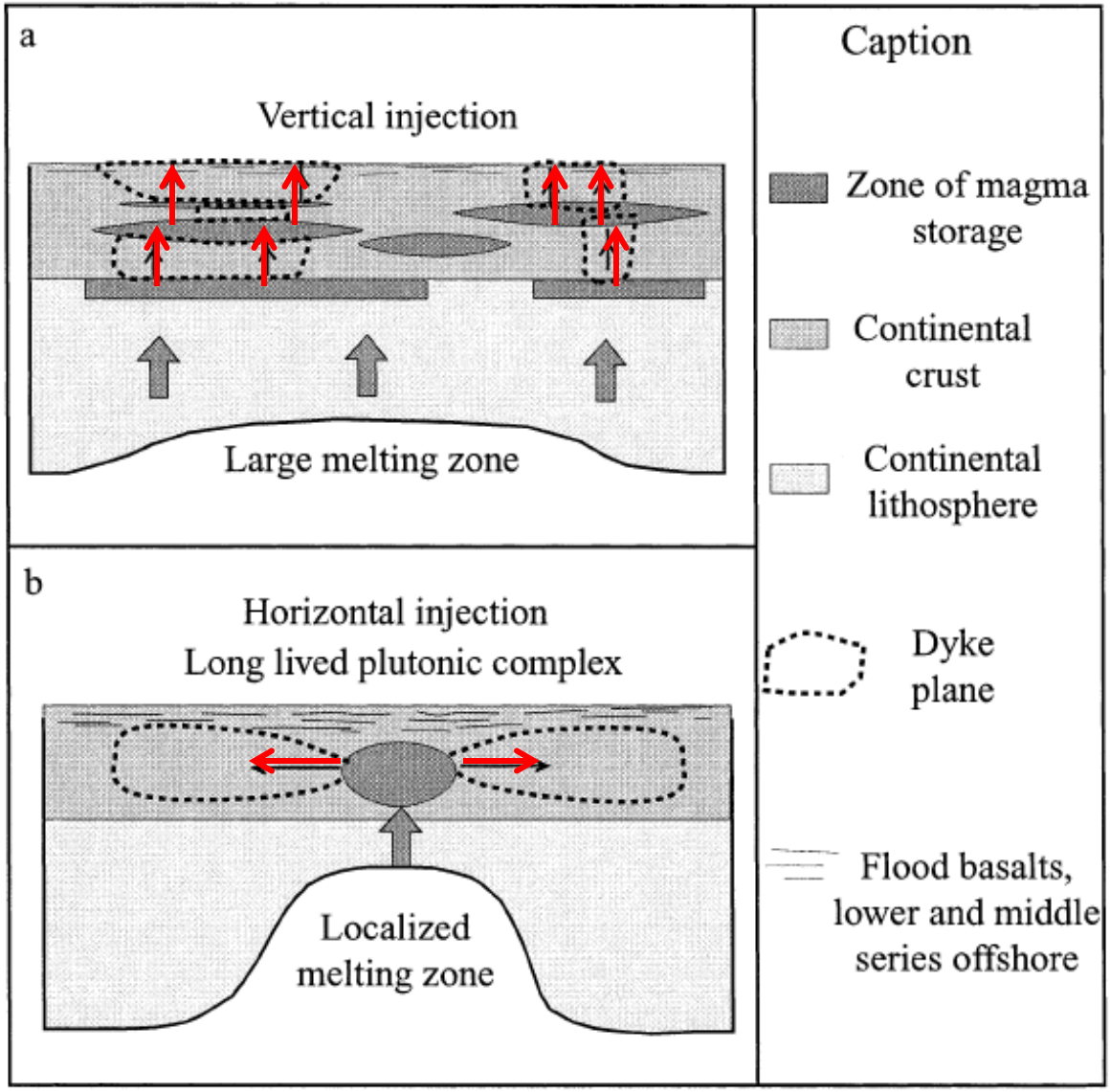




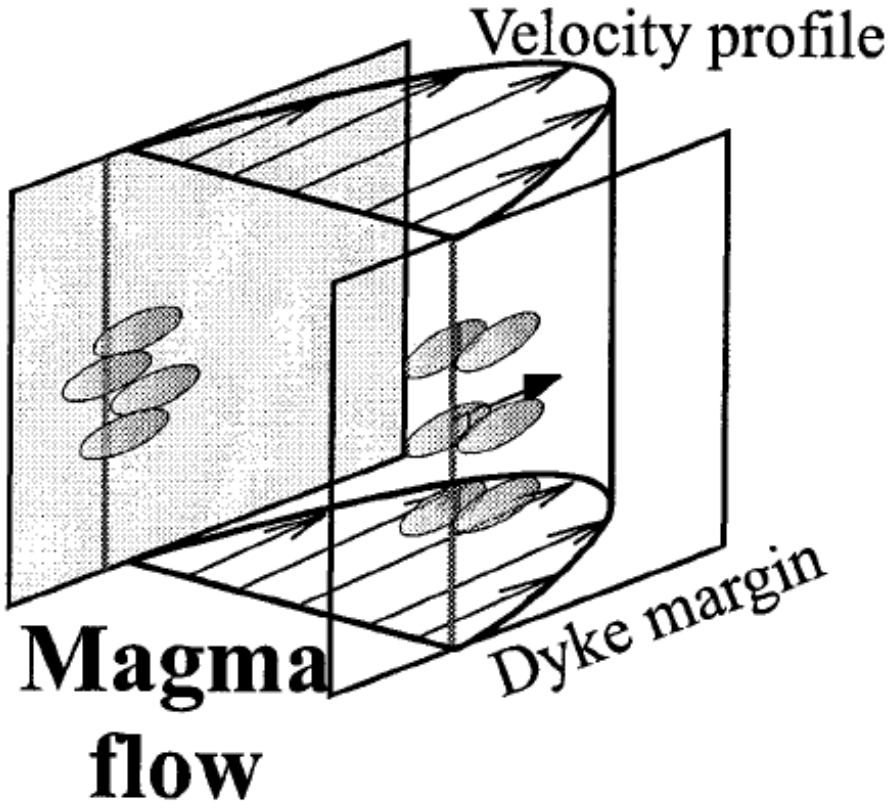
(Gurioli et al. 2005)

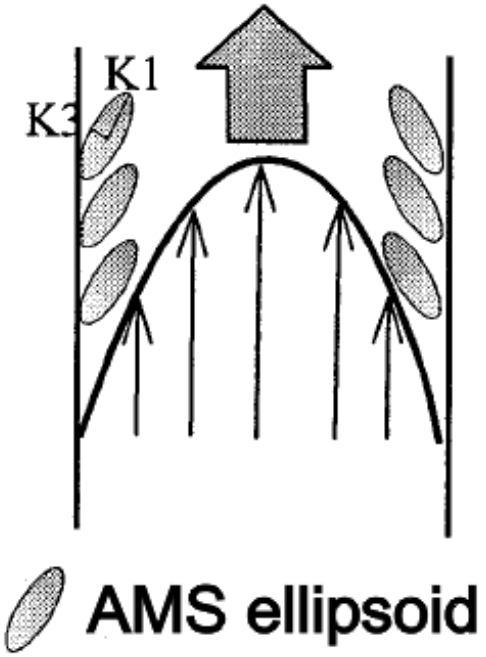
Dikes

Estimate of flow direction

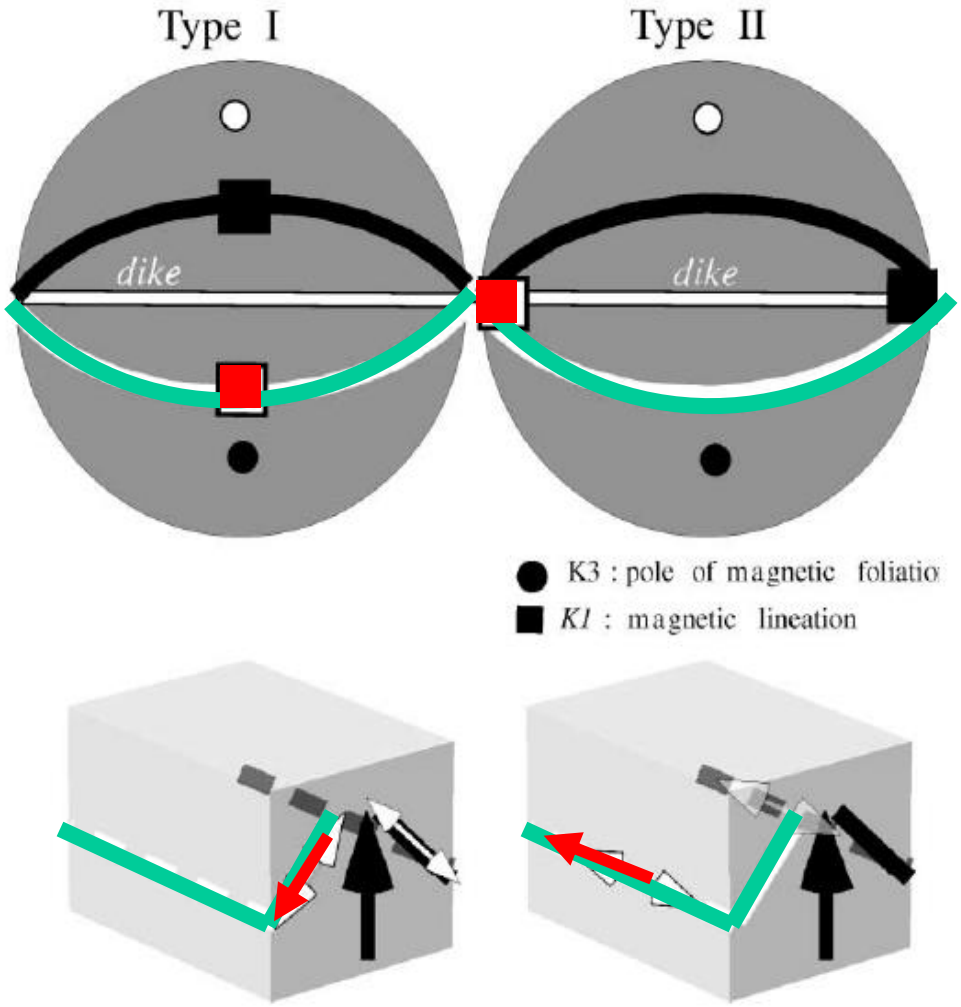


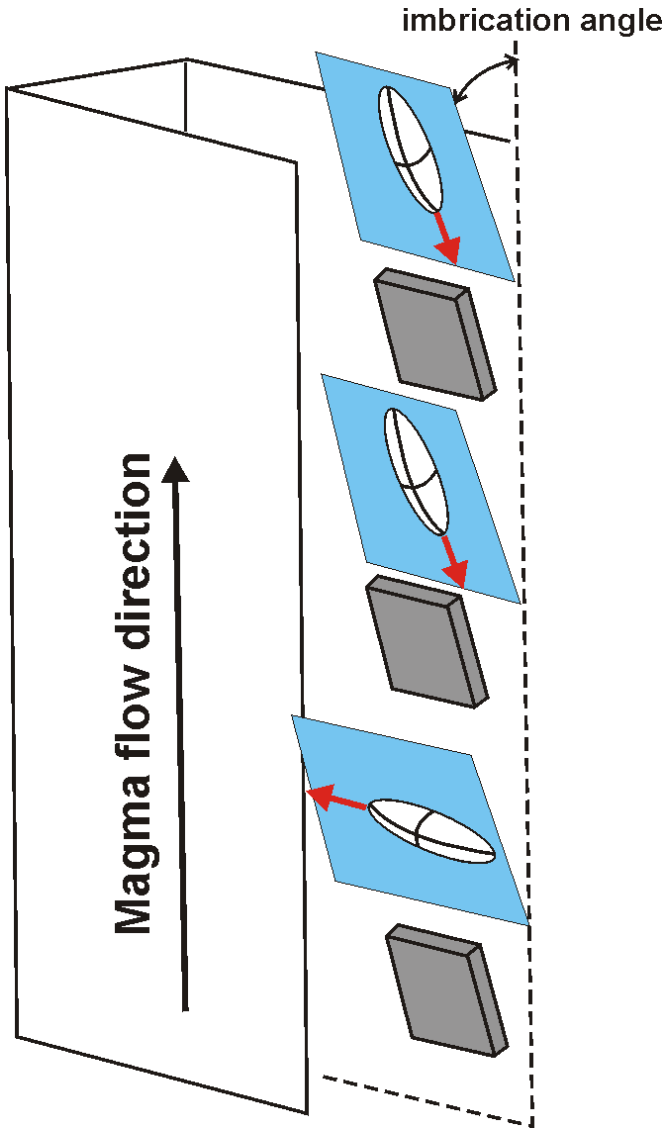
Dikes

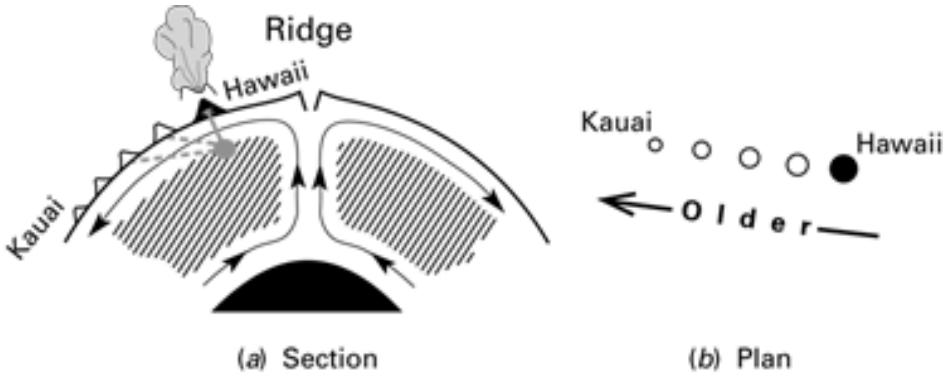

Velocity profile
Magma flow
Dyke margin

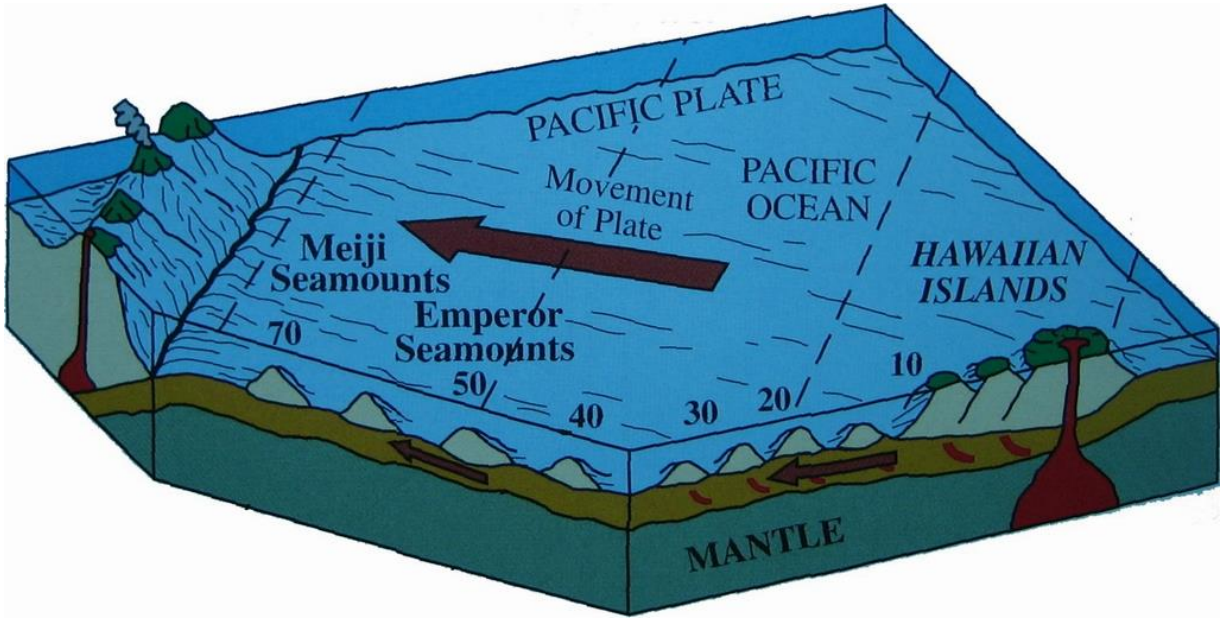

K1
K3
AMS ellipsoid

- magnetic lineation is not always parallel to flow direction
- preferably use imbrication of magnetic foliation

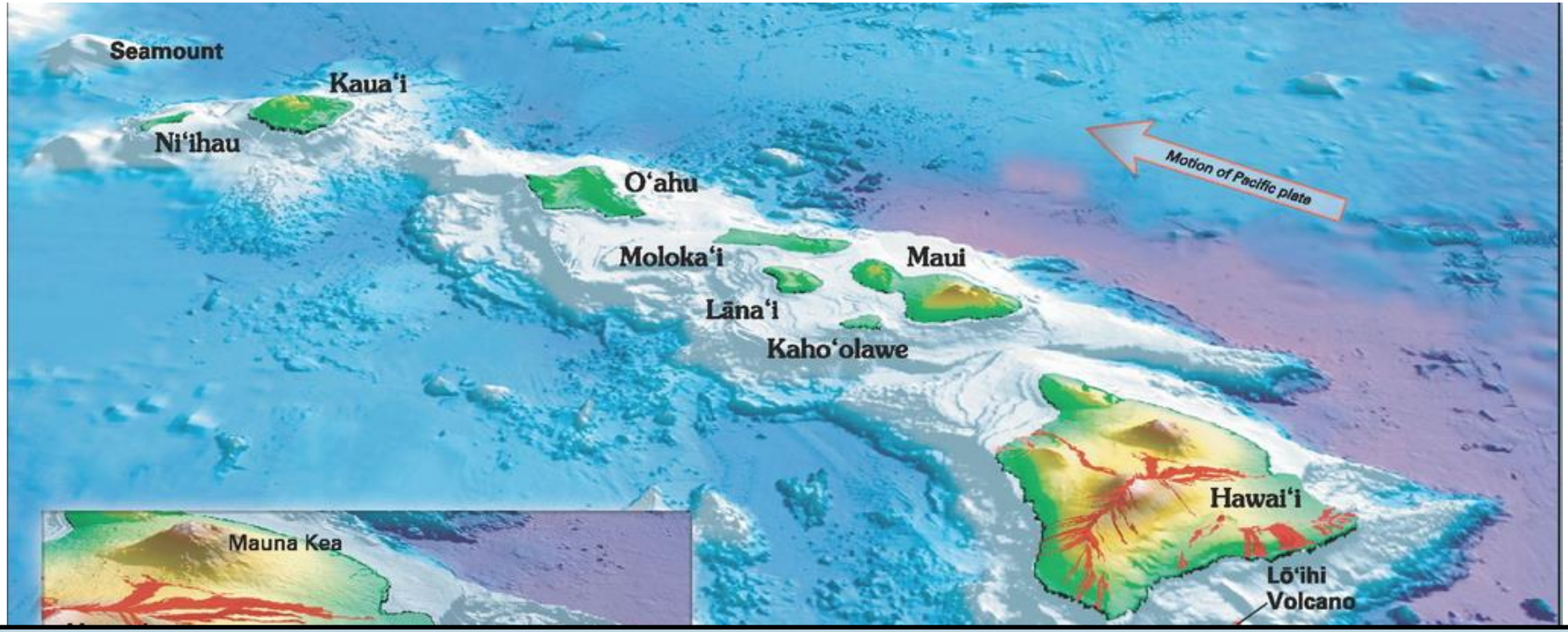


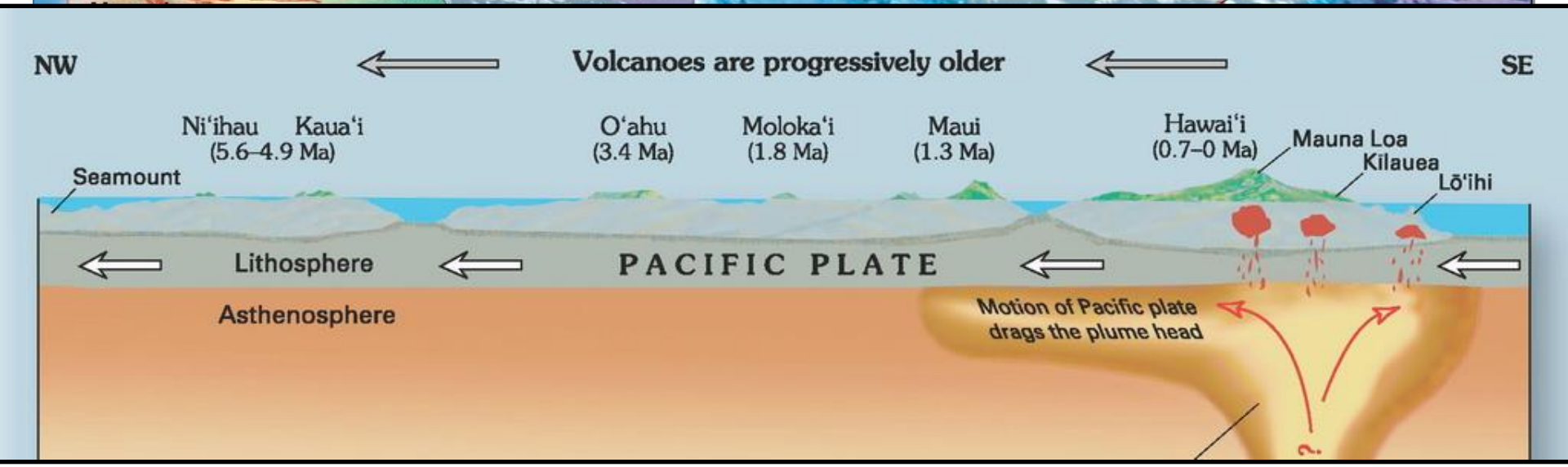




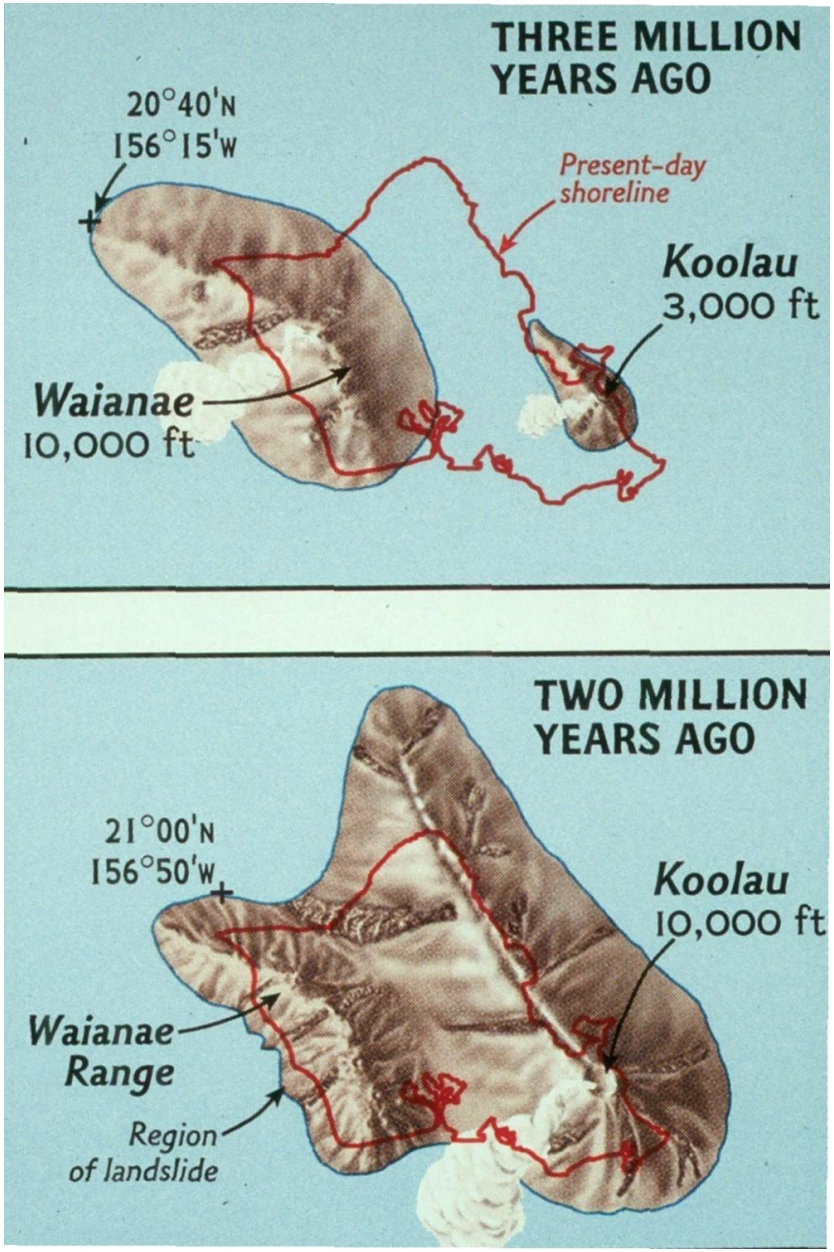


Wilson, J. T. 1963. A possible origin of the Hawaiian Islands. *Canadian Journal of Physics*, **41**, 863-670.

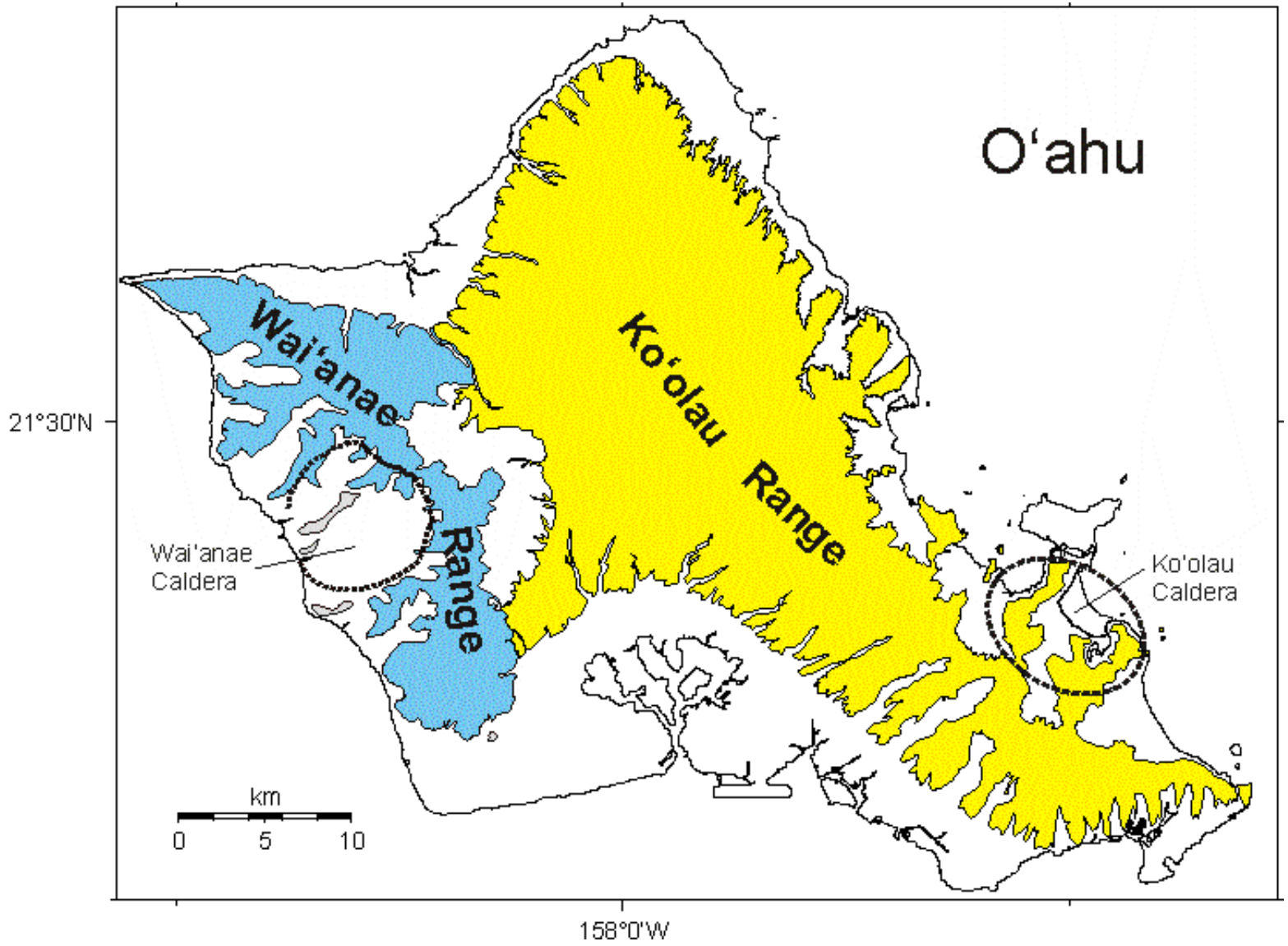

Seamount
Kaua'i
Ni'ihau
O'ahu
Moloka'i
Maui
Lāna'i
Kaho'olawe
Motion of Pacific plate
Hawai'i
Mauna Kea
Lō'ihi
Volcano


NW
Volcanoes are progressively older
SE
Ni'ihau
Kaua'i
(5.6–4.9 Ma)
O'ahu
(3.4 Ma)
Moloka'i
(1.8 Ma)
Maui
(1.3 Ma)
Hawai'i
(0.7–0 Ma)
Mauna Loa
Kilauea
Lō'ihi
Seamount
Lithosphere
PACIFIC PLATE
Asthenosphere
Motion of Pacific plate
drags the plume head

Island of Oahu

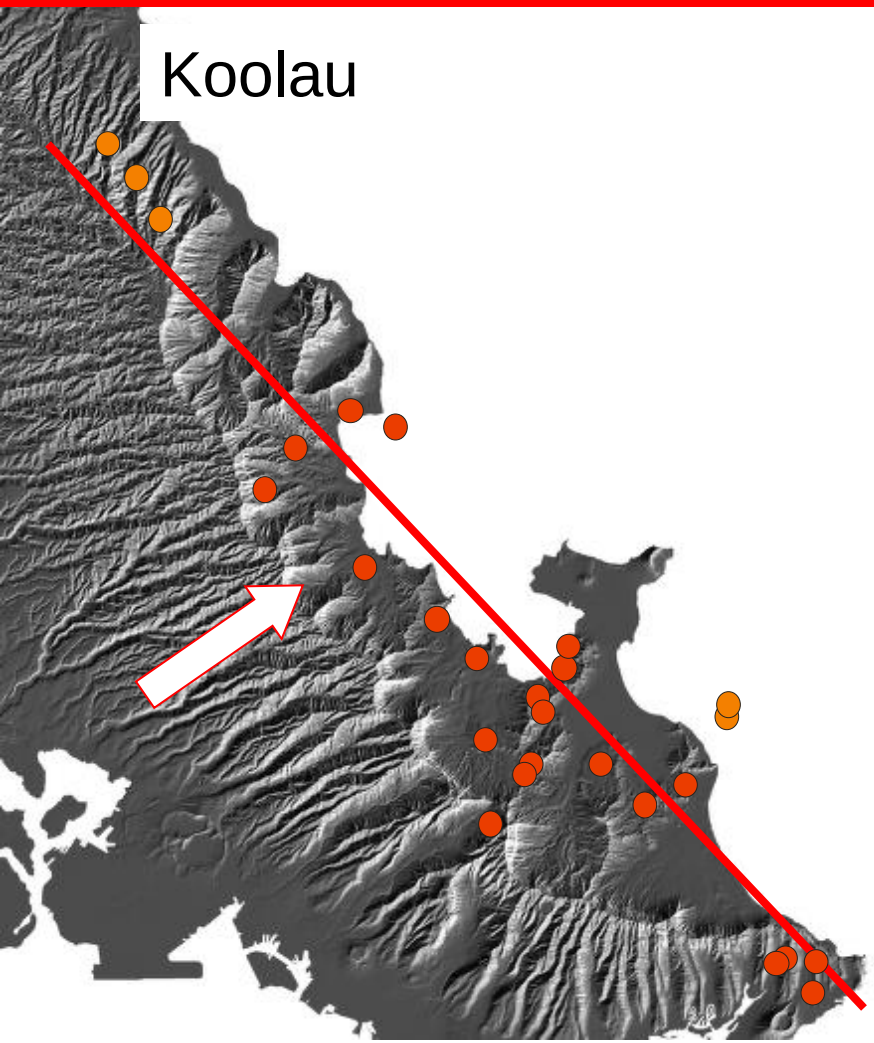


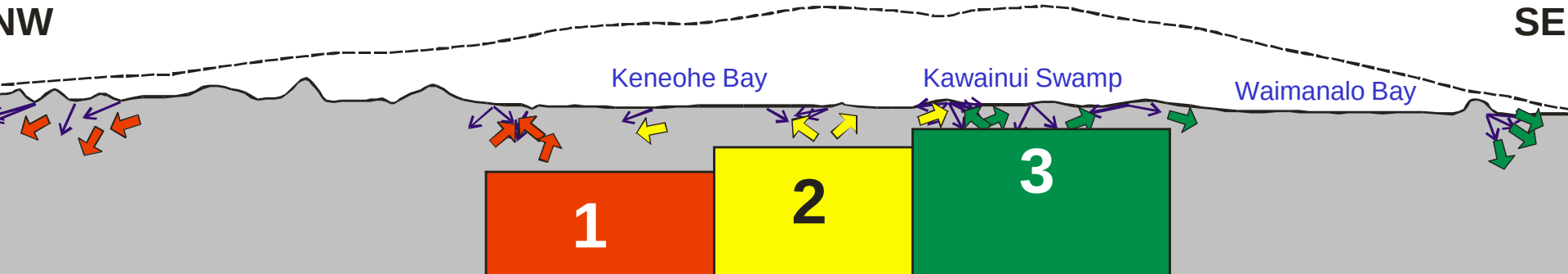
Geology of Oahu



Koolau

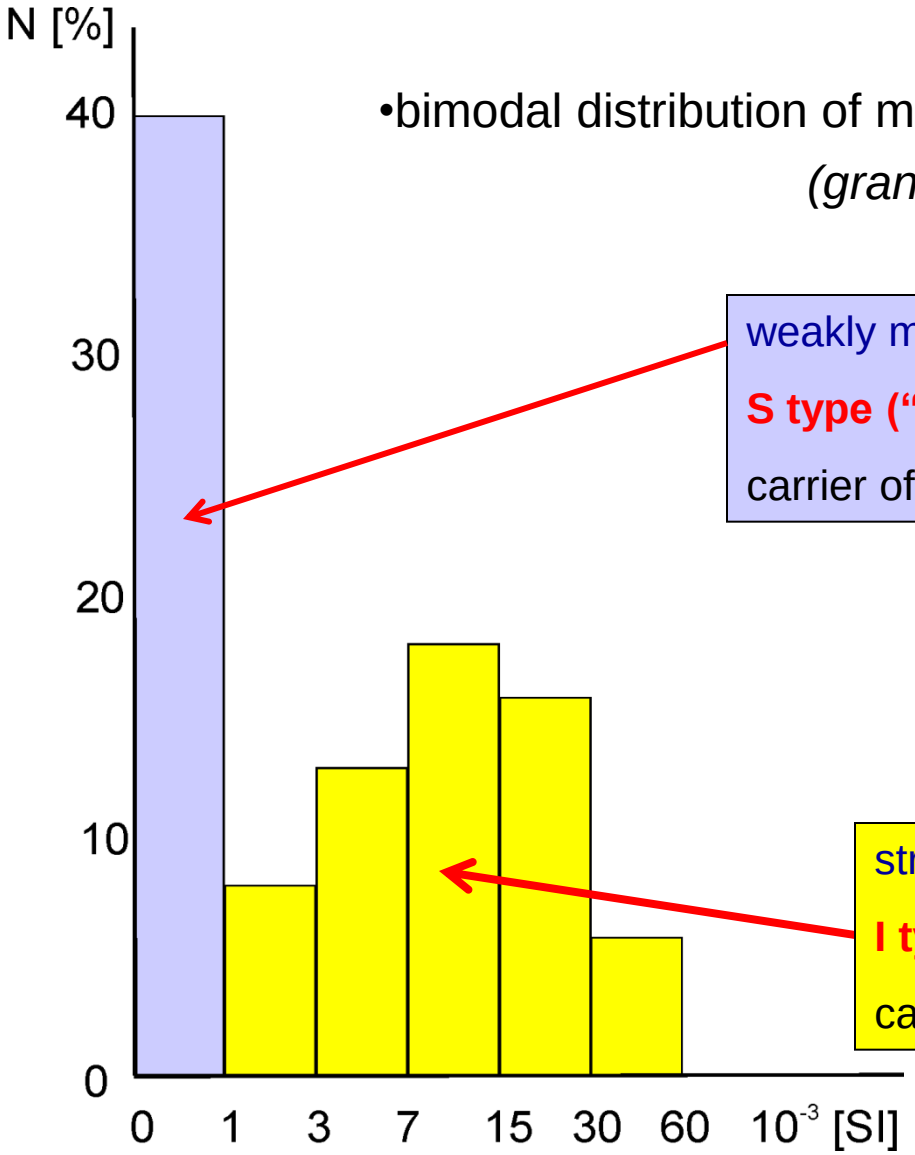
(Knight & Walker 1988)





Plutonic rocks

Plutonic rocks



•bimodal distribution of magnetic susceptibility

(granitoids of former USSR)

weakly magnetic (paramagnetic) granitoides

S type ("Sedimentary")

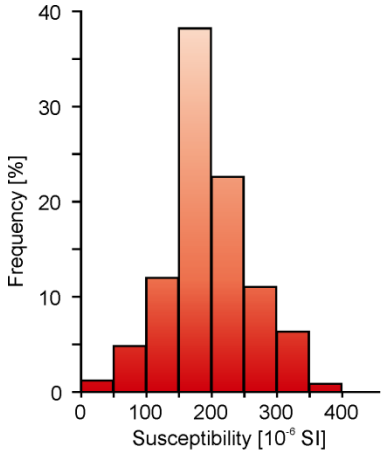
carrier of magnetization mainly **biotite (hornblende)**

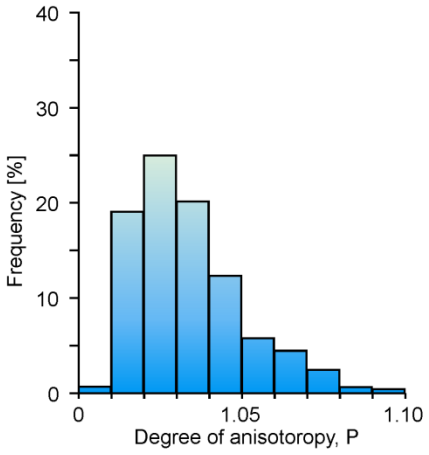
strongly magnetic (ferromagnetic) granitoides

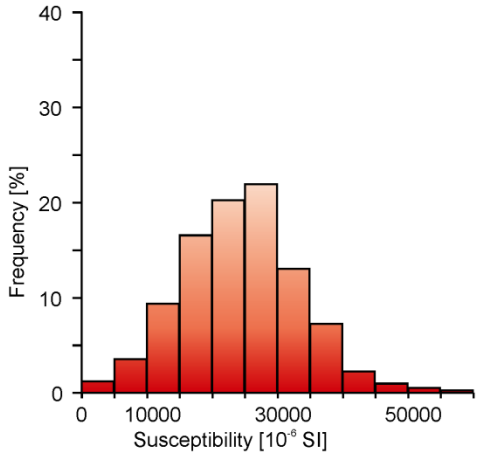
I type (Igneous)

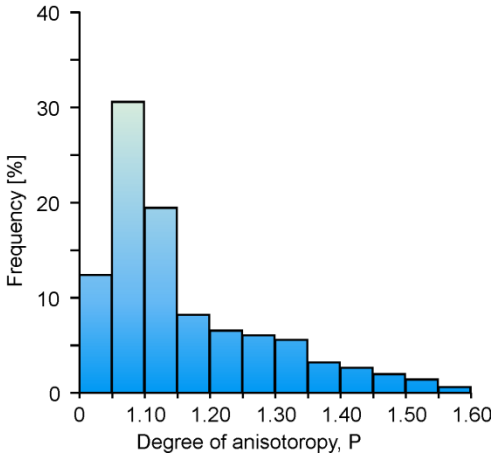
carrier of magnetization mainly **magnetite**

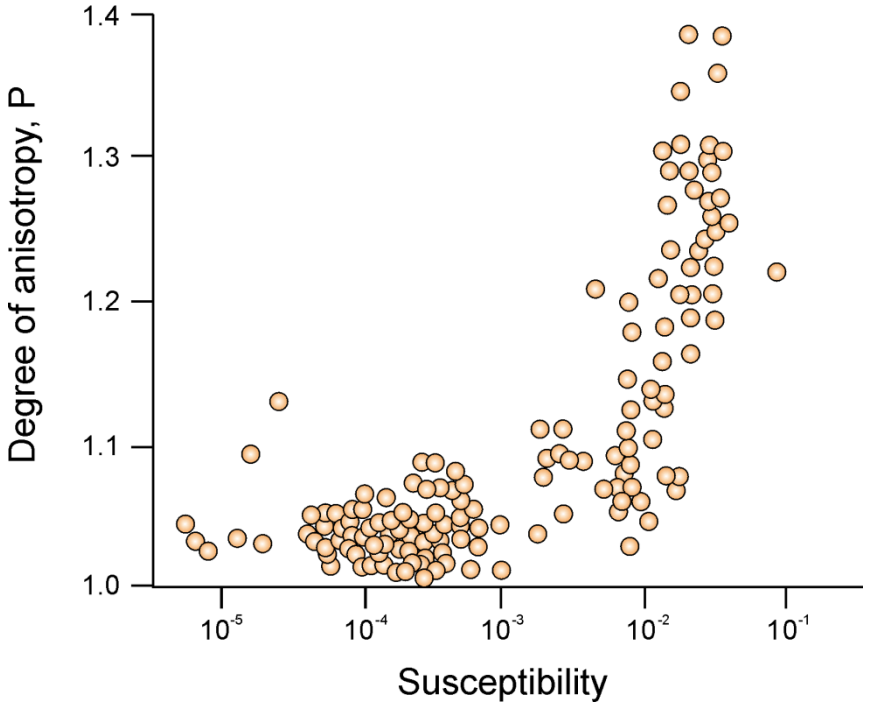
5. Magnetic fabric of igneous rocks

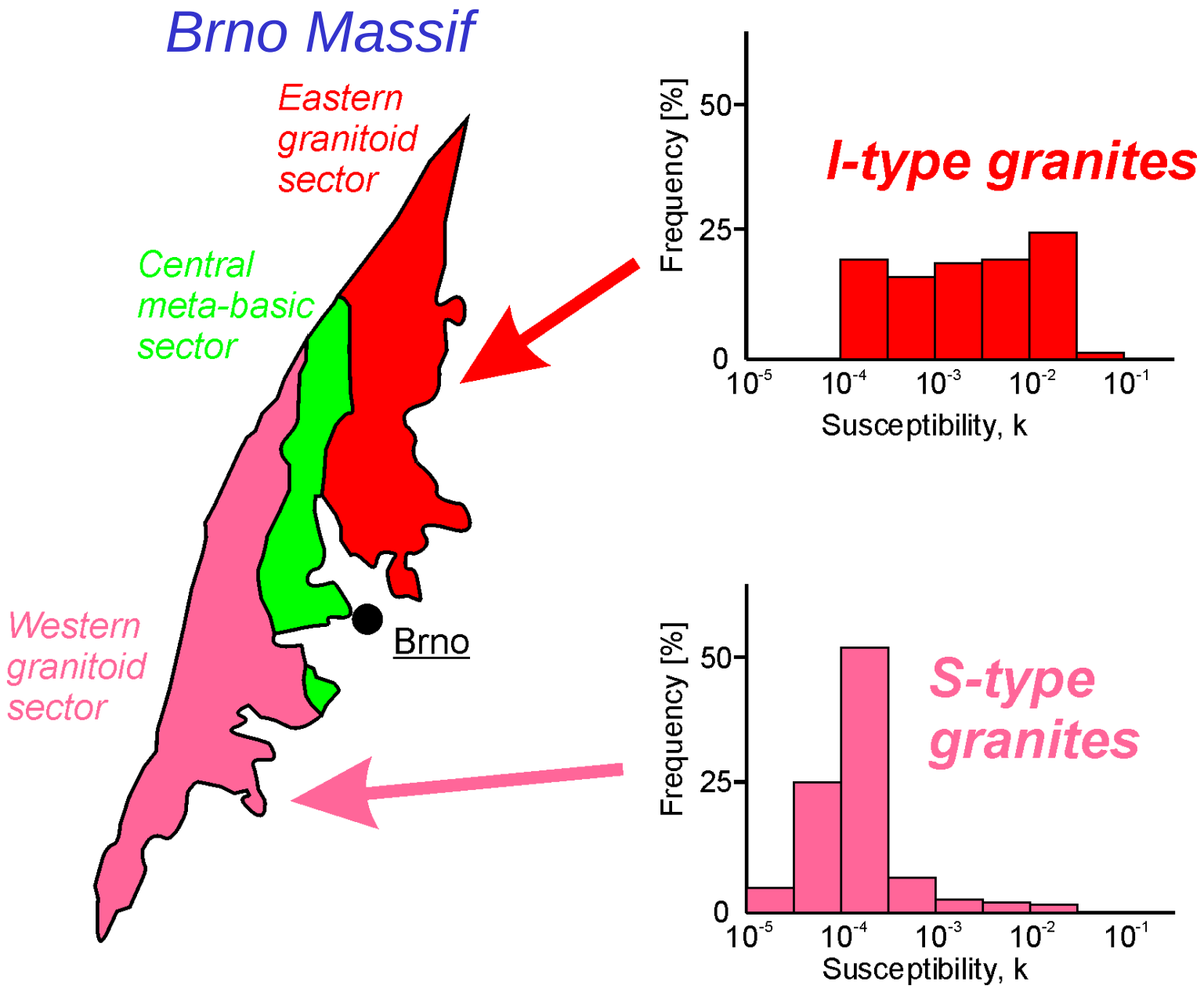


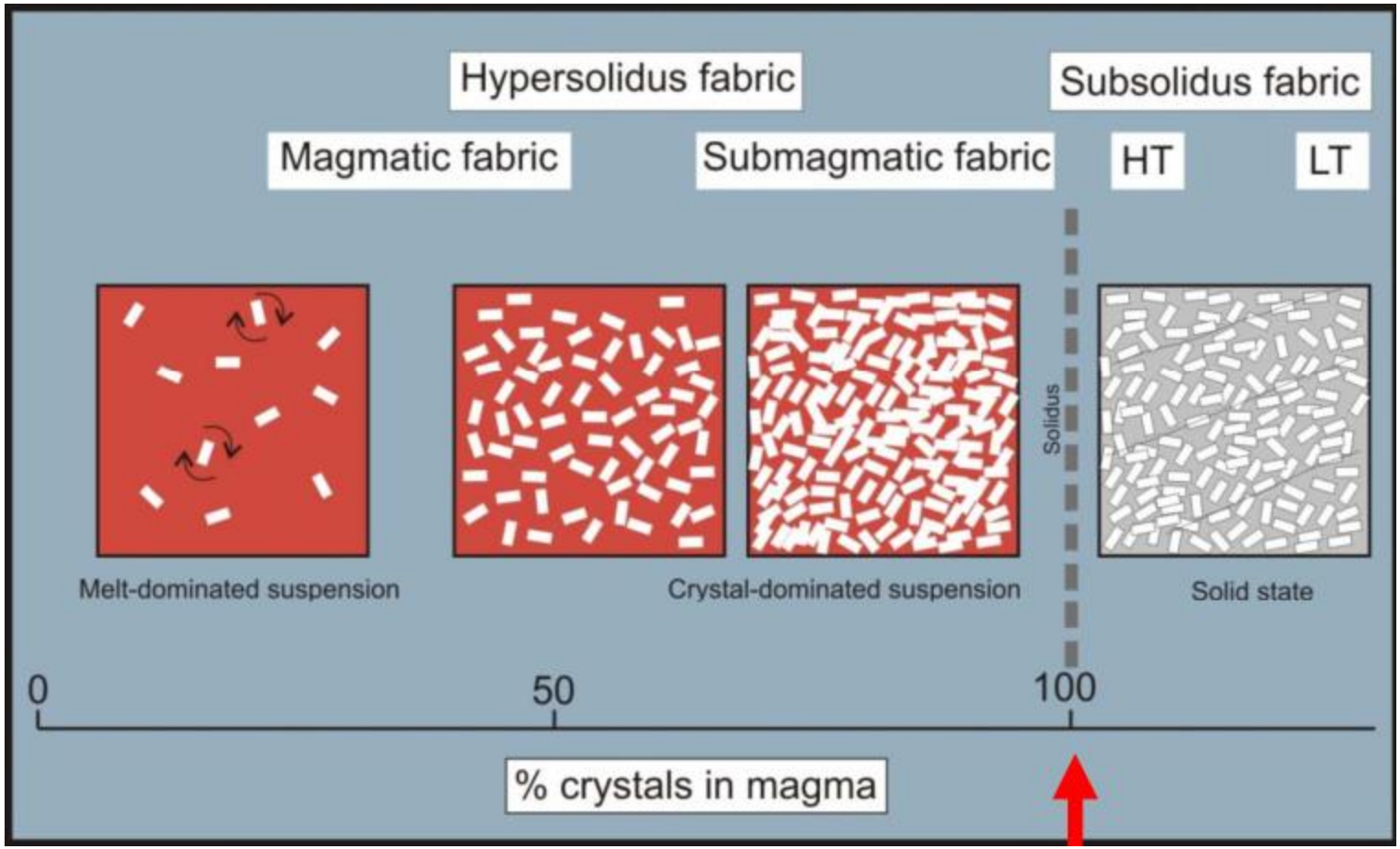




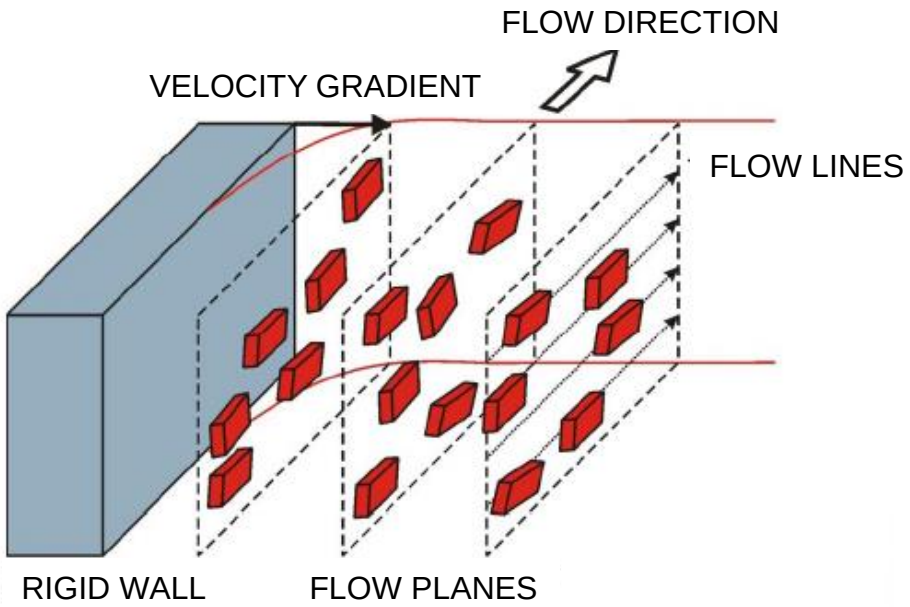


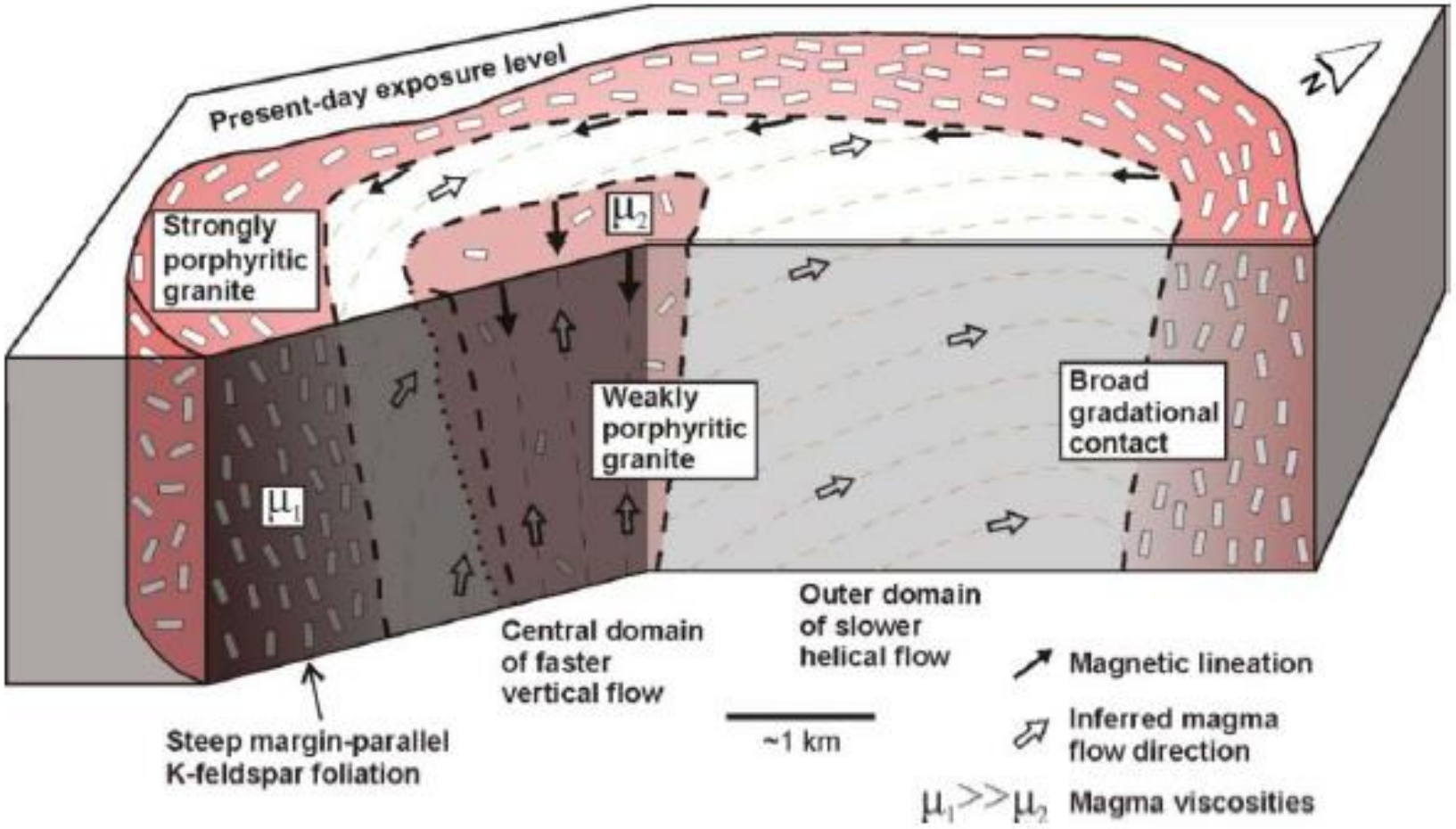



Brno Massif
Eastern granitoid sector
Central meta-basic sector
Western granitoid sector
Brno
Frequency [%]
50
25
0
I-type granites
10-5
10-4
10-3
10-2
10-1
Susceptibility, k
Frequency [%]
50
25
0
S-type granites
10-5
10-4
10-3
10-2
10-1
Susceptibility, k

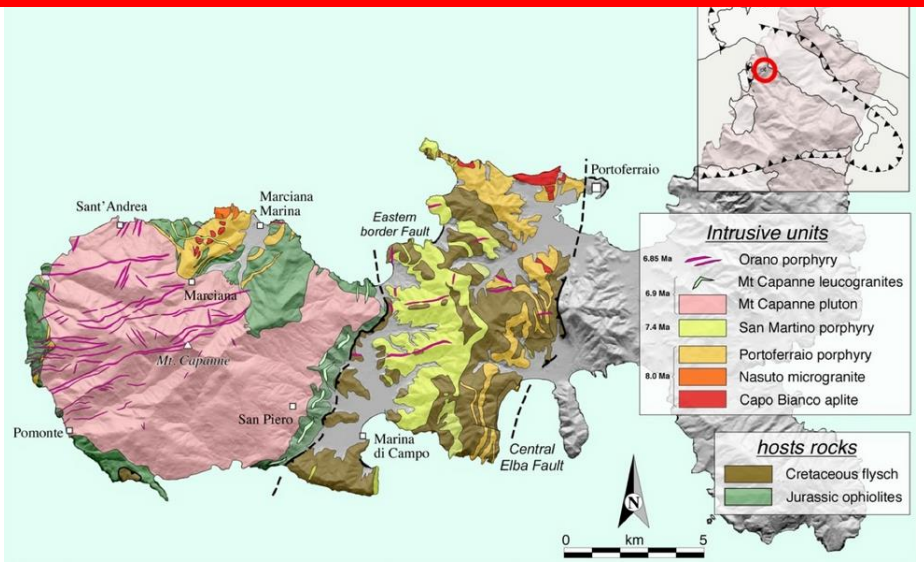

Hypersolidus fabric
Subsolidus fabric
Magmatic fabric
Submagmatic fabric
HT
LT
Solidus
Melt-dominated suspension
Crystal-dominated suspension
Solid state
0
50
100
% crystals in magma

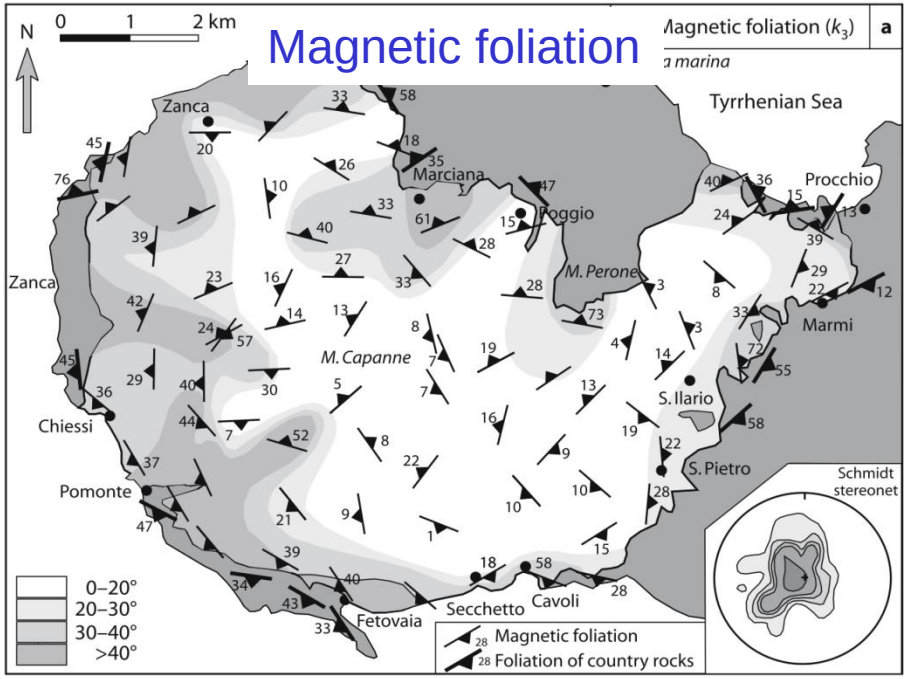
- Foliations and lineations in plutons originate by magma flow
- Magnetic foliation = magma flow plane
- Magnetic lineation = magma flow line
- Regional-scale investigation of magnetic fabric helps to decipher magma flow within whole pluton

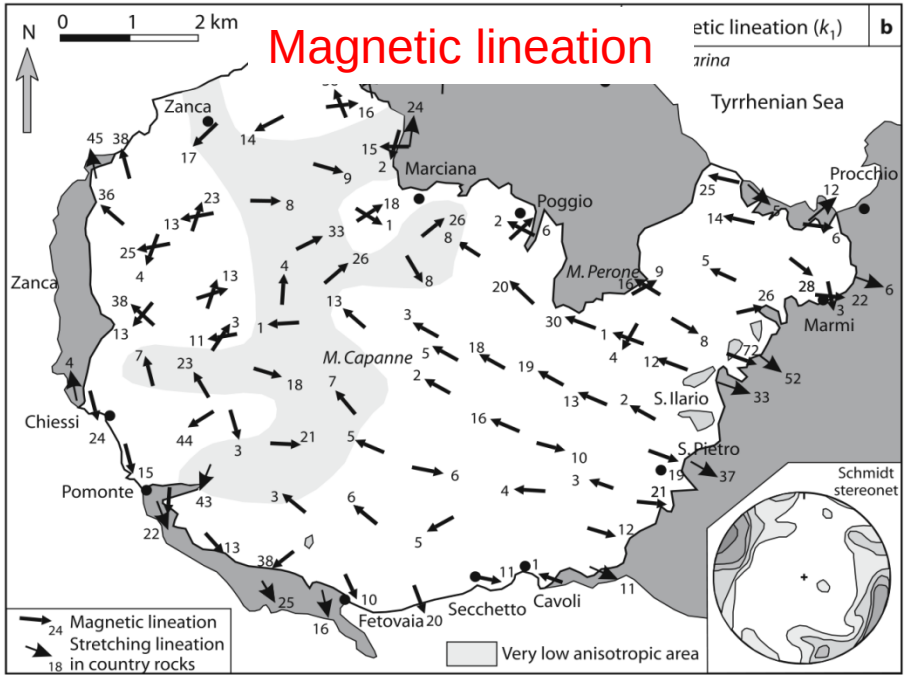



Present-day exposure level
N
Strongly porphyritic granite
μ_2
Weakly porphyritic granite
Broad gradational contact
μ_1
Steep margin-parallel K-feldspar foliation
Central domain of faster vertical flow
Outer domain of slower helical flow
~1 km
Magnetic lineation
Inferred magma flow direction
$\mu_1 >> \mu_2$ Magma viscosities

Magnetic anisotropy in pluton scale





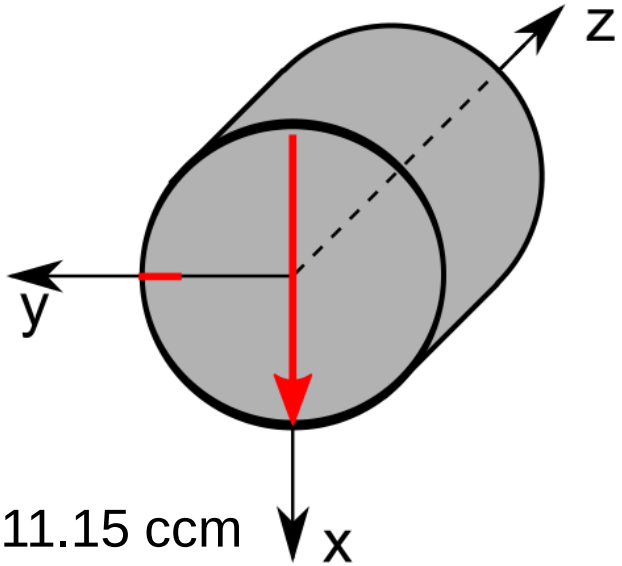


Monte Capanne granodiorite pluton (Elba Island, northern Tyrrhenian Sea, Italy) (Bouillin et al. 1993)

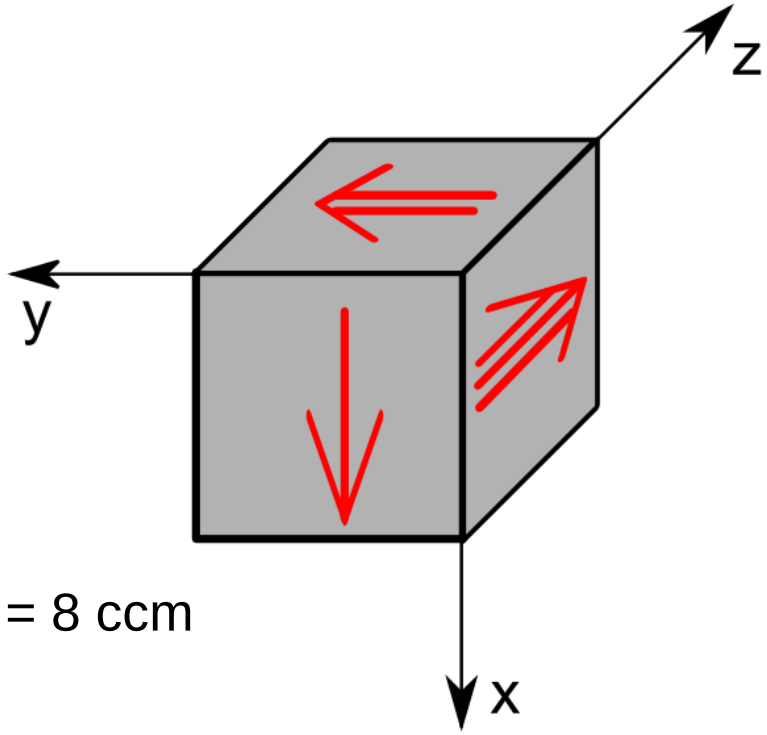
Agenda

1. Definition and application in geology
2. Magnetic anisotropy of minerals
3. Magnetic fabric vs. texture of rocks
4. Magnetic fabric of sedimentary, deformed, and metamorphosed rocks
5. Magnetic fabric of igneous rocks
6. Sampling, measurement and data processing

Oriented samples



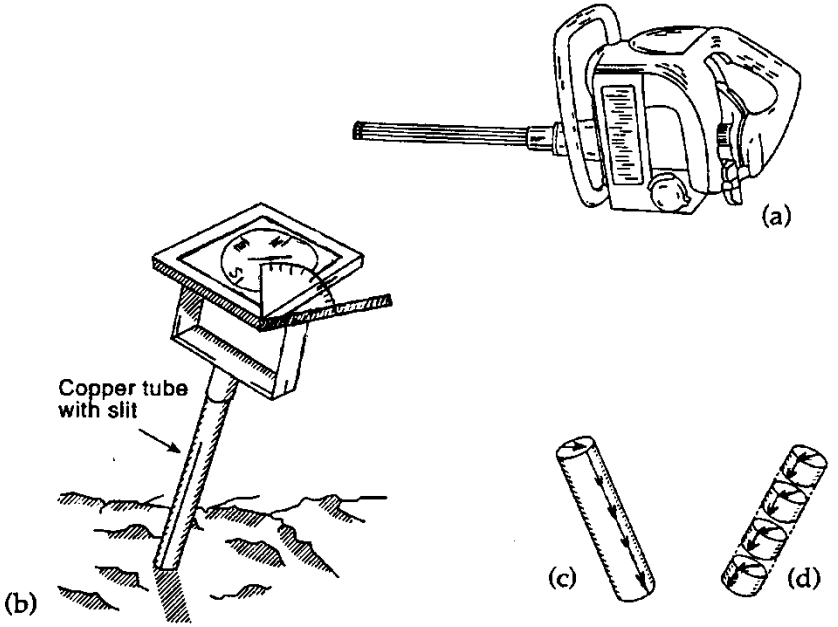
V = 11.15 ccm

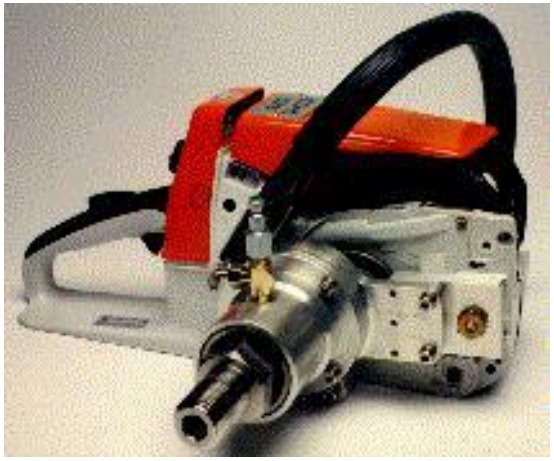


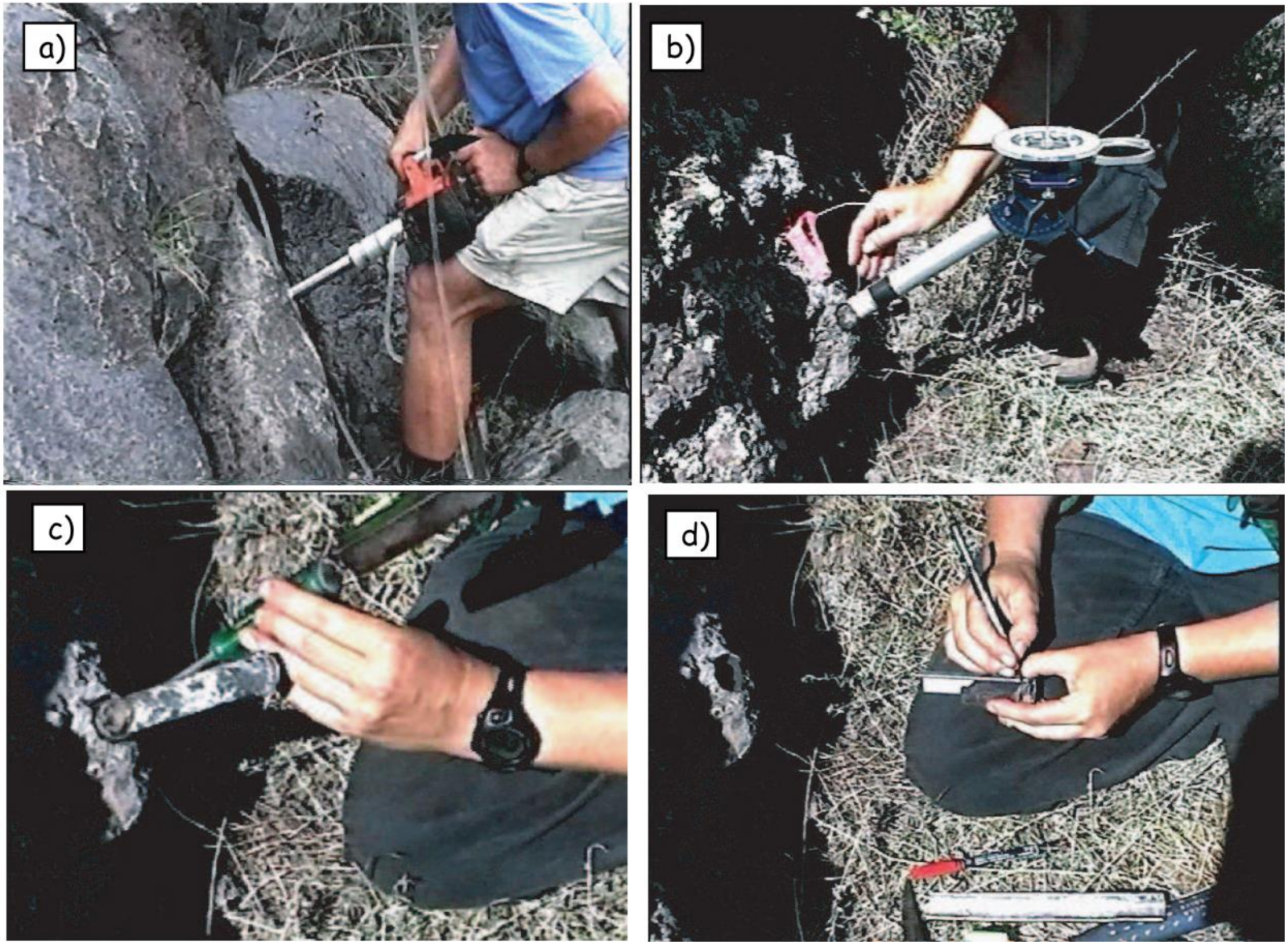
V = 8 ccm

Field Drilling Oriented Cores

Petrol powered portable drilling machine

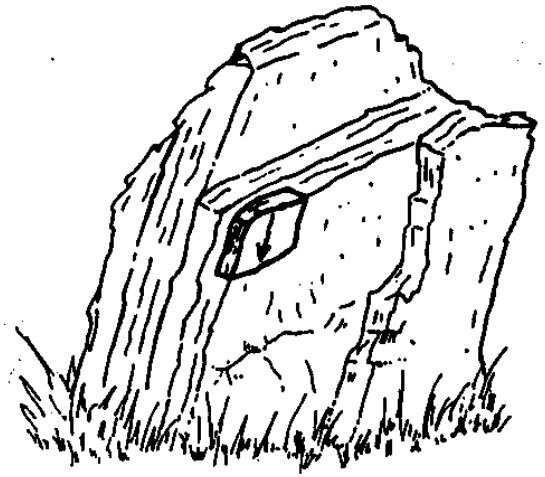


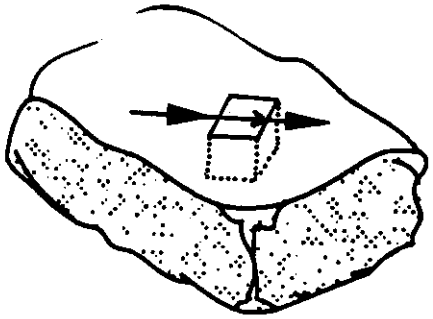


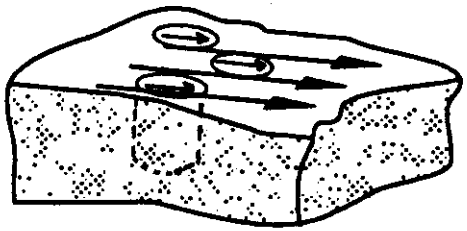


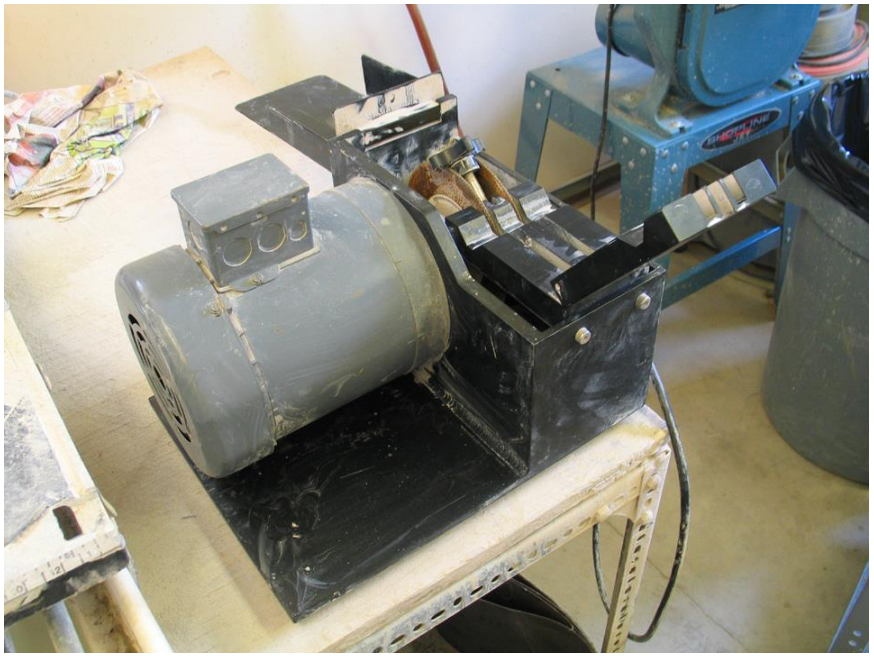
(Tauxe. 2005)

Block specimens





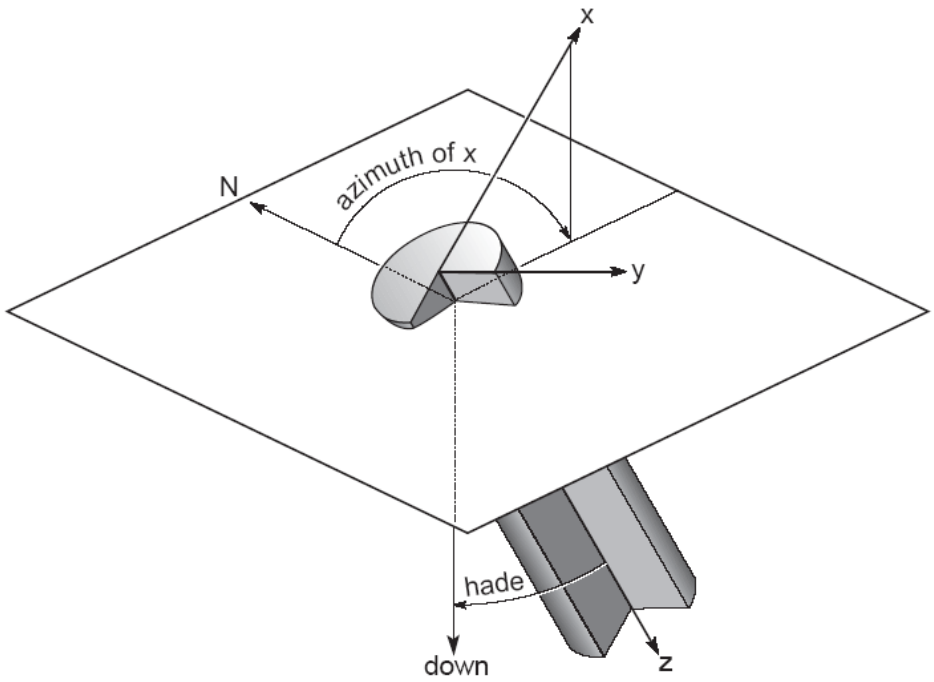




Sample to geographical coordinate system transformation

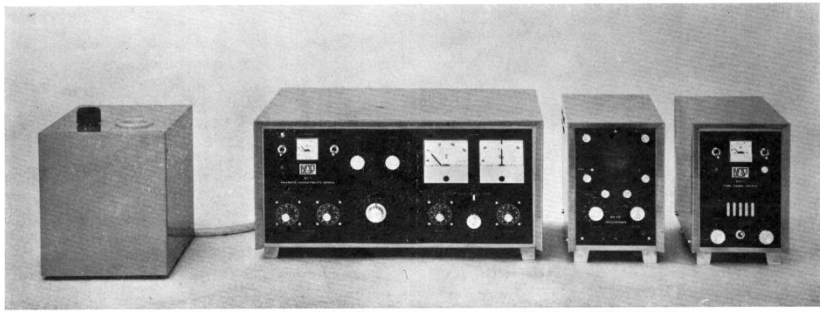
$$R = T\,r, \qquad K = T\,k\,T',$$

- ***r***, ***R*** *vectors in sample or geographical coordinate systems*
- ***k, K*** *tensors in sample or geographical coordinate systems*
- ***T*** *transformation matrix (**T'** transposed matrix of **T**)*



Kappabridge (and PC) evolution

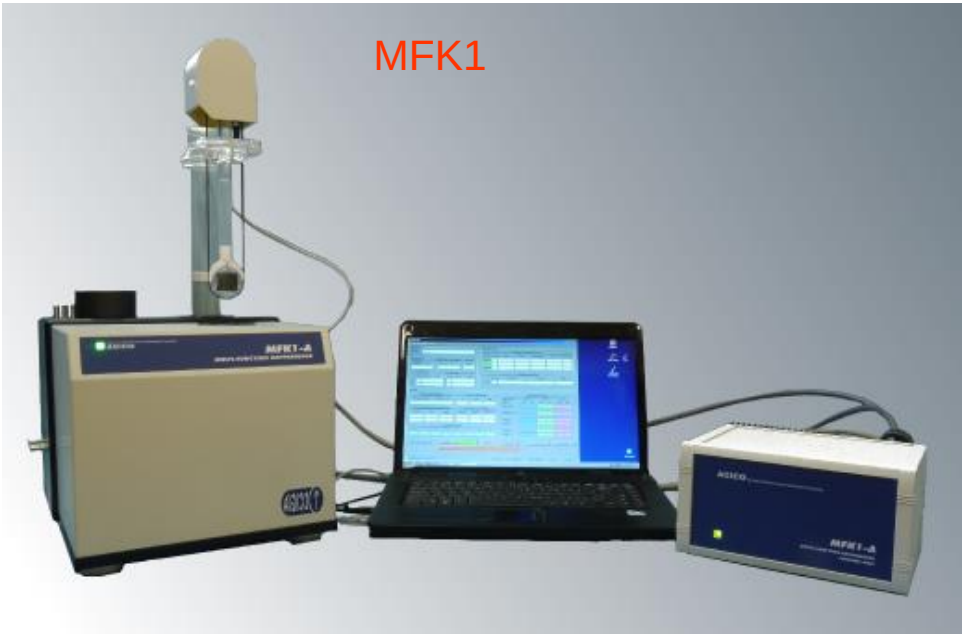
KLY-1 (1967)



KLY-2

KLY-3 & 4

MFK1

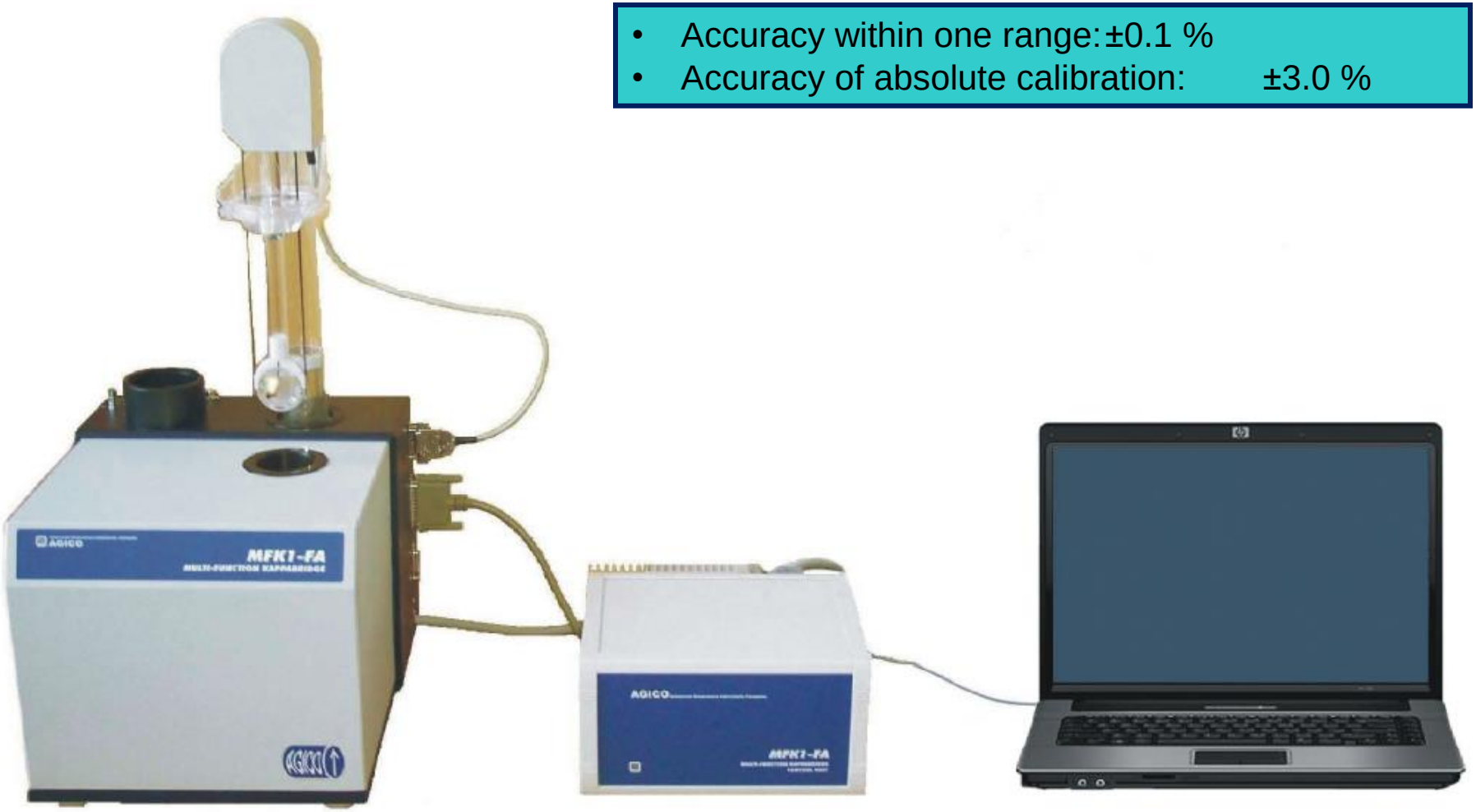


MFK1-FA

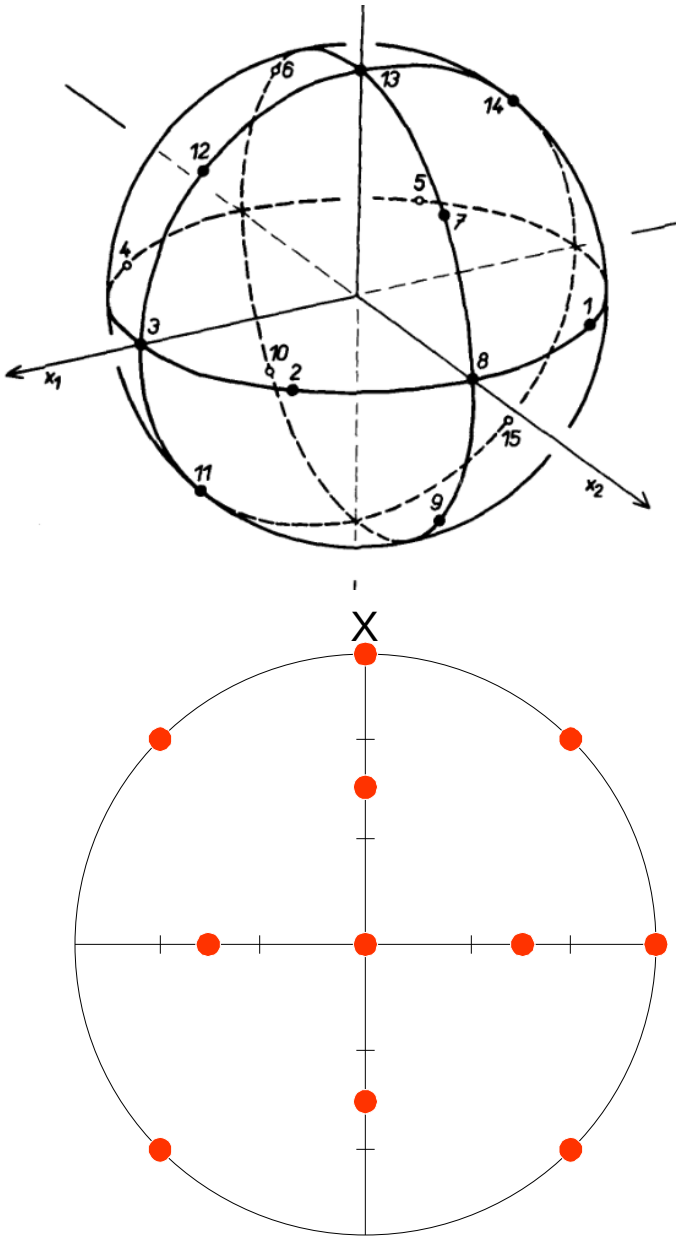
Three operating frequencies and respective field ranges (peak values):

- **F1** (976 Hz): 2 - 700 A/m
- **F2** (3904 Hz): 2 - 350 A/m
- **F3** (15616 Hz): 2 - 200 A/m

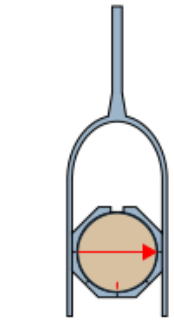
- Accuracy within one range: ±0.1 %
- Accuracy of absolute calibration: ±3.0 %

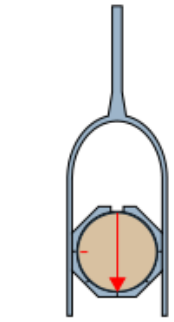


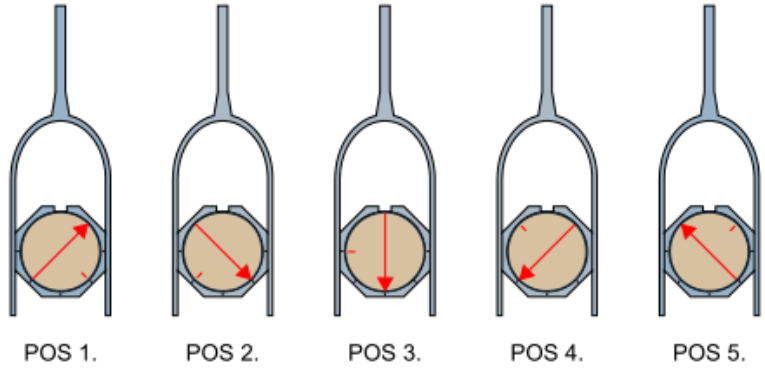
15 position design

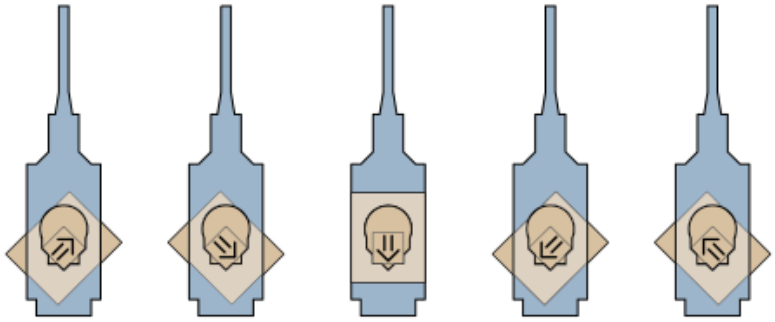


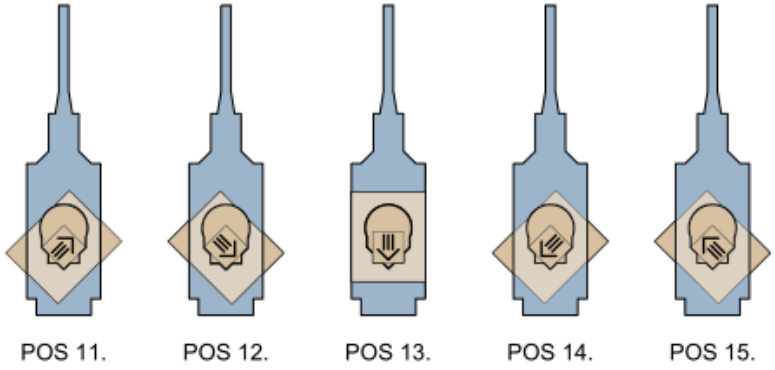
- 15 directional measurements
- Duration: ca. 9 min


Initial position P6 - P10


Initial position P11 - P15

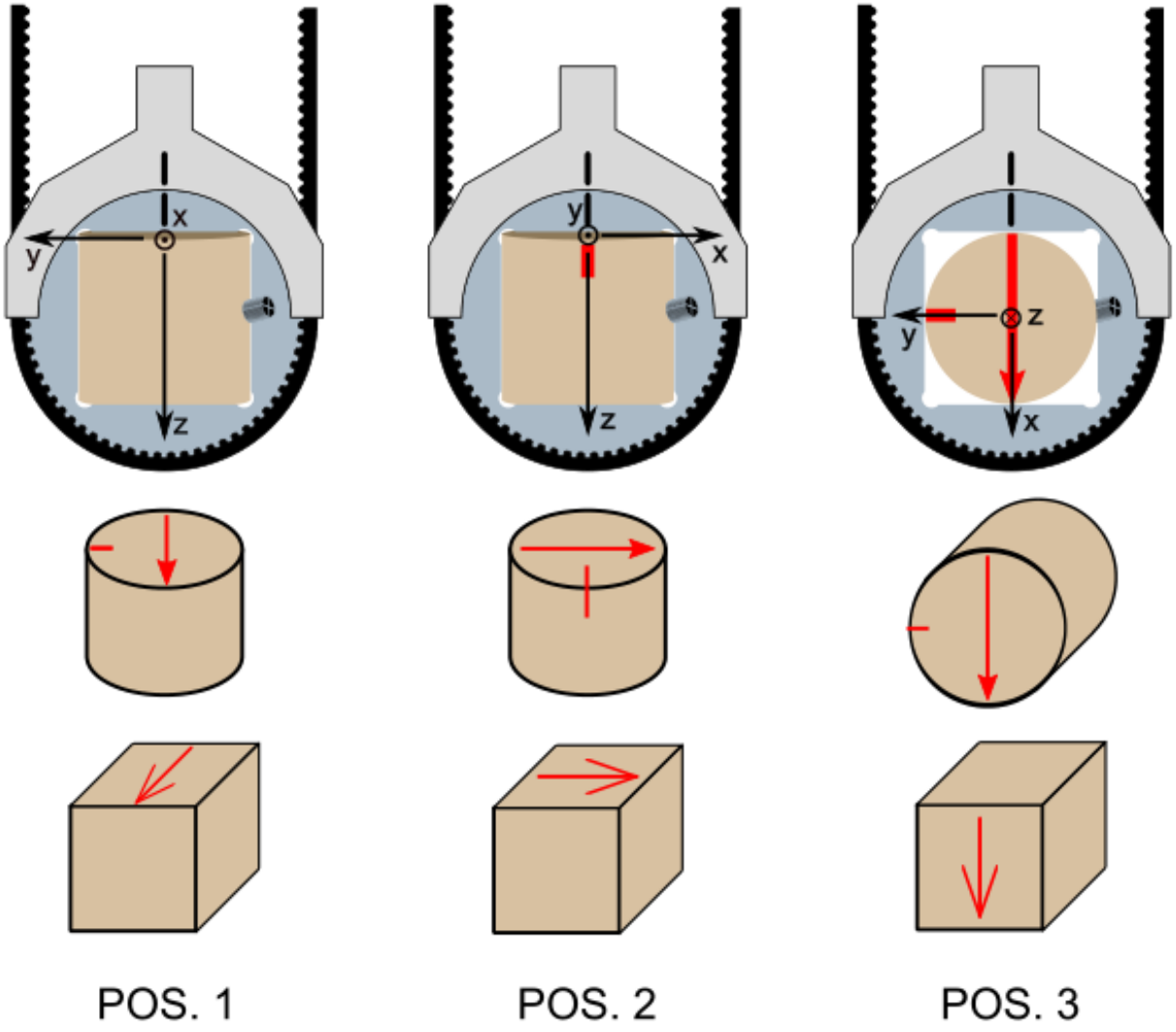






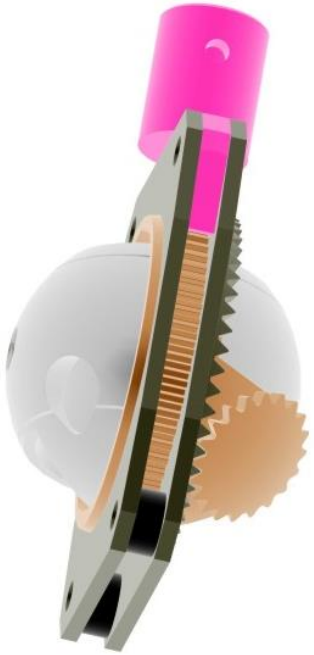
Three plane rotation

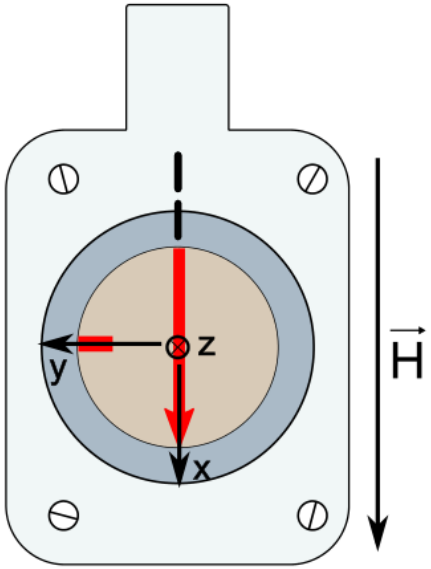
- 64 readings during each rotation
- Multiple rotations
- Duration: ca. 3-4 min

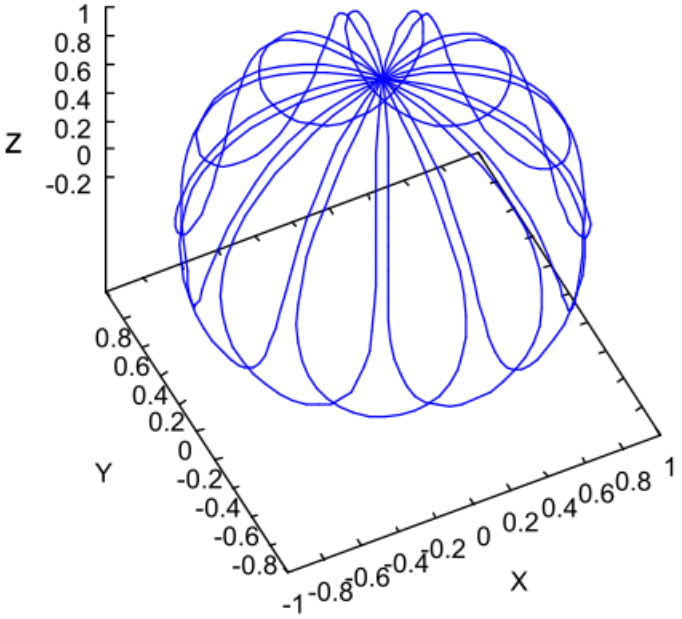


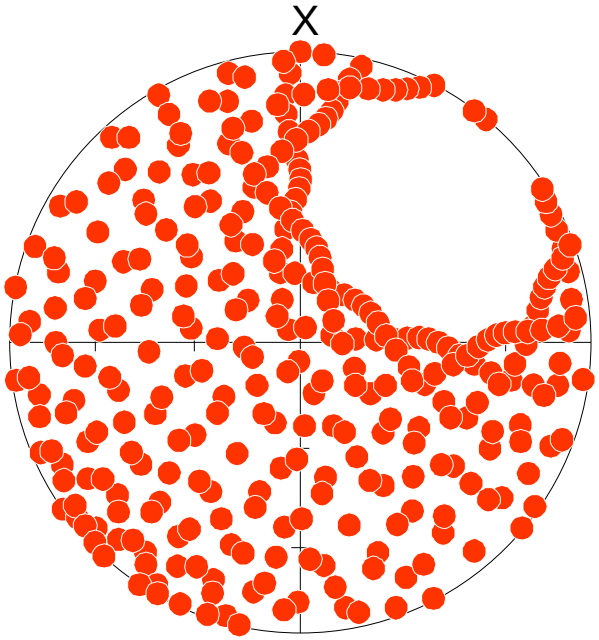
3D Rotator

- 320 readings during full rotation
- Repeated two times
- 640 directional measurements
- Duration: ca. 1.5 min

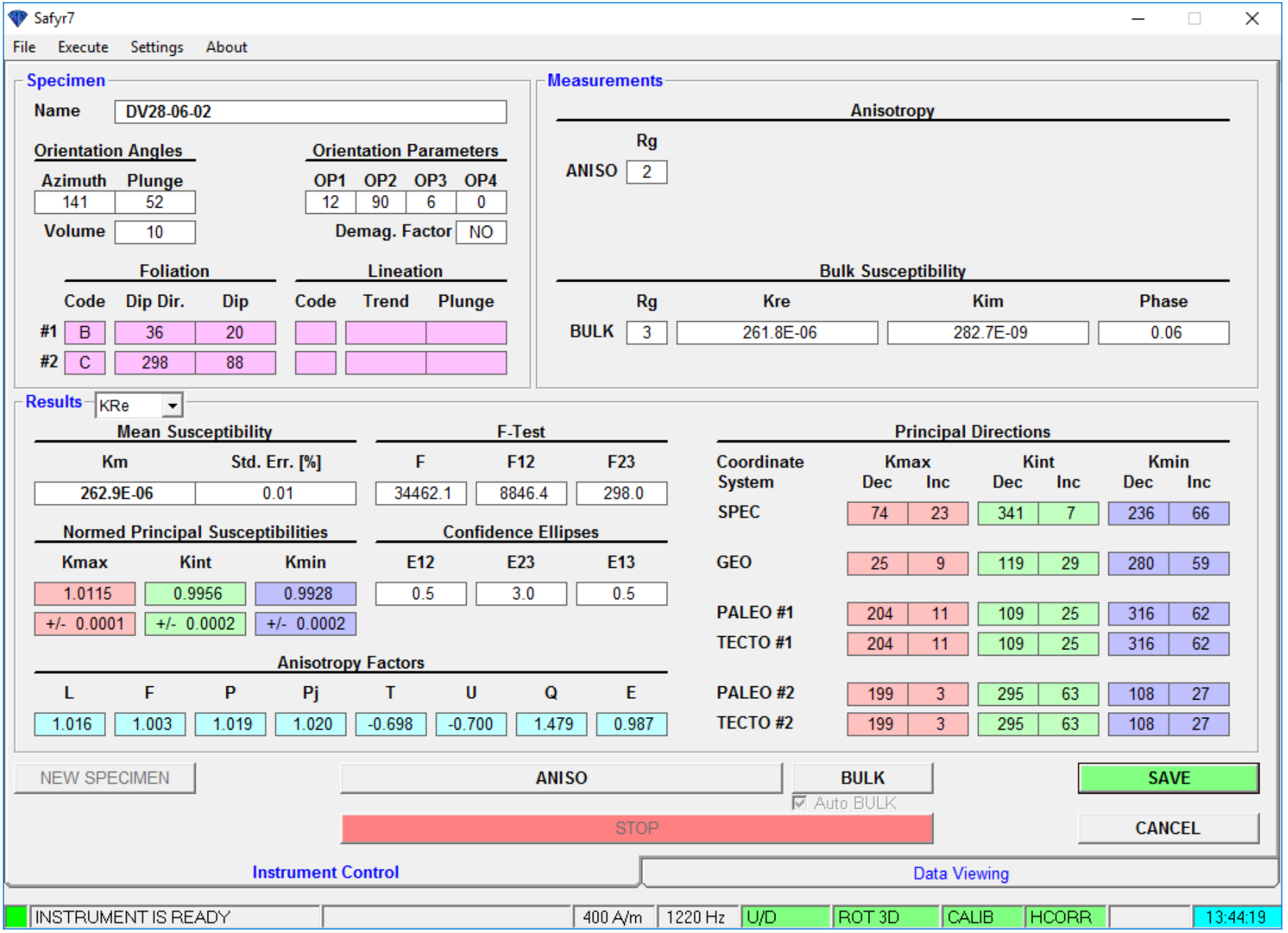








Safyr - Data acquisition software


Safyr7
File Execute Settings About
Specimen
Name DV28-06-02
Orientation Angles
Azimuth Plunge
141 52
Volume 10
Orientation Parameters
OP1 OP2 OP3 OP4
12 90 6 0
Demag. Factor NO
Foliation
Code Dip Dir. Dip
#1 B 36 20
#2 C 298 88
Lineation
Code Trend Plunge
Measurements
Anisotropy
Rg
ANISO 2
Bulk Susceptibility
Rg Kre Kim Phase
BULK 3 261.8E-06 282.7E-09 0.06
Results
KRe
Mean Susceptibility
Km Std. Err. [%]
262.9E-06 0.01
F-Test
F F12 F23
34462.1 8846.4 298.0
Normed Principal Susceptibilities
Kmax Kint Kmin
1.0115 0.9956 0.9928
+/- 0.0001 +/- 0.0002 +/- 0.0002
Confidence Ellipses
E12 E23 E13
0.5 3.0 0.5
Anisotropy Factors
L F P Pj T U Q E
1.016 1.003 1.019 1.020 -0.698 -0.700 1.479 0.987
Principal Directions
Coordinate System
Kmax Dec Kmax Inc Kint Dec Kint Inc Kmin Dec Kmin Inc
SPEC 74 23 341 7 236 66
GEO 25 9 119 29 280 59
PALEO #1 204 11 109 25 316 62
TECTO #1 204 11 109 25 316 62
PALEO #2 199 3 295 63 108 27
TECTO #2 199 3 295 63 108 27
NEW SPECIMEN
ANISO
BULK
Auto BULK
SAVE
STOP
CANCEL
Instrument Control
Data Viewing
INSTRUMENT IS READY
400 A/m
1220 Hz
U/D
ROT 3D
CALIB
HCORR
13:44:19

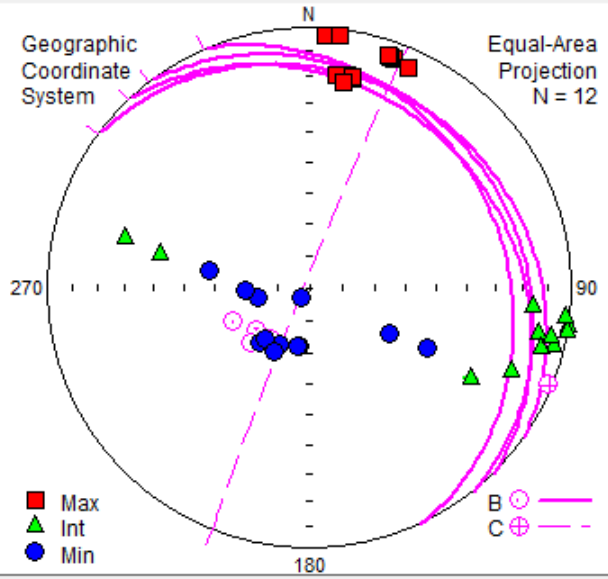
Safyr7 - [C:\Agico\Data\DV\DV28.ams] (N = 14)

File Execute Settings About

Graphics | Table | KRe | GEO | B | 0 | Horizontal | North

Name
DV28-07-01
DV28-07-02
DV28-07-03
DV28-08-01
DV28-08-02
DV28-08-03
DV28-09-01
DV28-09-02
DV28-09-03
DV28-06-02
DV28-15-01
DV28-15-02

Export Graphics

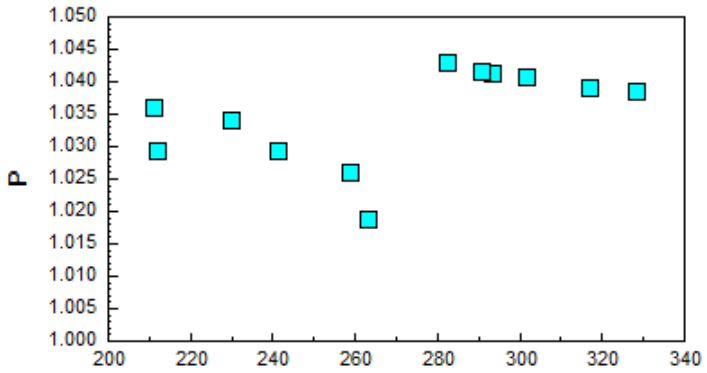


Group Statistics (N = 12)

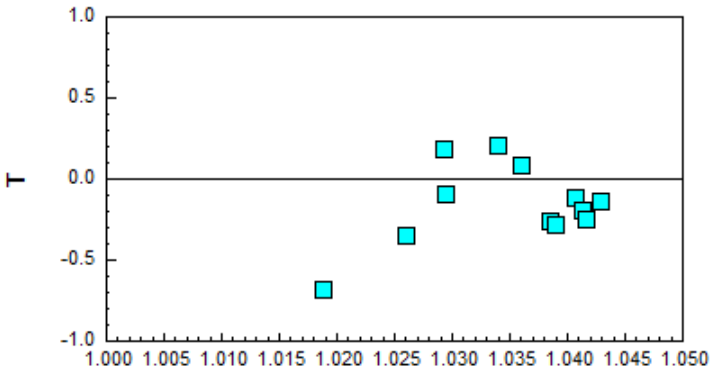
Mean Tensor	Normed Semi-Axes	Dec	Inc	Conf. Ellips.	
Kmax	1.017	11.8	14.4	7.4	4.4
Kint	0.997	102.2	1.4	19.2	5.2
Kmin	0.985	197.6	75.5	19.2	6.7

Mean Tensor	Mean Tensor	Average	Std. Err.
Km	N/A	269.2E-06	39.49E-06
L	1.020	1.020	0.005
F	1.012	1.015	0.005
P	1.032	1.035	0.007
Pj	1.033	1.035	0.007
T	-0.262	-0.160	0.246
U	-0.269	-0.168	0.244
Q	0.929	0.845	0.258
E	0.992	0.995	0.007

Export Graphics



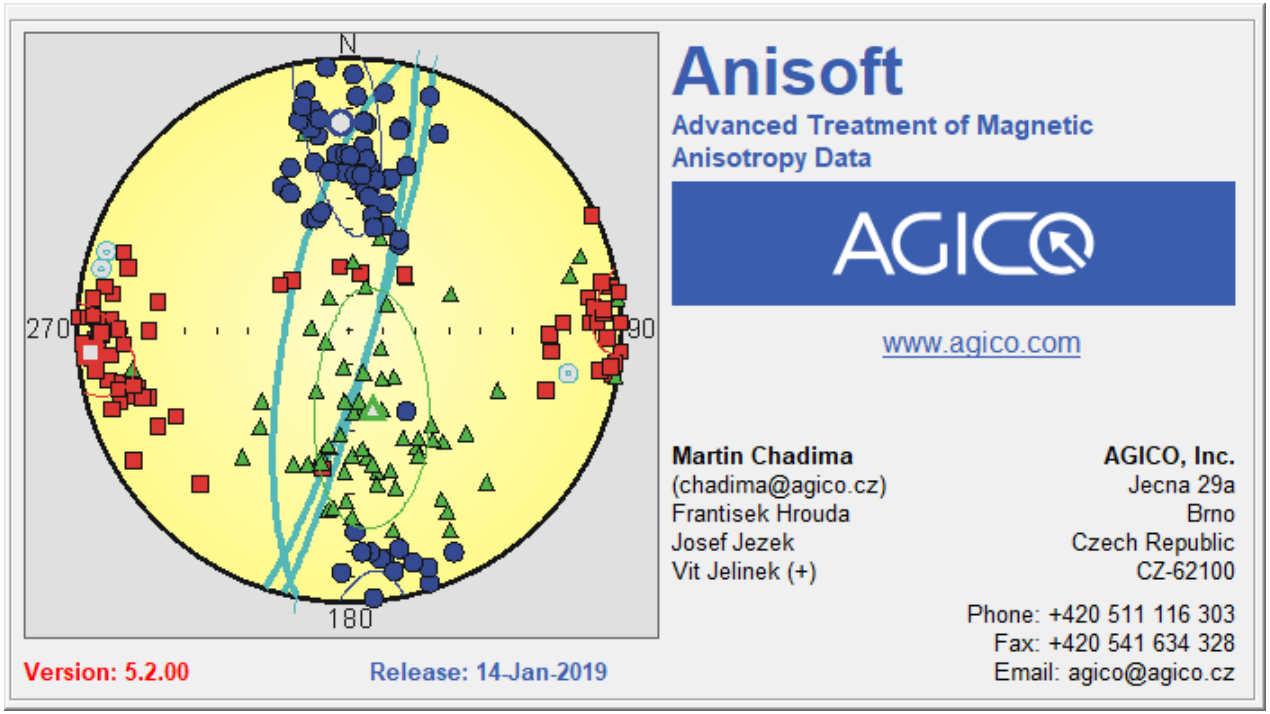
Export Graphics

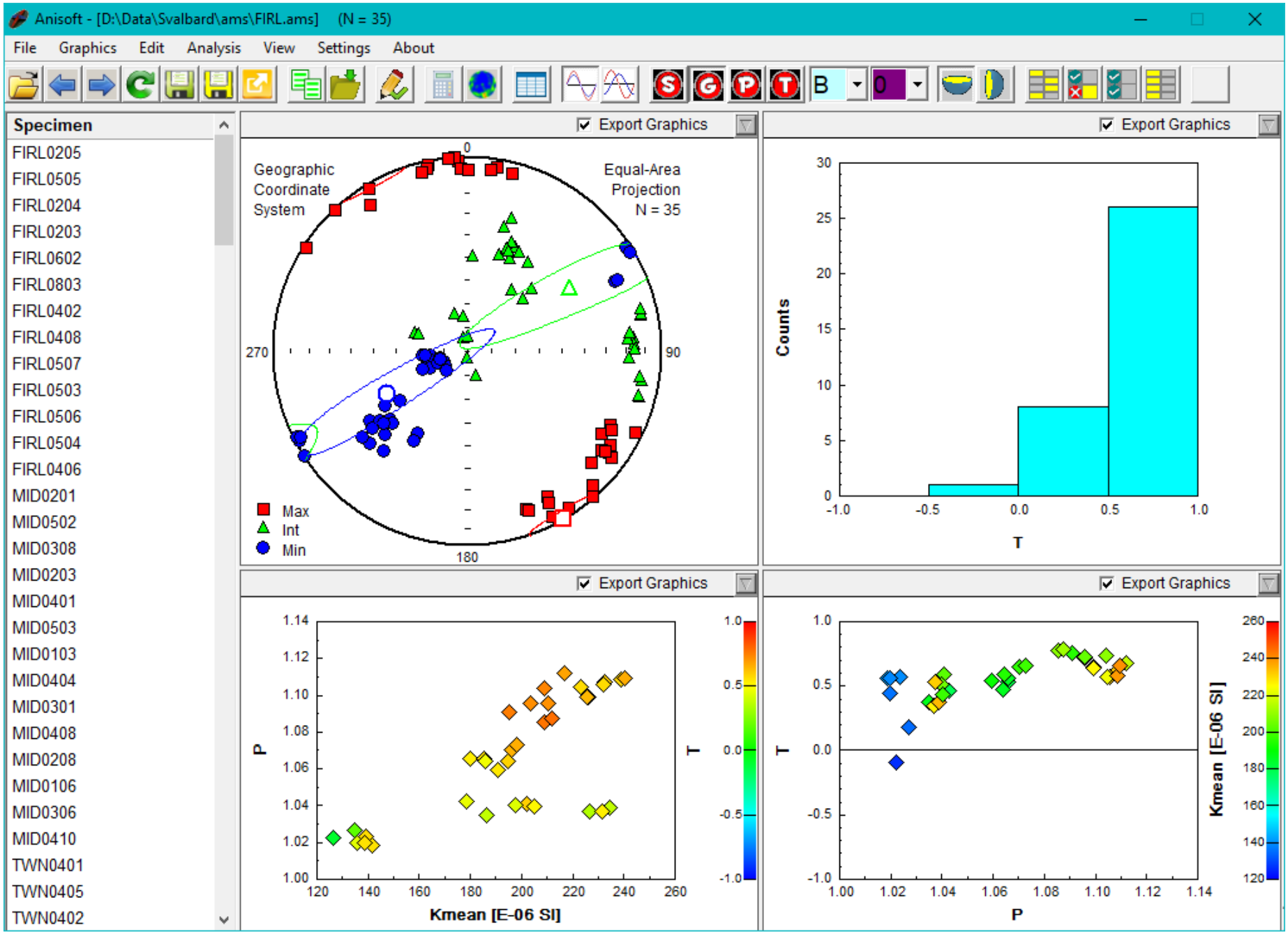


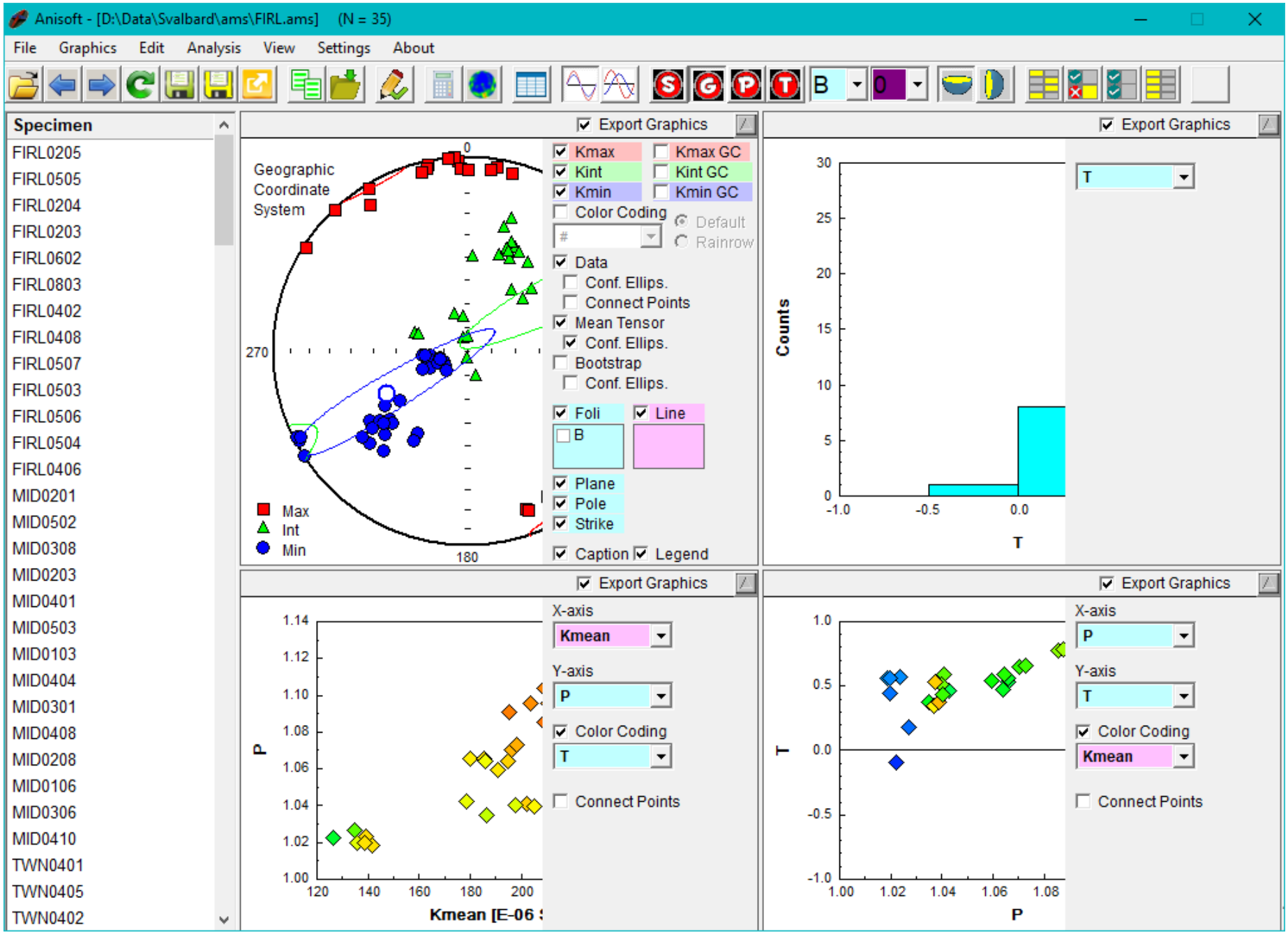
Instrument Control | Data Viewing

INSTRUMENT IS READY | 400 A/m | 1220 Hz | U/D | ROT 3D | CALIB | HCORR | 13:46:24

Anisoft - Data processing software




Anisoft - [D:\Data\Svalbard\ams\FIRL.ams] (N = 35)
File Graphics Edit Analysis View Settings About
Specimen
FIRL0205
FIRL0505
FIRL0204
FIRL0203
FIRL0602
FIRL0803
FIRL0402
FIRL0408
FIRL0507
FIRL0503
FIRL0506
FIRL0504
FIRL0406
MID0201
MID0502
MID0308
MID0203
MID0401
MID0503
MID0103
MID0404
MID0301
MID0408
MID0208
MID0106
MID0306
MID0410
TWN0401
TWN0405
TWN0402
Export Graphics
Geographic Coordinate System
Equal-Area Projection
N = 35
0
90
180
270
Max
Int
Min
Export Graphics
Counts
T
Export Graphics
P
Kmean [E-06 SI]
T
Export Graphics
T
P
Kmean [E-06 SI]


Anisoft - [D:\Data\Svalbard\ams\FIRL.ams] (N = 35)
File Graphics Edit Analysis View Settings About
Specimen
FIRL0205
FIRL0505
FIRL0204
FIRL0203
FIRL0602
FIRL0803
FIRL0402
FIRL0408
FIRL0507
FIRL0503
FIRL0506
FIRL0504
FIRL0406
MID0201
MID0502
MID0308
MID0203
MID0401
MID0503
MID0103
MID0404
MID0301
MID0408
MID0208
MID0106
MID0306
MID0410
TWN0401
TWN0405
TWN0402
Export Graphics
Geographic Coordinate System
0
270
180
Max
Int
Min
Kmax
Kint
Kmin
Kmax GC
Kint GC
Kmin GC
Color Coding
Default
Rainrow
Data
Conf. Ellips.
Connect Points
Mean Tensor
Conf. Ellips.
Bootstrap
Conf. Ellips.
Foli
Line
B
Plane
Pole
Strike
Caption
Legend
Export Graphics
T
Counts
30
25
20
15
10
5
0
-1.0
-0.5
0.0
T
Export Graphics
X-axis
Kmean
Y-axis
P
Color Coding
T
Connect Points
P
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
120
140
160
180
200
Kmean [E-06
Export Graphics
X-axis
P
Y-axis
T
Color Coding
Kmean
Connect Points
T
1.0
0.5
0.0
-0.5
-1.0
1.00
1.02
1.04
1.06
1.08
P

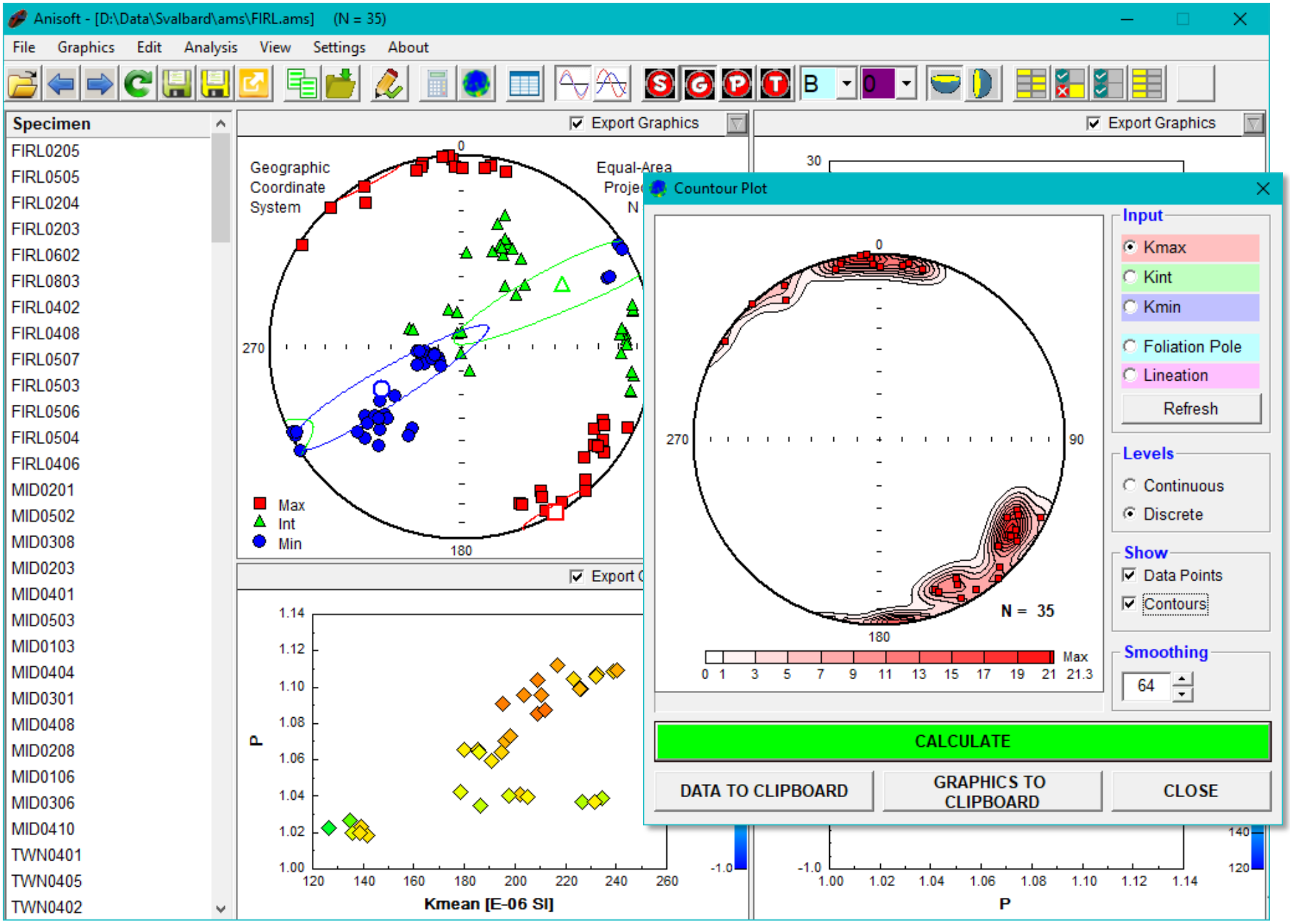
Anisoft - [D:\Data\Svalbard\ams\FIRL.ams] (N = 35)

File Graphics Edit Analysis View Settings About

Data Table

ID	Specimen	Field	Freq	Km	Kmax		Kint		Kmin		L	F	P	Pj	T	U	Q	E
1	FIRL0205	400	1220	180.0E-06	355.5	0.7	85.7	15.8	263.1	74.2	1.015	1.050	1.066	1.069	0.533	0.522	0.271	1.035
2	FIRL0505	400	1220	210.2E-06	9.3	4.5	100.1	10.4	256.1	78.6	1.013	1.082	1.096	1.104	0.715	0.704	0.160	1.068
3	FIRL0204	400	1220	190.8E-06	357.1	2.6	87.9	15.9	258.1	73.9	1.013	1.046	1.060	1.062	0.543	0.533	0.264	1.032
4	FIRL0203	400	1220	185.3E-06	356.1	0.5	86.3	18.8	264.8	71.2	1.014	1.051	1.066	1.069	0.557	0.546	0.256	1.036
5	FIRL0602	400	1220	185.8E-06	357.9	6.5	89.7	15.6	246.0	73.0	1.016	1.047	1.064	1.066	0.472	0.460	0.312	1.030
6	FIRL0803	400	1220	195.1E-06	354.1	0.2	84.2	17.5	263.4	72.5	1.011	1.079	1.091	1.100	0.755	0.746	0.136	1.068
7	FIRL0402	400	1220	196.1E-06	348.1	2.2	78.5	10.6	246.5	79.2	1.012	1.058	1.070	1.075	0.653	0.643	0.196	1.045
8	FIRL0408	400	1220	198.2E-06	347.5	4.1	78.2	10.1	235.5	79.1	1.012	1.060	1.073	1.078	0.658	0.648	0.193	1.047
9	FIRL0507	400	1220	209.1E-06	0.2	7.7	92.8	18.3	248.4	70.0	1.013	1.090	1.104	1.114	0.740	0.729	0.145	1.076
10	FIRL0503	400	1220	208.9E-06	14.2	6.8	105.4	9.7	249.4	78.1	1.009	1.075	1.085	1.094	0.773	0.765	0.125	1.065
11	FIRL0506	400	1220	203.6E-06	7.4	6.5	98.7	11.7	249.0	76.6	1.013	1.082	1.096	1.104	0.722	0.711	0.156	1.068
12	FIRL0504	400	1220	211.7E-06	14.0	6.3	105.2	10.2	253.0	78.0	1.009	1.078	1.088	1.097	0.785	0.777	0.118	1.068
13	FIRL0406	400	1220	194.5E-06	345.8	5.8	76.8	10.1	226.3	78.3	1.013	1.051	1.064	1.068	0.587	0.576	0.237	1.037
14	MID0201	400	1220	134.7E-06	117.1	18.6	3.1	50.3	220.0	33.5	1.011	1.016	1.027	1.027	0.181	0.174	0.520	1.005
15	MID0502	400	1220	186.5E-06	125.7	12.0	24.9	41.4	228.4	46.1	1.011	1.024	1.035	1.036	0.378	0.370	0.374	1.013
16	MID0308	400	1220	141.6E-06	316.7	0.2	47.1	58.5	226.6	31.5	1.004	1.015	1.019	1.020	0.558	0.555	0.251	1.010
17	MID0203	400	1220	126.2E-06	121.5	20.9	16.3	34.5	236.6	48.0	1.012	1.010	1.022	1.022	-0.088	-0.093	0.752	0.998
18	MID0401	400	1220	226.4E-06	115.9	4.4	22.1	40.3	211.1	49.4	1.012	1.025	1.037	1.038	0.347	0.339	0.396	1.013
19	MID0503	400	1220	178.4E-06	118.5	16.9	18.4	29.9	234.0	54.7	1.011	1.031	1.043	1.044	0.459	0.450	0.319	1.019
20	MID0103	400	1220	202.2E-06	123.4	13.4	18.3	47.5	224.7	39.4	1.008	1.033	1.041	1.043	0.592	0.585	0.231	1.024
21	MID0404	400	1220	205.1E-06	131.9	15.4	24.5	47.4	234.6	38.5	1.009	1.030	1.040	1.041	0.515	0.508	0.281	1.020
22	MID0301	400	1220	139.4E-06	136.8	6.5	36.1	58.6	230.6	30.6	1.005	1.018	1.023	1.025	0.569	0.565	0.244	1.013
23	MID0408	400	1220	234.4E-06	126.4	9.4	27.6	42.6	226.2	45.8	1.012	1.027	1.039	1.040	0.376	0.368	0.375	1.014
24	MID0208	400	1220	135.6E-06	126.4	15.7	21.0	43.5	231.2	42.3	1.005	1.014	1.020	1.020	0.441	0.437	0.327	1.009
25	MID0106	400	1220	197.8E-06	126.2	13.9	22.3	44.1	229.3	42.6	1.011	1.029	1.040	1.041	0.434	0.426	0.335	1.017
26	MID0306	400	1220	138.6E-06	139.3	2.3	46.3	52.7	231.0	37.2	1.004	1.015	1.020	1.021	0.557	0.554	0.251	1.011
27	MID0410	400	1220	231.7E-06	302.6	1.8	34.4	44.5	210.8	45.5	1.009	1.028	1.037	1.039	0.531	0.524	0.270	1.020
28	TWN0401	400	1220	232.5E-06	147.2	5.3	337.9	84.6	237.3	1.0	1.021	1.085	1.108	1.114	0.598	0.581	0.234	1.063

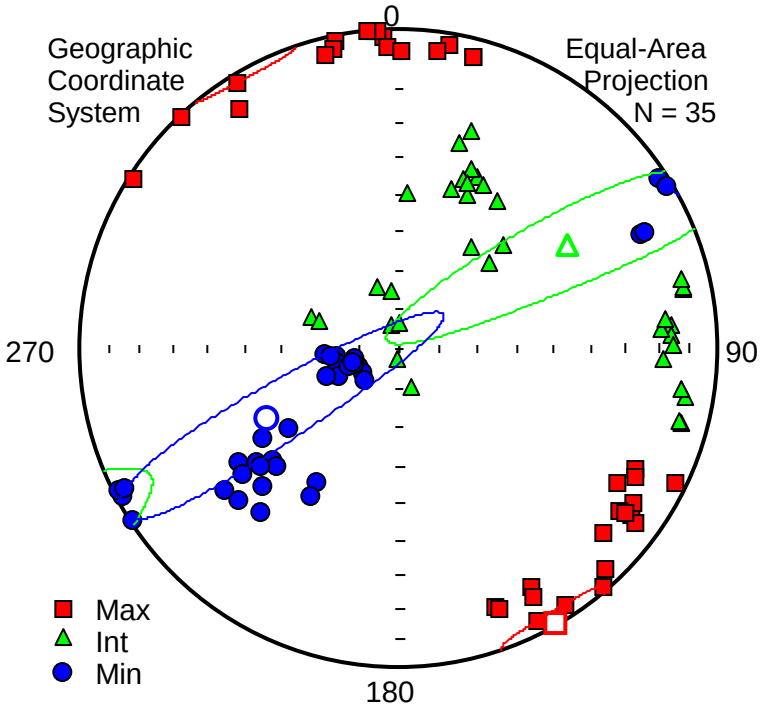
TWN0402 | Kmean [E-06 SI] | P


Anisoft - [D:\Data\Svalbard\ams\FIRL.ams] (N = 35)
File Graphics Edit Analysis View Settings About
Specimen
FIRL0205
FIRL0505
FIRL0204
FIRL0203
FIRL0602
FIRL0803
FIRL0402
FIRL0408
FIRL0507
FIRL0503
FIRL0506
FIRL0504
FIRL0406
MID0201
MID0502
MID0308
MID0203
MID0401
MID0503
MID0103
MID0404
MID0301
MID0408
MID0208
MID0106
MID0306
MID0410
TWN0401
TWN0405
TWN0402
Export Graphics
Geographic Coordinate System
Equal-Area Proje
N
0
90
180
270
Max
Int
Min
Export Graphics
30
Countour Plot
Input
Kmax
Kint
Kmin
Foliation Pole
Lineation
Refresh
Levels
Continuous
Discrete
Show
Data Points
Contours
Smoothing
64
N = 35
0 1 3 5 7 9 11 13 15 17 19 21 21.3
Max
CALCULATE
DATA TO CLIPBOARD
GRAPHICS TO CLIPBOARD
CLOSE
P
Kmean [E-06 SI]
1.00 1.02 1.04 1.06 1.08 1.10 1.12 1.14
120 140 160 180 200 220 240 260
-1.0
140
120

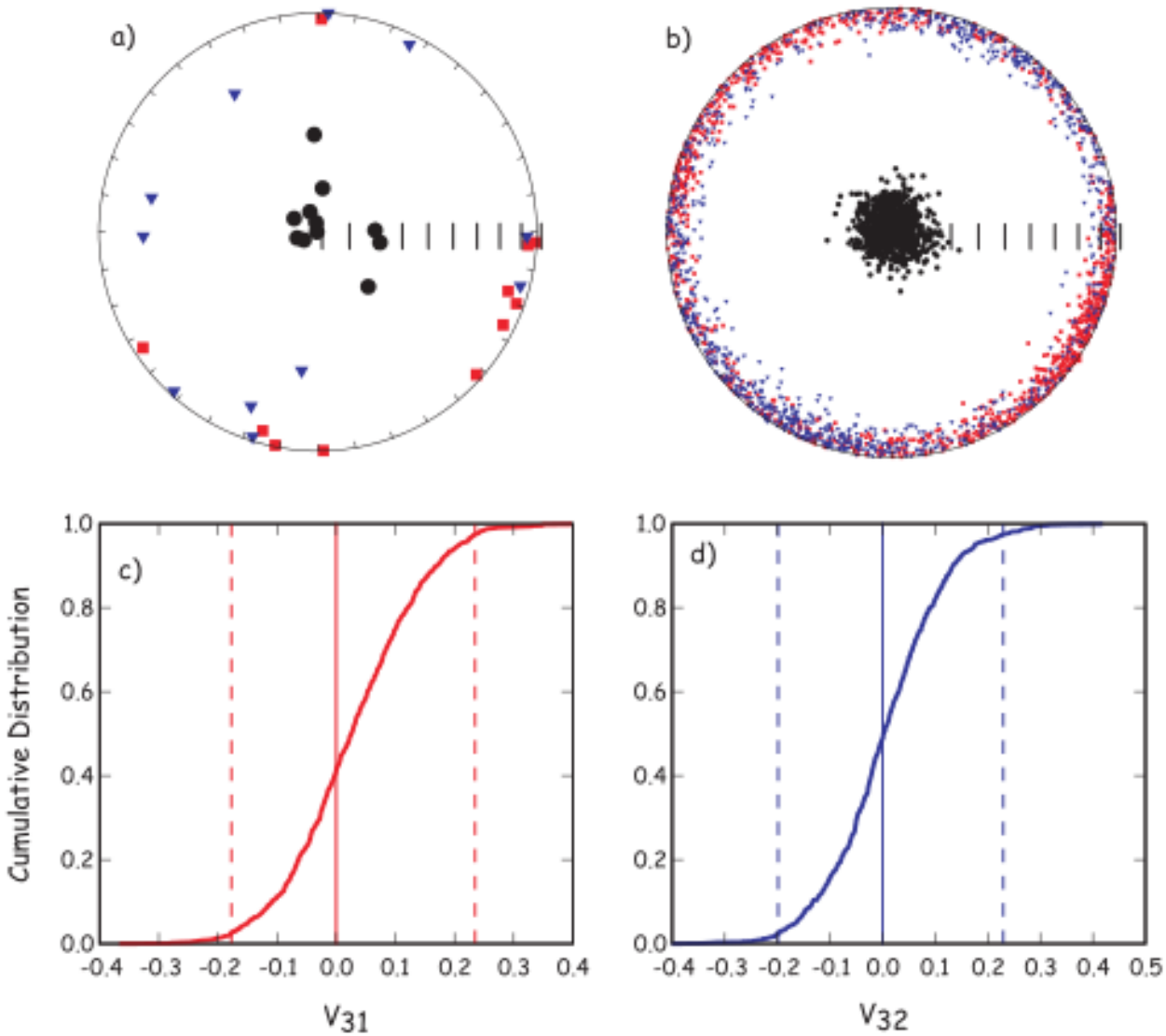
Mean tensor (Jelinek 1978, Hext 1963)

- Mean directions
- Confidence ellipses

$$\mathbf{F} = \begin{pmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{pmatrix} = \frac{1}{n} \begin{pmatrix} \sum_{i=1}^{n} k_{11i} & \sum_{i=1}^{n} k_{12i} & \sum_{i=1}^{n} k_{13i} \\ \sum_{i=1}^{n} k_{21i} & \sum_{i=1}^{n} k_{22i} & \sum_{i=1}^{n} k_{23i} \\ \sum_{i=1}^{n} k_{31i} & \sum_{i=1}^{n} k_{32i} & \sum_{i=1}^{n} k_{33i} \end{pmatrix} = \frac{1}{n} \sum_{i=1}^{n} \mathbf{k}_i$$

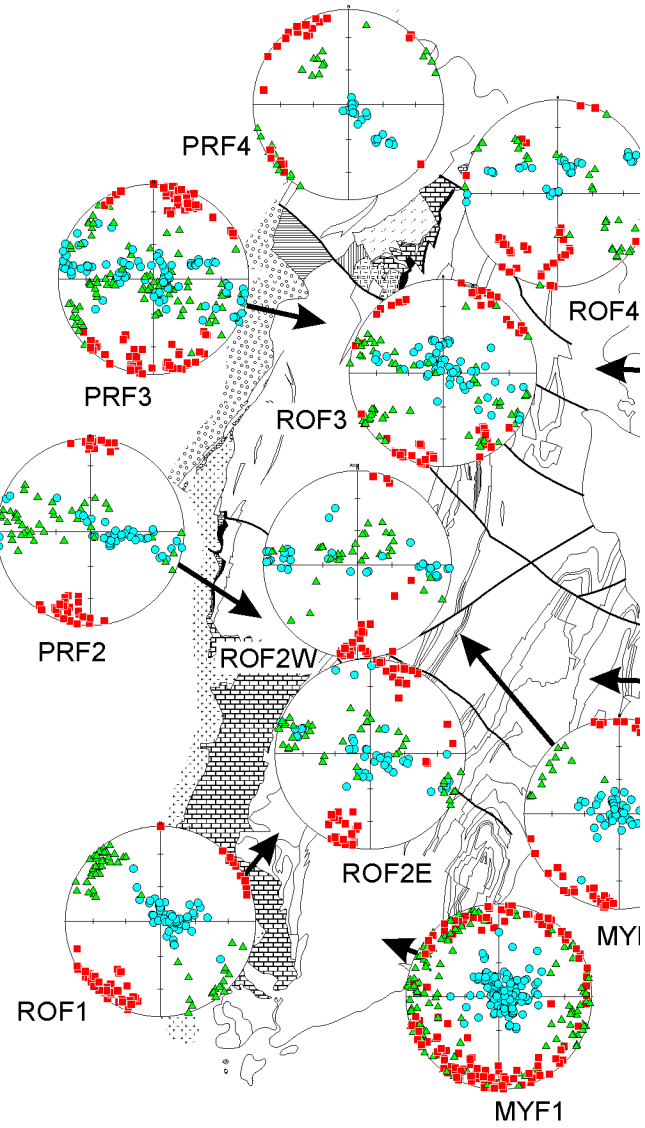


Bootstrap (Constable & Tauxe 1990)

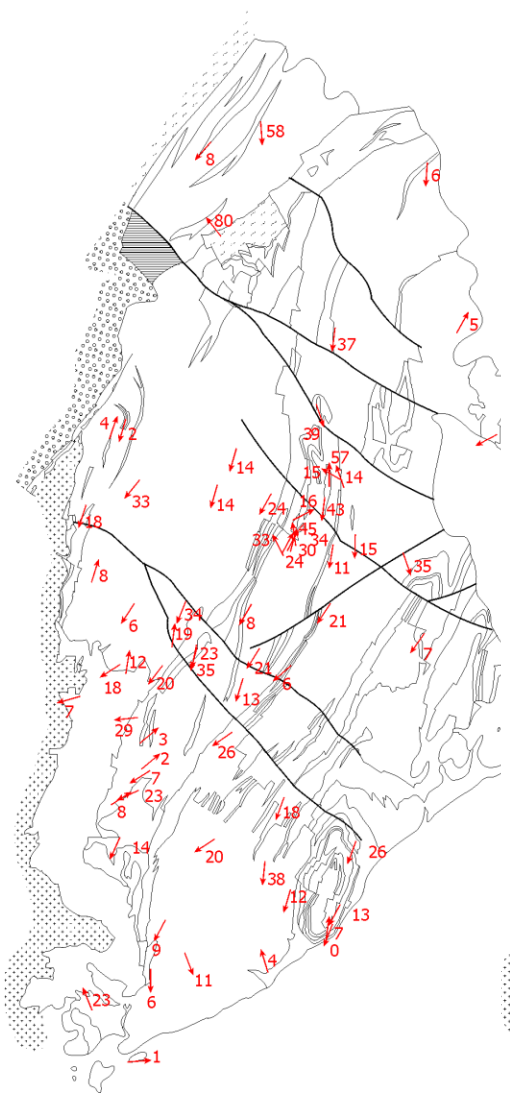


Data presentation in regional scale

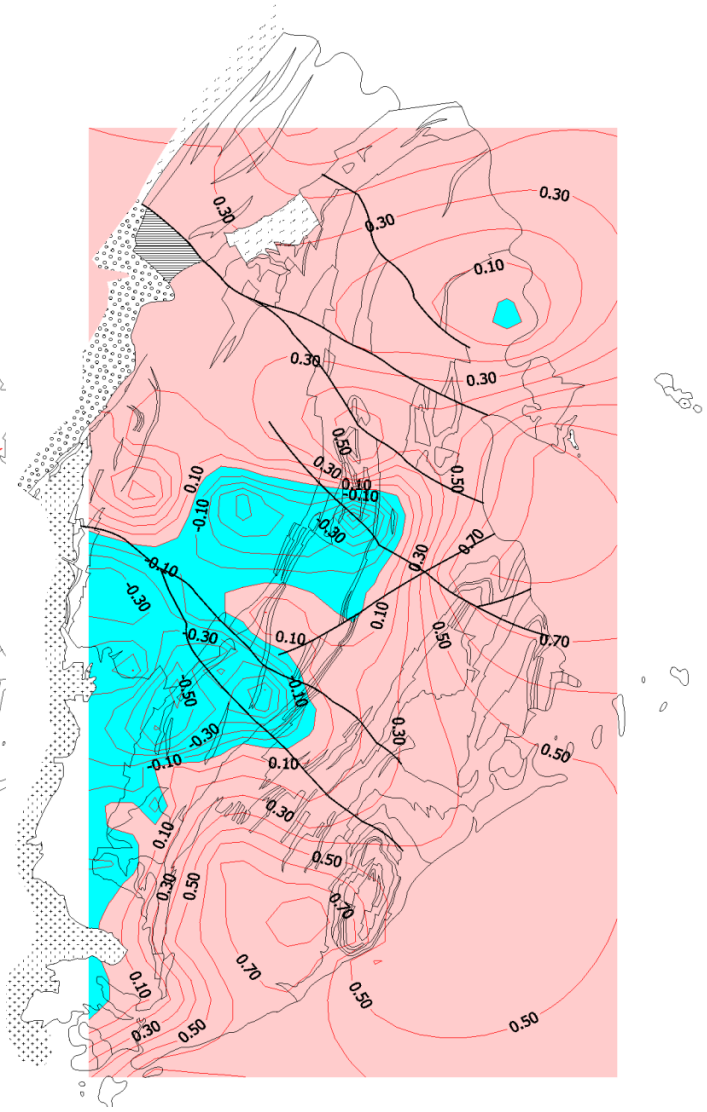
•projection of mean susceptibilities



•magnetic lineation of mean tensor

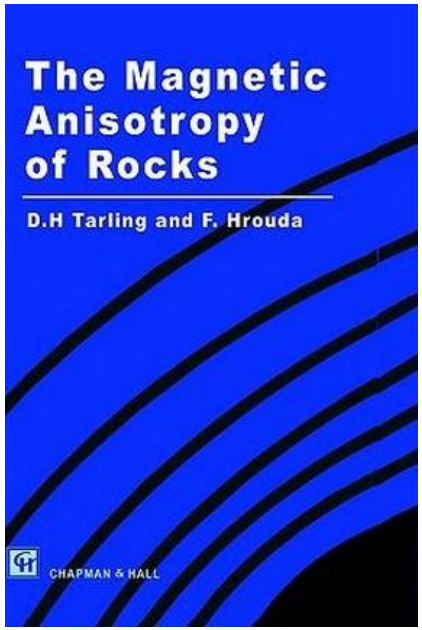


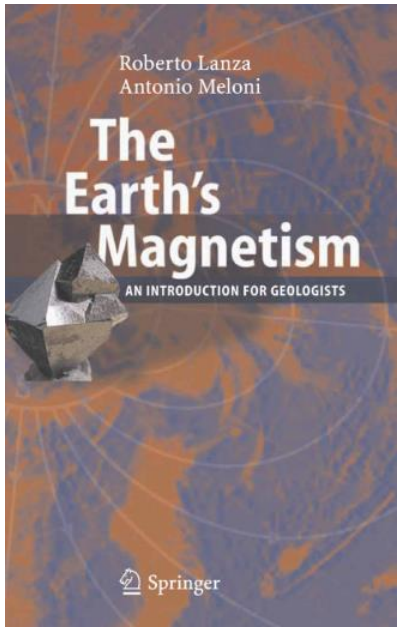
•isolines of shape parameter (T)

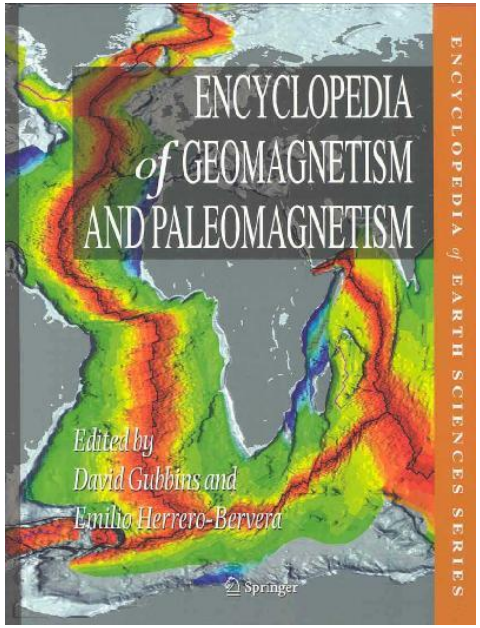


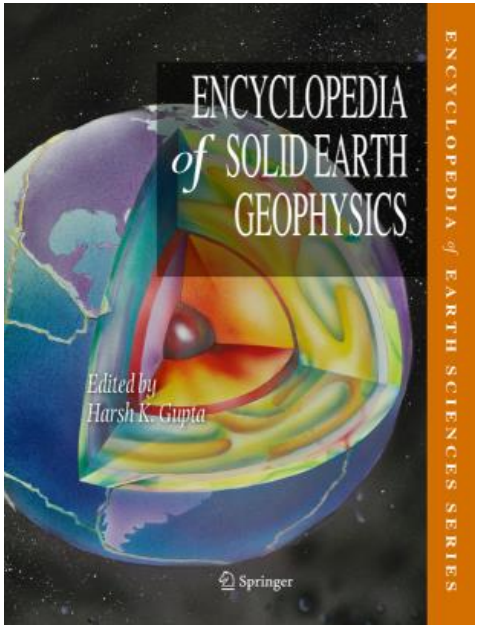
Literature

- Tarling, D.H. & Hrouda, F. 1993. The Magnetic Anisotropy of Rock. *Chapman & Hall*, 217 pp.
- Lanza, R. & Meloni, A. 2006. The Earth's Magnetism: An Introduction for Geologist. *Springer*, 278 pp. (Chapter 5).
- Hrouda, F. 2007. Magnetic Susceptibility, Anisotropy. Encyclopedia of Geomagnetism and Paleomagnetism. *Springer*. 546-560.
- Sagnotti, L. 2009. Magnetic anisotropy. Encyclopedia of Solid Earth Geophysics. *Springer*. 717-729.
- Tauxe, L. 2013. Lectures in paleomagnetism. http://magician.ucsd.edu/Essentials_2/WebBook2ch13.html#x15-15500013.
- Hrouda, F., 1982. Magnetic anisotropy of rocks and its application in geology and geophysics. *Geophysical Surveys*, 5, 37–82.
- Borradaile, G. J. & Henry, B. 1997. Tectonic applications of magnetic susceptibility and its anisotropy. *Earth Science Reviews*, 42, 49–93.
- Jackson,M.J. & Tauxe, L. 1991. Anisotropy of magnetic susceptibility and remanence: developments in the characterization of tectonic, sedimentary, and igneous fabric. *Reviews of Geophysics*, 29, 371–376.
- Rochette, P., Jackson, M. J. & Aubourg, C. 1992. Rock magnetism and the interpretation of anisotropy of magnetic susceptibility. *Reviews of Geophysics*, 30, 209–226.

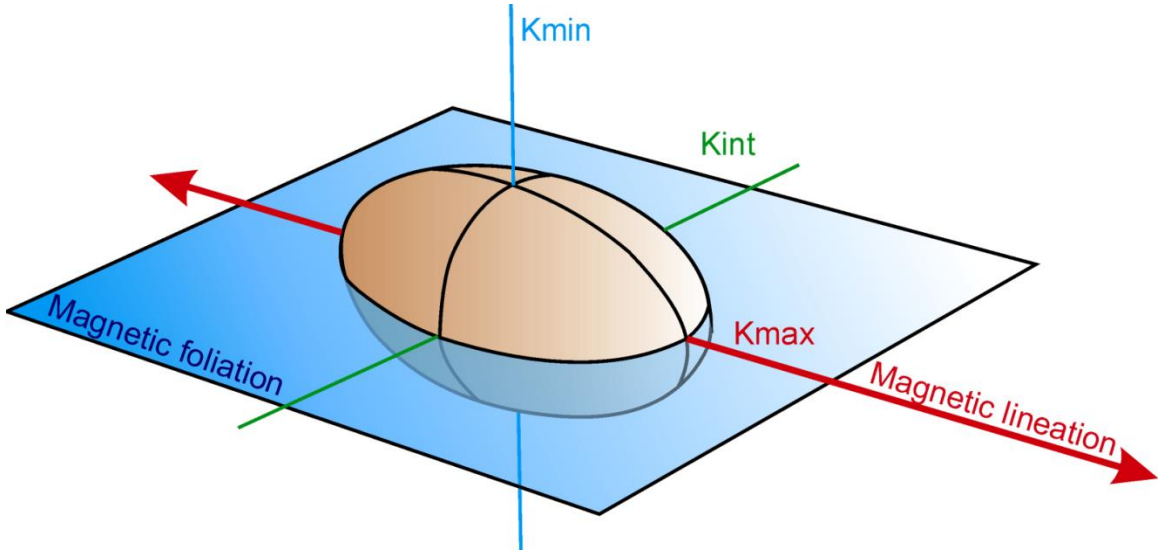








Thanks for your Attention!



AGICO
ADVANCED
GEOSCIENCE
INSTRUMENTS
COMPANY

Institute of Geology of the CAS, v. v. i.

AGICO

ADVANCED
GEOSCIENCE
INSTRUMENTS
COMPANY

Telephone	+420 511 116 303
FAX	+420 541 634 328
Postal Address	Ječná 29a, CZ-621 00 Brno, Czech Republic
Electronic Mail	agico@agico.cz
ICO	60731354
VAT No. (DIC)	CZ60731354

www.agico.com

agico@agico.cz

chadima@agico.cz