20694 Vorlesung mit Übungen Strukturgeologie und Tektonik

Module:
Fachkompetenz Geologie
Wahlmodul Geologie

Voraussetzung:
System Erde I und II
Übungen System Erde I und II

Leistungsüberprüfung:

8 Übungen PASS/FAIL
1 Schlussprüfung benotet

2KP

Bestehen = Voraussetzung für ↗

14358 Exkursion Geländepraktikum II (Geologie)

Modul:
Methodenkompetenz Geologie

Voraussetzung:
Kartenlesen und Profilzeichnen
Strukturgeologie und Tektonik

Leistungsüberprüfung:
Kartierung, Exkursionsbericht (PASS-FAIL)
(3KP)

Semesterplan FS 2016

	Datum		Thema		Übungen	abgeben
1	26. Feb.	1	Druck, Spannung, Mohr Kreis, Spannungsfeld	1	Stress	29. 3.
2	4. März	2	Deformation, Strainellipse, strain marker, Strainmessung	2	Strain	29. 3.
3	11. März		fällt aus (Tromsø workshop)			
4	18. März		fällt aus (Tromsø workshop)			
5	25. März		fällt aus (Ostern)			
6	1. April	3	Mohr-Coulomb, Reibung, Klüfte und Brüche	3	Mohr-Coulomb	6. 4.
7	8. April	4	Bruchsysteme, Stereonetz Verwerfungen	4	Stereonetz	13. 4.
8	15. April	5	Scherzonen, Foliation, Lineation	5	Trajektorien	27. 4.
9	22. April		fällt aus (EGU)			
10	29. April	6	Falten, Geometrie, Faltenbildung	6	Devils Island	11.5.
11	6. Mai		fällt aus (Himmelfahrt)			
12	13. Mai	7	Mikrostrukturen, Deformationsmechanismen, Rheologie	7	Inverse SURFOR	18. 5.
13	20. Mai	8	Subduktion, Gebirgsbildung, Transformstörungen	8	Critical taper	25. 5.
14	27. Mai	9	Extensionstektonik, rifting, MOR, MCC, LANF			
15	3. Juni	10	Test			

Literatur

- Fossen, H. (2012) Structural Geology, Cambridge University Press.
- Twiss, R.J., Moores, E.M. (2007) Structural Geology. W.H. Freeman.
- Passchier, C.W., Trouw, R.A.J. (2005) Microtectonics. Springer Verlag.

Deutsch:

- Frisch, W., Meschede, M. (2009) Plattentektonik. Primus Verlag.
- Eisbacher, G.H. (1991) Einführung in die Tektonik, Enke Verlag.

Klassiker:

- Moores, E.M., Twiss, R.J. (1996) Tectonics. W.H. Freeman.
- Hobbs, B.E., Means, W.D., Williams, P.F. (1976) An Outline of Structural Geology. Wiley International.
- Ramsay, J.G., Huber, M.I. (1987) Modern Structural Geology I & II. Academic Press.

Theoretisch-mathematisch:

- Pollard, D.D., Fletcher, R.C. (2005) Structural geology. Cambridge University Press.
- Means, W.D. (1976) Stress and Strain. Springer Verag.
- Nye, J.F. (1985) Physical properties of crystals, Clarendon Press.

Internet

E-modules by H. Fossen (http://folk.uib.no/nglhe/):

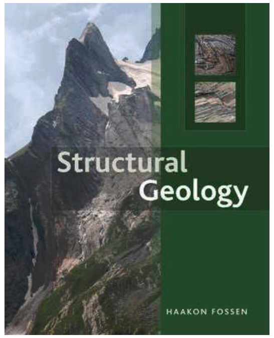
- To go with book:
  - http://folk.uib.no/nglhe/StructuralGeoBookEmodules.html
- Structural Geology Primer:
  - http://folk.uib.no/nglhe/Emodules/Structure%20intro%20module.swf

Twiss and Moores (Figures only - 47 MB download):

- http://www.whfreeman.com/Catalog/product/structuralgeology-secondedition-twiss

Burg, ETH Zürich (PDF):

- Einführung in die Strukturgeologie:
  - http://e-collection.library.ethz.ch/eserv/eth:24456/eth-24456-01.pdf



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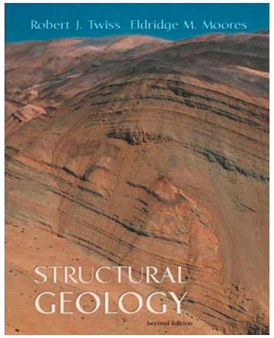

Robert J. Twiss Eldridge M. Moores
STRUCTURAL
GEOLOGY
Second Edition

I

1 Druck - Spannung - Mohrkreis - Spannungsfeld

VL-Themen:

- Druck und Spannung in der Erdkruste
- Spannungsellipse
- Spannungstensor
- Hauptspannungen

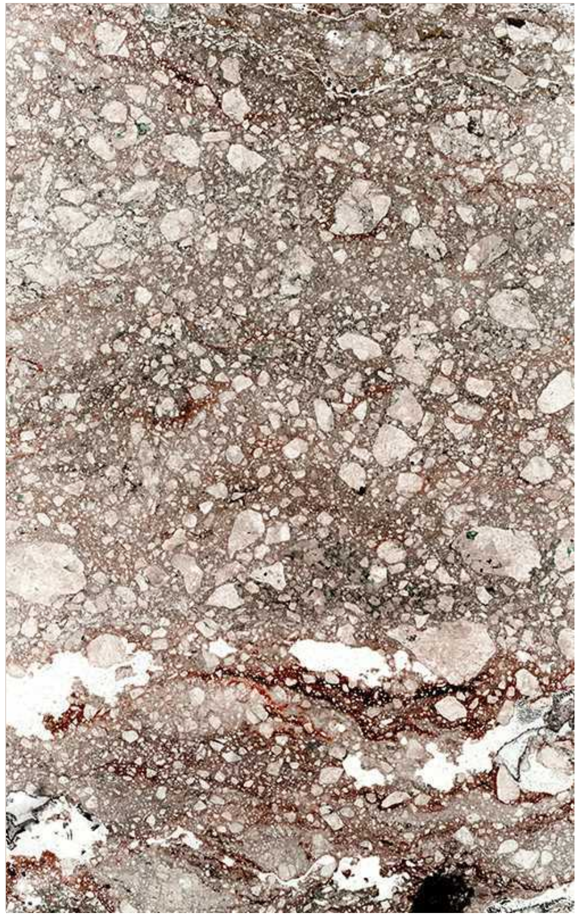
- Mohr-Kreis
- Mohr'sche Brüche
- Spannungszustände (Experiment & Natur)

- Spannungsmessungen
- Spannungsfeld

Druck und Spannung

Kontinuumsmechanik

Material ist
- kontinuierlich (keine Diskontinuitäten, keine Partikel etc.)
- homogen
- isotrop



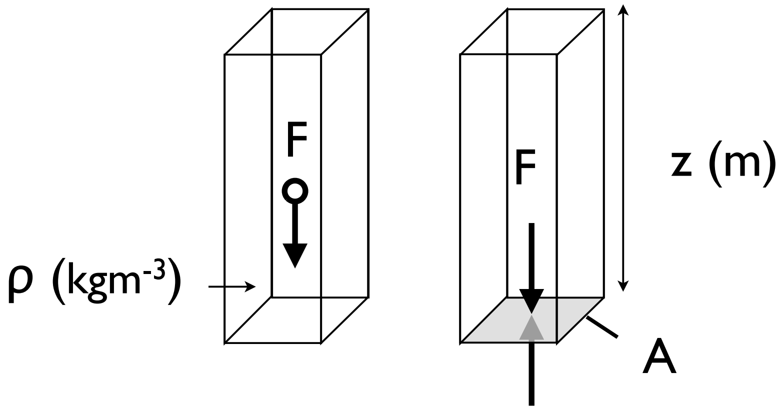
Druck

Gravitation (Kraft)

$F = m \cdot g = \rho \cdot V \cdot g = \rho \cdot z \cdot A \cdot g$

Kraft = Masse $\cdot$ Beschleunigung
1 Newton (N) = 1 kg $\cdot$ m / s^2 = 1 $kgms^{-2}$

$g = 9.81 ms^{-2}$
$\rho = 2.85 \cdot 10^3\ kgm^{-3}$



Druck = p = F/A
Spannung = σ = F/A

Lithostatischer Druck (= Gravitation / Fläche)

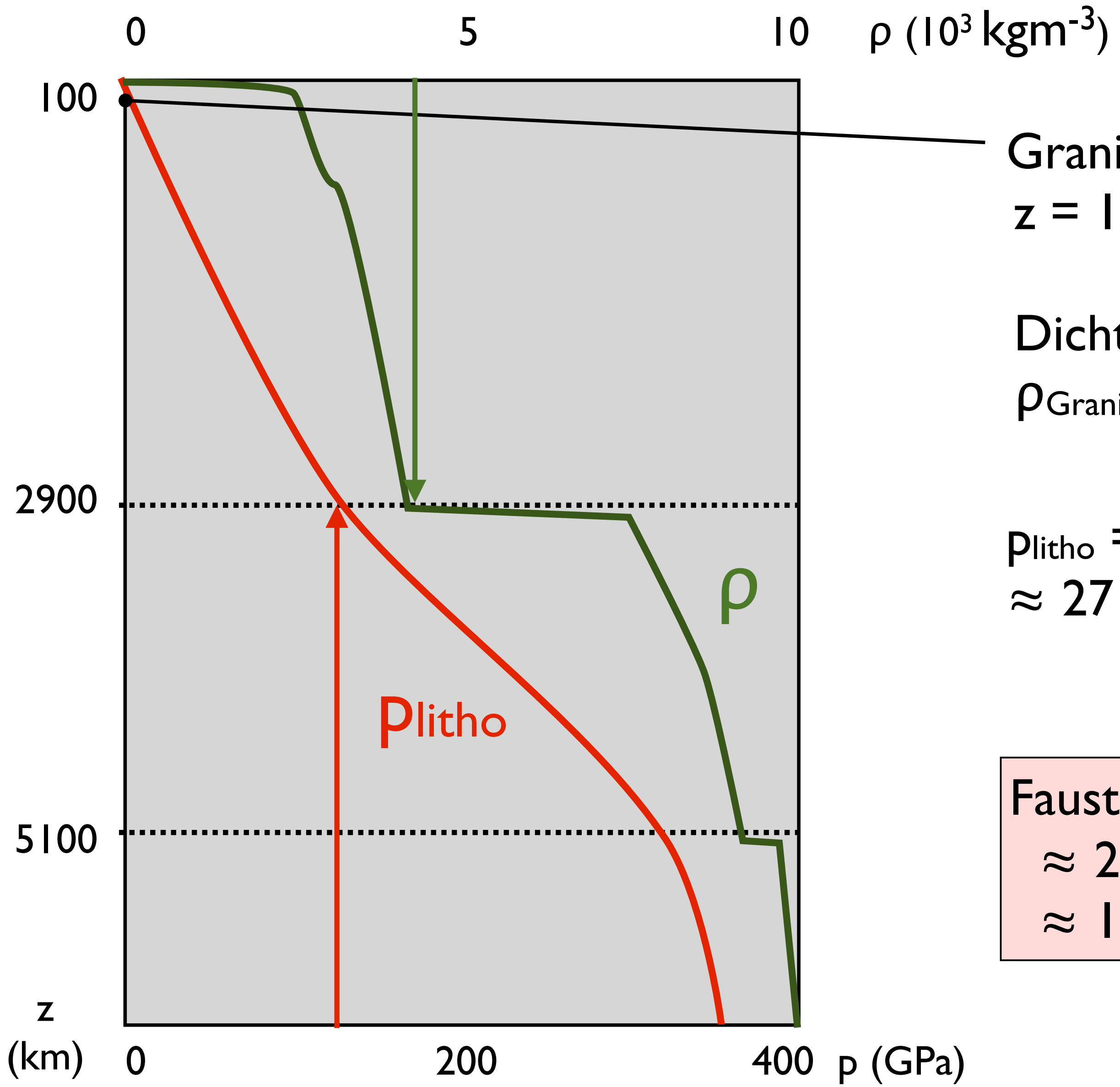
$\sigma_{lith} = \rho \cdot g \cdot V / A = \rho \cdot g \cdot (z \cdot A) / A = \rho \cdot g \cdot z$

Spannung = Kraft / Fläche
1 Pascal (Pa) = 1 N / m^2 = 1 Nm^{-2}

Beispiel:
σ_{lith} = f (z) = 27'959 Pa / m = 28 MPa / km

Pascal	andere Einheiten
10^2 Pa (1 Hektopascal)	1 mbar
10^5 Pa	1 bar
100 MPa	1 kb
1 GPa	10 kb
10^5 Pa	14.5 psi (pound / $inch^2$)
1 MPa	0.145 kpsi

Lithostatischer Druck



Granit in 100 km Tiefe

$z = 100 \cdot 10^3$ m

Dichte ρ

$\rho_{Granit} = 2.75 \cdot 10^3\ kgm^{-3}$

$p_{litho} = \rho \cdot g \cdot z$

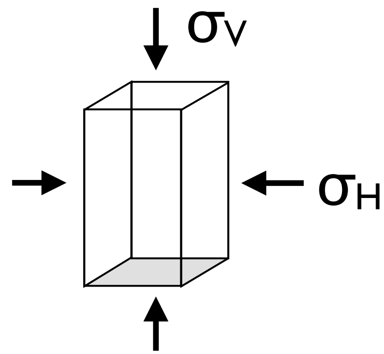
$\approx 27 \cdot 10^8$ Pa = 2.7 GPa

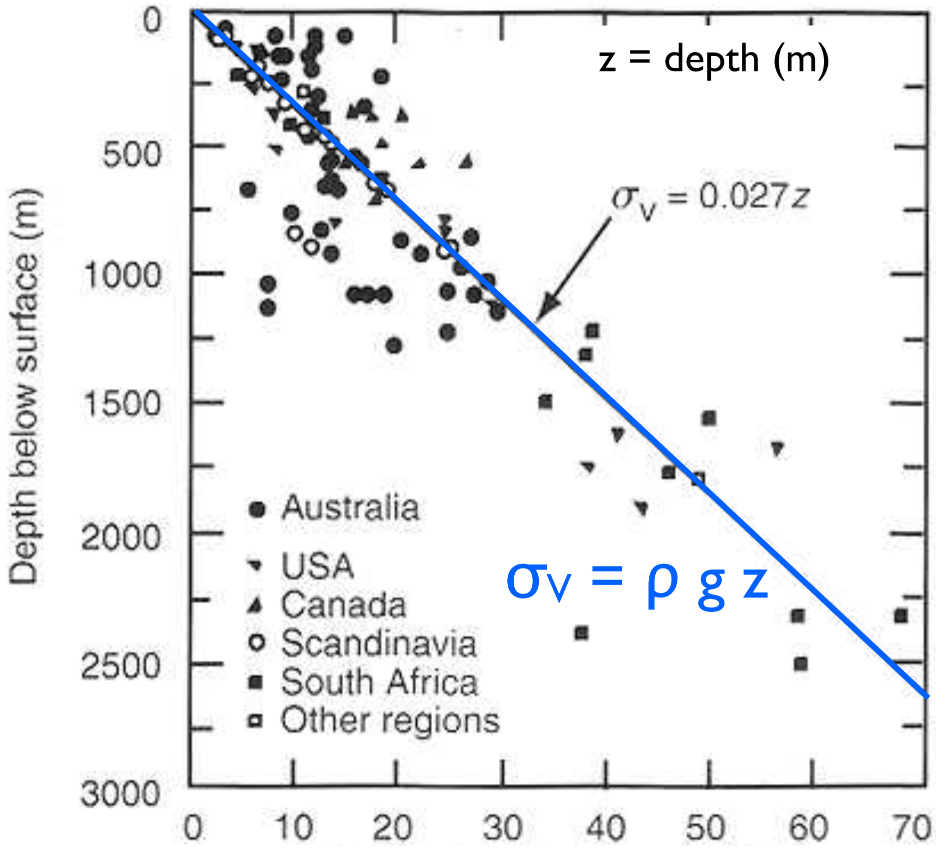
Faustregel für Druckzunahme

≈ 27 MPa / km

≈ 1 kb / 4 km

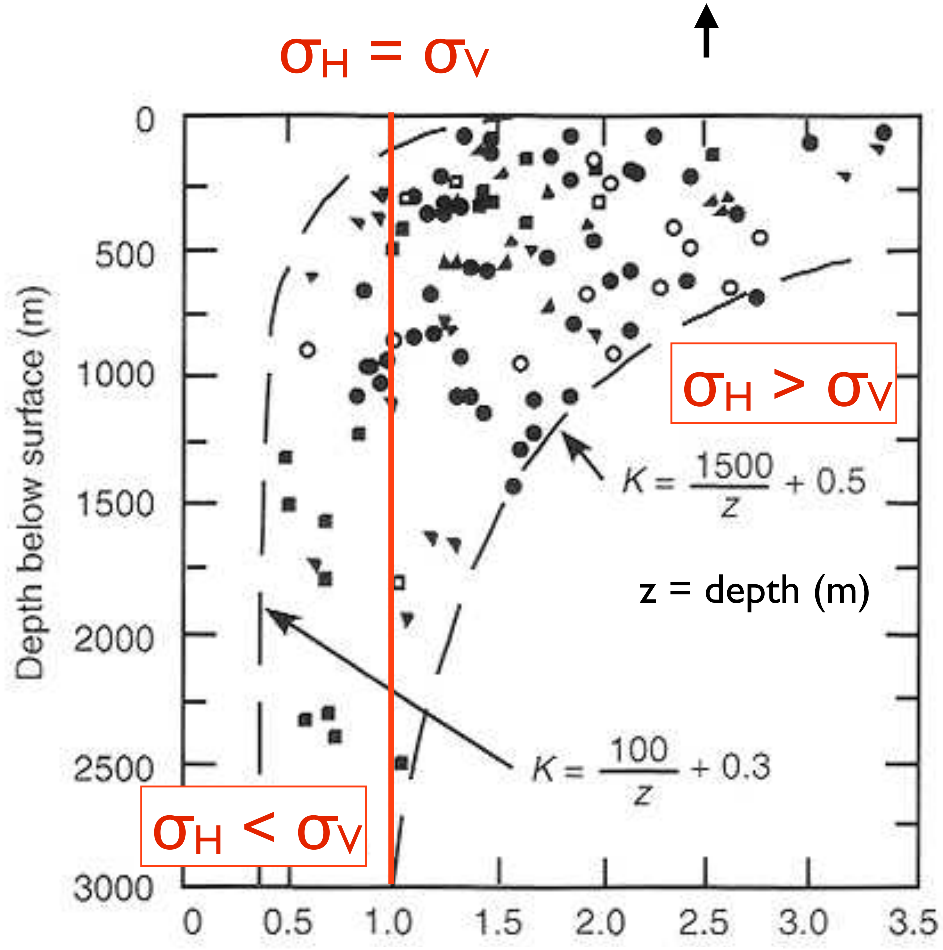
Spannungsmessungen





vertical stress, σ_V (MPa)

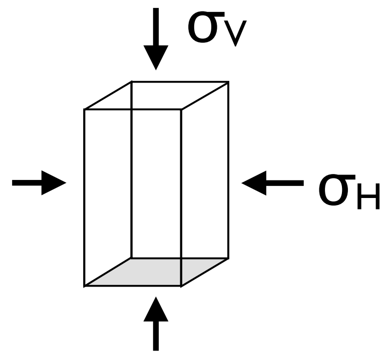
Fletcher & Pollard (2005)

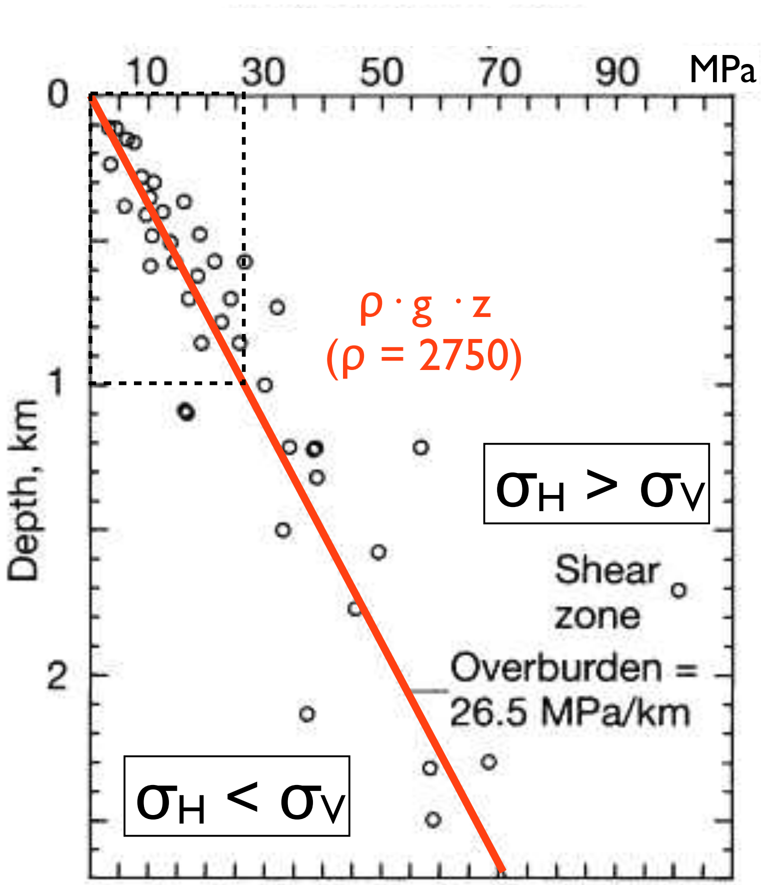


ratio $K = \sigma_H / \sigma_V$

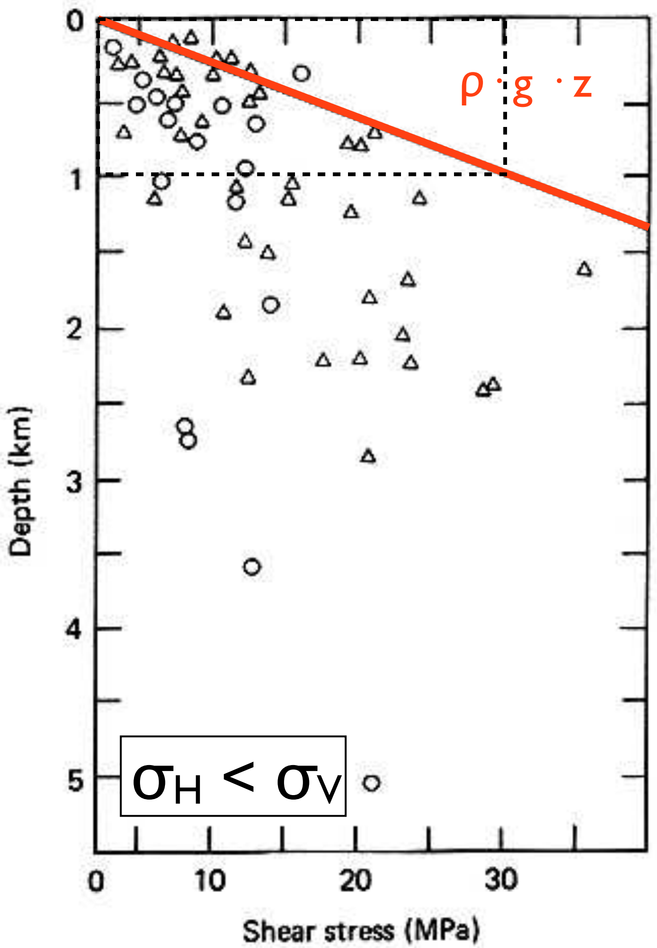
mit zunehmender Tiefe: $\sigma_H \leq \sigma_V$

Spannungsmessungen





measured vertical stress, σ_V
Twiss & Moores (2007)



Turcotte & Schubert (1982)

$\rho \cdot g \cdot z$

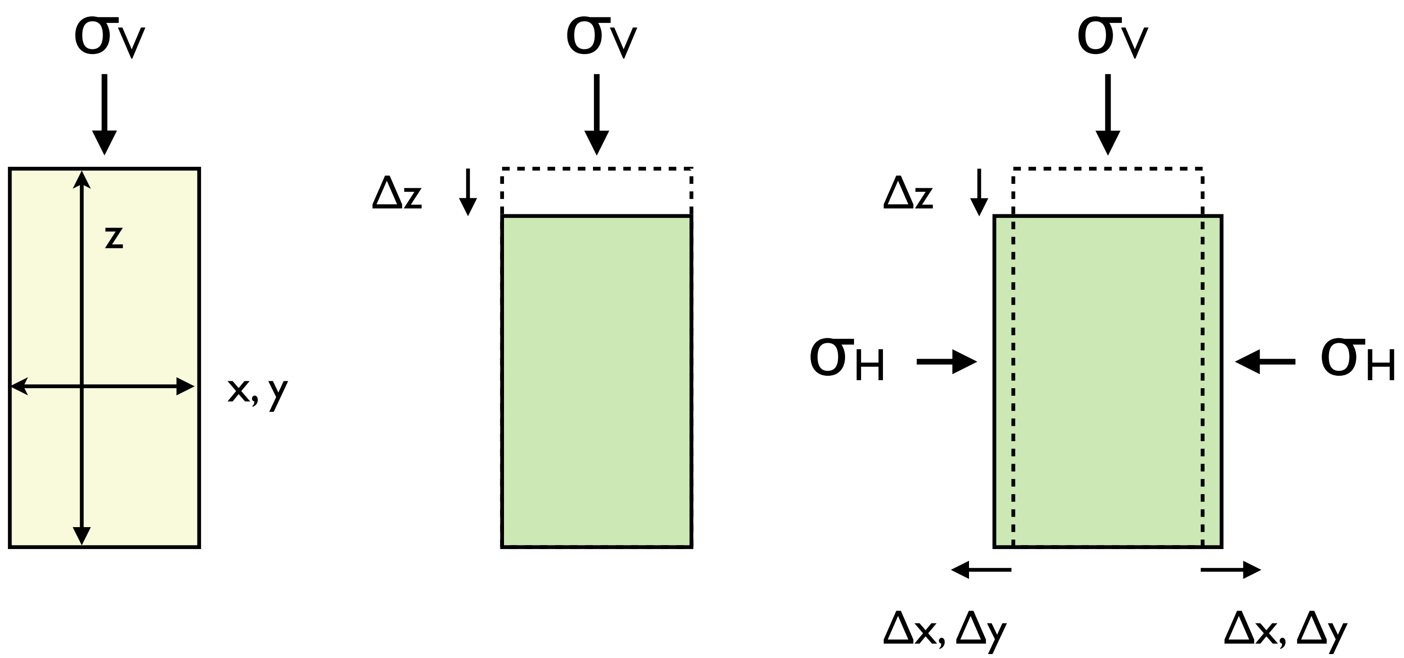
= lithostatic pressure

= overburden pressure

$\tau = {}^1/_2\,(\sigma_V - \sigma_H)$

wenn $\sigma_V \approx \sigma_H$
$\tau \rightarrow 0$

Elastizitätskonstante E, ν



$e_z = \sigma_V / E = \sigma_z / E$ $\quad e_z = \Delta z / z$

$e_x = e_y = \nu \cdot \sigma_z / E$ $\quad e_x = \Delta x / x \quad e_y = \Delta y / y$

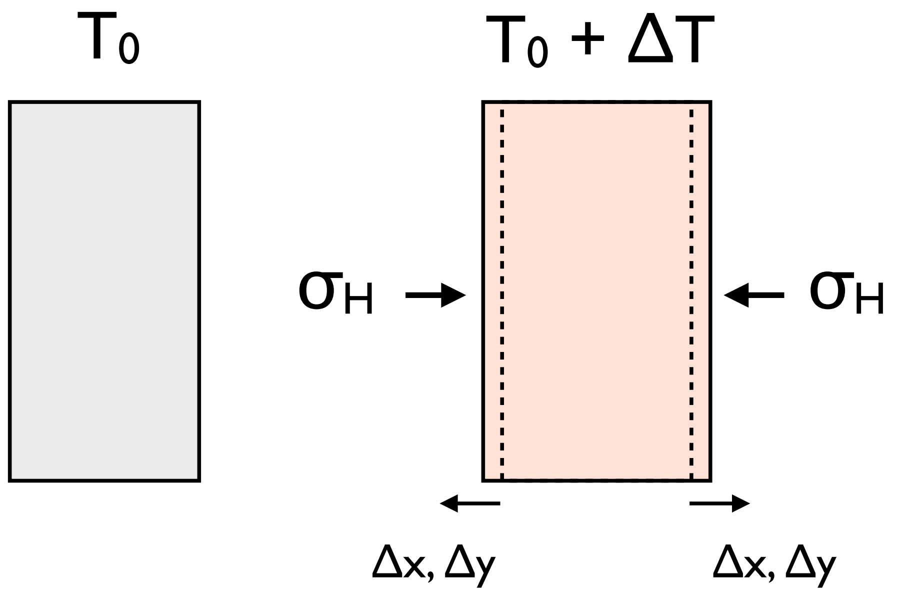
E = Elastizitätsmodul
(Young's module)

ν = Poissonzahl
(Querdehungszahl)

$$\sigma_H = \kappa \cdot \sigma_V = \frac{\nu}{(1-\nu)} \cdot \sigma_V$$

$\sigma_H = \sigma_x = \sigma_y$

Wärmeausdehnung α



$\Delta x = \Delta y = \alpha \cdot x_0 \cdot \Delta T$

α = Längenausdehungskoeffizient
(thermal expansion coefficient)

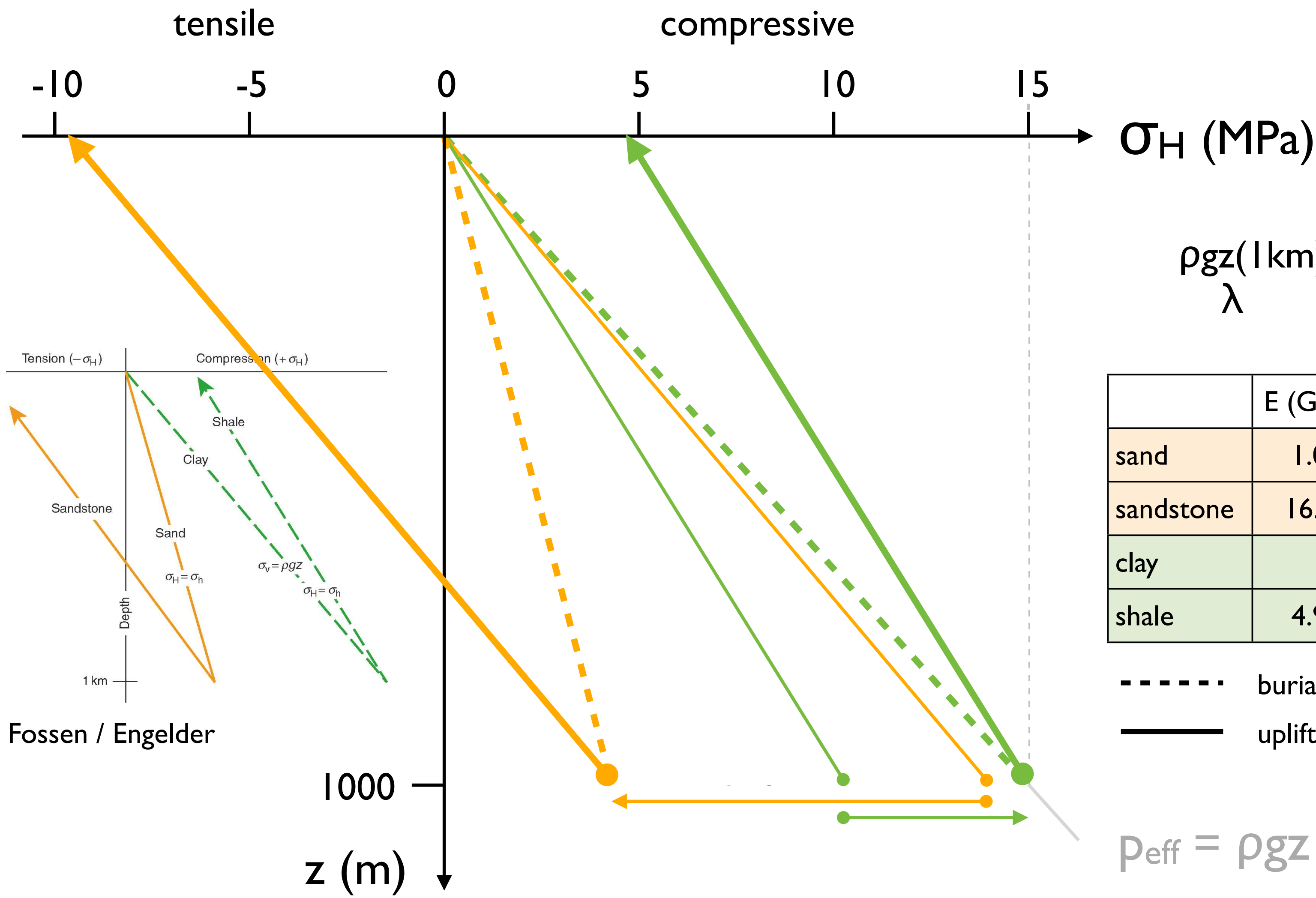
$$\sigma_H = \frac{E}{(1-\nu)} \cdot \alpha \cdot \Delta T$$

$\sigma_H = \sigma_x = \sigma_y$

zusammen:

$$\sigma_H = \kappa \cdot \sigma_V = \frac{\nu}{(1-\nu)} \cdot \sigma_V + \frac{E}{(1-\nu)} \cdot \alpha \cdot \Delta T$$

Stress during burial and uplift



$\rho gz(1km) = 25$ MPa
$\lambda = 0.40$

	E (GPa)	ν	α (10^{-6} °C^{-1})
sand	1.0	0.21	10.0
sandstone	16.5	0.33	10.8
clay		0.50	0.0
shale	4.9	0.36	10.0

- - - - - burial
——— uplift

$p_{eff} = \rho gz - p_p$ (MPa)

$$\sigma_H = \frac{\nu}{(1-\nu)} \cdot \sigma_V + \frac{\alpha \cdot E}{(1-\nu)} \Delta T$$

Beispiele

Fossen Structural Geology: Colorado River

http://www.igiltd.com/petroleum-geology.html

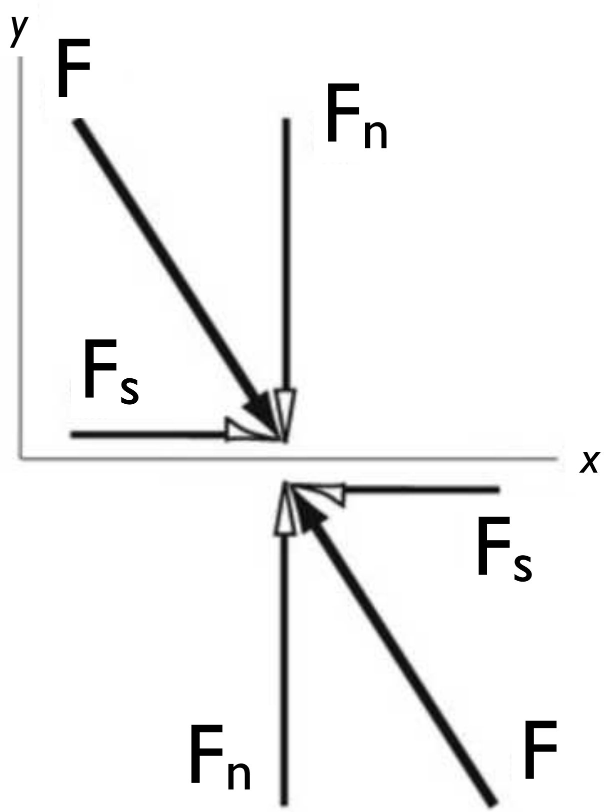
http://written-in-stone-seen-through-my-lens.blogspot.ch/2011/09/flight-plan-part-ii-geology-of-circle.html

http://academic.brooklyn.cuny.edu/geology/leveson/core/topics/weathering/picture_gallery/display/yorkshire_27.html

Spannungsellipse

Gleichgewicht der Kräfte

Kräfte

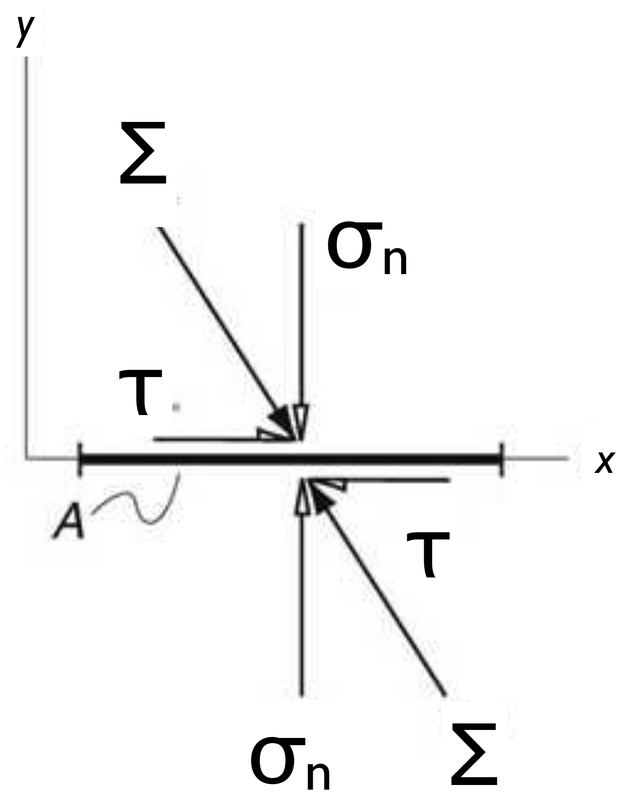


F_n, F_s: Normal- und Scherkomponenten

Kräftegleichgewicht

$F_{oben} = F_{unten}$

Kräfte = Spannung · Fläche

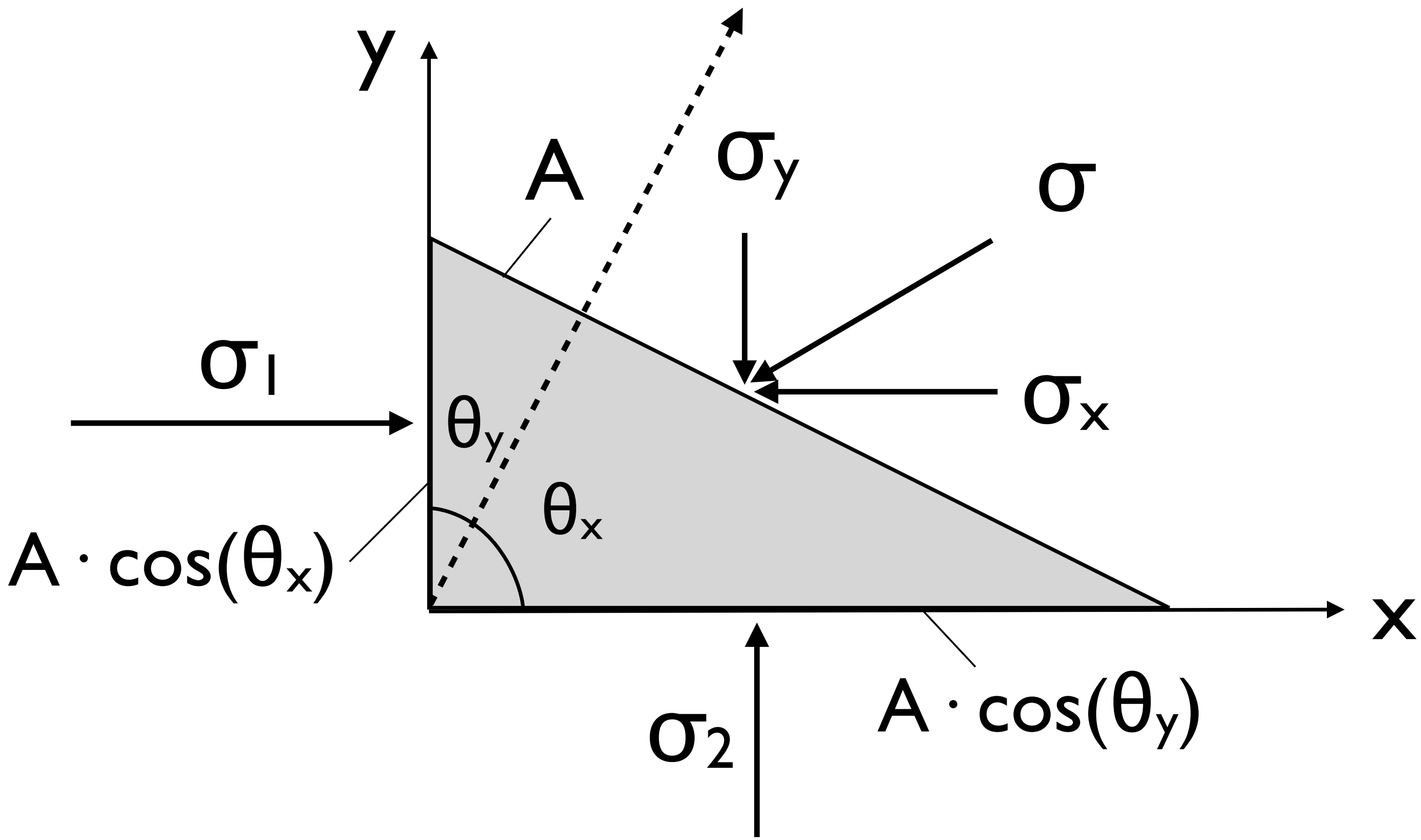


σ, τ: Normal- und Scherkomponenten

'traction' - Gleichgewicht

$\Sigma_{oben} = \Sigma_{unten}$

Gleichgewicht der Kräfte



Kräftegleichgewicht

$F_{x\text{-Richtung}} = F_{-x\text{-Richtung}}$ $\sigma_1 \cdot A \cdot \cos(\theta_x) = \sigma_x \cdot A$

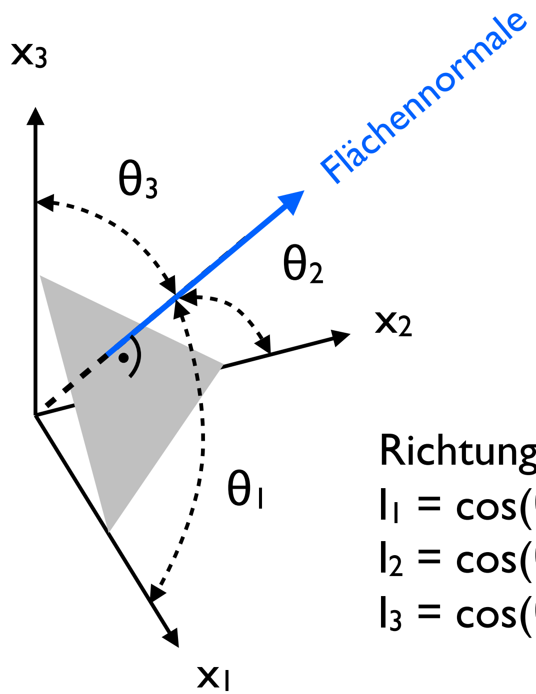
$F_{y\text{-Richtung}} = F_{-y\text{-Richtung}}$ $\sigma_2 \cdot A \cdot \cos(\theta_y) = \sigma_y \cdot A$

Spannungsellipse / - ellipsoid

Gleichgewicht:

$\sigma_1 \cdot A \cdot \cos(\theta_x) = \sigma_x \cdot A$

$\sigma_2 \cdot A \cdot \cos(\theta_y) = \sigma_y \cdot A$



Richtungscosinus

$l_1 = \cos(\theta_x)$

$l_2 = \cos(\theta_y)$

$l_3 = \cos(\theta_z)$

$l_x = \cos(\theta_x)$

$l_y = \cos(\theta_y) = \sin(\theta_x)$

$l_x = \sigma_x / \sigma_1$ $\qquad \cos^2\theta + \sin^2\theta = 1$

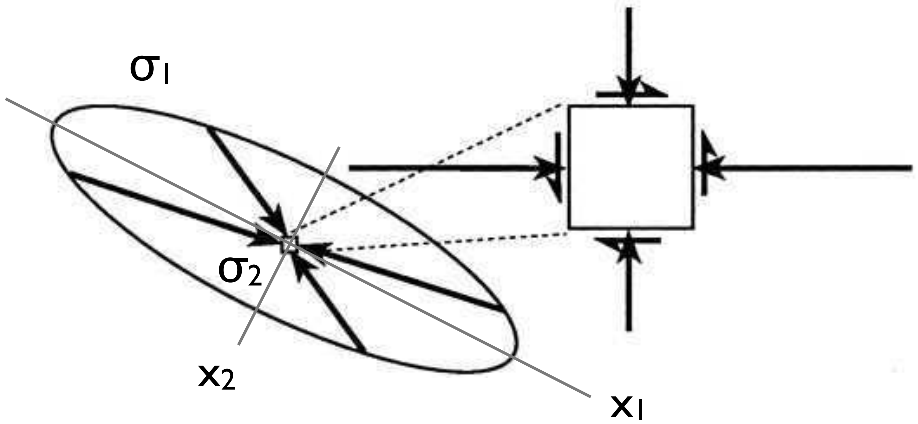
$l_y = \sigma_y / \sigma_2$

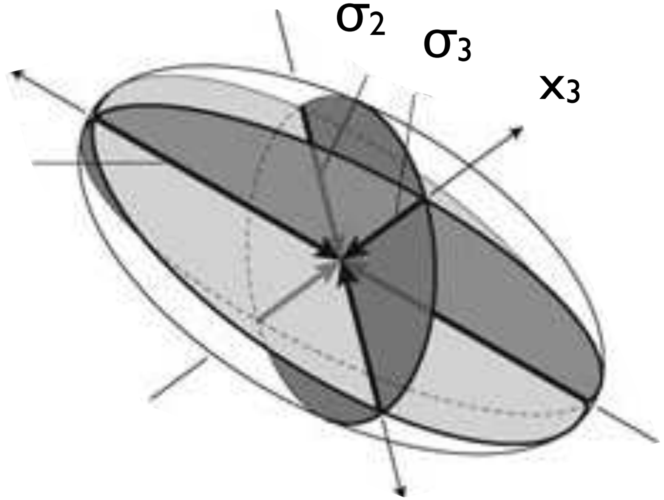
$$\frac{\sigma_x^2}{\sigma_1^2} + \frac{\sigma_y^2}{\sigma_2^2} = 1$$

analog in 3D:

$$\frac{\sigma_x^2}{\sigma_1^2} + \frac{\sigma_y^2}{\sigma_2^2} + \frac{\sigma_z^2}{\sigma_3^2} = 1$$

Spannungsellipse / - ellipsoid





Hauptkomponenten
$\sigma_1 > \sigma_2 > \sigma_3$
= Achsen des Spannungsellipsoids

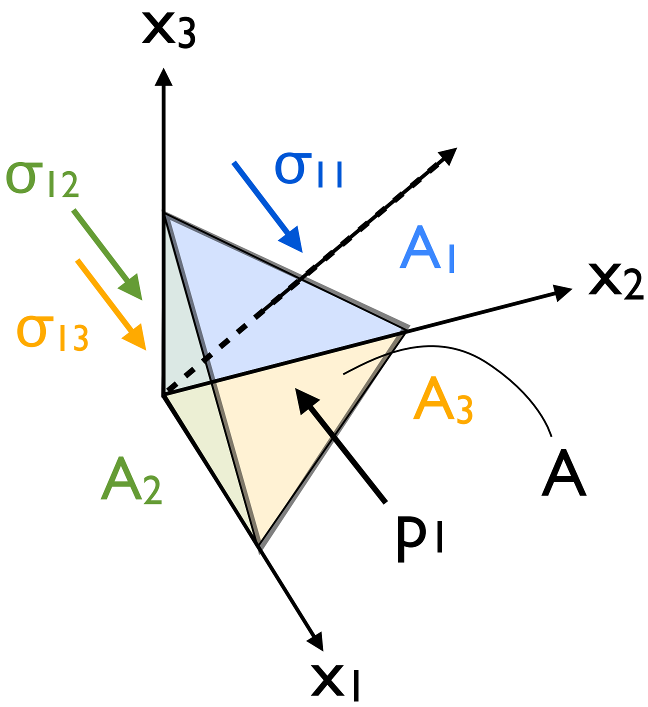
$$\frac{\sigma_x^2}{\sigma_1^2} + \frac{\sigma_y^2}{\sigma_2^2} = 1$$

$$\frac{\sigma_x^2}{\sigma_1^2} + \frac{\sigma_y^2}{\sigma_2^2} + \frac{\sigma_z^2}{\sigma_3^2} = 1$$

Spannungstensor

Spannungstensor

der Spannungstensor verknüpft zwei Vektoren:
den 'Spannungsvektor' (traction) bzw. die Kraft, p_i , und die Flächennormale, l_i , auf welche die Kraft wirkt.



Gleichgewicht:

$p_1 = l_1\sigma_{11} + l_2\sigma_{12} + l_3\sigma_{13}$

$p_2 = l_1\sigma_{21} + l_2\sigma_{22} + l_3\sigma_{23}$

$p_3 = l_1\sigma_{31} + l_2\sigma_{32} + l_3\sigma_{33}$

$$p_i = \sigma_{ij} \cdot l_j$$

p_i = Kraftkomponenten
σ_{ij} = Spannungstensor
l_j = Richtungscosinus

Schreibweise:
σ_{12} $_1$ in Richtung $_2$ auf Fläche

Spannungstensor - Symmetrie

der 3-dimensionale Spannungstensor beschreibt den Spannungszustand auf drei orthogonalen Flächen.

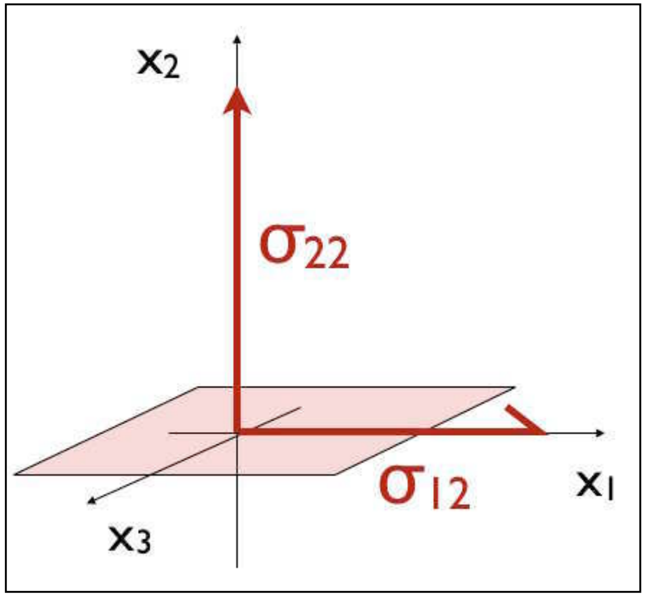
$$\sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$

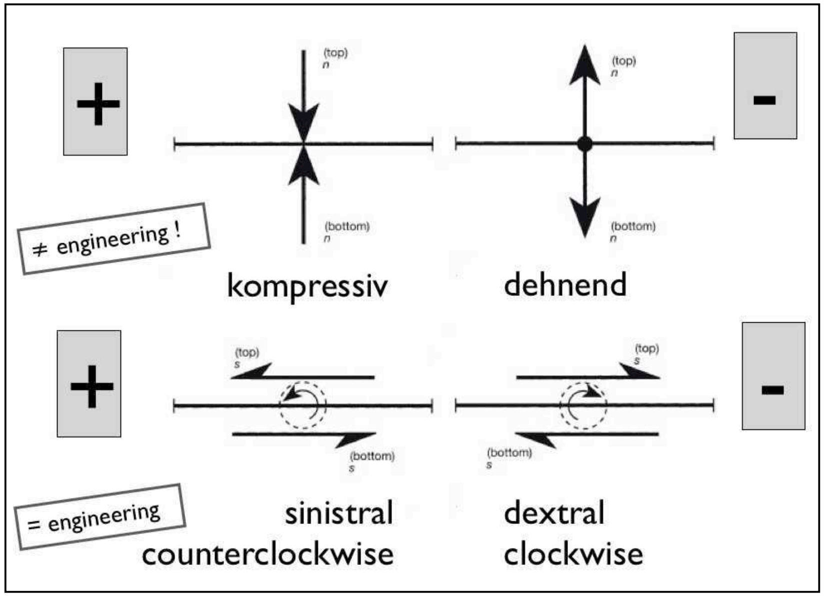
Im Gleichgewicht muss der 3-dimensionale Spannungstensor symmetrisch sein.

$$\sigma_{ij} = \sigma_{ji}$$

wo $i = j$: Normalspannungen
wo $i \neq j$: Scherspannungen

Spannungskomponenten, -vorzeichen





Bezeichnungen:

Normalkomponenten

σ_{11} σ_{22} σ_{33}

Scherkomponenten oder

σ_{12} σ_{13} σ_{21} τ_{12} τ_{13} τ_{21}

σ_{23} σ_{31} σ_{32} τ_{23} τ_{31} τ_{32}

Vorzeichen:

Normalkomponenten

kompressiv = positiv

Scherkomponenten

sinsitral = positiv

Hauptspannungen

Hauptspannungen und Invariante

Die Hauptspannungen gewinnt man aus den Eigenwerten des Spannungs-tensors. In Richtung der Hauptspannungen sind die Scherspannungen = 0

Hauptspannungen
$\sigma_1 > \sigma_2 > \sigma_3$

$$\begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix}$$

1. Invariante I_1 Spur $(\sigma_{11} + \sigma_{22} + \sigma_{33})$
$= \sigma_{ii}$

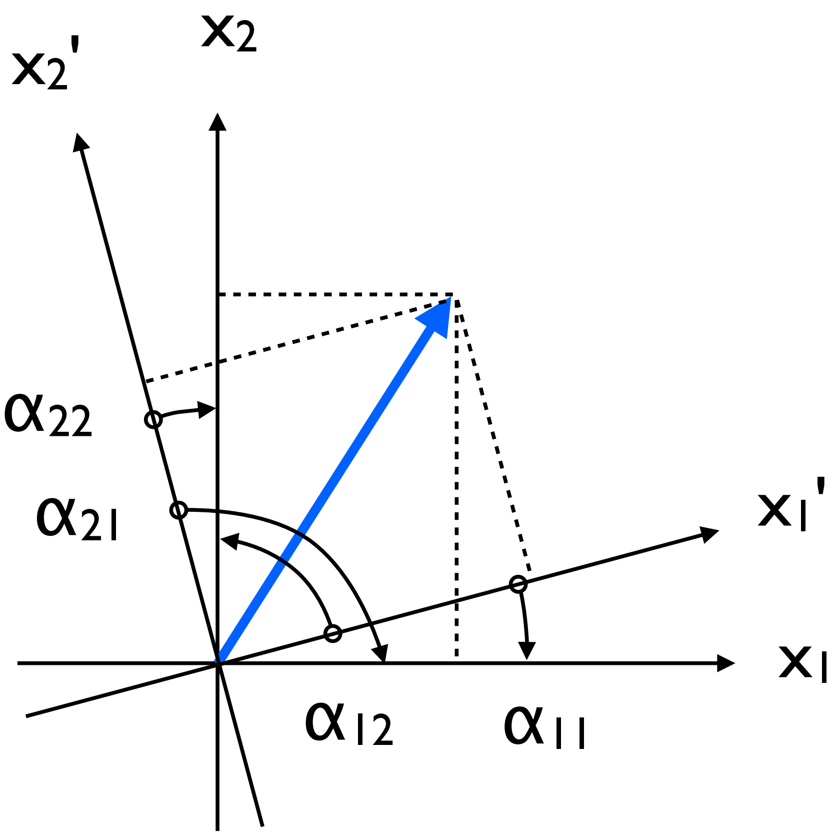
2. Invariante I_2
$\sigma_{11}\sigma_{22} + \sigma_{22}\sigma_{33} + \sigma_{33}\sigma_{11} - \sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2$
$= {}^1/_2 \, (\sigma_{ii}\sigma_{jj} - \sigma_{ij}\sigma_{ji})$

3. Invariante I_3 Determinante $= \det(\sigma_{ij})$

Invariante sind gegenüber Koordinatentransformationen invariant...
Praktisch, denn die Grösse der Spannung sollte nicht vom Koordinatensystem abhängen, in welchem sie beschrieben wird.

Koordinatentransformation

Koordinatentransformation
2 Dimensionen



$$a_{ij} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

$$a_{11} = \cos(\alpha_{11}) = \cos(\alpha)$$
$$a_{12} = \cos(\alpha_{12}) = \sin(\alpha)$$
$$a_{21} = \cos(\alpha_{21}) = -\sin(\alpha)$$
$$a_{22} = \cos(\alpha_{22}) = \cos(\alpha)$$

$$a_{ij} = \begin{bmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{bmatrix}$$

Koordinatentransformation

Transformation des Spannungstensors

$\sigma_{ij}' = a_{ip}\, a_{jq}\, \sigma_{pq}$ $\qquad \sigma' = A\, \sigma\, A^T$ $\qquad a_{ij} = \begin{bmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{bmatrix}$

Beispiel für 2D - Expansion:

$\sigma_{11}' = a_{1p}\, a_{1q}\, \sigma_{pq}$ $\qquad i=1 \quad j=1 \quad p=1...2 \quad q=1...2$

$\sigma_{11}' = a_{11}\, a_{1q}\, \sigma_{1q} + a_{12}\, a_{1q}\, \sigma_{2q}$

$\sigma_{11}' = a_{11}\, a_{11}\, \sigma_{11} + a_{11}\, a_{12}\, \sigma_{12} + a_{12}\, a_{11}\, \sigma_{21} + a_{12}\, a_{12}\, \sigma_{22}$

sei $\sigma_1 = 100$ MPa, $\sigma_2 = 50$ MPa, $\alpha = 90°, 45°, 30°$

$\sigma = \begin{bmatrix} 100 & 0 \\ 0 & 50 \end{bmatrix}$ $\qquad \sigma' = \begin{bmatrix} 50 & 0 \\ 0 & 100 \end{bmatrix} \begin{bmatrix} 75 & -25 \\ -25 & 75 \end{bmatrix} \begin{bmatrix} 87.5 & -22 \\ -22 & 62.5 \end{bmatrix}$

$a = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} .7 & .7 \\ -.7 & .7 \end{bmatrix} \begin{bmatrix} .87 & .5 \\ -.5 & .87 \end{bmatrix}$

Test: $I_1 = 150$

Spannungsdeviator (deviatoric stress)

Deviator

$$\begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix} =$$

Spannung — Spannung — Deviator

$$\begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix} - \begin{bmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{bmatrix} = \begin{bmatrix} \sigma_x - p & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y - p & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z - p \end{bmatrix}$$

$$p = \frac{\sigma_x + \sigma_y + \sigma_z}{3}$$

$p = {}^1/_3\, \sigma_{ii} = {}^1/_3\, (\sigma_1 + \sigma_2 + \sigma_3)$ = mean stress

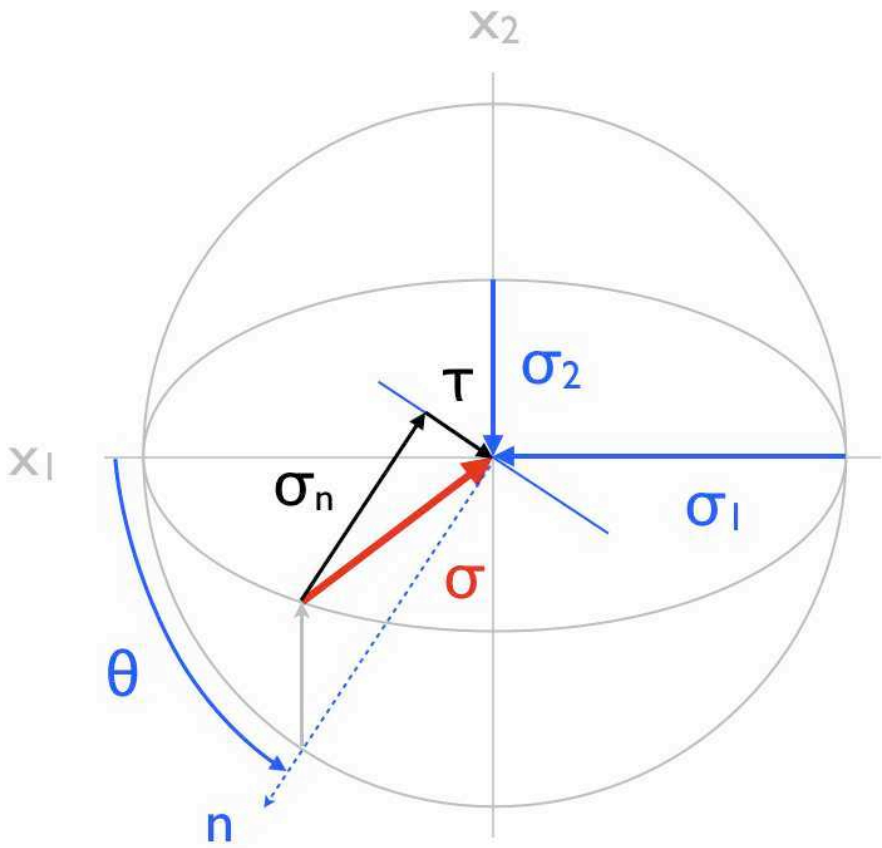
= hydrostatischer (lithostatischer) Druck

Spur von S = 0

Spannungen σ_n und τ aus σ_1 und σ_2

geg:
Fläche F,
Normale n,
Spannungsellipse (σ_1, σ_2)

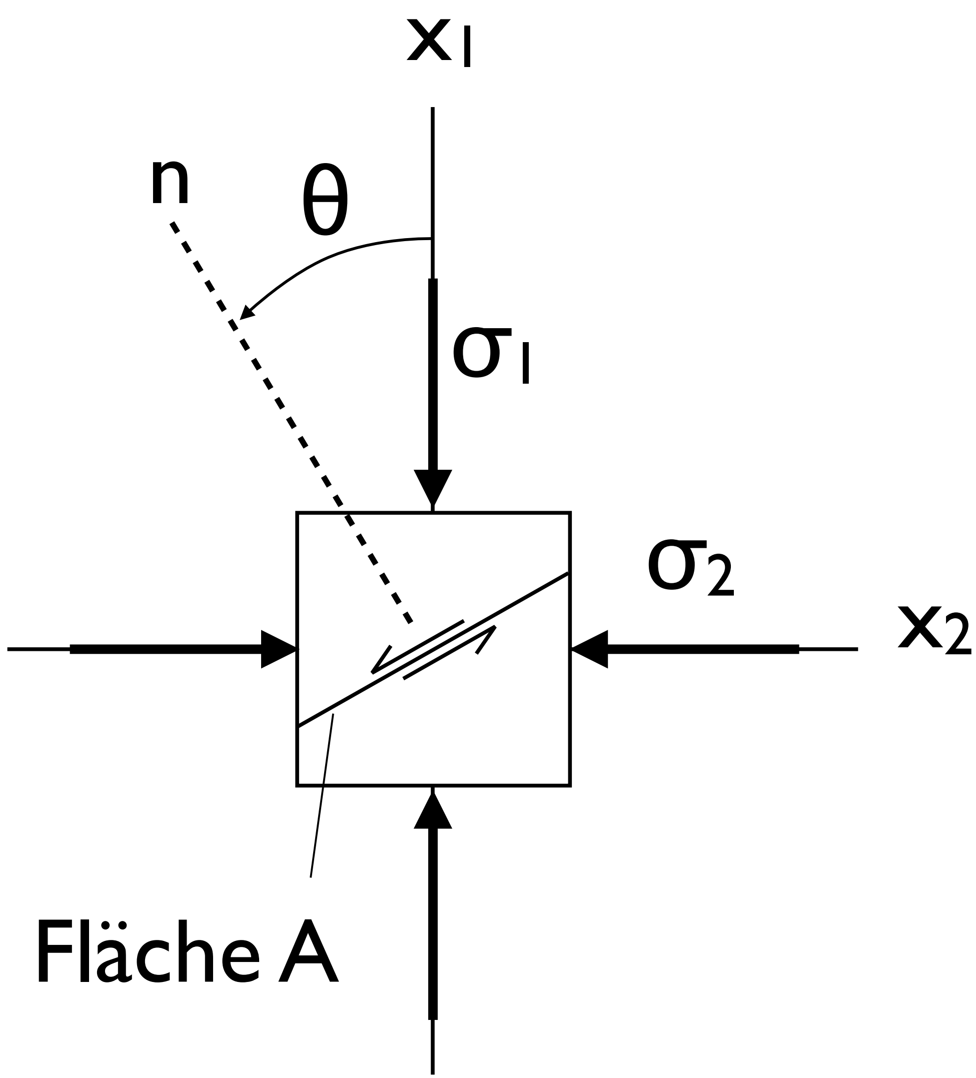
ges:
Spannung σ mit
Komponenten σ_n, τ
auf Fläche F



Möglichkeiten:
- über Spannungsellipse
- über Mohrkreis

Mohr-Kreis

Mohr Kreis in 2 Dimensionen



geg:
Hauptspannungen

$$\begin{pmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{pmatrix}$$

ges:
Normal- und Scherspannung auf Fläche A, Flächennormale n

Mohr Kreis in 2 Dimensionen

Koordinatentransformation: $\sigma_{ij}' = a_{ik}\, a_{jl}\, \sigma_{kl}$

$\sigma_{11}' = a_{11}\, a_{11}\, \sigma_{11} + a_{11}\, a_{12}\, \sigma_{12} + a_{12}\, a_{11}\, \sigma_{21} + a_{12}\, a_{12}\, \sigma_{22}$

$\sigma_{12}' = a_{11}\, a_{21}\, \sigma_{11} + a_{11}\, a_{22}\, \sigma_{12} + a_{12}\, a_{21}\, \sigma_{21} + a_{12}\, a_{22}\, \sigma_{22}$

$\sigma_{21}' = a_{21}\, a_{11}\, \sigma_{11} + a_{21}\, a_{12}\, \sigma_{12} + a_{22}\, a_{11}\, \sigma_{21} + a_{22}\, a_{12}\, \sigma_{22}$

$\sigma_{22}' = a_{21}\, a_{21}\, \sigma_{11} + a_{21}\, a_{22}\, \sigma_{12} + a_{22}\, a_{21}\, \sigma_{21} + a_{22}\, a_{22}\, \sigma_{22}$

Beispiel:

$\sigma_{11}' = \cos(\theta)\cos(\theta)\, \sigma_{11} + \cos(\theta)\sin(\theta)\, \sigma_{12} +$
$\sin(\theta)\cos(\theta)\, \sigma_{21} + \sin(\theta)\sin(\theta)\, \sigma_{22}$

weil $\sigma_{12} = \sigma_{21} = 0$:

$\sigma_{11}' = \cos(\theta)^2\, \sigma_{11} + \sin(\theta)^2\, \sigma_{22}$

Normalspannung

neu (σ') als Funktion von alt (σ) geschrieben:

$\sigma_{11}' = \sigma_n$
$\sigma_{11} = \sigma_1$
$\sigma_{22} = \sigma_2$

$$\sigma_n = \cos(\theta)^2 \sigma_1 + \sin(\theta)^2 \sigma_2$$

umgeformt:

$$\sin(\theta)^2 = {}^1/_2 (1 - \cos(2\theta))$$
$$\cos(\theta)^2 = {}^1/_2 (1 + \cos(2\theta))$$

$$\sigma_n = {}^1/_2 (1 + \cos(2\theta)) \sigma_1 + {}^1/_2 (1 - \cos(2\theta)) \sigma_2$$

$$\sigma_n = {}^1/_2 (\sigma_1 + \sigma_2) + {}^1/_2 (\cos(2\theta) \sigma_1 - \cos(2\theta) \sigma_2)$$

$$\sigma_n = {}^1/_2 (\sigma_1 + \sigma_2) + {}^1/_2 (\sigma_1 - \sigma_2) \cos(2\theta)$$

Scherspannung

$\sigma_{12}' = -\tau$
$\sigma_{11} = \sigma_1$
$\sigma_{22} = \sigma_2$

$$\sigma_{12}' = a_{11}\, a_{21}\, \sigma_{11} + a_{11}\, a_{22}\, \sigma_{12} + a_{12}\, a_{21}\, \sigma_{21} + a_{12}\, a_{22}\, \sigma_{22}$$
$$= \cos(\theta)(-\sin(\theta))\, \sigma_{11} + \sin(\theta)\cos(\theta)\, \sigma_{22}$$

(da $\sigma_{12} = \sigma_{21} = 0$)

$$-\tau = \cos(\theta)(-\sin(\theta))\, \sigma_1 + \sin(\theta)\cos(\theta)\, \sigma_2$$

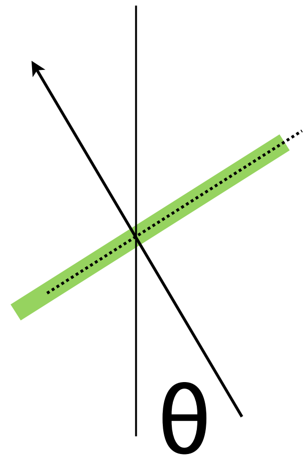
umgeformt: $\sin(\theta)\cos(\theta) = {}^1/_2 \sin(2\theta)$

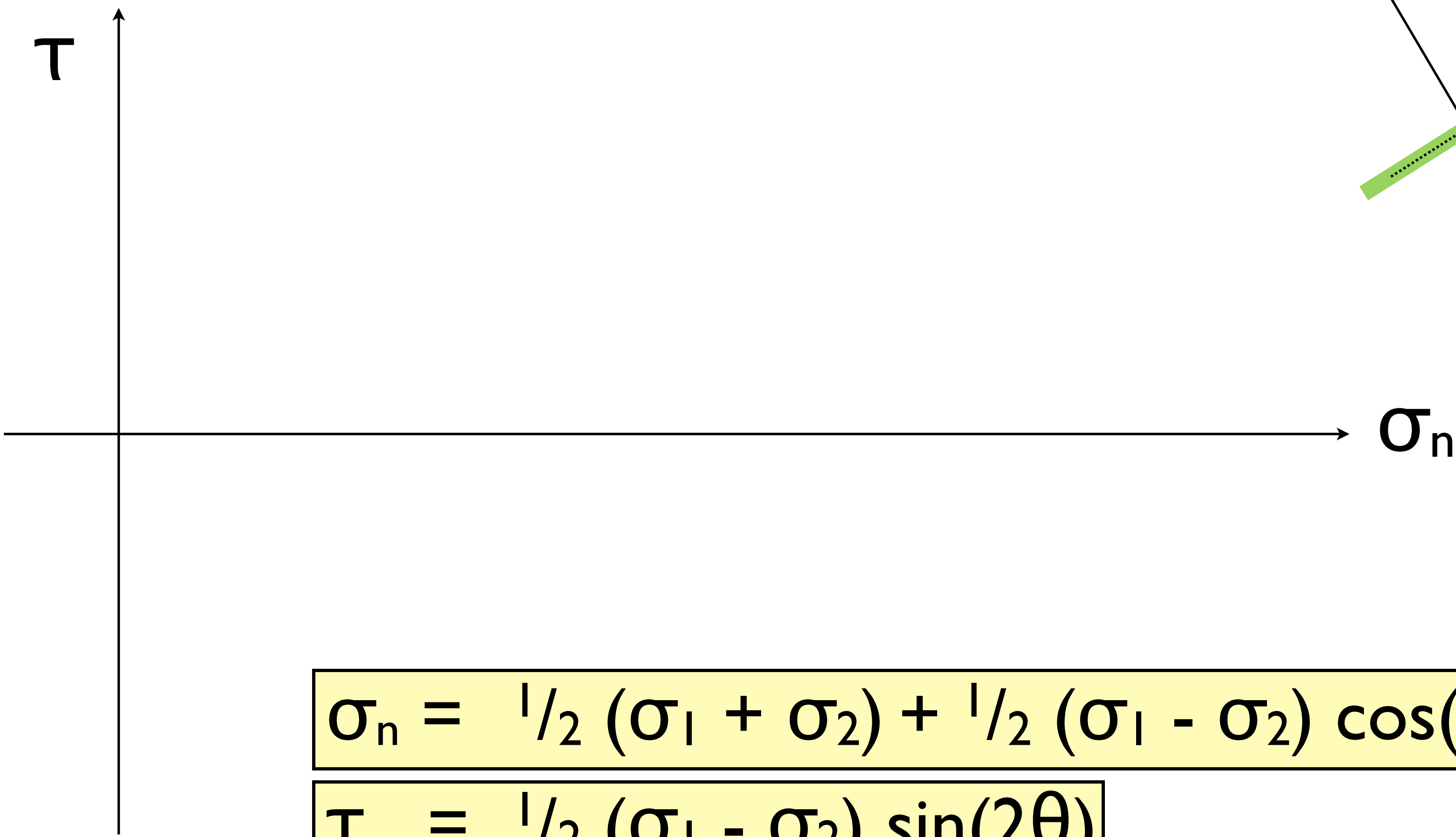
$$-\tau = -{}^1/_2 \sin(2\theta)\, \sigma_1 + {}^1/_2 \sin(2\theta)\, \sigma_2$$

$$\tau = {}^1/_2\, (\sigma_1 - \sigma_2) \sin(2\theta)$$

σ_n - τ - Koordinatensystem

sei σ_1 = 55 MPa, σ_2 = 15 MPa, und θ = 30°





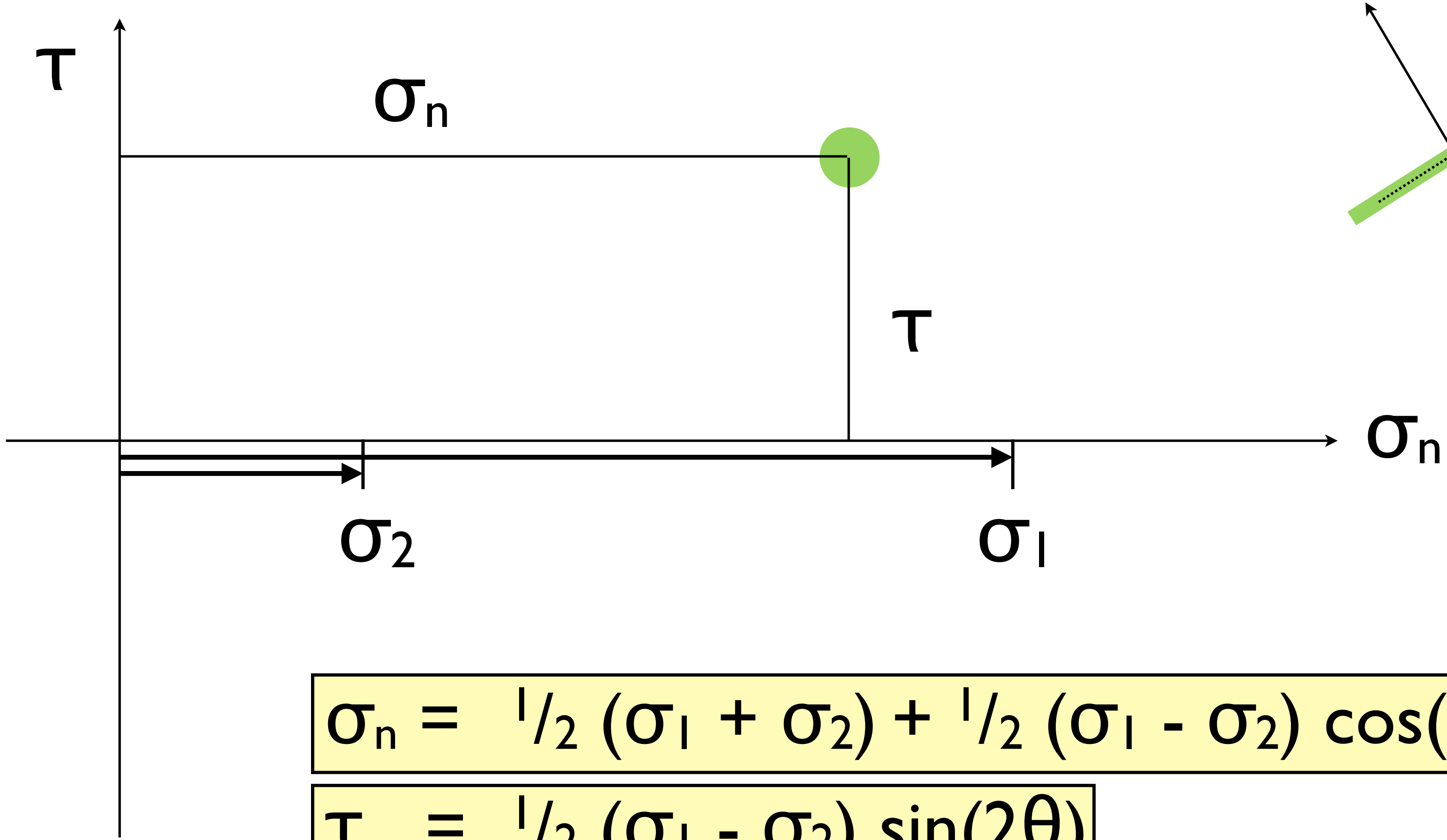
$$\sigma_n = \ ^1/_2\,(\sigma_1 + \sigma_2) + \ ^1/_2\,(\sigma_1 - \sigma_2)\cos(2\theta)$$

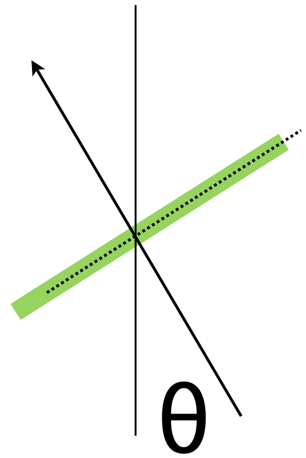
$$\tau = \ ^1/_2\,(\sigma_1 - \sigma_2)\sin(2\theta)$$

Beispiel

sei σ_1 = 55 MPa, σ_2 = 15 MPa, und θ = 30°

berechne σ und τ



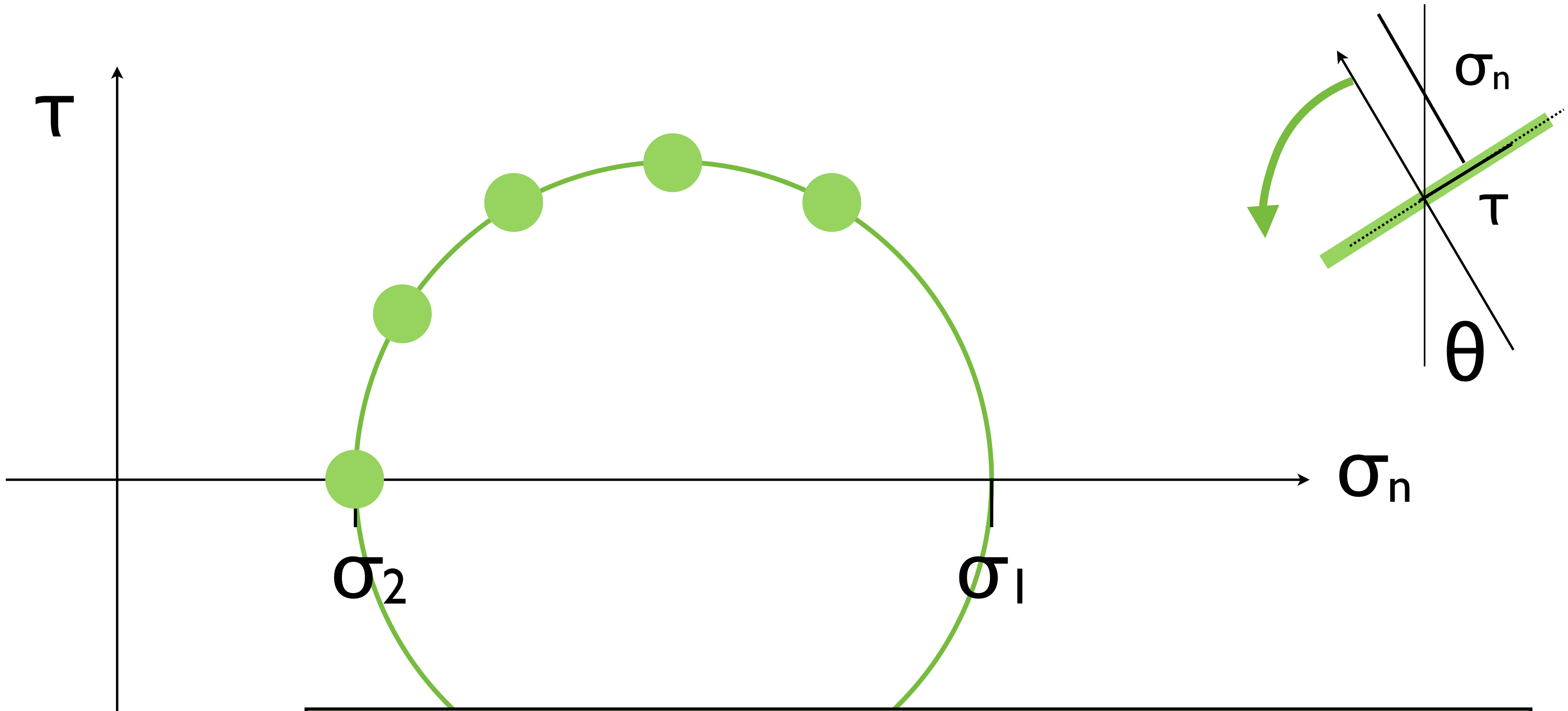


$$\sigma_n = \tfrac{1}{2}(\sigma_1 + \sigma_2) + \tfrac{1}{2}(\sigma_1 - \sigma_2)\cos(2\theta)$$

$$\tau = \tfrac{1}{2}(\sigma_1 - \sigma_2)\sin(2\theta)$$

weitere Orientierungen

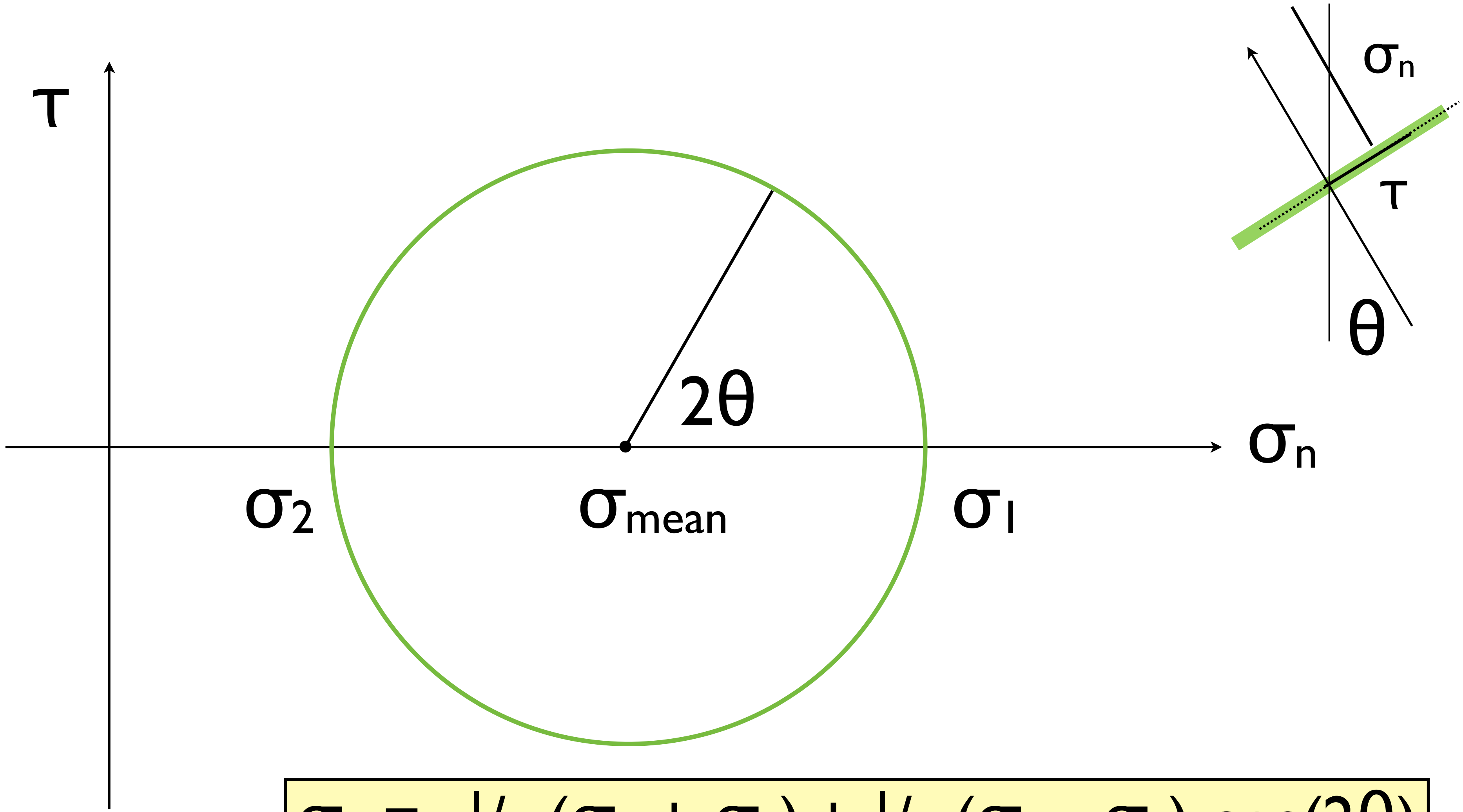
$\theta = 45°, 60°, 75°, 90°$



$$\sigma_n = {}^1/_2\,(\sigma_1 + \sigma_2) + {}^1/_2\,(\sigma_1 - \sigma_2)\cos(2\theta)$$

$$\tau = {}^1/_2\,(\sigma_1 - \sigma_2)\sin(2\theta)$$

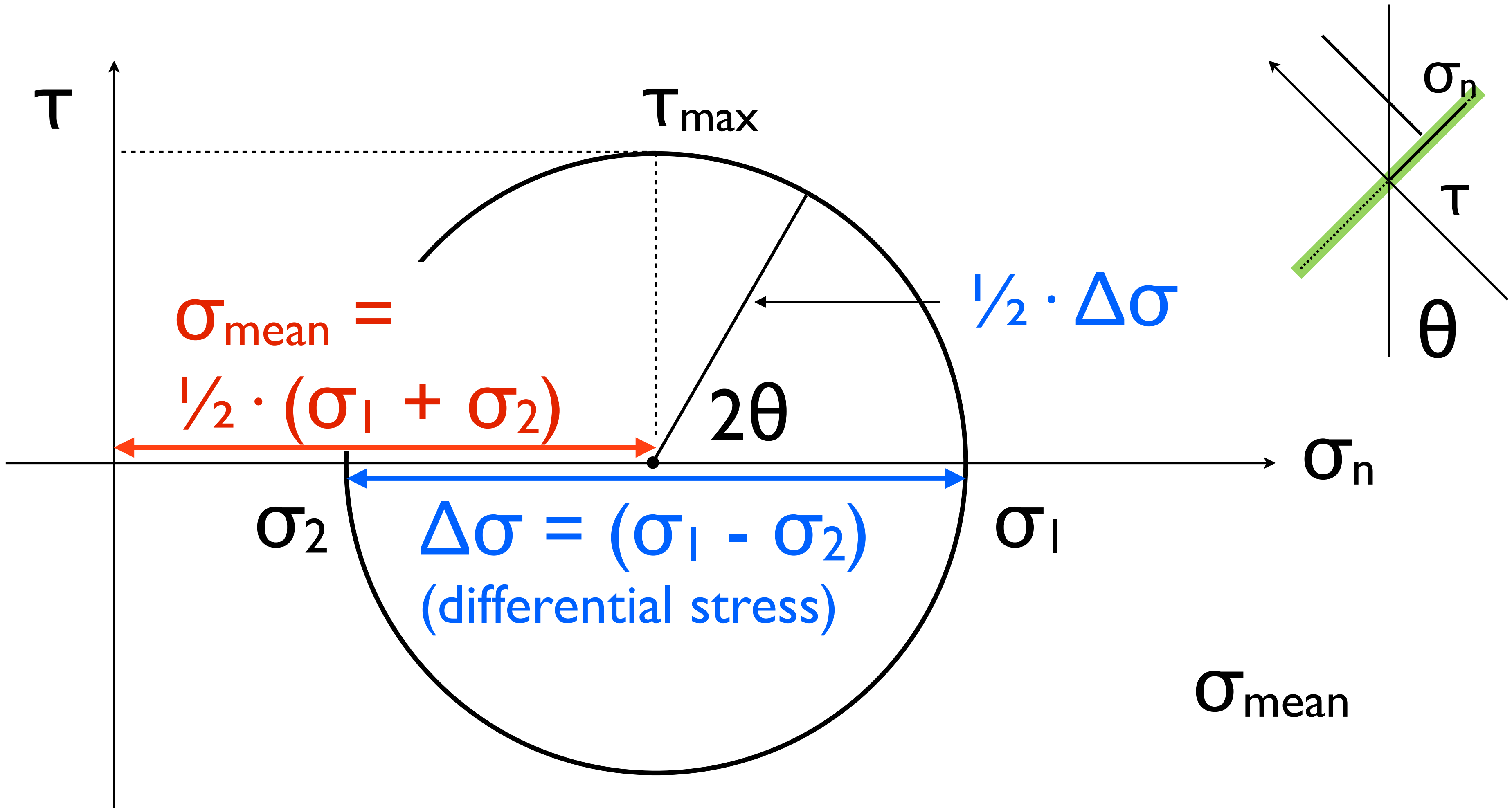
Mohr Kreis in 2 Dimensionen



$$\sigma_n = {}^1/_2\,(\sigma_1 + \sigma_2) + {}^1/_2\,(\sigma_1 - \sigma_2)\cos(2\theta)$$

$$\tau = {}^1/_2\,(\sigma_1 - \sigma_2)\sin(2\theta)$$

Mohr Kreis in 2 Dimensionen



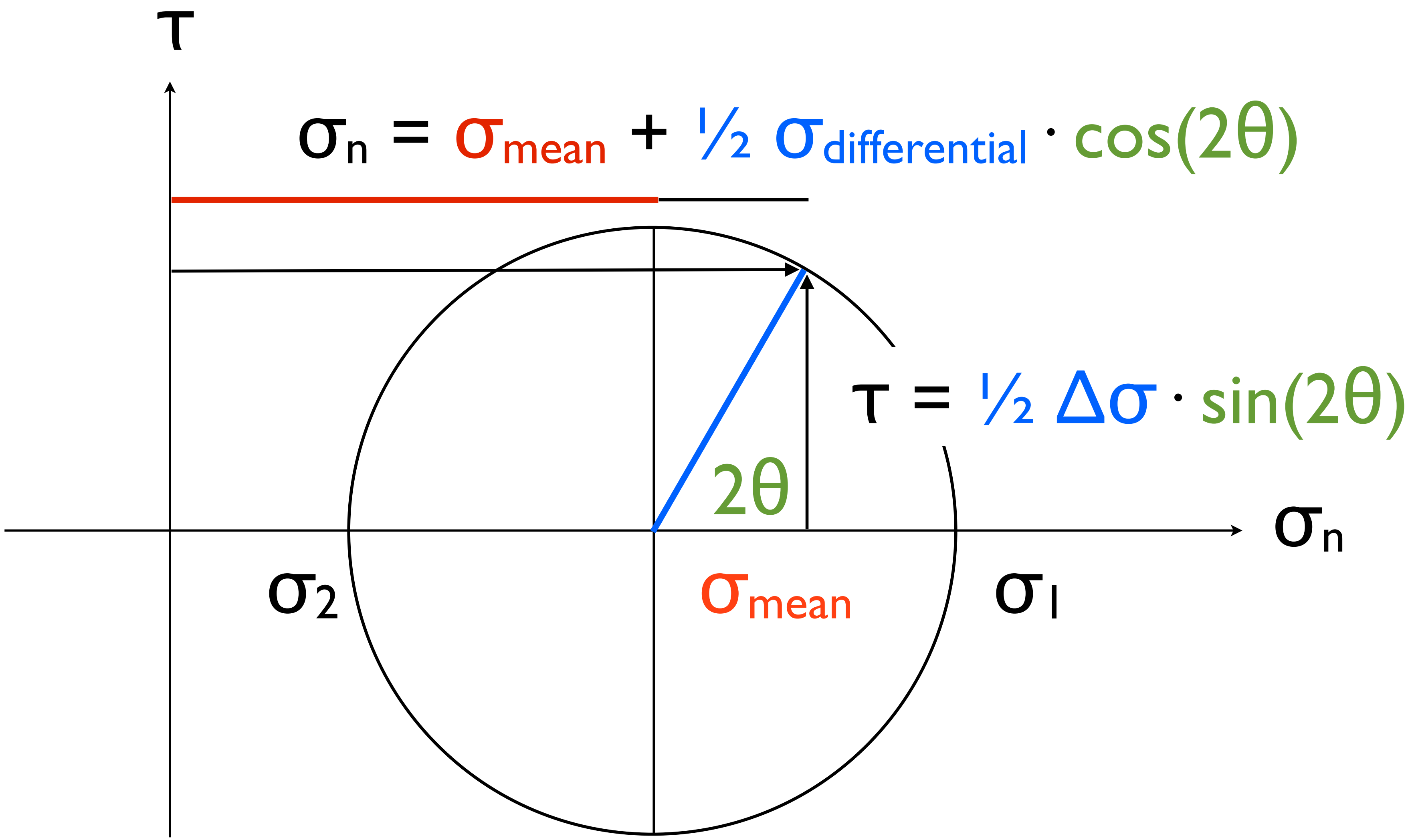
$$\sigma_n = \sigma_{mean} + \frac{1}{2} \cdot \Delta\sigma \cdot \cos(2\theta)$$

$$\tau = \frac{1}{2} \cdot \Delta\sigma \sin(2\theta)$$

$$\tau_{max} = \frac{1}{2} \cdot \Delta\sigma$$

bei $\theta = 45°$

Mohr Kreis in 2 Dimensionen



$\sigma_n\,,\ \tau = f\,(\sigma_{mean}, \Delta\sigma, \theta)$

$\Delta\sigma$ = differential stress

$\tau_{max} = \frac{1}{2} \cdot \Delta\sigma$

Spezielle Spannungen

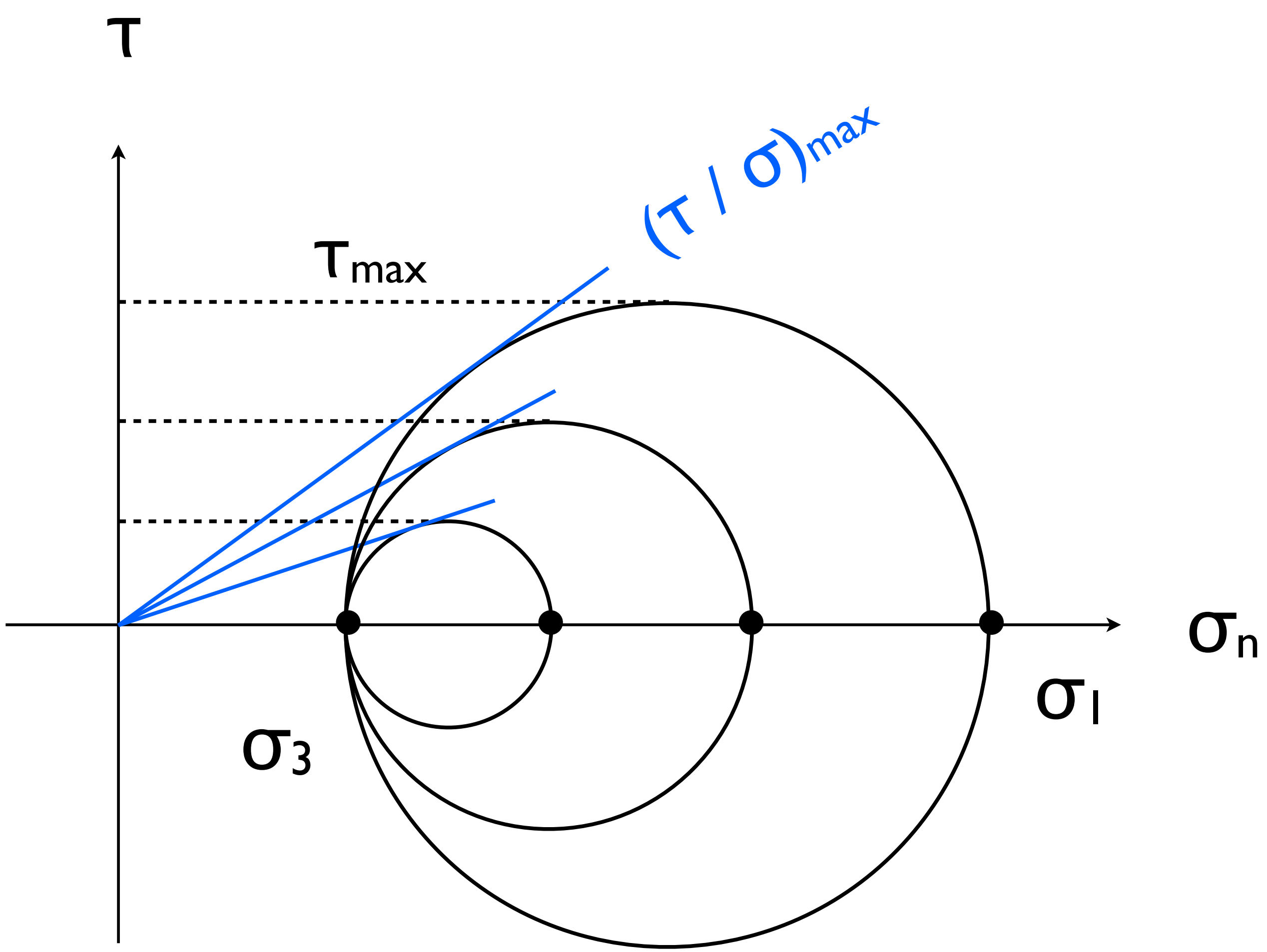
$\sigma > 0$, $\sigma < 0$	compressive stress, tensile stress
$\sigma_1, \sigma_2, \sigma_3$	principal stresses σ_1 = maximum compressive, σ_3 = minimum compressive or tensile
σ_{mean}	$^1/_3\ \sigma_{ii} = {}^1/_3\ (\sigma_1 + \sigma_2 + \sigma_3)$ = mean stress
$\rho \cdot g \cdot h$	lithostatic stress = $\sigma_{mean} \neq \sigma_3$
$\Delta\sigma = \sigma_1 - \sigma_3$	differential stress ≠ deviatoric stress
τ_{max}	$= {}^1/_2\ \Delta\sigma$ = maximum shear stress
S_1, S_2, S_3	deviatoric stress

Mohr'sche Brüche

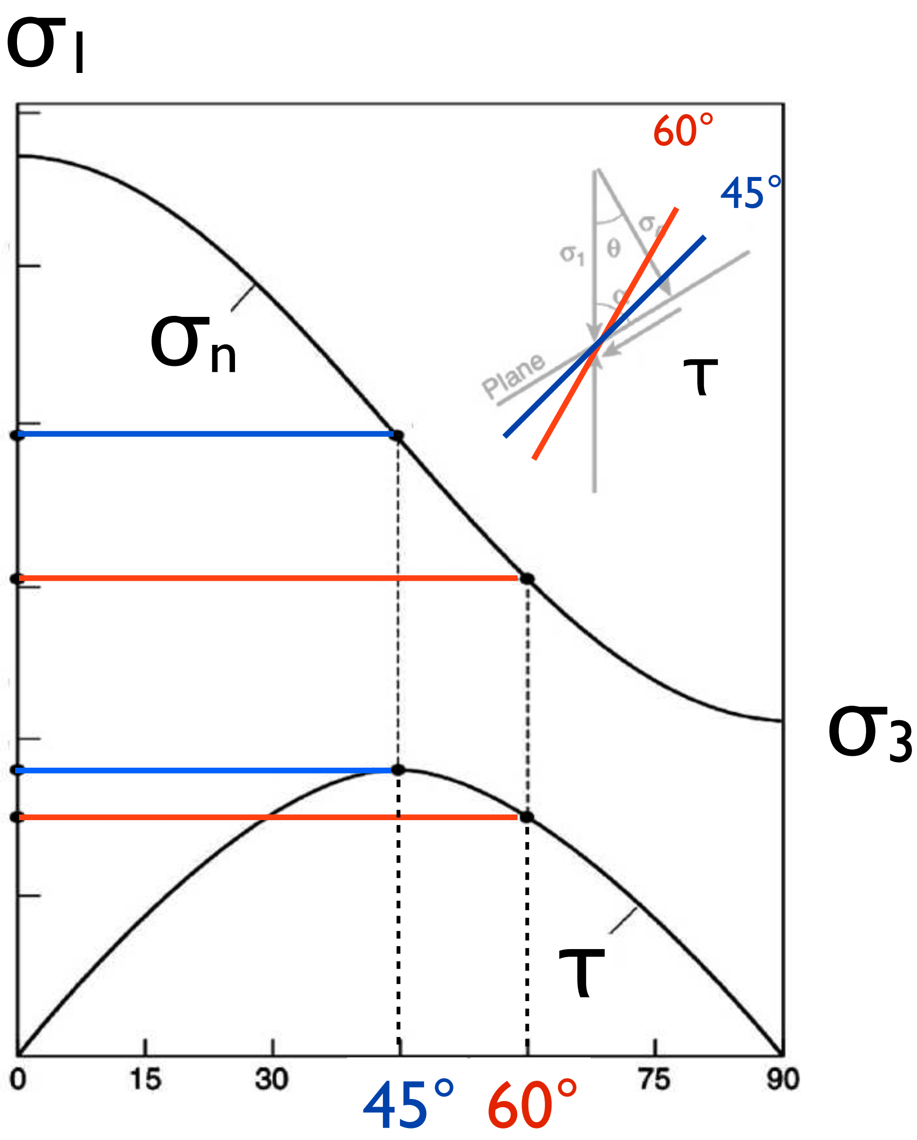
Scher- versus Normalspannung

maximale Scherspannung: τ_{max}

$\neq$ maximales Verhältnis: $(\tau / \sigma)_{max}$



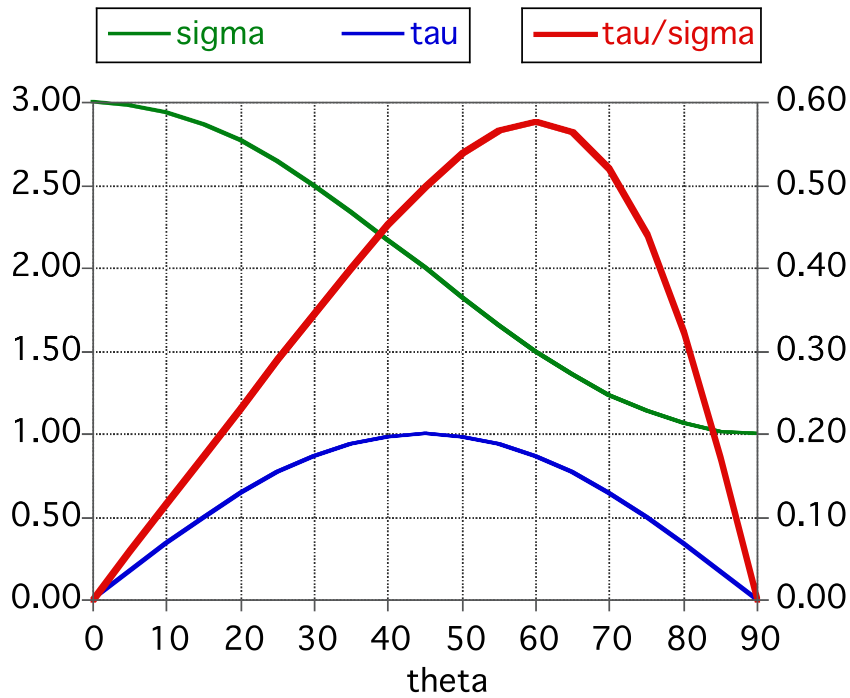
Scher- versus Normalspannung



maximum stress ratio τ/σ

$\sigma = (\sigma_1+\sigma_3) + (\sigma_1-\sigma_3) \cdot \cos(\theta)$

$\tau = (\sigma_1-\sigma_3) \cdot \sin(\theta)$

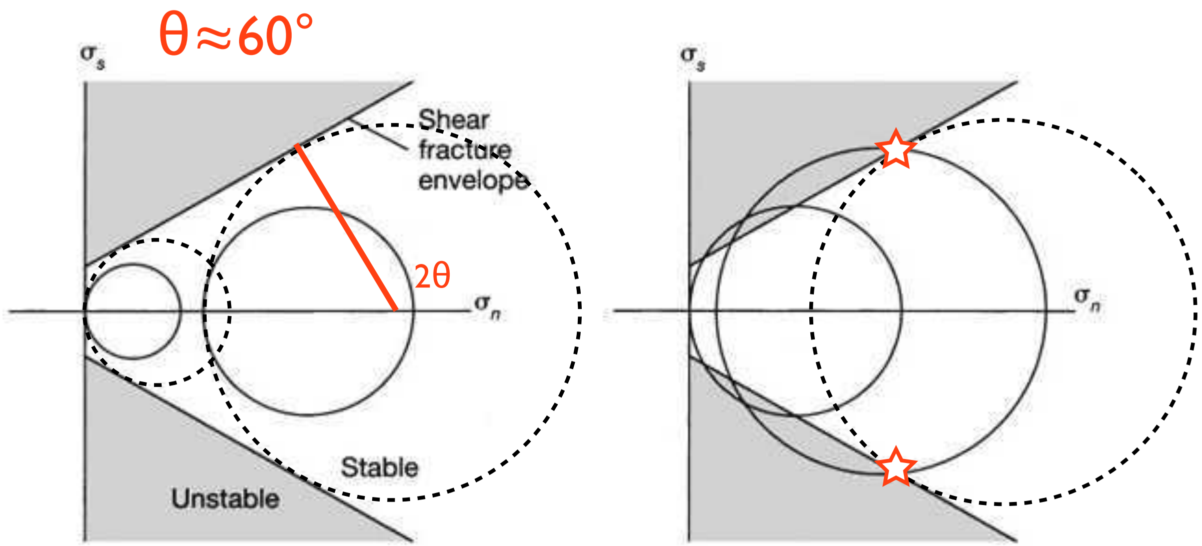


Stabilitätsbereich

Kompression ⇒

Scherbruch

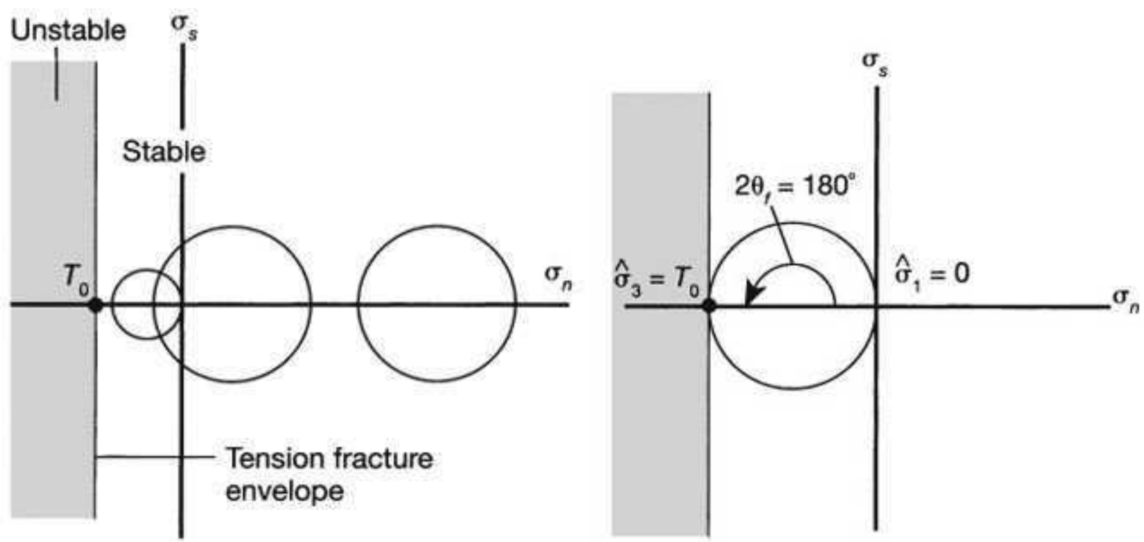
$\theta \approx 60°$ bedeutet
Bruchfläche 30° zu σ_I



Tension ⇒

Extensions-
bruch (Kluft)

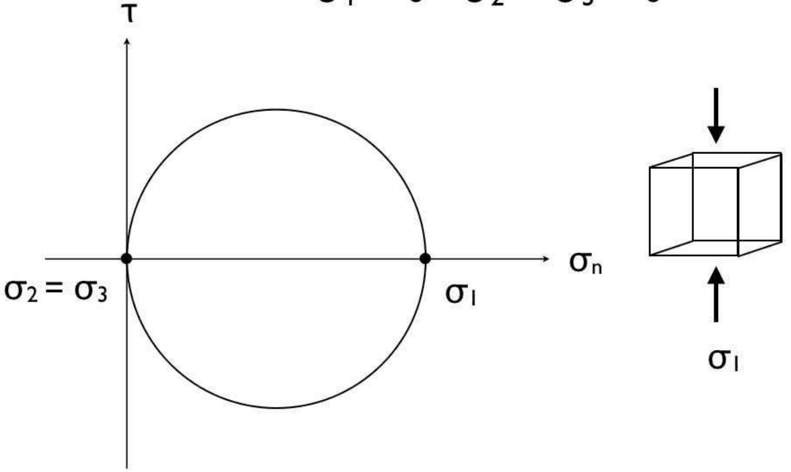
$\theta \approx 90°$ bedeutet
Bruchfläche // σ_I



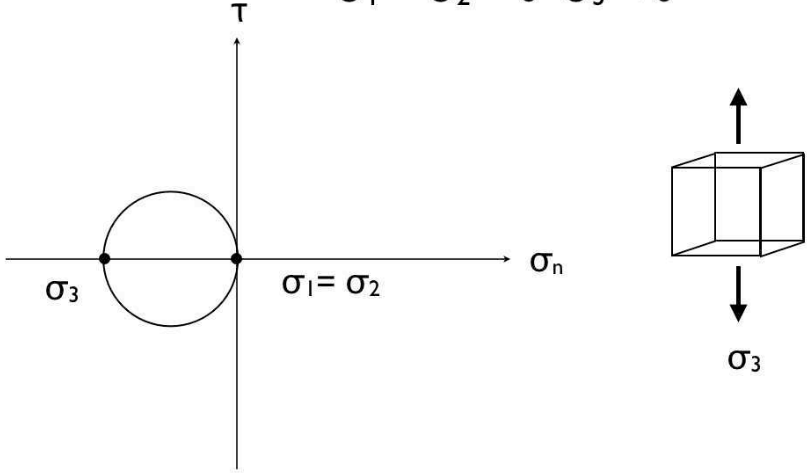
Spannungszustände

Spannungszustände

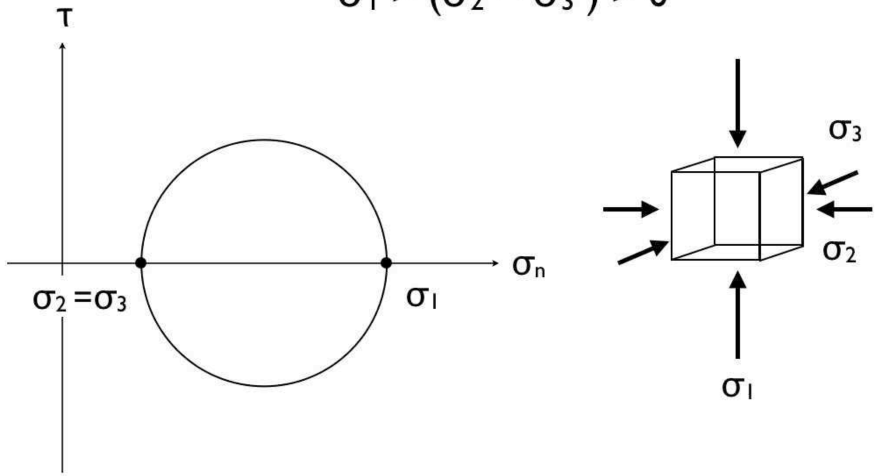
uniaxiale Kompression:
$\sigma_1 > 0 \quad \sigma_2 = \sigma_3 = 0$



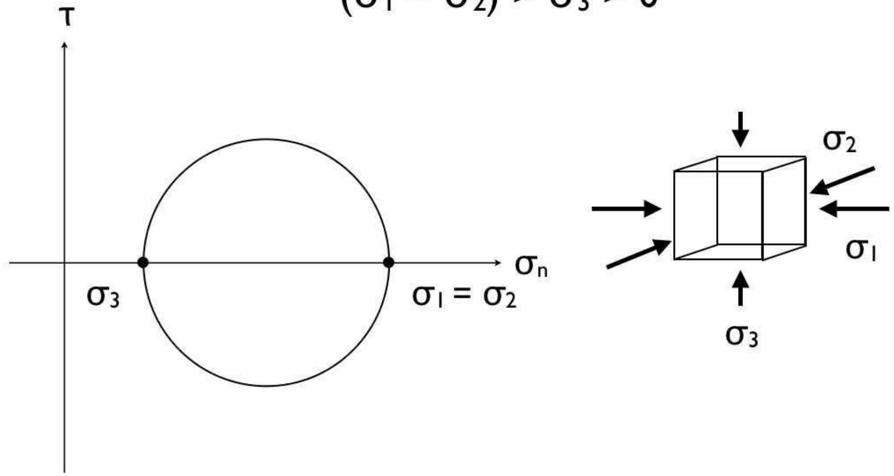
uniaxiale Tension:
$\sigma_1 = \sigma_2 = 0 \quad \sigma_3 < 0$



axiale Kompression:
$\sigma_1 > (\sigma_2 = \sigma_3) > 0$

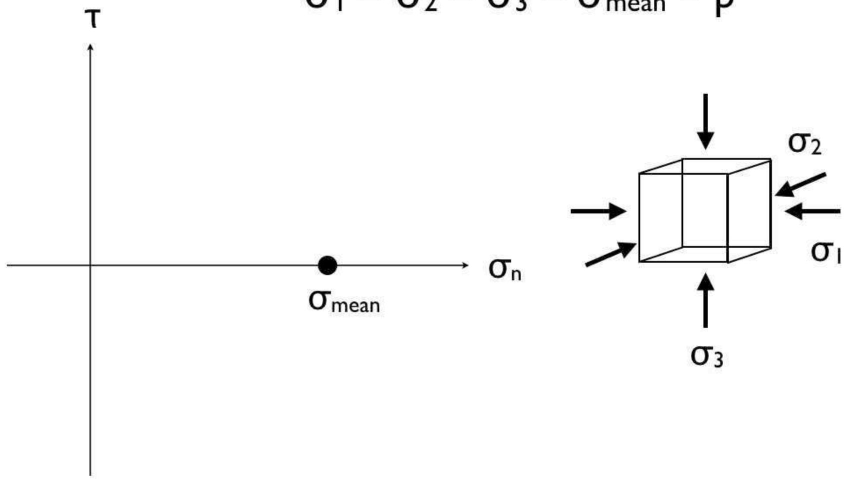


axiale Extension (≠ Tension):
$(\sigma_1 = \sigma_2) > \sigma_3 > 0$

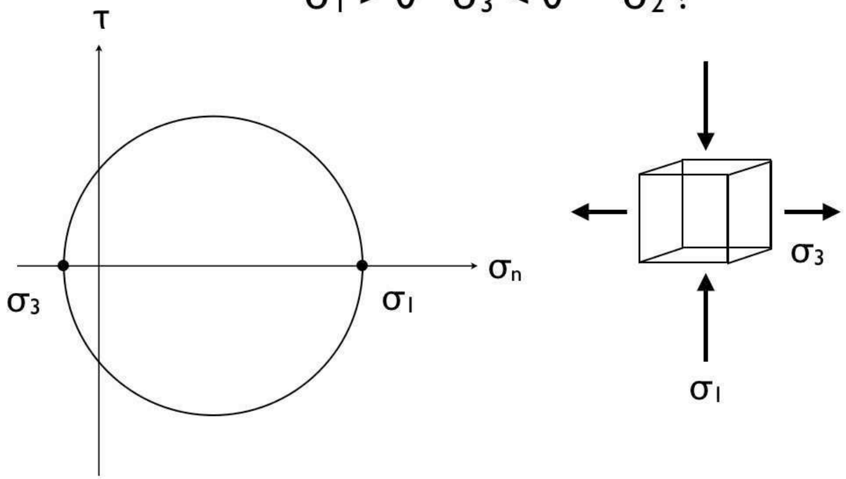


Spannungszustände

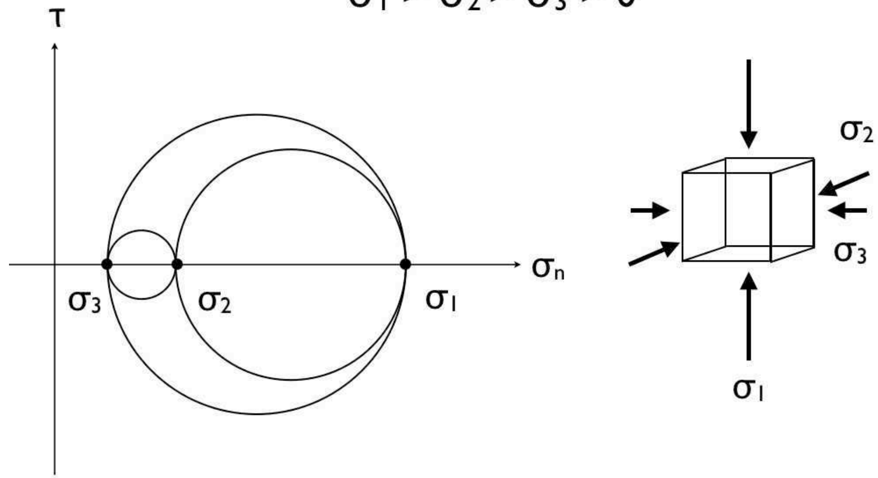
hydrostatischer Druck:
$\sigma_1 = \sigma_2 = \sigma_3 = \sigma_{mean} = p$



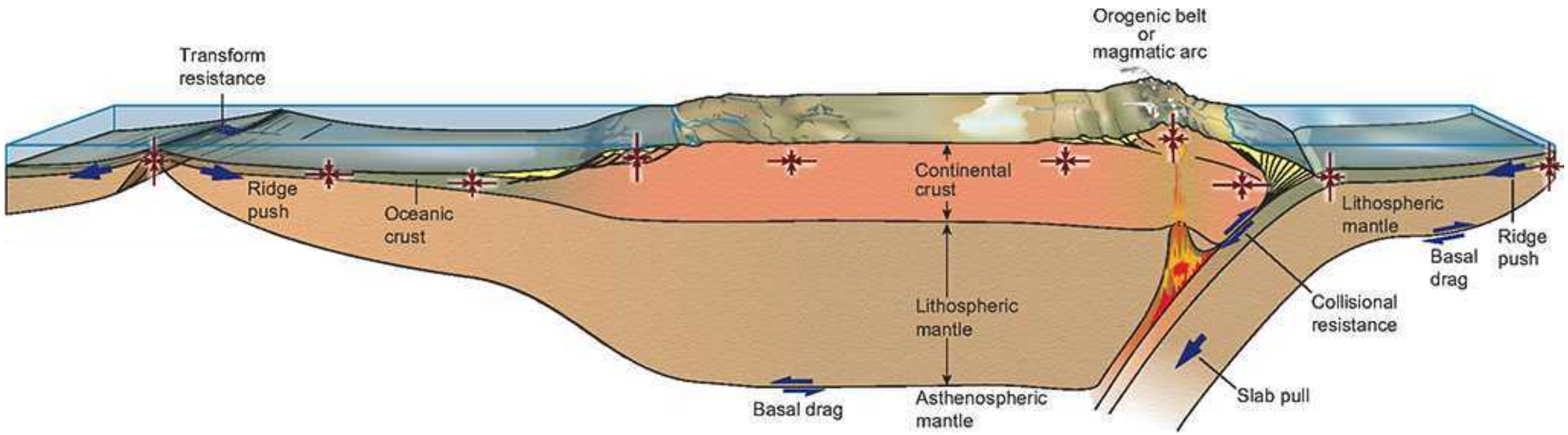
allgemeiner Spannungszustand:
$\sigma_1 > 0 \quad \sigma_3 < 0 \qquad \sigma_2$?



allgemeiner Spannungszustand:
$\sigma_1 > \sigma_2 > \sigma_3 > 0$



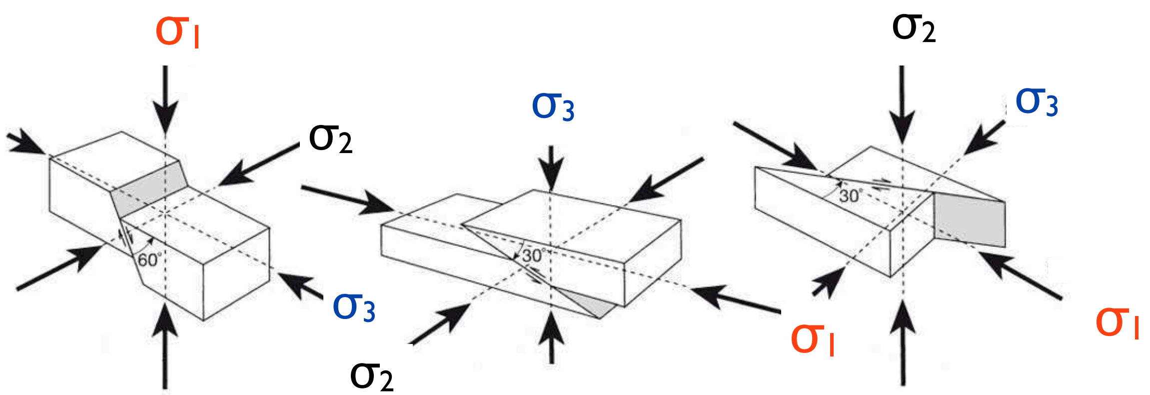
Spannungszustände



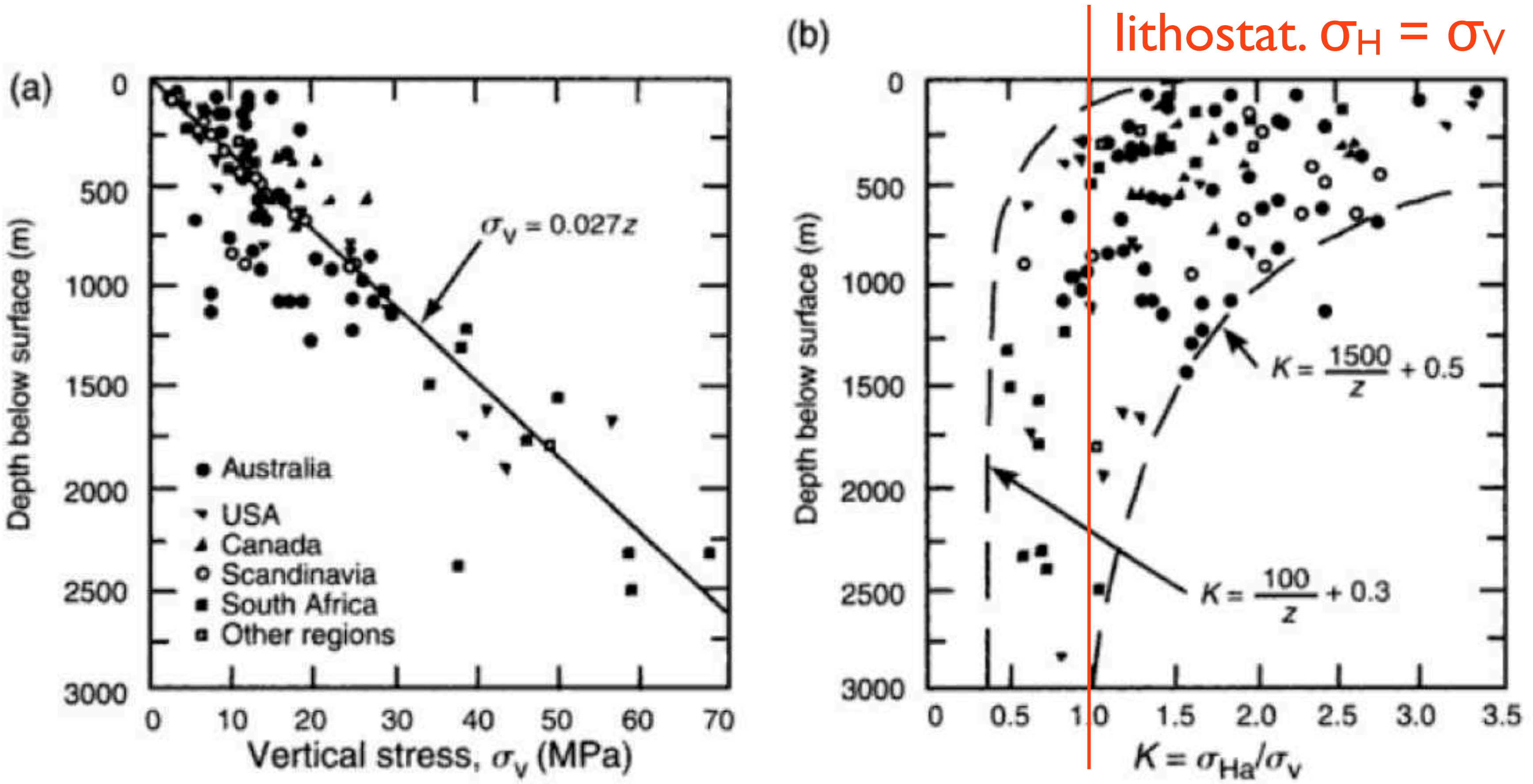
normal - fault
stress regime
σ_1 = vertikal

reverse - fault
stress regime
σ_1 = horizontal

strike slip
stress regime
σ_1 = horizontal



Horizontale / vertikale Spannung



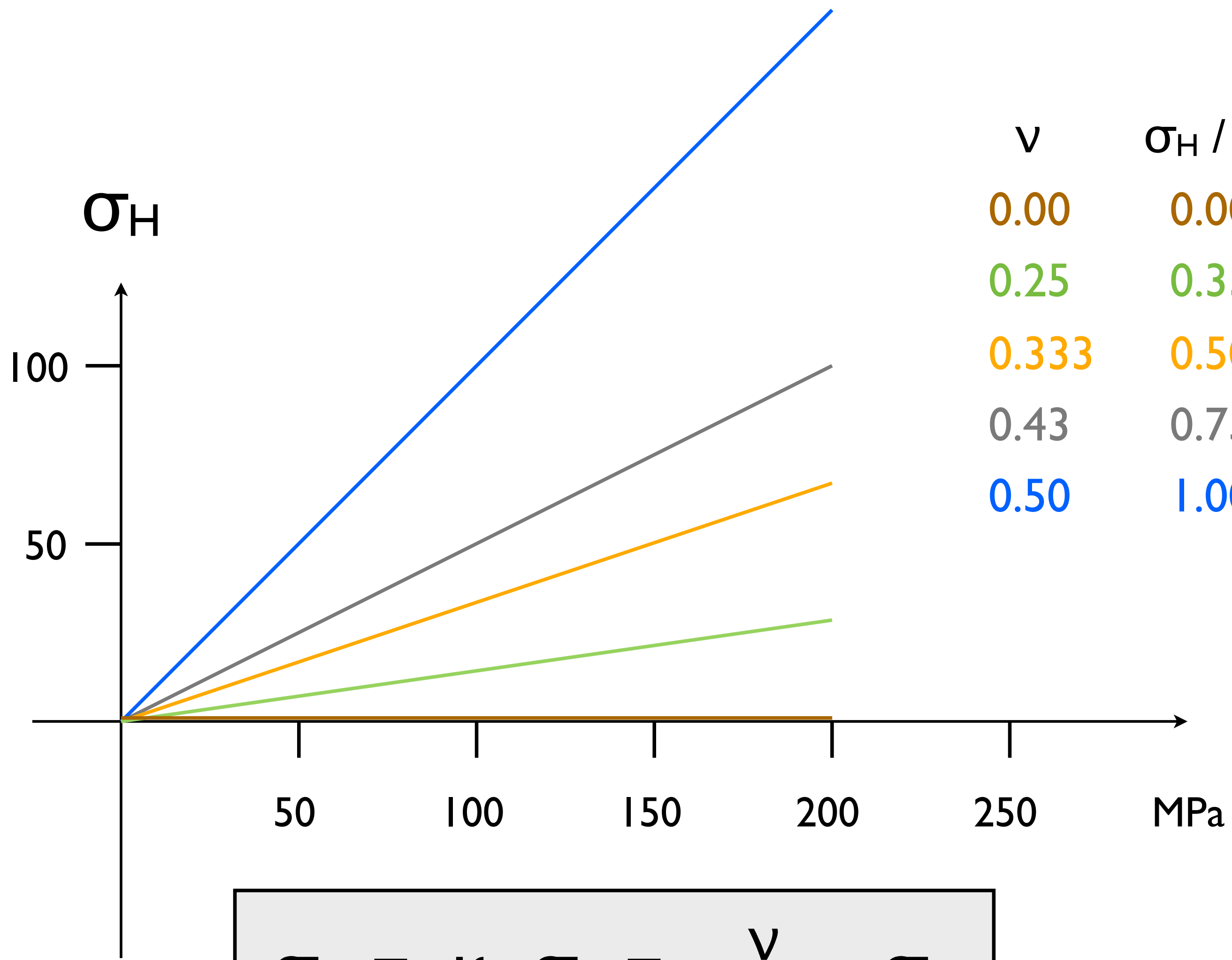
$\sigma_V = \rho\, g\, h$

$\sigma_H = \kappa \cdot \sigma_V$

Fig 6.26 Variation of the stress components to depths of 3 km from *in-situ* measurements. (a) Vertical normal stress. (b) Horizontal normal stress normalized by vertical stress. Reprinted from Brown and Hoek (1978) with permission of Elsevier.

Pollard & Fletcher (2005)

Einfluss der Poissonzahl

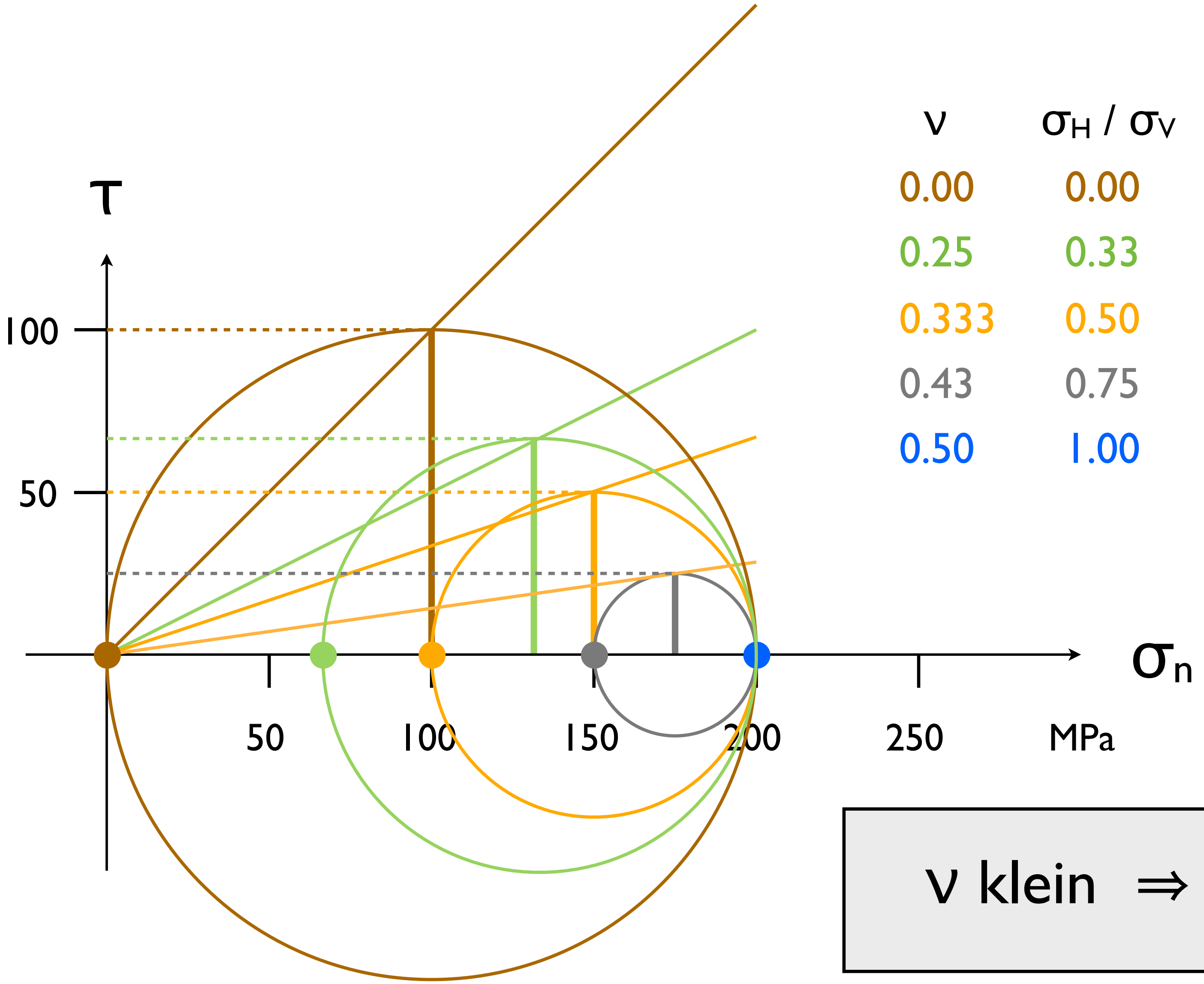


$\sigma_V = \rho\, g\, h$

ν	σ_H / σ_V	Materialbeispiele
0.00	0.00	Kork
0.25	0.33	Granit
0.333	0.50	Sandstein
0.43	0.75	Tongestein
0.50	1.00	Gummi, inkompressible Flüssigkeit

$$\sigma_H = \kappa \cdot \sigma_V = \frac{\nu}{(1-\nu)} \cdot \sigma_V$$

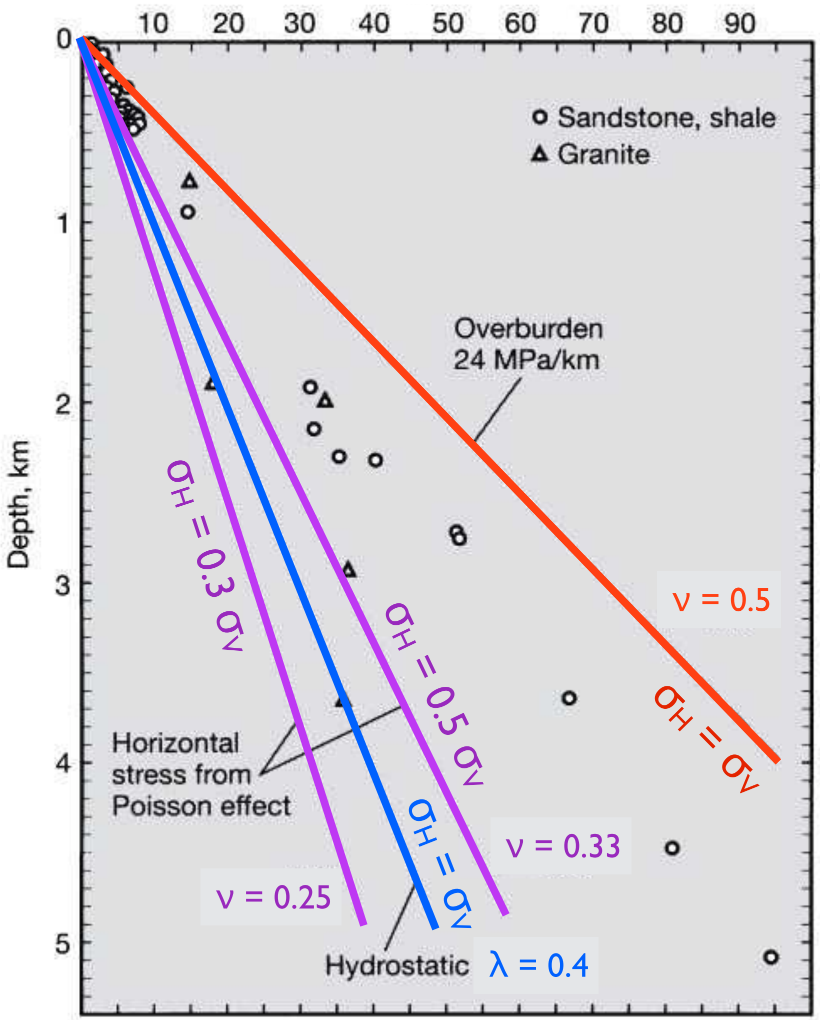
Effekt der Poissonzahl im Mohr Kreis



ν	σ_H / σ_V	$\Delta\sigma / \sigma_V$	τ_{max} / σ_V
0.00	0.00	1.00	0.50
0.25	0.33	0.67	0.33
0.333	0.50	0.50	0.25
0.43	0.75	0.25	0.125
0.50	1.00	0.00	0.00

ν klein ⇒ Δσ gross

Standard State



horizontal stress (measured by hydrofract technique)

Twiss & Moores (2007)

standard state

$\sigma_V = \rho \cdot g \cdot z$

$\sigma_H = \kappa \cdot \rho \cdot g \cdot z = \kappa \cdot \sigma_V$

$\sigma_H \neq \sigma_V$

= state of perfect confinement:

$\sigma_H = \kappa \cdot \sigma_V$

$\kappa = \dfrac{\nu}{(1-\nu)}$

ν	σ_H / σ_V	
0.333	0.50	sandstone
0.25	0.33	granite

≠ lithostatic pressure = $\rho \cdot g \cdot z$ (ρ = 2500)

$\sigma_H = \sigma_V$

hydrostatic pressure = $g \cdot z$ (ρ =1000)

$\lambda = g\,z / \rho\,g\,z \approx 0.40$

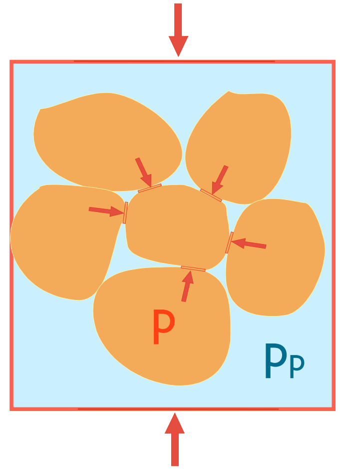
$\sigma_H = \sigma_V$

Porendruckeffekt

$(\sigma_1)_{eff} = \sigma_1 - p_P$

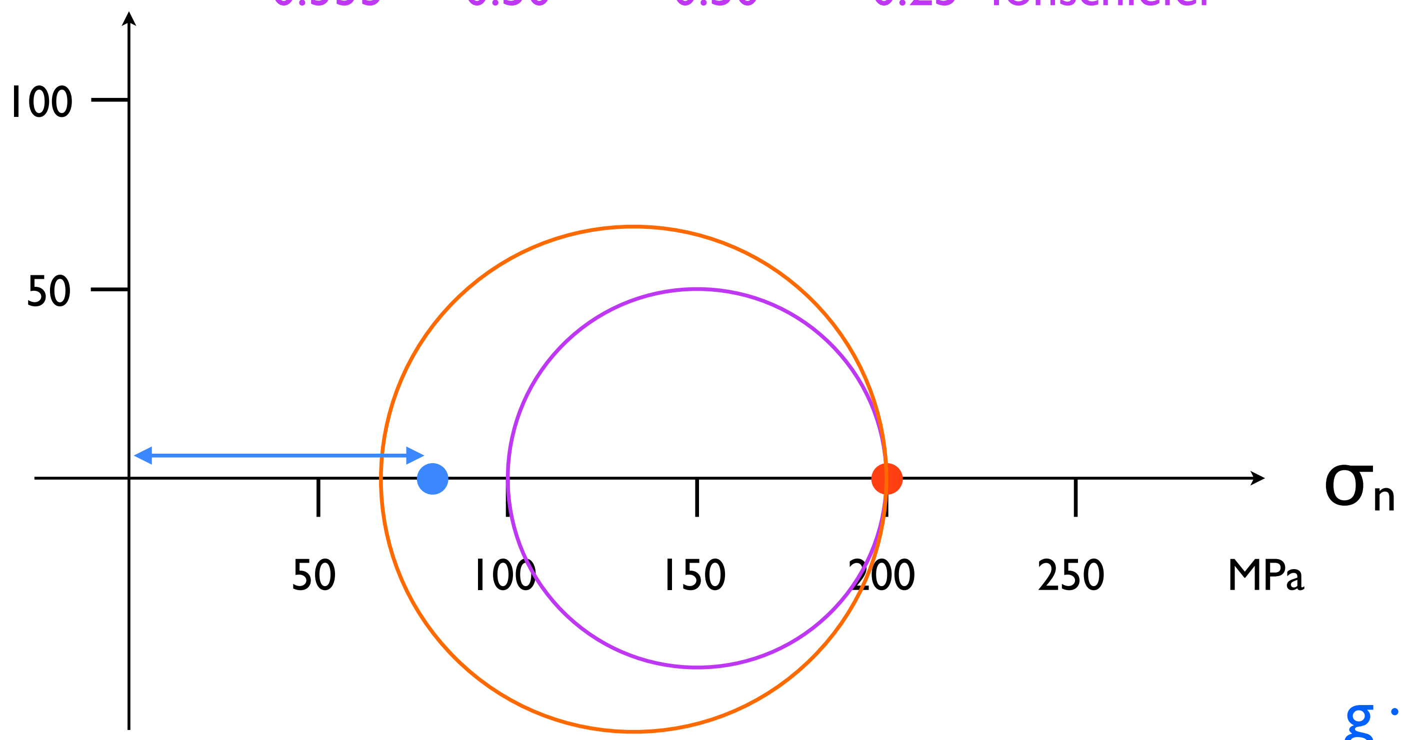
$(\sigma_3)_{eff} = \sigma_3 - p_P$

$p_{eff} = p - p_P$



ν	σ_H / σ_V	$\Delta\sigma / \sigma_V$	τ_{max}	
0.25	0.33	0.67	0.33	Quarzit
0.333	0.50	0.50	0.25	Tonschiefer

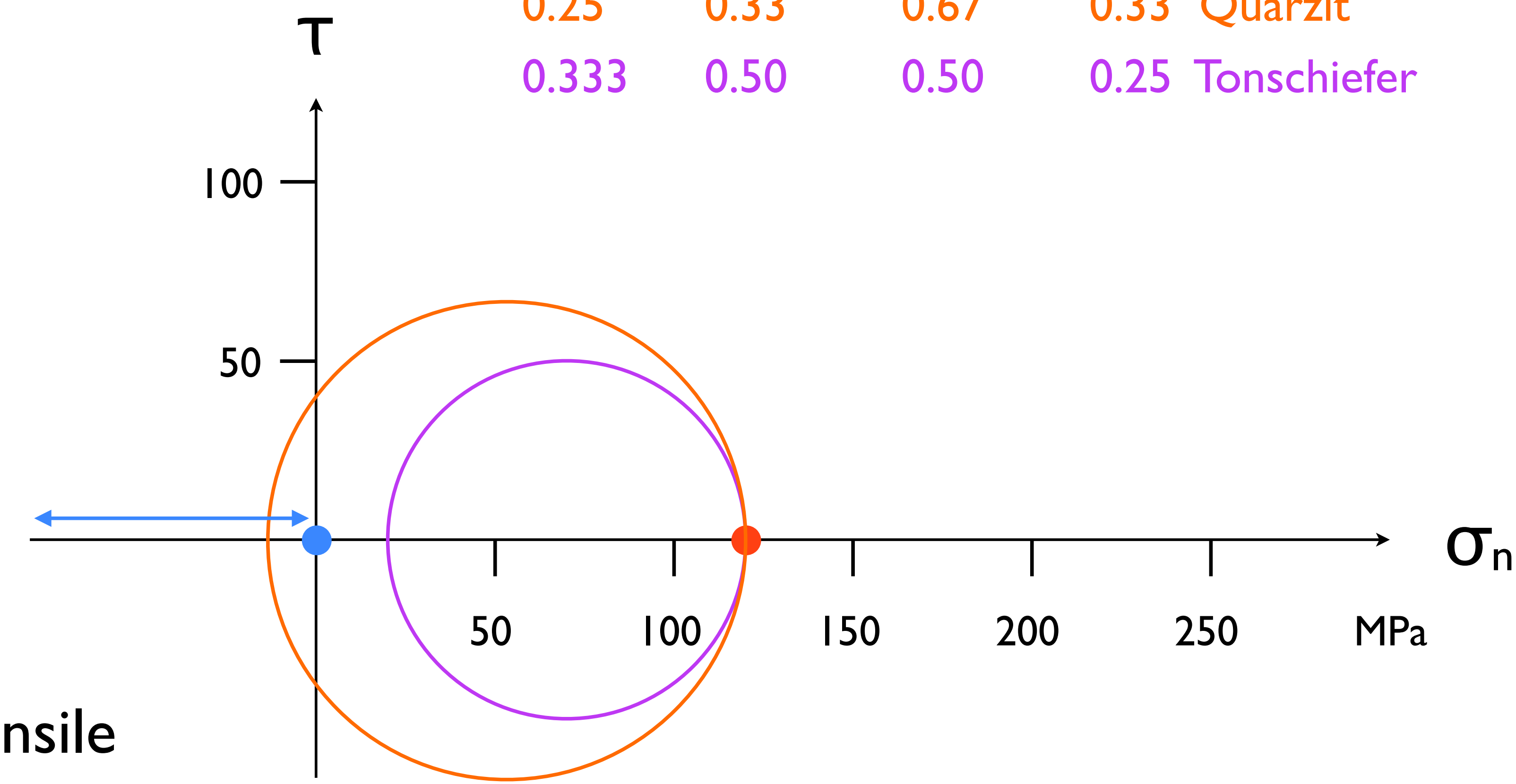
τ



$$\lambda = \frac{g \cdot z}{\rho \cdot g \cdot z} = 0.40$$

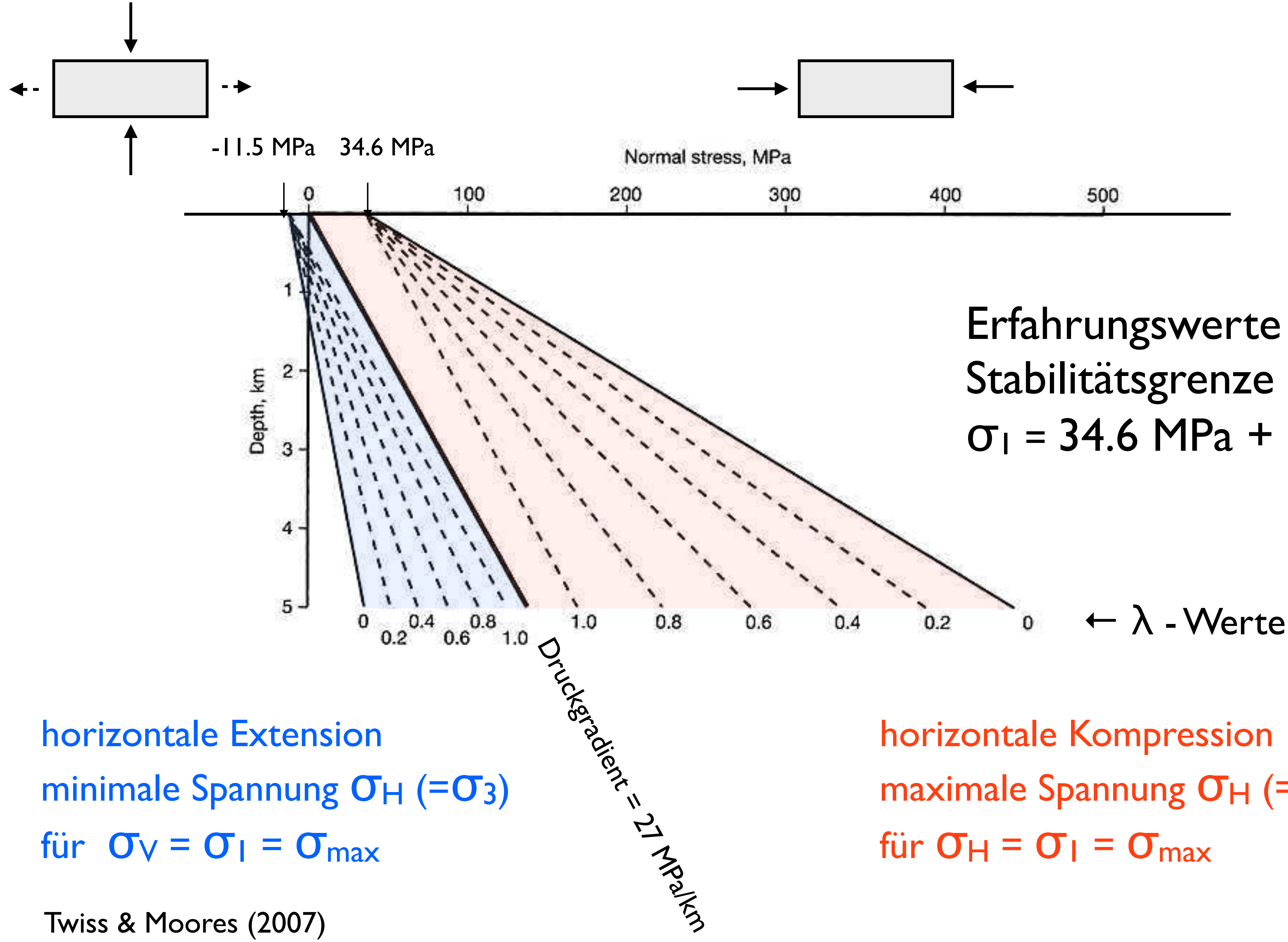
Porendruckeffekt

ν	σ_H / σ_V	$\Delta\sigma / \sigma_V$	τ_{max}	
0.25	0.33	0.67	0.33	Quarzit
0.333	0.50	0.50	0.25	Tonschiefer



Tensile
Spannung

Porendruck - Stabilitätsgrenze



Erfahrungswerte für Stabilitätsgrenze

$\sigma_1 = 34.6 \text{ MPa} + 3 \cdot \sigma_3$

horizontale Extension

minimale Spannung σ_H (=σ_3)

für $\sigma_V = \sigma_1 = \sigma_{max}$

horizontale Kompression

maximale Spannung σ_H (=σ_1)

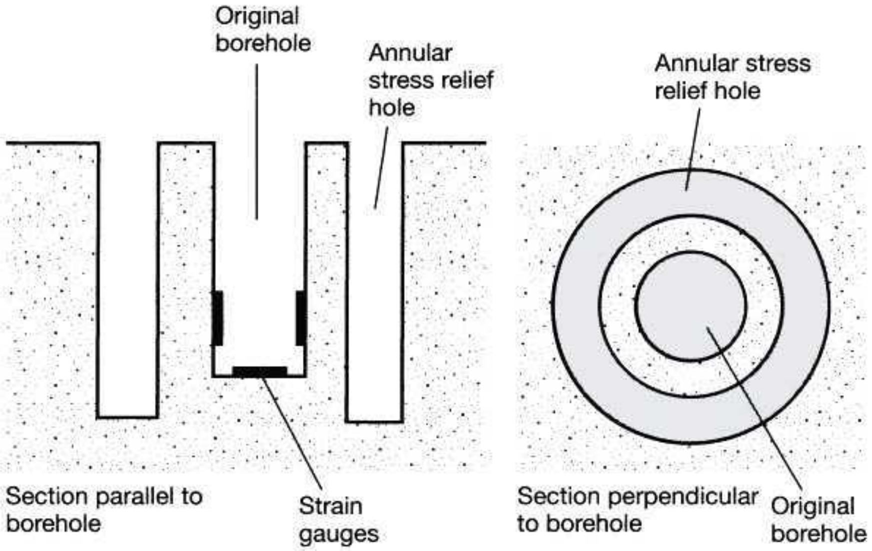
für $\sigma_H = \sigma_1 = \sigma_{max}$

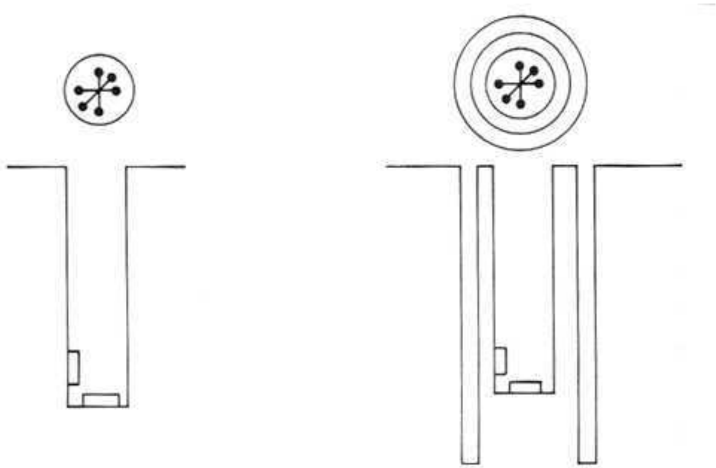
Twiss & Moores (2007)

Spannungsmessungen

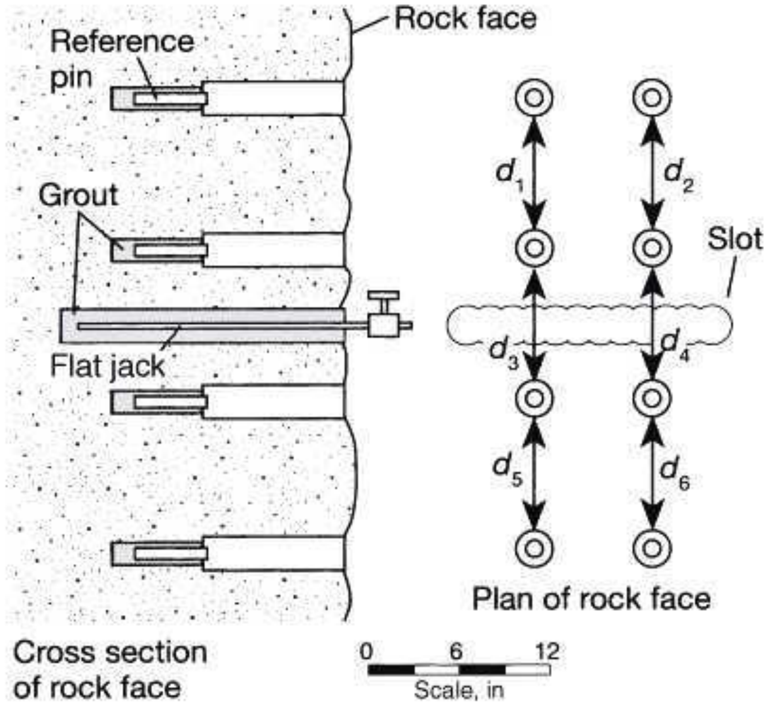
Spannungsmessung

Overcoring



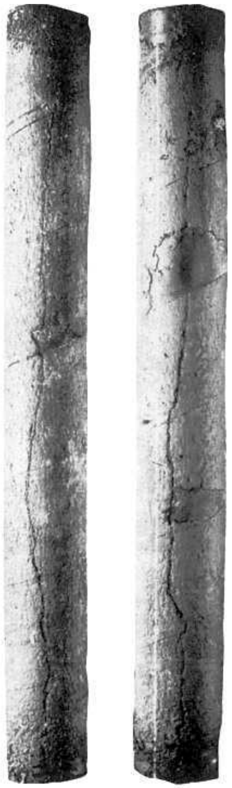


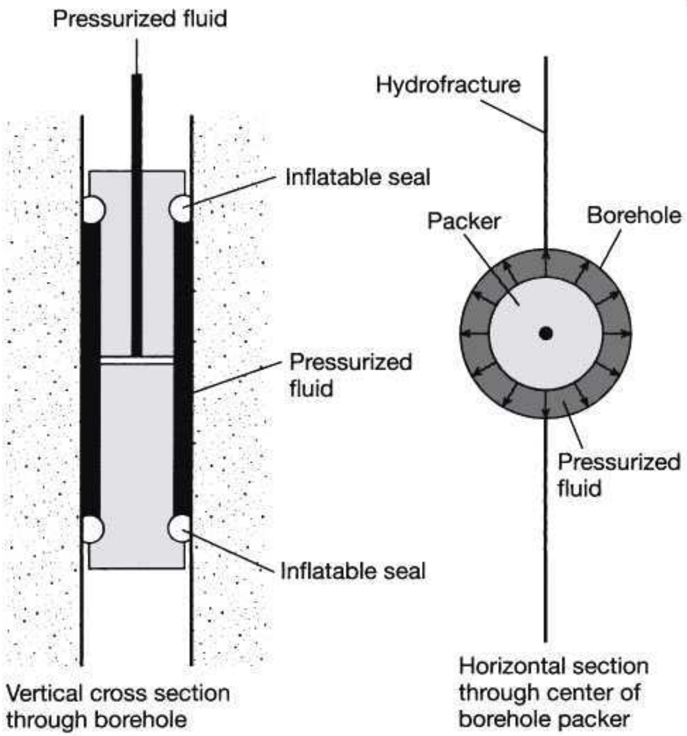
Flatjack technique

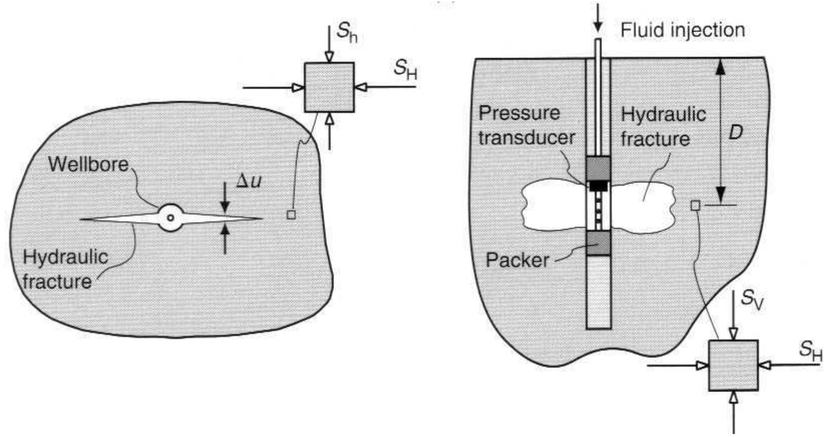


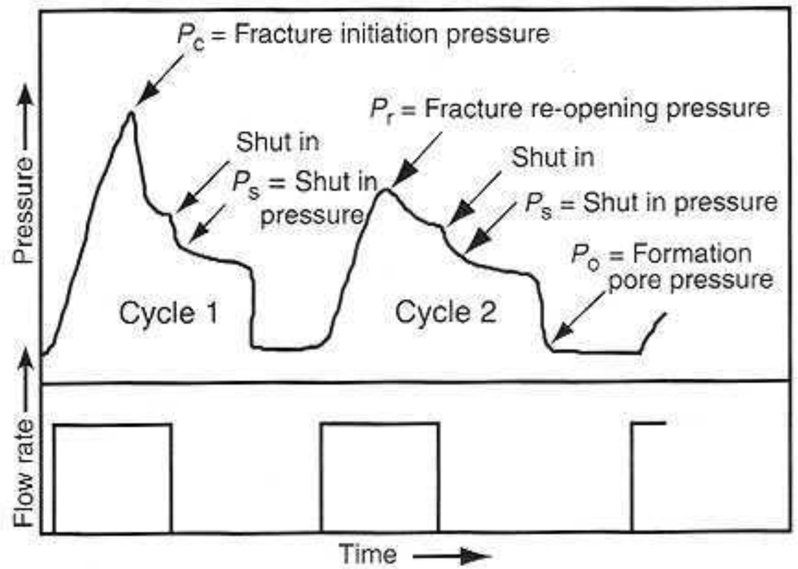
Spannungsmessung

Hydraulic fracturing (hydrofracting)





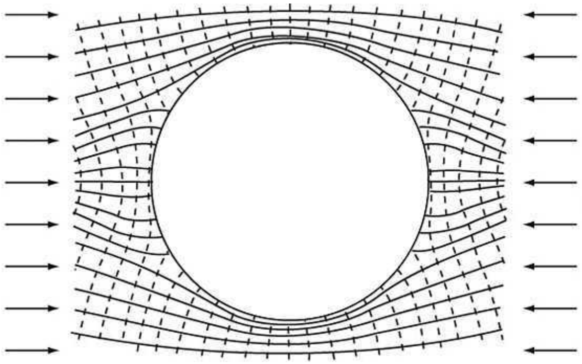




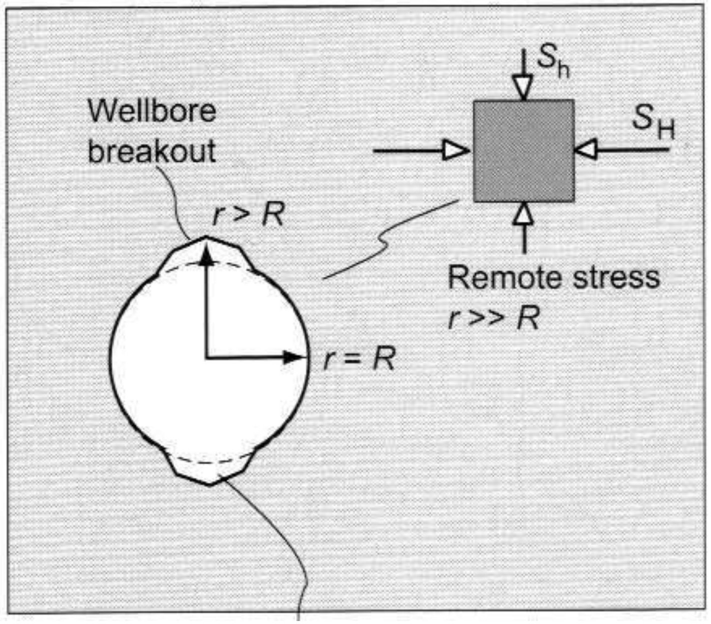
Spannungsmessung

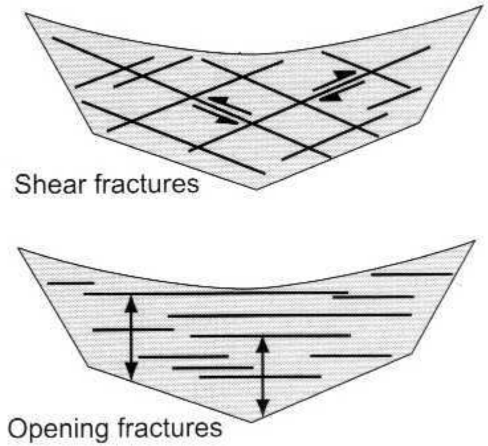
Borehole breakout

S_H max. horizontal
S_h min. horizontal



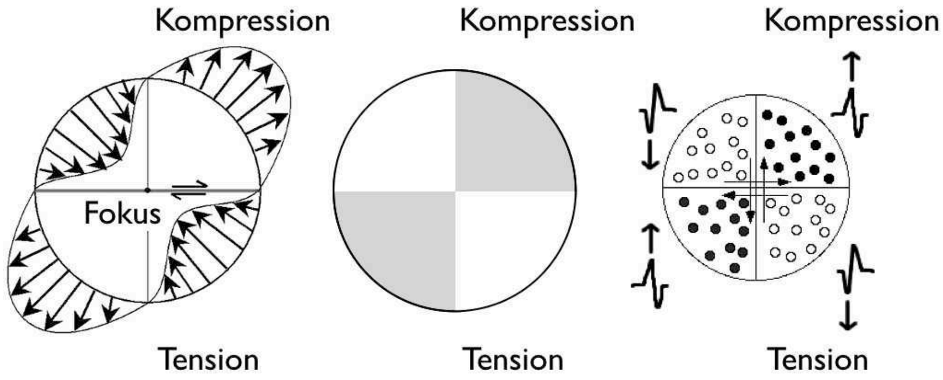
stress field



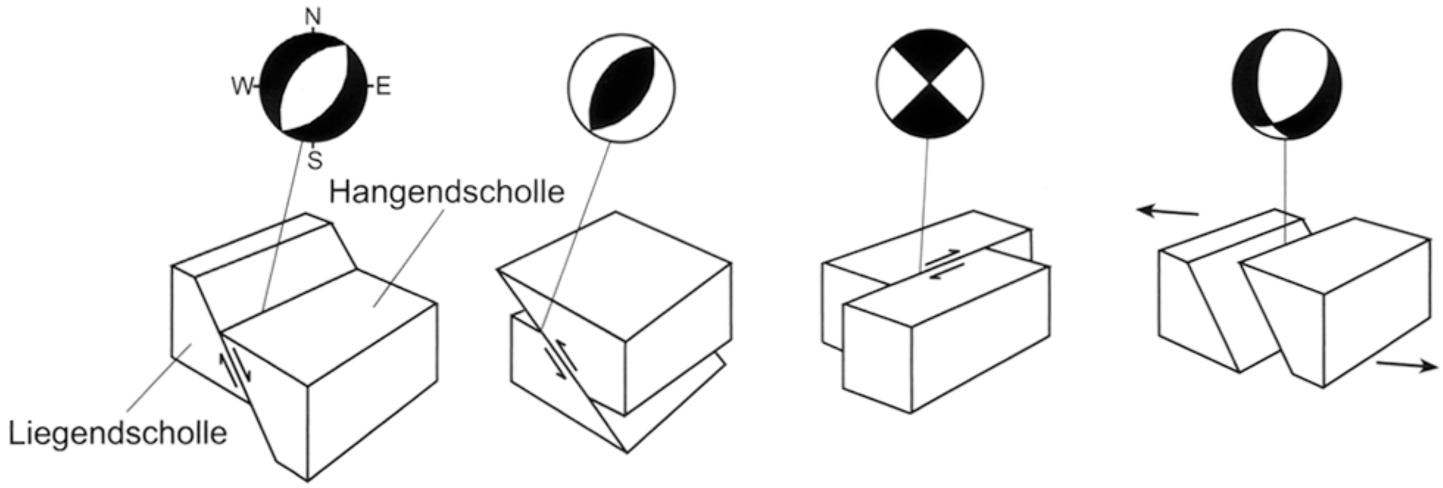


Spannungsmessung

First motion analysis



Erdbeben - Herdflächenlösung



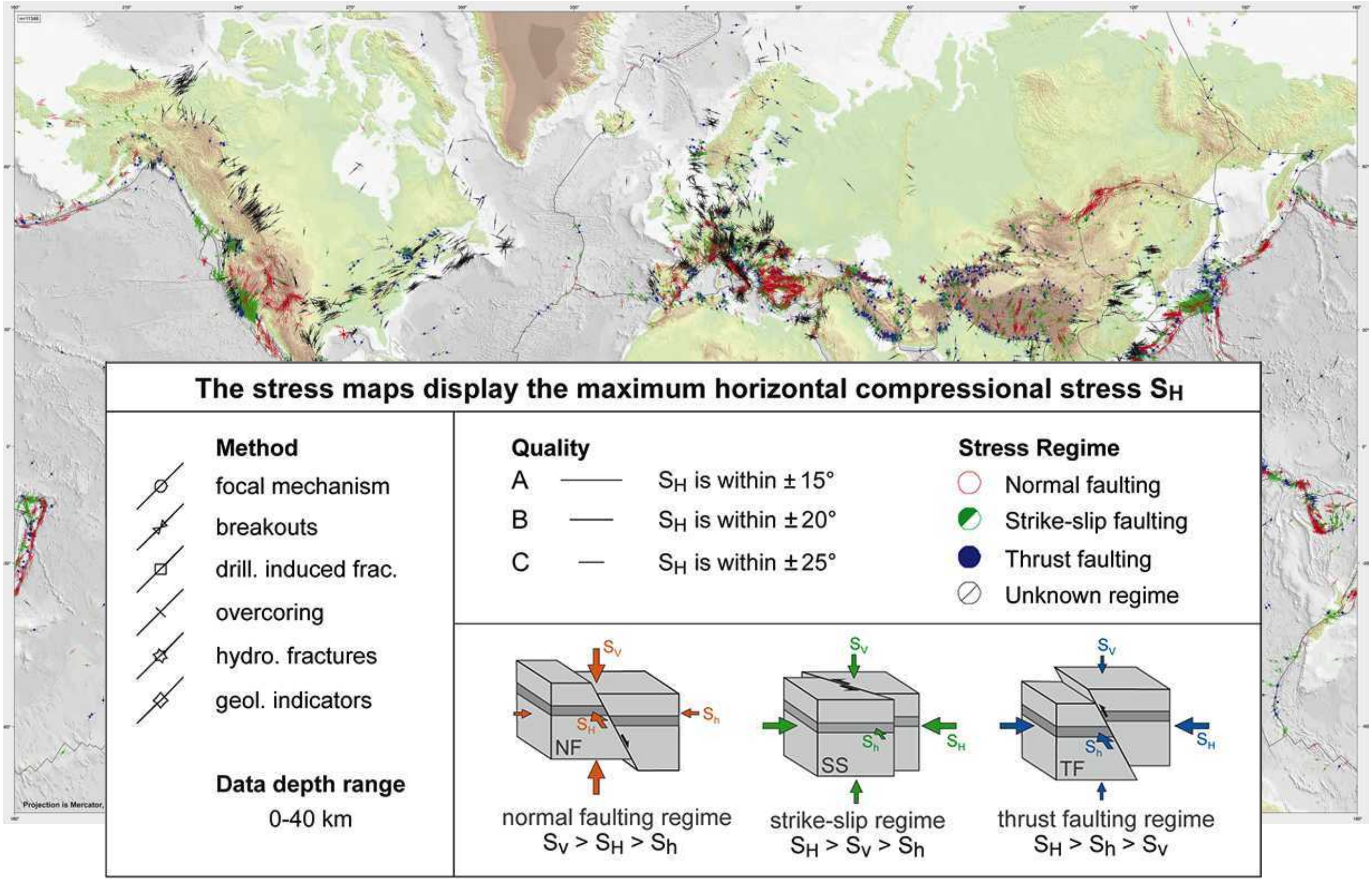
Abschiebung

Aufschiebung
Überschiebung
45° ≠ richtig

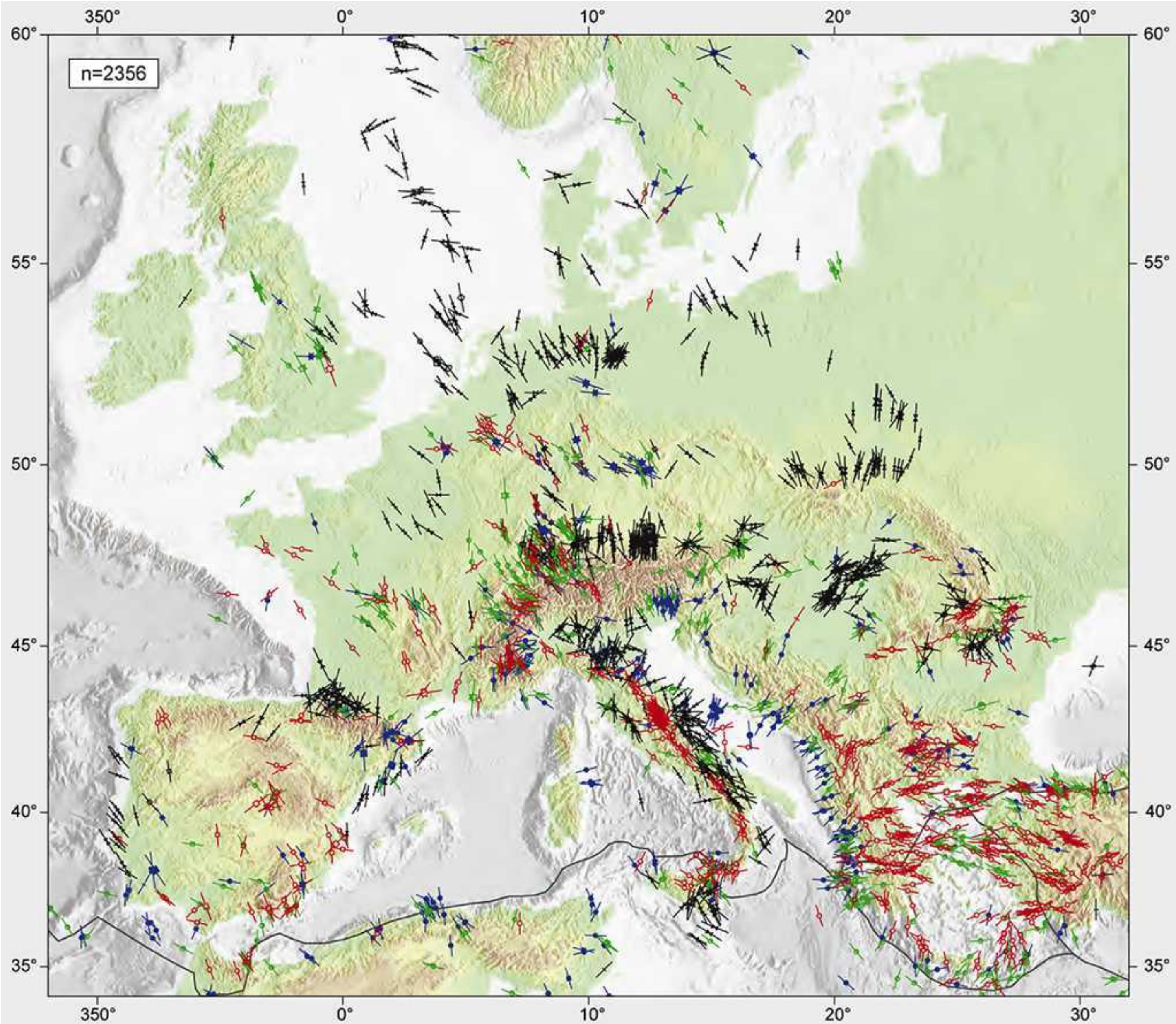
Blattverschiebung
Seitenverschiebung

Transtension

World Stress Map (GFZ Potsdam)



World Stress Map (GFZ Potsdam)



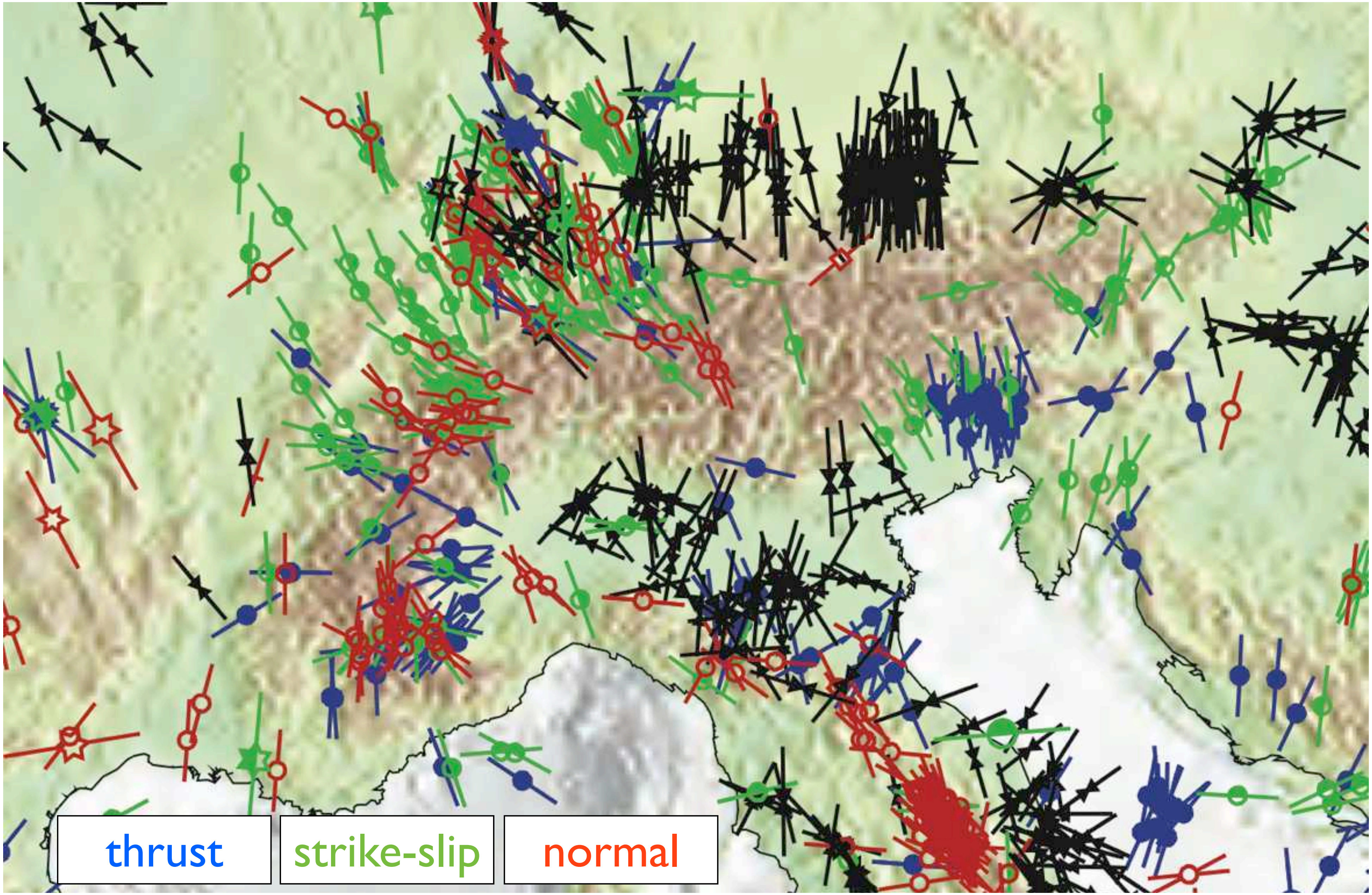
σhor_{max}

normal

strike-slip

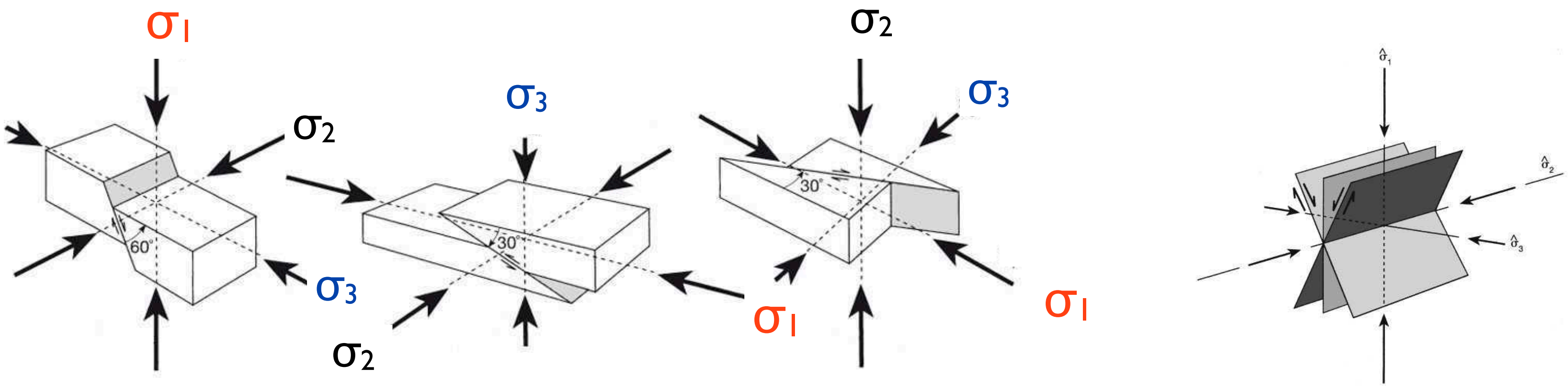
thrust

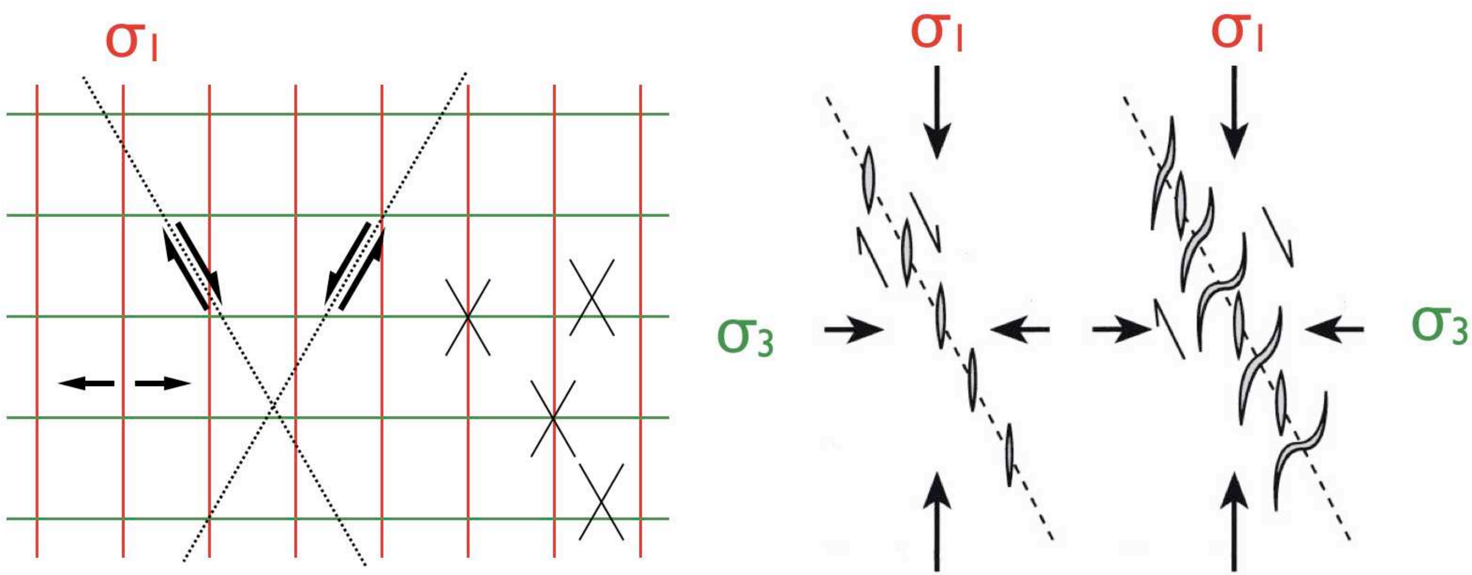
World Stress Map (GFZ Potsdam)



Spannungsfeld

Spannungsfeld an der Oberfläche





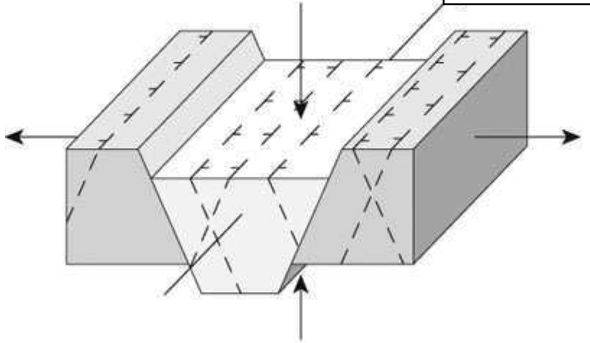
.... = Richtung von $(\tau/\sigma)_{max}$ = maximum stress ratio

--------- = Orientierung der Brüche gegenüber Hauptspannungen

Spannungsfeld in der Tiefe

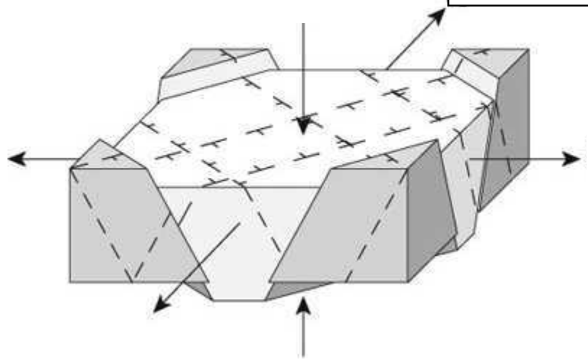
$\sigma_1 > 0$ $\sigma_2 = 0$

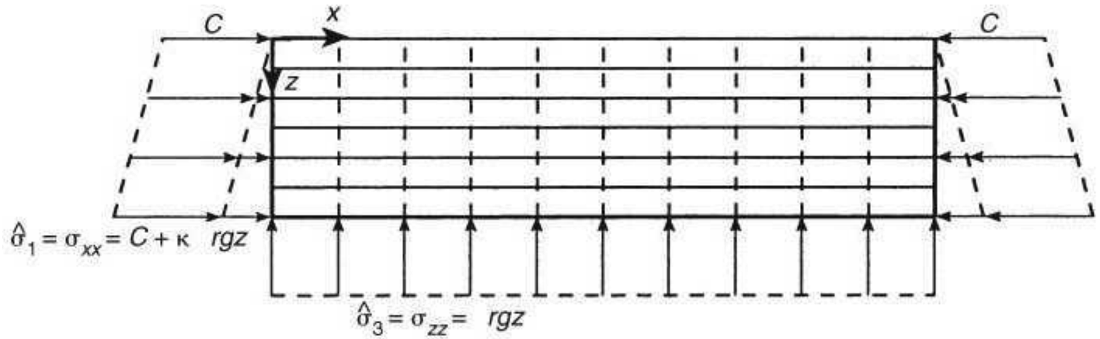
$\sigma_3 < 0$



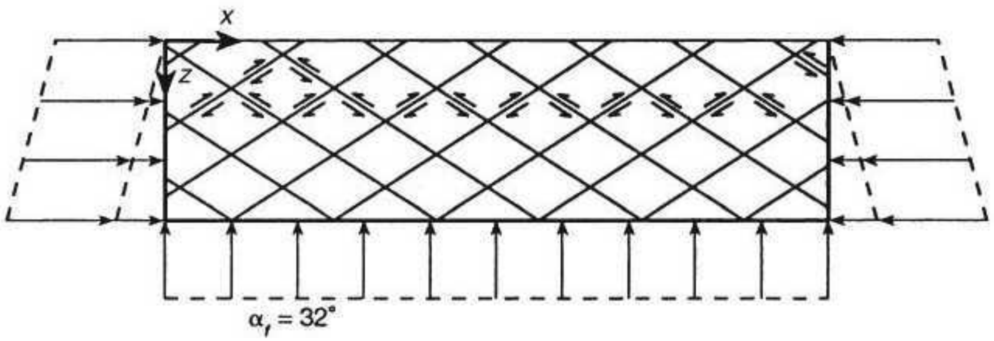
$\sigma_1 > 0$ $\sigma_2 < 0$

$\sigma_3 < 0$





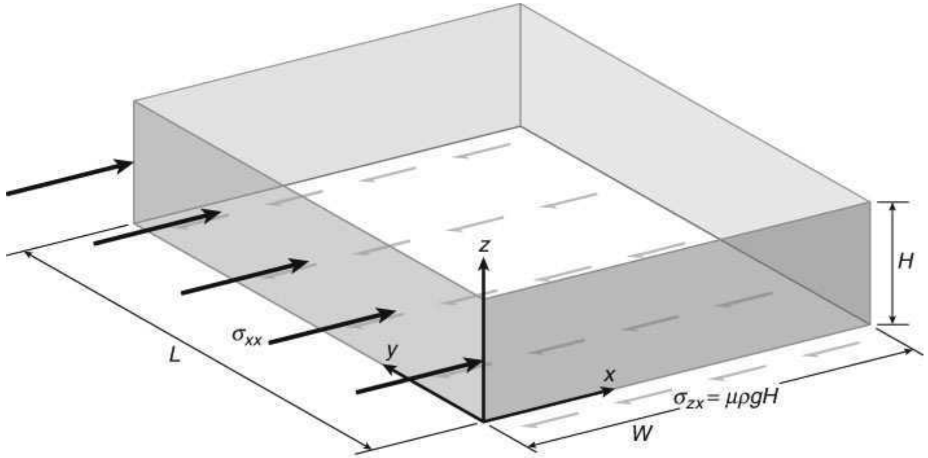
$\sigma_{max}, \sigma_{min}$



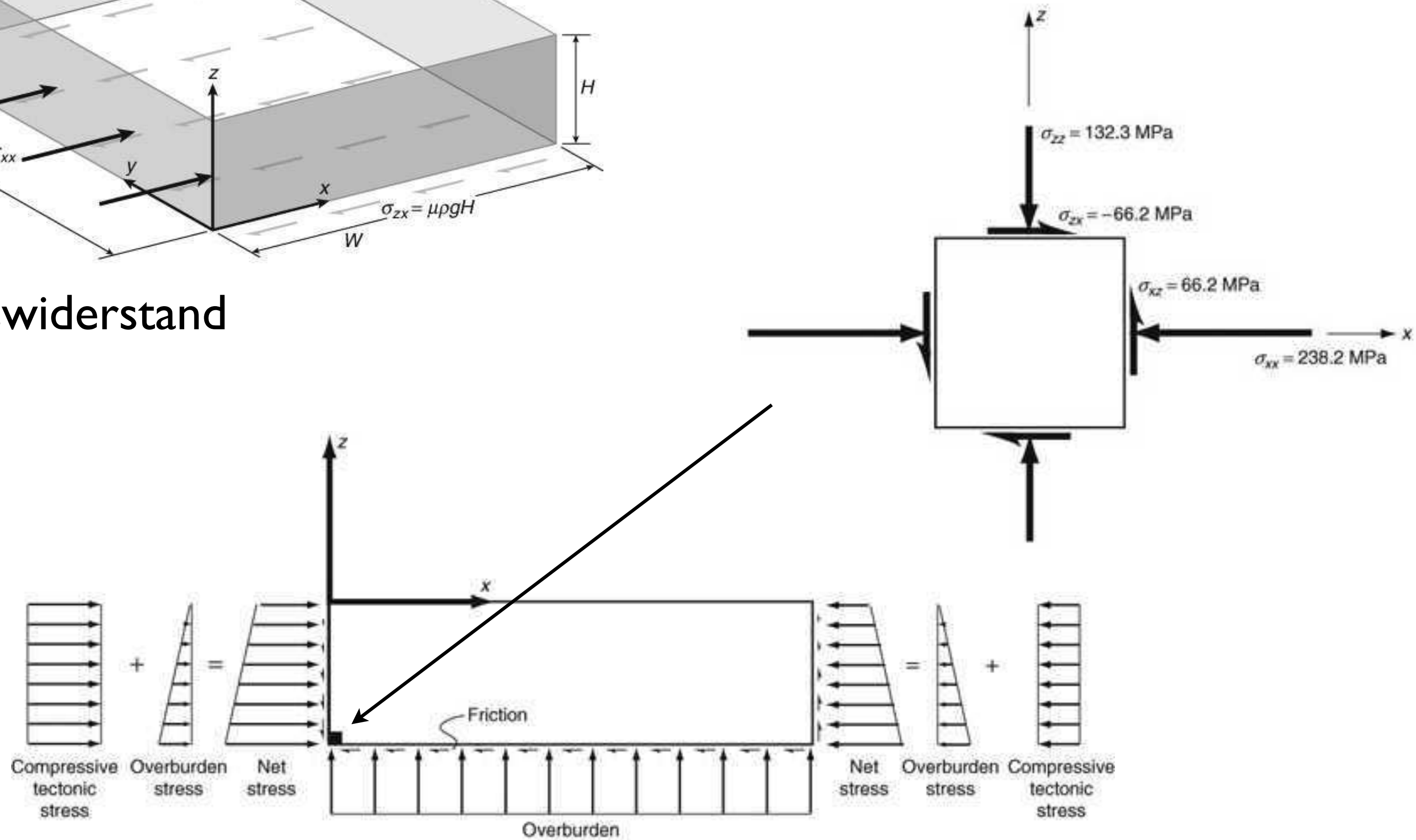
$(\tau/\sigma)_{max}$

Spannungsfeld bei Überschiebung

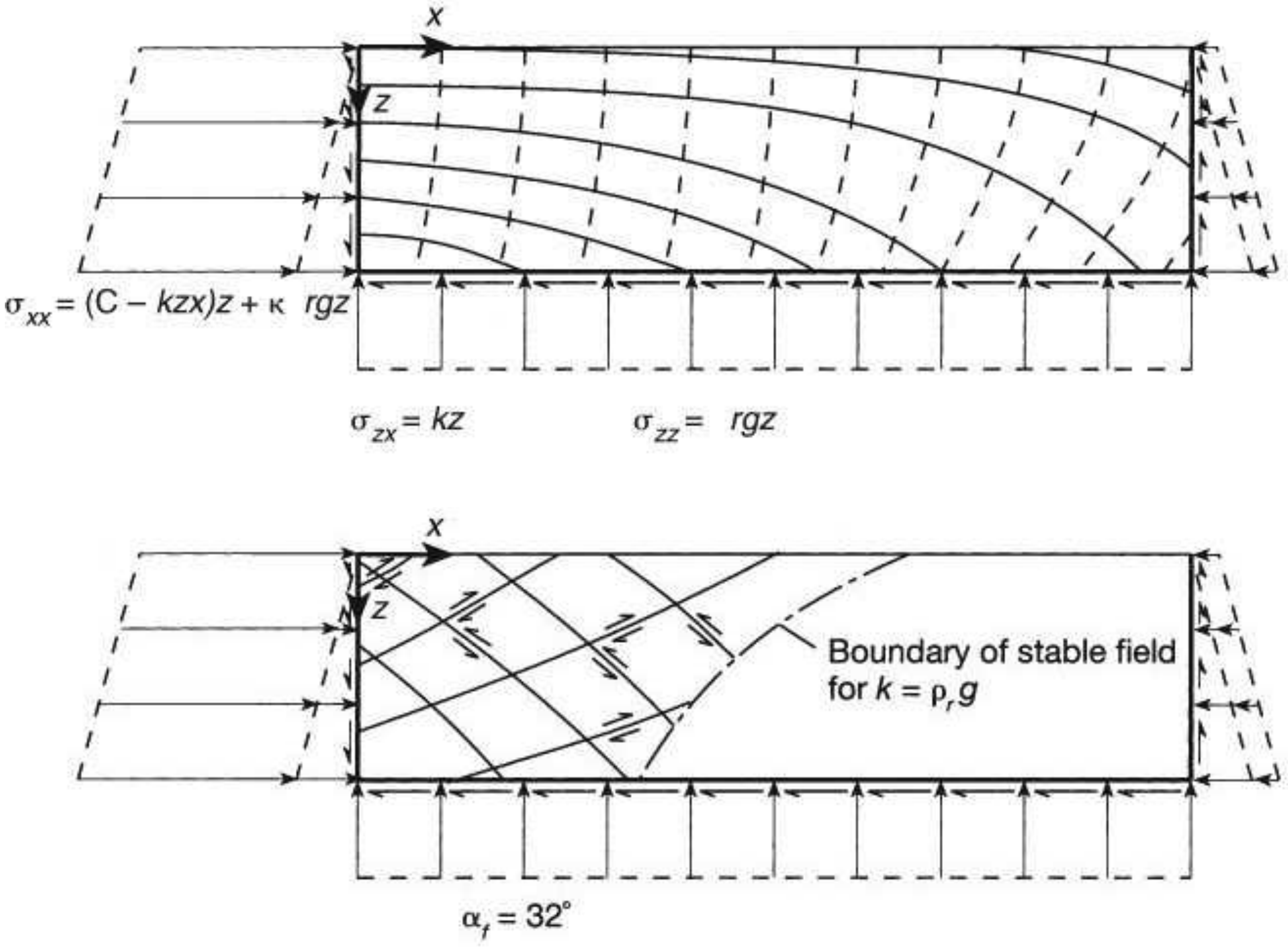
Seitlicher Schub



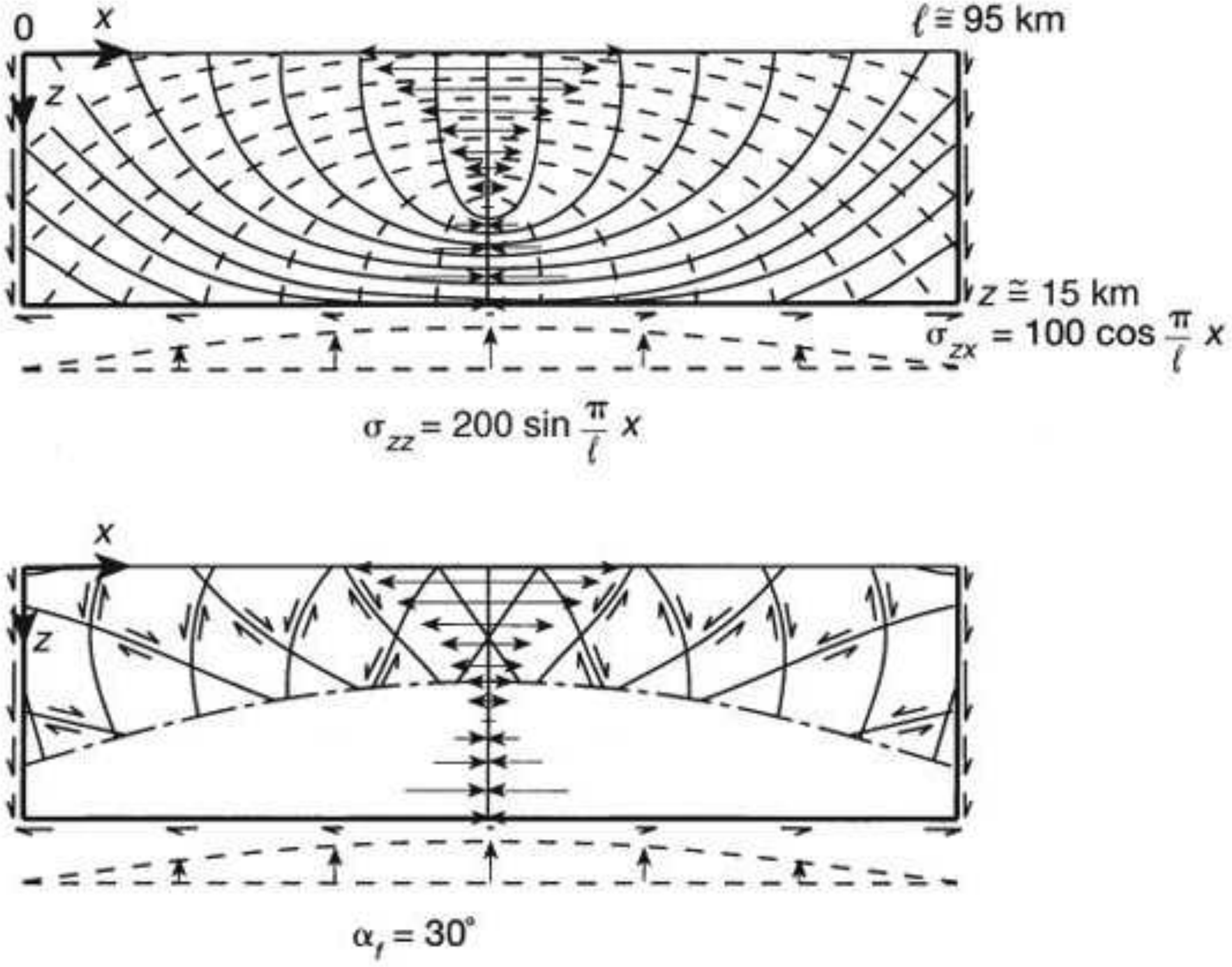
+ Reibungswiderstand



Spannungsfeld und Stabilkitätsbereich

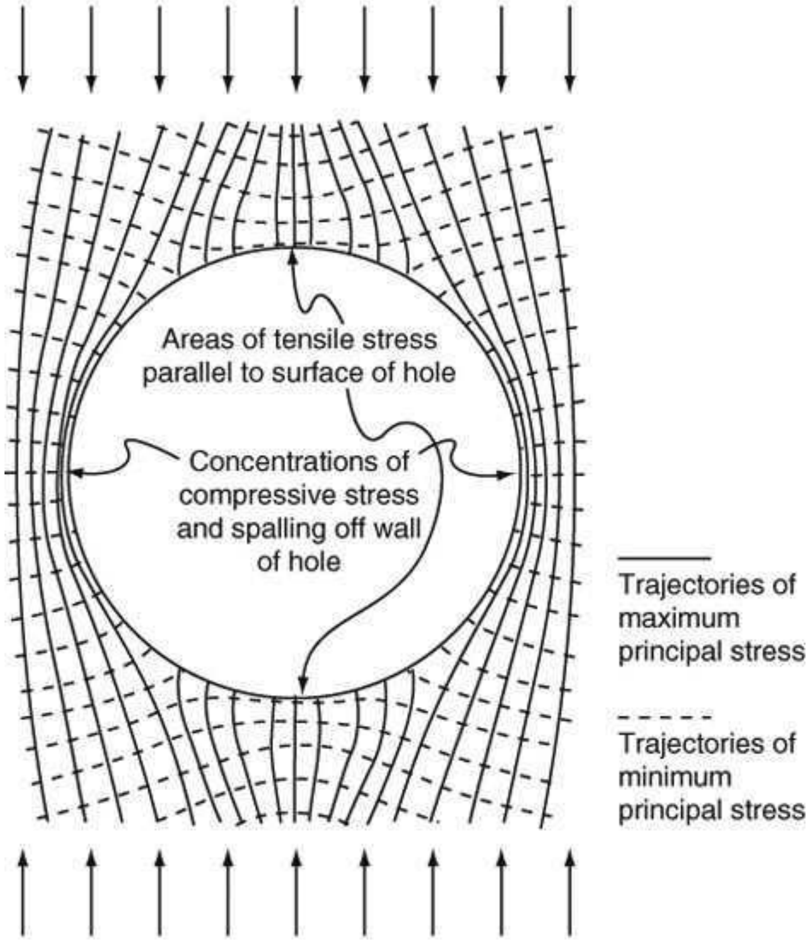


Spannungsfeld bei Krustendehnung

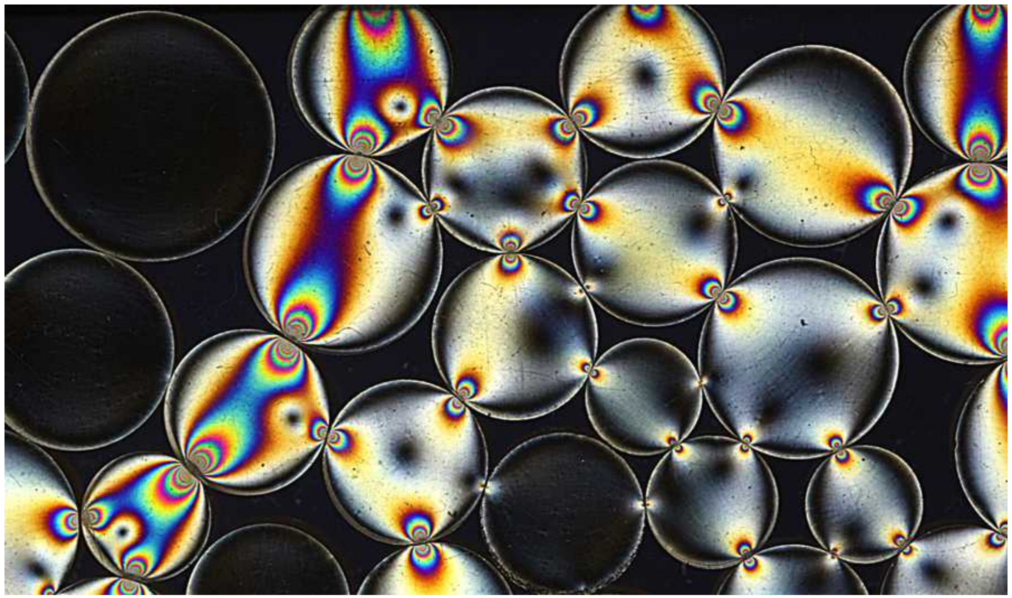


Hauptspannungstrajektorien

Spannungsverteilung
um einen Hohlraum



Spannungsverteilung
an Punkt-zu-Punkt-Kontakten



Visualisierung durch Spannungsoptik
(http://dutcgeo.ct.tudelft.nl/allersma/fotoelast/fotelast.htm)

2

2 Deformation - Strain - Strainmessung

VL-Themen:

- Deformation und Verformung
- Strain ellipse
- Progressive Deformation
- Flinn Diagramm

- Verkürzung - Falten
- Streckung - Boudinage
- Scherung - Scherzonen

- Verformungsmarker (strain marker)
- Strainmessung

Deformation und Verformung (deformation and strain)

Deformations - Zustand

Deformation = Geometrie
als Abweichung relativ zu unverformtem Zustand

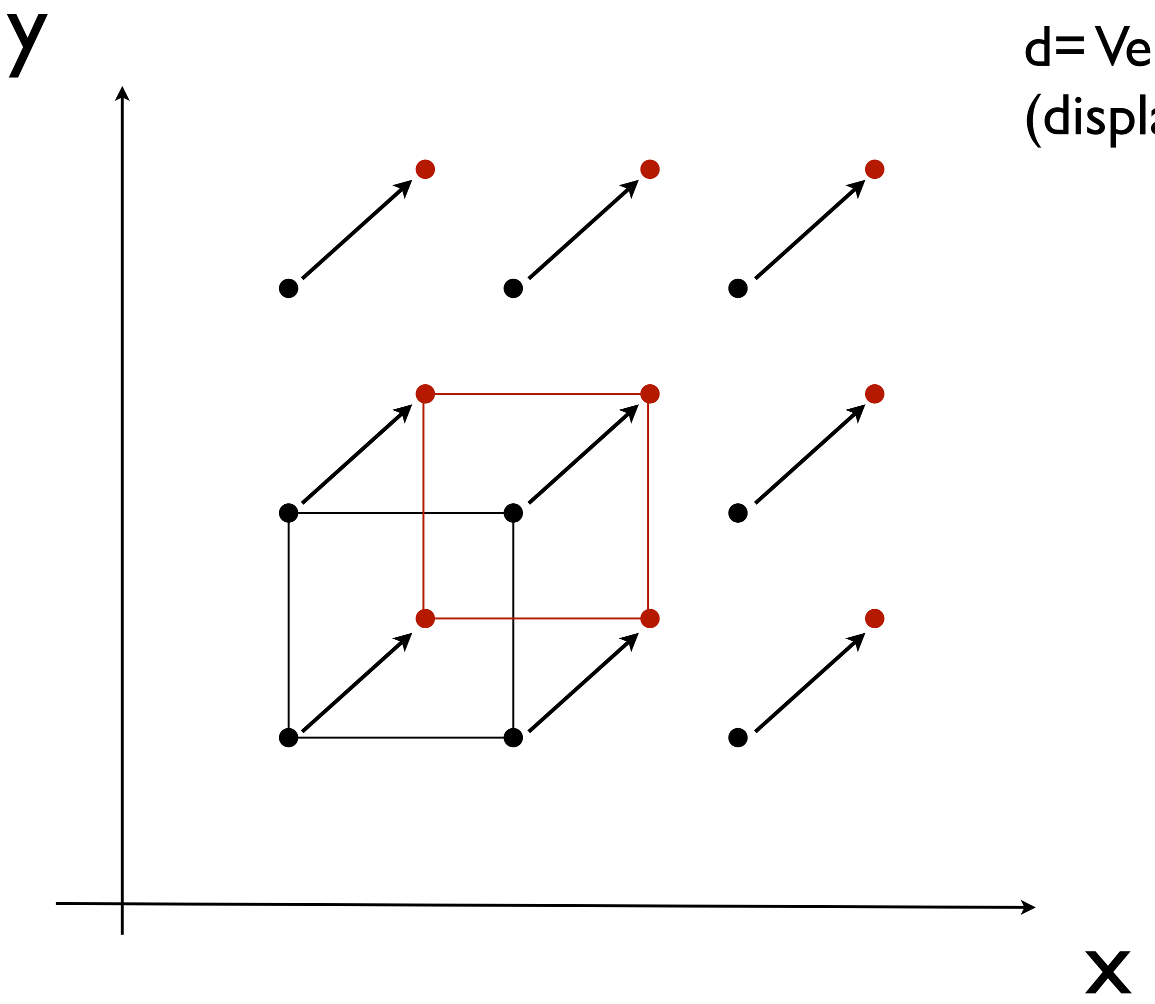
Deformation:
= Verschiebung (displacement) von Punkten
= Translation + Verformung (translation + strain)

Strain (Verformung): Streckung - Elongation
Scherung (sinistral - dextral)
Rotation (CLW - CCLW)

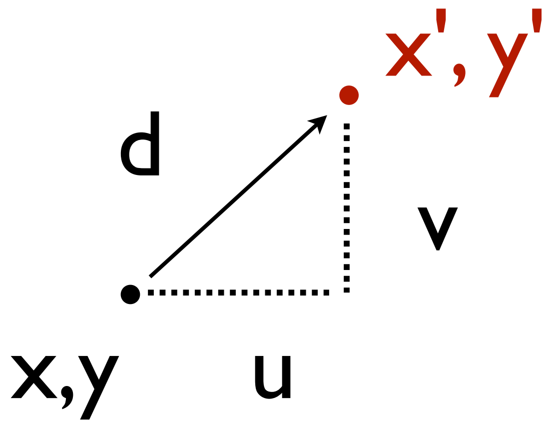
Dimension: Länge / Länge = dimensionslos

Translation (translation)

= Spezialfall der Verschiebung



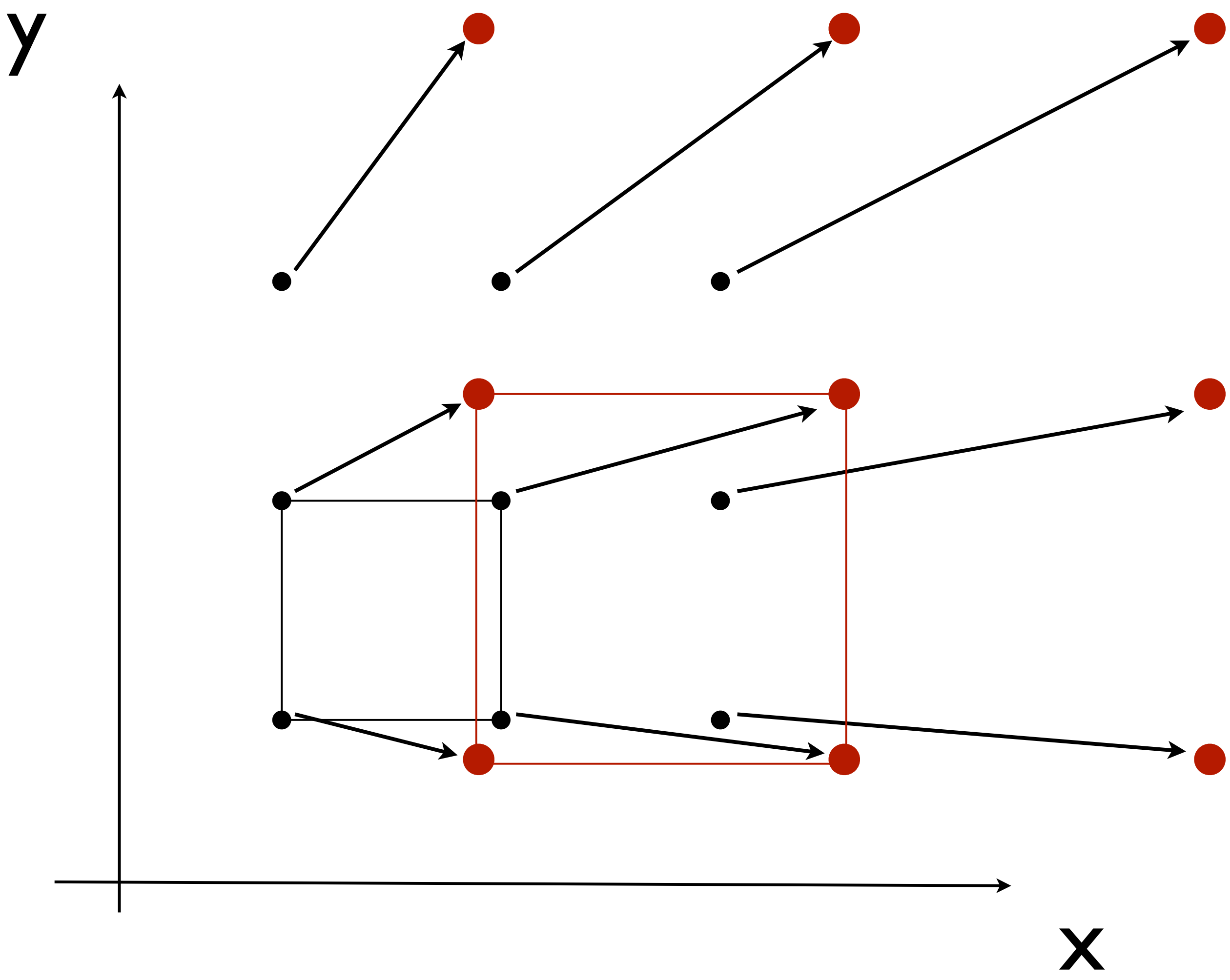
d= Verschiebungsvektor
(displacement vector)



u, v = Komponenten der Verschiebung
Wenn alle u, v gleich
=> Translation

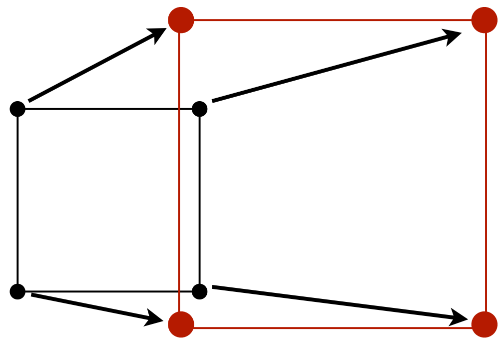
Verschiebung

= allgemeiner Fall



Alle u, v sind verschieden

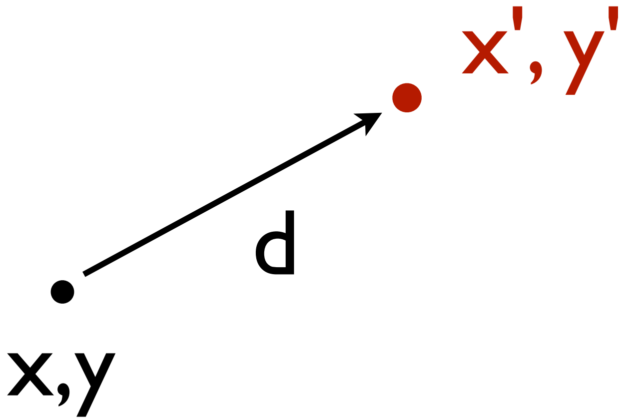
Koordinaten - Transformation



$$x' = f\,(x,y)$$
$$y' = f\,(x,y)$$

$$x' = A \cdot x + B \cdot y$$
$$y' = C \cdot x + D \cdot y$$

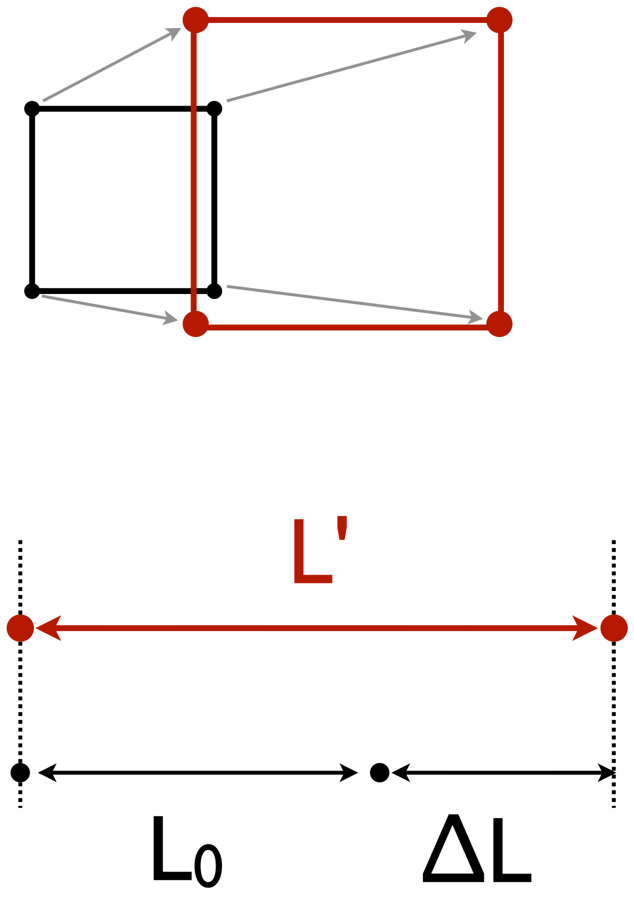
$$x'_1 = a_{11} \cdot x_1 + a_{12} \cdot x_2$$
$$x'_2 = a_{21} \cdot x_1 + a_{22} \cdot x_2$$



$$\begin{bmatrix} x'_1 \\ x'_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$x'_i = a_{ij} \cdot x_j$$

Strain 1D



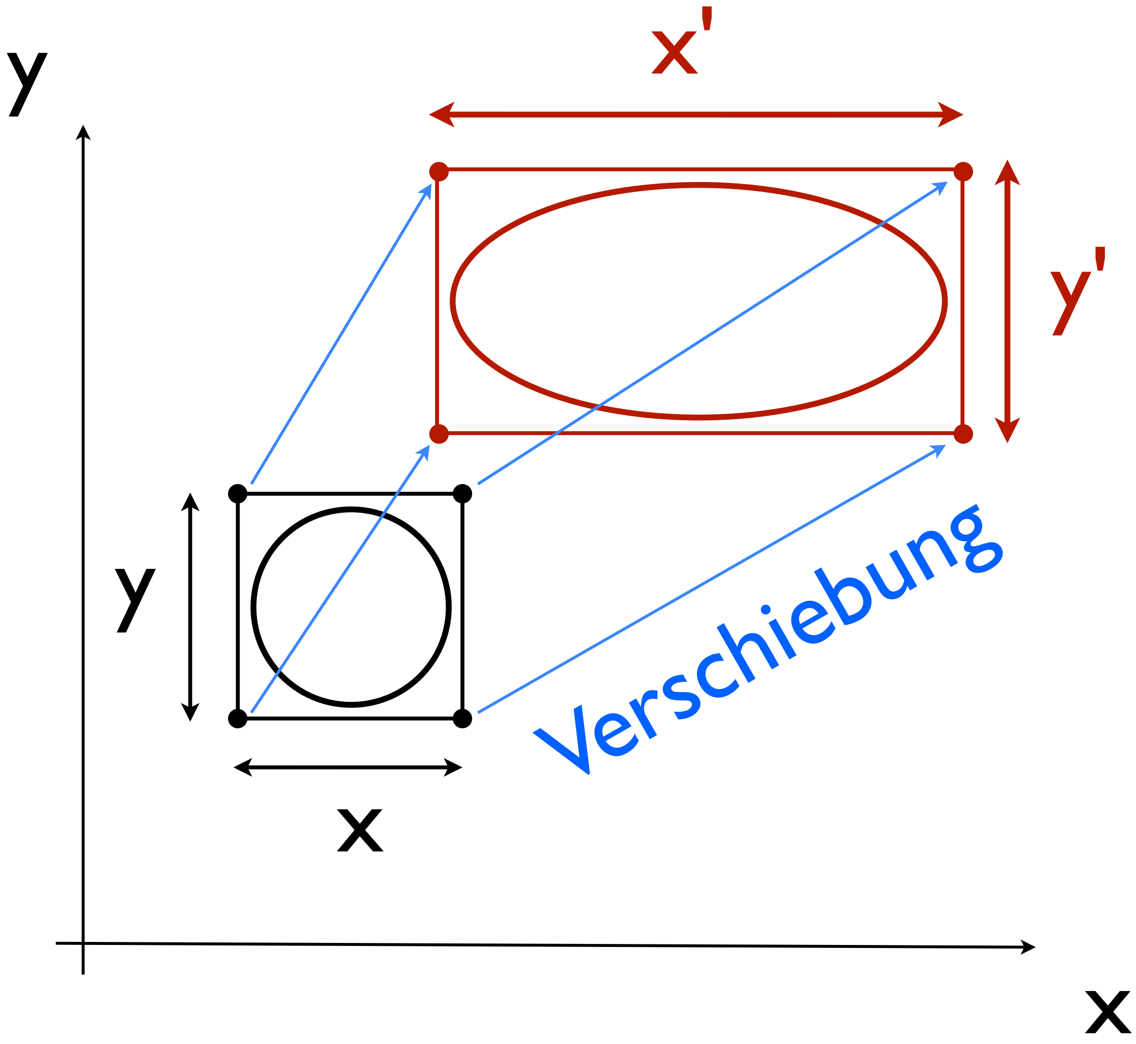
L_0 unverformt
L' verformt

$\Delta L = L' - L_0$

$e = \Delta L / L_0$
(dimensionslos)

$e > 0$ Streckung
$e < 0$ Verkürzung

Strain 2D



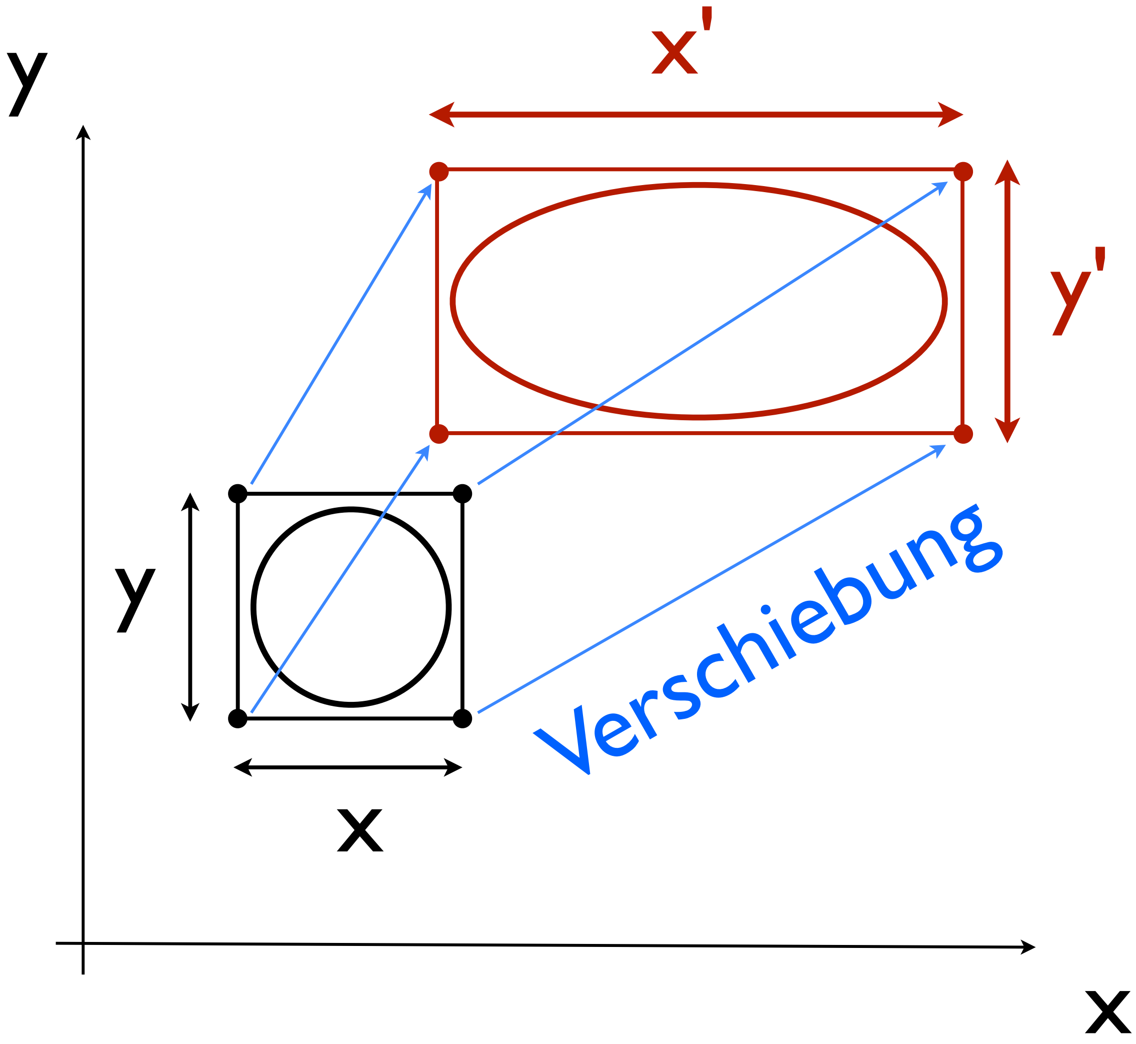
x, y unverformt
x', y' verformt

$e_x = \Delta x / x$
$e_y = \Delta y / y$

(dimensionslos)

$e > 0$ Streckung
$e < 0$ Verkürzung

stretch 2D



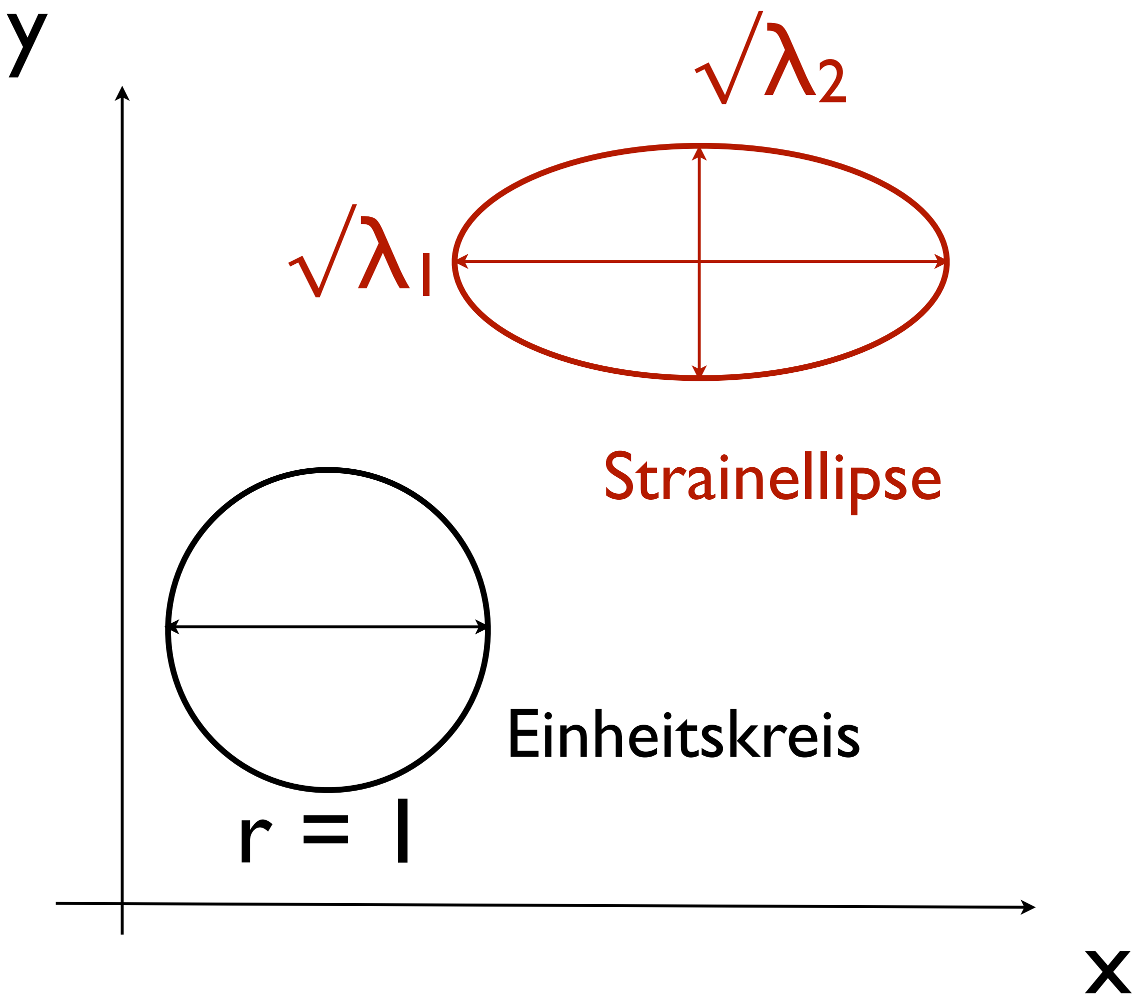
x, y unverformt
x', y' verformt

$s_x = L_x' / L_x$

$s_x = (1 + e_x)$

s > 1 Streckung
s < 1 Verkürzung

Strain 2D - strain ellipse



$e = \Delta L / L_0$

$L' = L_0 \cdot (1 + e)$

$\lambda_1 = (1 + e_1)^2$

$\lambda_2 = (1 + e_2)^2$

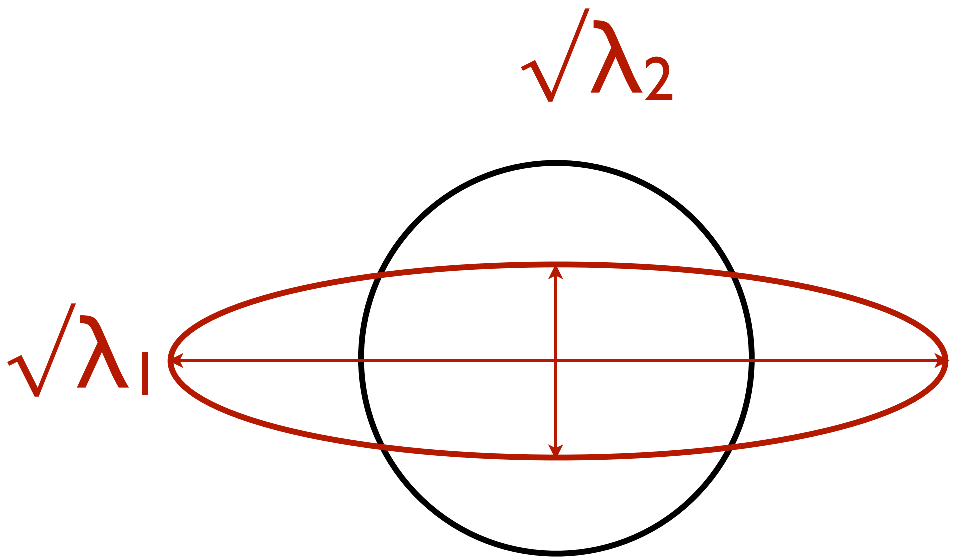
$\lambda_1 > \lambda_2$

$\lambda > 1$ Streckung

$\lambda < 1$ Verkürzung

λ = quadratische Elongation

Strainellipse 2D



Ellipsenachsen
$\sqrt{\lambda_1}$, $\sqrt{\lambda_2}$

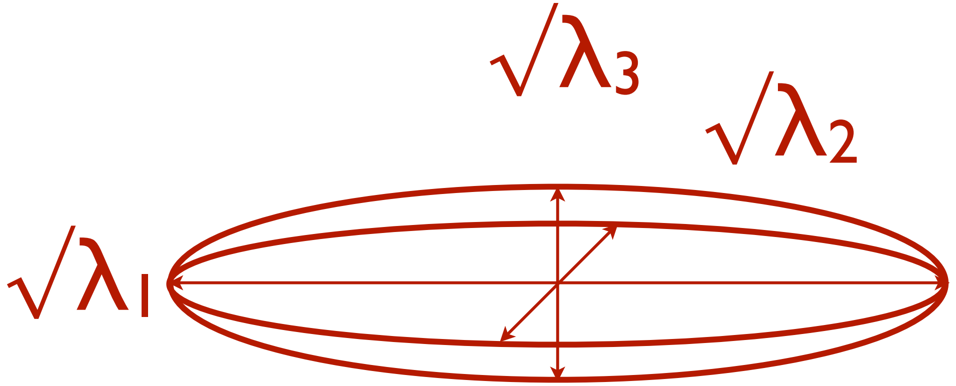
Achsenverhältnis
$R = \sqrt{\lambda_1} / \sqrt{\lambda_2}$
$R \geq 1.00$

bei $\Delta A = 0$:
$\sqrt{\lambda_1} \cdot \sqrt{\lambda_2} = 1$
$\sqrt{\lambda_2} = 1 / \sqrt{\lambda_1}$

$R = (\sqrt{\lambda_1})^2 = \lambda_1$

Beispiel:
$\sqrt{\lambda_1} = 2.0$
$\sqrt{\lambda_2} = 0.5$
$R = 4.00$

Strainellipsoid 3D



Ellipsenachsen
$\sqrt{\lambda_1}$, $\sqrt{\lambda_2}$, $\sqrt{\lambda_3}$

bei $\Delta V = 0$, $\sqrt{\lambda_2} = 1$
(plane strain):

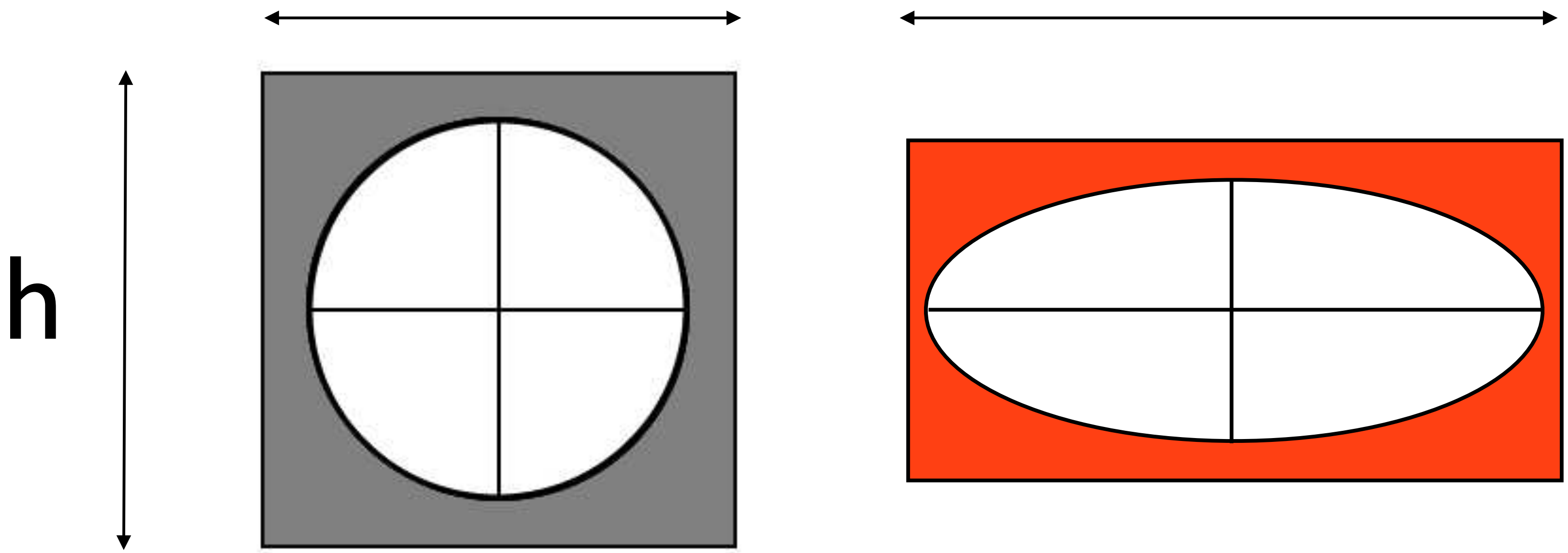
$R_{13} = \sqrt{\lambda_1} / \sqrt{\lambda_3}$
$\sqrt{\lambda_1} \cdot \sqrt{\lambda_3} = 1$
$\sqrt{\lambda_3} = 1 / \sqrt{\lambda_1}$

$R_{13} = (\sqrt{\lambda_1})^2 = \lambda_1$

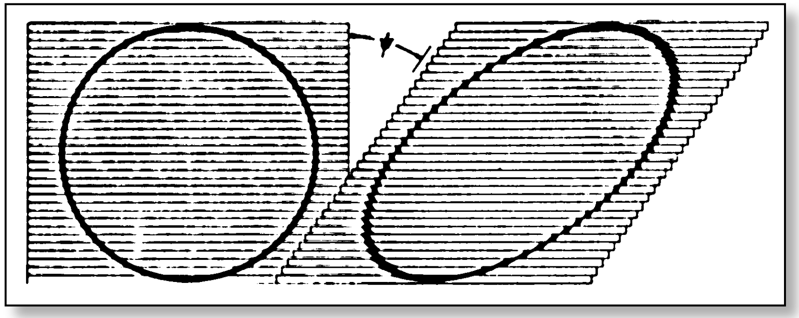
Beispiel:
$\sqrt{\lambda_1} = 2.0$ $\sqrt{\lambda_2} = 1.0$
$\sqrt{\lambda_3} = 0.5$
$R_{13} = 4.00$

Reine Scherung - koaxial

keine Rotation
der Achsen



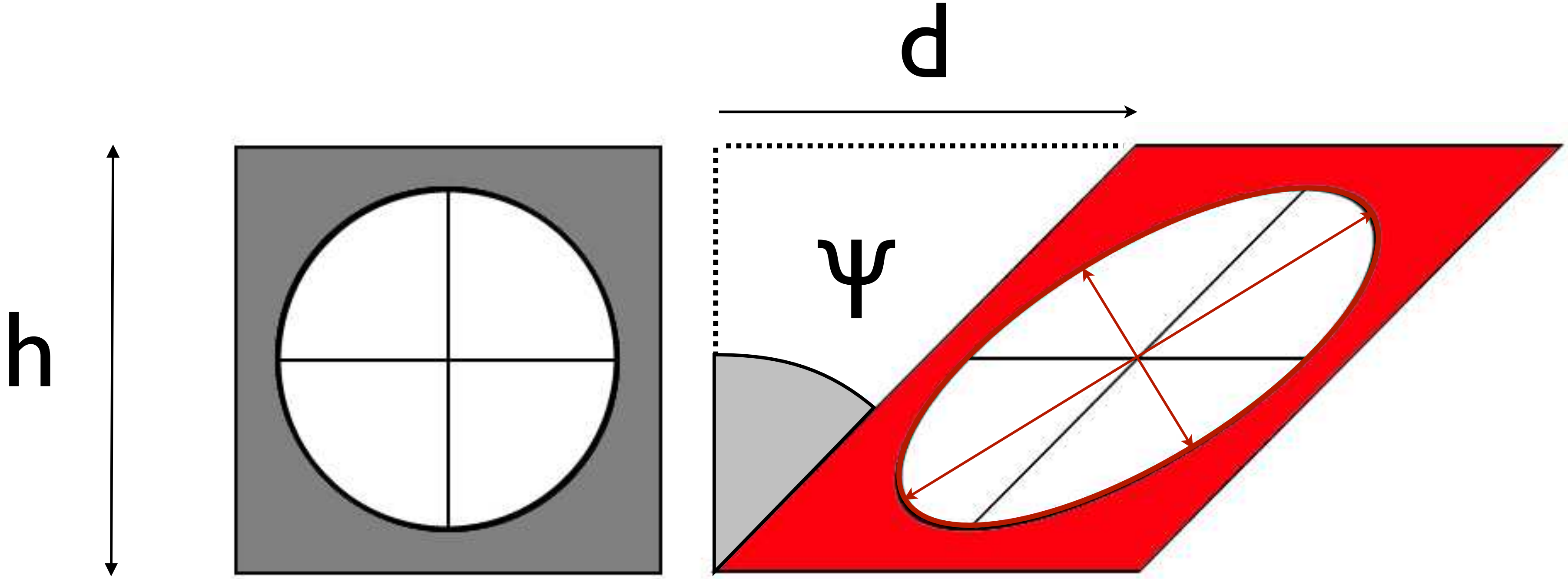
Einfache Scherung - rotational



shear strain

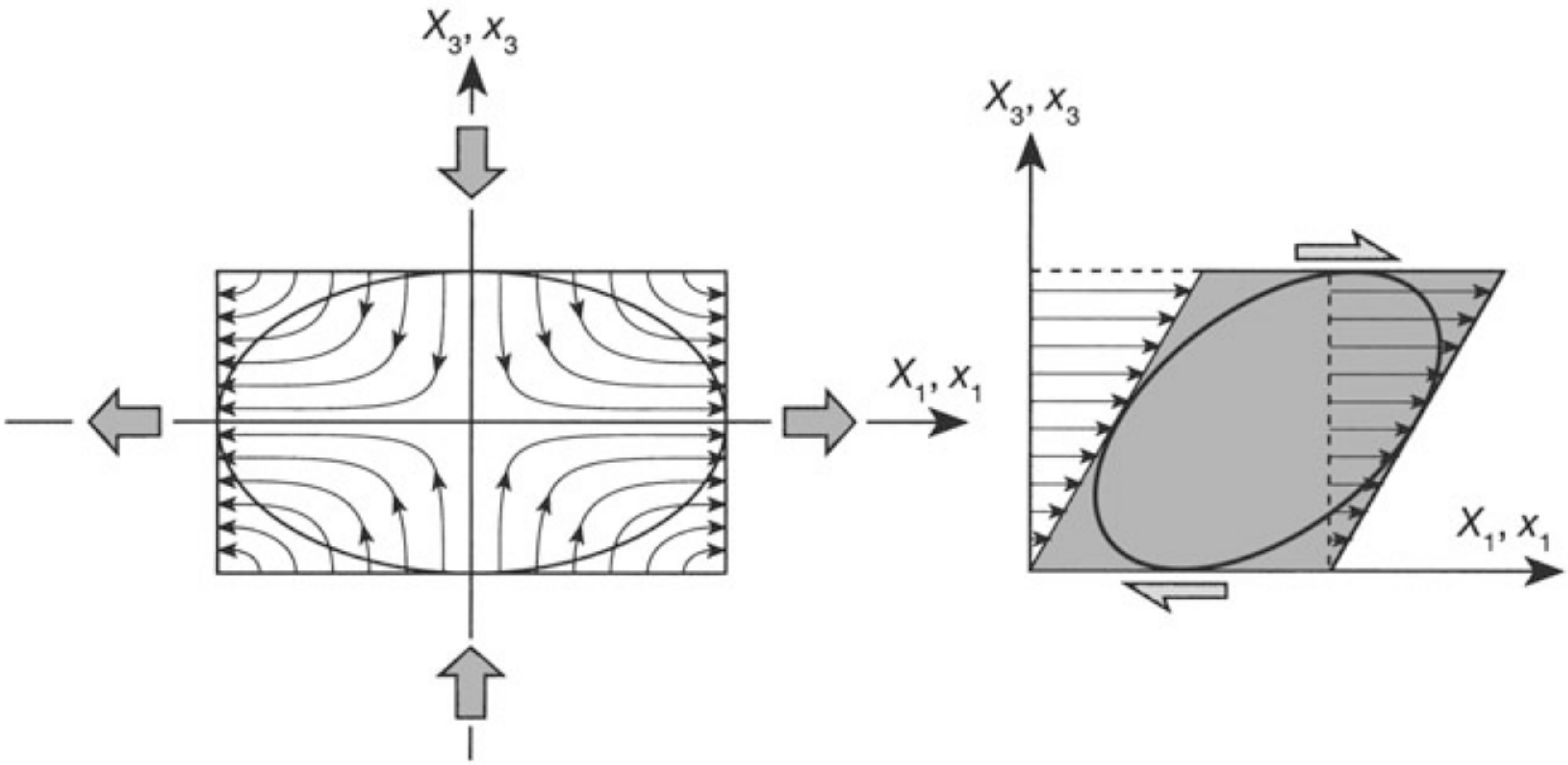
$\gamma = \tan(\psi)$

$\gamma = d / h$



Progressive Deformation (progressive deformation)

Progressive Deformation



A. Progressive pure shear

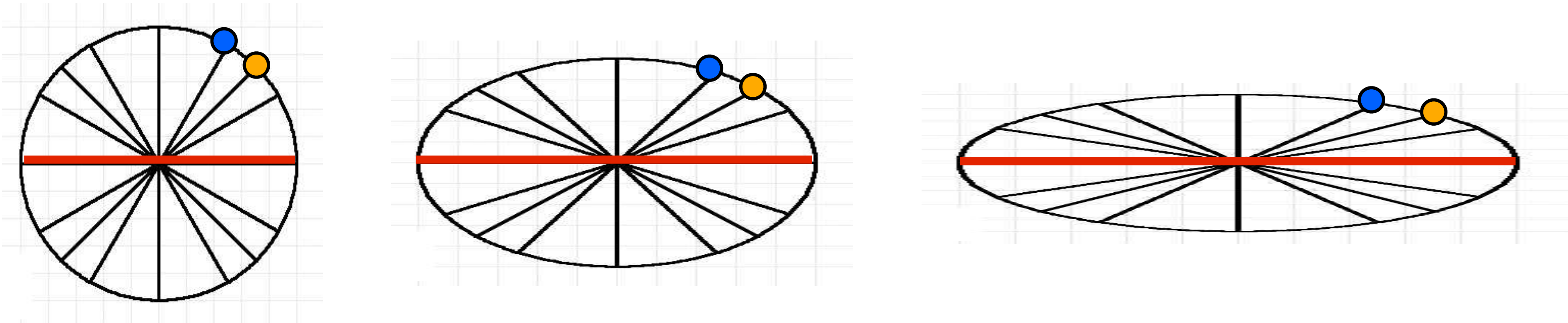
B. Progressive simple shear

Reine Scherung - pure shear

Koachsiale progressive Deformation
(coaxial progressive deformation)

Achsen der Strainellipse

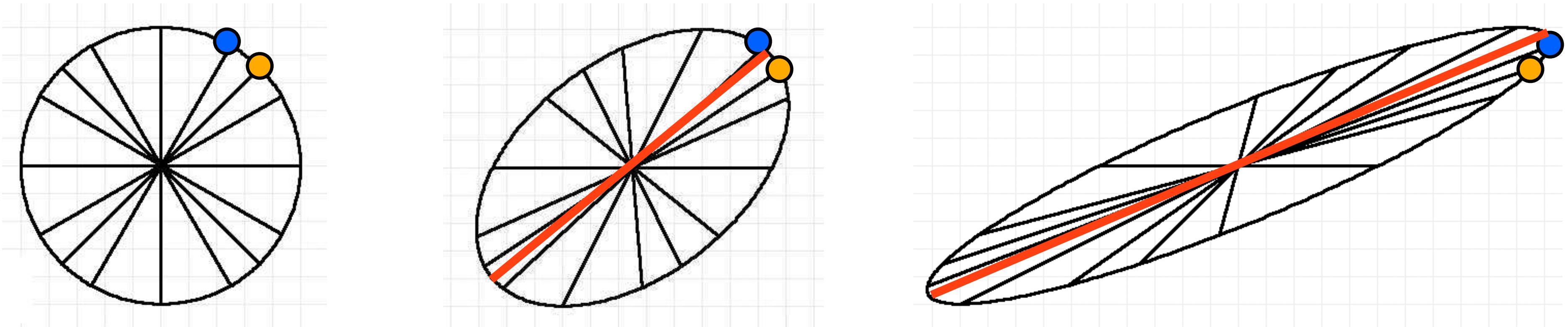
- rotieren nicht
- sind Materiallinien



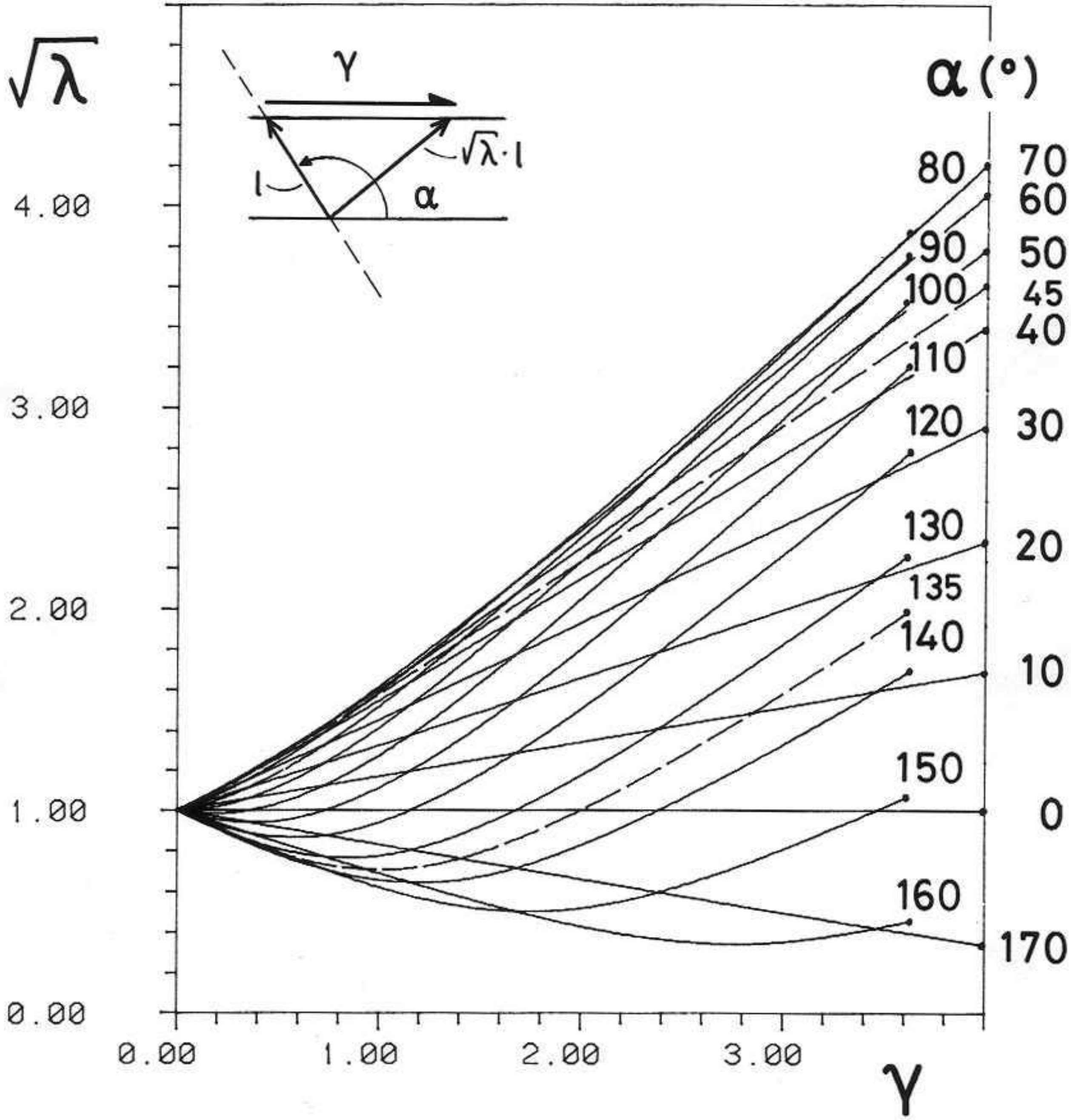
Einfache Scherung - simple shear

Nicht-koachsiale progressive Deformation
(non-coaxial progressive deformation)

Achsen der Strainellipse
- rotieren
- sind keine Materiallinien

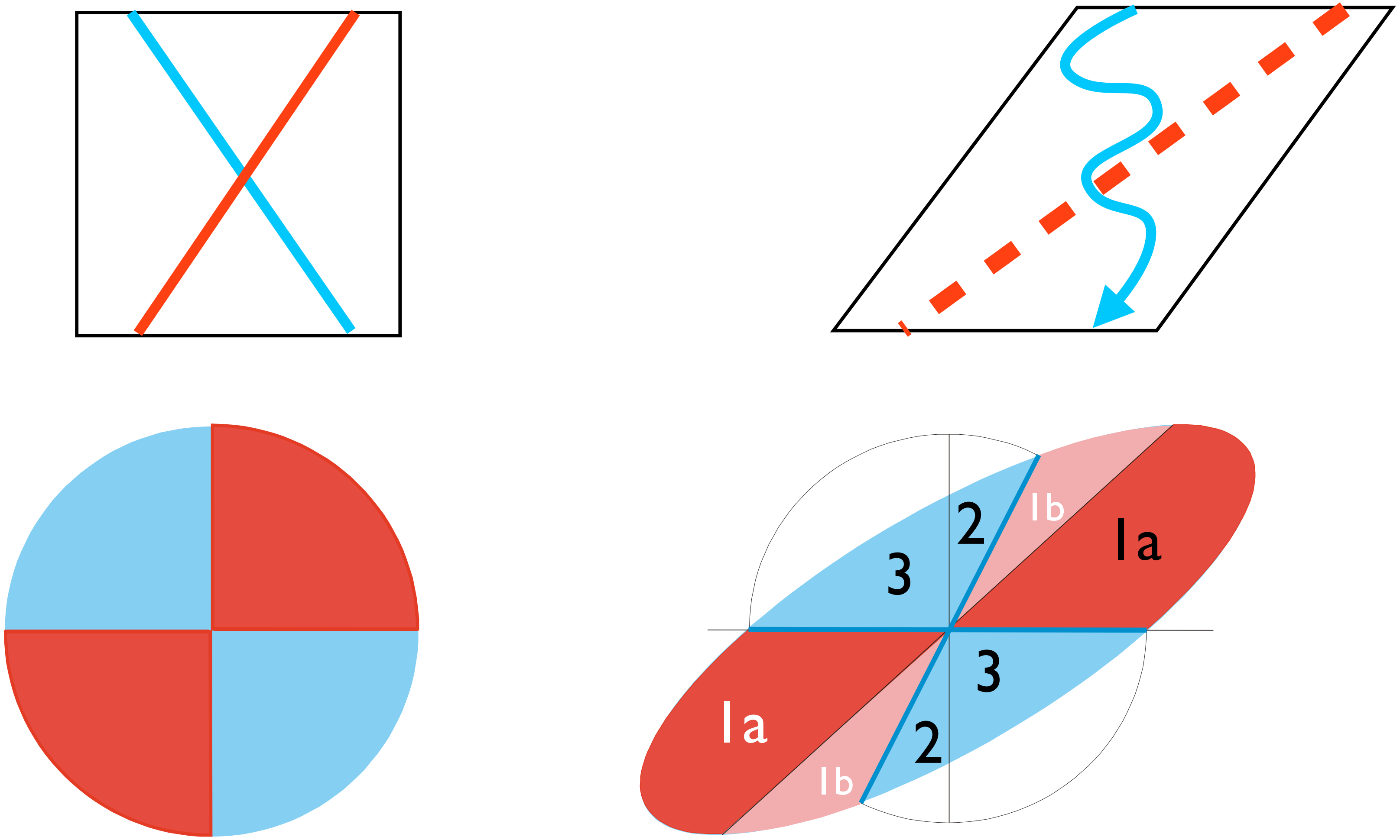


looks familiar



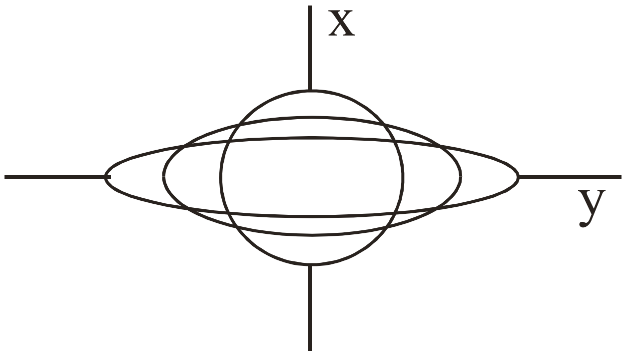
progressive simple shear

finite strain



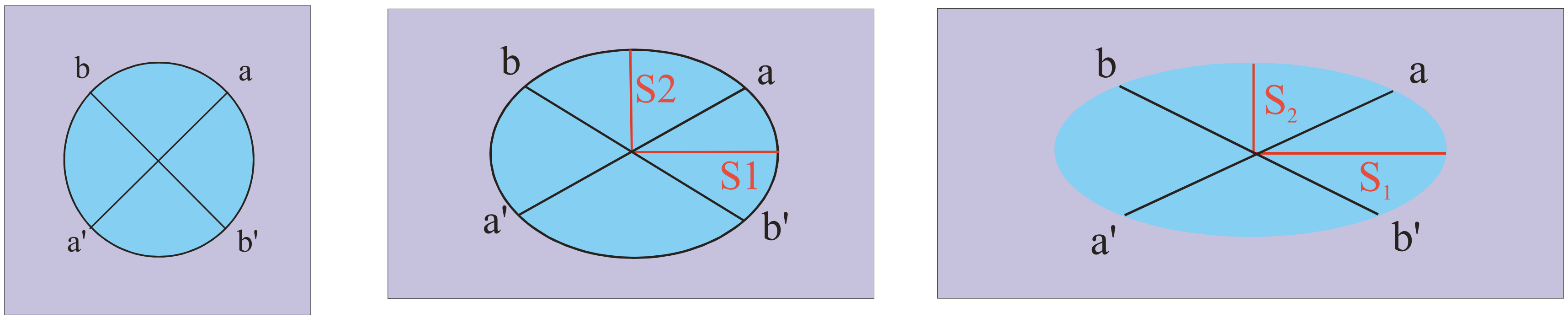
Feld 1a & 1b: Streckung (Boudinage)
Feld 2 & 3 : Stauchung (Falten)

Reine Scherung - pure shear



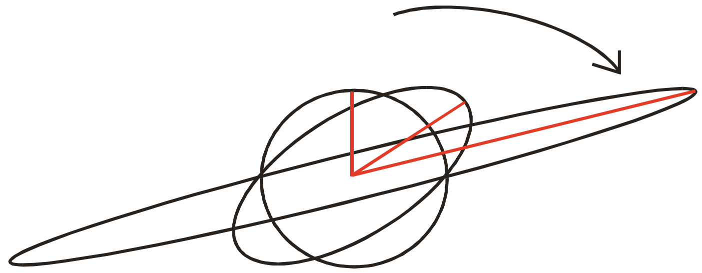
1.) Plättung (flattening)
reine Scherung
(pure shear)

koachsiale progressive Deformation
(coaxial progressive deformation)



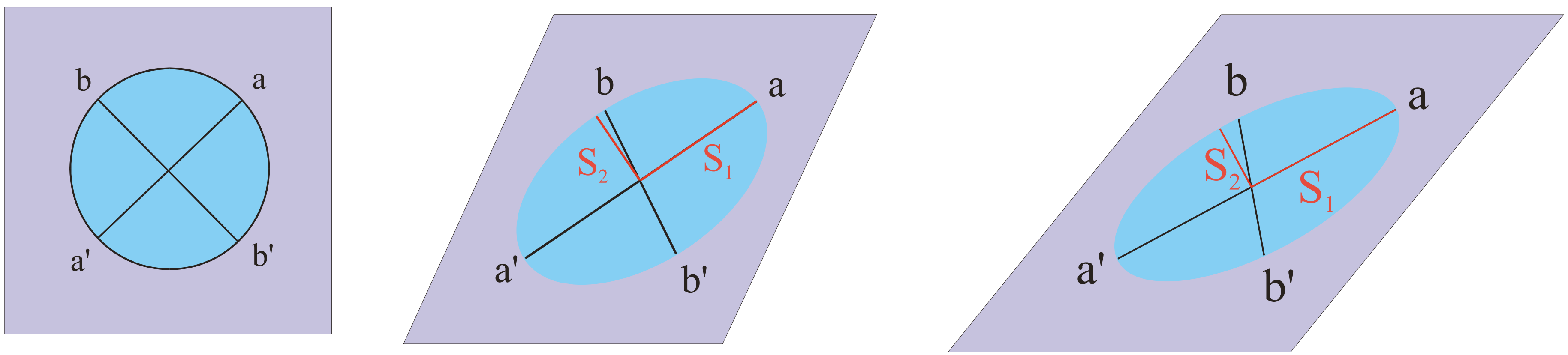
a und b sind Materiallinien, sie bewegen sich in Richtung S_1.
Diese Richtung ist der fabric attractor

Einfache Scherung - simple shear



2.) Scherung
einfache Scherung
(simple shear)

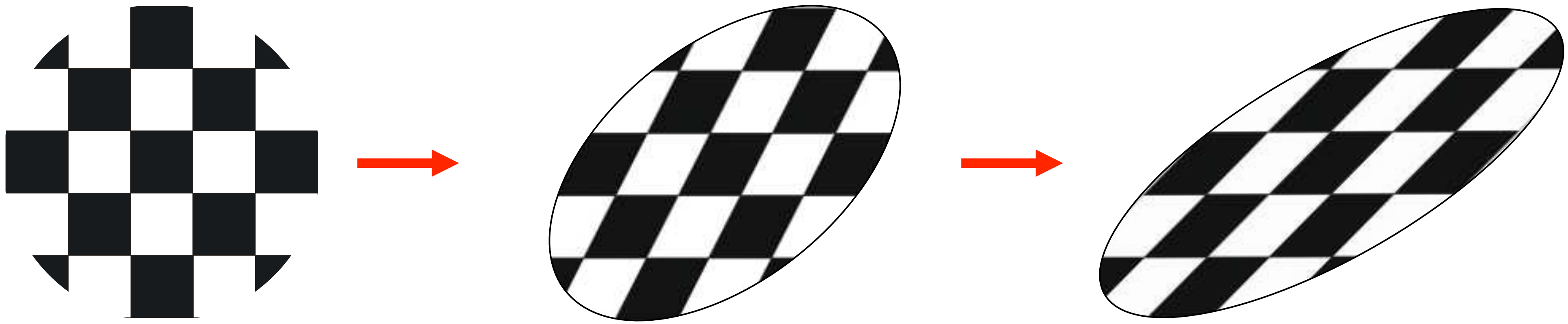
Nicht-koachsiale progressive Deformation
non-coaxial progressive deformation



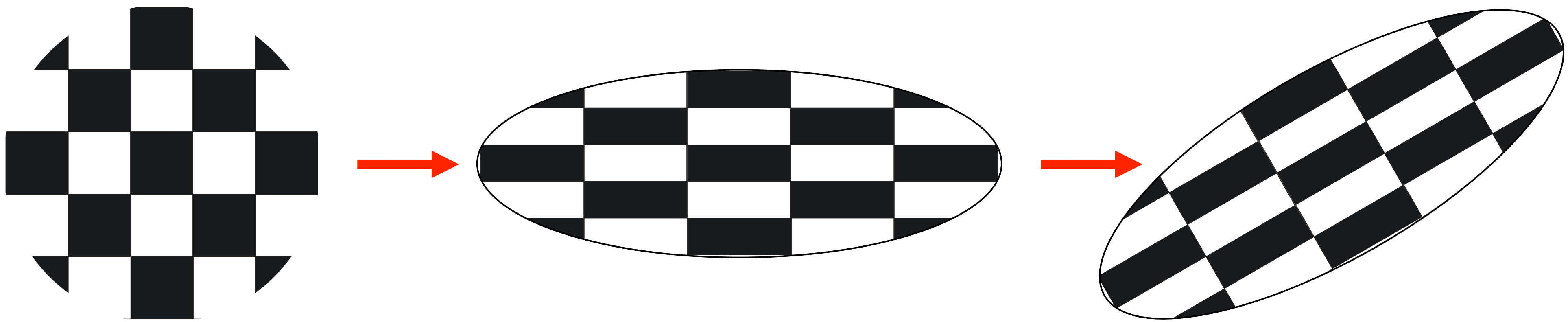
Materiallinie aa‘ wird immer gelängt.
bb‘ wird zuerst verkürzt, dann gelängt

strain ≠ strain history

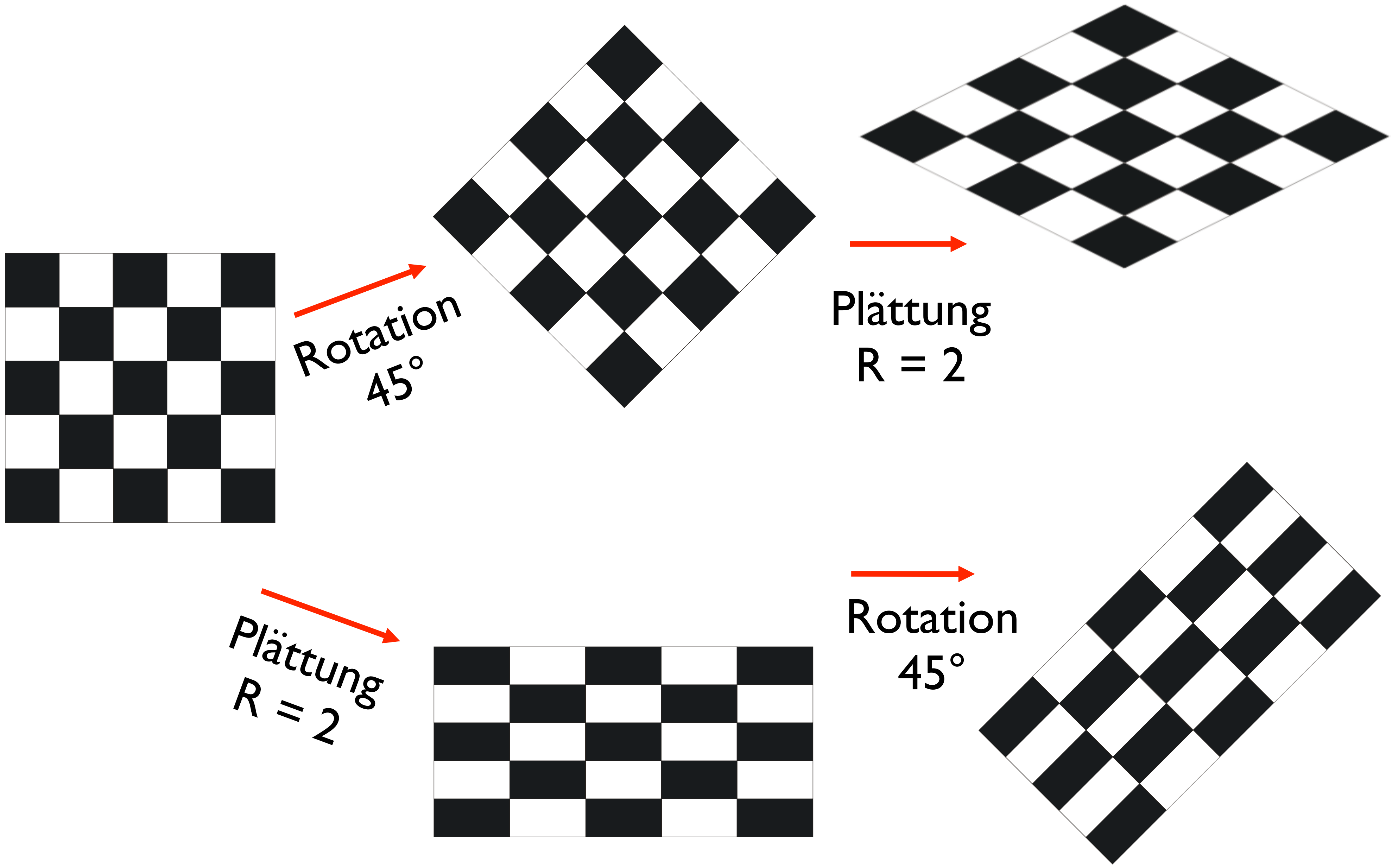
continued simple shear



flattening and rotation



Reihenfolge der Verformung



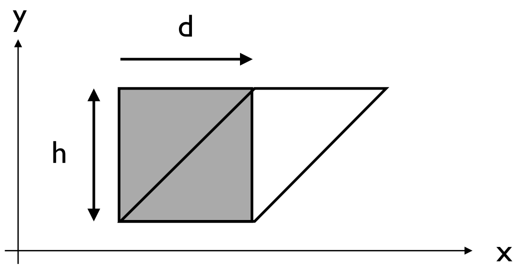
Übung 2
strain

Übung 2

Scherverformung in der Scherbox (simple shear in 2 D)

Ziel dieser Übung ist es, die verschiedenen geometrischen Aspekte der einfachen Scherung (in 2 Dimensionen) kennenzulernen und quantitativ beschreiben zu können. Die Übung kann auf zwei Arten gelöst werden: durch Messen oder durch Rechnen.

Einfache Scherung wird wie folgt beschrieben:



$\Upsilon = d / h$
wo d = Versetzungsbetrag und h = Höhe des gescherten Körpers.

Das Experiment

Ein Stapel Computerkarten wird geschert (diese Karten existieren in der Tat immer noch - sie sind im Übungsraum zusammen mit einer real existierenden Scherbox zu finden).

Auf den Karten ist seitlich ein Einheitskreis (Radius = 1.00) aufgemalt, sowie 8 Durchmesser in den Orientierungen 0°, 30°, 45°, 60°, 90°, 120°, 135°, 150°.

Das Resultat des Scherexperimentes ist auf der beigelegten Abbildung dargestellt:

1 - Unverformter Zustand
2 - $\Upsilon = 0.5$
3 - $\Upsilon = 1.0$
4 - $\Upsilon = 2.0$
5 - $\Upsilon = 3.0$

Der Kreis verformt sich zu zunehmend schlankeren Ellipsen (= Verformungsellipsen), die verschiedenen Durchmesser werden länger oder kürzer und ändern die Orientierung.

Aufgaben

1. Bestimmen Sie den Scherwinkel, Ψ, in den 4 Verformungsschritten. Beschreiben Sie das Vorgehen.

2. Schreiben Sie die Gleichungen der Koordinaten-Transformation für $\Upsilon = 0.5, 1.0, 2.0, 3.0$.

3. Bestimmen sie die Extension, e, und die Orientierung, ϕ, der eingezeichneten Durchmesser (A-A', B-B', etc.) bzw. der Radien (0-A', 0-B', etc.) in den 4 Verformungsschritten.

   $\Delta L = L - L_0$
   $e = \Delta L / L_0$
   wo L_0 = ursprüngliche Länge und L = verformte Länge

   Die Radius des ursprünglichen Kreises ist = 1.00. Sie können nun entweder alle Durchmesser oder Radien messen oder die Koordinaten der verformten Radiusvektoren berechnen und daraus die verformte Länge gewinnen. Dazu nehmen Sie am besten an, dass sich der Koordinatenursprung immer im Mittelpunkt der Ellipsen befindet.
   Welches Vorgehen wählen Sie? Beschreiben Sie es.

4. Stellen Sie die Extension, e, und die Orientierung, ϕ, der Linien A-A', B-B' etc. als Funktion von Υ dar (2 separate Diagramme) und kommentieren Sie. Welche Linien, d.h. welche ursprünglichen Orientierungen, werden kürzer, welche werden länger ? Wie schnell rotieren sie?

4*. Finden Sie die mathematische Gleichung, welche die Extension, e, und die Orientierung, ϕ, einer gescherten Geraden in Abhängigkeit der Scherung, Υ, und der ursprünglichen Orientierung, ϕ_0, der Geraden beschreibt.

5. Zeichnen Sie die lange Achse, a, und die kurze Achse, b, der Ellipsen ein, messen Sie die Längen a und b, berechnen Sie das Achsenverhältnis, R_f ($R_f = a/b$), und bestimmen Sie die Orientierung, ϕ, der langen Achse.

   Tragen Sie die Resultate in den entsprechenden Diagramme der Aufgabe 4 ein.

6. Vergleichen Sie die Sie Rotation der langen Ellipsenachse mit der Rotation der gescherten Durchmesser. Zeichnen Sie die Lagen der langen und kurzen Achsen auf den Verformungsellipsen im ursprünglichen Einheitskreis ein. Kommentieren sie. Sind zusammengehörige Achsen senkrecht aufeinander ? Sind die Ellipsenachsen Materiallinien ?

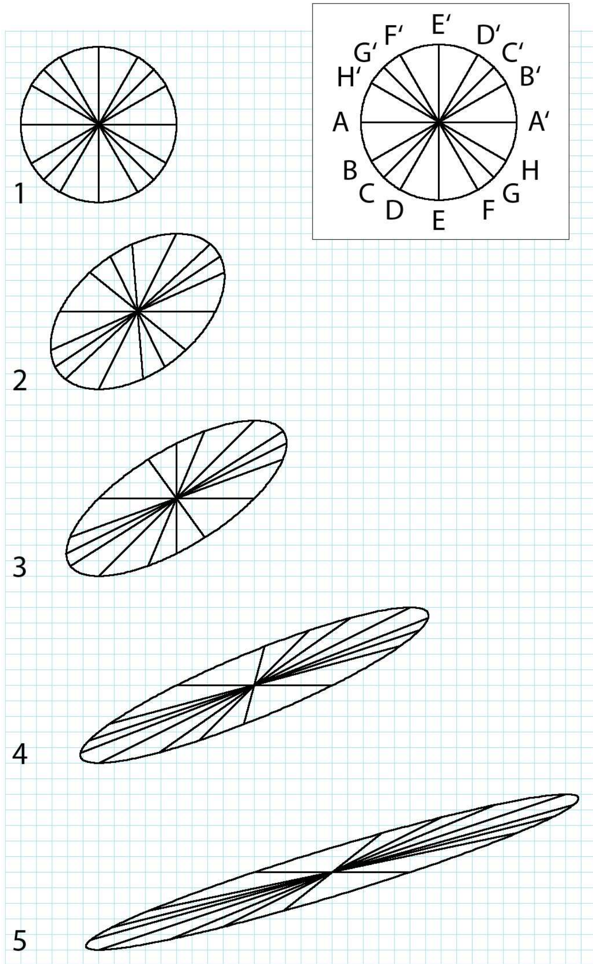
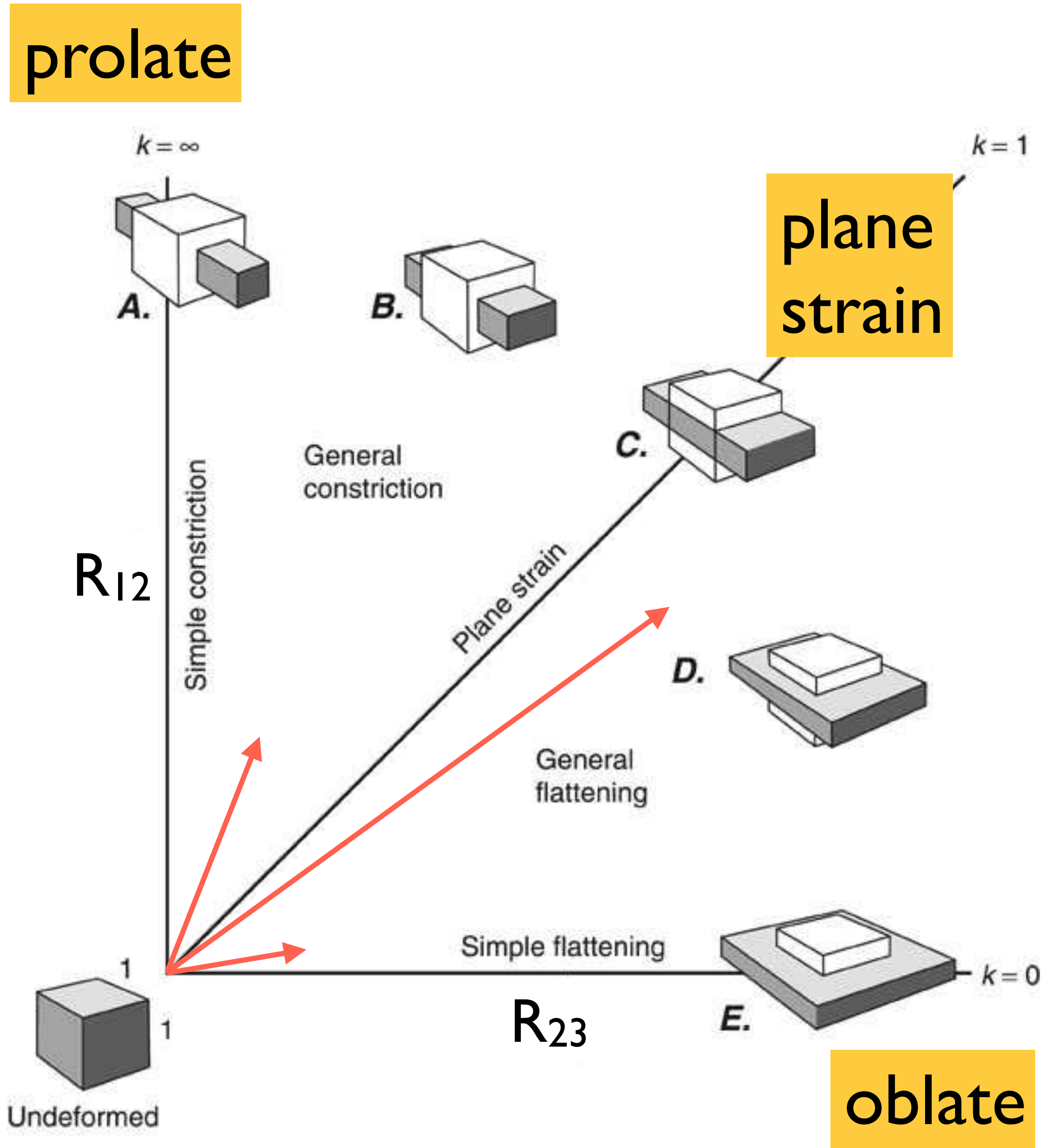


Abbildung: Resultat des Scherexperimentes

Flinn Diagramm (strain types)

Flinn - Diagramm



$k = (R_{12} - 1) / (R_{23} - 1)$

$R_{12} = (1+e_1)/(1+e_2)$

$R_{23} = (1+e_2)/(1+e_3)$

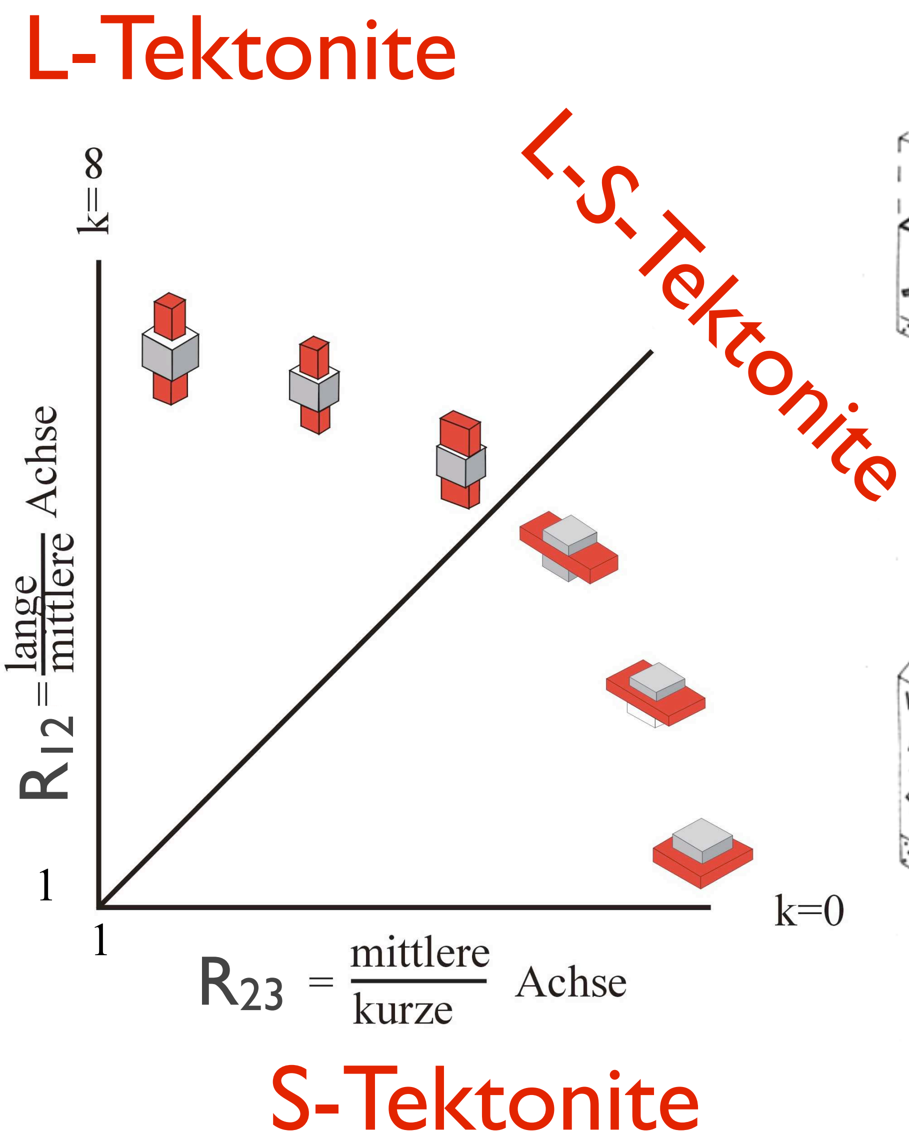
symmetrische Streckung
constrictional strain
$k = \infty \Rightarrow e_2 = e_3 < e_1$

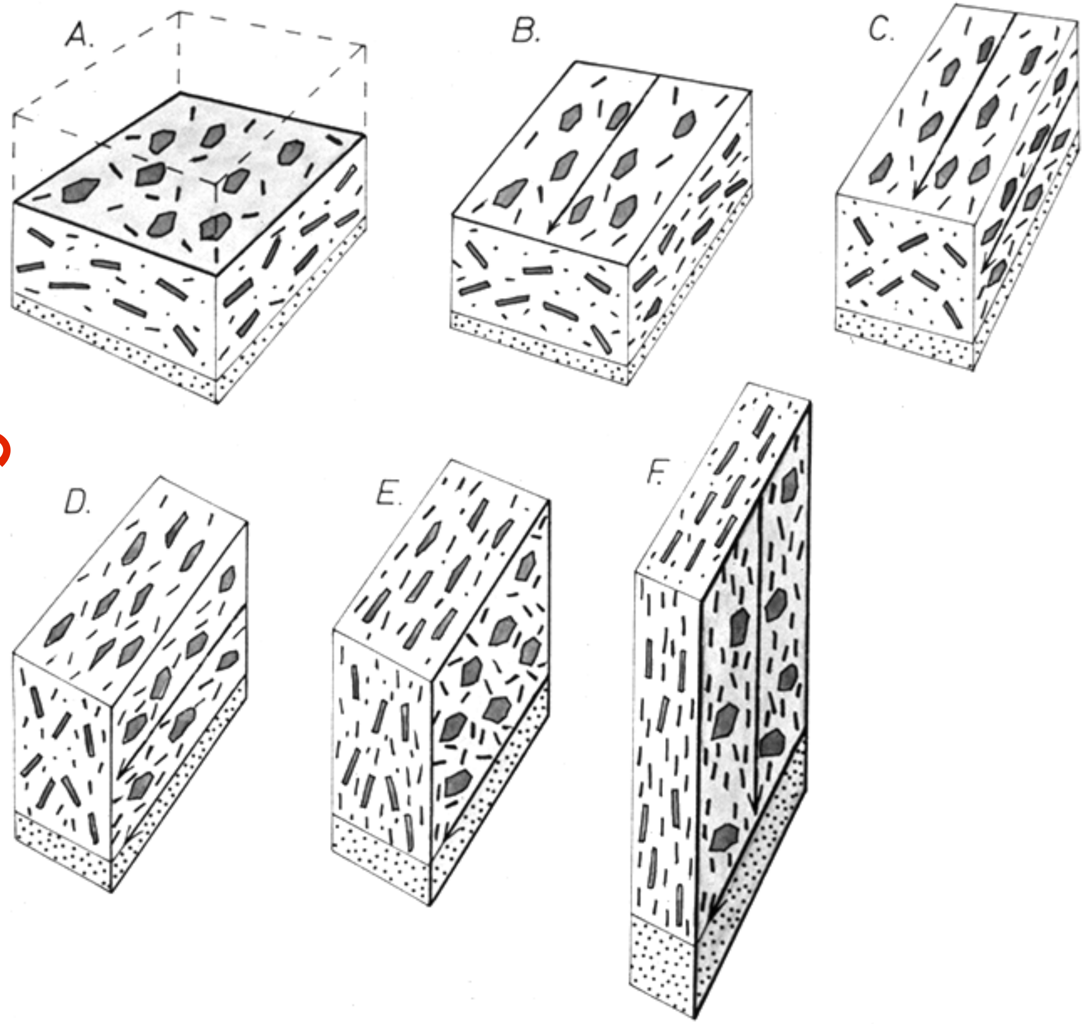
plane strain
$k = 1 \Rightarrow e_2 = 0$

symmetrische Plättung
flattening strain
$k = 0 \Rightarrow e_1 = e_2 > e_3$

ε_s = strain magnitude

Flinn - Diagramm



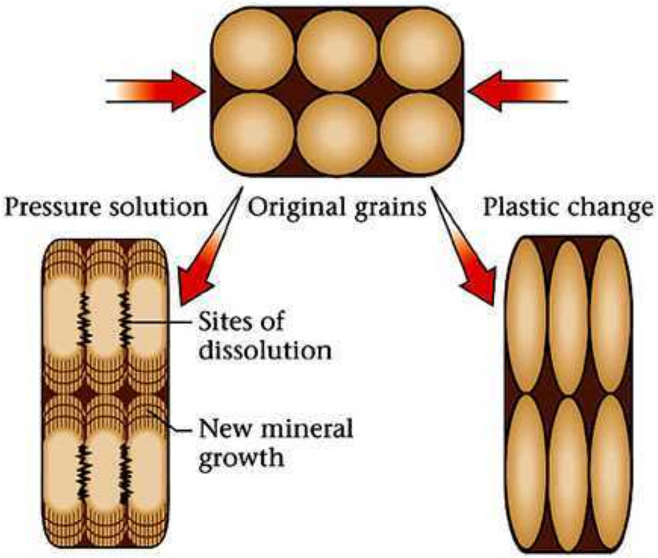


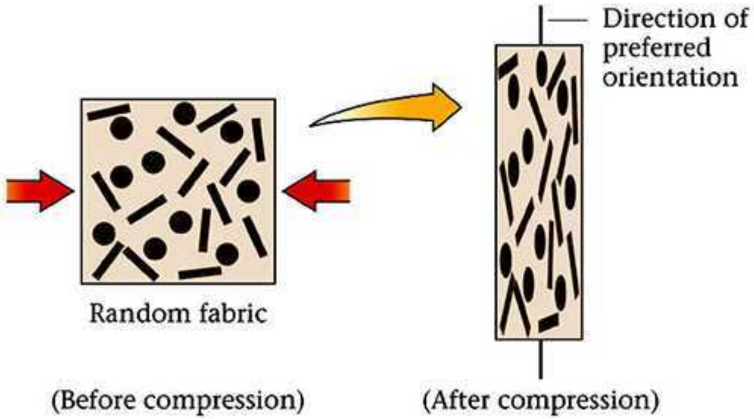
Deformation:

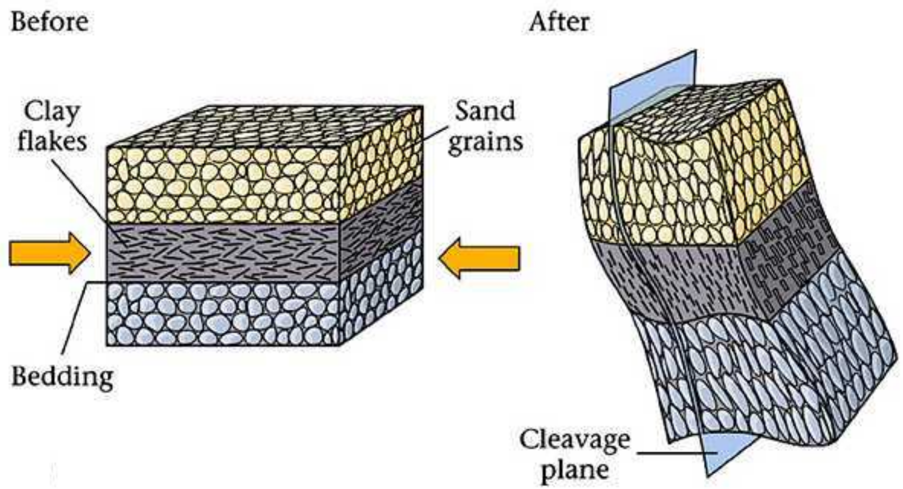
➠ strain

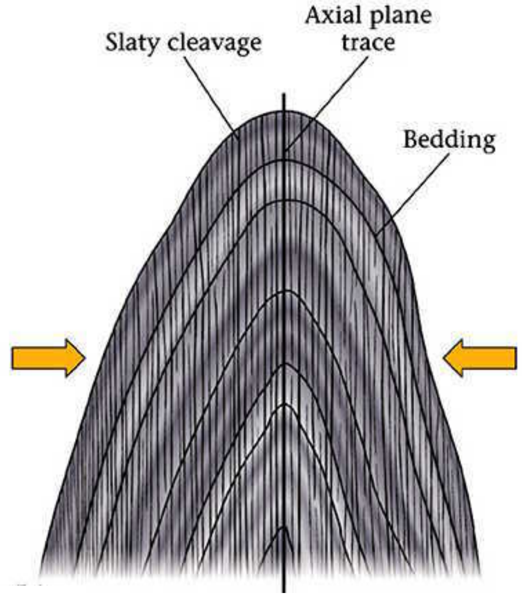
(strain marker !)

➠ foliation

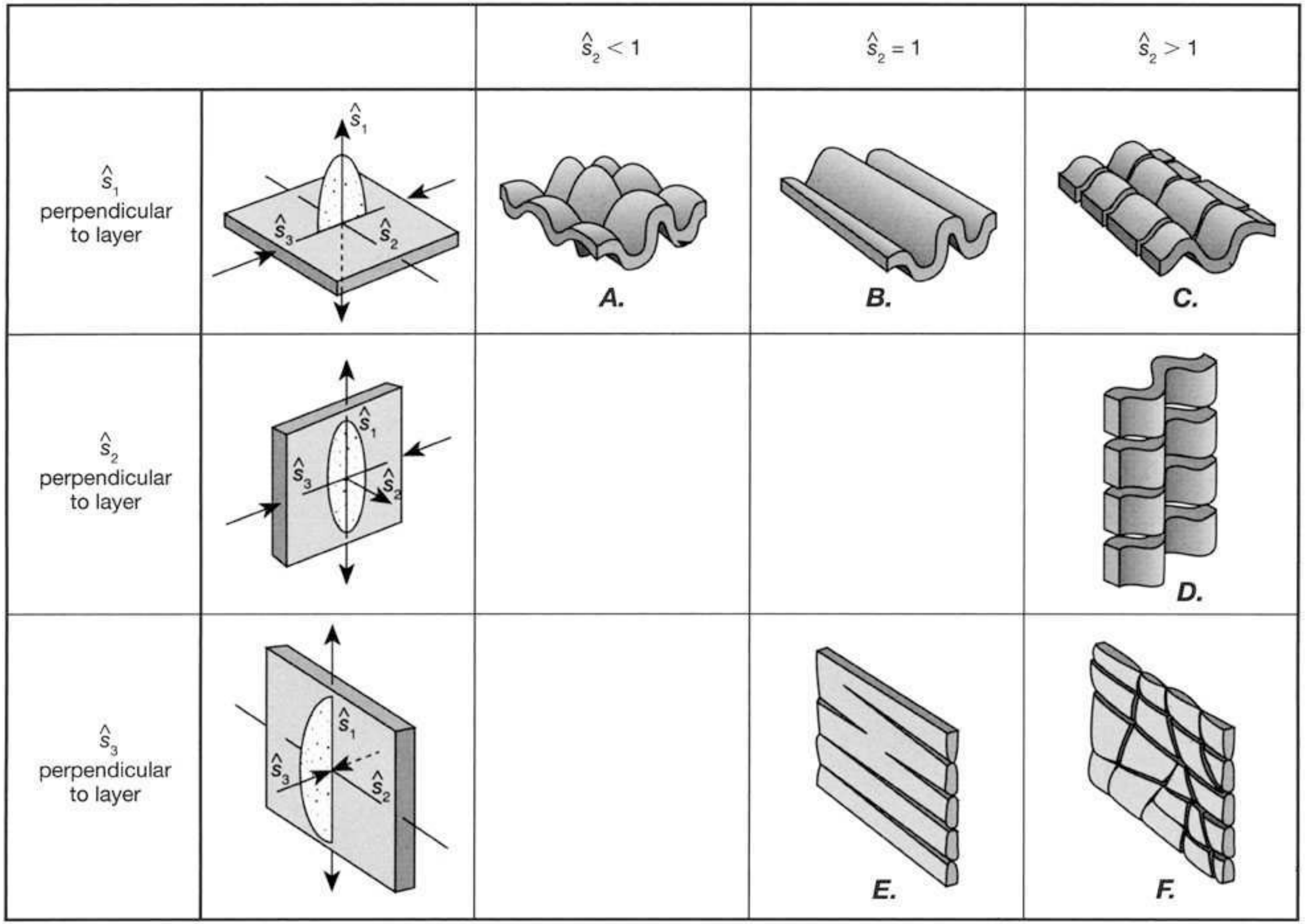






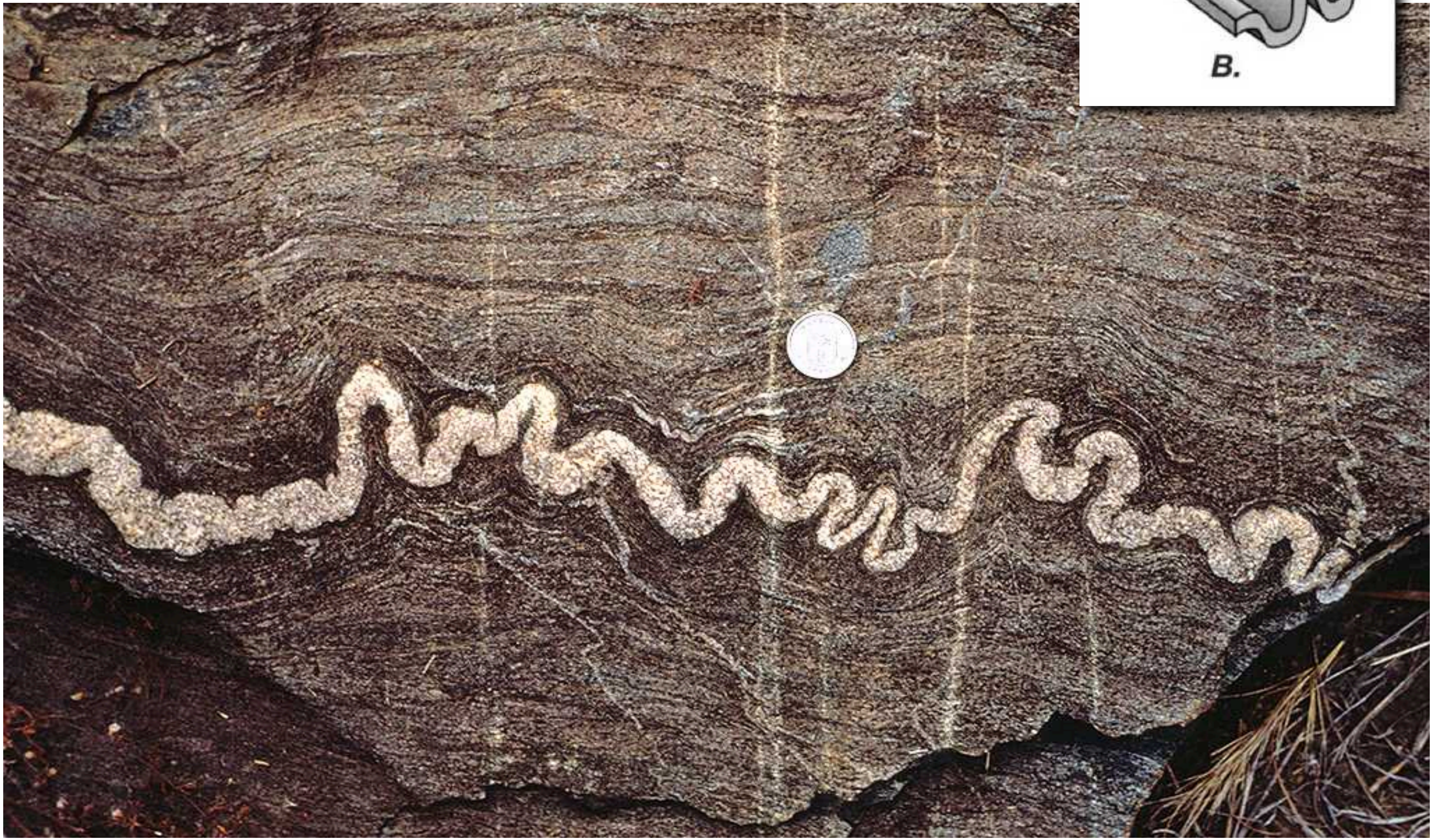


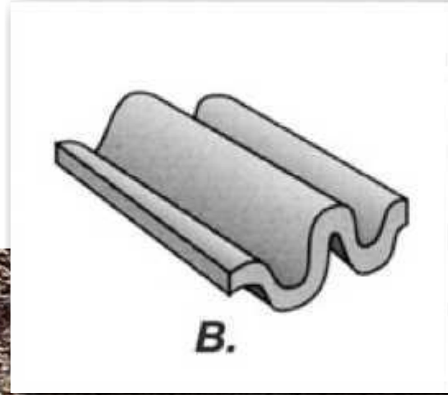
➠ shortening and extension in layers



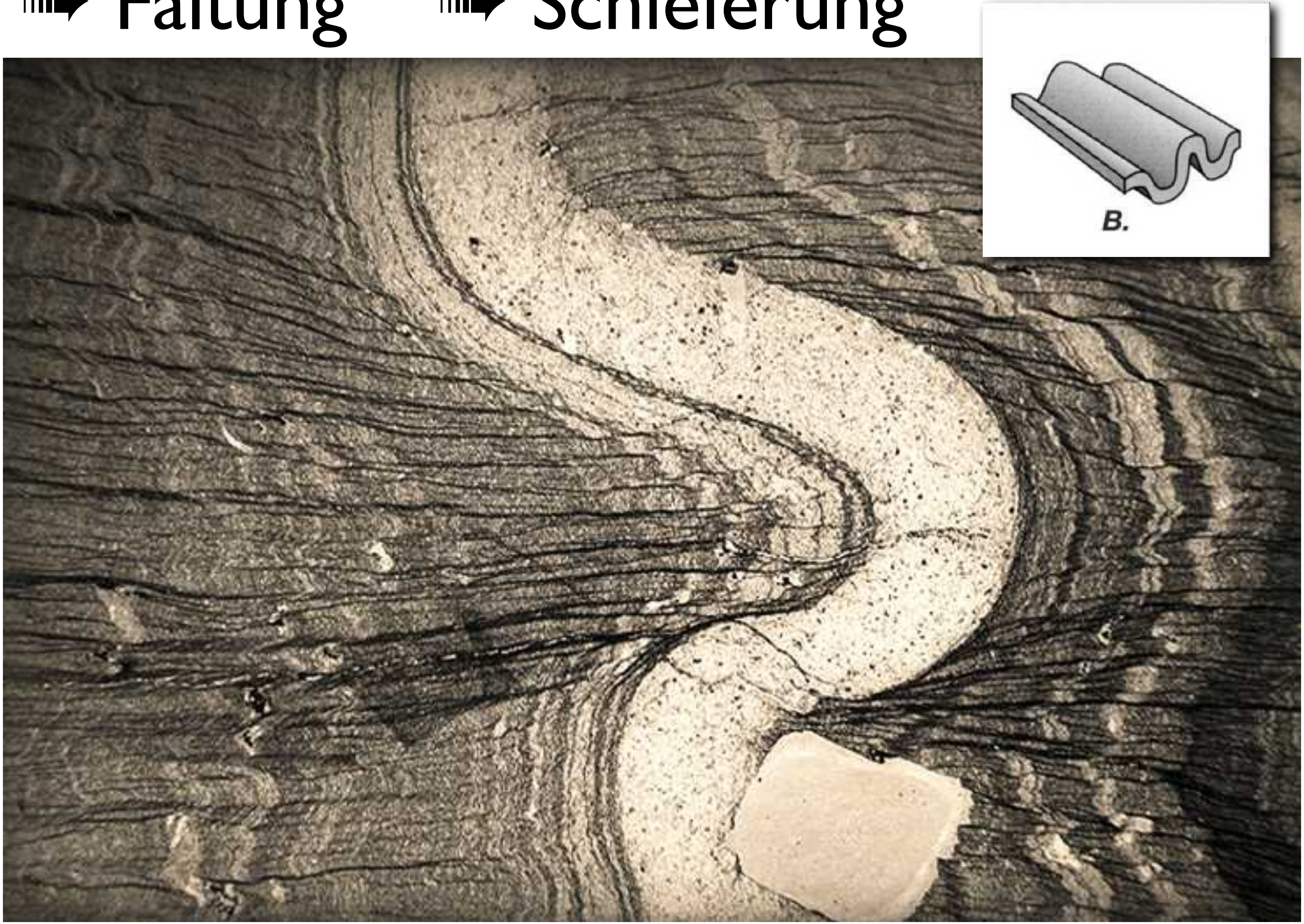
Verkürzung - Falten
Streckung - Boudinage

Verkürzung:
➠ Ptygmatische Faltung

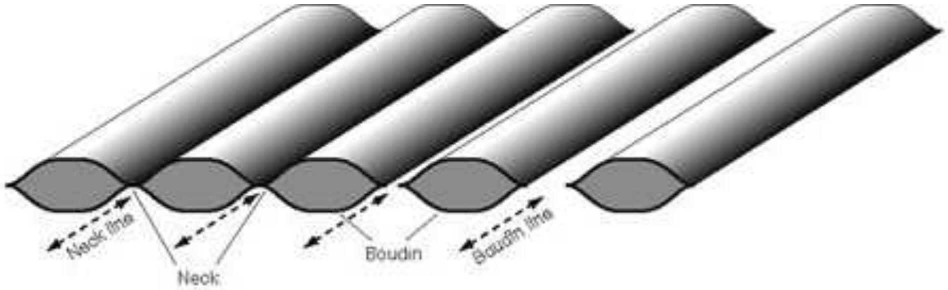


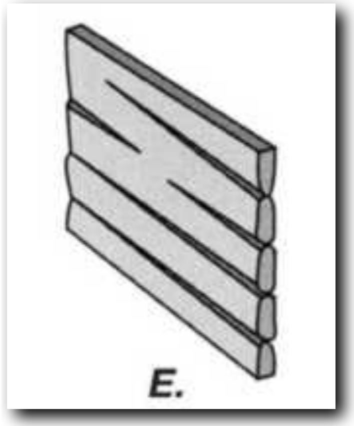


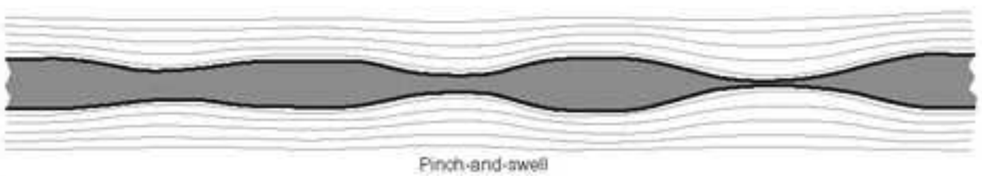
➠ Faltung ➠ Schieferung

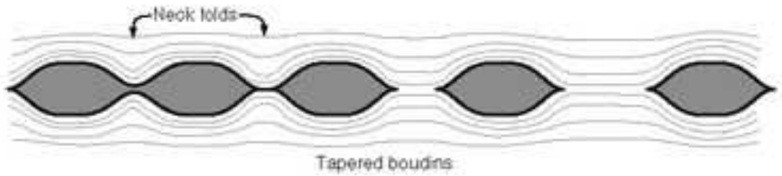


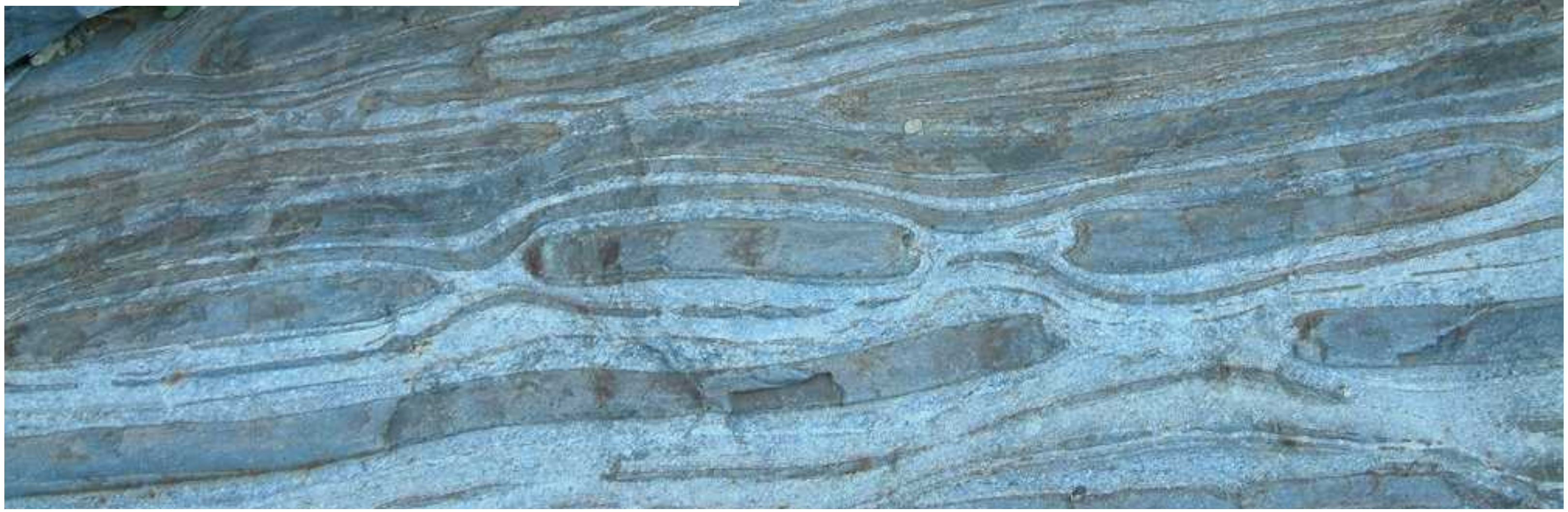
Boudinage


Neck line
Neck
Boudin
Boudin line

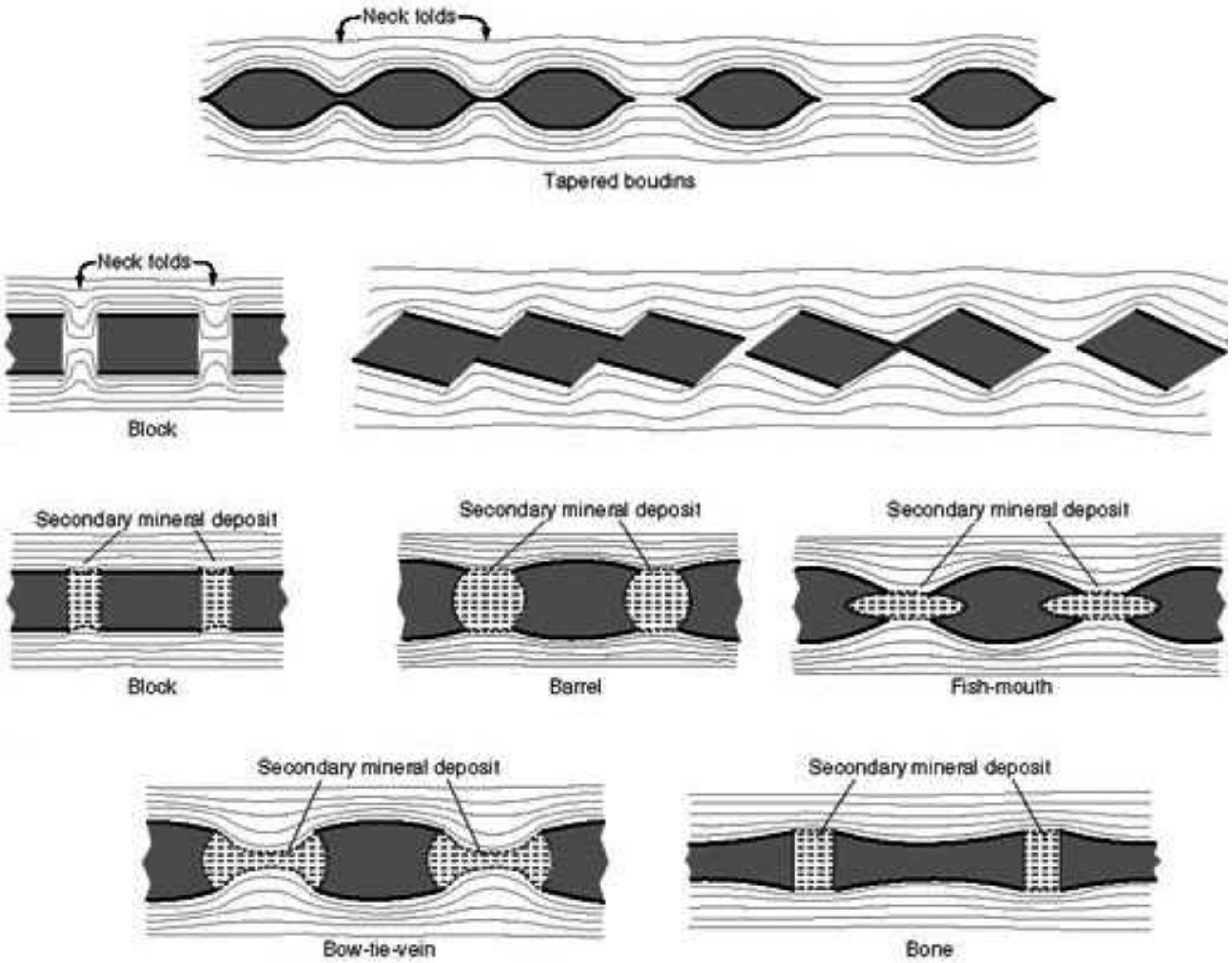

E.

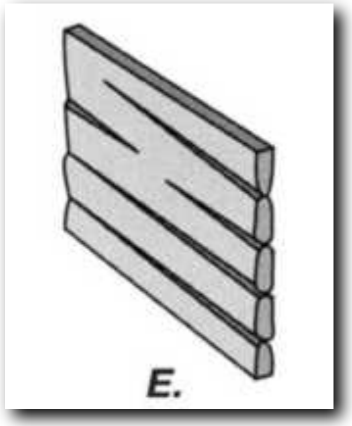

Pinch-and-swell


Neck folds
Tapered boudins

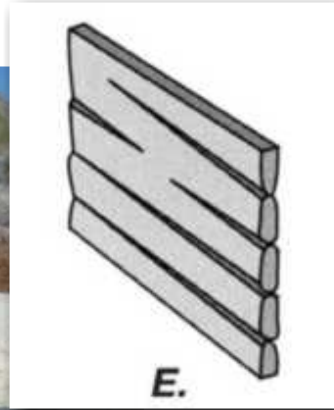


Boudinage

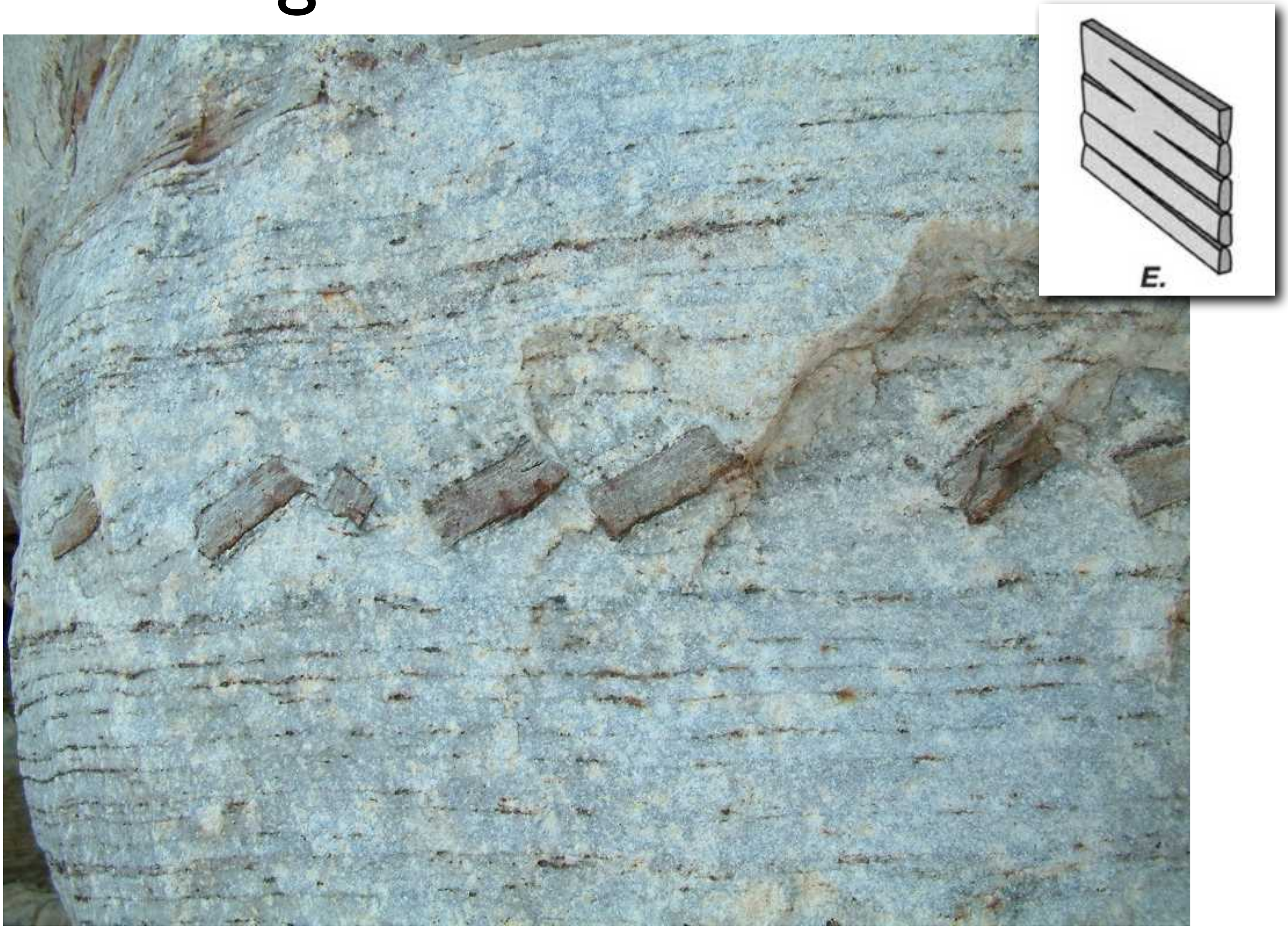

Neck folds
Tapered boudins
Neck folds
Block
Secondary mineral deposit
Block
Secondary mineral deposit
Barrel
Secondary mineral deposit
Fish-mouth
Secondary mineral deposit
Bow-tie-vein
Secondary mineral deposit
Bone


E.

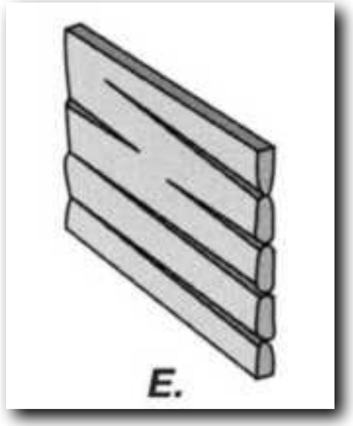
Boudinage



Boudinage

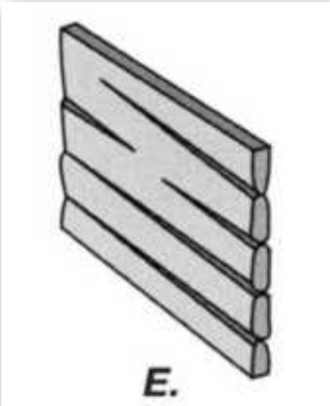


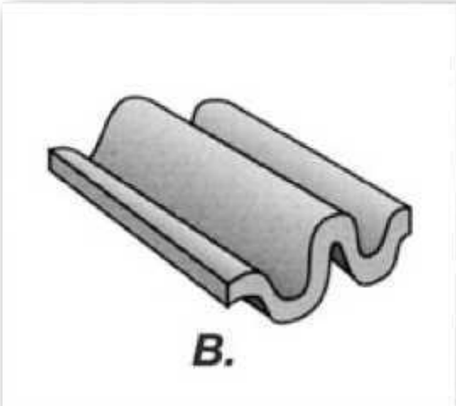
Boudinage

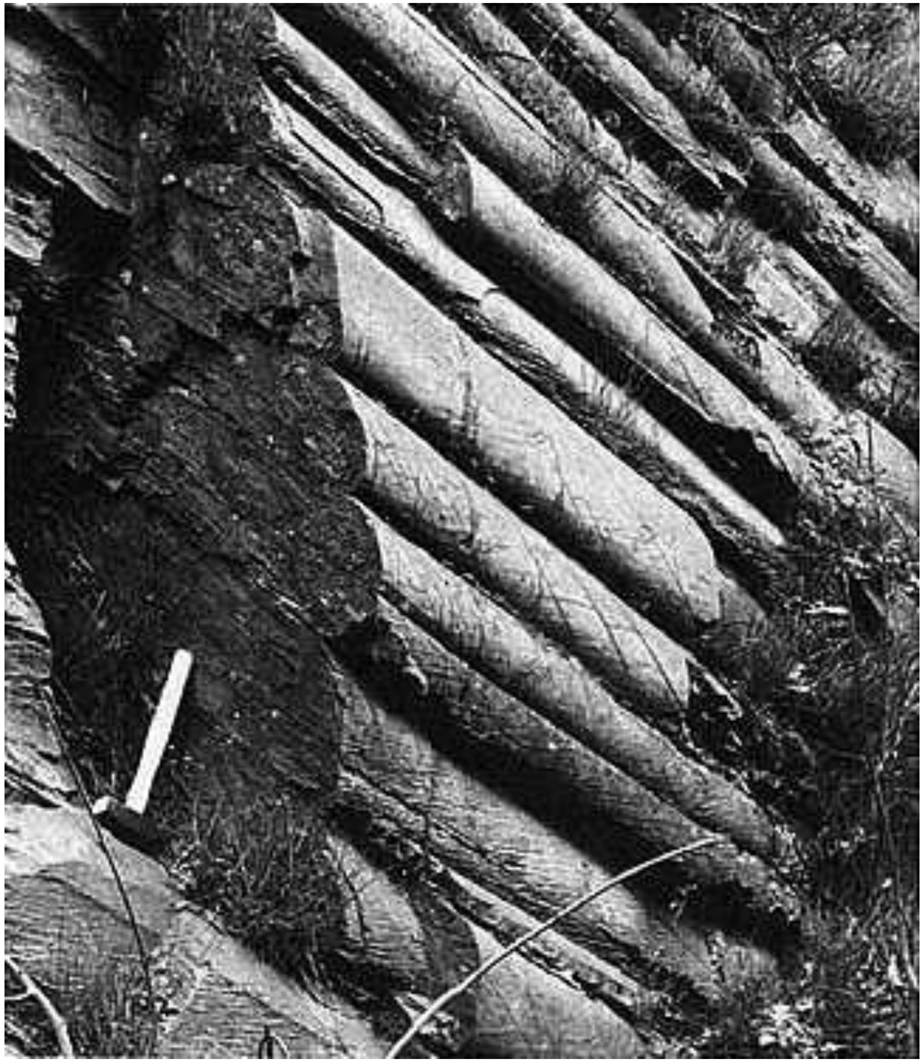


Boudinage

Mullionstrukturen (mullions)







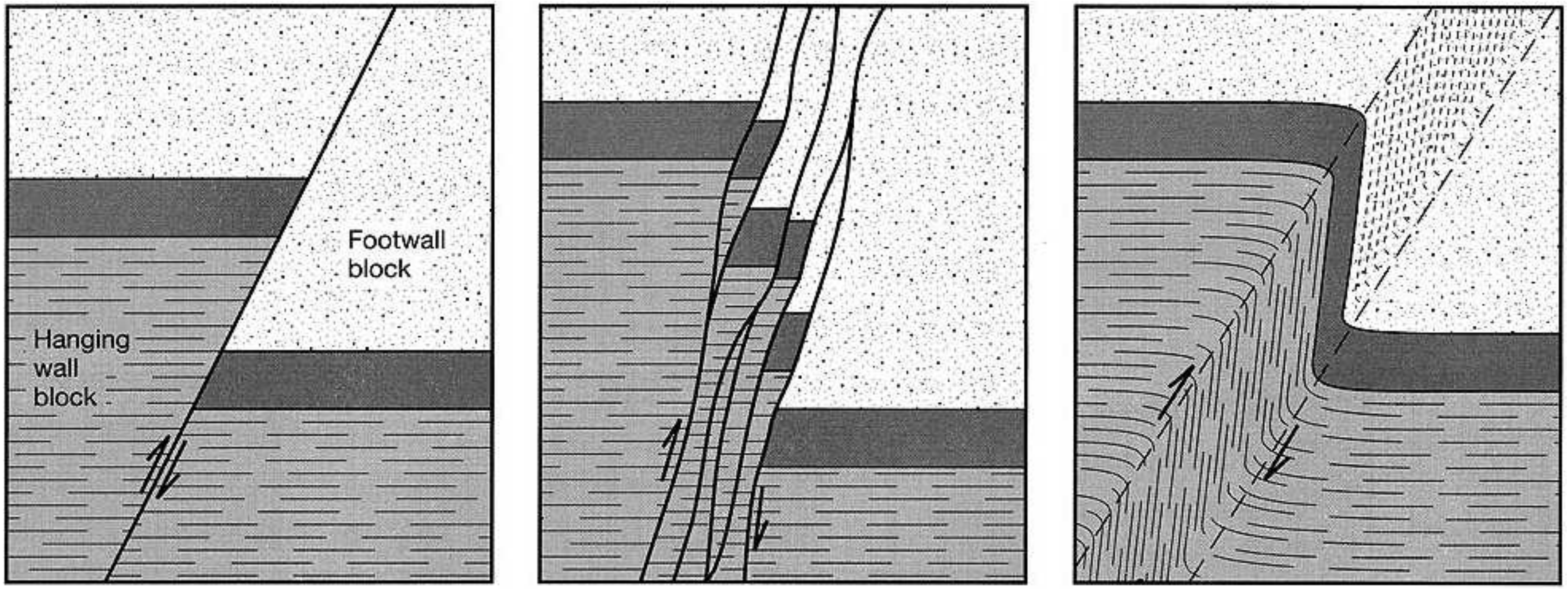
'chocolate tablet structure'

Scherung - Scherzonen

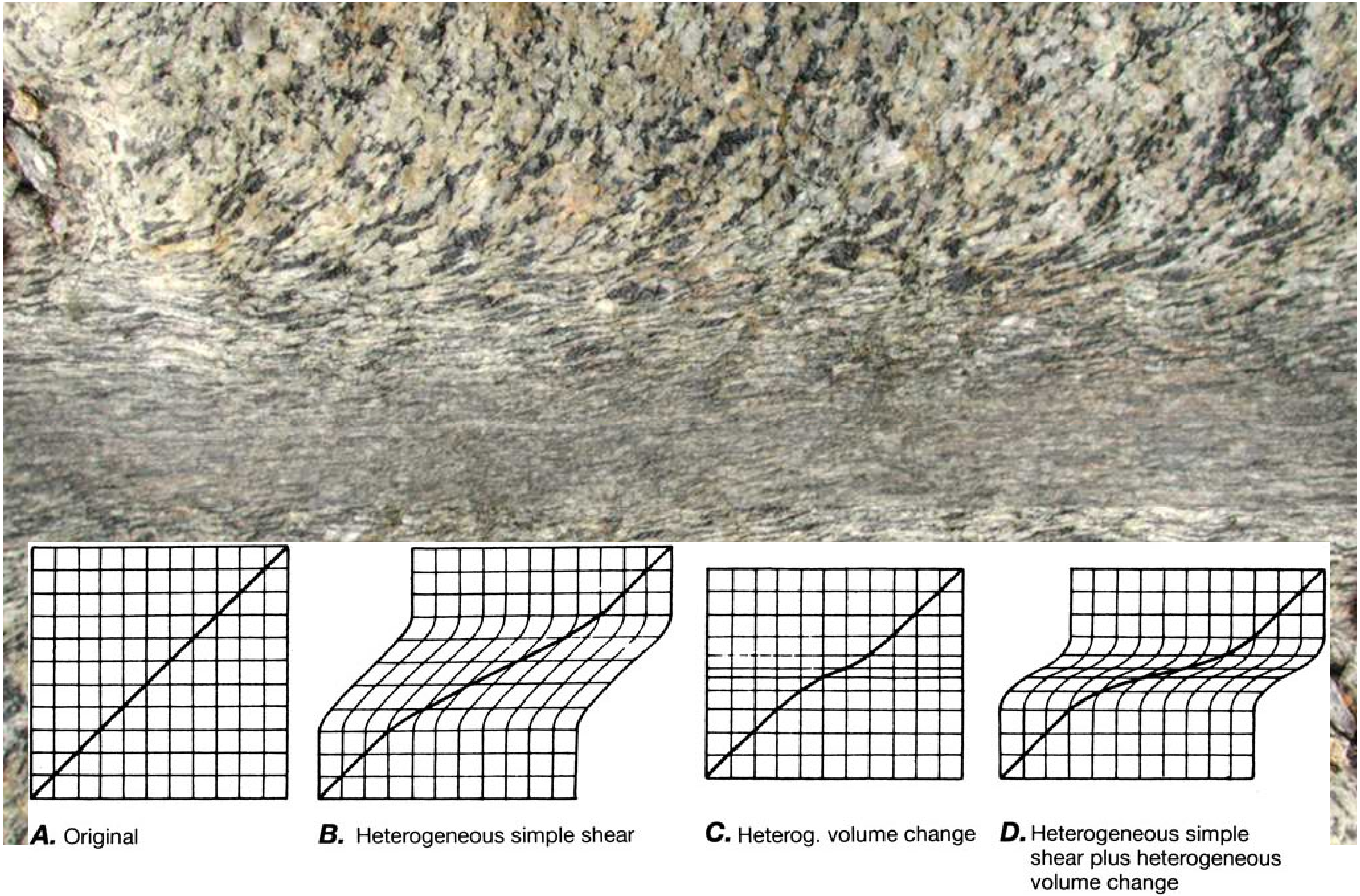
Scherverformung

spröd
duktil

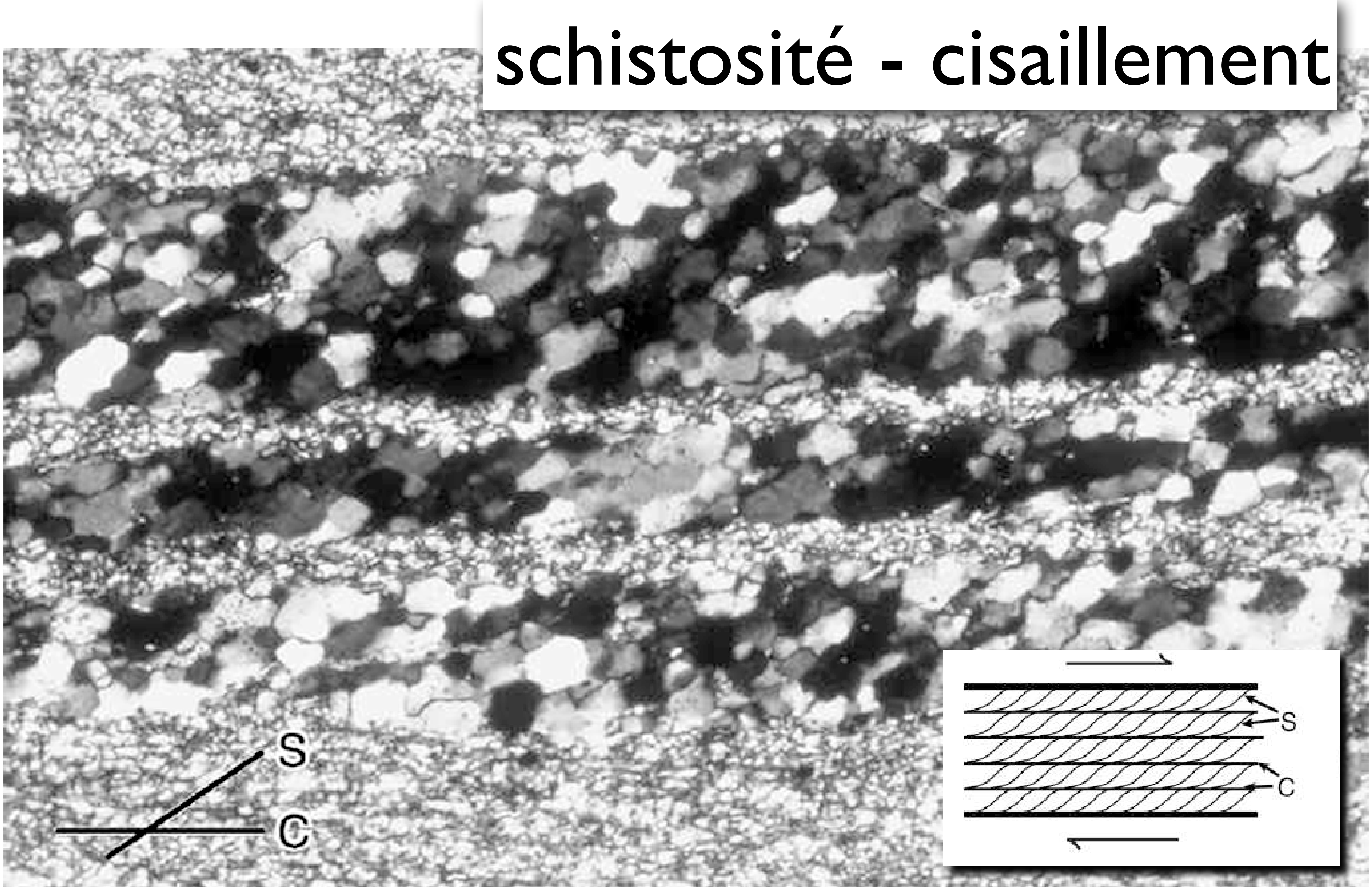
lokalisiert
homogen



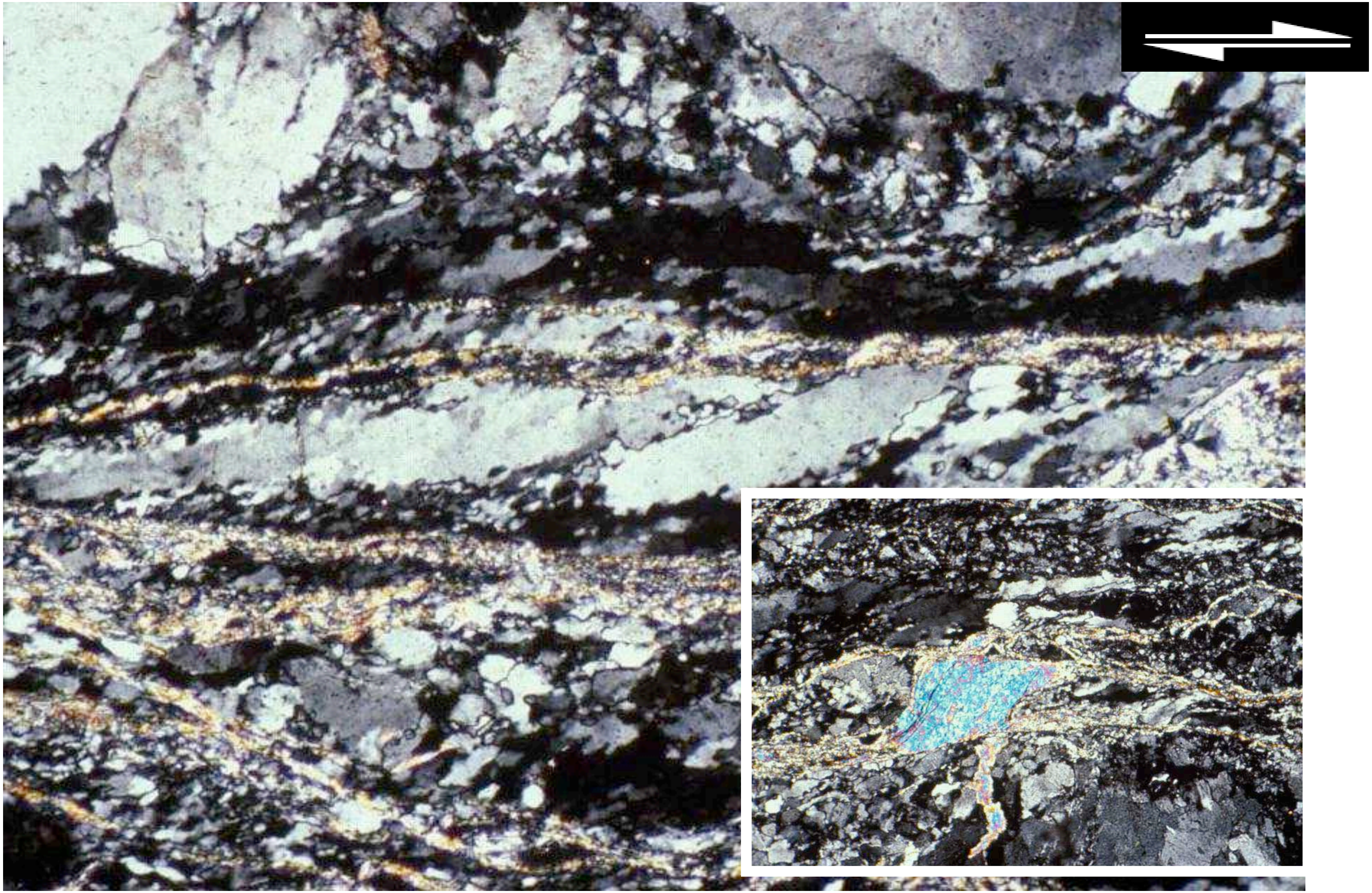
Schersinn: Duktile Scherzonen



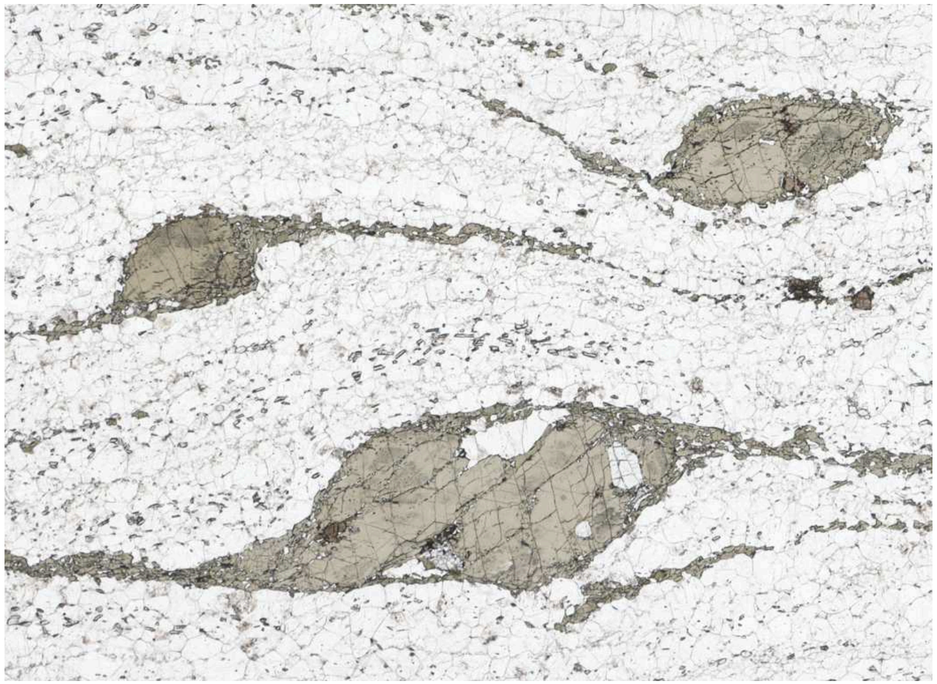
Schersinn: S - C - Gefüge



Schersinn - Kriterien



Schersinn - Kriterien



Verformungsmarker
(strain marker)

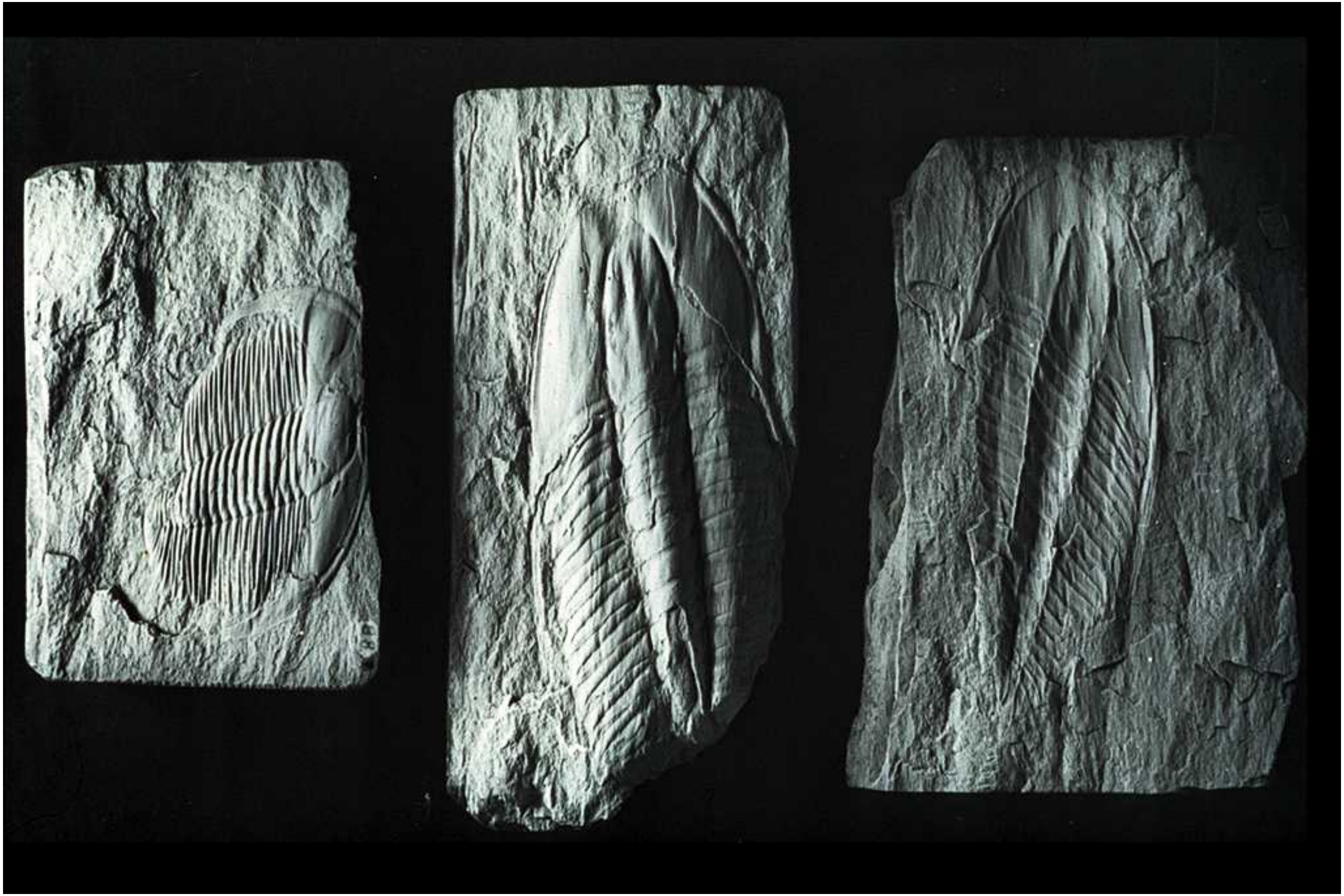
deformed pebbles

deformed pebbles

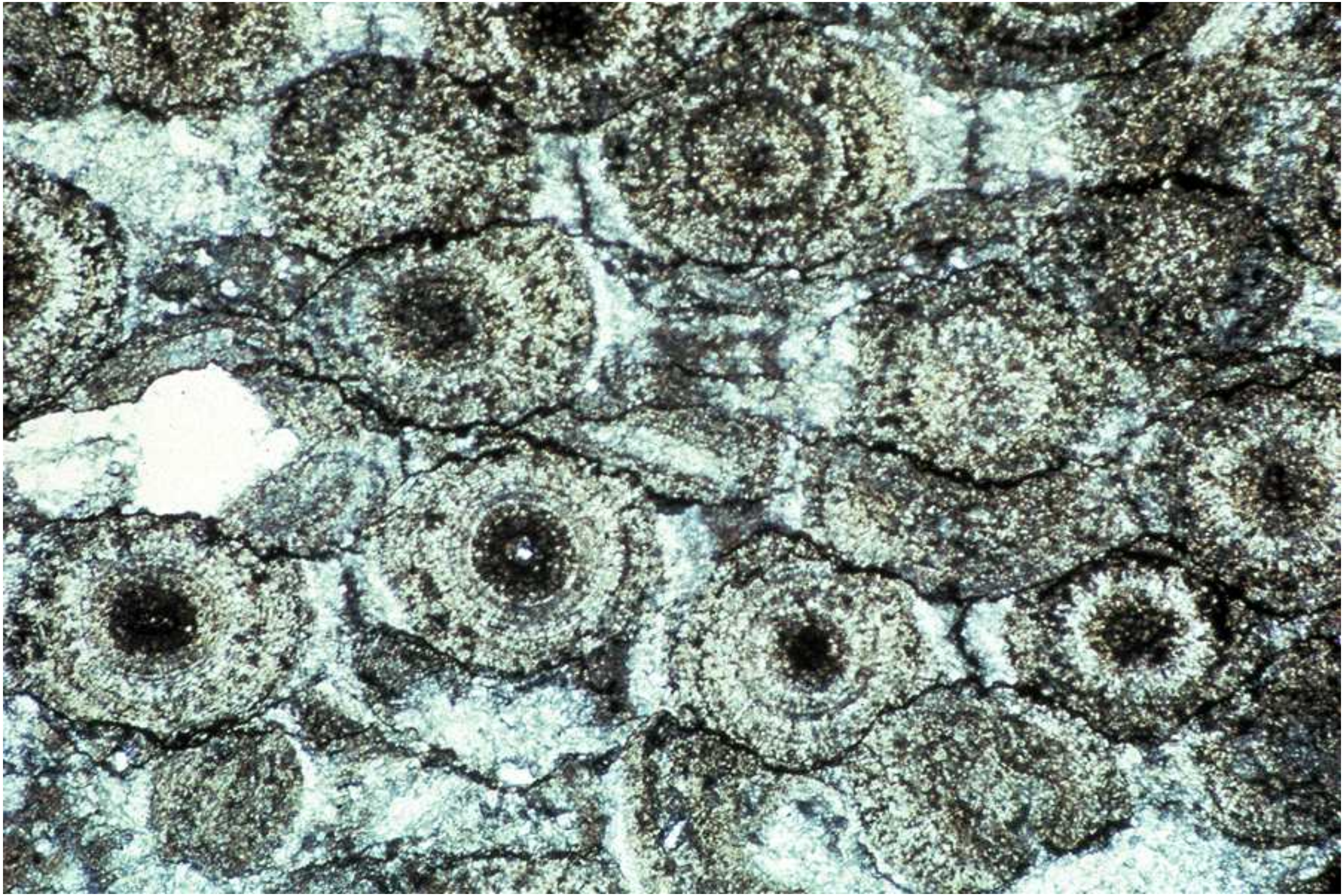
reduction spots

reduction spots

deformed trilobites



solution - precipitation

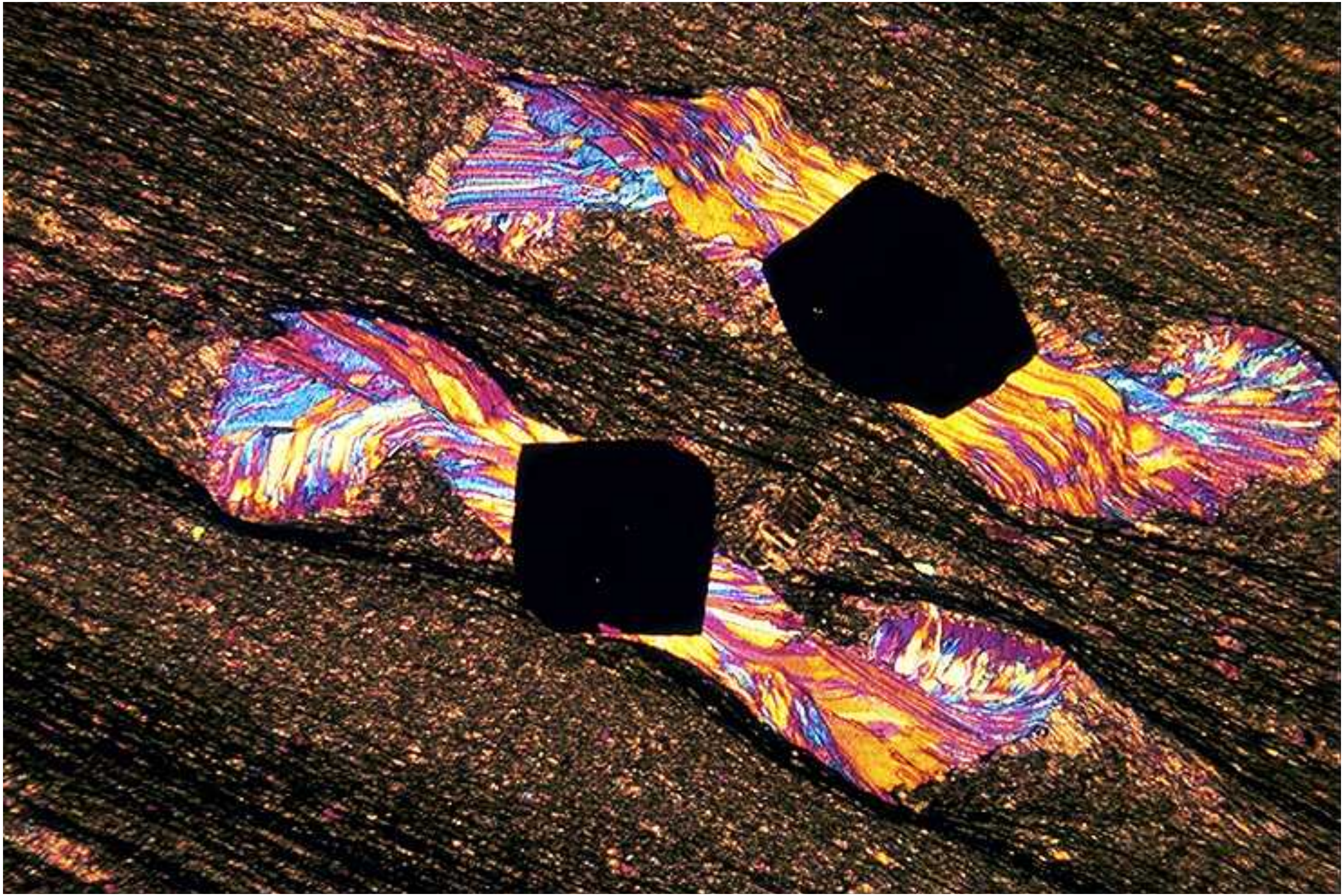


tectonic stylolites

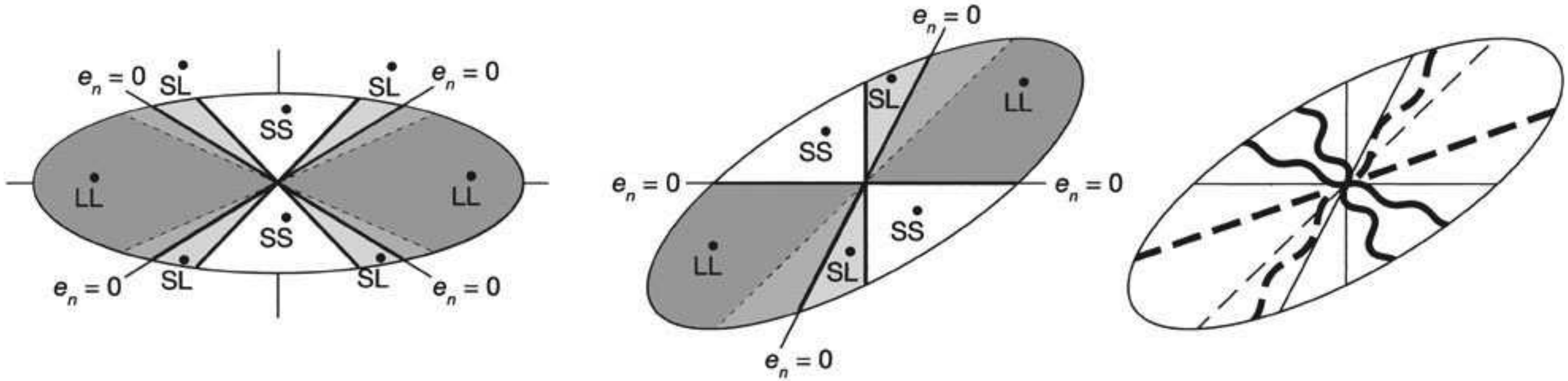
strain partitioning

matrix - particle strain

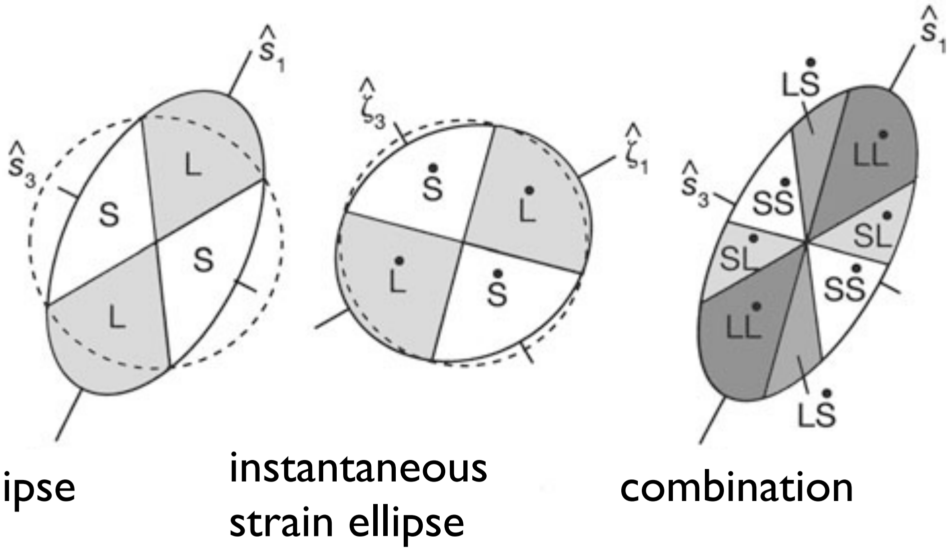
fibres

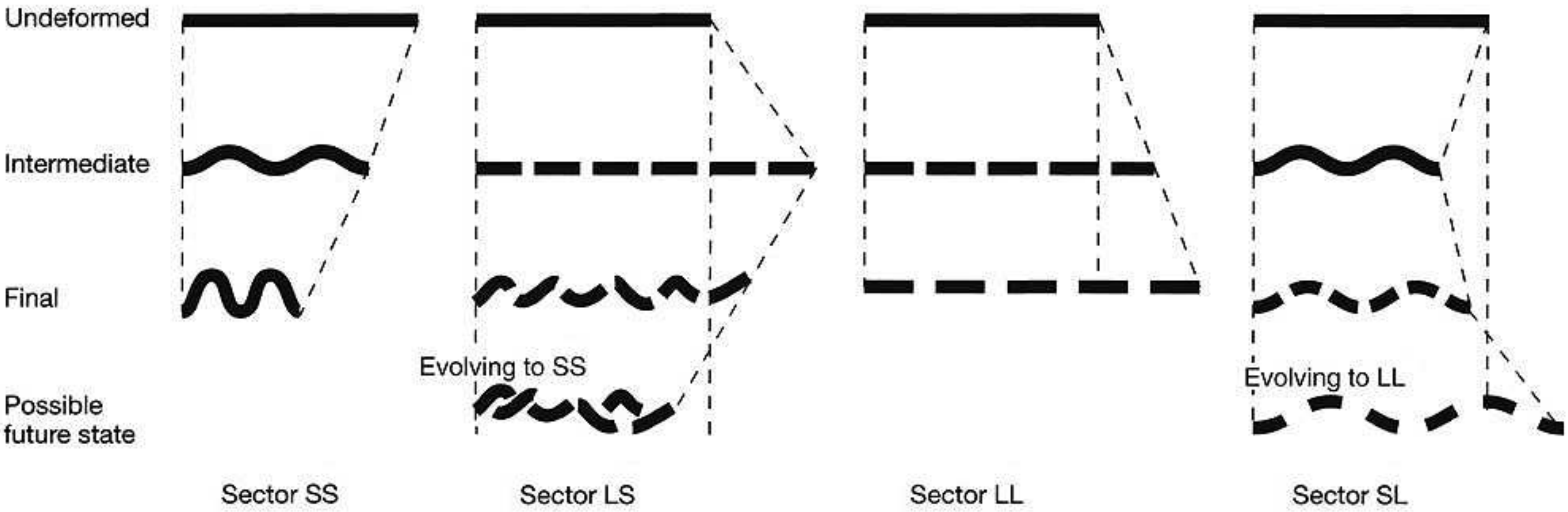


strain history



strain history - superposition

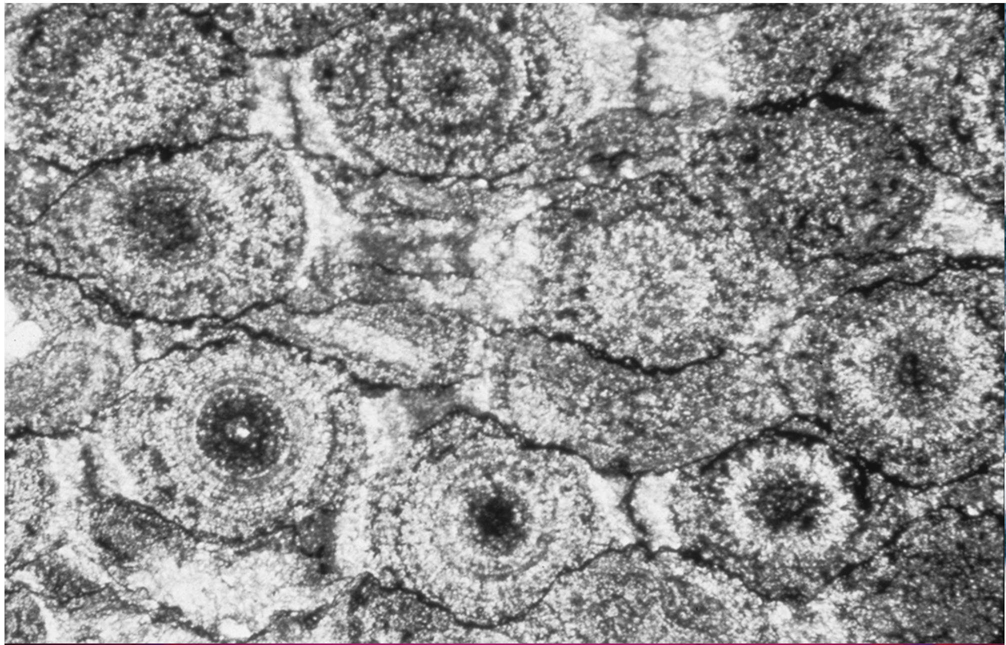


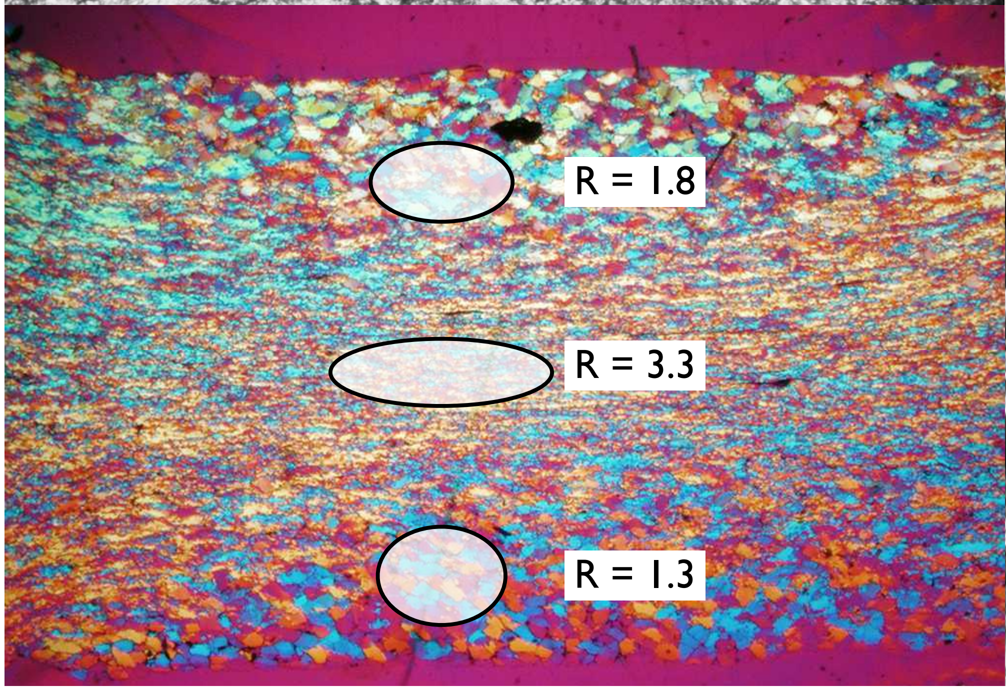


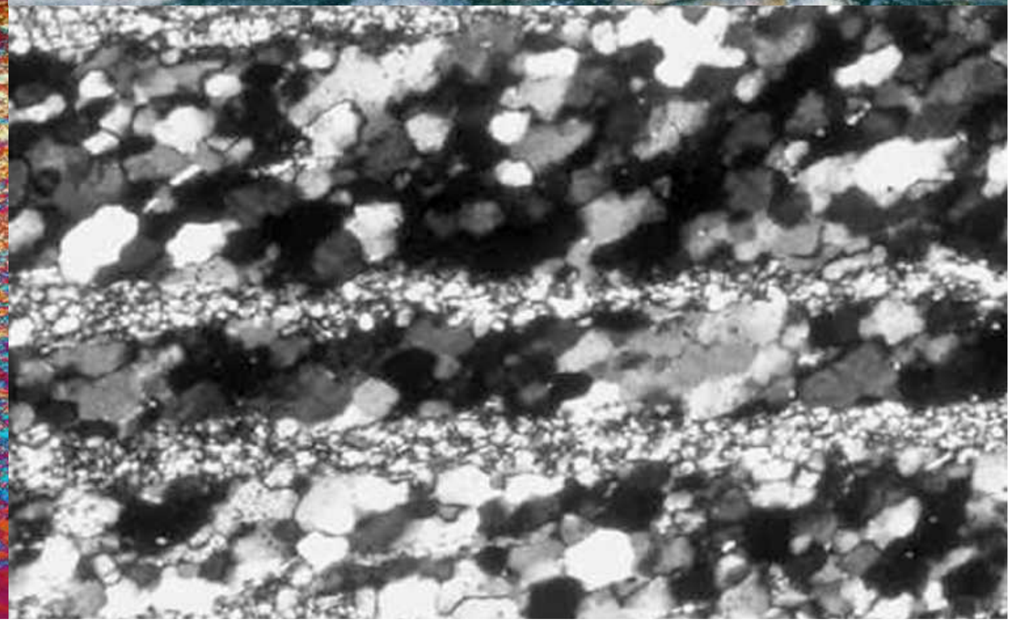
strain history: LS field

Strain Messungen

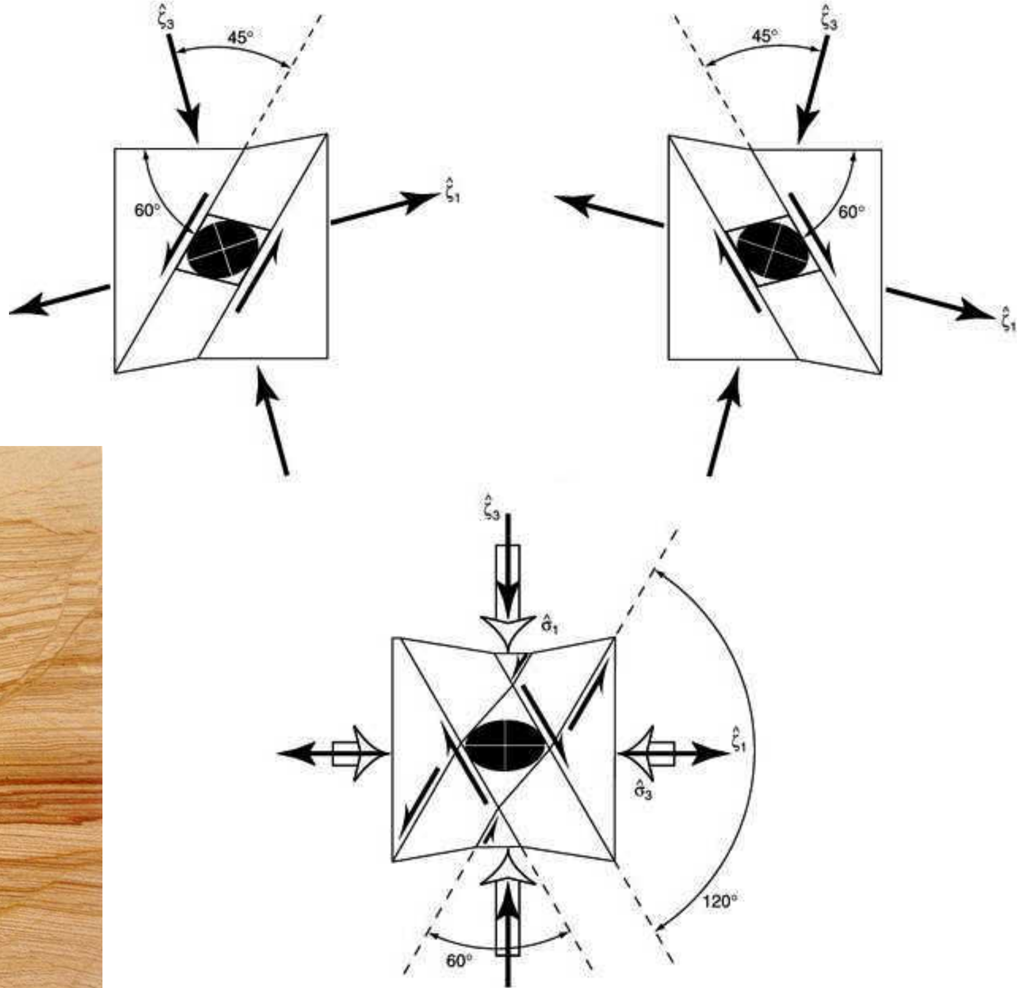
Strain marker - Homogenitätsbereich

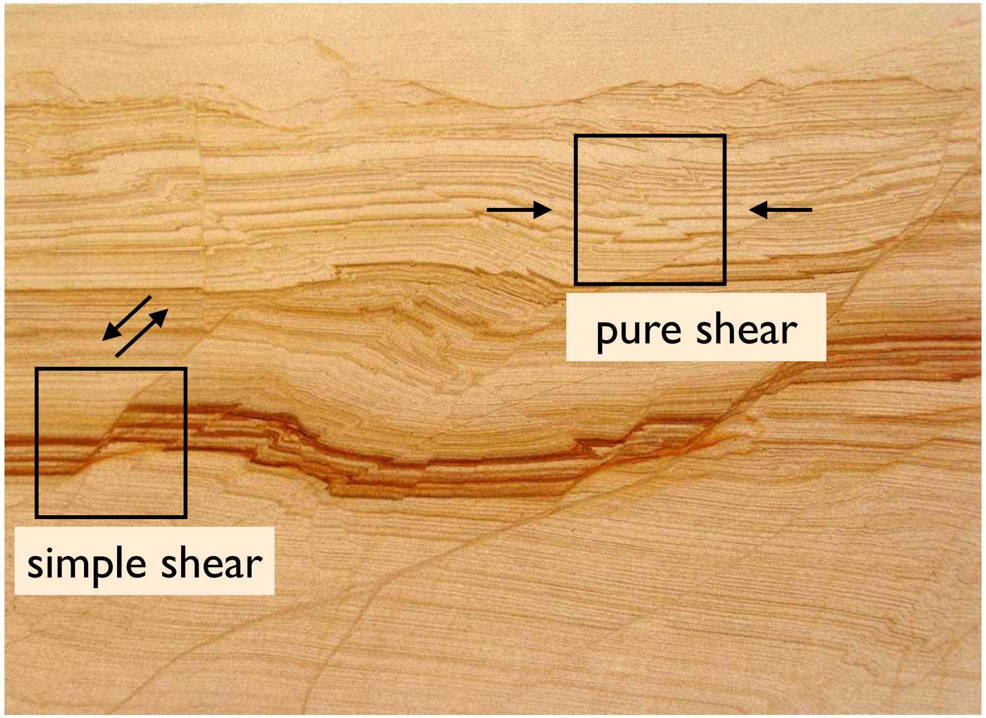




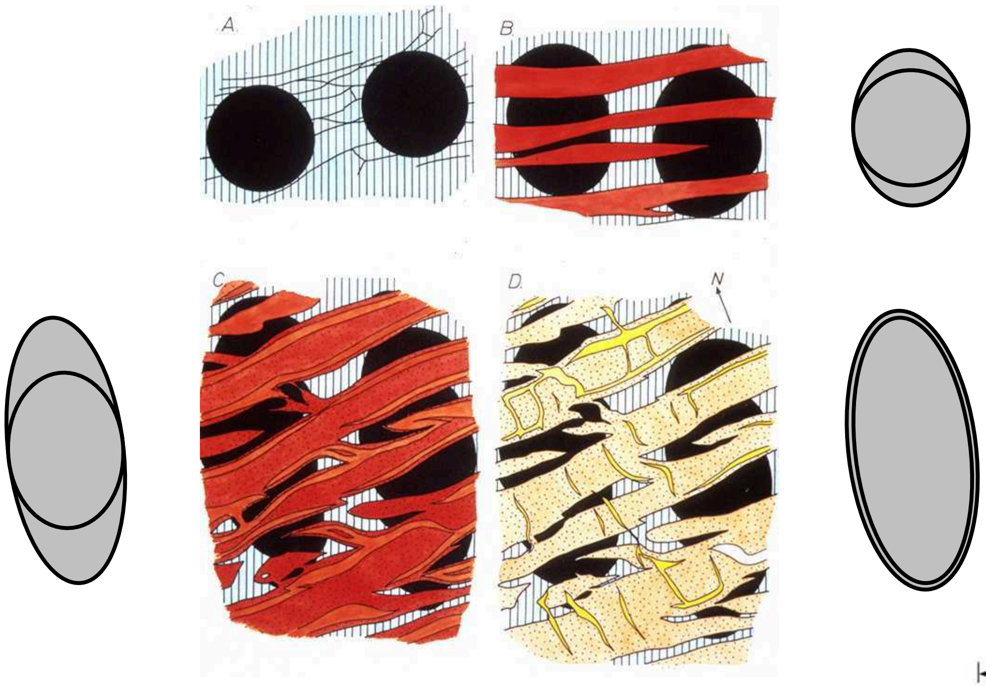


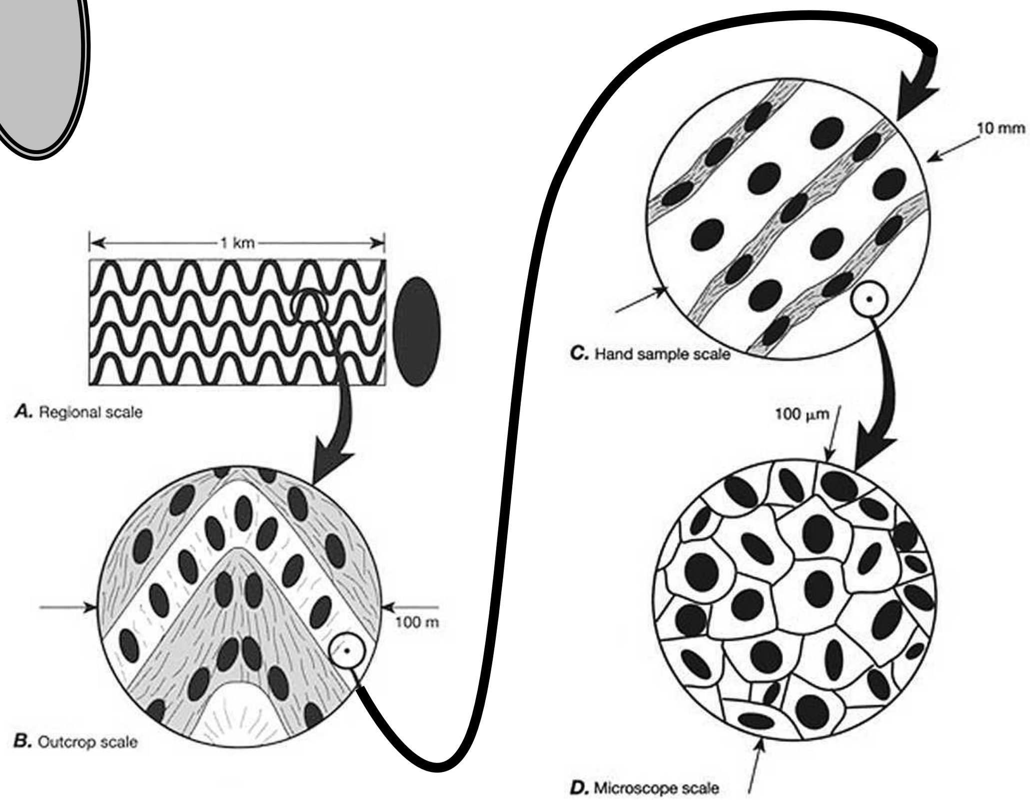
Lokalisierung und bulk strain



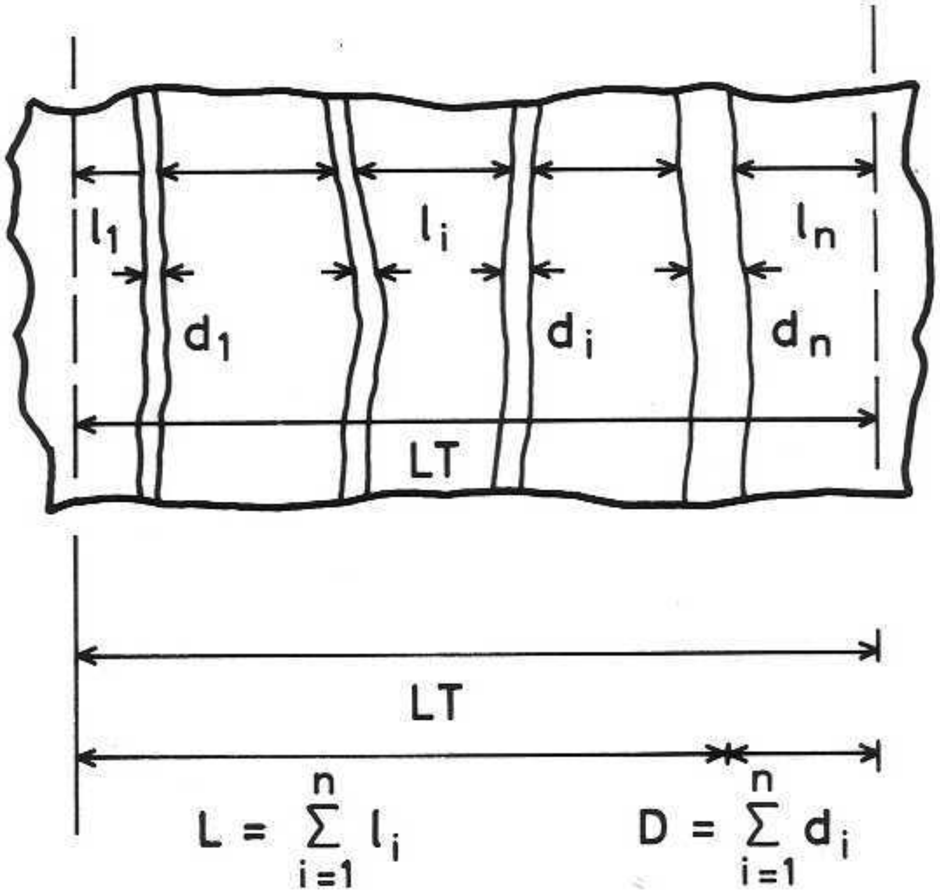


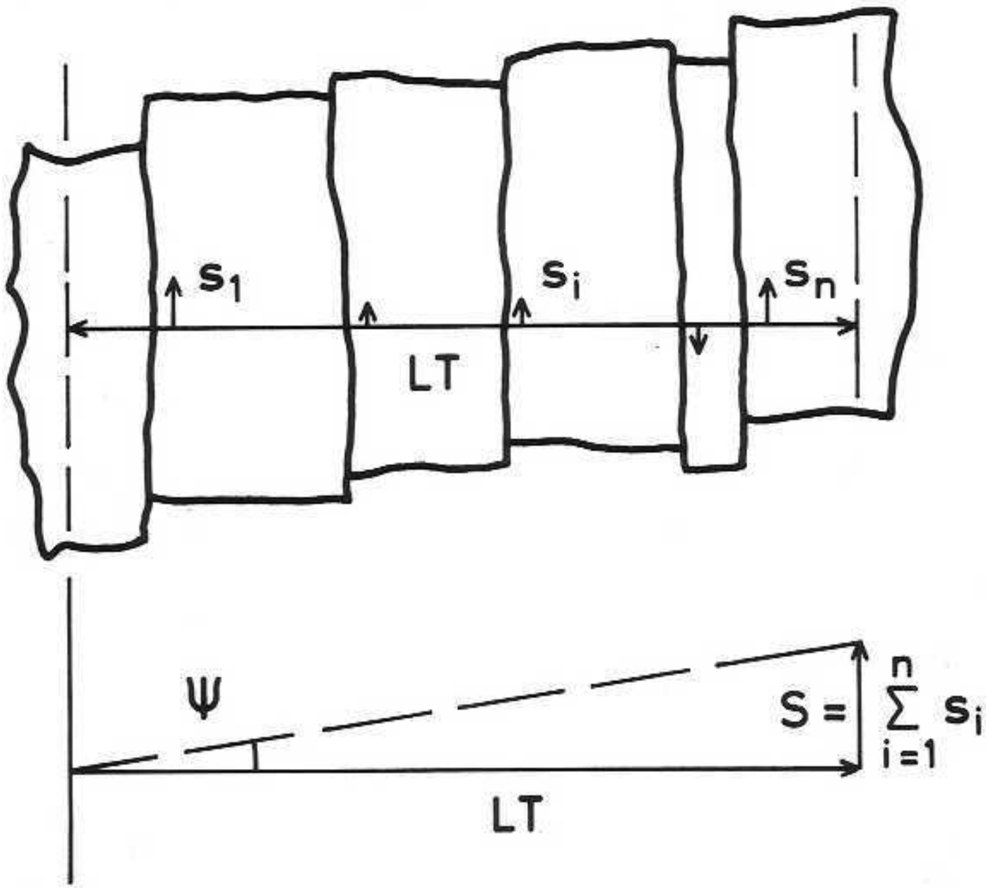
Massstab


A.
B.
C.
D.
N

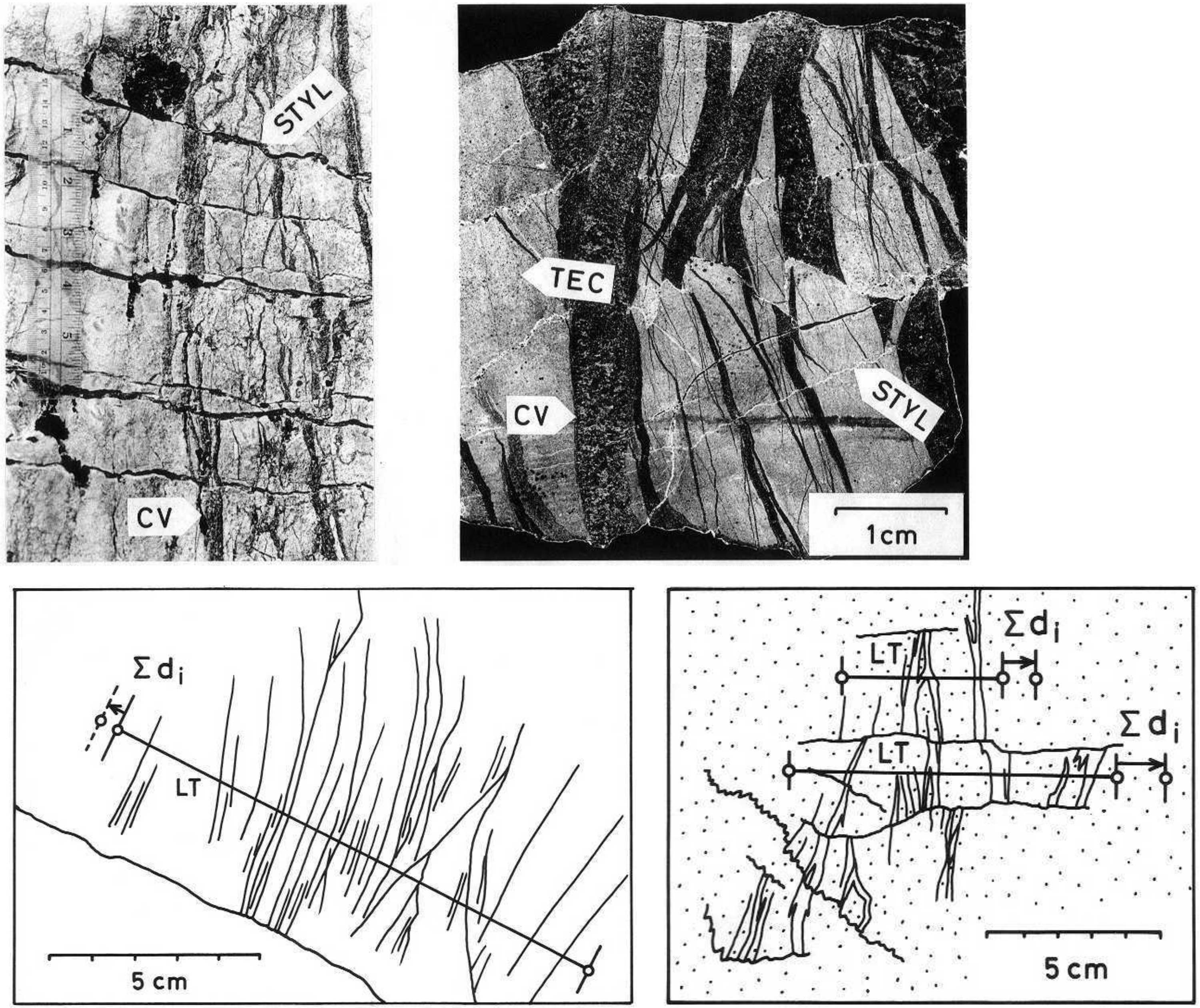

1 km
A. Regional scale
B. Outcrop scale
100 m
10 mm
C. Hand sample scale
100 µm
D. Microscope scale

strain from displacements

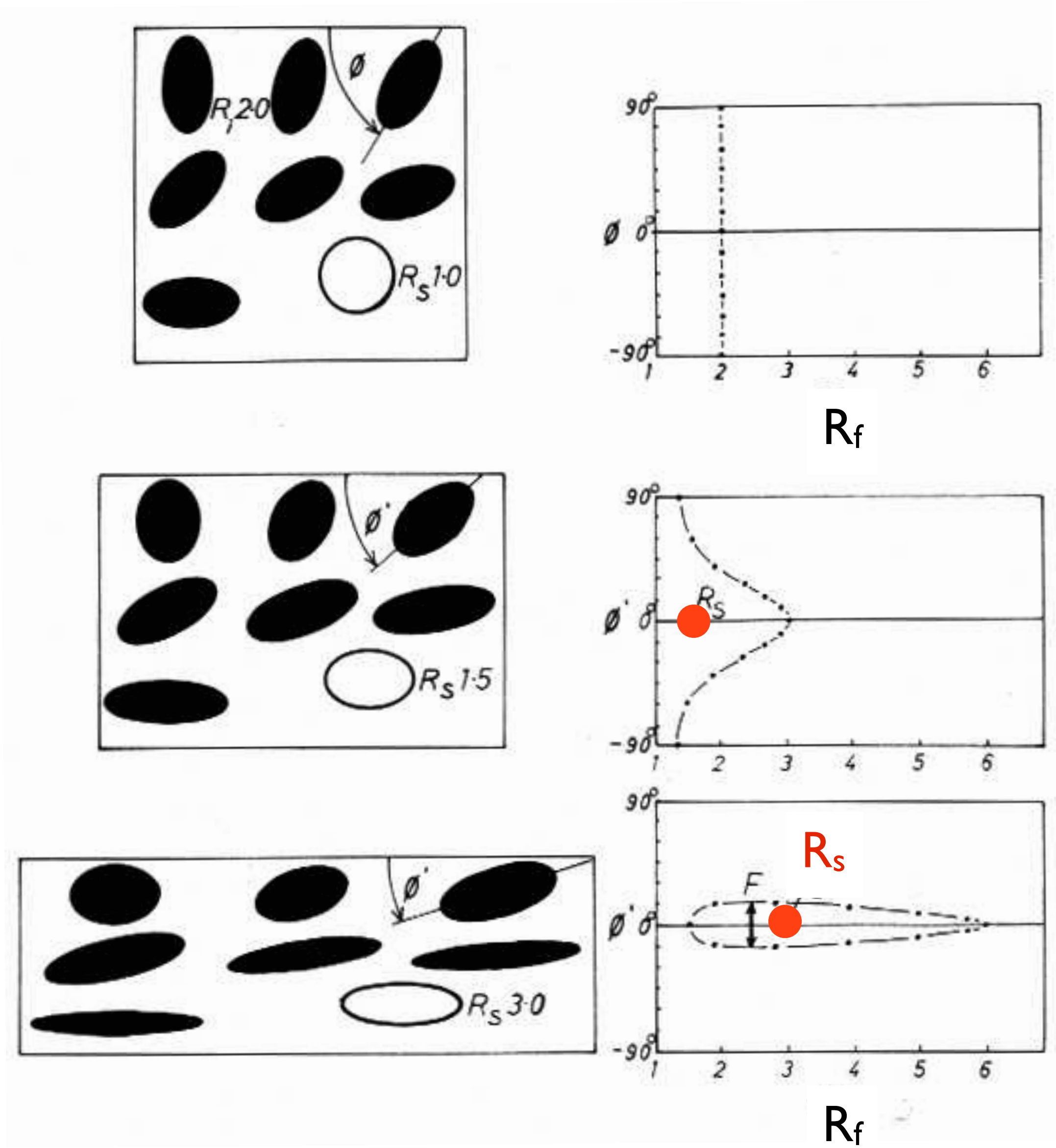




extensional strain from healed cracks



Rf - φ method (Ramsay)



F fluctuation

R_i initial ellipses

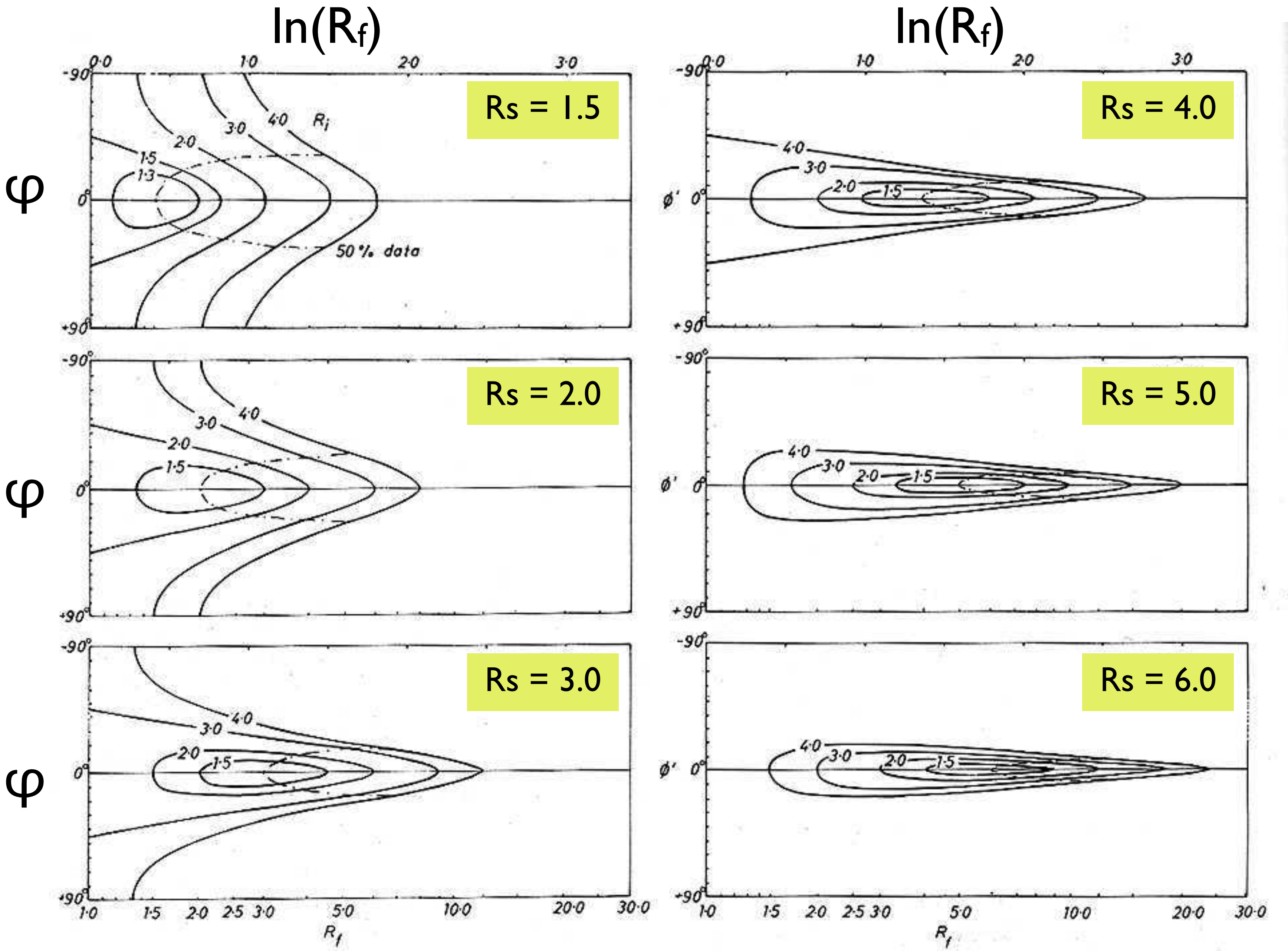
ursprüngliches Achsenverhältnis der unverformten Elllipsen

R_f deformed ellipses

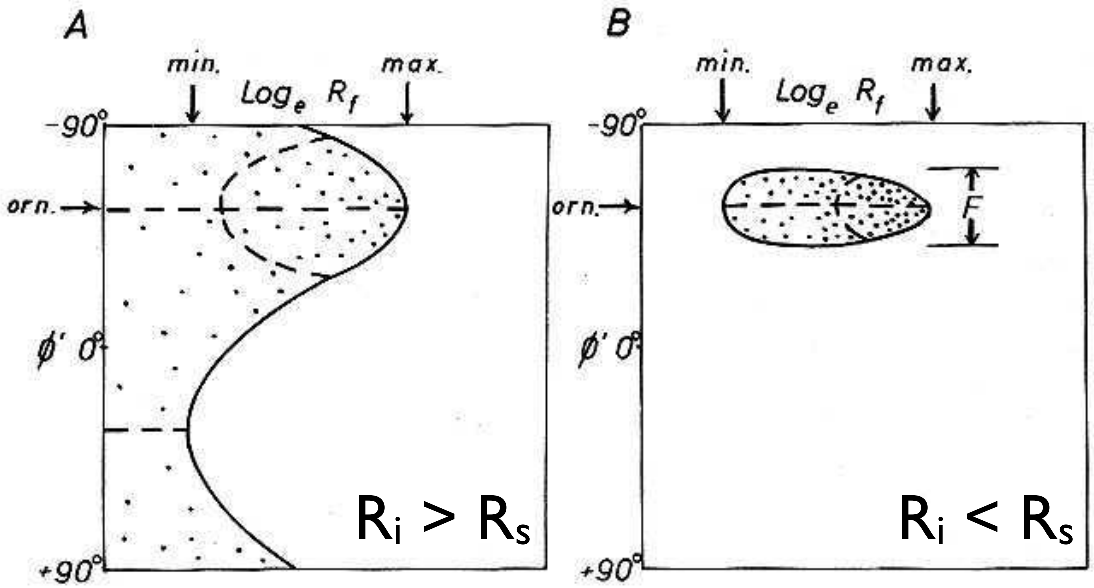
Achsenverhältnis der verformten Elllipsen

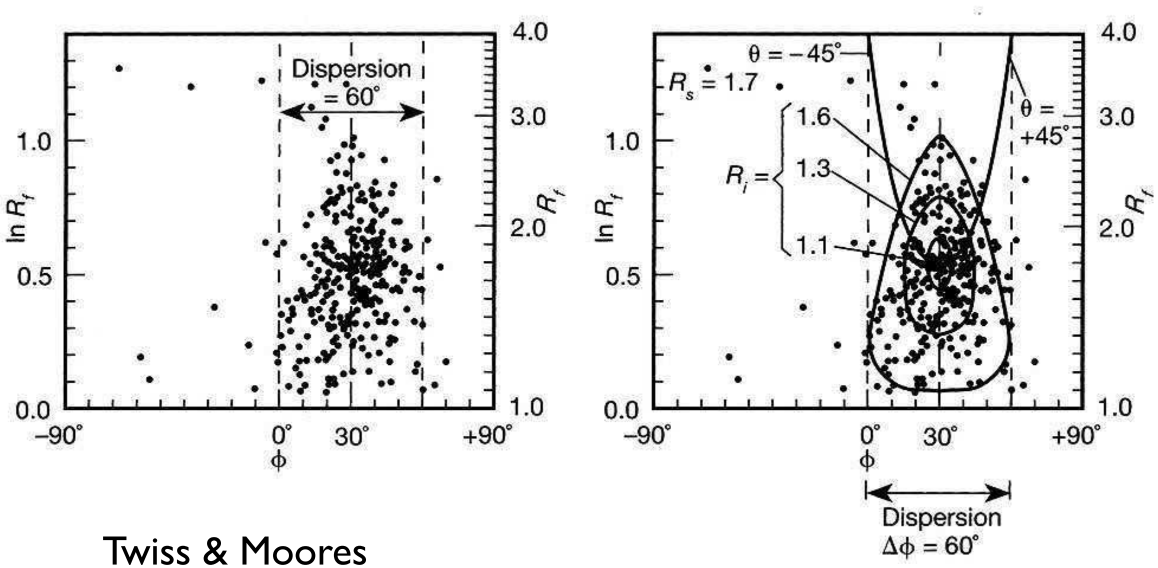
R_s strain ellipse

Rf - φ method (Ramsay)



Rf - φ method (Ramsay)





Twiss & Moores

$$F = \frac{R_s\,(R_i^2-1)}{\sqrt{(R_i^2R_s^2-1)\,(R_s^2-R_i^2)}}$$

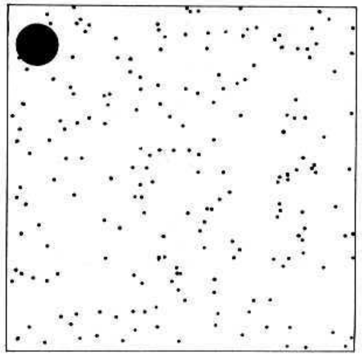
F fluctuation

R_i initial ellipses

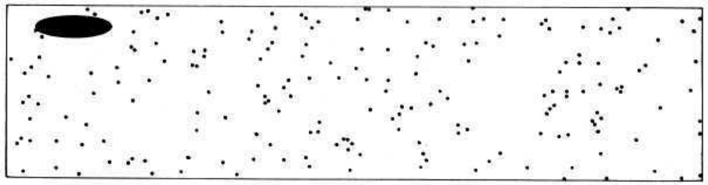
ursprüngliches Achsenverhältnis der unverformten Elllipsen

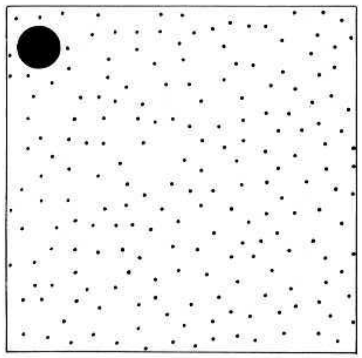
R_s strain ellipse

Fry method

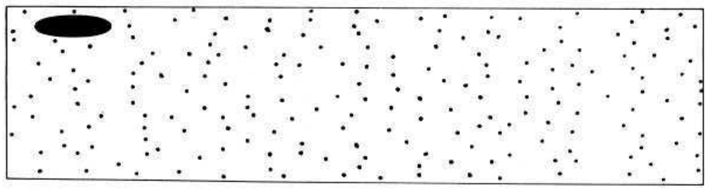


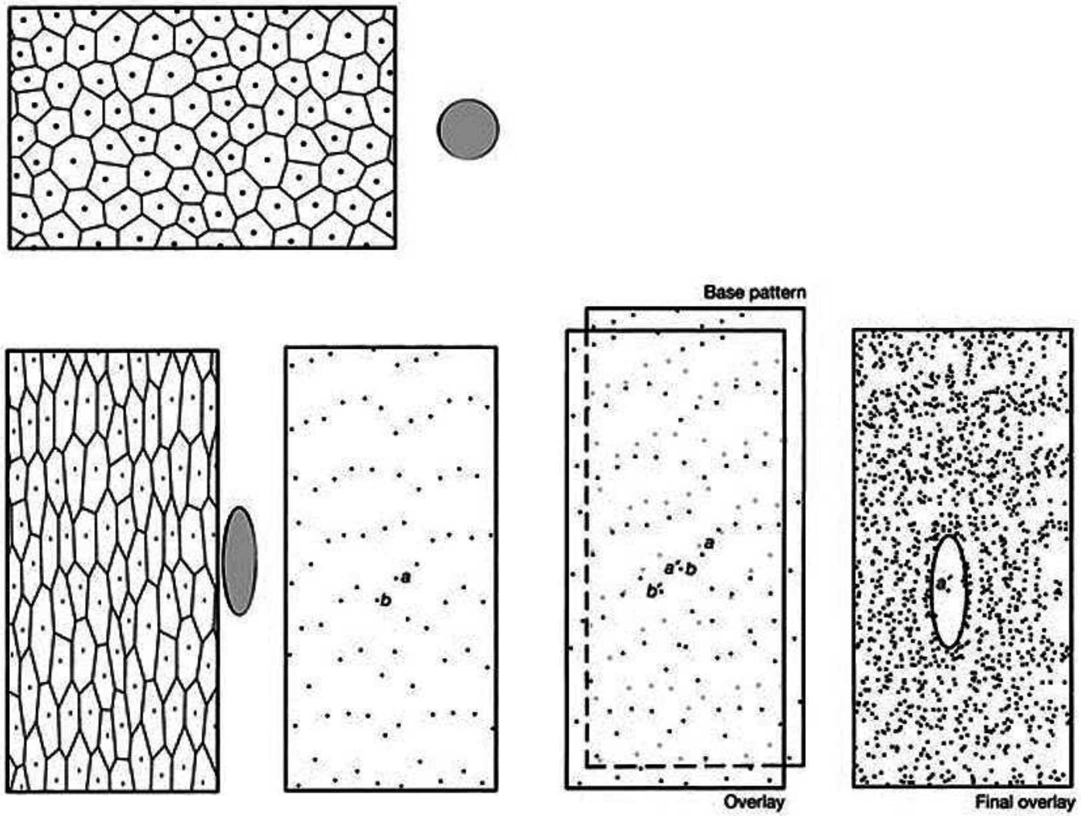
Poisson verteilt



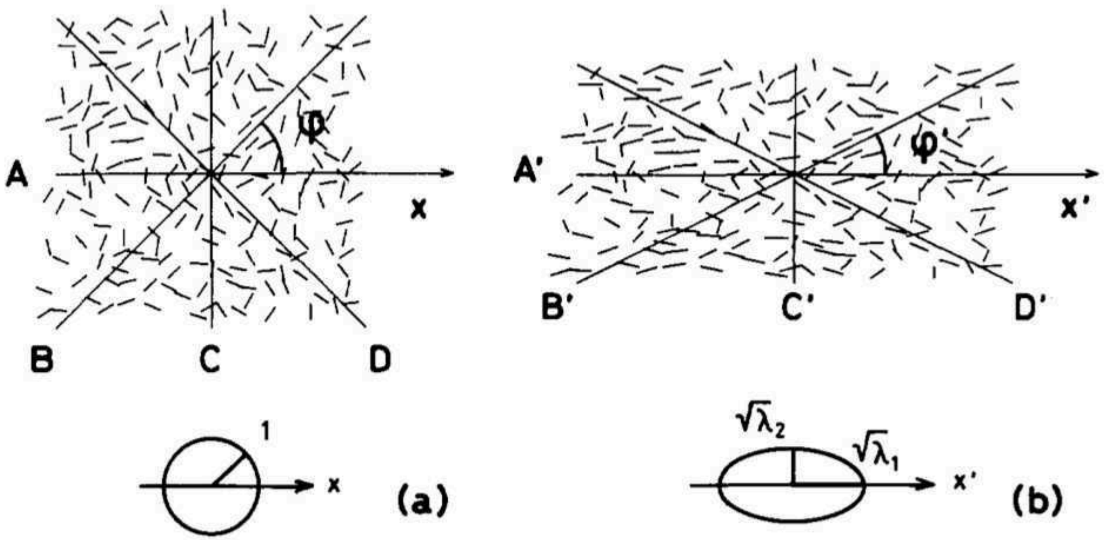


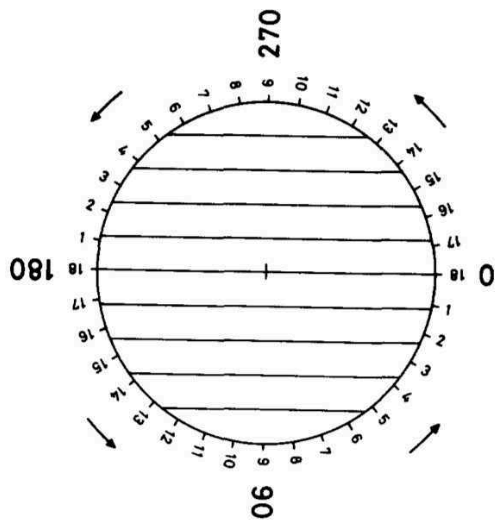
antikorreliert

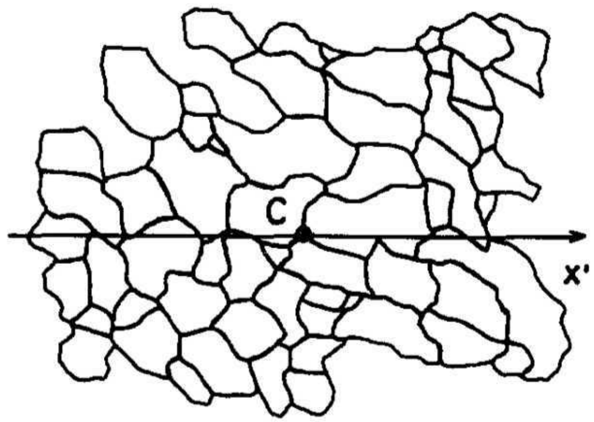


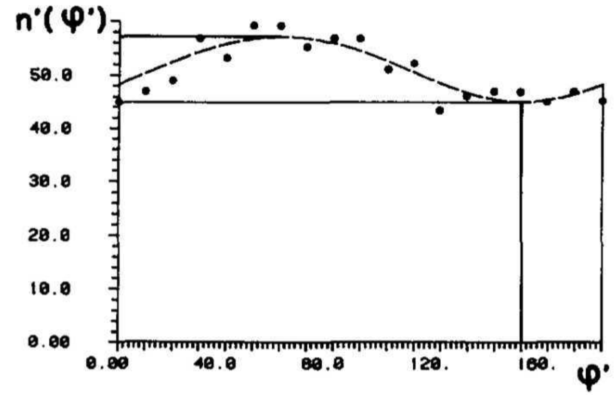


inverse SURFOR (Panozzo)









PAROR SURFOR (Panozzo)

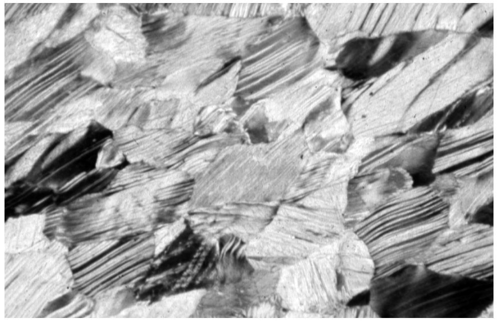
Special Research Paper*

Simple shear experiments on calcite rocks: rheology and microfabric

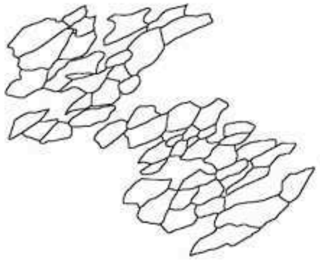
S. M. Schmid,† R. Panozzo† and S. Bauer‡

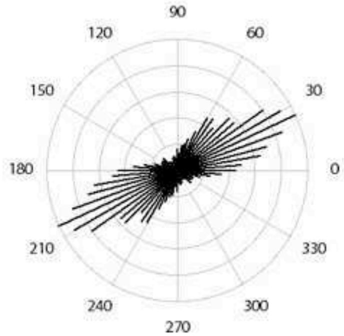
†Geologisches Institut, ETH-Zentrum, 8092 Zürich, Switzerland and ‡Center for Tectonophysics, Texas A & M University, College Station, Texas 77843. Now at: Sandia National Laboratories, Div. 6314, Albuquerque, NM 87185, U.S.A.

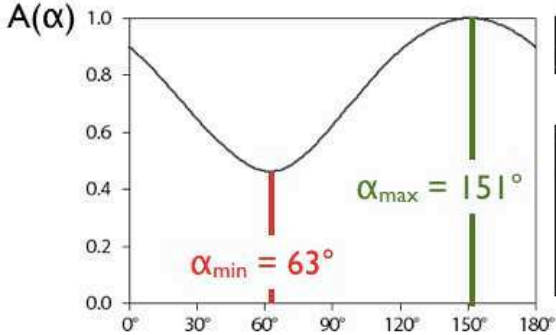
CT5   500°C



γ = 1.08



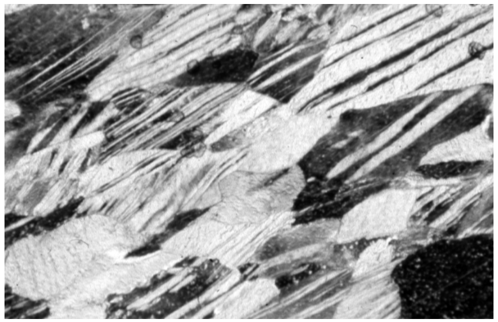




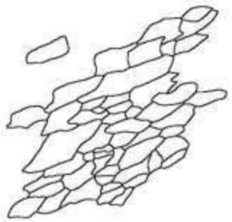
$\Delta\alpha$ = 88°

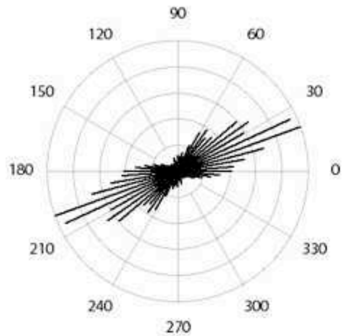
b/a = 0.46
α_{p1} = 29°
α_{p2} = 27°

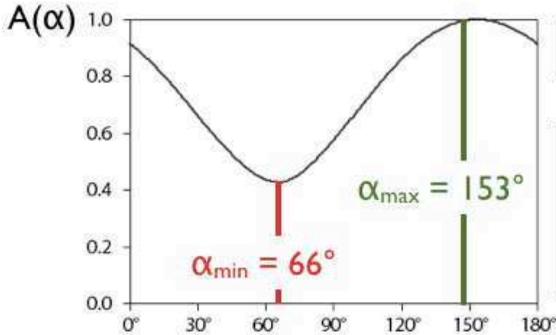
CT1   600°C



γ = 1.22







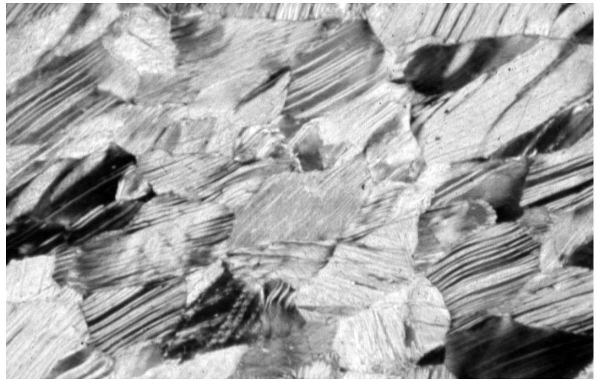
$\Delta\alpha$ = 87°

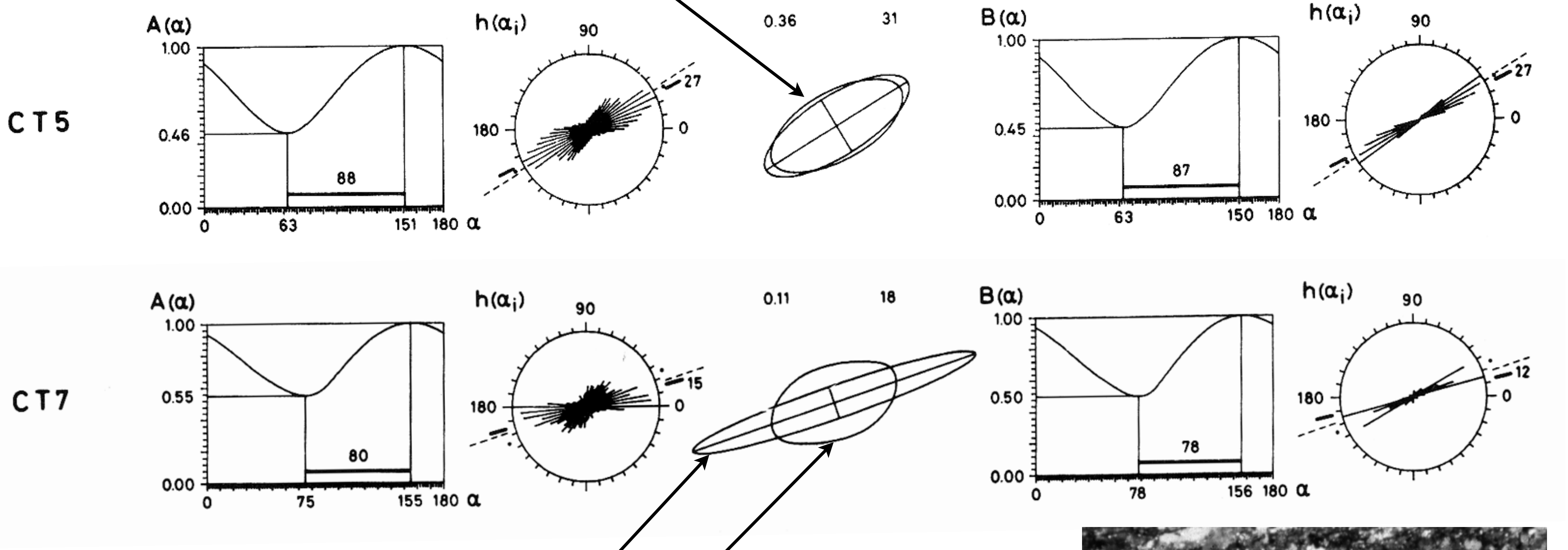
b/a = 0.43
α_{p1} = 27°
α_{p2} = 24°

strain test

characteristic shape
(= ellipse)
= strain ellipse ?

CT5 500°C





strain ellipse

characteristic shape
(≠ ellipse)

CT7 800°C

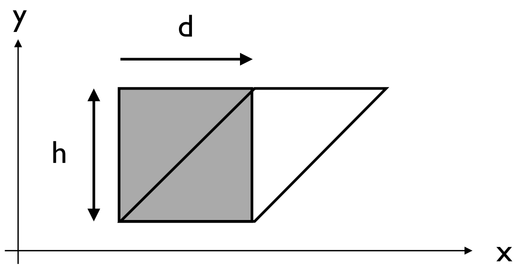
Übung 2
strain

Übung 2

Scherverformung in der Scherbox (simple shear in 2 D)

Ziel dieser Übung ist es, die verschiedenen geometrischen Aspekte der einfachen Scherung (in 2 Dimensionen) kennenzulernen und quantitativ beschreiben zu können. Die Übung kann auf zwei Arten gelöst werden: durch Messen oder durch Rechnen.

Einfache Scherung wird wie folgt beschrieben:



$\Upsilon = d / h$
wo d = Versetzungsbetrag und h = Höhe des gescherten Körpers.

Das Experiment

Ein Stapel Computerkarten wird geschert (diese Karten existieren in der Tat immer noch - sie sind im Übungsraum zusammen mit einer real existierenden Scherbox zu finden).

Auf den Karten ist seitlich ein Einheitskreis (Radius = 1.00) aufgemalt, sowie 8 Durchmesser in den Orientierungen 0°, 30°, 45°, 60°, 90°, 120°, 135°, 150°.

Das Resultat des Scherexperimentes ist auf der beigelegten Abbildung dargestellt:

1 - Unverformter Zustand
2 - $\Upsilon = 0.5$
3 - $\Upsilon = 1.0$
4 - $\Upsilon = 2.0$
5 - $\Upsilon = 3.0$

Der Kreis verformt sich zu zunehmend schlankeren Ellipsen (= Verformungsellipsen), die verschiedenen Durchmesser werden länger oder kürzer und ändern die Orientierung.

Aufgaben

1. Bestimmen Sie den Scherwinkel, Ψ, in den 4 Verformungsschritten. Beschreiben Sie das Vorgehen.

2. Schreiben Sie die Gleichungen der Koordinaten-Transformation für $\Upsilon = 0.5, 1.0, 2.0, 3.0$.

3. Bestimmen sie die Extension, e, und die Orientierung, ϕ, der eingezeichneten Durchmesser (A-A', B-B', etc.) bzw. der Radien (0-A', 0-B', etc.) in den 4 Verformungsschritten.

   $\Delta L = L - L_0$
   $e = \Delta L / L_0$
   wo L_0 = ursprüngliche Länge und L = verformte Länge

   Die Radius des ursprünglichen Kreises ist = 1.00. Sie können nun entweder alle Durchmesser oder Radien messen oder die Koordinaten der verformten Radiusvektoren berechnen und daraus die verformte Länge gewinnen. Dazu nehmen Sie am besten an, dass sich der Koordinatenursprung immer im Mittelpunkt der Ellipsen befindet.
   Welches Vorgehen wählen Sie? Beschreiben Sie es.

4. Stellen Sie die Extension, e, und die Orientierung, ϕ, der Linien A-A', B-B' etc. als Funktion von ϒ dar (2 separate Diagramme) und kommentieren Sie. Welche Linien, d.h. welche ursprünglichen Orientierungen, werden kürzer, welche werden länger ? Wie schnell rotieren sie?

4*. Finden Sie die mathematische Gleichung, welche die Extension, e, und die Orientierung, ϕ, einer gescherten Geraden in Abhängigkeit der Scherung, ϒ, und der ursprünglichen Orientierung, ϕ_0, der Geraden beschreibt.

5. Zeichnen Sie die lange Achse, a, und die kurze Achse, b, der Ellipsen ein, messen Sie die Längen a und b, berechnen Sie das Achsenverhältnis, R_f ($R_f = a/b$), und bestimmen Sie die Orientierung, ϕ, der langen Achse.

   Tragen Sie die Resultate in den entsprechenden Diagramme der Aufgabe 4 ein.

6. Vergleichen Sie die Sie Rotation der langen Ellipsenachse mit der Rotation der gescherten Durchmesser. Zeichnen Sie die Lagen der langen und kurzen Achsen auf den Verformungsellipsen im ursprünglichen Einheitskreis ein. Kommentieren sie. Sind zusammengehörige Achsen senkrecht aufeinander ? Sind die Ellipsenachsen Materiallinien ?

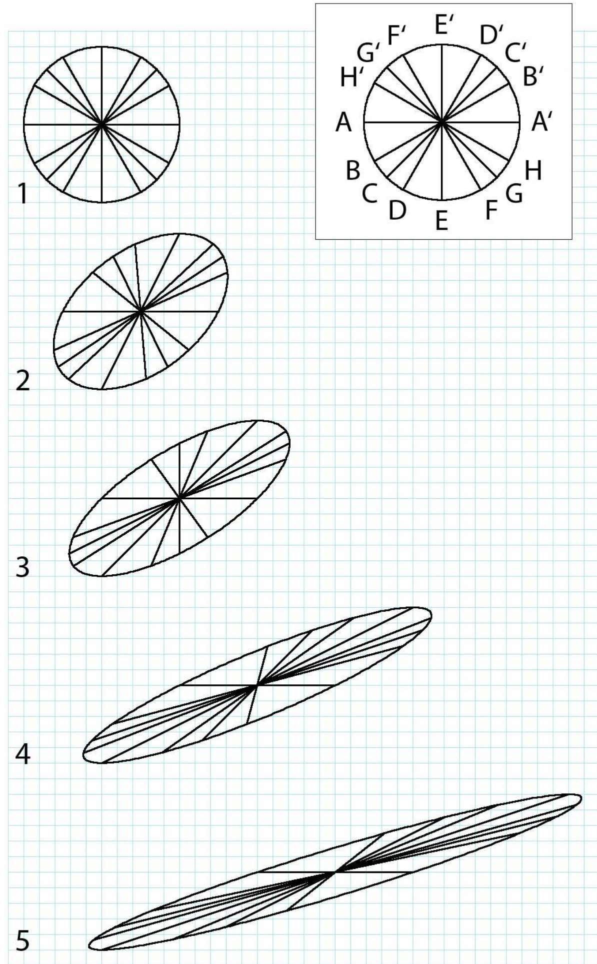


Abbildung: Resultat des Scherexperimentes

3

3 Mohr Coulomb - Reibung - Klüfte und Brüche

VL-Themen:

- Elastizität
- Deformationsexperimente
- Versagenskriterien
- Mohr Coulomb Failure
- Bruchbildung und -entwicklung

- Reibung
- Gleitreibung

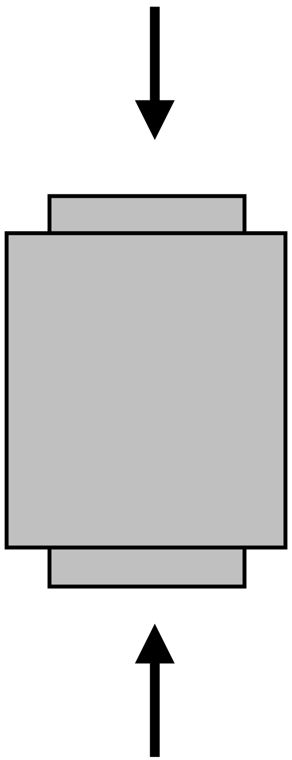
- Klüfte und Brüche

Elastizität

Spröddeformation

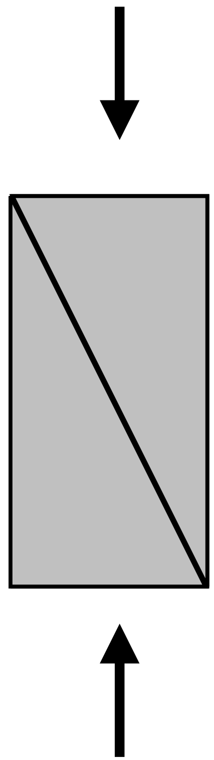
elasticity

Elastizität



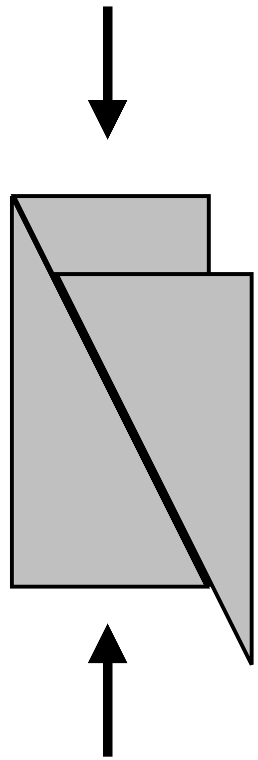
brittle failure

Bruchbildung
Versagen



friction

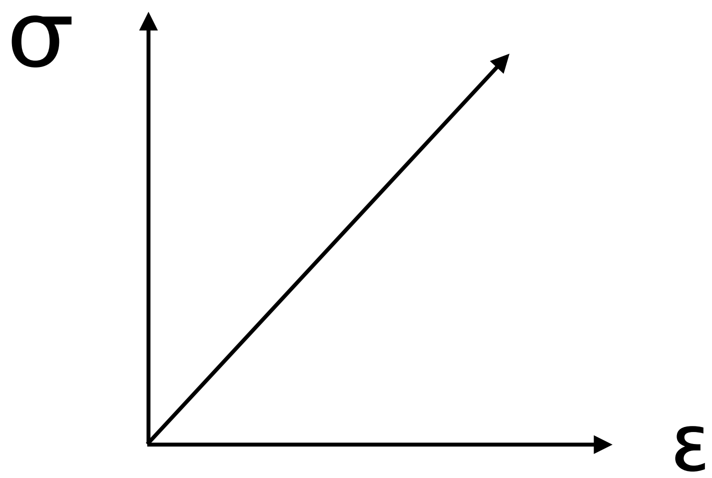
Reibung



Elastizität

Spannung = Materialeigenschaft · Verformung

$$\sigma_{ij} = E_{ijkl} \cdot \varepsilon_{kl}$$



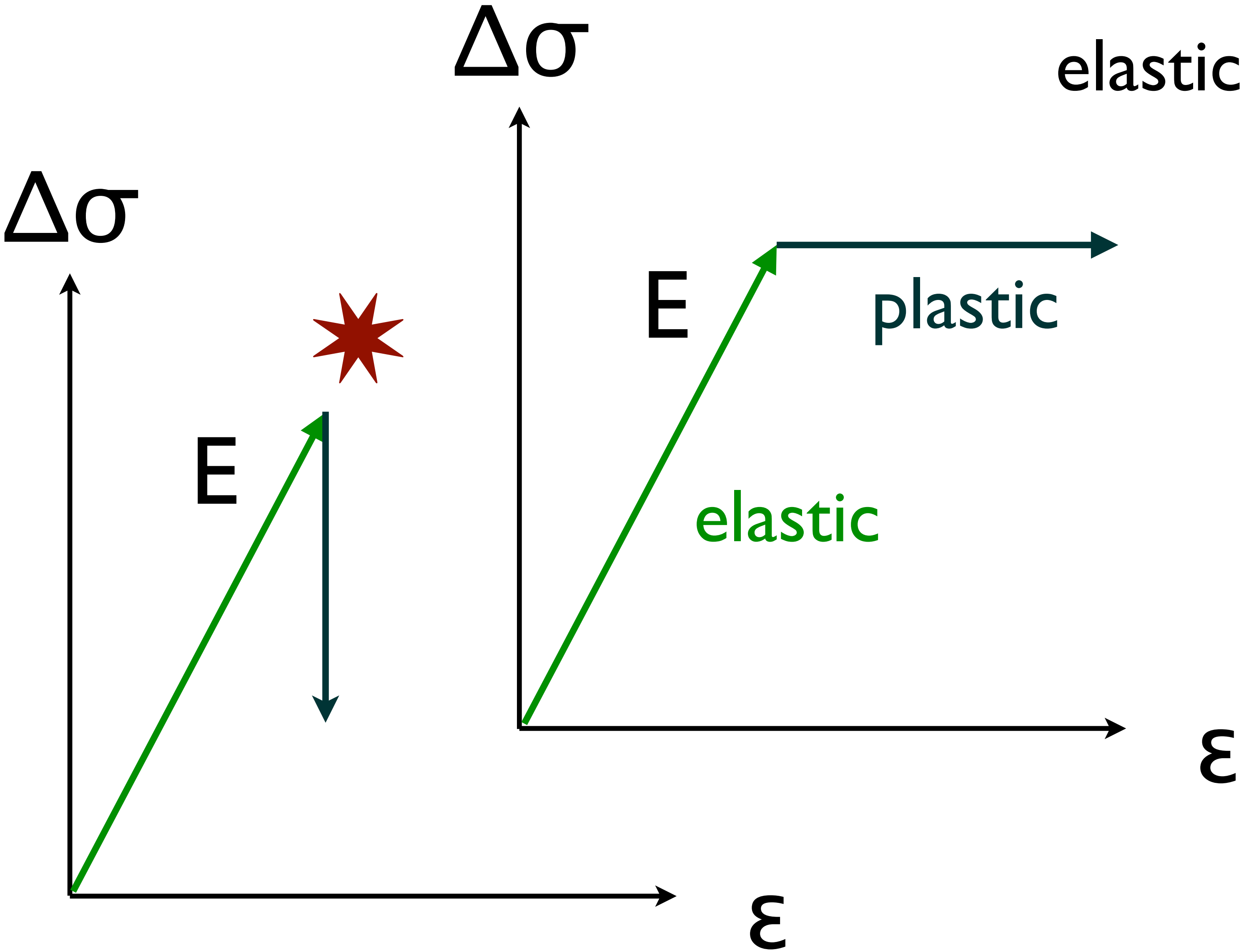
Seismische Geschwindigkeiten

$$\text{speed} = \sqrt{\frac{\text{elastic modulus}}{\text{density}}}$$

$$v_P = \left(\frac{K + \frac{4\mu}{3}}{\rho} \right)^{\frac{1}{2}} \qquad v_S = \left(\frac{\mu}{\rho} \right)^{\frac{1}{2}}$$

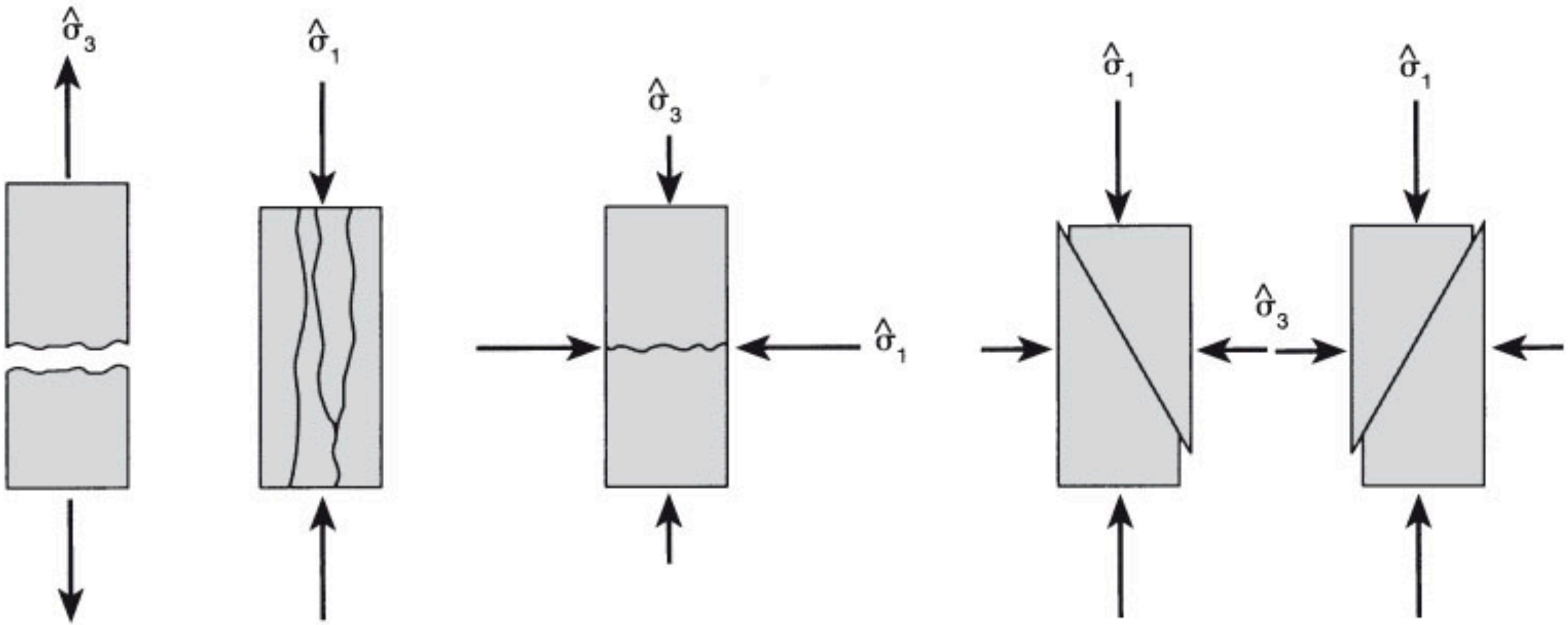
Spröddeformation

elastic ≠ brittle



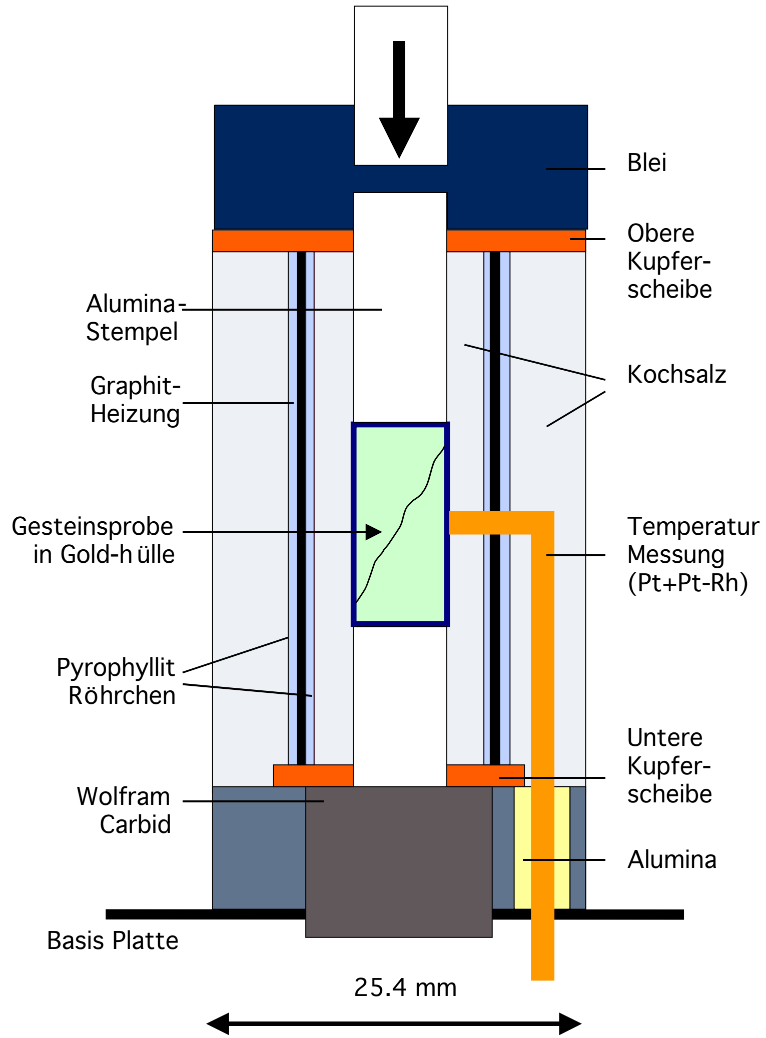
Experimente Gesteinsmechanik

Experimentelle Gesteinsverformung

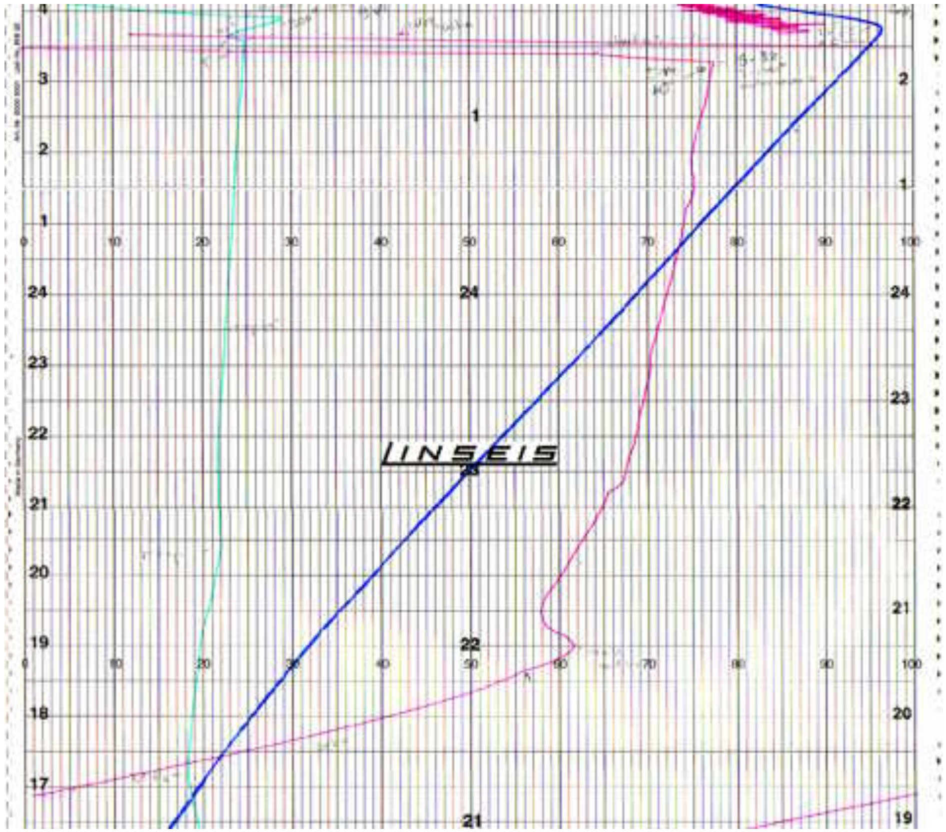


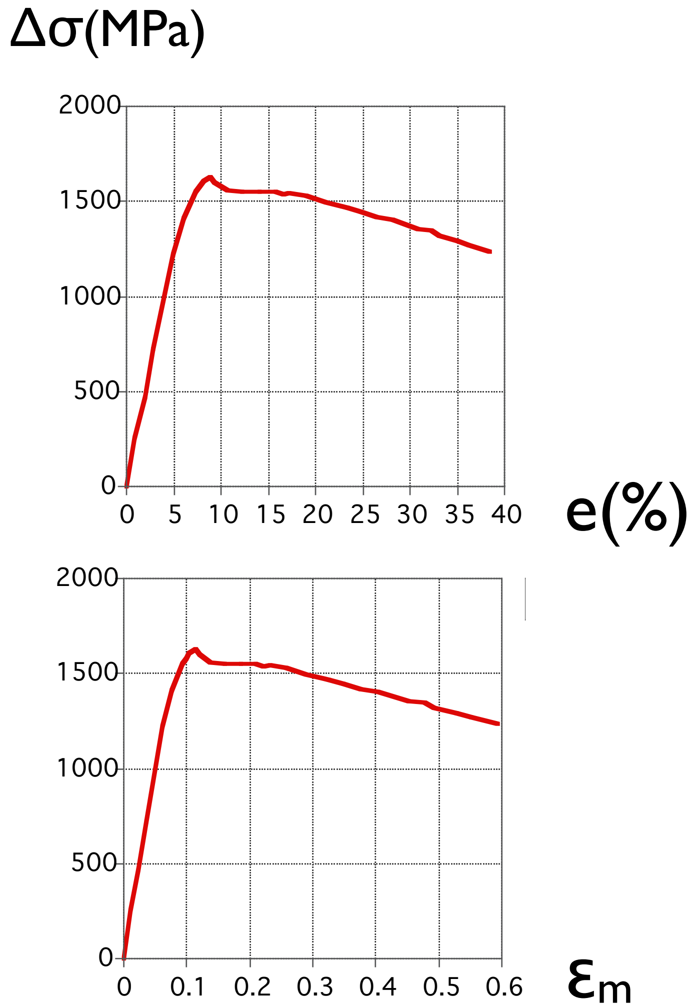
A. Tension fracture ***B.*** Longitudinal splitting ***C.*** Extension fracture ***D.*** Conjugate shear fractures

Rock deformation experiments



Rock deformation experiments





$$e(\%) = 100 \cdot (-\Delta L) / L$$

$$\varepsilon_m = {}^{1}/_{\sqrt{3}} \cdot \sqrt{(\varepsilon_1-\varepsilon_2)^2 + (\varepsilon_2-\varepsilon_3)^2 + (\varepsilon_3-\varepsilon_1)^2}$$

$$\varepsilon = \ln (L' / L) = \ln (s)$$

Versagenskriterien
Failure criteria

Versagen

Was ist Versagen:

Bruch ? Kohäsionverlust ?

Verformung ?

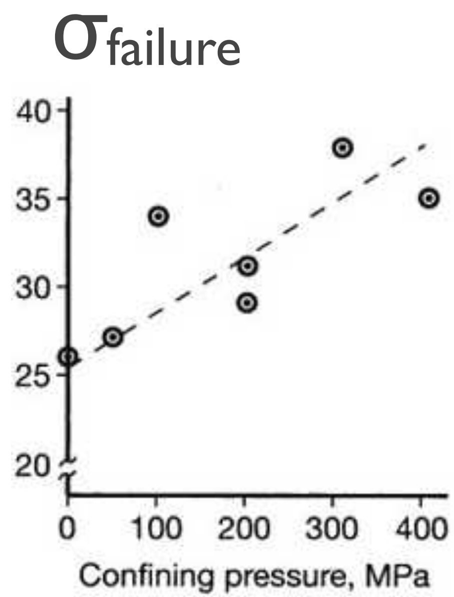
Verformungrate ?

Bei welchem Spannungzustand tritt Versagen ein:

maximales σ_1 oder σ_3 ?

maximales $\Delta\sigma$ (= $\sigma_1 - \sigma_3$) ?

maximales σ_n oder τ ?



dry Bera sandstone (Handin 1966)

Versagenskriterien

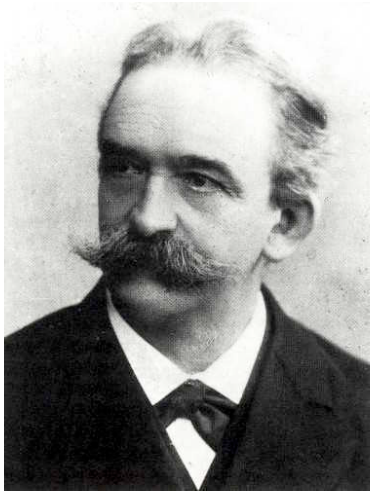
Coulomb Mohr failure criterion

$$\tau = \tau_0 + \mu \cdot \sigma$$

τ_0 = cohesion
μ = internal friction

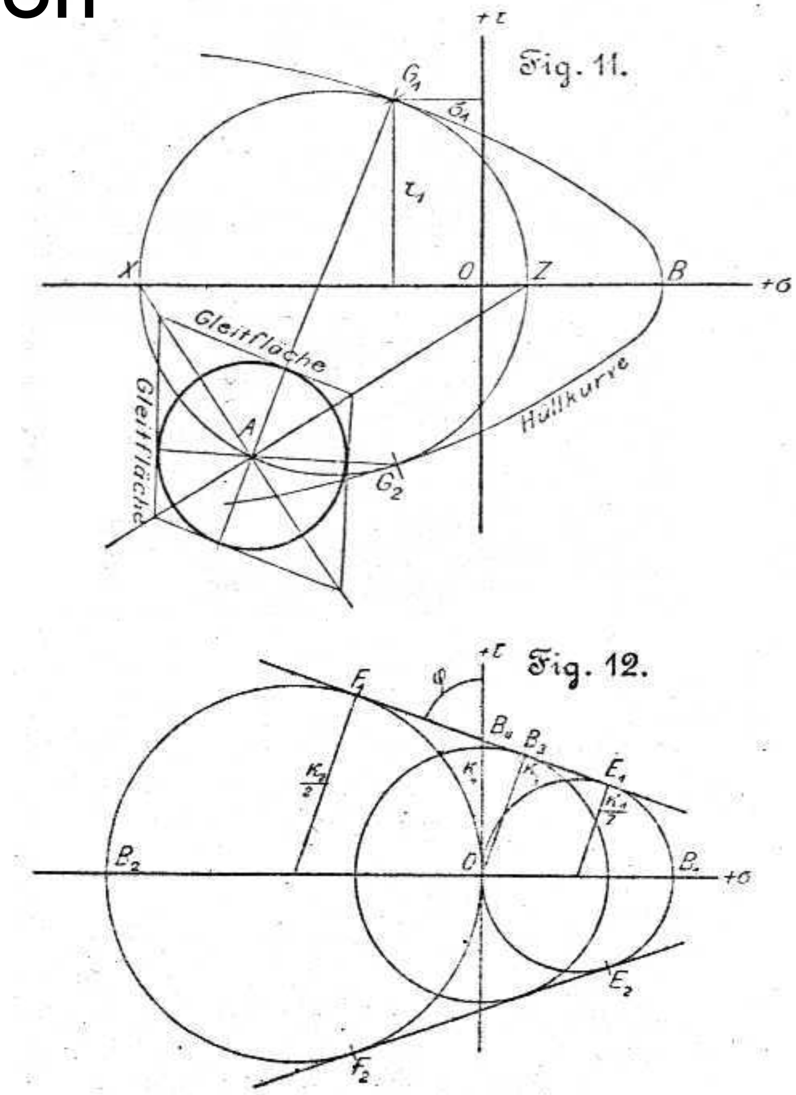
Charles Augustin de Coulomb

* 14. Juni 1736 in Angoulême
† 23. August 1806 in Paris



Christian Otto Mohr

* 8. Oktober 1835 in Wesselbüren
† 2. Oktober 1918 in Dresden



Mohr (1900)

Versagenskriterien

van Mises (Critical Distortional Energy)

$$^{1}/_{2}\,((\sigma_1 - \sigma_2)^2 + (\sigma_3 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2) \leq T^2$$

T = tensile strength

(maximum octahedral shear stress)

$$\tau_{oct} = \sqrt{^{2}/_{3}\, J_2}$$

Richard Edler von Mises

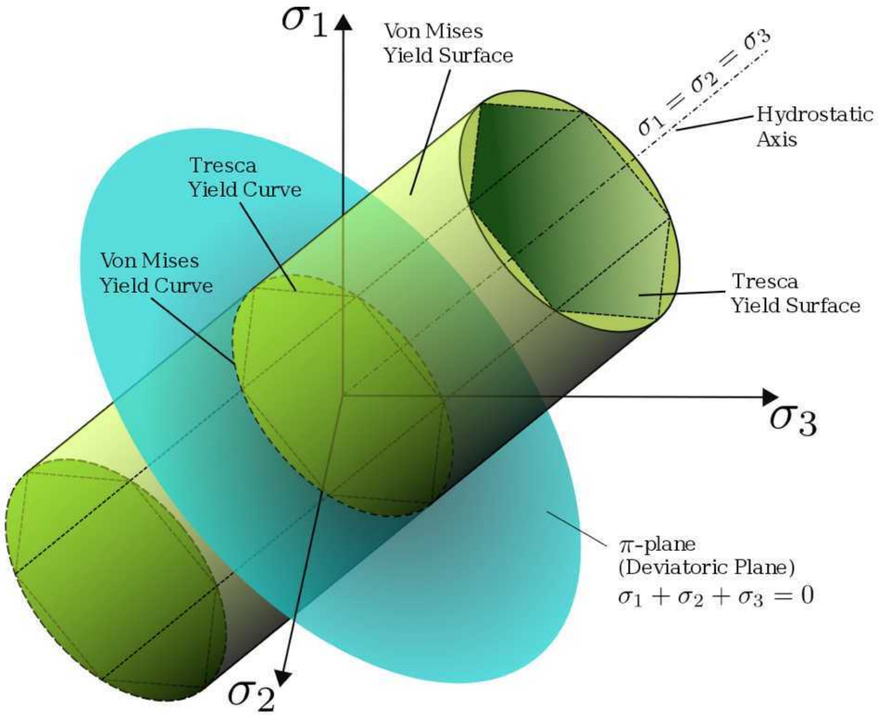
* 19 April 1883 in Lwów
† 14 July 1953 in Boston

Versagenskriterien

Tresca (Critical Shear Stress)

$^1/_2\ (\sigma_1 - \sigma_3) \leq S$

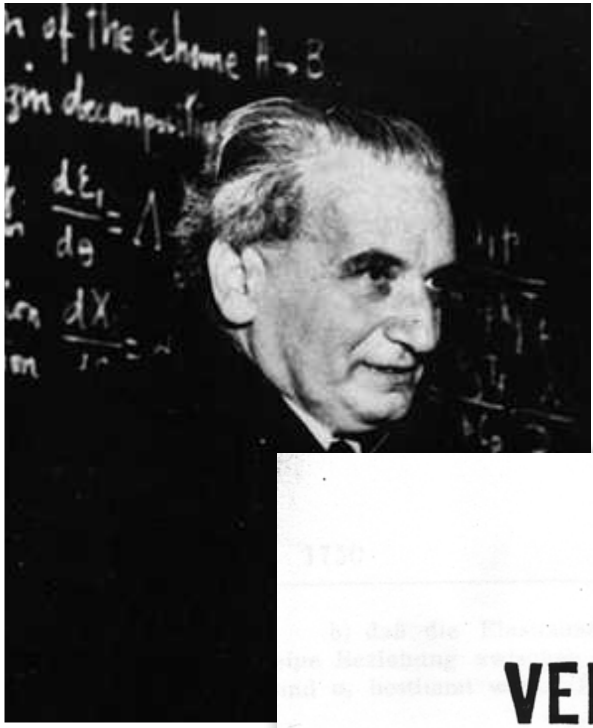
S = shear strength



Henri Édouard Tresca

* 12. Oktober 1814 in Dünkirchen
† 21. Juni 1885 in Paris

Coulomb Mohr Failure



Theodore von Kármán

* 11. Mai 1881 in Budapest als Tódor Kármán
† 7. Mai 1963 in Aachen

ZEITSCHRIFT DES VEREINES DEUTSCHER INGENIEURE.

Nr. 42. Sonnabend, den 21. Oktober 1911. Band 55.

Inhalt:

(hierzu Textblatt 29)

Festigkeitsversuche unter allseitigem Druck.

Von Dr. **Th. v. Kármán** in Göttingen.

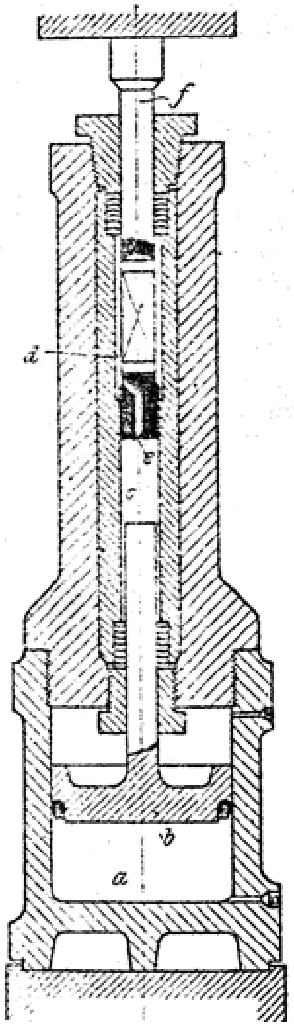
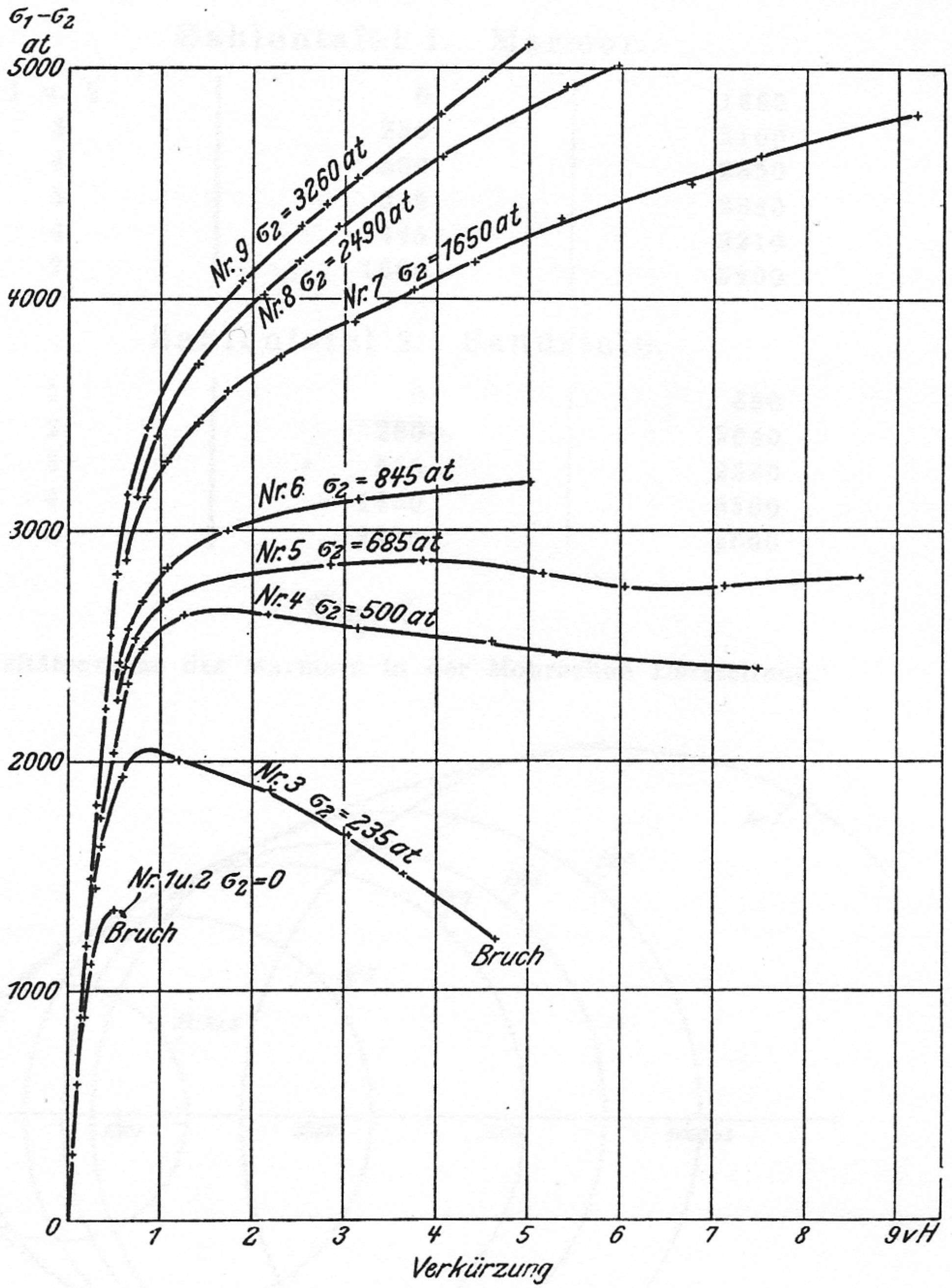


Fig. 5.

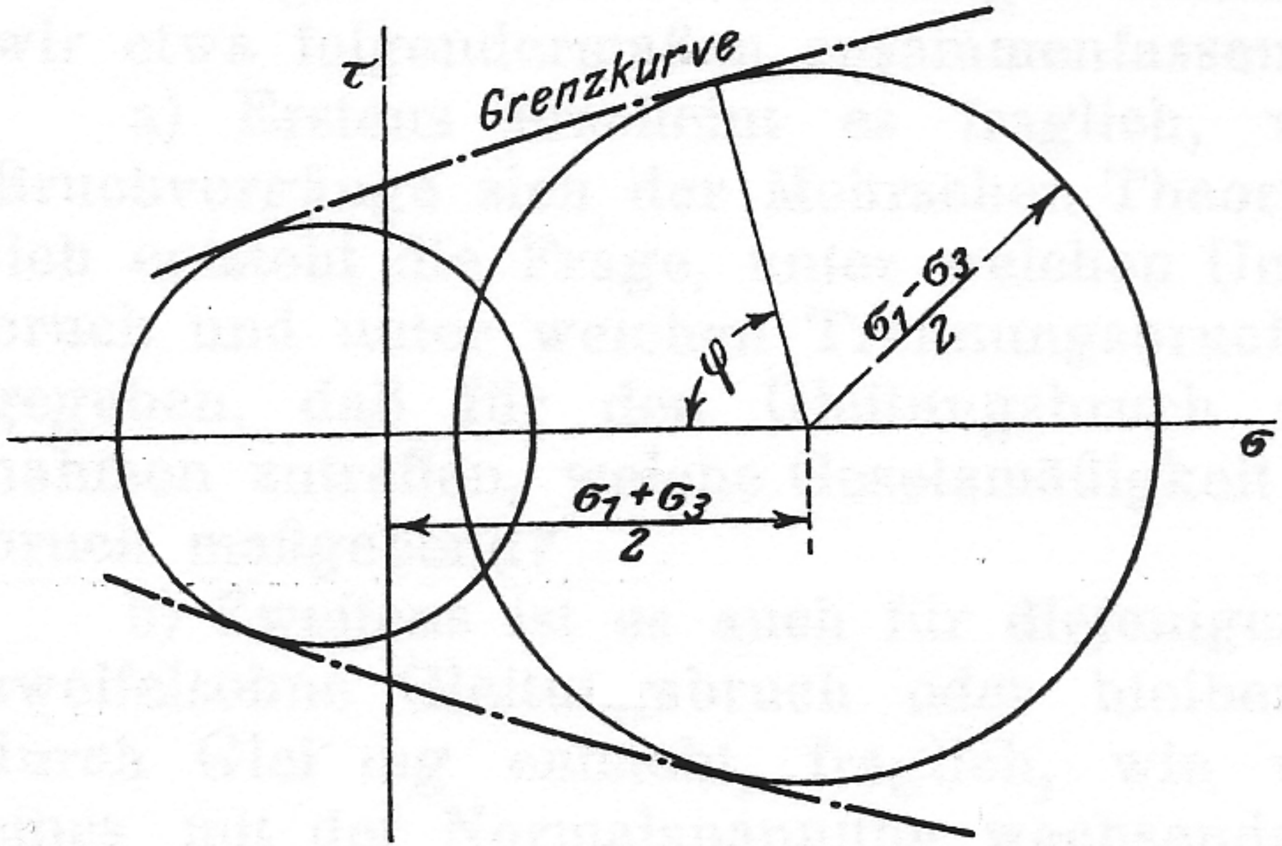
Formänderungskurve des Marmors beim Versuch unter allseitigem Druck.

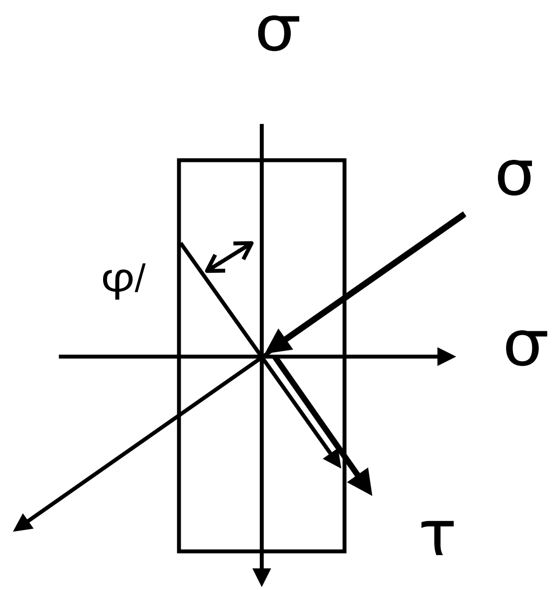


Spannungszustand bei Versagen

Fig. 1.

Darstellung der Grenzzustände nach Mohr.





Versagen

Elastizitätsgrenze

Fig. 7.

Elastizitätsgrenze des Marmors in der Mohrschen Darstellung.

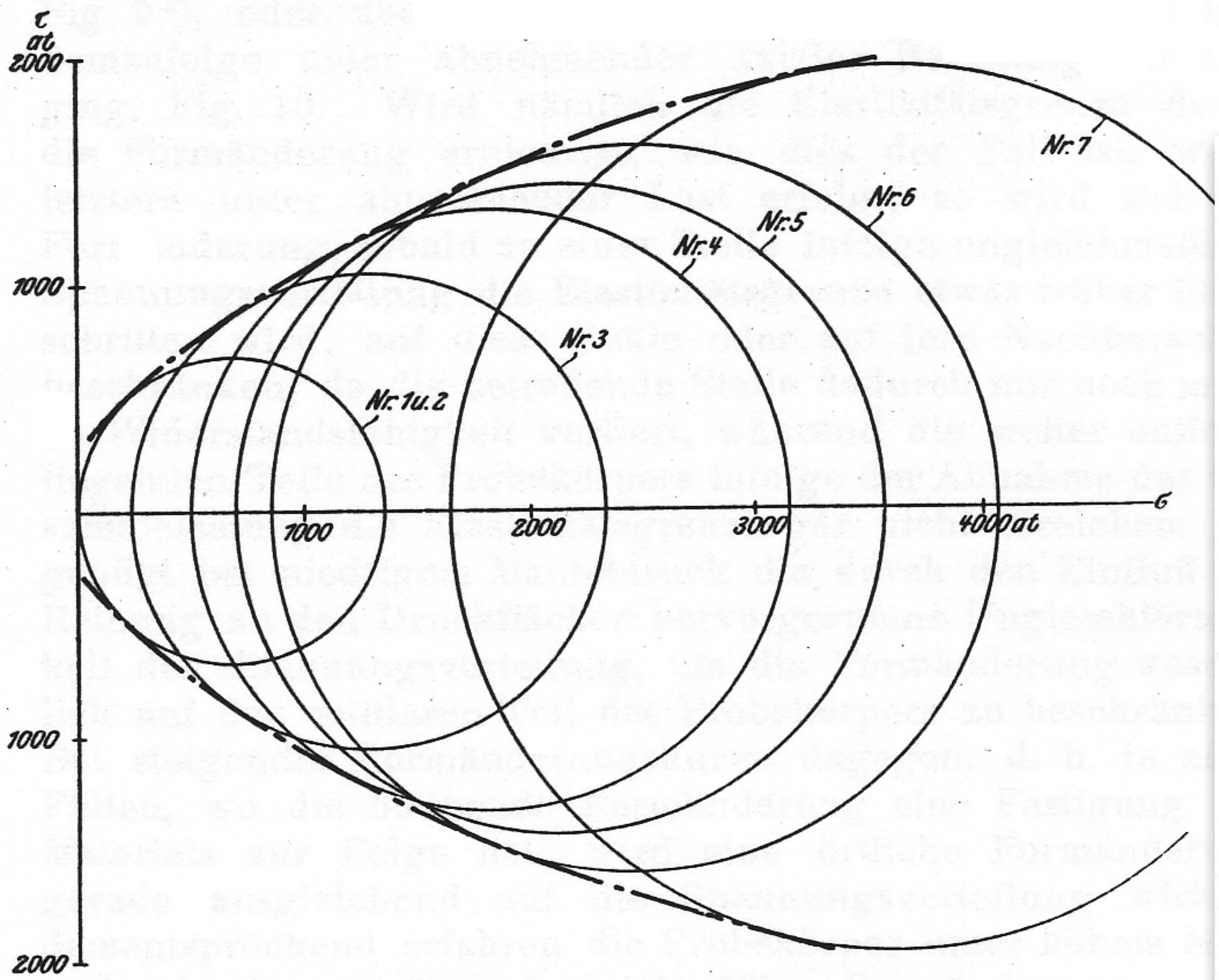
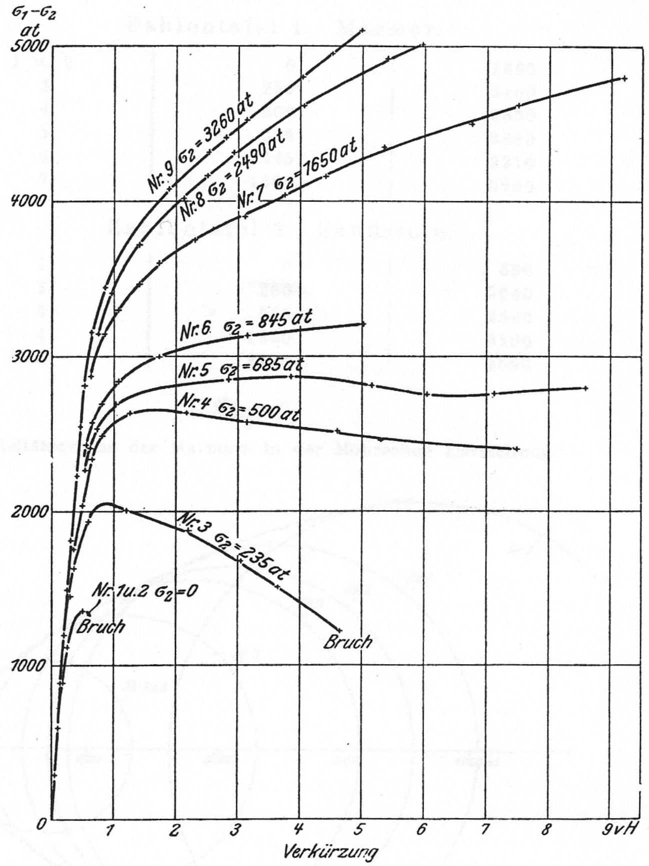


Fig. 5.

Formänderungskurve des Marmors beim Versuch unter allseitigem Druck.



Versagen

Plastizitätsgrenze

Fig. 8.

Kurven gleicher bleibender Dehnung bei Marmor in der Mohrschen Darstellung.

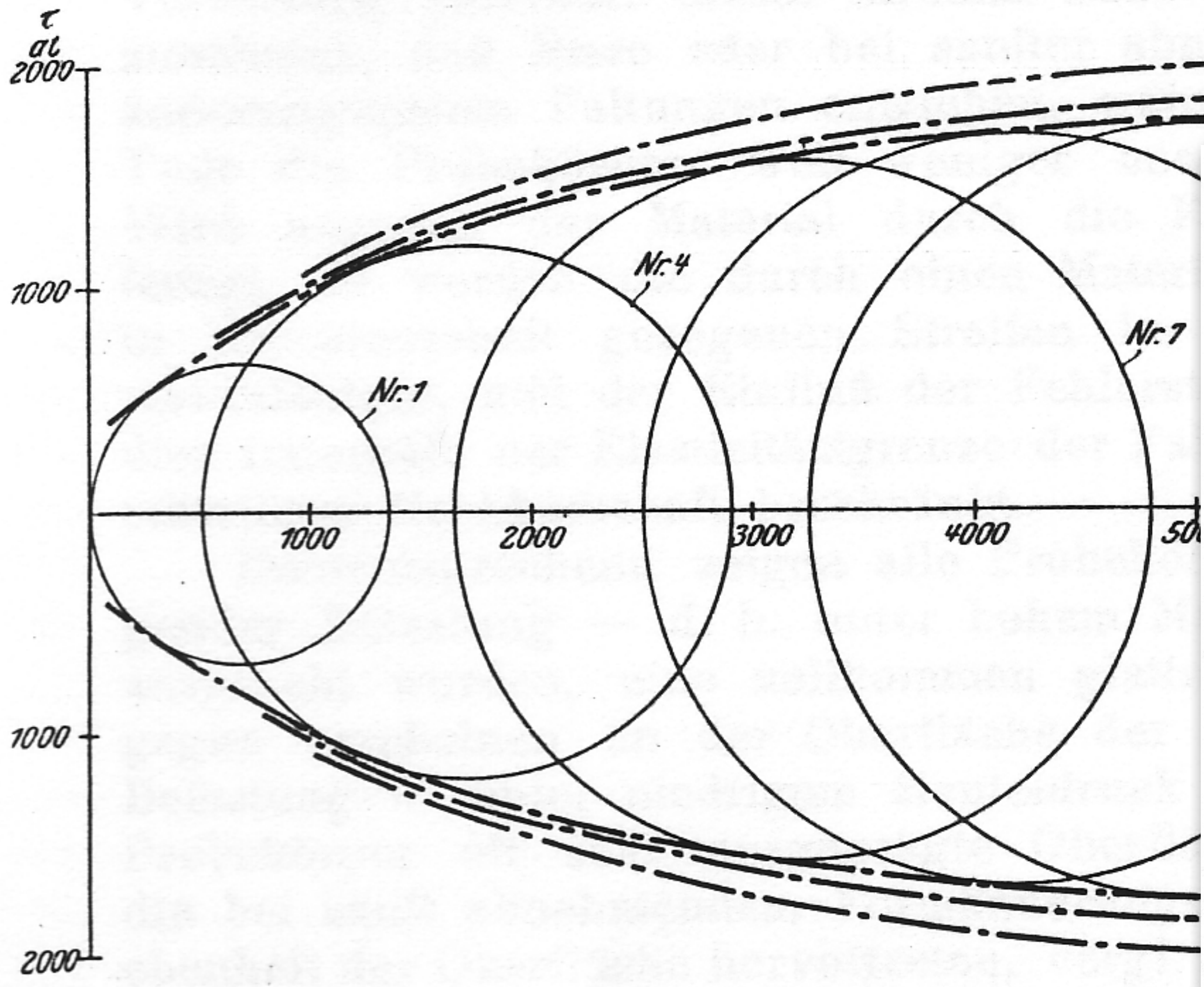
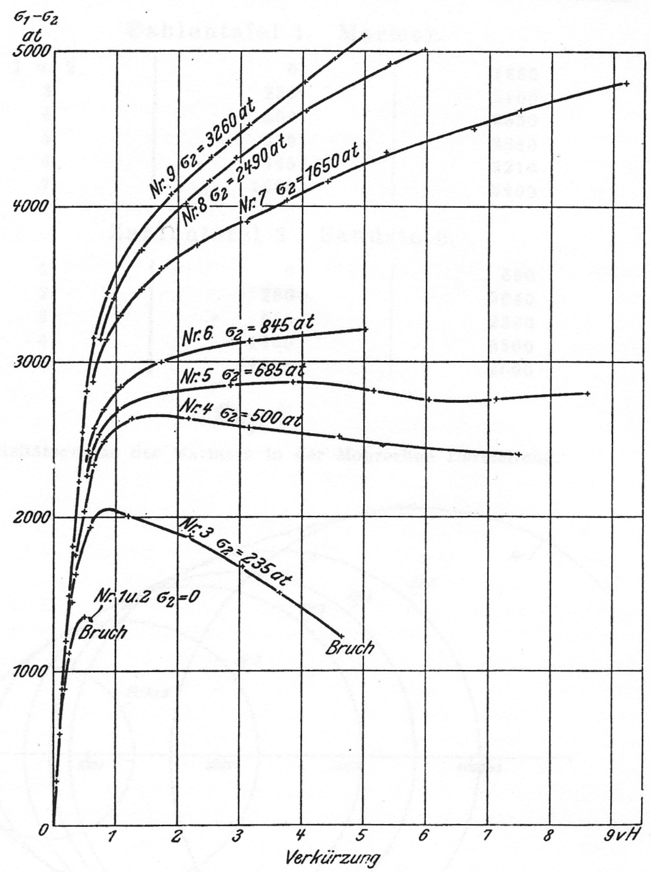
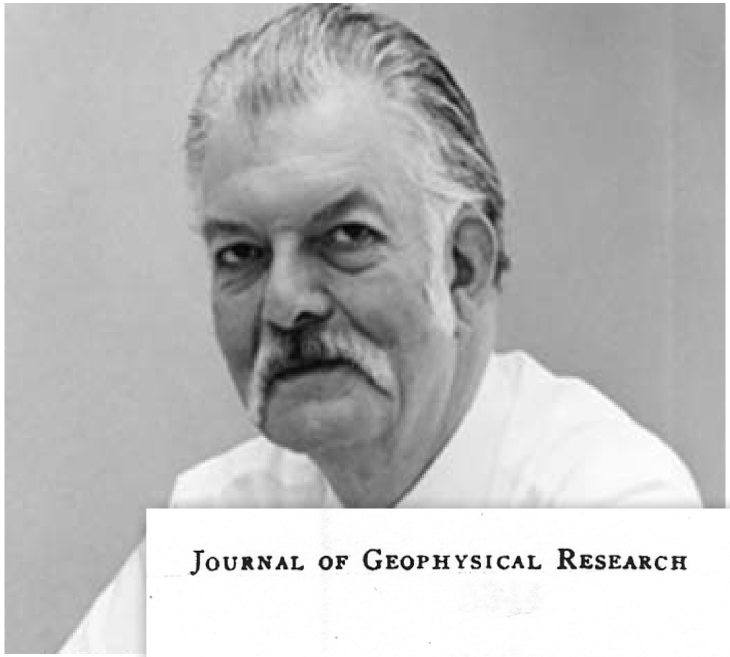


Fig. 5.

Formänderungskurve des Marmors beim Versuch unter allseitigem Druck.





JOURNAL OF GEOPHYSICAL RESEARCH VOL. 74, NO. 22, OCTOBER 15, 1969

On the Coulomb-Mohr Failure Criterion

JOHN HANDIN

Center for Tectonophysics, Texas A&M University
College Station, Texas 77843

Coulomb's criterion for the shear fracture of a brittle material is that total shearing resistance is the sum of the cohesive shear strength (independent of direction) and the product of the effective normal stress and the coefficient of internal friction (a constant independent of normal stress). Mohr generalized this criterion by extending it to a three-dimensional state of stress, and by allowing for a variable coefficient. The coefficients of internal and external (sliding) friction are not the same in general. Both tend to decrease with increasing normal stress, and their relative magnitudes may determine if failure occurs by new shear fracturing or by slip on pre-existing cohesionless surfaces like joints in rocks.

Coulomb Mohr Failure Criterion

Coulomb's [1776] problem was the shear fracture in a prism of isotropic material under uniaxial compression σ_1 (compressive stresses counted positive). He wrote down the equations for the shear stress τ and normal stress σ on a plane inclined at an angle, say θ, to the loading direction. He assumed that 'la cohésion se mesure par la résistance que les corps solides opposent à la désunion directe de leur parties', and 'je suppose ici que l' adhérence oppose une egalé résistance, soit que la force soit dirigée parallèlment ou perpendiculairement au plan de rupture.' He then solved for the value of θ for whi … break-ing st … and he found,

τ_{max} at $\theta = 45°$

During the following two centuries, writers of authority have erroneously stated that Coulomb proceeded no further. For example, in the first edition of his widely known book on faulting *Anderson* [1942] ascribed the notion of internal friction to Navier. *Jaeger* [1962] repeated this mistake. In one edition of his great book, *The Earth*, *Jeffreys* [1952] in turn credits Anderson with this concept!

internal friction $n \cdot \sigma$

slope $n = \tan(\Phi)$

$$\tau = \tau_0 + n \cdot \sigma$$

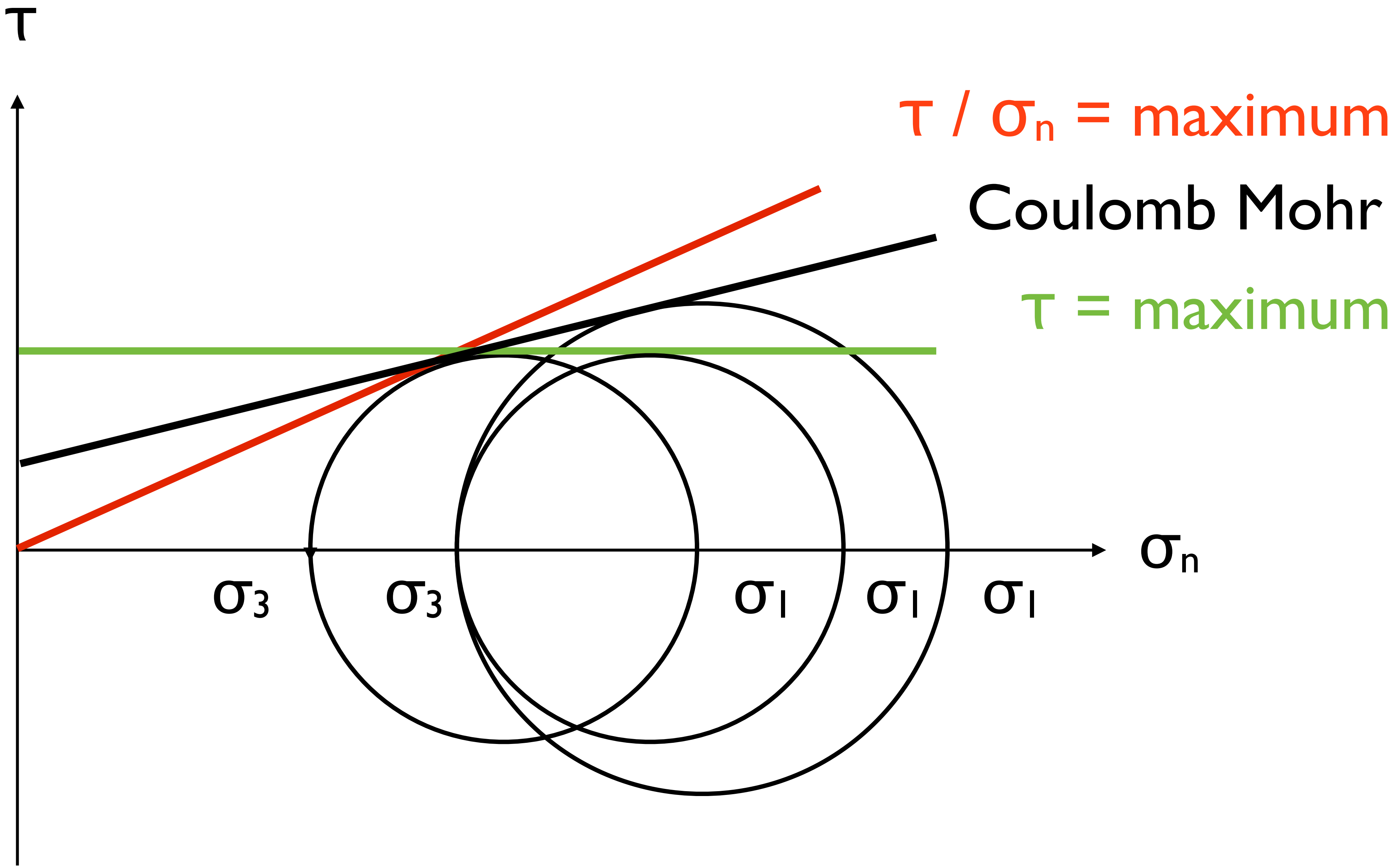
cohesion τ_0

$$\theta_f = \pm 45° \mp \Phi / 2$$

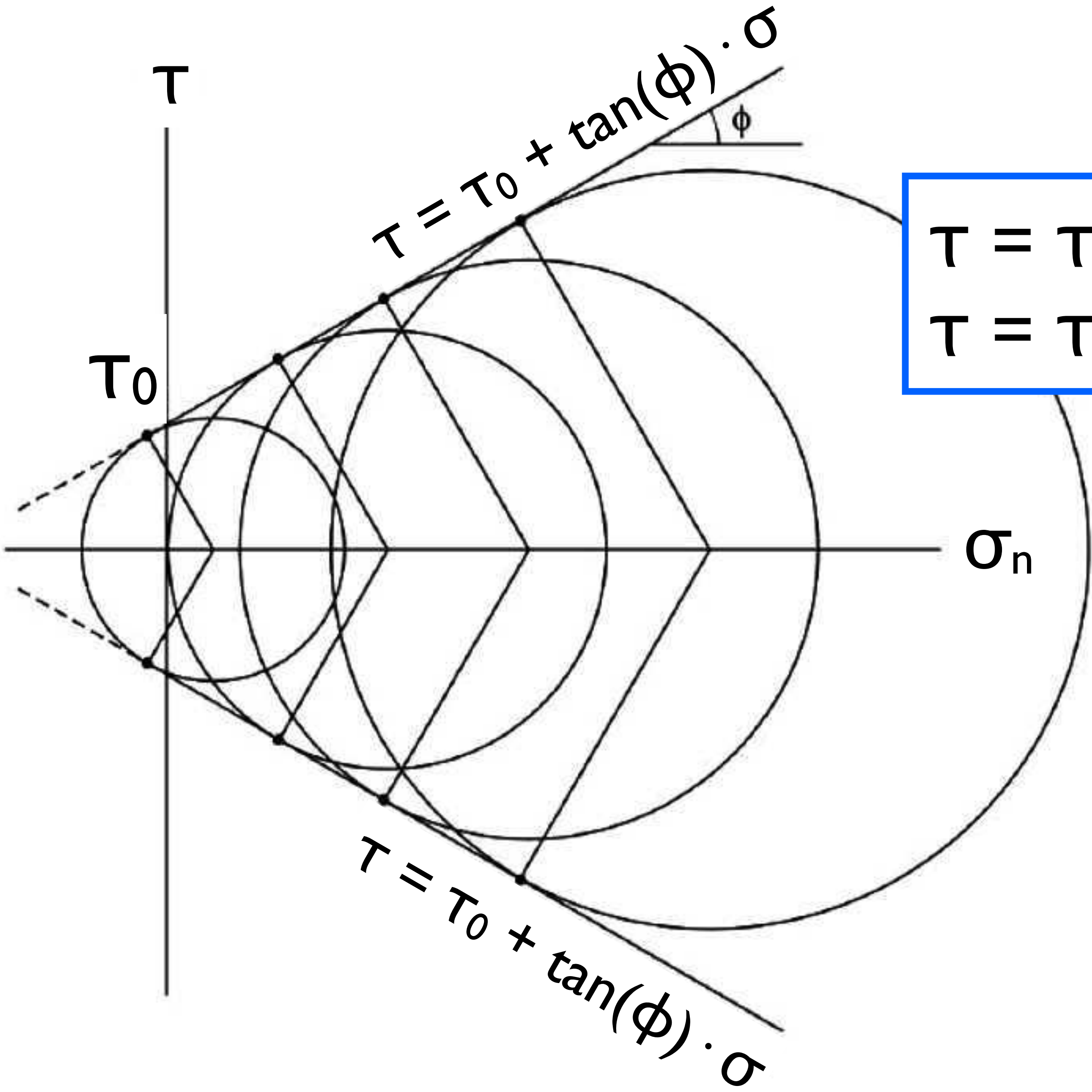
θ_f angle of failure

Φ angle of internal friction

Coulomb Mohr Failure Criterion



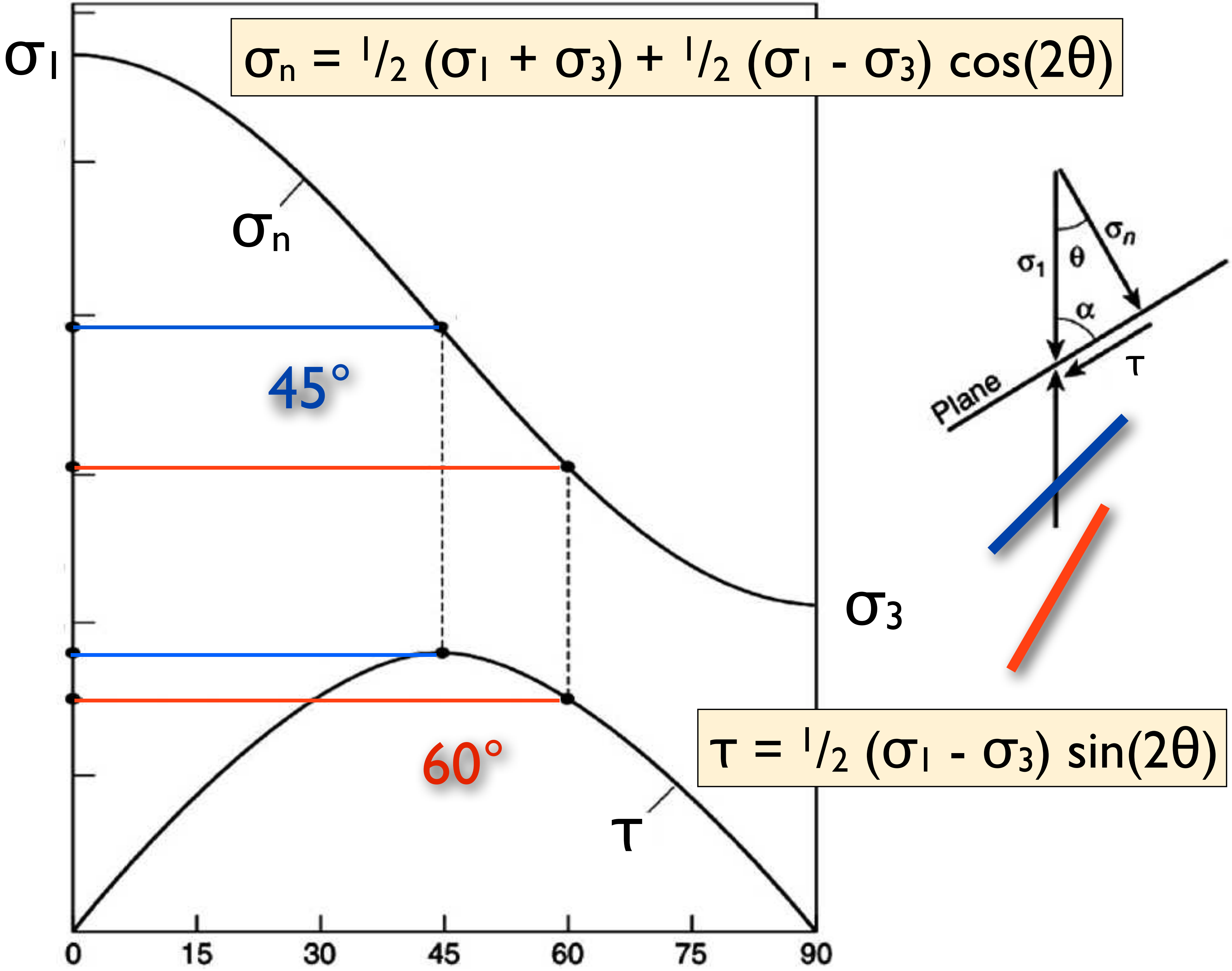
Coulomb Mohr Failure Criterion



$$\tau = \tau_0 + n \cdot \sigma$$

$$\tau = \tau_0 + \tan(\phi) \cdot \sigma$$

$$\sigma_n = \tfrac{1}{2}(\sigma_1 + \sigma_3) + \tfrac{1}{2}(\sigma_1 - \sigma_3)\cos(2\theta)$$

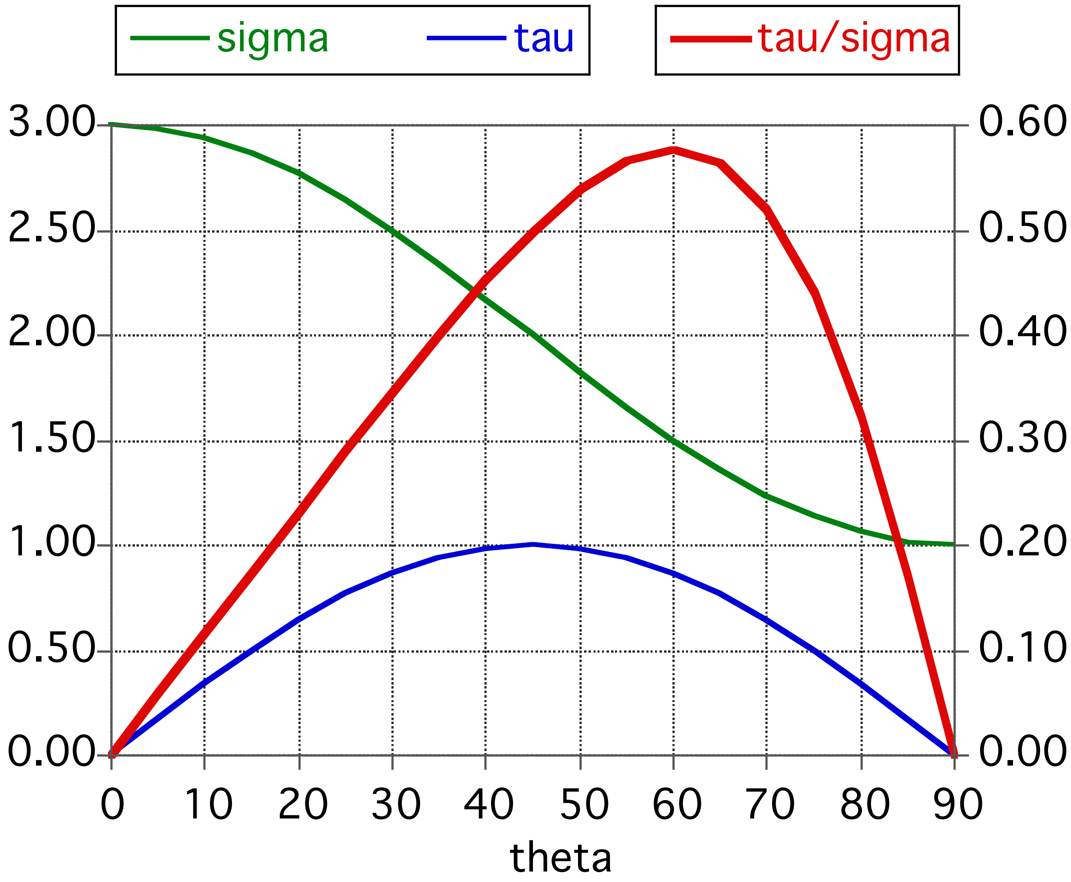


$$\tau = \tfrac{1}{2}(\sigma_1 - \sigma_3)\sin(2\theta)$$

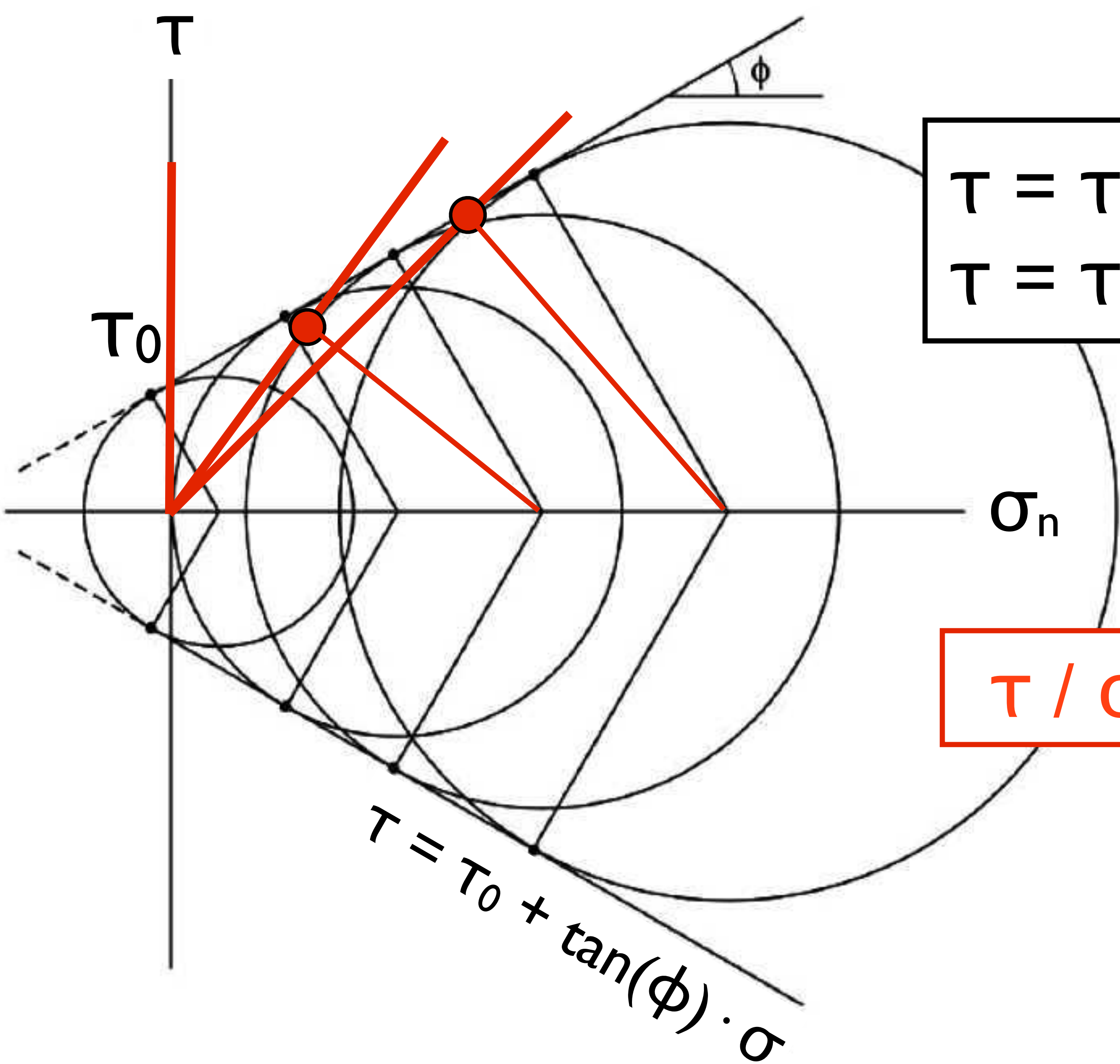
maximum stress ratio τ/σ

$$\sigma = (\sigma_1+\sigma_3) + (\sigma_1-\sigma_3) \cdot \cos(\theta)$$

$$\tau = (\sigma_1-\sigma_3) \cdot \sin(\theta)$$



Coulomb Mohr Failure Criterion



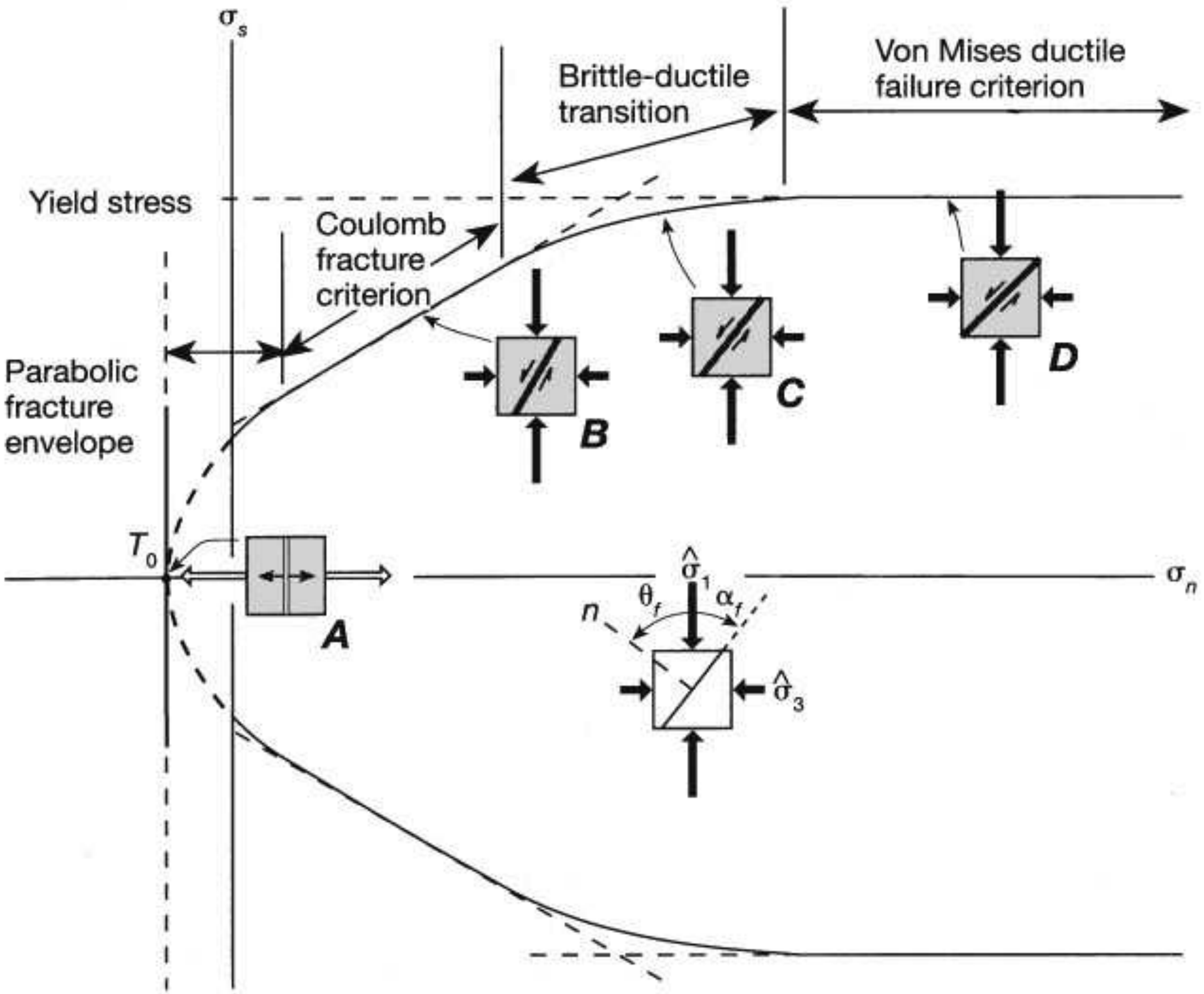
$\tau = \tau_0 + n \cdot \sigma$

$\tau = \tau_0 + \tan(\phi) \cdot \sigma$

≠

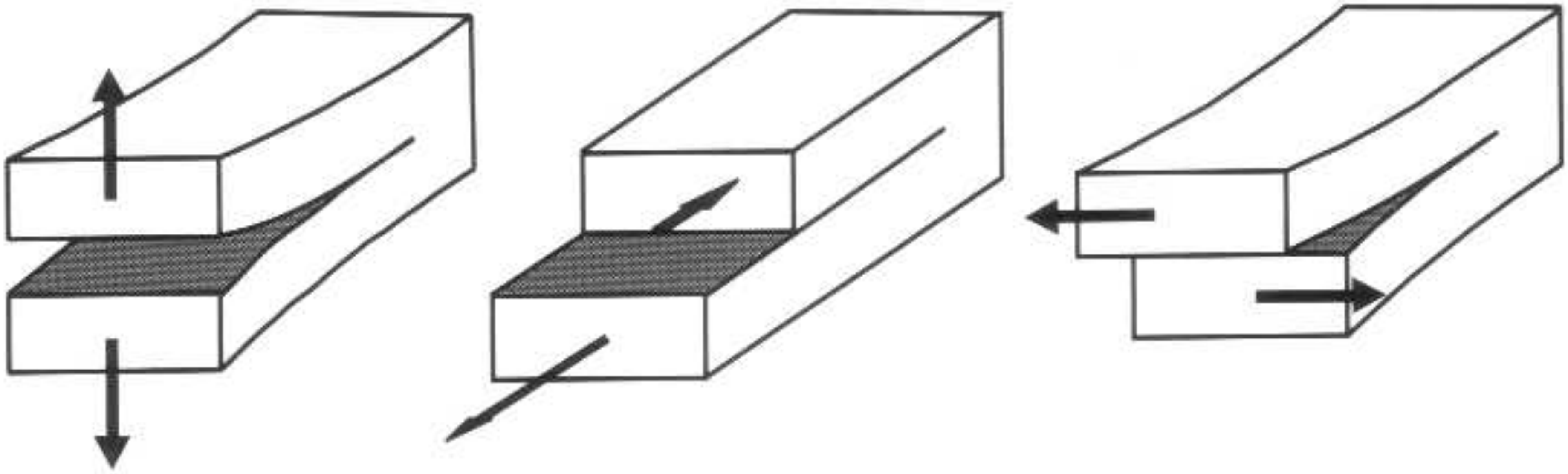
τ / σ_n = maximum

Mohr'sche Umhüllende



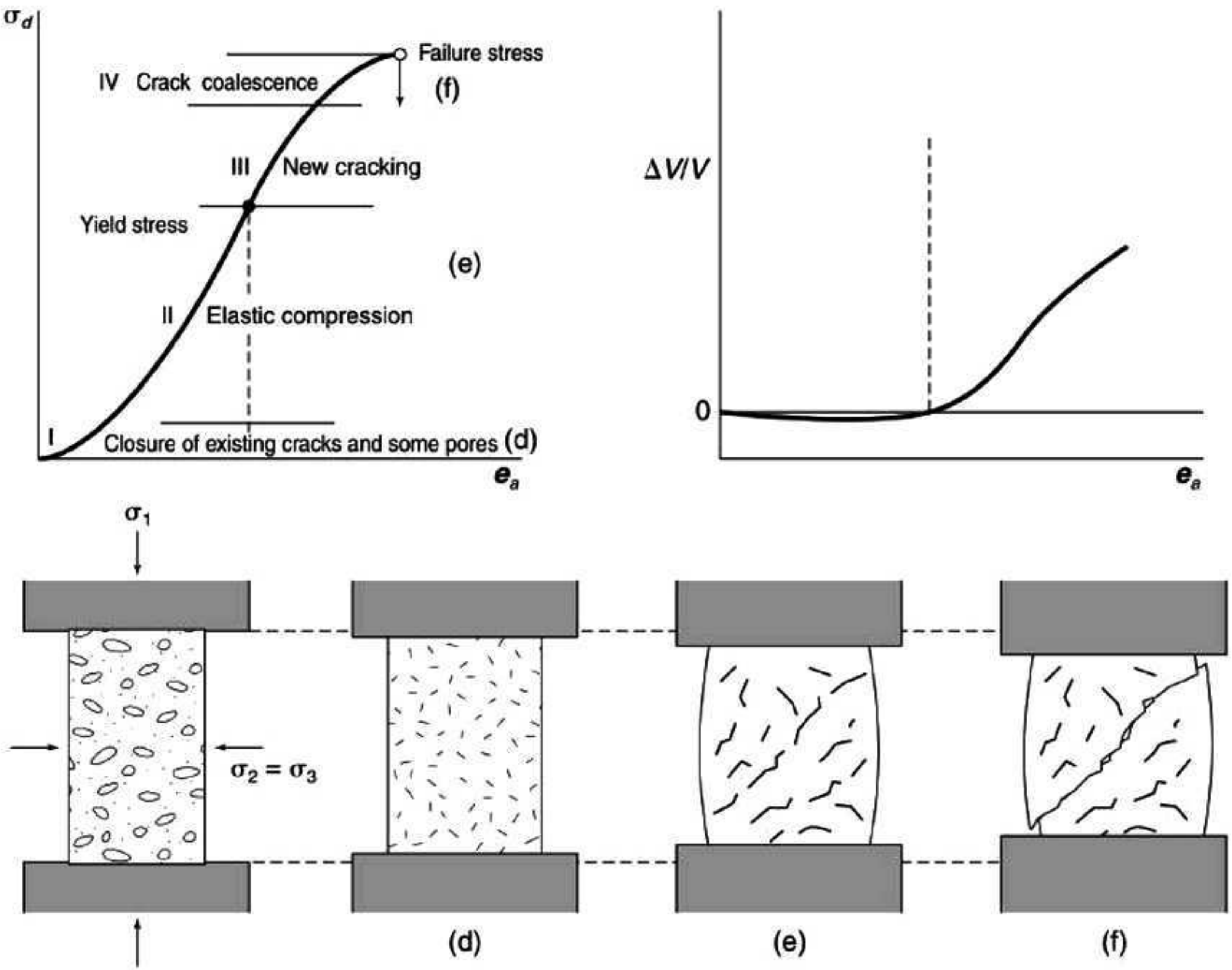
Bruchbildung

Fracture mode



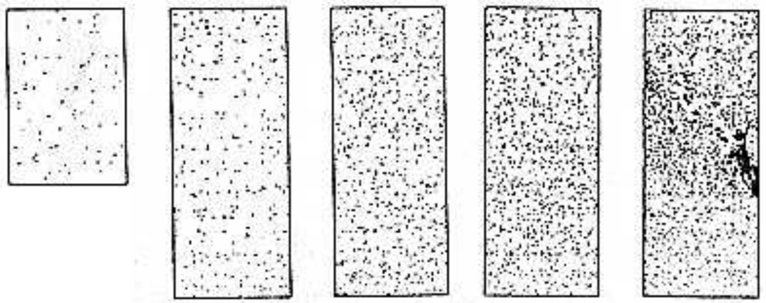
mode I mode II mode III

Fracture formation



Fracture formation

Microfracturing of sandstone 50 ·127 mm cylinders

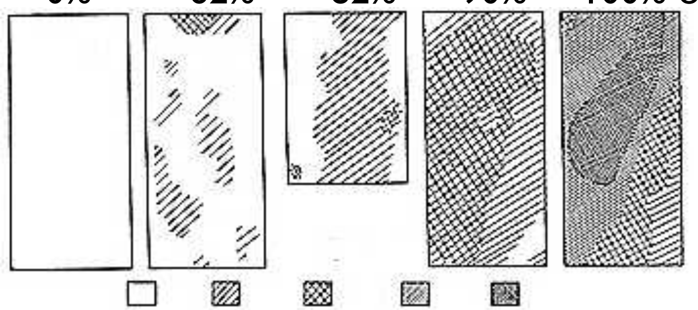


0% 25% 50% 83% 100%
of maximum stress (vertical, pc=0)

Sangha, C.M., Talbot, C.J., Dhir, R.K., 1974. Microfracturing of a sandstone in uniaxial compression. Int. J. Rock Mech. Min. Sci., Abstr. Vol. 11, 107-113

Microfracturing of gabbro 50 ·100mm cylinders

0% 62% 82% 90% 100% $\sigma_{ultimate}$

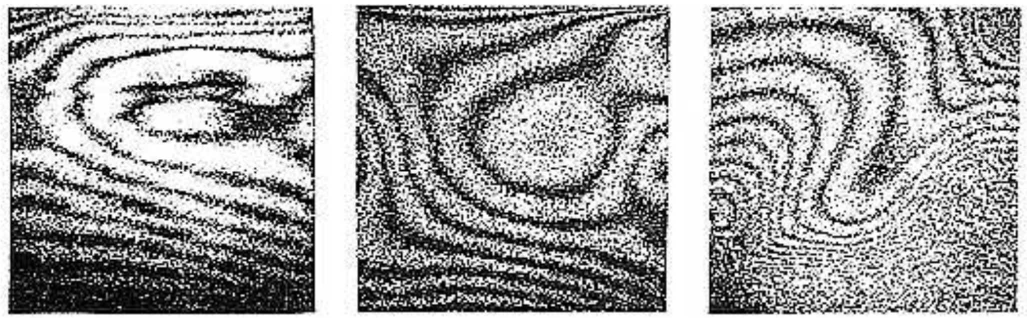


0-2 2-3 3-4 6-12 >12

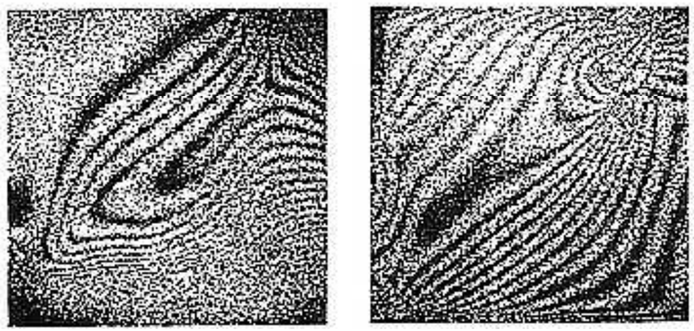
Optical reflectivity ratio (= microcrack density) w/r to average reflectivity (pc = 130 MPa

Chen Rong, Yao Xiao-Xin, Xie Hung-Sen, 1979. Studies of fracture of gabbro. Int. J. Rock Mech. Min. Sci., Abstr. Vol. 16,

Dilatancy of pyrophyllite blocks 30 ·30 ·33 mm



0% 50% 81%

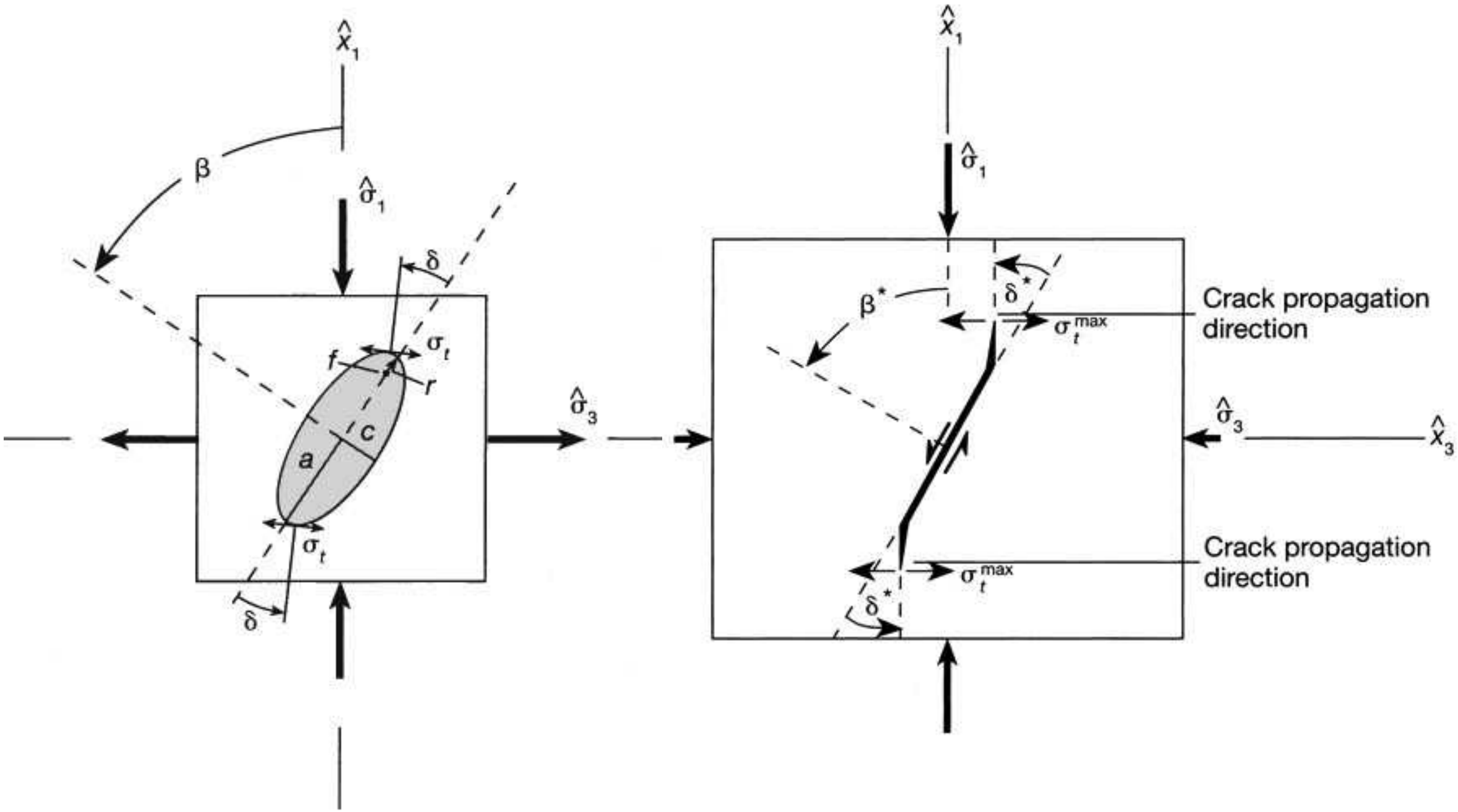


84% 100%

Doubly exposed holograms; % of $\sigma_{ultimate}$ (vertical)

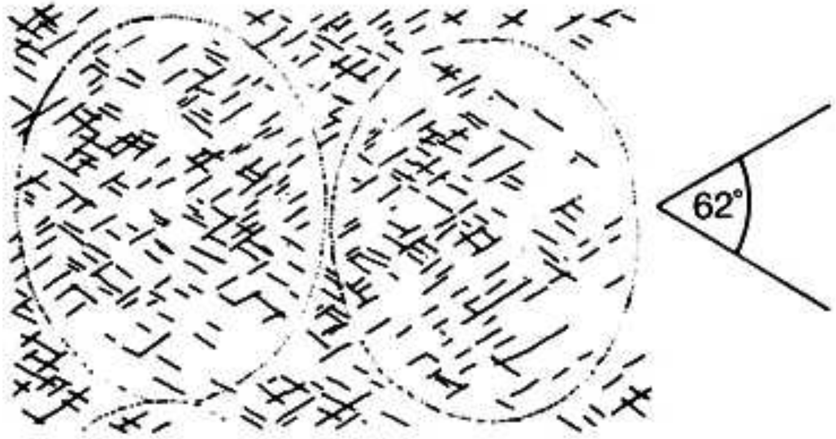
Sobolev G, Spetzler H., Salov, B., 1978.
Precursors to failure in rocks while undergoing anelastic deformation.
JGR 83, 1775-1784

Bruchentwicklung

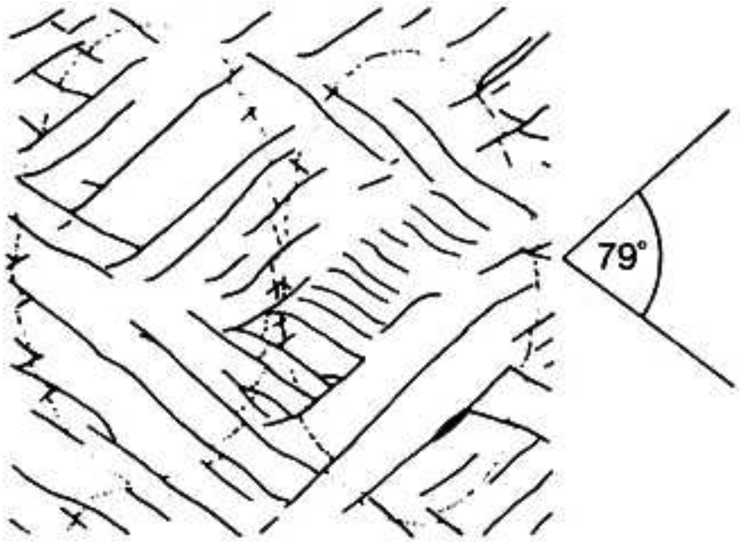


Shear Fractures

s_1 = 1.12 $\hat{s}_3$ = s_3 = 0.89



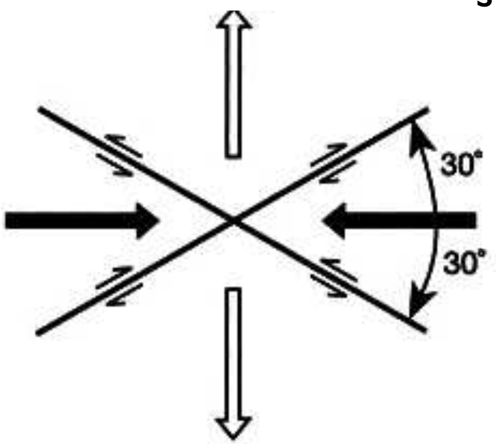
s_1 = 1.37 s_3 = 0.73



layer of clay on rubber sheet
intitial stretch:
pervasive Mohr Coulomb

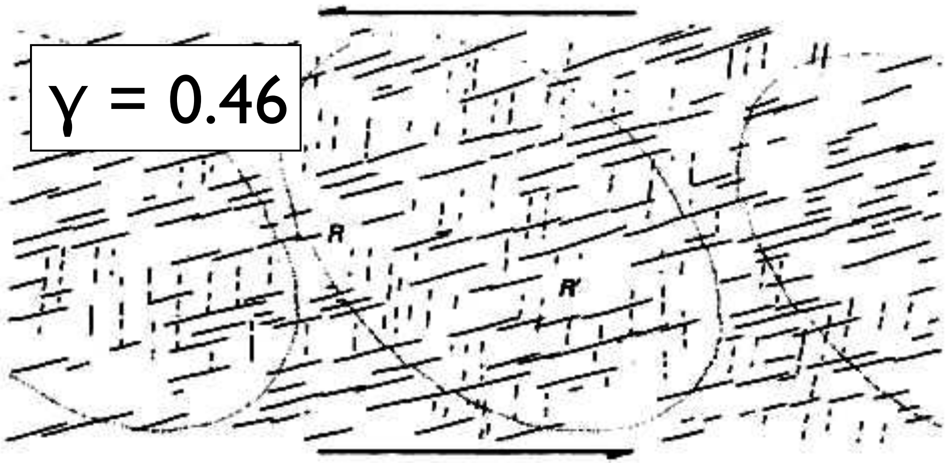
continued stretch:
separation of regions

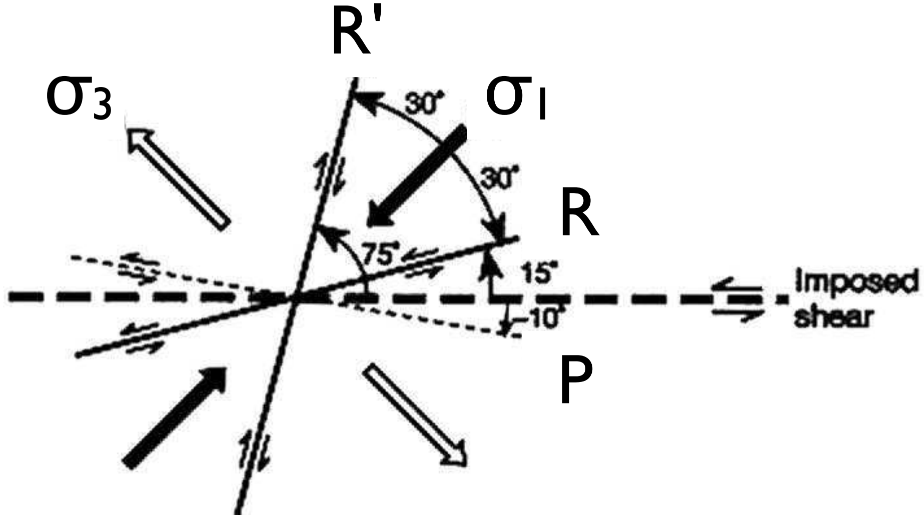
σ_3

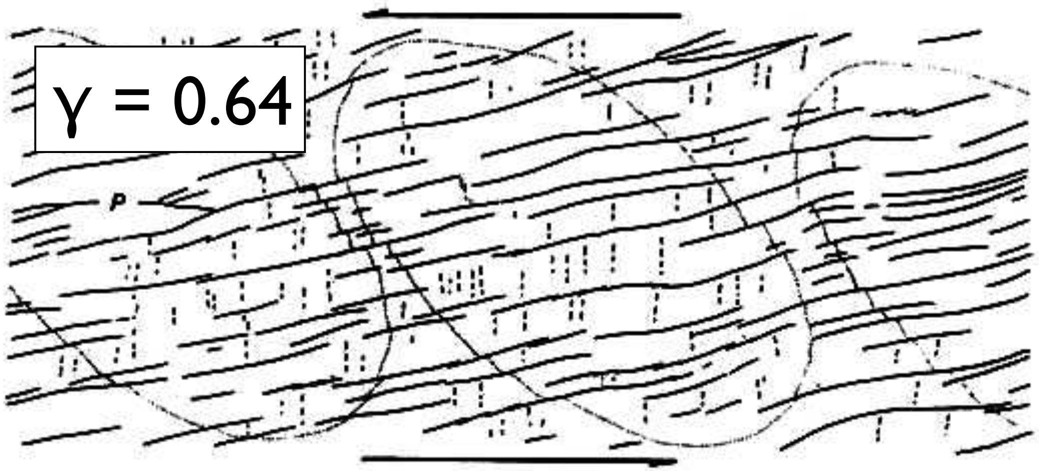


σ_1

Riedel Shear Fractures



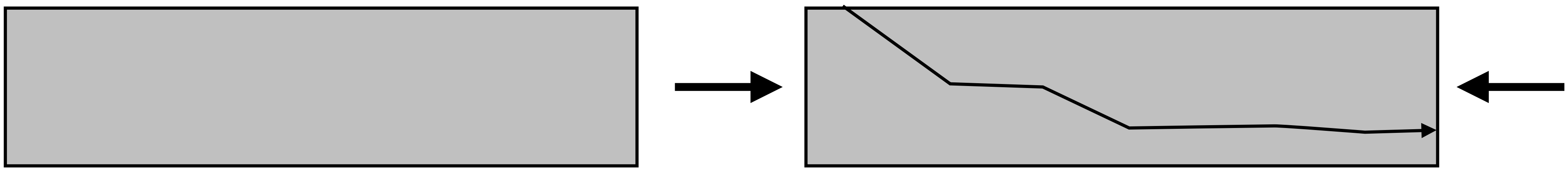




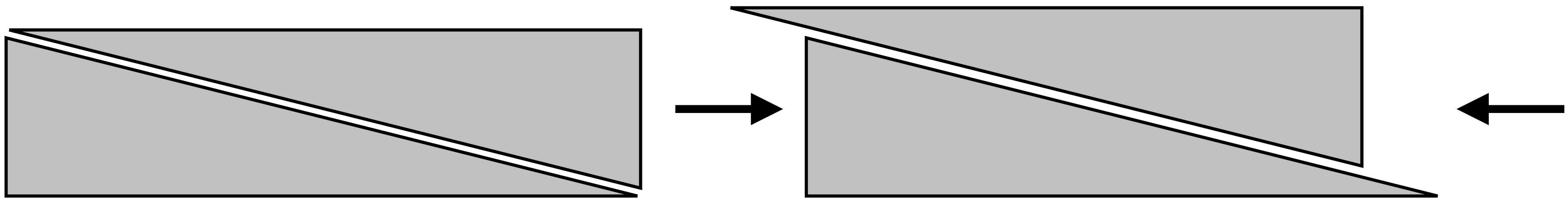
Reibung

fracture - friction

Intakter Körper: Bruchbildung



Bruchfläche vorhanden: Gleiten auf Bruch



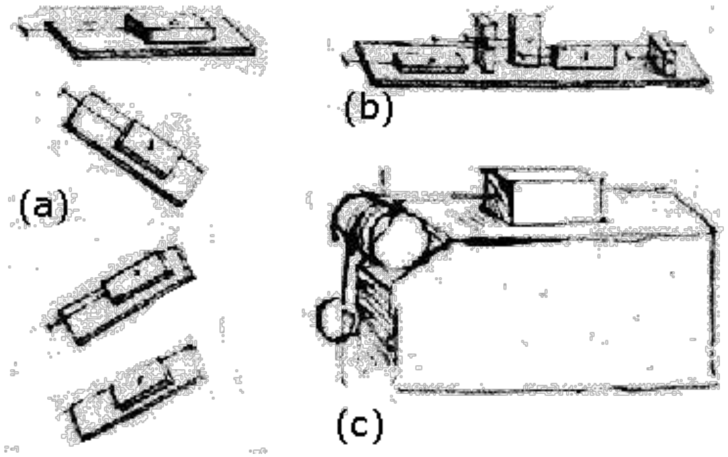
Friction

Law of Leonardo da Vinci:
Friction is independent of the area of contact

Leonardo Da Vinci (1452-1519)

Leonardo da Vinci stated the two basic laws of friction 200 years before Newton even defined what force is.

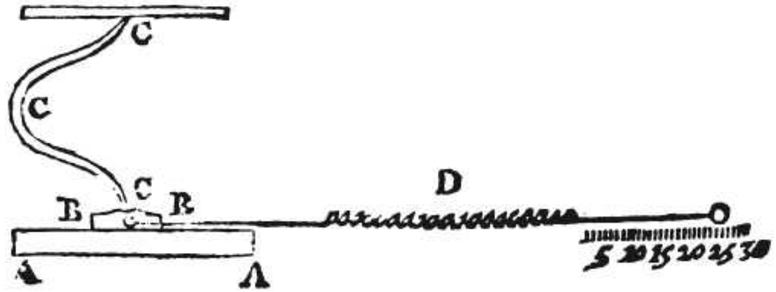
1. the areas in contact have no effect on friction.
2. if the load of an object is doubled, its friction will also be doubled.



http://www.nano-world.org/ area.mov

Friction

Law of Euler and Amontons:
Friciton is proportional to
the loading force



Versuchsaufbau von G. Amontons zur Messung der kinetischen Reibkraft. Die Reibung zwischen den Oberflächen A und B wird mittels der Auslenkung einer Feder D gemessen. Die Feder C dient der Einstellung der Normalkraft.

(De la résistance causée dans les machines (1699) in Memoires de l'Académie des Sciences.)

Guillaume Amontons (1663-1705)
Leonhard Euler (1701-1783)

- Reibung verändert sich mit der Last (Normalkraft) nicht aber mit der Berührungsfläche der reibenden Körper.
- Die Reibung ist mehr oder weniger dieselbe für Eisen, Blei, Kupfer und Holz in beliebiger Kombination, wenn die Flächen mit Schweinefett eingerieben sind.
- Die Reibkraft entspricht ungefähr einem Drittel der Last (Normalkraft).

http://www.nano-world.org/ normalforce.mov

Friction

Law of Coulomb:
Friction is independent of the velocity

Essaie sur la théorie du frottement

Holz auf Holz: Reibung nimmt anfänglich zu, erreicht Maximum, danach ist die Reibkraft proportional zur Normalkraft.

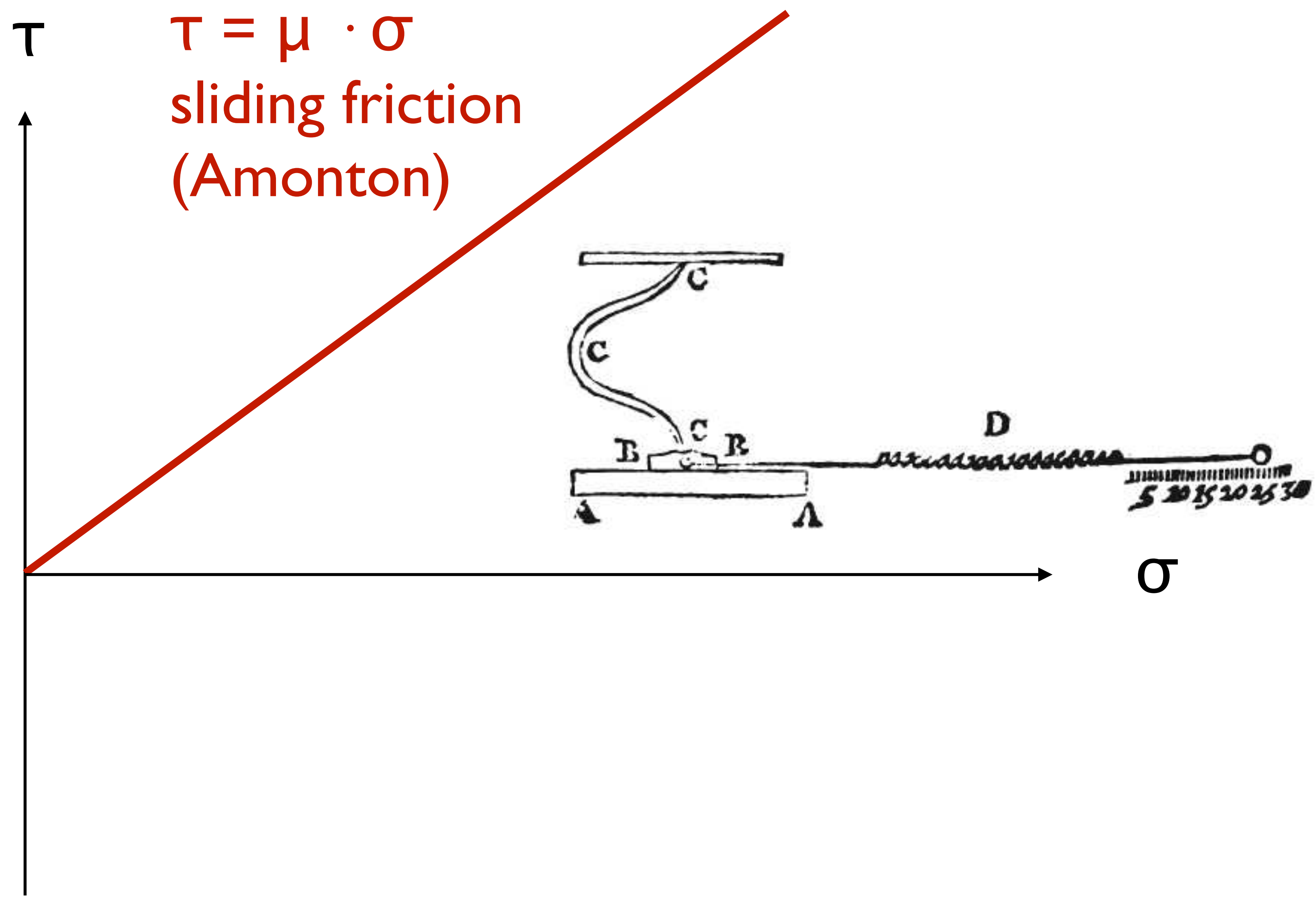
Holz auf Holz: Reibung proportional zur Normalkraft bei jeder Geschwindigkeit.
Kinetische Reibung ist einiges geringer als statische Reibung gemessen nach langer Ruhezeit der Materialien.

Metall auf Metall: Reibung ist proportional zu Normalkraft
Kein Unterschied zwischen statischer und kinetischer Reibung.

http://www.nano-world.org/ velocity.mov

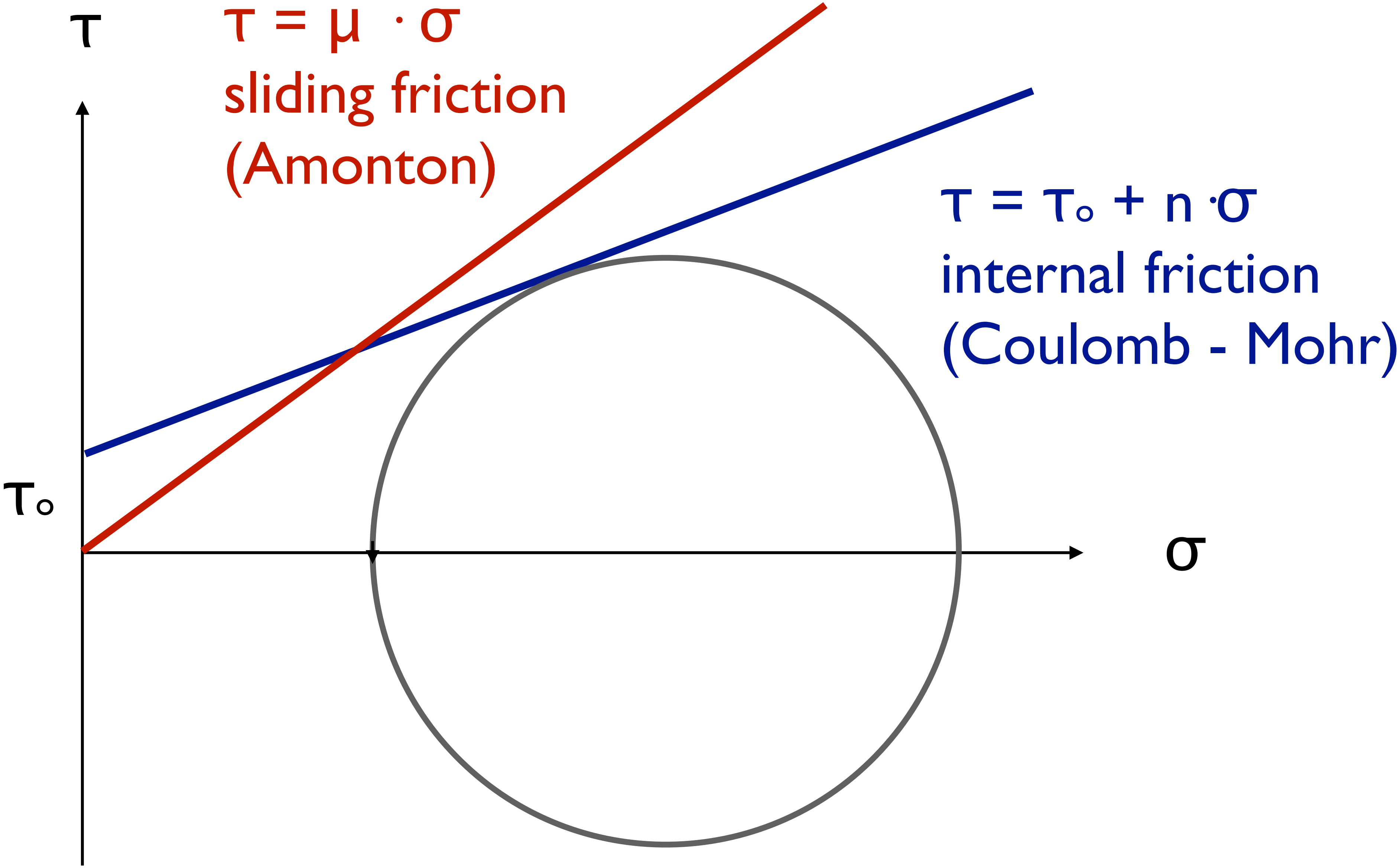
sliding friction

Gleitreibung



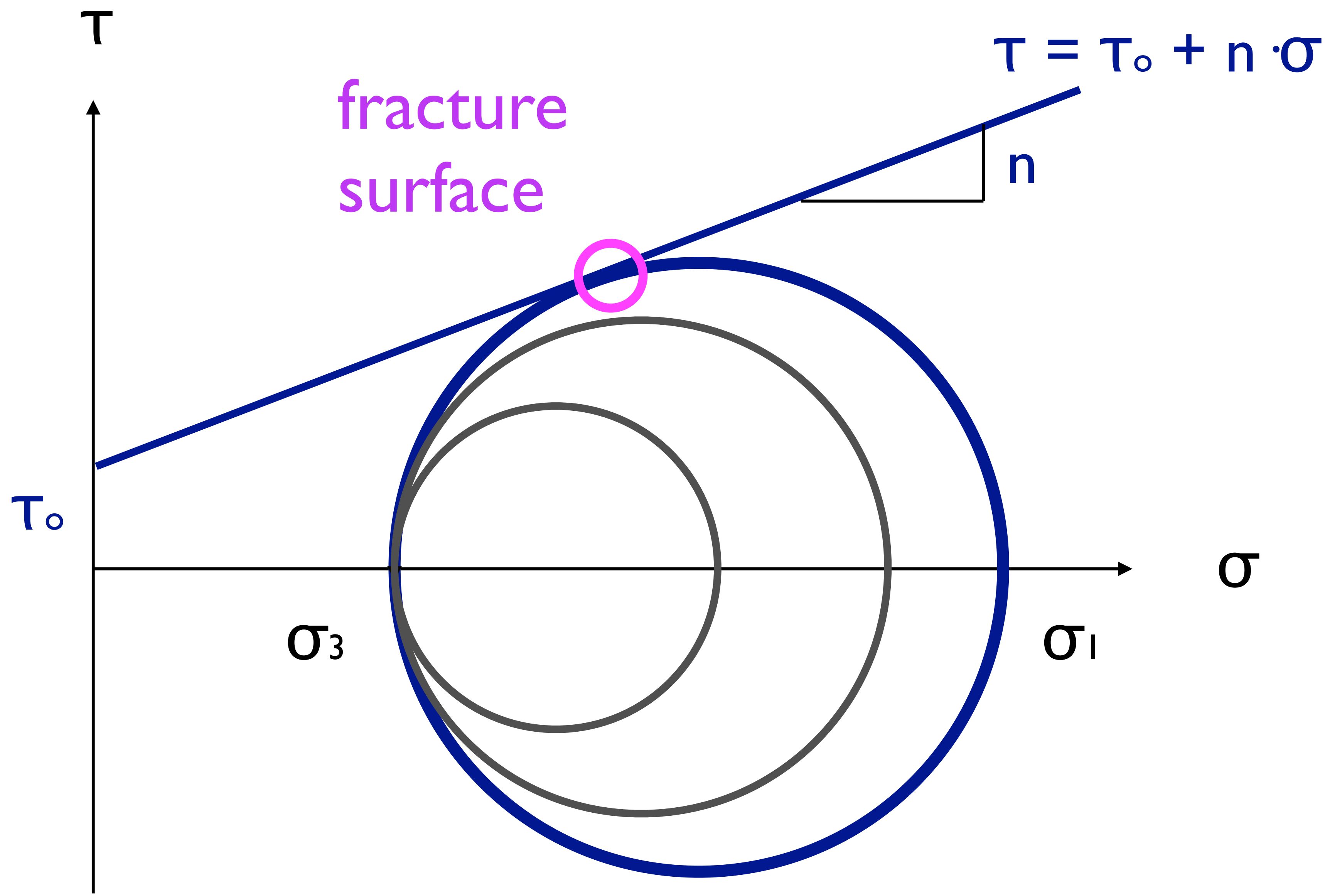
Byerlee's rule

Sliding friction



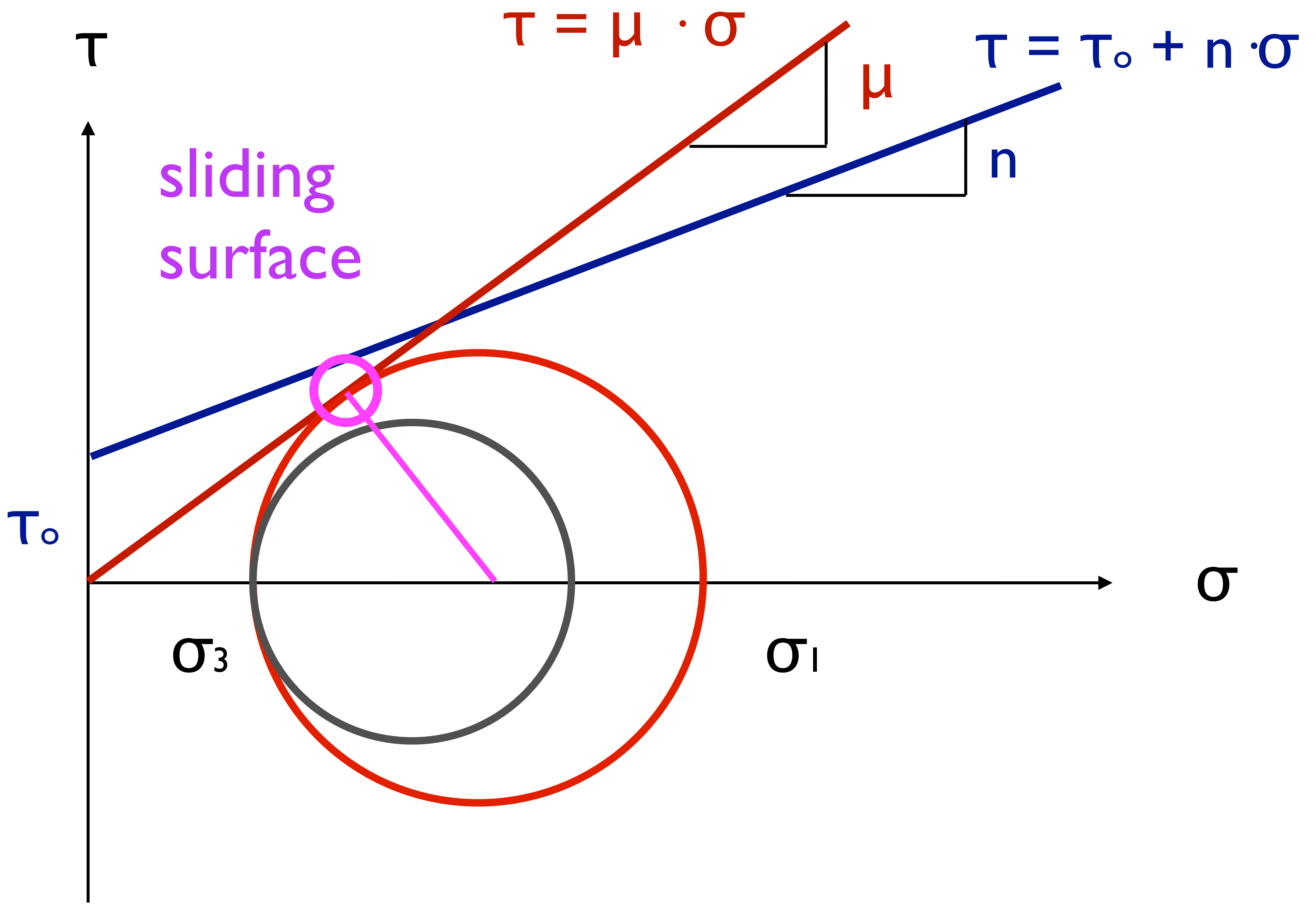
fracture

Bruchbildung

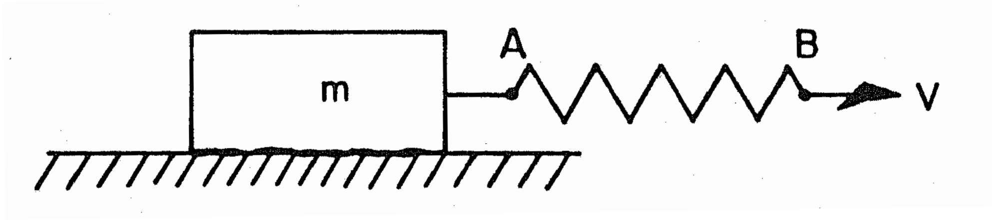


friction

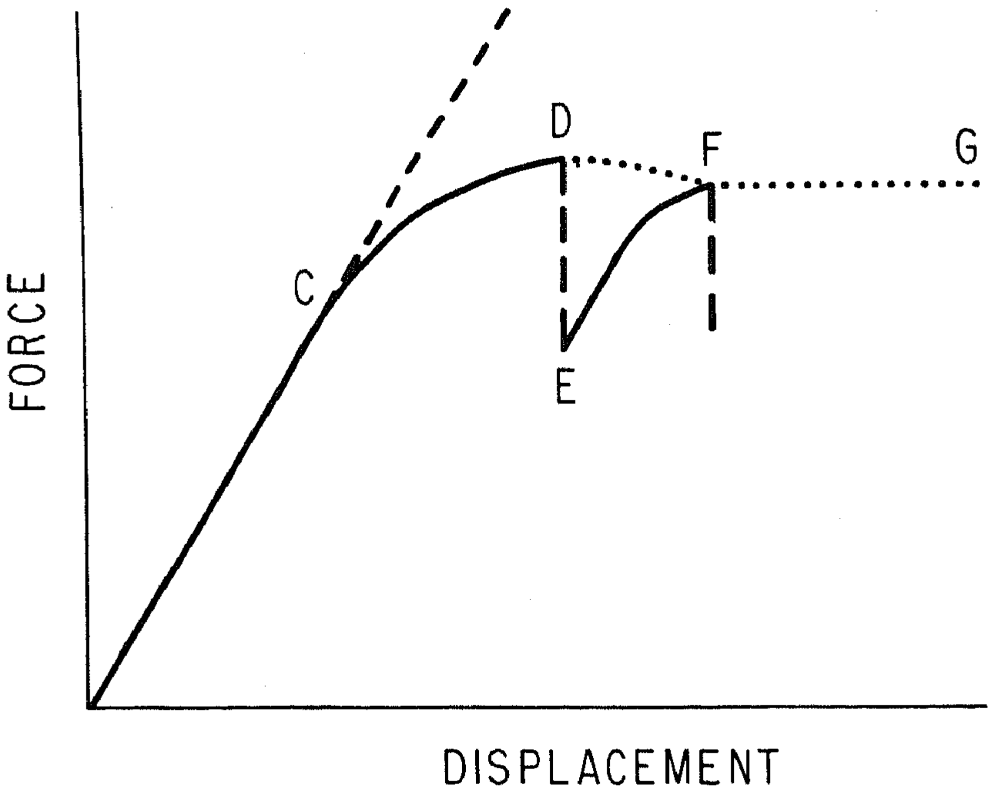
Reibung



Byerlee's rule



C=initial friction
D=maximum friction
G= residual friction



Byerlee's rule

7. Conclusions

The experimental results show that at the low stresses encountered in most civil engineering problems the friction of rock can vary between very wide limits and the variation is mainly because at these low stresses friction is strongly dependent on surface roughness. At intermediate pressure such as encountered in mining engineering problems and at high stresses involved during sliding on faults in the deep crust the initial surface roughness has little or no effect on friction. At normal stresses up to 2 kb the shear stress required to cause sliding is given approximately by the equation

$$\tau = 0.85\sigma_n.$$

At normal stresses above 2 kb the friction is given approximately by

$$\tau = 0.5 + 0.6\sigma_n.$$

These equations are valid for initially finely ground surfaces, initially totally interlocked surfaces or on irregular faults produced in initially intact rocks. Rock types have little or no effect on friction.

If however, the sliding surfaces are separated by large thicknesses of gouge composed of minerals such as montmorillonite or vermiculite the friction can be very low. Since natural faults often contain gouge composed of alteration minerals the friction of natural faults may be strongly dependent on the composition of the gouge.

Byerlee's rule

static friction

for σ_n =

0 - 2 GPa

(0 - 20 kb)

≈ 80 km

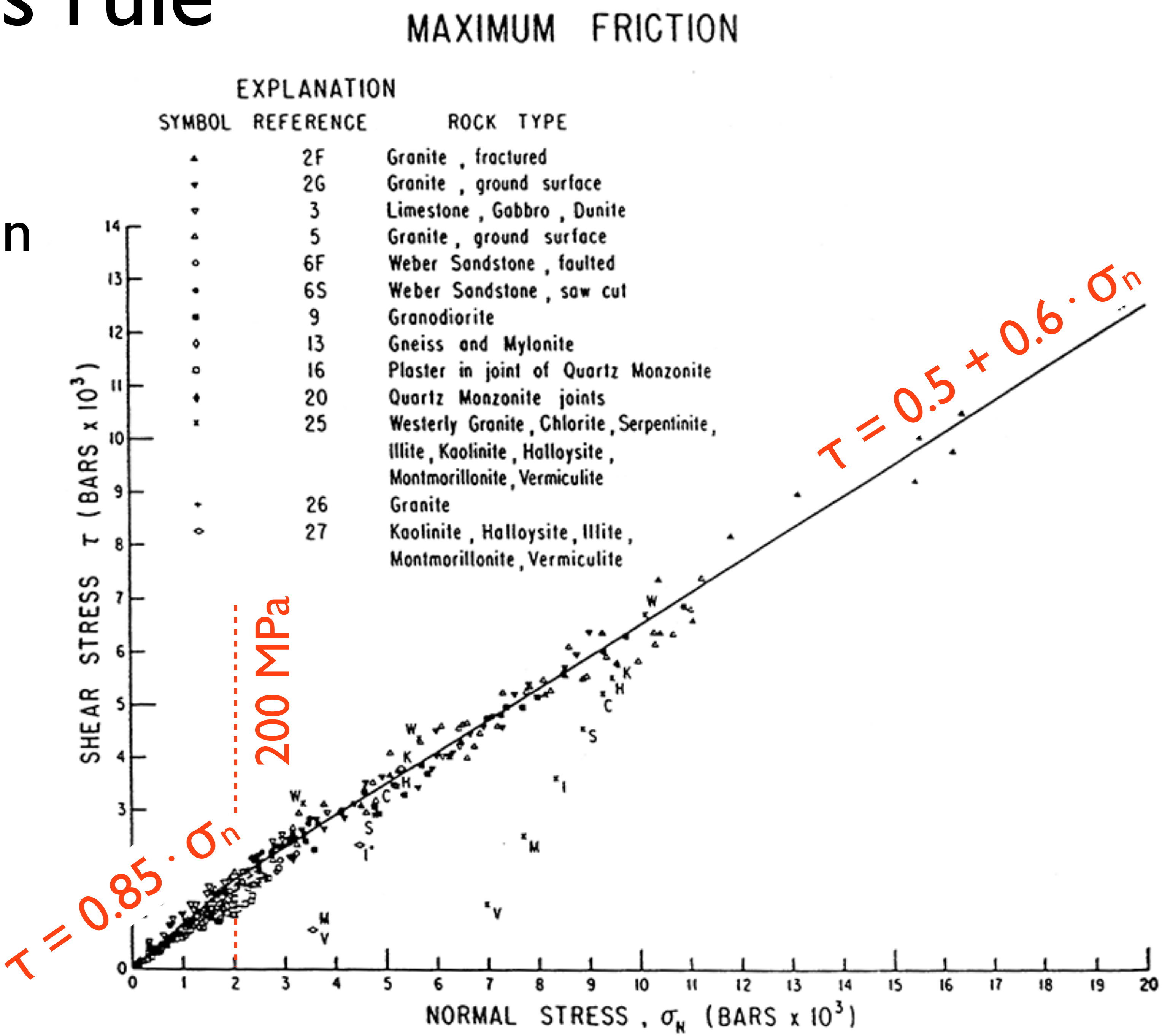


fig. 7 (Byerlee, 1978)

Klüfte und Brüche
joints & fractures

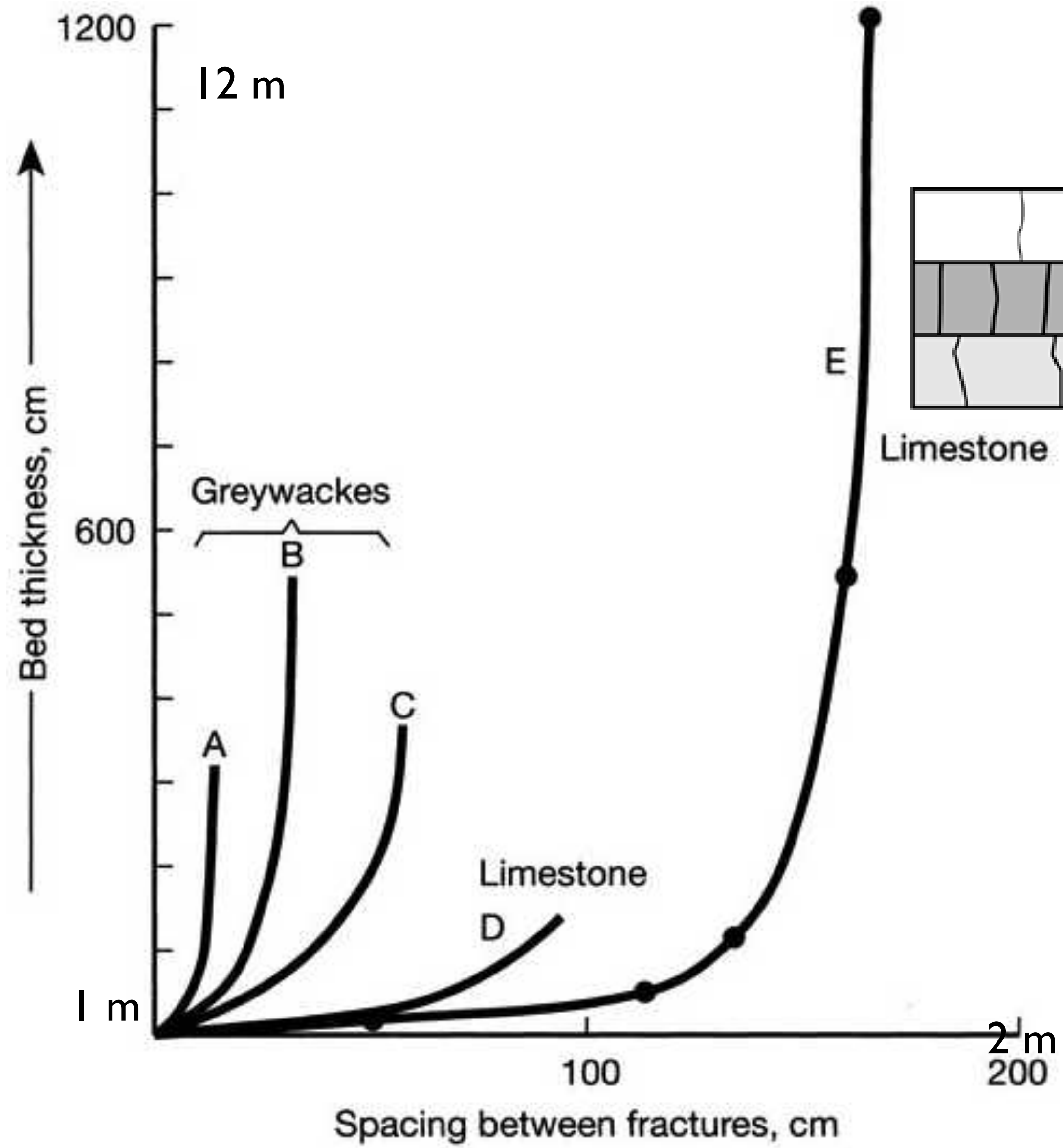
Klüfte - Verwerfungen (joints - faults)

Definition Klüfte:
- planare Diskontinuität ohne Kohäsion (Extensionsbrüche)
- kein Versatz
- minimale Extension

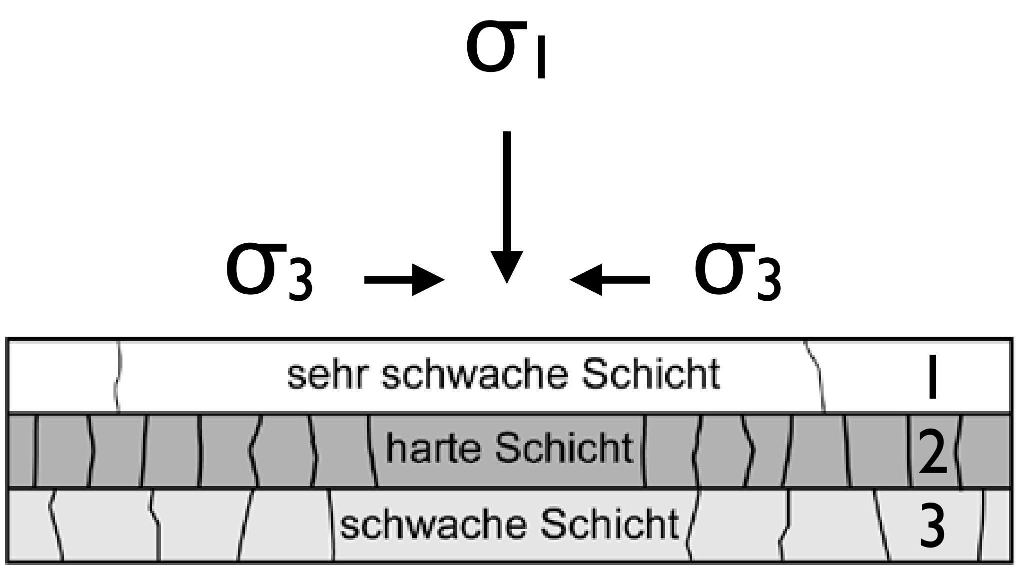
Unterschied:

joints:	faults:
no displacement	displacement
static	dynamic
elasticity	frictional glide
stress indicators	displacement indicators

Schichtklüfte



Twiss & Moores, 2007



$E_1 < E_3 < E_2$

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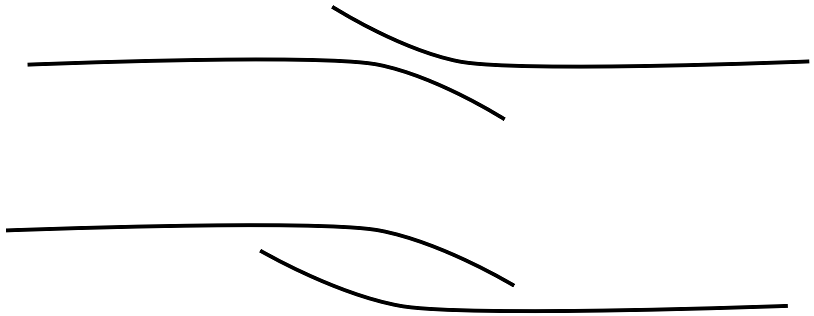
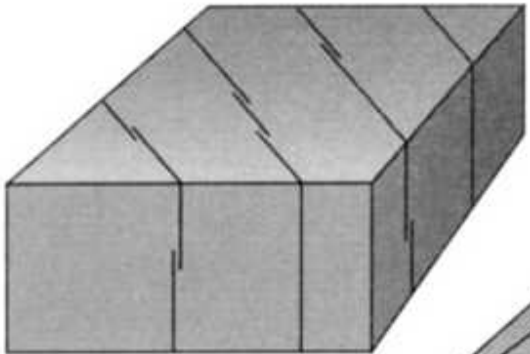
Kluftsysteme

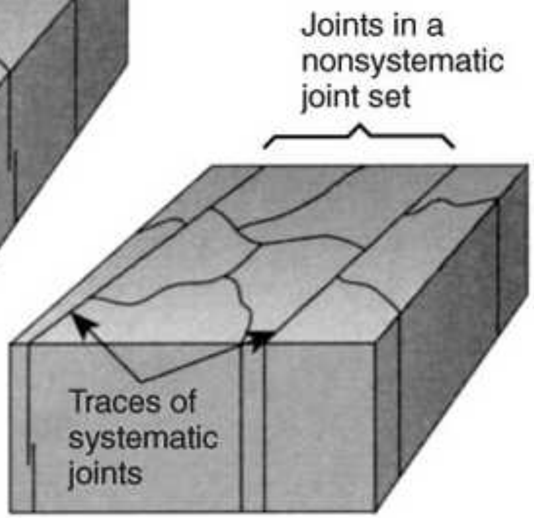
Interaktion



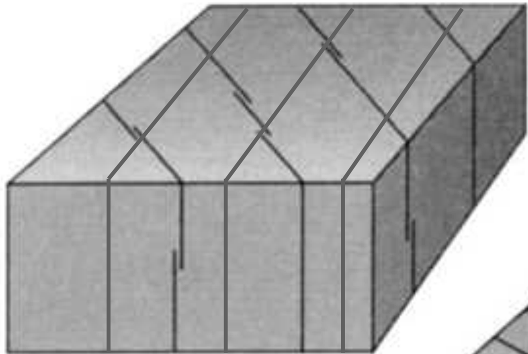
Kluftschar systematisch - unsystematisch



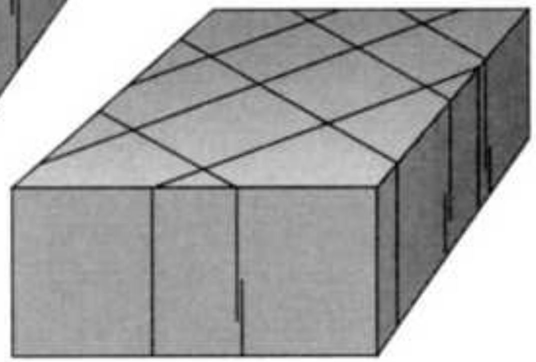
systematisch



unsystematisch



konjugiert



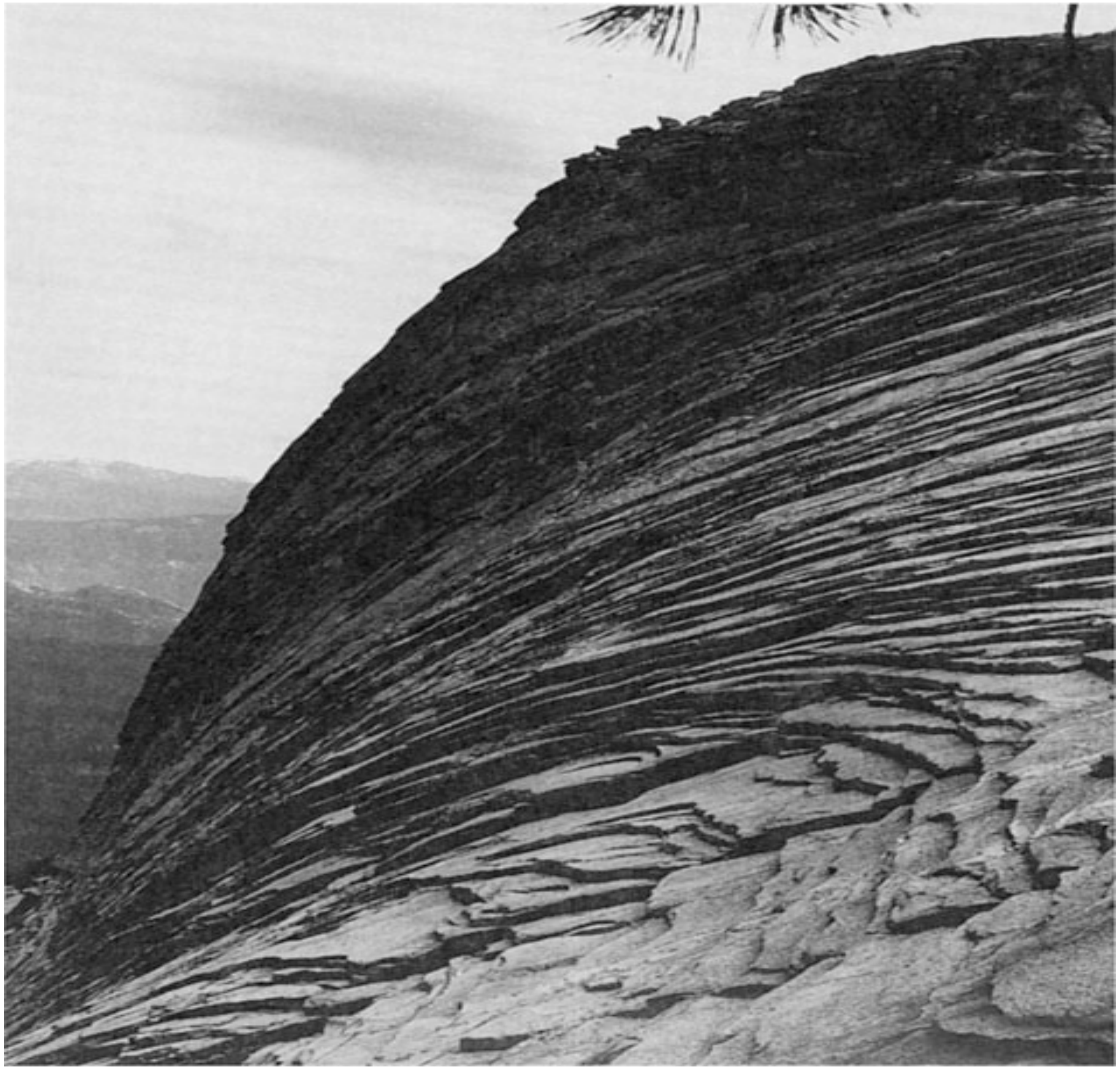
orthogonal

Twiss & Moores, 2007

Klüfte im Aufschluss

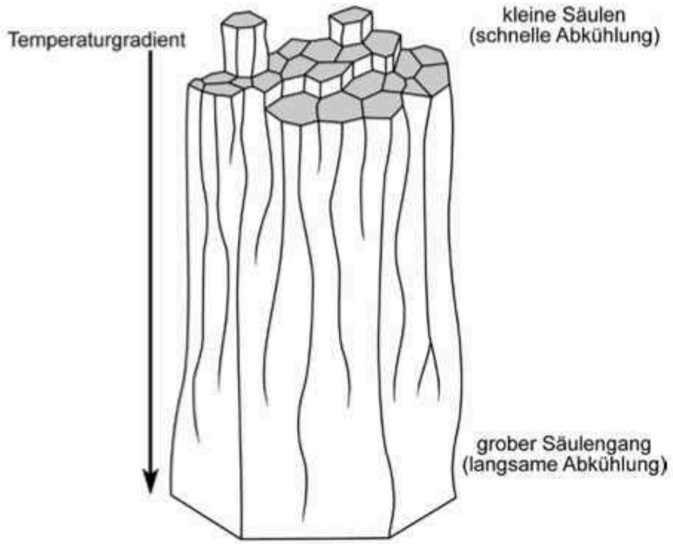
Rectangular joints in siltstone and black shale within the Utica Shale (Ordovician) near Fort Plain, New York.

Entlastungsklüfte

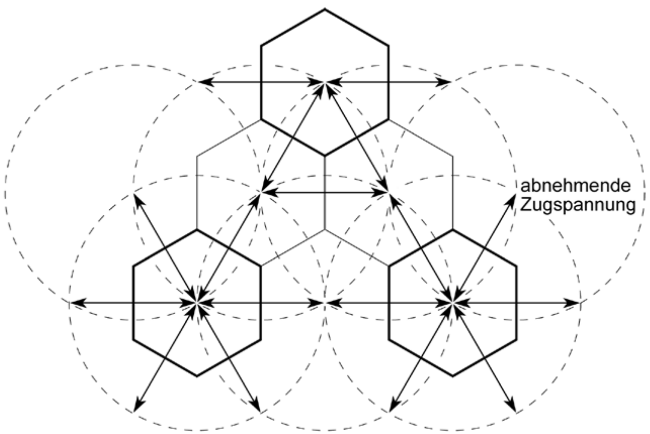


Twiss & Moores, 2007

Abkühlungsklüfte



Skizzierte Vergröberung eines säulenförmigen Kluftmusters
nach Goehring & Morris 2005 *Europhys. Lett.* **69(5)** 739-745



Entwicklung eines sechseckigen Kluftmusters
infolge des Dehnungszuges zu den gleichmässig verteilten abgekühlten
oder trockenen Zentralbereichen innerhalb eines homogenen Materiales

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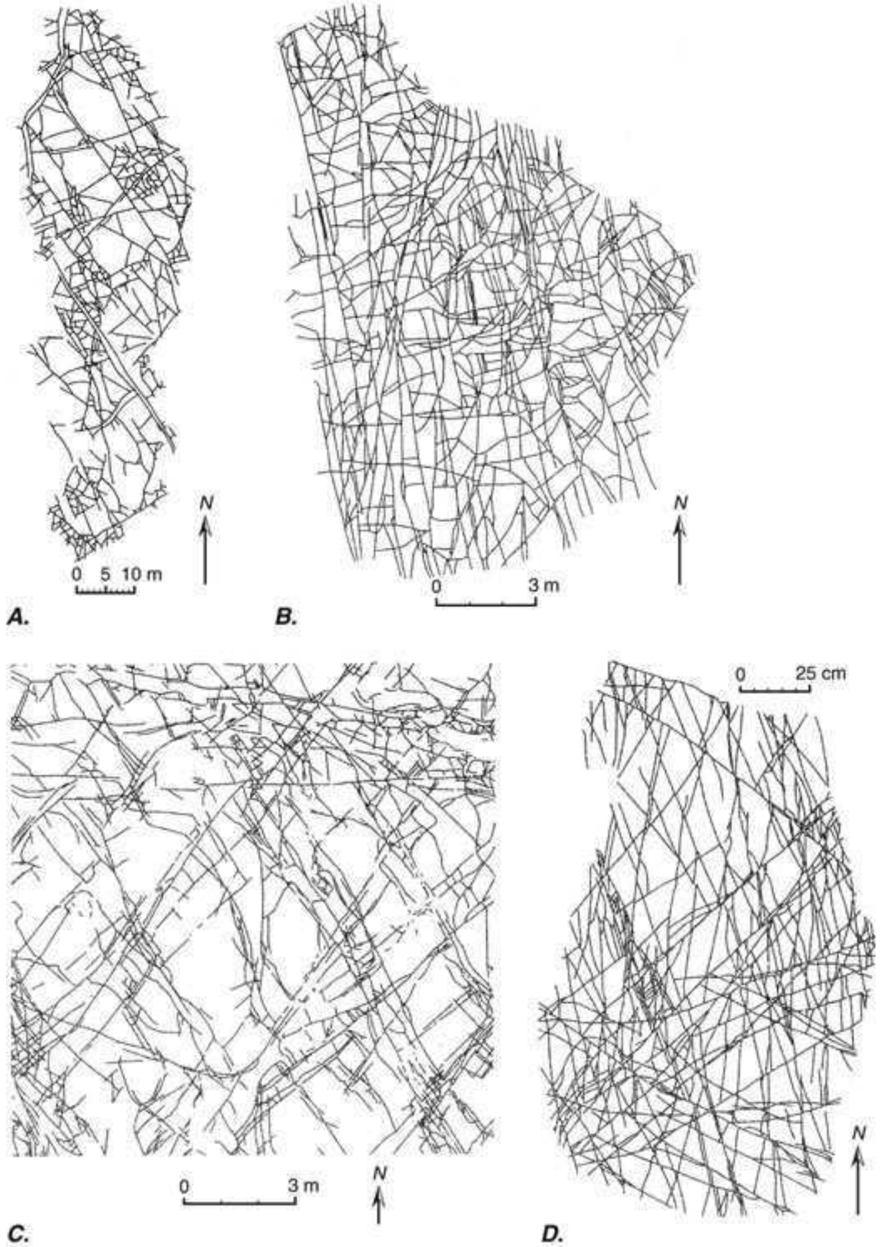
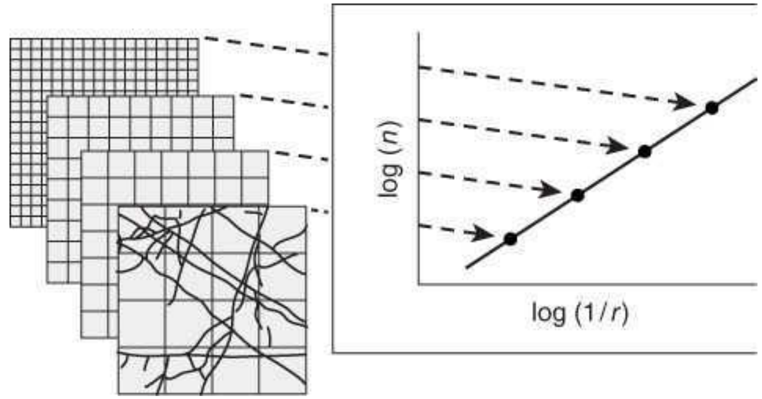
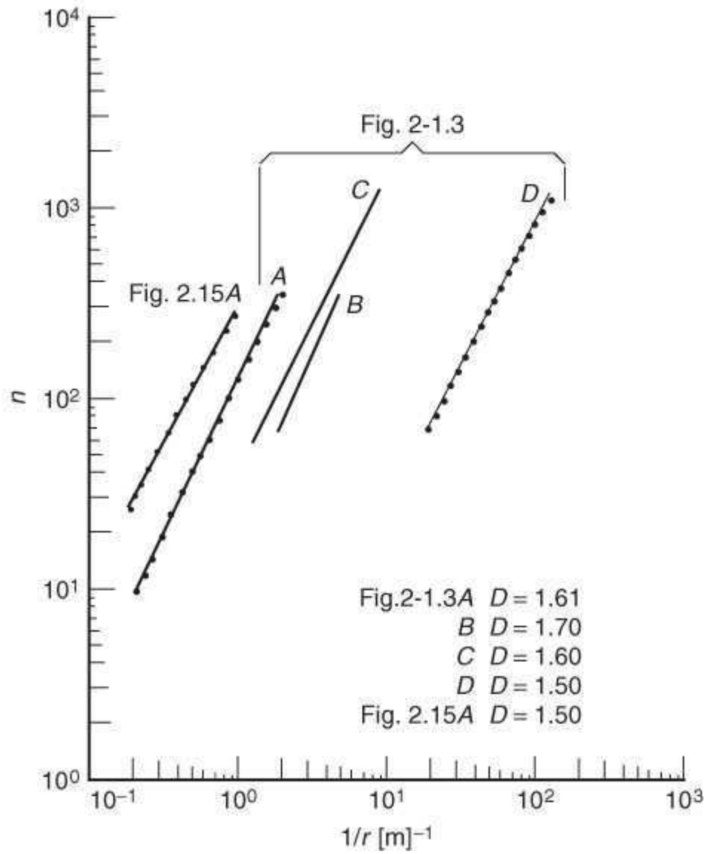
Kluftsysteme im Appalachian Plateau

Twiss & Moores, 2007

Kluftmuster

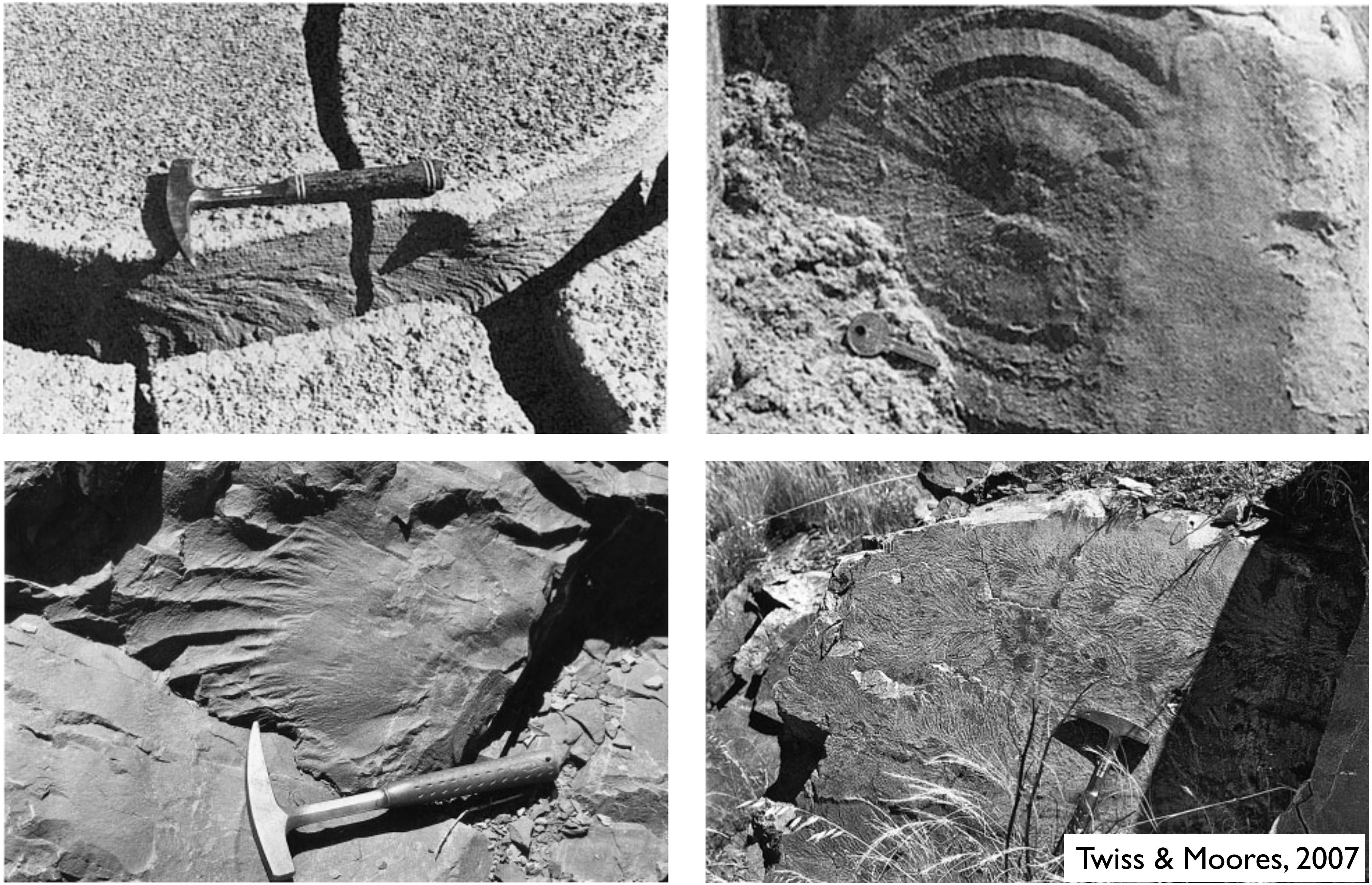






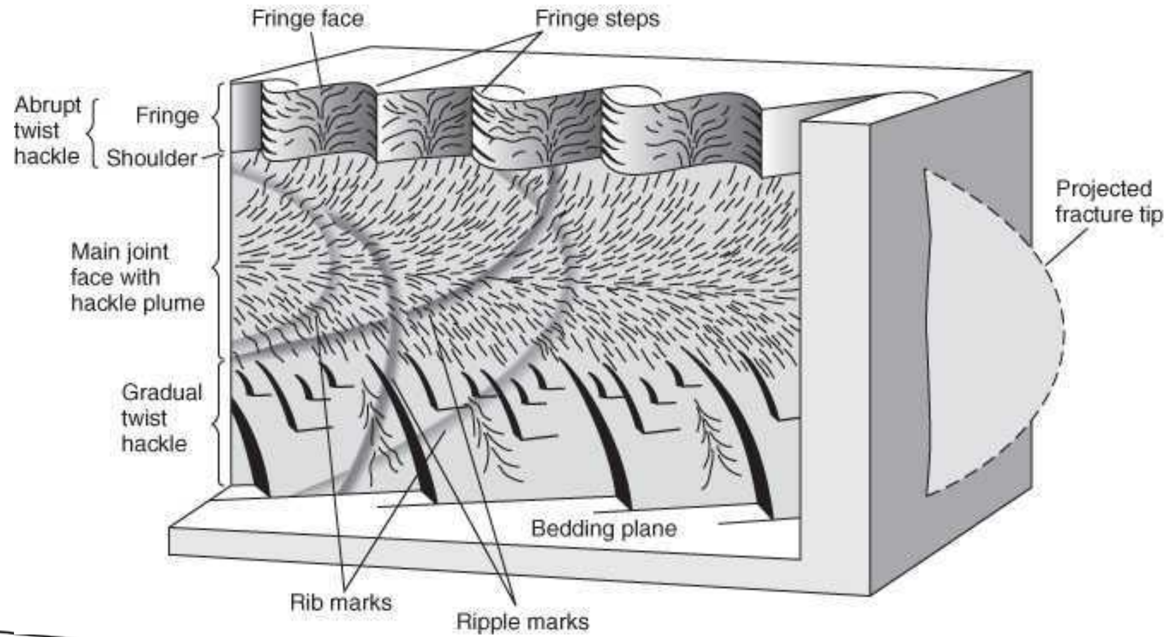
Twiss & Moores, 2007

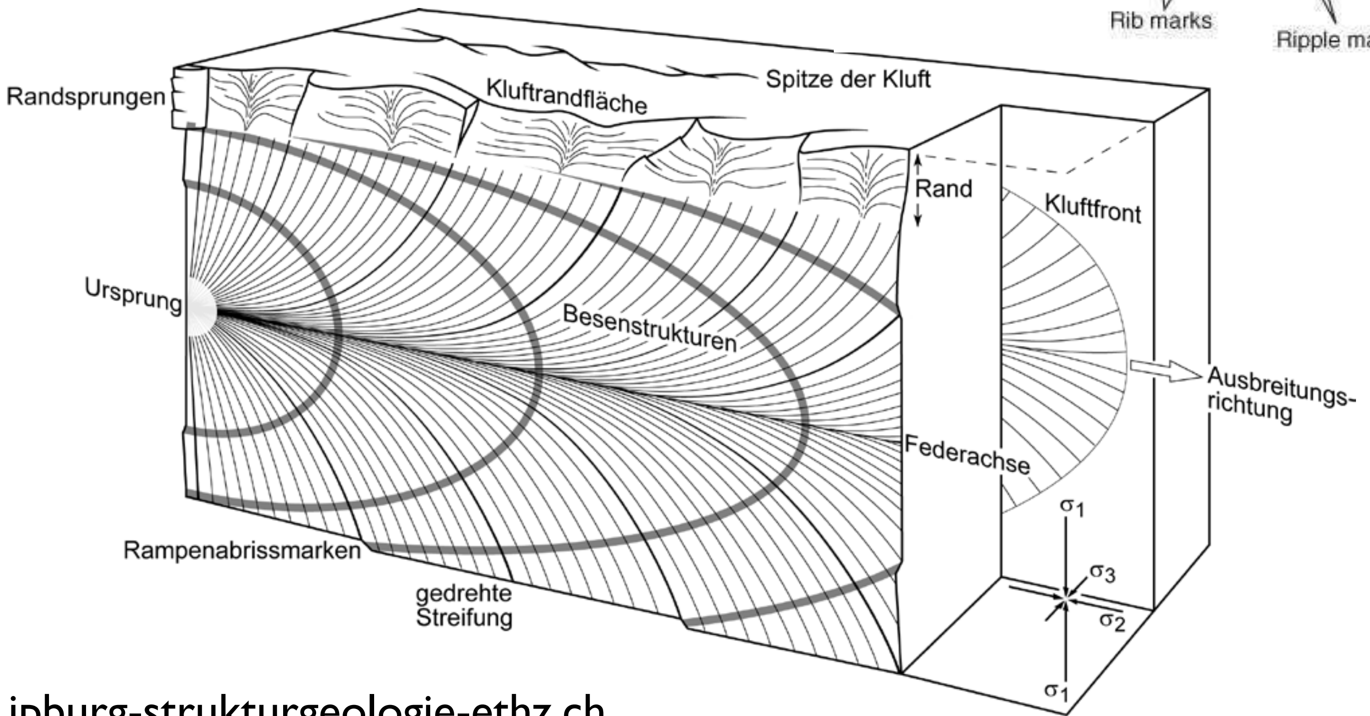
Bruchoberflächen



Twiss & Moores, 2007

Morphologie von Bruchflächen





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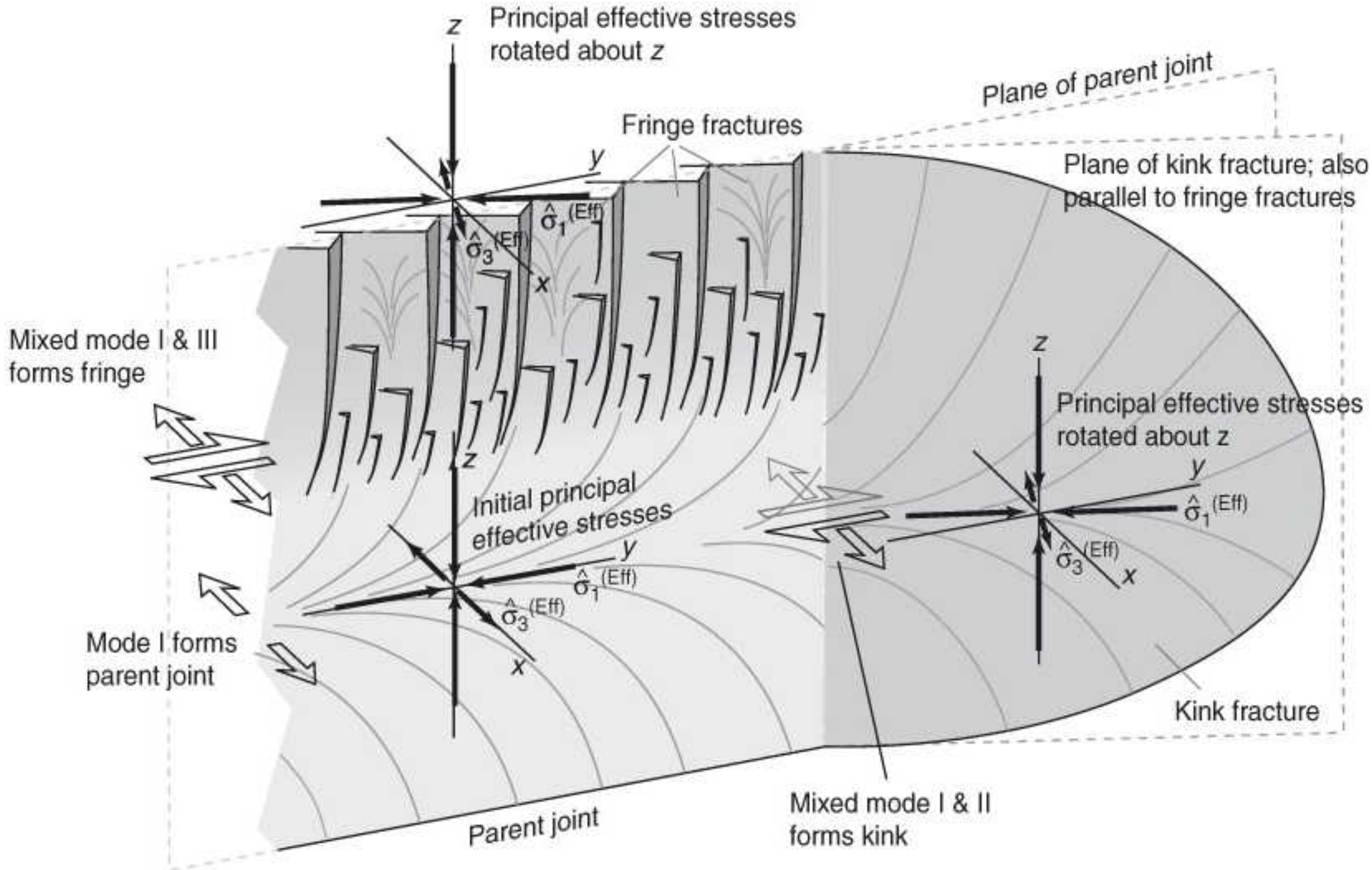
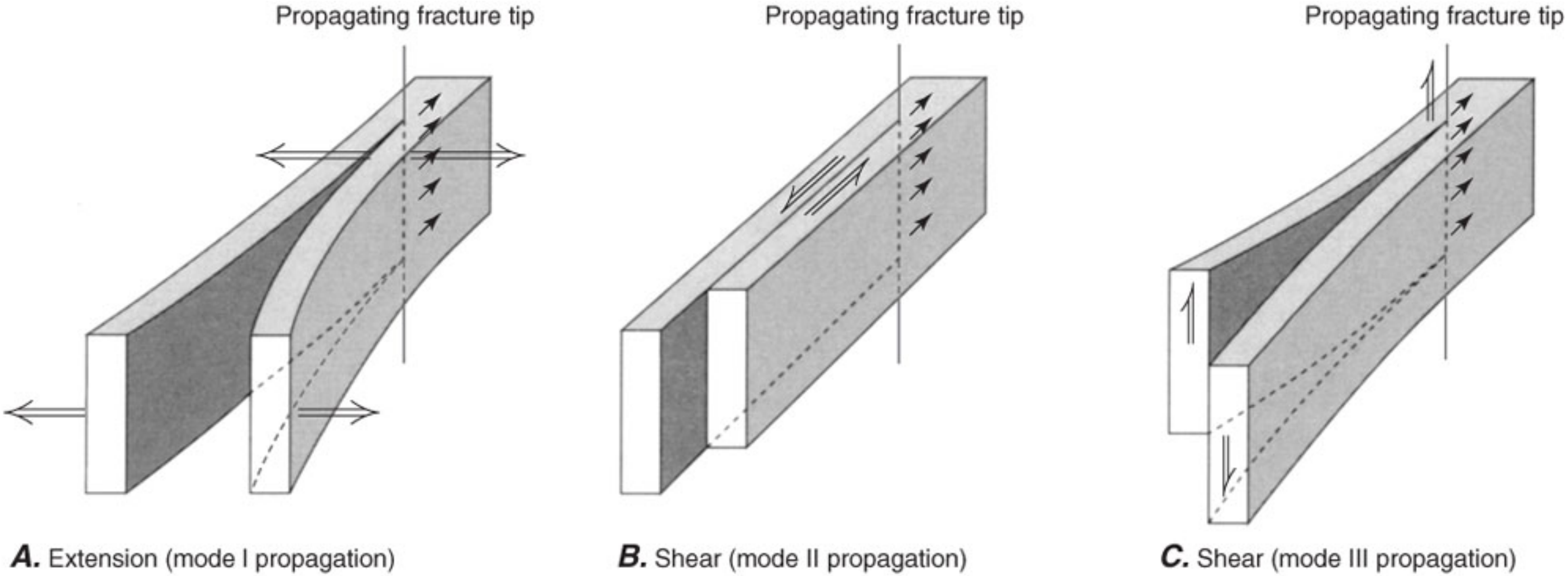
Bruchflächen im Spannungsfeld



Twiss & Moores, 2007

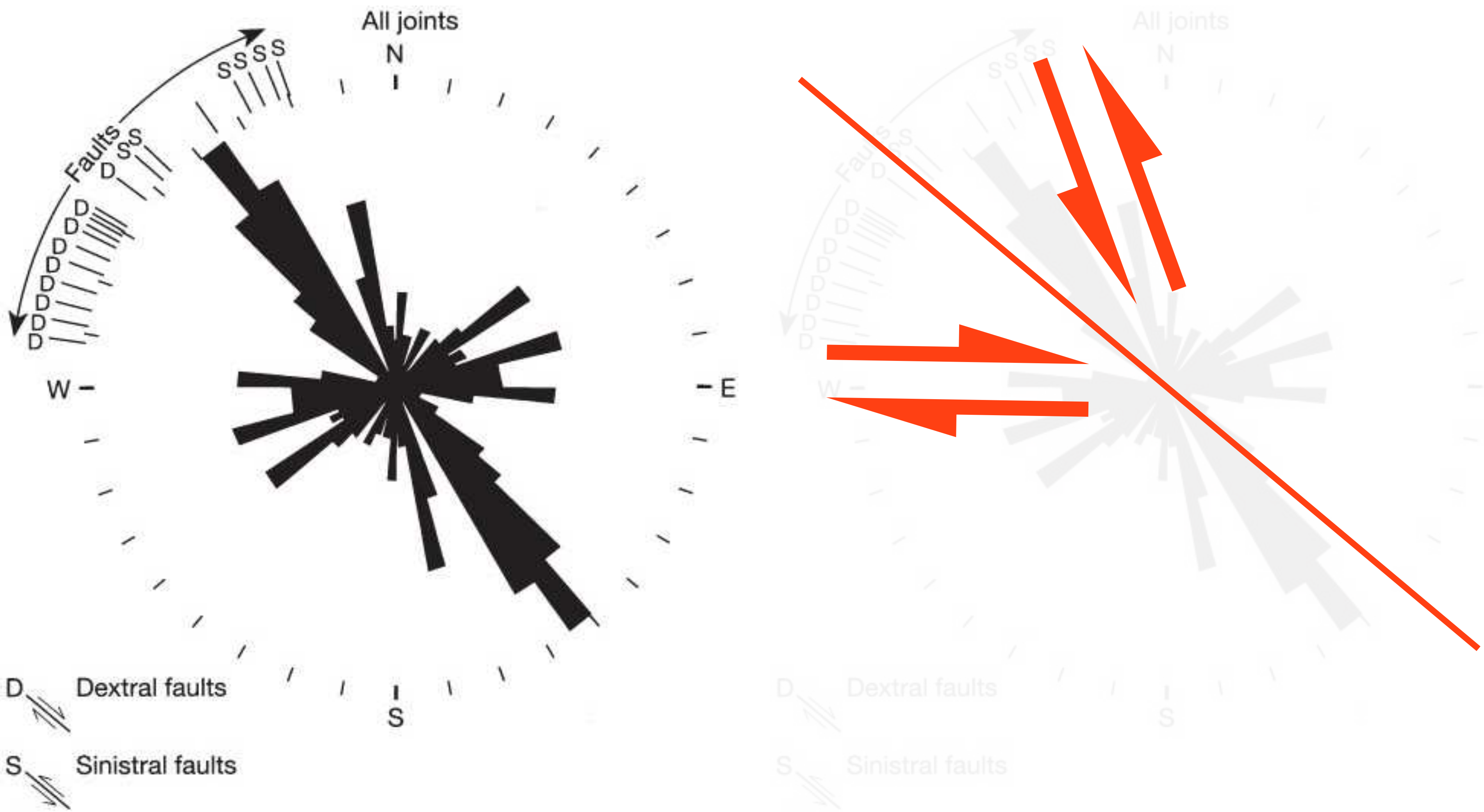
Bruchbildung



Extensionsbruch Scherbruch Scherbruch

Twiss & Moores, 2007

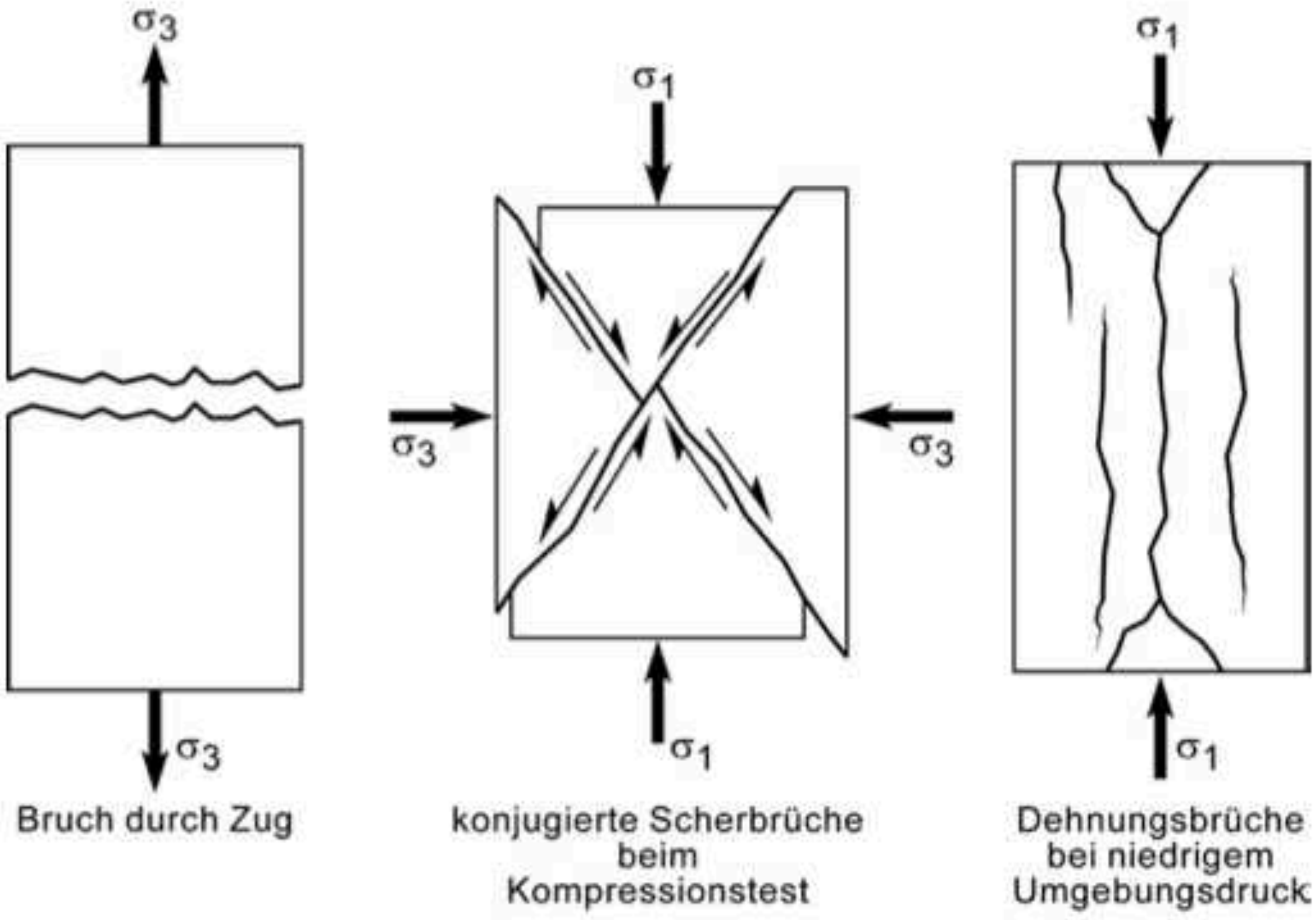
Orientierung von Klüften



Twiss & Moores, 2007

Brüche in Laborexperimenten

Extensionsbruch | Scherbruch | Extensionsbruch



$\sigma_3 < 0$ | $\sigma_1 > \sigma_3 > 0$ | $\sigma_3 = 0$

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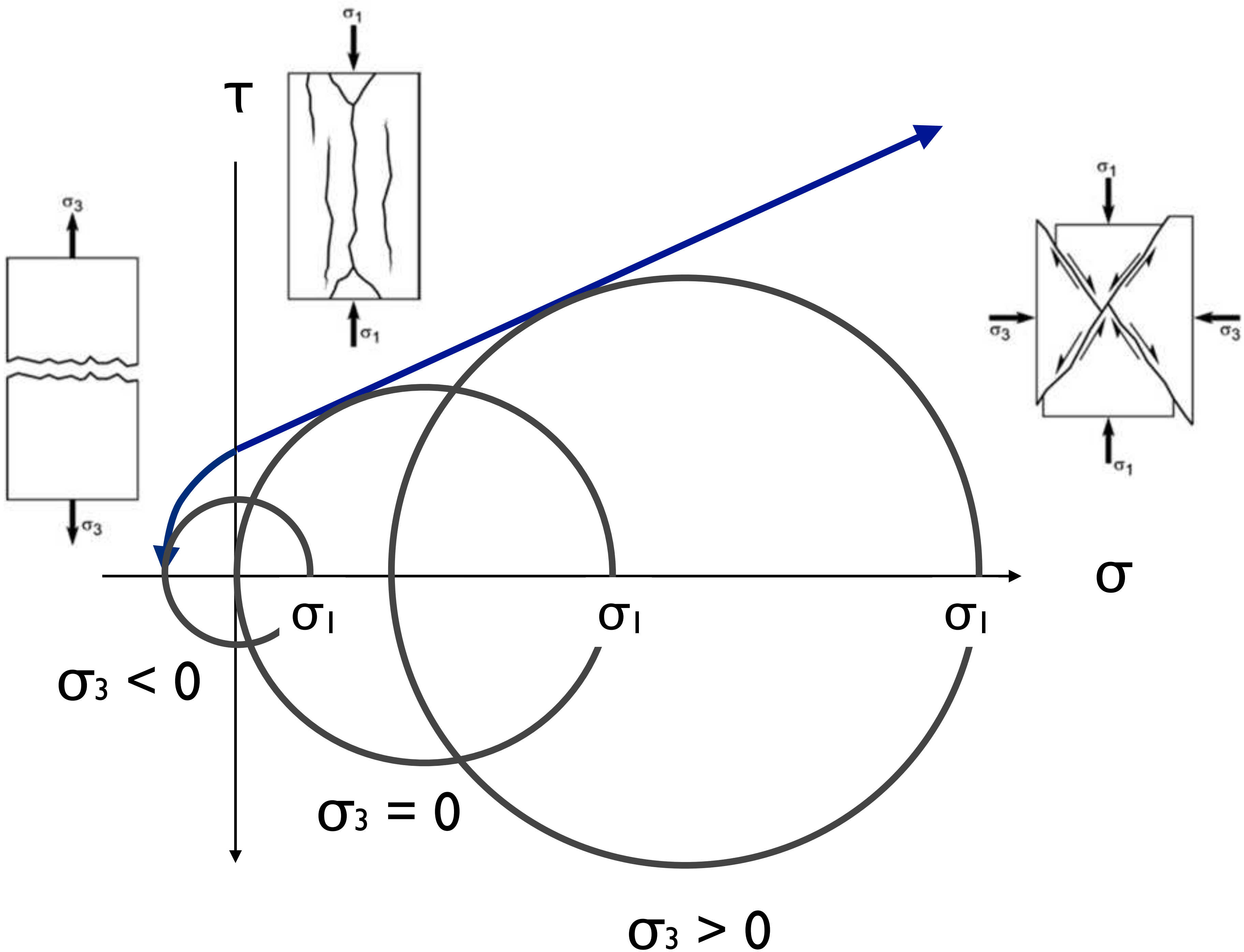
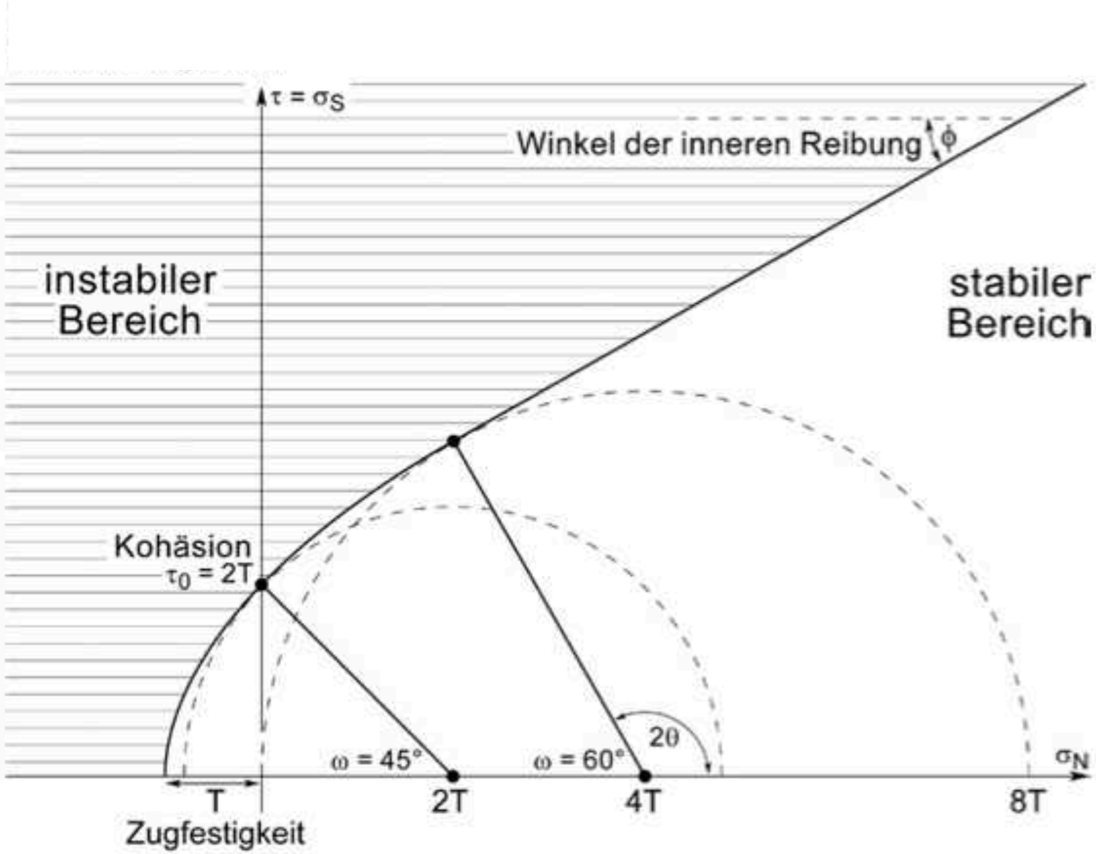
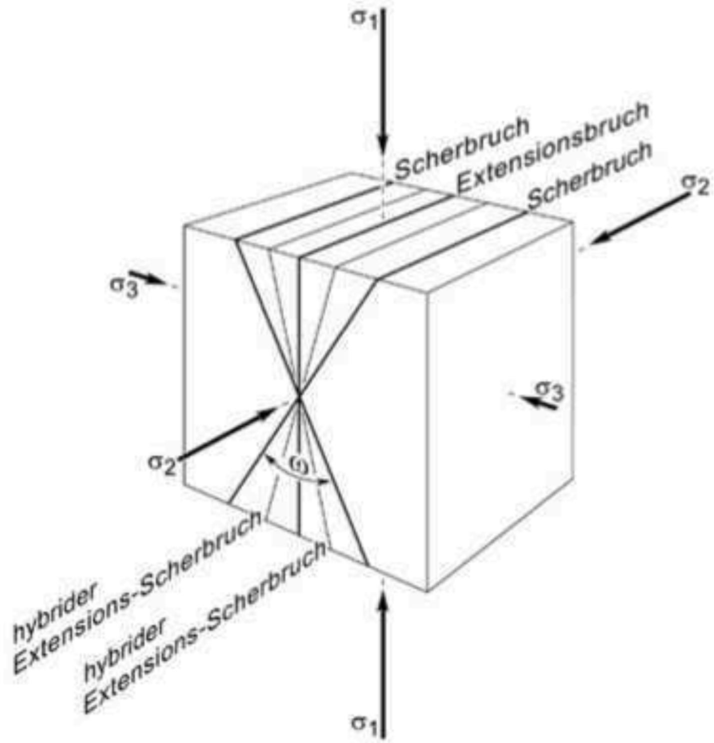


τ
σ
σ1
σ1
σ1
σ3 < 0
σ3 = 0
σ3 > 0

Typen von Brüchen

Bruch Modus	Klasse	$(\sigma_1 - \sigma_3)$	Öffnungswinkel
Dehnungsversagen	Extensionsbrüche	<4T	0°
Hybride Scherbrüche	Scher-Extensionsbrüche	4T – 8T	bis 60°
Scherbrüche	Kompressionelle Scherbrüche	>8T	>60°





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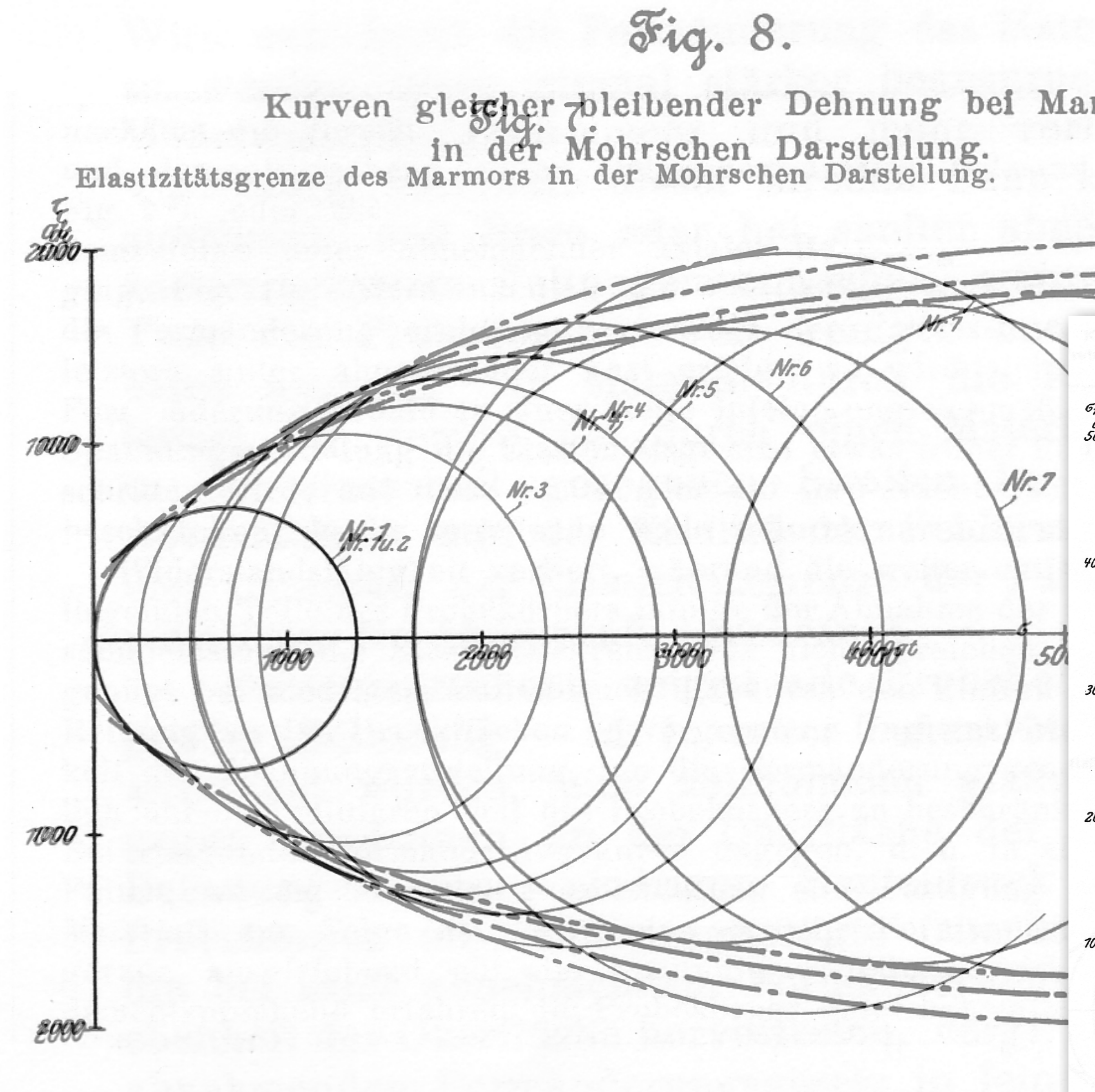
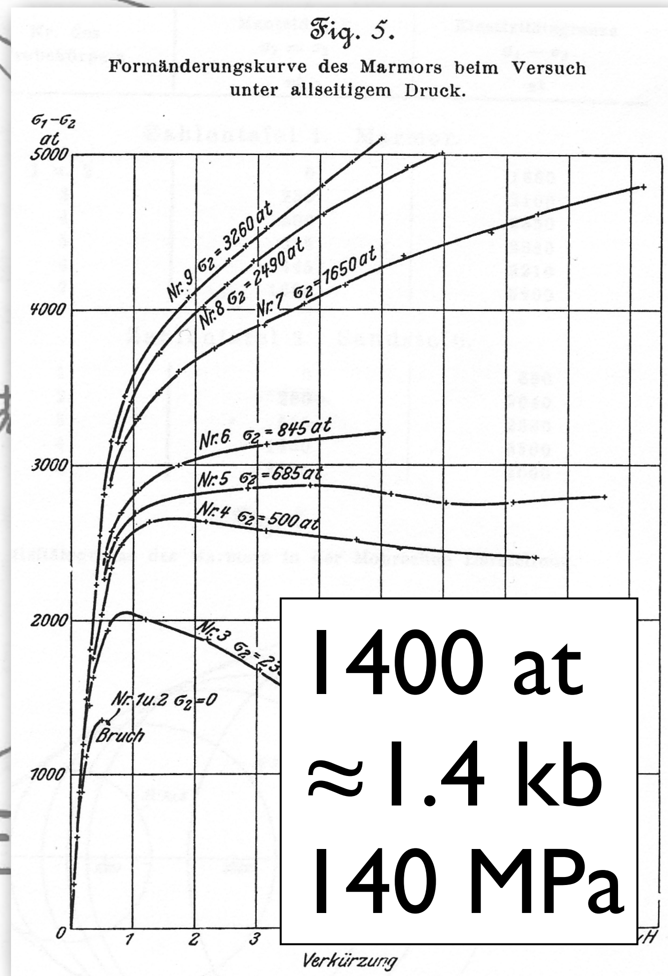
Elastizitätsgrenze





1400 at

≈1.4 kb

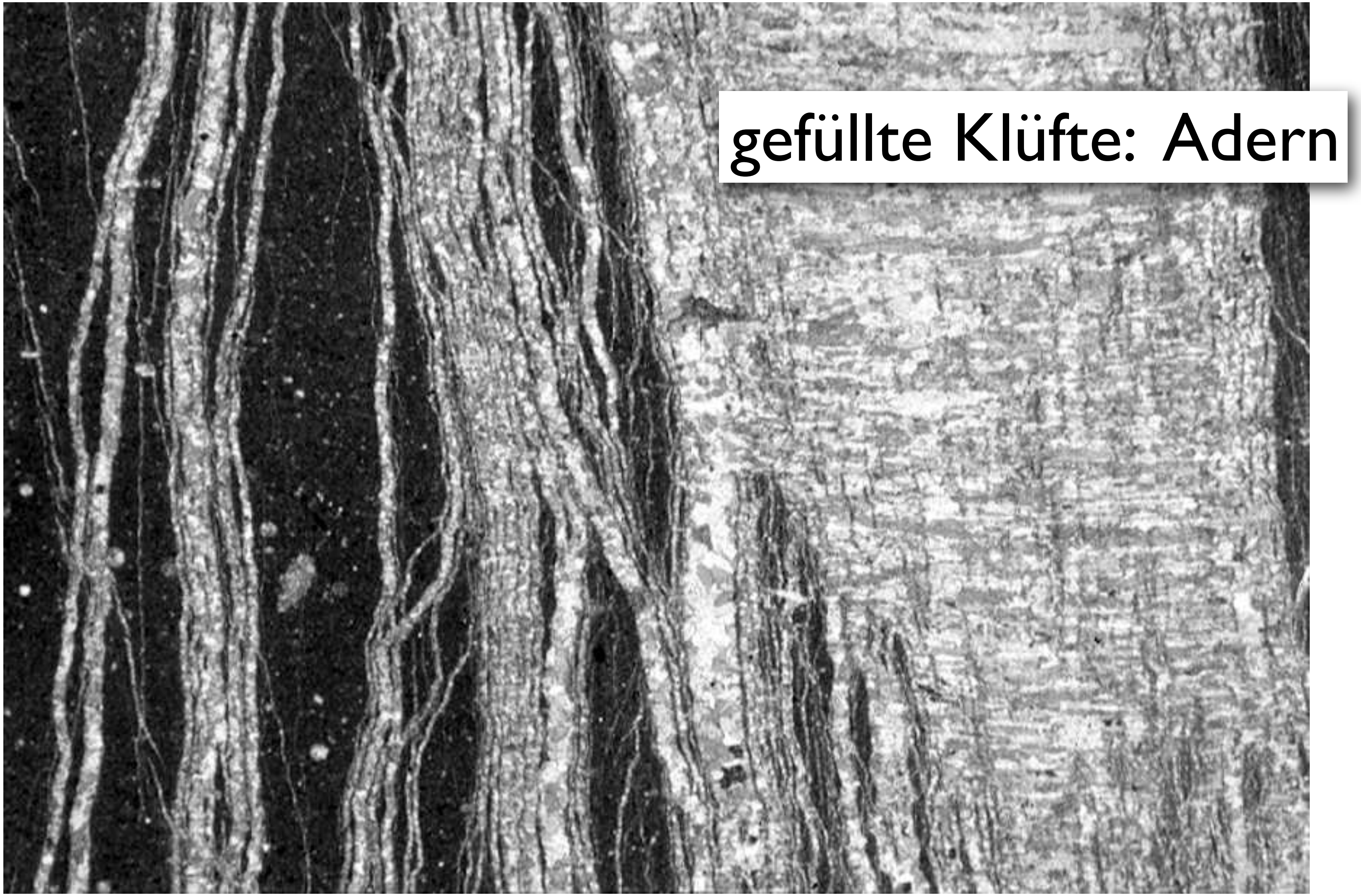
140 MPa

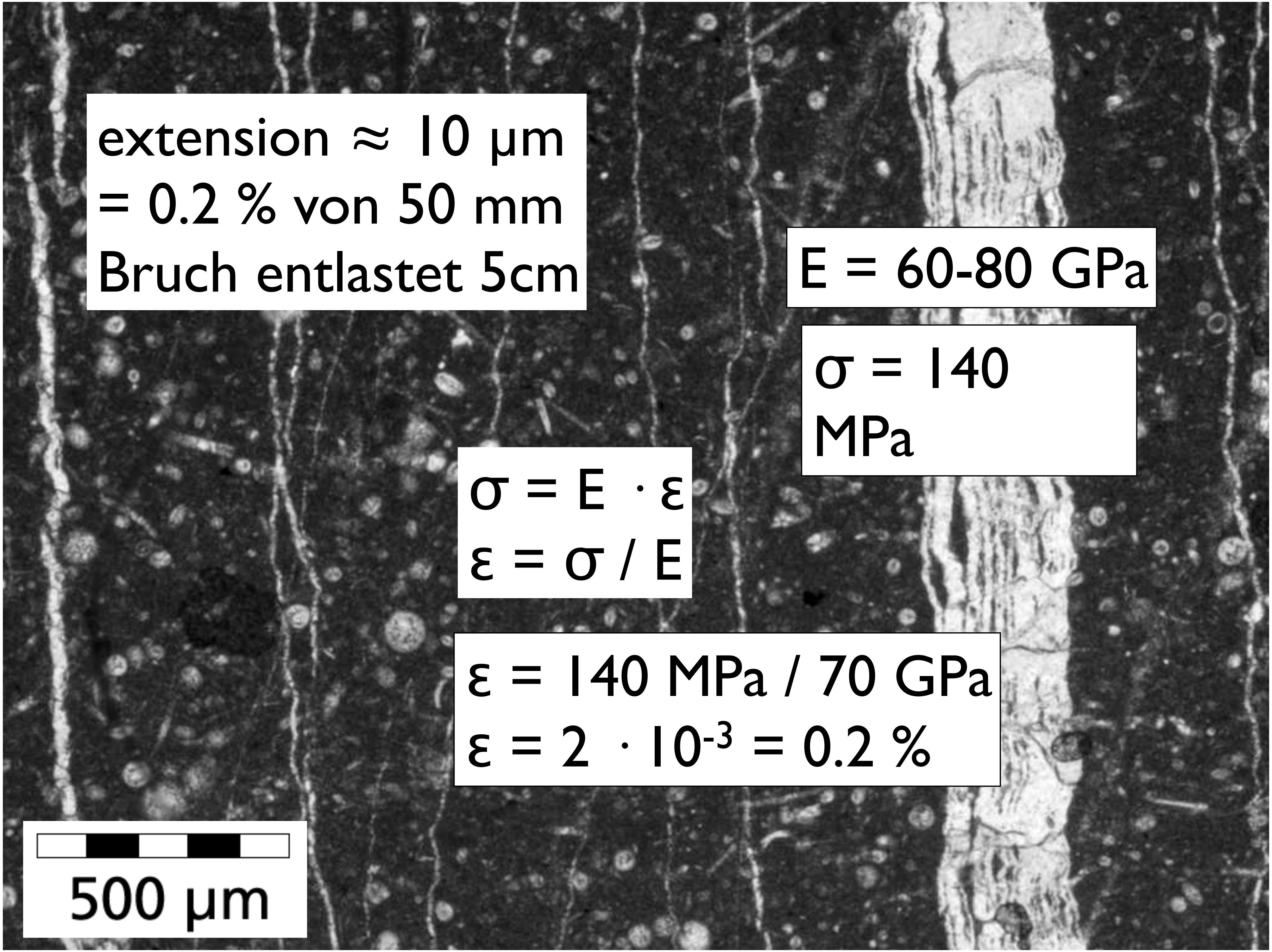
	Density kg m^{-3}	E 10^{11} Pa	G 10^{11} Pa	ν	k W m^{-1} °K^{-1}	α 10^{-5} °K^{-1}
Sedimentary						
Shale	2100–2700	0.1–0.3	0.14		1.2–3	
Sandstone	2200–2700	0.1–0.6			1.5–4.2	3
Limestone	2200–2800	0.6–0.8			2–3.4	2.4
Dolomite	2200–2800	0.5–0.9			3.2–5	
Marble	2200–2800	0.3–0.9	0.2–0.35	0.1–0.4	2.5–3	
Metamorphic						
Gneiss	2,700	0.04–0.7	0.1–0.35	0.04–0.15	2.1–4.2	
Amphibole	3,000		0.5–1.0	0.4	2.5–3.8	
Igneous						
Basalt	2,950	0.6–0.8	0.3	0.25	1.3–2.9	
Granite	2,650	0.4–0.7	0.2–0.3	0.1–0.25	2.4–3.8	2.4
Diabase	2,900	0.8–1.1	0.3–0.45	0.25	1.7–2.5	
Gabbro	2,950	0.6–1.0	0.2–0.35	0.15–0.2	1.9–2.3	1.6
Diorite	2,800	0.6–0.8	0.3–0.35		2.8–3.6	
Pyroxenite	3,250				4.1–5	
Anorthosite	2,750	0.83	0.35	0.25	1.7–2.1	
Granidiorite	2,700				2.6–3.5	
Mantle						
Peridotite	3,250				2.3–3	
Dunite	3,250	1.4–1.6	0.6–0.7		3.7–4.6	
Miscellaneous						
Halite			0.3	0.15	5.4–7.2	
Ice			0.092	0.033	2.2	

= 60-80 GPa

1400 at
≈1.4 kb
140 MPa

Extensionsbrüche





extension ≈ 10 µm
= 0.2 % von 50 mm
Bruch entlastet 5cm
E = 60-80 GPa
σ = 140 MPa
$\sigma = E \cdot \varepsilon$
$\varepsilon = \sigma / E$
ε = 140 MPa / 70 GPa
$\varepsilon = 2 \cdot 10^{-3} = 0.2\ \%$
500 µm

4

4 Bruchsysteme - Stereonetz - Verwerfungen

VL-Themen:

- Brüche - Bruchsysteme

- Stereonetz

- Verwerfungen
- fault zones
- assozierte Strukturen (displacement markers)

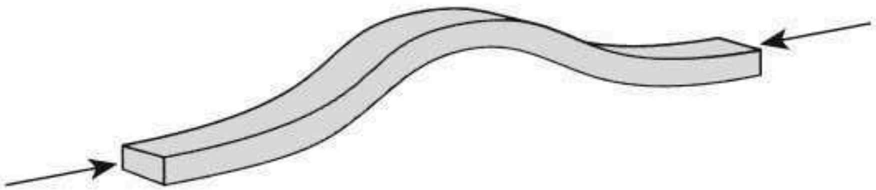
- Abschiebung (normal faults)
- Auf-/Überschiebung (reverse faults, thrusts)
- Strike-slip Verwerfungen

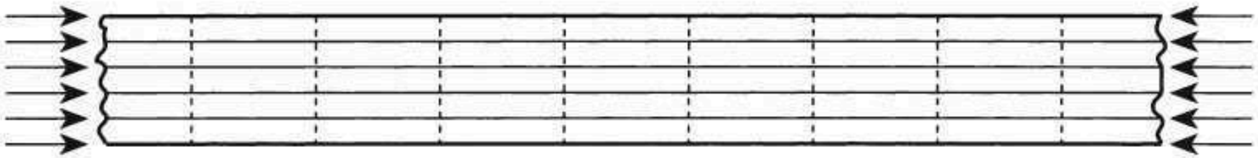
Klüfte assoziert mit Biegung

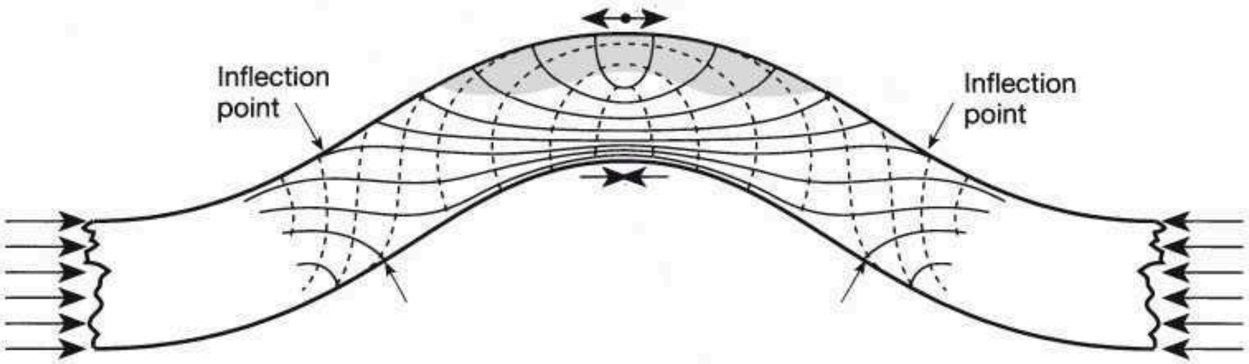
Earth's surface is free surface: $\tau = 0$

$\sigma_1, \sigma_2, \sigma_3$ are parallel and perpendicular

Angle of failure is 30° w/r to σ_1

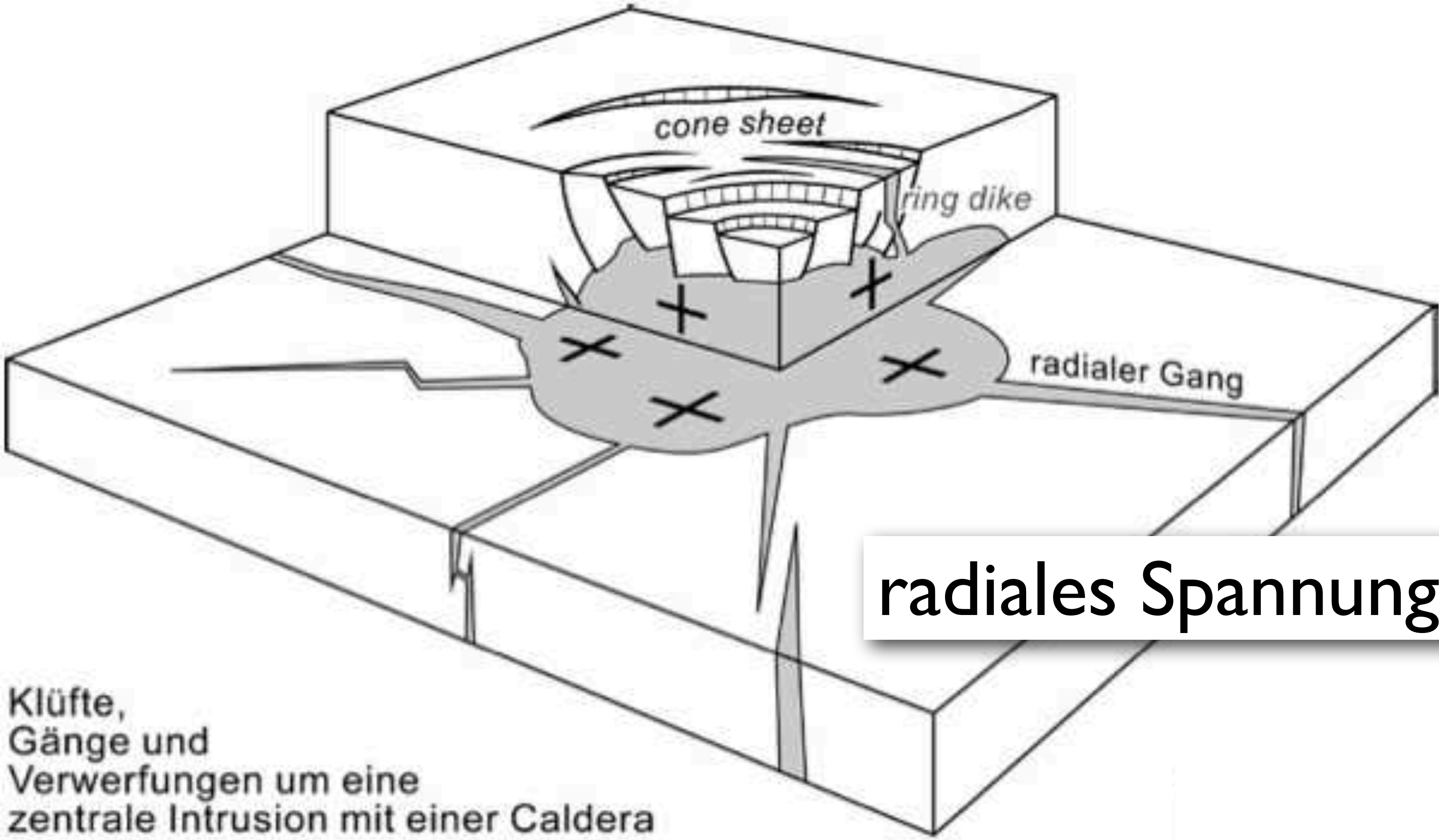






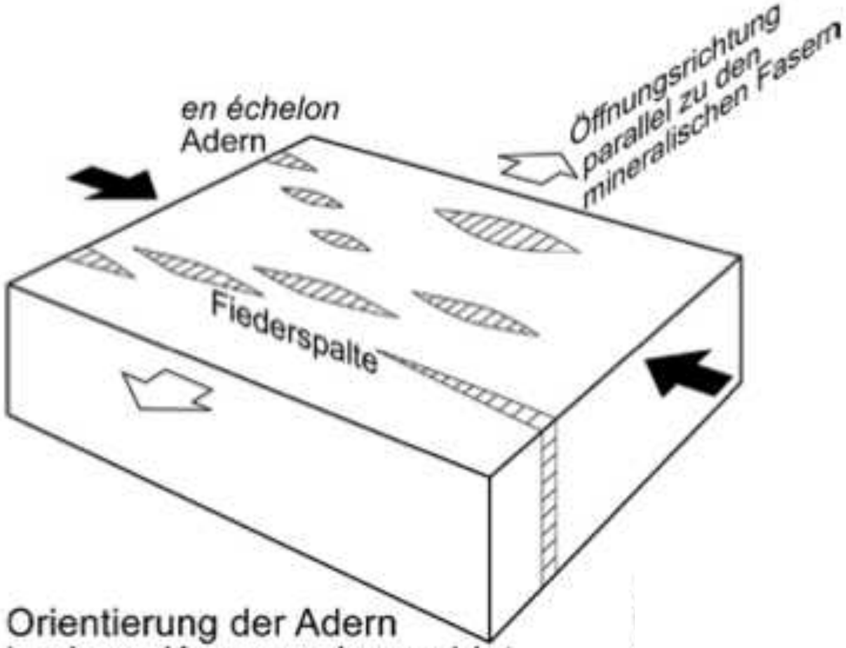
elastische Biegung

Klüfte assoziert mit Intrusivkörper

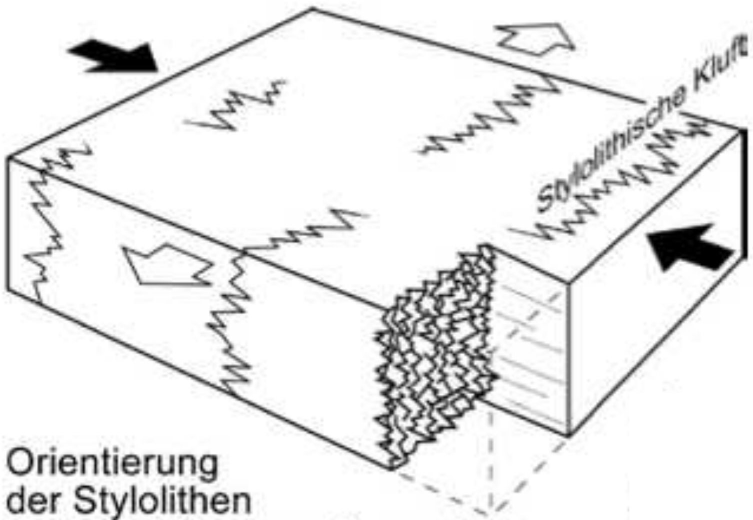


radiales Spannungsfeld

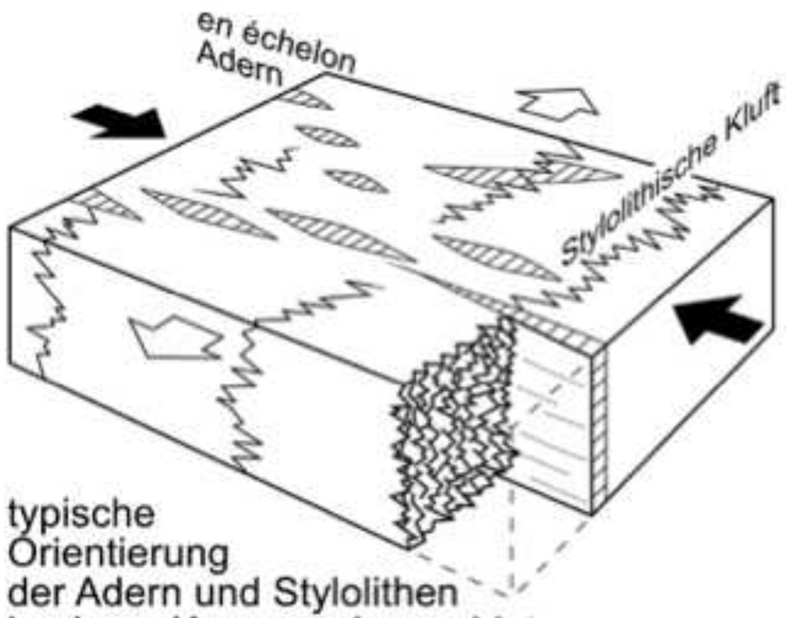
"Antiklüfte": Stylolithe



Orientierung der Adern
in einem Kompressionsgebiet

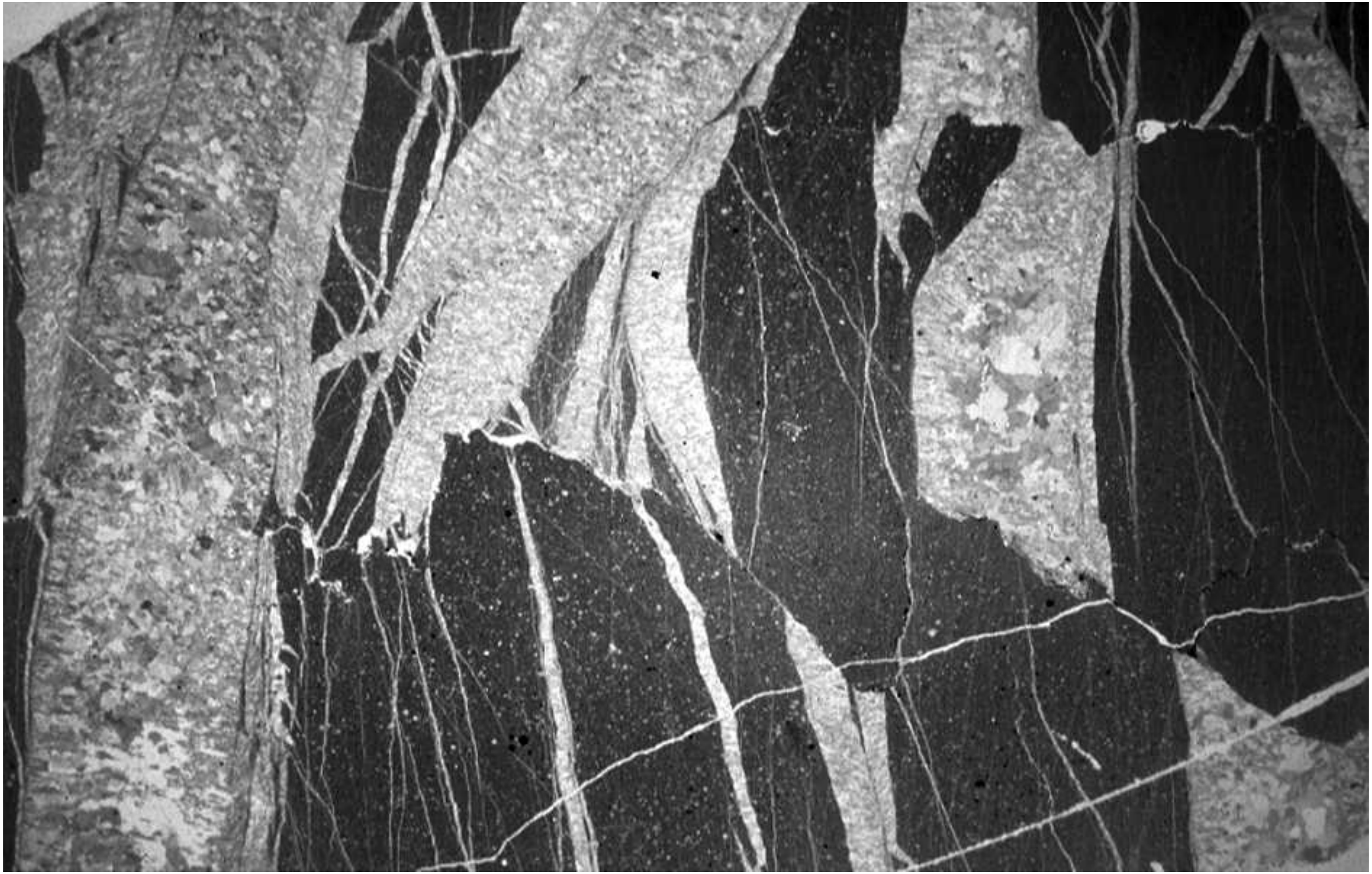


Orientierung
der Stylolithen
in einem Kompressionsgebiet

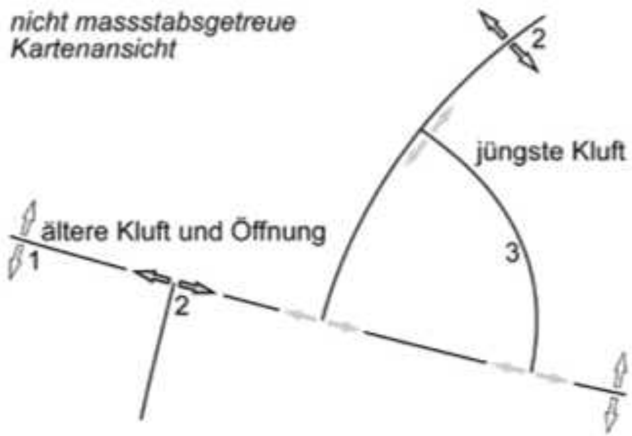


typische
Orientierung
der Adern und Stylolithen
in einem Kompressionsgebiet

Klüfte und "Antiklüfte"



Zeitliche Abfolge



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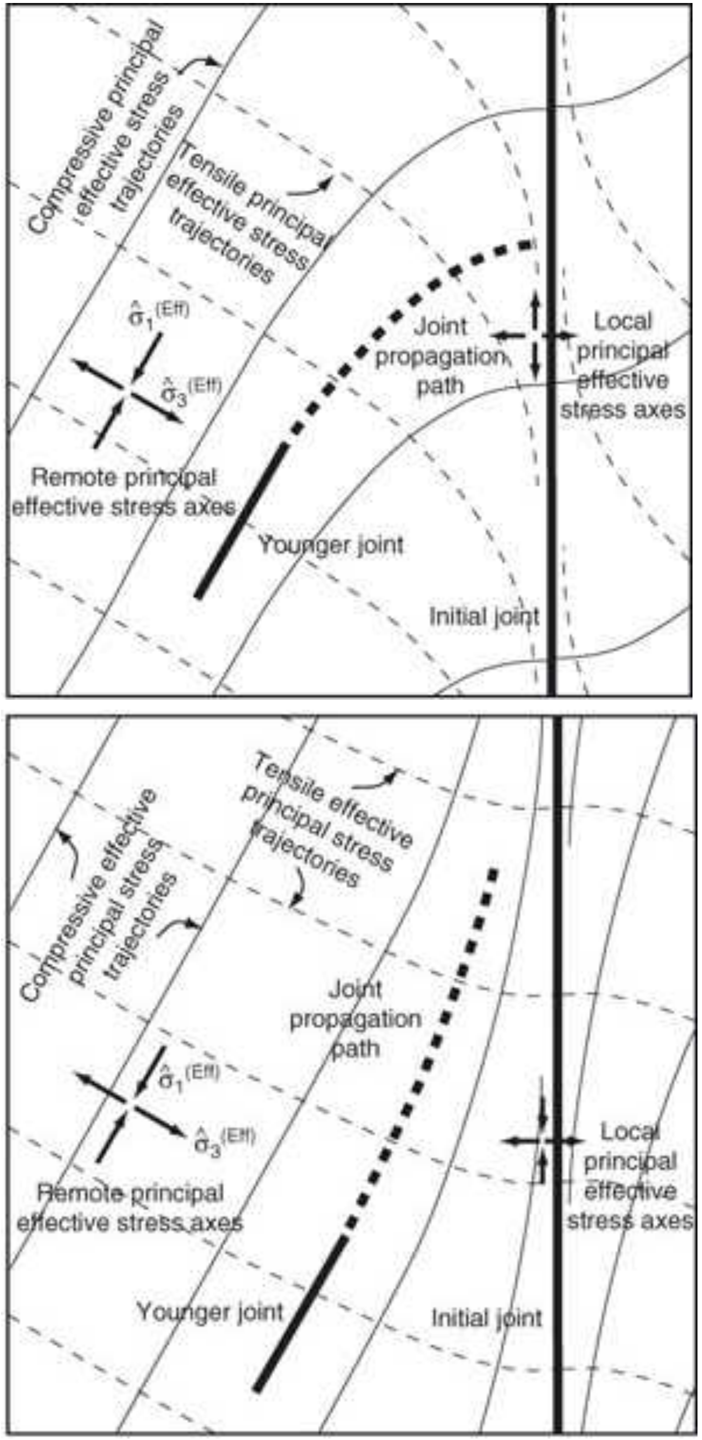
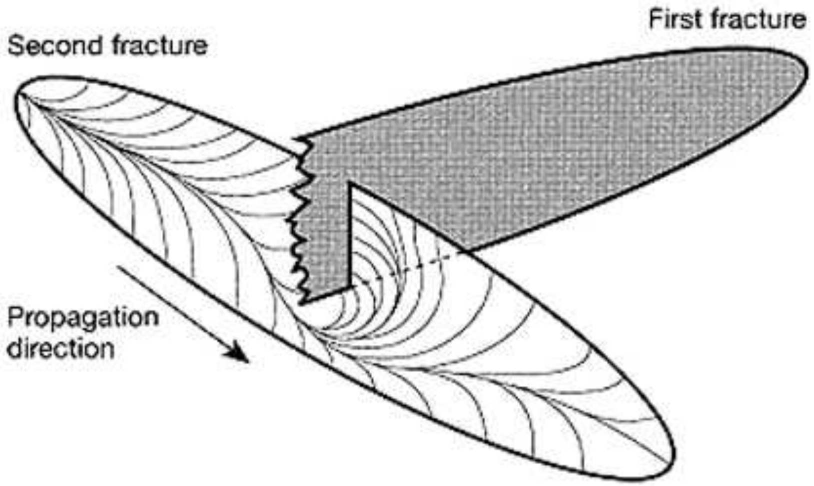


Twiss & Moores, 2007

Zeitliche Abfolge

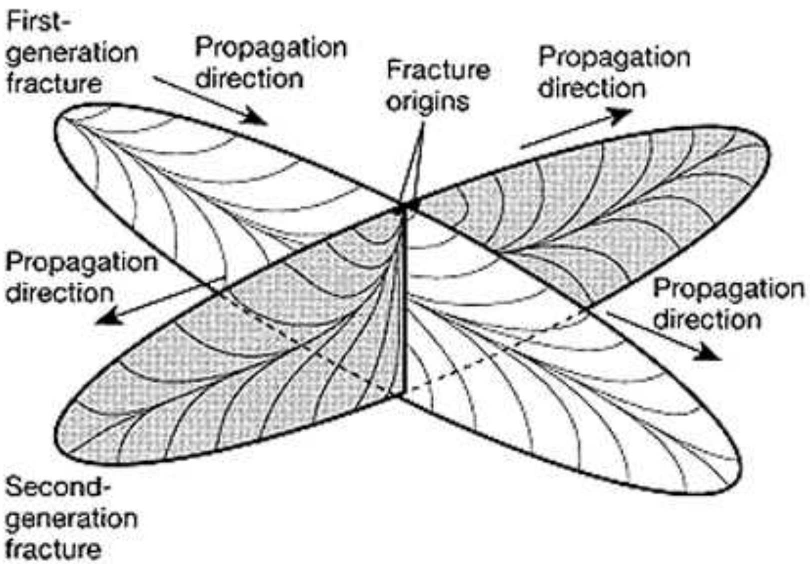
2



1

gleichzeitig

1



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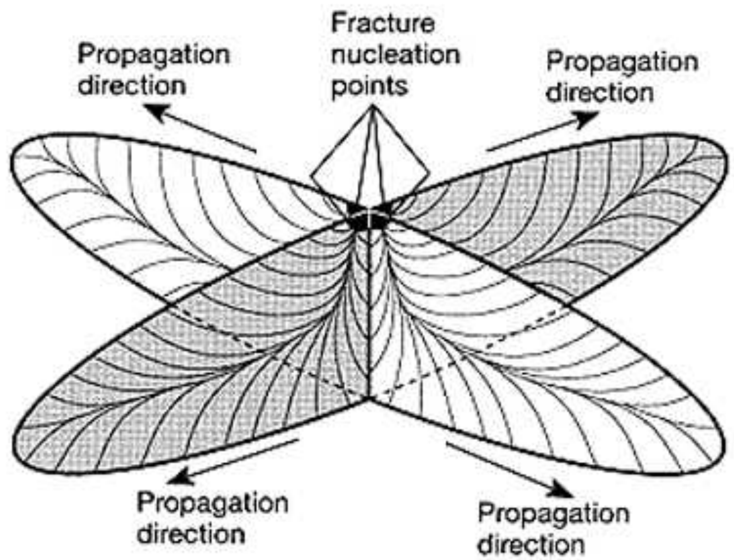
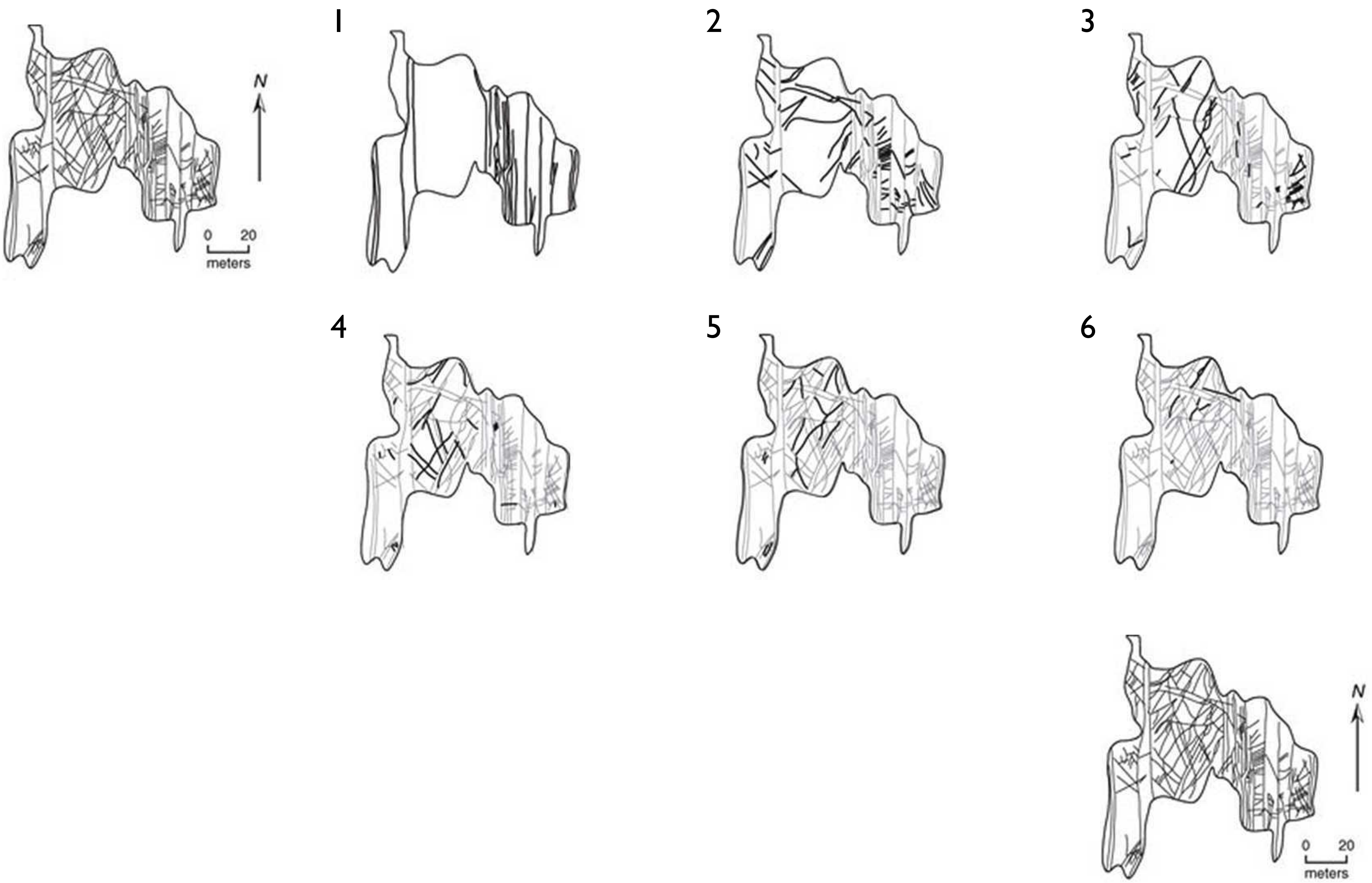
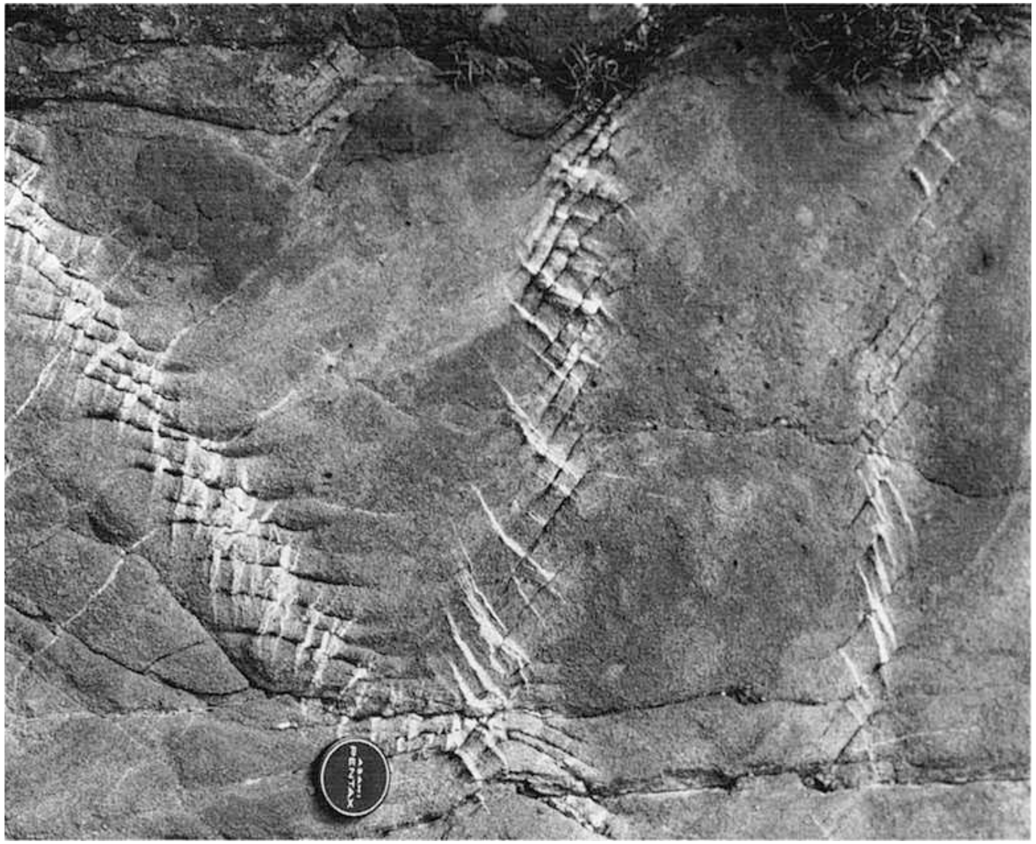


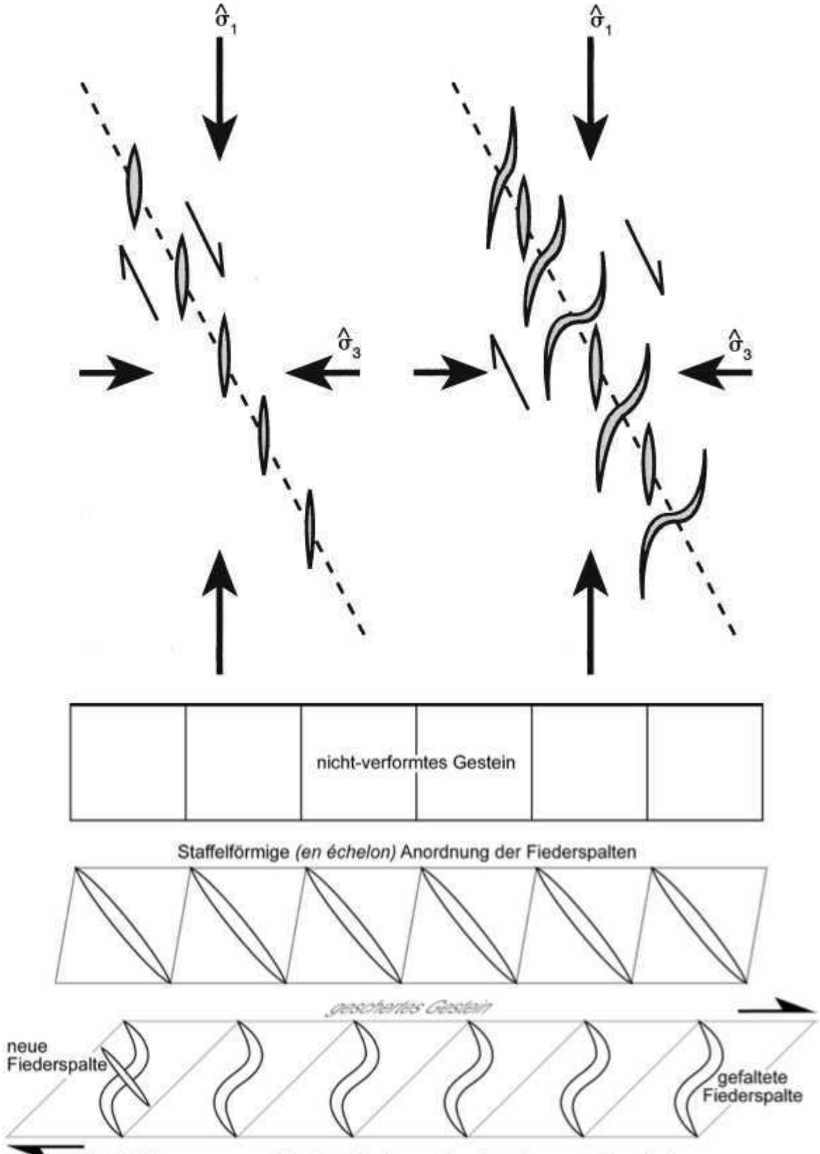
Twiss & Moores, 2007

Zeitliche Abfolge in Bruchsystemen



Fiederklüfte   en echelon





Entwicklung von *en échelon* Fiederspalten in einer spröden Scherzone
(sofortige Streckungs- und Verkürzungsrichtungen drehen sich nicht während der Scherung)

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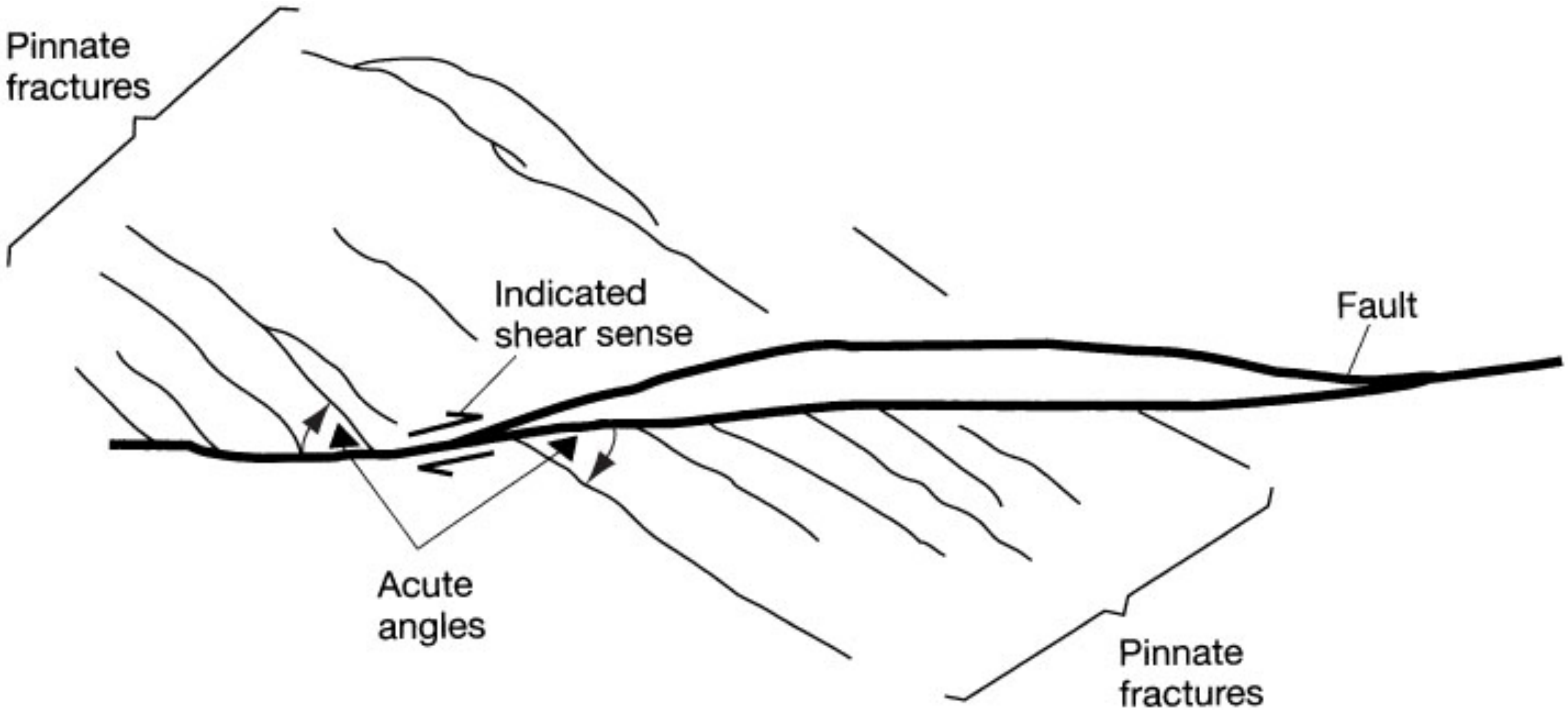
Klüfte assoziert mit Verwerfung

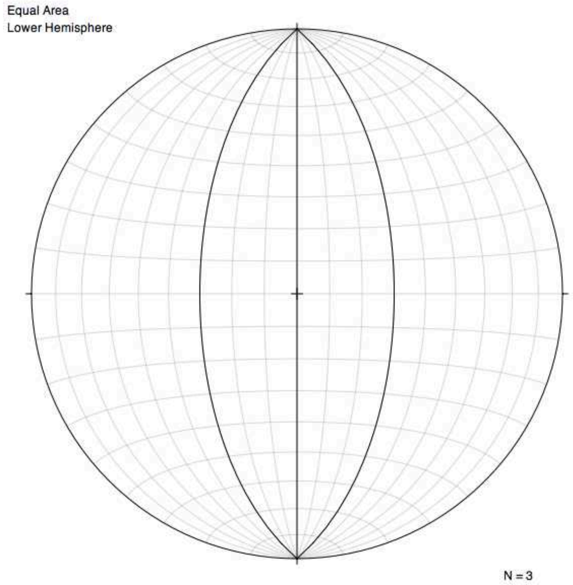


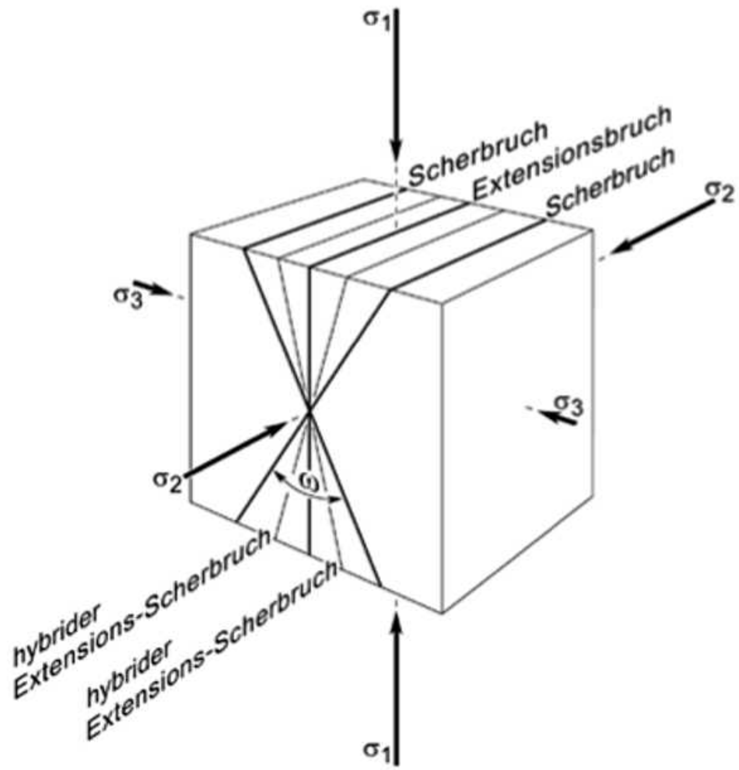
feather fractures

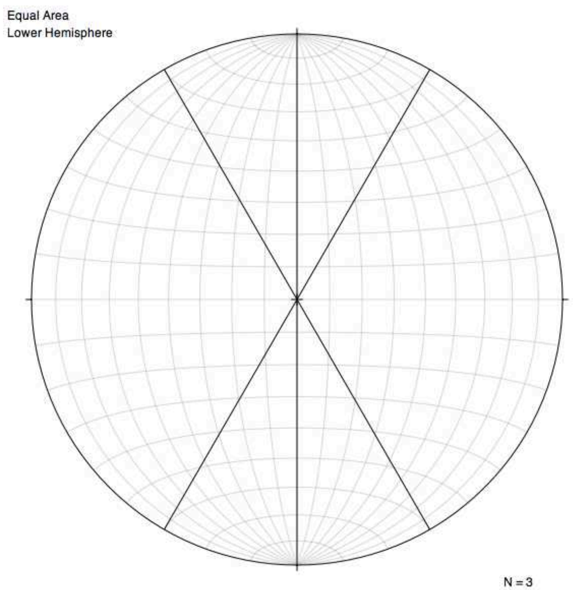
Twiss & Moores, 2007

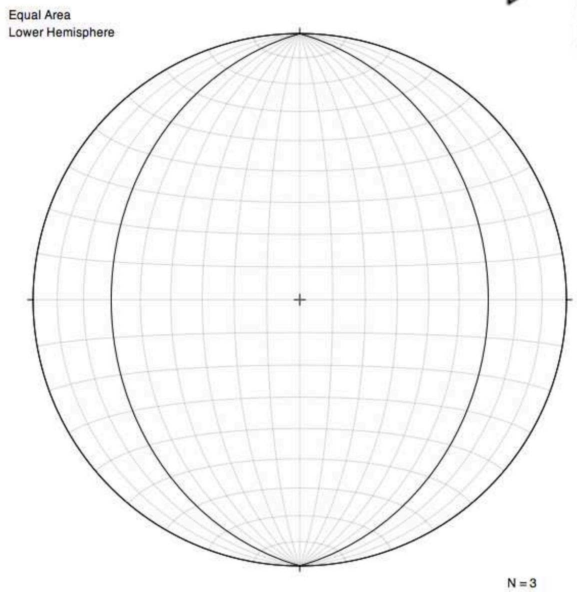
Stereonetz

Klüfte und Brüche im Stereonetz



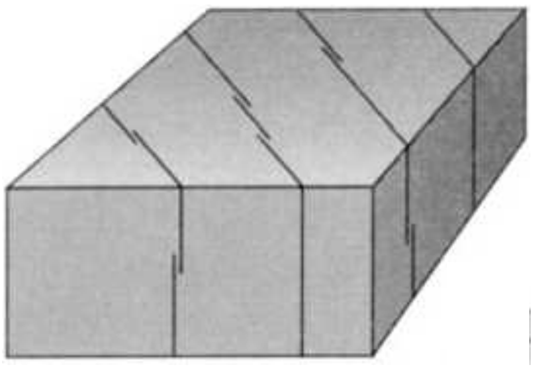


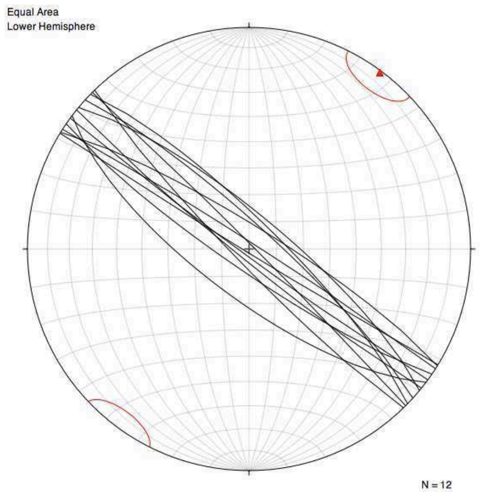




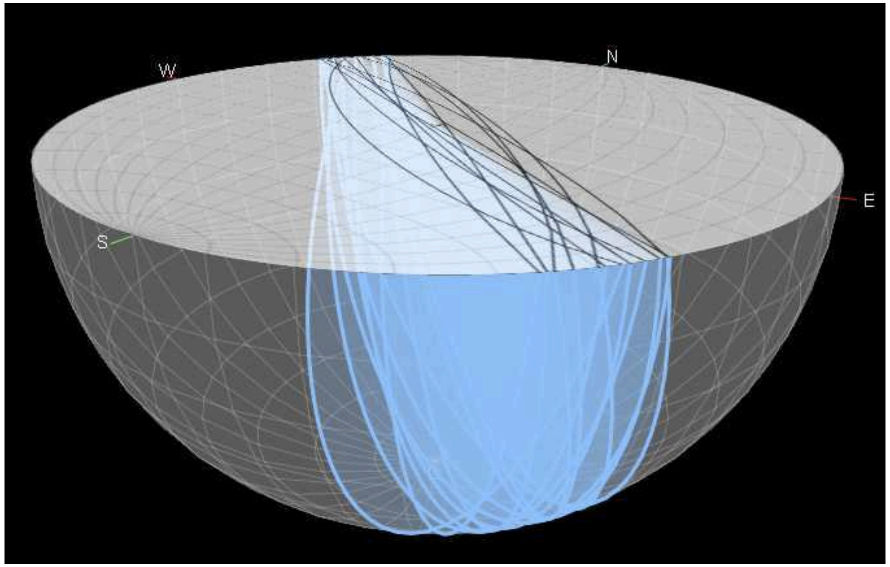
Fallazimuth / Fallen
051 / 34 (XXX/XX)
Streichen / Fallen
N141E / 34 E

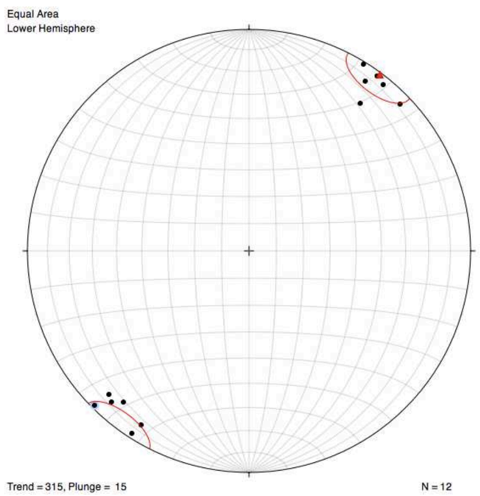
Klüfte und Brüche im Stereonetz



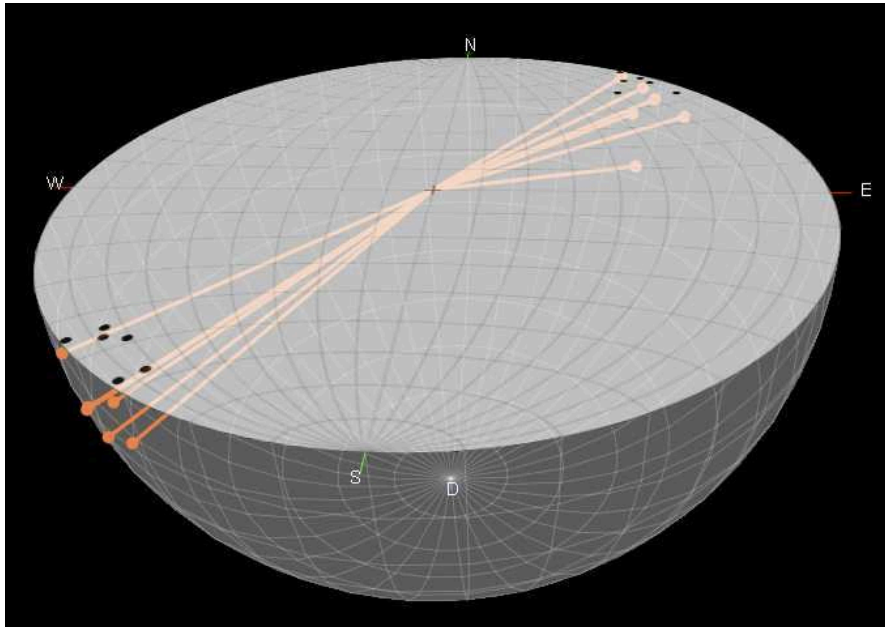


Flächen

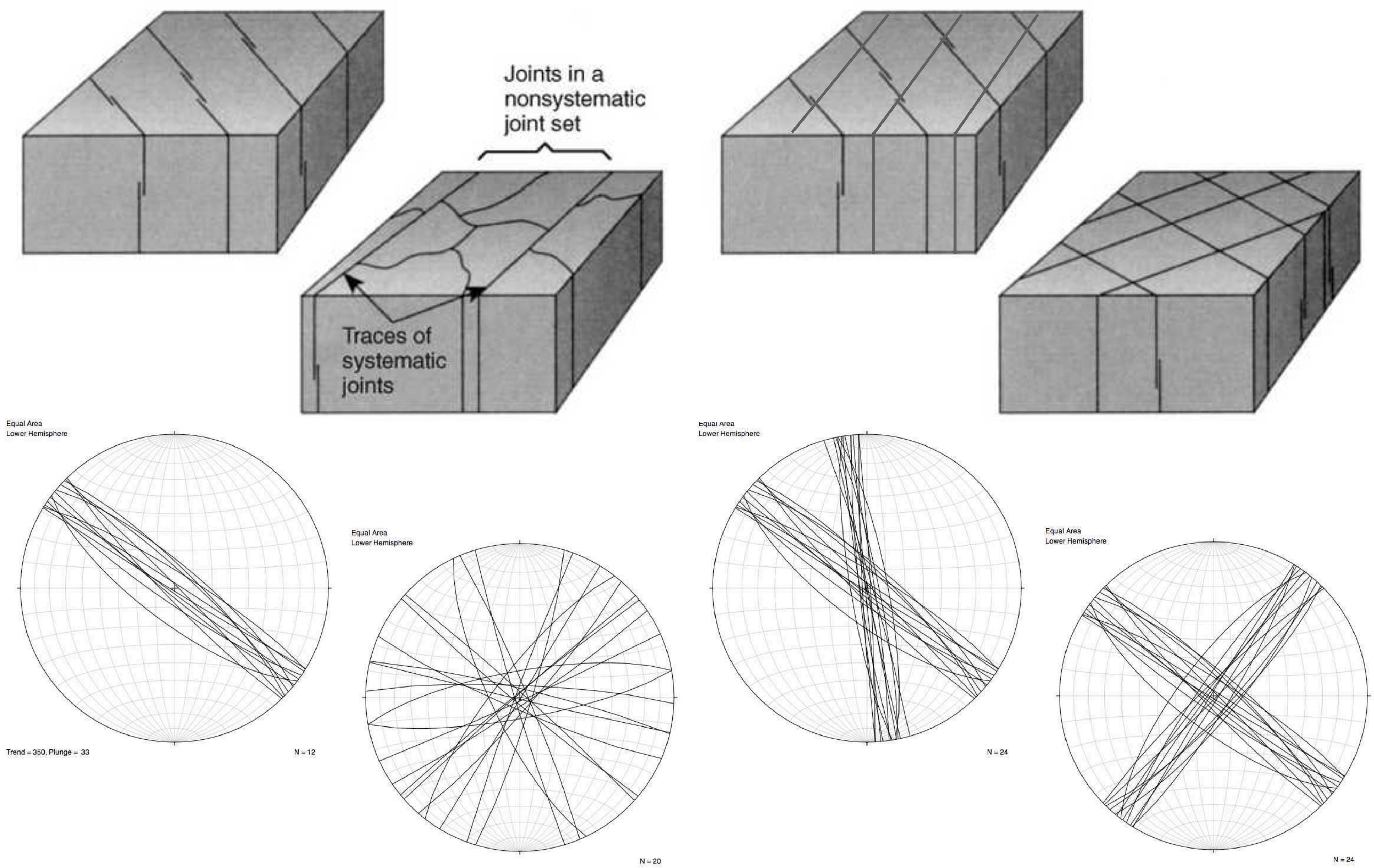




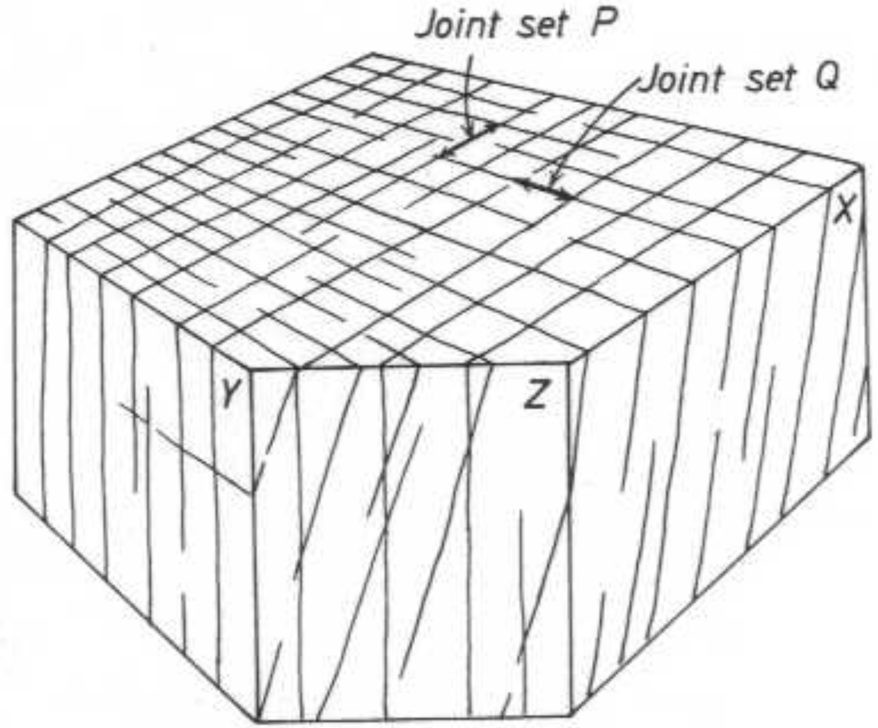
Flächenpole

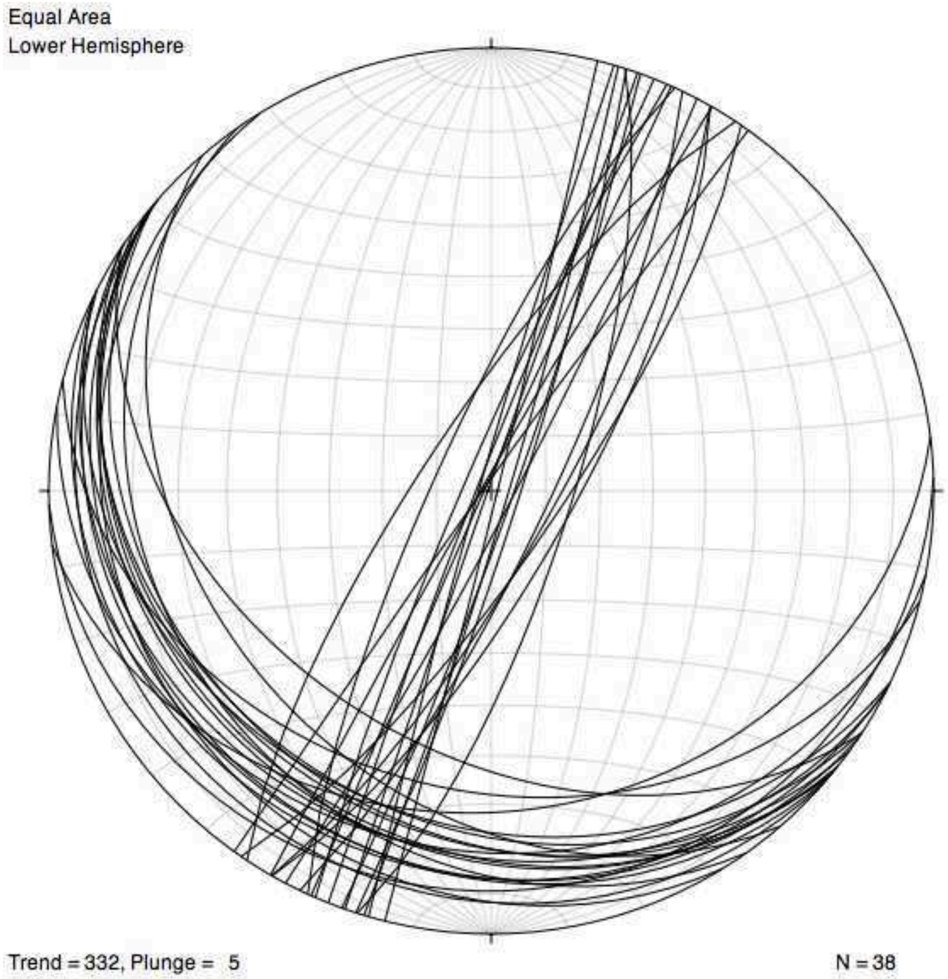


Klüfte und Brüche im Stereonetz

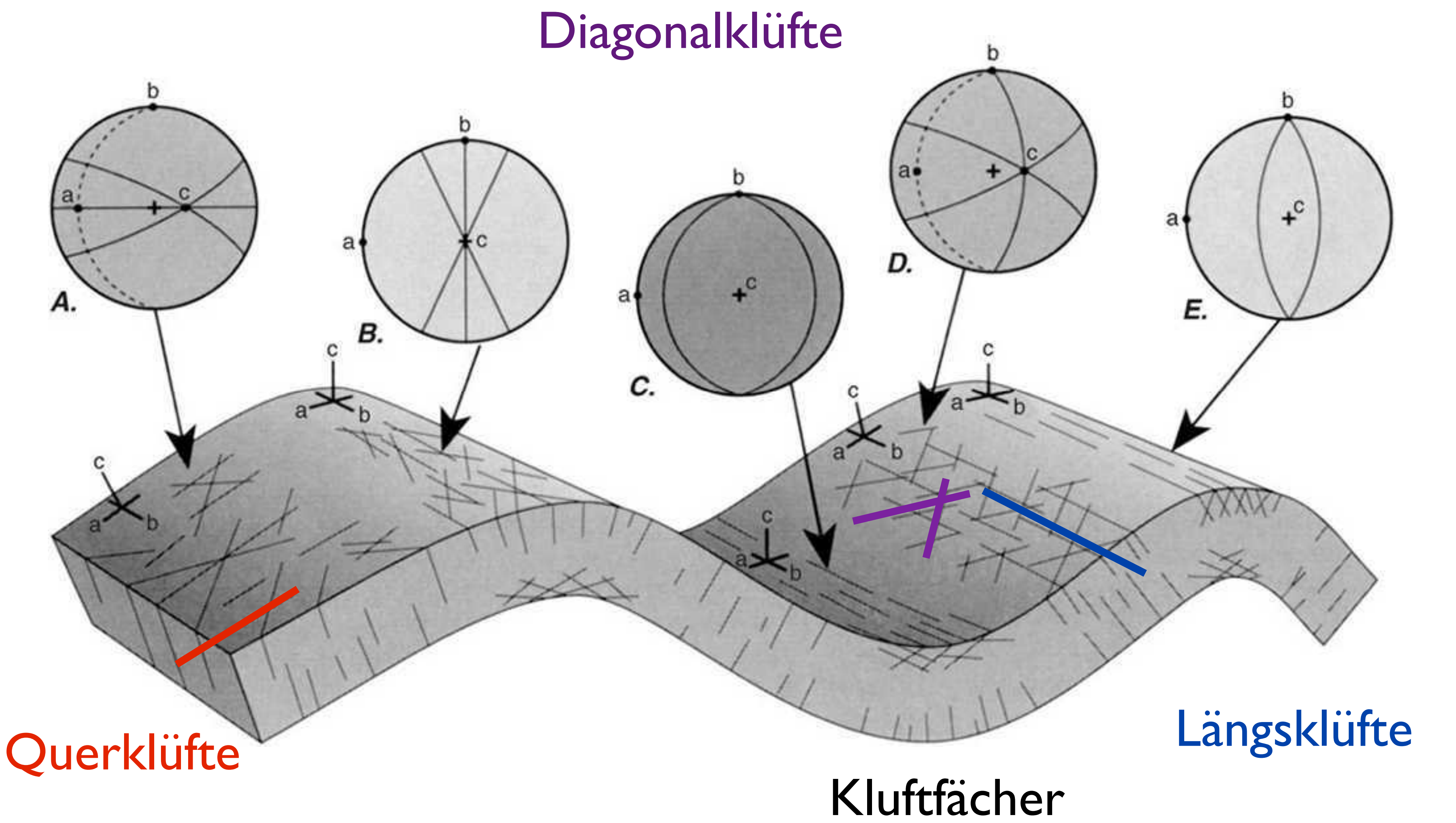


Klüfte und Brüche im Stereonetz





Klüfte assoziert mit Falten



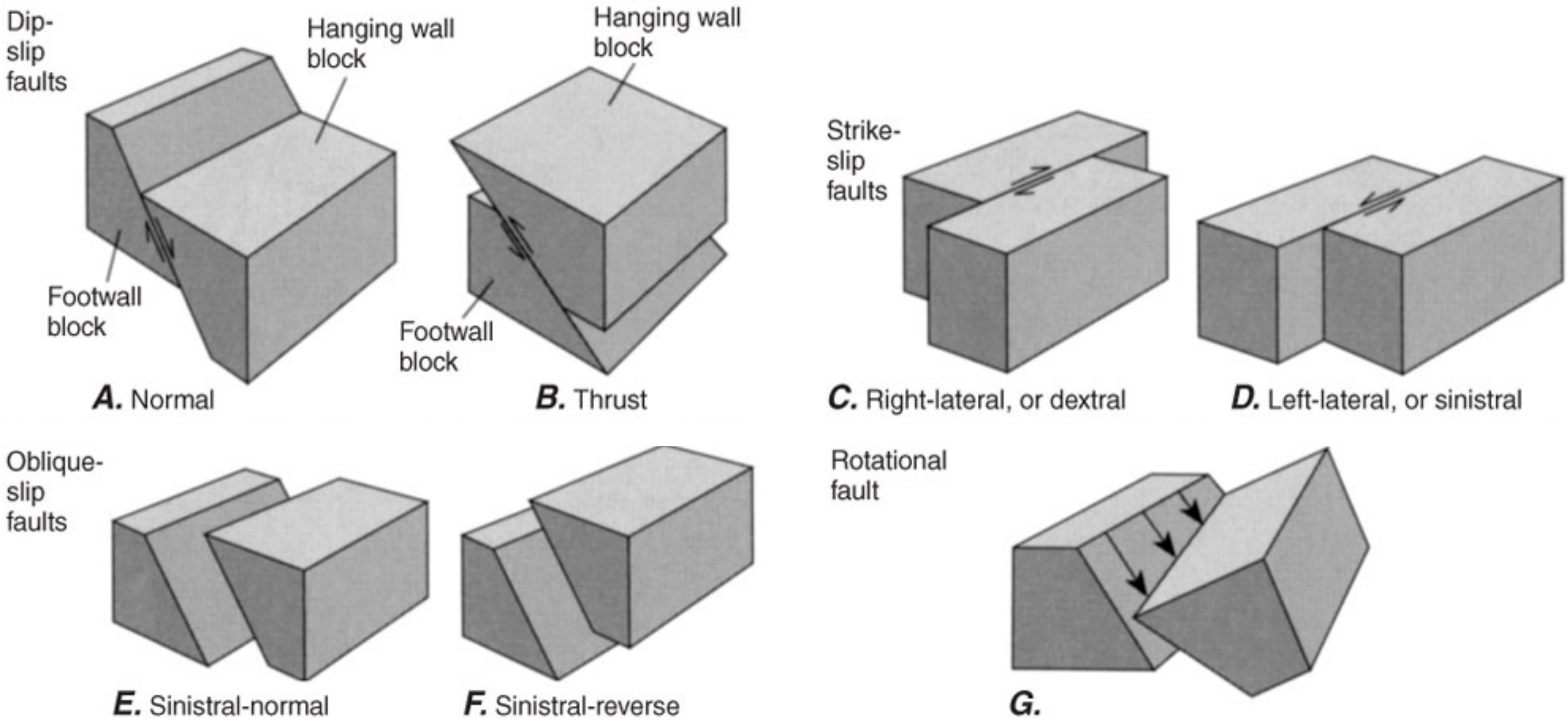
b = Richtung der Faltenachse

Twiss & Moores, 2007

faults

types of faults

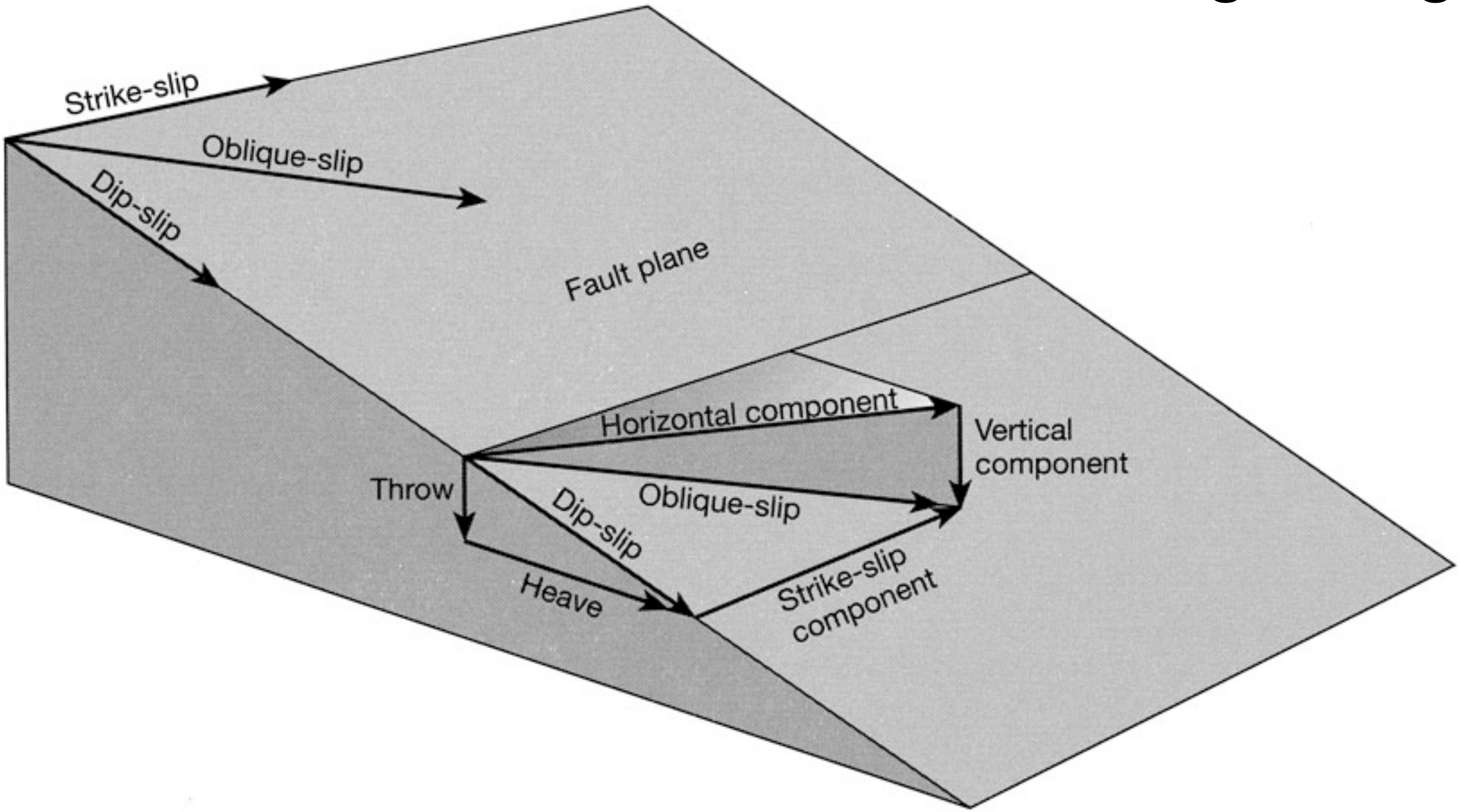
Verwerfungstypen



Hangendes - Liegendes

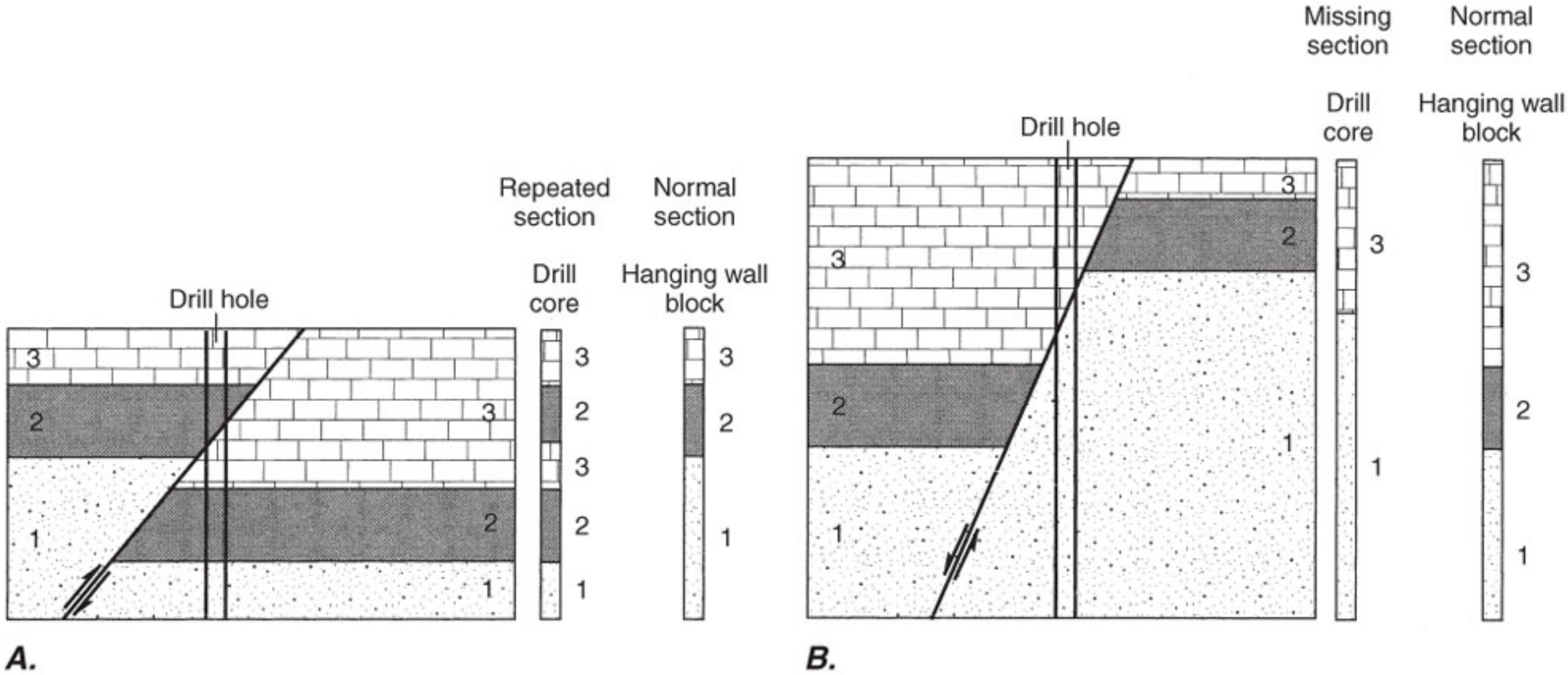
displacement

Versetzung
Versetzungsbetrag

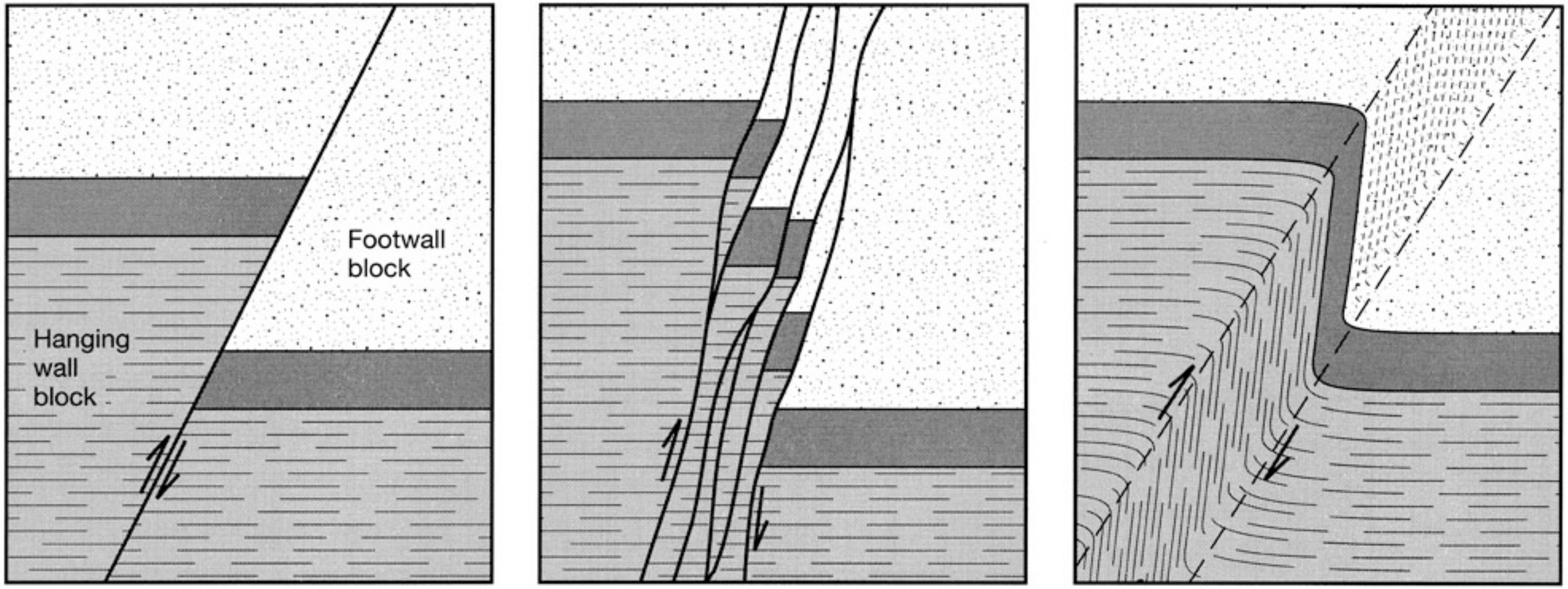


relative displacement defined by slip vector

Bohrung durch Auf-/Abschiebung



fault - fault zone - shear zone

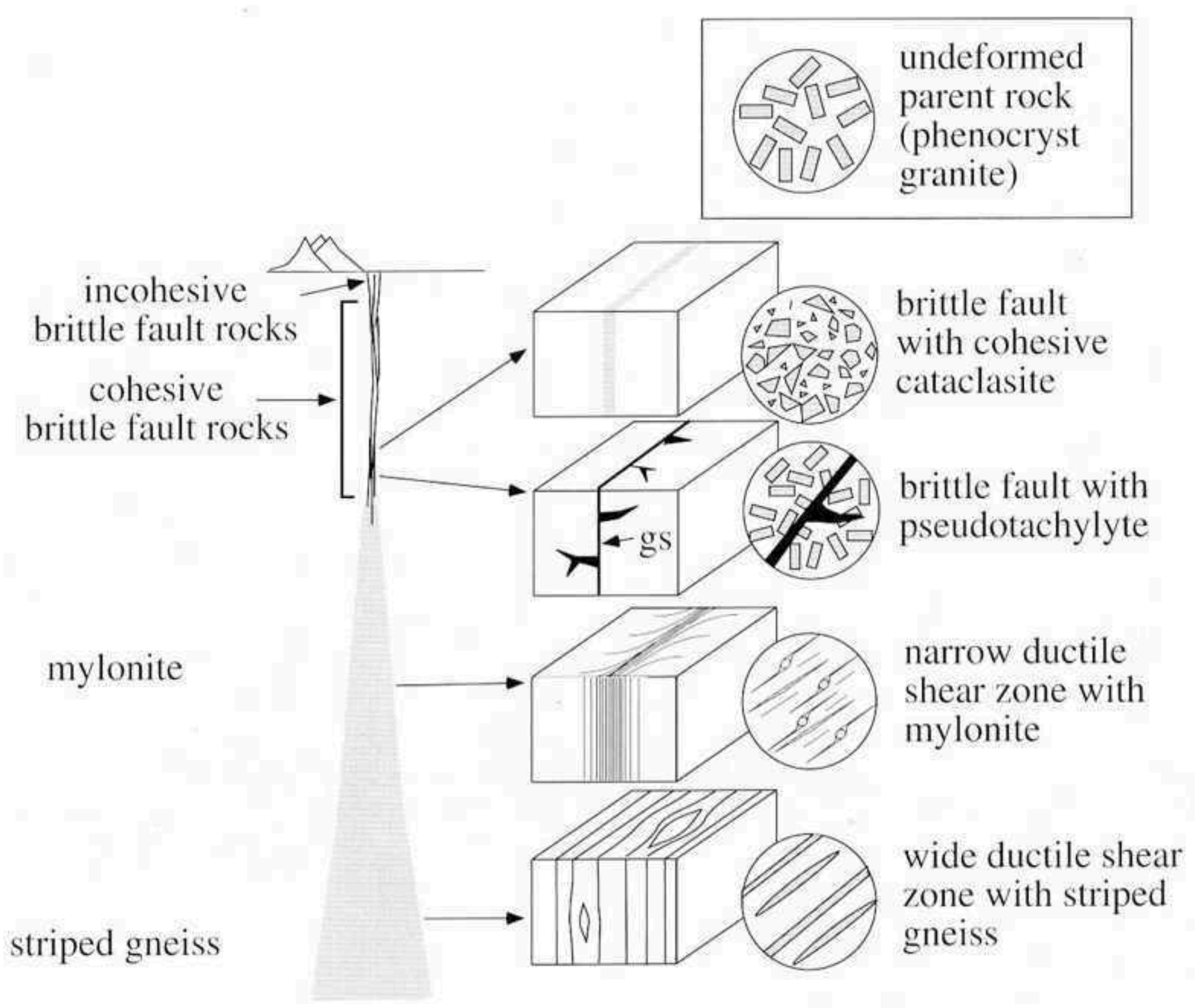


Verwerfung - Verwerfungszonezone - Scherzone

high angle fault: > 45 ° inclination
low angle fault: < 45 ° inclination

fault zone

Verwerfungszone



intaktes Gestein

Brekkzie
fault gouge

Kataklasite
Ultrakataklasite

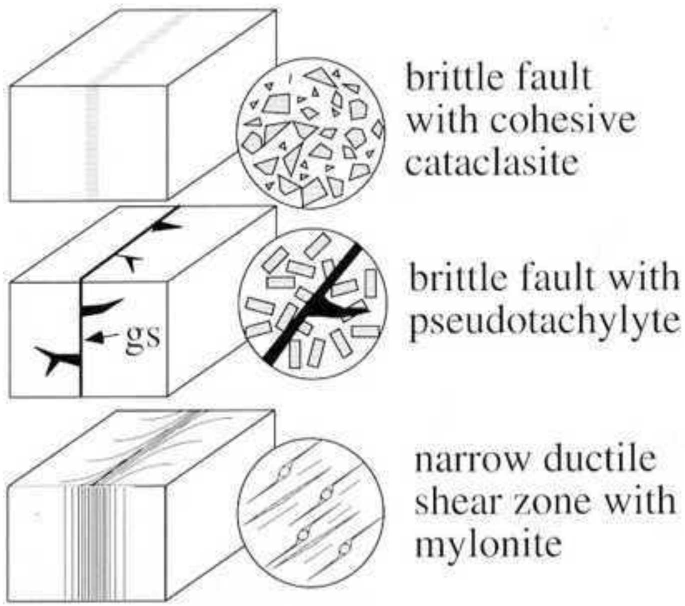
Pseudotachylite

Mylonite
Ultramylonite

Gneiss

fault zone

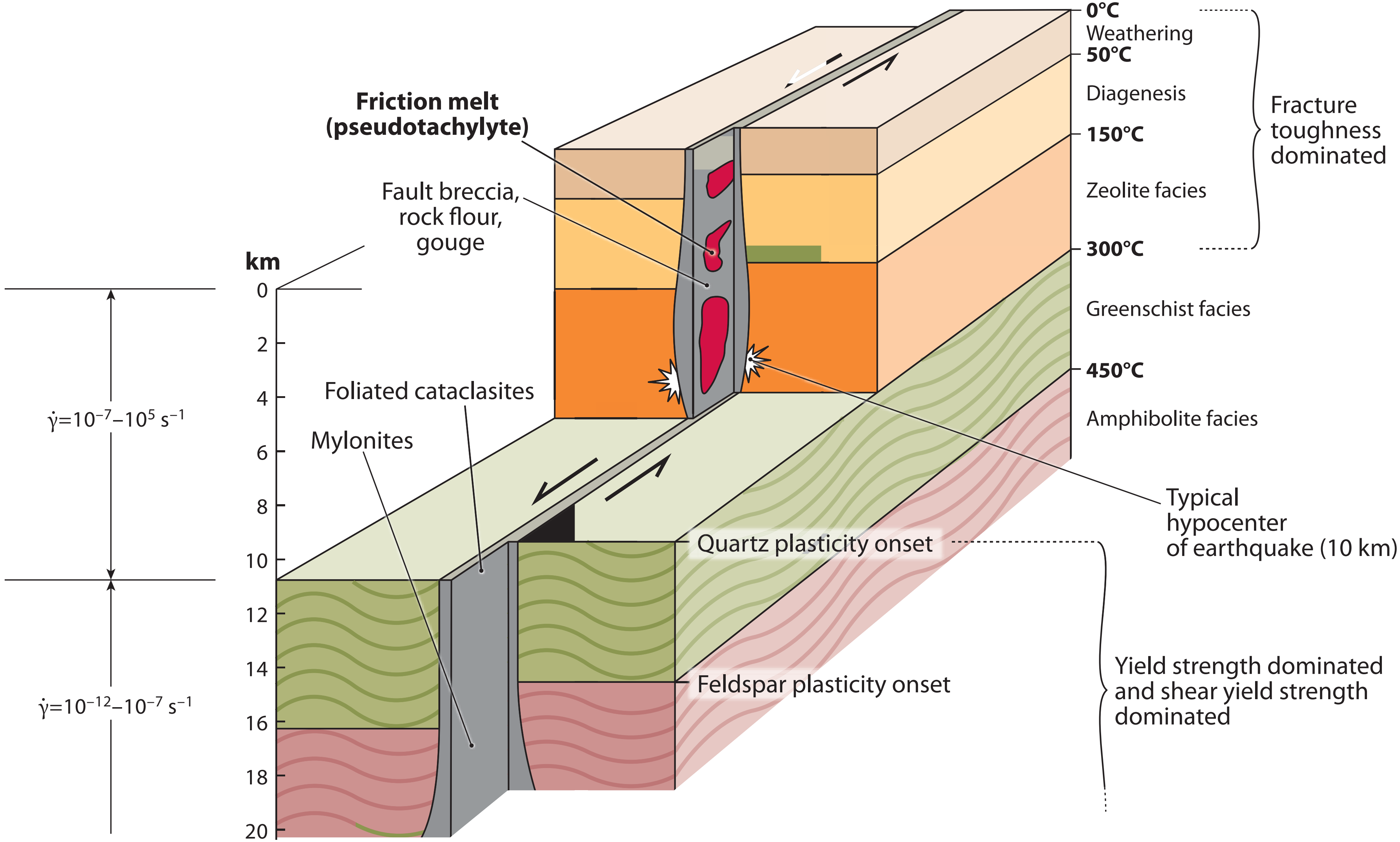
Typische Gesteine



Kohäsionsloses Lockermaterial:	
Gesteinsmehl (gouge)	feinkörnige Matrix
Unverfestigte Brekzie	erkennbare Klasten
Festes Gestein (ohne Foliation):	
Protokataklasit / Brekzie	> 50% erkennbare Klasten
Kataklasit	50-90% Matrix
Ultrakataklasit	> 90% Matrix
Festes Gestein (mit Foliation):	
Protomylonit	< 50% rekristallisiert
Mylonit	50-90% rekristallisiert
Ultramylonit	> 90% rekristallisiert

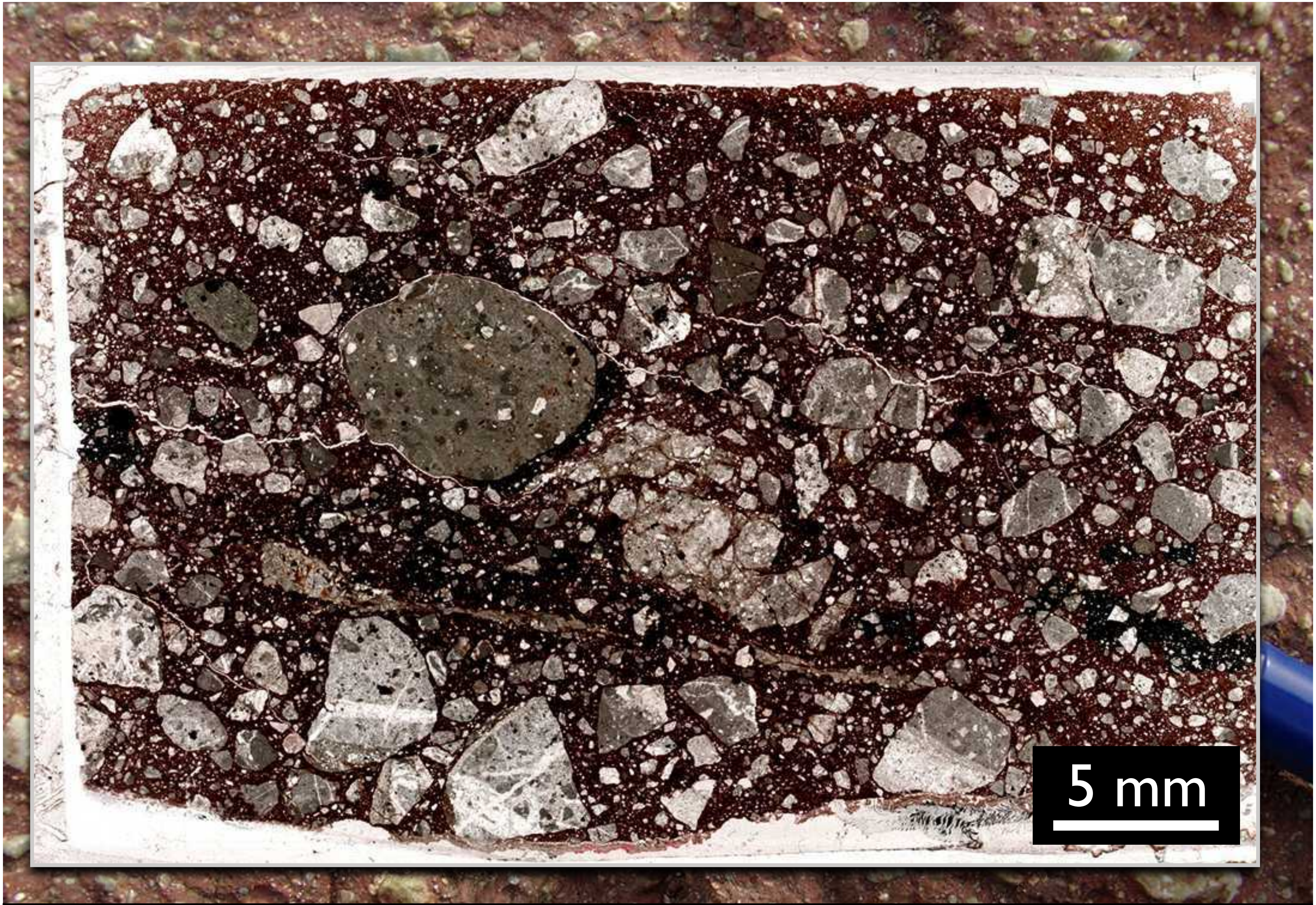
nach: Roland Vinx (2005): Gesteinsbestimmung im Gelände, Elsevier

fault zone



Friction melt
(pseudotachylyte)
Fault breccia,
rock flour,
gouge
km
0
2
4
6
8
10
12
14
16
18
20
$\dot{\gamma}=10^{-7}$–10^{5} s^{-1}
$\dot{\gamma}=10^{-12}$–10^{-7} s^{-1}
Foliated cataclasites
Mylonites
0°C
Weathering
50°C
Diagenesis
150°C
Zeolite facies
300°C
Greenschist facies
450°C
Amphibolite facies
Fracture
toughness
dominated
Typical
hypocenter
of earthquake (10 km)
Quartz plasticity onset
Feldspar plasticity onset
Yield strength dominated
and shear yield strength
dominated

Bruchfläche

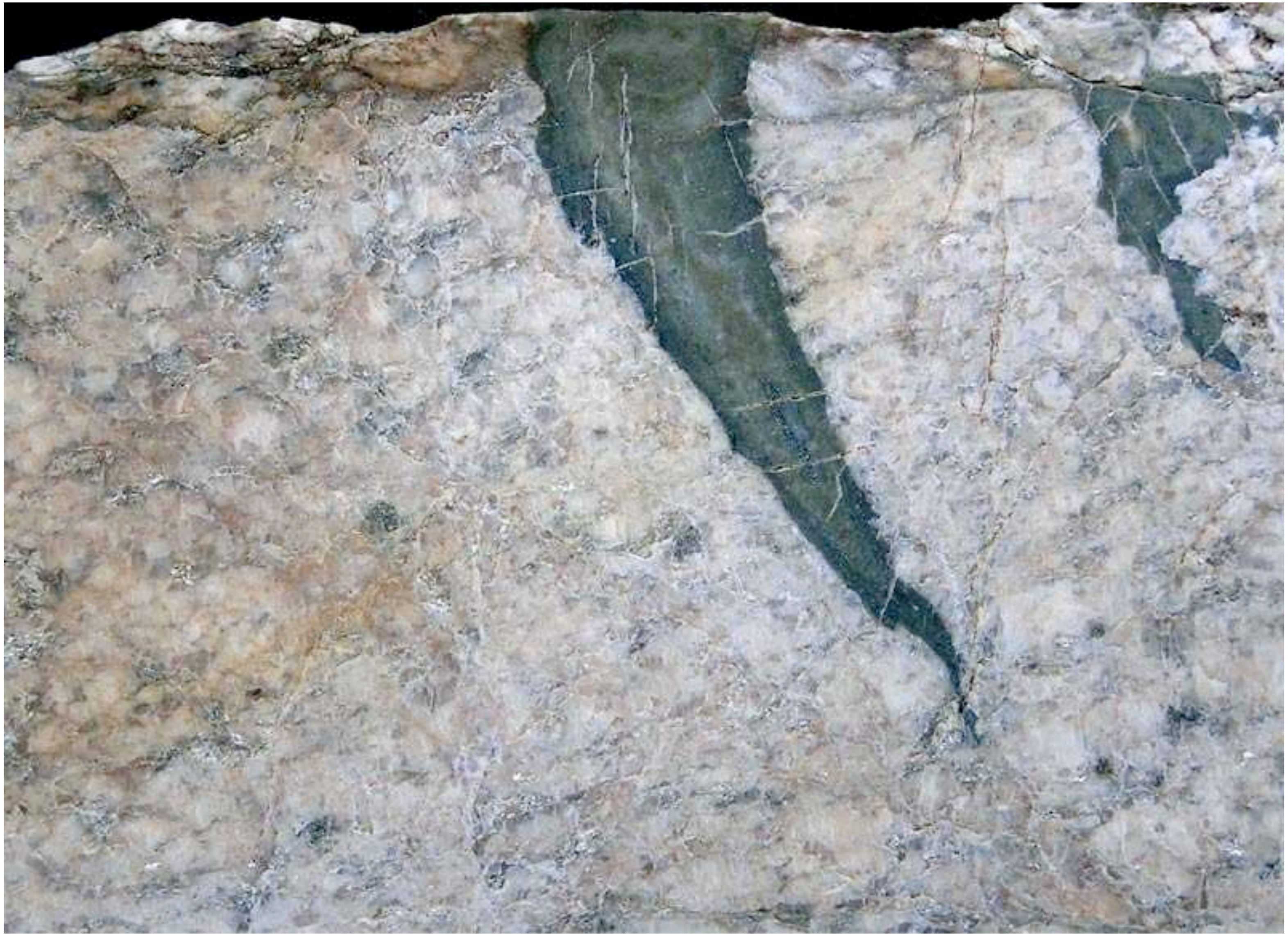


Kataklasit

Brekzie

Titus Canyon, Death Valley (Wikipedia)

Pseudotachylit



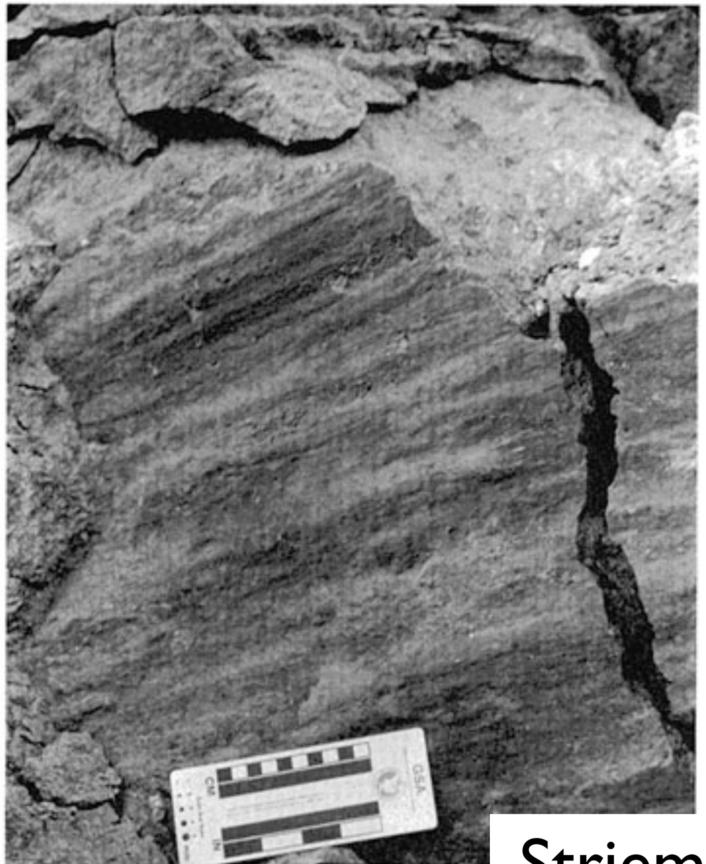
(geology.um.maine.edu)

slickensides / slickenfibres

Gleitflächen

- indicate direction and sense of movement
- constitute a lineation containing the movement vector

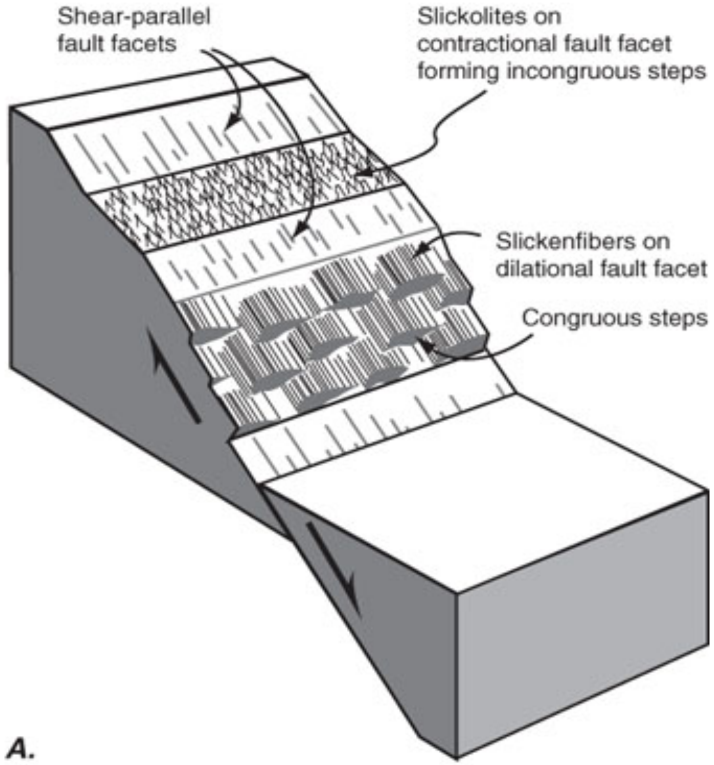
A.



B.

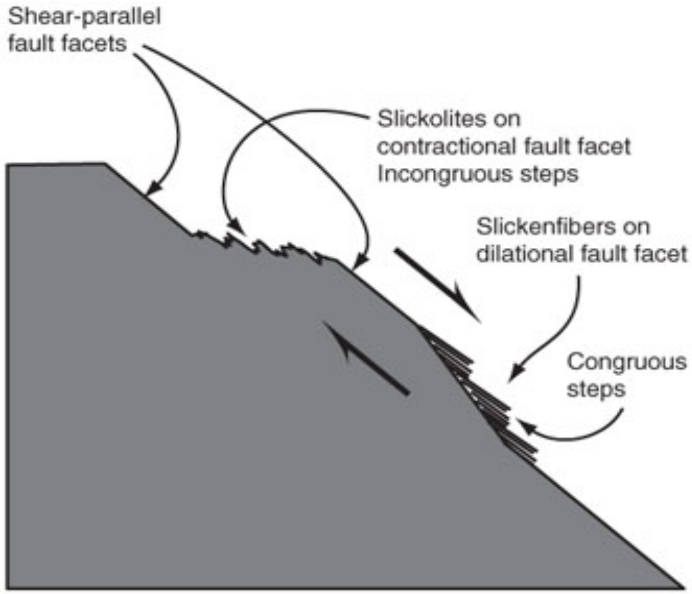
Striemungen - Rutschharnisch

slickenfibres

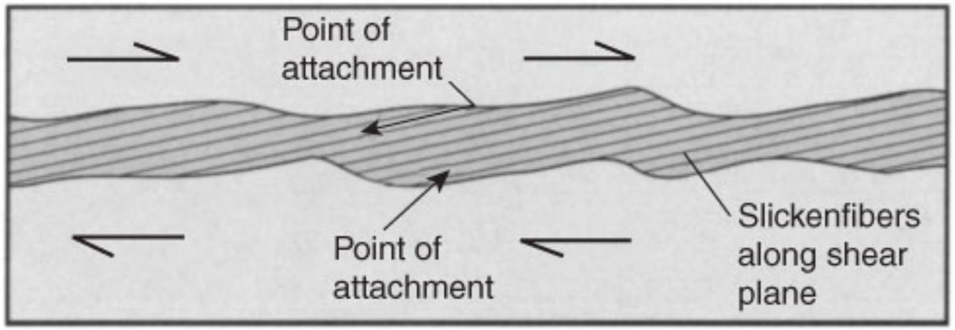


A.

solution-precipitation microstructures

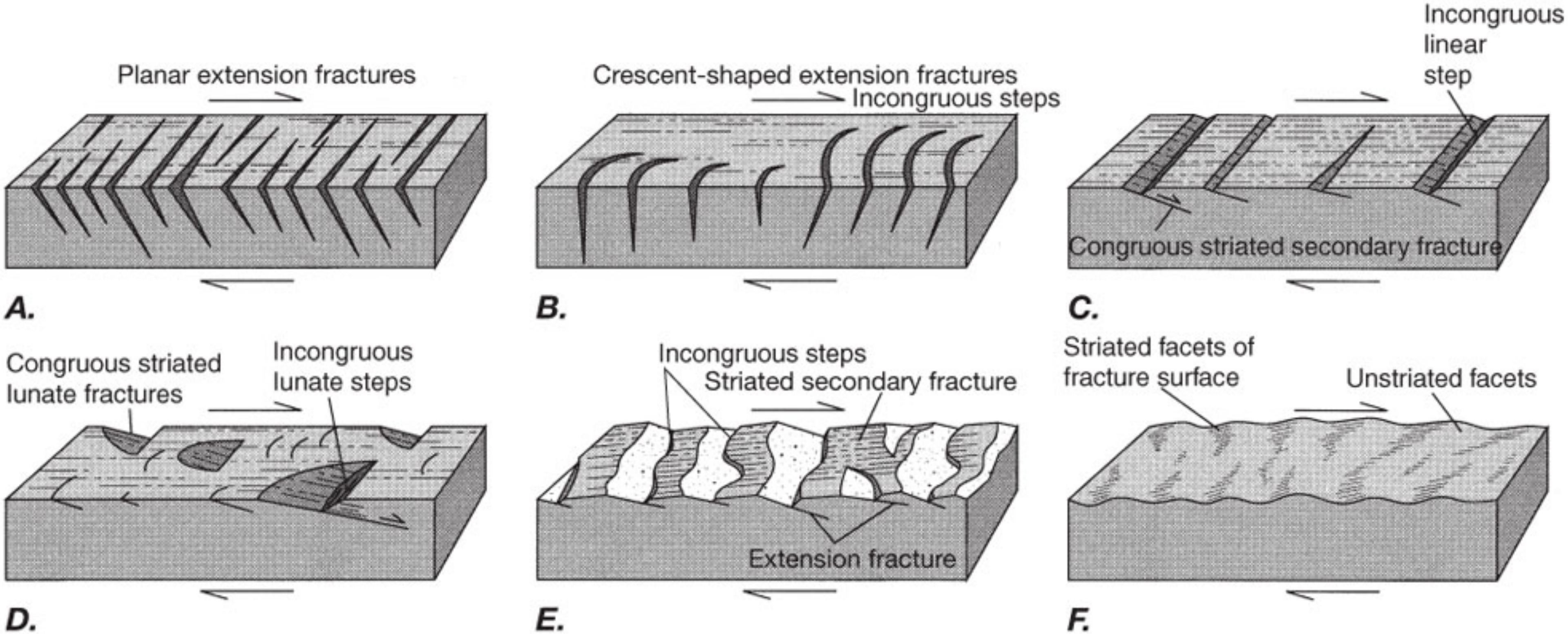


B.



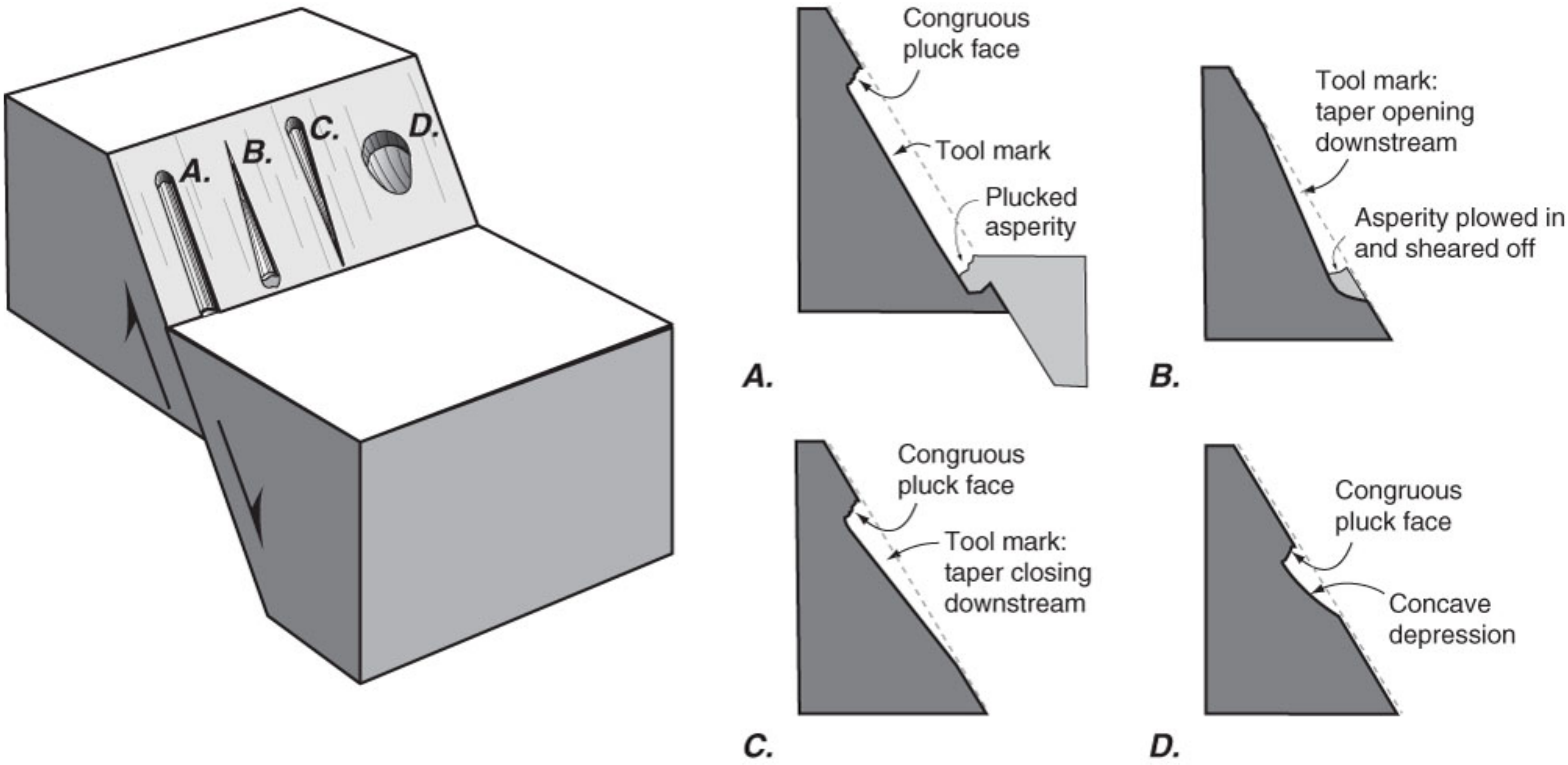
C.

displacement - micro scale



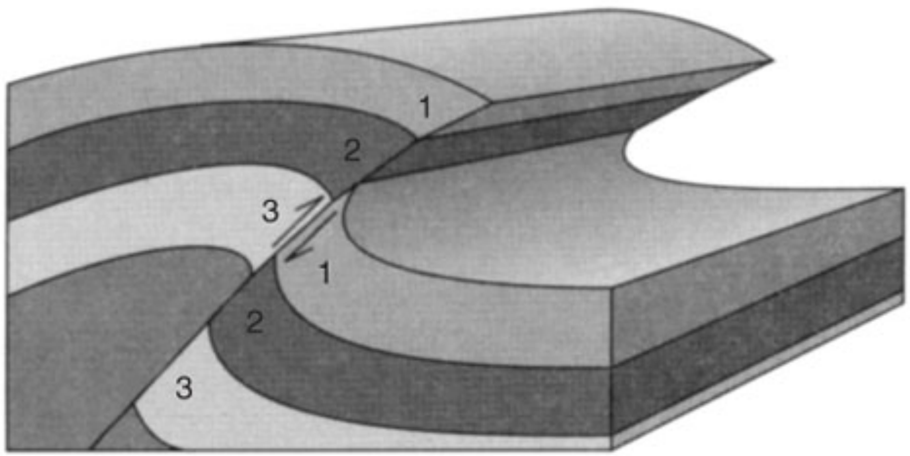
determination of movement sense from cracks associated with faults

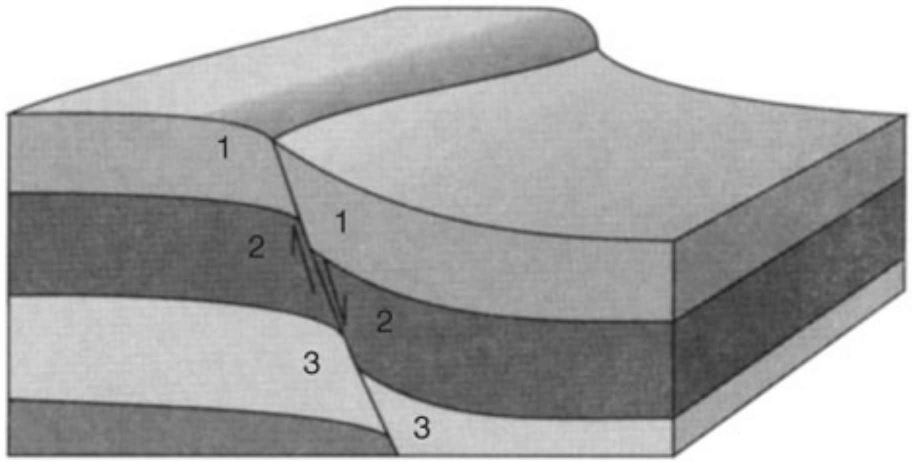
displacement - micro scale



determination of movement sense from tool marks

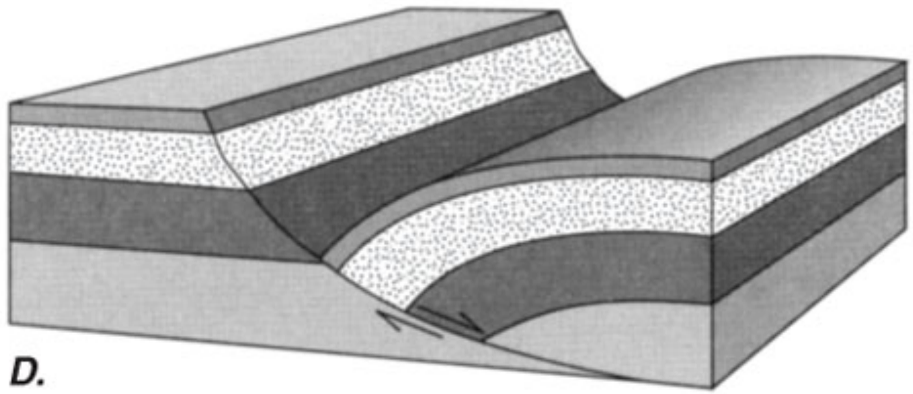
displacement - macro scale





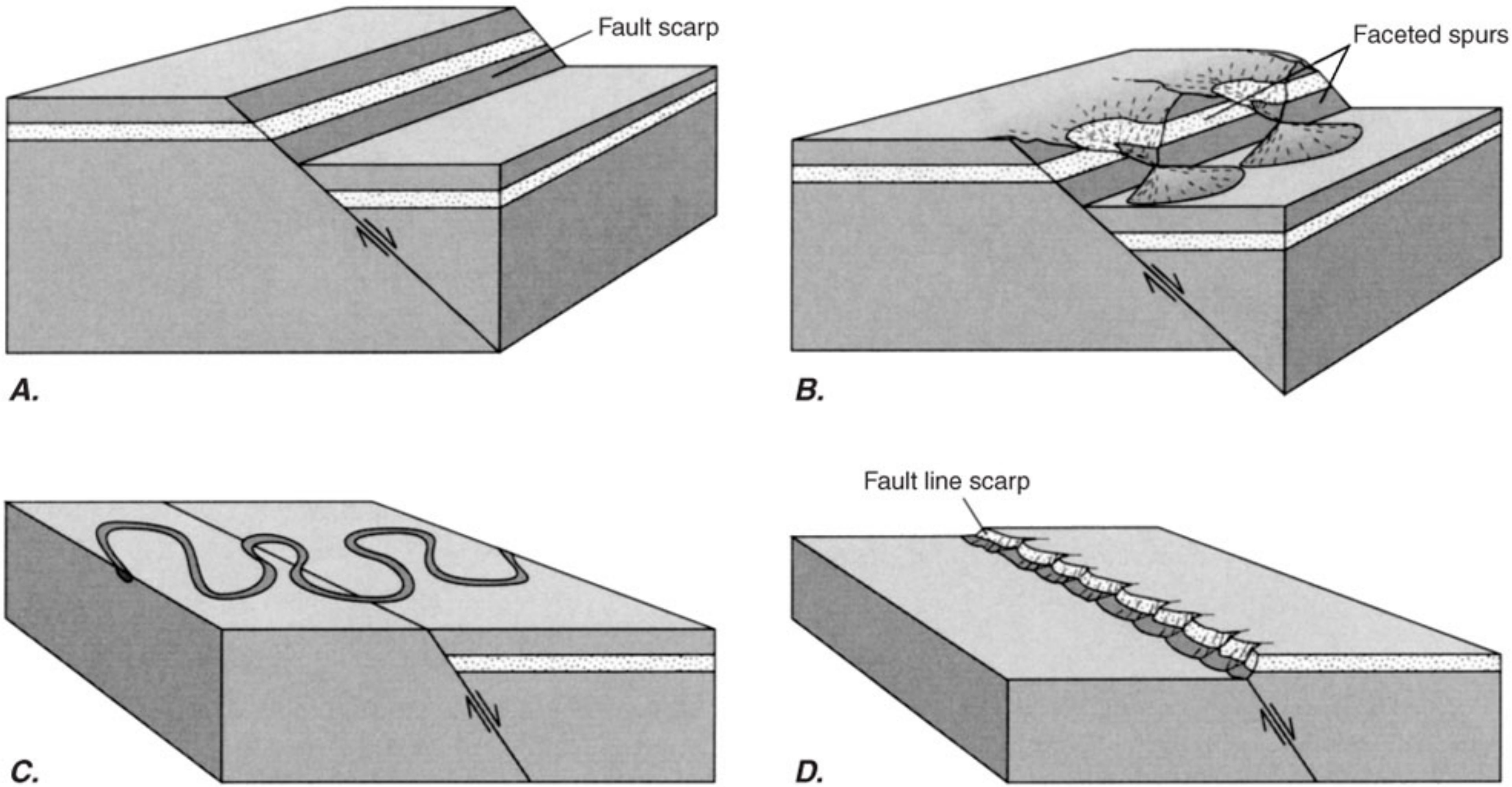
B.

Movement sense from
drag-folds and
roll-over anticlines



D.

displacement - macro scale

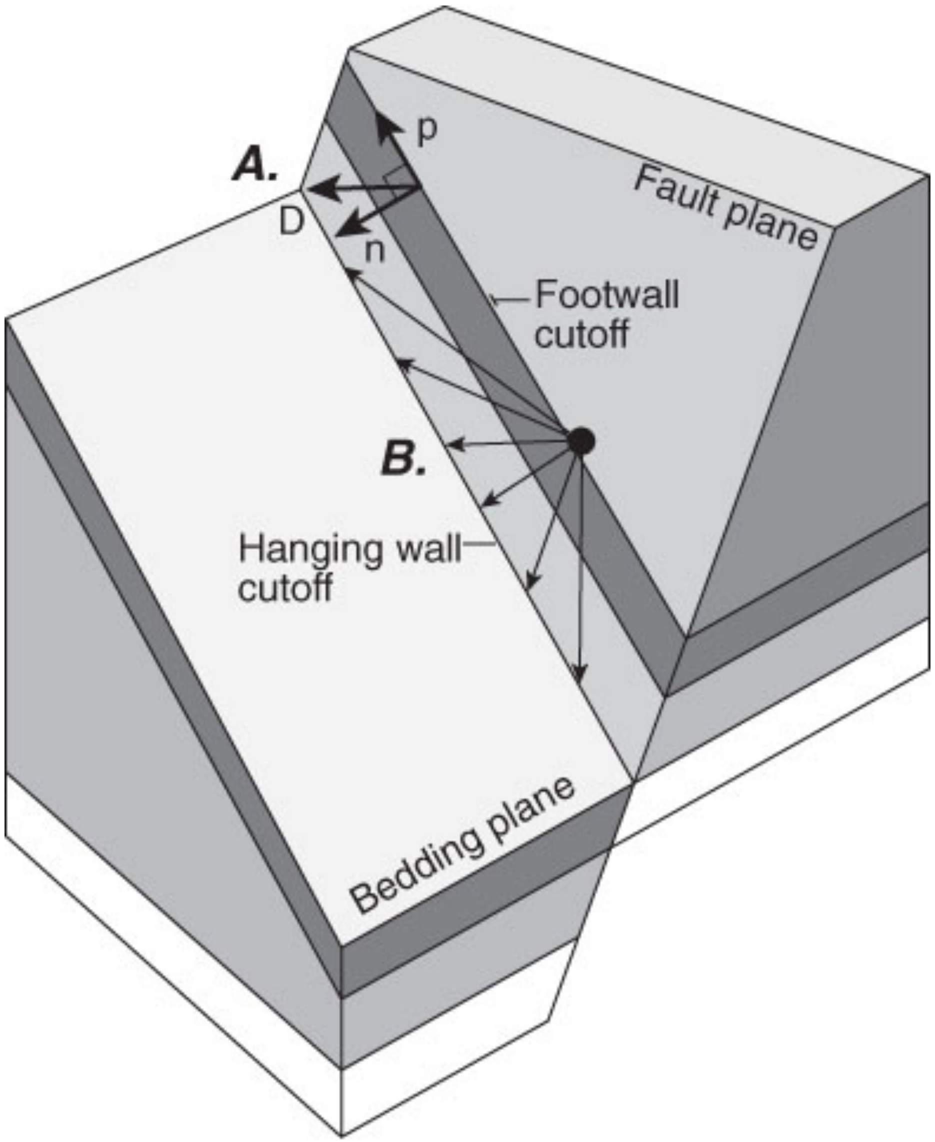


determination of movement sense from fault scarps, erosional features, stratigraphic displacement, eroded fault scarps

displacement - macro scale

Movement sense from displaced rivers

displacement - markers



faulted planar features are non-unique movement indicators

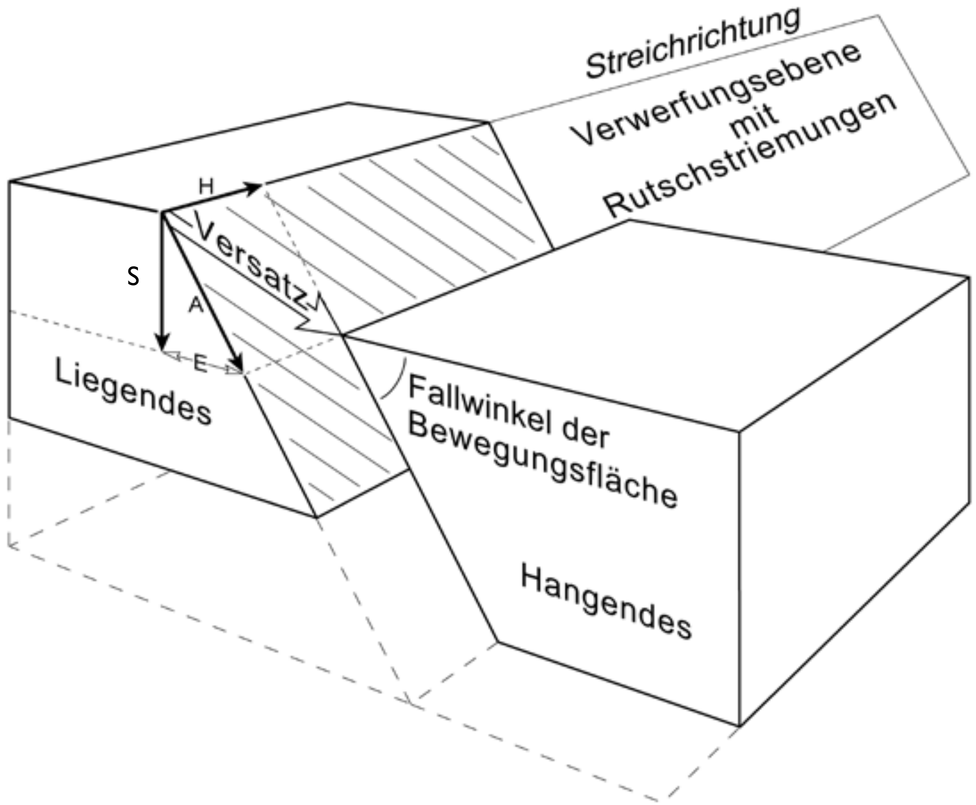
Verschiebungsvektor

In der Verwerfungsebene

- H Horizontale Verschiebungskomponente (strike-slip component)
- A Abschiebungkomponente (dip slip component)

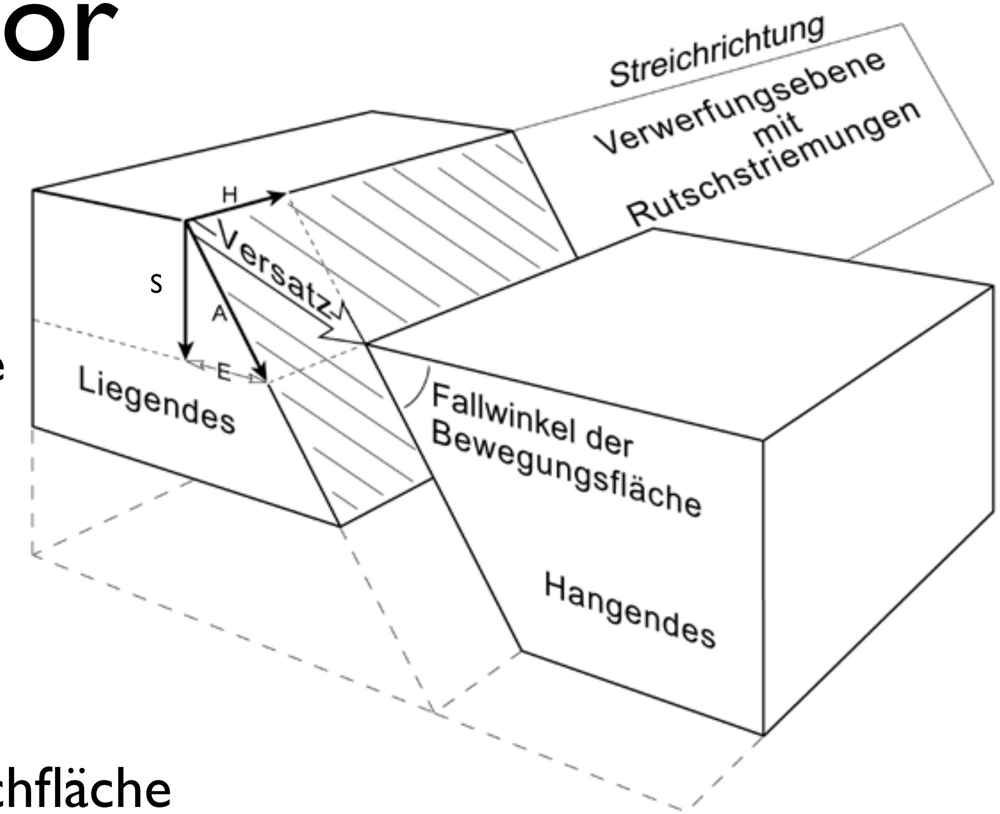
Im Profil

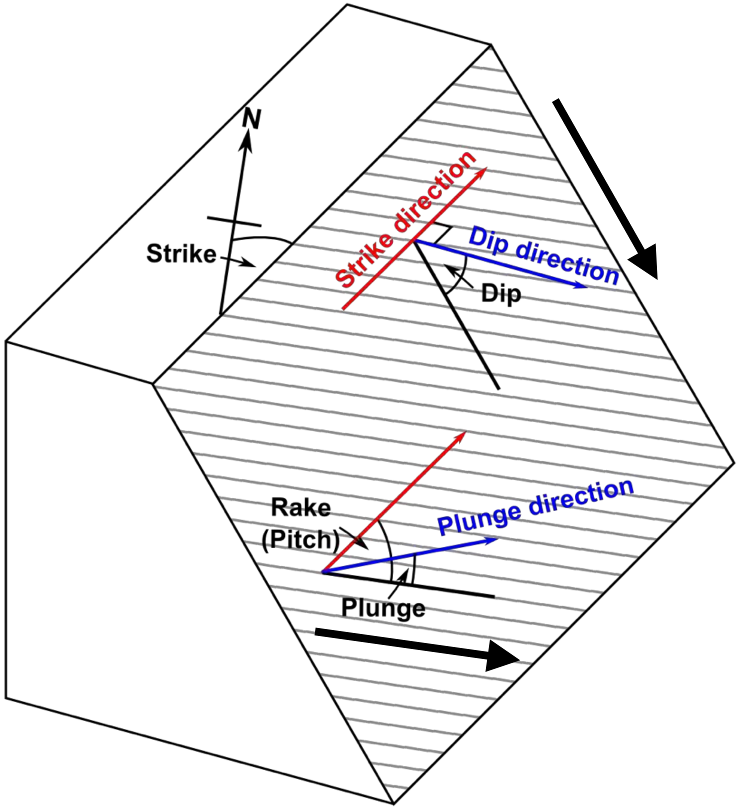
- E Dehnungsbetrag (heave)
- S Sprunghöhe (throw) (vertikale Verschiebungs-komponente)



Verschiebungsvektor

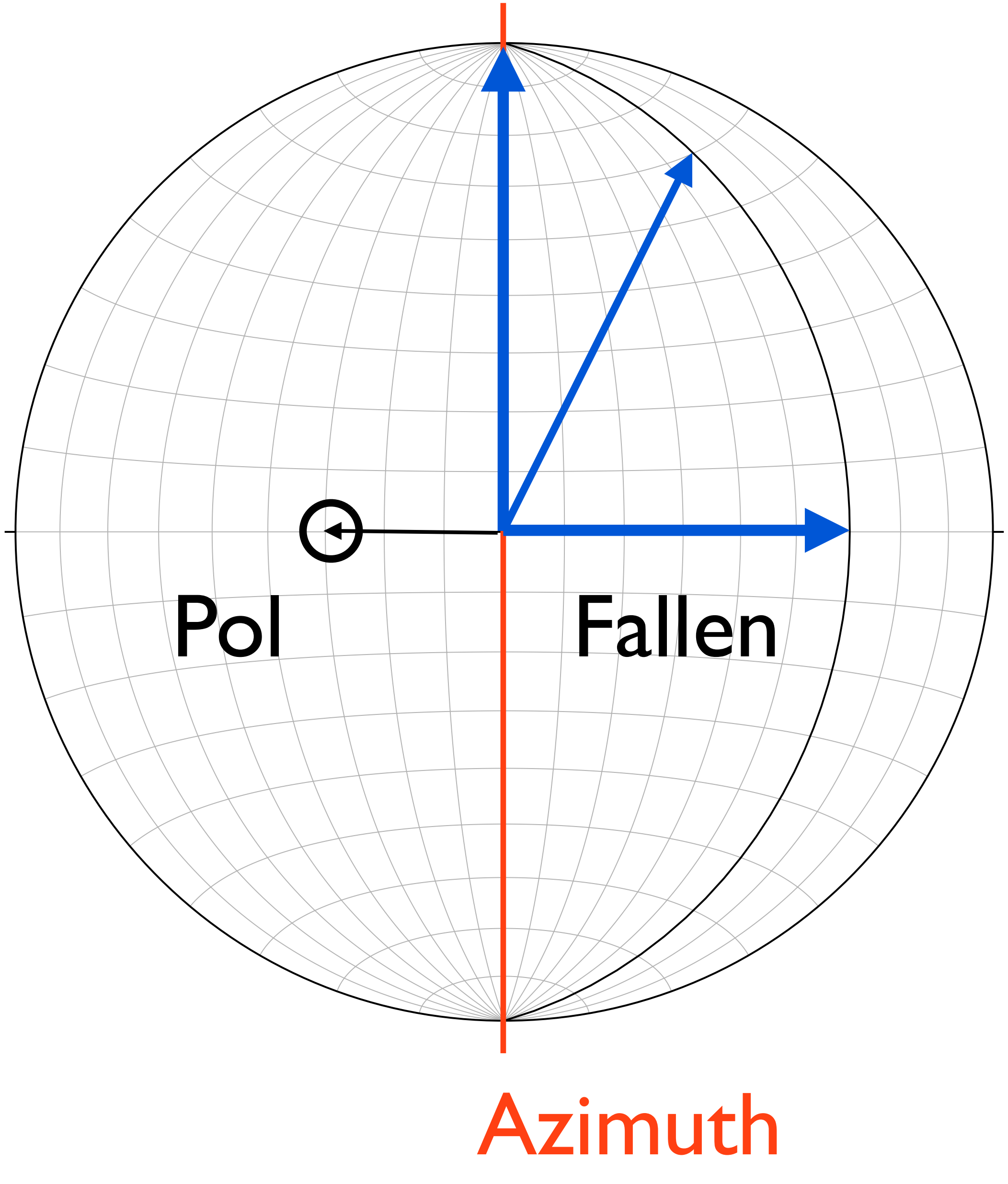
- E Dehnungsbetrag (heave)
- S Sprunghöhe (throw) (vertikale Verschiebungskomponente)
- H Horizontale Verschiebungskomponente (strike-slip component)
- A Abschiebungkomponente (dip slip component)

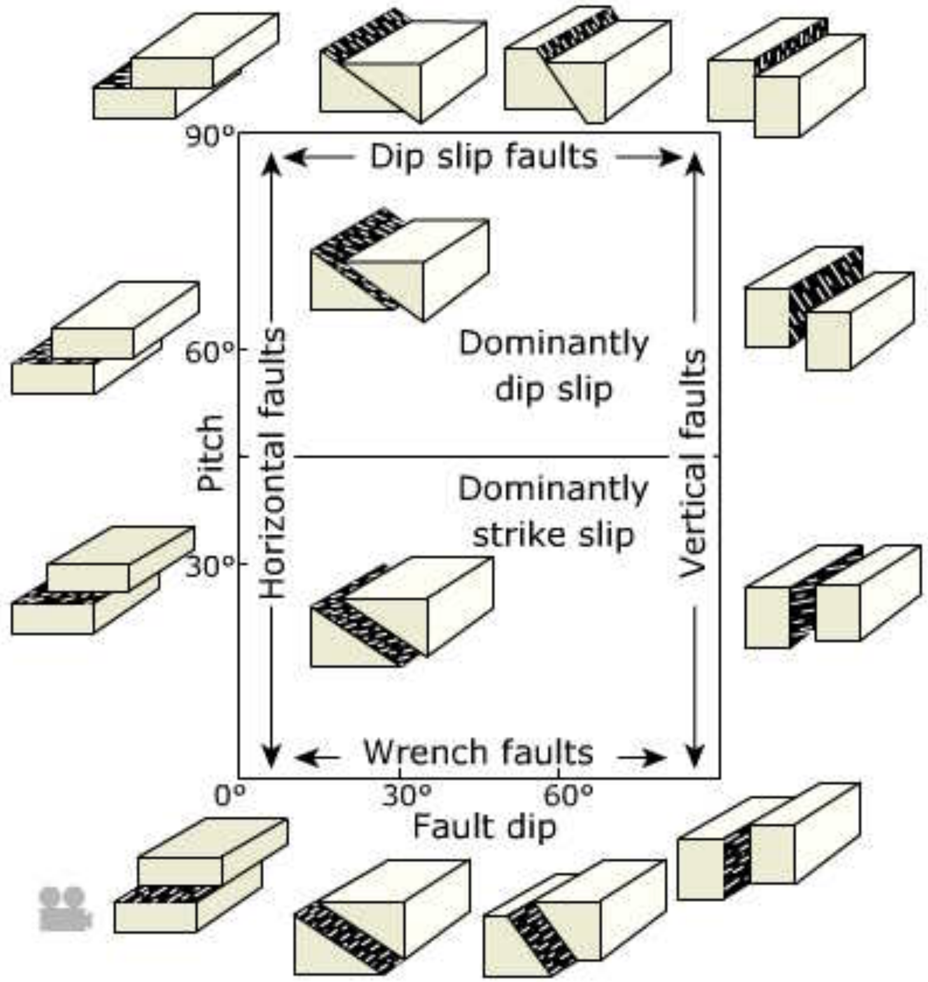


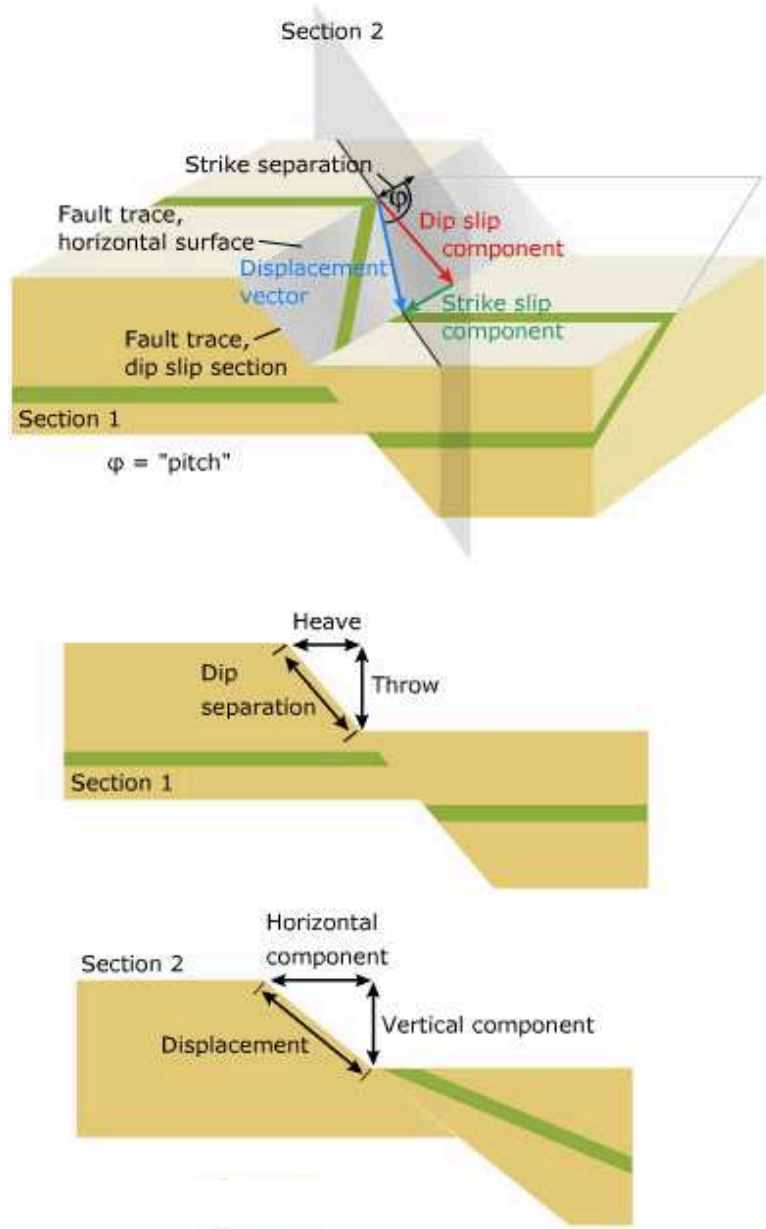


Bruchfläche
Raumlage: (Ein-)Fallen
dip-direction/dip

Linear (Striemung, Versatz, ...)
Raumlage: (Ein-)Tauchen
plunge-direction/plunge
pitch = Winkel 〈strike-direction, Linear〉


Pol
Fallen
Azimuth



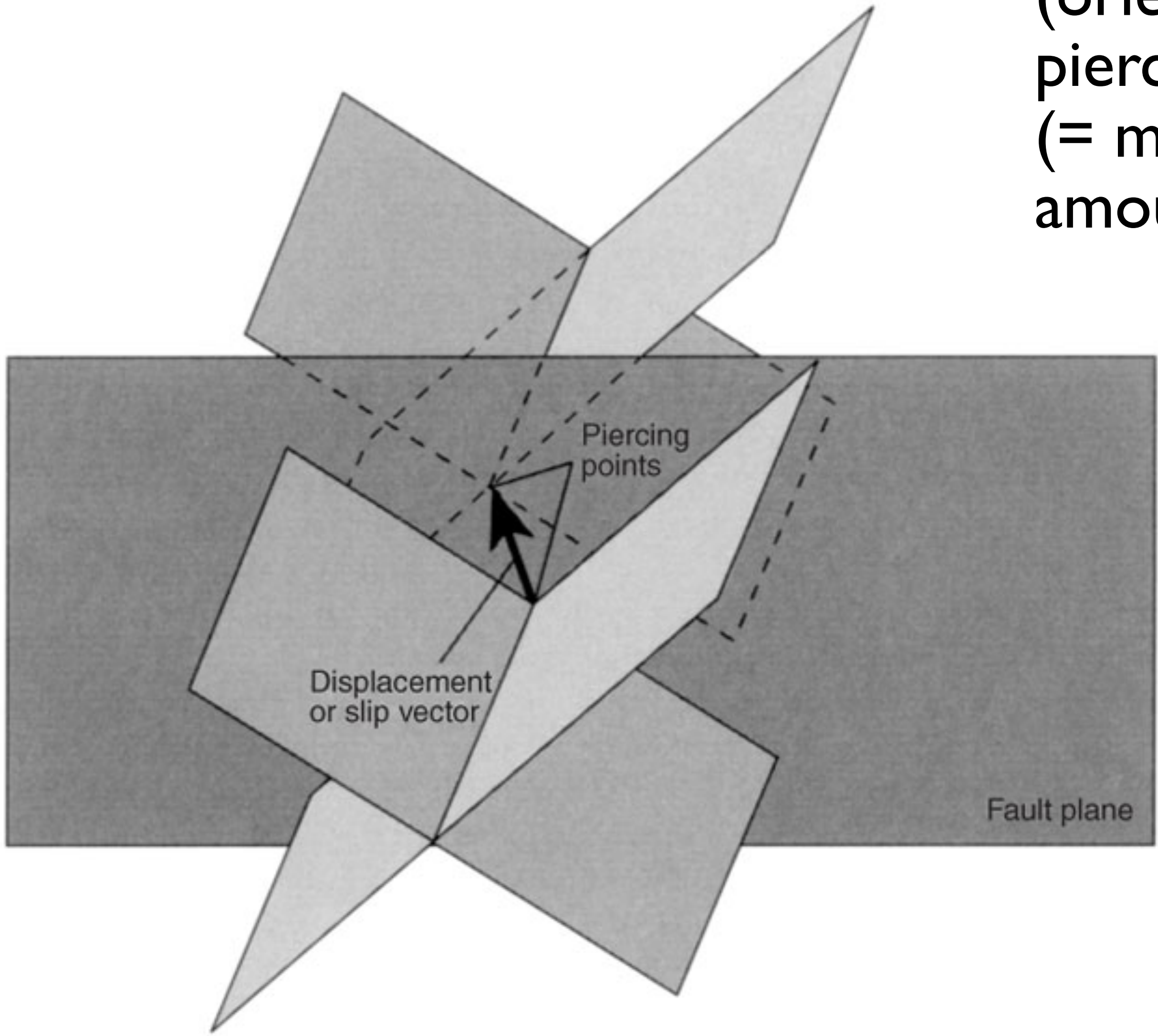


http://folk.uib.no/nglhe/Emodules.html

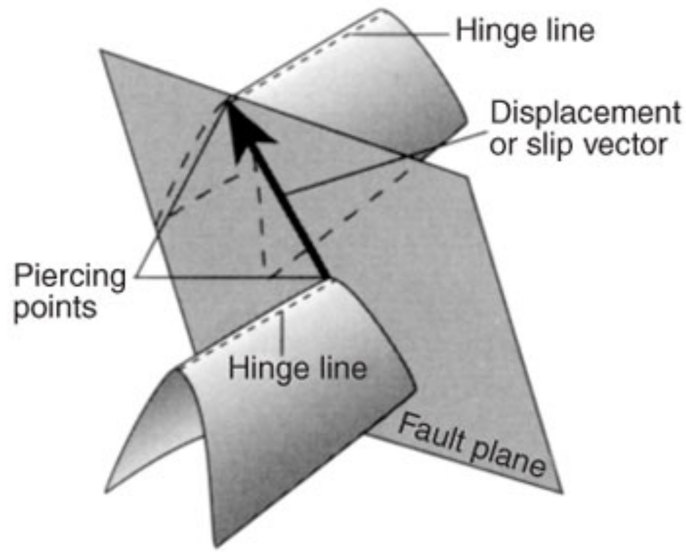
http://folk.uib.no/nglhe/e-modules/Chapter%208/08%20Faults.swf

piercing points

displacement vector (orientation + length) from piercing points
(= movement sense + amount of displacement)

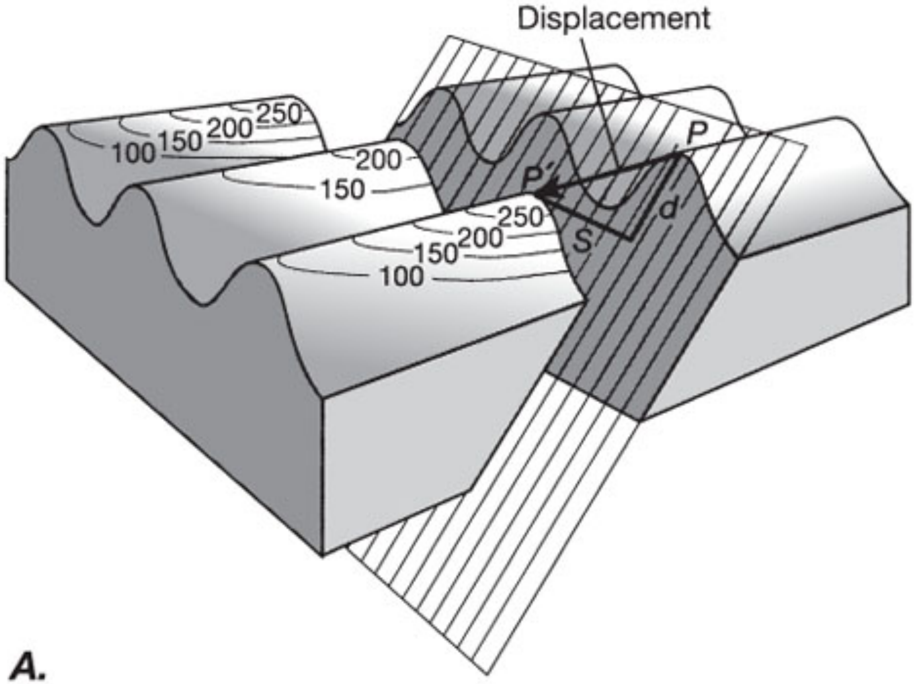


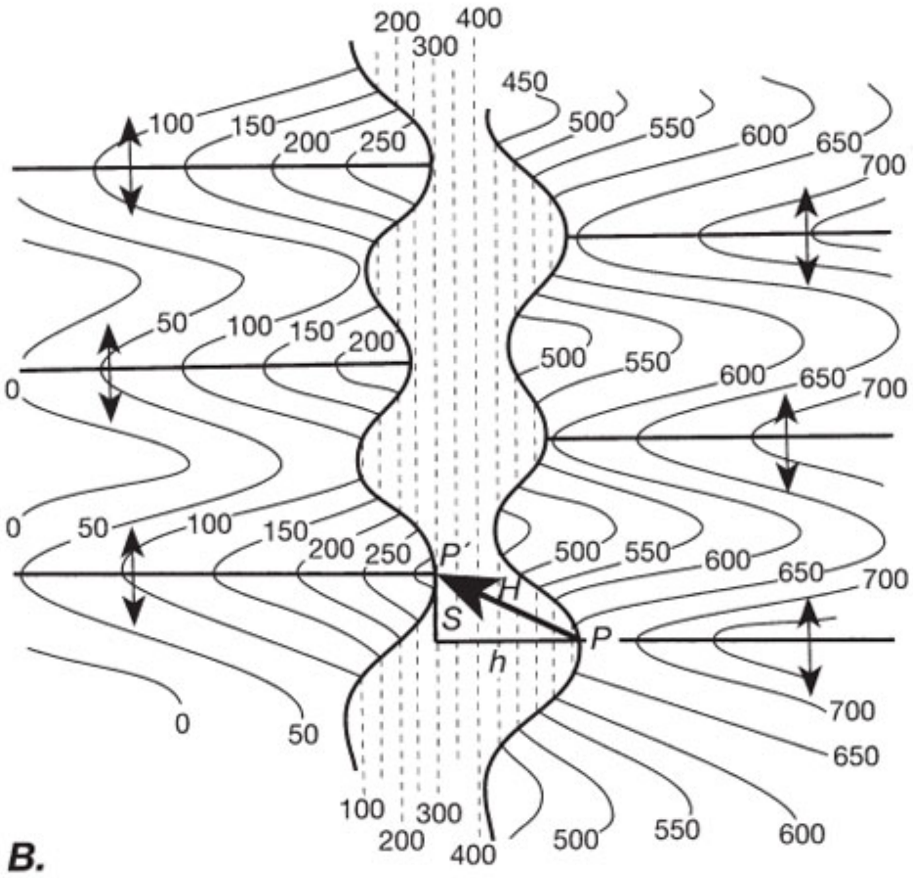
A.



B.

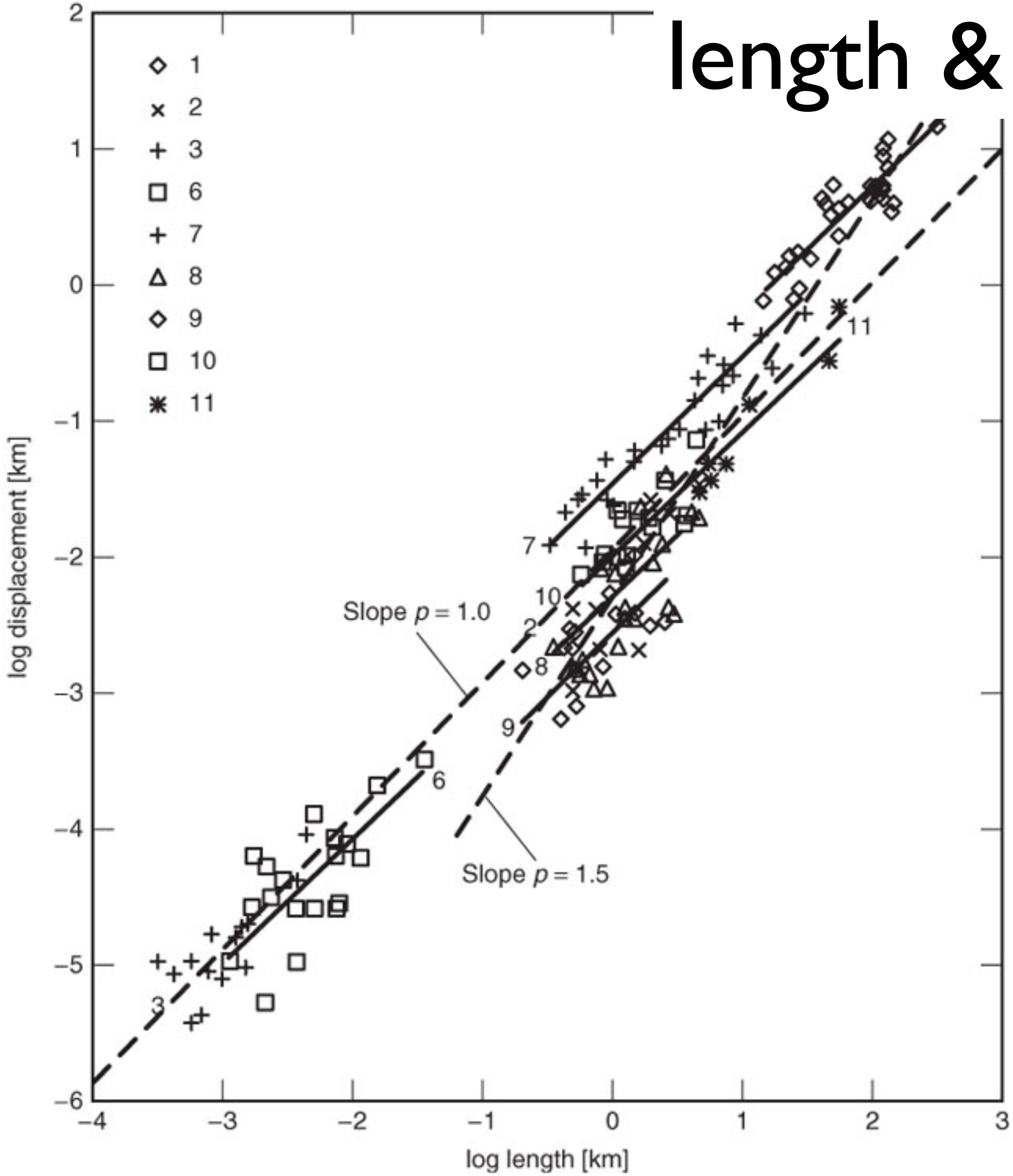
piercing points





Example of piercing point construction using structural elevations

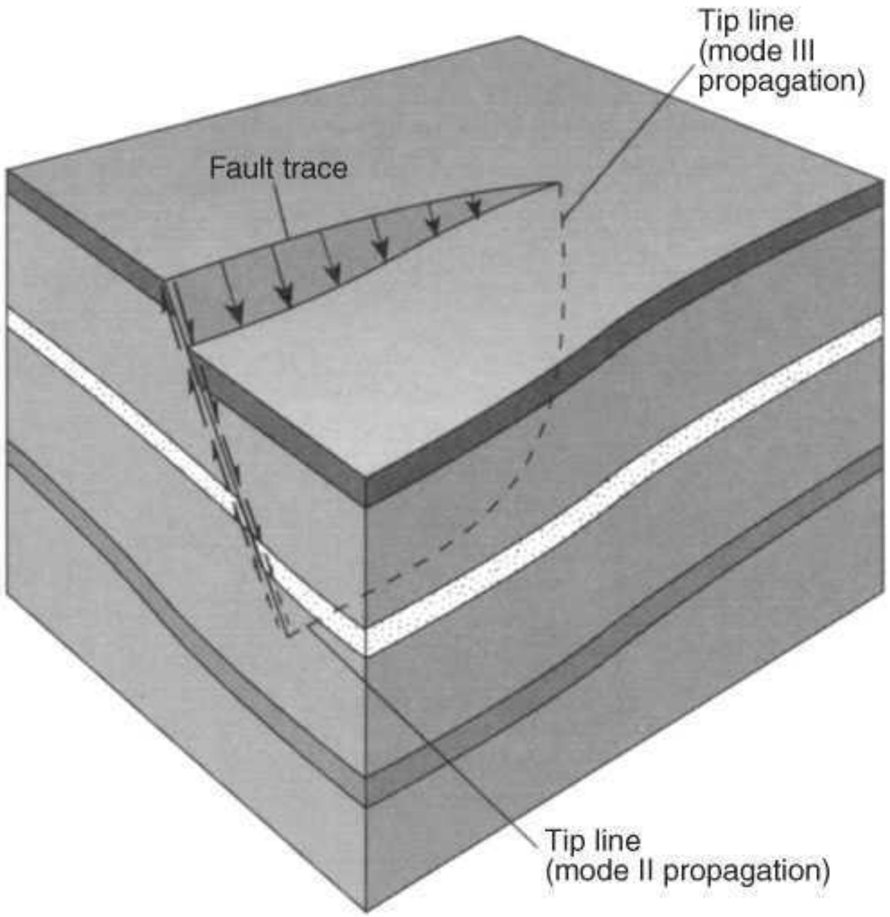
length & displacement

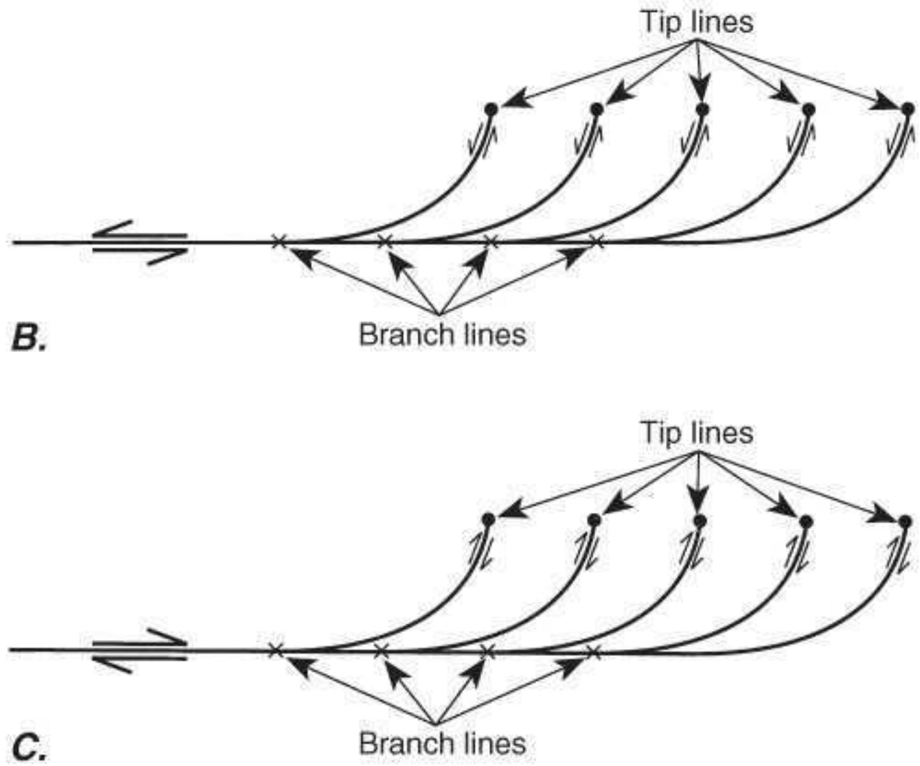


Relationship between fault displacement and fault length:

"Faults do not run across the earth"

fault termination

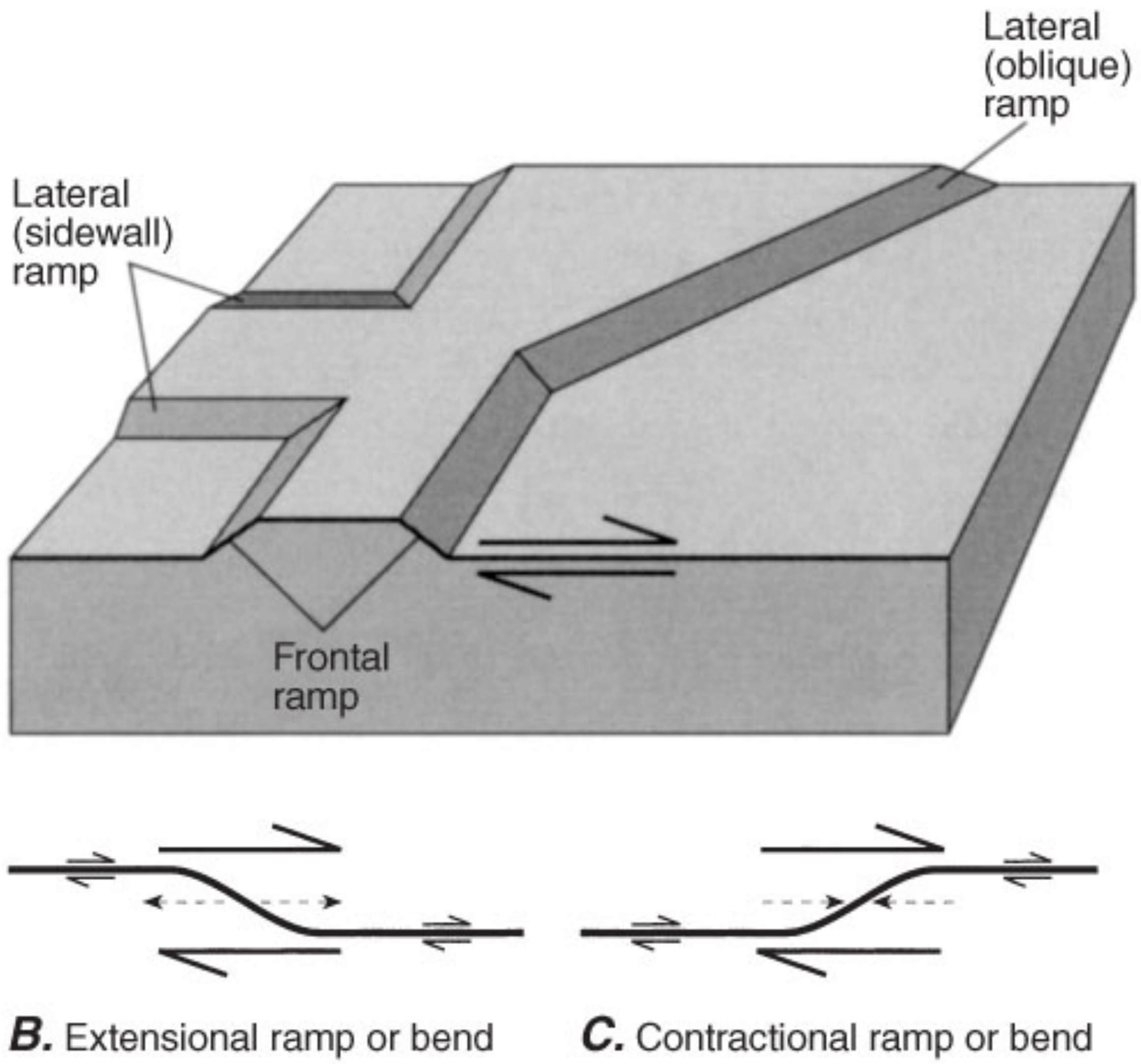




special termination line: the tip line marks the end of displacement

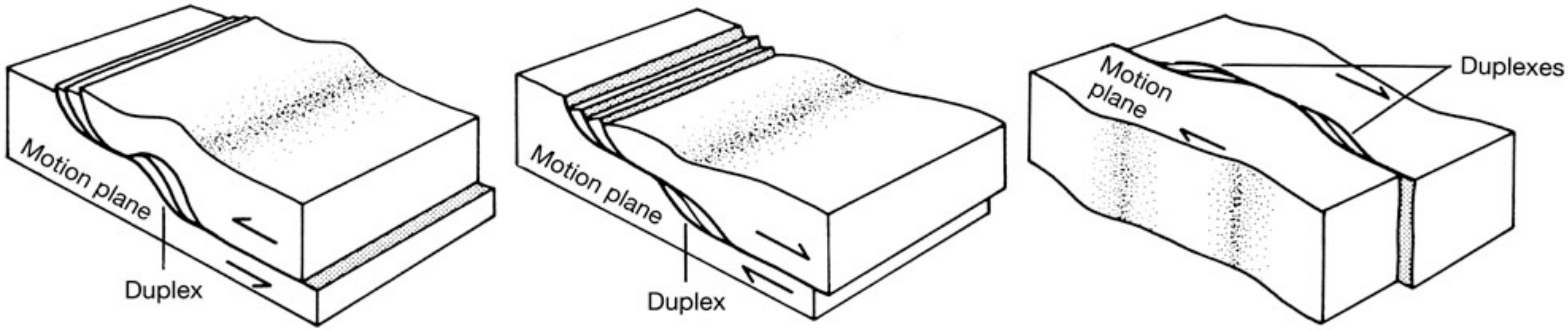
splay faults branch out from the main fault along branch lines

fault ramps



faults step up at ramps

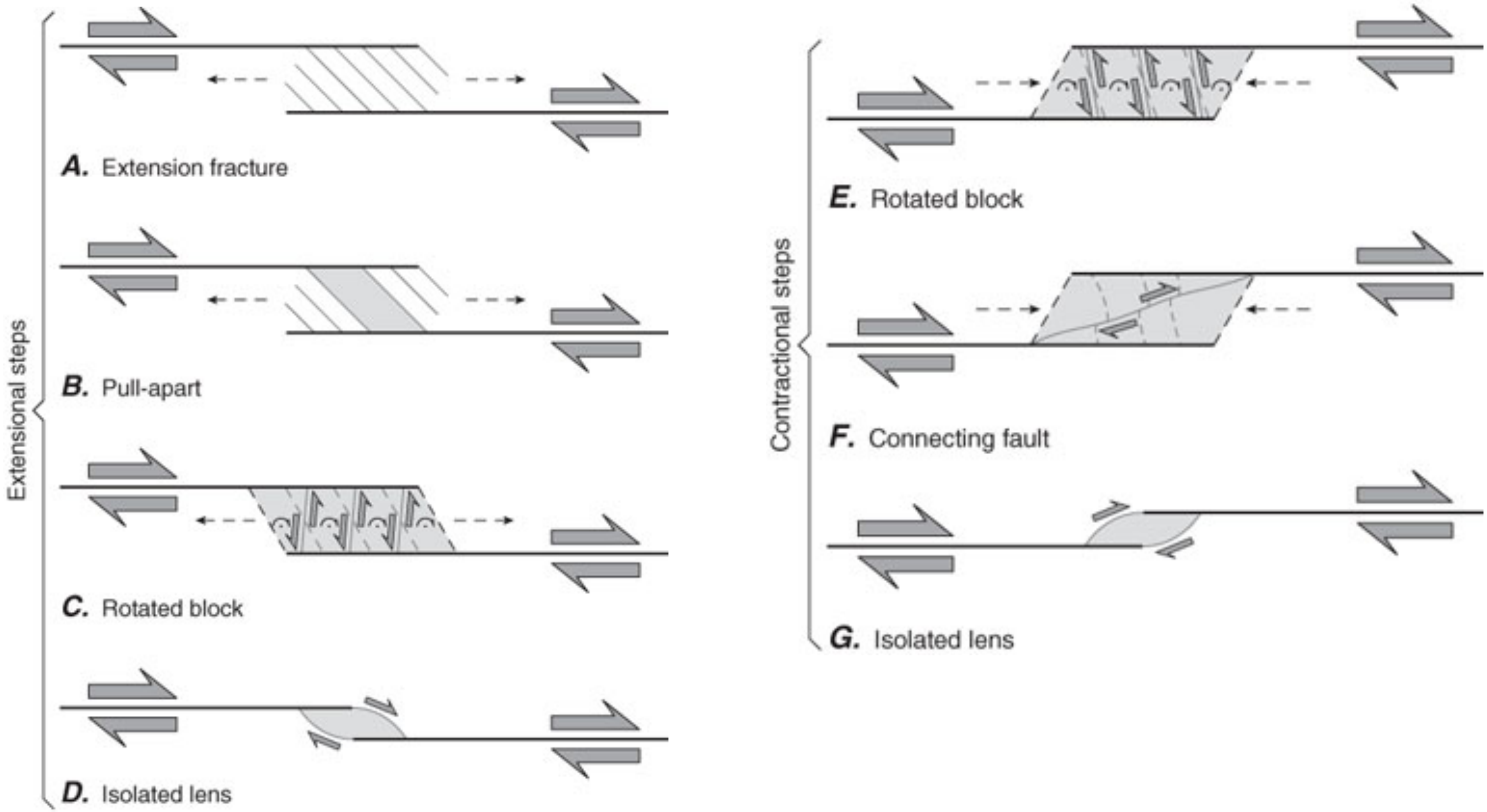
duplex structures



A. Thrust dip-slip **B.** Normal dip-slip **C.** Strike-slip dextral

duplexes are bounded by 2 faults

fault steps



extension

contraction

normal faults

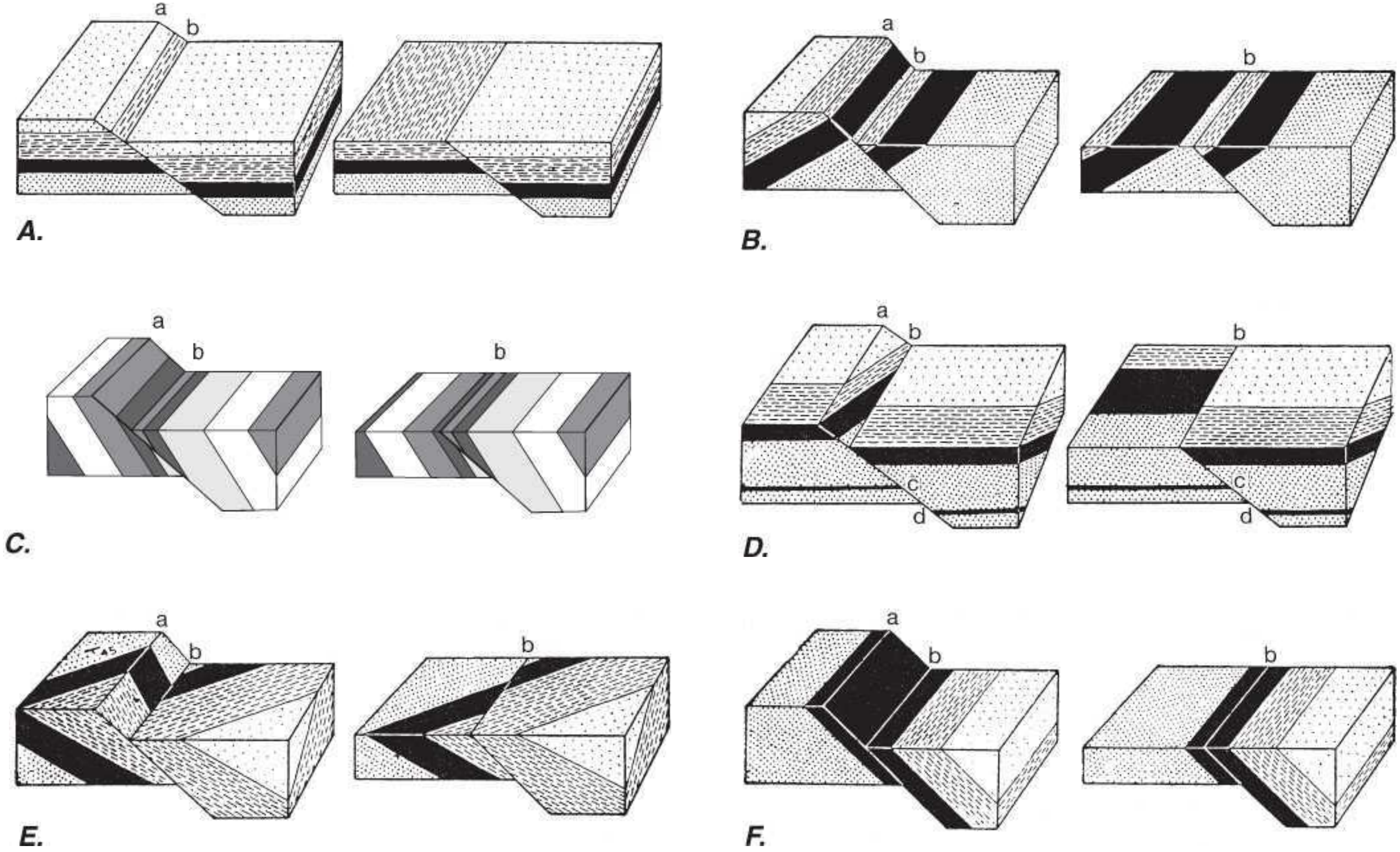
Definition Abschiebung

Normal Faults:

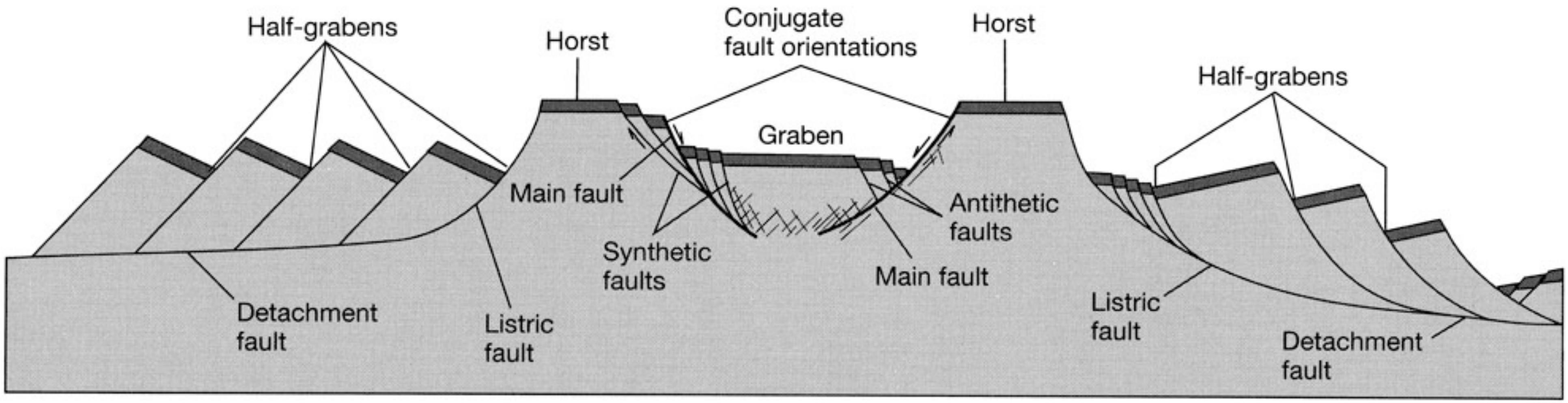
dominantly dip-slip faults

accommodate extension

normal faults Abschiebung



normal fault system

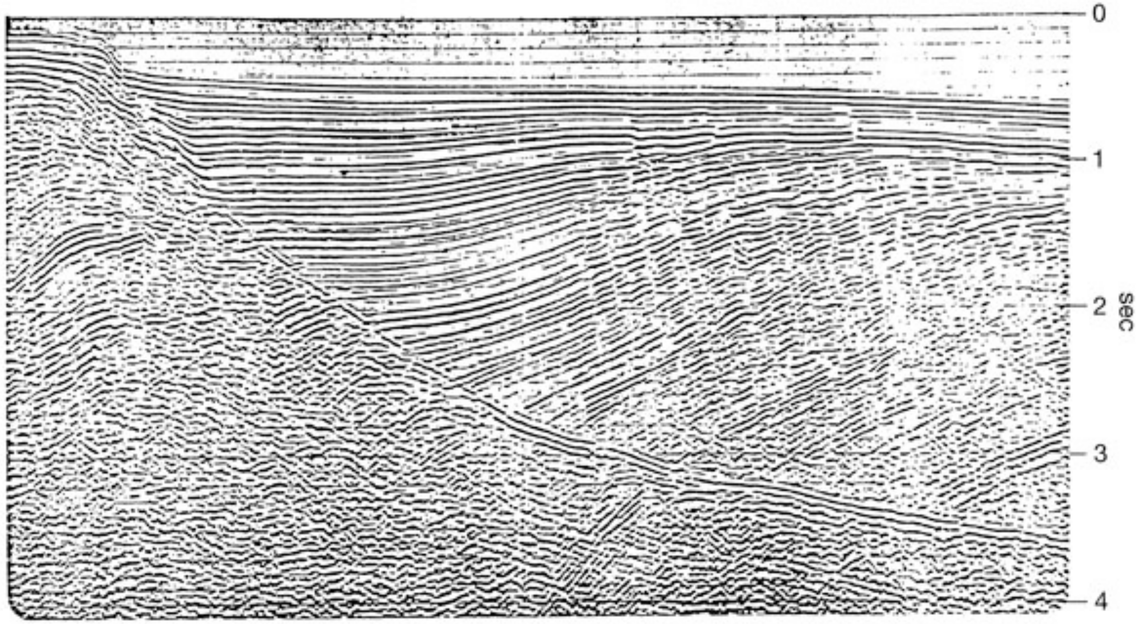


Horst, Graben, Halbgraben, listrische Abschiebung, Abscherhorizont

synthetisch - antithetisch

roll-over folds

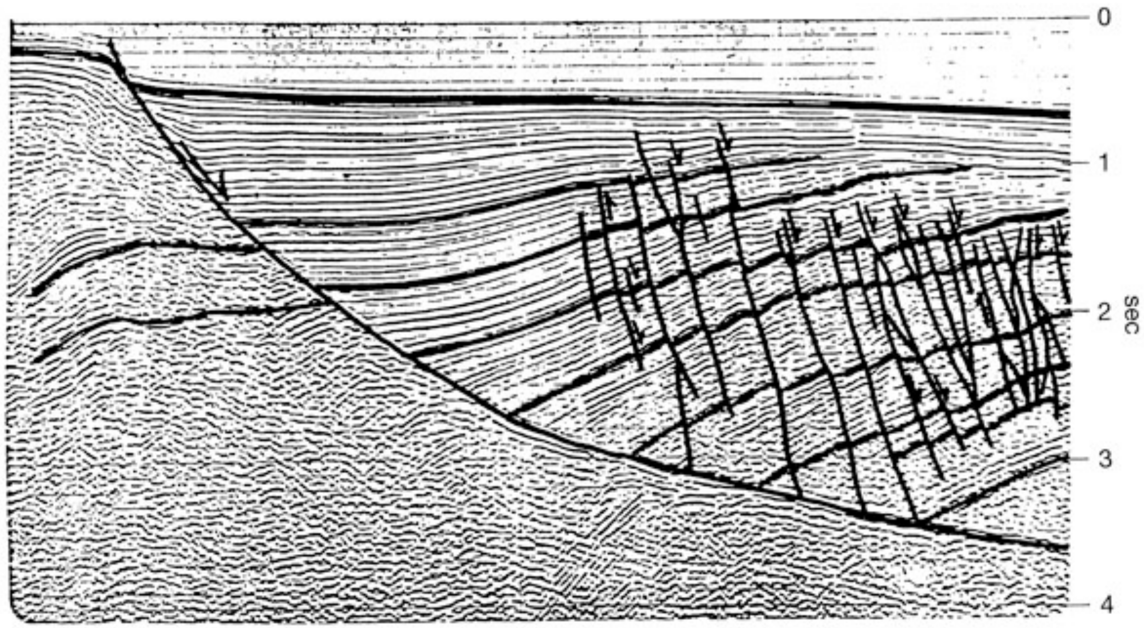
(mostly anticlines)



A.

associated with
listric faults

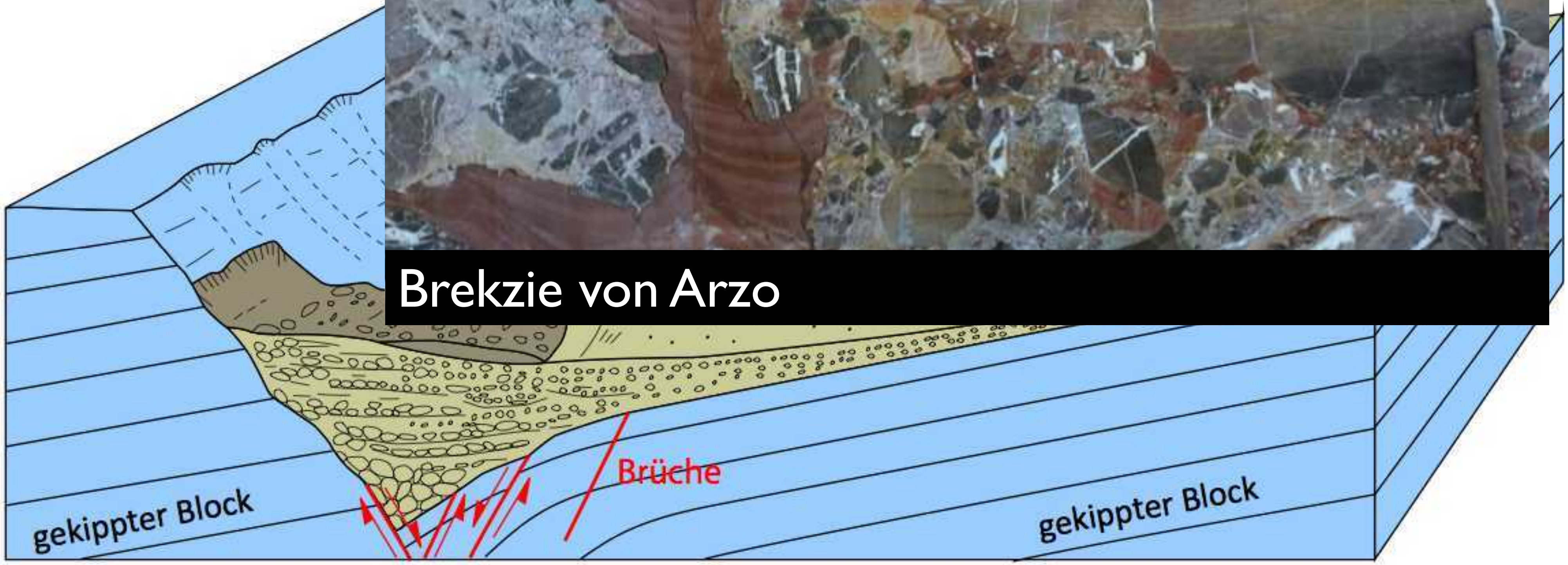
(+ synthetic faults)



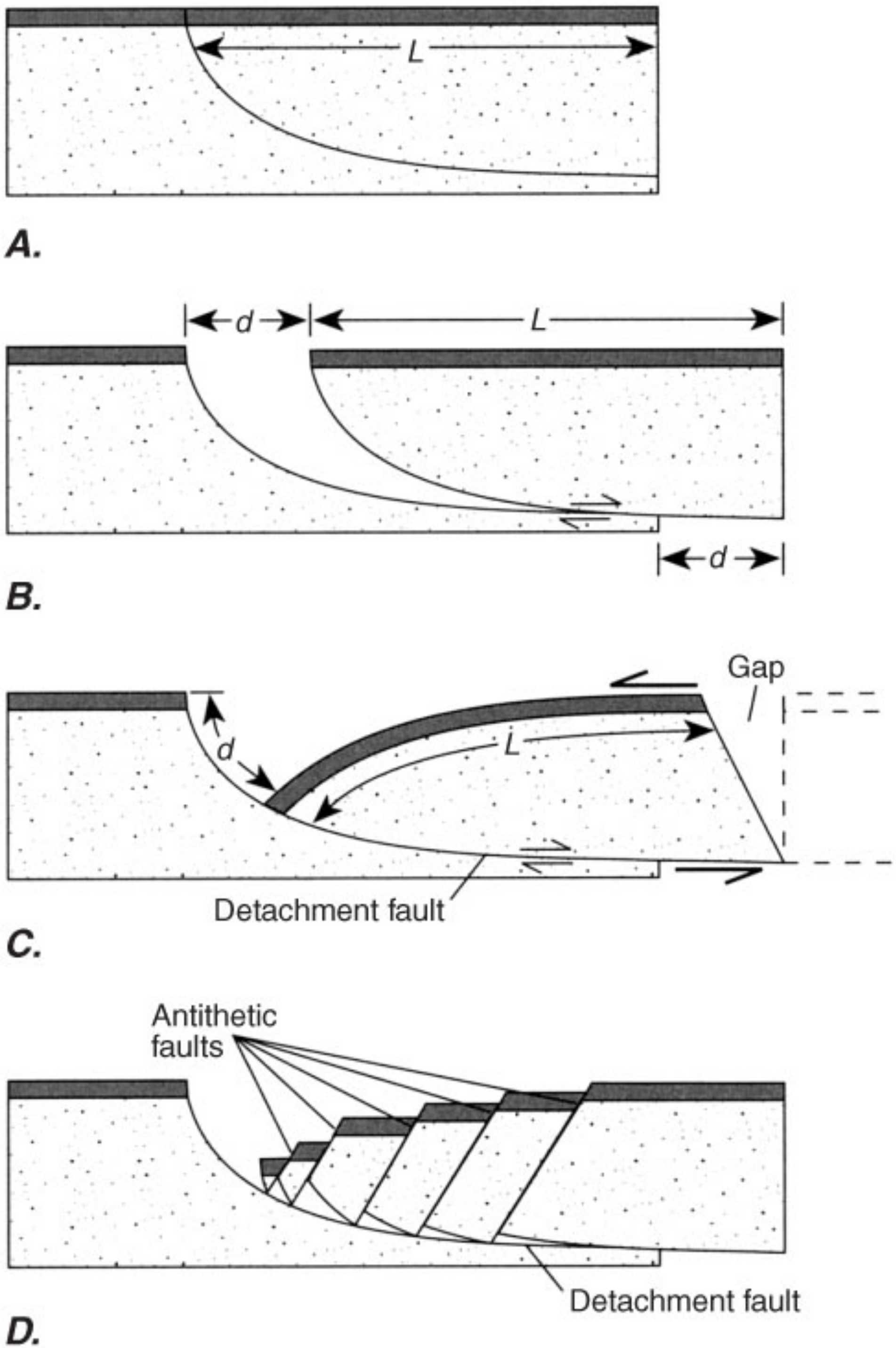
B.

Schwelle von Arzo

Brekzie von Arzo



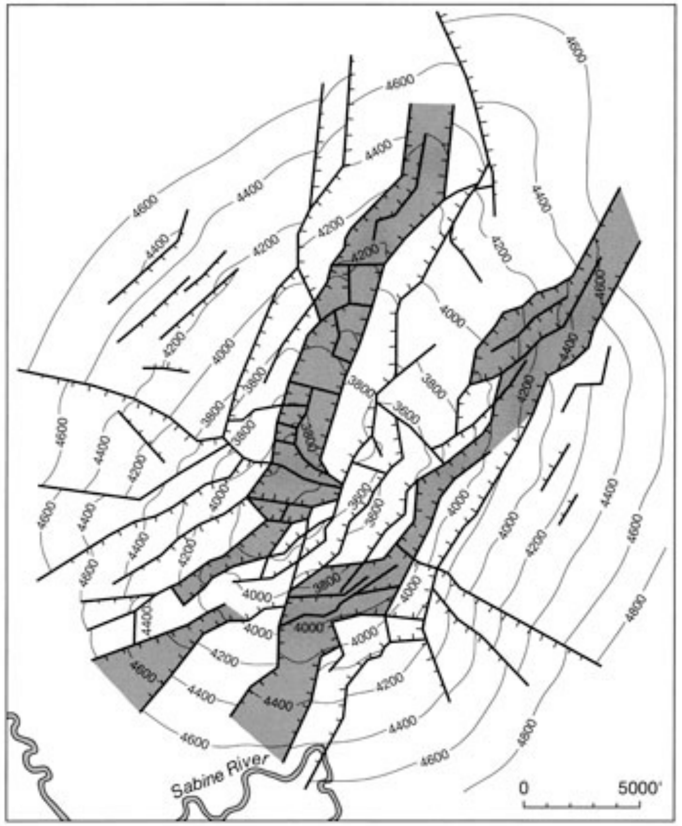
roll-over folds



antithetische
Flexur

antithetische
Brüche

normal faults



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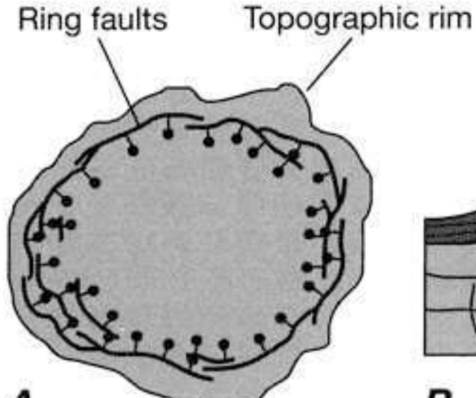

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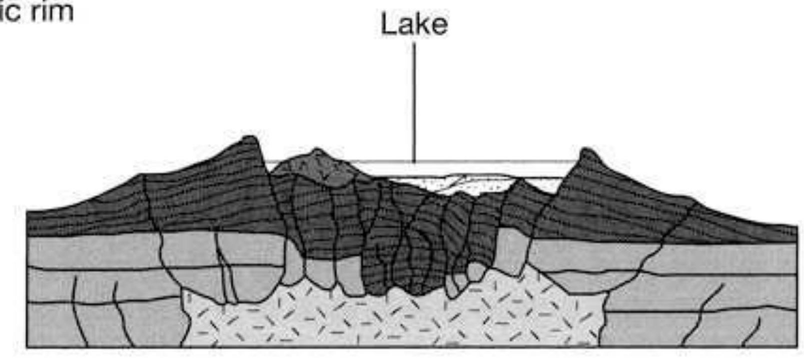

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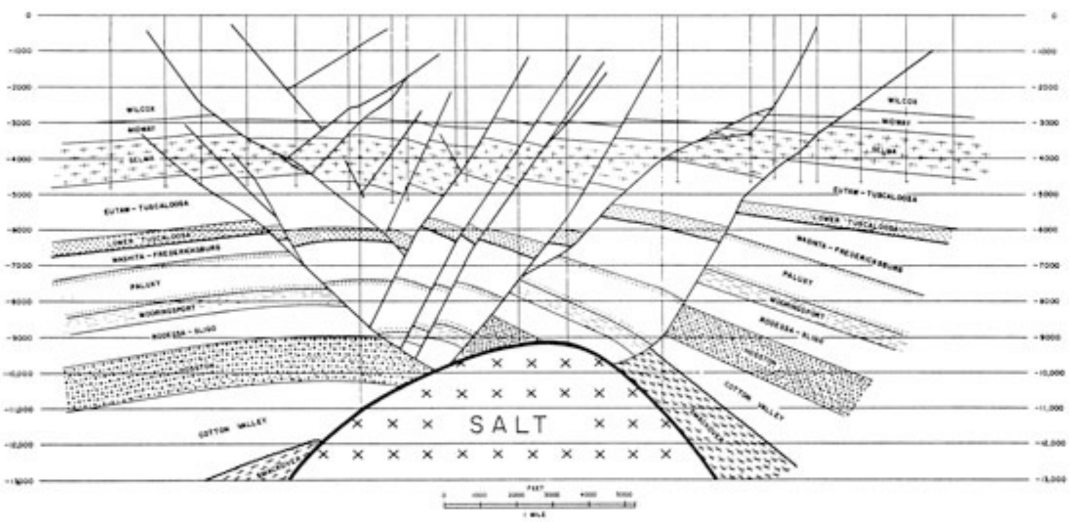
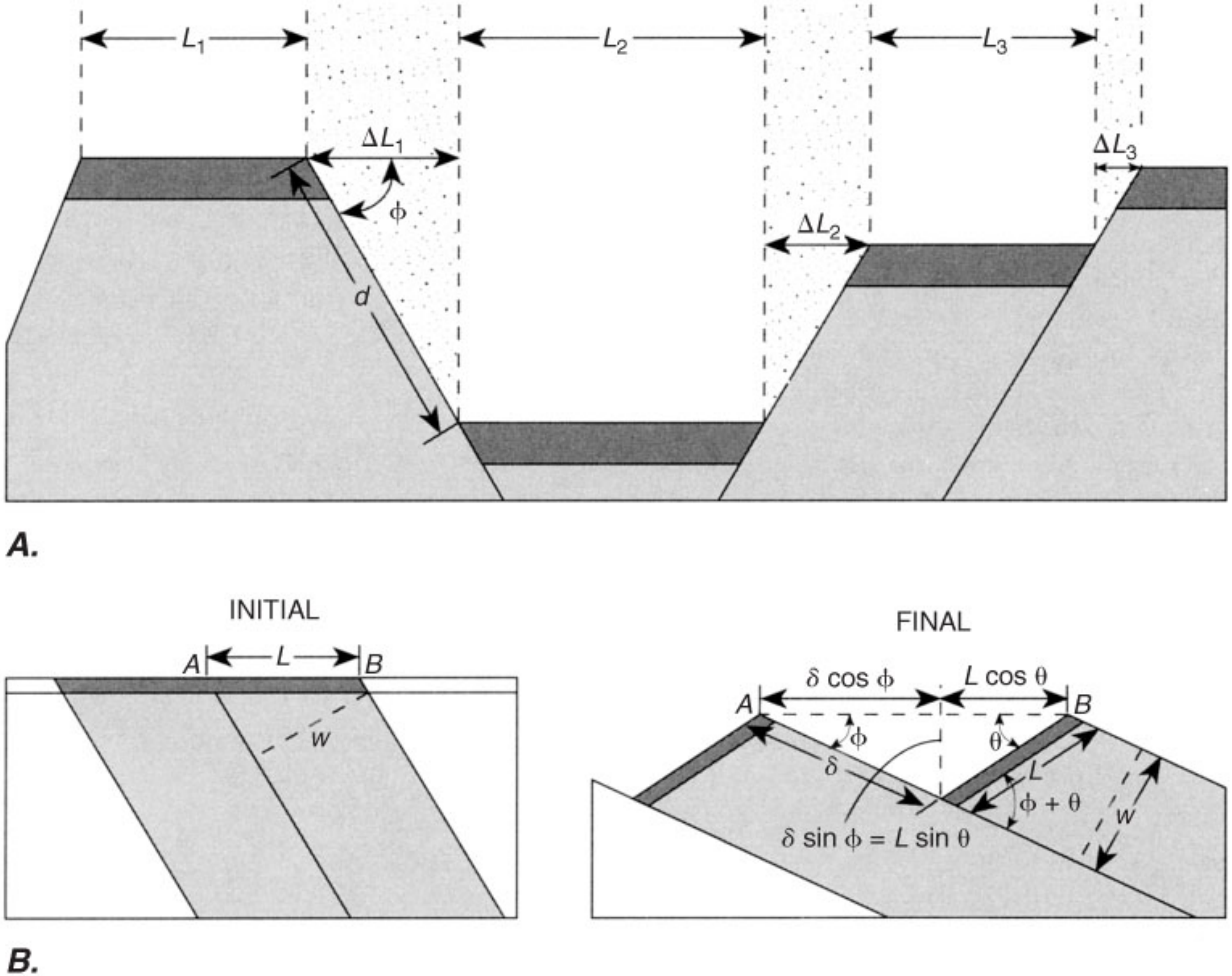


B.

associated with salt dome or intrusive body: consequence of uplift and crustal extension

calculating extension



reverse faults

Definition Auf- / Überschiebung

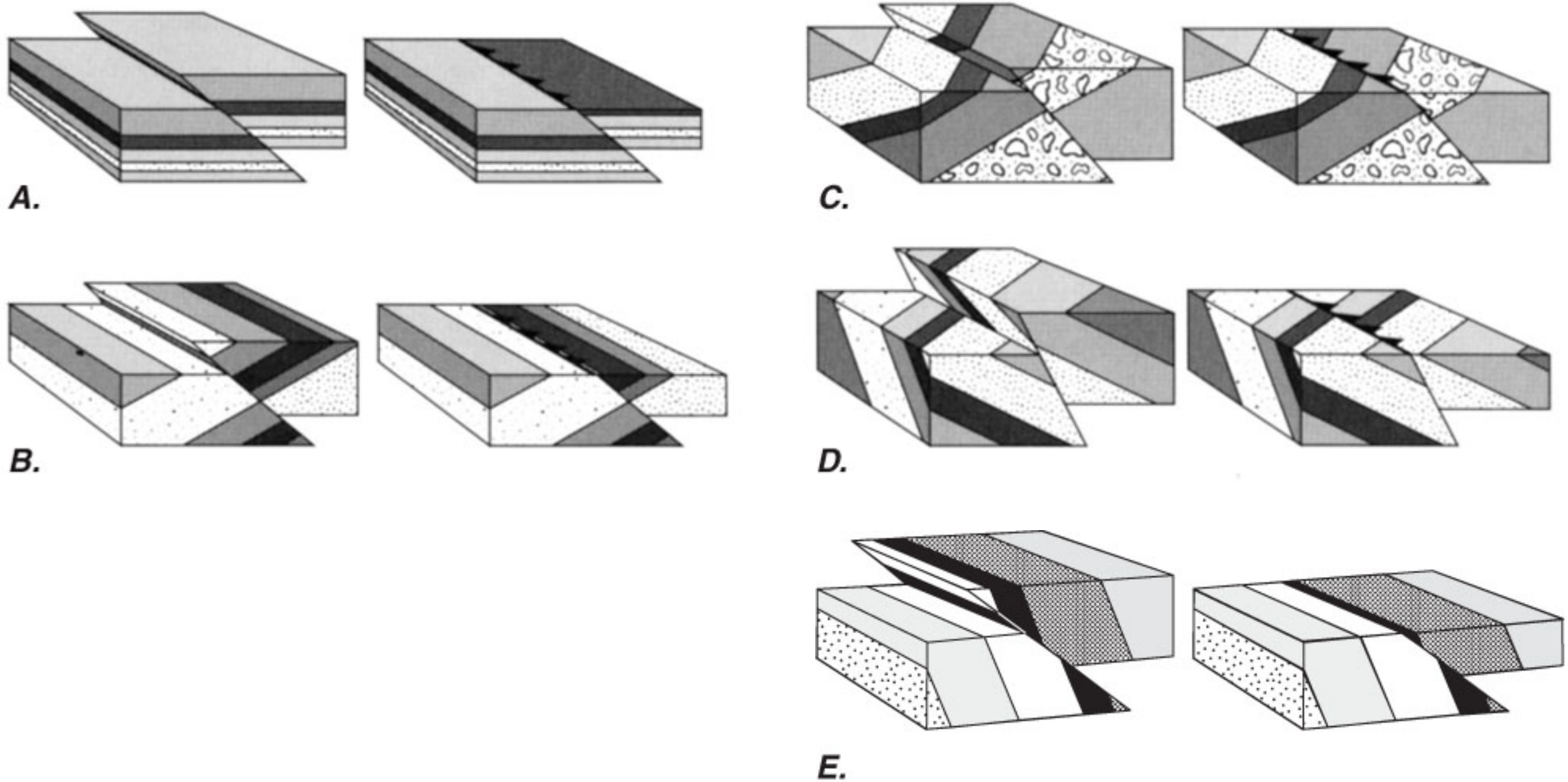
reverse or thrust faults:
commonly put older rocks over younger rocks

Reverse faults accommodate crustal shortening

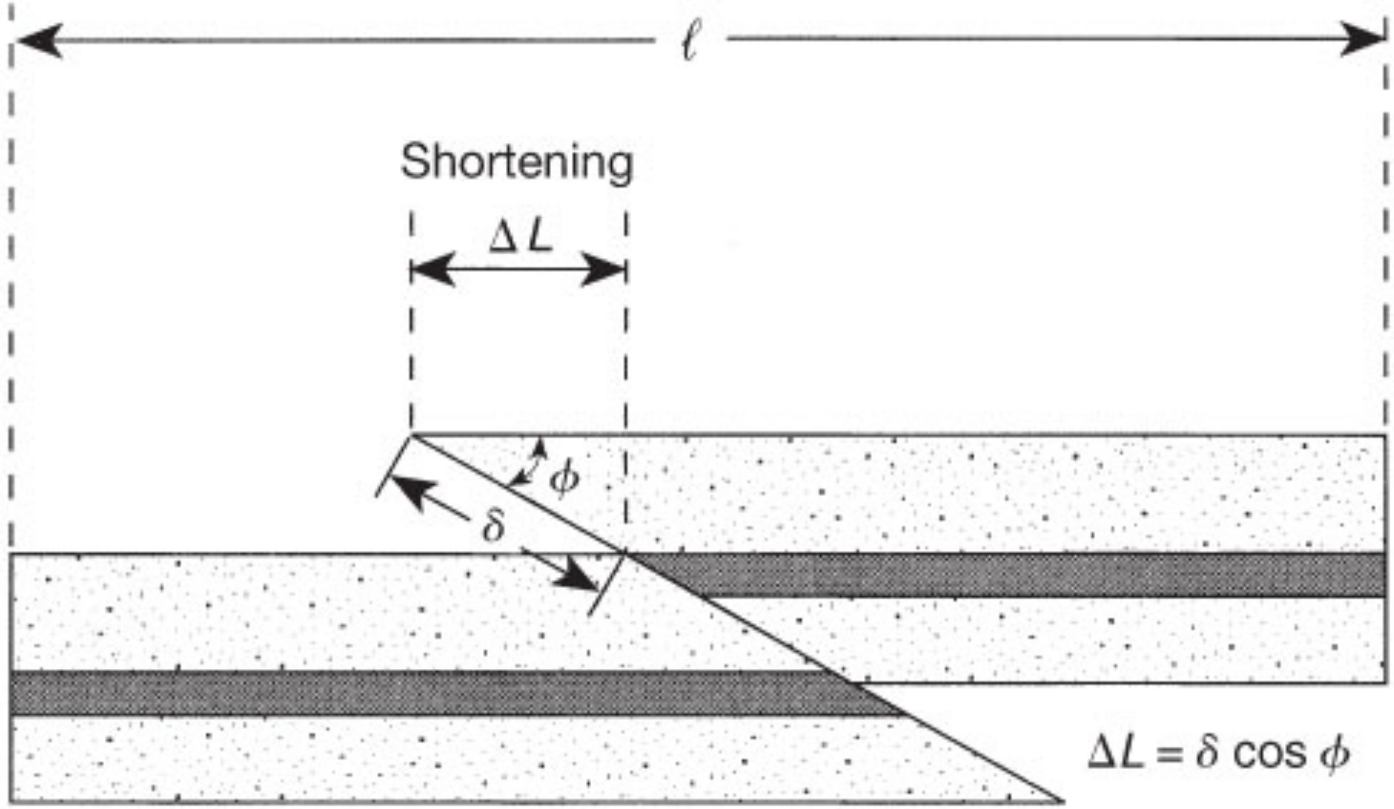
Large areas of thrusted rocks = nappes

reverse fault:	> 45 ° inclination
thrust:	~30° (< 45 °) inclination

revers fault / thrust Auf- / Überschiebung

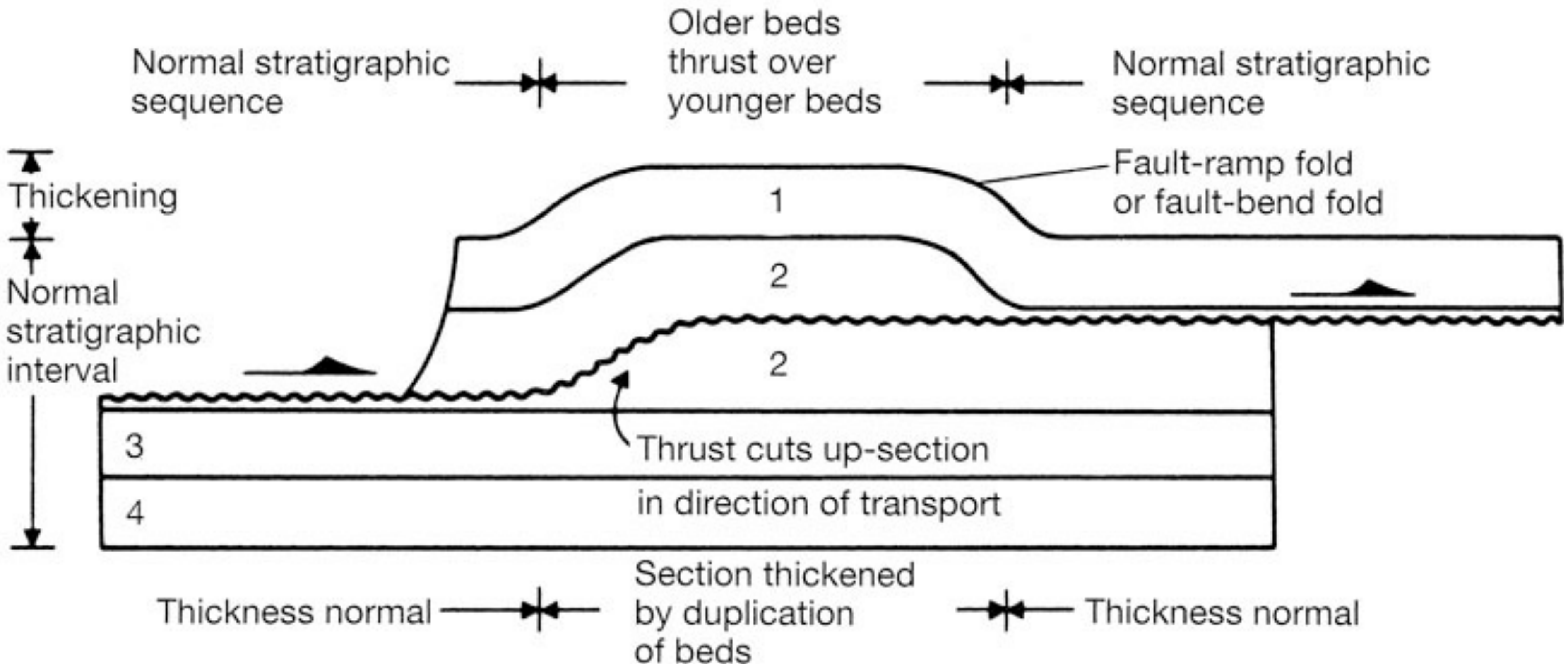


Verkürzung

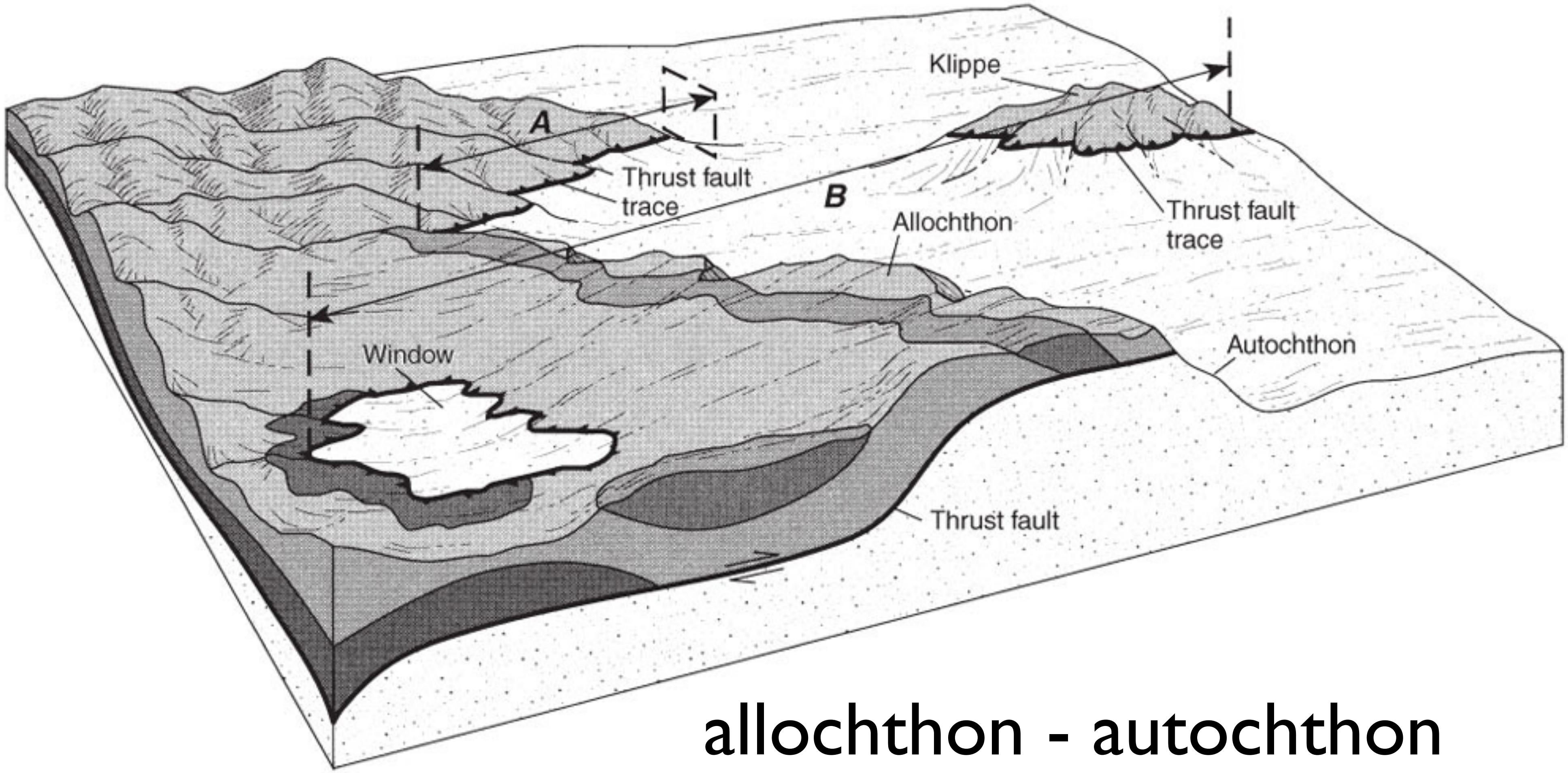


determination of shortening in thrust systems

Überschiebungsgeometrie



Fenster und Klippe



allochthon - autochthon

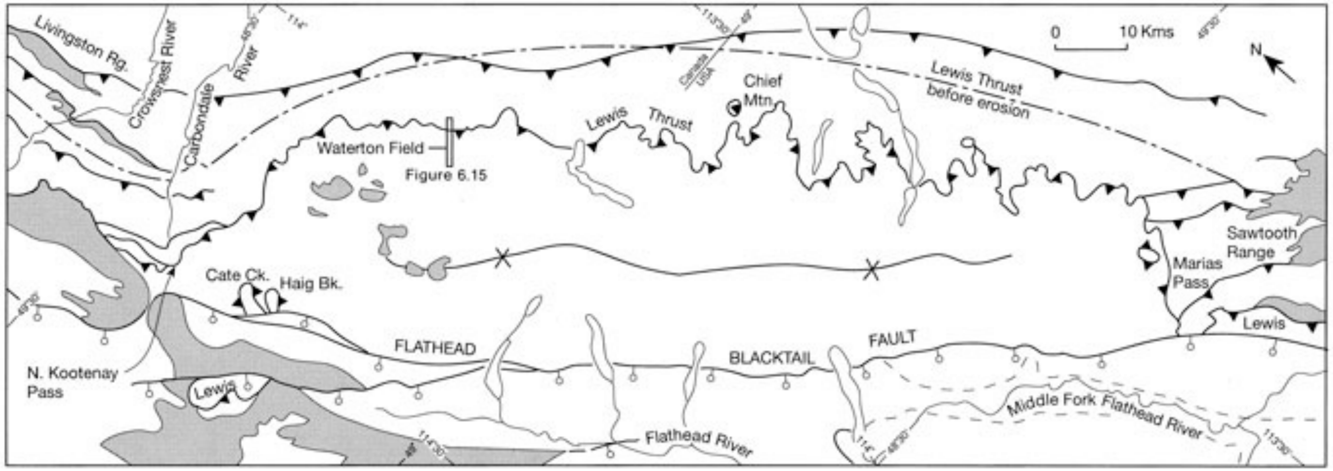
ἄλλος allos = anders, verschieden

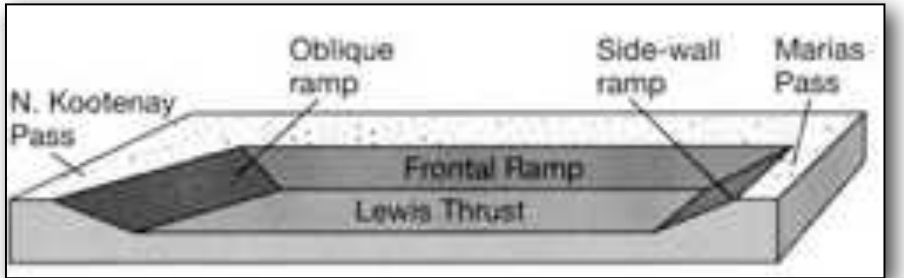
αὐτός autós = selbst

χθών chthōn = Erde

ramps and flats

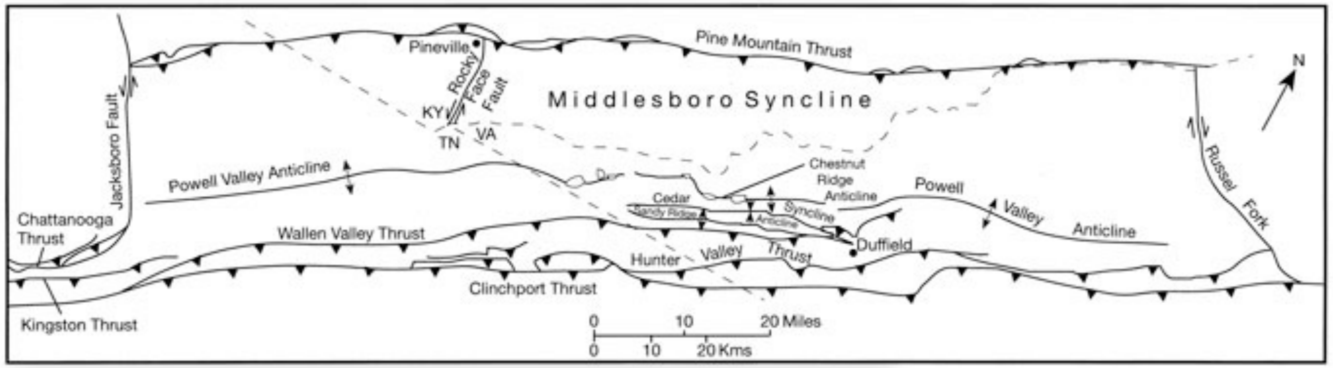
Rampe
Flachbahn

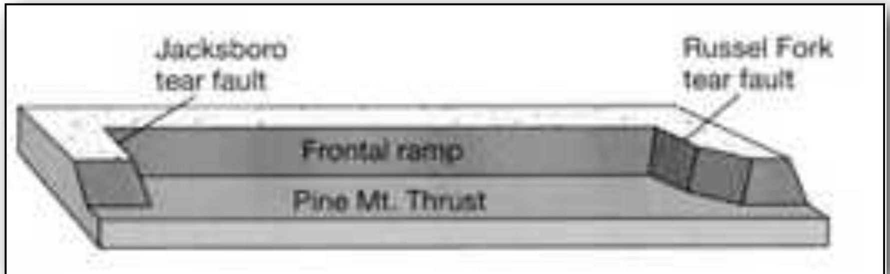




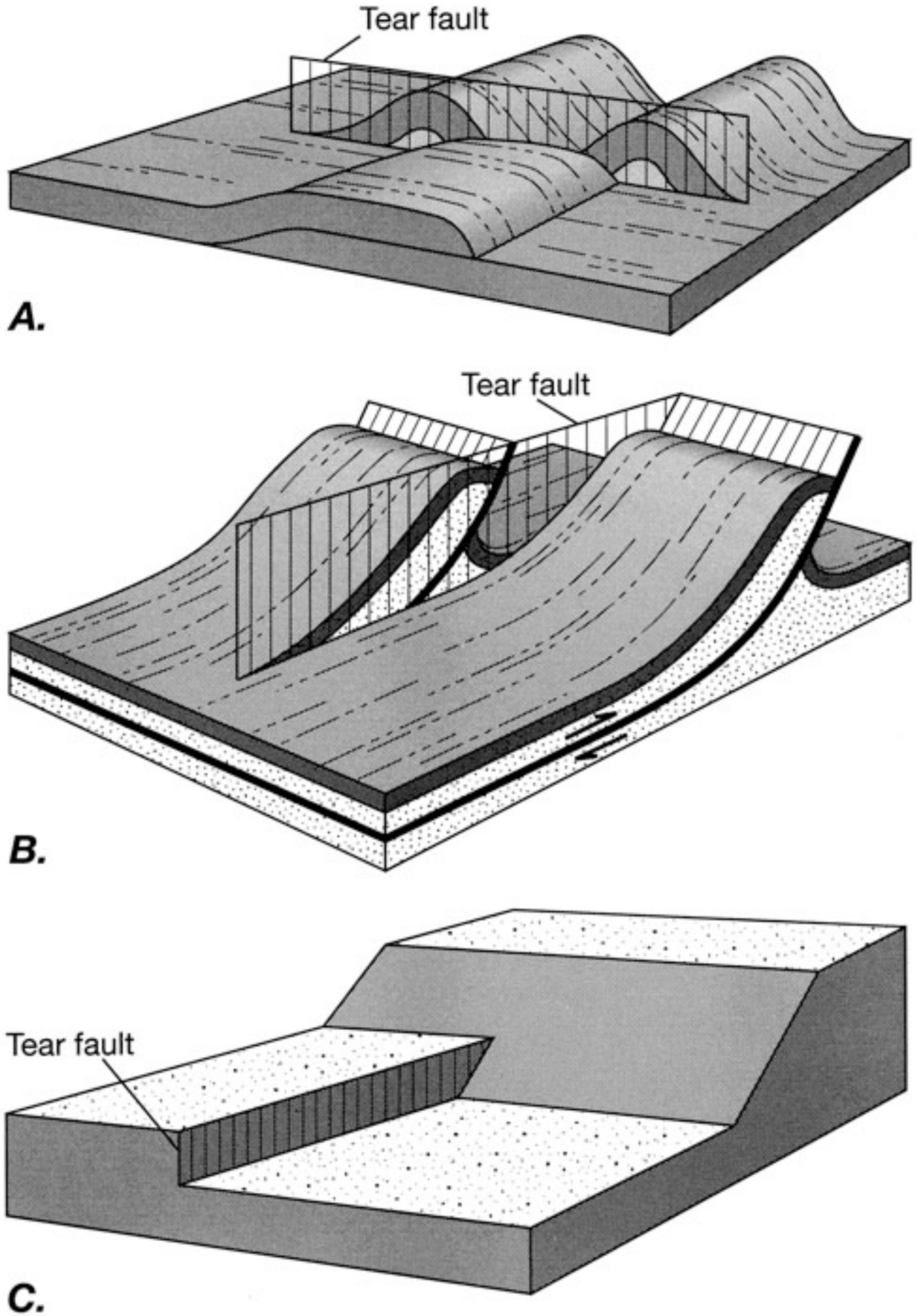
Lewis Thrust

frontal ramp
lateral ramp
(side-wall ramp)





Pine Mountain Thrust

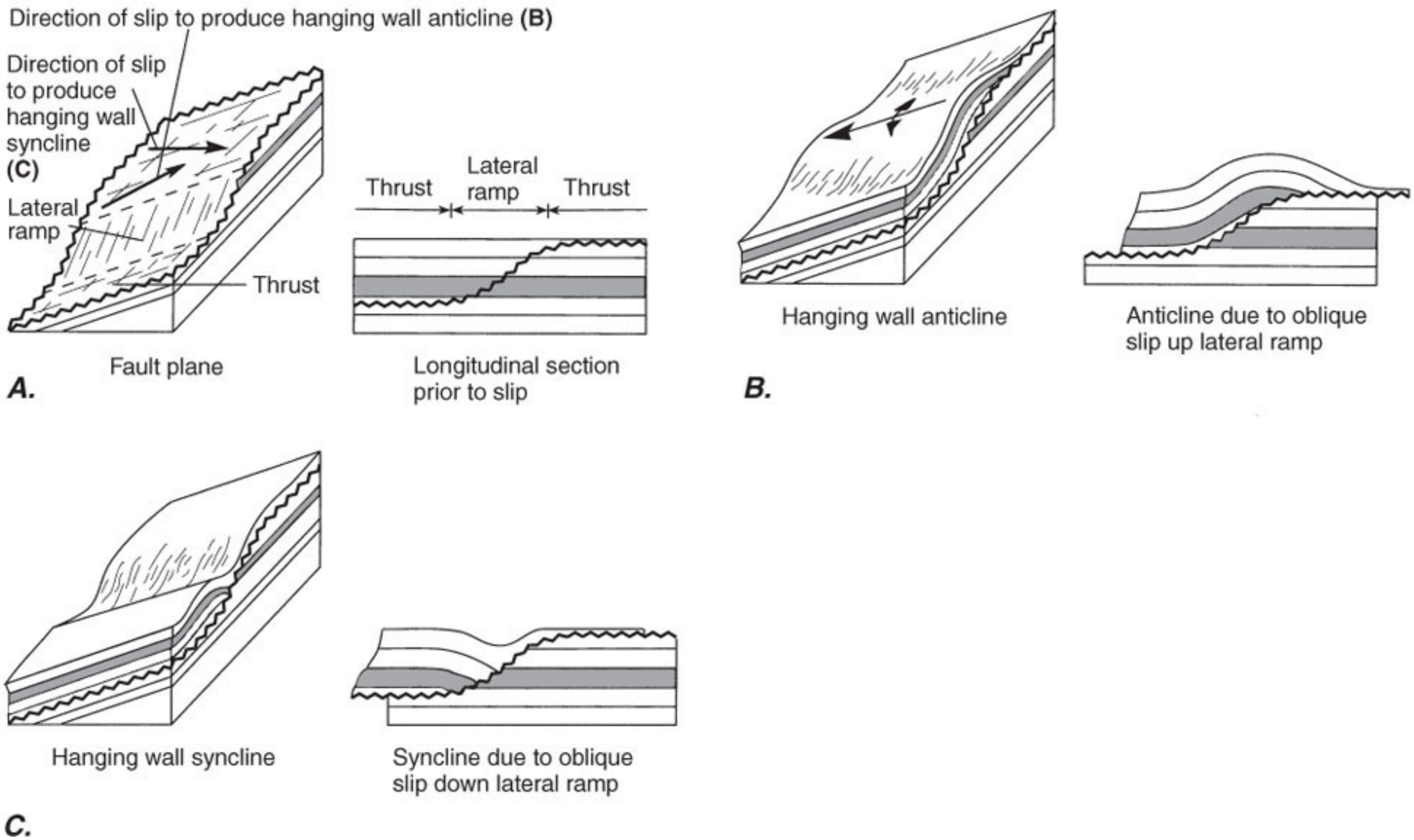


tear fault

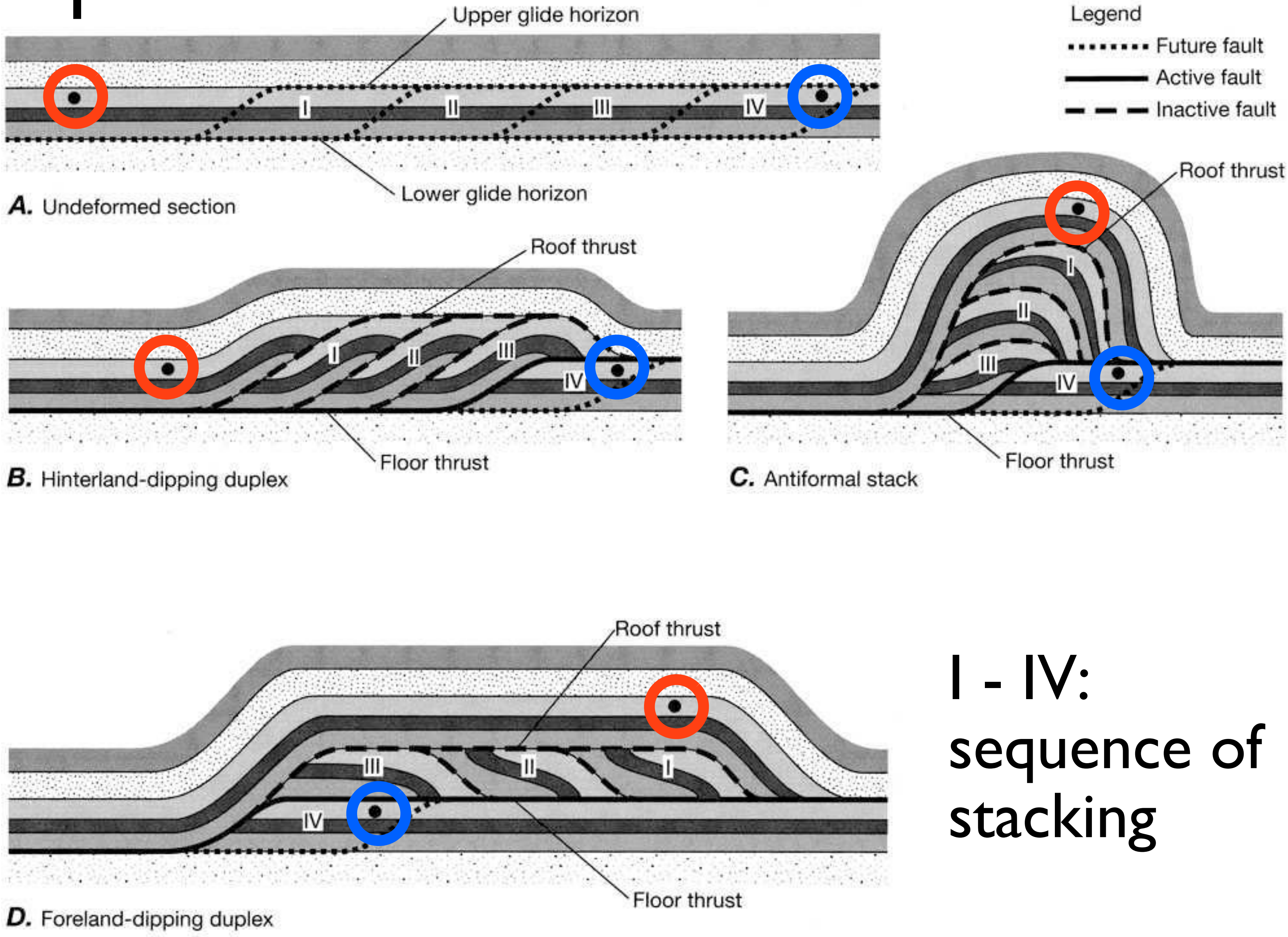
Querverschiebung

= local structure accommodates differential displacement along fault

hanging wall anticline / syncline



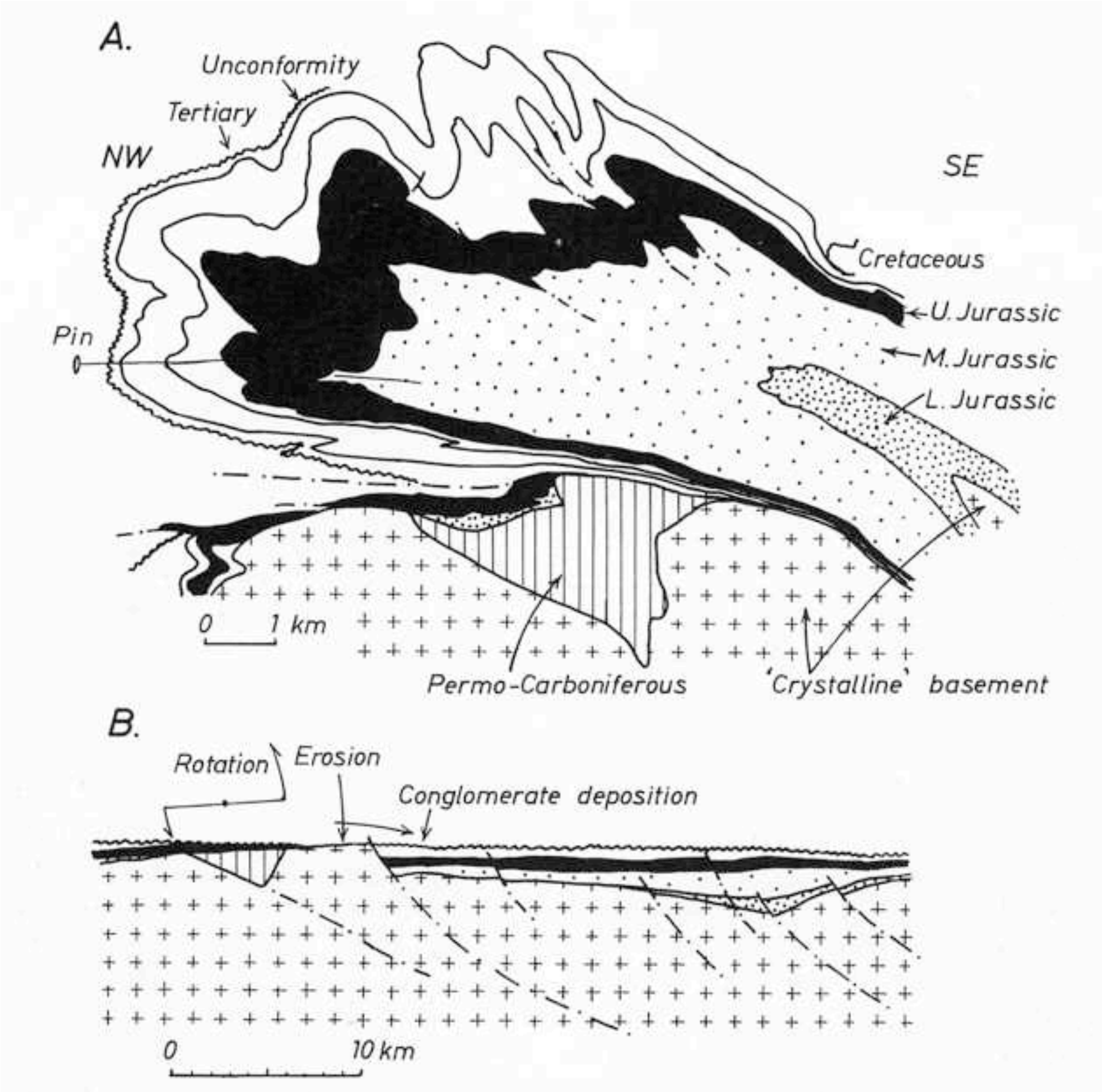
duplex



I - IV: sequence of stacking

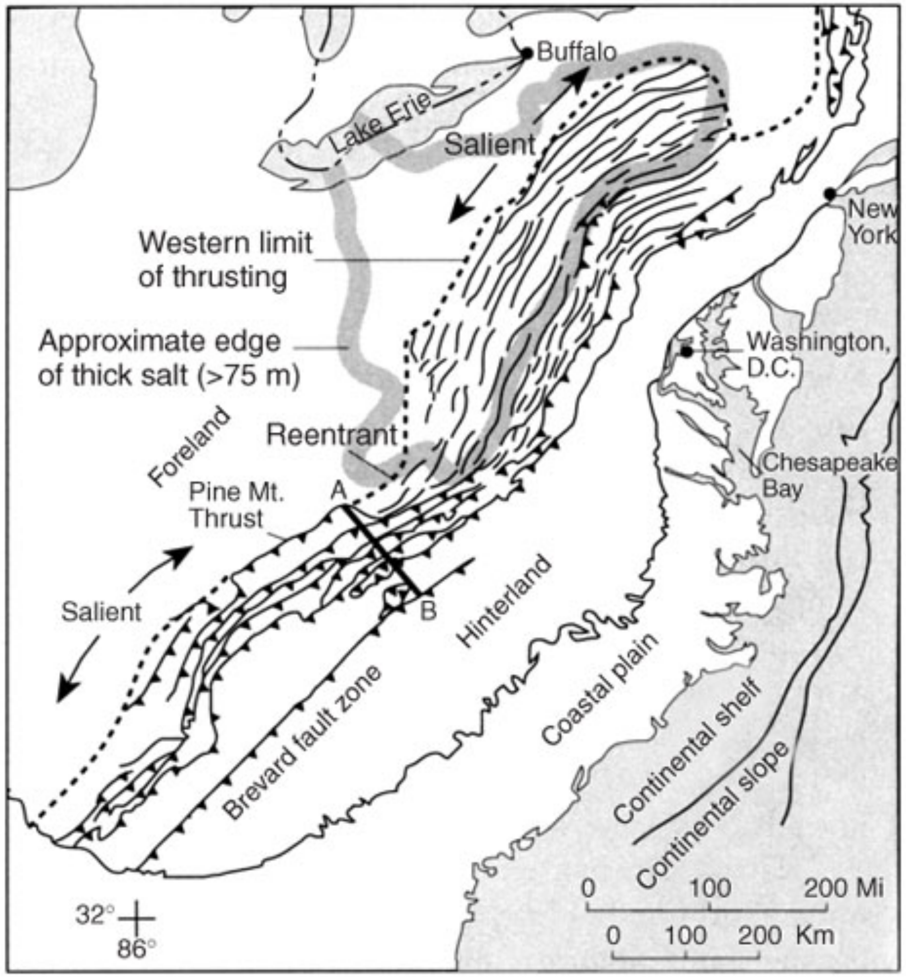
fold nappe

Faltendecke



Morcles nappe, Switzerland

regional thrust fault systems



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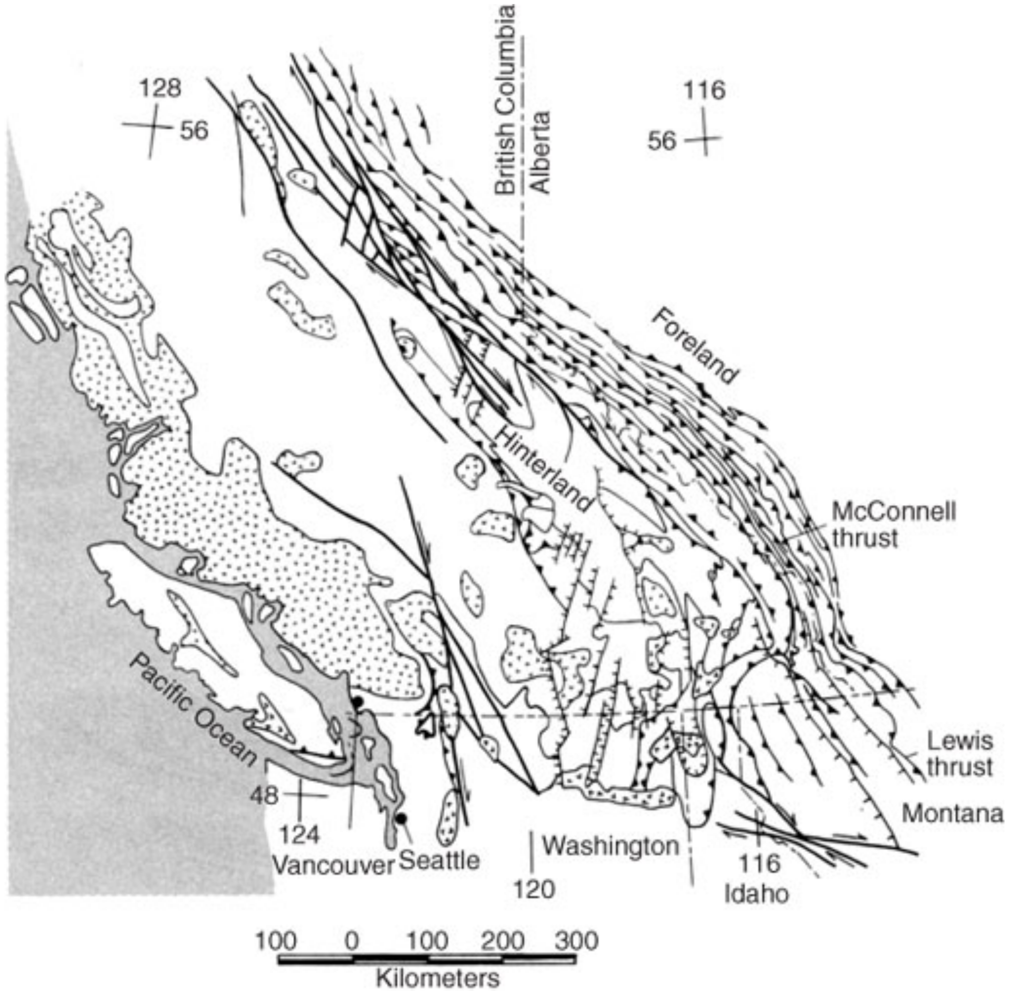
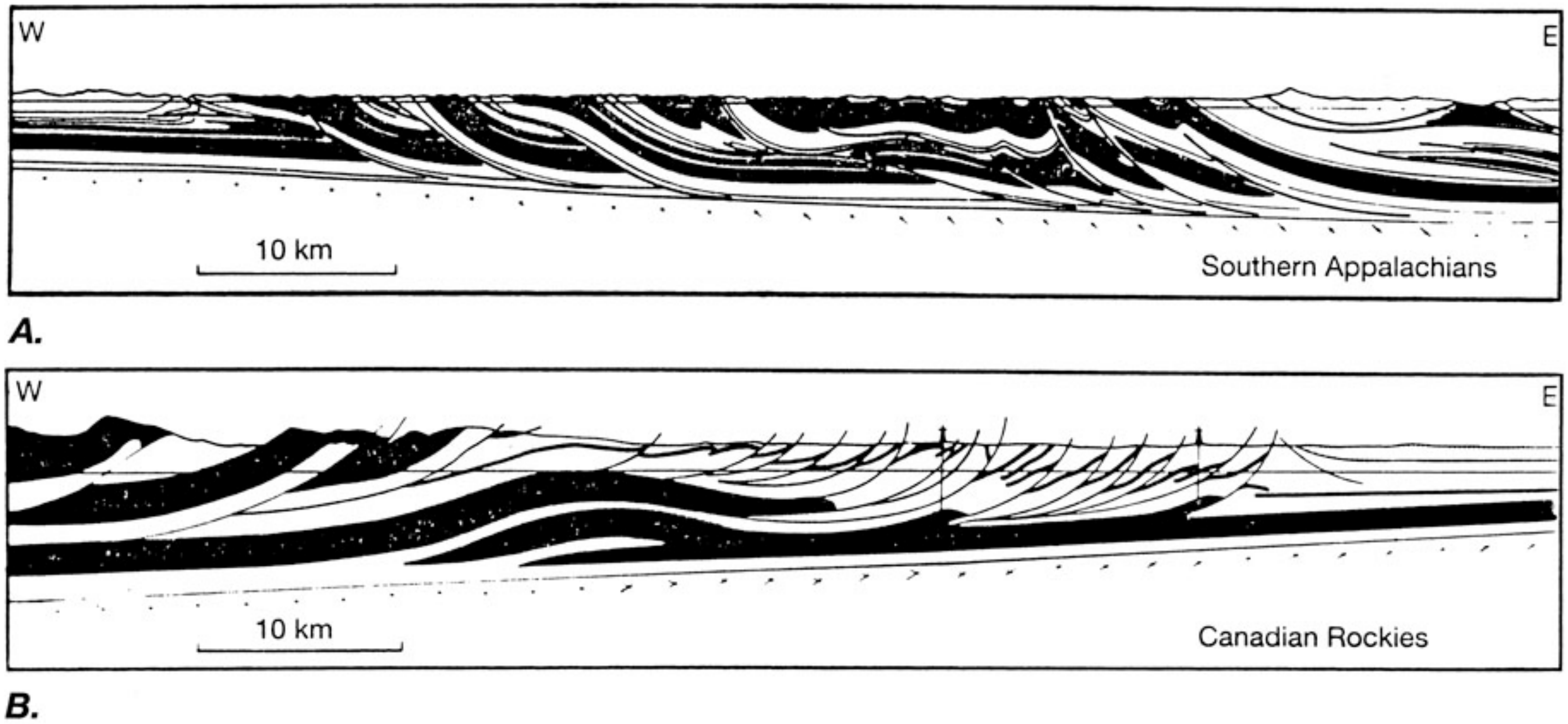


B.

Appalachians

Canadian Rockies

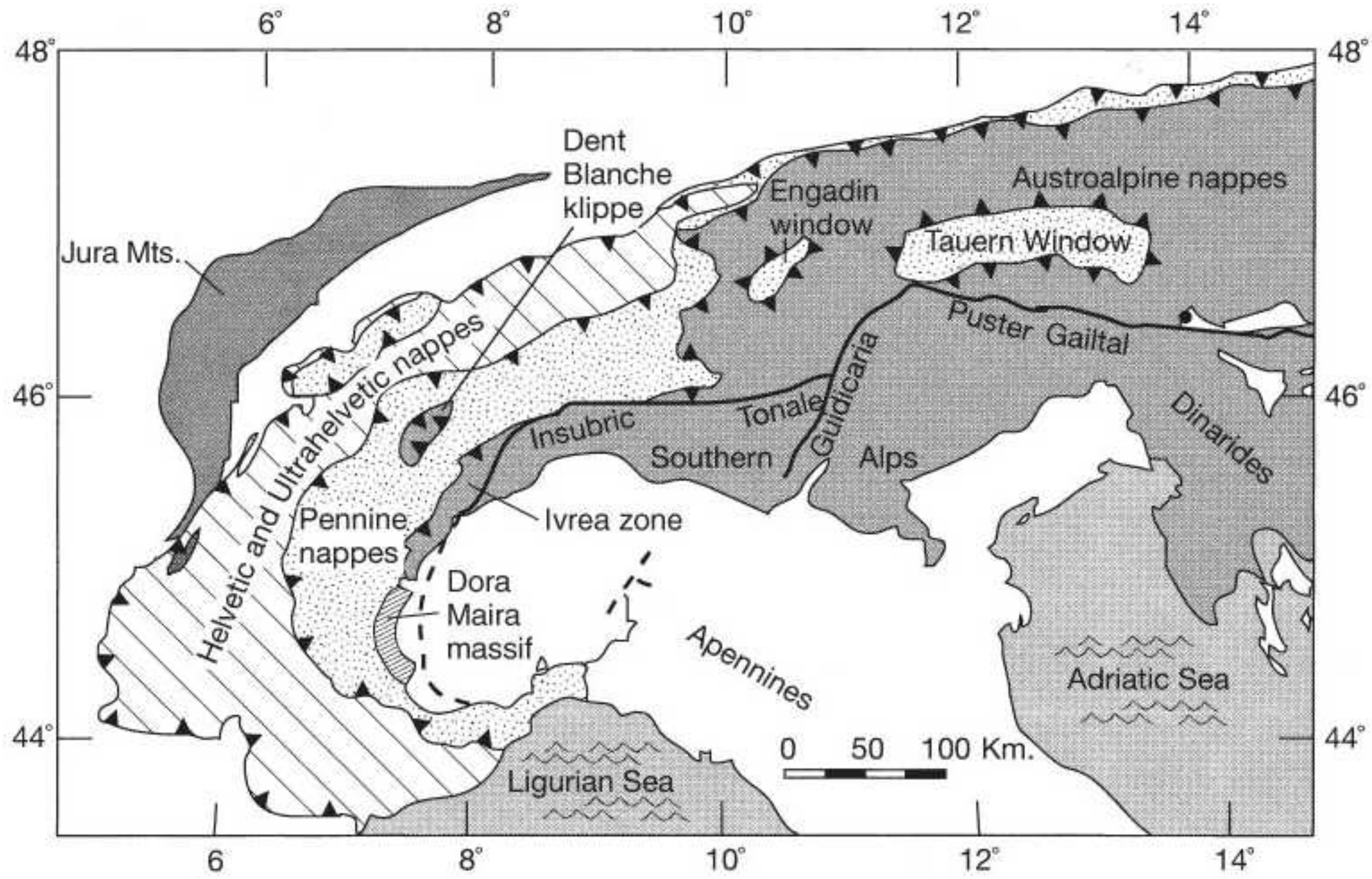
regional thrust fault systems



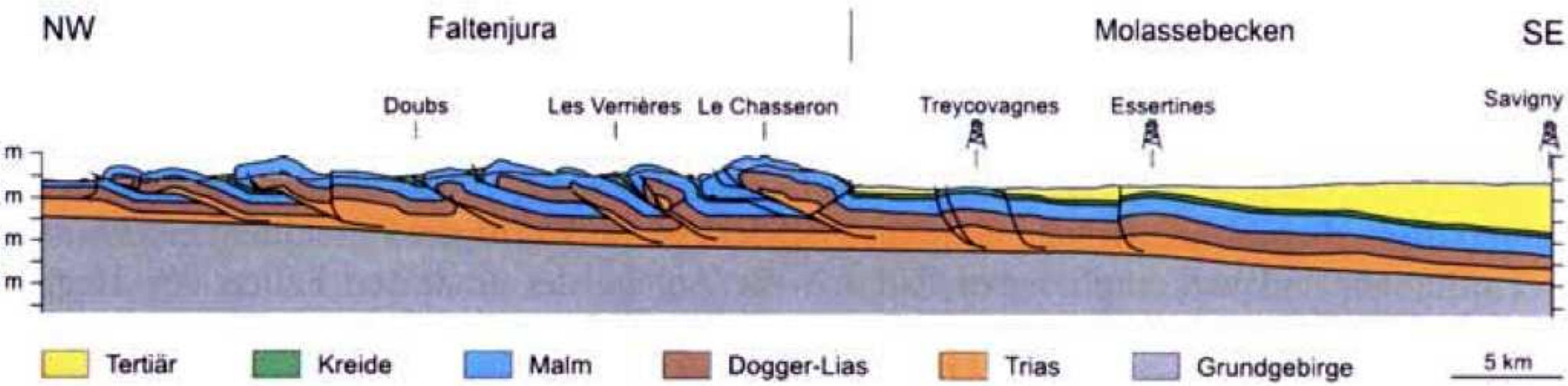
Appalachians

Canadian Rockies

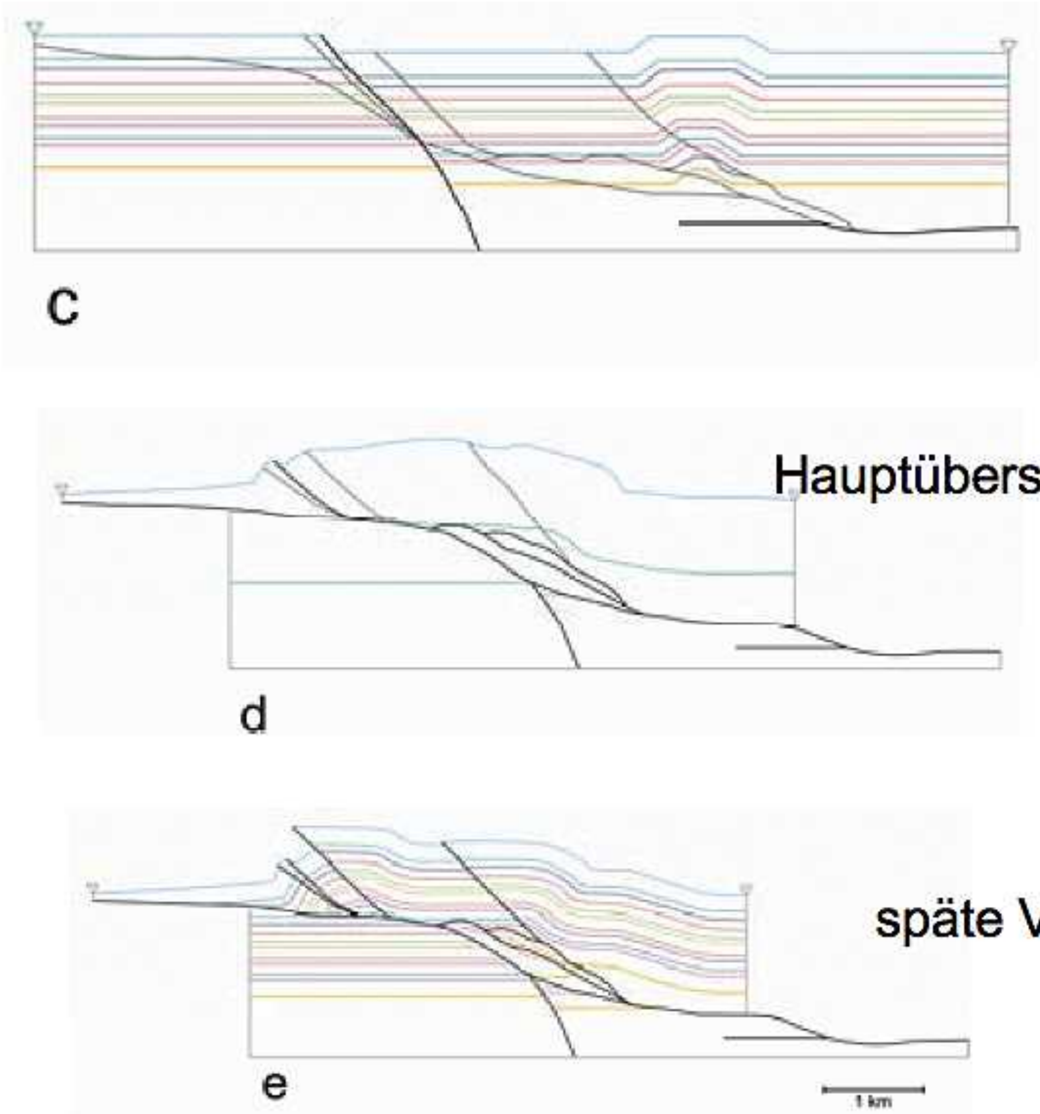
regional thrust fault systems



regional thrust fault systems



regional thrust fault systems



Hauptüberschiebungsphase

späte Verkürzung, ev. „thick-skinned“

Freivogel und Huggenberger 2003

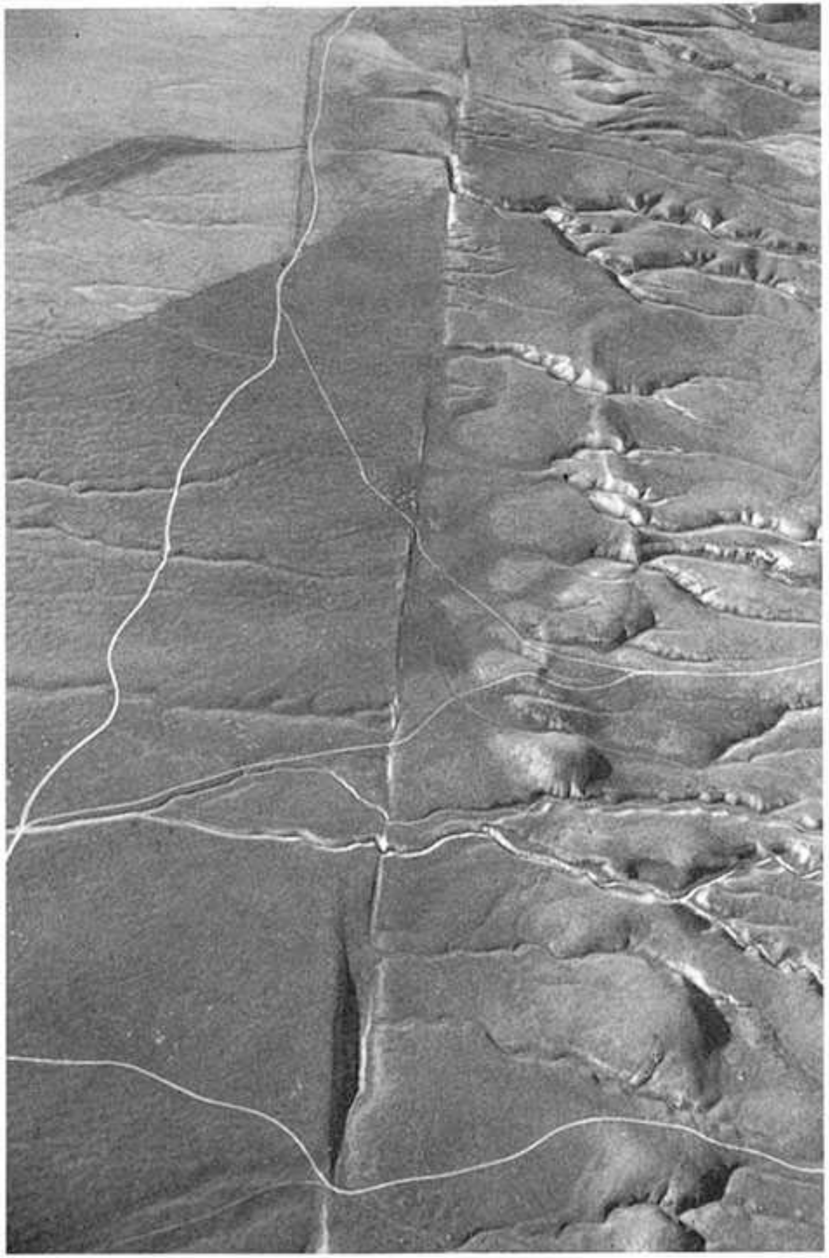
strike - slip faults

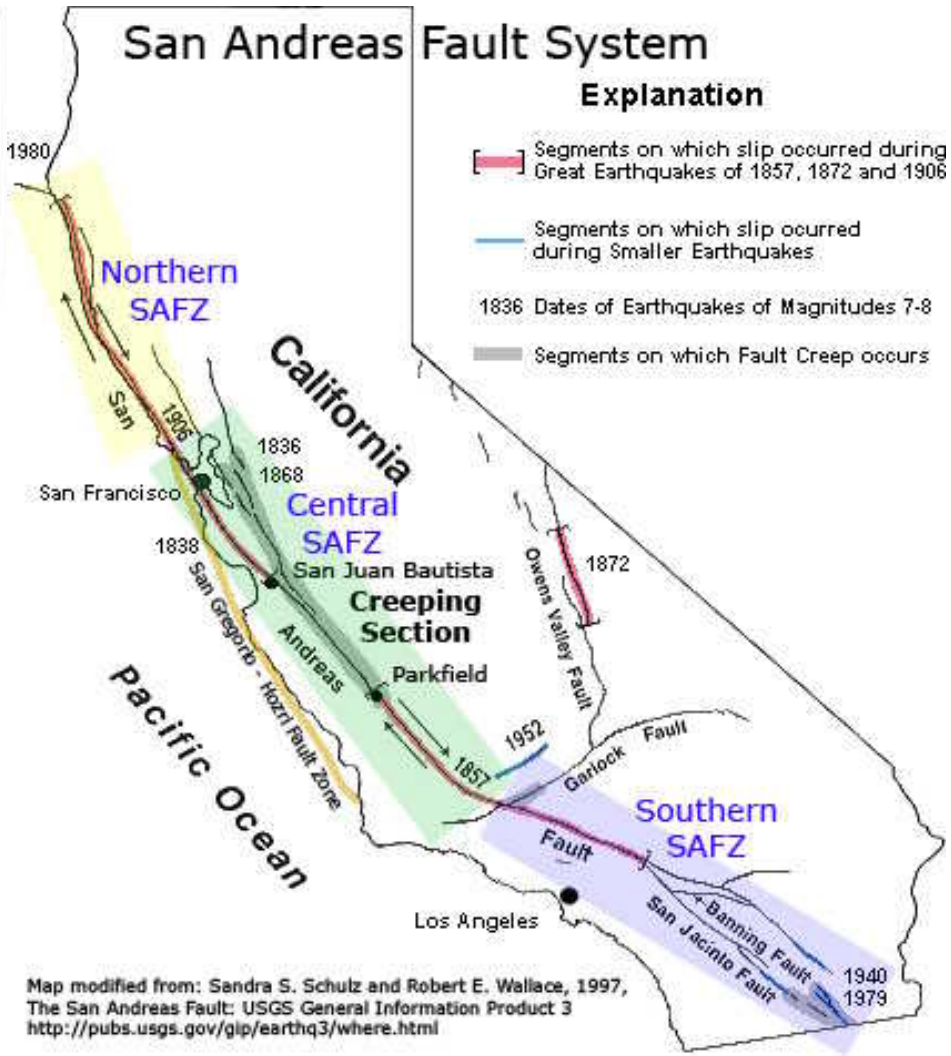
Definition Blattverschiebung

Approximately vertical faults

with horizontal displacement

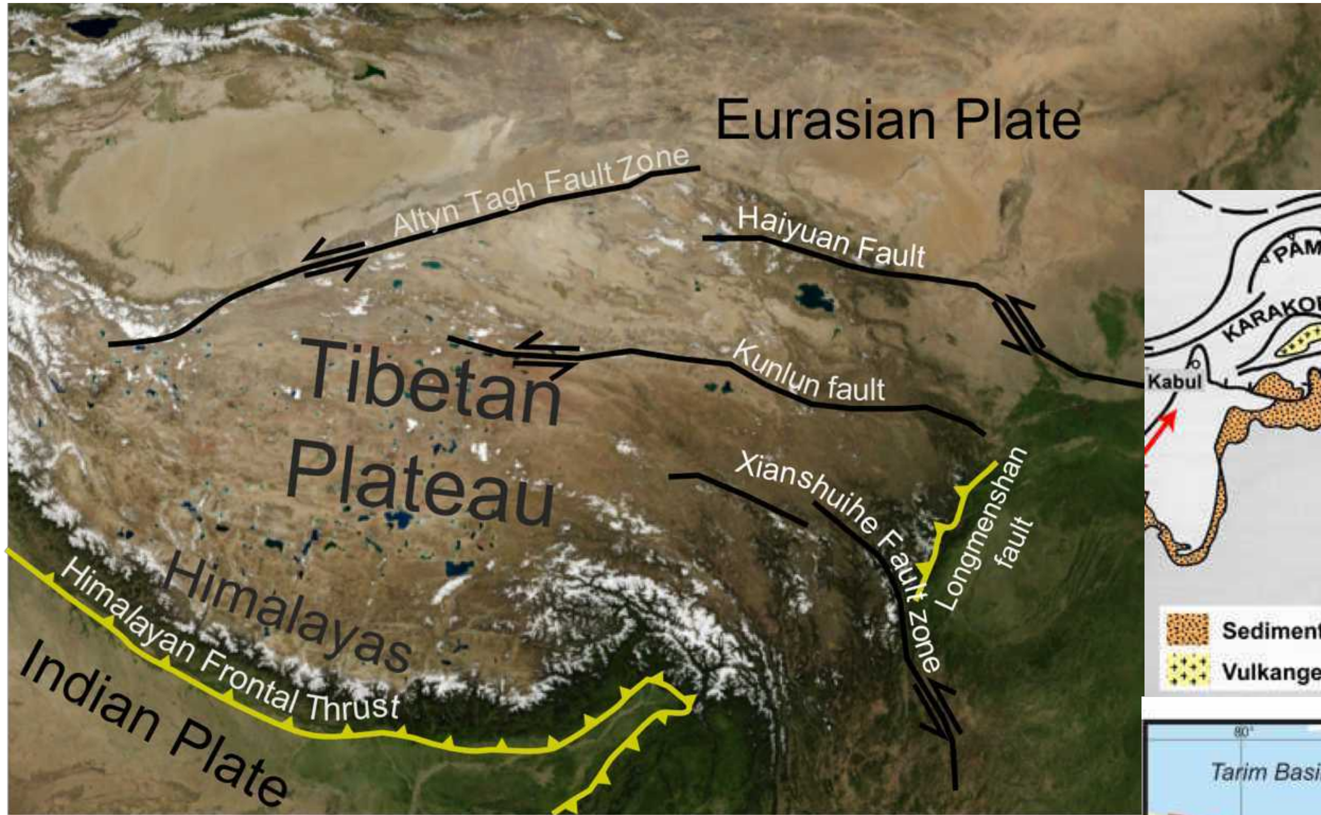
strike slip faults

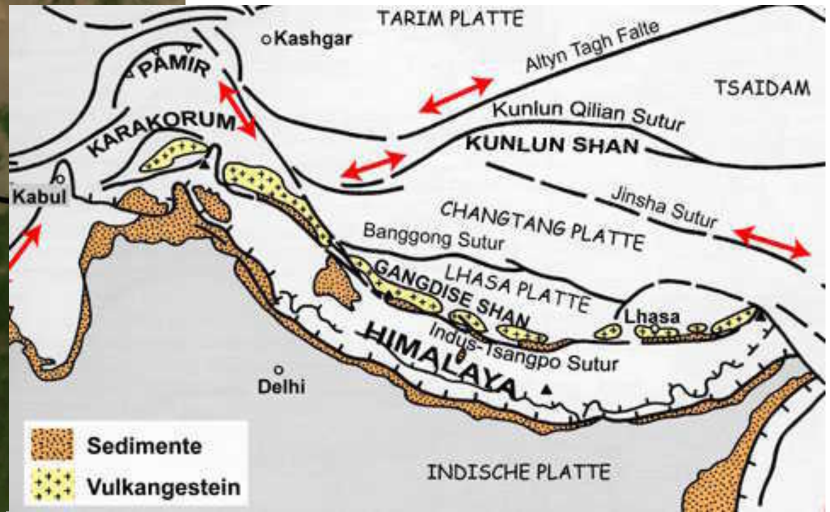


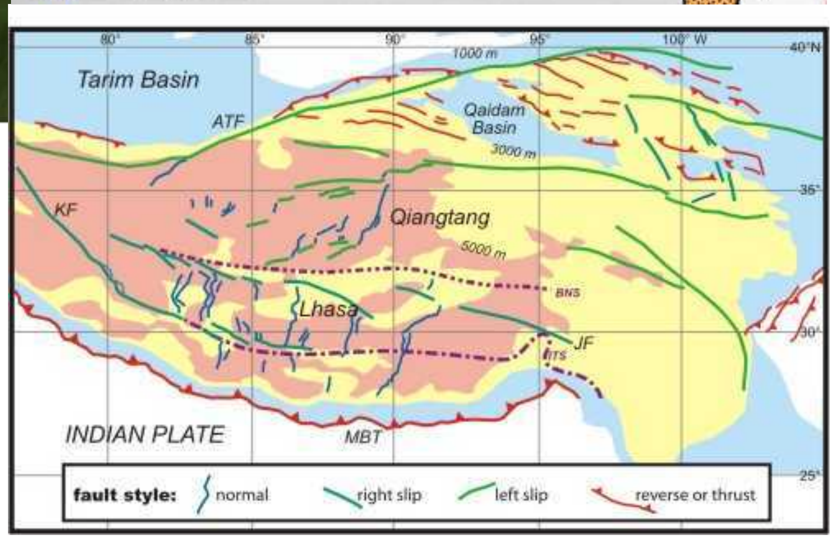


San Andreas Fault

strike slip faults

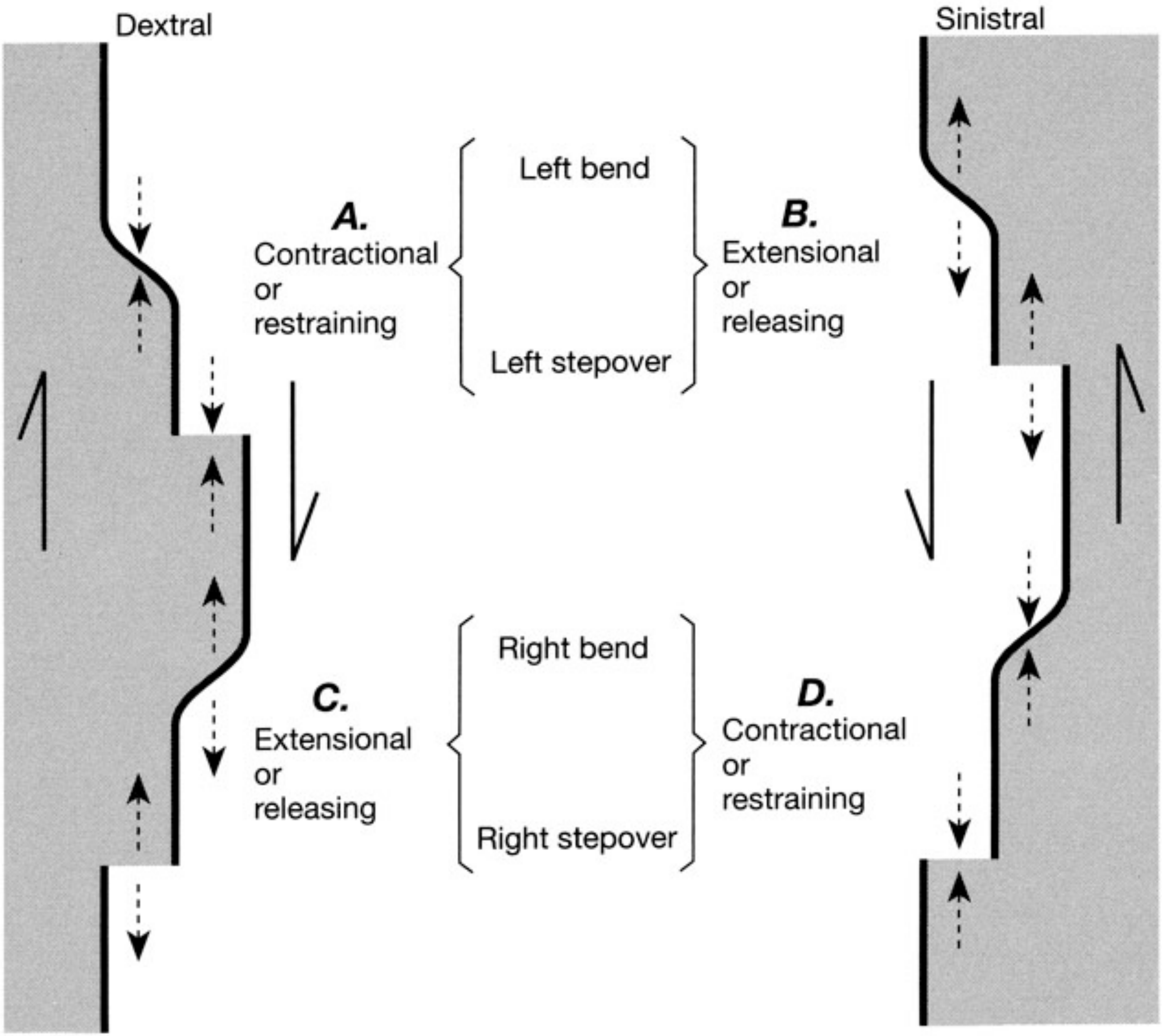




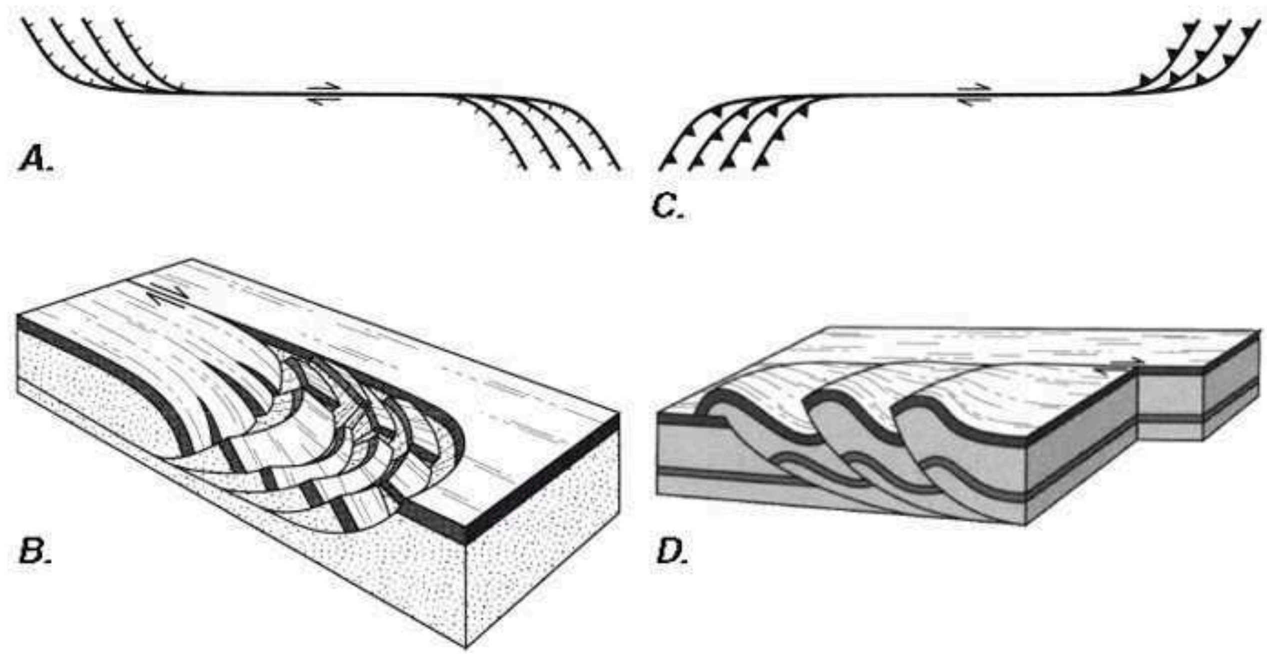


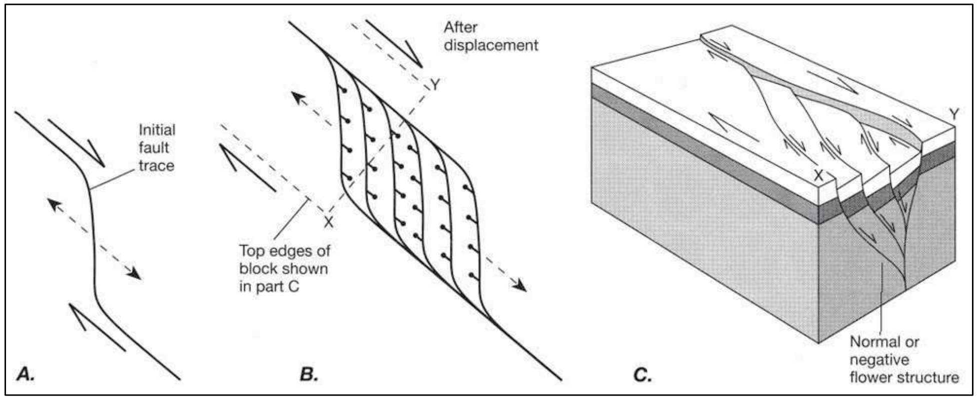
Altyn Tagh Fault

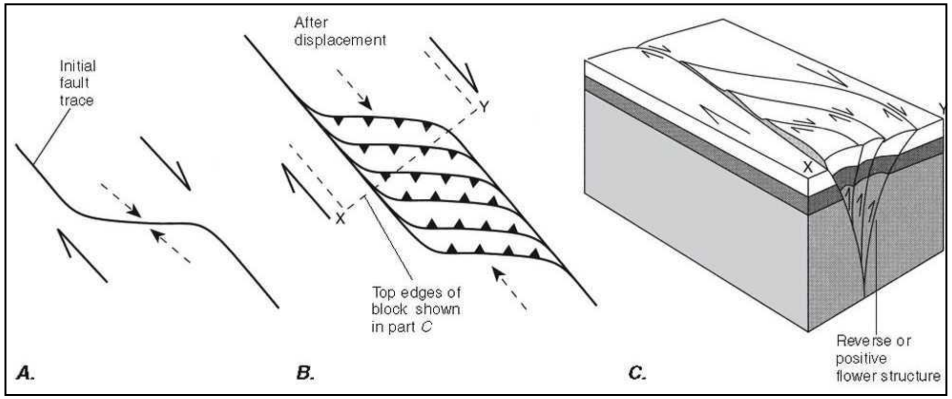
bends in fault surface



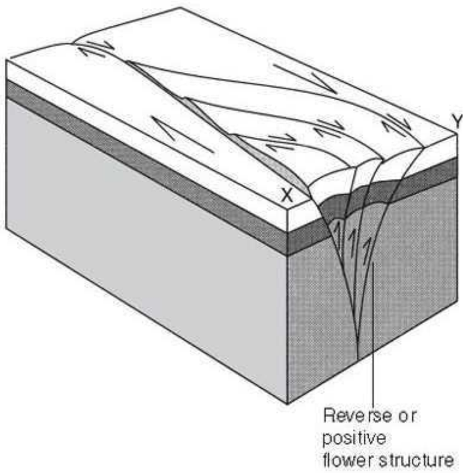
bends in fault surface

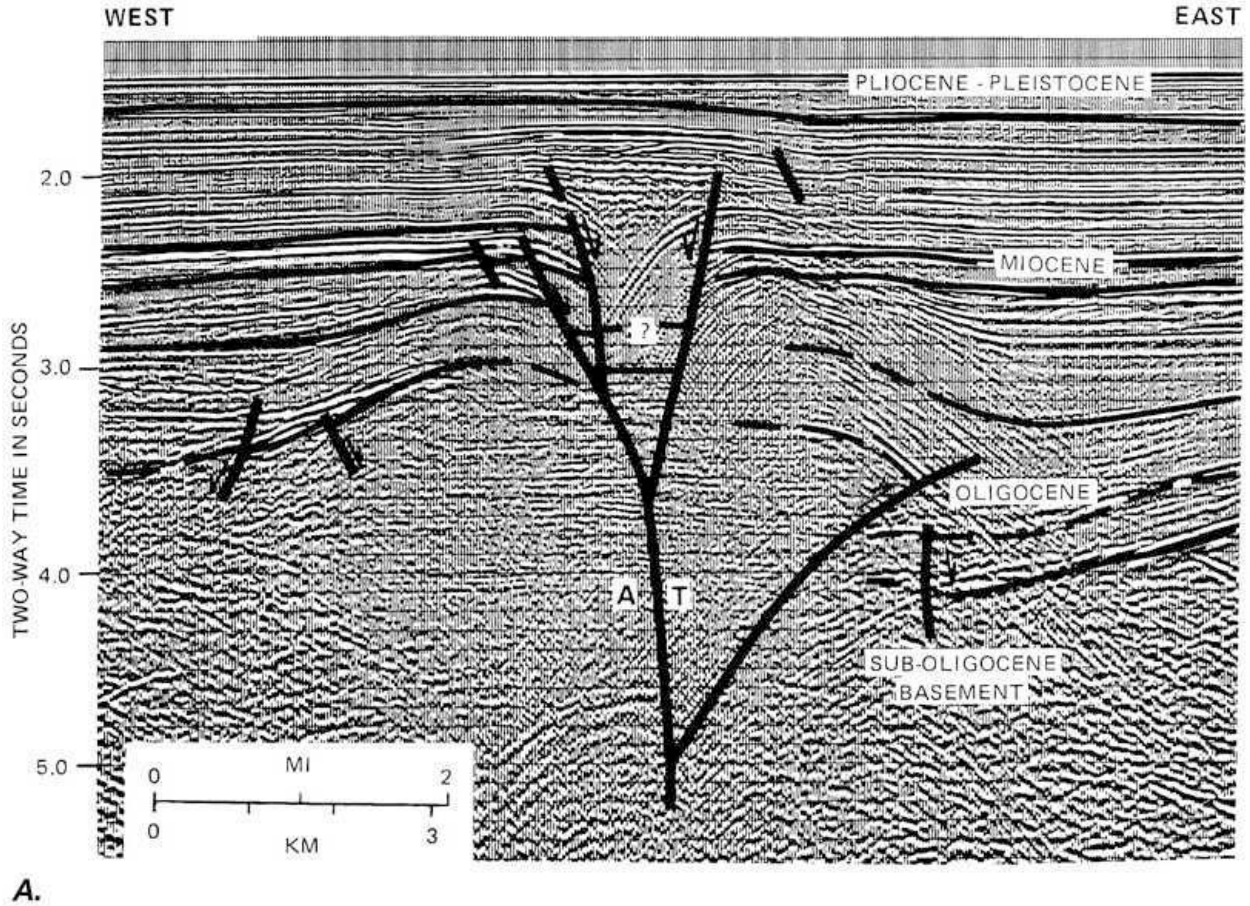






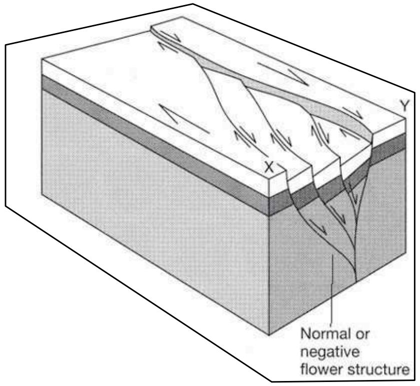
positive flower structure

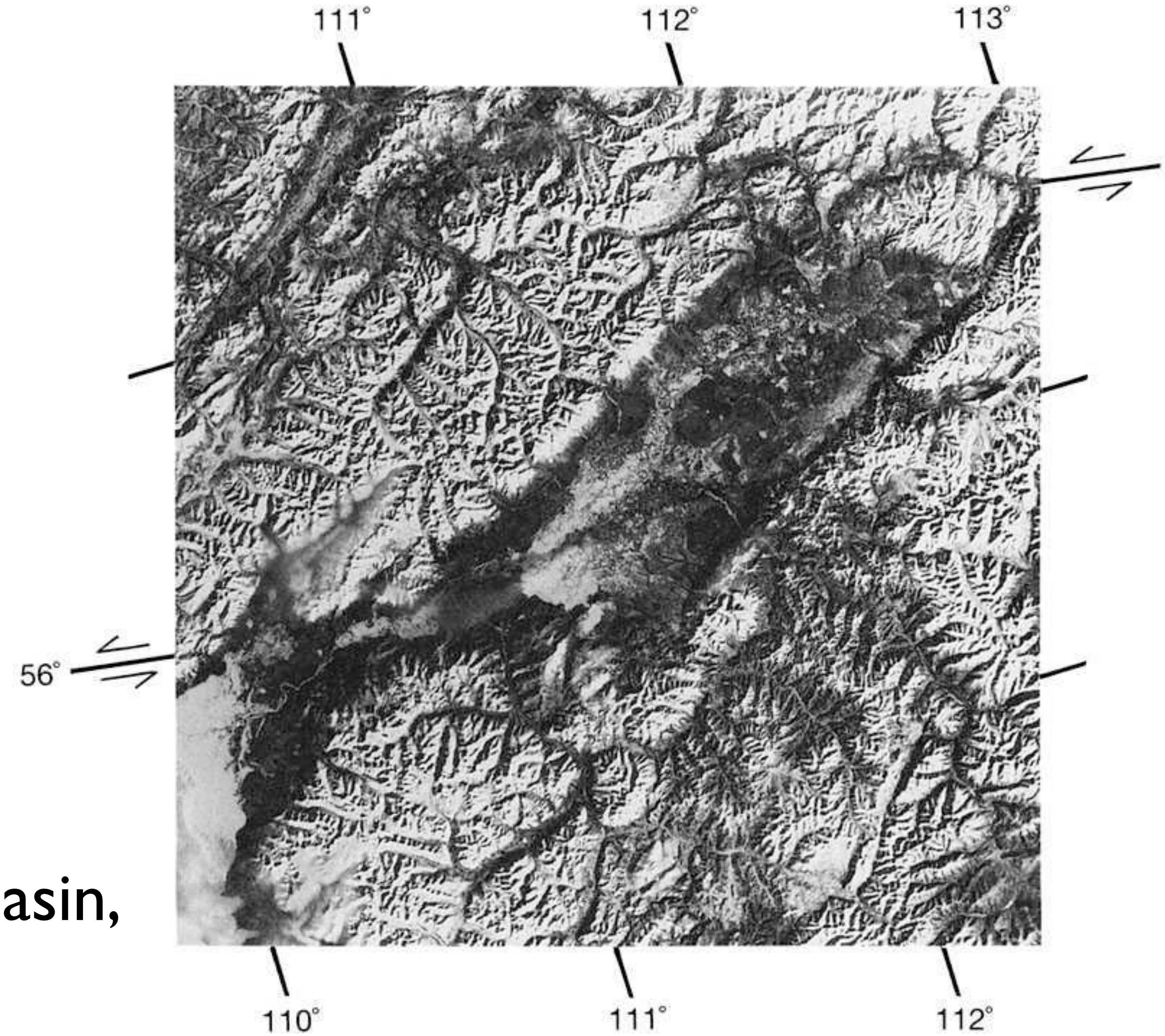




Example:
Andaman Sea (Malaysia - India)

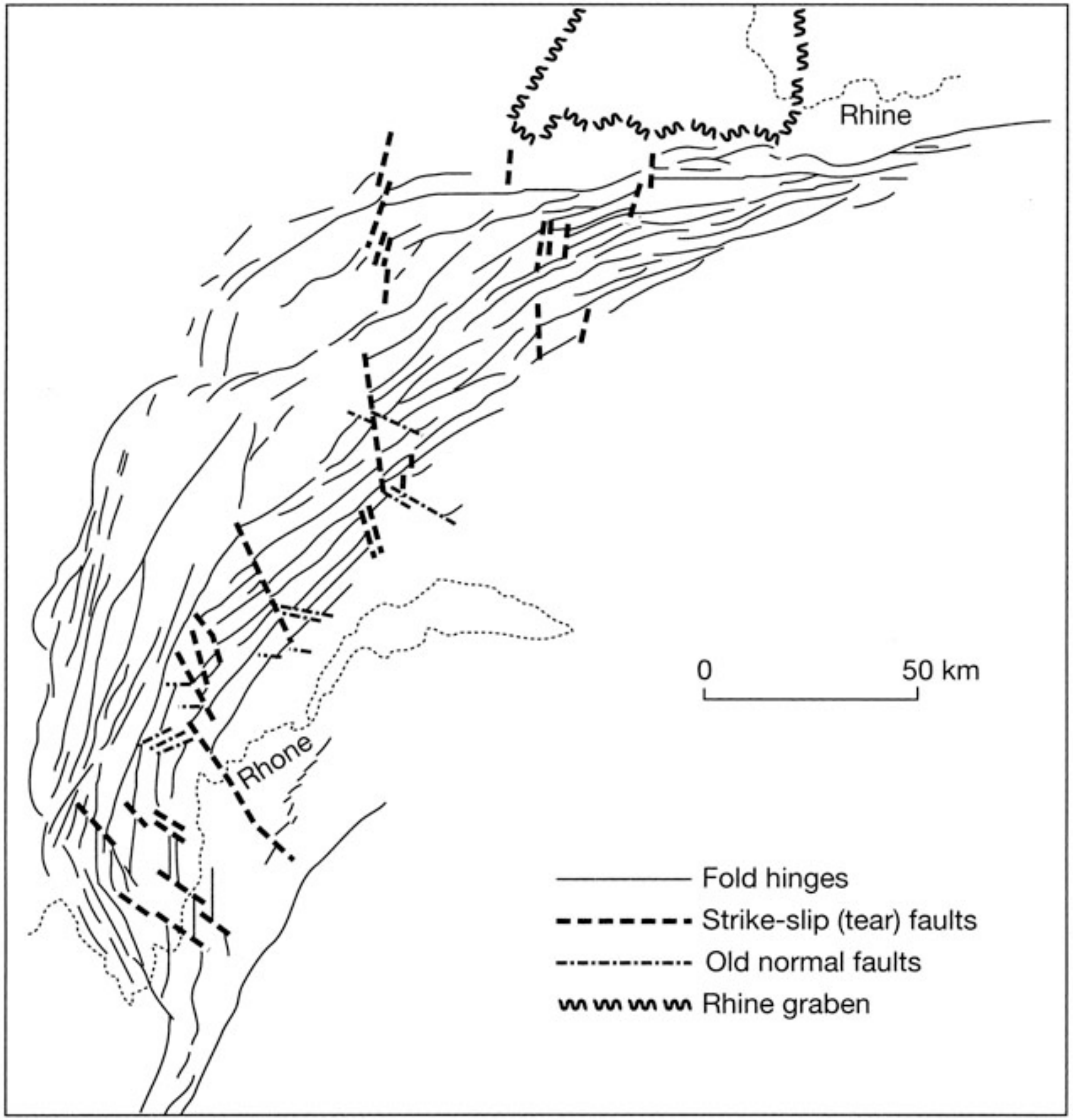
negative flower structure





Example:
Angara graben basin,
Siberia

regional tear faults



Example:
Jura
Mountains,
Switzerland

5

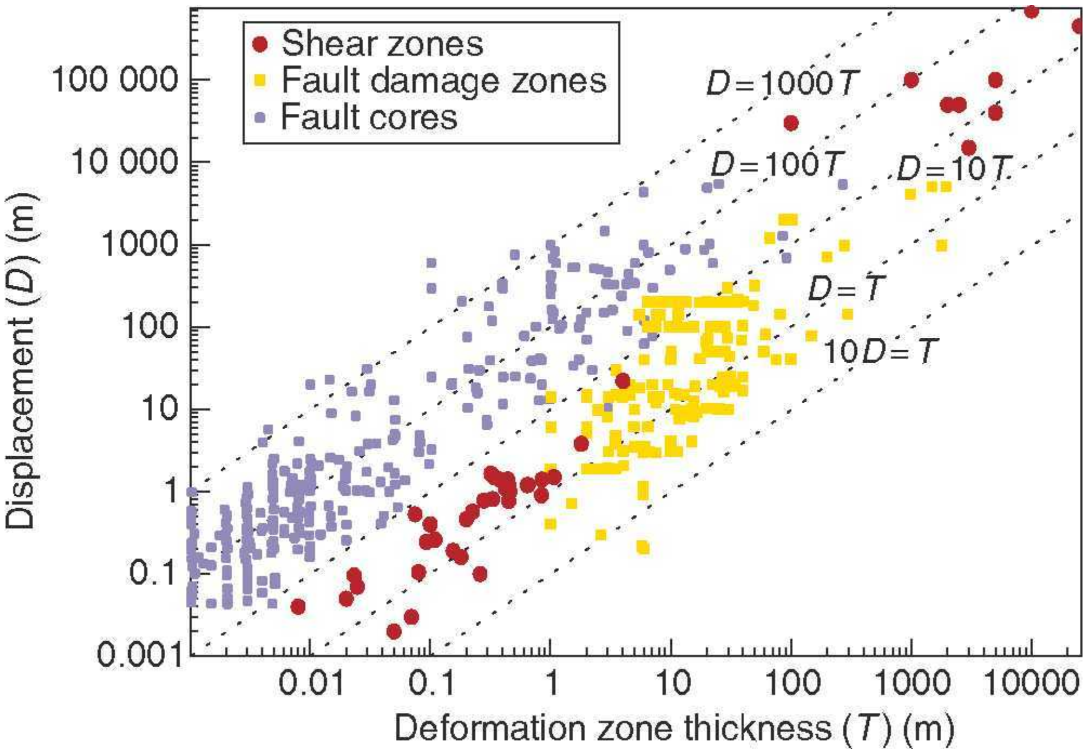
5 Scherzonen - Foliation - Lineation

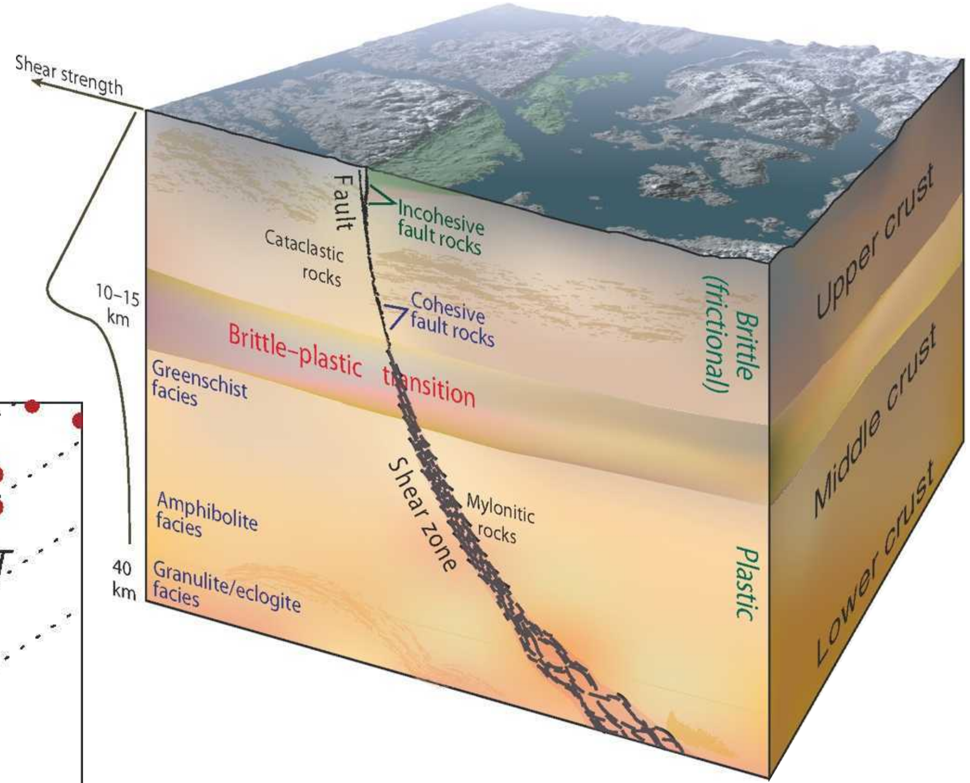
VL-Themen:

- Scherzonen
- Foliation & Lineation
- Schieferung und Verformung
- Mechanismen der Schieferungsbildung
- Bedeutung der Schieferung beim Kartieren
- Lineation

Scherzonen

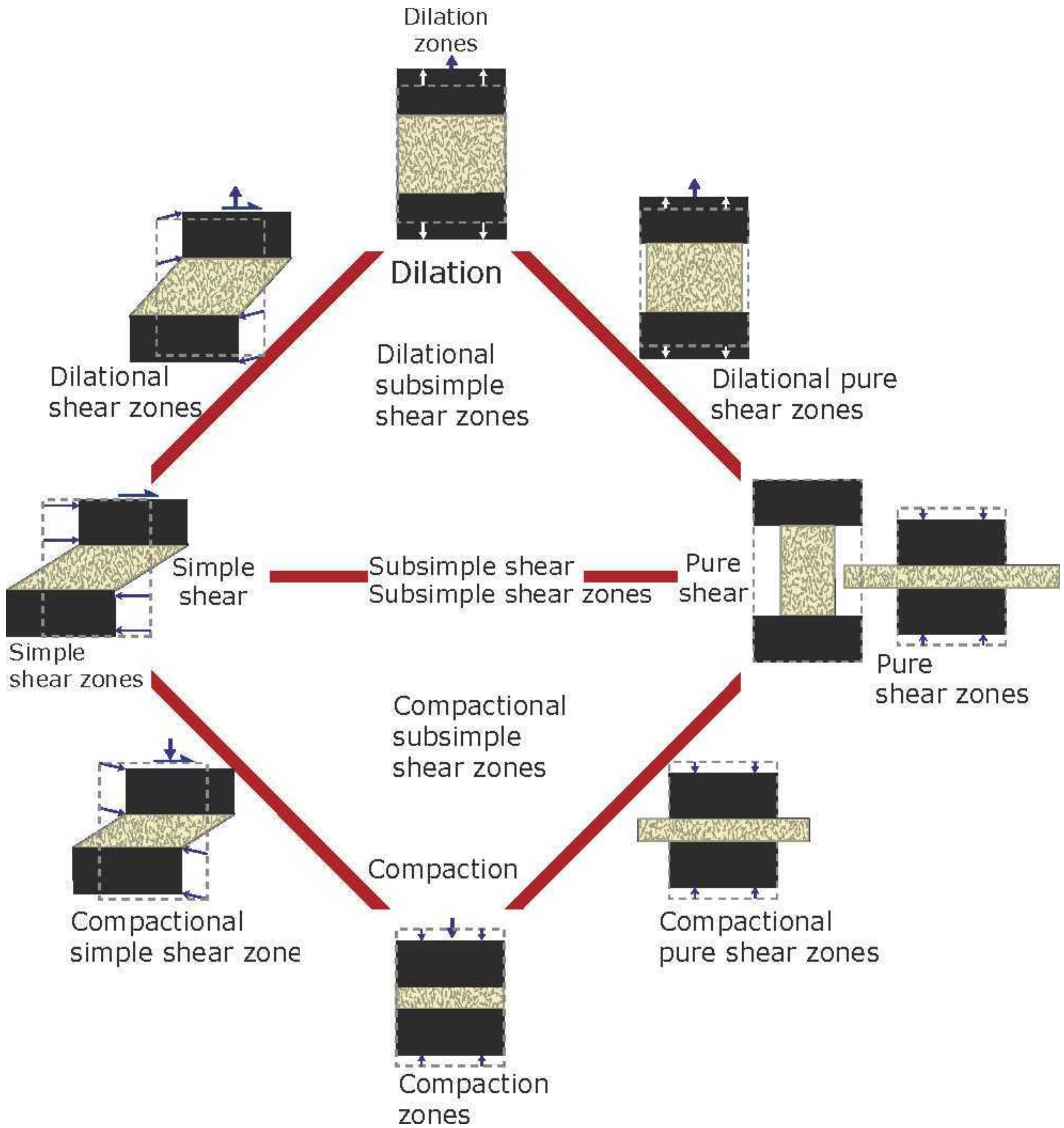
Spröde und duktile Scherzonen





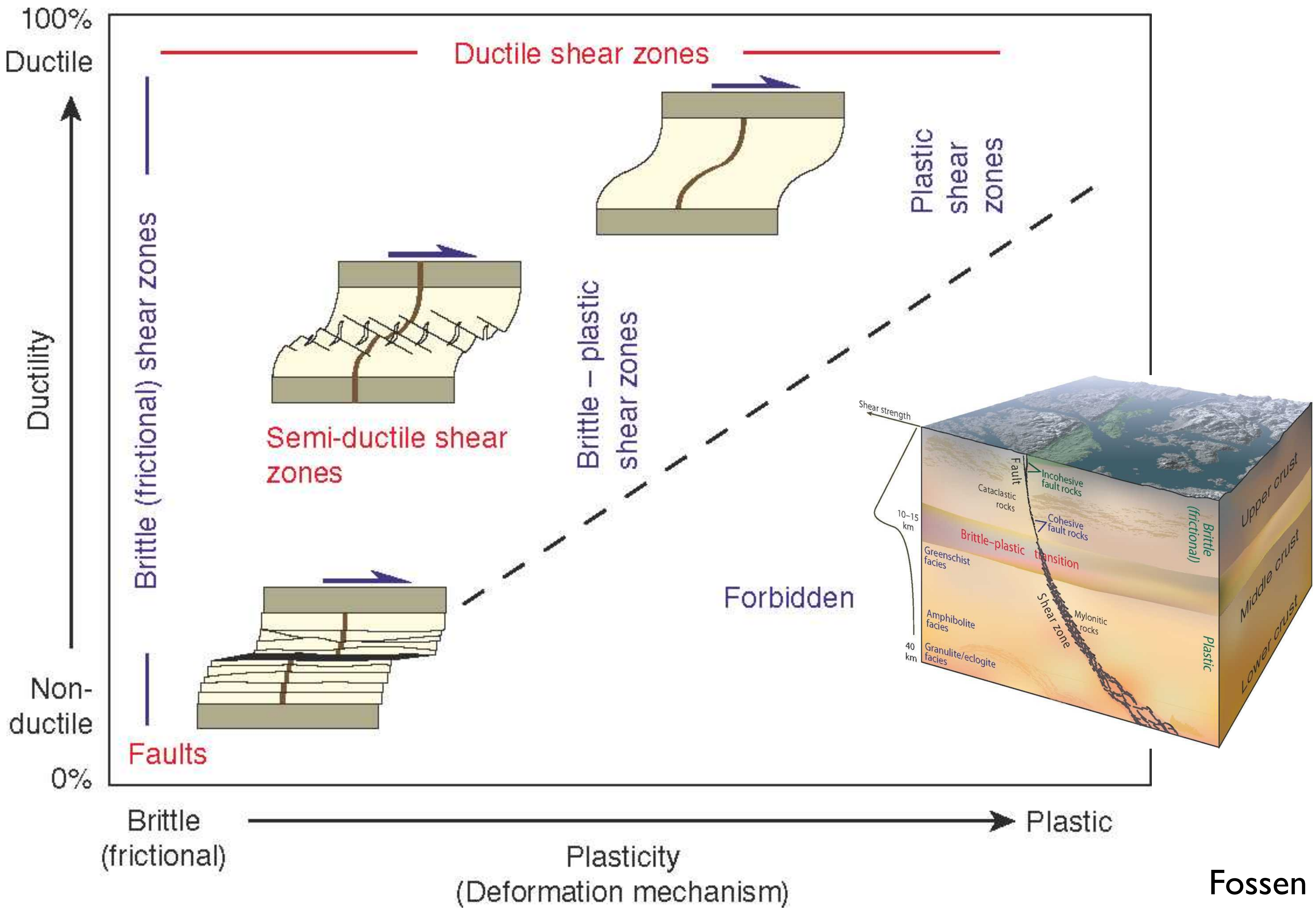
Fossen

Typen von Scherzonen



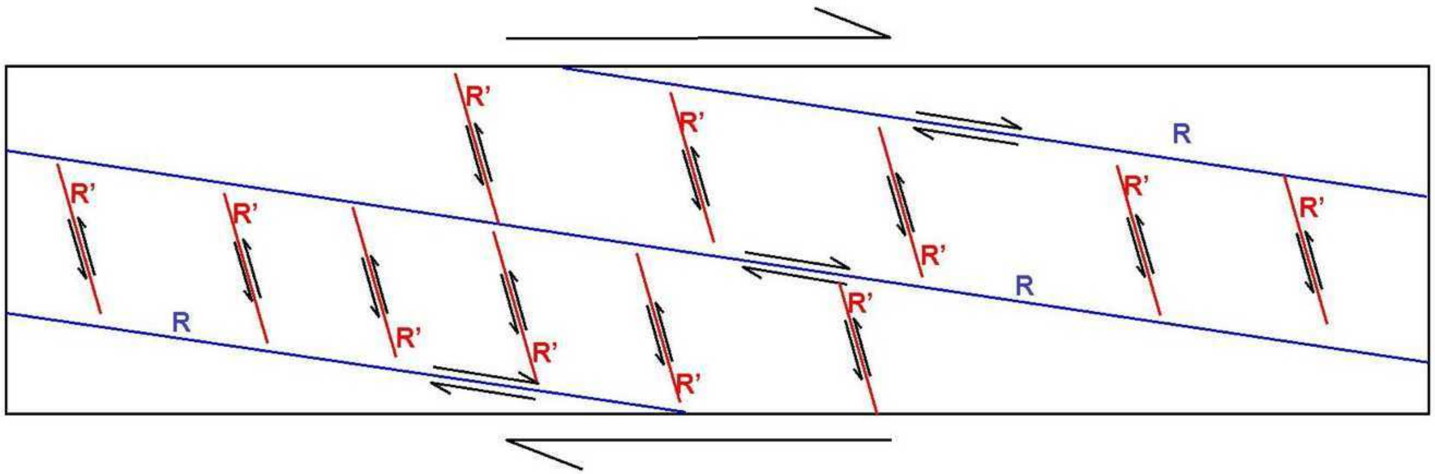
Fossen

Scherzonen Klassifikation

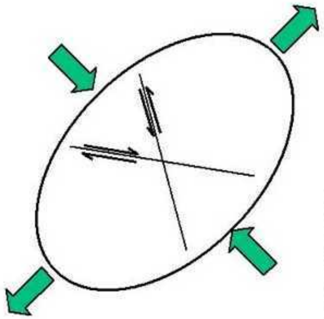


Fossen

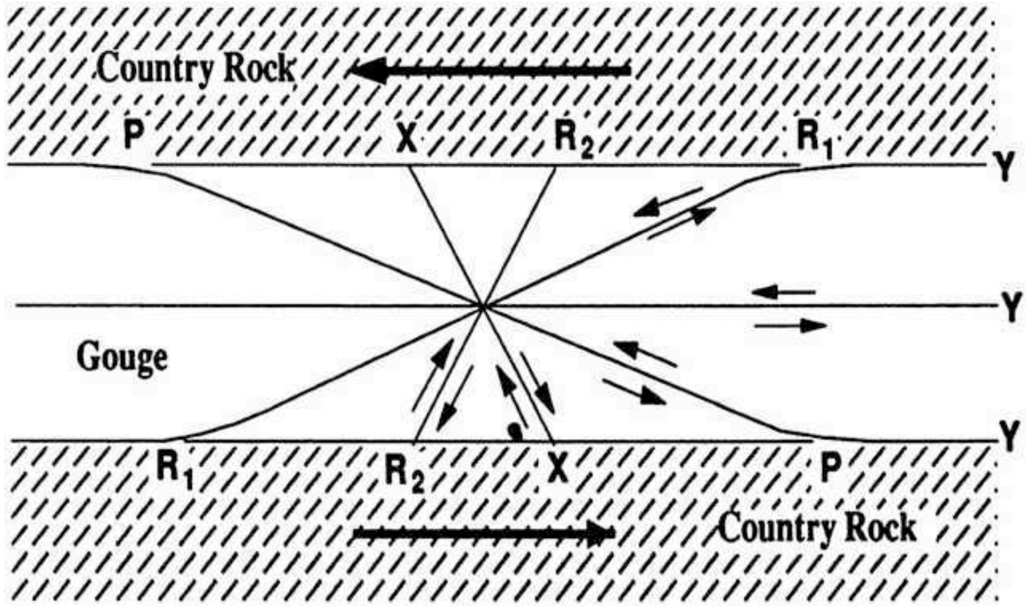
Riedel Scherzonen



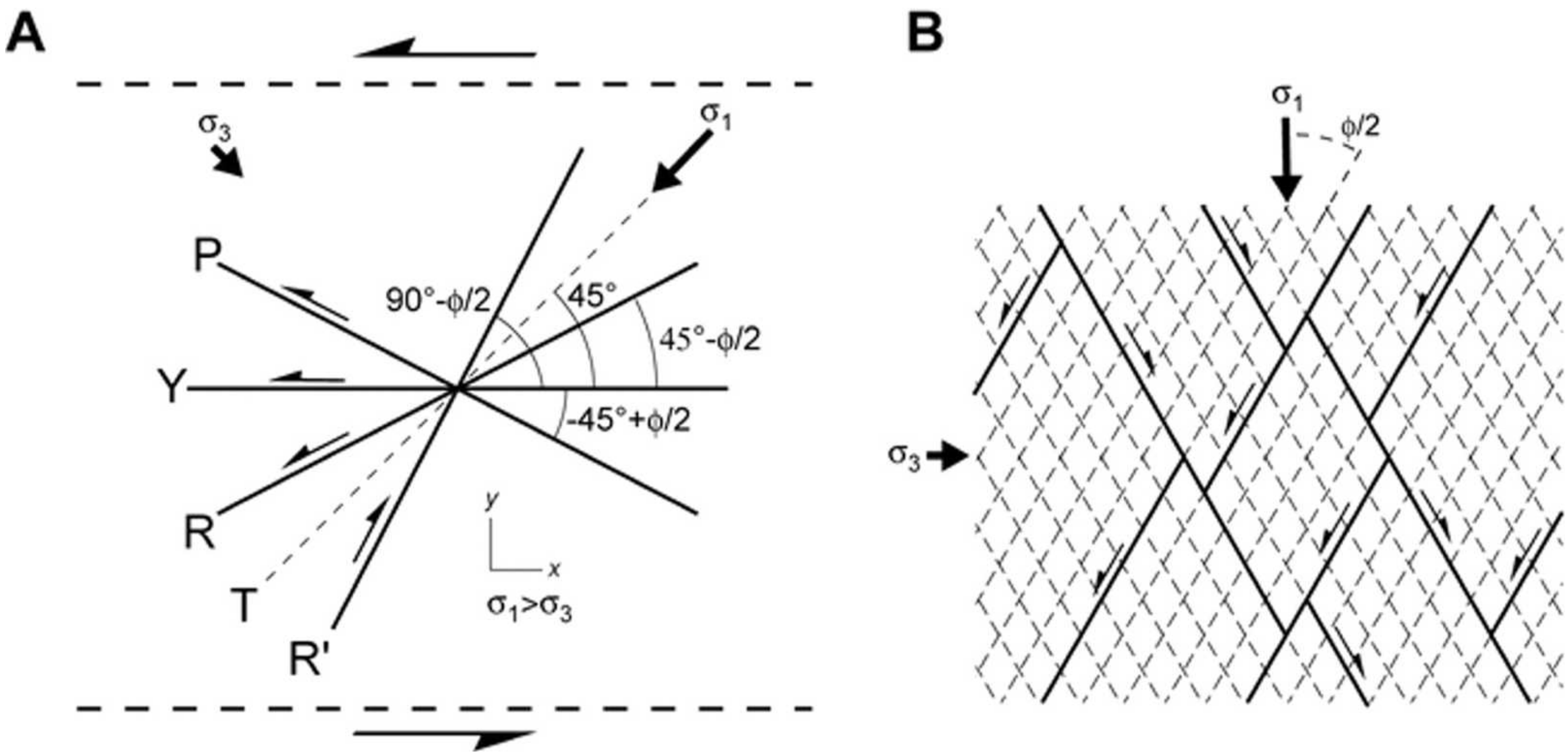
Infinitesimal strain ellipse for simple shear showing predicted fault orientations matching the two Riedel shear sets



http://upload.wikimedia.org/wikipedia/commons/f/f2/Riedel.jpg

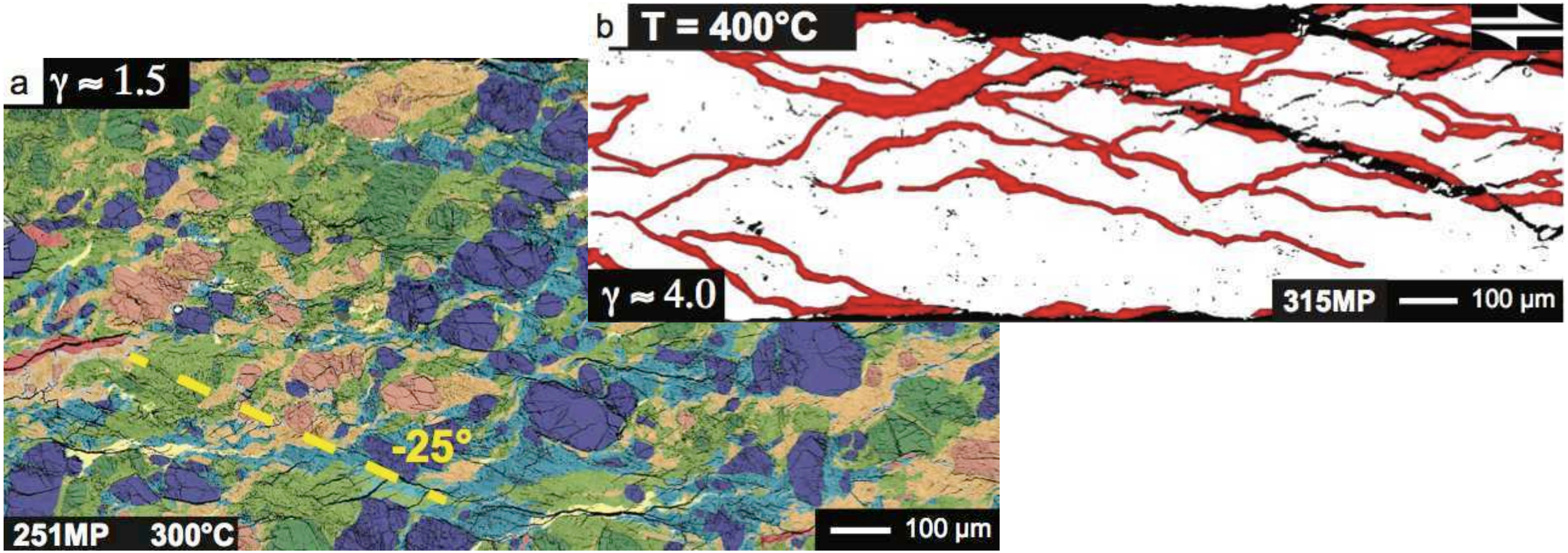


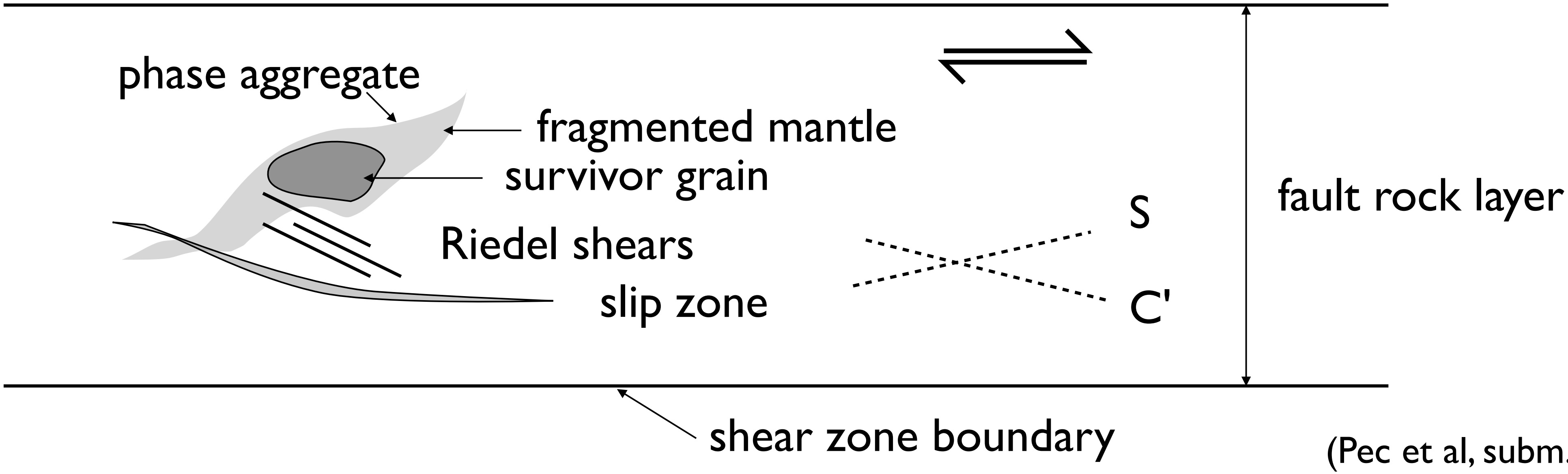
Spannungen in Riedel Scherzonen



http://bulletin.geoscienceworld.org

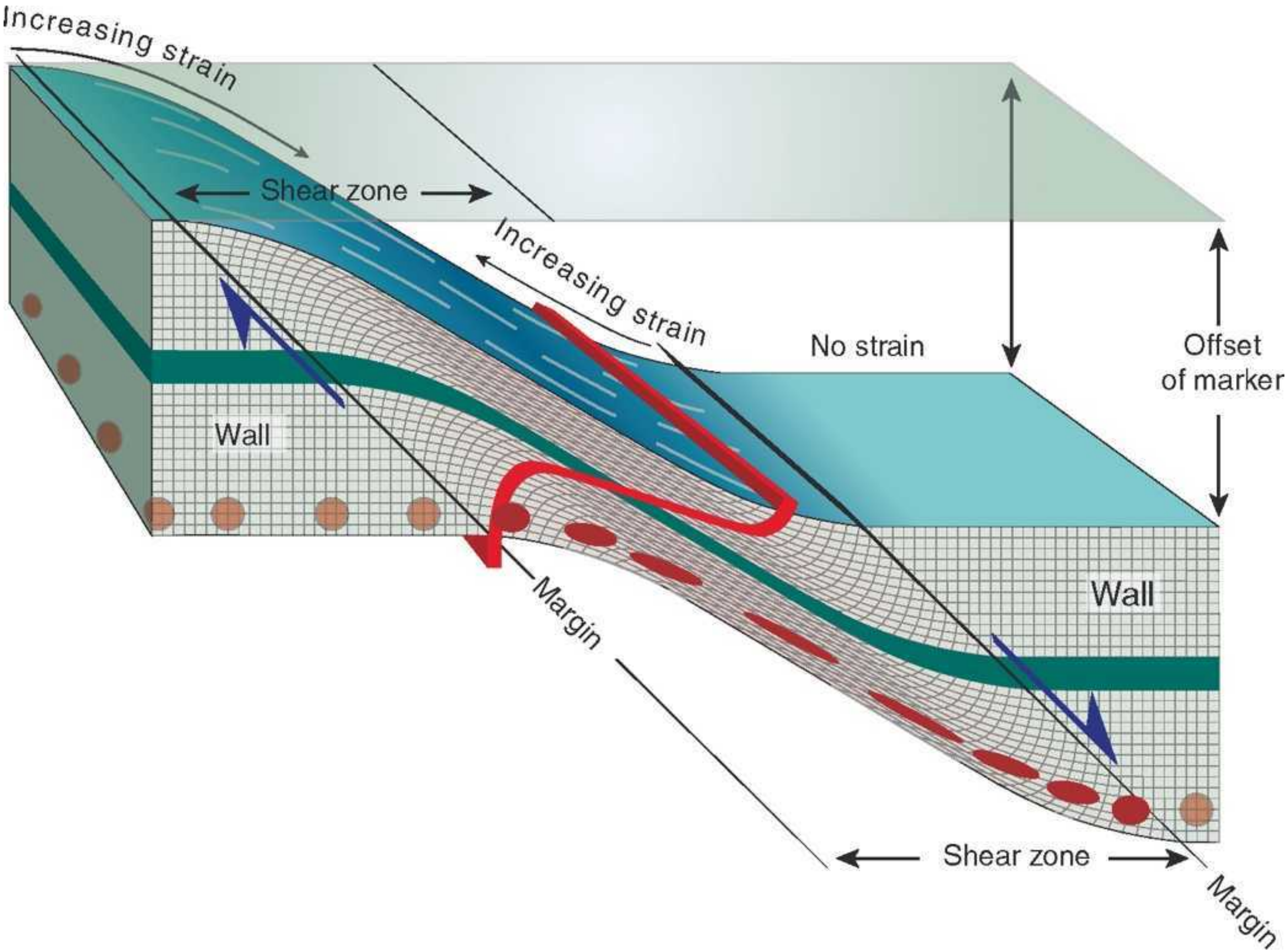
Riedel and S-C'





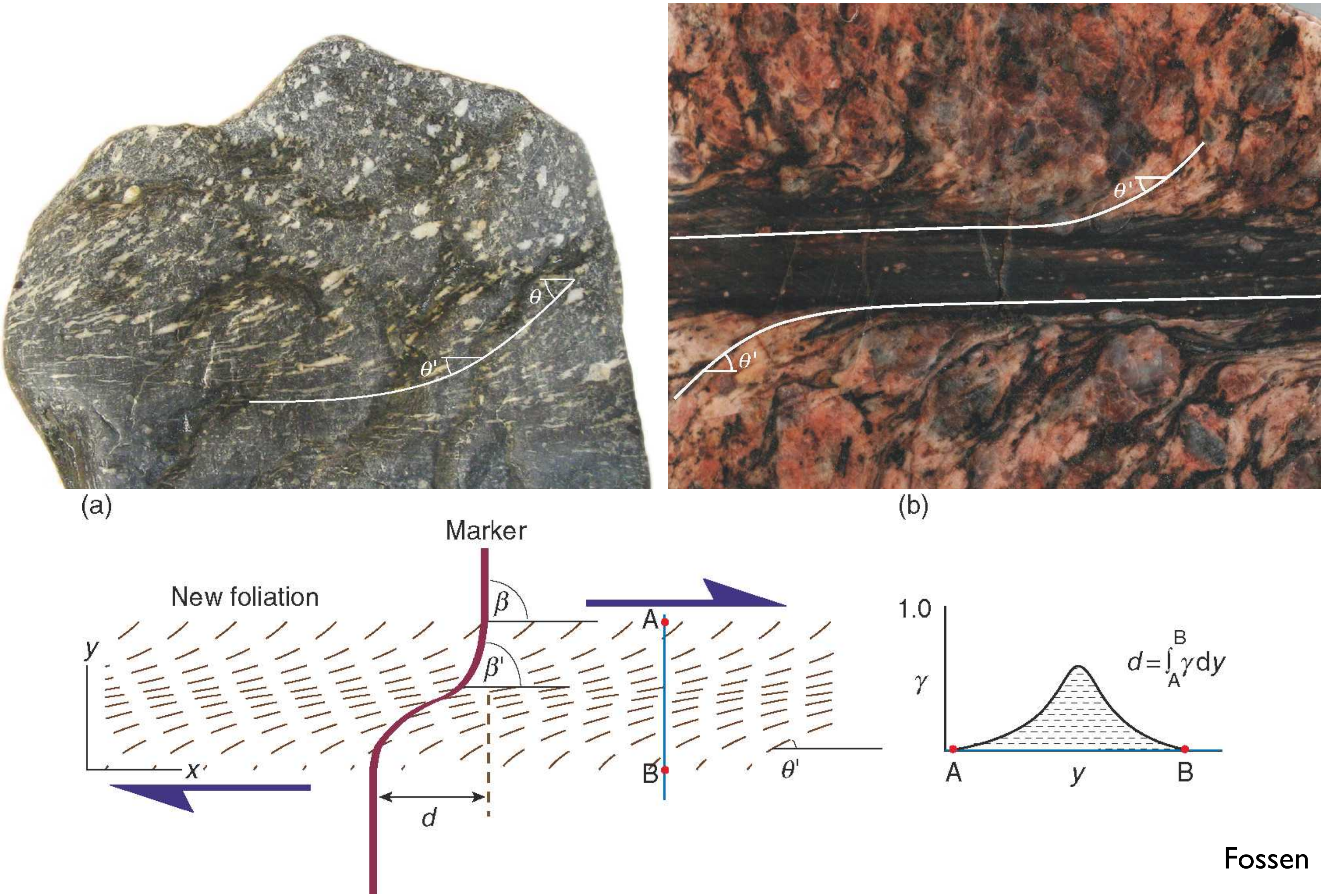
(Pec et al, subm.)

Duktile Scherzonen



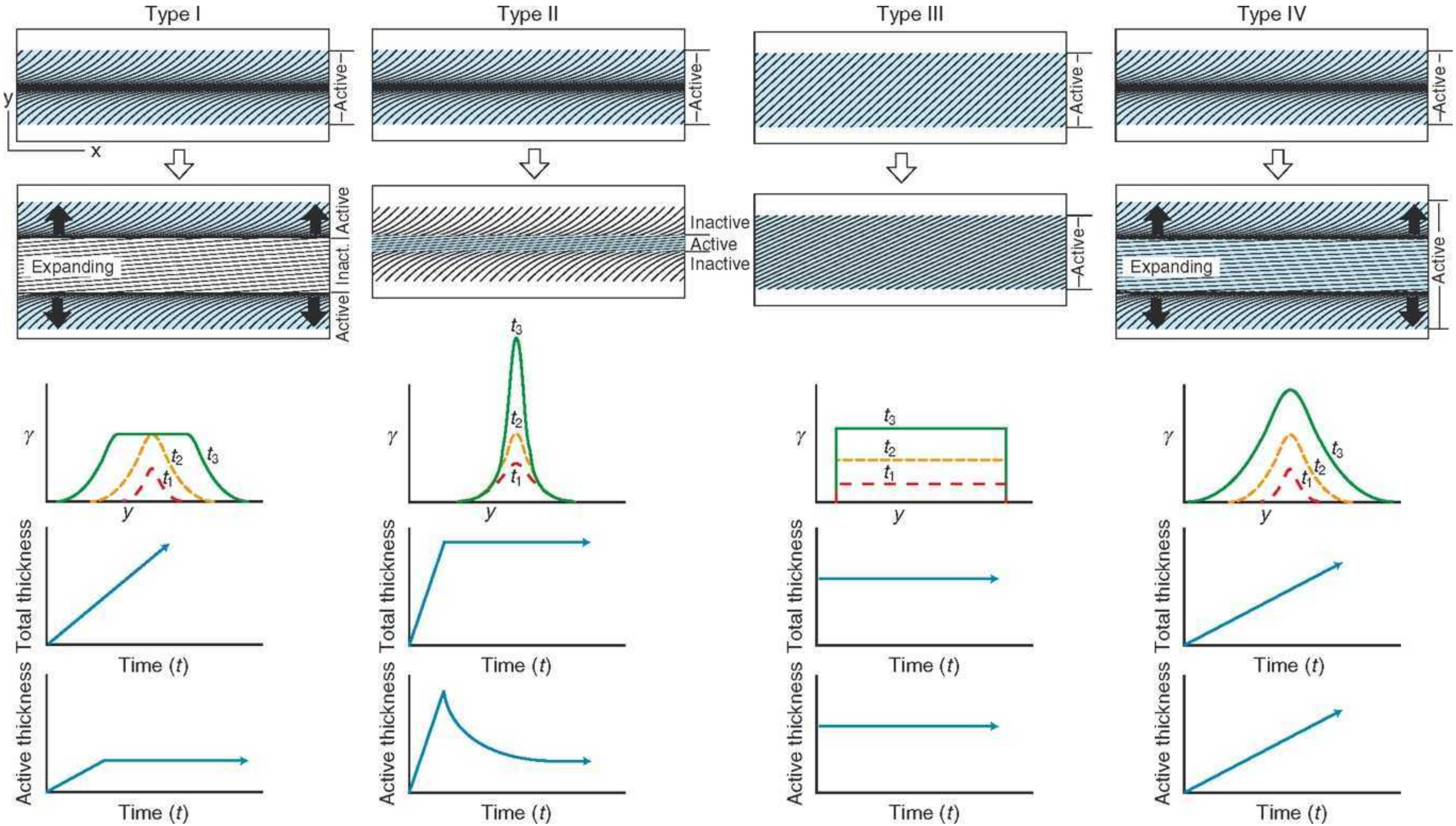
Fossen

Gefüge-Trajektorien



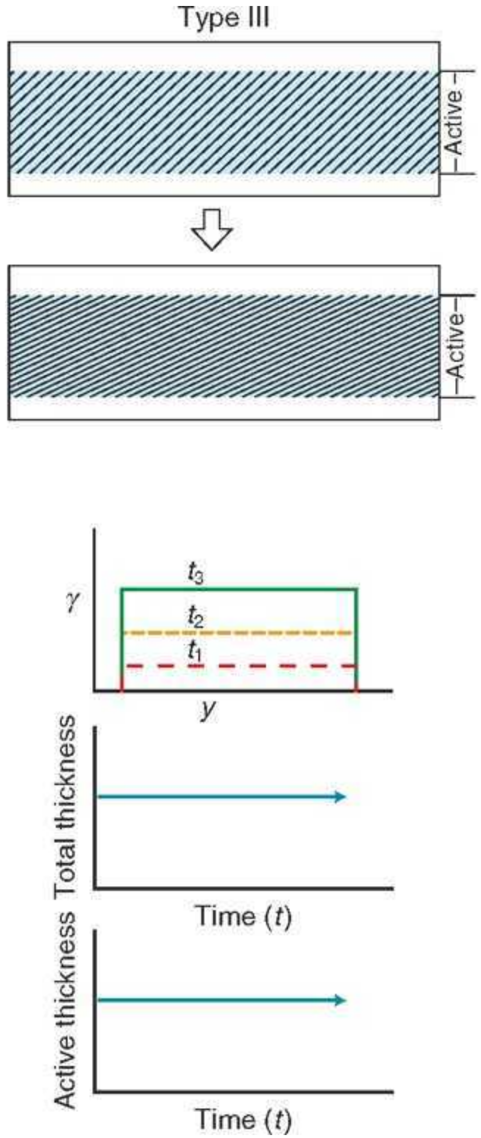
Fossen

Scherzonentypen



http://folk.uib.no/nglhe/e-modules/Chapter%2015/15%20Shear%20zones.swf

Scherzonentypen

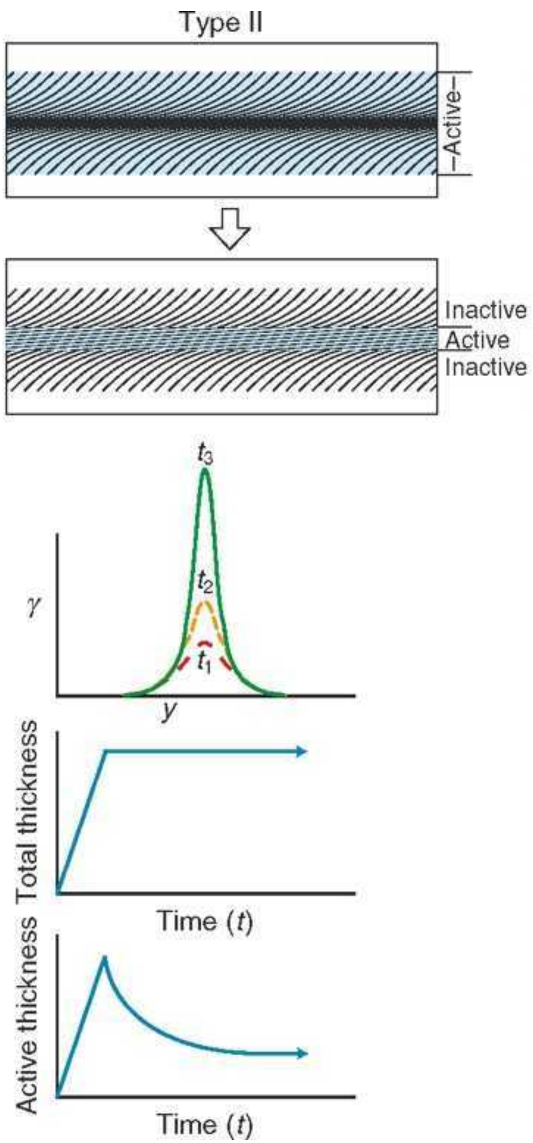


Type III

- Type III shear zones initiate with a certain thickness.
- This shear zone thickness remains constant, and the entire zone is always active.
- The result is a flat strain profile.
- This type of shear zone involves no pronounced softening or hardening mechanisms.
- Some kink-bands may represent shear zones of this type.

http://folk.uib.no/nglhe/e-modules/Chapter%2015/15%20Shear%20zones.swf

Scherzonentypen

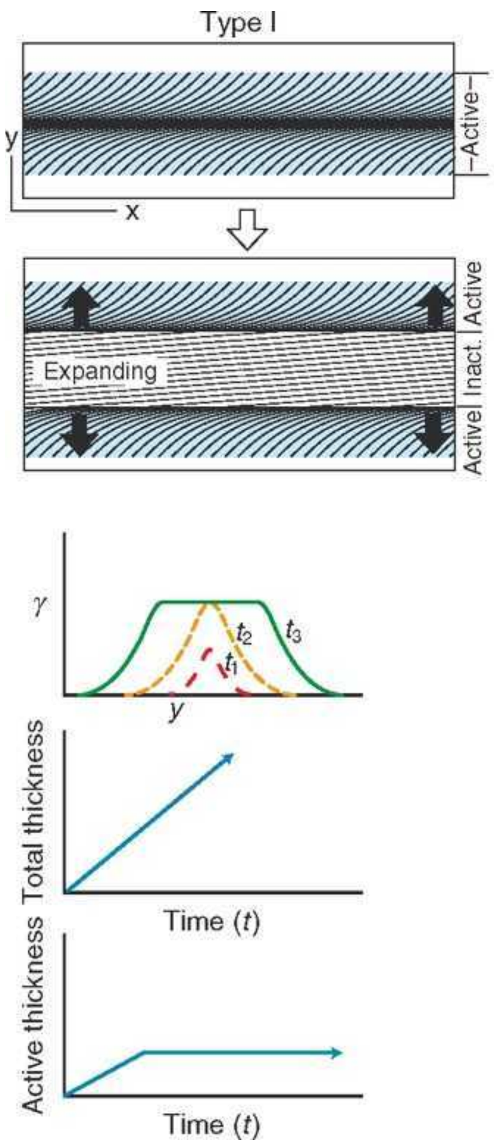


Type II

- Type II shear zones expand only for a limited period of time.
- Then the margins are left inactive, and all further deformation is concentrated in the central part of the zone.
- The result is a steep peak in the central part of the strain profile across the zone.
- This type of shear zone is normally explained by strain softening.

http://folk.uib.no/nglhe/e-modules/Chapter%2015/15%20Shear%20zones.swf

Scherzonentypen

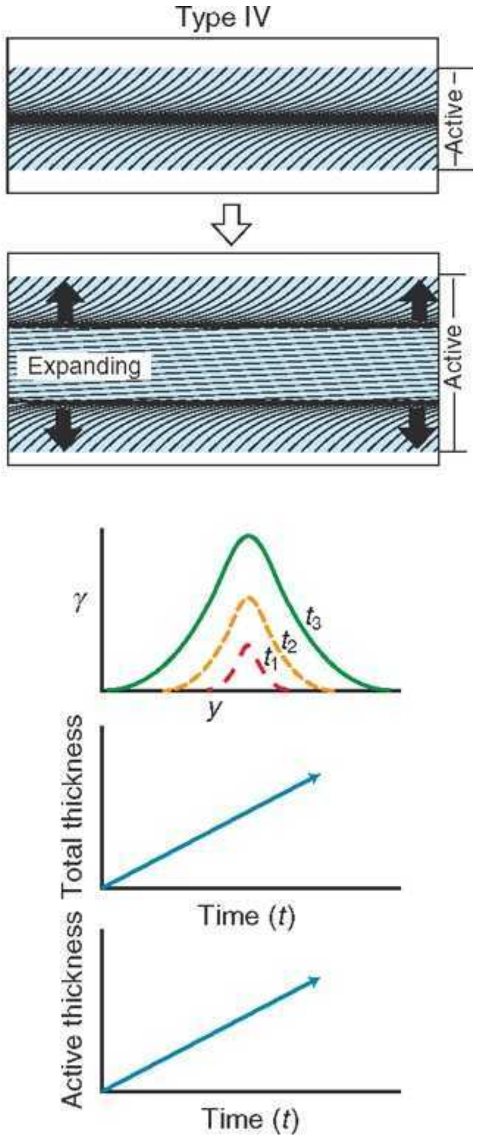


Type I

- Type I shear zones expand into its walls and thus becomes thicker with increasing offset.
- The central part of the zone is left behind (inactive) as the walls are being strained.
- The result is a flat peak in the strain profile in the central, inactive part of the zone.
- This type of development is normally attributed to strain hardening.

http://folk.uib.no/nglhe/e-modules/Chapter%2015/15%20Shear%20zones.swf

Scherzonentypen

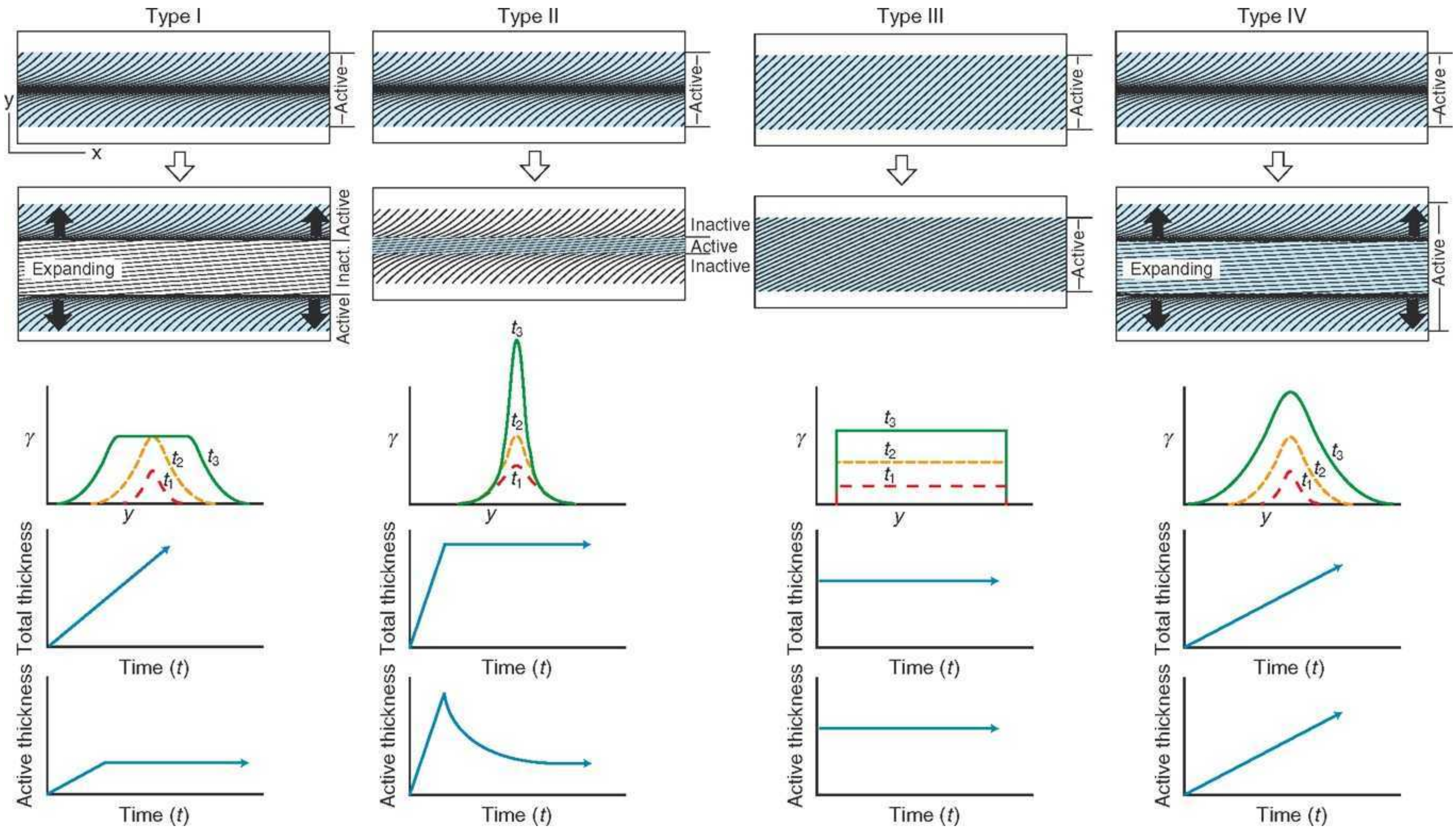


Type IV

- Type IV shear zones expand continuously during their lifetime.
- The entire zone is always active.
- The result is a steep peak-shaped strain profile through the zone.

http://folk.uib.no/nglhe/e-modules/Chapter%2015/15%20Shear%20zones.swf

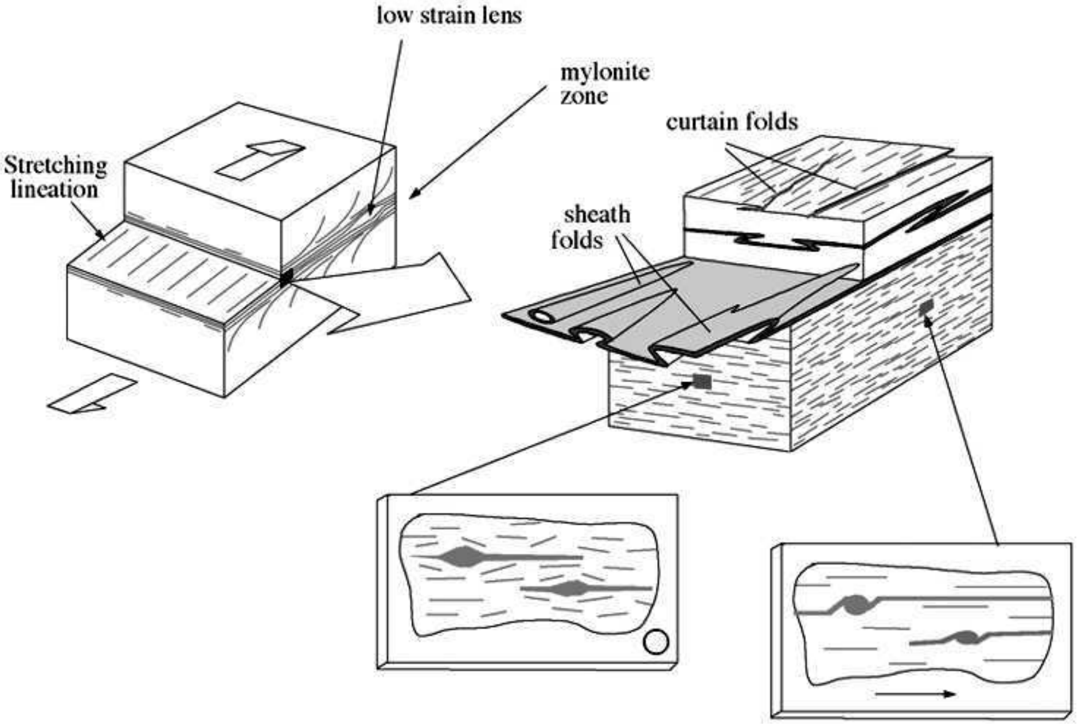
Scherzonentypen

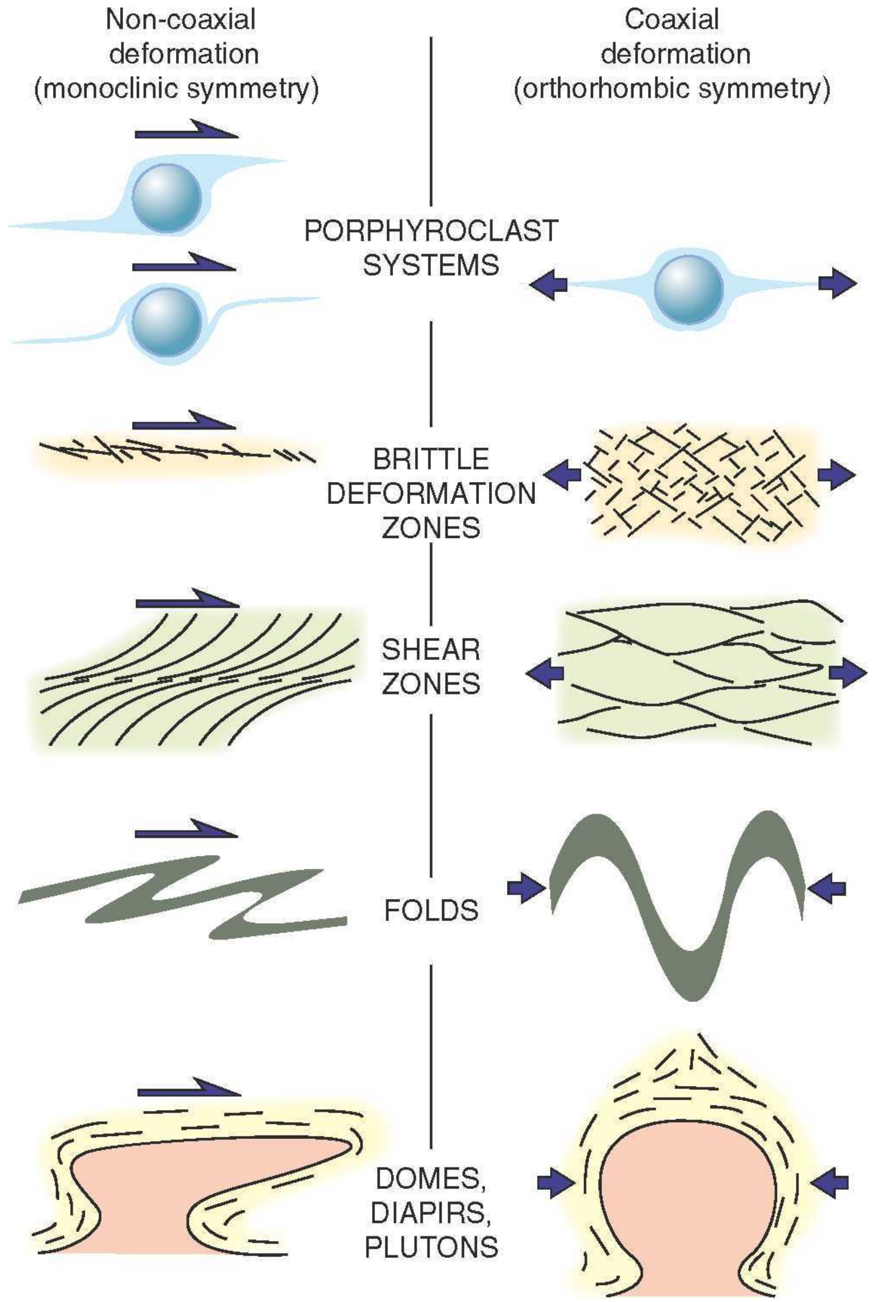


http://folk.uib.no/nglhe/e-modules/Chapter%2015/15%20Shear%20zones.swf

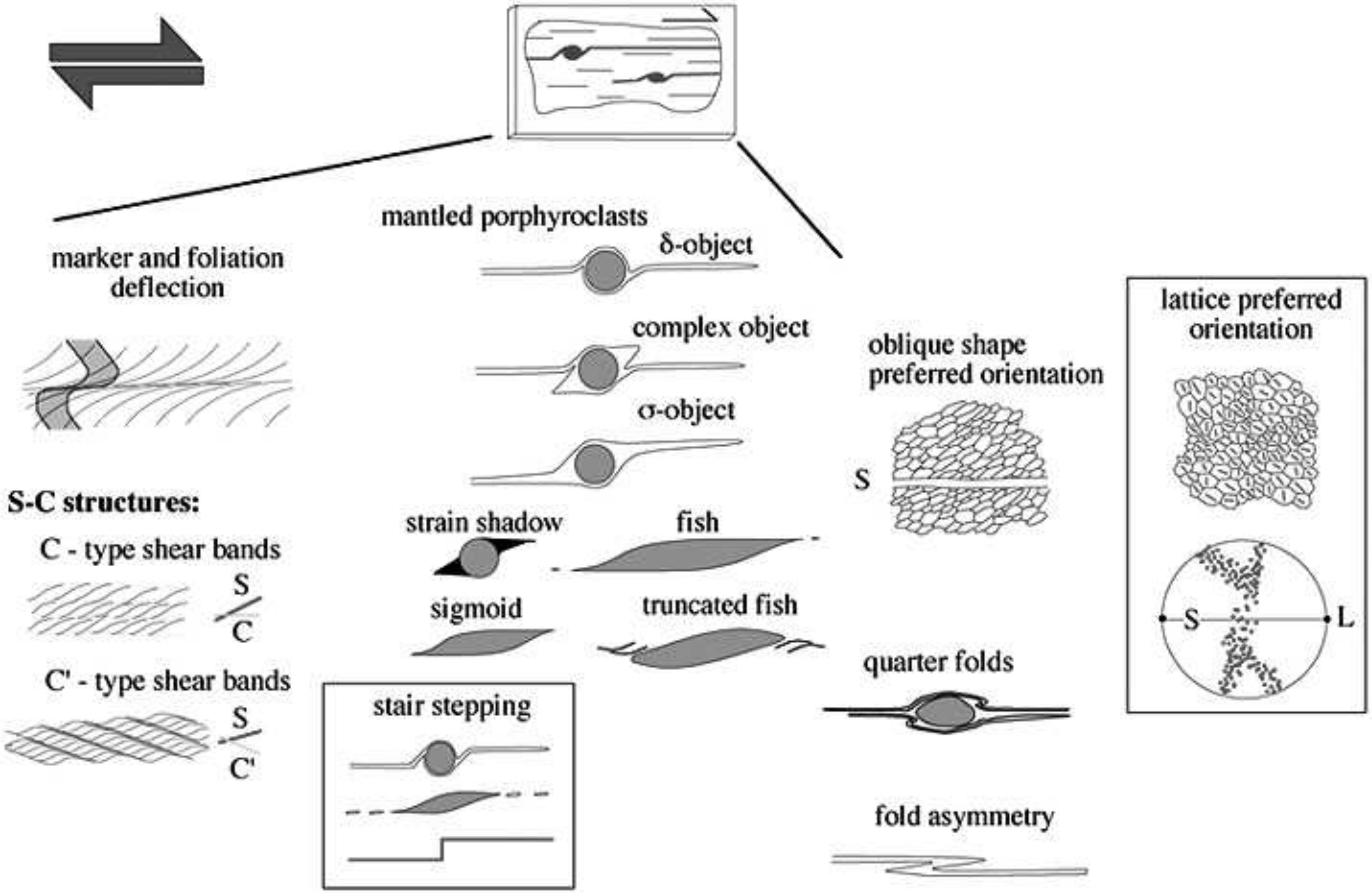
mit Scherzonen assoziierte (Mikro-)Strukturen

Scherzonen in 3D

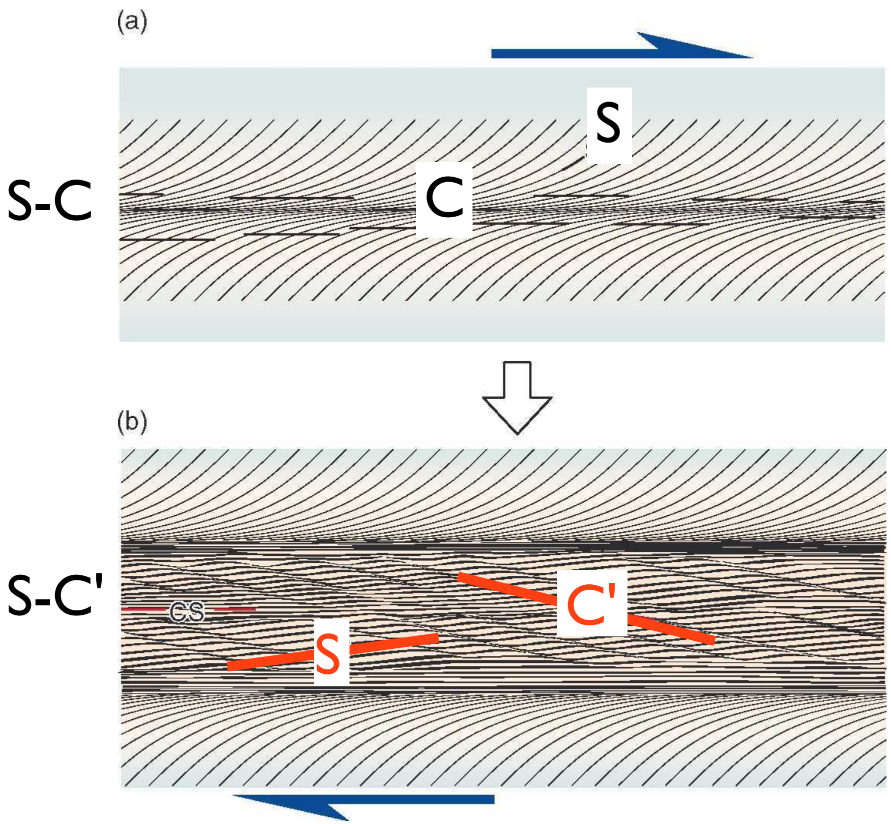


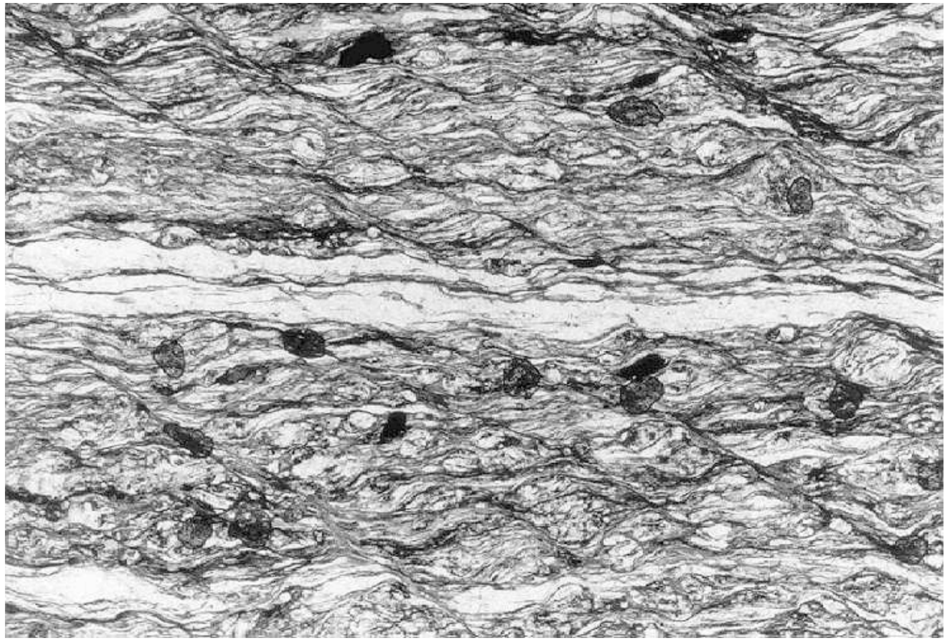


characteristic features of shear zones

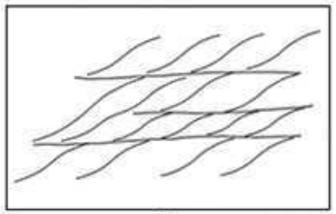


S-C and S-C' fabrics

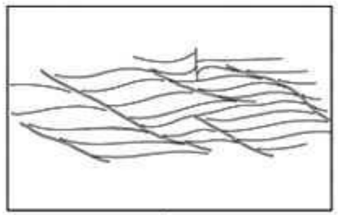




C-type shear bands

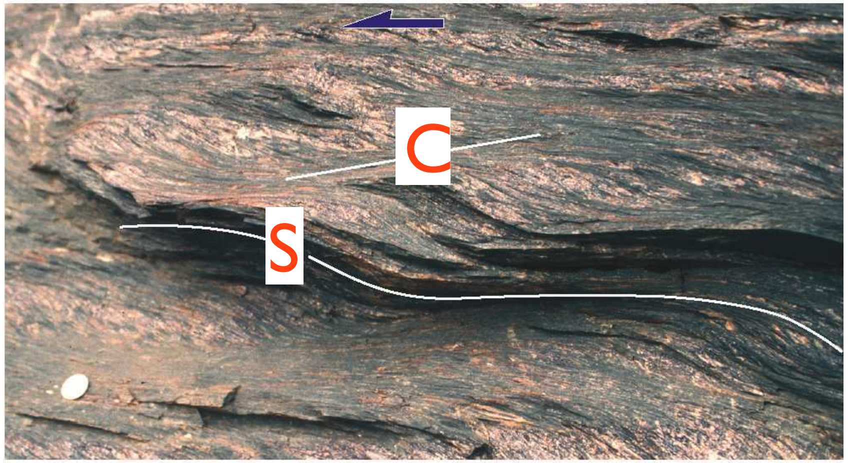


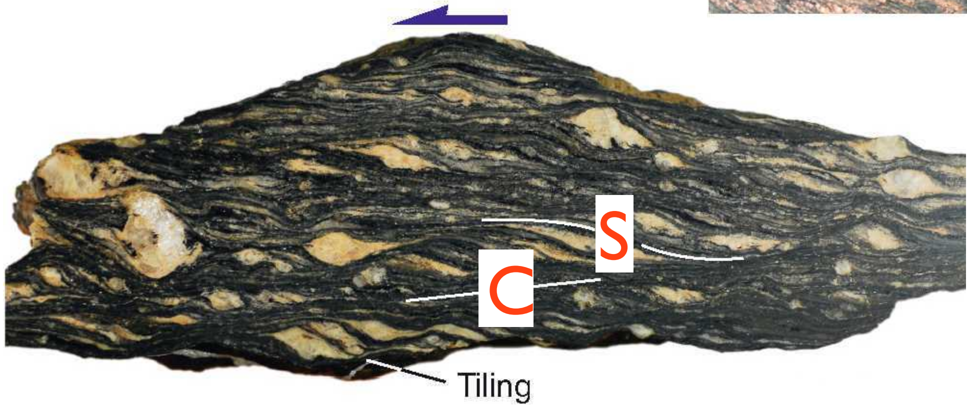
C'-type shear bands

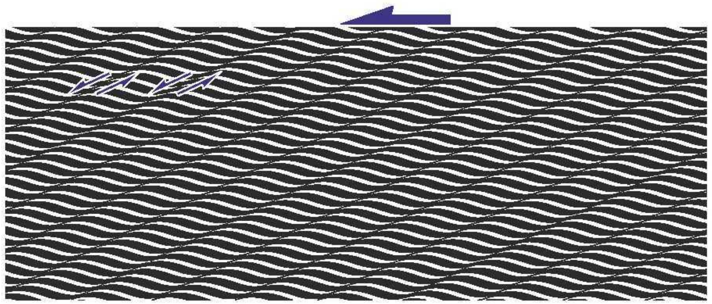


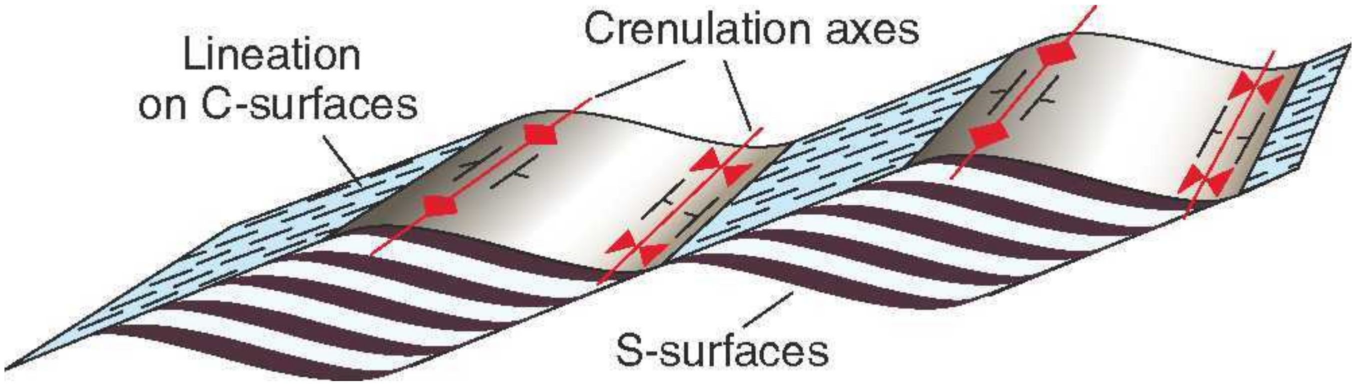
S = schistosité
C = cisaillement

S-C shear band geometry

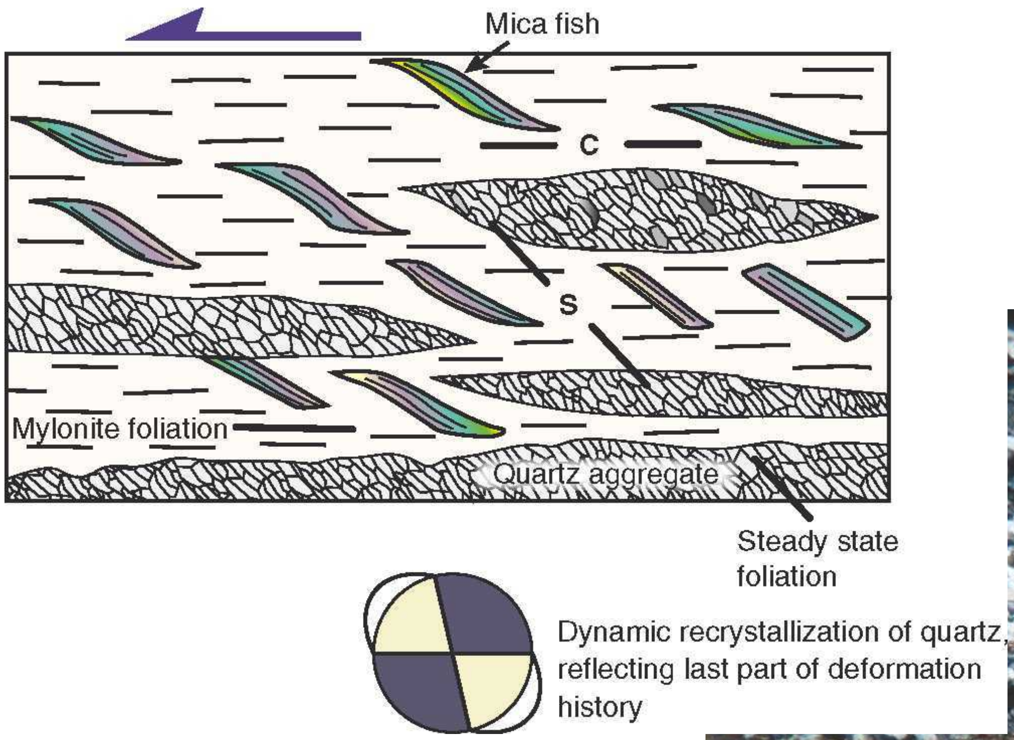


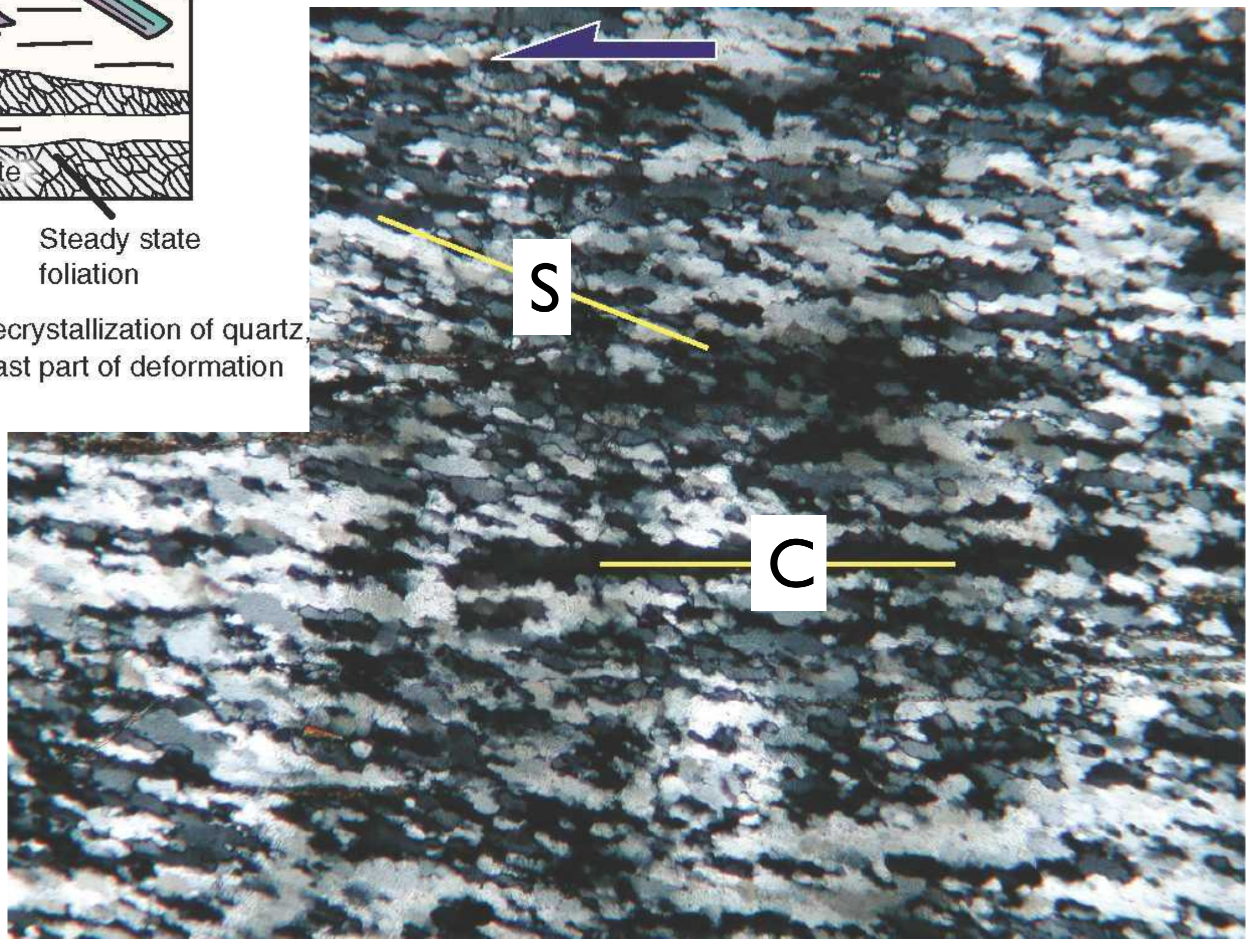




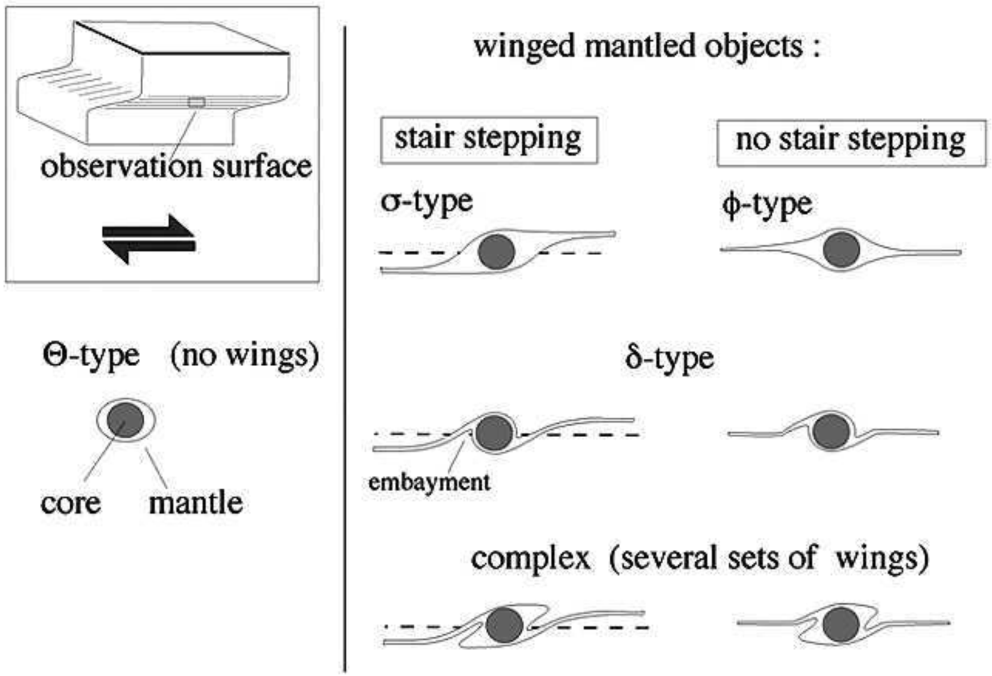


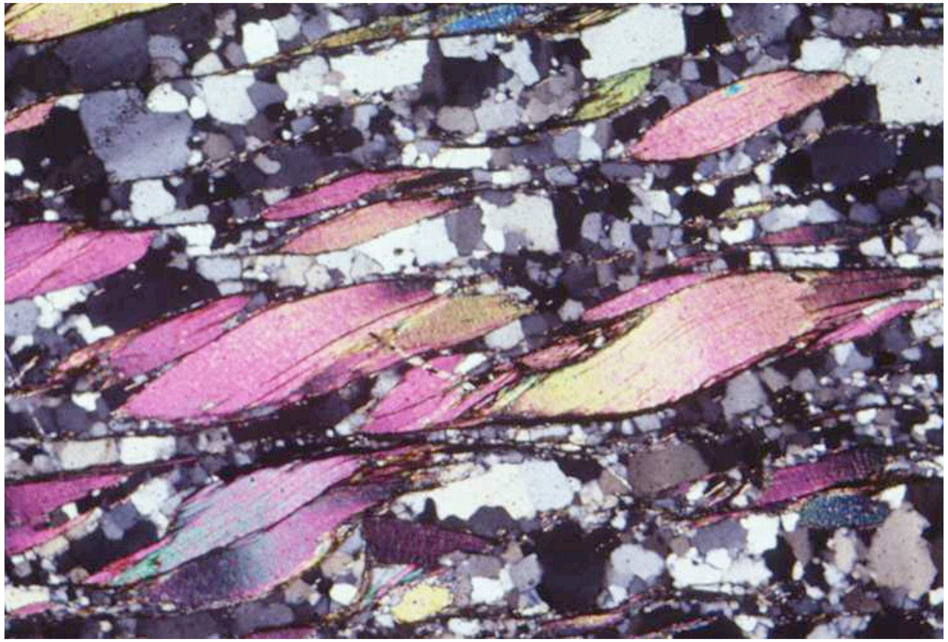
S-C microstructures

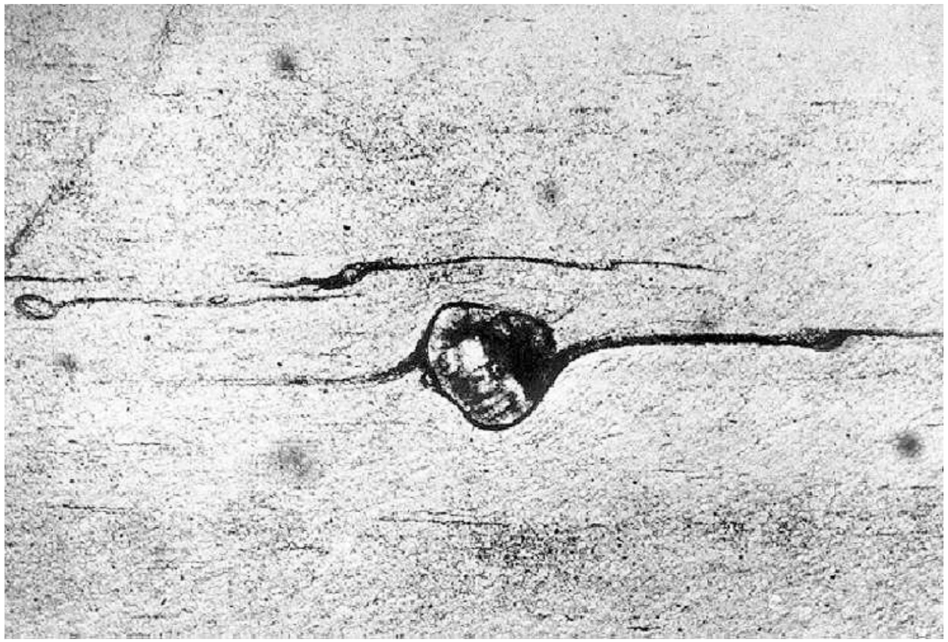




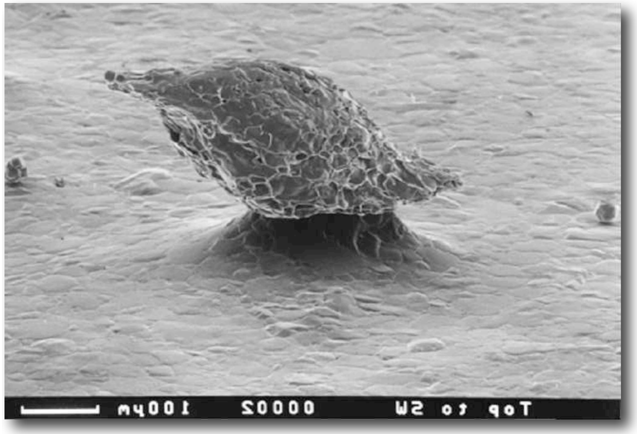
σ- and δ- clasts

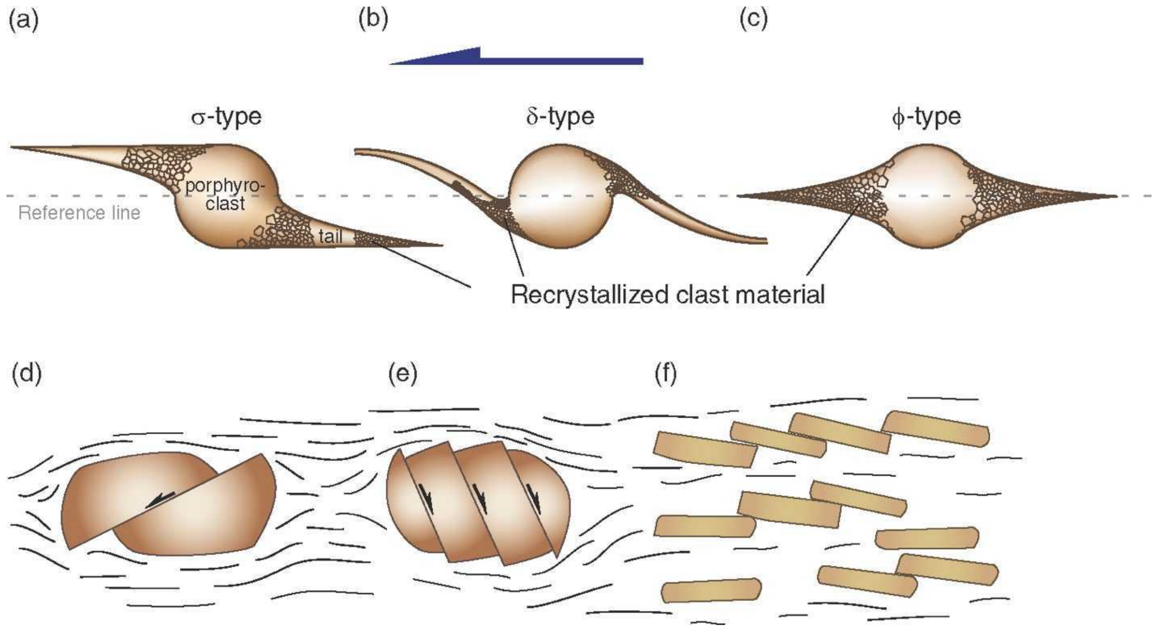




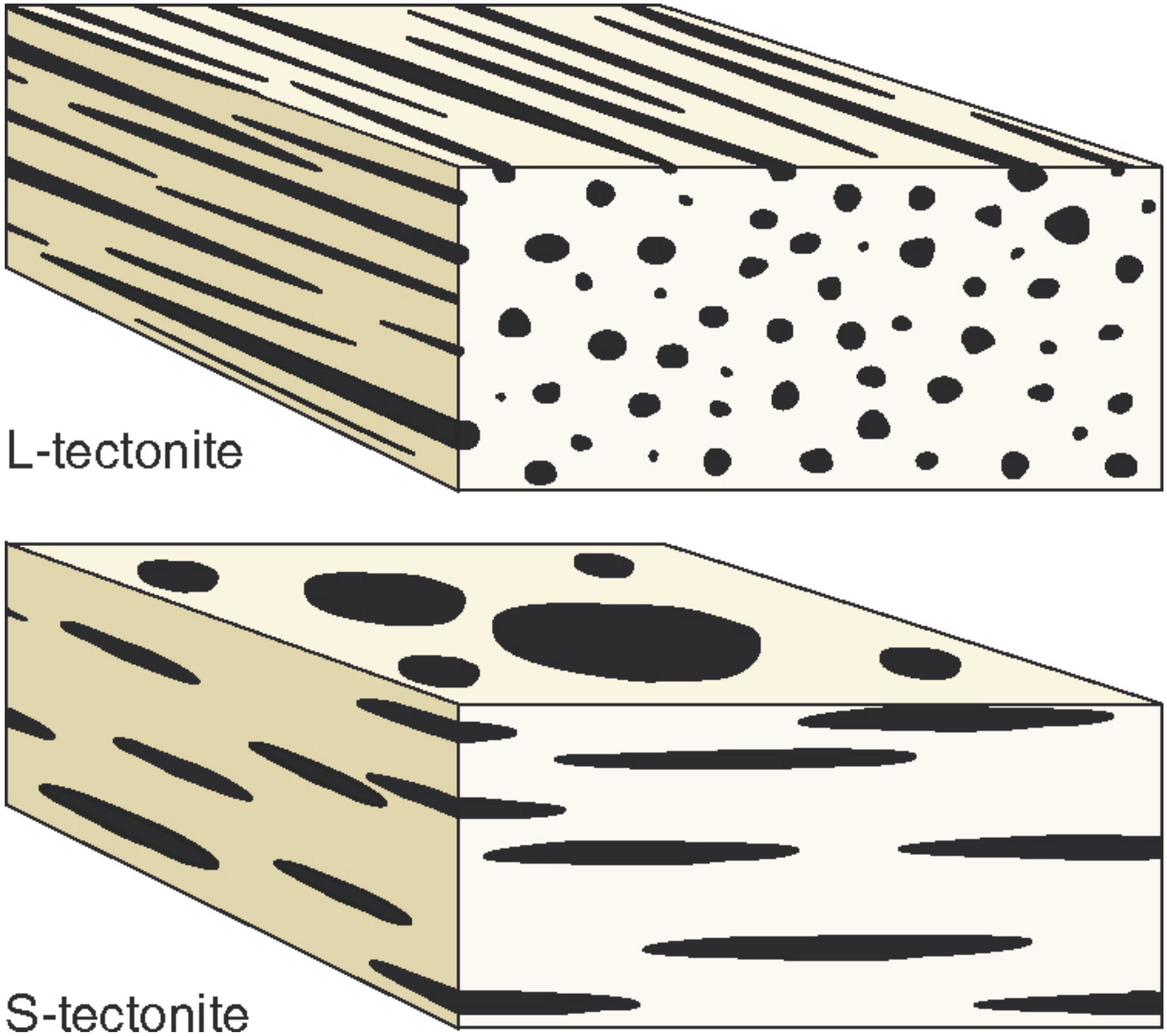


σ- δ- and ϕ- clasts

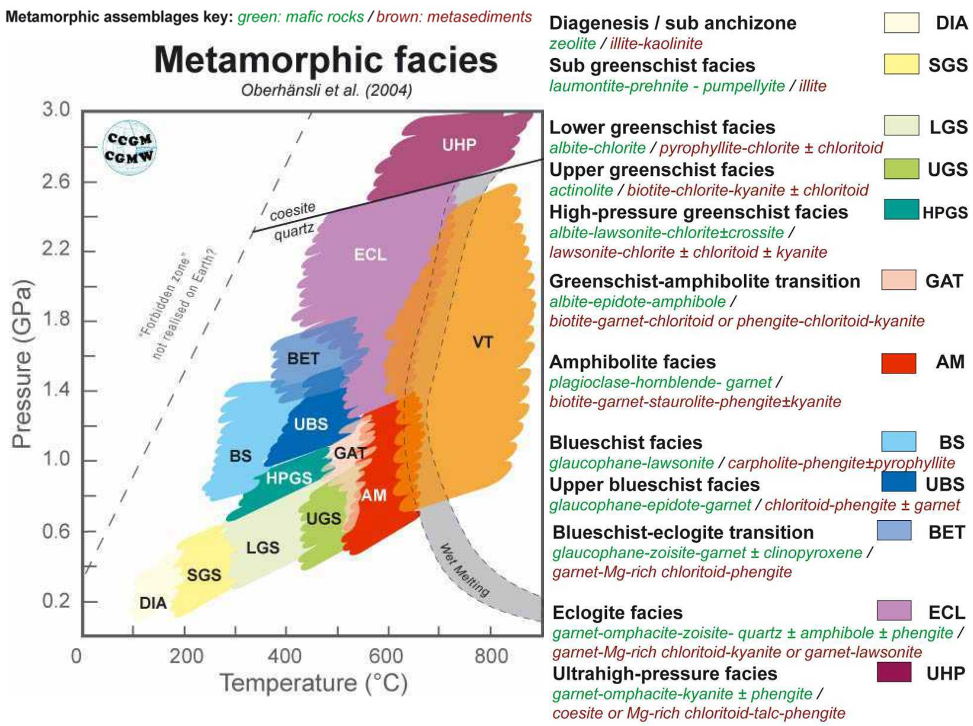




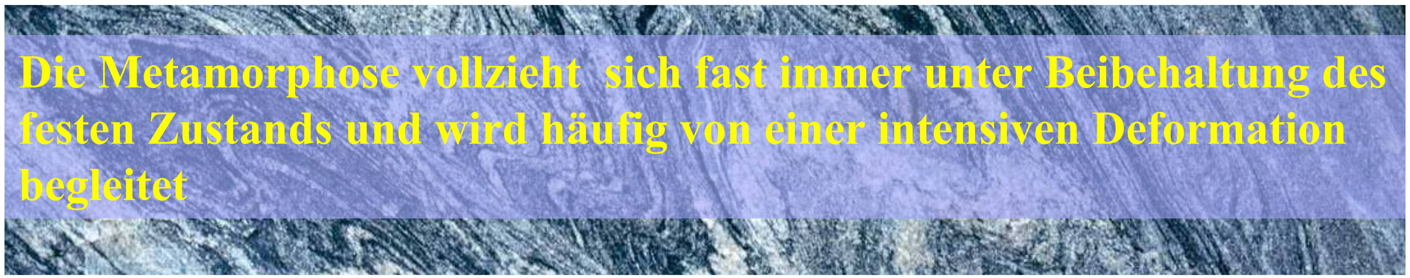
Beschreibung von Foliation & Lineation


L-tectonite
S-tectonite

recap: System Erde - Metamorphite



Die Klassifikation der metamorphen Gesteine basiert auf der Zusammensetzung (mineralogisch oder chemisch) und dem Gefüge



... und umgekehrt

Gesteine mit Planargefüge

Tonschiefer (slate)

Kompaktes, sehr feinkörniges metamorphes Gestein mit guter Spaltbar- keit. Rauhe (nicht glänzende) Bruchflächen. Phyllit

Phyllit

Fein geschiefertes metamorphes Gestein mit sehr feinkörnigen Phyllosilikaten (z.B. viel Serizit und Chlorit), die aber mit blossem Auge nicht erkennbar sind. Bruchflächen erhalten dadurch einen seidigen Glanz.

Schiefer (schist)

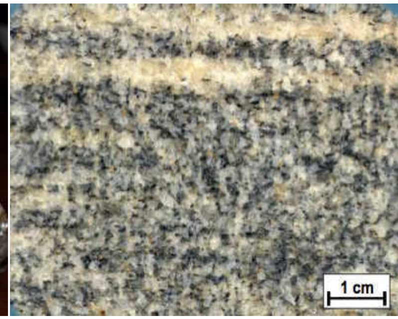
Metamorphes Gestein mit deutlicher Schieferung. Im Gegensatz zu Ton- schiefern und Phylliten sind in Schiefern die gefügedefinierenden Minerale (meist Glimmer) gut mit blossem Auge erkennbar.

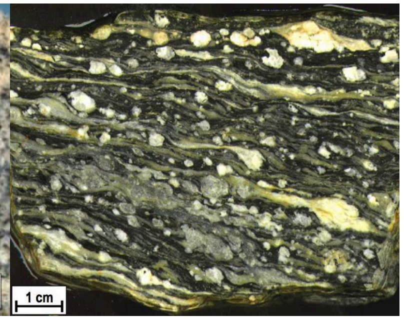
Gneis

Metamorphes Gestein mit schwach ausgeprägter Schieferung oder Stoff- bänderung im m- bis cm-Bereich; meist grobkörniges Gefüge. Spalten im dm-Bereich.

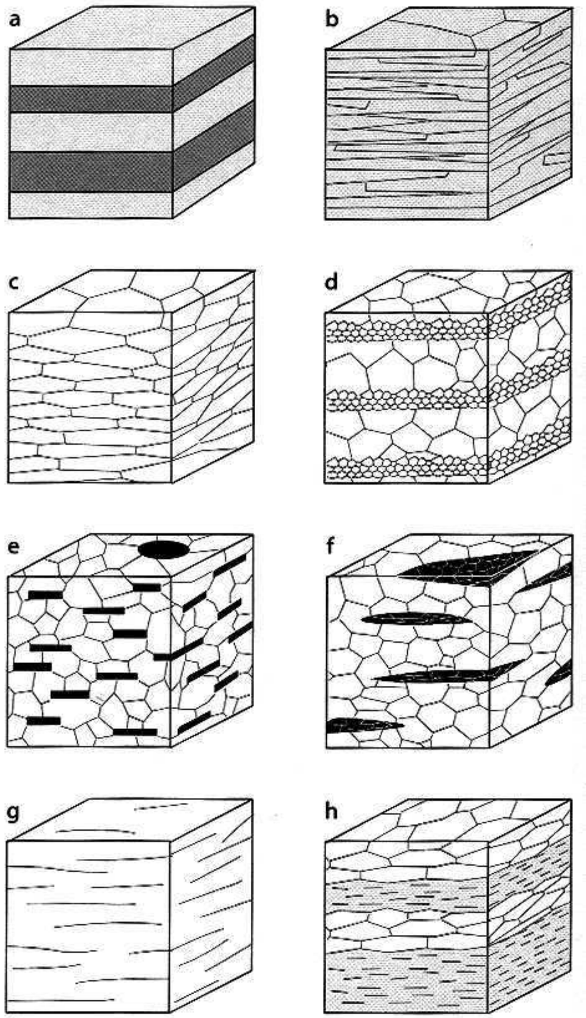
Mylonit

Extrem stark durchbewegter, rekristallisierter Metamorphit





Planare Gefüge (planar fabric)



a. Stoffbänderung
b. Orientierung tafeliger Minerale

a compositional layering
b preferred orientation of platy minerals

c. Deformierte Minerale
d. Korngrössen-Variation

c preferred orientation of grain shapes
d grain size variations

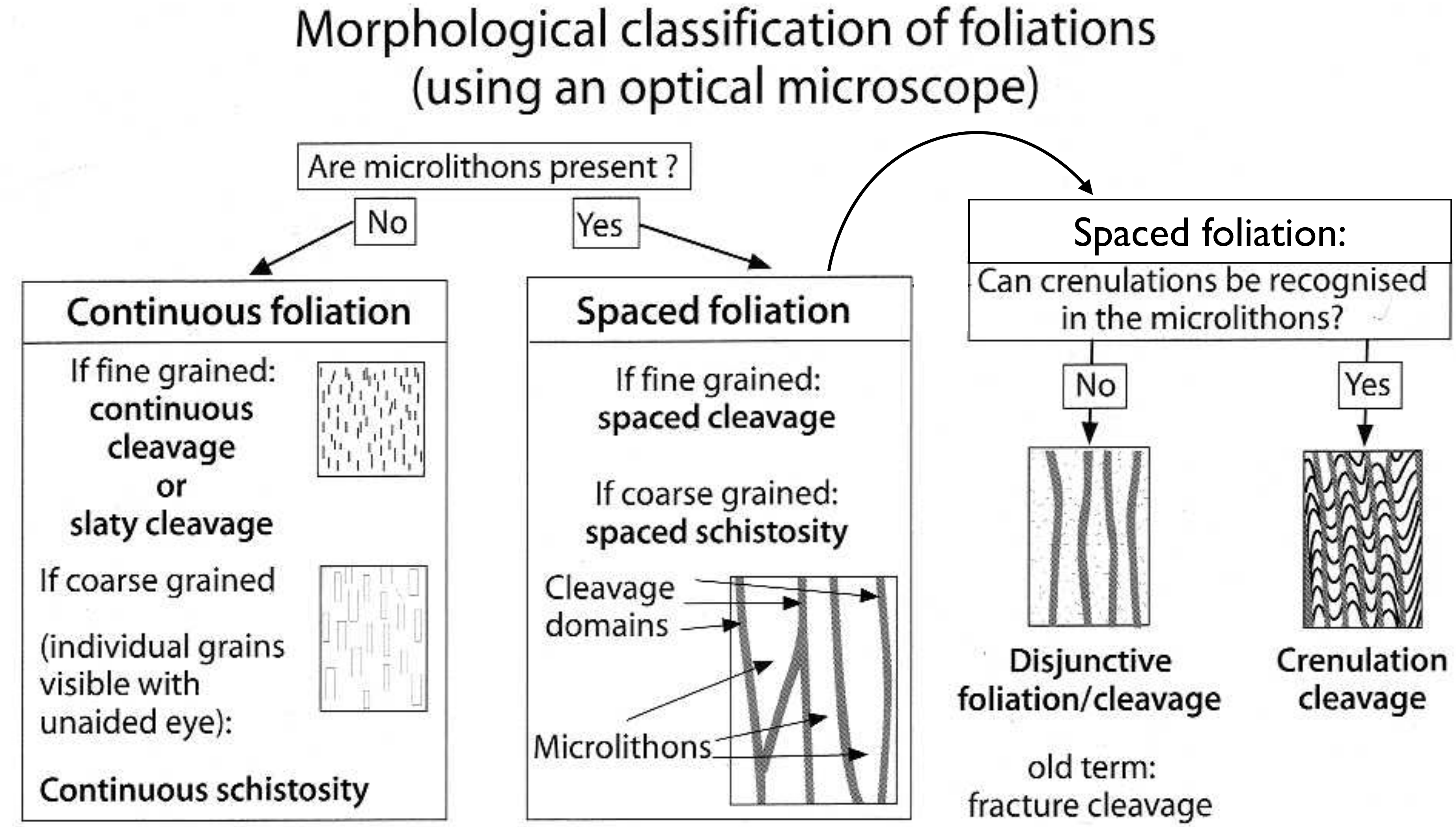
e. Orientierung tafeliger Minerale in einer Matrix ohne planare Gefüge
f. Orientierung linsenförmiger Mineral-Aggregate

e platy minerals in isotropic matrix
f lenticular aggregates in isotropic matrix

g. Orientierung von Rissen
h. Kombinationen

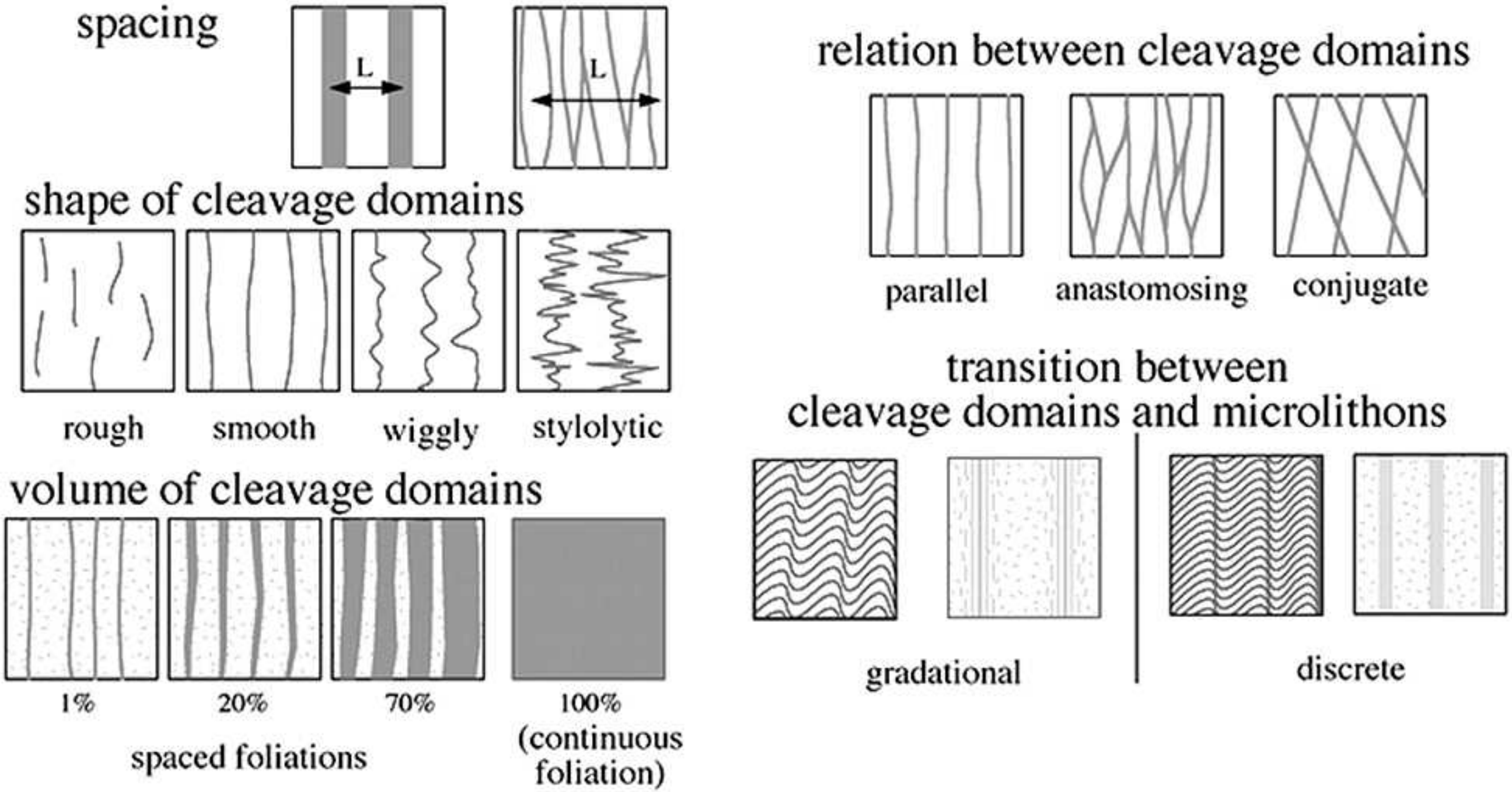
g preferred orientation of fractures
h combination a, b, c

Klassifikation von Foliationen

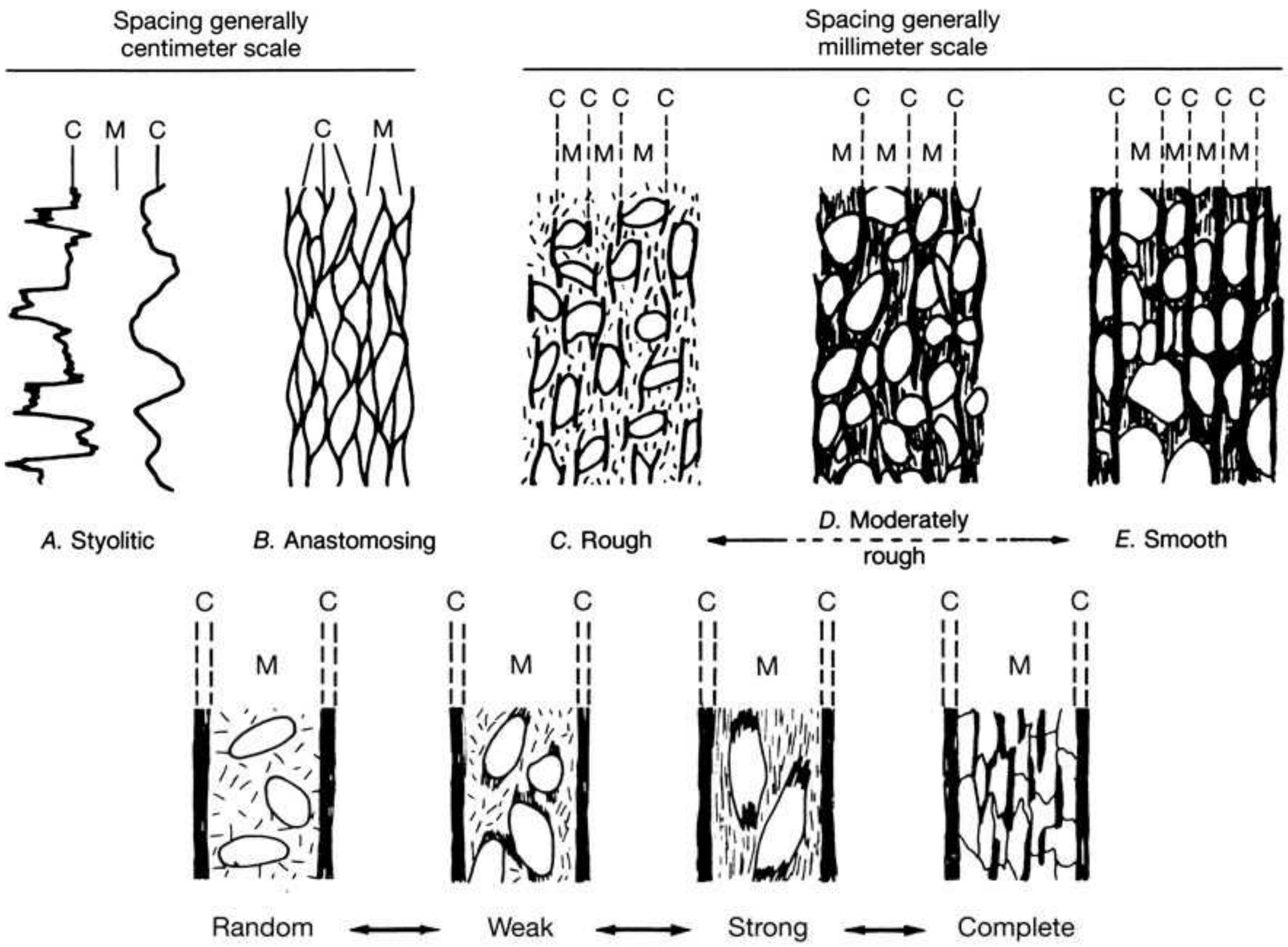


Penetrative Schieferung   Schieferung (mit Zwischenraum)

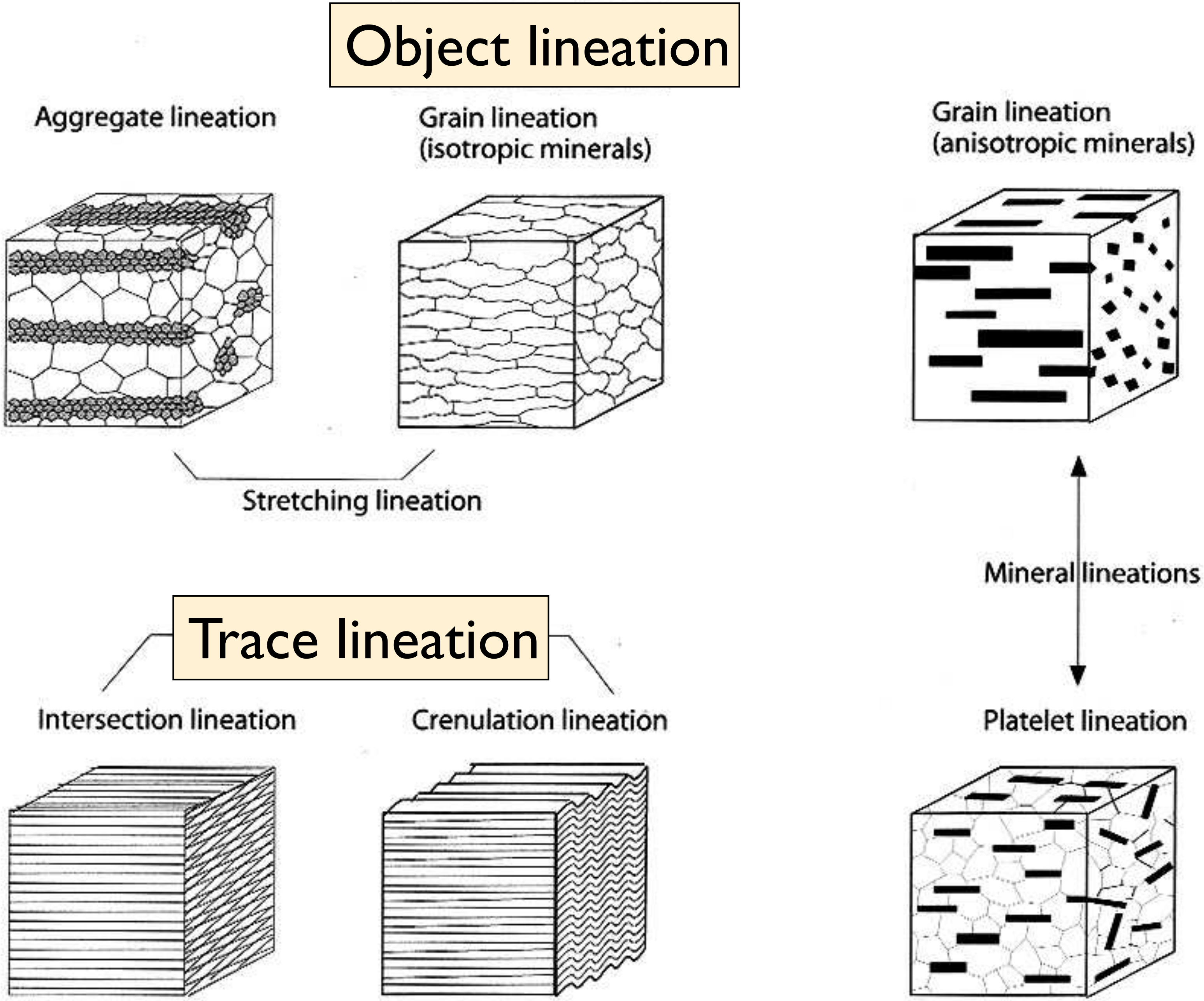
spaced foliation



cleavage domains & microlithons



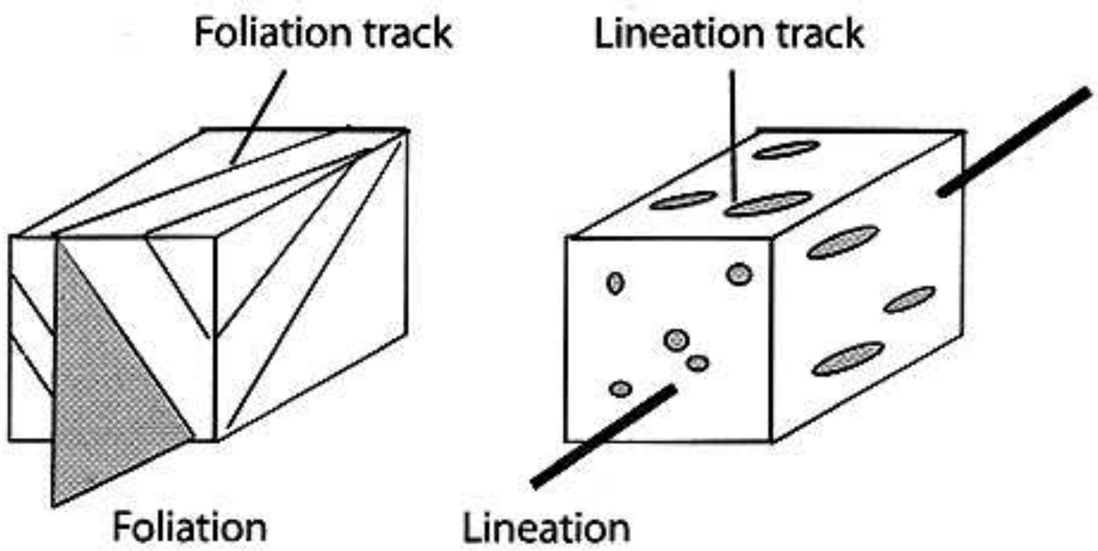
Lineare Gefüge (linear fabrics)

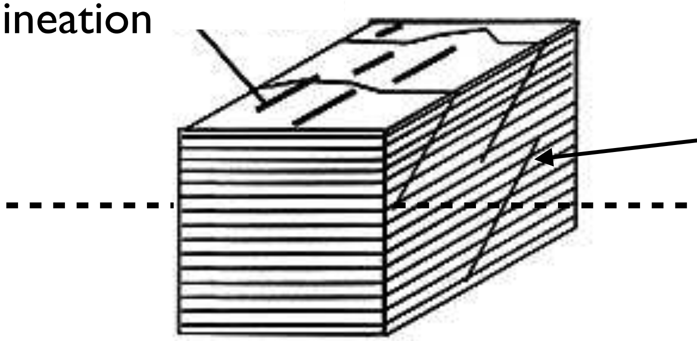


Lineation (Intersektions-)Lineare

Trace lineation

Object lineation





Nomenklatur

Foliation

Foliation and cleavage	Spaced	Compositional	Diffuse
			Banded
		Disjunctive	Stylolitic
			Anastomosing
			Rough
			Smooth
		Crenulation	Zonal
			Discrete
	Continuous	Fine	Microcrenulation
			Microdisjunctive
			Microcontinuous
		Coarse	Mineral grain
			Discrete

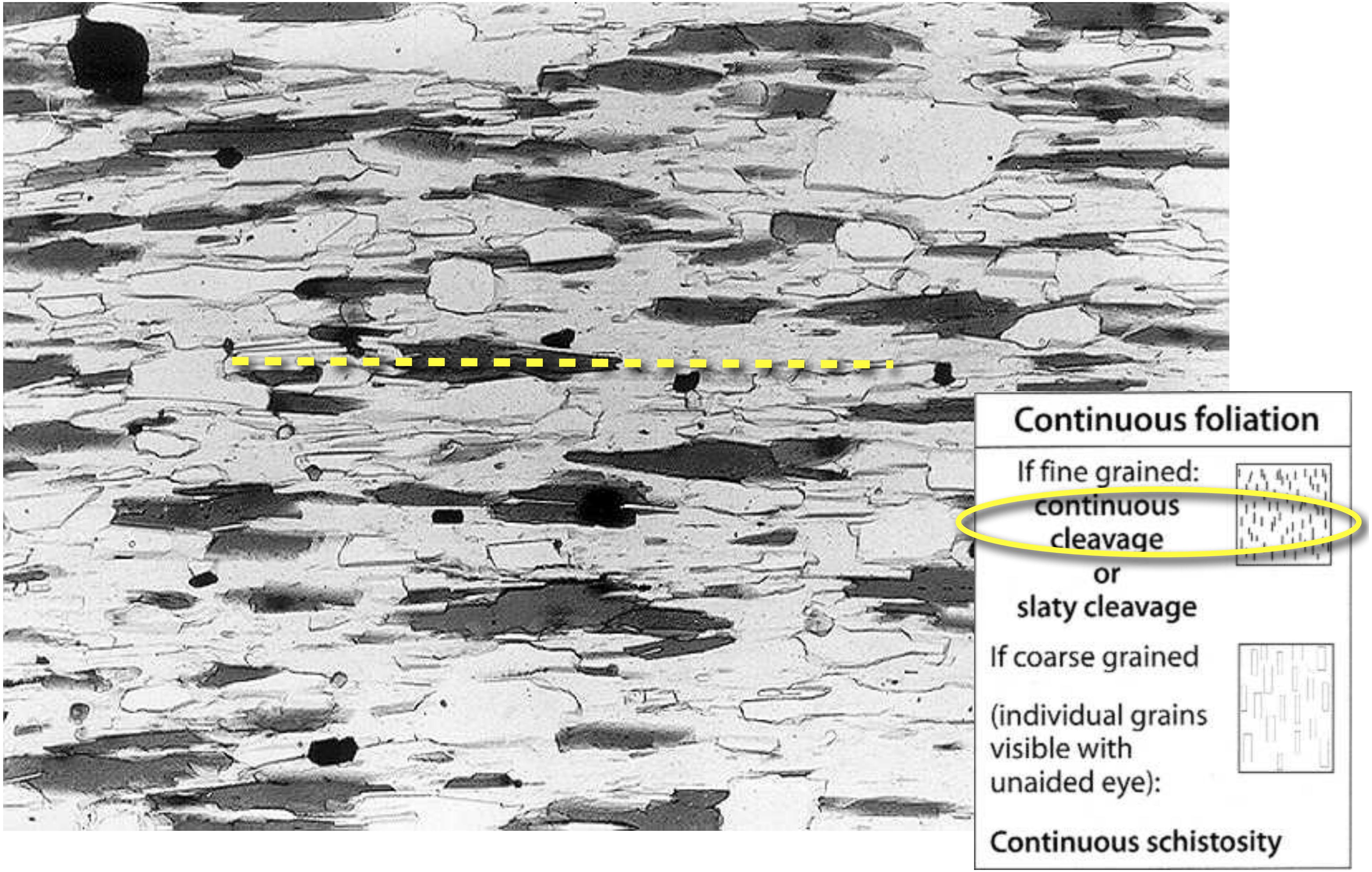
Lineation

Lineations in tectonites (surficial or penetrative)	Structural	Discrete	Pebbles Ooids Fossils Alteration spots
		Constructed	Intersections Hinge lines Boudin lines Mullions Structural slickenlines
	Mineral	Polycrystalline	Rods Mineral clusters Mineral slickenlines Nonfibrous overgrowths
		Mineral grain	Acicular habit grains Elongated grains Mineral fibers Fibrous vein filling Slickenfibers Fibrous overgrowths

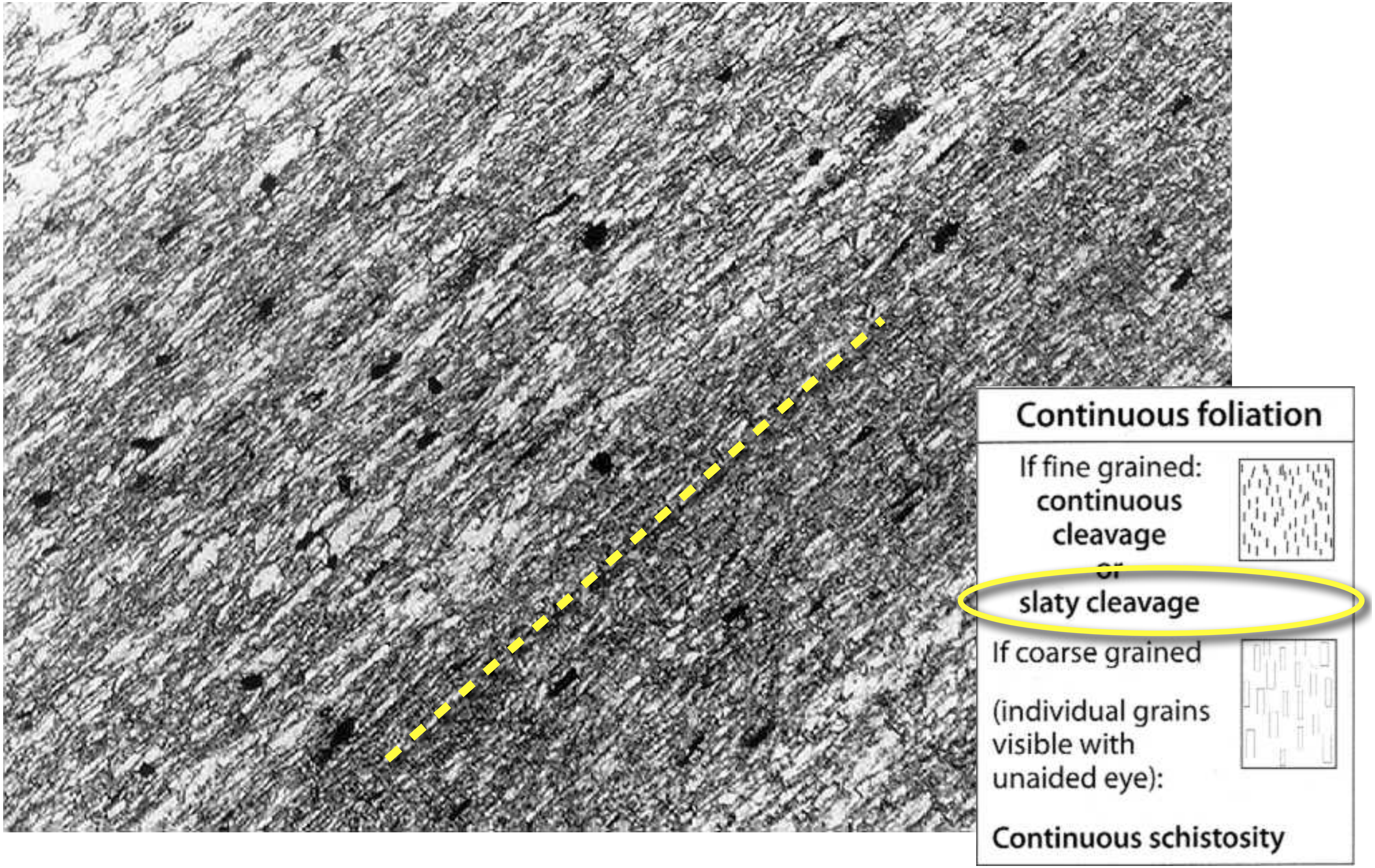
Schichtung s_0
Foliation: tektonometamorph entstandenes Planargefüge
Schieferung: cleavage (Transversalschieferung)
schistosity (Kristallisationsschieferung)

Beispiele

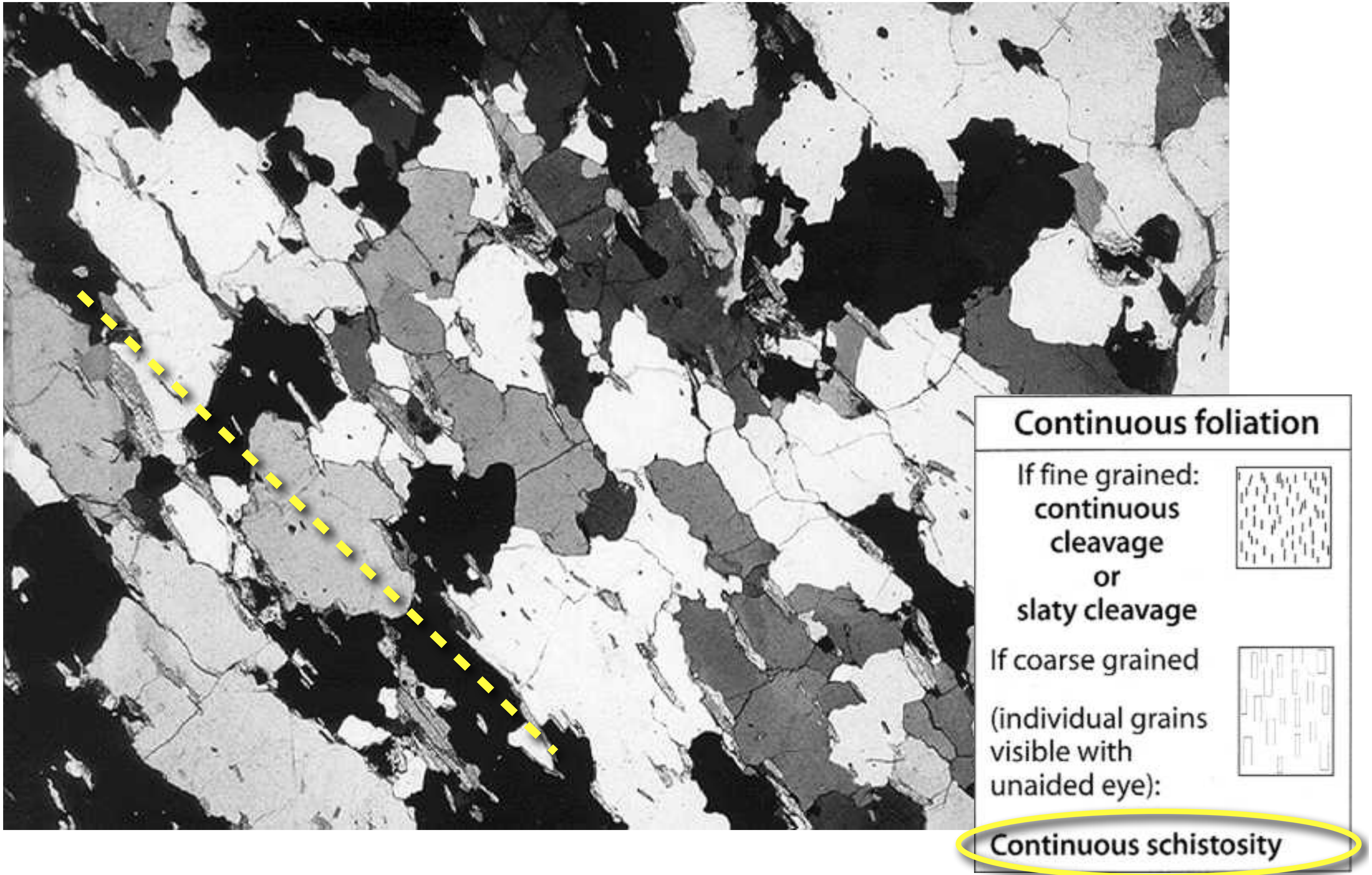
continuous schistosity



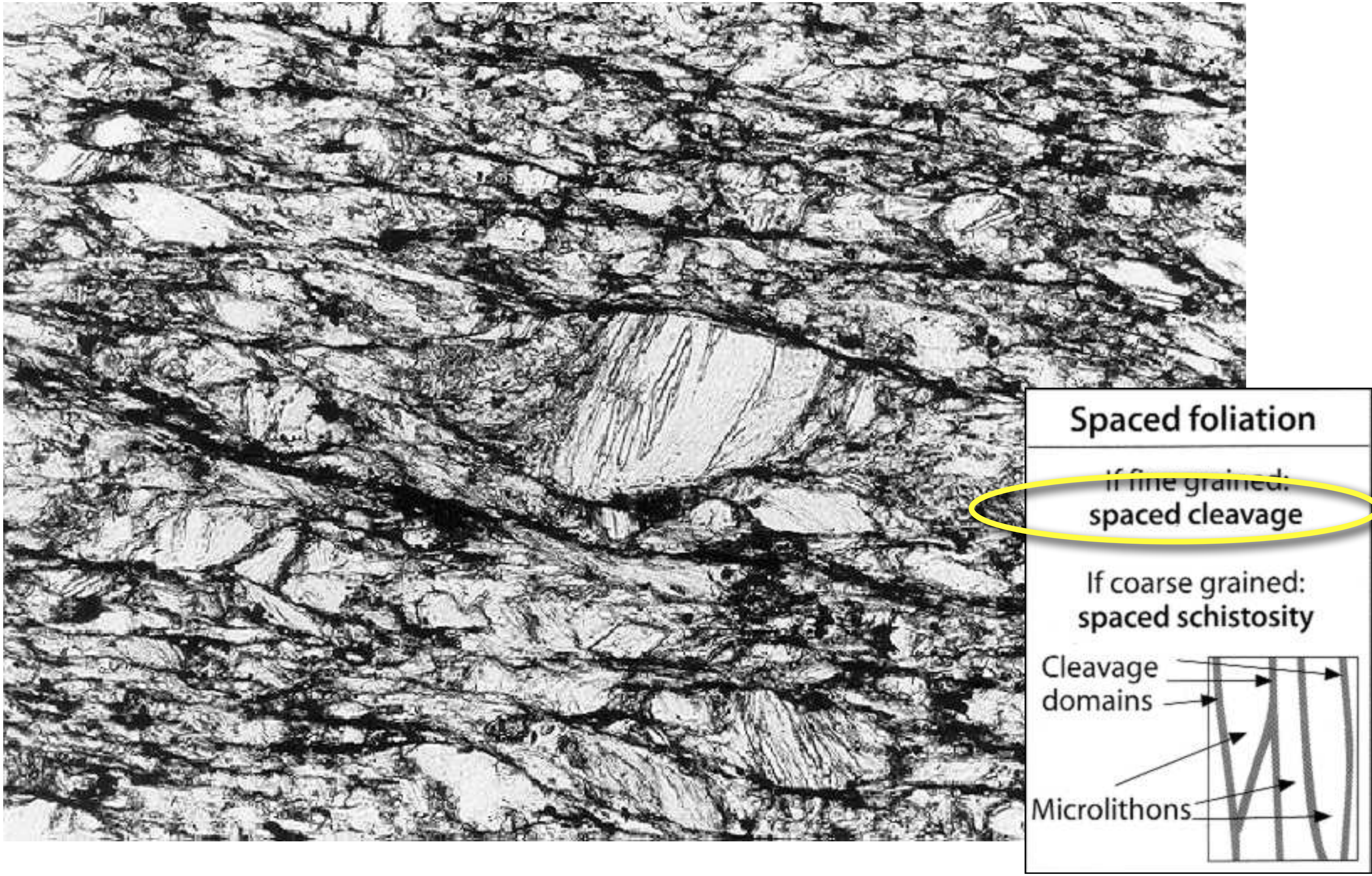
slaty cleavage



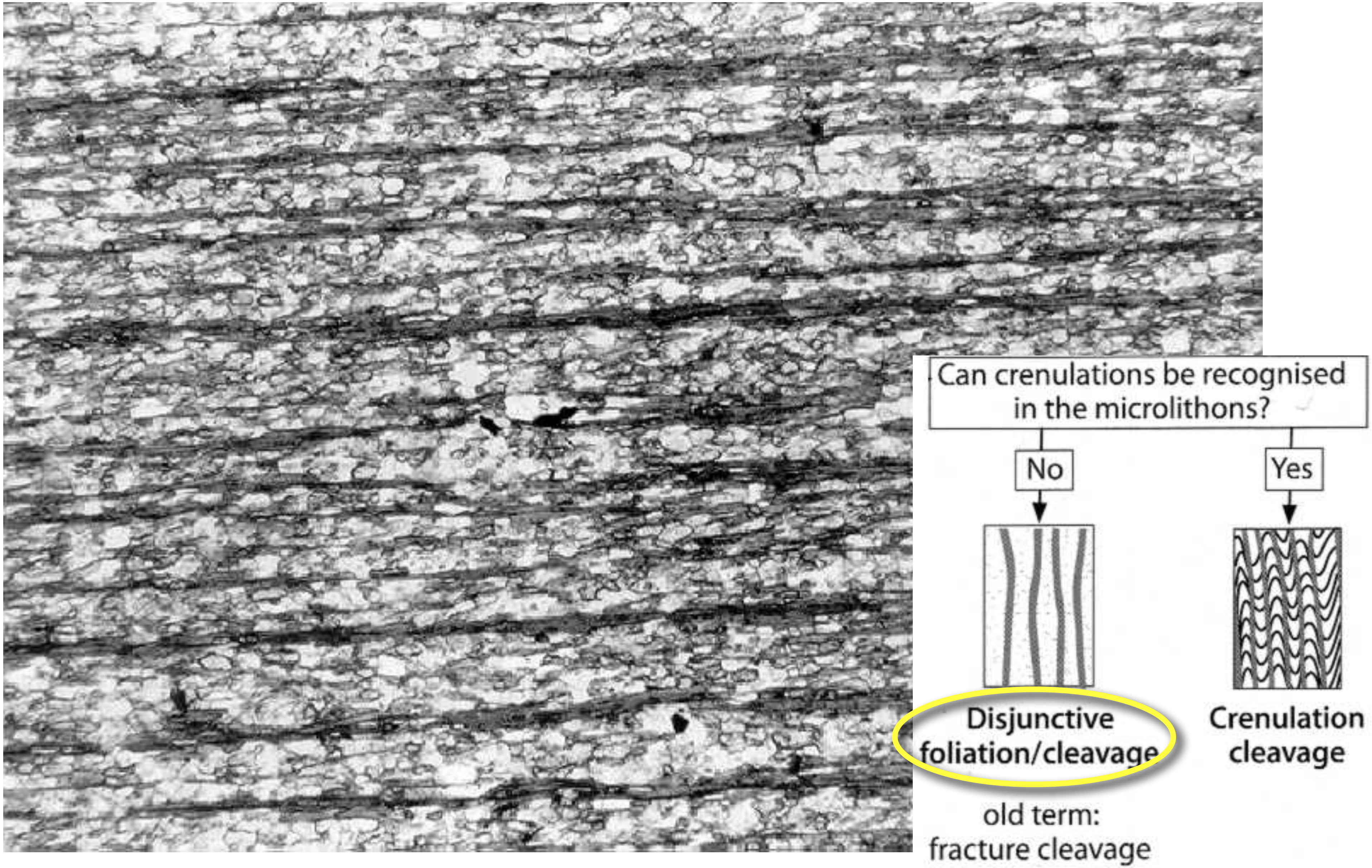
continuous foliation (schistosity)



domainal spaced cleavage

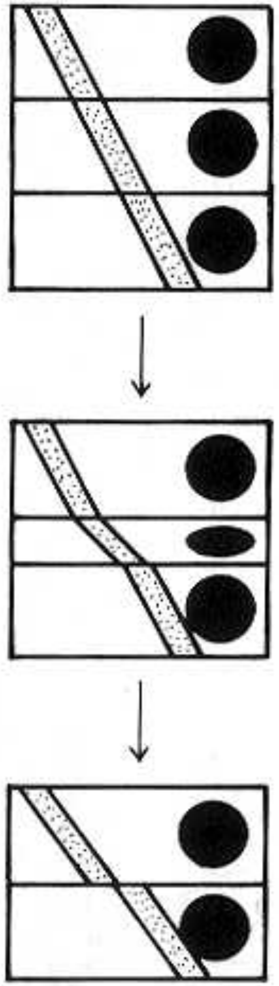


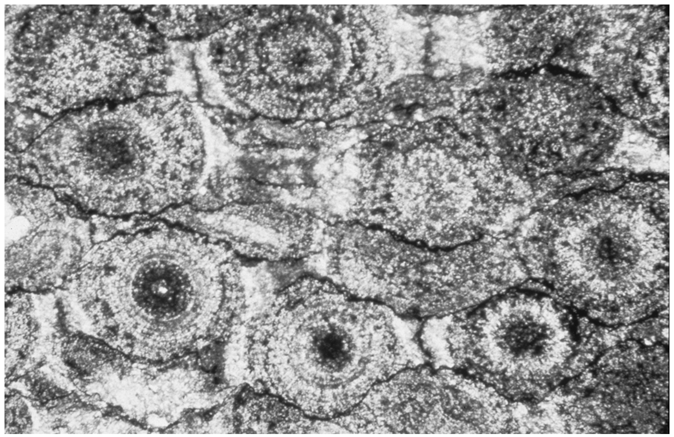
disjunctive cleavage

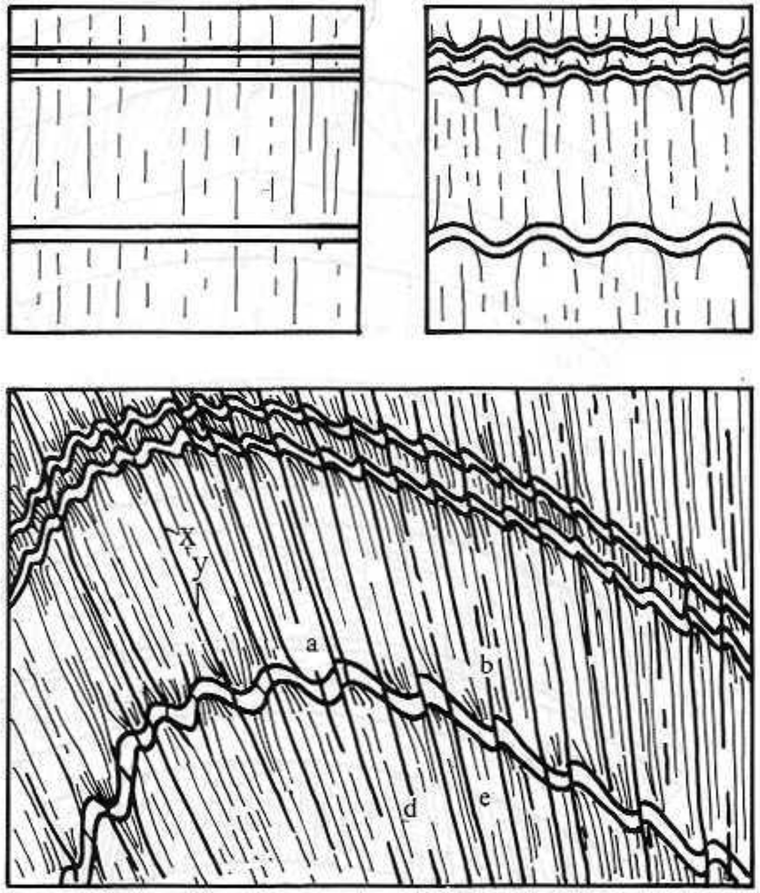


Spezielle Schieferungstypen

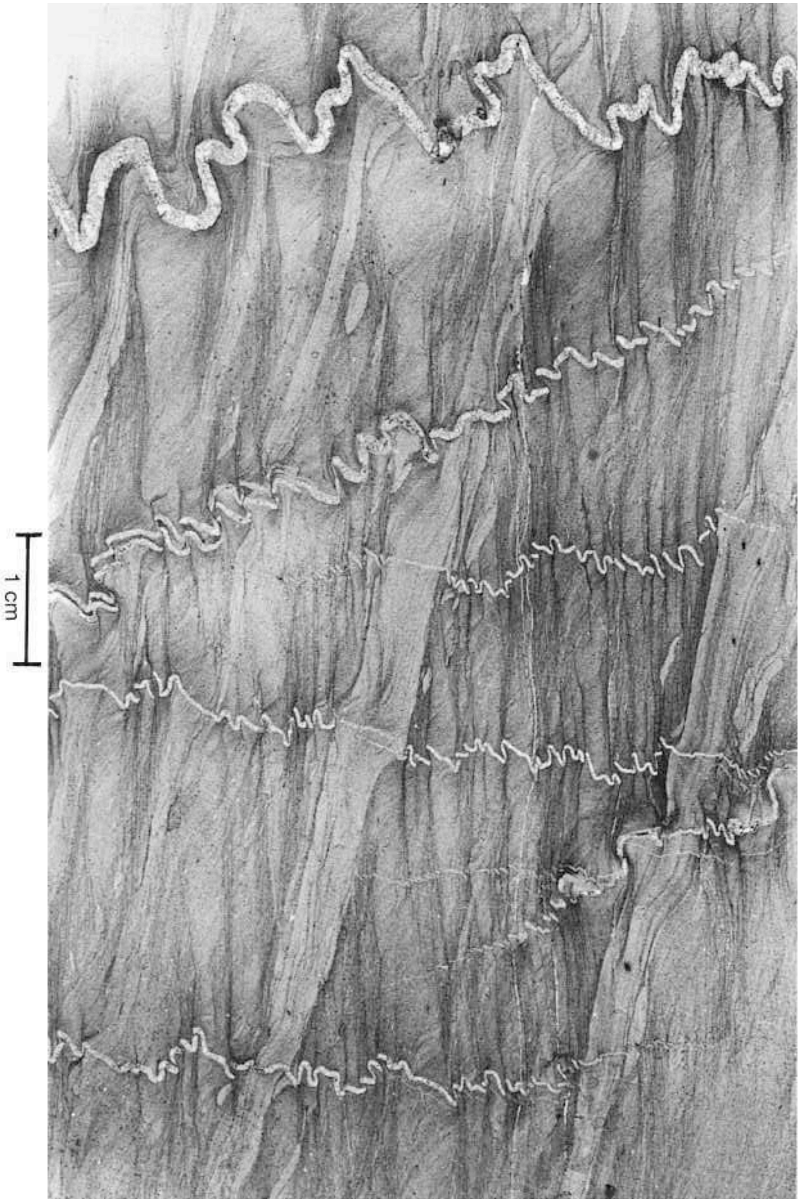
solution cleavage

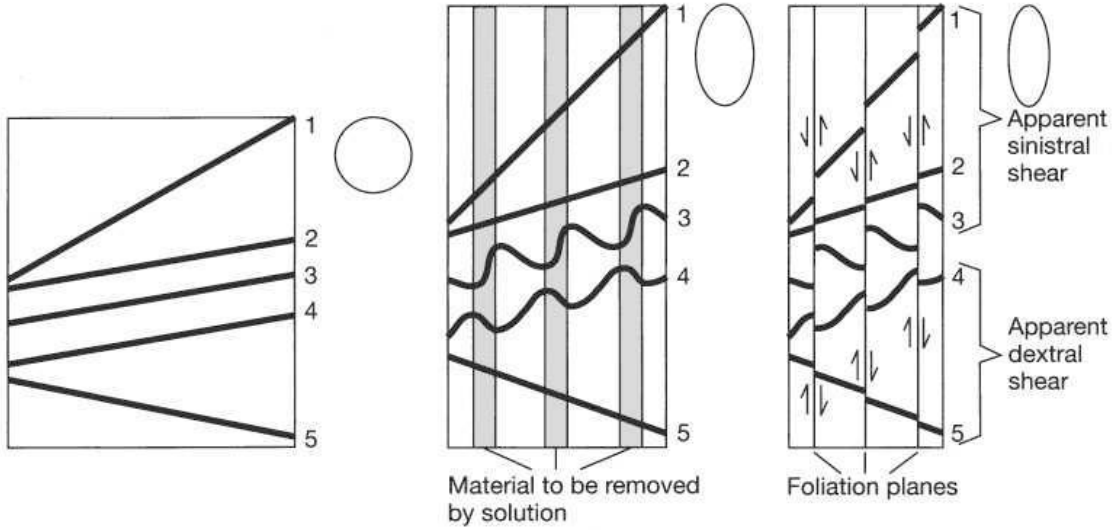






Drucklösung - pressures solution

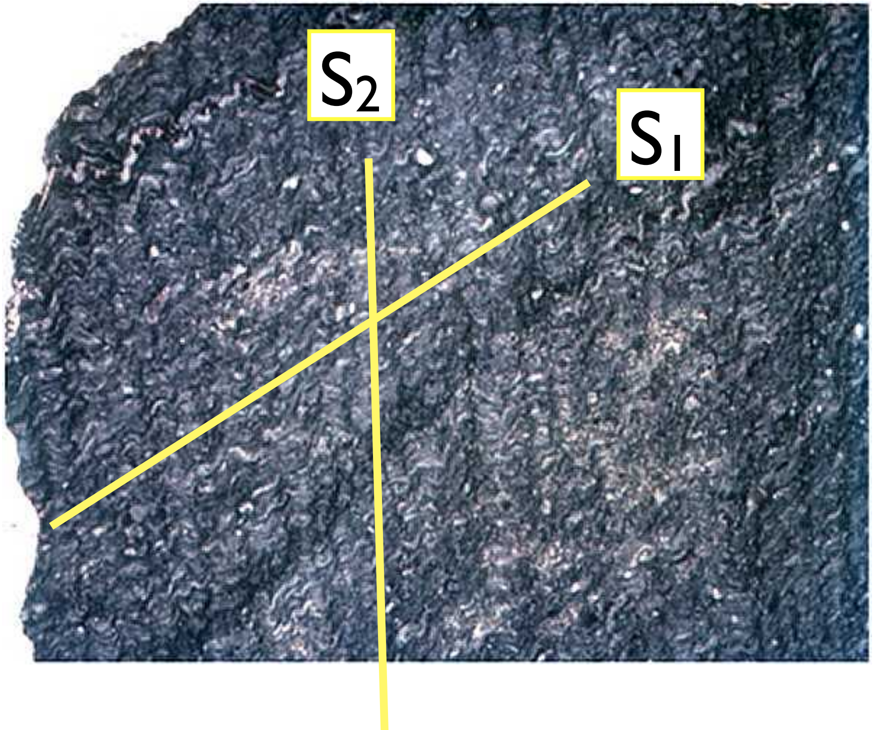


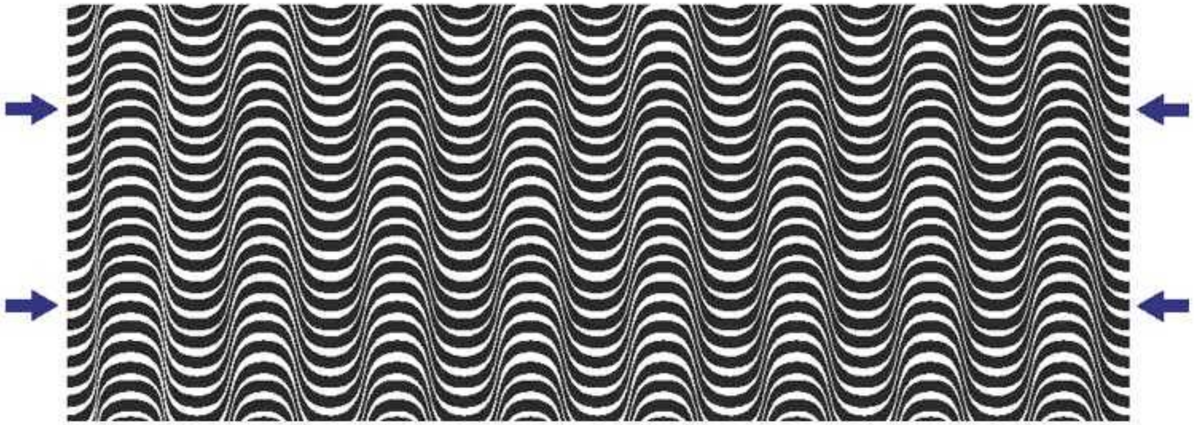


Apparent contradictory shear displacement from solution features

Apparent contradictory shear displacement from out-of plane shear

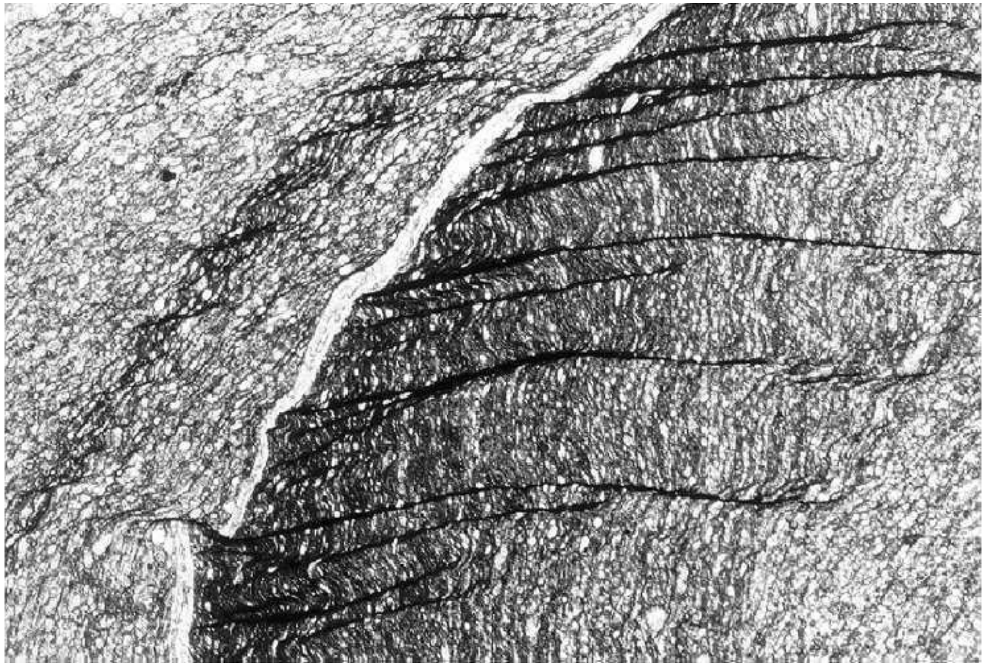
Krenulations- (Runzel-) Schieferung

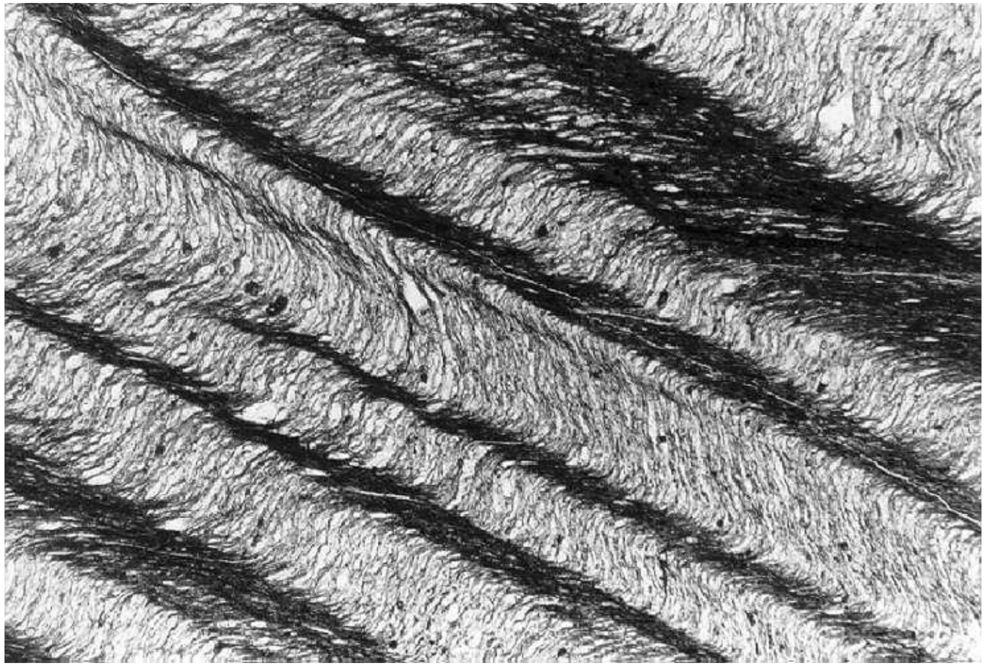


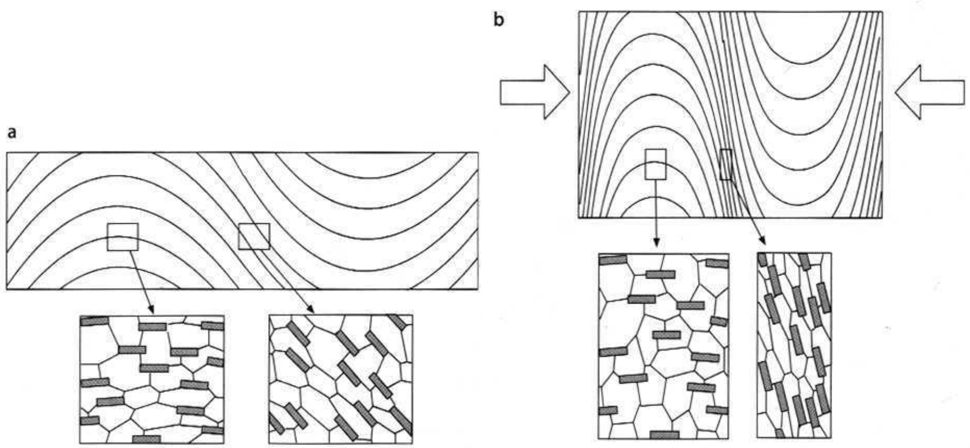


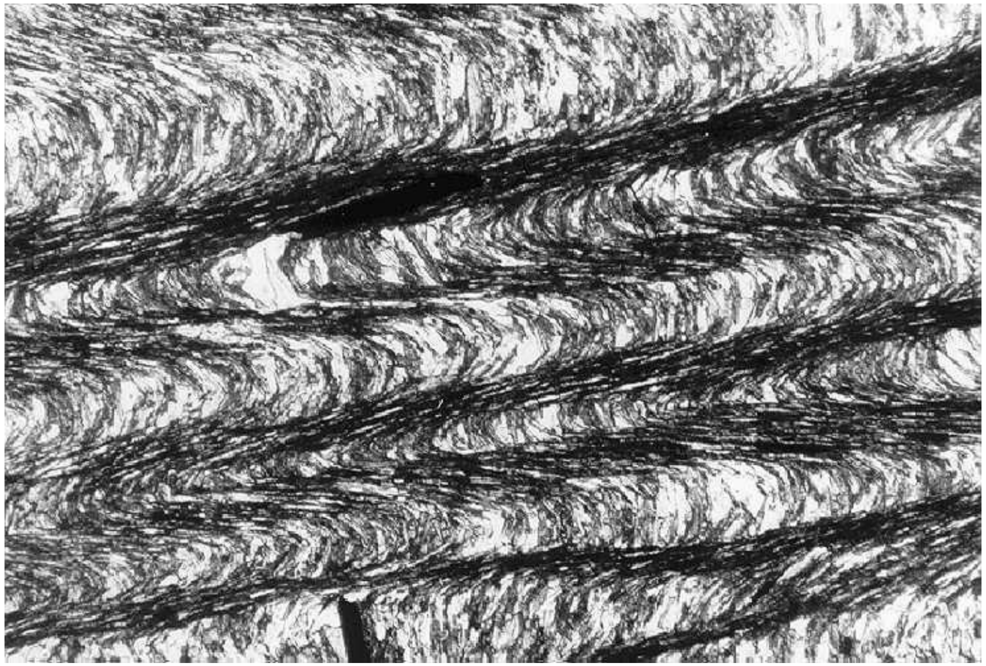
Fossen

Krenulations- (Runzel-) Schieferung



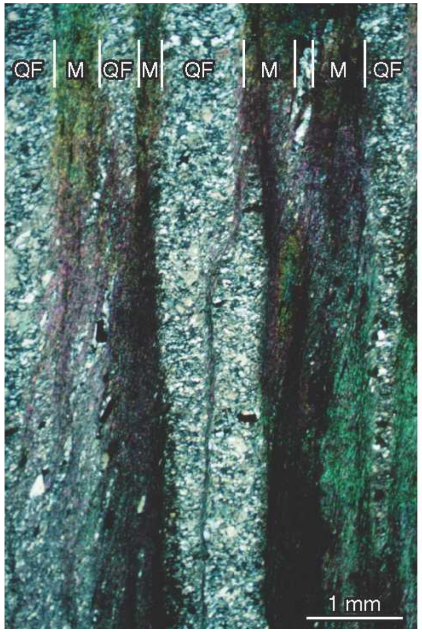


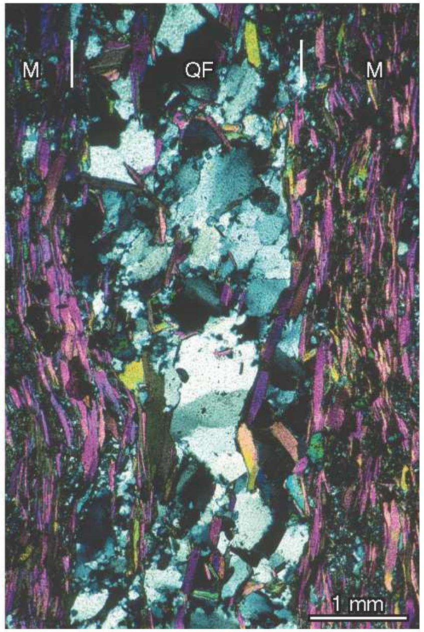


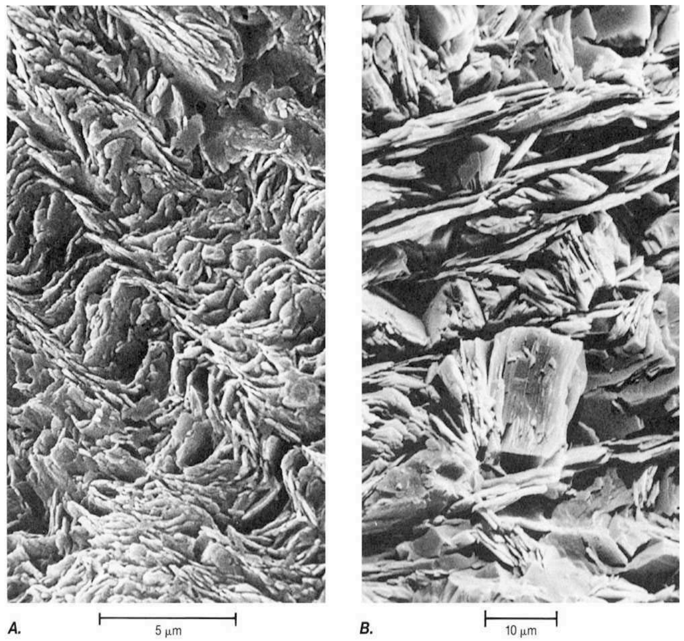


Passchier & Trouw

... von cm bis µm Masstab







Fossen

Not foliations ...

Fracture "cleavage" is a term from the past that reappear from time to time, but most modern structural geologists avoid using this term. It is used about densely spaced parallel fractures may look similar to cleavage, but the formation and kinematics are very different:

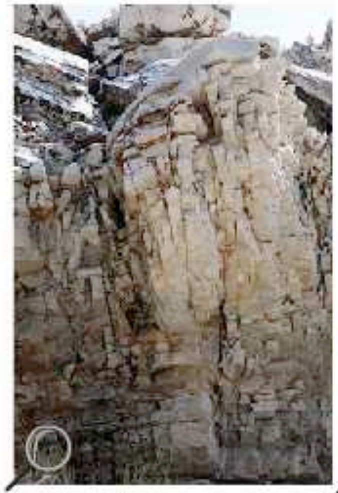
Cleavage involves shortening across the planar structure.

Fractures involve slip (shear fractures) or dilation (joints).

Shear bands in plastic shear zones have been called foliations by some geologists. Most of us prefer not to, because they do not involve shortening perpendicular to the bands.

Densely spaced shear bands in granular material (porous sandstone), known as **deformation bands**, may be regularly distributed to form a penetrative fabric, but do not classify as foliations. This is partly because they involve shear and partly because the deformation mechanism (frictional slip) is different.

Compaction bands, a type of deformation bands that form in highly porous sandstones, get very close since they involve compaction across the bands, but these are quite rare and seldom spaced densely enough to be confused with cleavage.

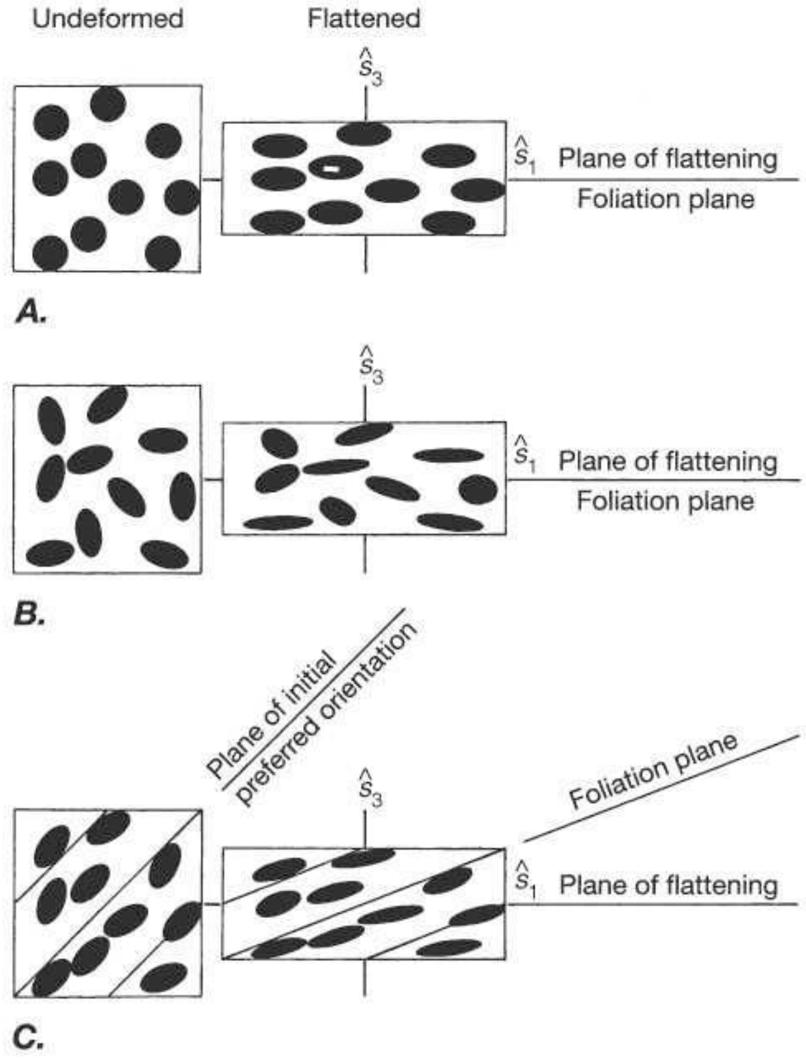



Various structures that are not foliations. Click to explore.

Fossen

Schieferung
und
Verformung

foliation - strain

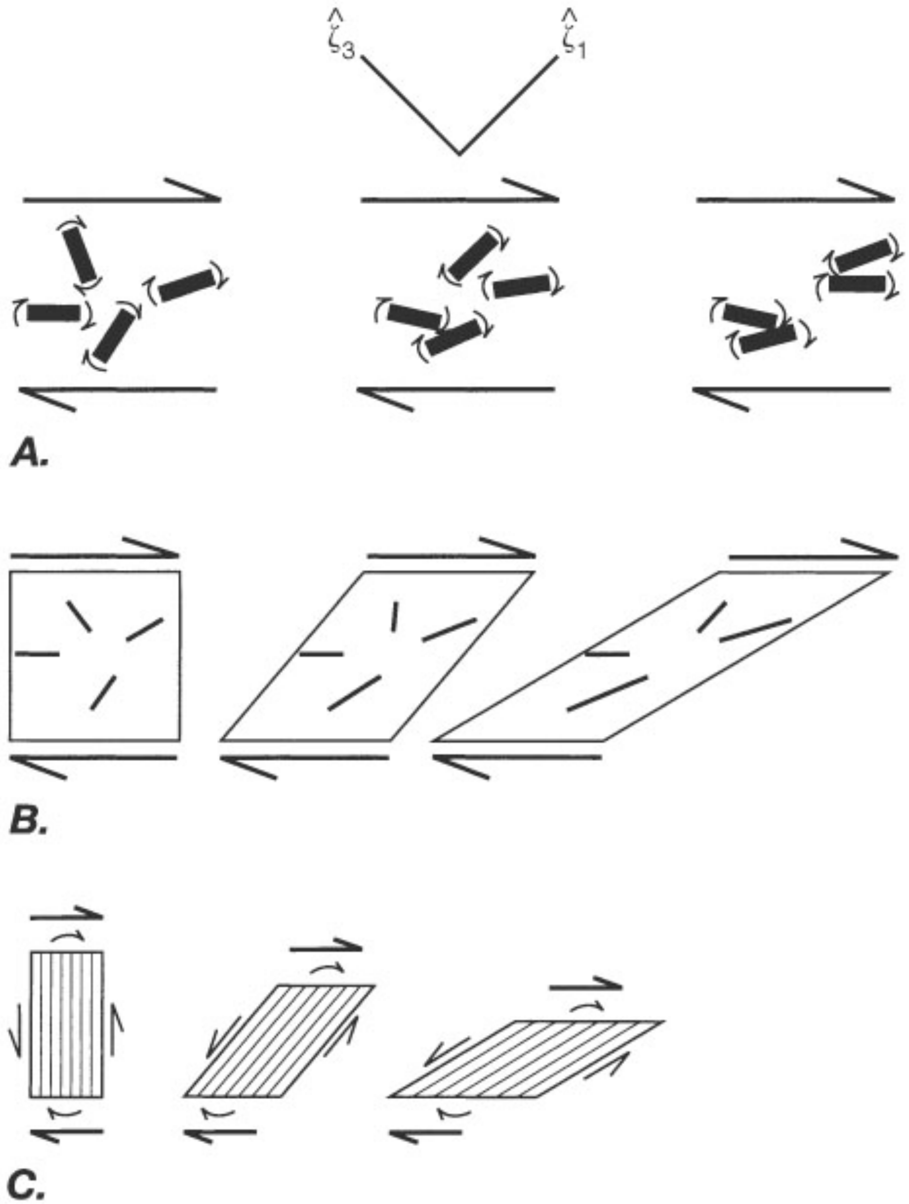


foliation =
plane of flattening
of the strain ellipsoid

foliation ≠
plane of flattening

Twiss & Moores

Schieferung: Geometrische Entwicklung

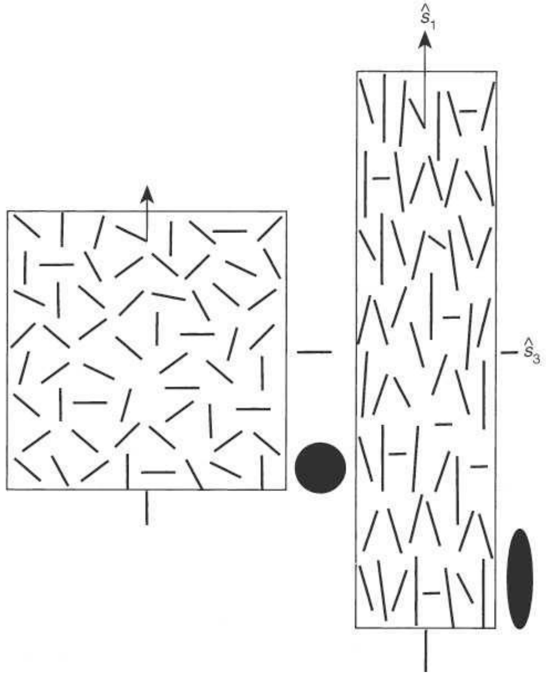


A.
Jeffrey model:
rotation of rigid particles

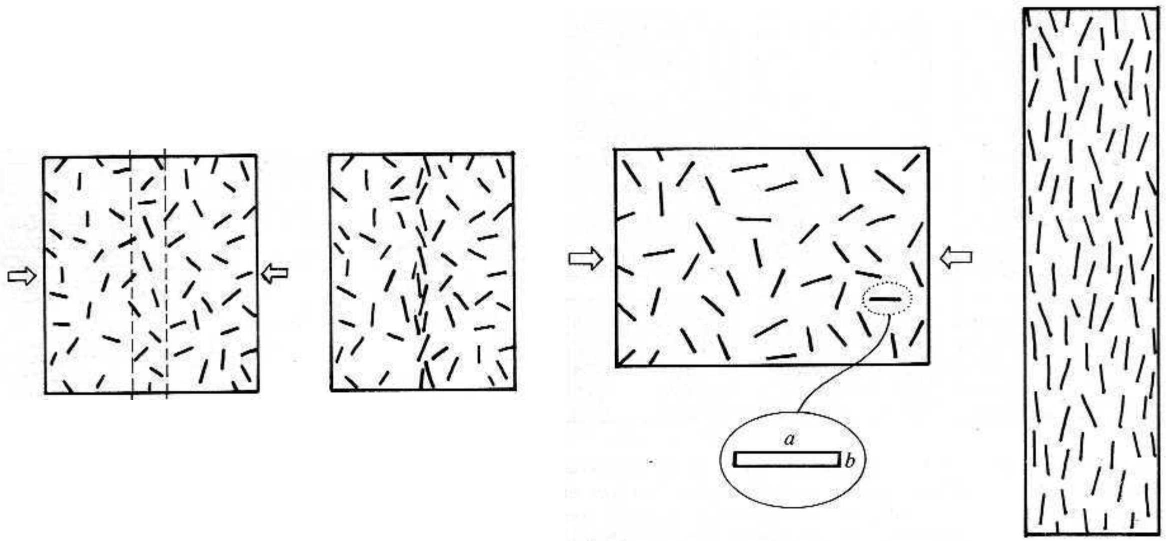
B.
March model:
rotation of passive markers

C.
Taylor-Bishop-Hill model:
rotation of crystallographic planes

Schieferung: Geometrische Entwicklung

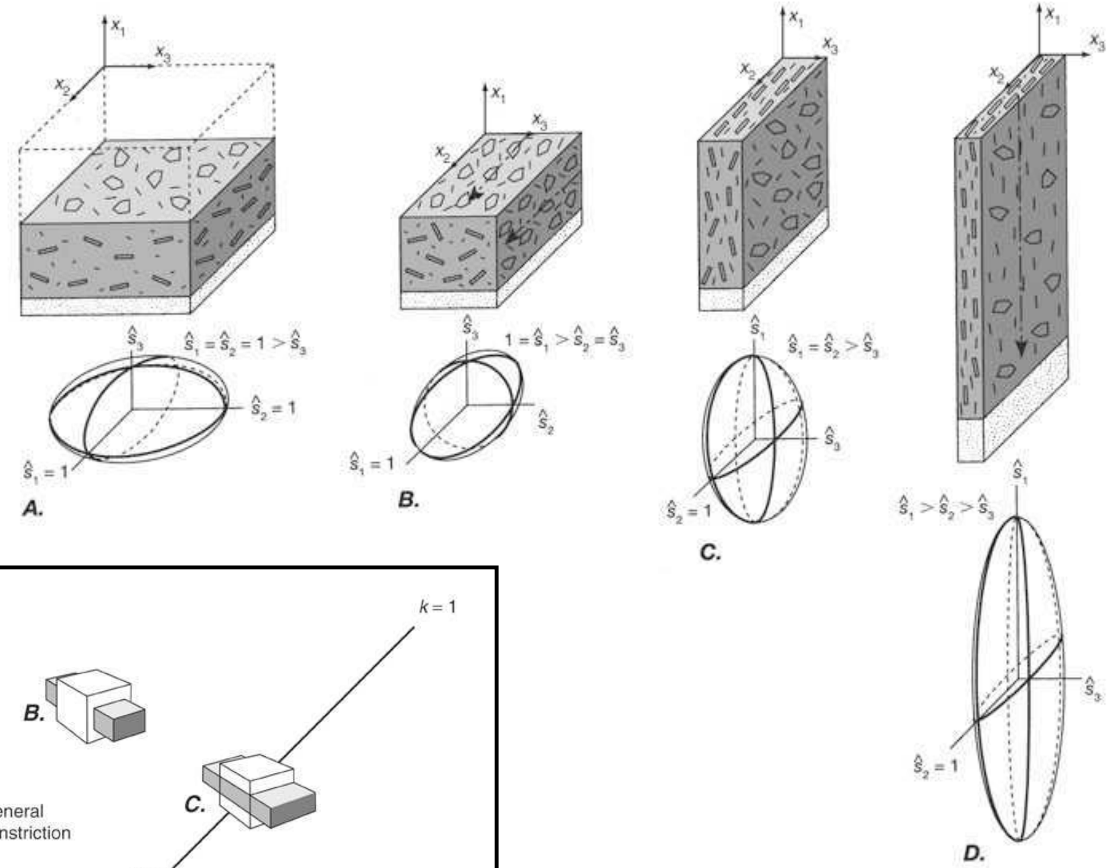


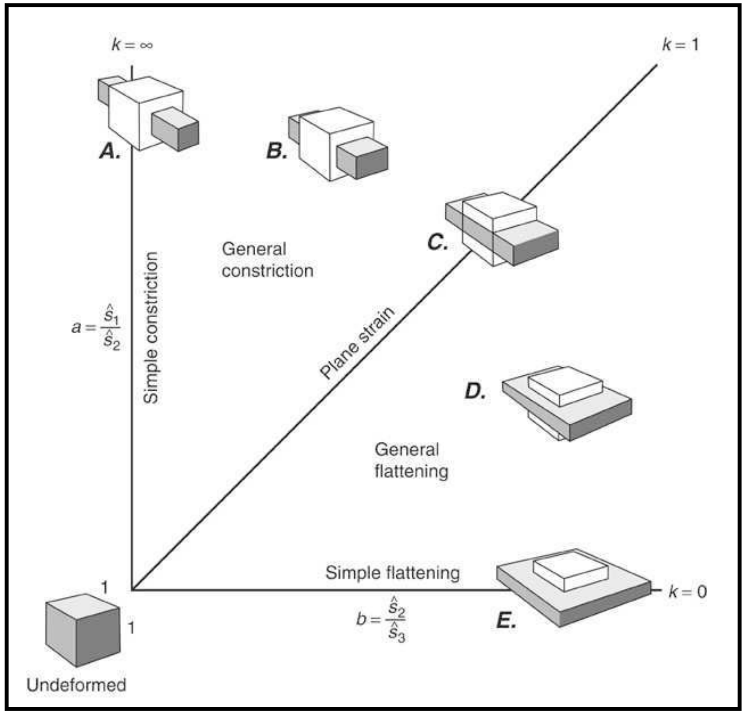
March model:
Rotation of passive markers in pure shear

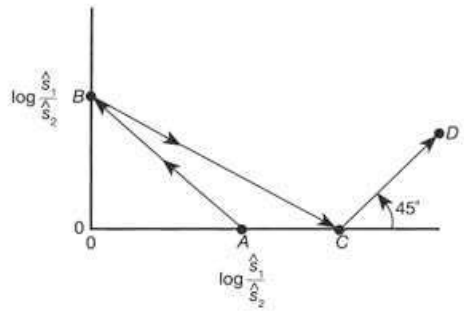


Observed:
Formation of a foliation by preferential orientation of marker planes normal to the shortening direction

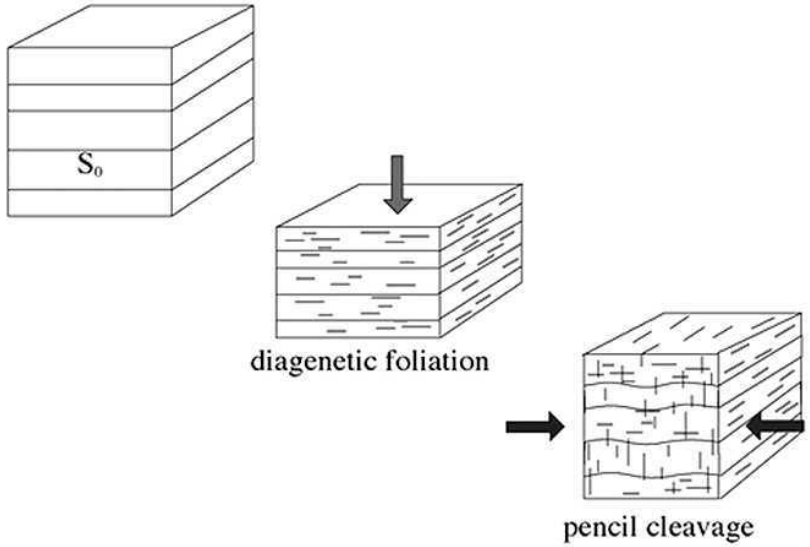
cleavage development - Flinn diagram

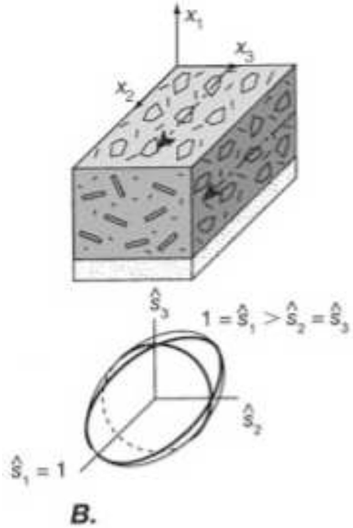


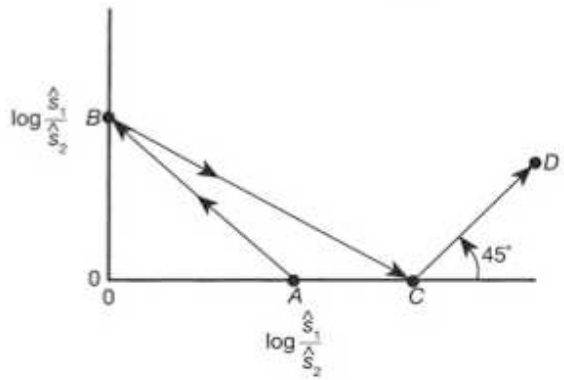




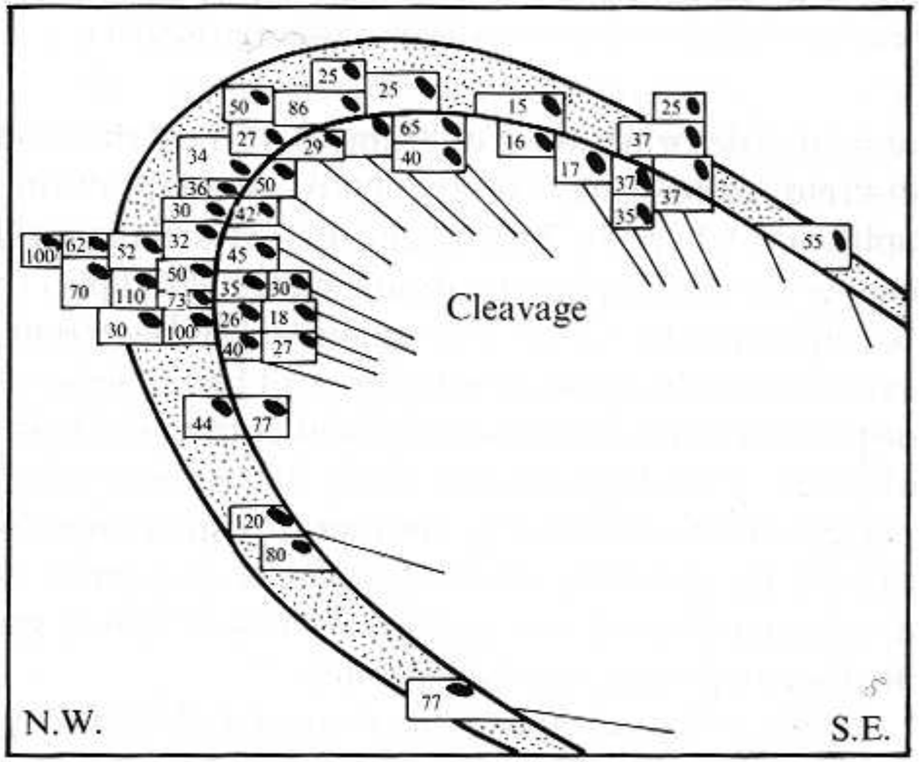
pencil cleavage







Achsenflächen-Schieferung und strain



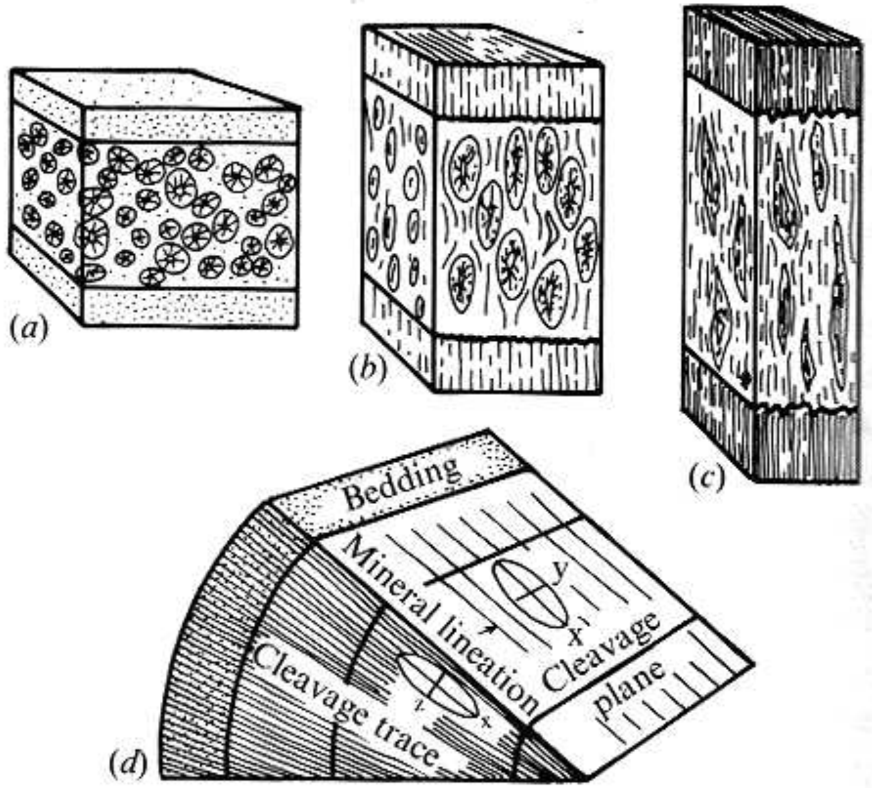
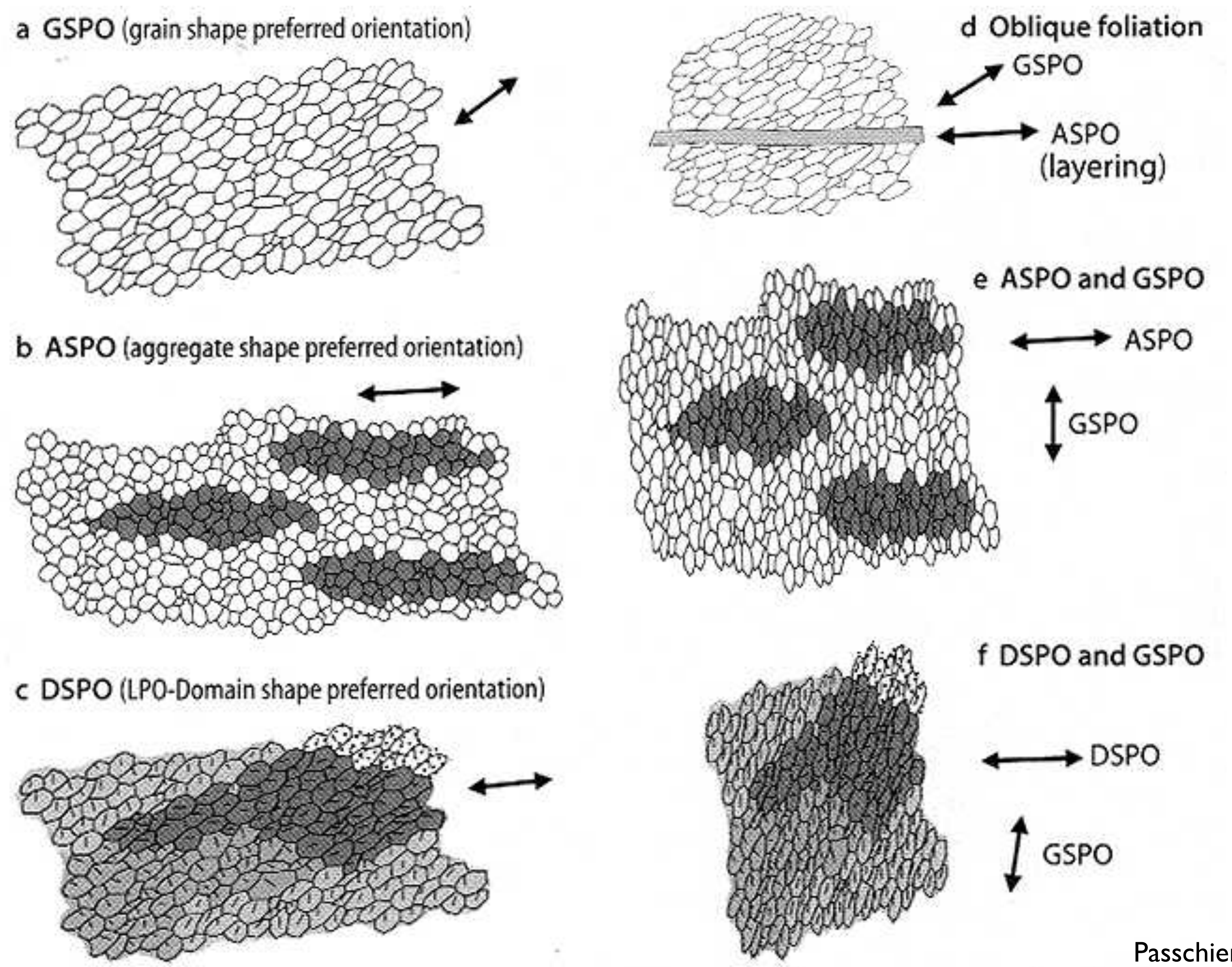


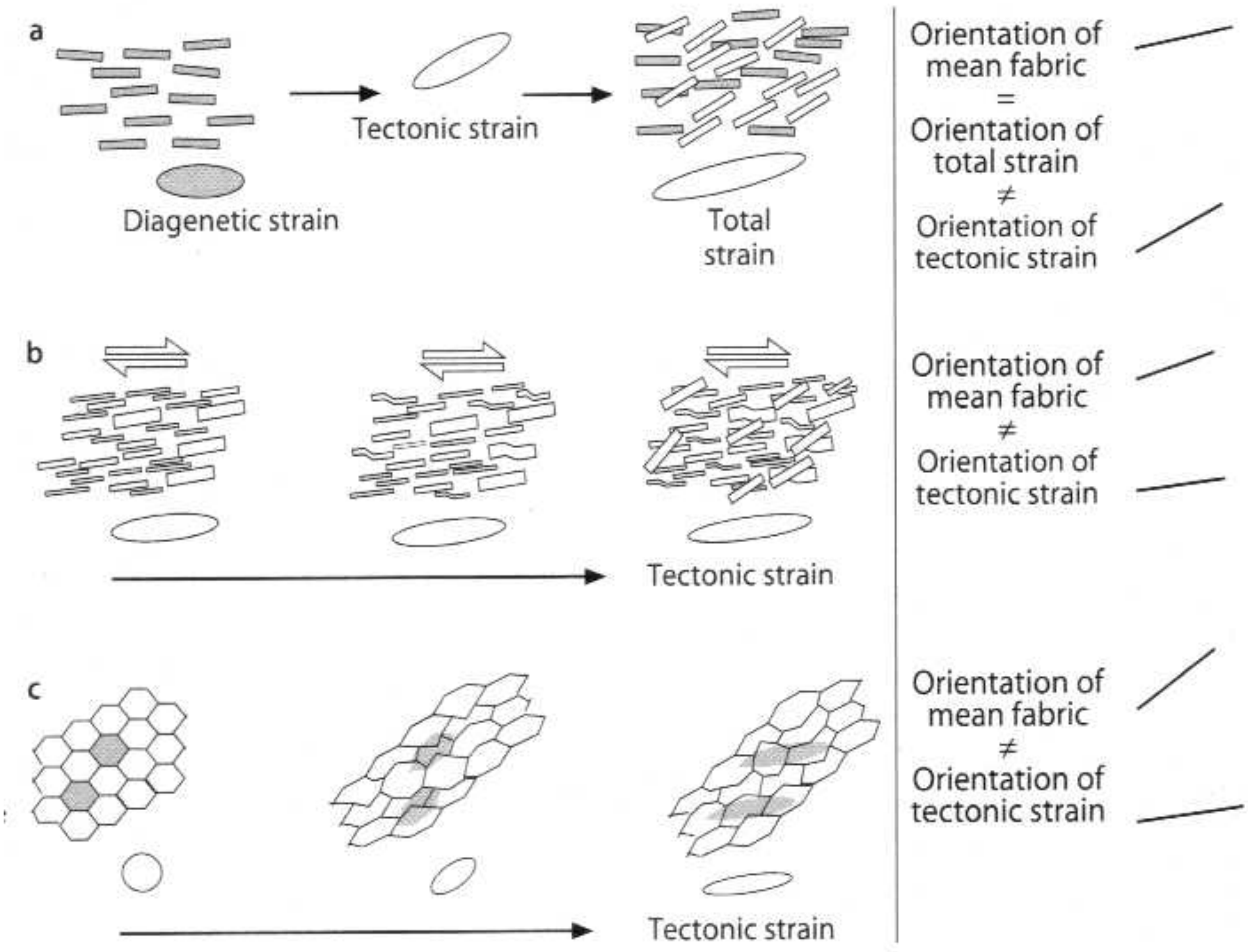
Fig. 17.37. Block diagrams of (*a*) an undeformed oolitic limestone sandwiched between beds of different lithologies; (*b*) appearance of (*a*) after 50 per cent deformation and (*c*) after 100 per cent deformation. (*d*) The relationship between the deformed ooliths and the cleavage. The major and intermediate axes of the oolith lie in the cleavage plane and the major axis is parallel to the mineral lineation. (After Cloos, 1947.)

Mikrostruktur



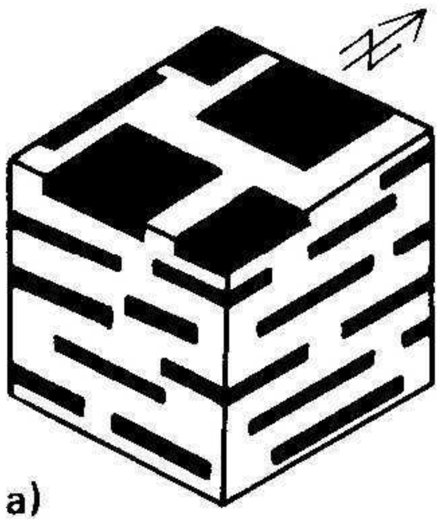
Passchier & Trouw

foliation microstructure

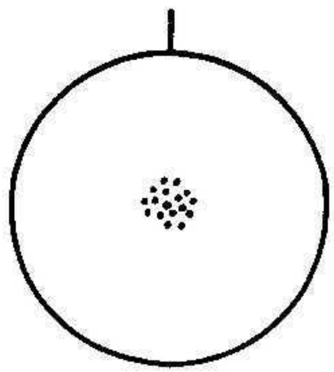


Mineralregelung

plattig

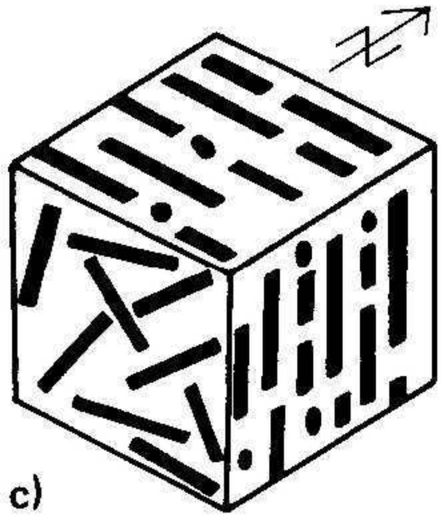


a)

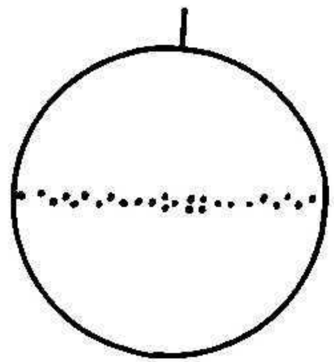


b)

stengelig



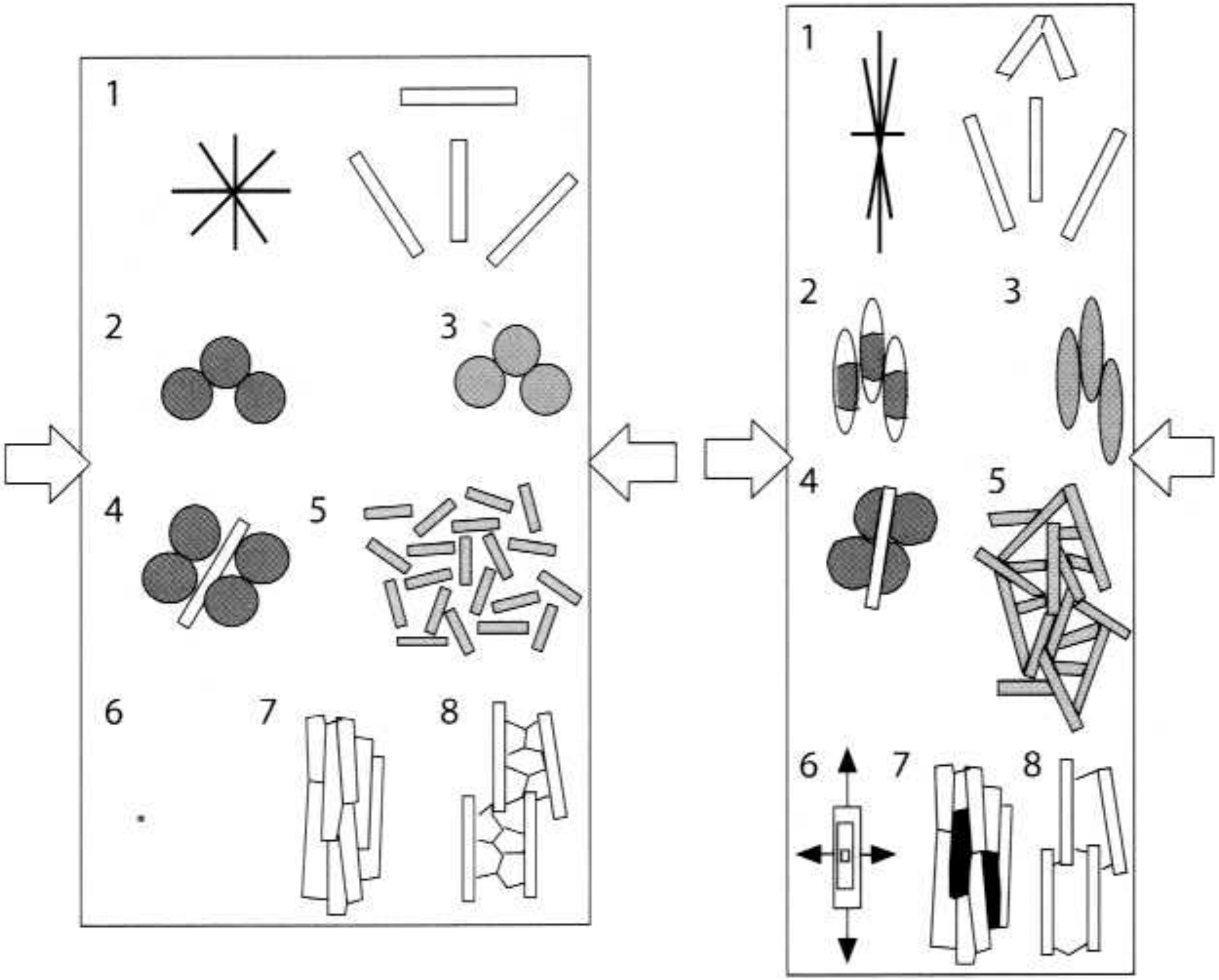
c)



d)

Mechanismen der Schieferungsbildung

mechanisms for foliation development



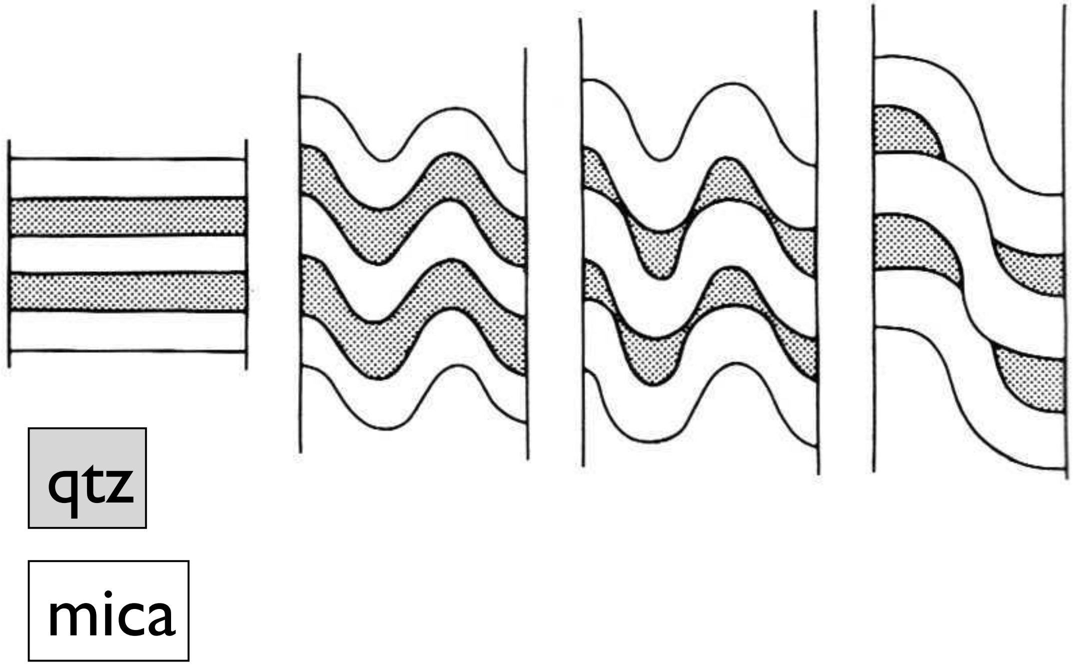
passive markers
rotate, bend

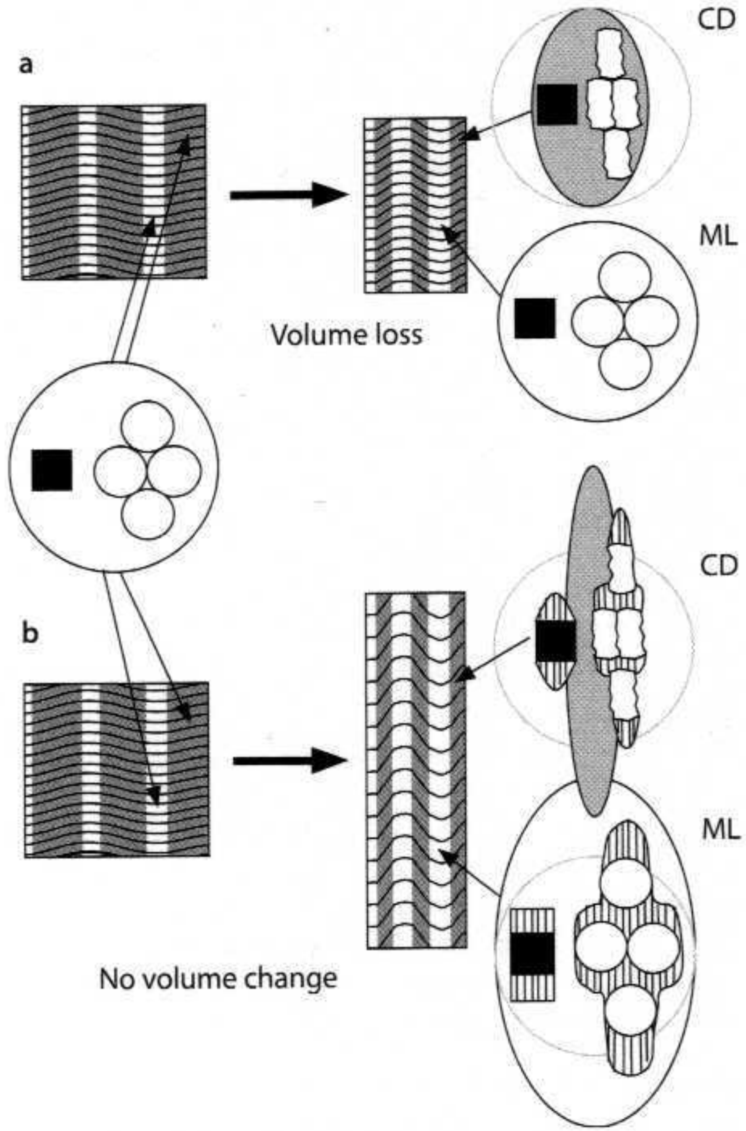
monomineralic:
solution-precipiation
crystal plasticity

polymineralic:
foliation formation
growth //(001)

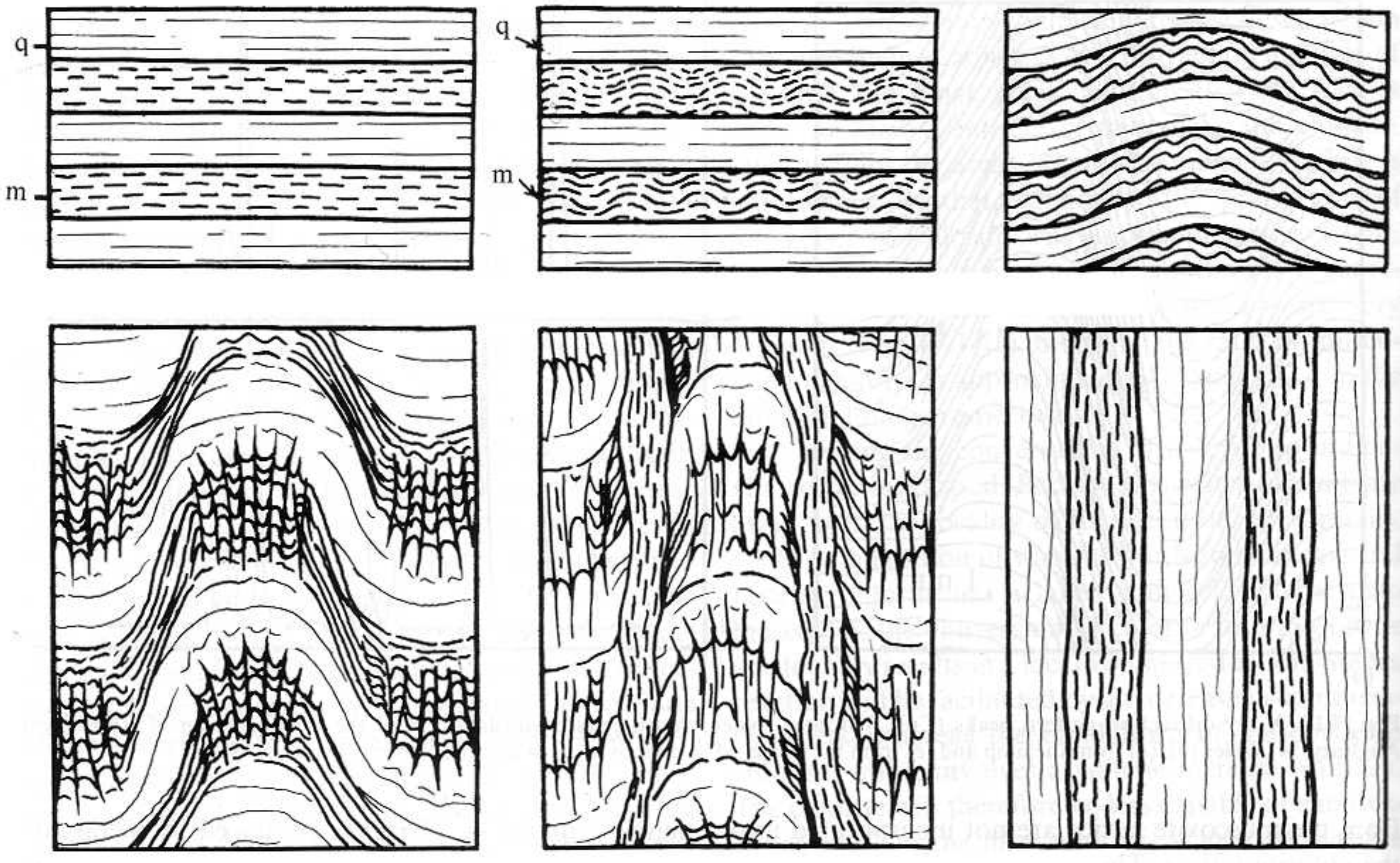
growth // stress field
restricted growth
- foliation
- platy minerals

crenulation cleavage in multilayer





Schieferungsentwicklung

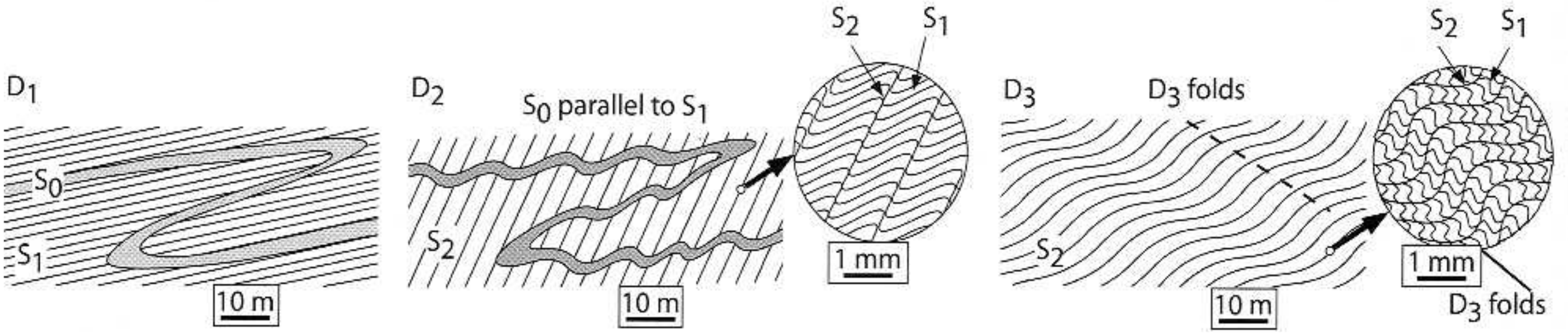


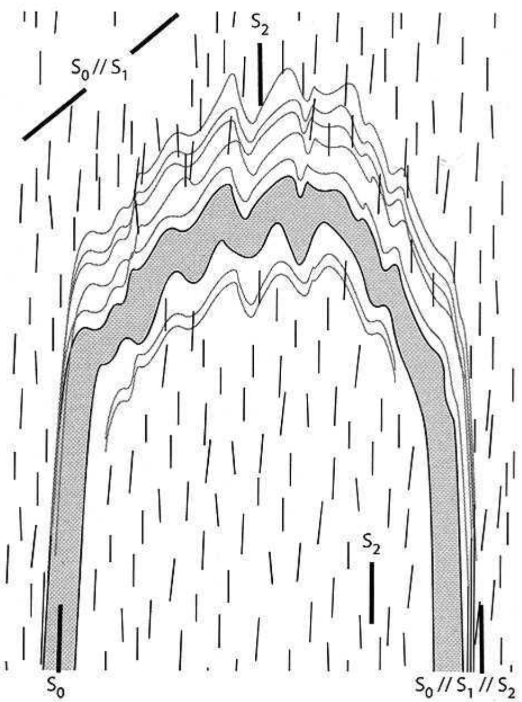
Anwendung in der Strukturgeologie: Überprägung

s_0, s_1, s_2, etc.

Beispiel für Schieferungsentwicklung

Deformationsphase 1 | Deformationsphase 2 | Deformationsphase 3





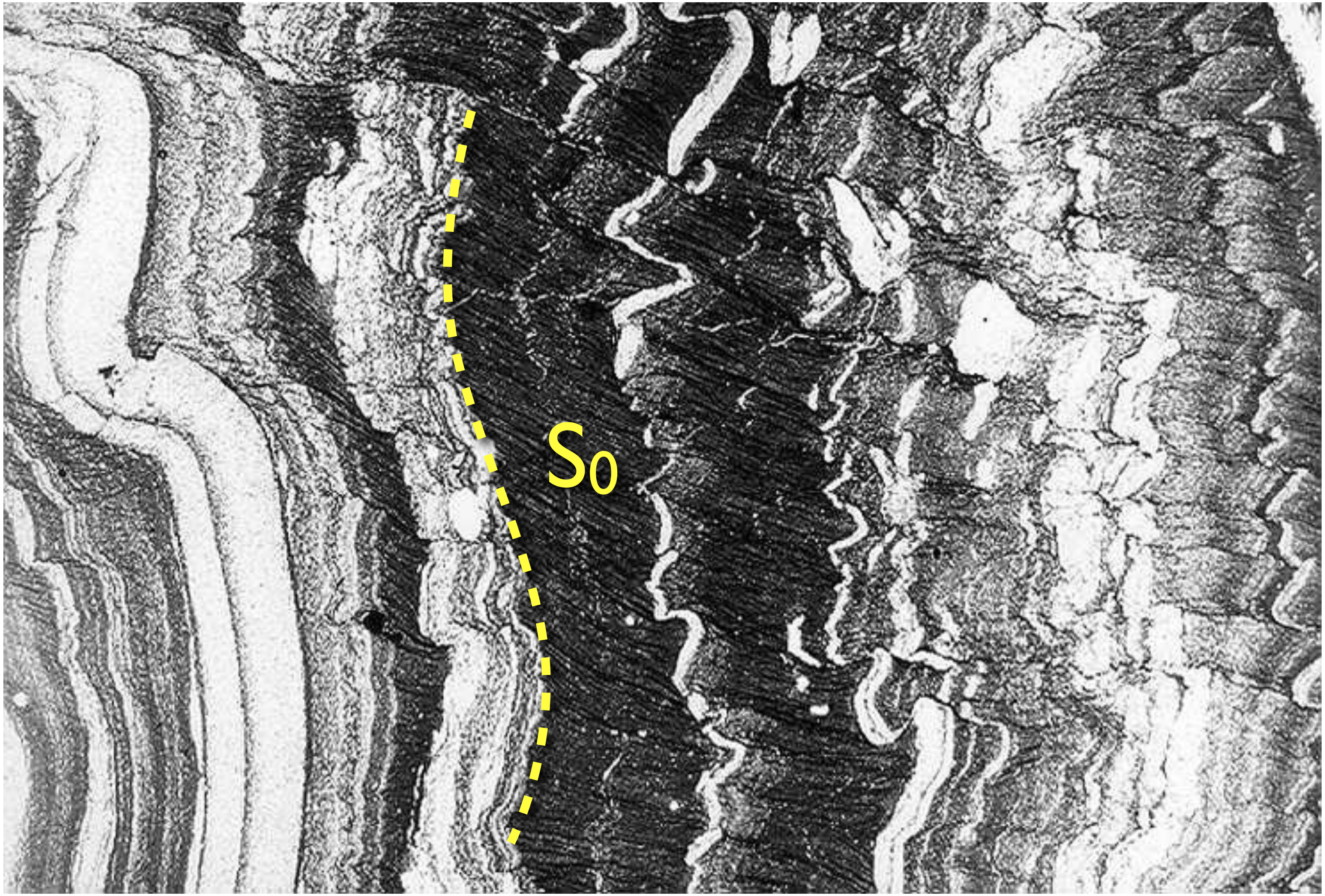
S_0 Ablagerung

D_1 Isolklinalfalten: Schieferung S_1

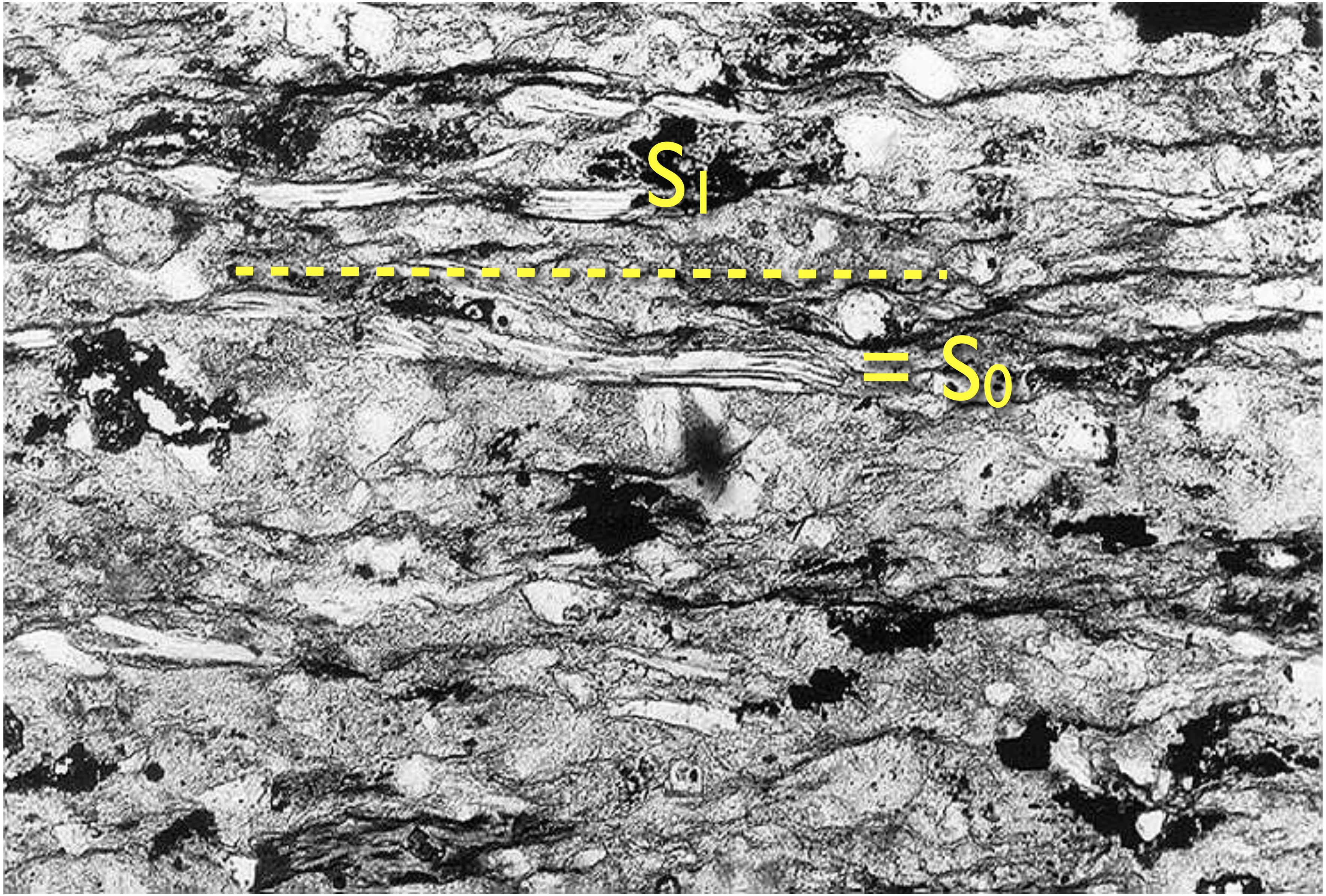
D_2 Krenulationsschieferung S_2

D_3 Offene Falten: S_3

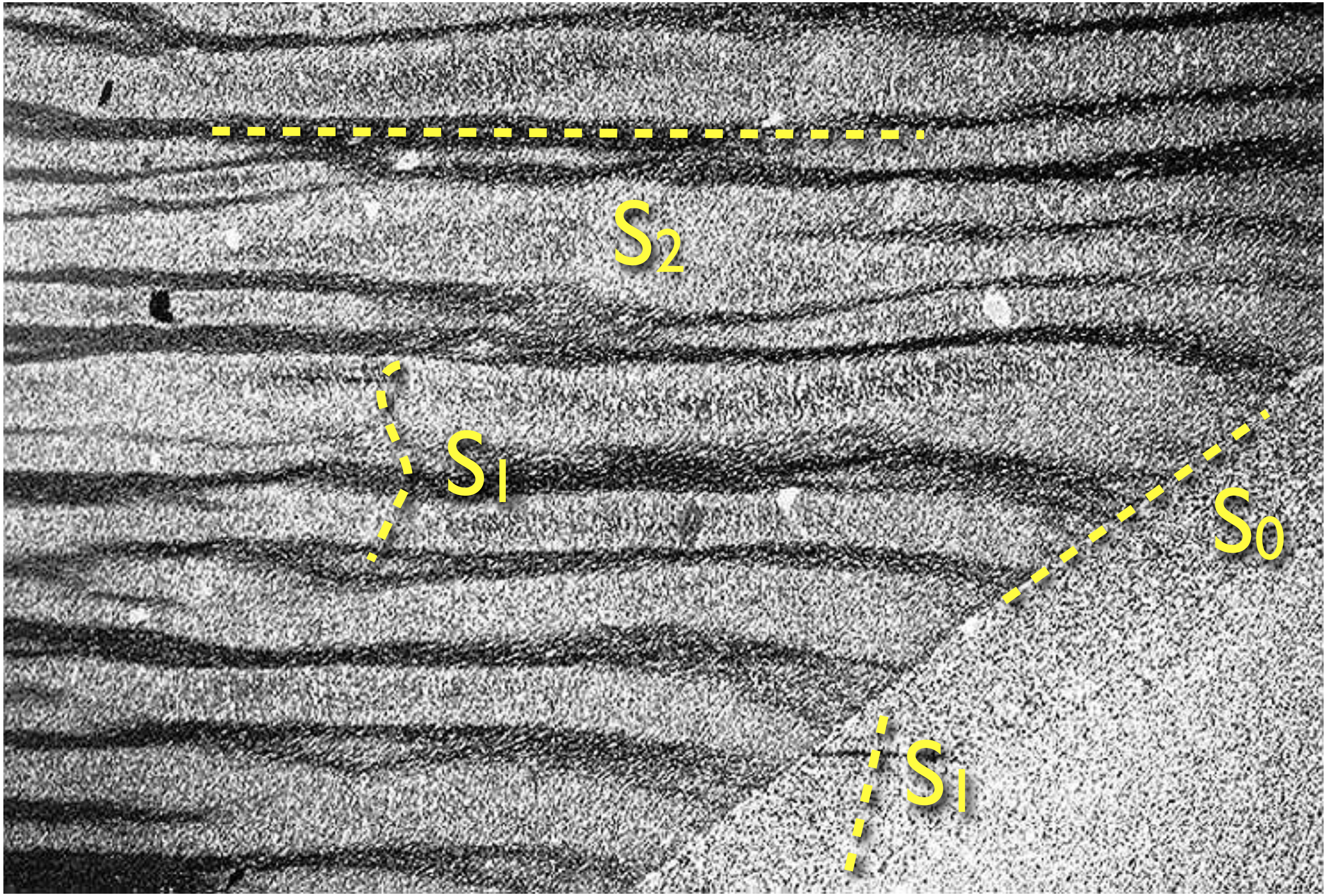
primary foliation S_0



diagenetic (bedding parallel) foliation



secondary foliation

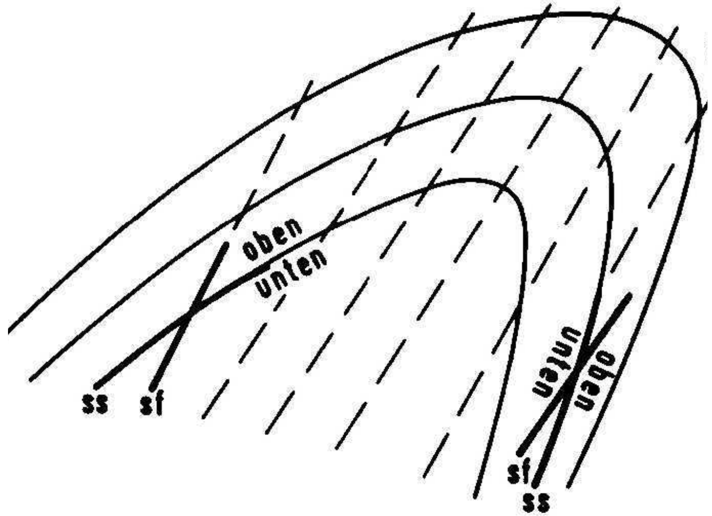


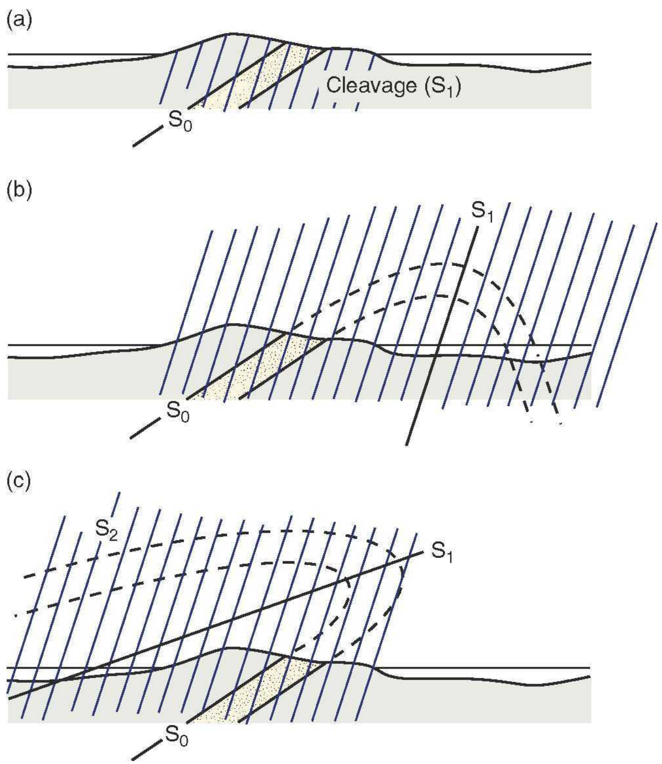
Bedeutung der Schieferung beim Kartieren

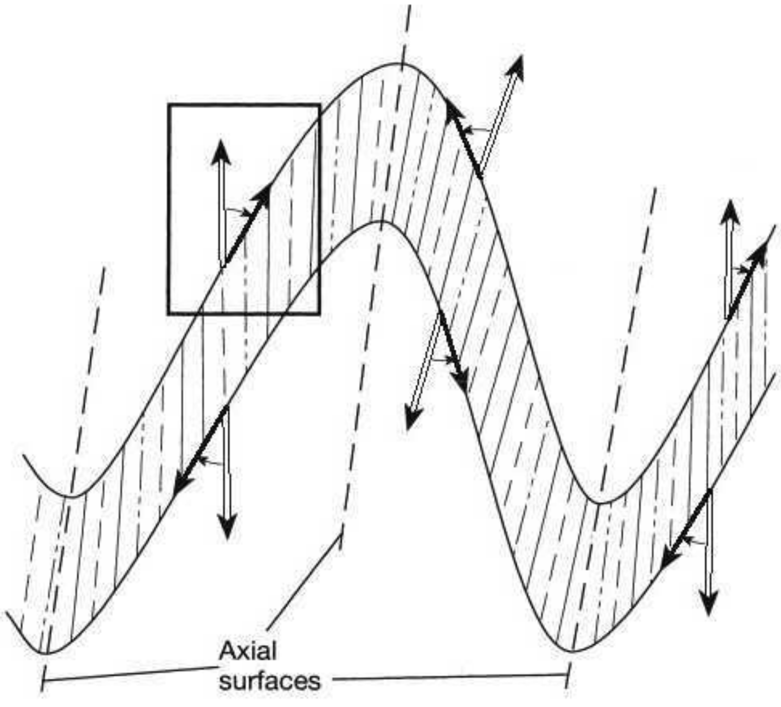
Achsenflächen-Schieferung

normale Lagerung
s_f steiler als s_s

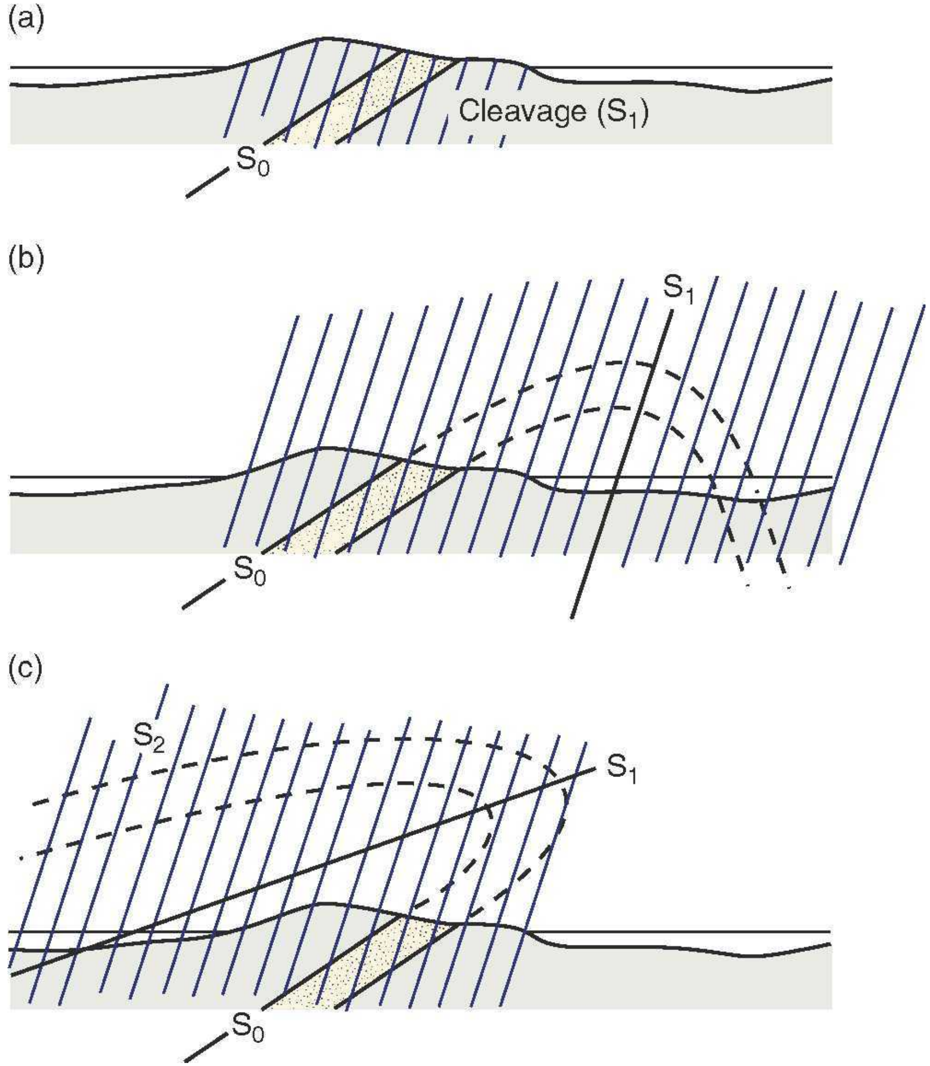
inverse Lagerung
s_f flacher als s_s





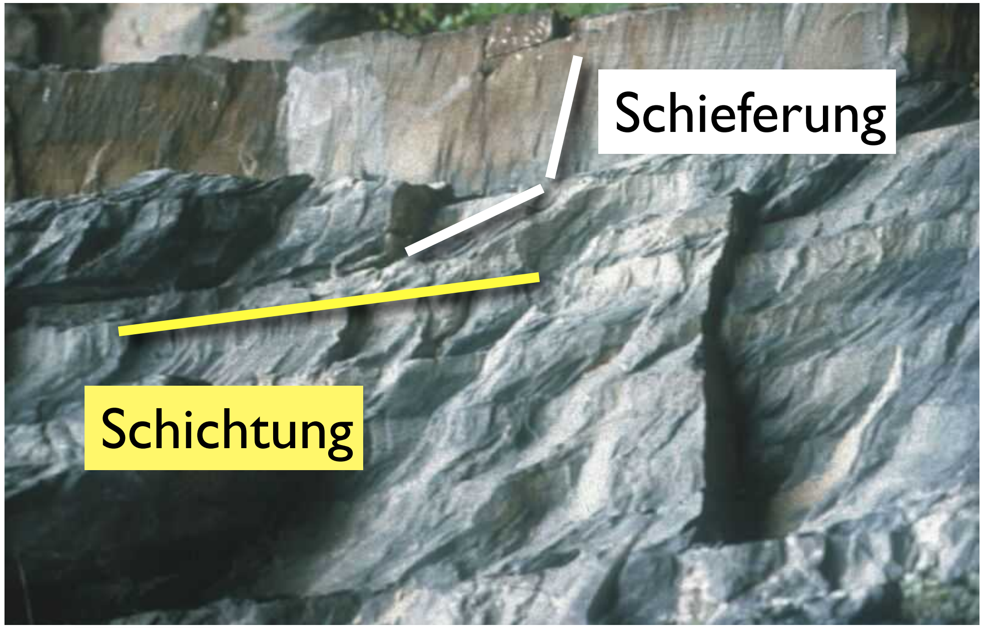


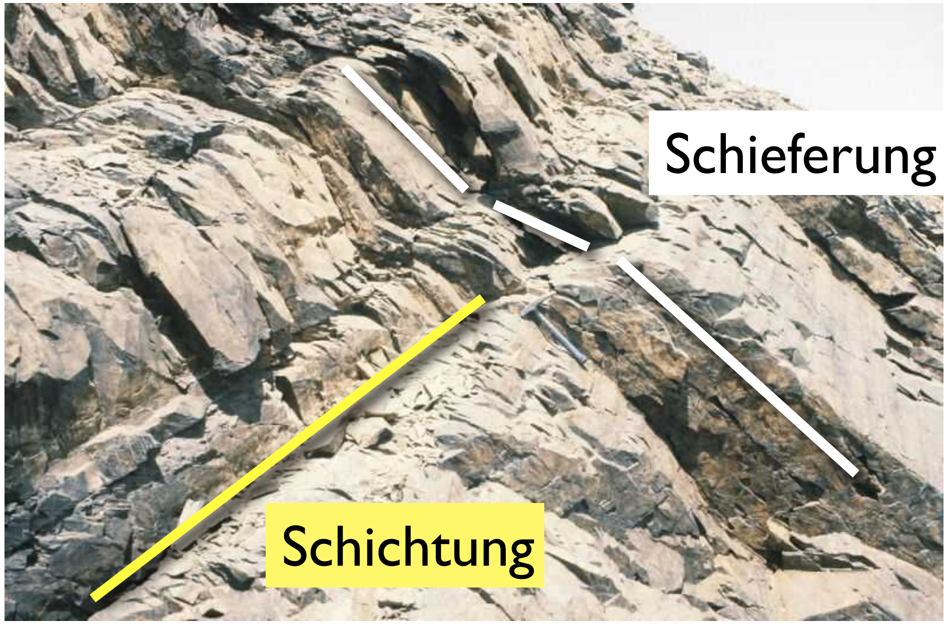
Schieferungsüberprägung

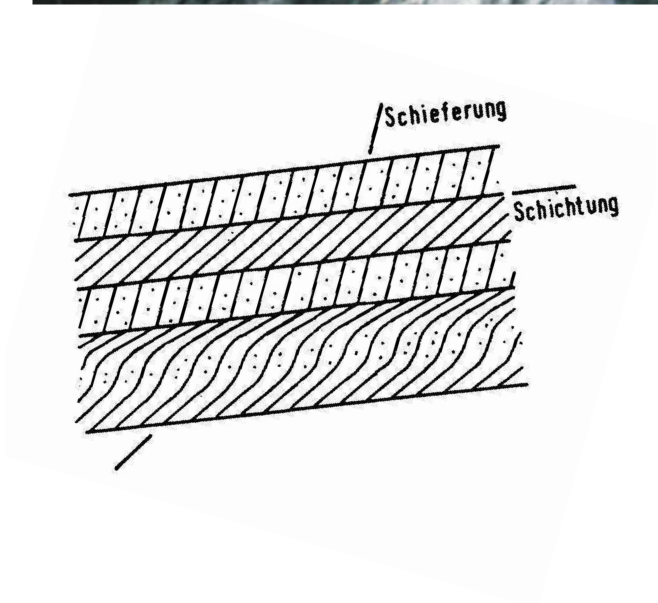


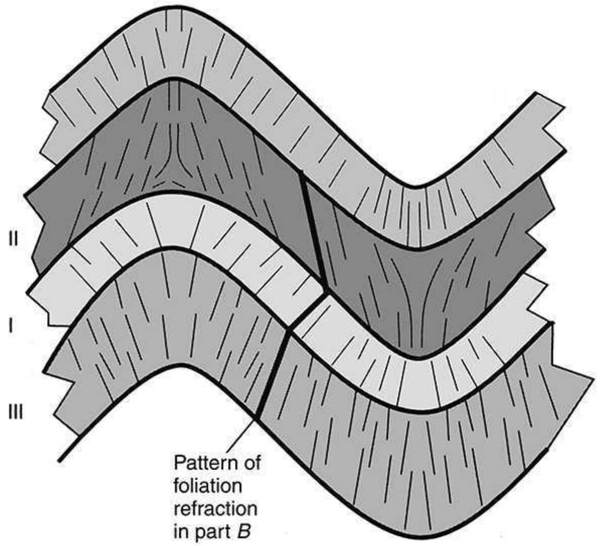
Fossen

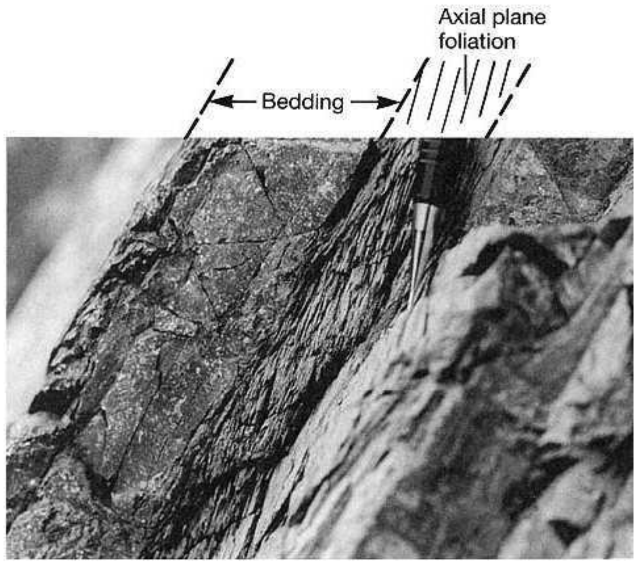
Schieferungsbrechung



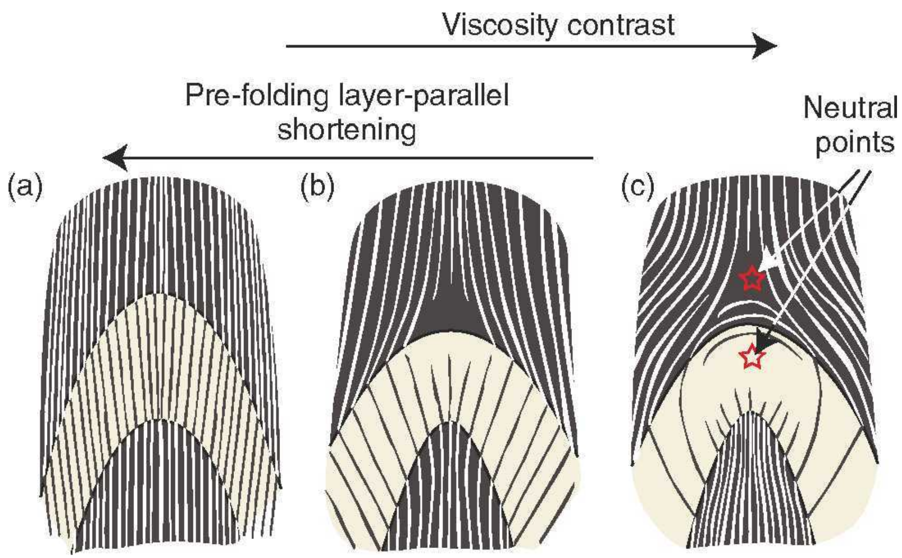


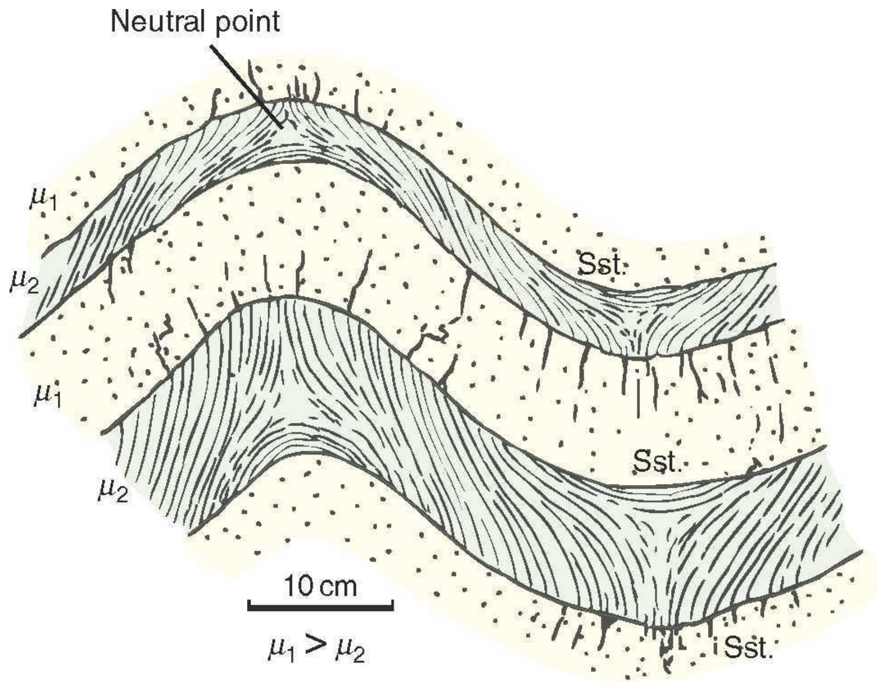




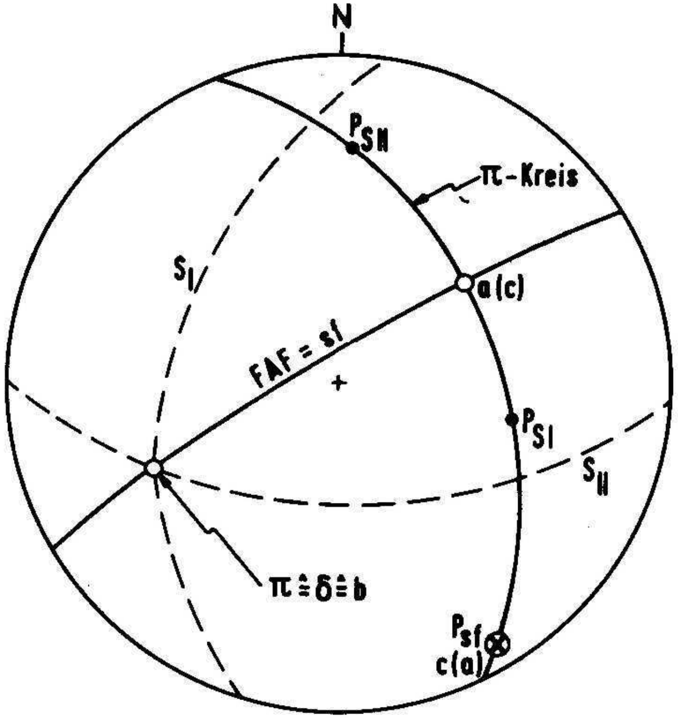


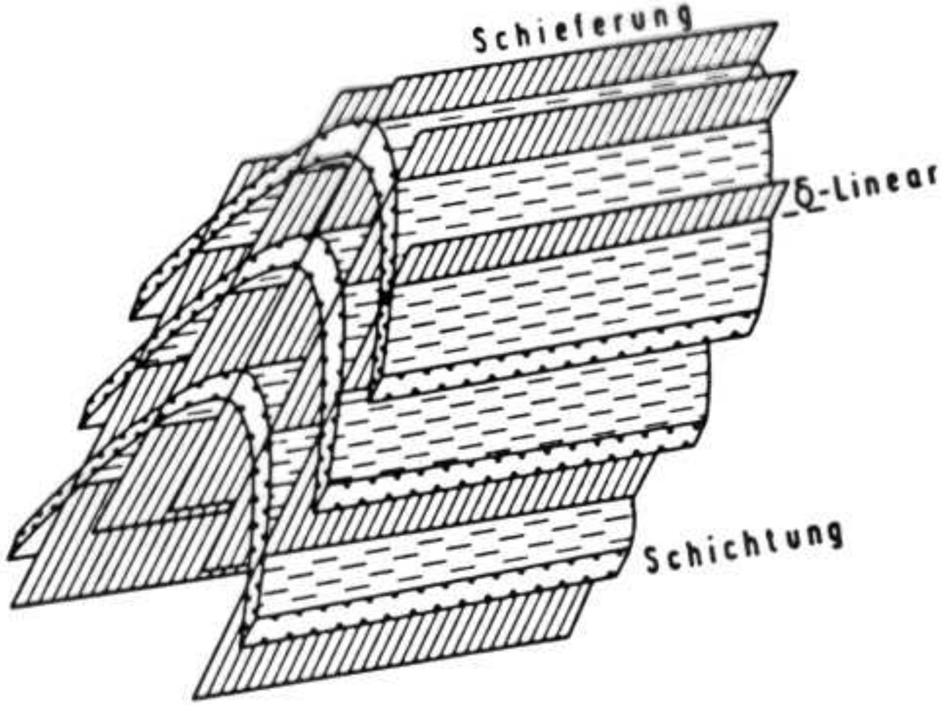
Mechanische Bedeutung





Schieferung-Schichtung b - δ - π





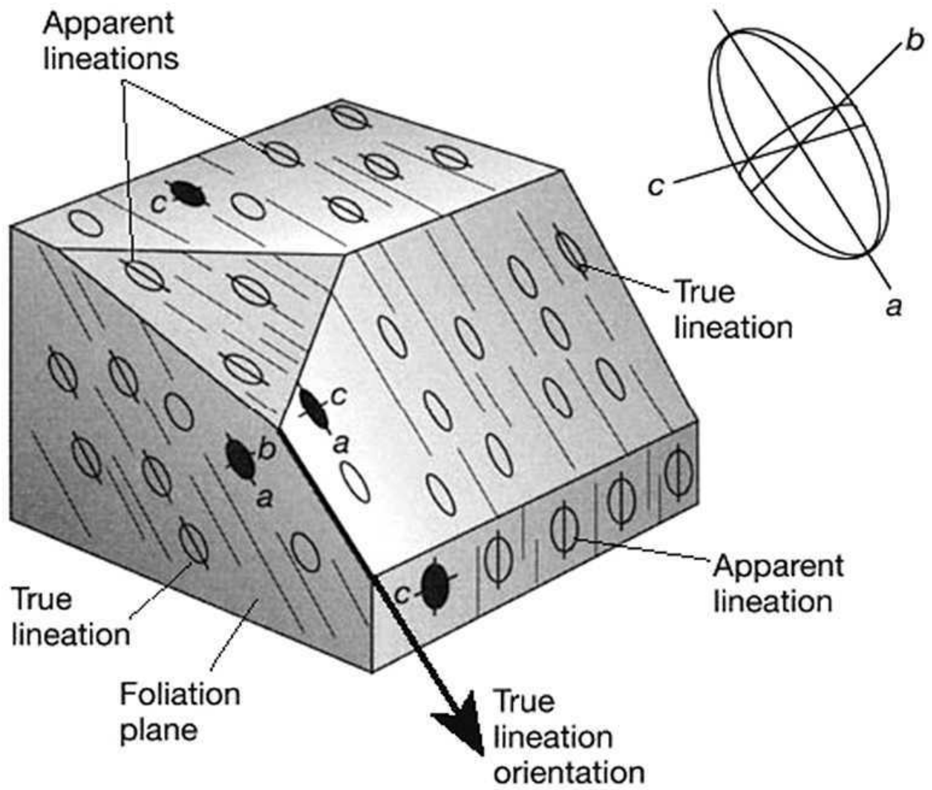
π = Pol zum π-Kreis

b = Linear = Faltenachse

δ = Linear = Intersektion (Achsenflächenschieferung / Schichtung)

Lineare Gefüge

Lineation



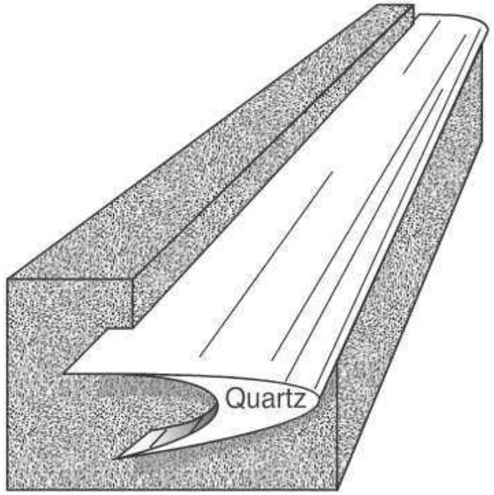
penetrative stretching
mineral
rodding

geometric (virtual) fold axes
intersection lienation

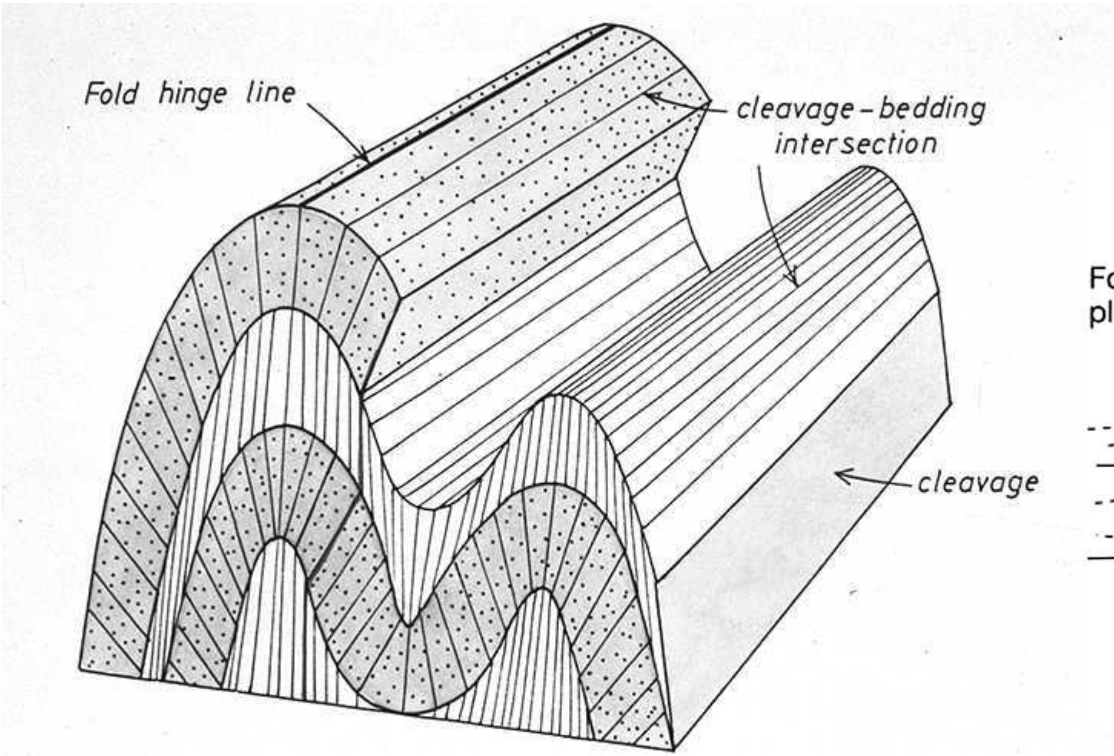
surface mullions
slickenfibres
striations, corrugations

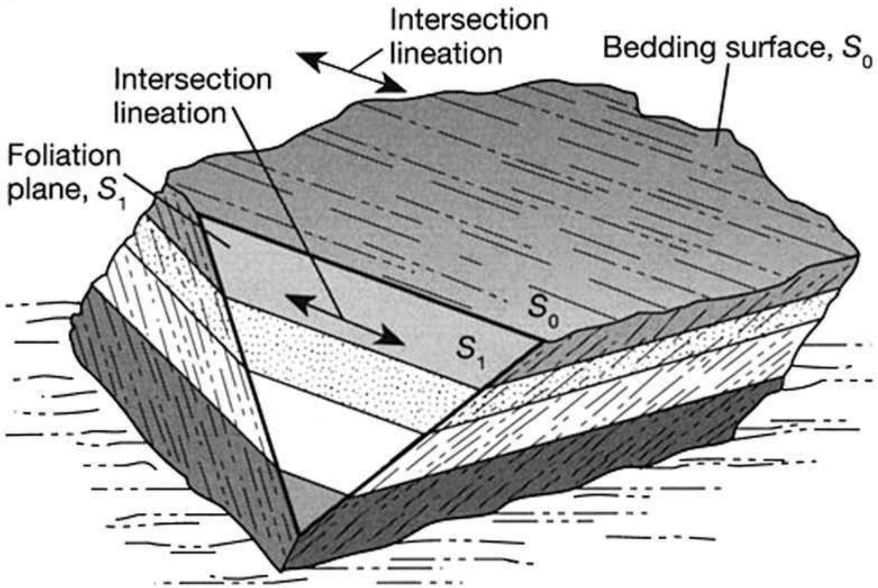
penetrative lineation

rodding lineation



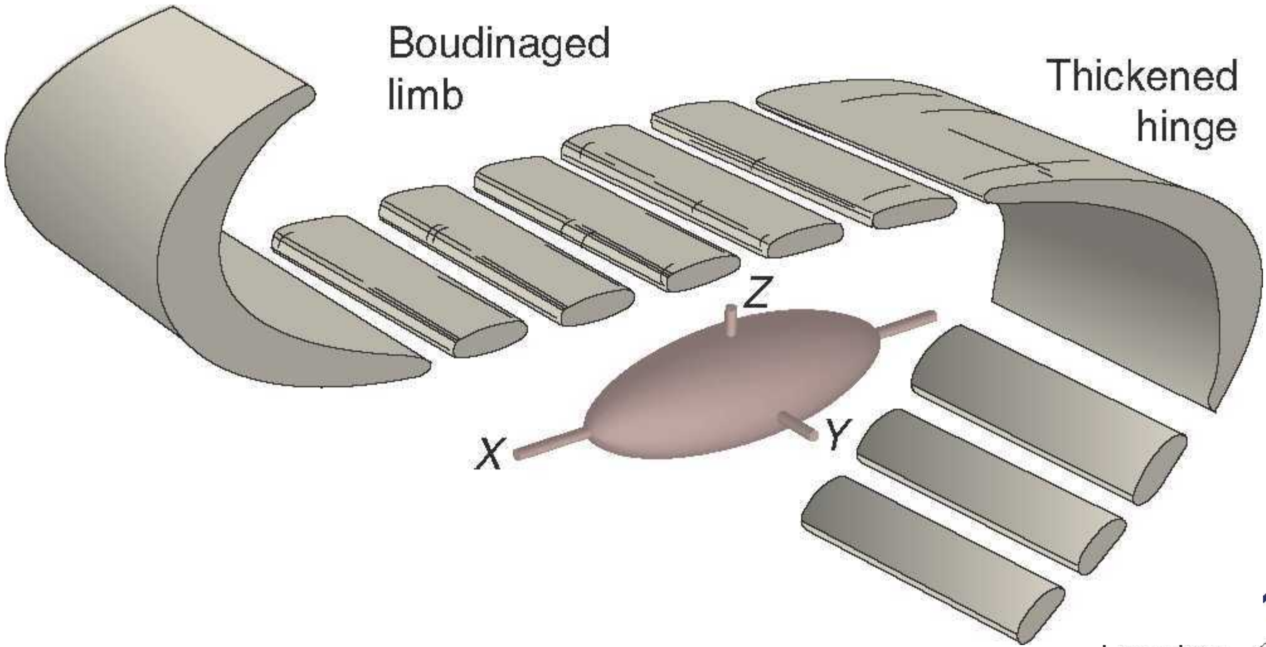
geometric (virtual) lineations

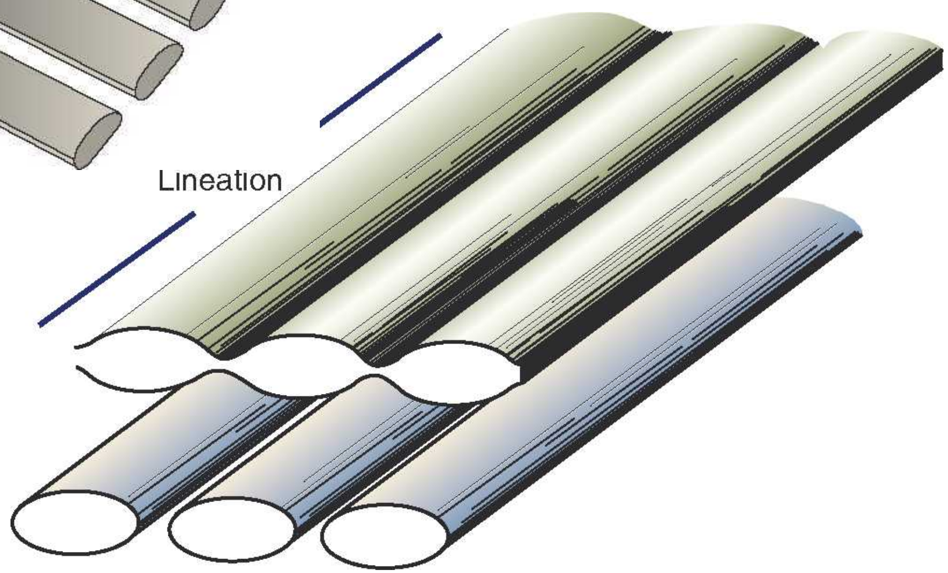




Intersektionslineare
Faltenachsen

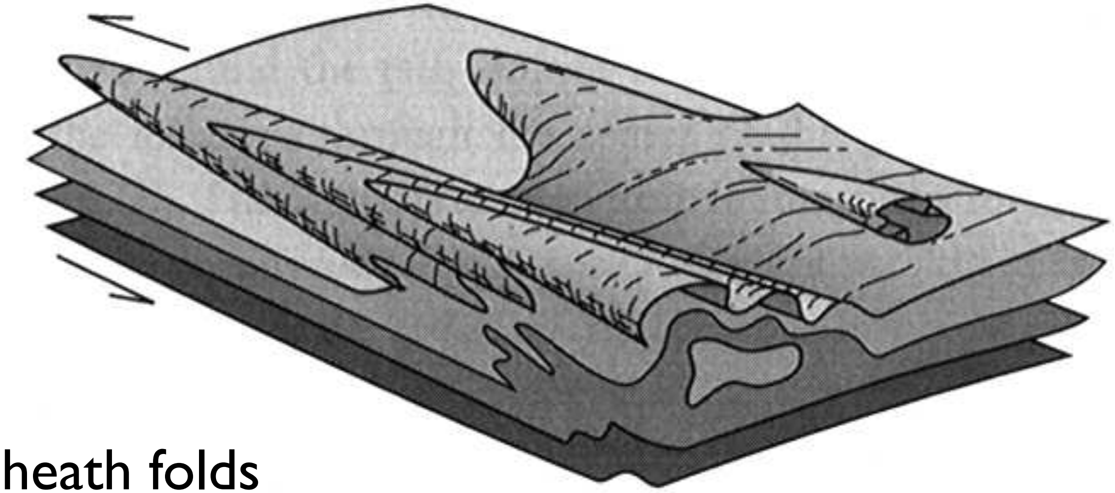
boudinage



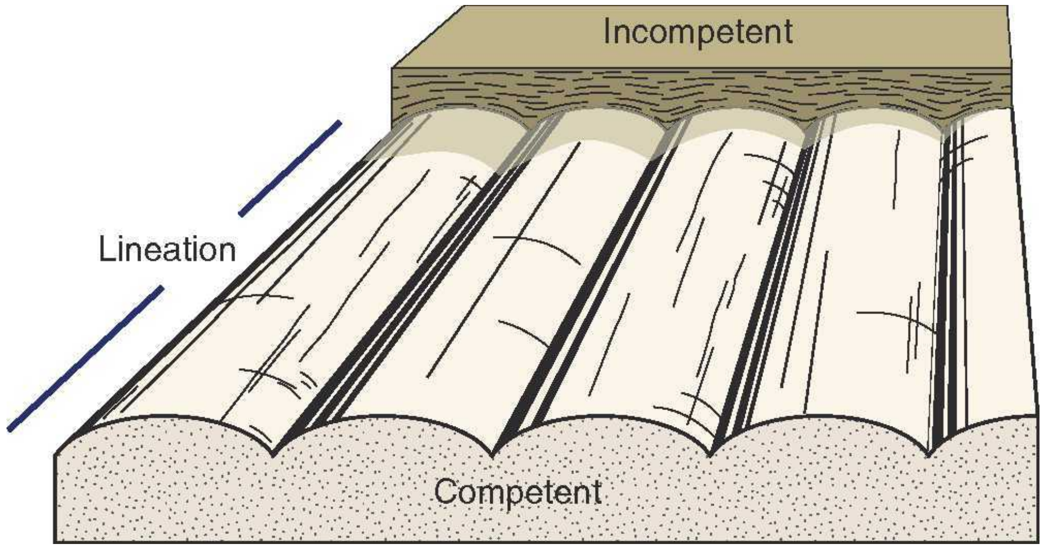


surface lineations

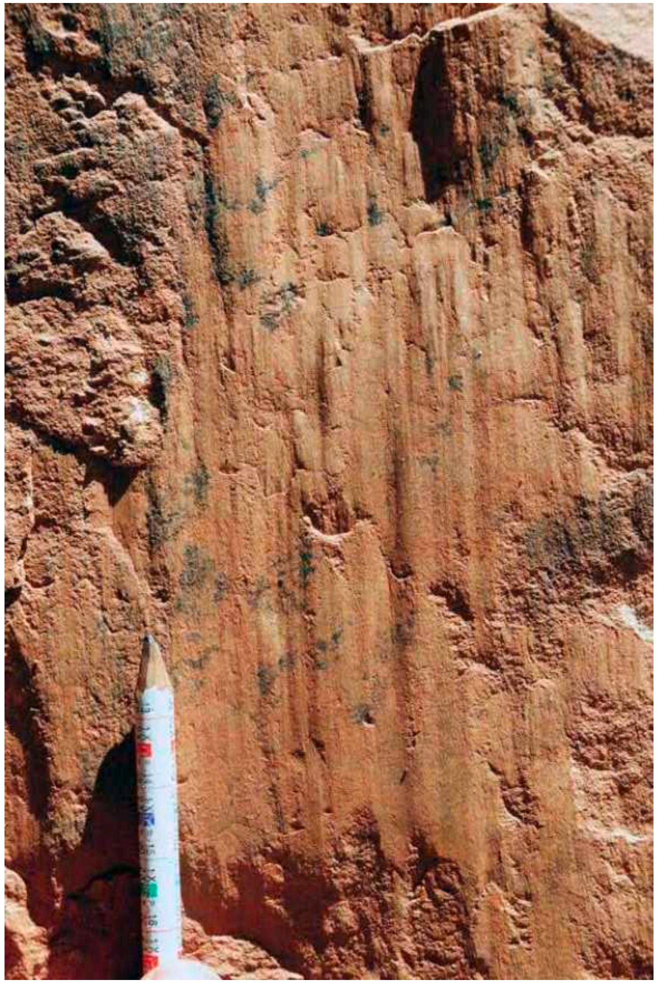
mullions



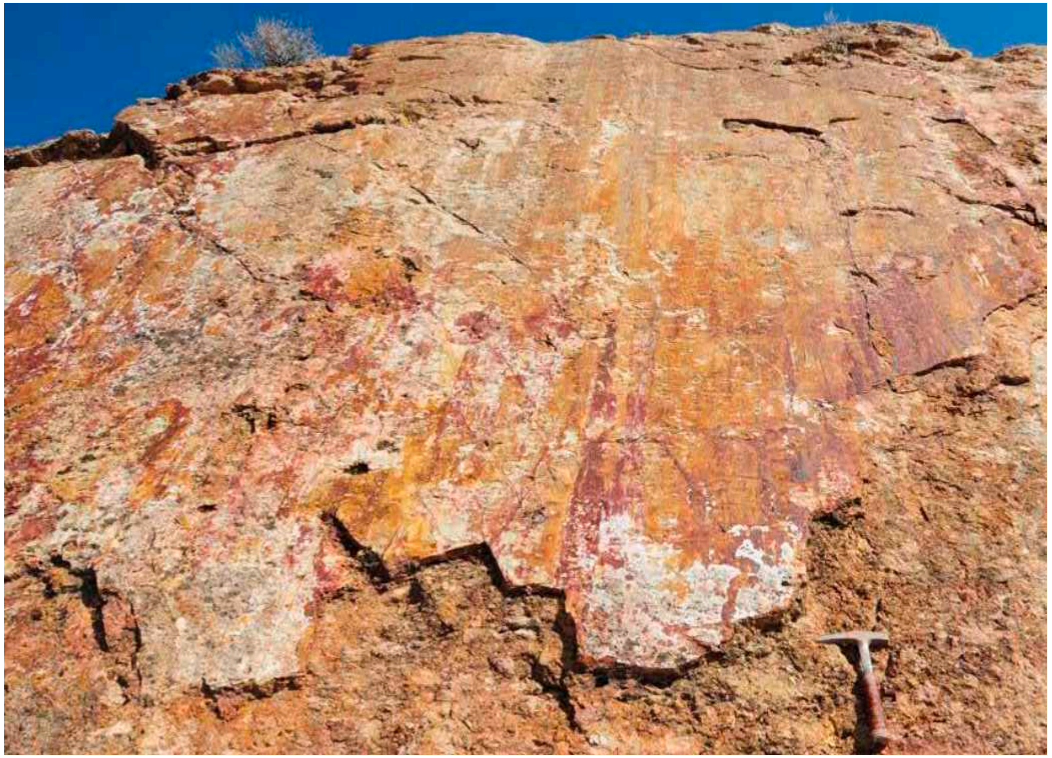
sheath folds



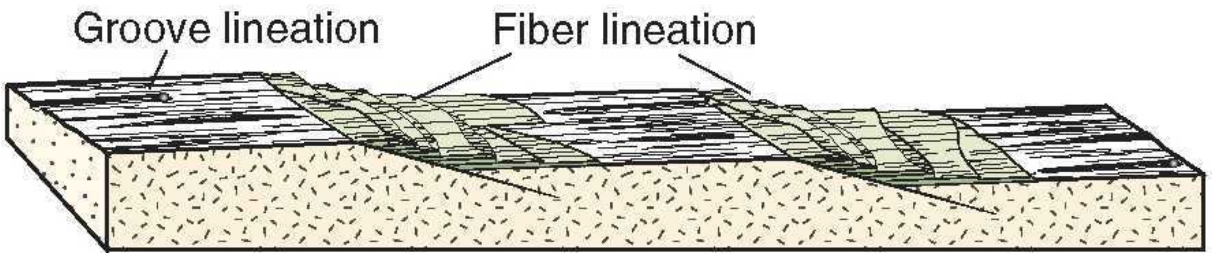
surface lineations



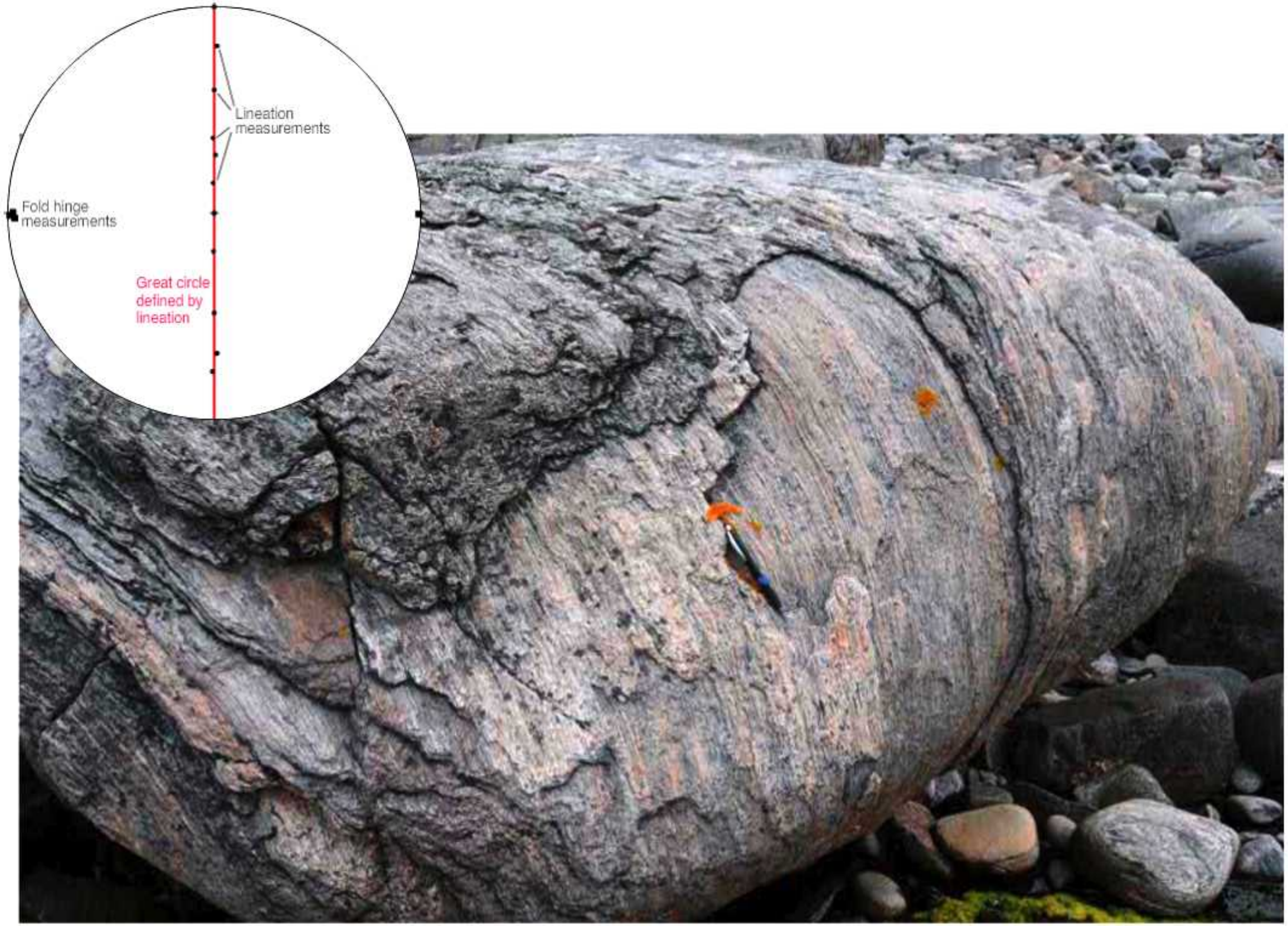
striations



slickenfibres



gefaltete Lineare



6

Semesterplan FS 2016

	Datum		Thema		Übungen	abgeben
1	26. Feb.	1	Druck, Spannung, Mohr Kreis, Spannungsfeld			
2	4. März	2	Deformation, Strainellipse, strain marker, Strainmessung			
3	11. März		fällt aus (Tromsø workshop)			
4	18. März		fällt aus (Tromsø workshop)	1	Stress	29. 3.
5	25. März		fällt aus (Ostern)	2	Strain	29. 3.
6	1. April	3	Mohr-Coulomb, Reibung, Klüfte und Brüche		-	
7	8. April	4	Bruchsysteme, Stereonetz Verwerfungen	3	Mohr-Coulomb	13. 4.
8	15. April	5	Scherzonen, Foliation, Lineation	4	Klüfte Mönthal	27. 4.
9	22. April		fällt aus (EGU)	5(6)	Inv. SURFOR, Fry	27. 4.
10	29. April	6	Falten, Geometrie, Faltenbildung		Trajektorien	11.5.
11	6. Mai		fällt aus (Himmelfahrt)	7		
12	13. Mai	7	Mikrostrukturen, Deformationsmechanismen, Rheologie	8	Def.Mech.	18. 5.
13	20. Mai	8	Subduktion, Gebirgsbildung, Transformstörungen	9	Critical taper	25. 5.
14	27. Mai	9	Extensionstektonik, rifting, MOR, MCC, LANF			
15	3. Juni	10	Test			

6 Falten - Geometrie - Faltenbildung

VL-Themen:

- Faltengeometrie
- superposed folding

- Falten im Stereonetz
- Strain in Falten
- Falten in tektonischen Strukturen

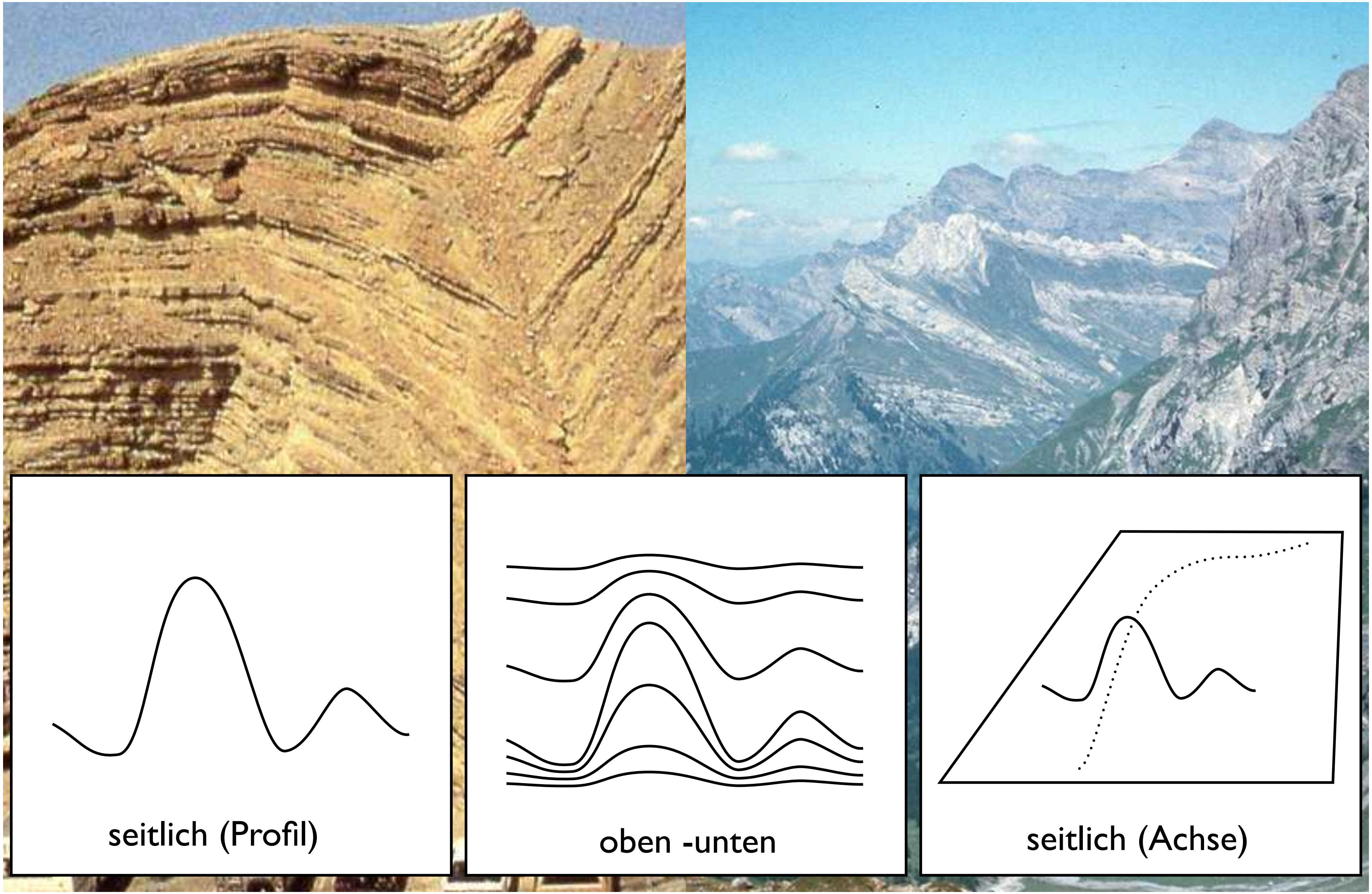
- Faltung (Mechanik)
  buckling - bending - passive

folds

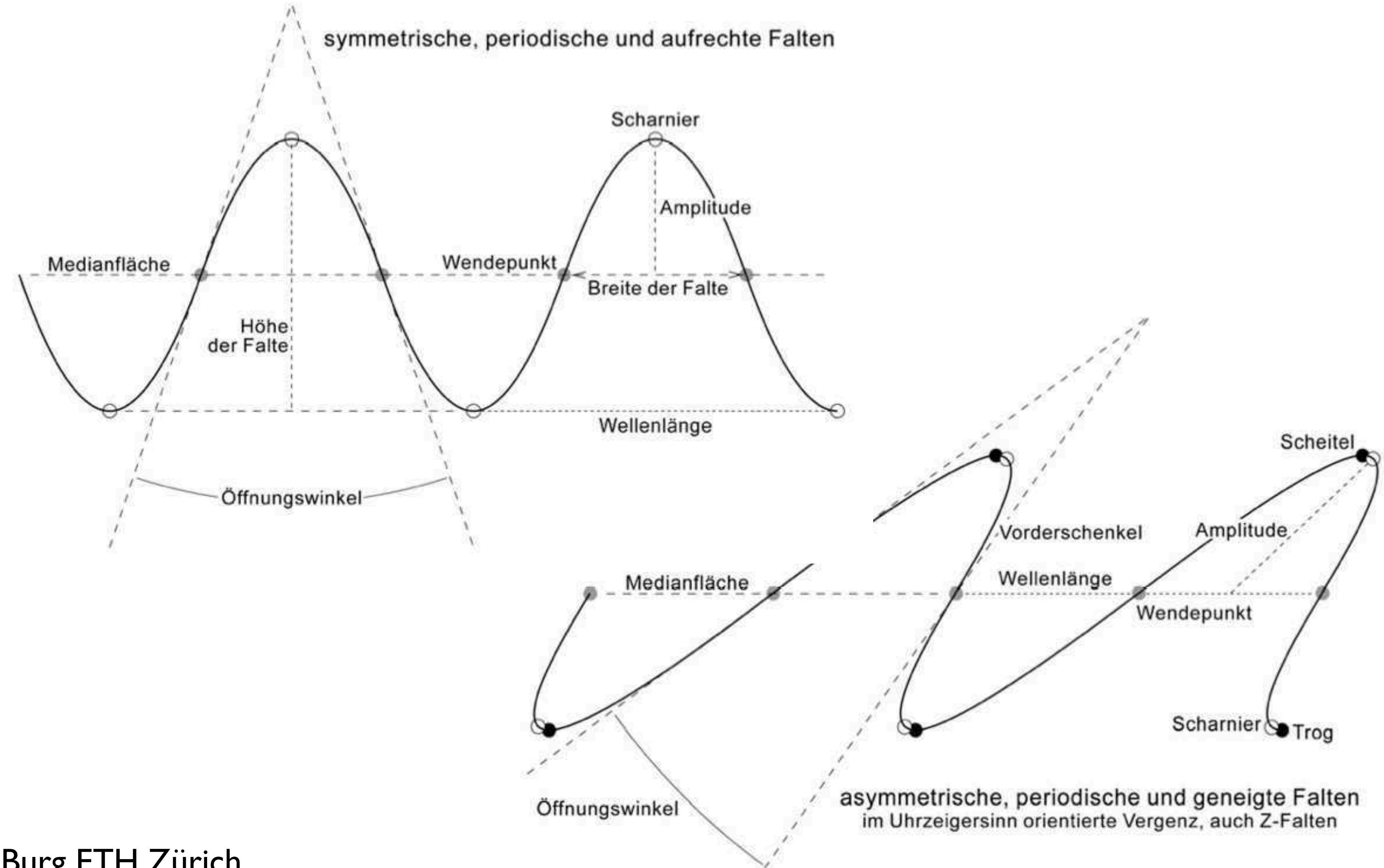
http://folk.uib.no/nglhe/e-modules/Chapter%2011/11%20Folding.swf

fold
geometry

Falten = 3D Objekte

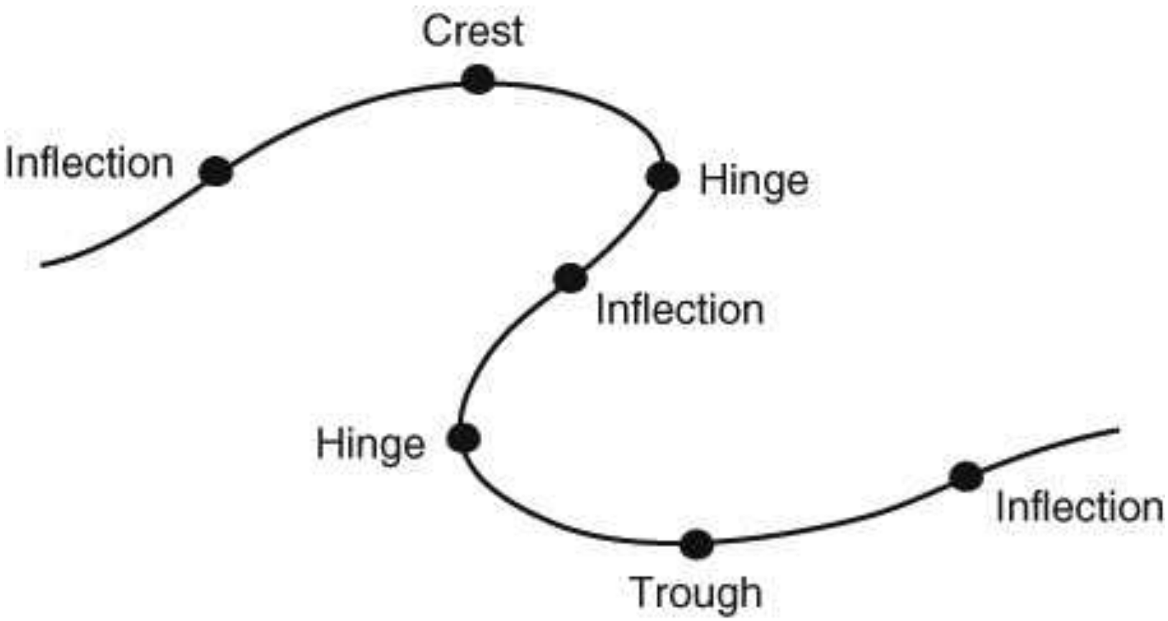


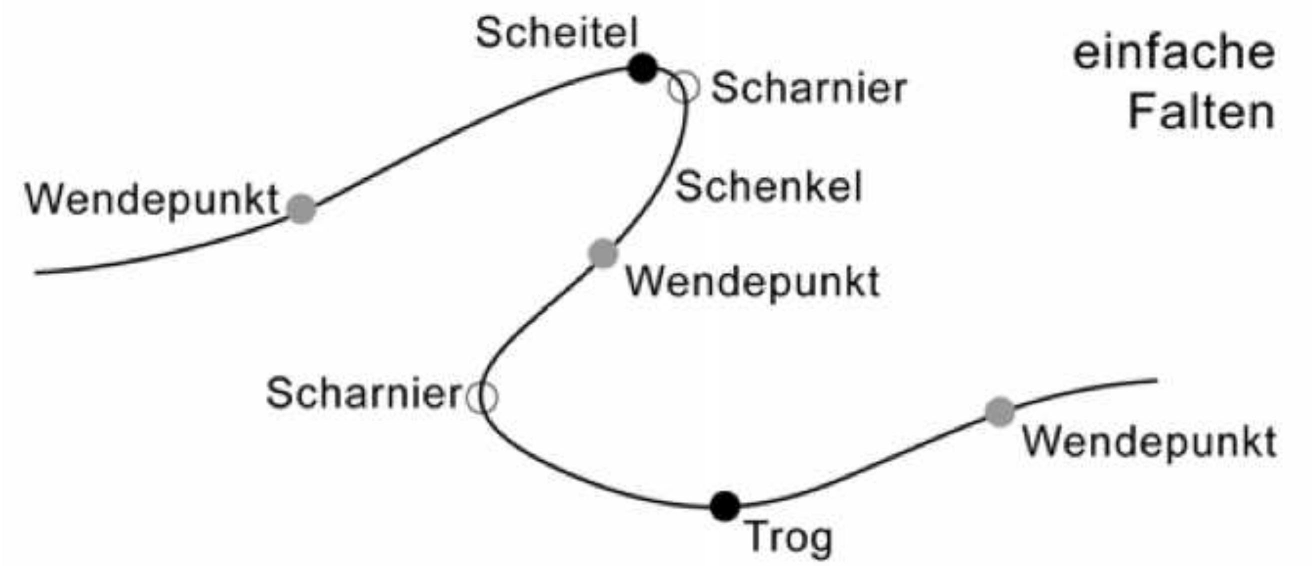
Falte als Welle



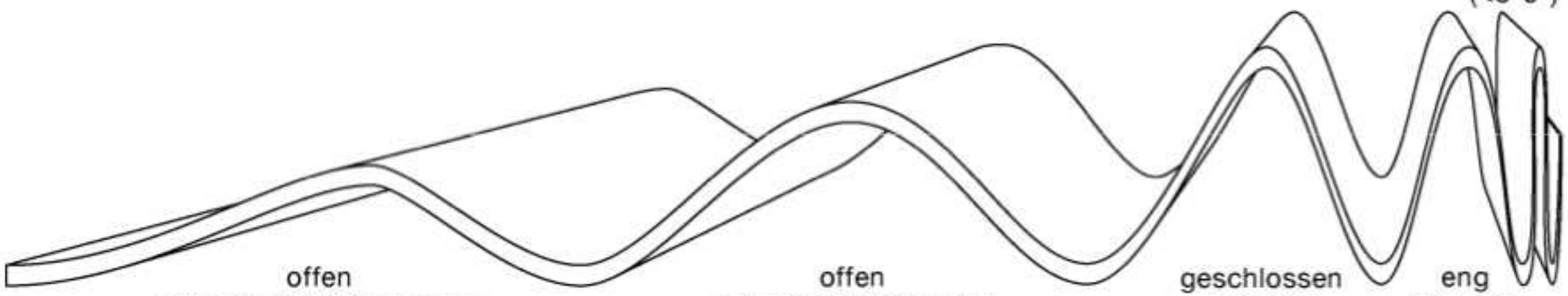
Burg ETH Zürich
http://e-collection.library.ethz.ch/eserv/eth:24456/eth-24456-01.pdf

Falten: Terminologie

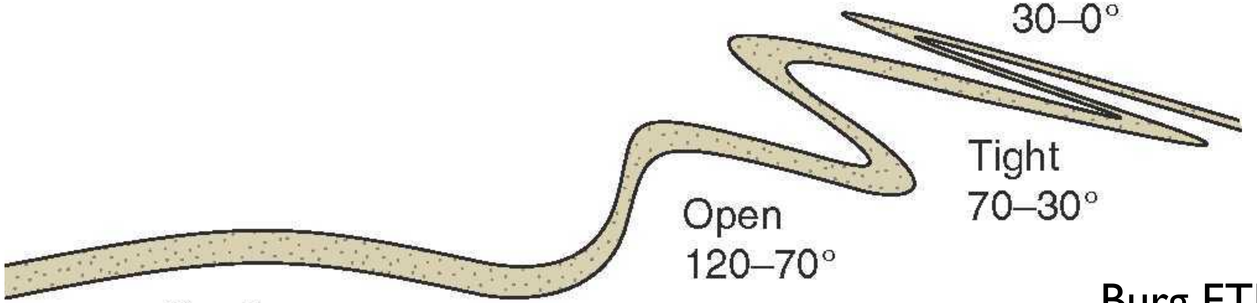




Öffnungswinkel

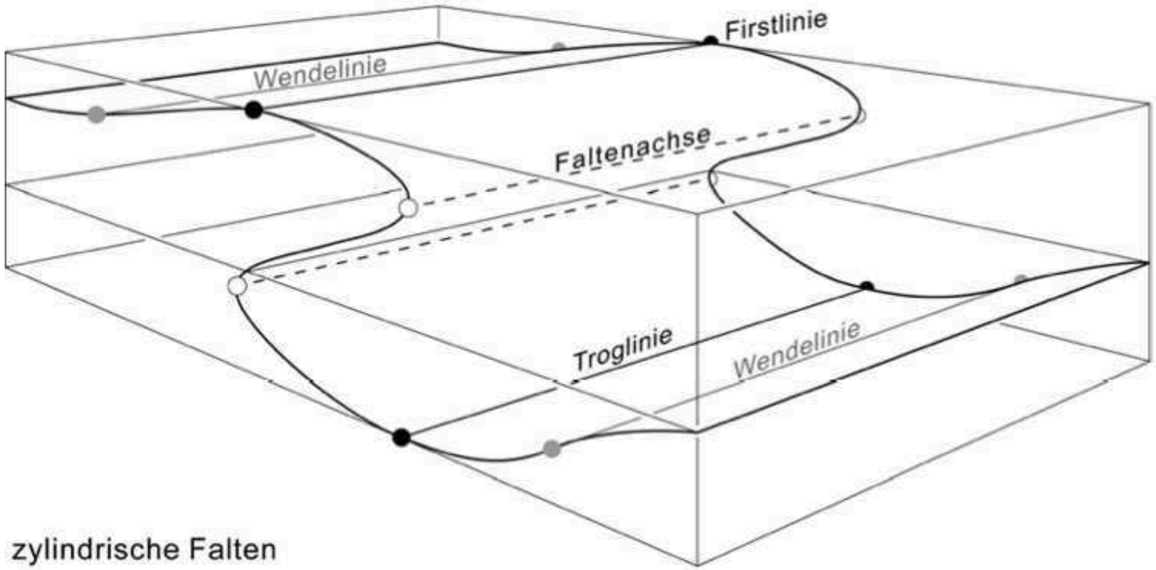


Öffnungswinkel	Klassen	*englische Bezeichnung*
180 bis ca. 120°	**offen stumpfwinklig**	*gentle*
120 -- 70°	**offen spitzwinklig**	*open*
70 -- 30°	**geschlossen**	*close*
kleiner als 30°	**eng**	*tight*
0°, d.h. parallele Schenkel	**isoklinal**	*isoclinal*

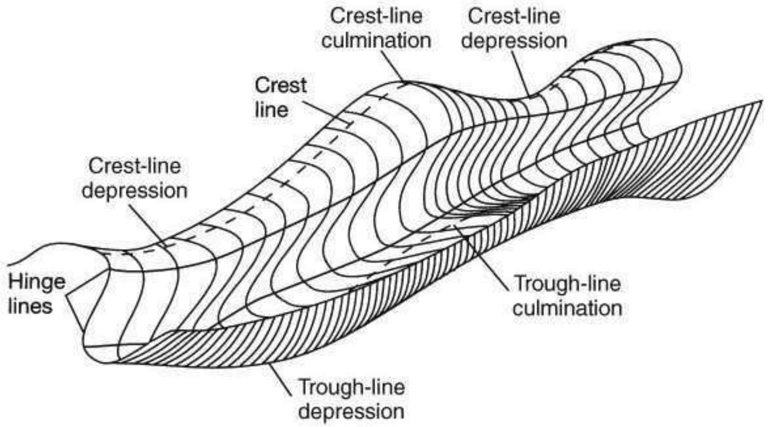


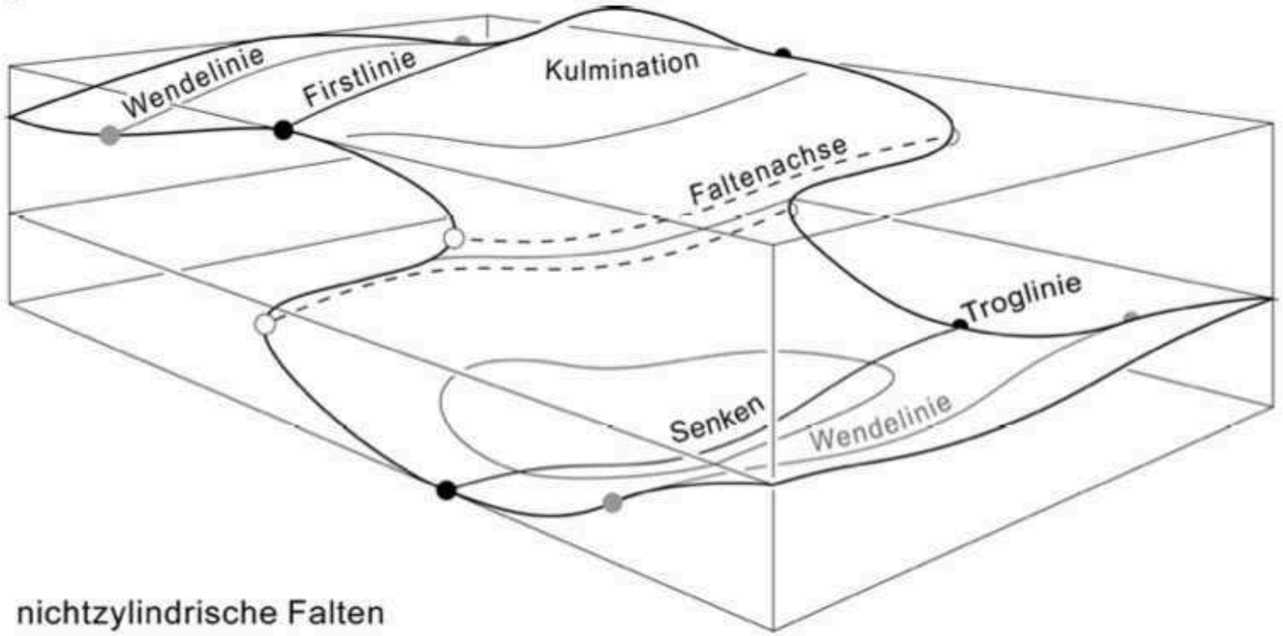
Burg ETH Zürich
Fossen Structural Geology

zylindrisch - nichtzylindrisch



zylindrische Falten





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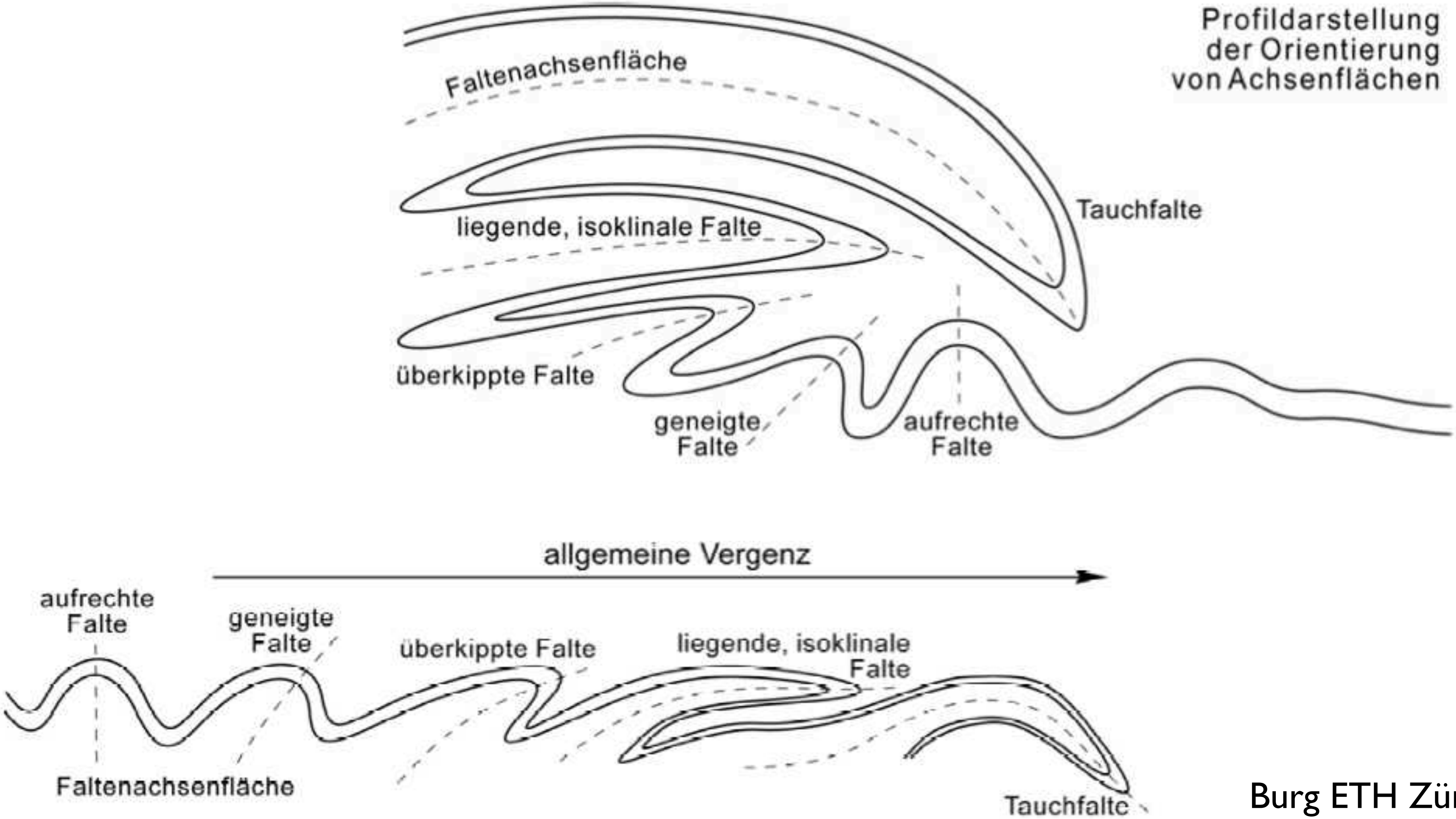
nichtzylindrische Falten

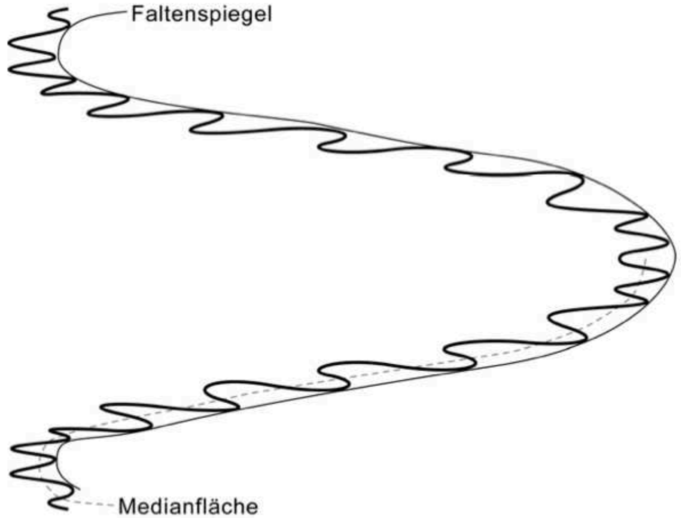
Vergenz

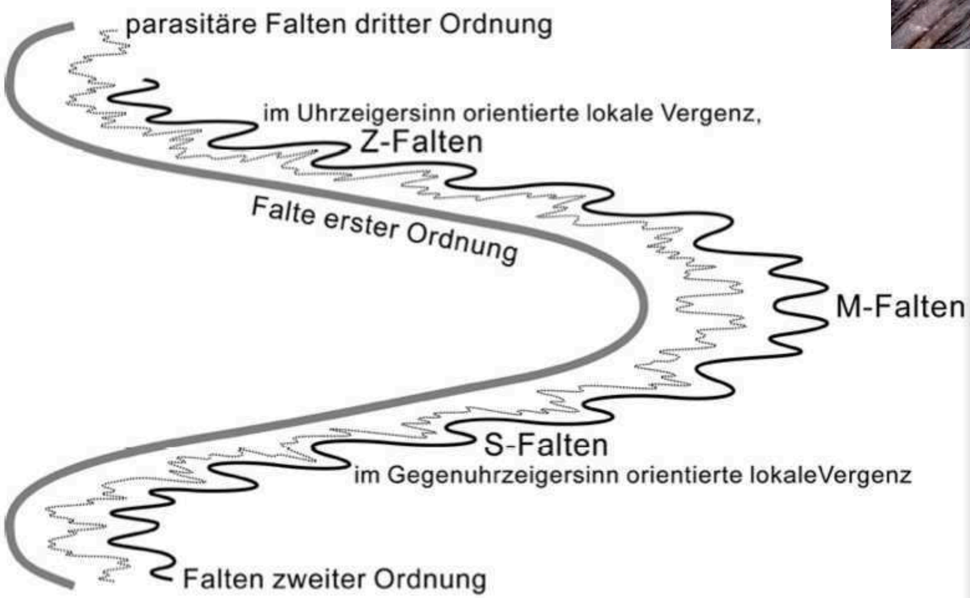


Burg ETH Zürich

Facing (= wahre Vergenz):
younging direction along the fold axial surface

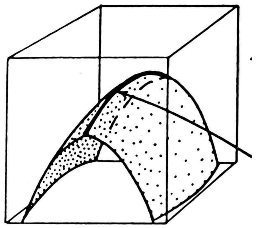
Falten höherer Ordnung

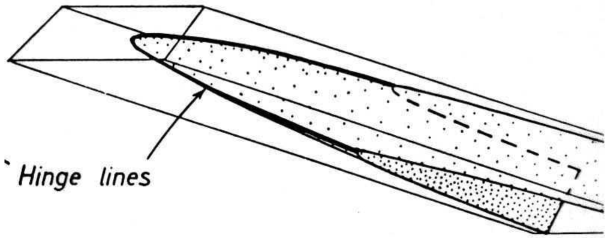


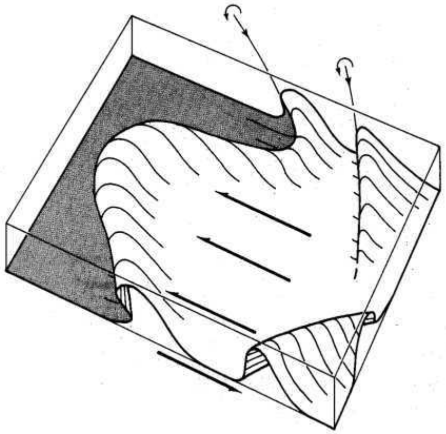


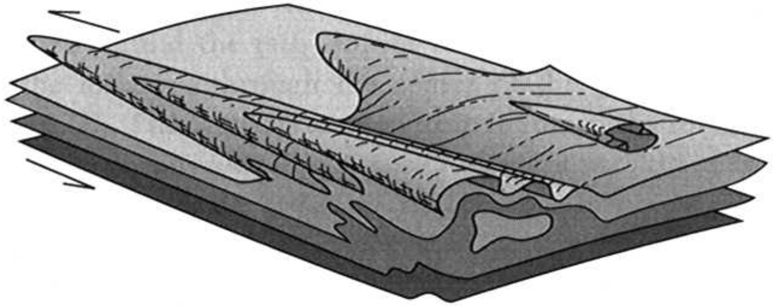
Burg ETH Zürich

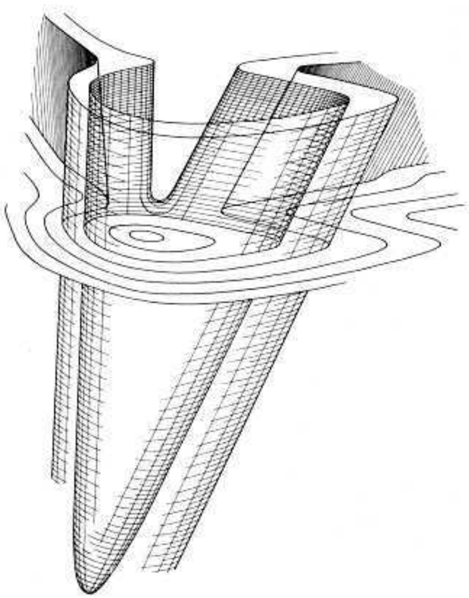
Spezialfall: Futteralfalte (sheath fold)





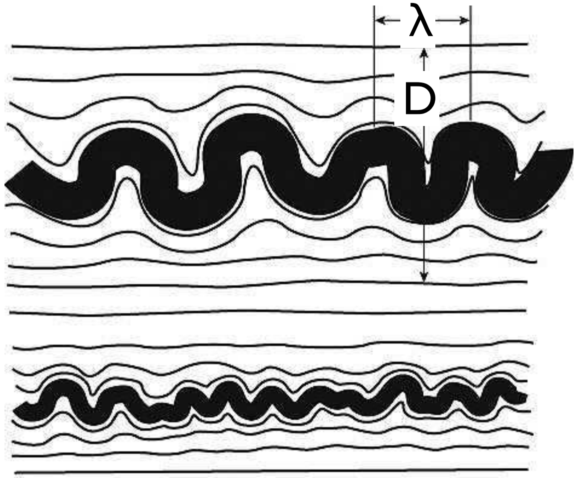




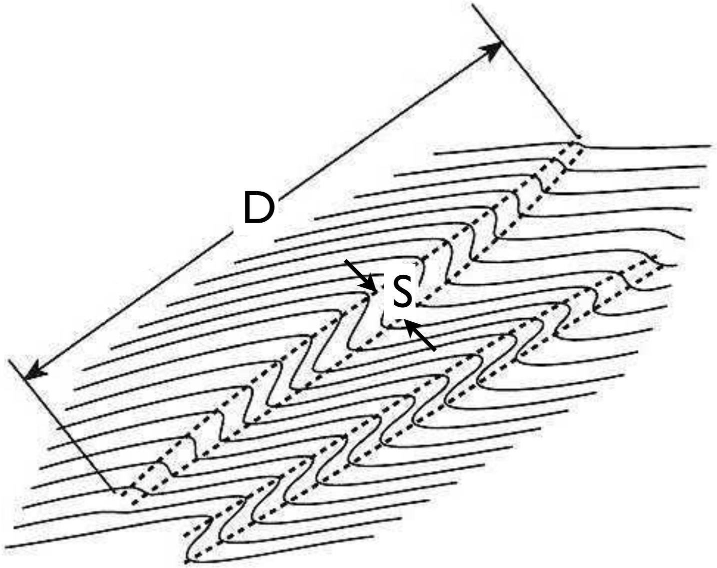


Twiss & Moores

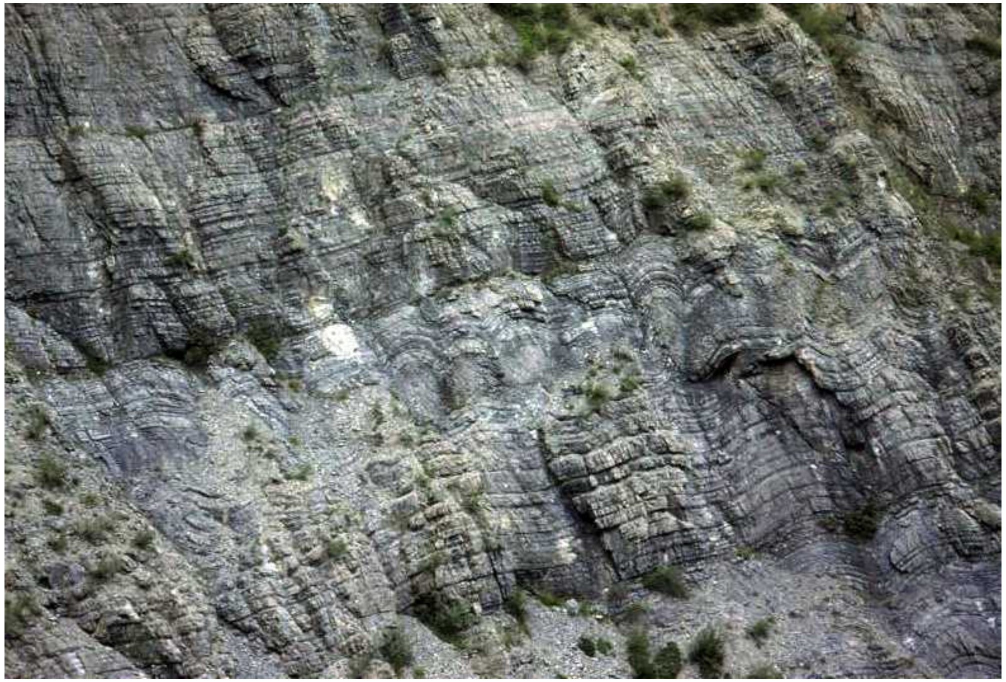
Harmonie - Disharmonie



H = 2D/λ ≈5



H = D/S ≈12



H = harmony ratio

H = D/S = 2D/λ

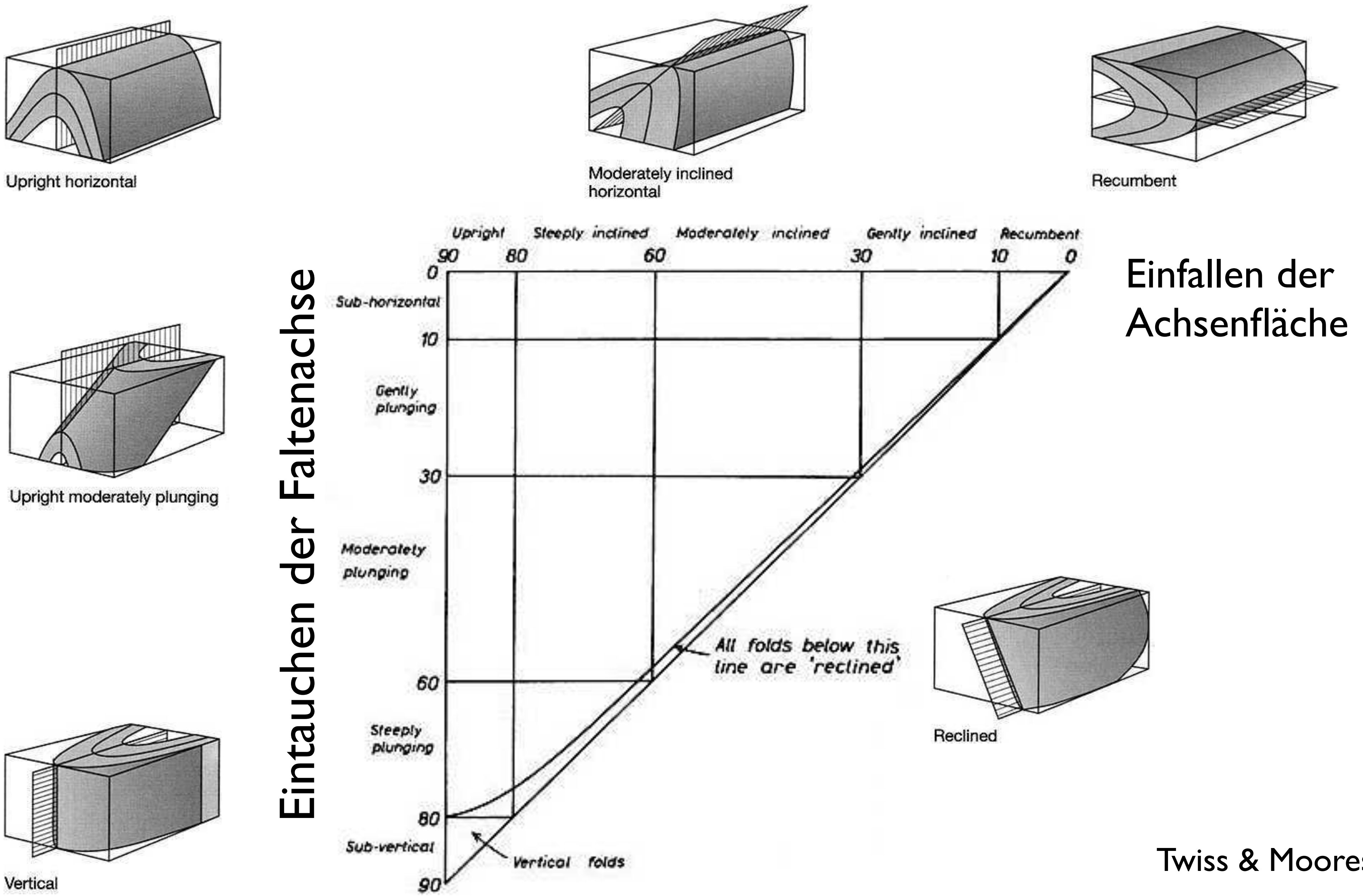
D = Ausdehnung der Falte // Achsenfläche

λ = Wellenlänge

S = λ / 2 = Schenkel

fold
Klassifikationen

Klassifikation: Faltenachse / Achsenfläche



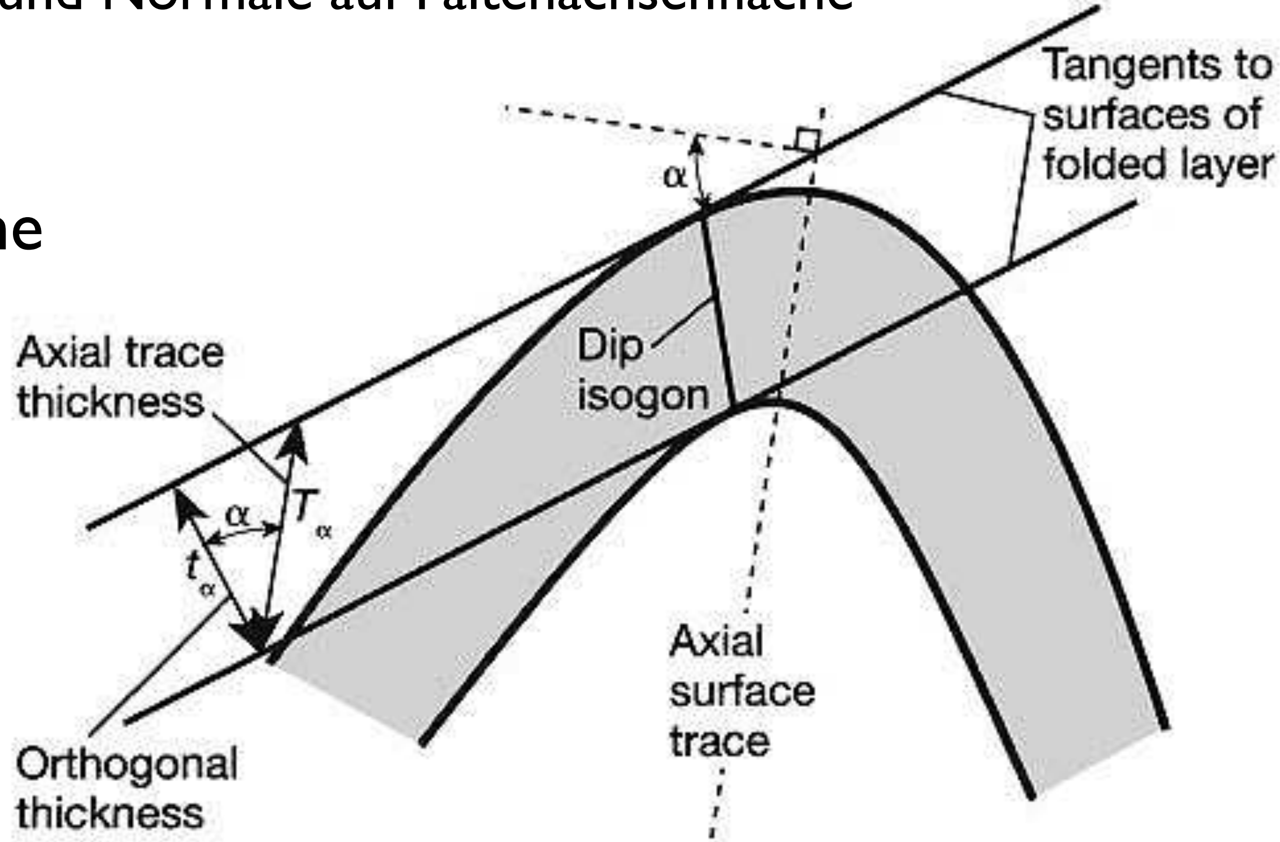
Twiss & Moores

Isogonen

α = Winkel zwischen Schicht
und Normale auf Faltenachsenfläche

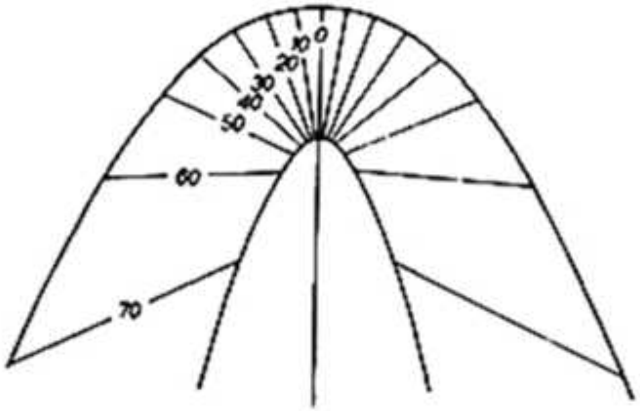
T = Dicke der Schicht
parallel zur Achsenfläche

$$t_\alpha = \cos(\alpha) \cdot T_\alpha$$

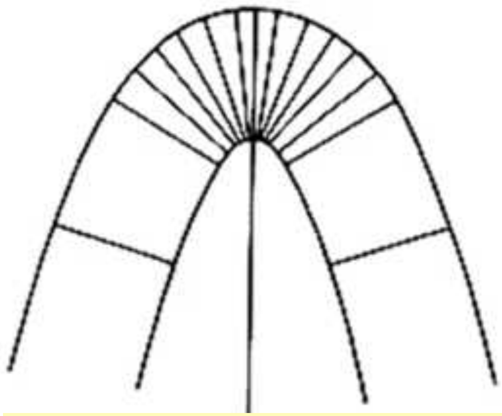


t = Dicke der Schicht
senkrecht zur Schichtfläche

Ramsay's classification of folds



Typ 1A



Typ 1B parallele Falte

Typ 1C

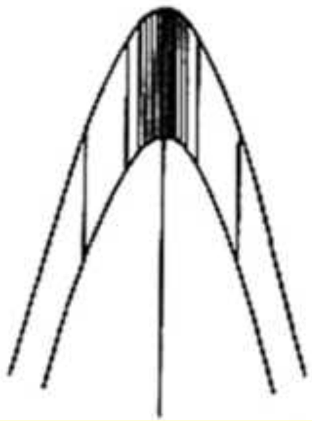
Isogonen sind im...

Typ 1 - konvergent

Typ 2 - parallel

Typ 3 - divergent

... bezüglich des Faltenkerns



Typ 2 kongruente Falte

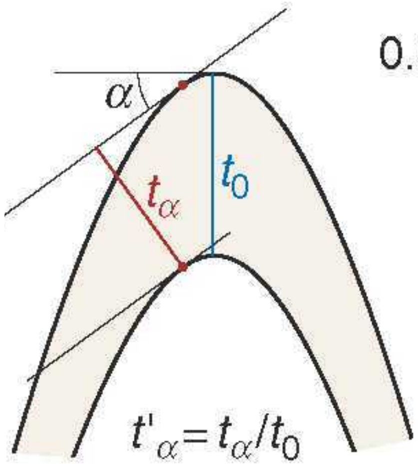
Typ 3

Schichtdicke nimmt zu

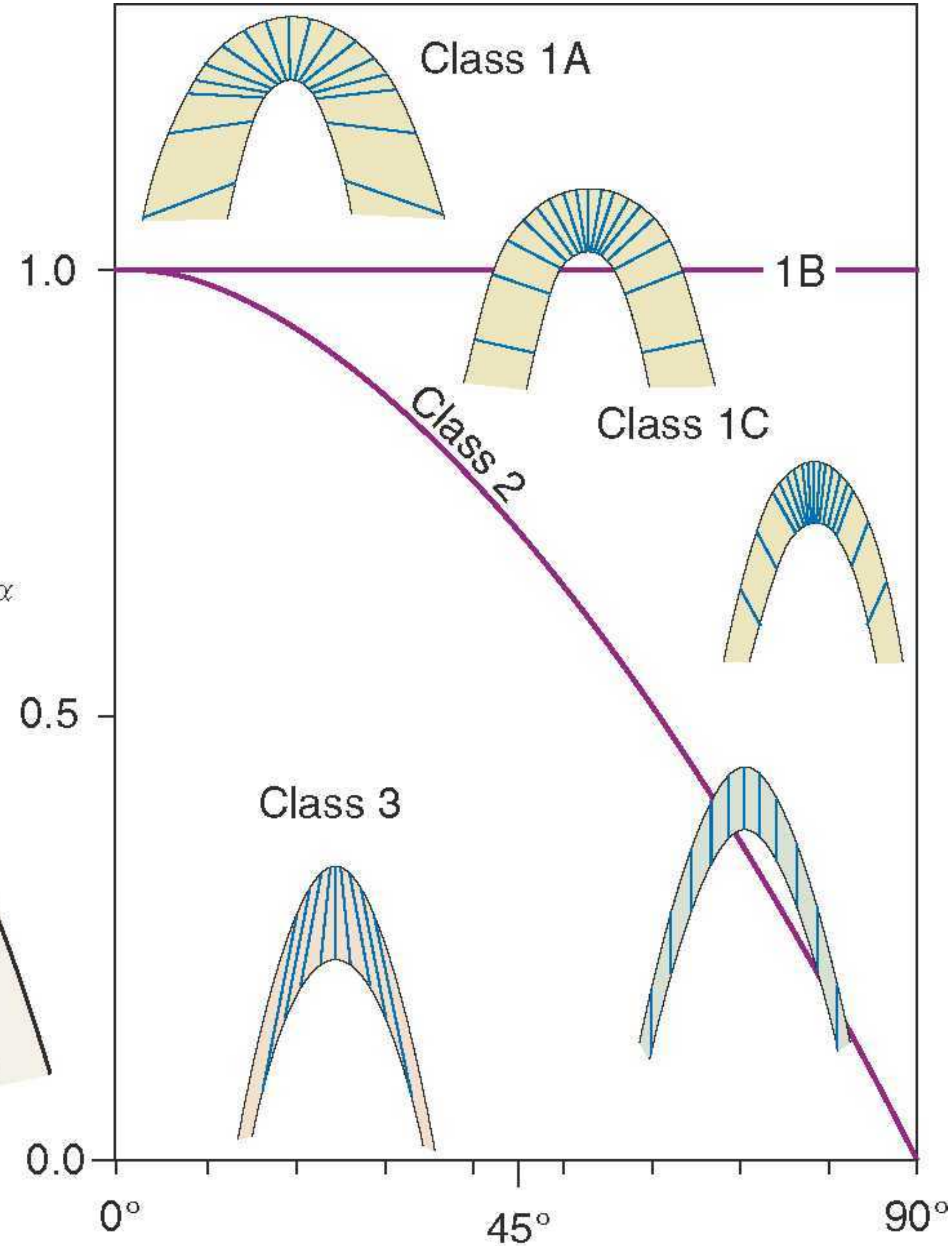
Schichtdicke konstant

Schichtdicke nimmt ab

α
Winkel zwischen Schicht und Normale auf Faltenachsenfläche
=
Einfallswinkel der Schicht, wenn Achesnfläche senkrecht

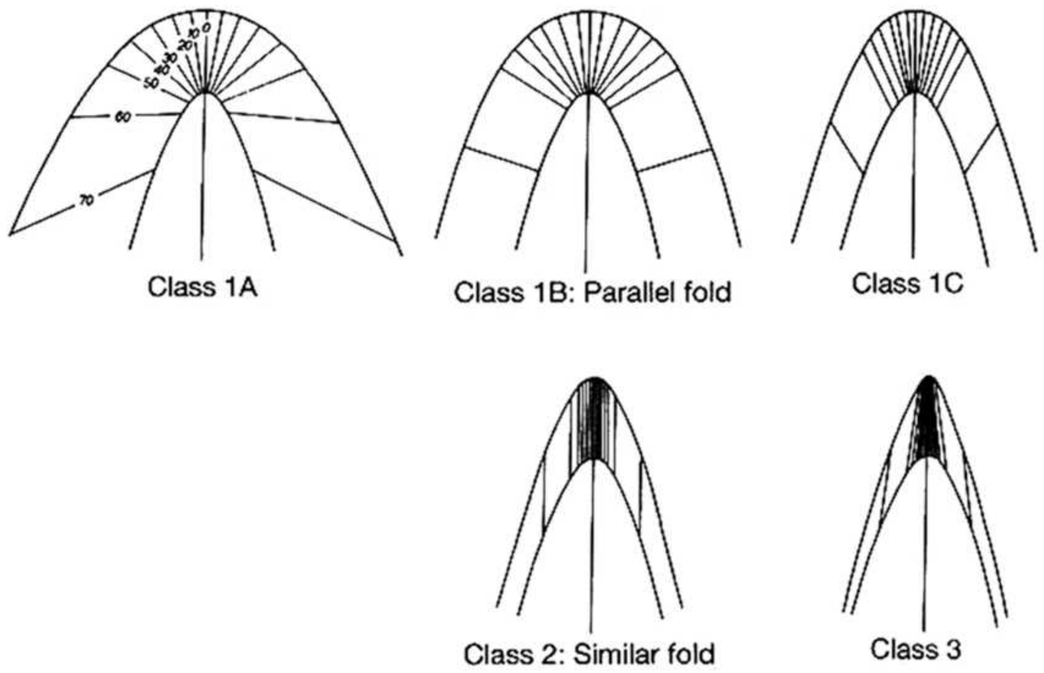


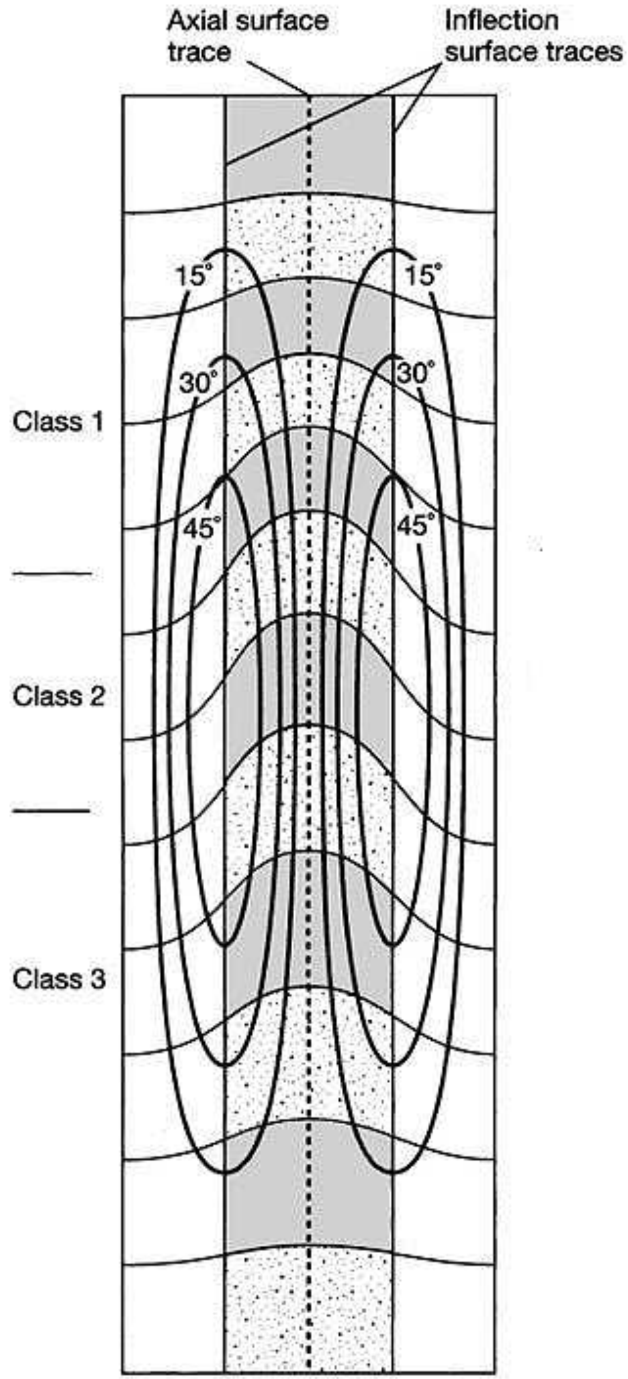
Fossen



Lokales Einfallen der Schicht (α)

Beispiel

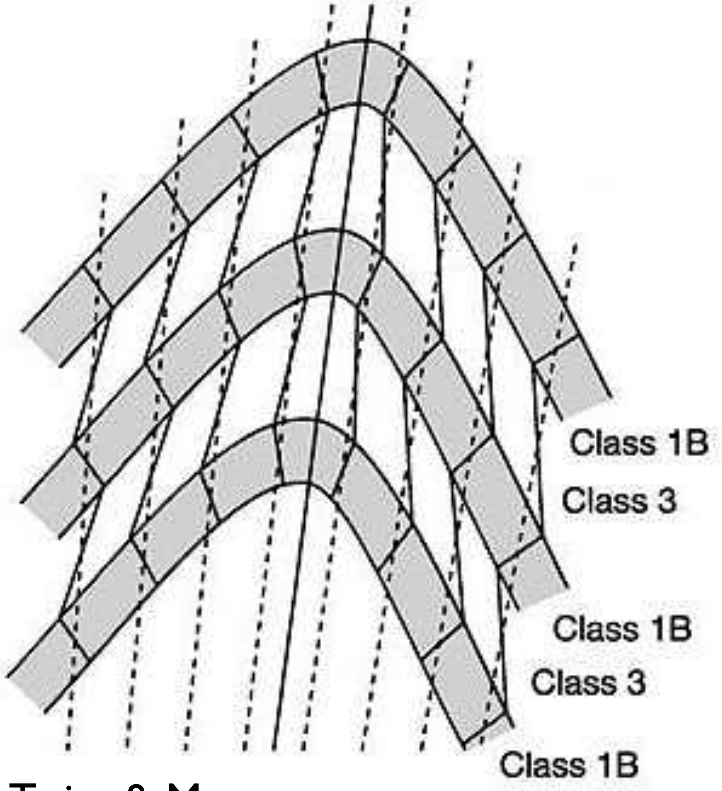




oberes Ende: Class 1
Mitte: Class 2
unteres Ende: Class 3

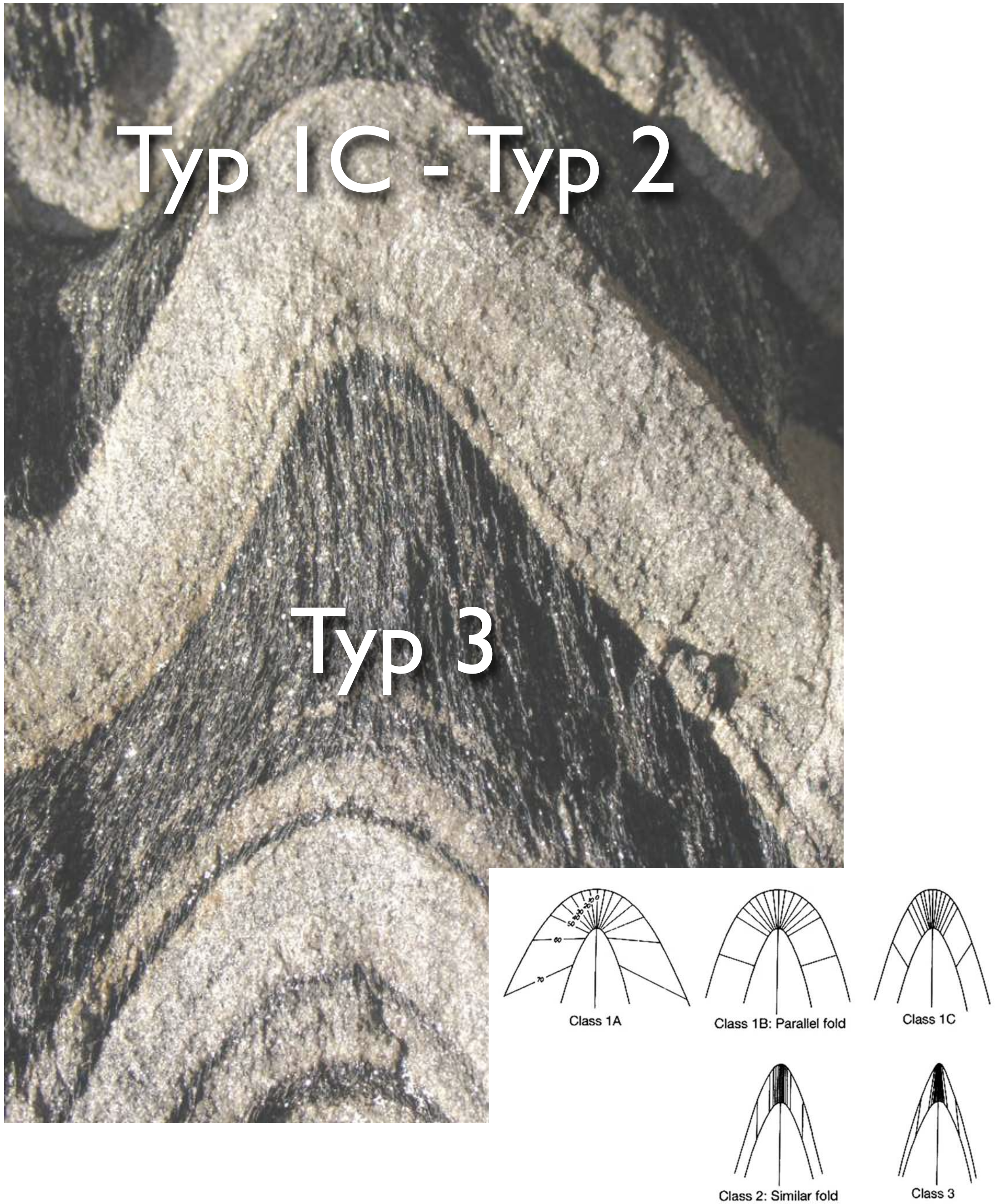
Twiss & Moores

Beispiel

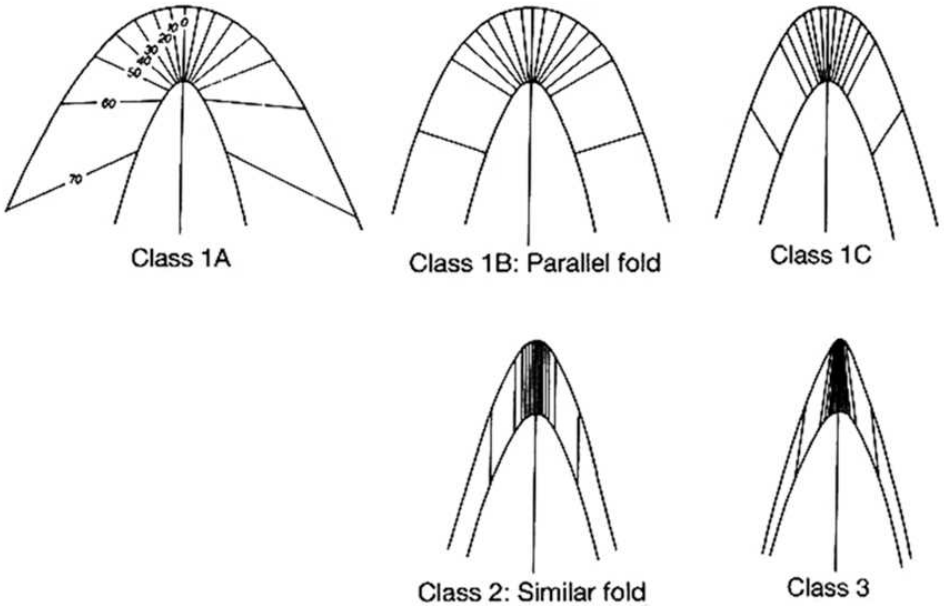


Twiss & Moores

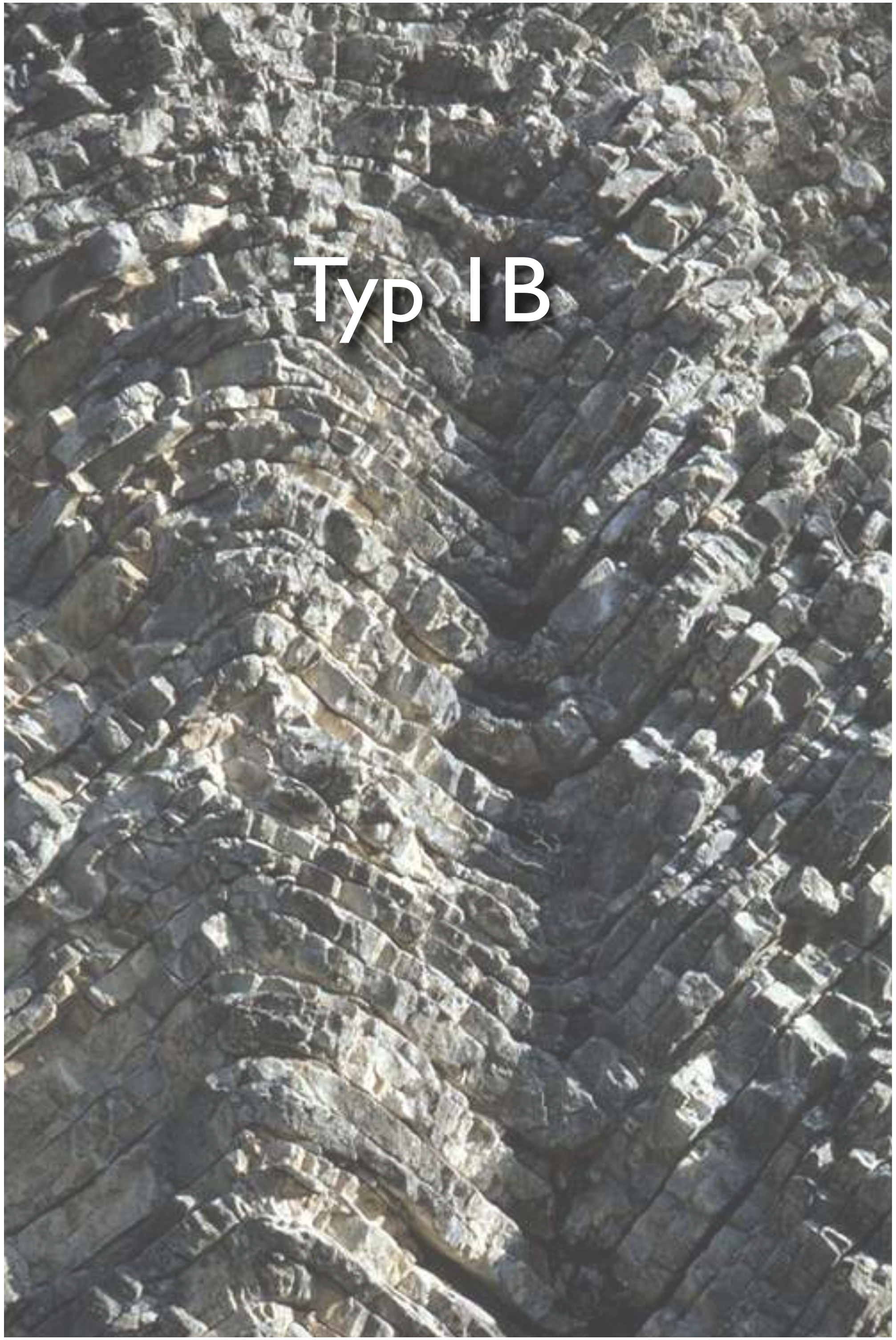
Verschieden Schichten:
Grau: Class 1B
(konstante Schichtdicke)
Weiss: Class 3
(divergente Isogonen)



Beispiel



Knickfalten im Jura und Chaines Subalpines: Konstante Schichtdicke

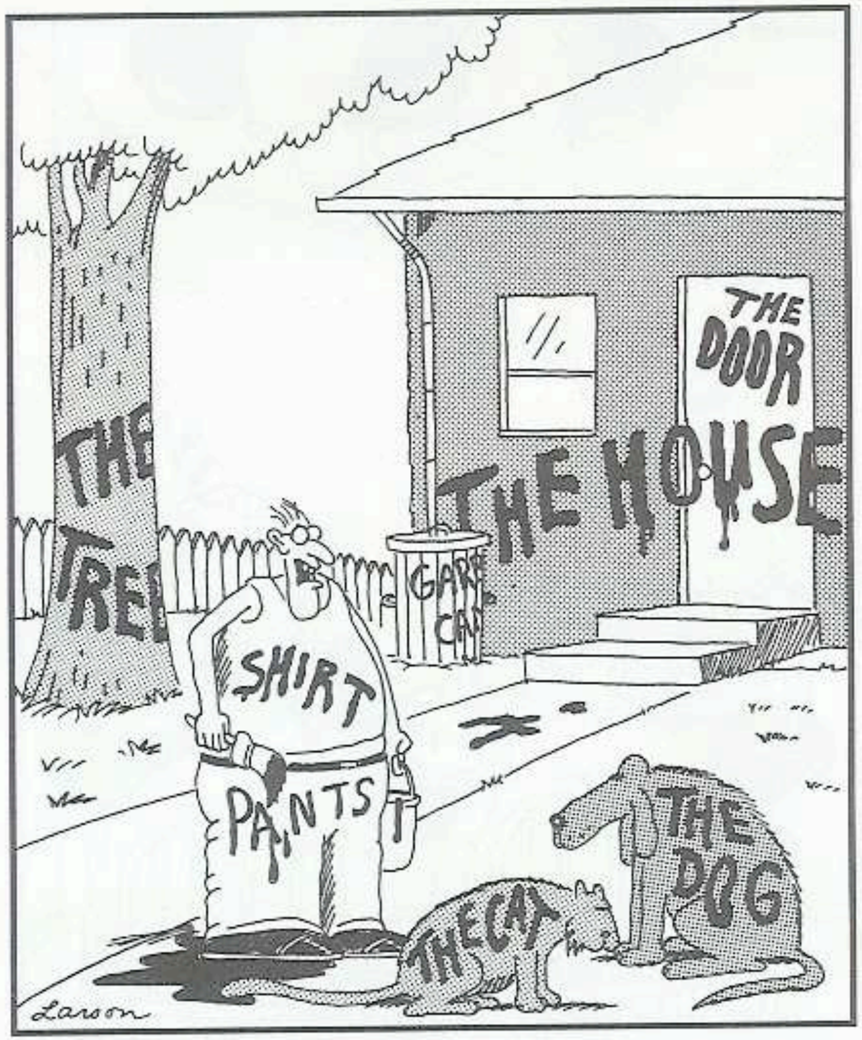


Klassifikation sind ...

... gut,
wenn sie beschreibend
geometrisch
(beobachtbar)

... schlecht,
wenn sie genetisch,
interpretierend
prozess-abhängig
(nicht beobachtbar)

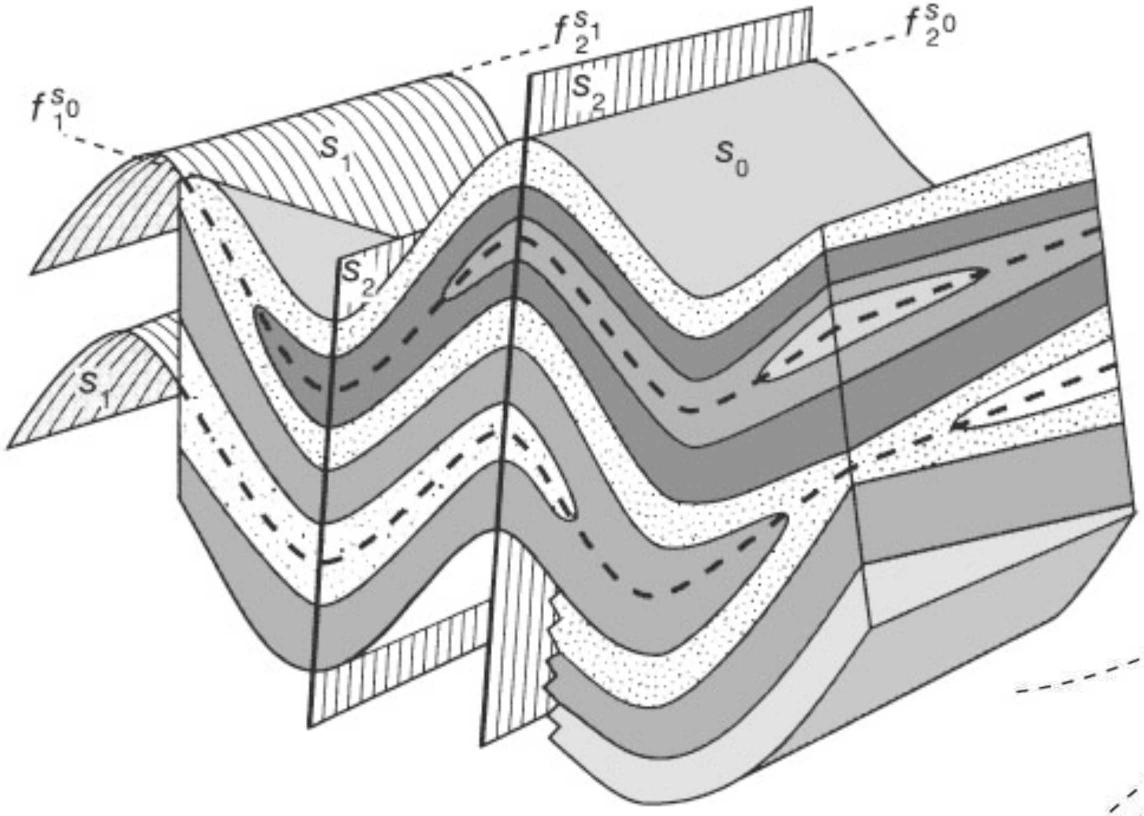
sind



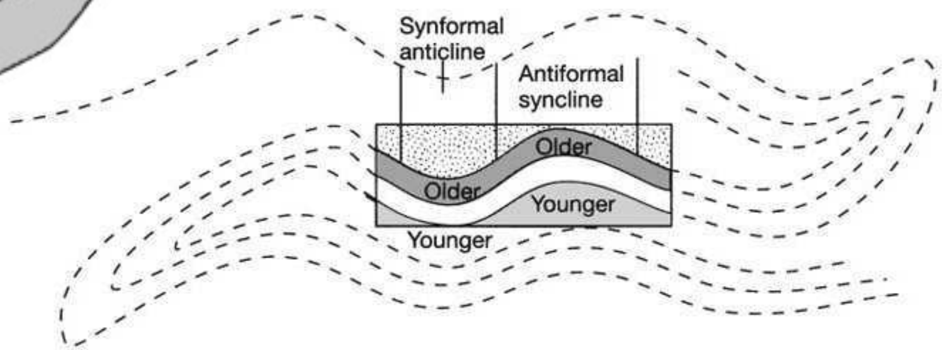
"Now! ... *That* should clear up a few things around here!"

superposed folding

Superposed folding



Twiss & Moores



Overturned beds

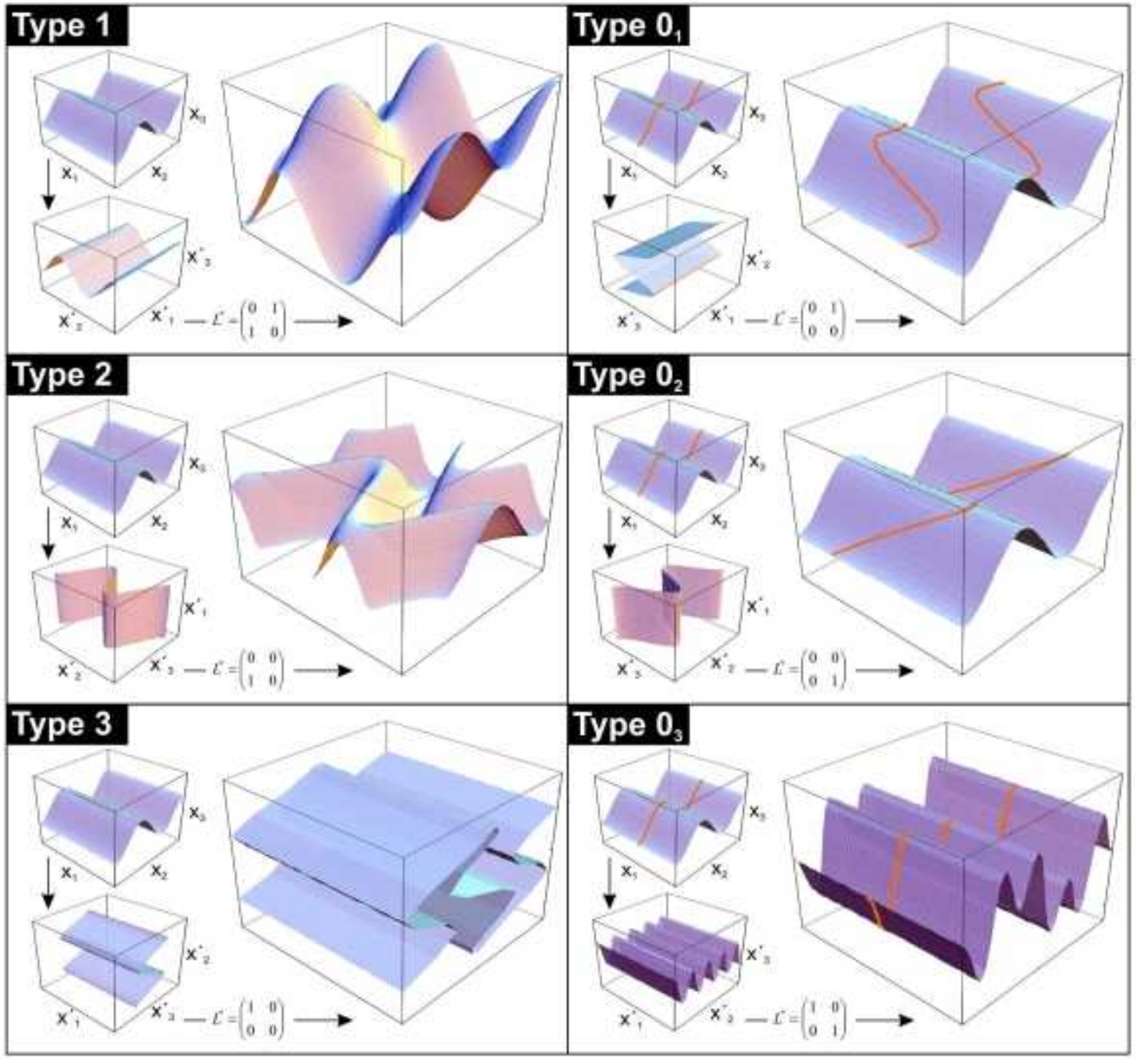
several phases of folding;
requires geometric analysis;
most important: fold axial surfaces (S = plane), fold axis (F = direction)
fold axis = axis of rotation

Superposition

$S_1 \perp S_2$
$F_1 \perp F_2$
$F_1 \# S_2$

$S_1 \perp S_2$
$F_1 \perp F_2$
$F_1 \# S_2$

$S_1 \perp S_2$
$F_1 // F_2$
$F_1 // S_2$



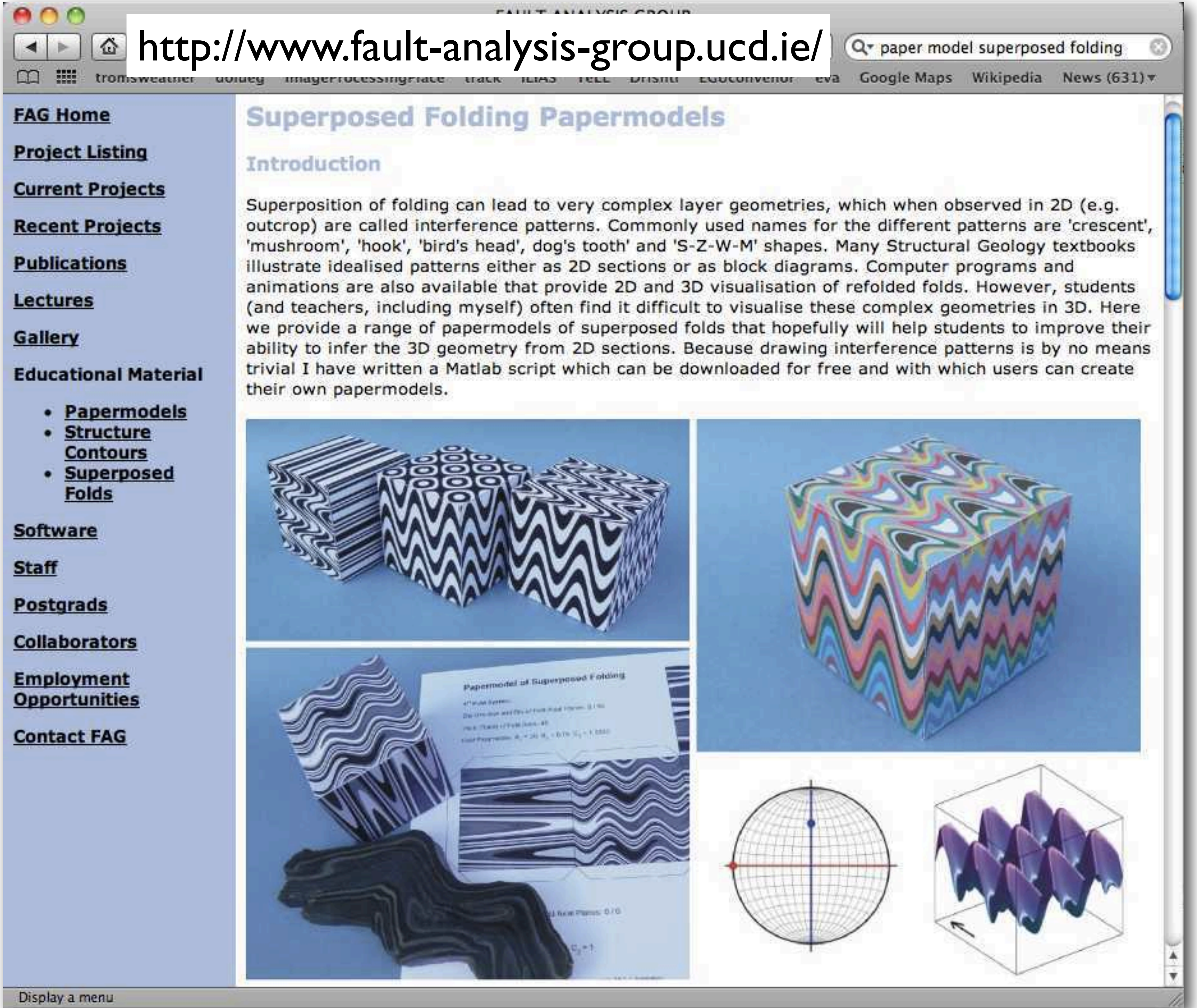
$S_1 \perp S_2$
$F_1 \perp F_2$
$F_1 // S_2$

$S_1 \perp S_2$
$F_1 \perp F_2$
$F_1 // S_2$

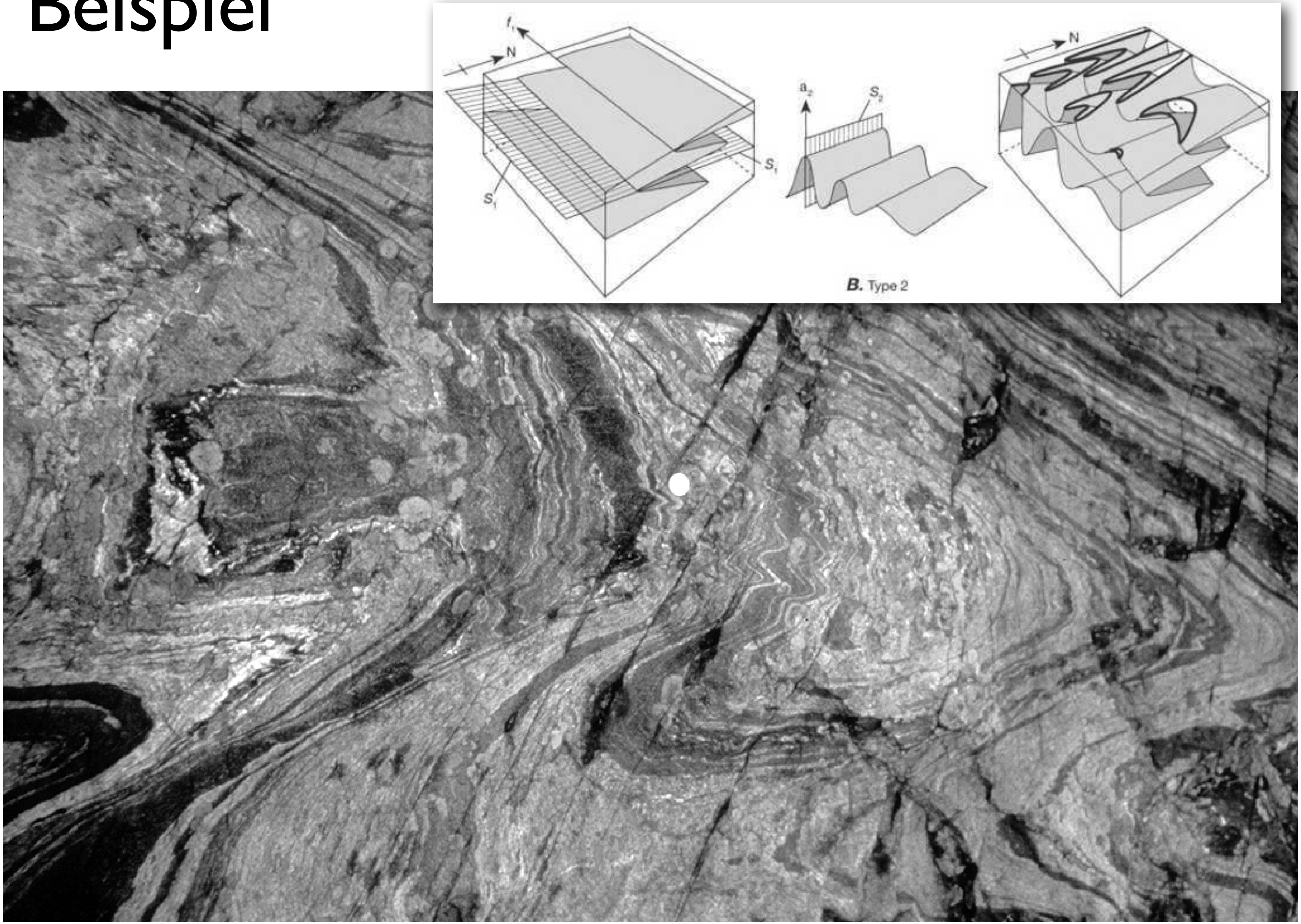
$S_1 // S_2$
$F_1 // F_2$
$F_1 // S_2$

University College Dublin http://www.fault-analysis-group.ucd.ie/

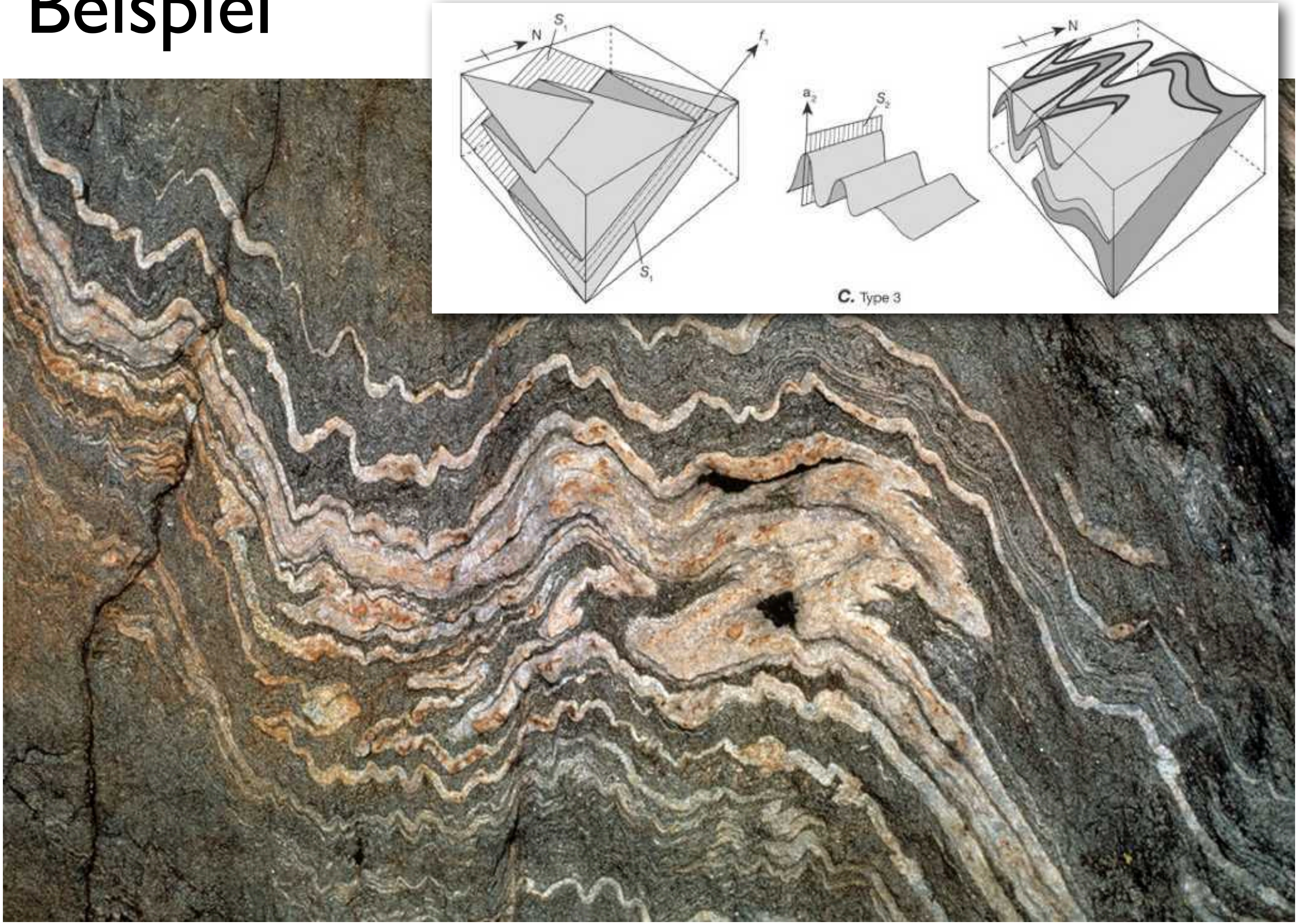
Faltenachsenfläche (S), Faltenachse (F)


http://www.fault-analysis-group.ucd.ie/
paper model superposed folding
Google Maps
Wikipedia
News (631)
FAG Home
Project Listing
Current Projects
Recent Projects
Publications
Lectures
Gallery
Educational Material
Papermodels
Structure Contours
Superposed Folds
Software
Staff
Postgrads
Collaborators
Employment Opportunities
Contact FAG
Superposed Folding Papermodels
Introduction
Superposition of folding can lead to very complex layer geometries, which when observed in 2D (e.g. outcrop) are called interference patterns. Commonly used names for the different patterns are 'crescent', 'mushroom', 'hook', 'bird's head', dog's tooth' and 'S-Z-W-M' shapes. Many Structural Geology textbooks illustrate idealised patterns either as 2D sections or as block diagrams. Computer programs and animations are also available that provide 2D and 3D visualisation of refolded folds. However, students (and teachers, including myself) often find it difficult to visualise these complex geometries in 3D. Here we provide a range of papermodels of superposed folds that hopefully will help students to improve their ability to infer the 3D geometry from 2D sections. Because drawing interference patterns is by no means trivial I have written a Matlab script which can be downloaded for free and with which users can create their own papermodels.
Papermodel of Superposed Folding
Display a menu

Beispiel



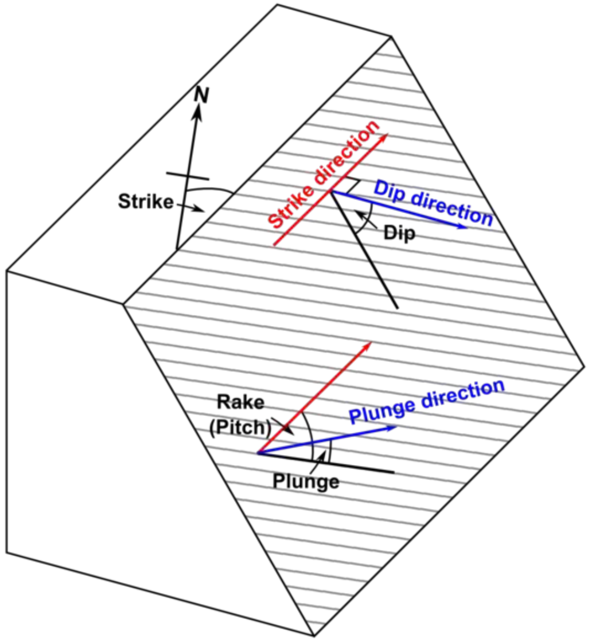
Beispiel



C. Type 3

Falten im Stereonetz

Flächen, Lineare im Stereonetz

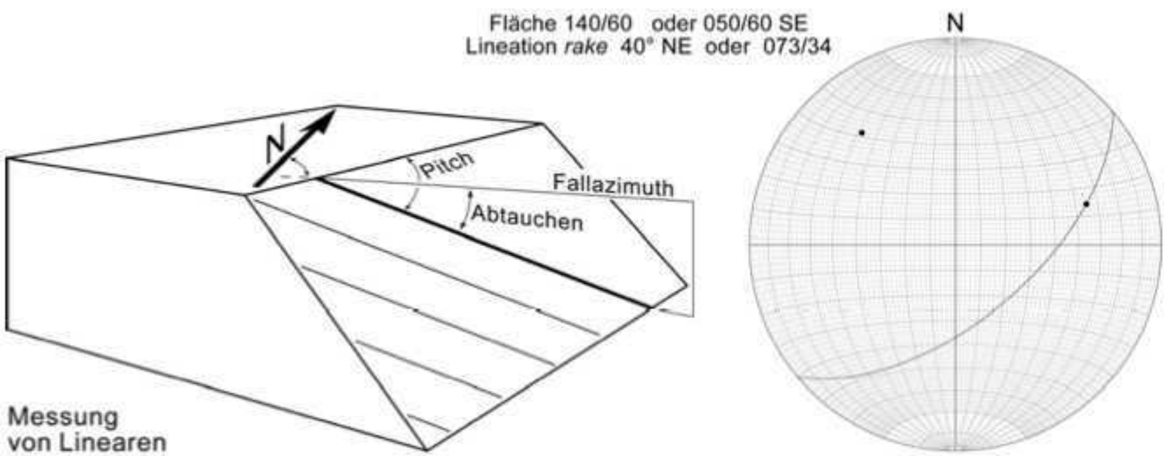


Fläche:

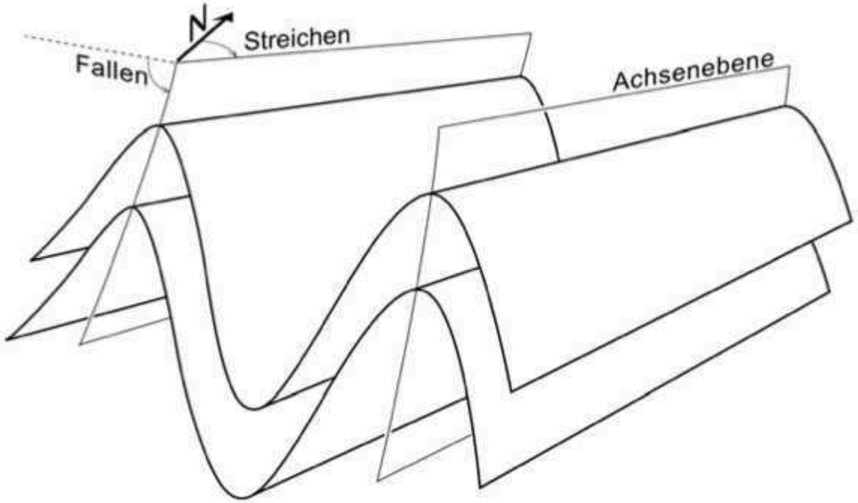
Fallazimuth	dip direction
Fallen	dip
Streichen	strike (direction)

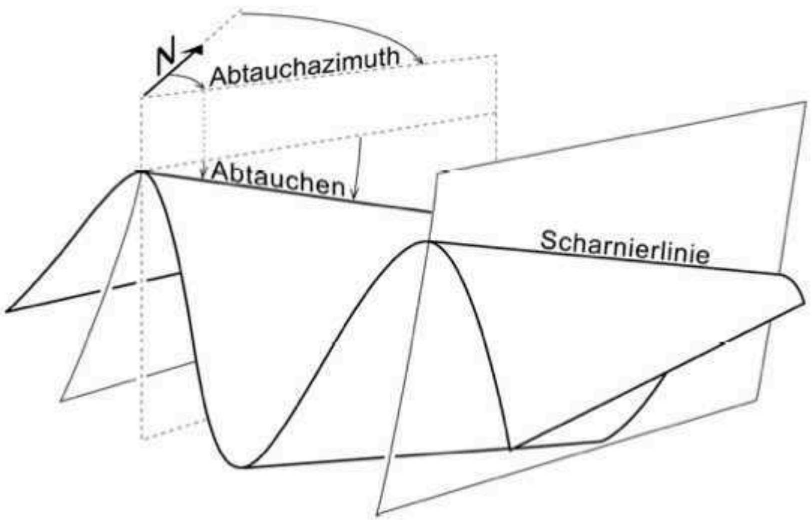
Lineare:

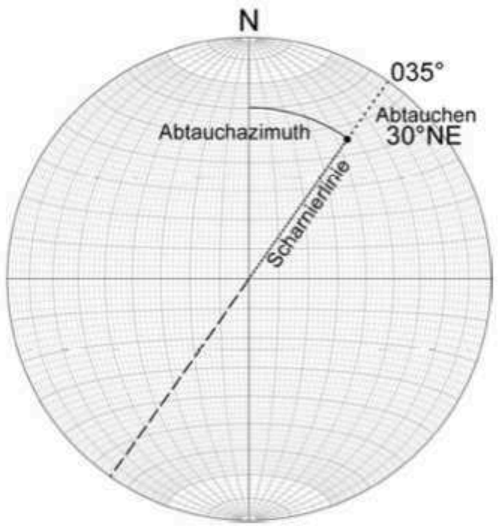
Azimuth	plunge direction
(Ab-)Tauchwinkel	plunge
Winkel mit Streichen	rake, pitch



Achsenebene, Scharnier im Stereonetz

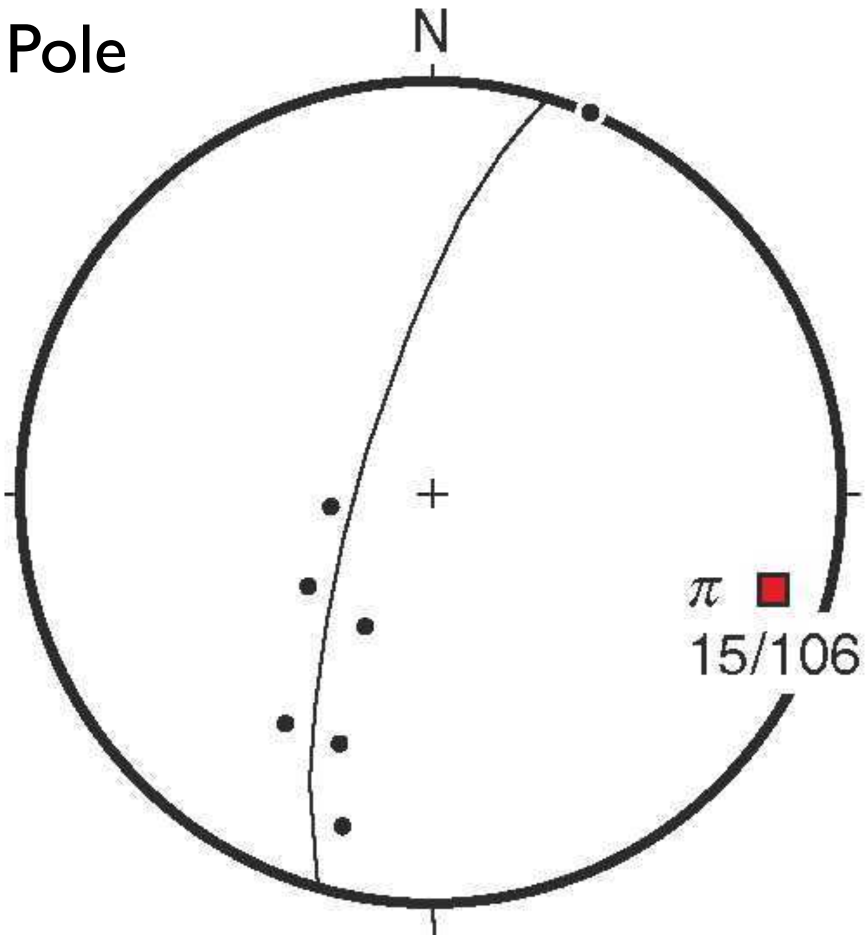




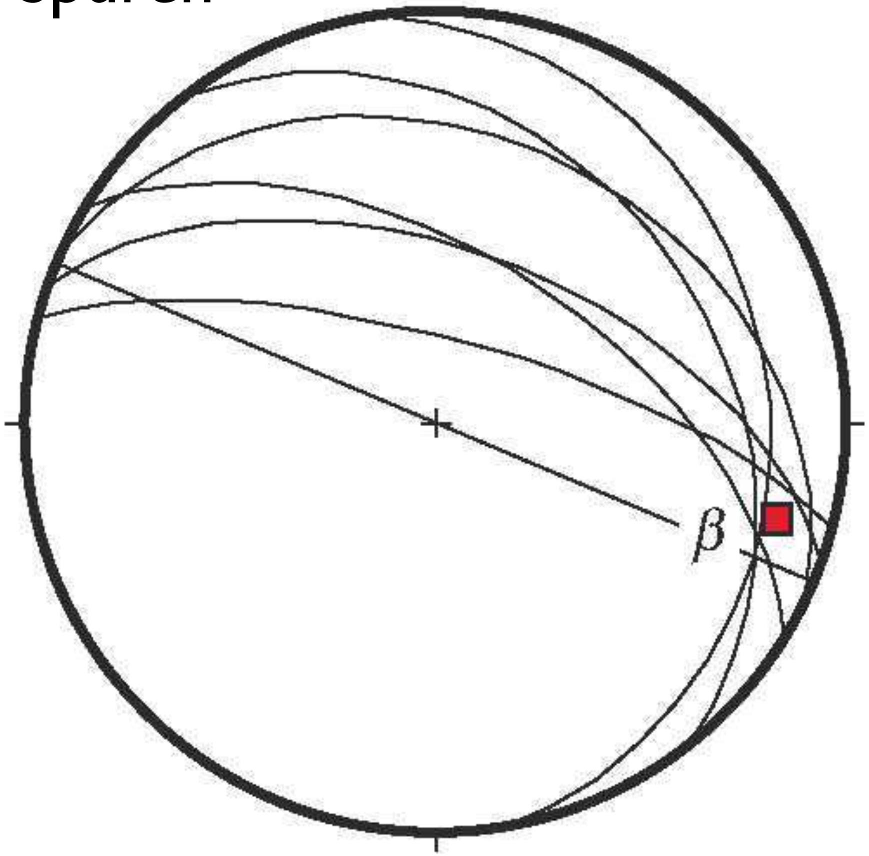


Konstruktion der Faltenachse

Pole



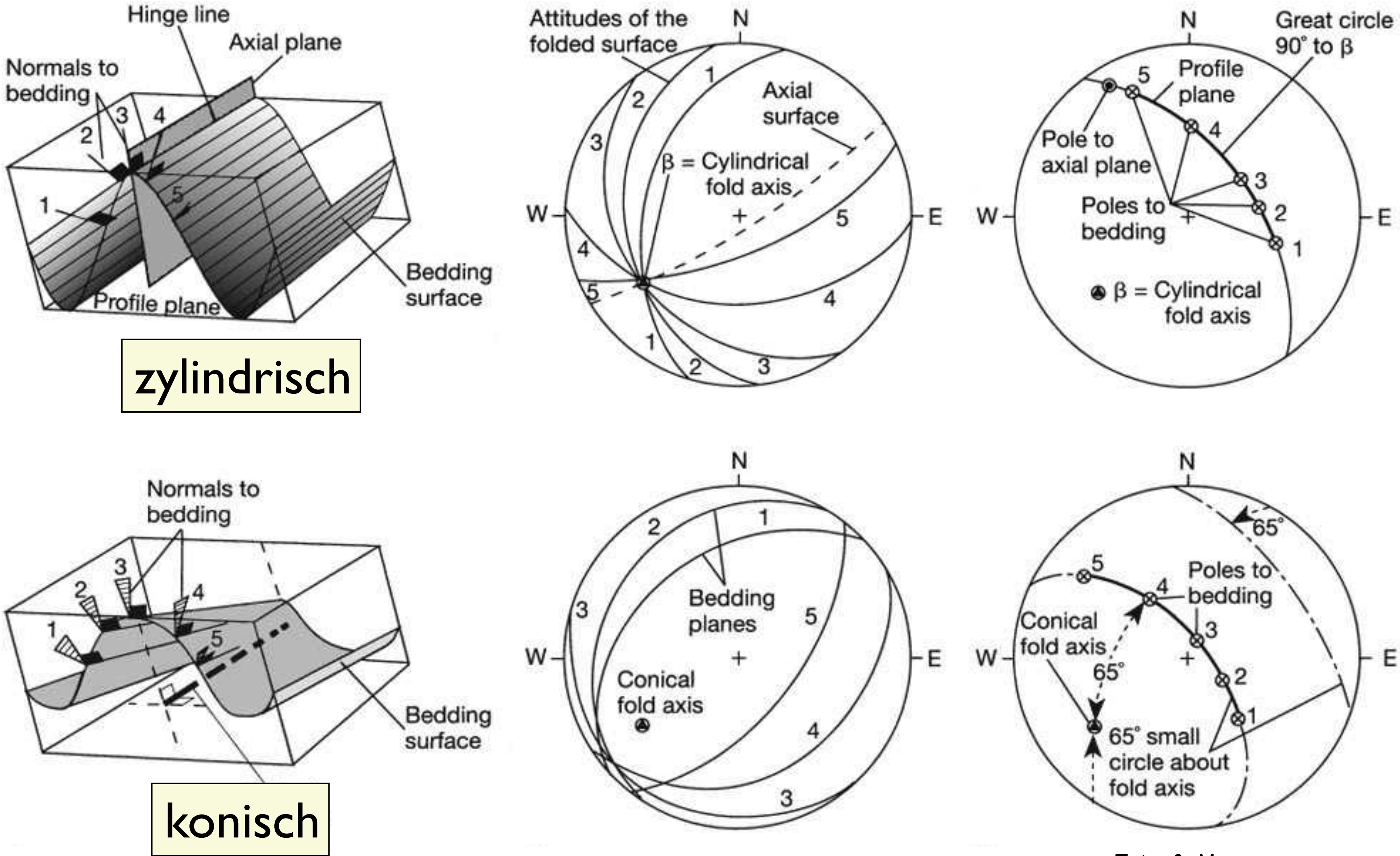
Spuren



Faltenachse (π) =
Pol zur Fläche durch Flächenpole

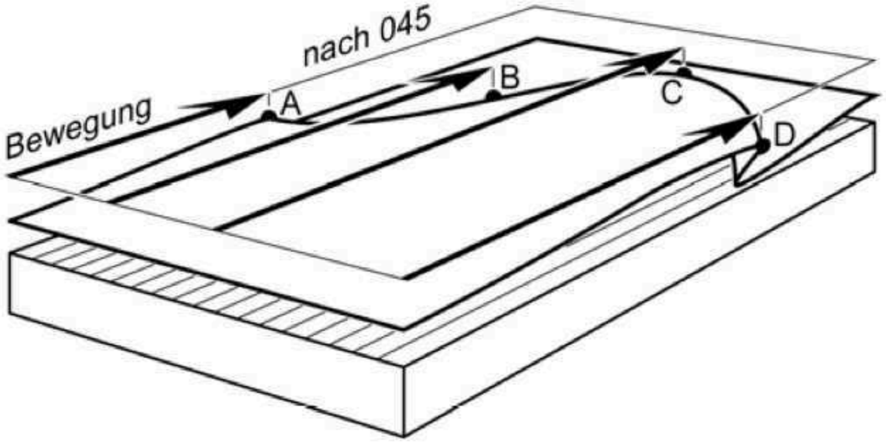
Faltenachse (β) =
Schnittpunkt der Flächenspuren

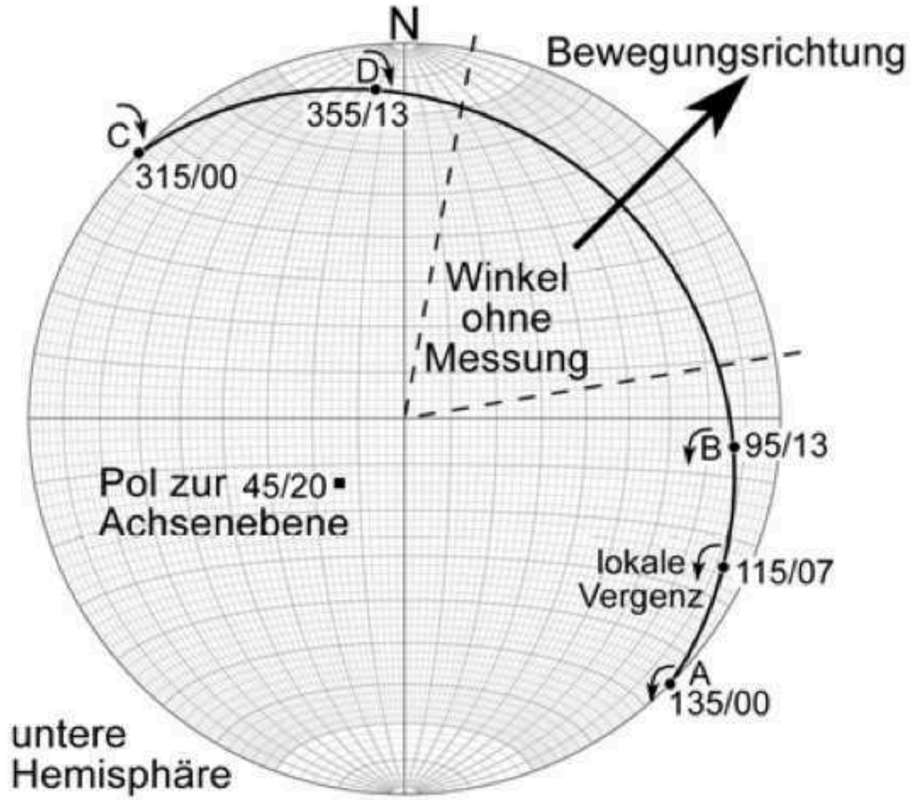
zylindrische - konische Falten



Twiss & Moores

sheat folds (Zungenfalten)





Lokale Vergenz berücksichtigen

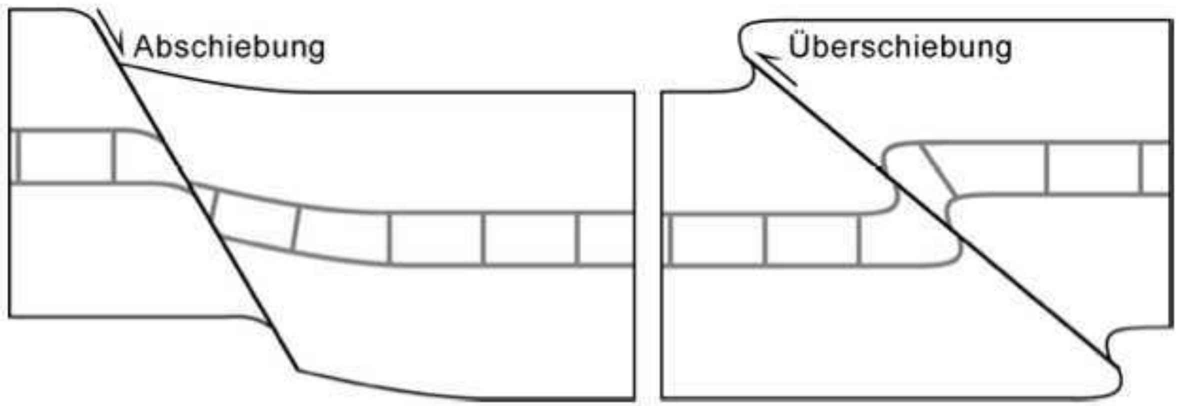
↷ dextral (C, D) ↶ sinistral (A, B)

Burg ETH Zürich

folds and structures

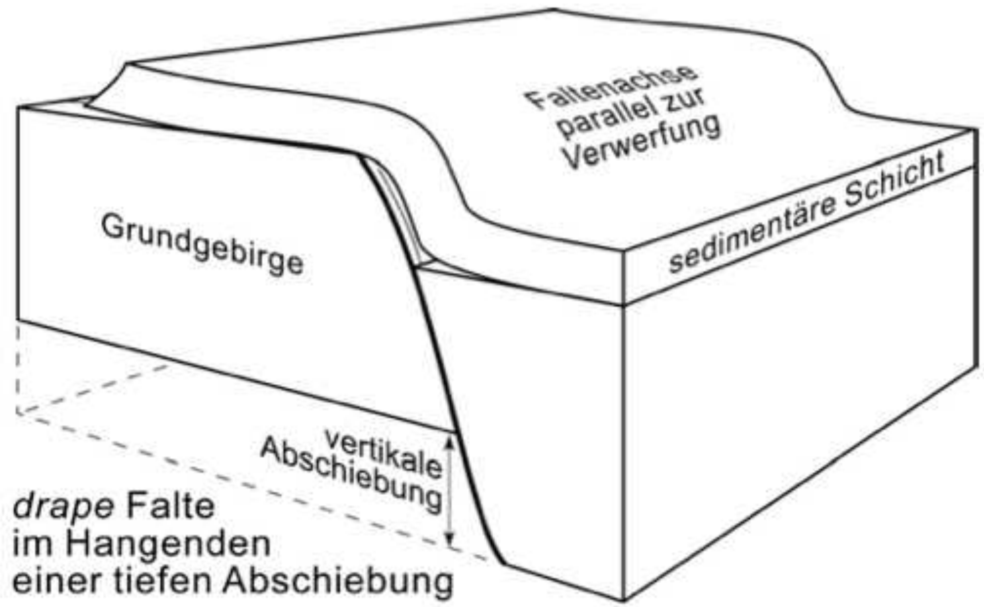
Schleppfalten

... an Verwerfungsflächen



Burg ETH Zürich

Falten an Abschiebungen

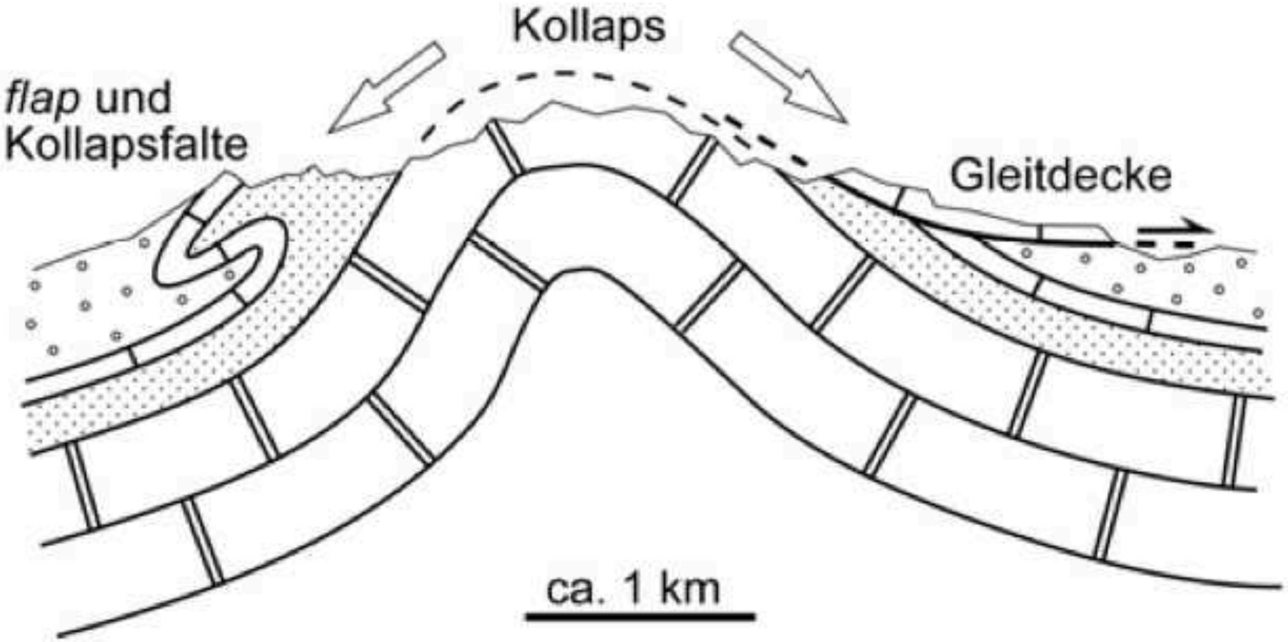


Burg ETH Zürich

extensives regime

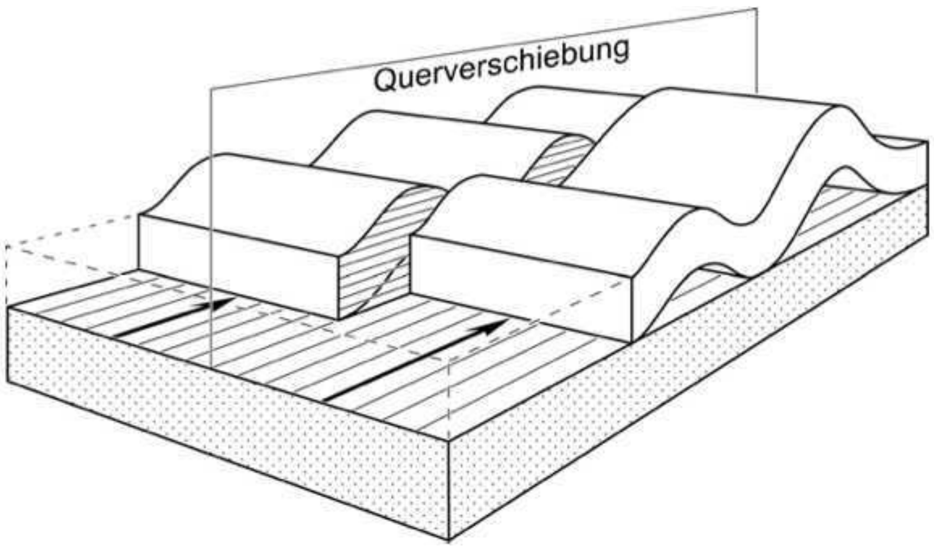
Kollapsfalten

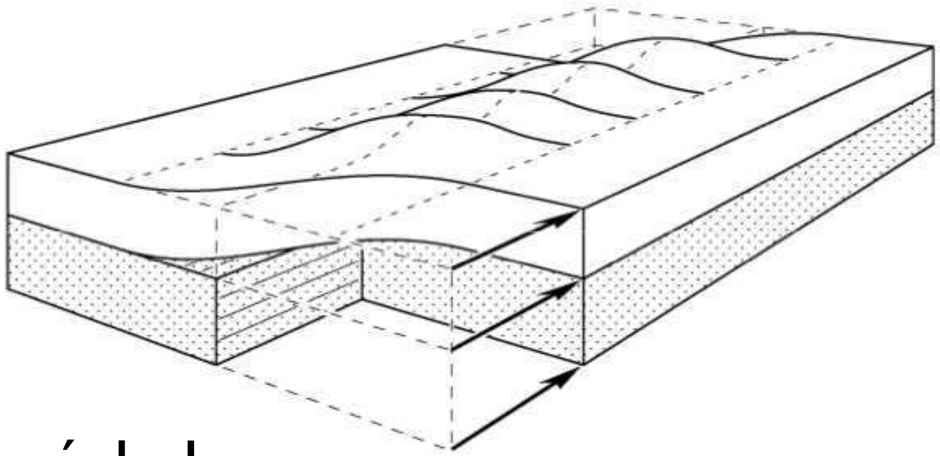
Kollaps Strukturen an den Schenkeln einer grossen Antiklinale
nach Harrison & Falcon 1934 *Geol. Mag.* **71**, 529-539



Burg ETH Zürich

Falten an Blattverschiebungen





en échelon

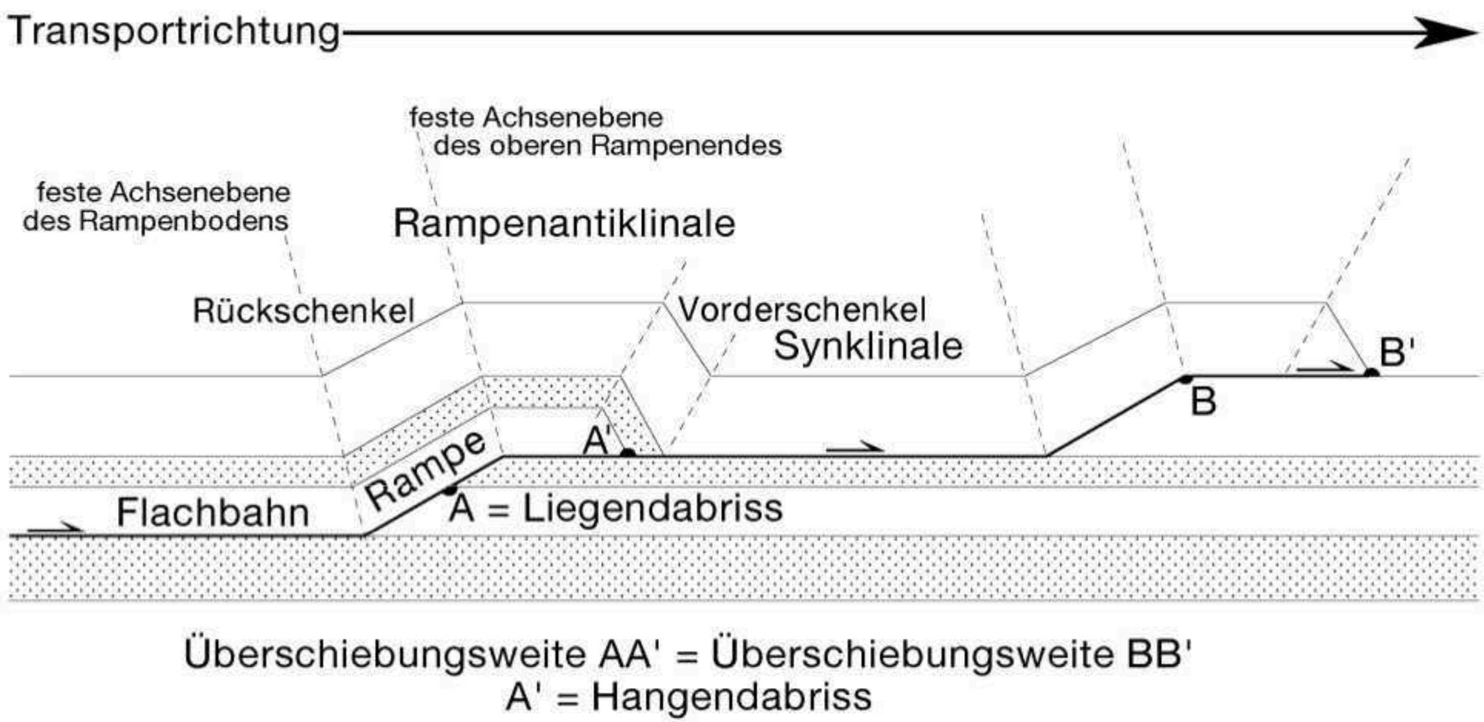
Burg ETH Zürich

strike slip regime

Rampenfalten FBF überschiebungsbezogen

fault bend fold

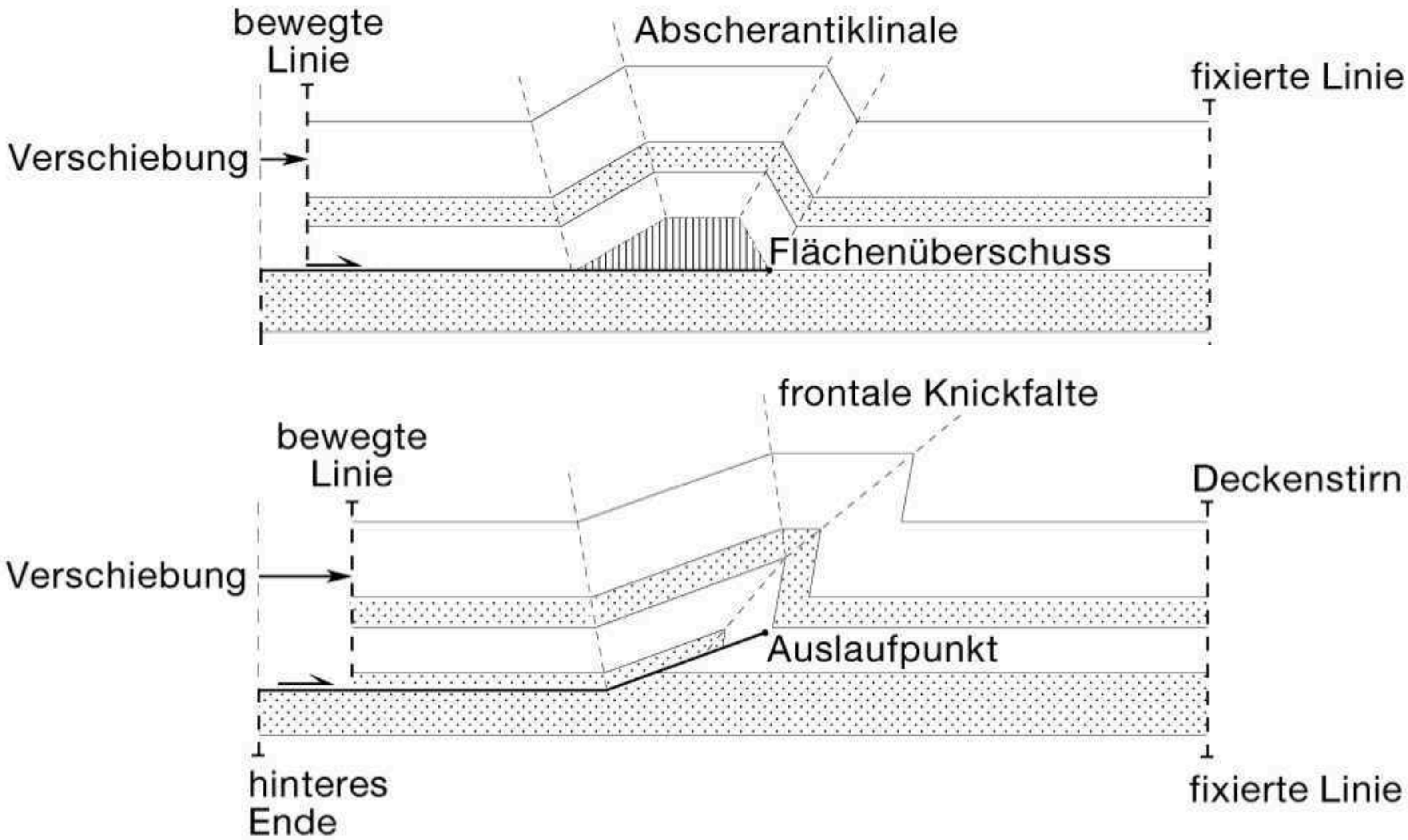
kompressives regime



Burg ETH Zürich

Rampenfalten FPF überschiebungsbezogen

fault propagation fold

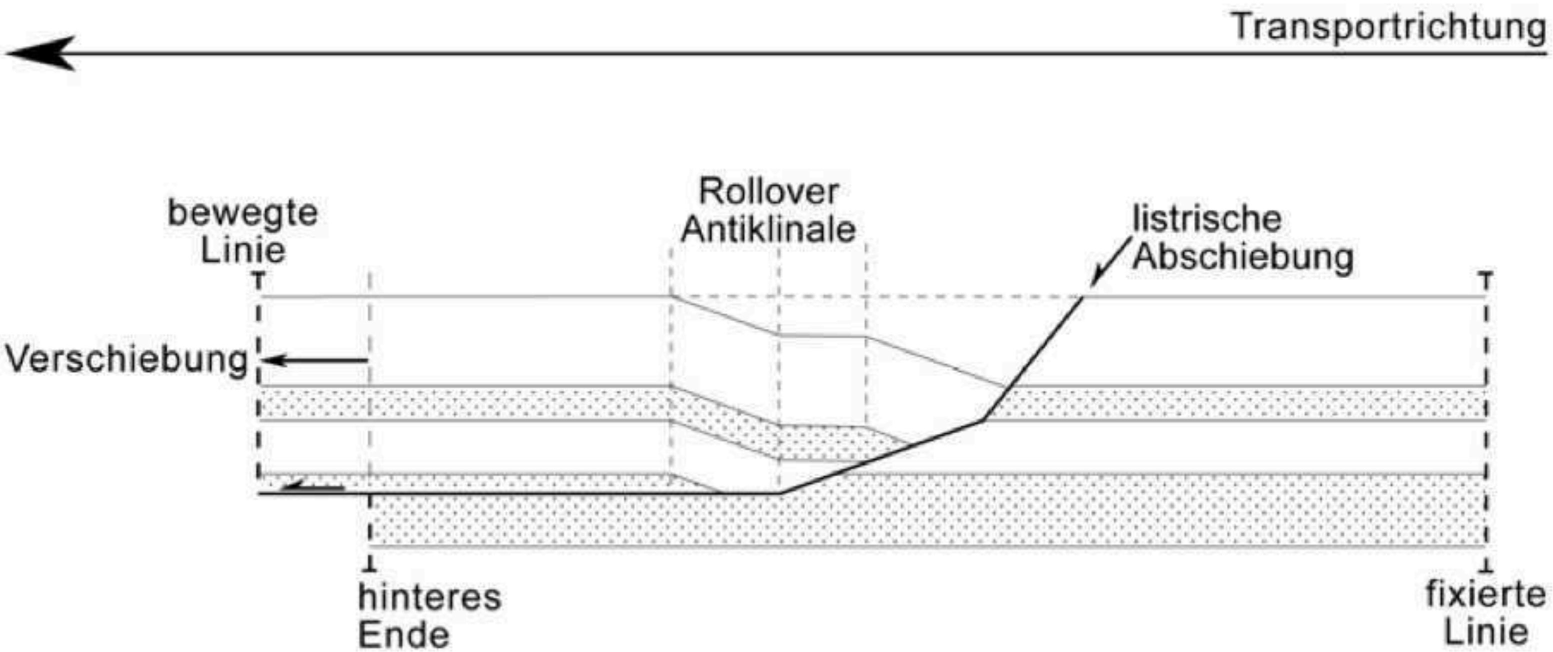


Burg ETH Zürich

Rampenfalten

abschiebungsbezogen

extensives regime

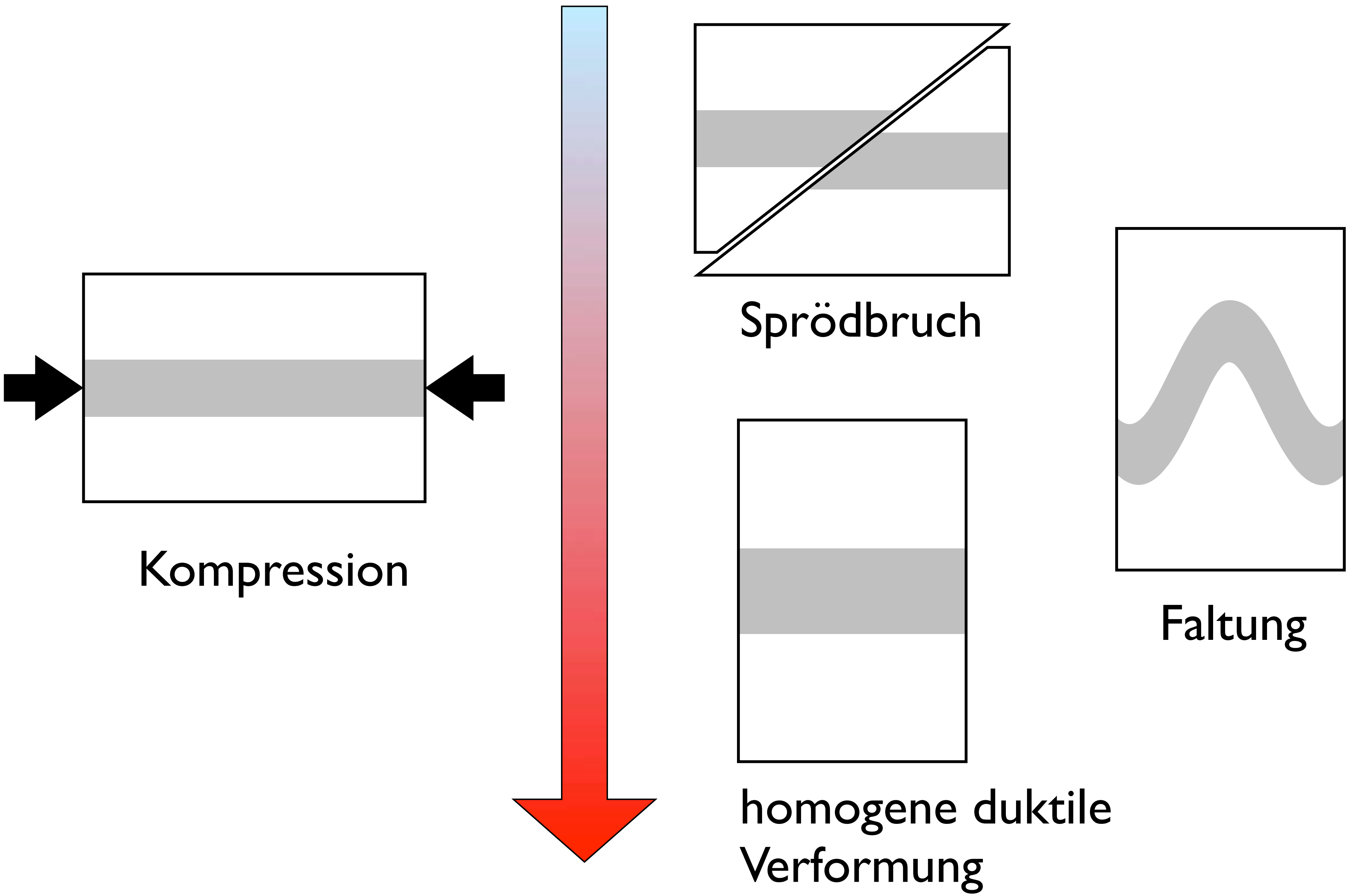


Abschiebungsbezogene antithetische-Flexur

Burg ETH Zürich

folding

Faltung als Versagen (failure)

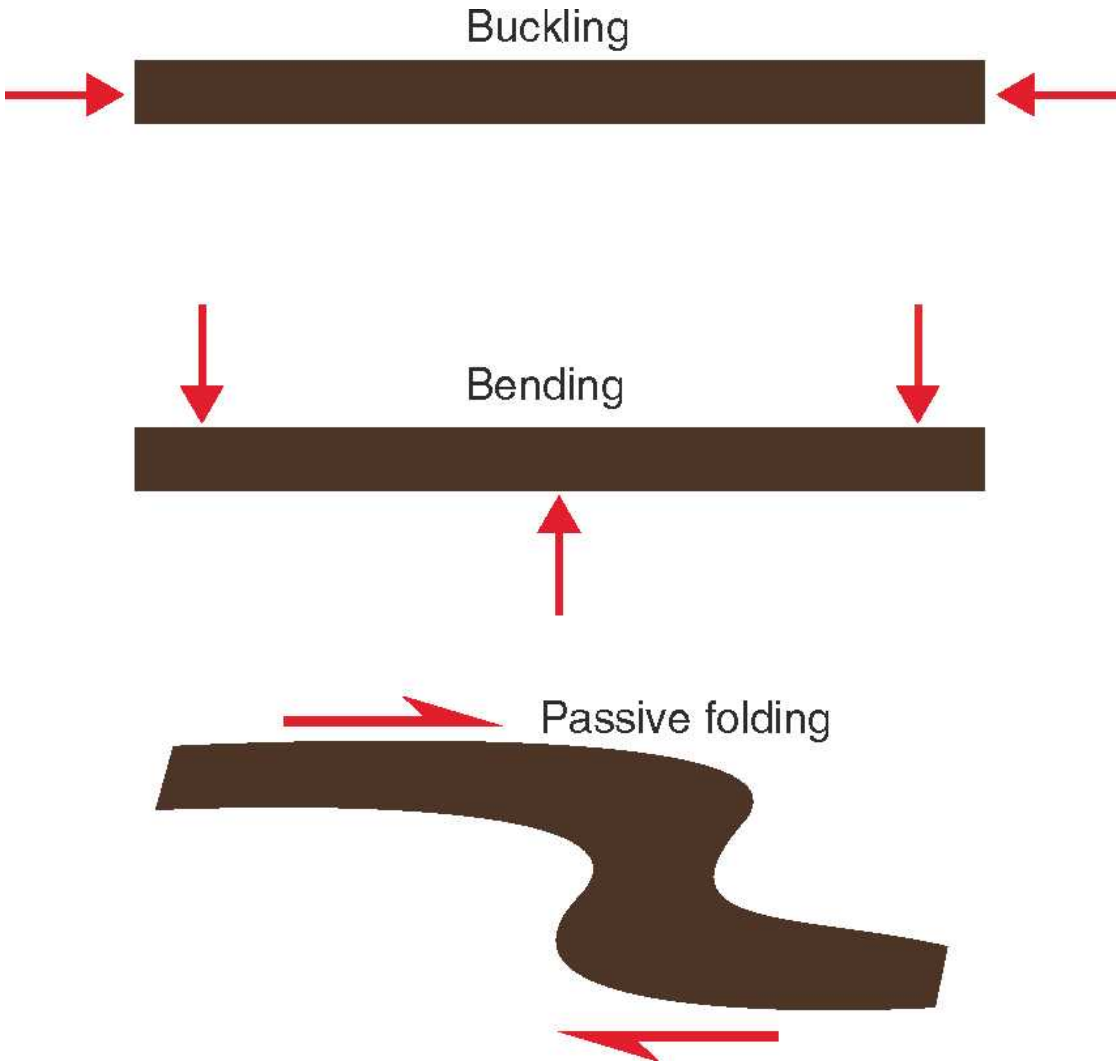


Faltung

Kompression - Faltung

Extension - Boudinage

Faltungsmechanismus



Stauchung
Stauchfaltung

Biegung
Biegefaltung

Scherung
Scherfaltung

mechanisch aktiv

mechanisch passiv

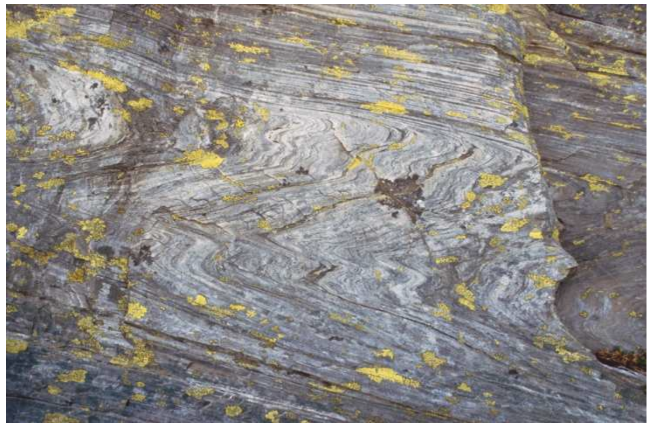
Fossen

aktiv - passiv

mechanisch ...

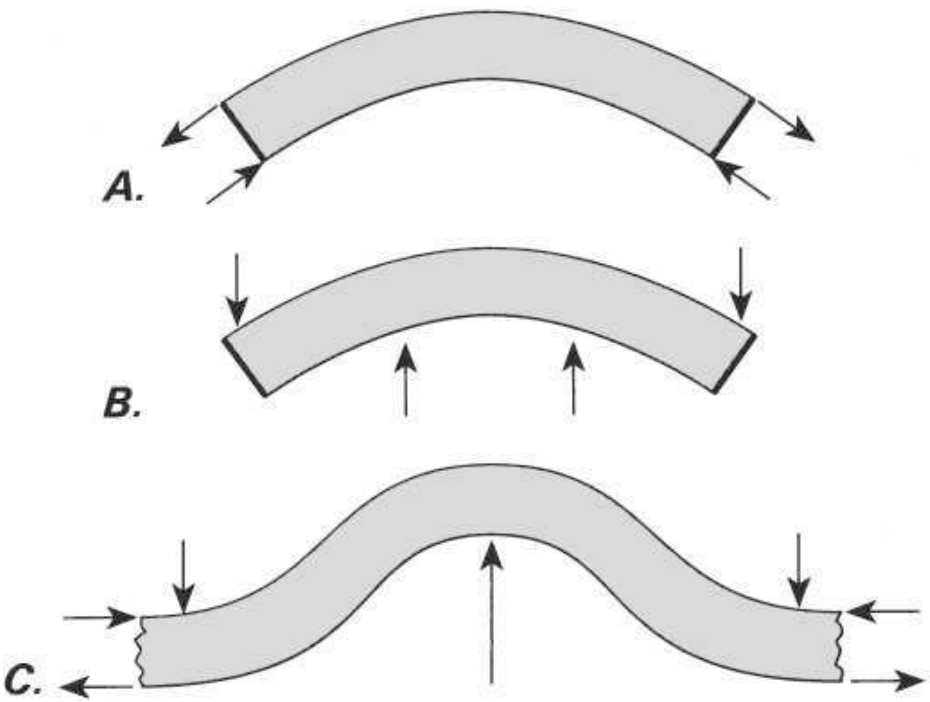
aktiv Kompetenzkontrast
Biegefaltung
(flexural folding)
Kartenstapel

passiv kein Kompetenzkontrast
Passive Faltung
(passive folding)
farbige Plastilin-Schichten



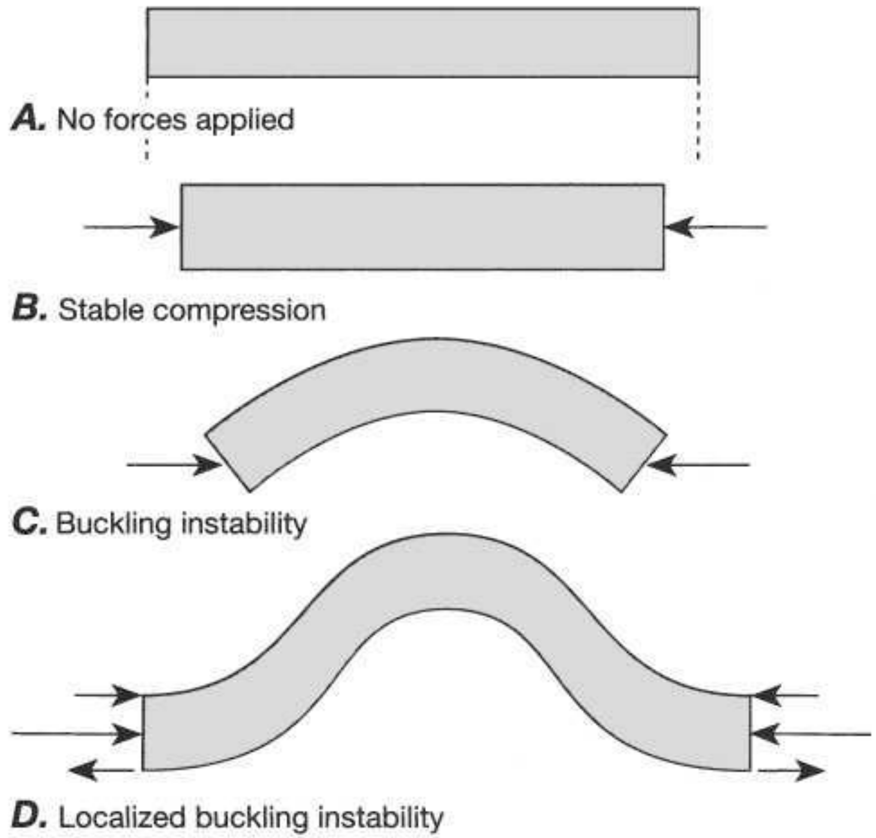
Randbedingungen

flexure of a plate by
bending



Biegefaltung

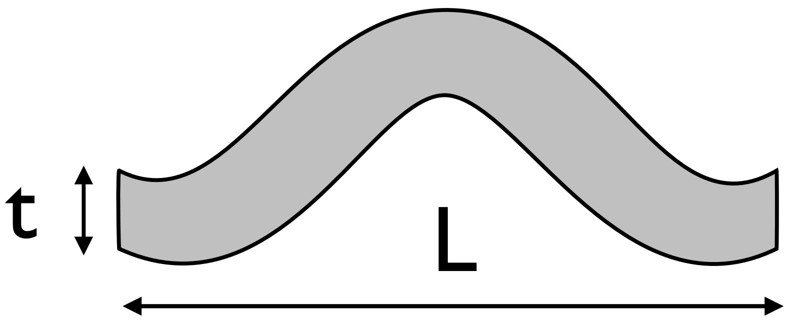
flexure of a plate by
buckling

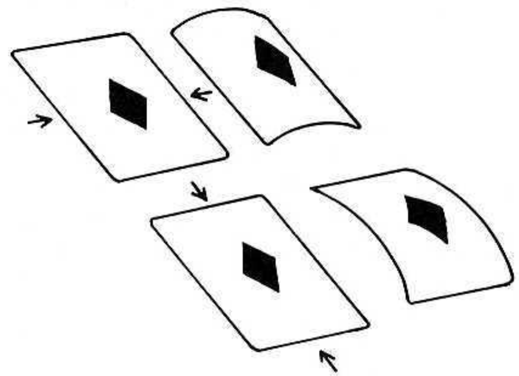


Stauchfaltung

Biegung nach Euler (1757)

elastische Schicht (im freien Raum)





$$F_{crit} = \frac{4\,\pi^2\,E\,I}{L^2}$$

$$I = \frac{t^3 \cdot w}{12}$$

$$L = \sqrt{\frac{4\,\pi^2\,E\,I}{F}} = 2\pi\sqrt{\frac{E\,I}{F}}$$

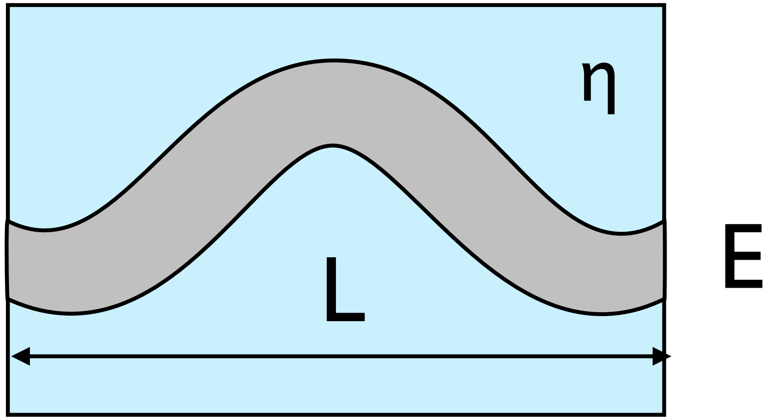
L = Länge
w = Breite
t = Dicke

F = Kraft
E = E-modul (Pa)

Lange Wellenlänge,
wenn F klein, E gross

Biegung nach Biot (1961)

elastische Schicht in visköser Matrix



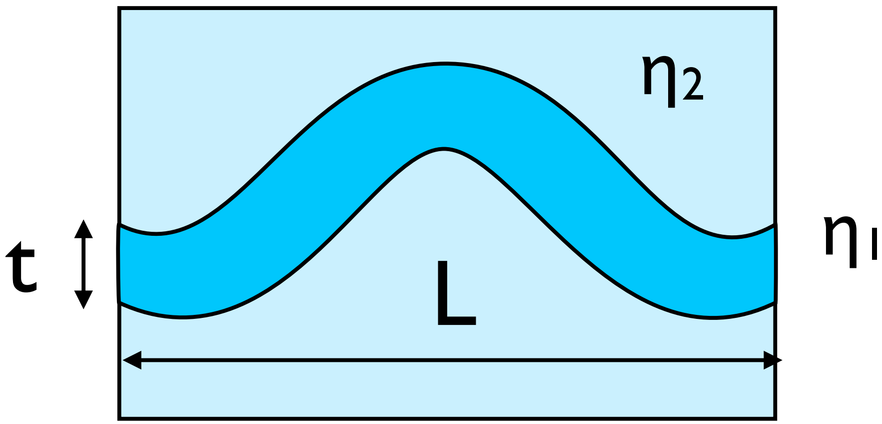
L hängt nur von den mechanische Eigenschaften der elastischen Schicht ab

$$L = \sqrt{\frac{E}{(1-\nu^2)\,\sigma}}$$

Lange Wellenlänge, wenn σ klein, E gross

Biot (1957) - Ramberg (1961)

visköse Schicht in visköser Matrix



$$L = 2\pi \cdot t \sqrt[3]{\frac{\eta_1}{6\eta_2}}$$

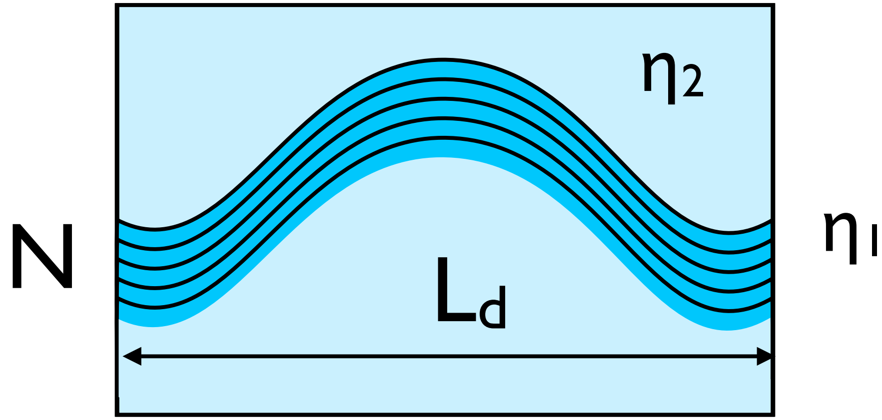
$$\frac{L}{t} = 2\pi \sqrt[3]{\frac{\eta_1}{6\eta_2}}$$

L = Länge
t = Dicke
η = Viskositätskoeffizient (Pas)

Wellenlänge:Dicke ist Funktion des Viskositätsverhältnisses
$\eta_1 : \eta_2$ klein → 'dicke' Falten
$\eta_1 : \eta_2$ gross → 'schlanke' Falten

Biot (1957) - Ramberg (1961)

visköser Schichtstapel in visköser Matrix



kein Scherwiderstand
zwischen Schichten

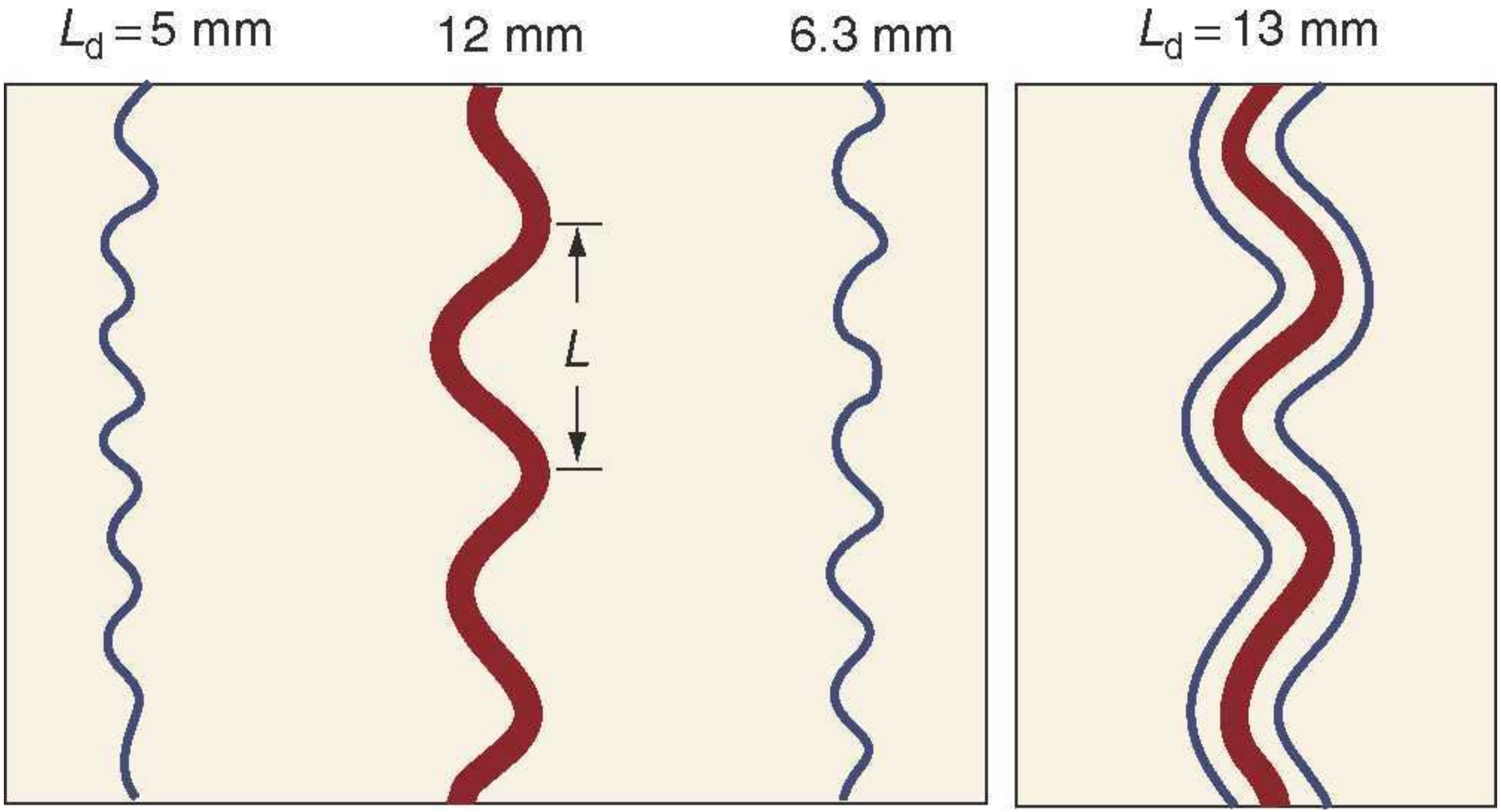
$$L_d = 2\pi \cdot t \sqrt[3]{\frac{N \cdot \eta_1}{6\eta_2}}$$

$$\frac{L_{multi}}{L_{single}} = \sqrt[3]{N^2}$$

Wellenlänge eines Schichtstapels ist grösser als einer einzelnen Schicht

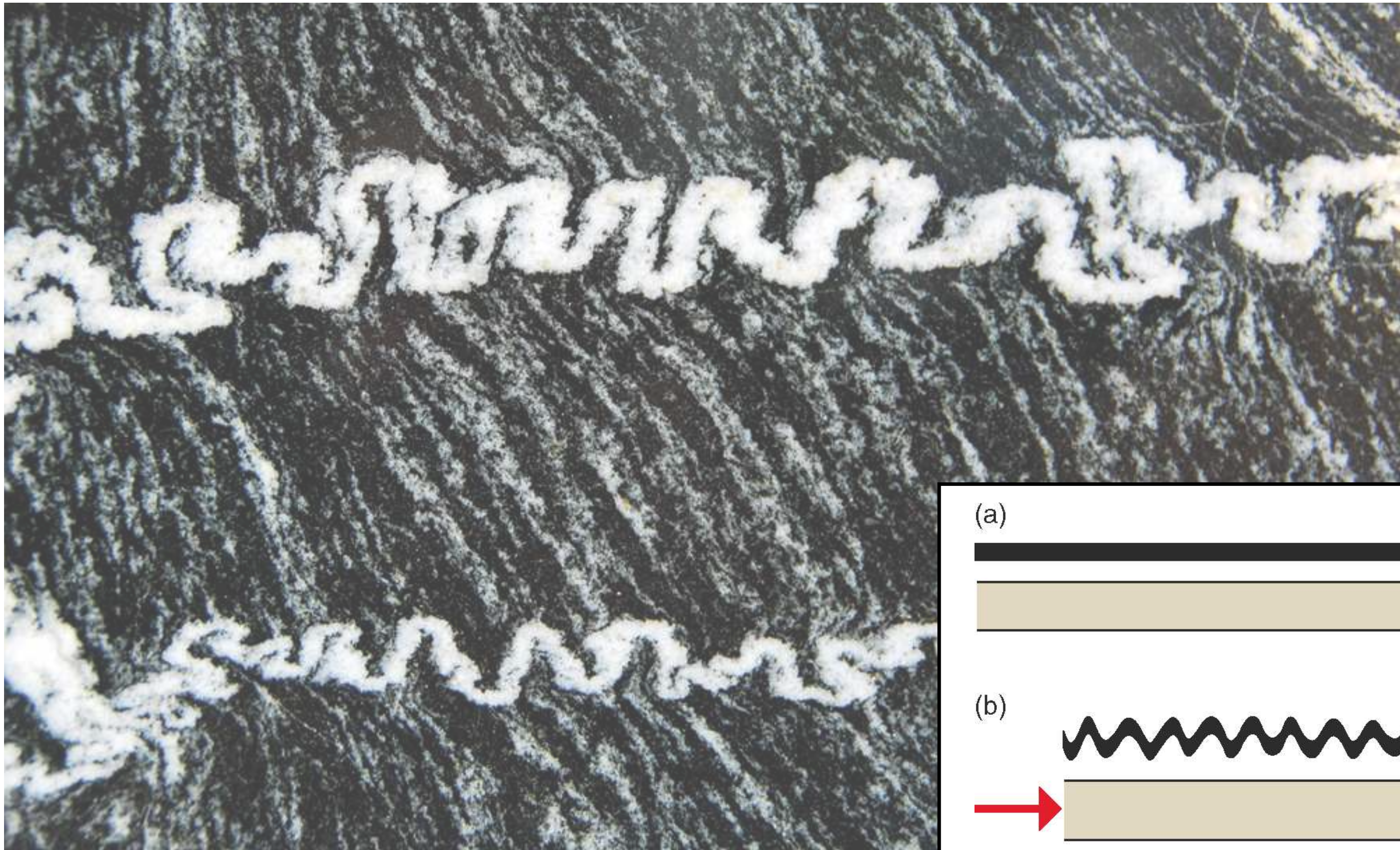
L_d = dominante Länge
N = Anzahl Schichten
η = Viskositätskoeffizient (Pas)

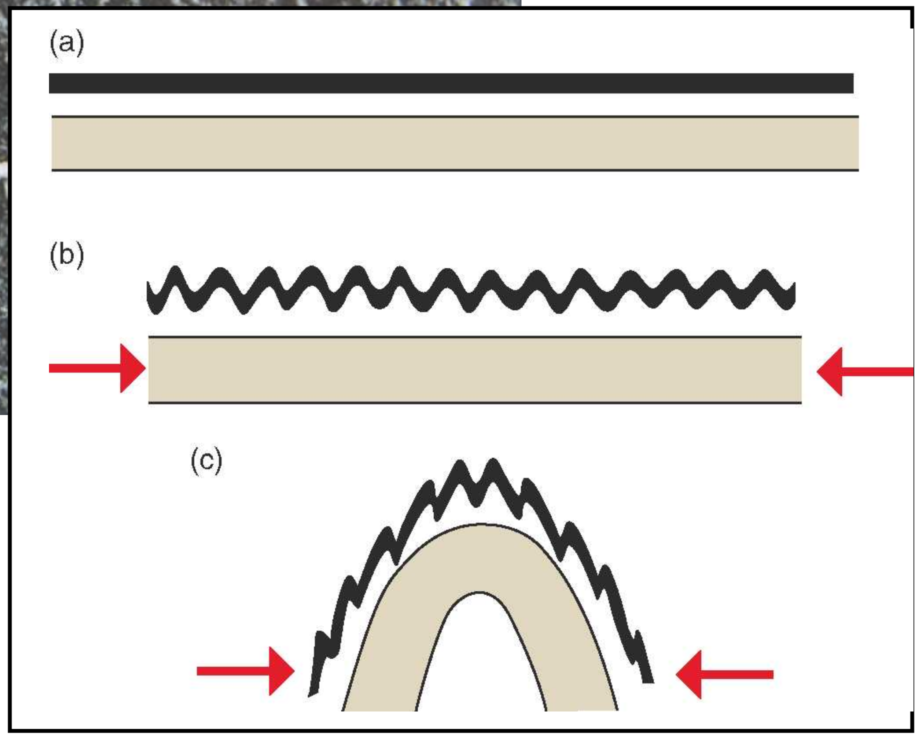
single layer - multilayer folding



Fossen

Parasitärfalten

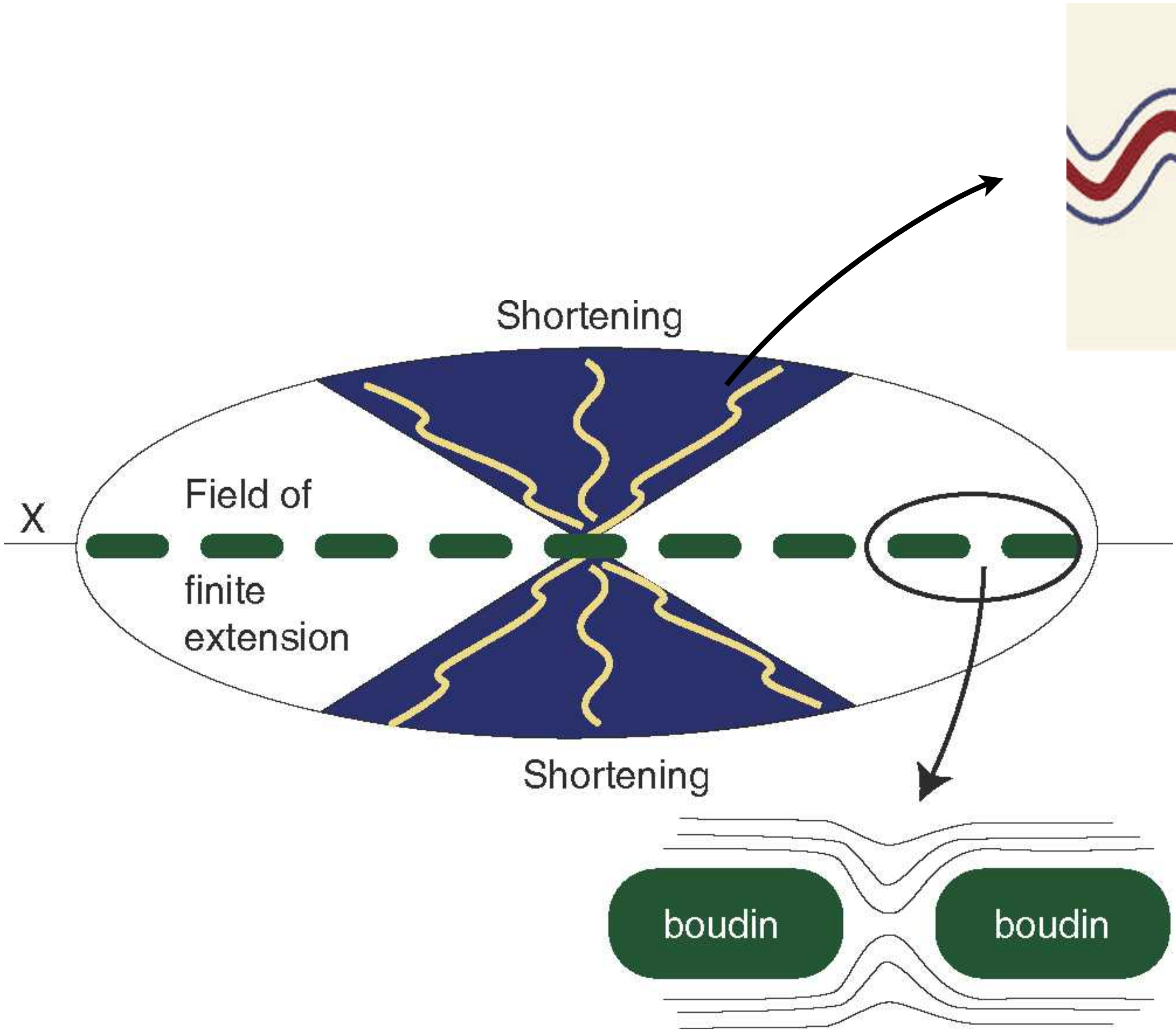




Fossen

folds and strain

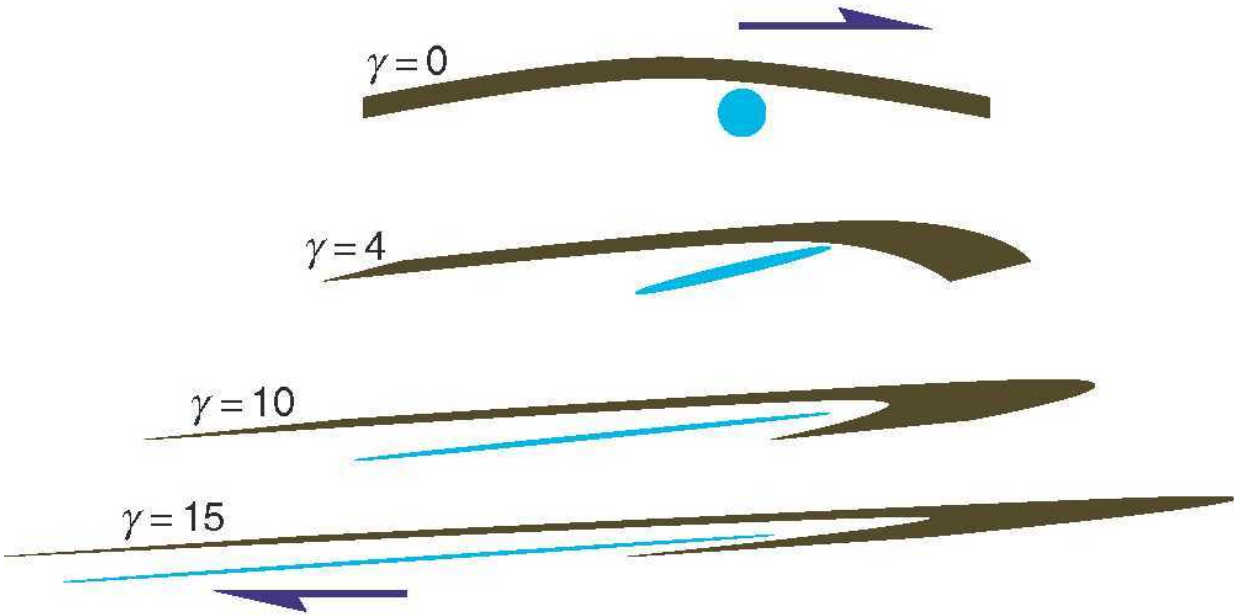
Faltung (Boudinage) und Verformung



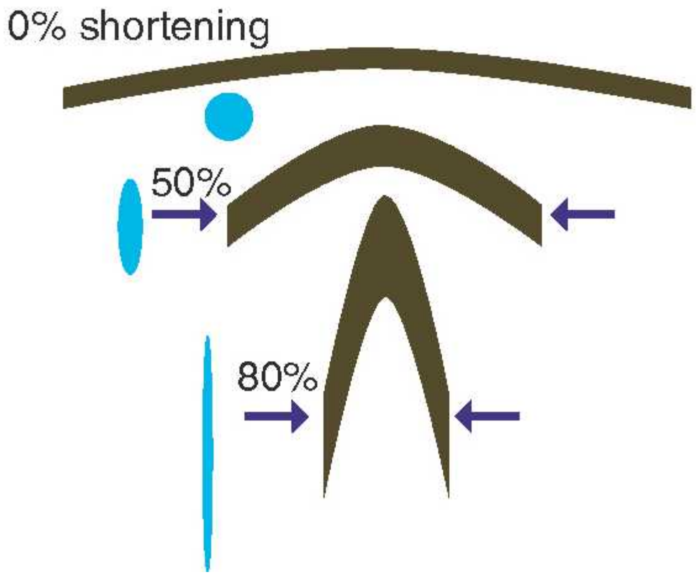
Fossen

Passive Faltung

einfache Scherung
(simple shear)



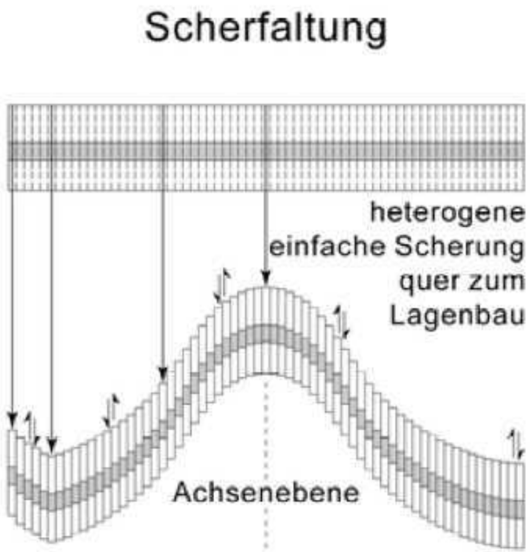
reine Scherung
(pure shear)

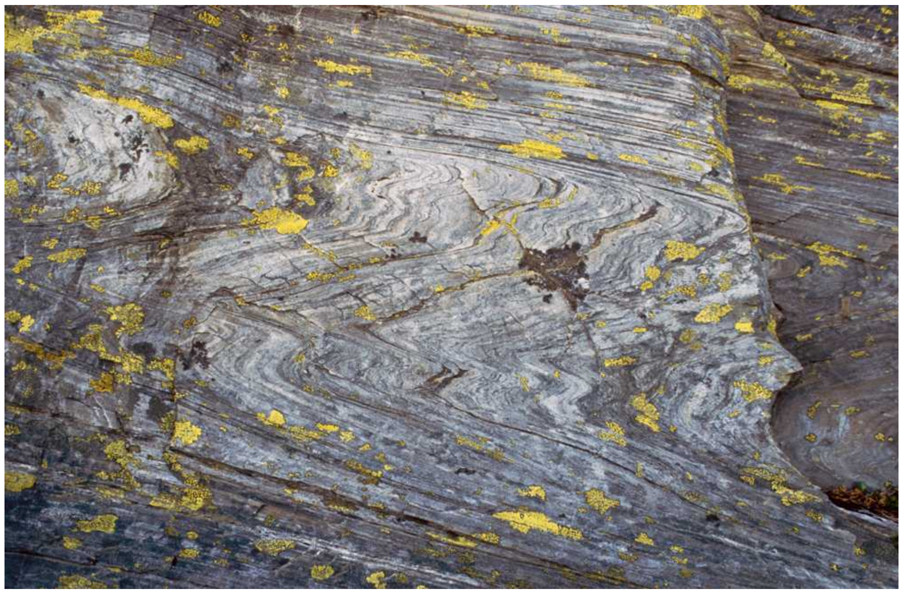


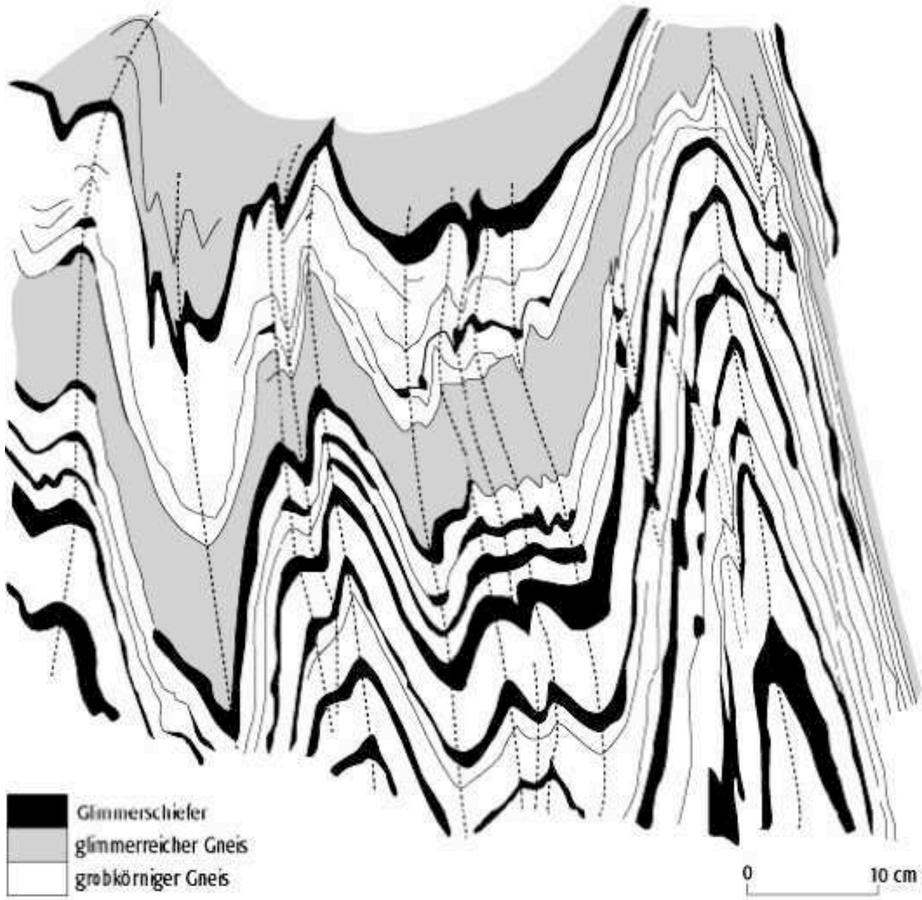
Fossen

Passive Faltung

passive shear folding

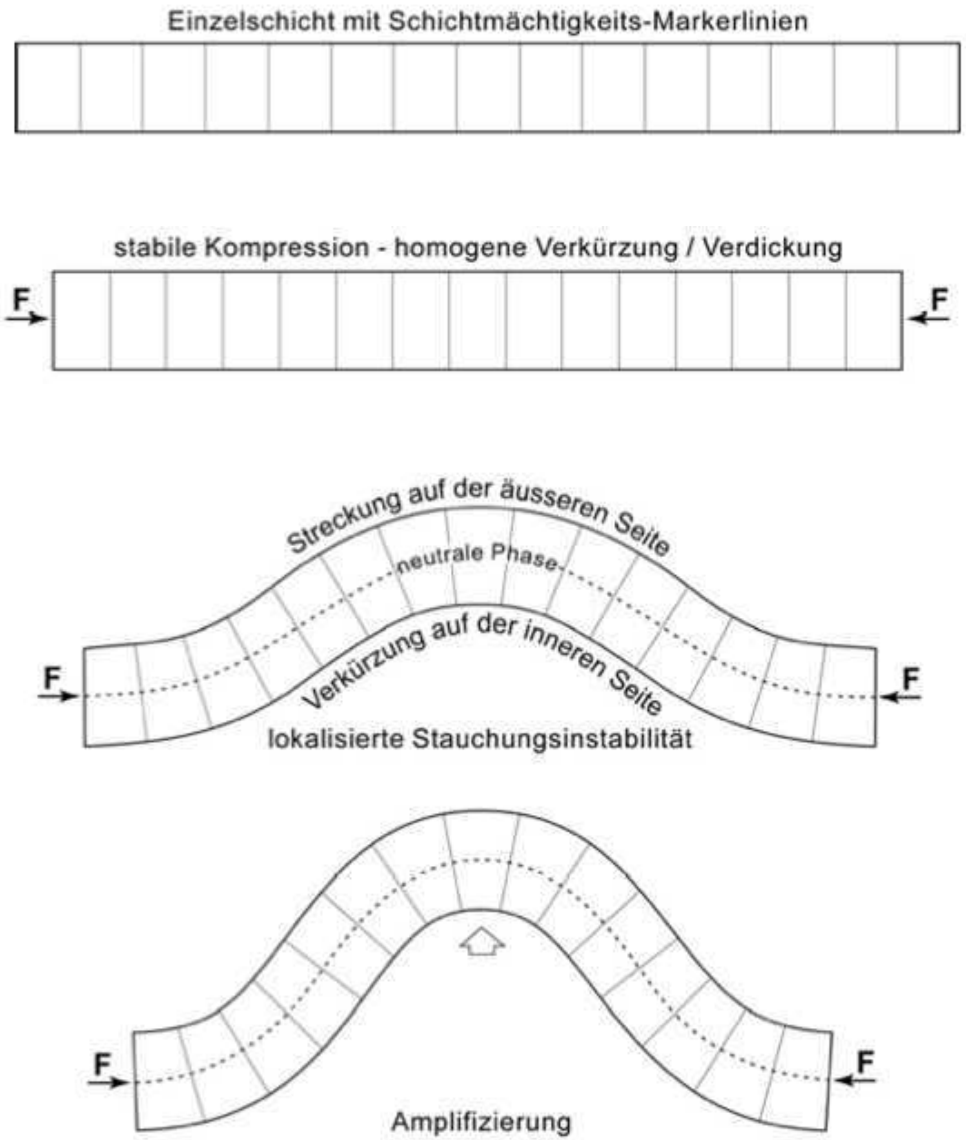






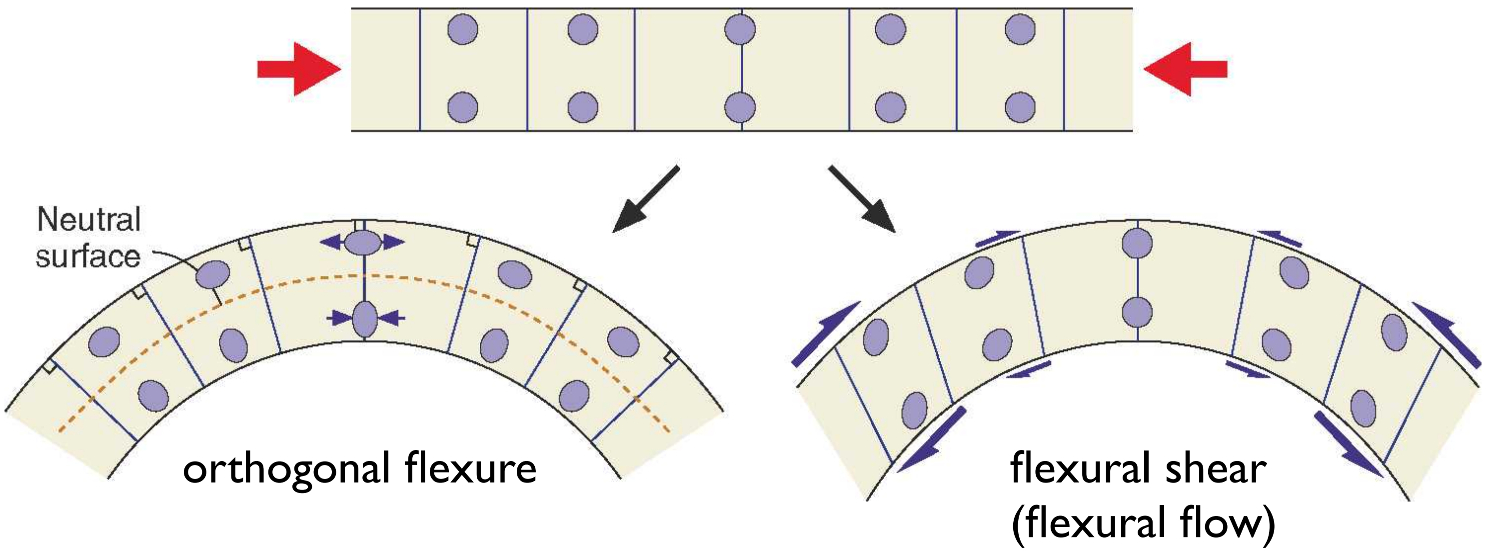
http://www.geodz.com/deu/d/Scherfalte

Verformung bei Stauchfaltung

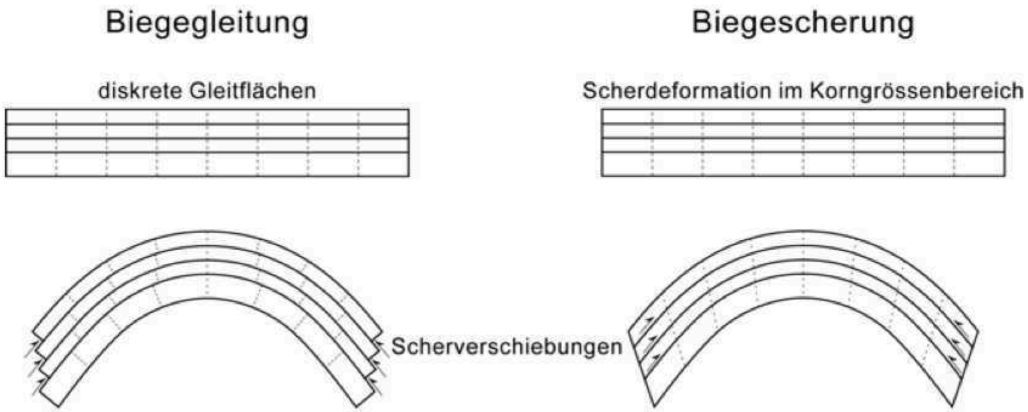


Burg ETH Zürich

Verformung bei Biegefaltung



Fossen

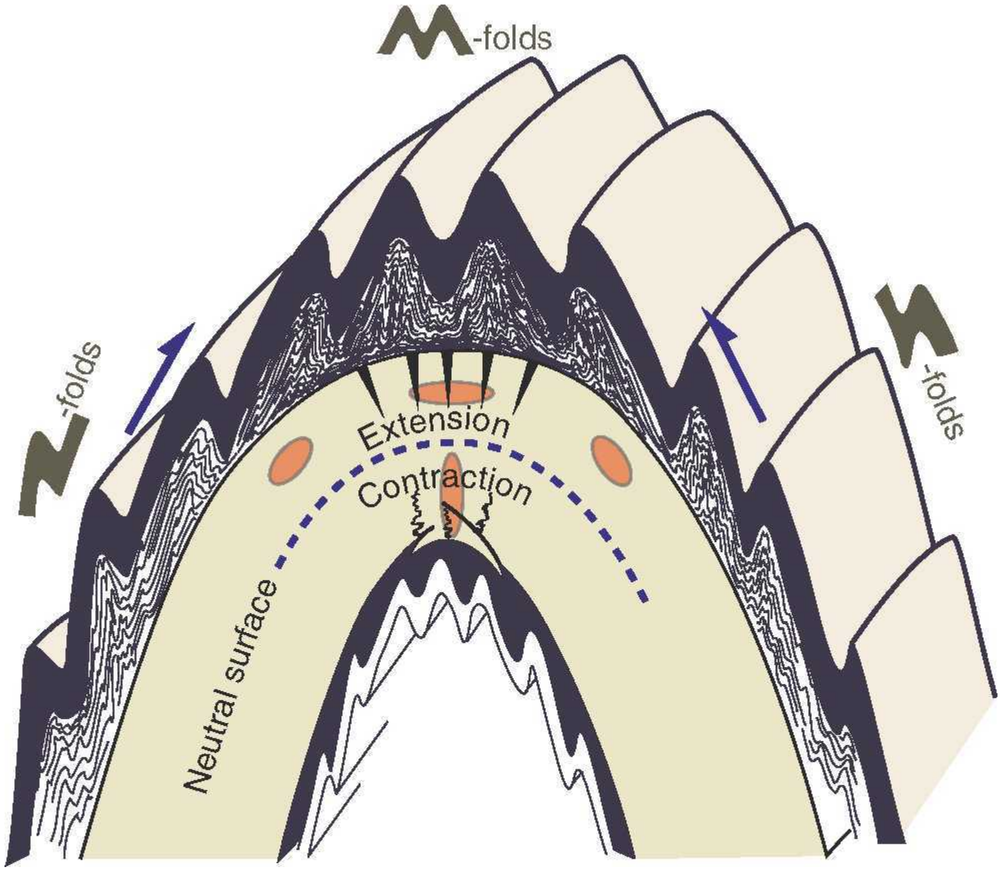


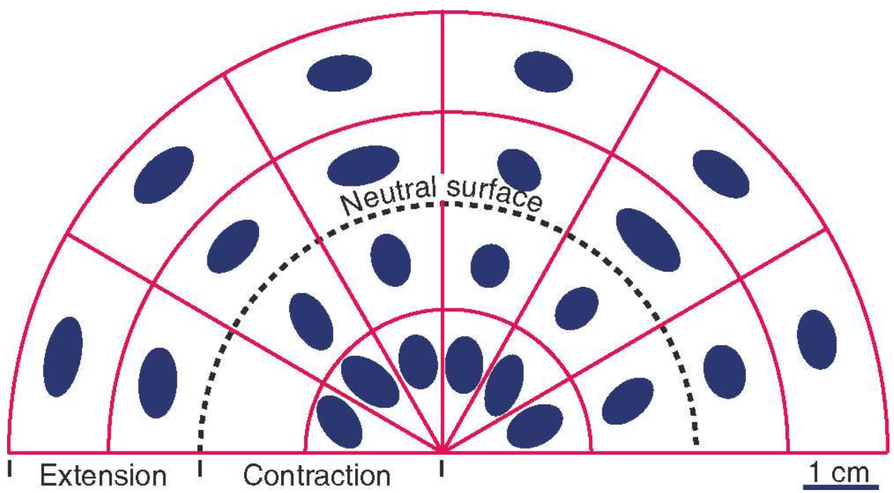
Schichtdicke bleibt erhalten

Burg ETH Zürich

Verformung bei Biegefaltung

orthogonal flexure

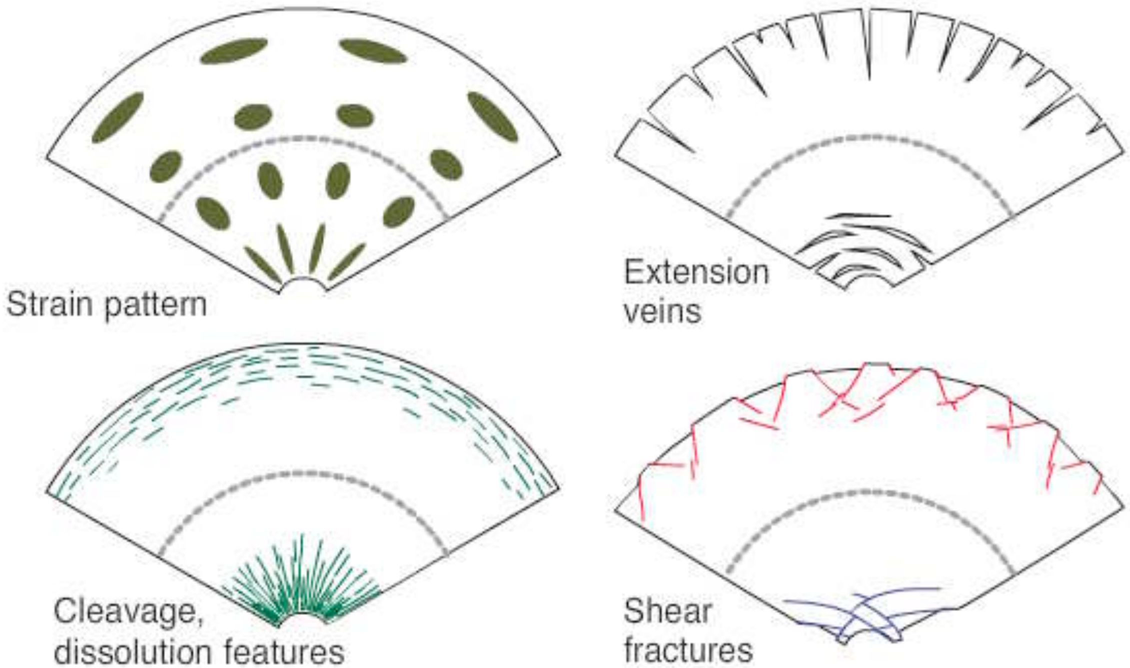




Fossen

Verformung bei Biegefaltung

orthogonal flexure

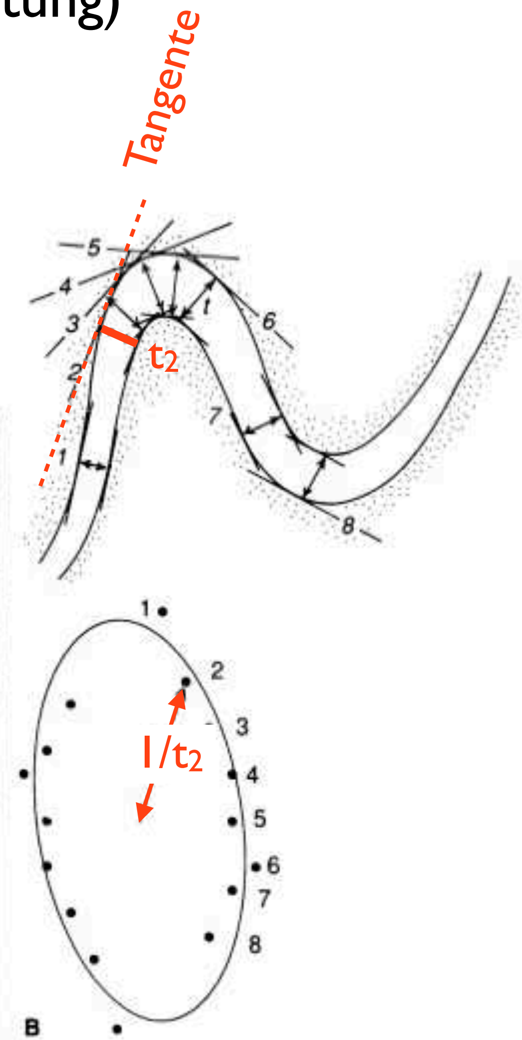


Fossen

Verformungsmessung in passiver Falte

Voraussetzungen:
Start = bestehende Falte vom Typ 1B (konzentrisch & parallel)
Nach der Faltenbildung homogene Verformung (passive Faltung)
progressive Plättung der ganzen Falte
Schenkel verdünnt
Scharnier verdickt

nach Lisle (1992)
Geology **14**, 369-371

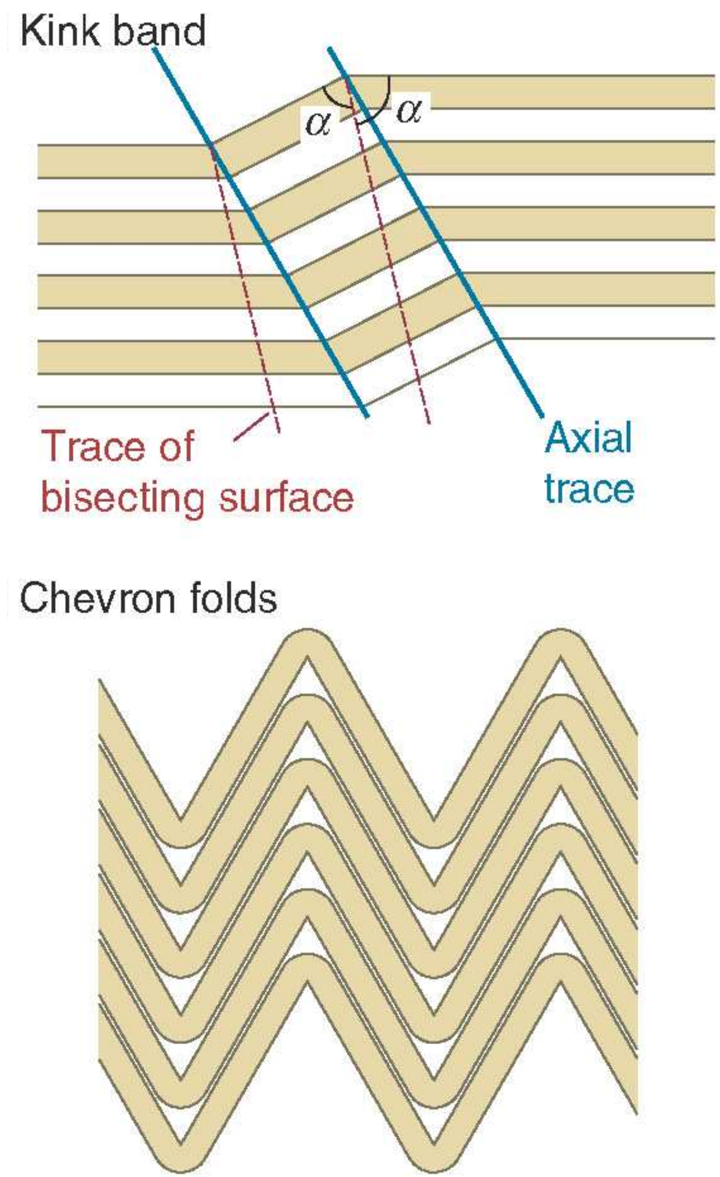


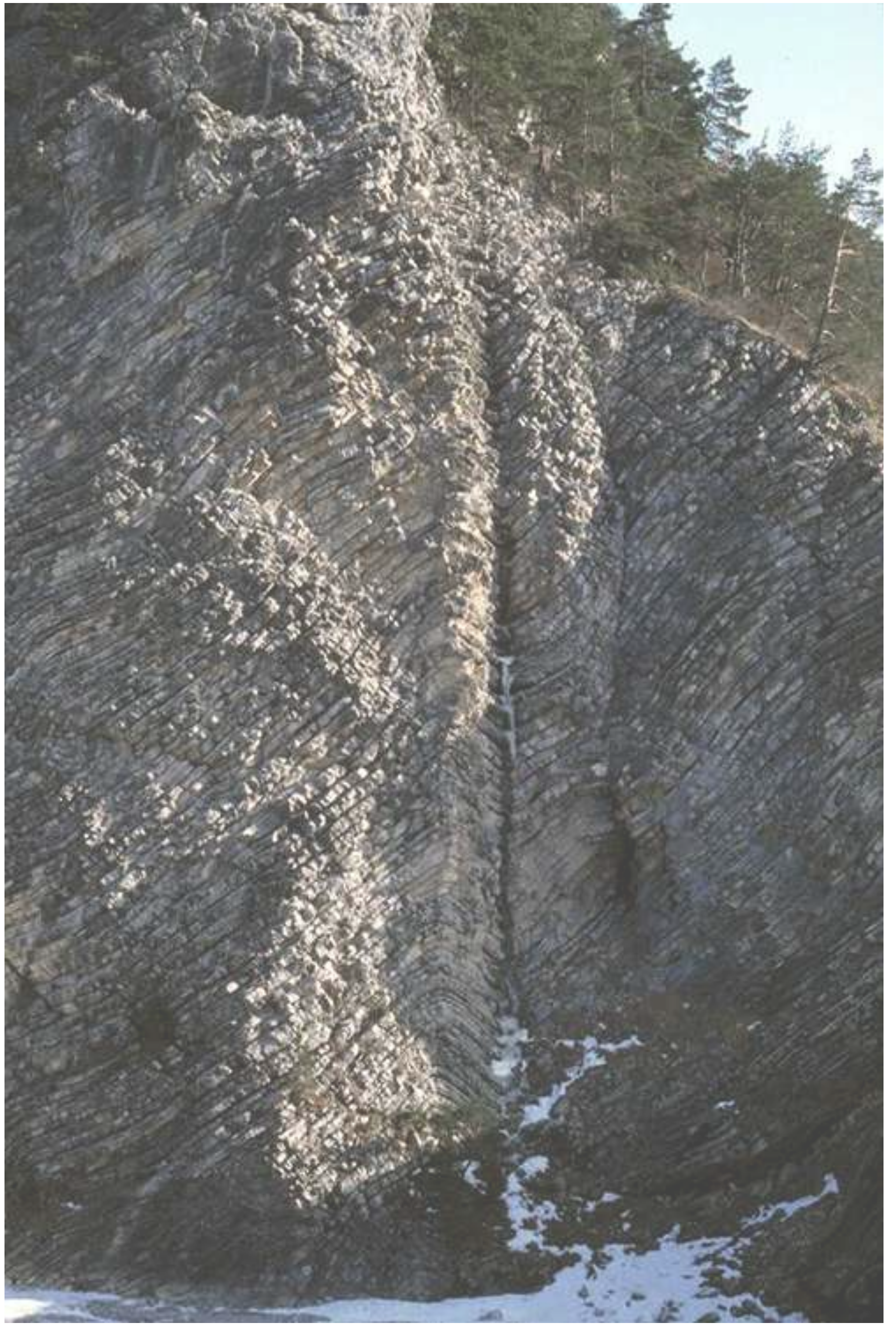
Vorgehen:

1. orthogonale Mächtigkeit, t, senkrecht zur Tangente messen
2. inverse Mächtigkeit, 1/t, parallel zu Tangente um Nullpunkt eintragen

Knickfalten

Knickfalten



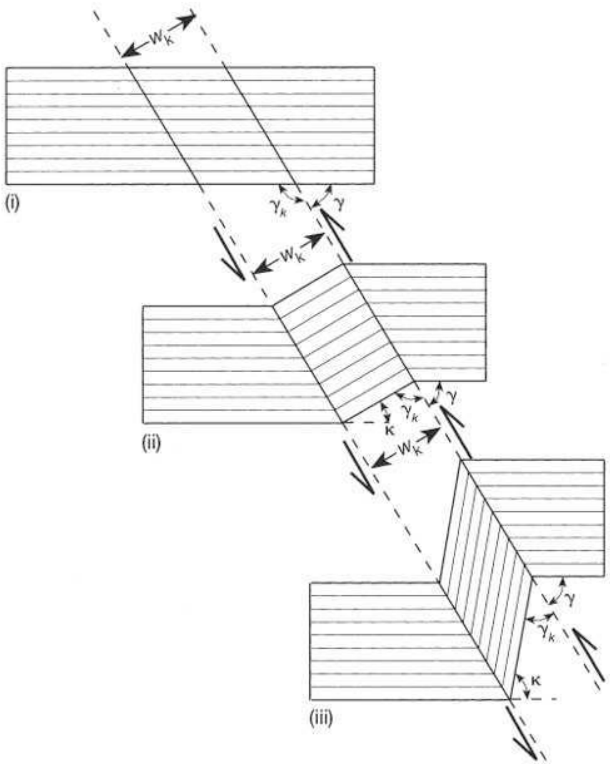


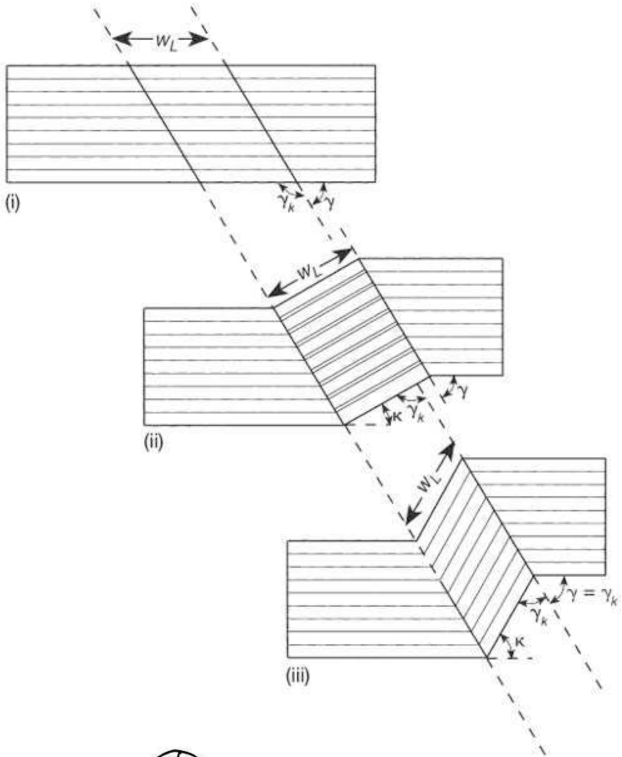
Knickfalten

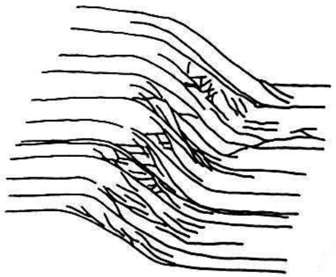
shear kinkband

rotation kinkband

Twiss & Moores

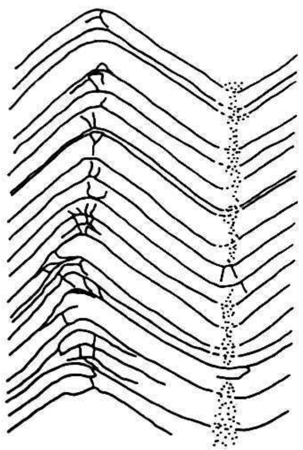






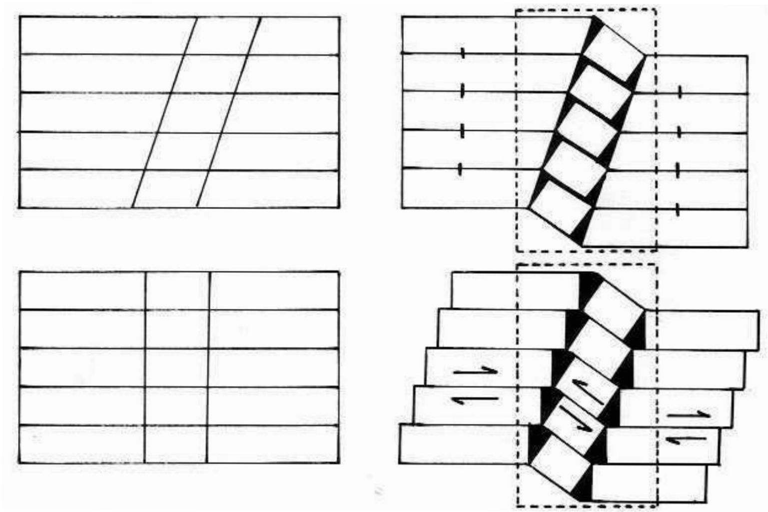
Panozzo PhD TAMU

2 m

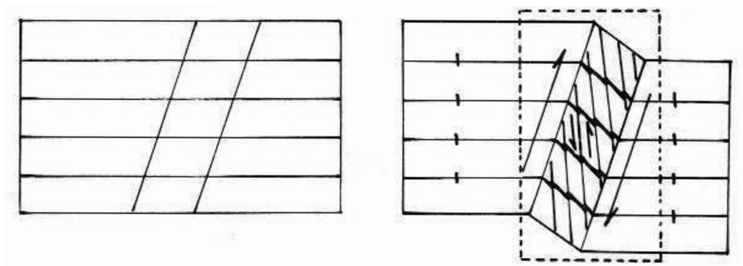


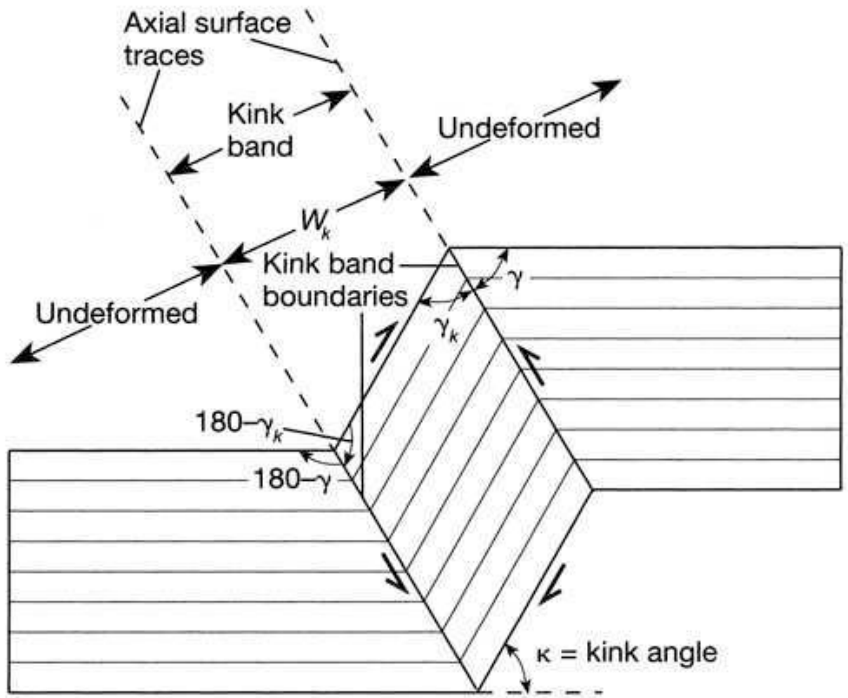
kinkband development

rotation kinkband



shear kinkband





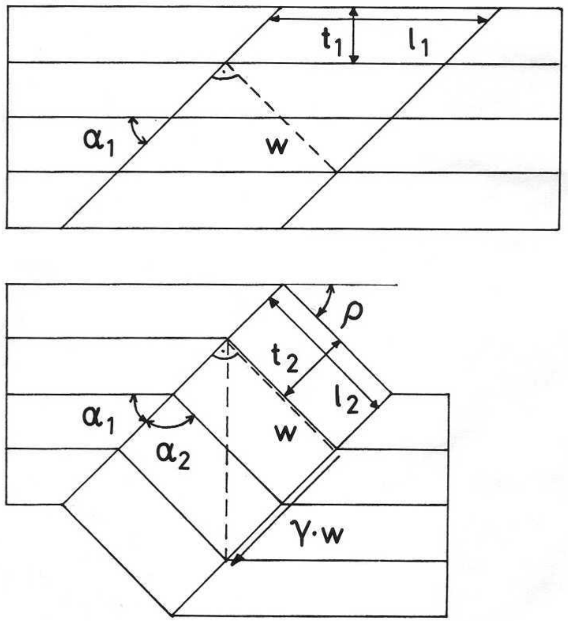
locking angle

Panozzo PhD TAMU

Twiss & Moores

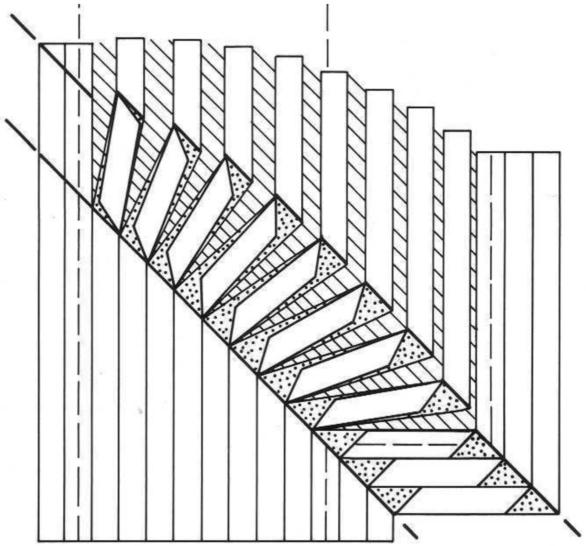
volume change in kinkbands

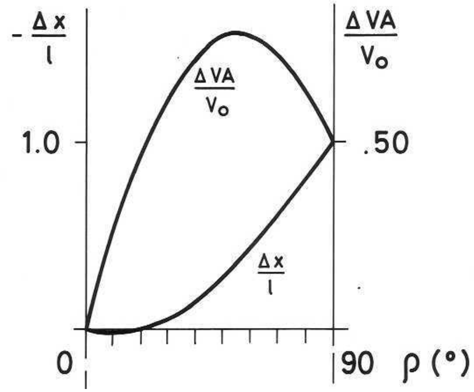
shear kinkband



SKB
no volume change
no locking angle

rotation kinkband





RKB
volume change
locking angle

Panozzo PhD TAMU

7

7 Mikrostrukturen - Deformationsmechanismen

VL-Themen:

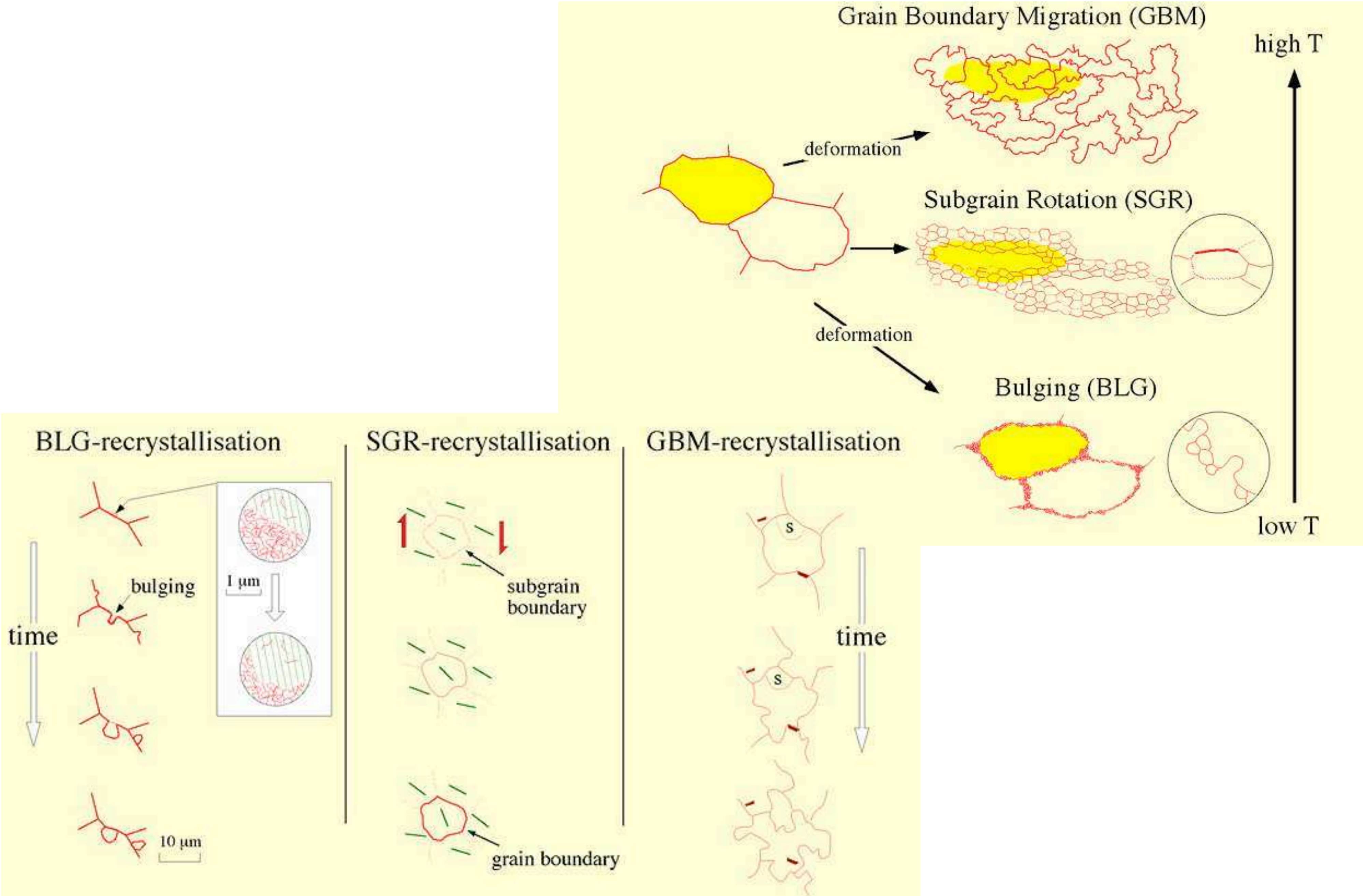
- Mikrostrukturen statische-dynamische
- Versetzungen Dislokationen
- Rekristallisation und recovery

- Deformationsmechanismen
- mikromechanische Modelle
- Fliessgesetze
- deformation mechanism maps

- Gleitsysteme
- Kristallographische Einregelung CPO

microstructures
dynamic
static

dynamic recrystallization



dynamic recrystallization

M. Stipp et al. / Journal of Structural Geology 24 (2002) 1861–1884

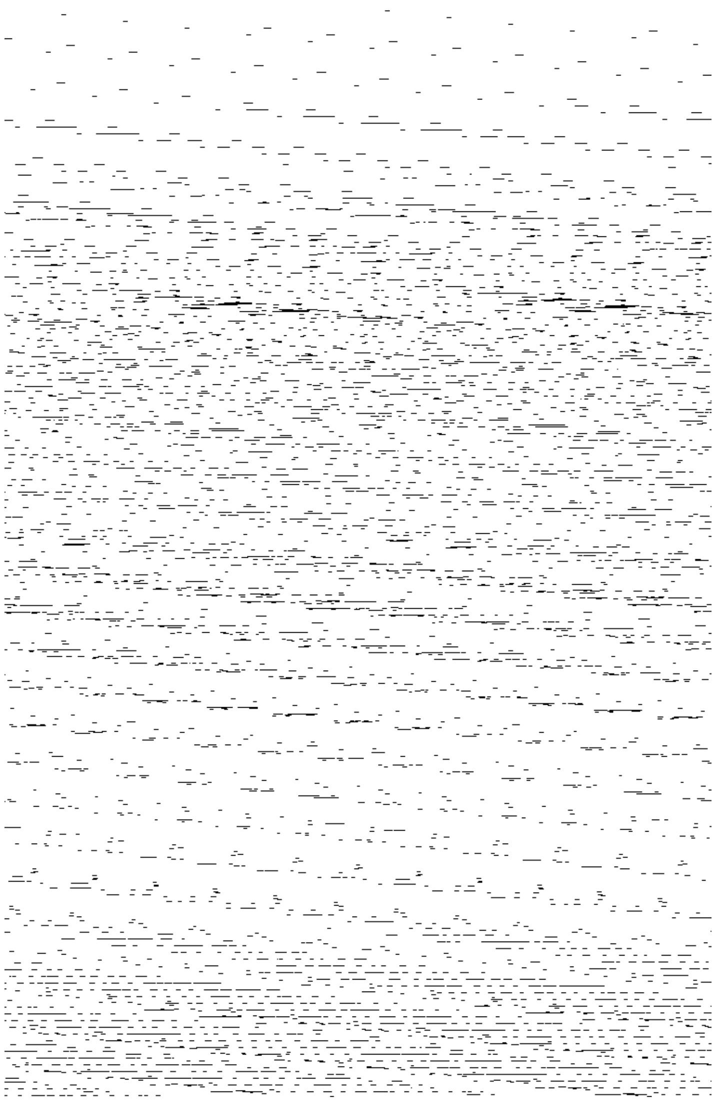


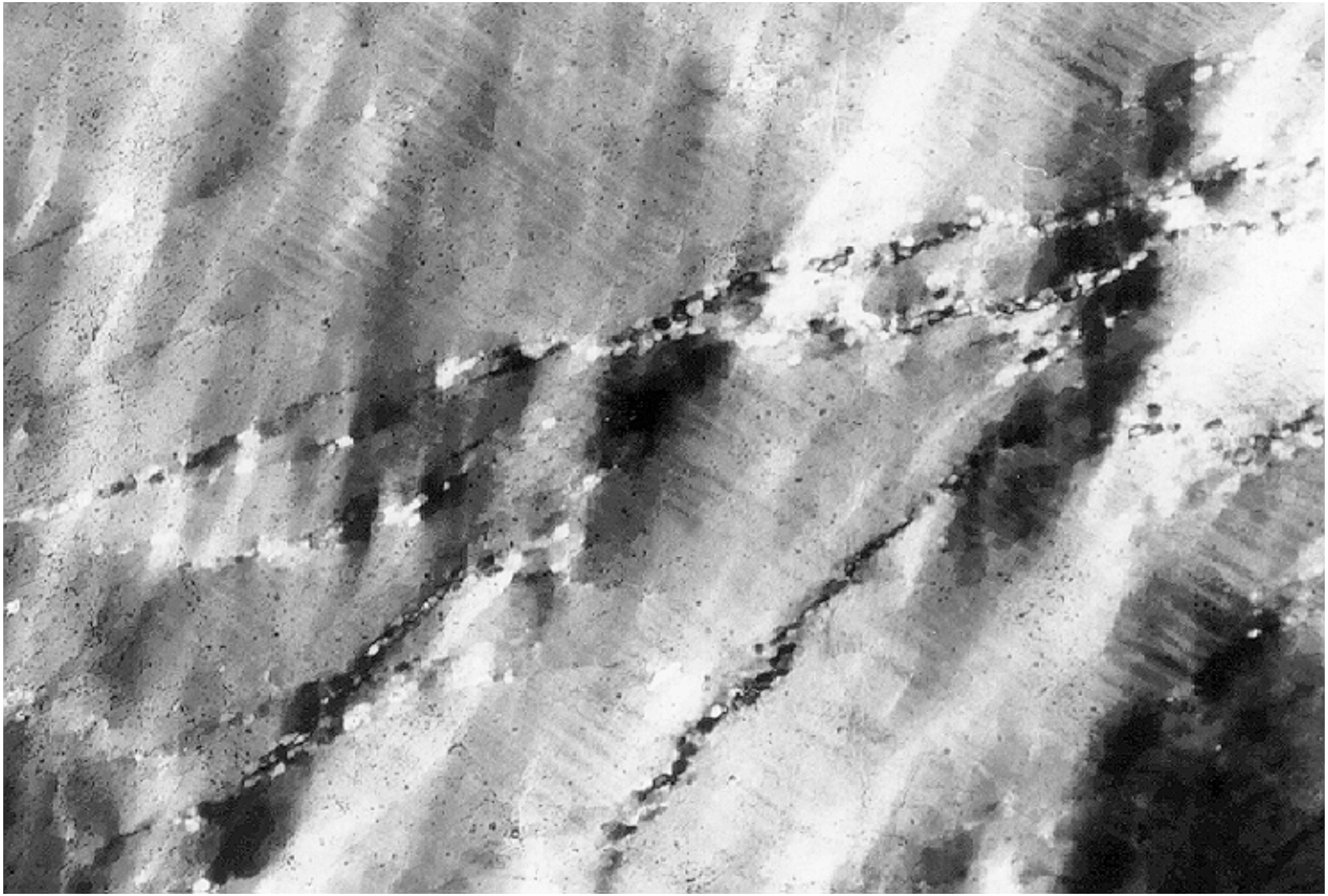
Fig. 1. Characteristic microstructures of the three dynamic recrystallization mechanisms of quartz shown at the same relative scale.

(a) Bulging recrystalliza- tion (low T): bulges and recrystallized grains are present along grain boundaries and to a lesser extent along microcracks.

(b) Subgrain rotation recrystallization (intermediate T): core and mantle structures of porphyroclastic ribbon grains and recrystallized subgrains. Polygonization by progressive subgrain rotation can completely consume the ribbon grains.

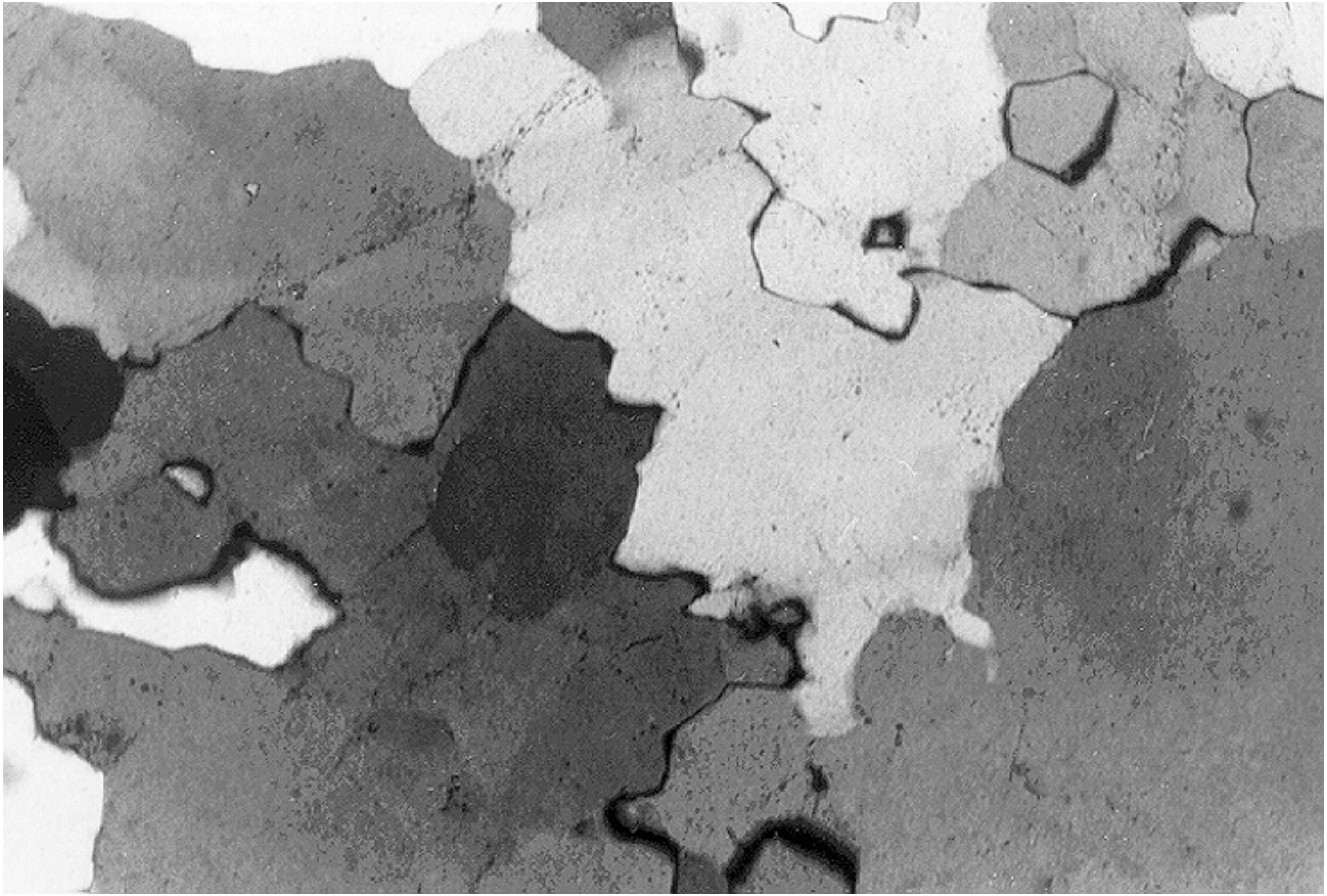
(c) Grain boundary migration recrystallization (high T): irregular grain shapes and grain sizes; grain boundaries consist of interfingering sutures.

Bulging Recrystallization in Quartz

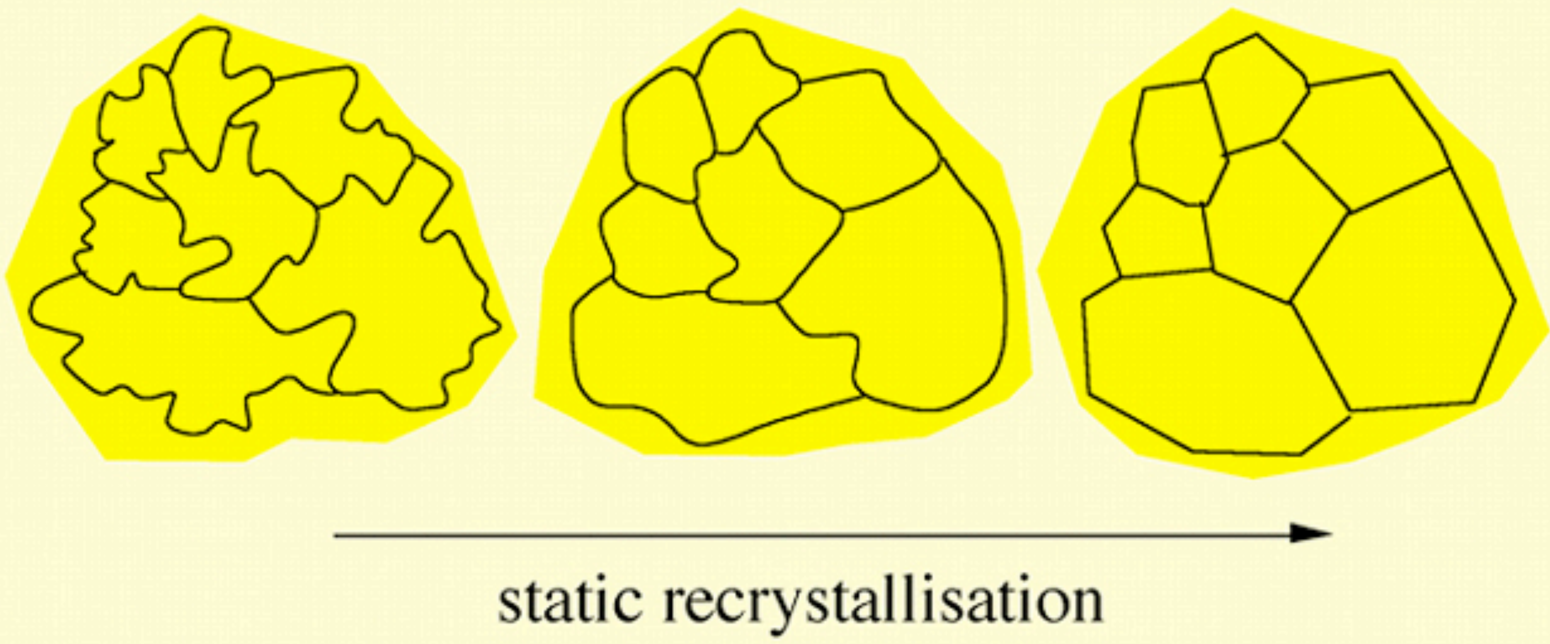


Rotation Recrystallization in Quartz

Grain Boundary Migration Recrystallization

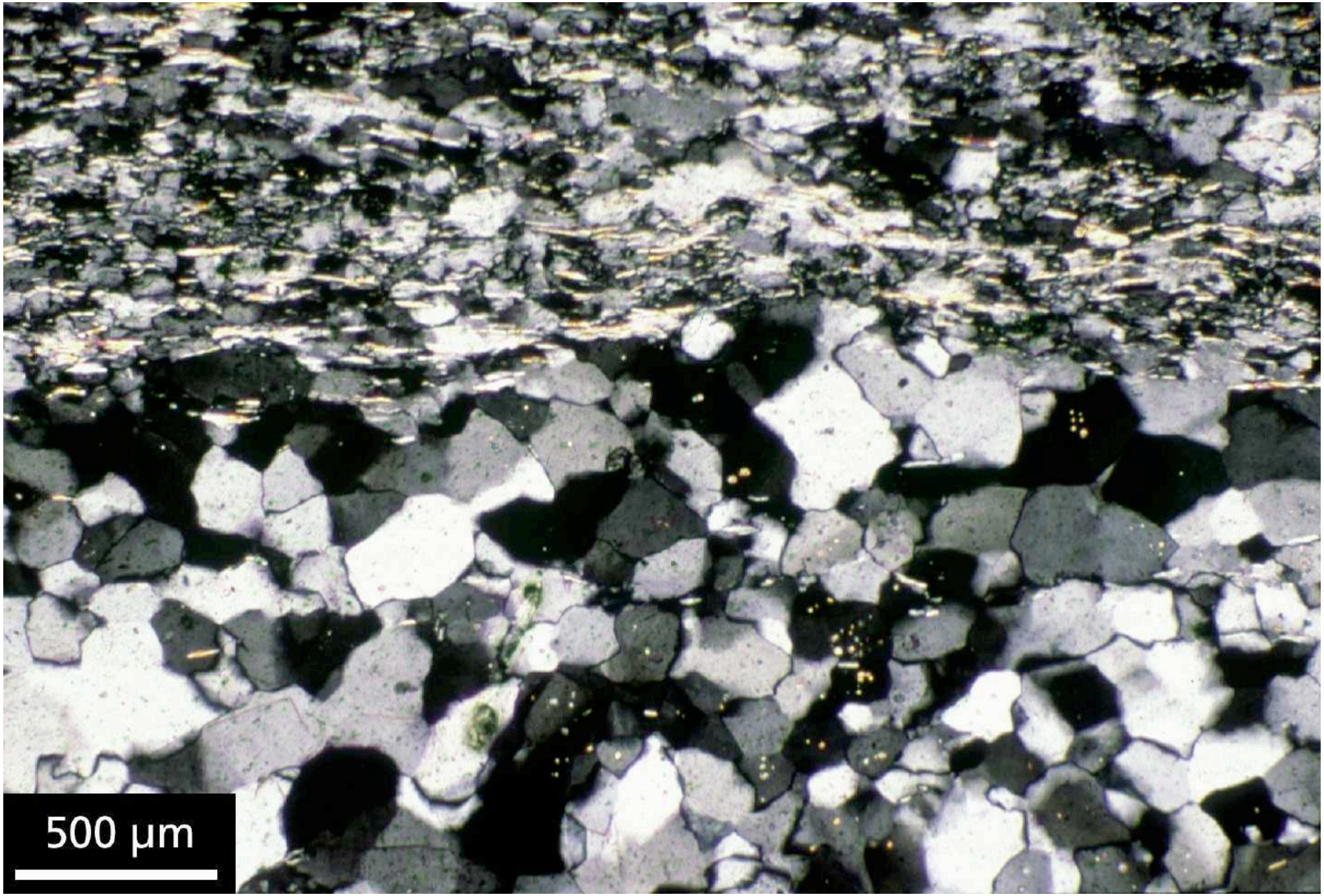


static recrystallization - annealing



Reduction of grain boundary area

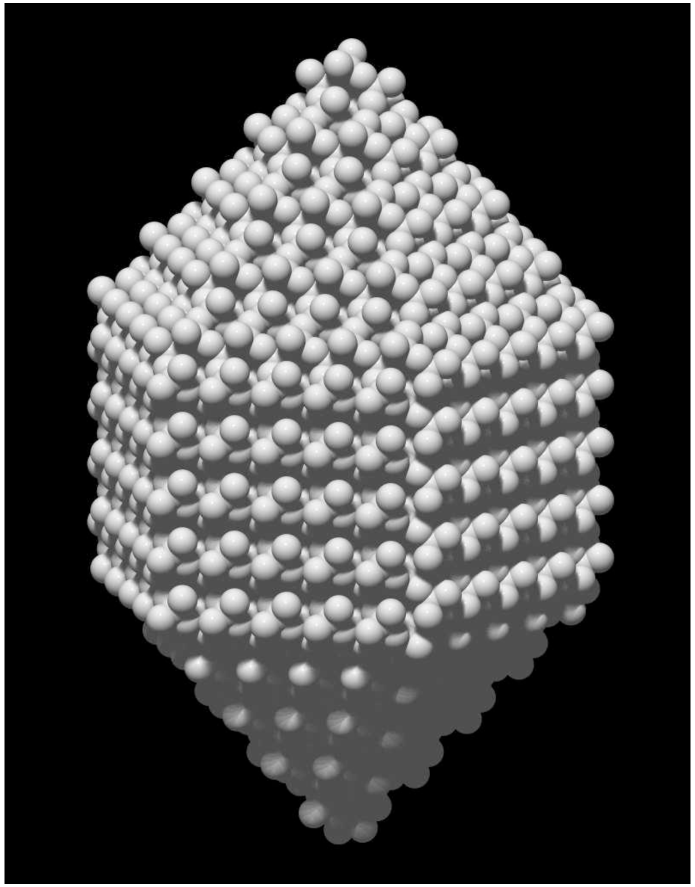
Example of grain growth due to annealing



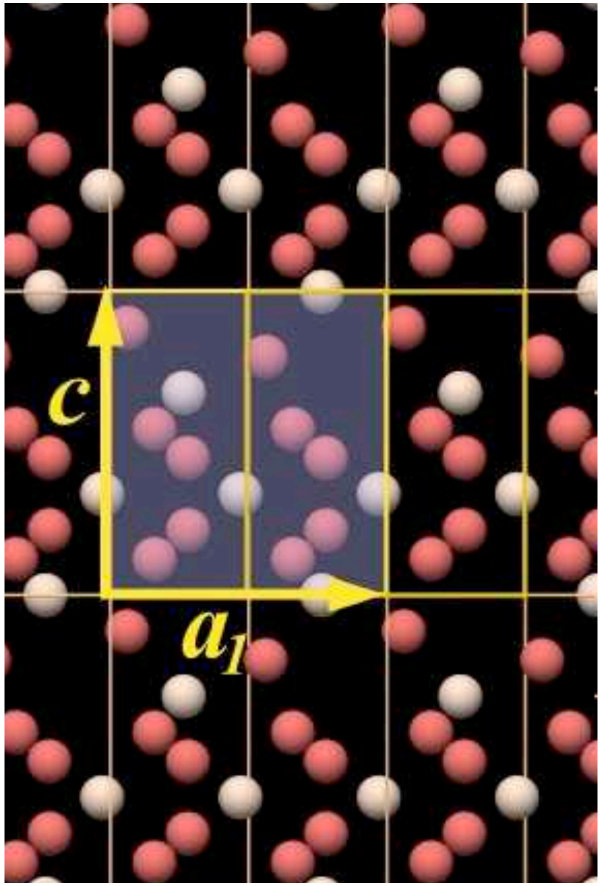
Versetzungen
Burgers vector
edge dislocations
screw dislocations

Diskontinua

Kristalle ≠ Kontinuumsmechanik

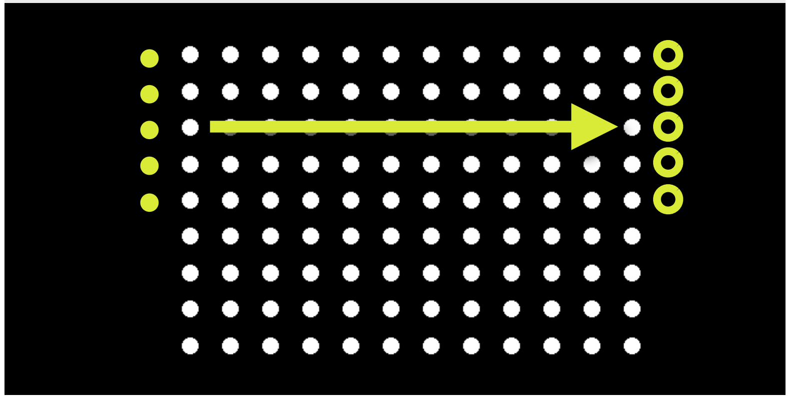


Quarz

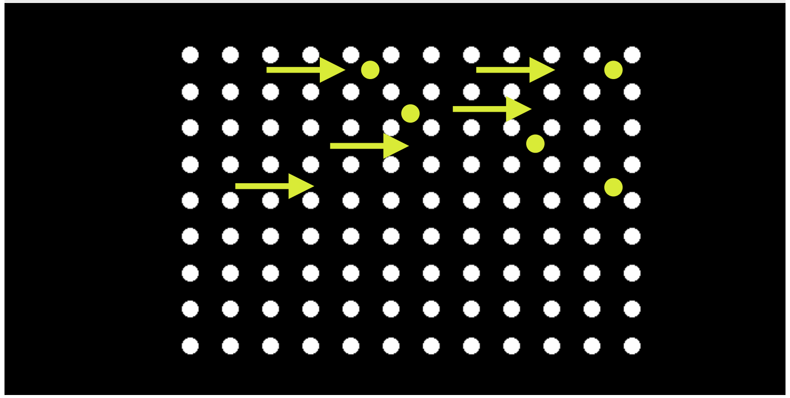


diffusion

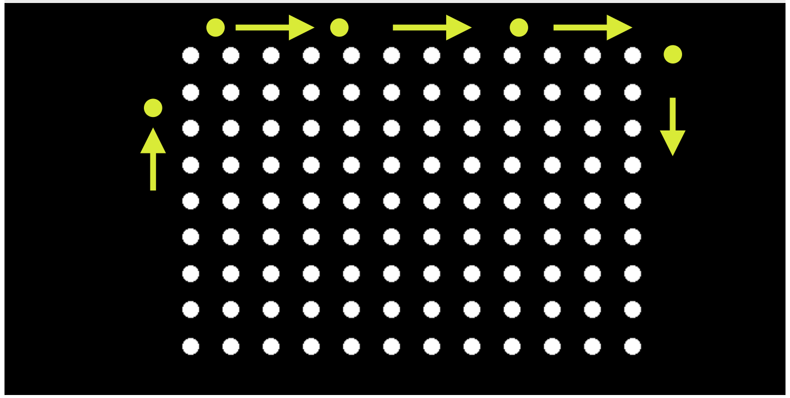
wie verformt man Kristalle ?



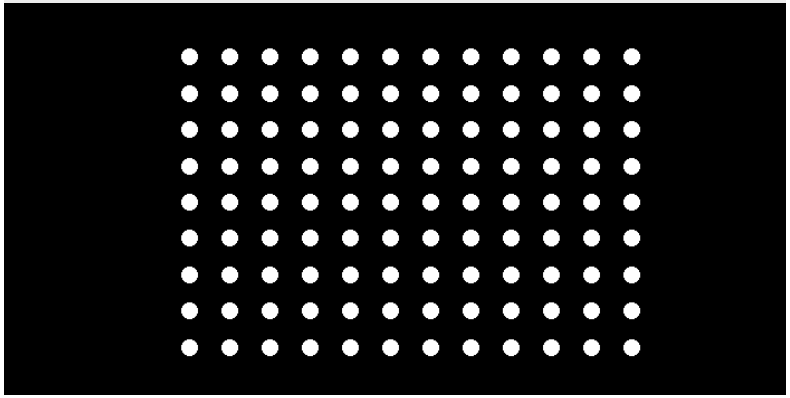
volume diffusion



grain boundary diffusion

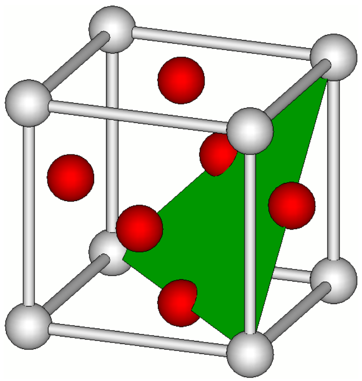


dislocation glide

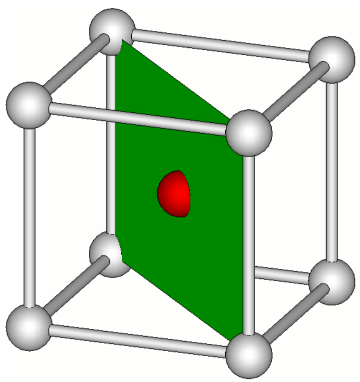


Gleitsysteme

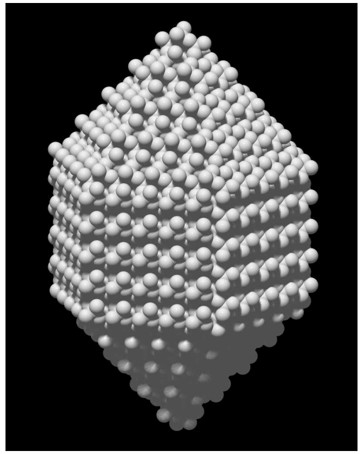
{111}-Gleitebene in einem kubisch- flächenzentrierten Gitter

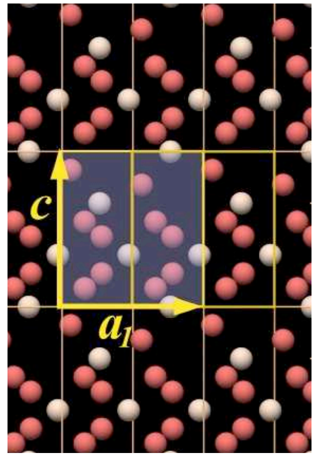


{110}-Gleitebene in einem kubisch- raumzentrierten Gitter



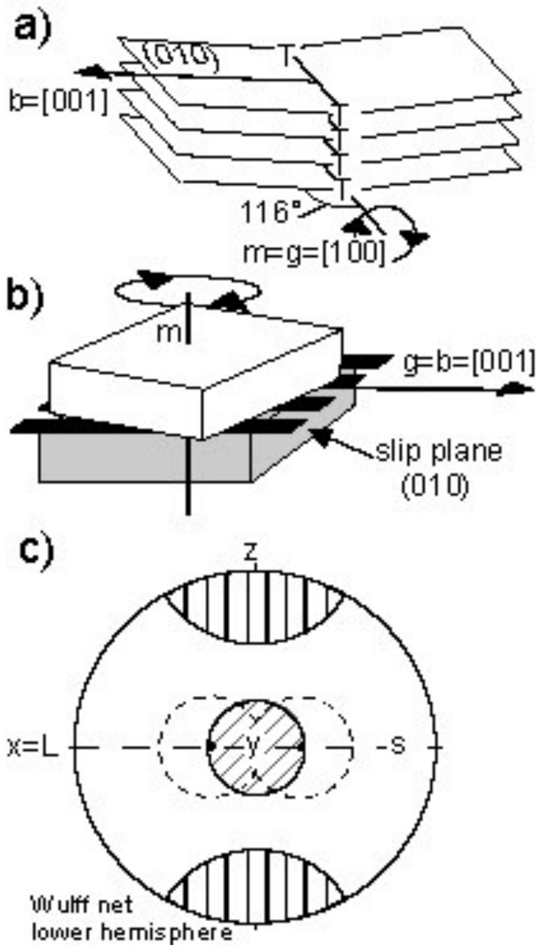
Quarz

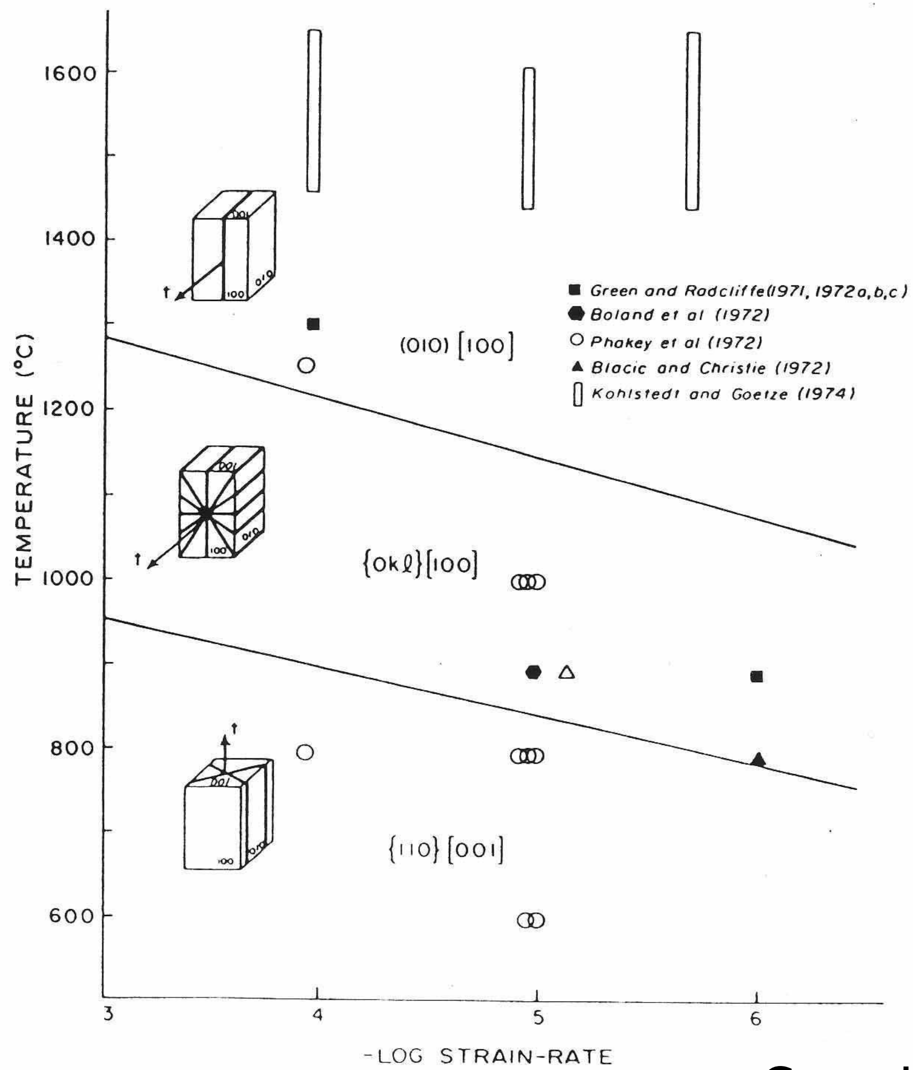




Kristallstruktur	Gleitebene	Gleitrichtung	
kfz	{111}	<110>	
krz	{110}	<111>	
	{112}	<111>	
	{123}	<111>	
hex	{0001}	<1120>	basal <a>
	{1010}	<1120>	prism <a>
	{1011}	<1120>	rhomb <a>
	{1010}	<0001>	prism <c>

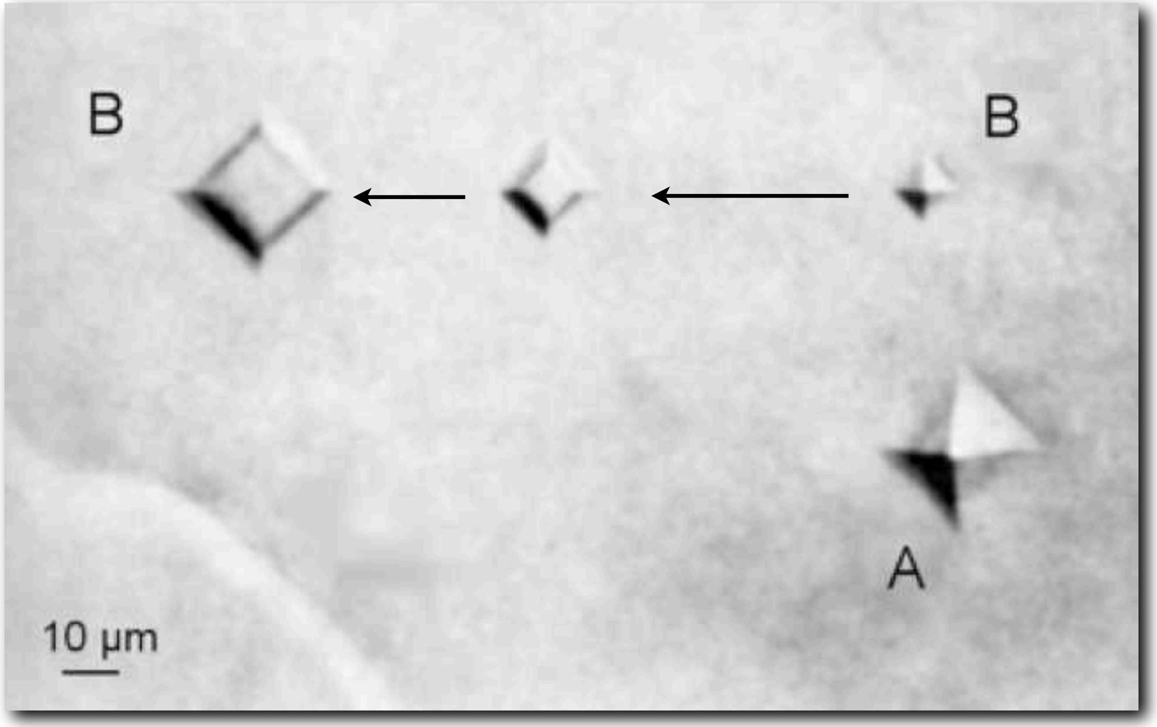
Gleitsysteme



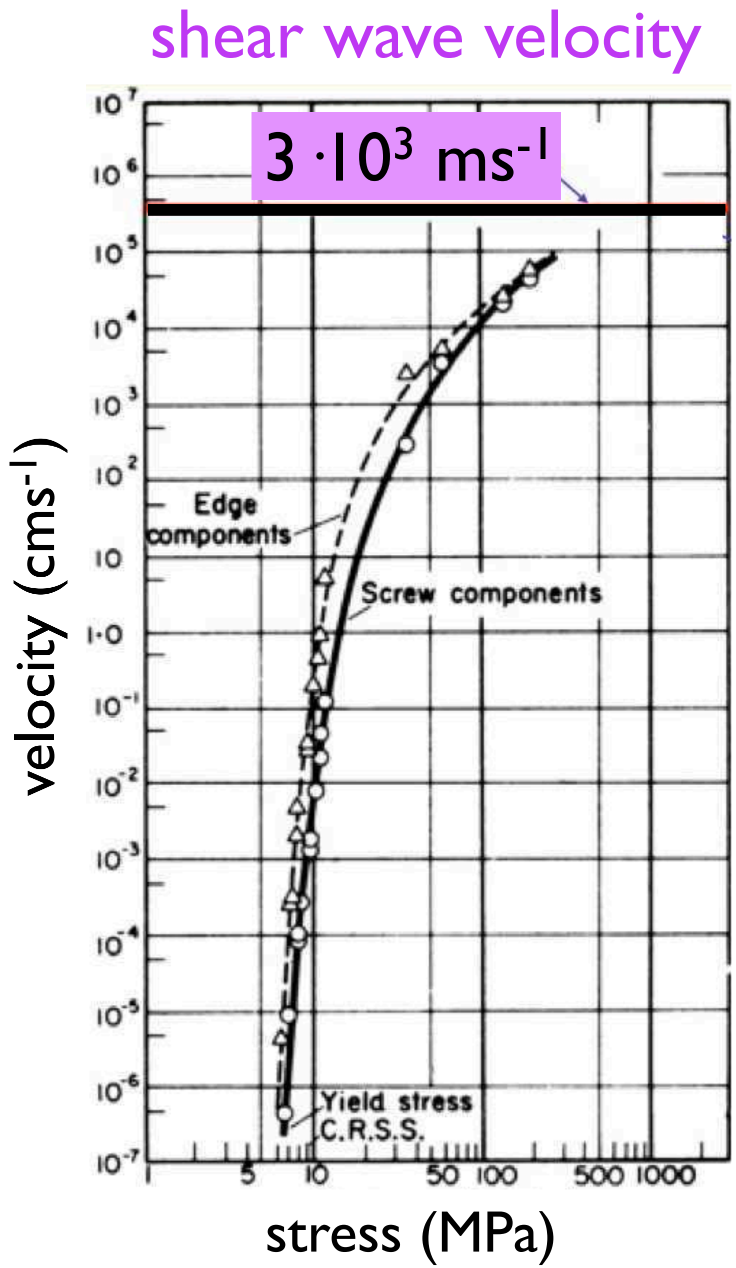


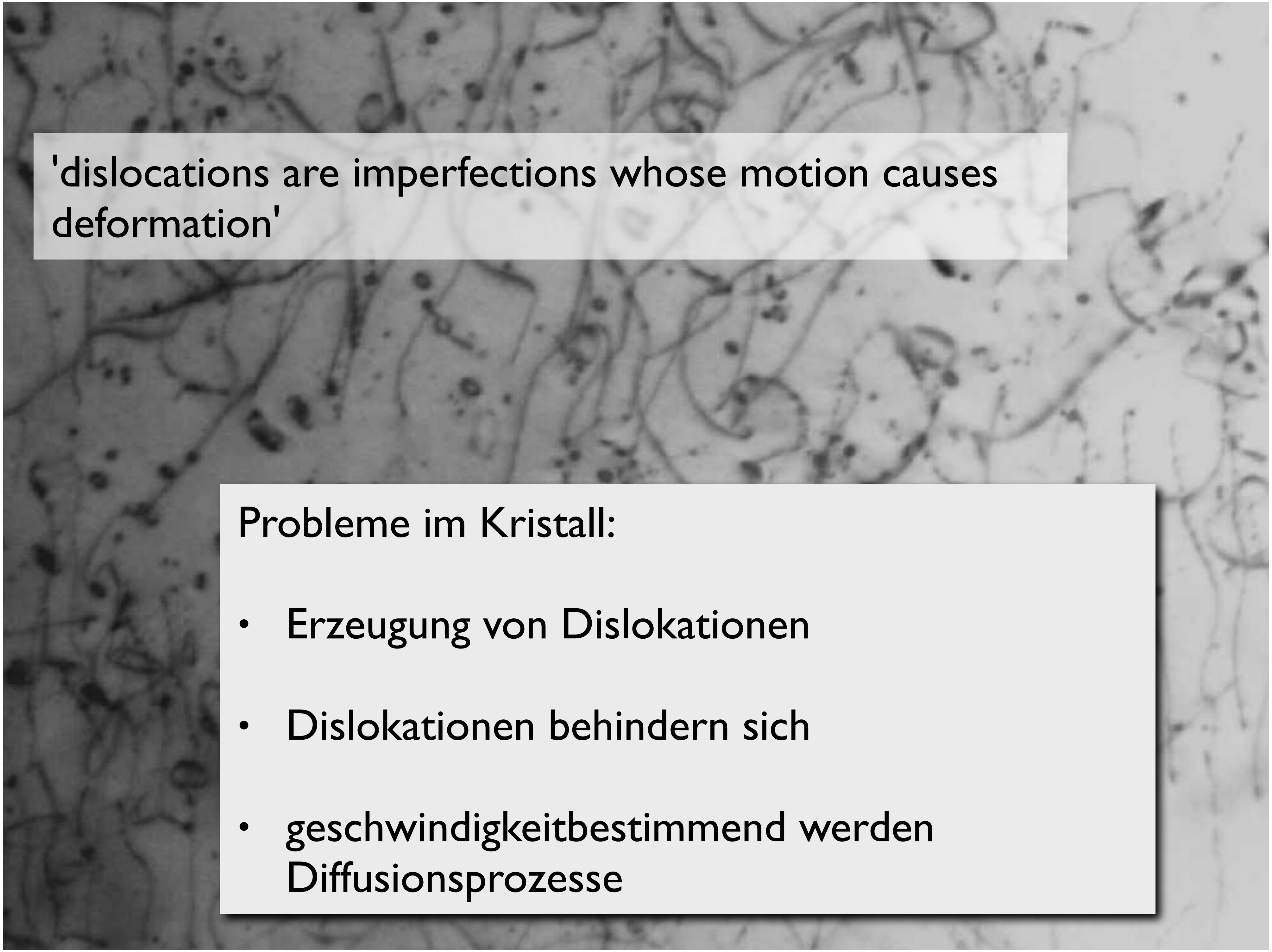
Green 1974

Versetzungen - dislocations



Ätzgrube = Dislokation



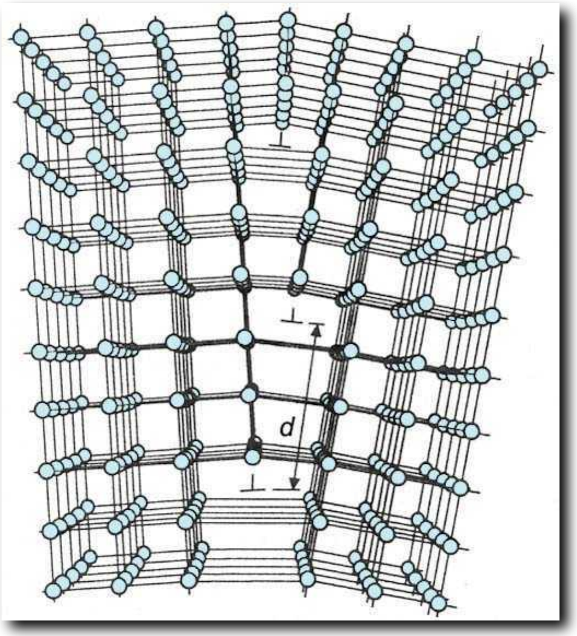


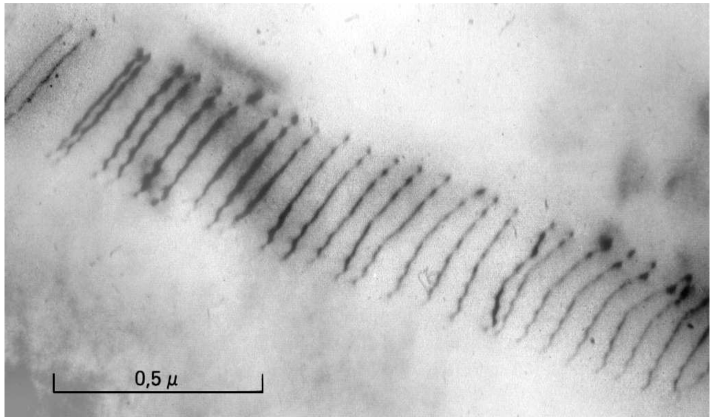
'dislocations are imperfections whose motion causes deformation'

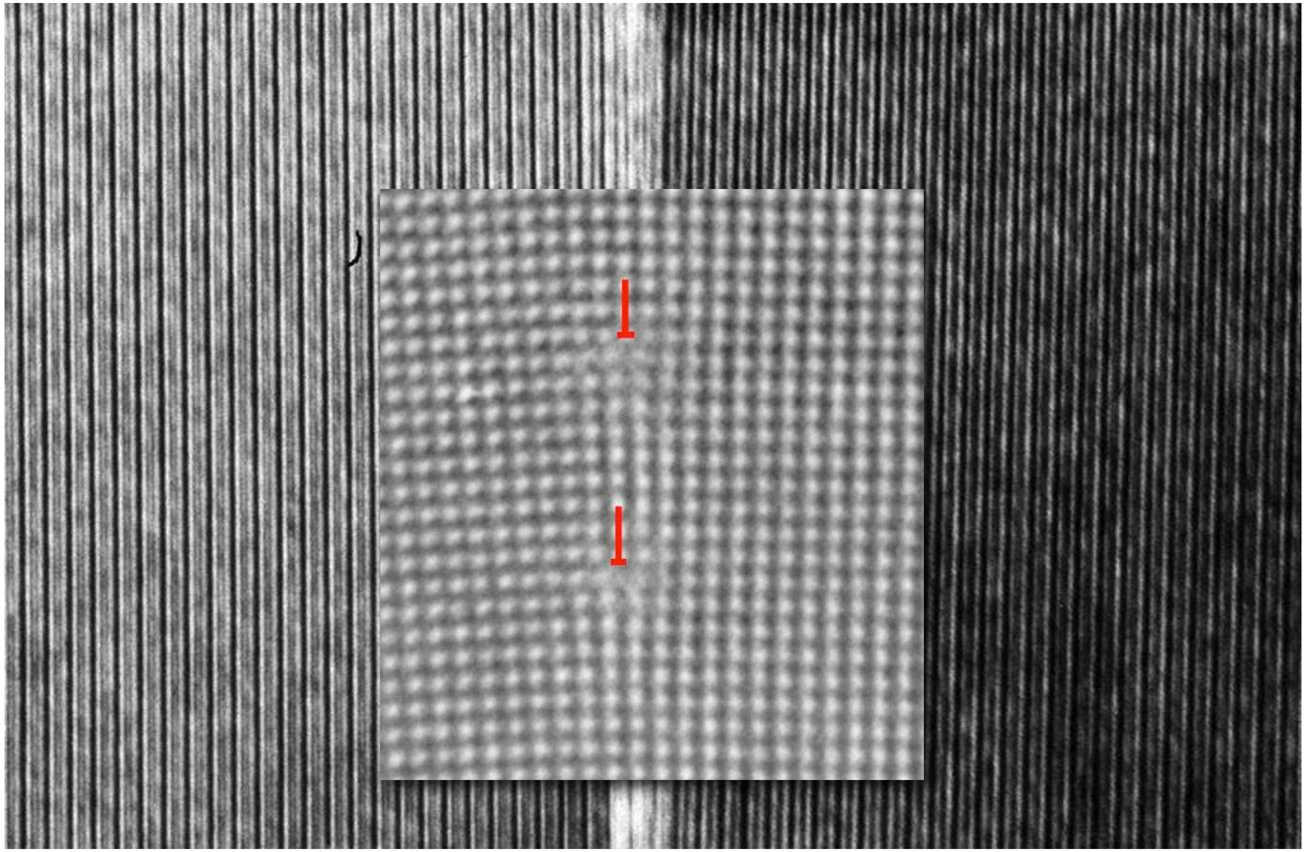
Probleme im Kristall:

- Erzeugung von Dislokationen
- Dislokationen behindern sich
- geschwindigkeitbestimmend werden Diffusionsprozesse

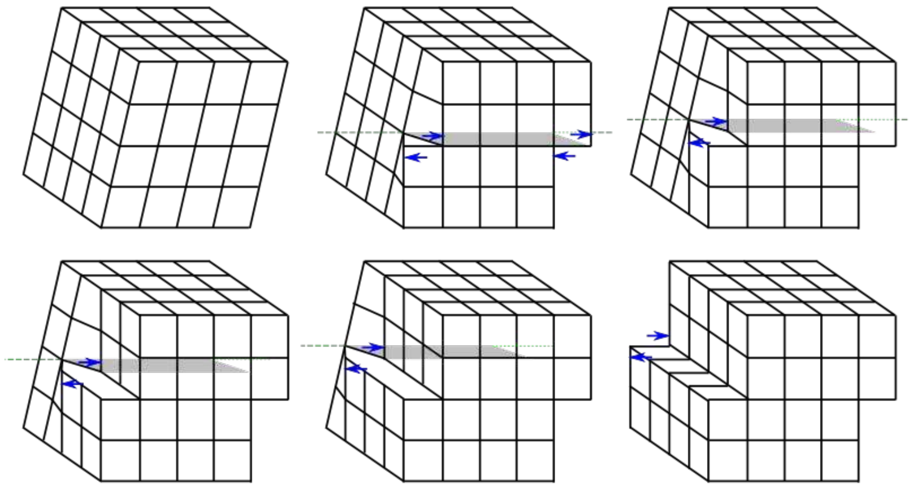
Stufenversetzungen - edge dislocations



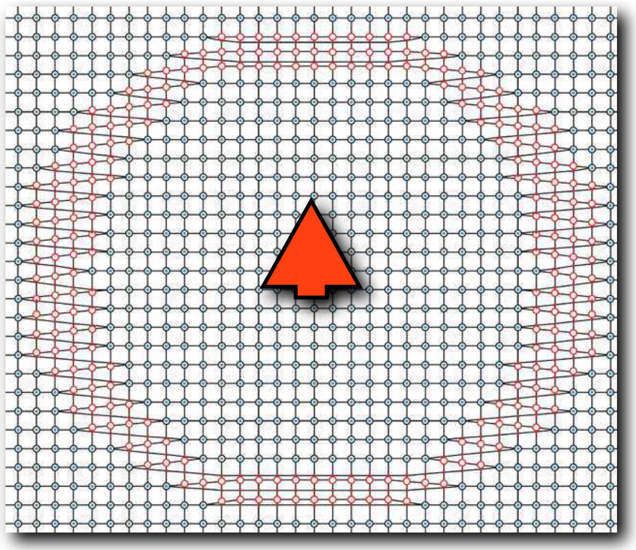




Schraubenversetzungen - screw dislocations

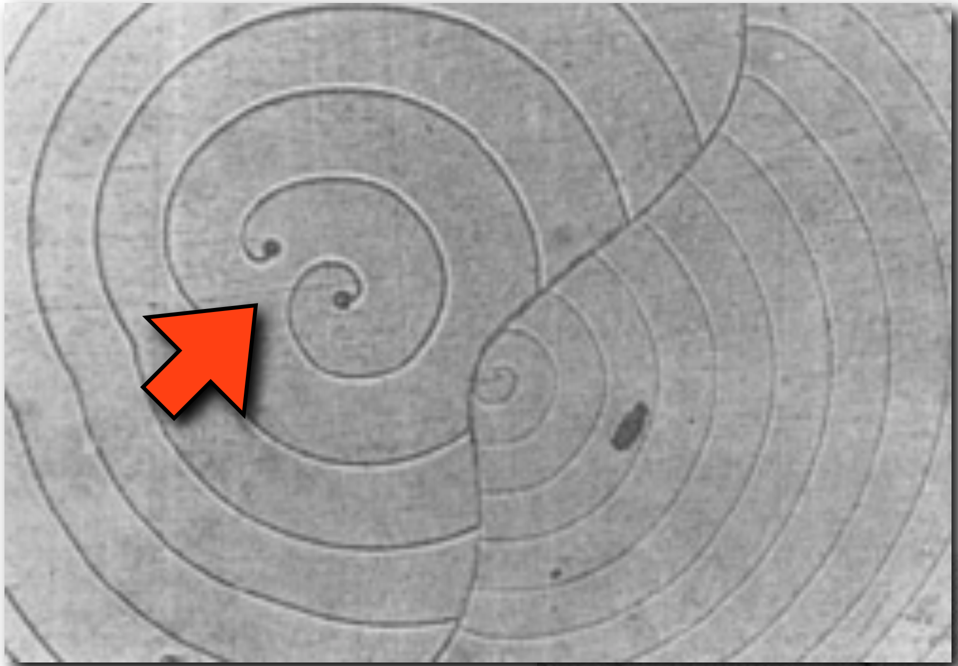


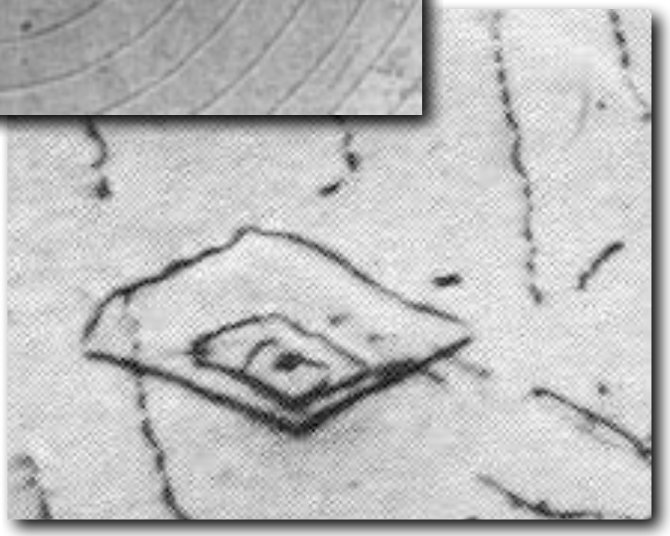
dislocation loop

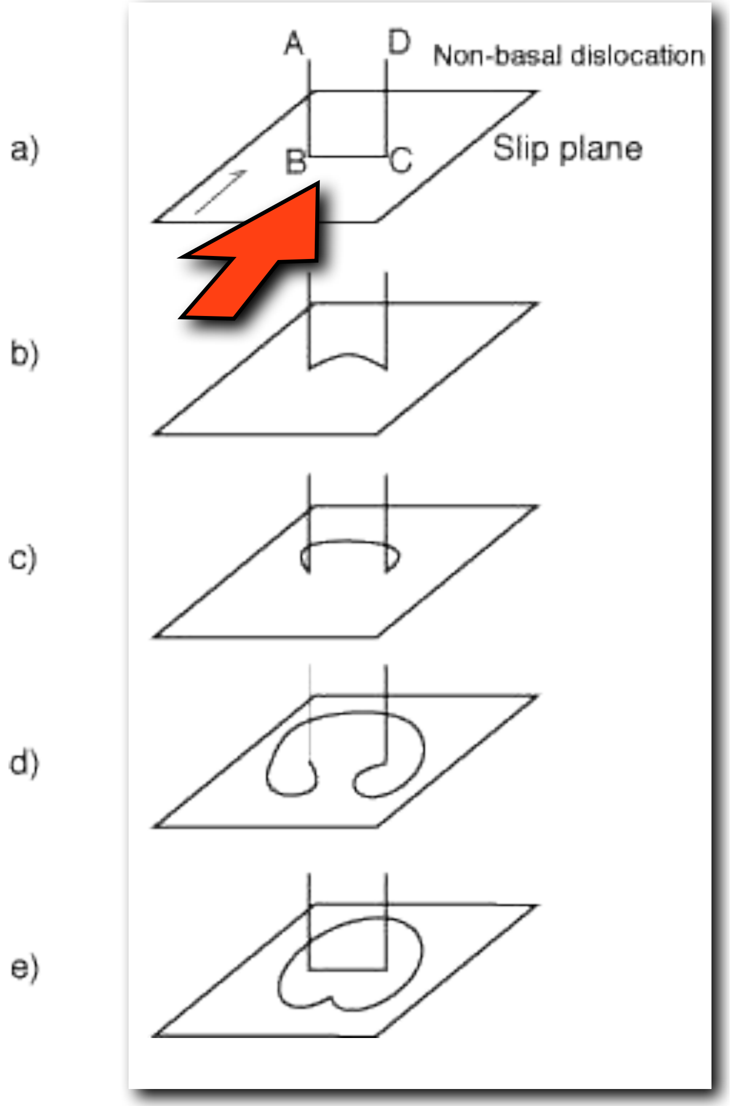


gemischte Versetzungen

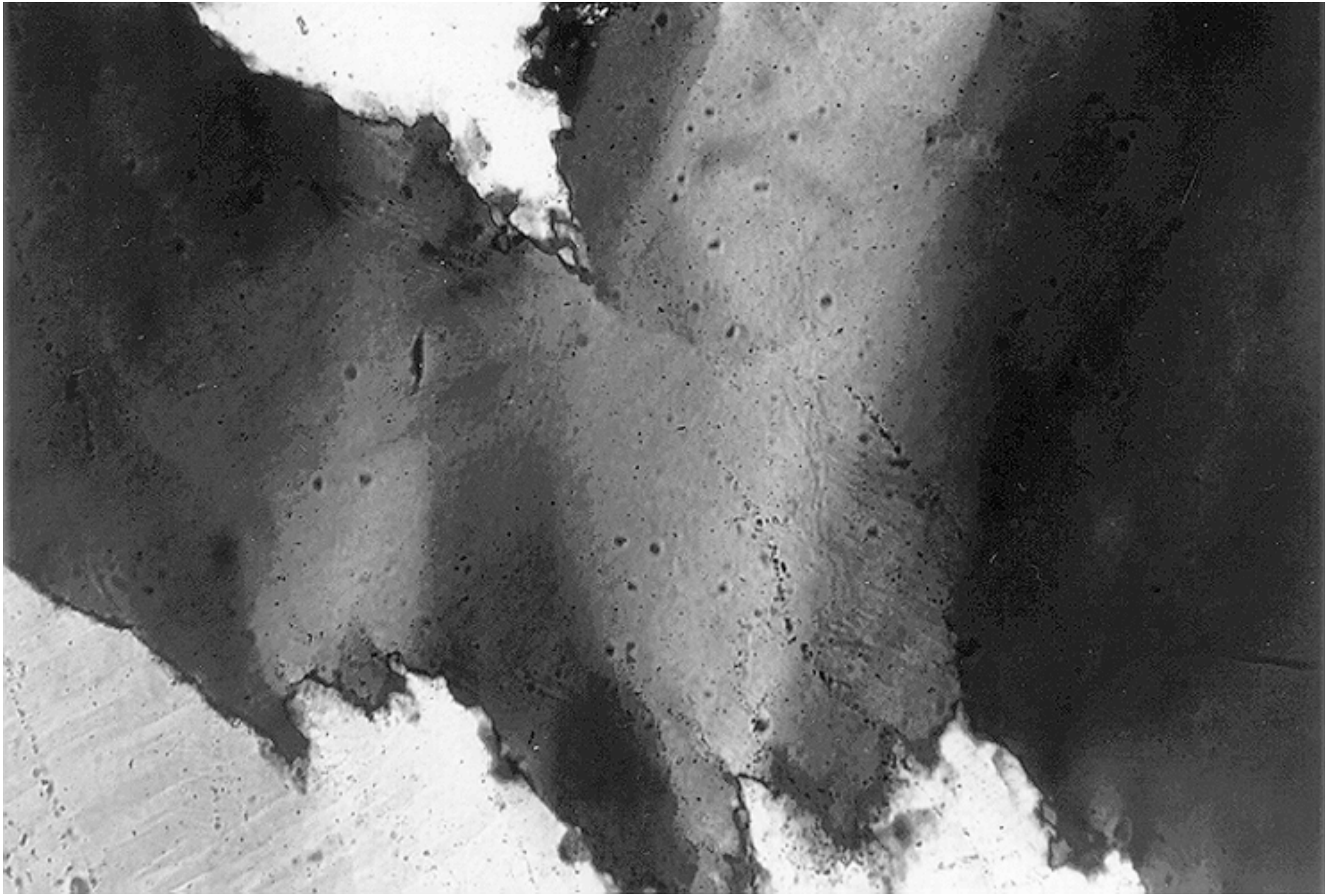
Frank-Reed sources



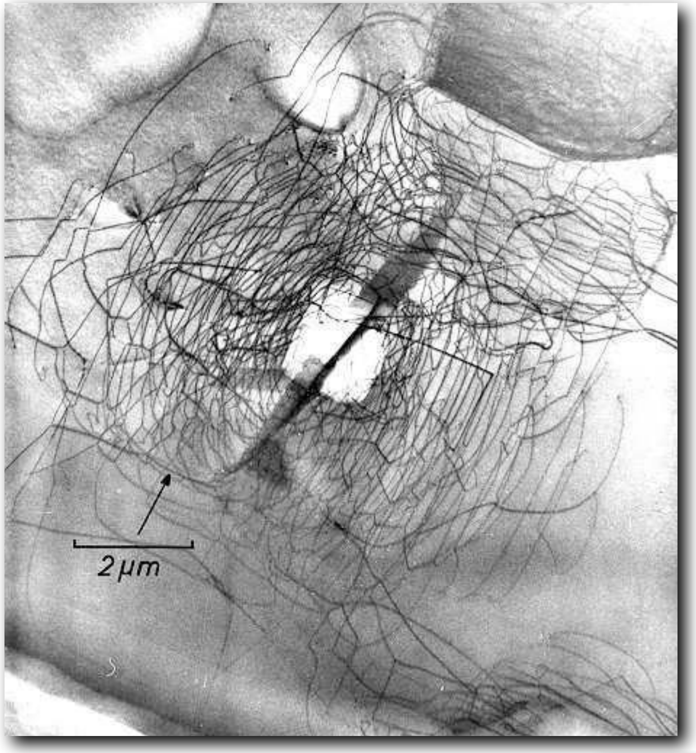




Undulatory extinction in quartz - evidence for dislocation glide

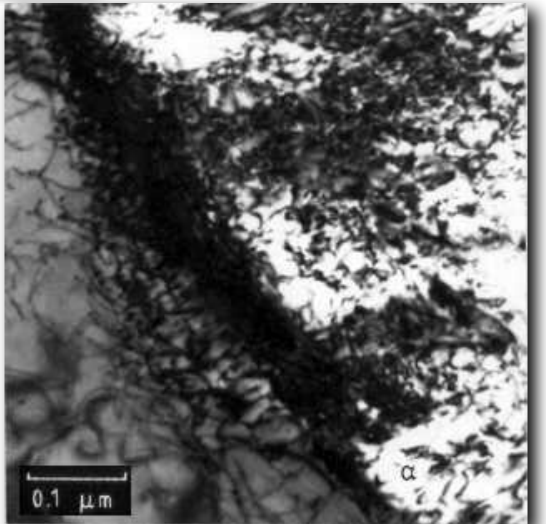


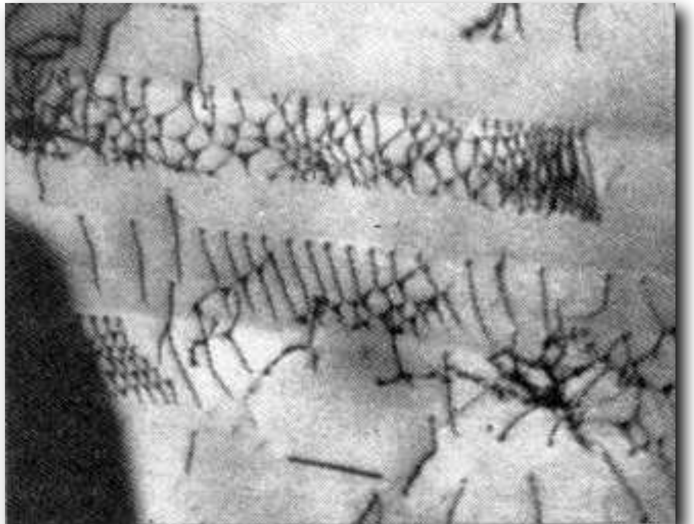
Versetzungen - dislocations



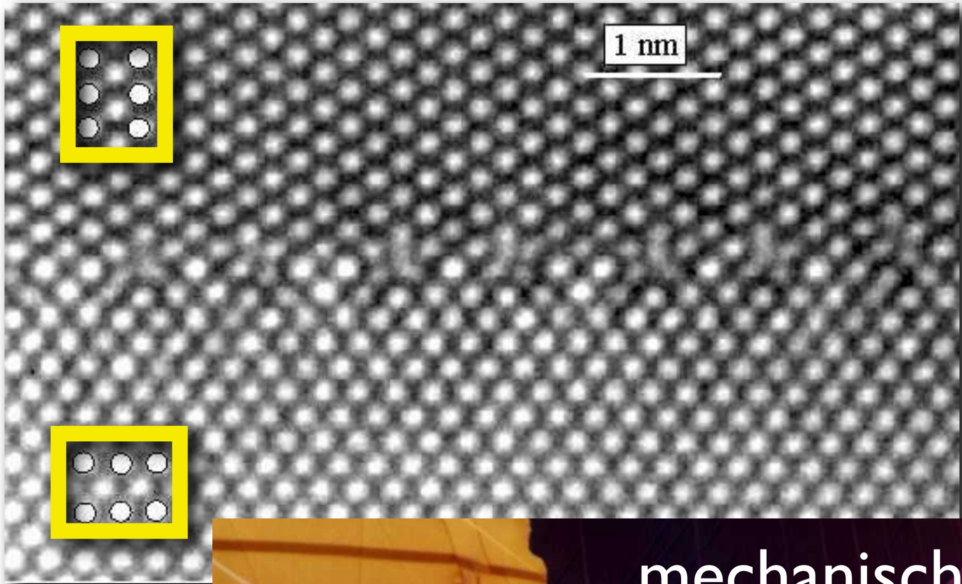
dislocation tangles:
aus glissil wird sessil

Diffusionsprozesse werden
geschwindigkeitbestimmend

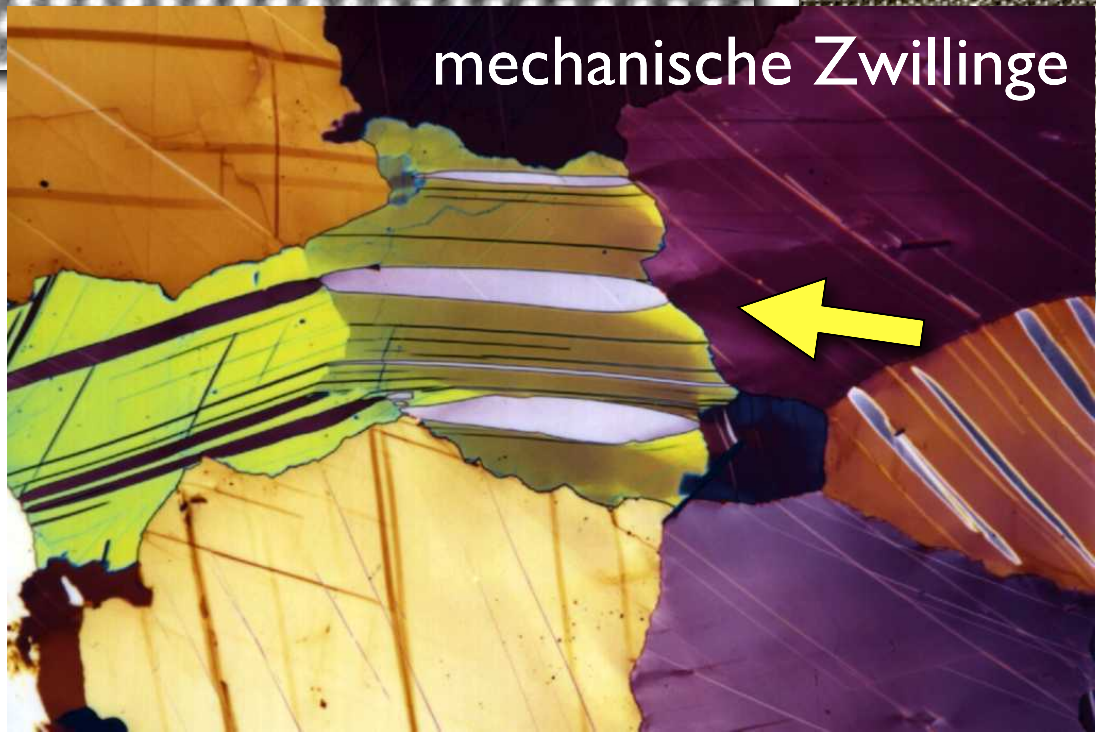




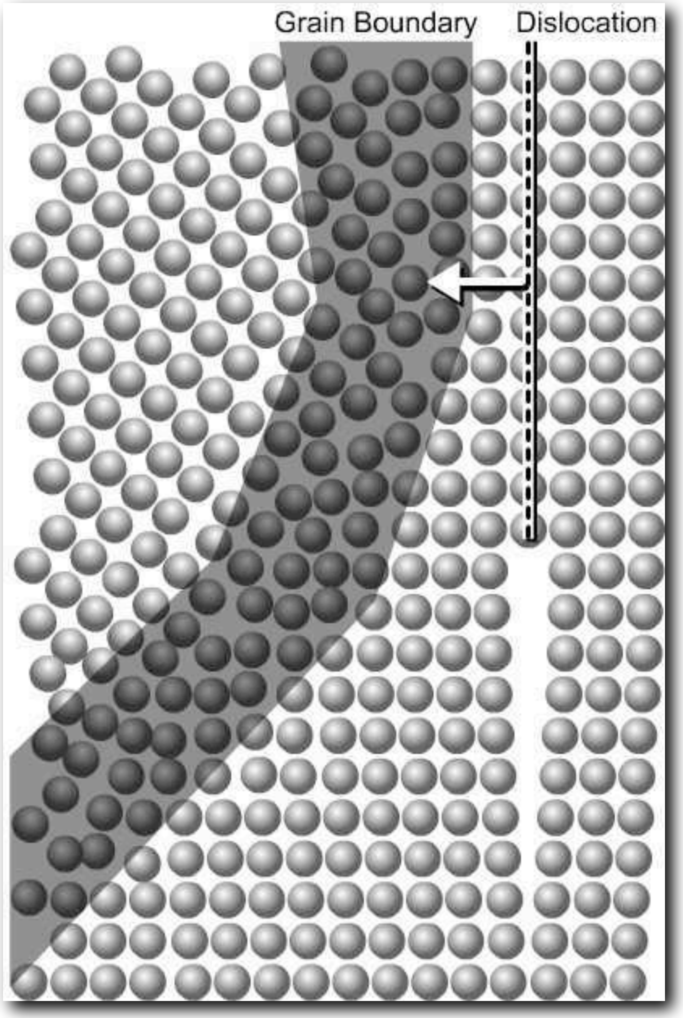
(sub)grain boundaries



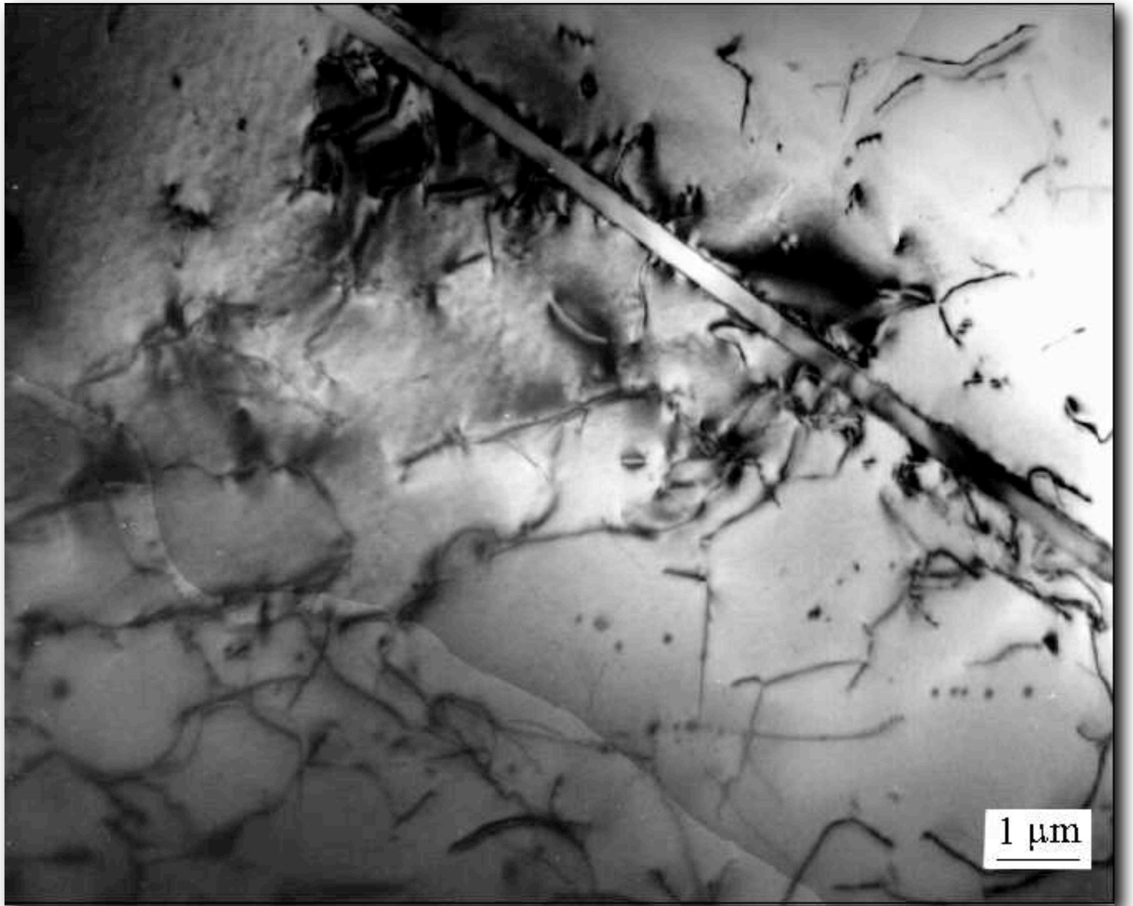
Probleme mit den Nachbarn



grain boundaries



Korngrenzen
eine 'zusätzliche Phase'



reccrystallization

&

recovery

dislocation climb

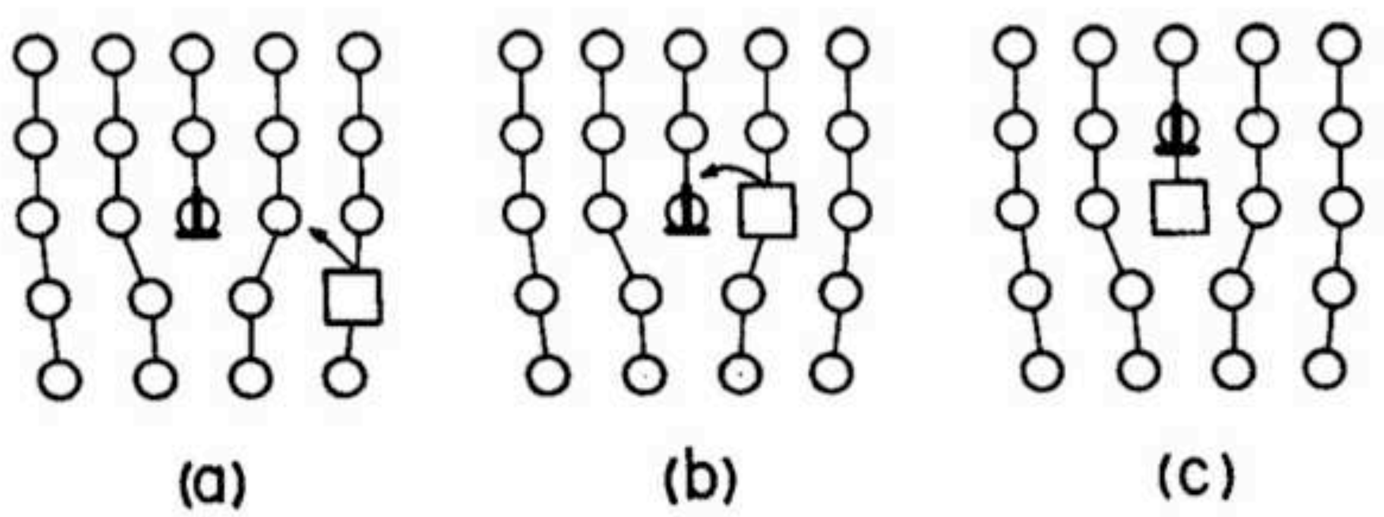
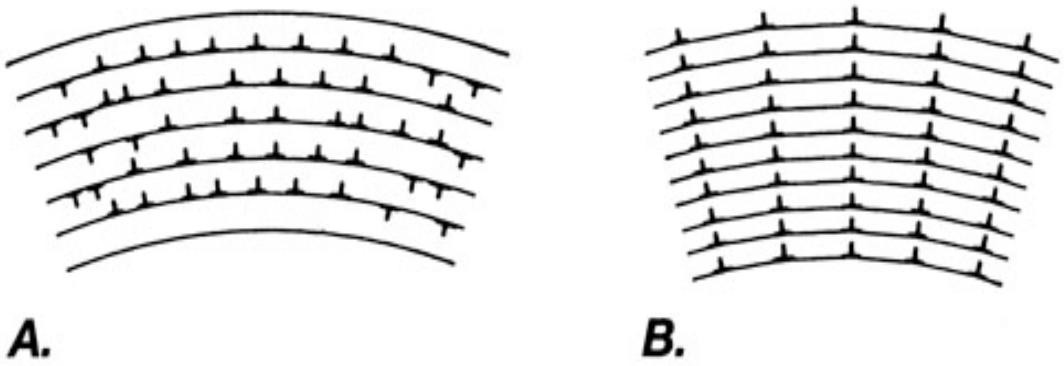


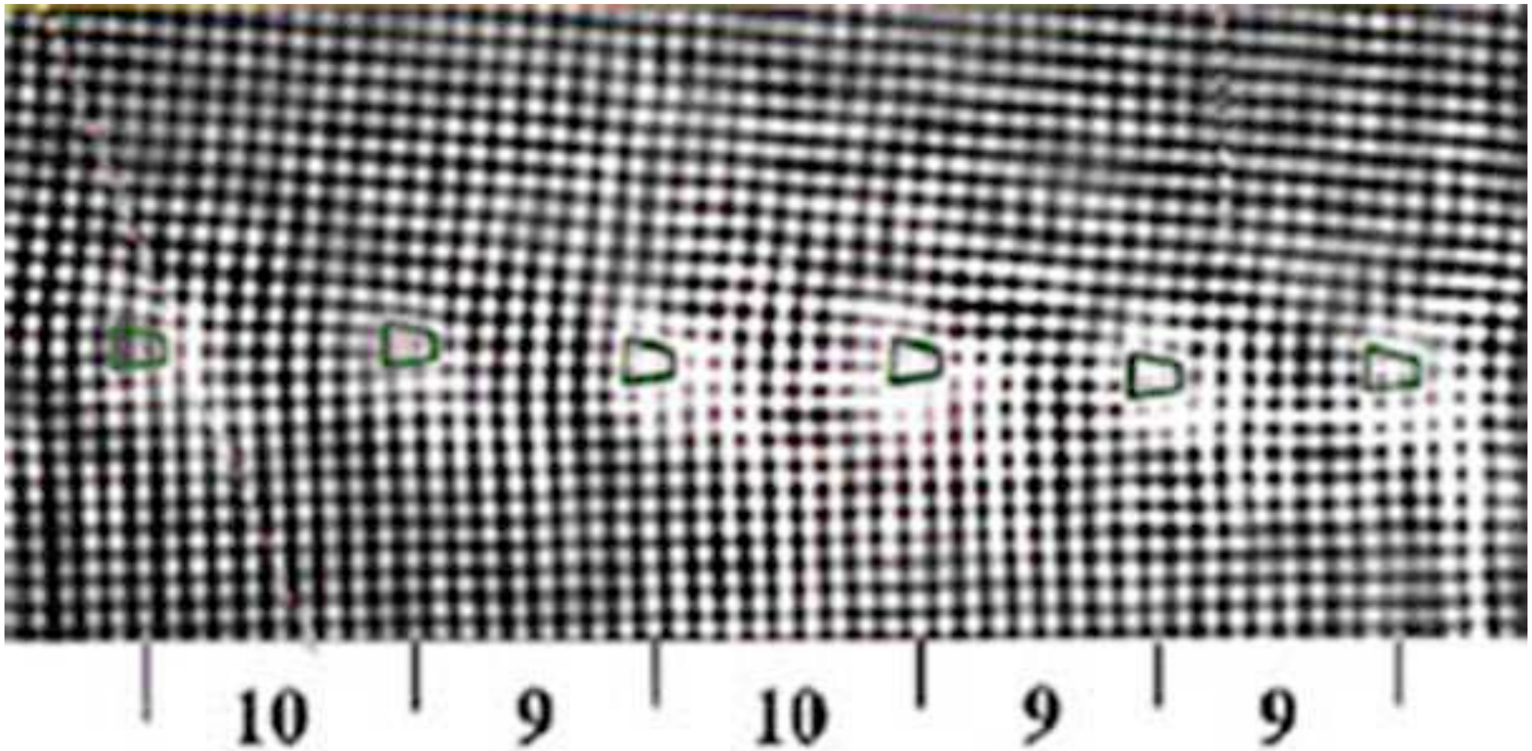
FIGURE 3–10. Dislocation climb.

Weertman &Weertman 1992

recovery



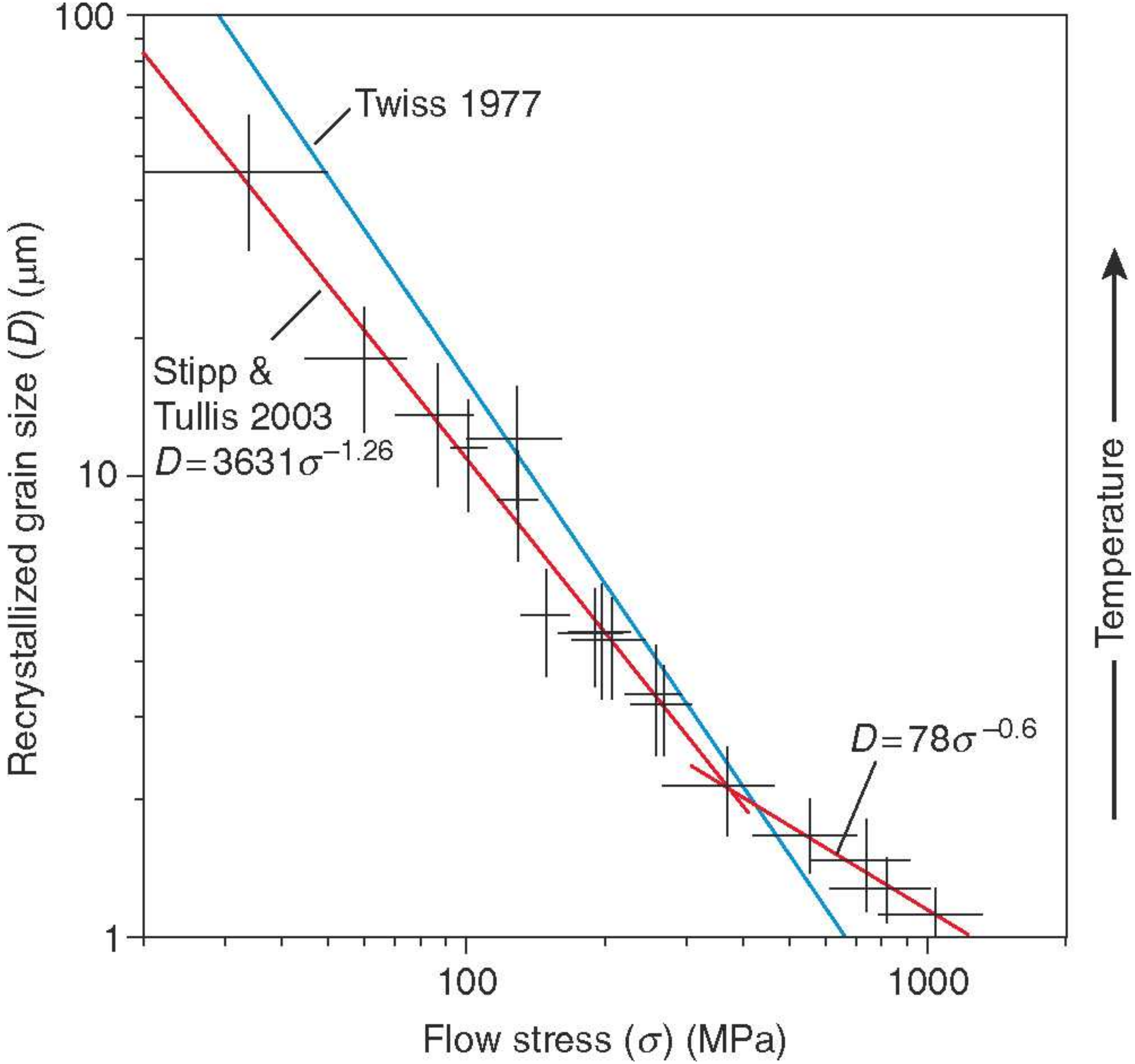
tilt boundaries



Subgrain boundaries in quartz

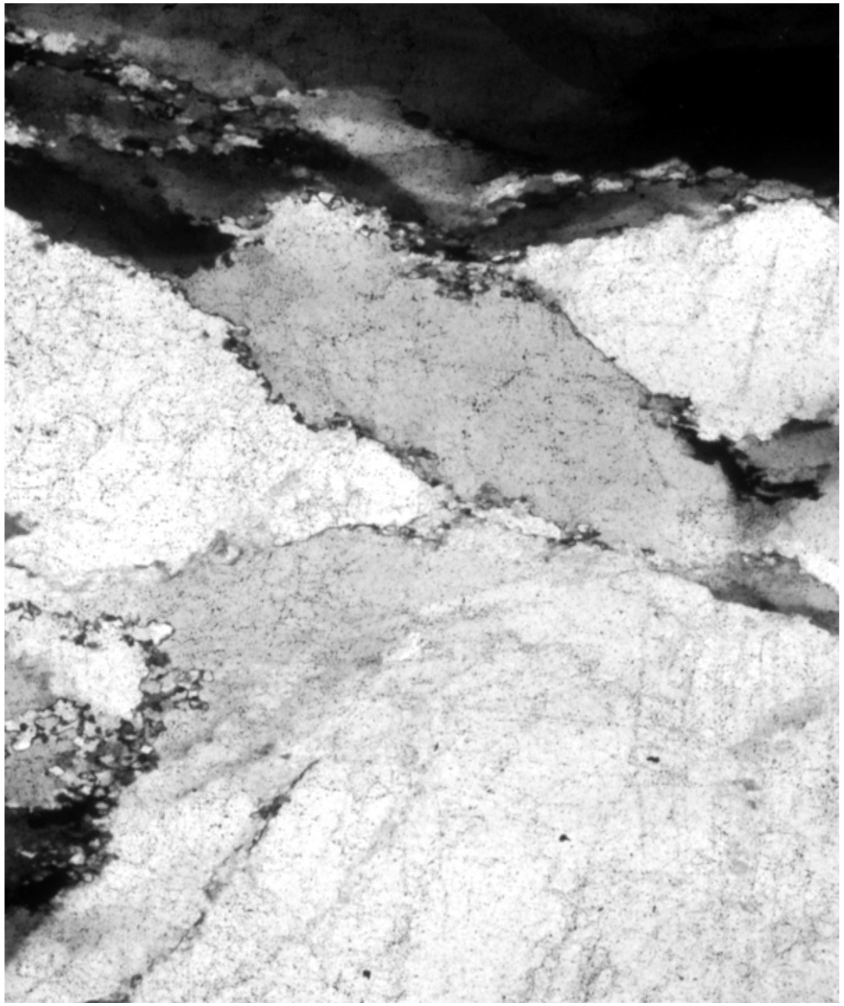
Grain boundary migration causes recrystallization - driven by dislocation density difference

Paläo-Piezometer



deformation mechanisms

microstructures

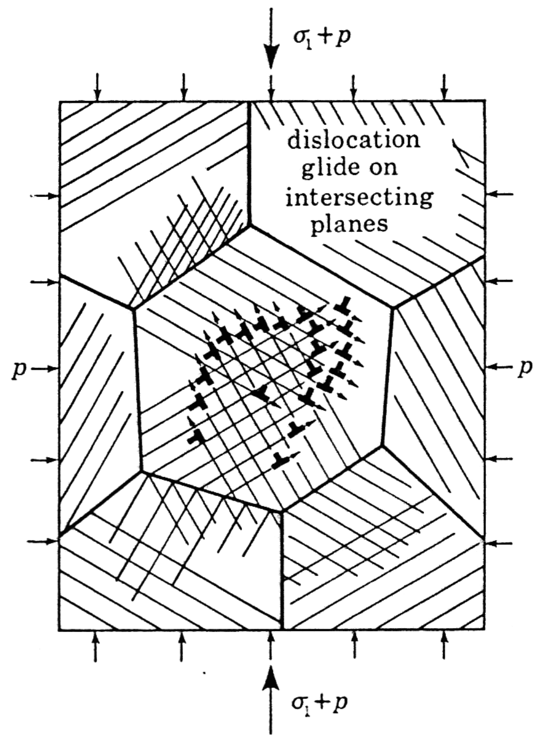


100 µm

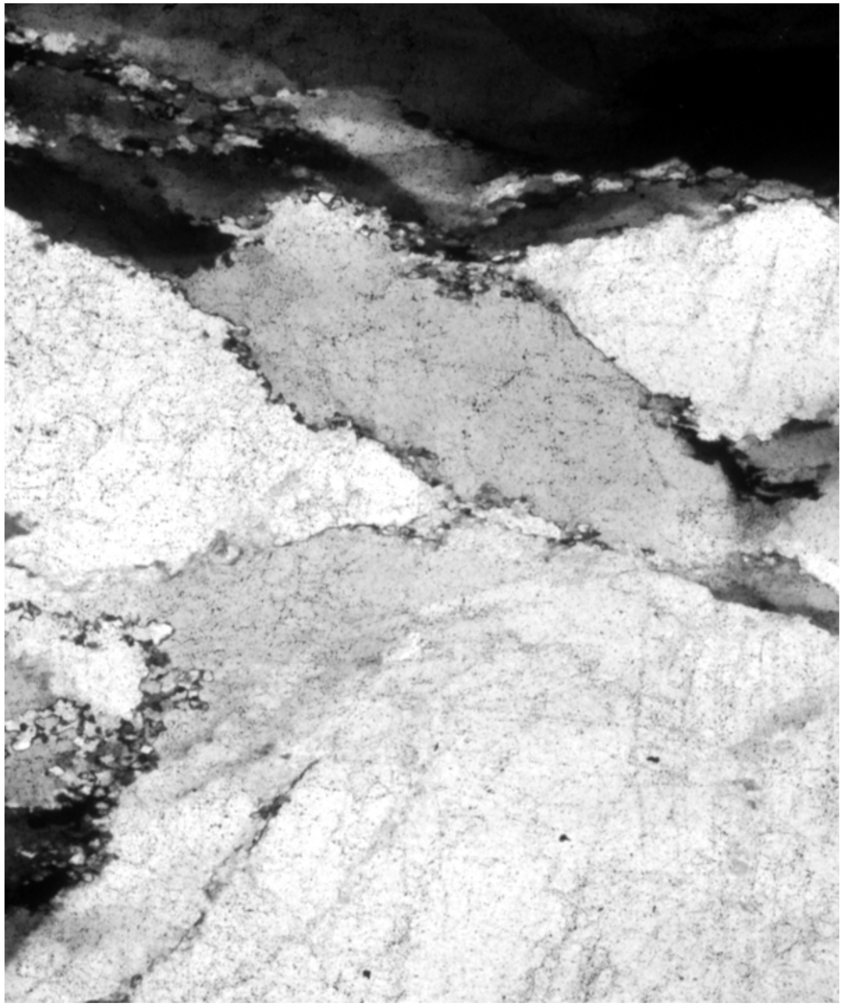
Stavel quartzite

intracrystalline plasticity

dislocation glide



microstructures

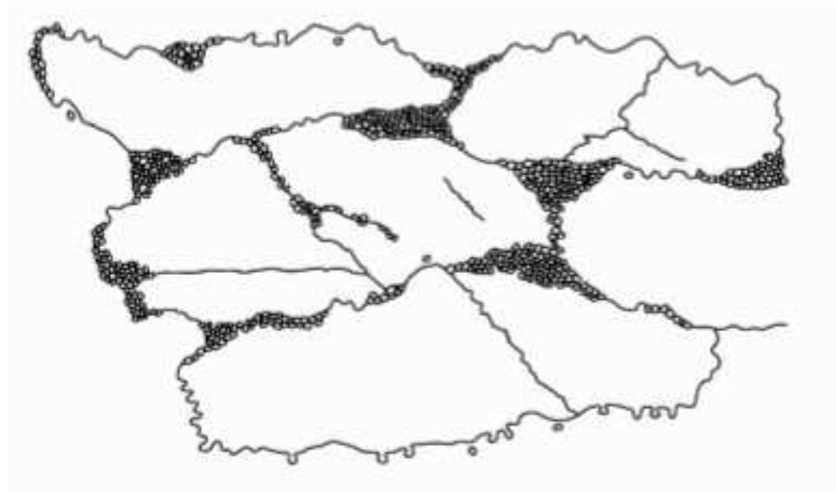


100 μm

Stavel quartzite

bulging recrystallization

dislocation creep



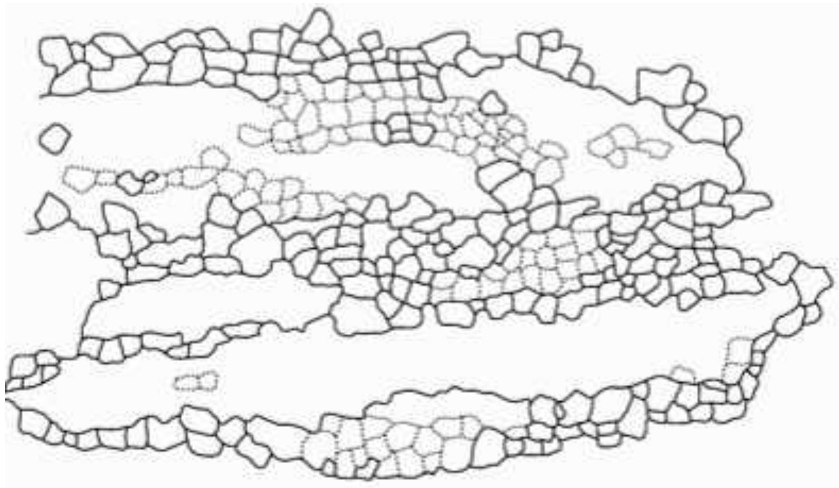
microstructures

100 μm

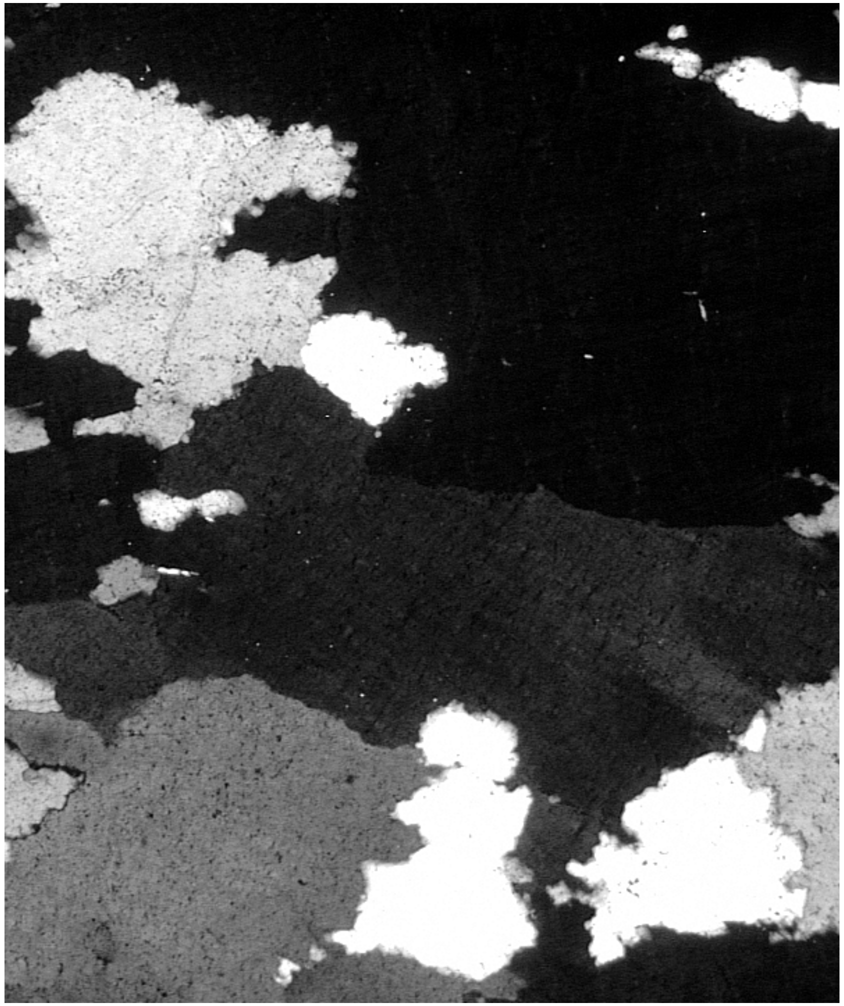
Stavel quartzite

subgrain rotation
recrystallization

dislocation creep



microstructures

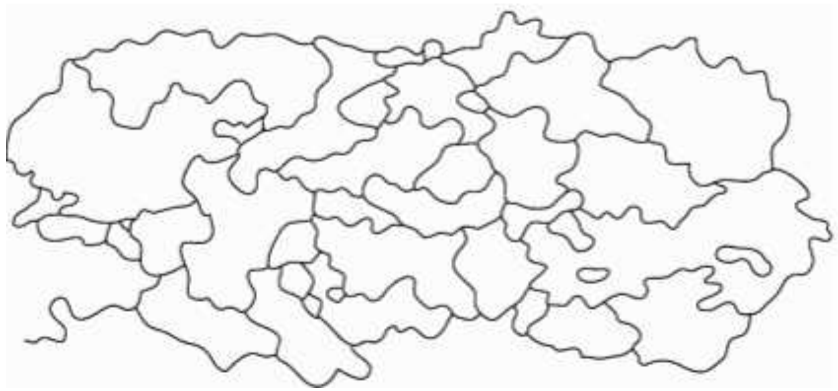


100 μm

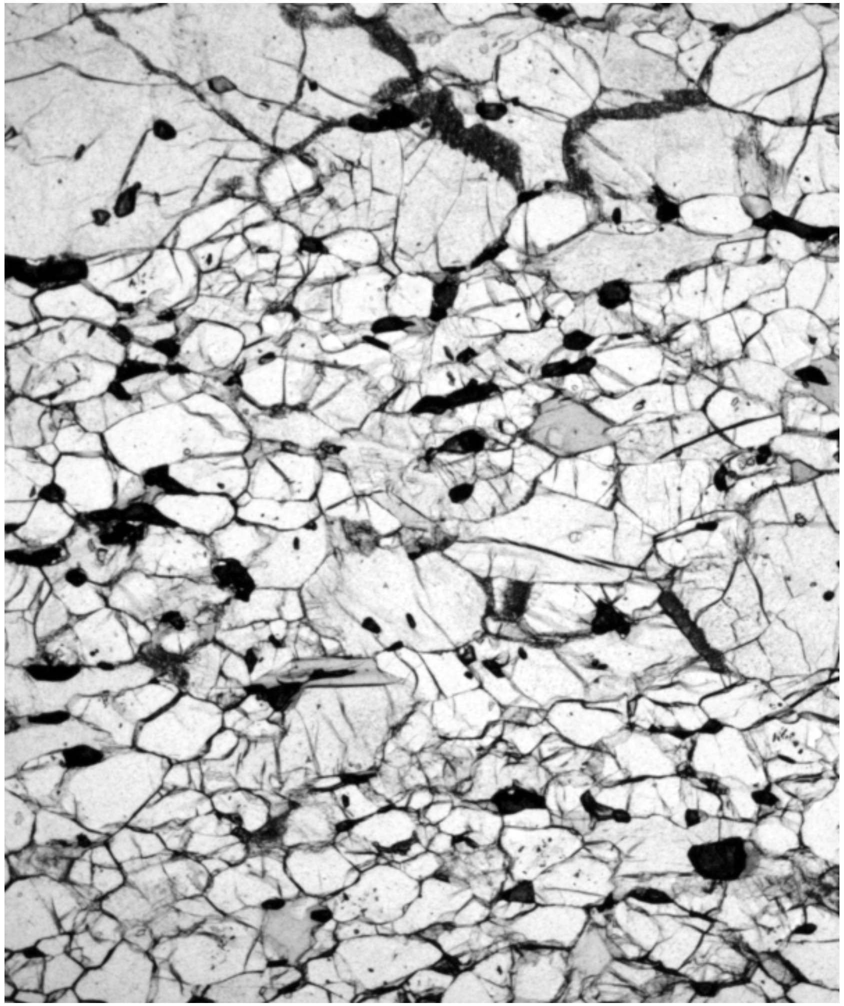
Stavel quartzite

grain boundary migration recrystallization

dislocation creep



microstructures

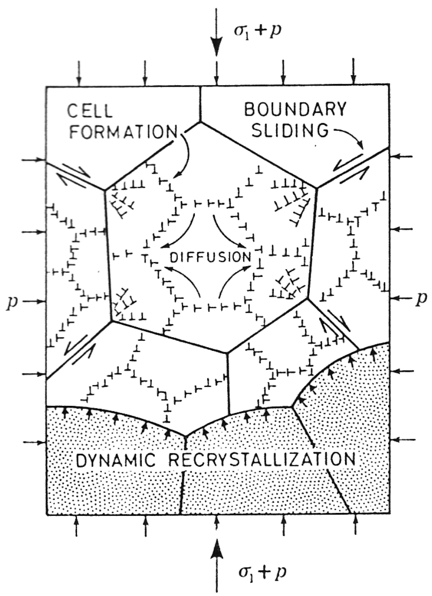


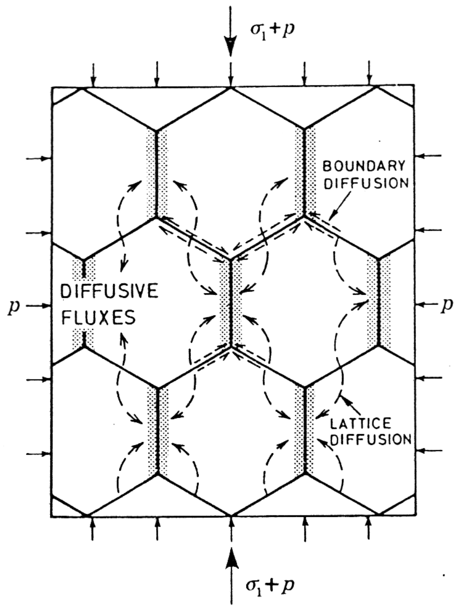
500 µm

Meluzina ecolgite

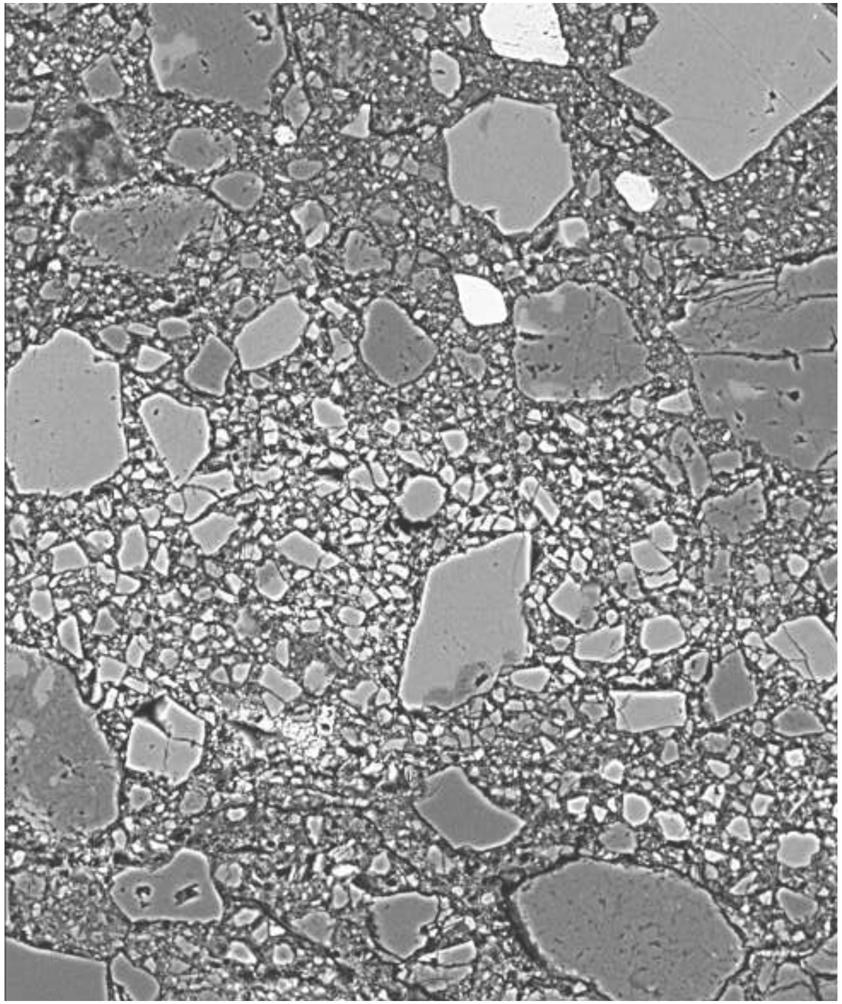
grain boundary sliding
bulk diffusion
boundary diffusion

diffusion creep





microstructures

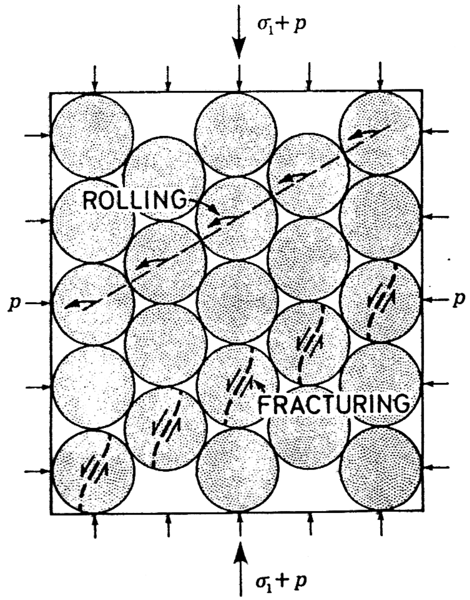


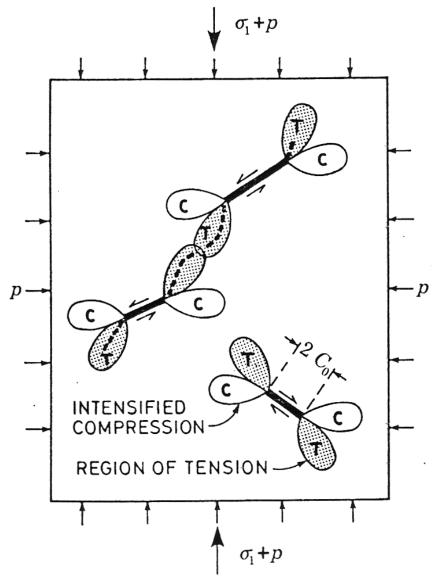
500 μm

Nojima fault rock

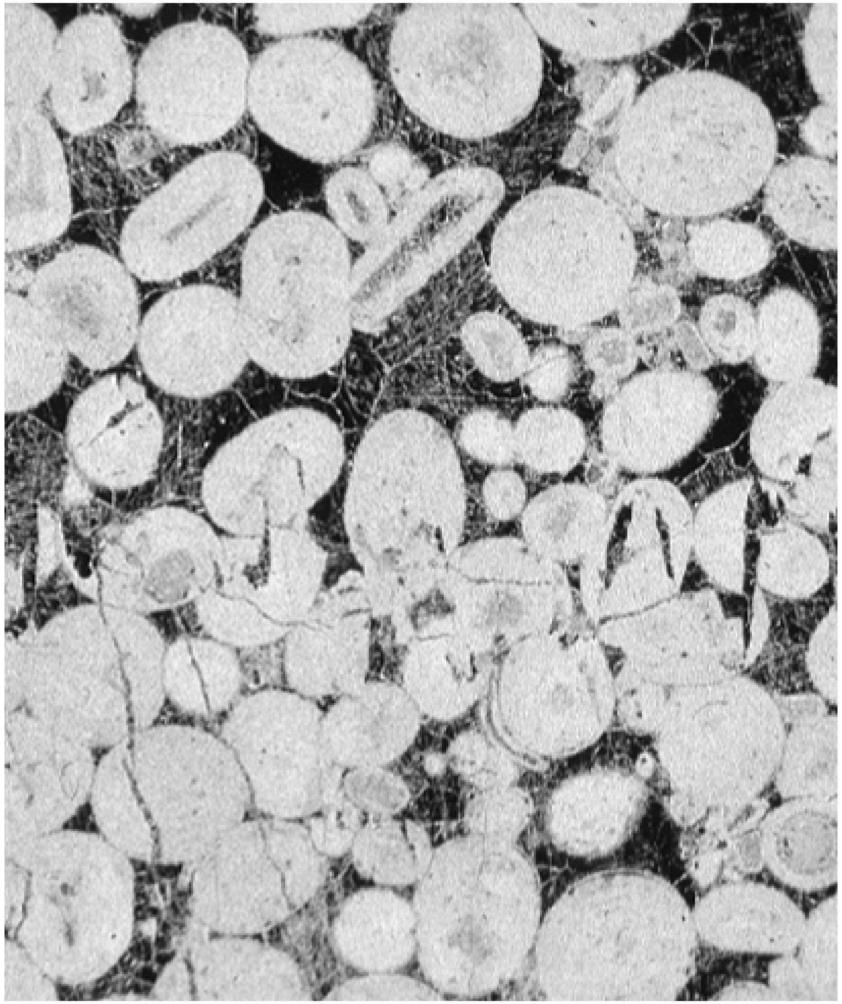
rolling
fracturing

granular flow
(diffusion creep)





microstructures

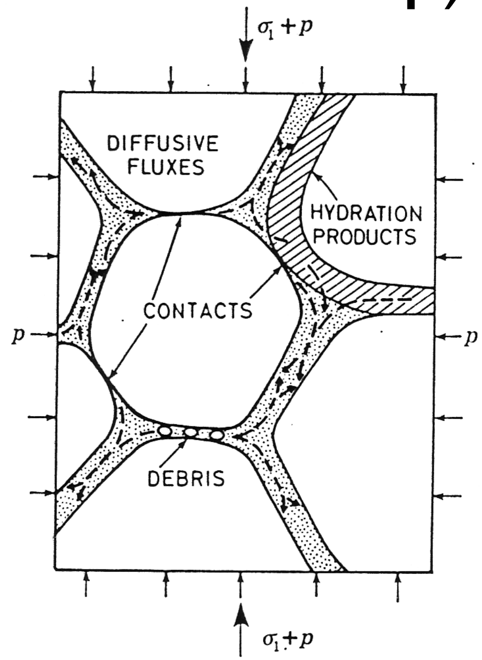


1 mm

Oolithic limestone

solution - diffusion - precipitation

pressure solution (diffusion creep)

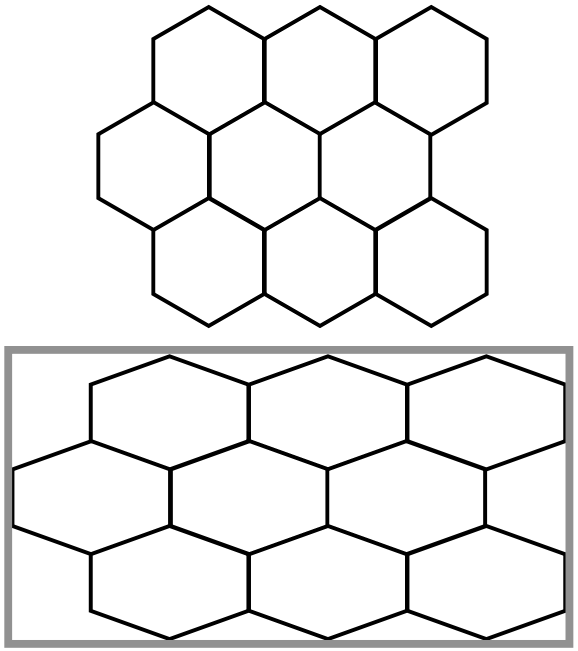


micromechanical
models
intracrystalline plasticity
grain boundary sliding
Nabarro Herring /Coble
cataclastic flow

micromechanical models

intracrystalline plasticity
dislocation glide
(facilitated by:)

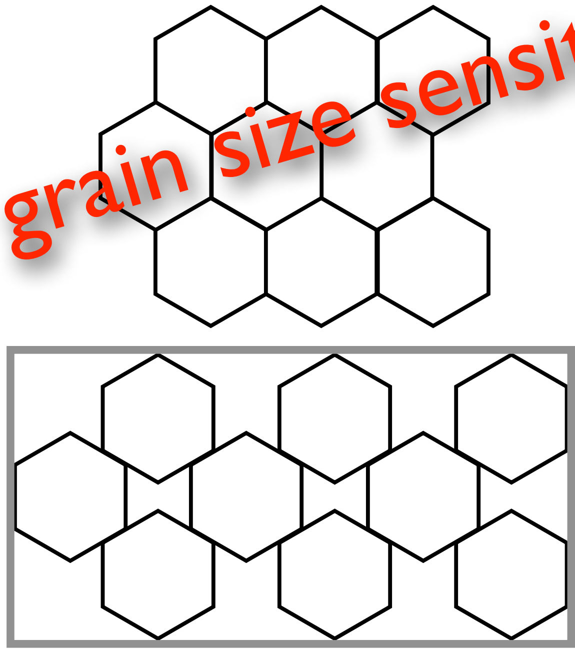
dislocation creep



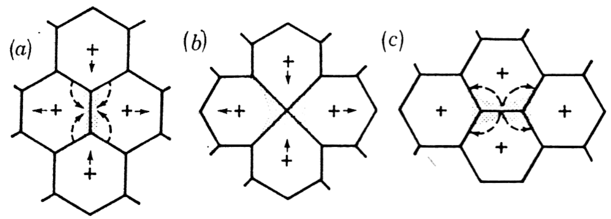
granular flow
grain boundary sliding
pressure solution

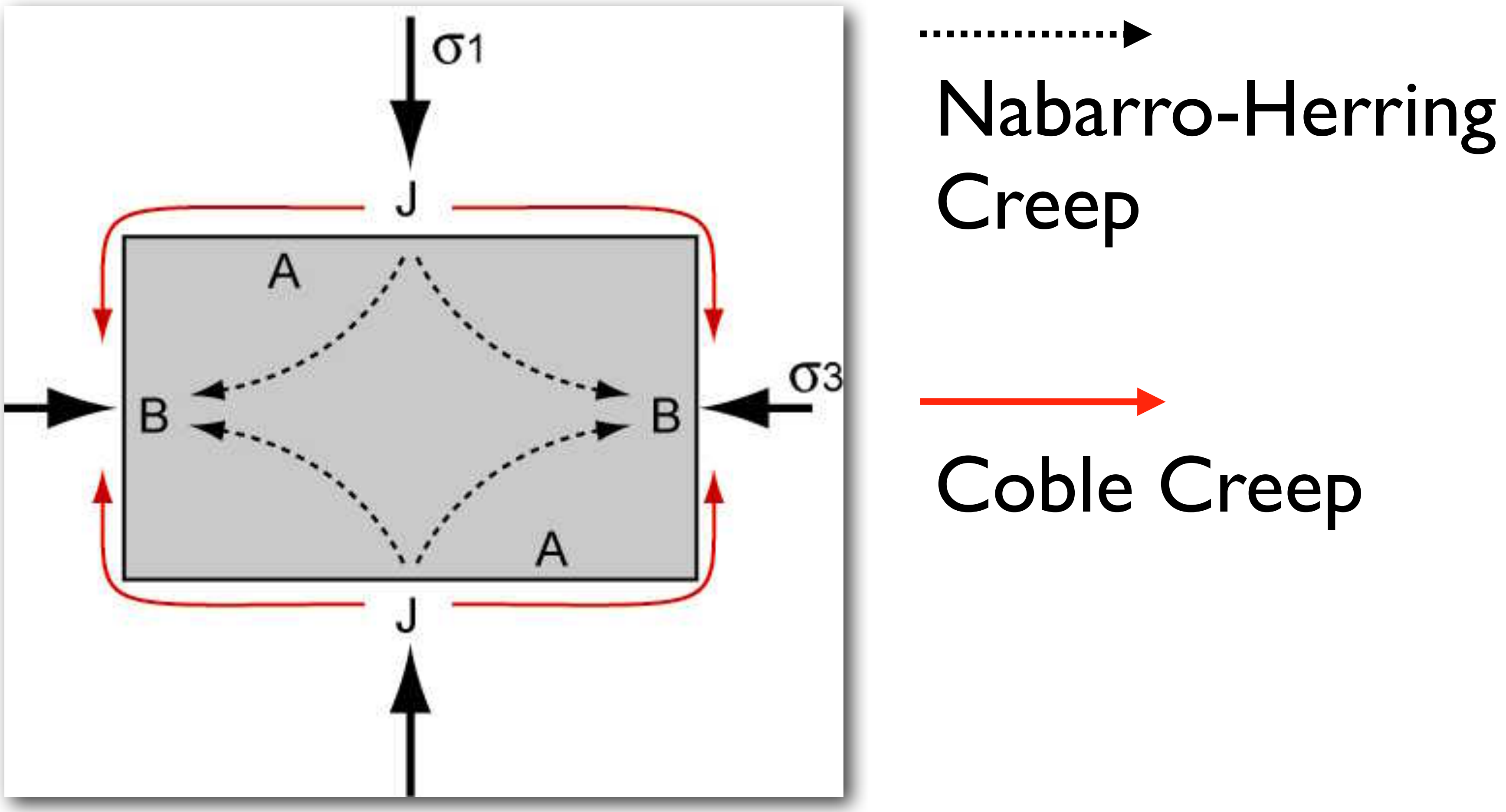
diffusion creep

grain size sensitive



neighbor switching





- Grain-scale diffusive mass transfer
- Grain-scale pressure solution

$$\dot{\varepsilon} = A \frac{\sigma^n}{d^p} \exp\left(-\frac{Q}{RT}\right)$$

ε´ = strain rate
A = constant
σ = differential stress
n = stress exponent
d = grain size
p = grain size exponent
Q = activation energy
T = temperature
R = gas constant

Dislocation Creep:

n = 3 - 5
p = 0

→ grain size insensitive !

Diffusion Creep:

n = 1 - 2
p = 2 - 3

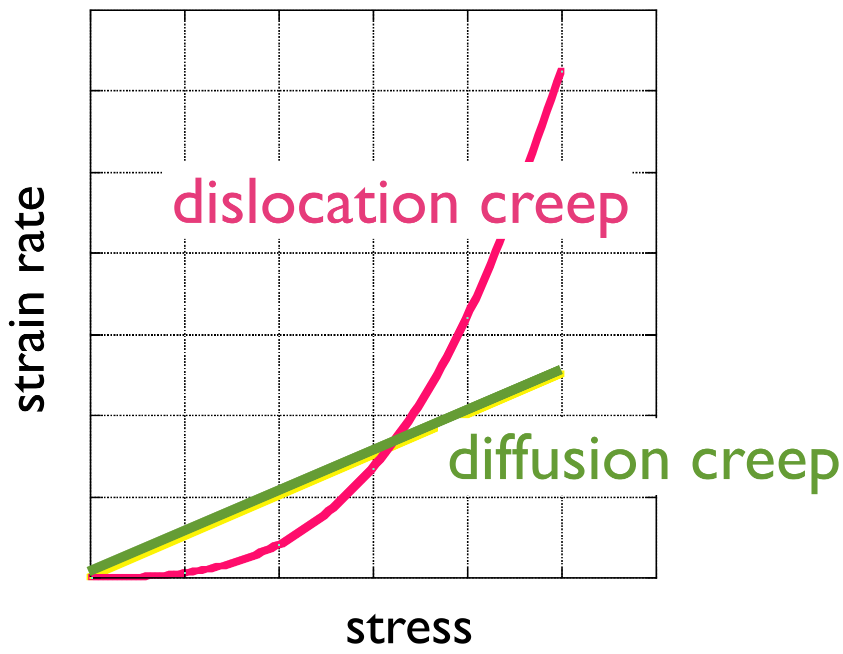
→ grain size sensitive !

Dislocation Creep:
(Crystal Plastic Deformation)

Strain rate = $A\ \sigma^n\ e^{-(Q/RT)}$

$n = 3 - 5$

grain size insensitive !



Diffusion Creep:
(Granular Flow, Grain boundary Sliding)

Strain rate = $A\ \sigma^n \cdot d^{-p}\ e^{-(Q/RT)}$

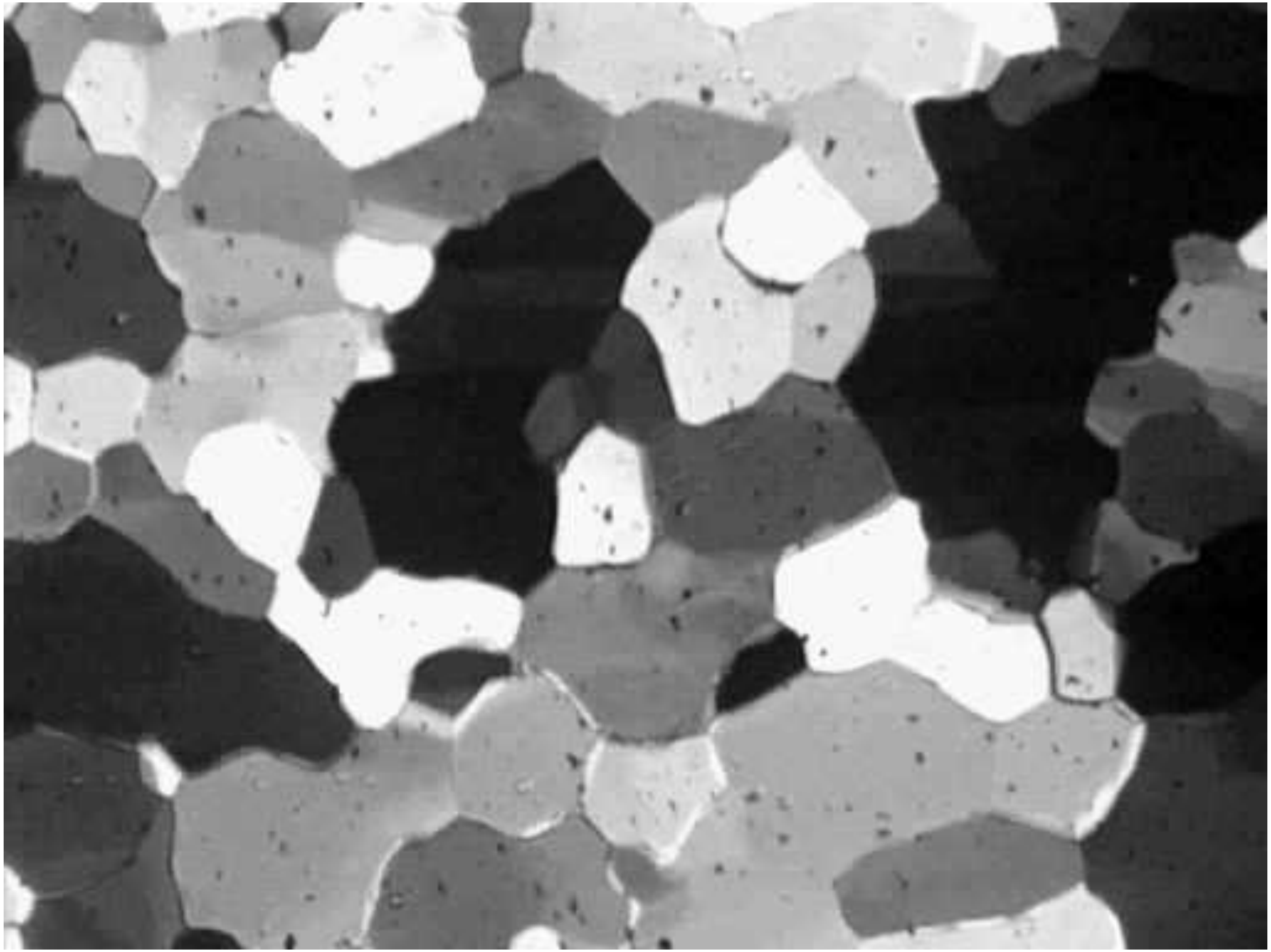
$n = 1 - 2$

$p = 2 - 3$

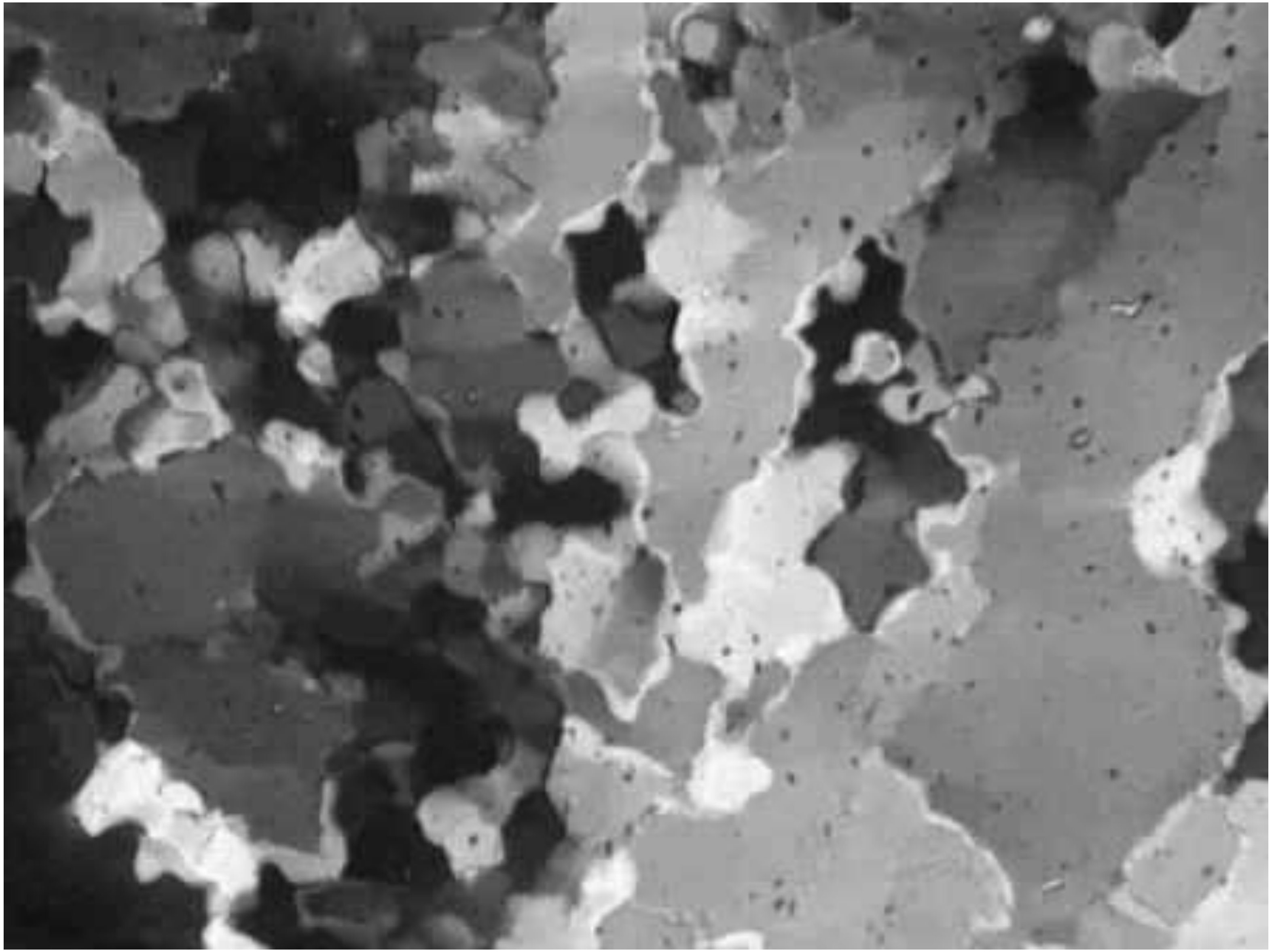
grain size sensitive !

from flow laws to deformation mechanism maps

dynamic recrystallization OCP



static recrystallization OCP

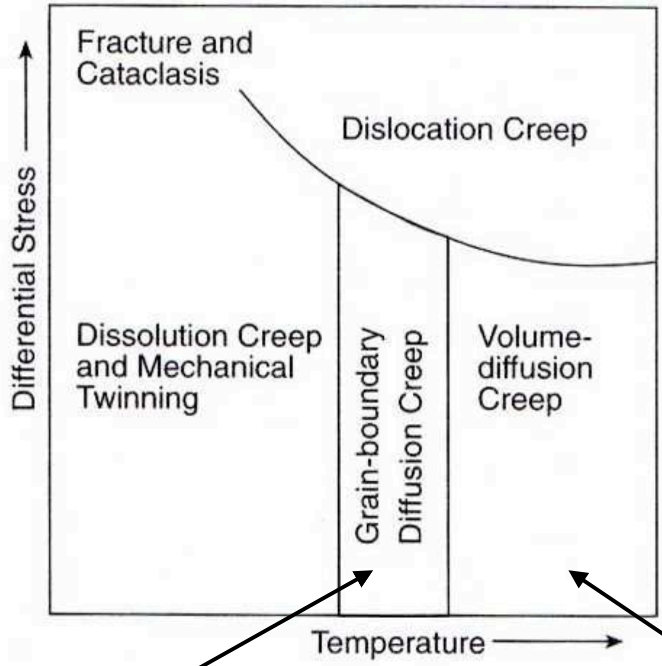


(annealing)

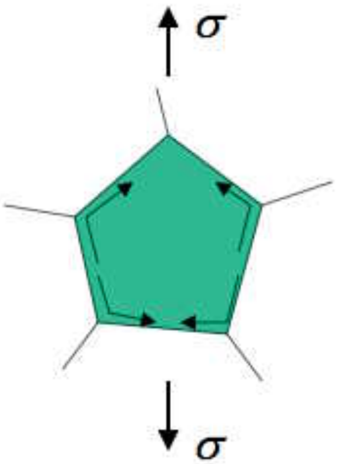
dynamic recryst. in polycrystalline ice

grain boundary migration, kinking

Deformation Mechanism Map

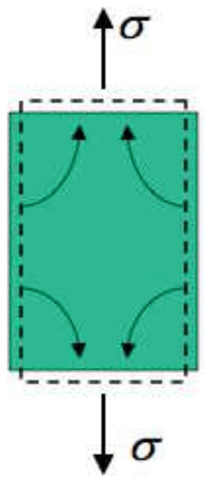


Davis and Reynolds, Structural Geology of Rocks and Regions, 1996.



Coble creep

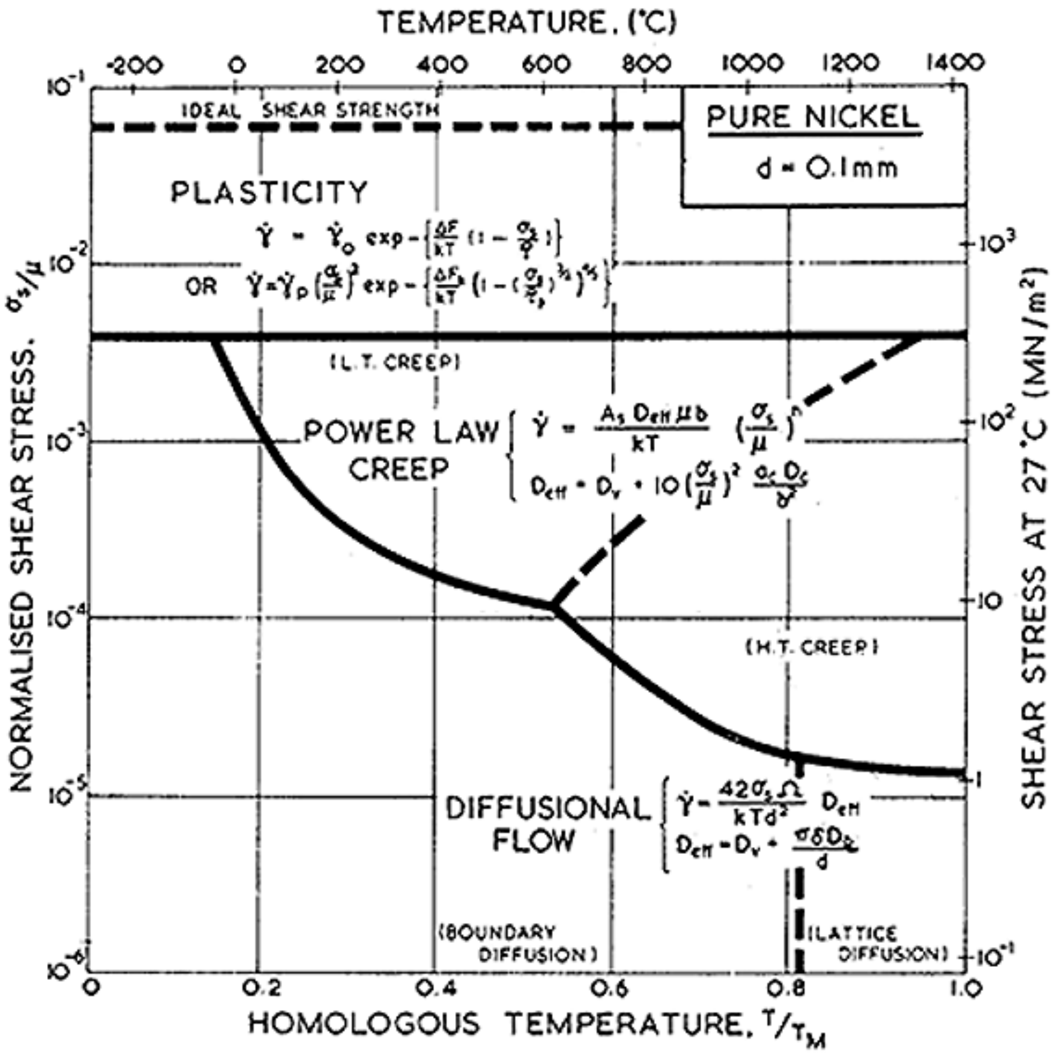
$$\dot{\varepsilon}_C = A\frac{\delta D_{GB}}{d^3}\frac{\sigma\Omega}{kT}$$



Nabarro-Herring creep

$$\dot{\varepsilon}_{NH} = A\frac{D}{d^2}\frac{\sigma\Omega}{kT}$$

deformation mechanism maps - flow laws



ideal strength

plasticity

power law creep

low temperature

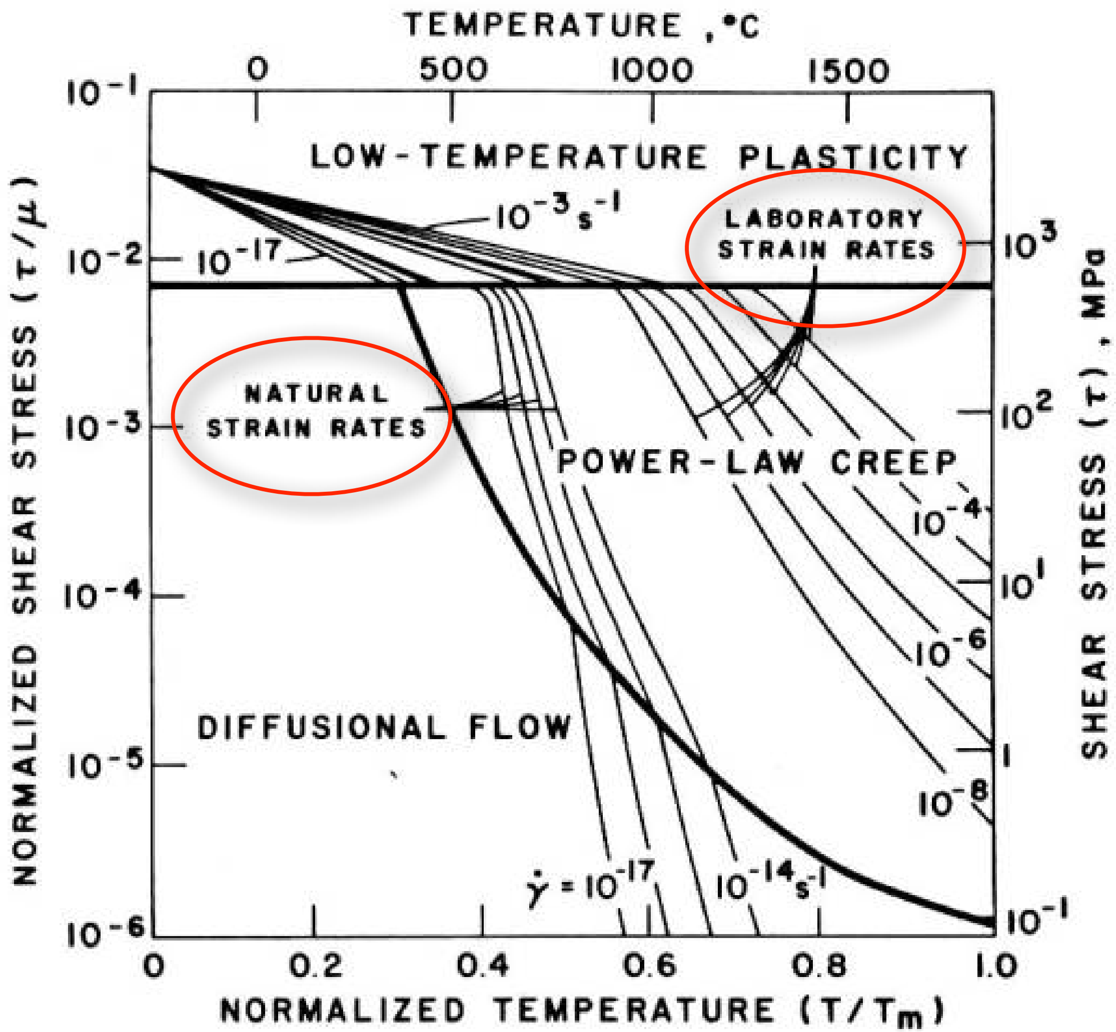
high temperature

diffusional flow

boundary diffusion

lattice diffusion

deformation mechanism maps - rheologies



ideal strength

plasticity

power law creep

low temperature

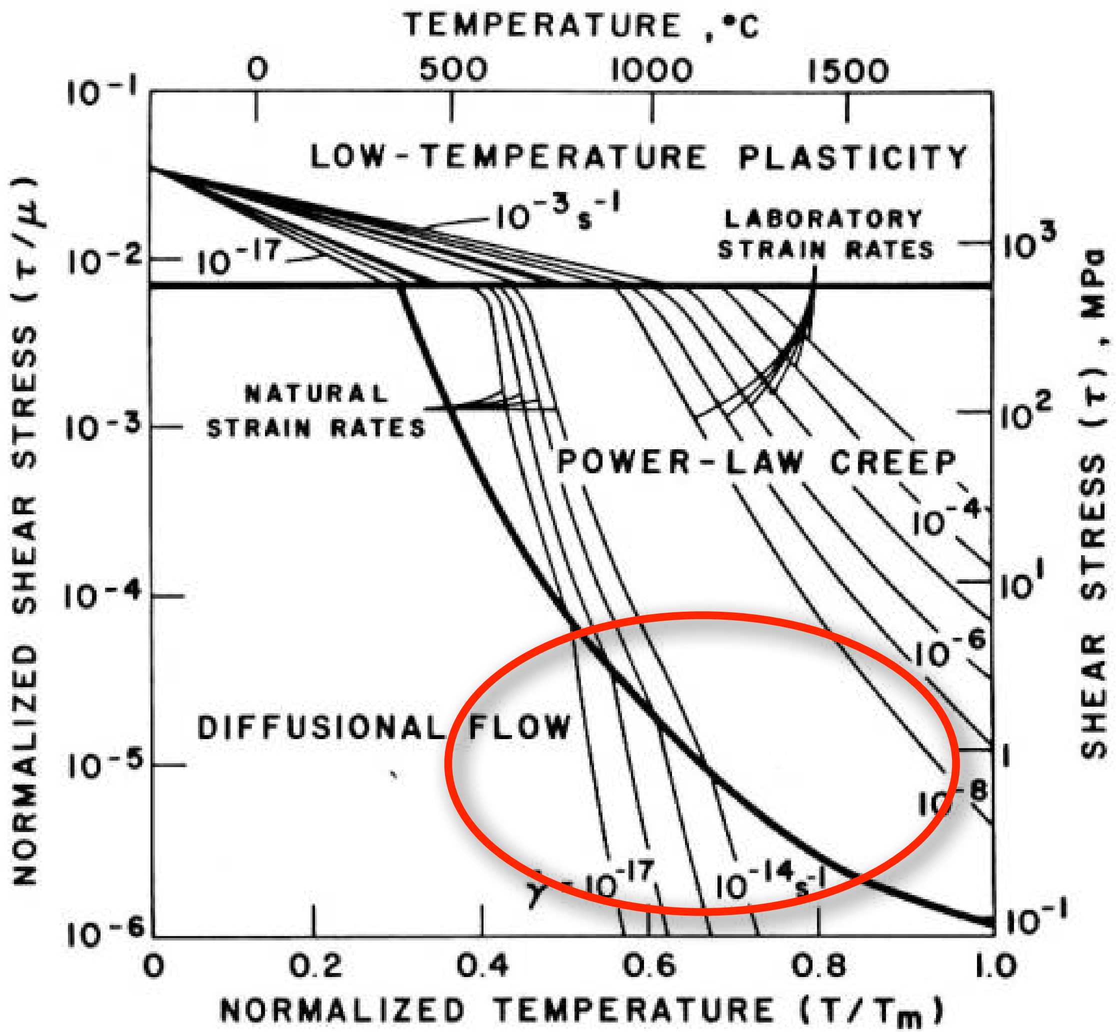
high temperature

diffusional flow

boundary diffusion

lattice diffusion

deformation mechanism maps - regimes



fracture

dislocation glide

dislocation creep

low n

high n

diffusion creep

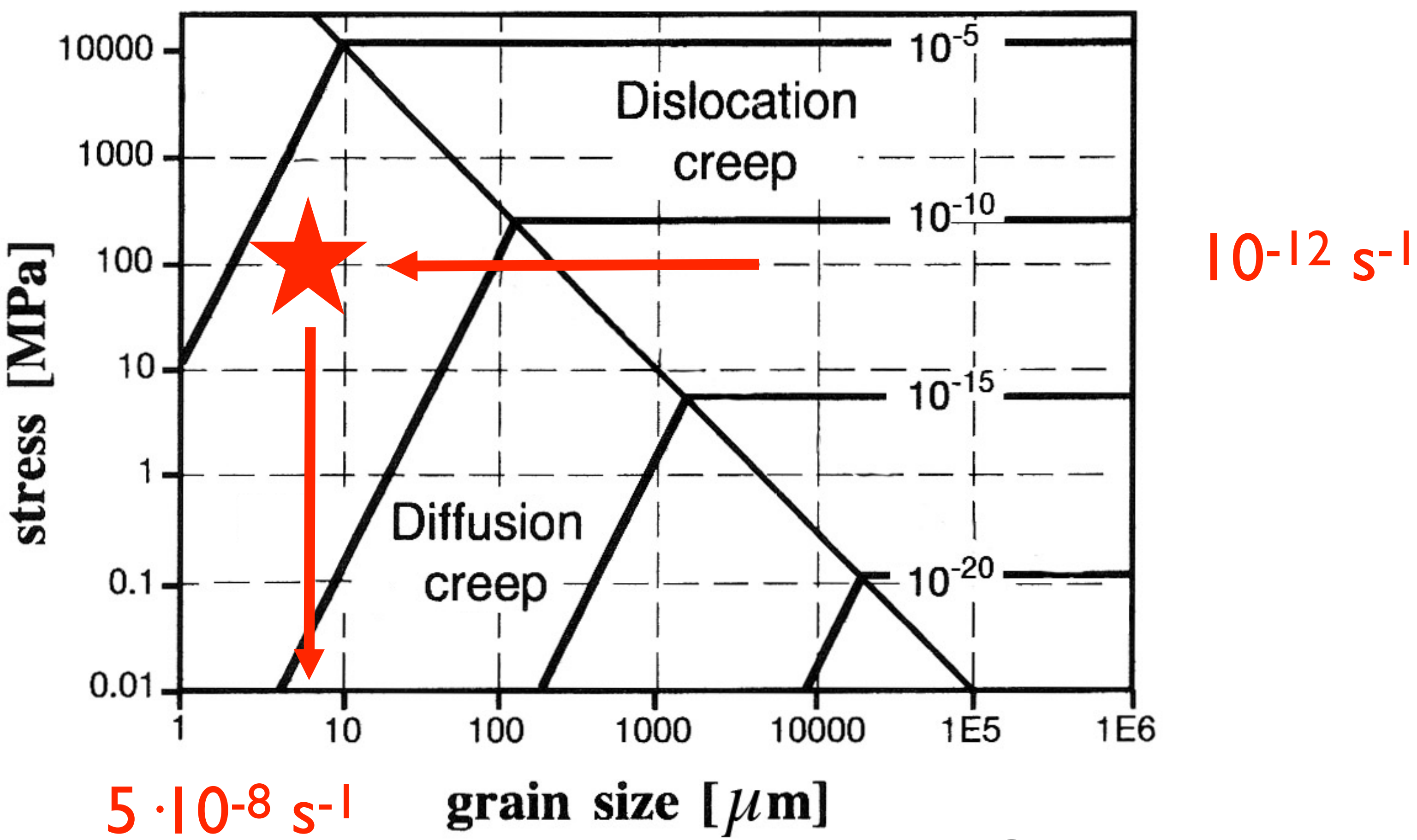
boundary diffusion

lattice diffusion

low stress - high T

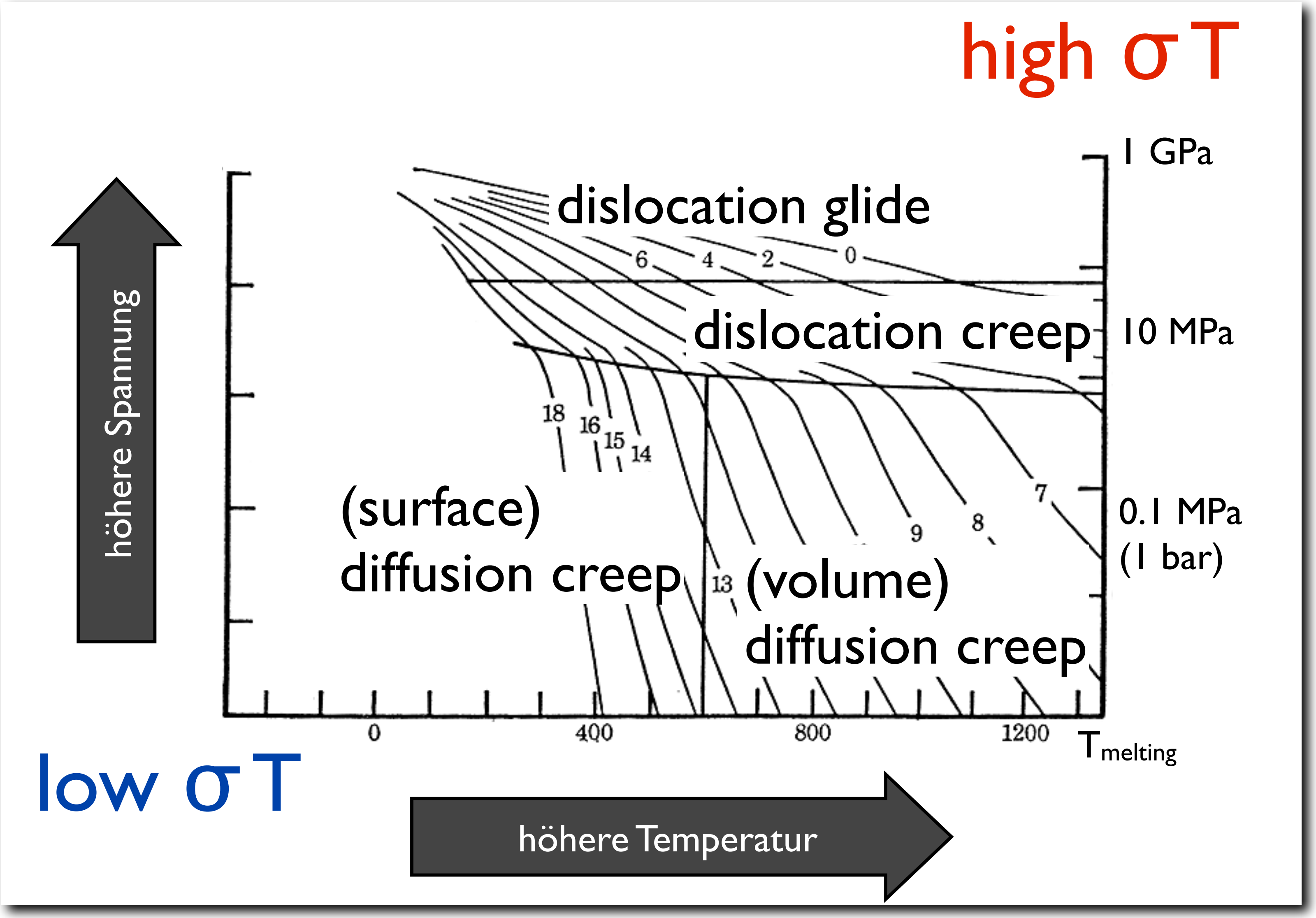
deformation mechanism maps - grain size

T = constant

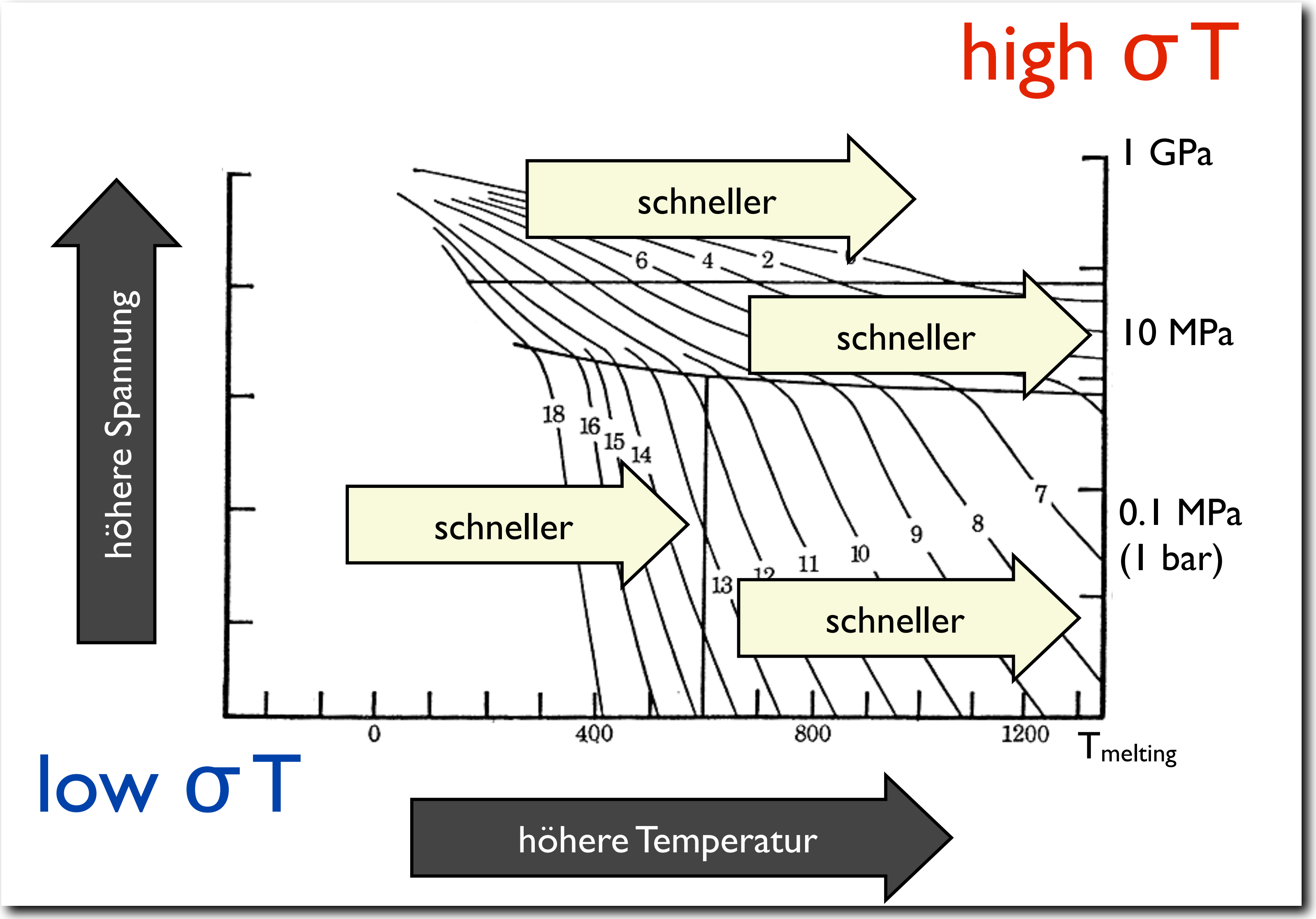


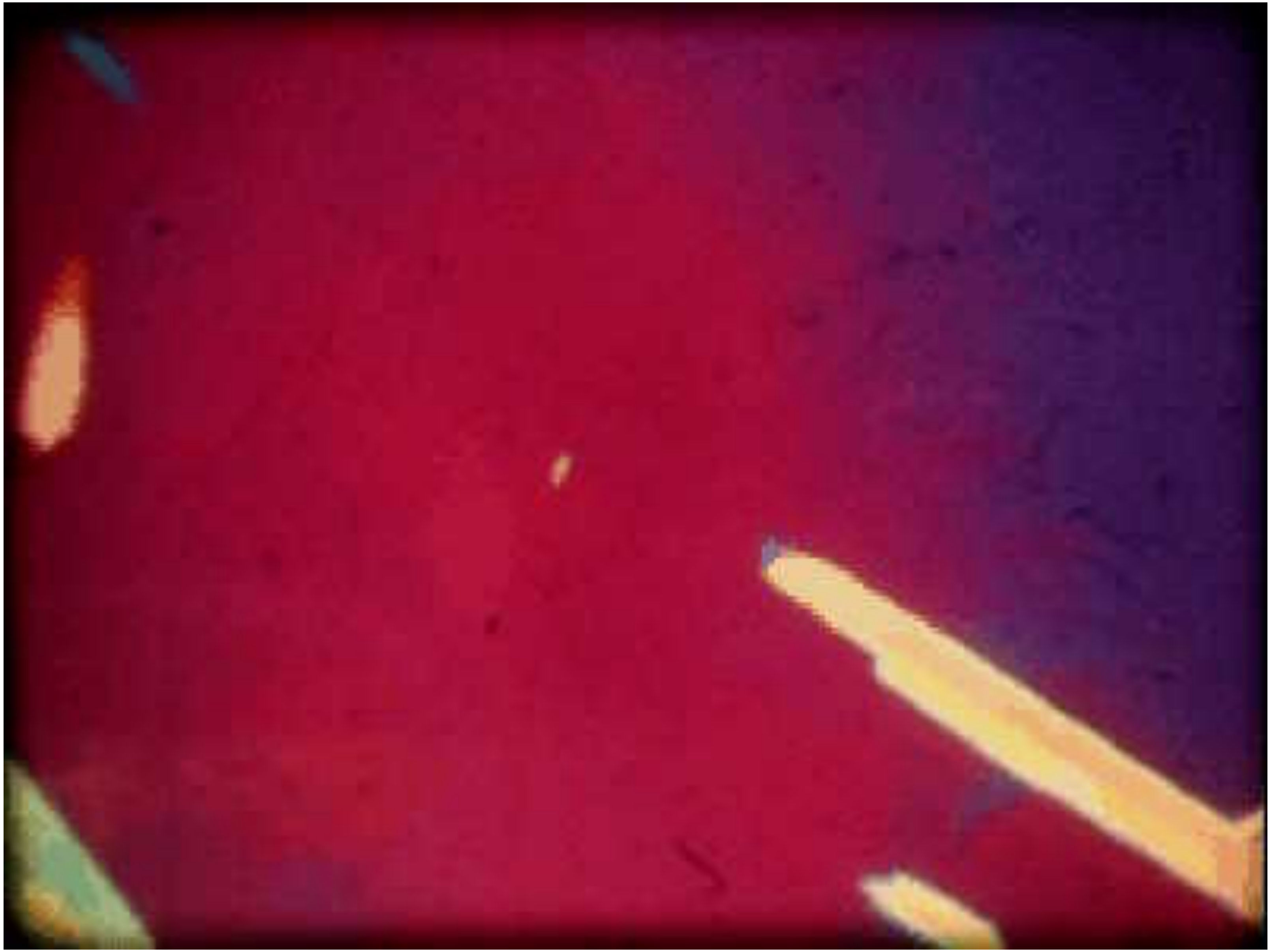
Olivine
after De Bresser et al. 1998

deformation mechanism map



deformation mechanism map

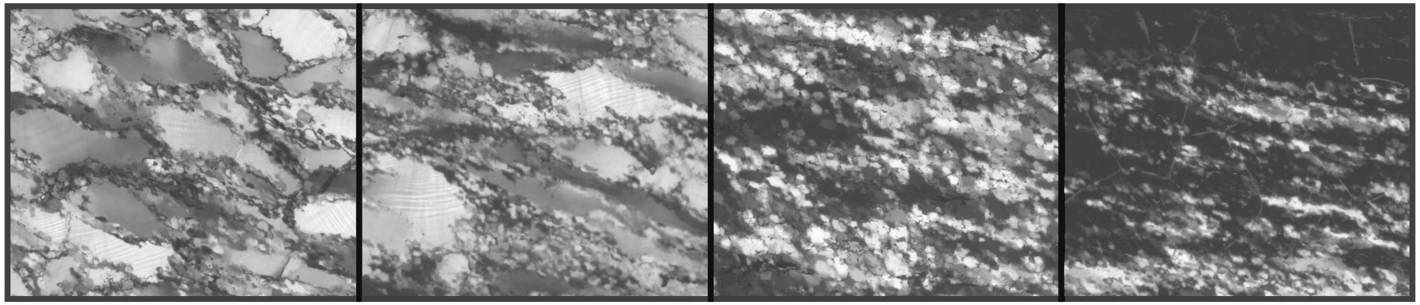


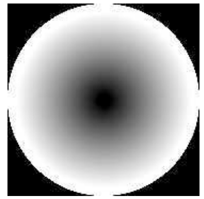


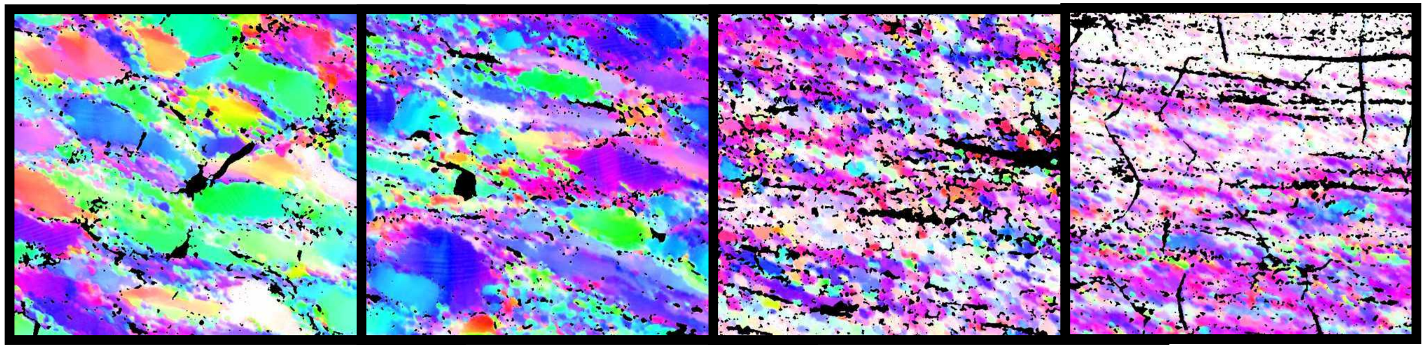
crystallographic preferred orientation (CPO) characteristic pole figures

pole figure development

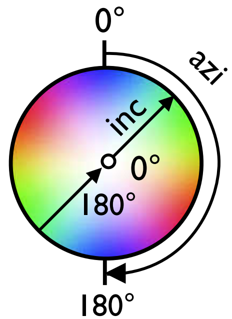
Dislocation creep regime 3



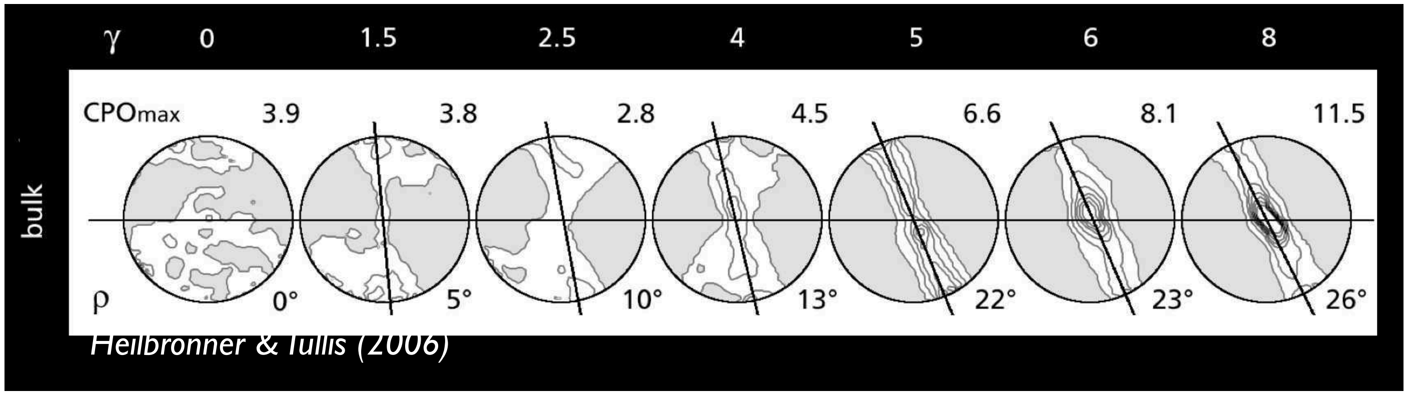




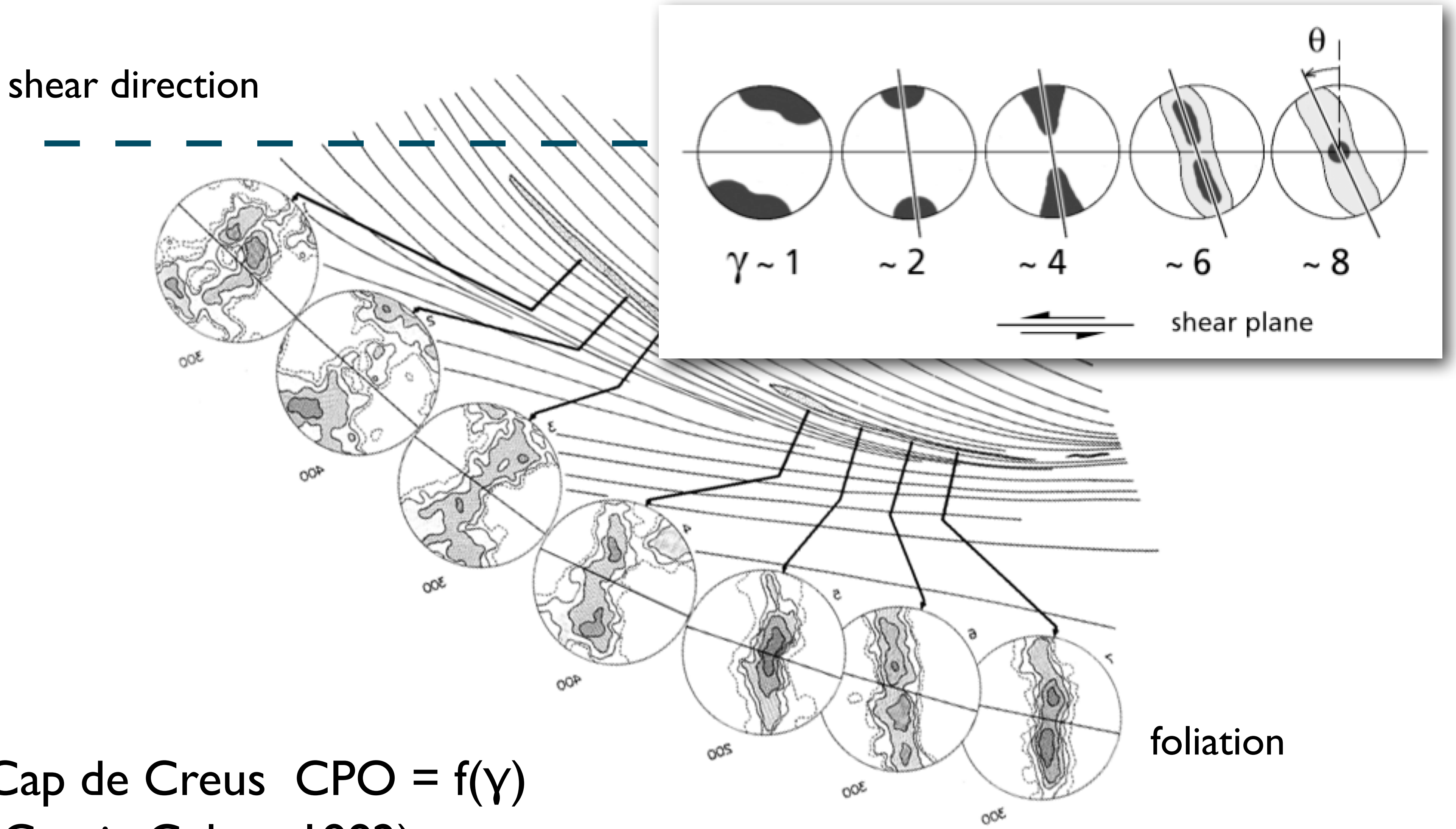
circular polarization



c-axis coloring

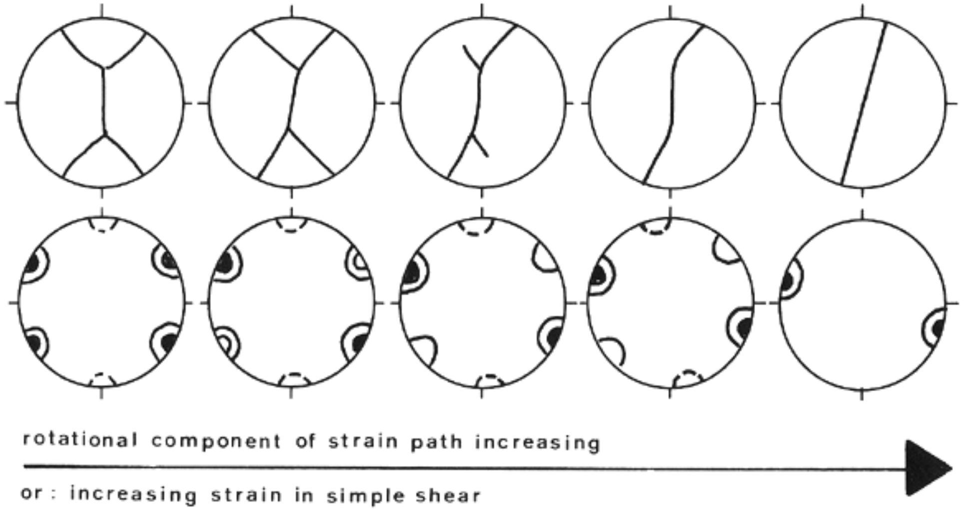


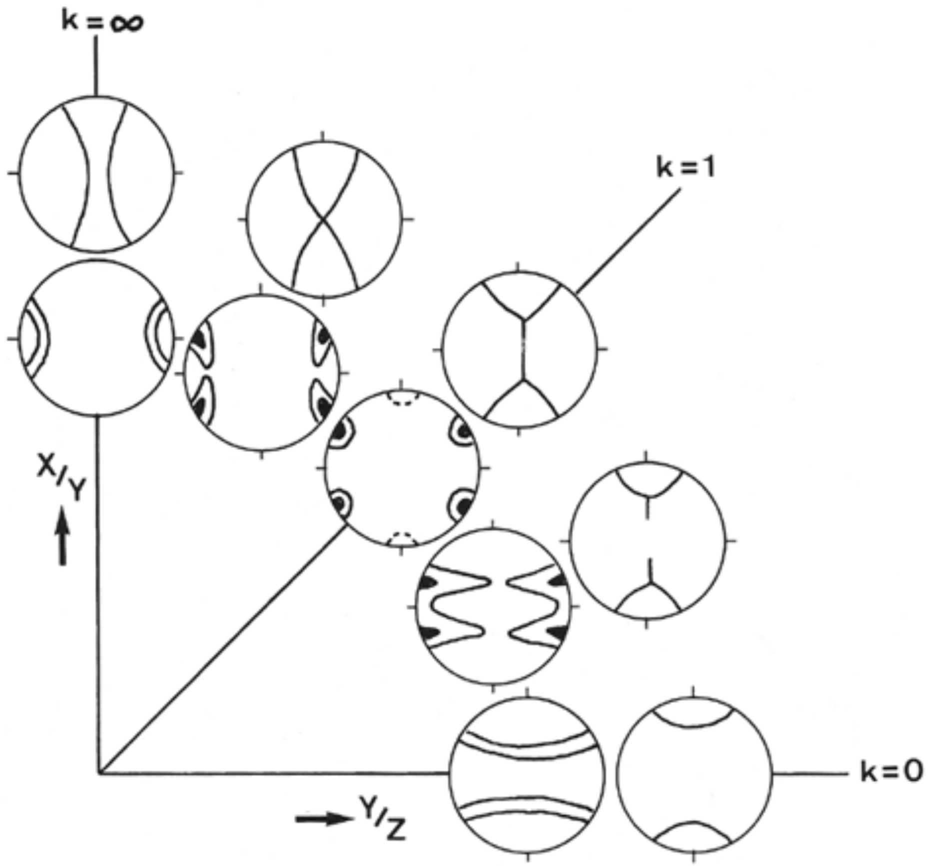
comparison nature - experiment



Cap de Creus CPO = f(γ)
(Garcia Celma, 1982)
(Carreras & Garcia Celma, 1982)

use texture to quantify dislocation creep



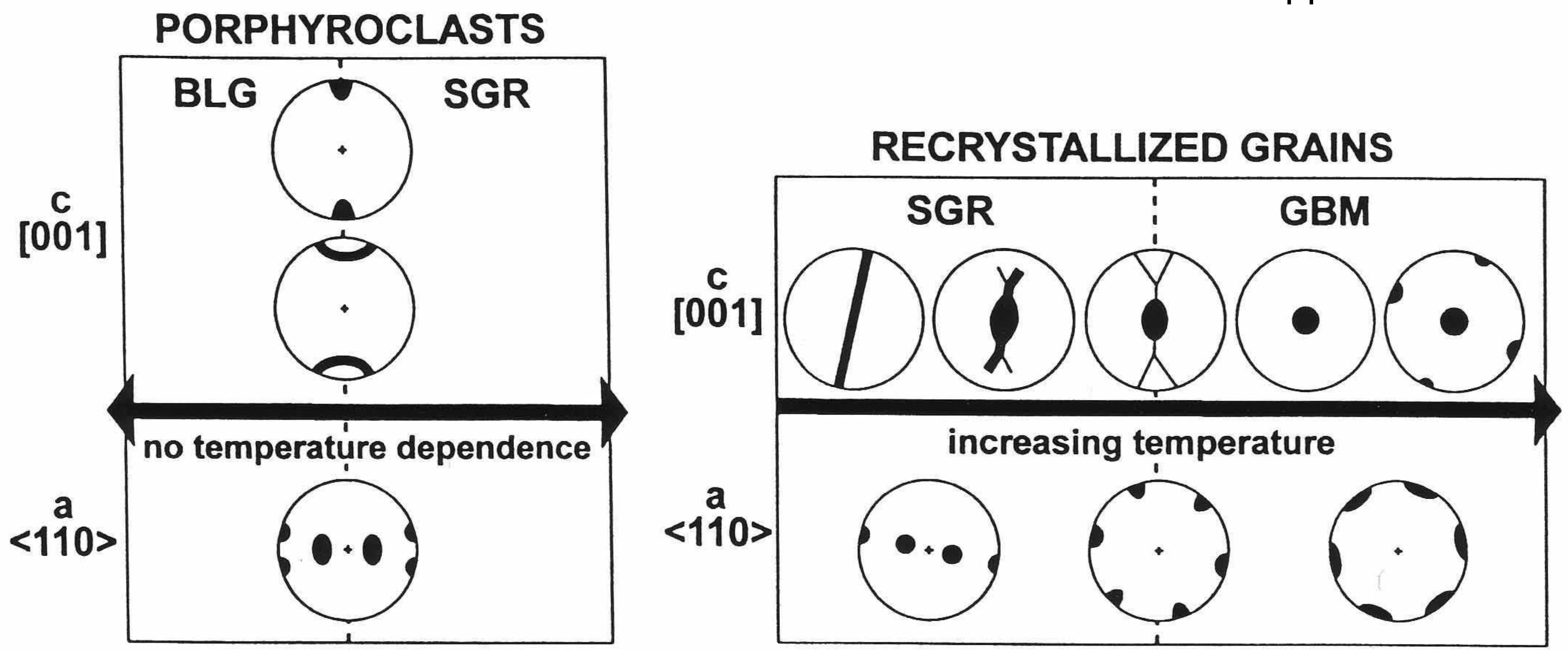


coaxial - shear

prolate - oblate

use texture to quantify dislocation creep

Stipp et al 2002



8

8 Subduktion - Kollision - Transformstörungen

VL-Themen:

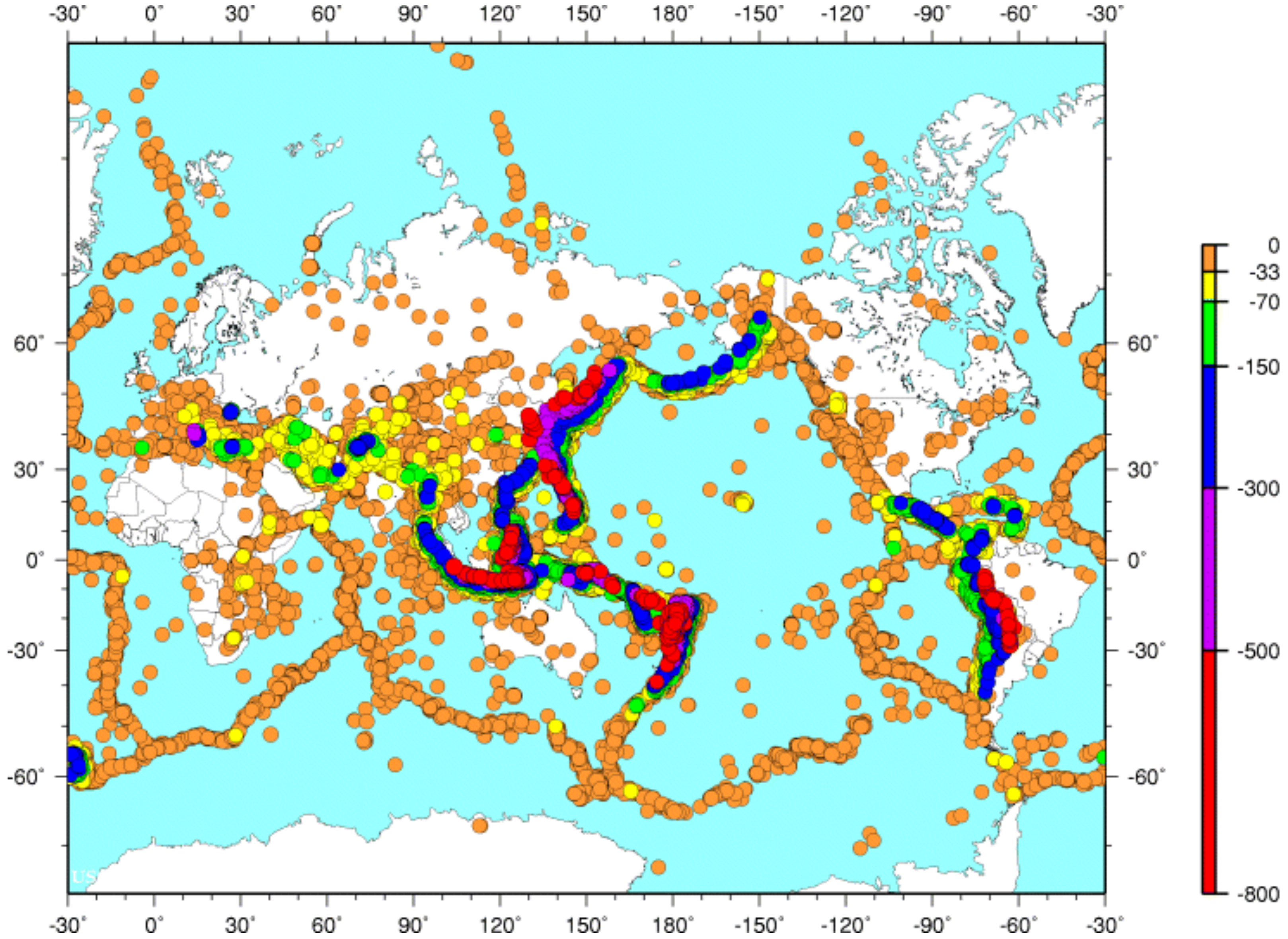
- Subduktion

- accreationary wedges - orogenic wedges
- subduction channel
- Orogene

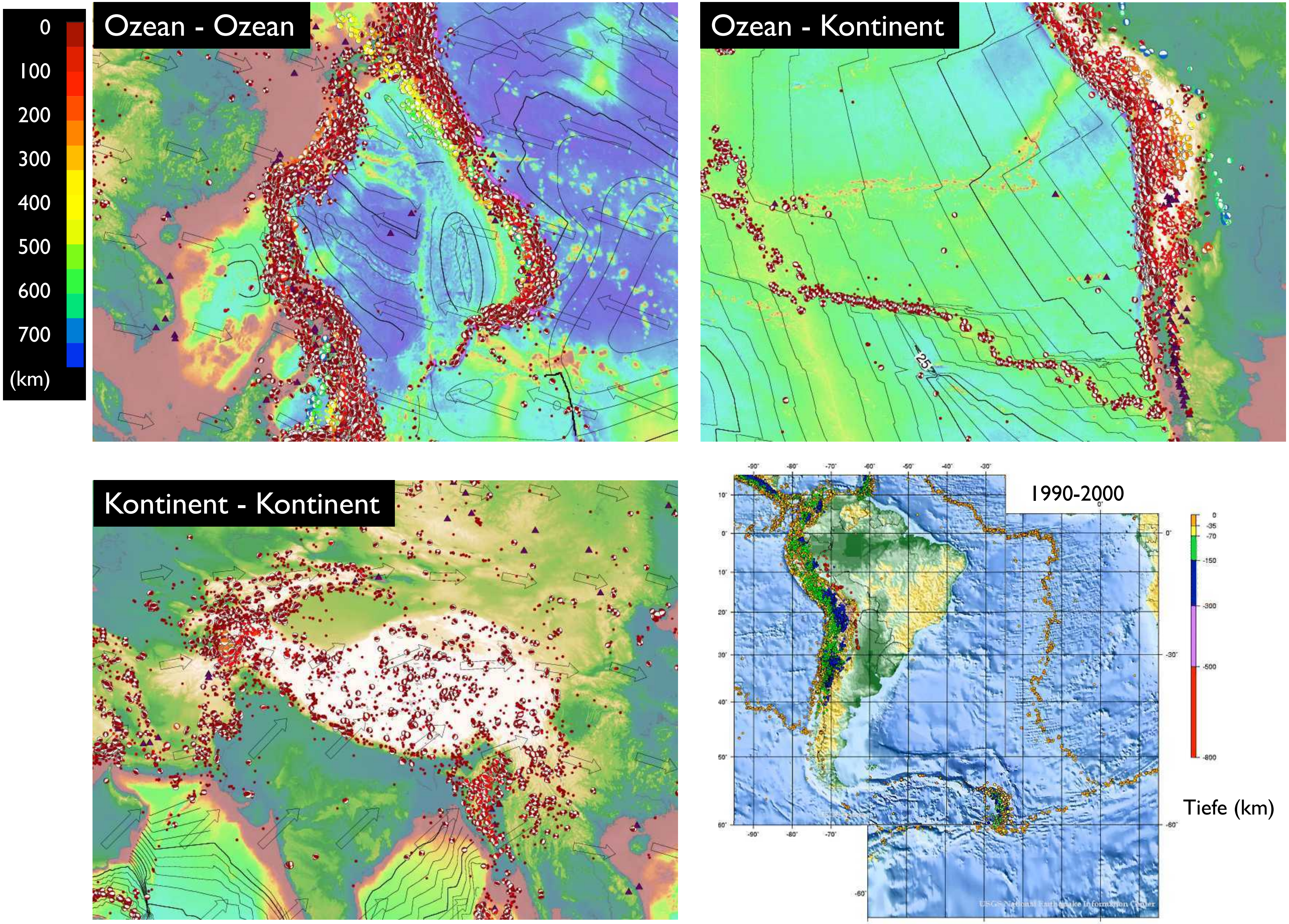
- Strikeslip - Transformstörungen
- Geometrie und Kinematik
- Transform Systeme

- Aktive Verwerfungen

Konvergente Plattengrenzen



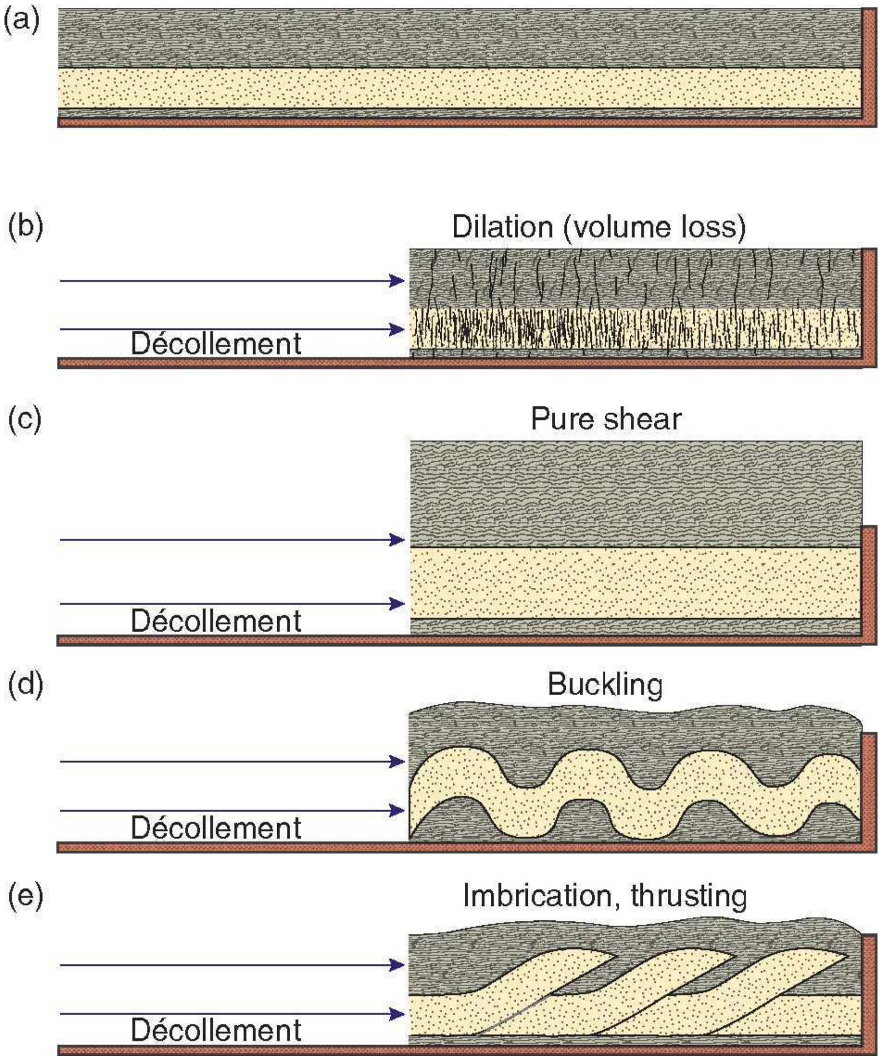
http://neic.usgs.gov/neis/epic/epic_global.html

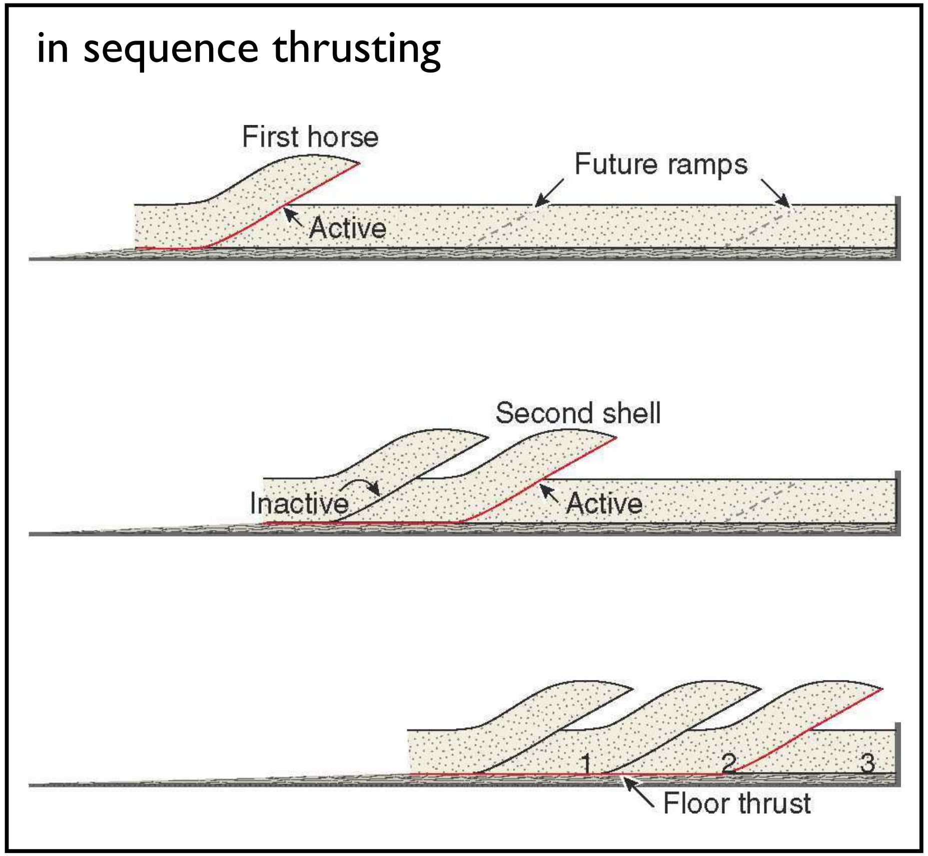


http://earthquake.usgs.gov/regional/world/seismicity/

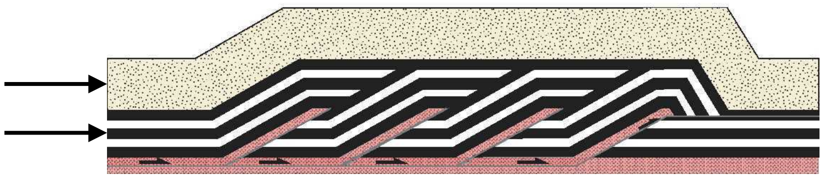
geometry & morphology of contraction

Verkürzung



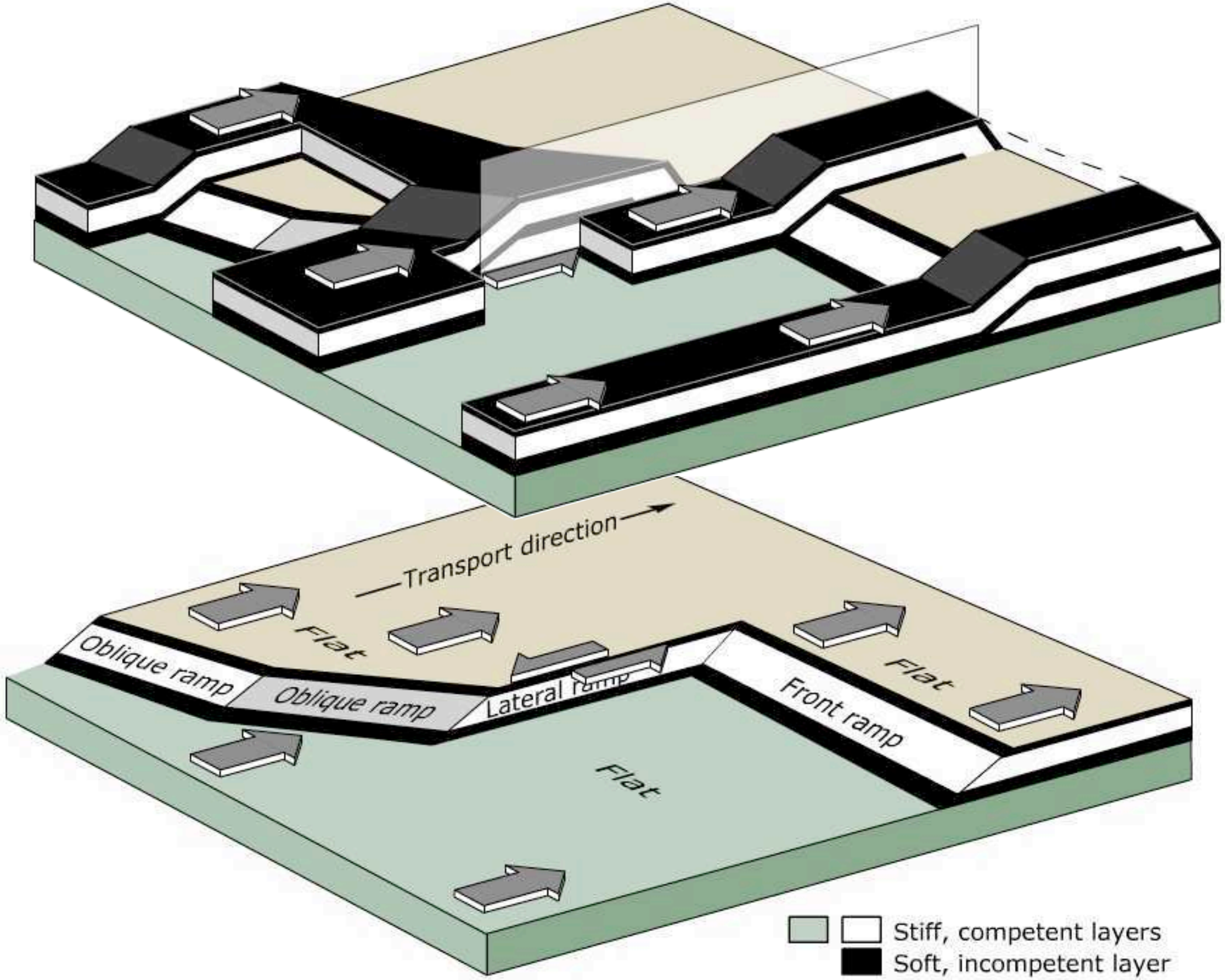


IMBRICATION
on floor thrust, fault blocks (horses)



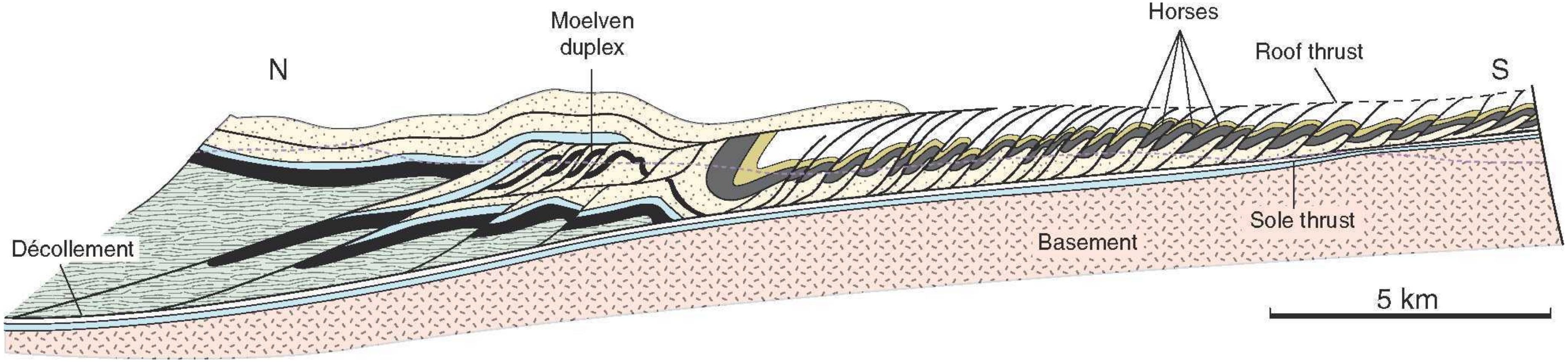
DUPLEX
between floor and roof thrust

ramps + flats

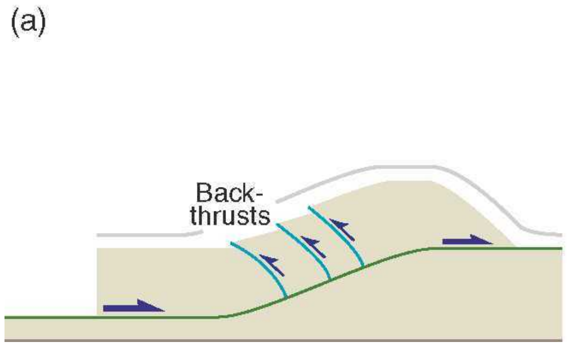


Transport direction
Flat
Oblique ramp
Oblique ramp
Lateral ramp
Flat
Front ramp
Flat
Stiff, competent layers
Soft, incompetent layer

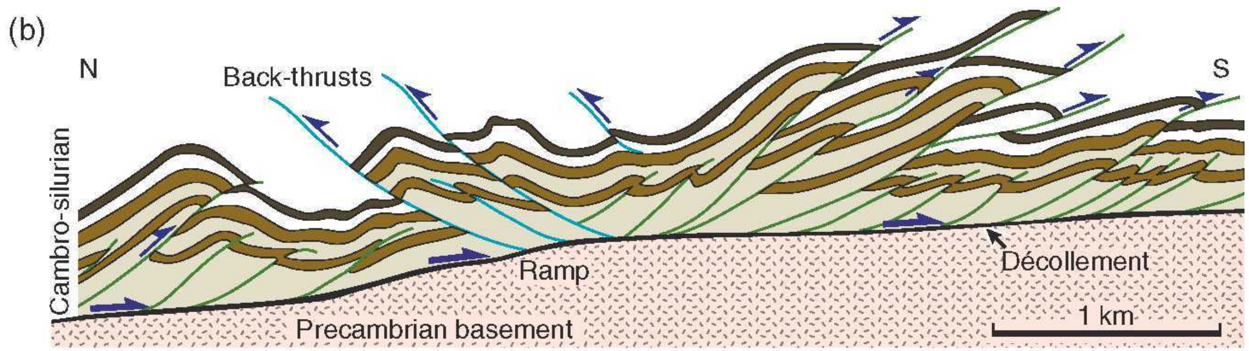
thrusting



Moelven duplex
Horses
Roof thrust
N
S
Décollement
Sole thrust
Basement
5 km



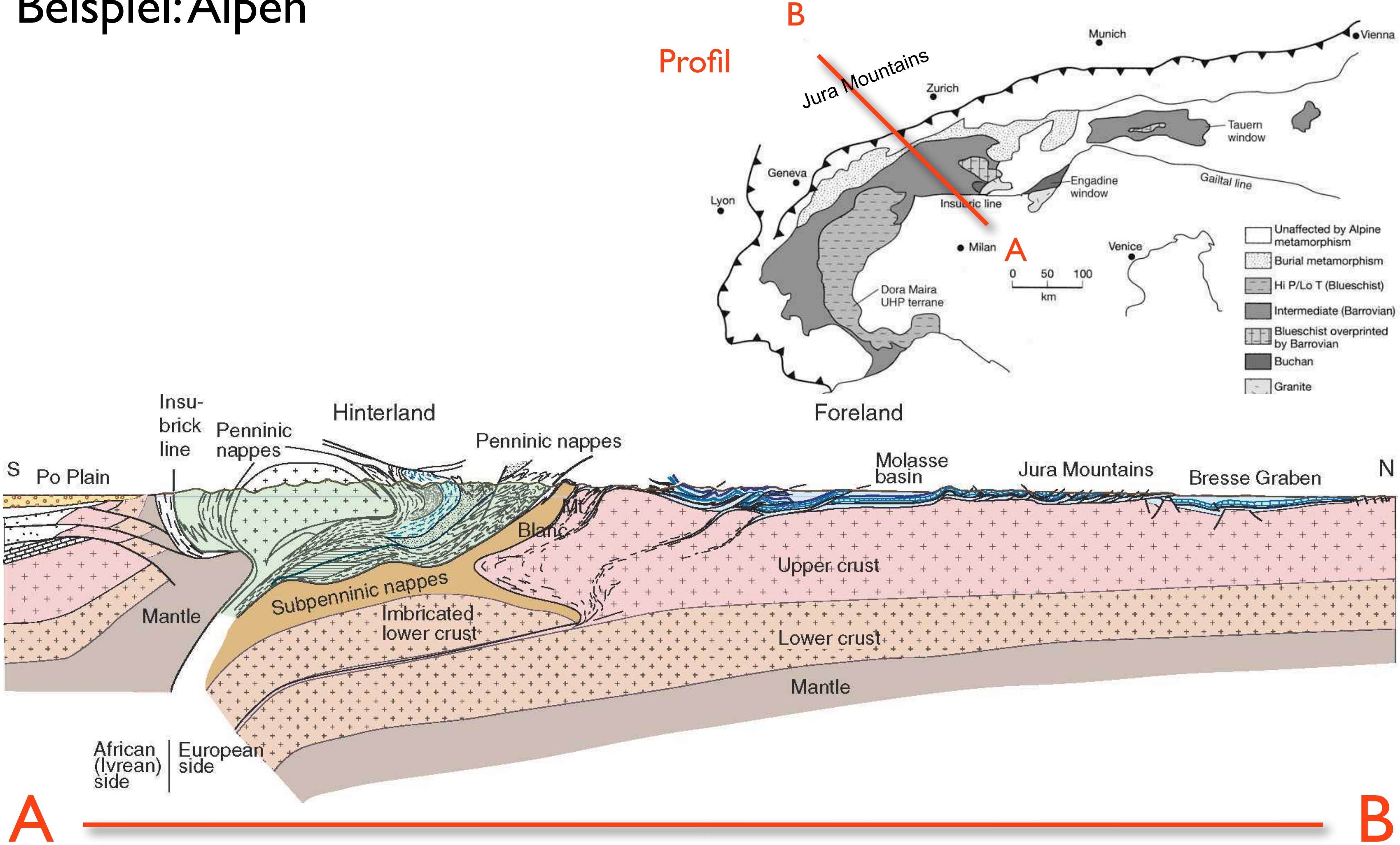
(a)
Back-thrusts



(b)
N
Back-thrusts
S
Cambro-silurian
Ramp
Décollement
Precambrian basement
1 km

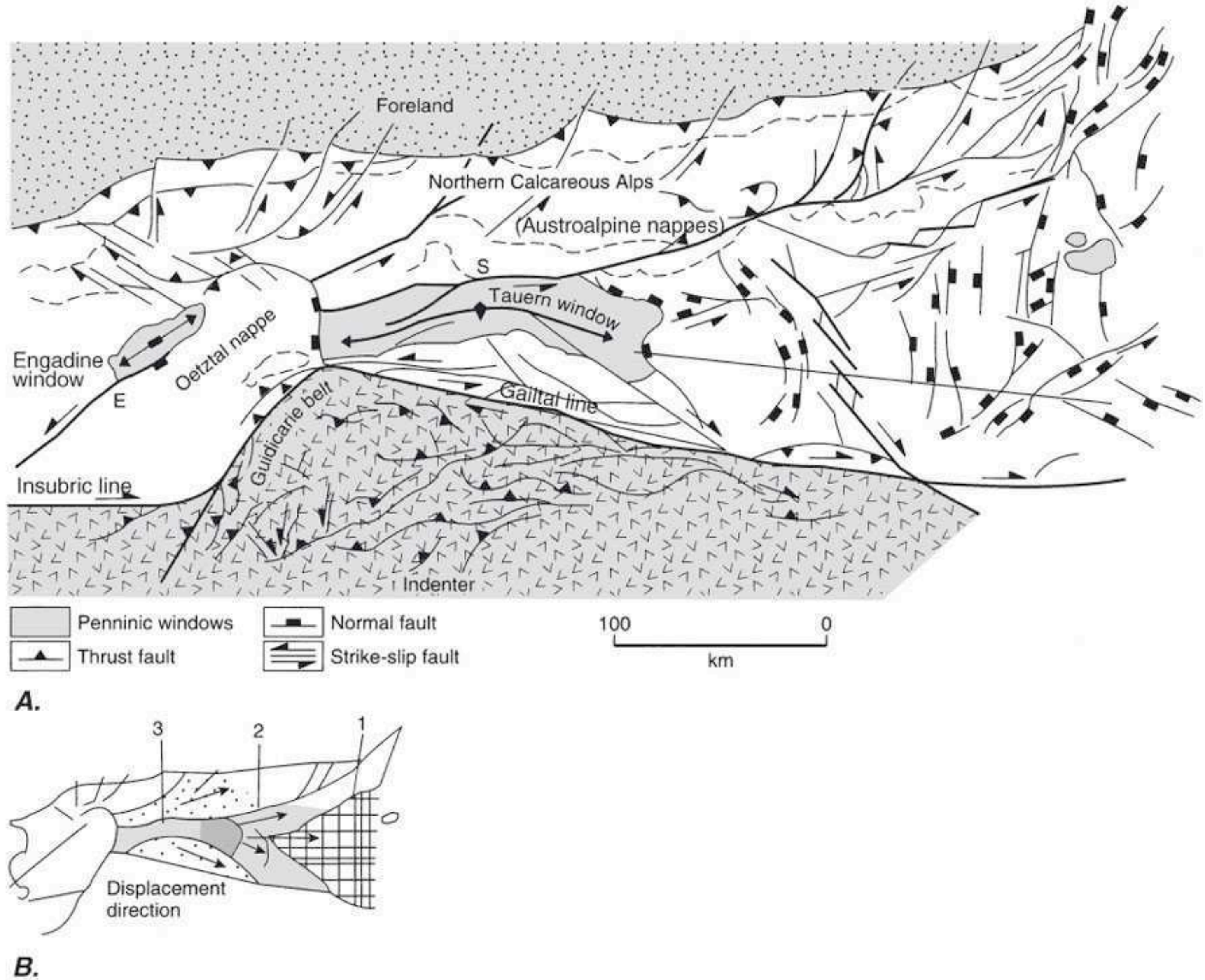
Decken- und Faltengebirge

Beispiel: Alpen



lateral escape

Beispiel: Alpen



Fold-Thrust Belt Terminology

allochthon
autochthon
basale Abscherung
décollement
detachment
fold-thrust belt

Allochthon	A mass of rock, comprising a thrust sheet (i.e., a hanging-wall block), that has been displaced by movement on a thrust fault; commonly, use of the term implies that the mass has moved a considerable distance on a detachment from its point of origin.
Allochthonous	Adjective describing "out-of-place" rocks that have moved a large distance from their point of origin.
Autochthonous	Adjective describing rocks that are still at the site where they originally formed and have not been displaced by movement on a thrust fault or detachment.
Backarc	The region that lies behind the volcanic arc along a convergent plate boundary; the backarc and the trench are on opposite sides of the volcanic arc.
Backstop	A representation of the boundary load in the hinterland of a fold-thrust belt. The backstop generates horizontal compressional stress, which contributes to driving fold-thrust belt development. The backstop represents rock of the hinterland that is moving toward the foreland. As such, a backstop is like a snowplow pushing snow toward the foreland.
Backthrust	A thrust on which the transport direction is opposite to the regional transport direction.
Basal detachment	The lowest detachment of a thrust system; the regional basal detachment in a fold-thrust belt separates shortened crust above from unshortened crust below. In the foreland part of a fold-thrust belt, it typically lies at or near the basement-cover contact (also called a basal décollement).
Blind thrust	A thrust that, while it is active, terminates in the subsurface.
Branch line	The line of intersection between two fault surfaces, e.g., where a ramp branches (splays) off of a detachment, or where one ramp splays off another.
Break-forward sequence	A sequence of thrusting during which younger thrusts initiate to the foreland of older thrusts (also called a foreland-breaking sequence).
Break-thrust fold	A fold that initiates prior to thrusting, but later ruptures so that a thrust cuts through its forelimb.
Cutoff (cutoff line)	The line of intersection between a fault and a bedding plane.
Décollement	A subhorizontal fault (also called a detachment)
Detachment	A subhorizontal fault (also called a décollement)
Detachment fold	A fold that forms in response to slip above a subhorizontal fault, much like fold in a rug that wrinkles above a slick floor.
Duplex	A type of thrust system where a series of thrusts branch from a lower detachment to an upper detachment.
Fault-bend fold	A fold that forms in response to movement over bends in a fault surface.
Fault-propagation fold	A fold that forms immediately in advance of a propagating fault tip (also called a **tip fold**).
Floor thrust	The lower detachment of a duplex; it forms the base of the duplex.
Fold nappe	A thrust sheet that contains a regional-scale recumbent fold.
Fold-thrust belt	A geologic terrane in which upper-crustal shortening is accommodated by development of a system of thrust faults and related folds.
Footwall block	The body of rock beneath the fault.
Footwall cutoff	The intersection between bedding planes of footwall strata and a fault surface.
Footwall flat	The portion of the footwall where bedding surfaces parallel the fault.
Footwall ramp	The portion of the footwall where bedding surfaces truncate against the fault (i.e., the portion of the footwall along which there are **footwall cutoffs**).

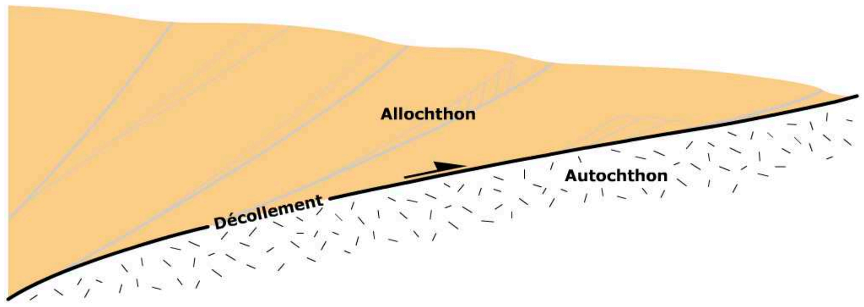
foreland
hinterland
inversion tectonics
mechanical stratigraphy
tear fault

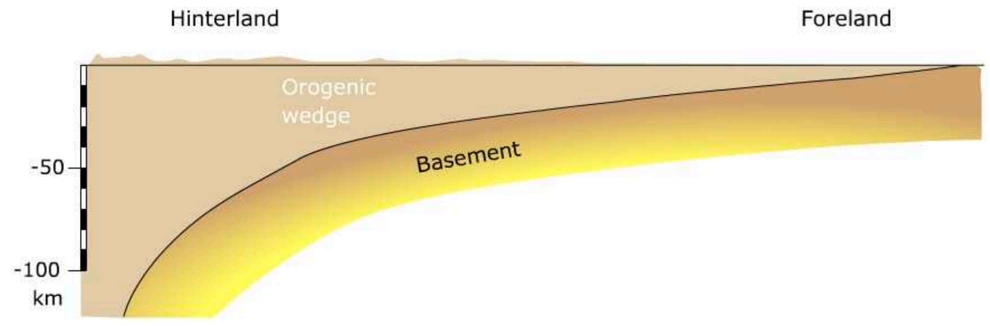
Forearc	The region to the trench side of the volcanic arc of a convergent plate boundary. The forearc is not the same as the foreland. The forearc lies on the ocean side of a continental volcanic arc.
Foreland	The part of the undeformed craton adjacent to an orogenic belt; some authors have used the term in a more general sense to include the portion of an orogenic belt closer to the undeformed continental interior.
Foreland basin	A sedimentary basin formed on the continent side of a fold-thrust belt that forms because the weight of the stack of thrust sheets in the belt depresses the lithosphere.
Forethrust	A thrust on which the transport direction is the same as the regional transport direction for the whole fold-thrust belt.
Frontal ramp	A ramp that strikes perpendicular to transport direction.
Hanging-wall block	The rock mass that has been transported above a fault surface.
Hanging-wall cutoff	The intersection between bedding planes of hanging-wall strata and the fault surface.
Hanging-wall flat	The portion of the hanging wall where bedding surfaces parallel the fault.
Hanging-wall ramp	The portion of the hanging wall where bedding surfaces truncate against the fault (i.e., the portion of the hanging wall where there are **hanging-wall cutoffs**).
Hinterland	The region closer to the high-grade core of an orogen; as a directional reference, it is the direction opposite to the foreland direction.
Horse	A body of rock in a duplex that is completely enveloped by faults.
Imbricate fan	A type of thrust system where a series of thrusts branch from a lower detachment without merging into an upper detachment horizon.
Inversion tectonics	The process by which a site of extension (e.g., a rift or passive margin basin) transforms into a site of shortening. During inversion, faults that had initiated as normal faults reactivate as thrust faults, and the sedimentary fill of the rift or passive-margin basin is shoved up and over the margins of the basin.
Klippe	An erosional outlier of a thrust sheet that is completely surrounded by footwall rocks; it is an isolated remnant of the hanging-wall block above a thrust.
Lateral ramp	A ramp that strikes parallel to transport direction.
Mechanical stratigraphy	The succession of rock types comprising the stratigraphy of a region, defined in terms of their relative strength.
Oblique ramp	A ramp that strikes oblique to transport direction.
Out-of-sequence thrust	A thrust that initiates to the hinterland of preexisting thrusts.
Out-of-plane strain	The strain due to movement outside the plane of cross section.
Regional transport direction	The dominant direction in which thrust sheets of a thrust belt moved during faulting. Some authors use the term **regional vergence direction** as a synonym.
Roof thrust	The upper detachment of a duplex.
Stair-step geometry	The geometry of a thrust that cuts upsection via a series of flats and ramps. The shape of the fault resembles a staircase in cross section. Typically, the ramps form in stronger units, and the flats in weaker units.
Tear fault	A nearly vertically dipping fault in a thrust sheet that that is parallel or subparallel to the regional transport direction. Motion on a tear fault is dominantly strike-slip and may accommodate differential displacement of one part of a thrust sheet relative to another (i.e., a tear fault is a nearly vertically dipping **oblique ramp** or **lateral ramp**).

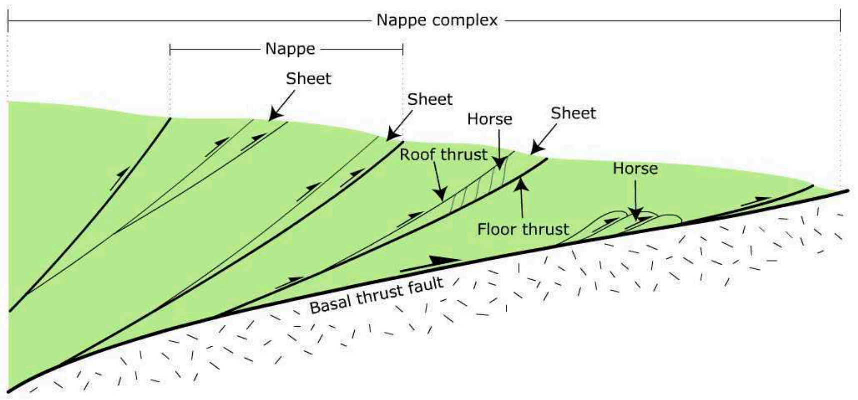
tectonic inversion
thick-skinned tectonics
thin-skinned tectonics
thrsut
thrust sheet

Tectonic inversion	The reactivation of preexisting faults by a reversal of slip direction on the faults.
Thick-skinned tectonics	The process of deformation that involves slip on basement-penetrating reverse faults; this movement uplifts basement and causes monoclinal forced-folds ("drape folds") to develop in the overlying cover.
Thin-skinned tectonics	The process of deformation in which folding and faulting are restricted to rock above a detachment. Some authors restrict the term to situations in which the detachment lies at or above the basement-cover contact. Others use the term even when basement occurs in thrust sheets, to imply that the basement has been transported or detached.
Thrust fault (thrust)	A shallowly to moderately dipping (< 30°) contractional fault with dip-slip reverse movement; in detail, thrusts may include several ramps and flats, and thus on a regional scale, do not necessarily have a uniform dip.
Thrust sheet	The hanging-wall block, above a thrust surface, that has been transported as a consequence of slip on the thrust (also called a **thrust slice**)
Thrust system	An array of related thrusts that connect at depth; a regional-scale thrust system may represent shortening above a specific regional detachment.
Tip line	The line along which displacement on the thrust becomes zero.
Triangle zone	A region in which a wedge of rock is bounded below by a forethrust and is bounded above by a backthrust.
Window (fenster)	An erosional hole through a thrust sheet that exposes the footwall (i.e., an exposure of the footwall completely surrounded by hanging wall rocks).

nappe complex







Foreland:

- thin-skinned contractional tectonics
- basement undefromed
- localized deformation
- formation of nappe systems
- sediments form eroding hinterland

Hinterland:

- thick-skinned deformation
- basement and cover (wedge) deformed
- underplating
- penetrative deformation
- formation of metamorphic nappes
- extenisve internal nappe folding

wedge accretion:

- folds
- duplexes
- imbrications

Subduktionszonen

terminology

Subduction zones

... are the three-dimensional manifestation of convective downwelling. Subduction zones are defined by the inclined array of earthquakes known as the "Wadati-Benioff Zone" after the two scientists who first identified it.

Convergent plate margins

... are the surficial manifestations of downwelling

Arcs

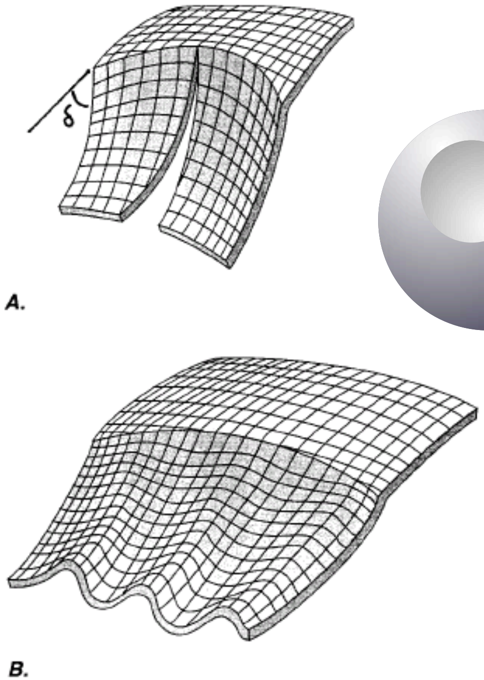
... (better referred to as arc-trench complexes) are surficial and crustal manifestations of a subduction zone that is operating beneath it.

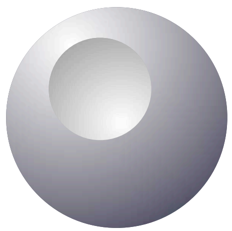
Slabs

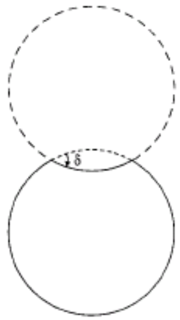
Subducted sediments, crust, and mantle lithosphere may be described separately or in combination and may be called "subducted slab" or just "slab."

geometry

young thin hot → shallow



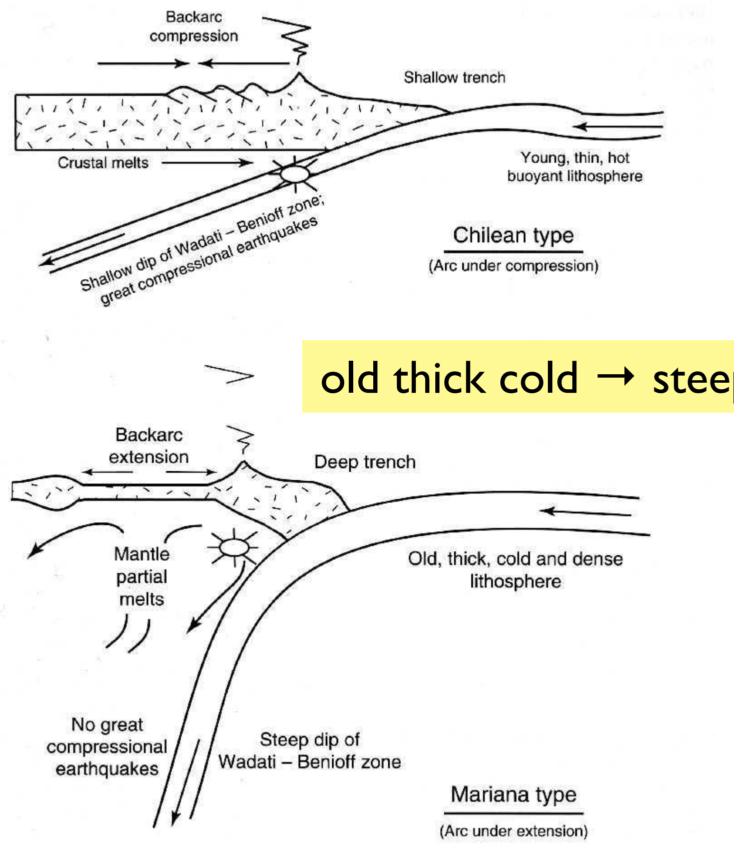




ping pong ball

Moores & Twiss (1995)

old thick cold → steep



Kearey et al. 2009

Subduktionssystem sind conkav gegen oben

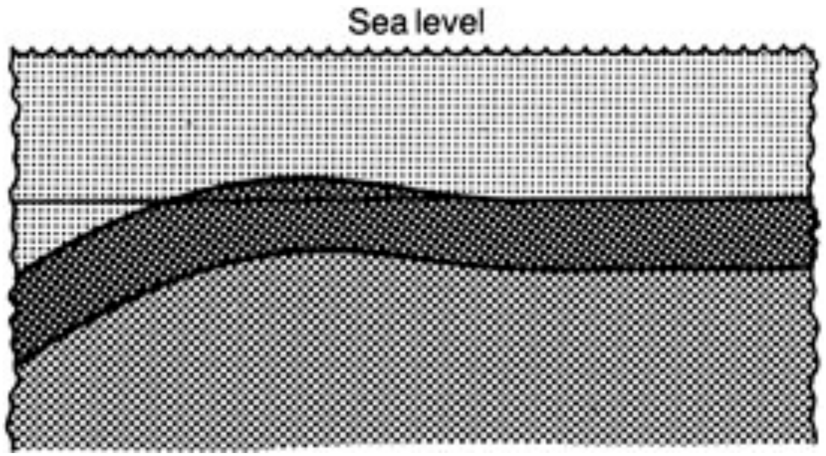
Tiefe des Grabens (Subduktions-winkel) hängt vor allem von Alter der abtauchendn Lithosphäre ab

outer swell

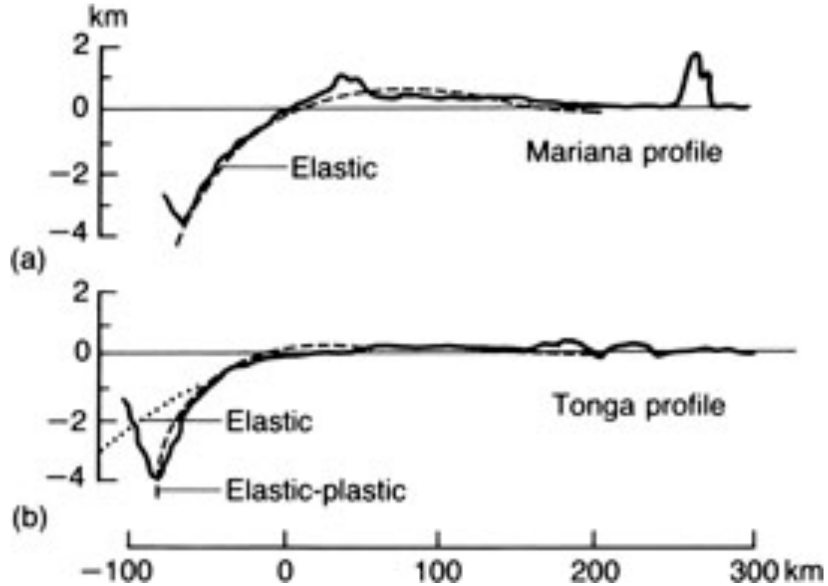
Bending of the lithosphere gives rise to the topographic bulge (outer swell).

Generally located 100-200 km from the trench axis.

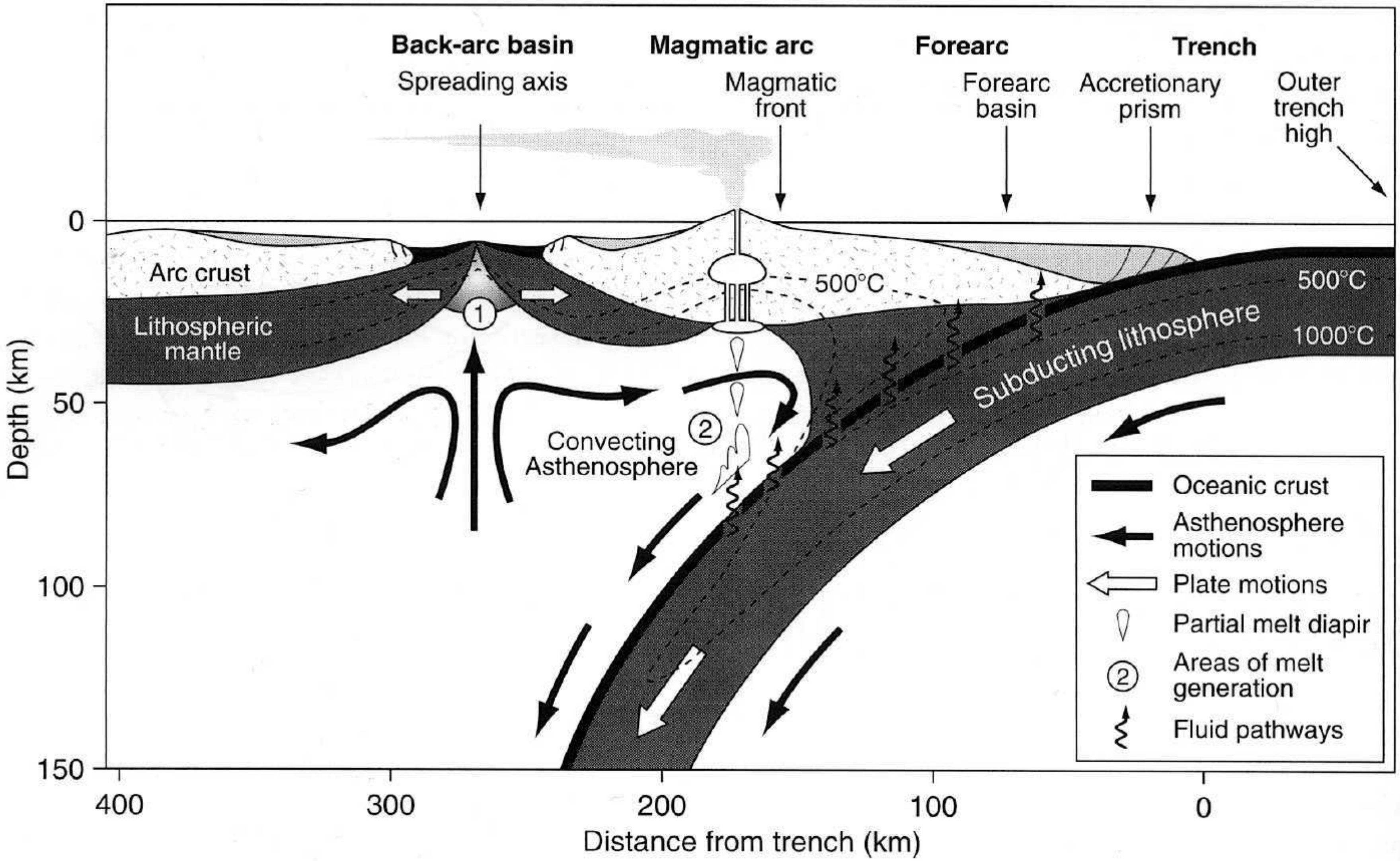
Bending model, using elastic behavior



Kearey et al. 2009

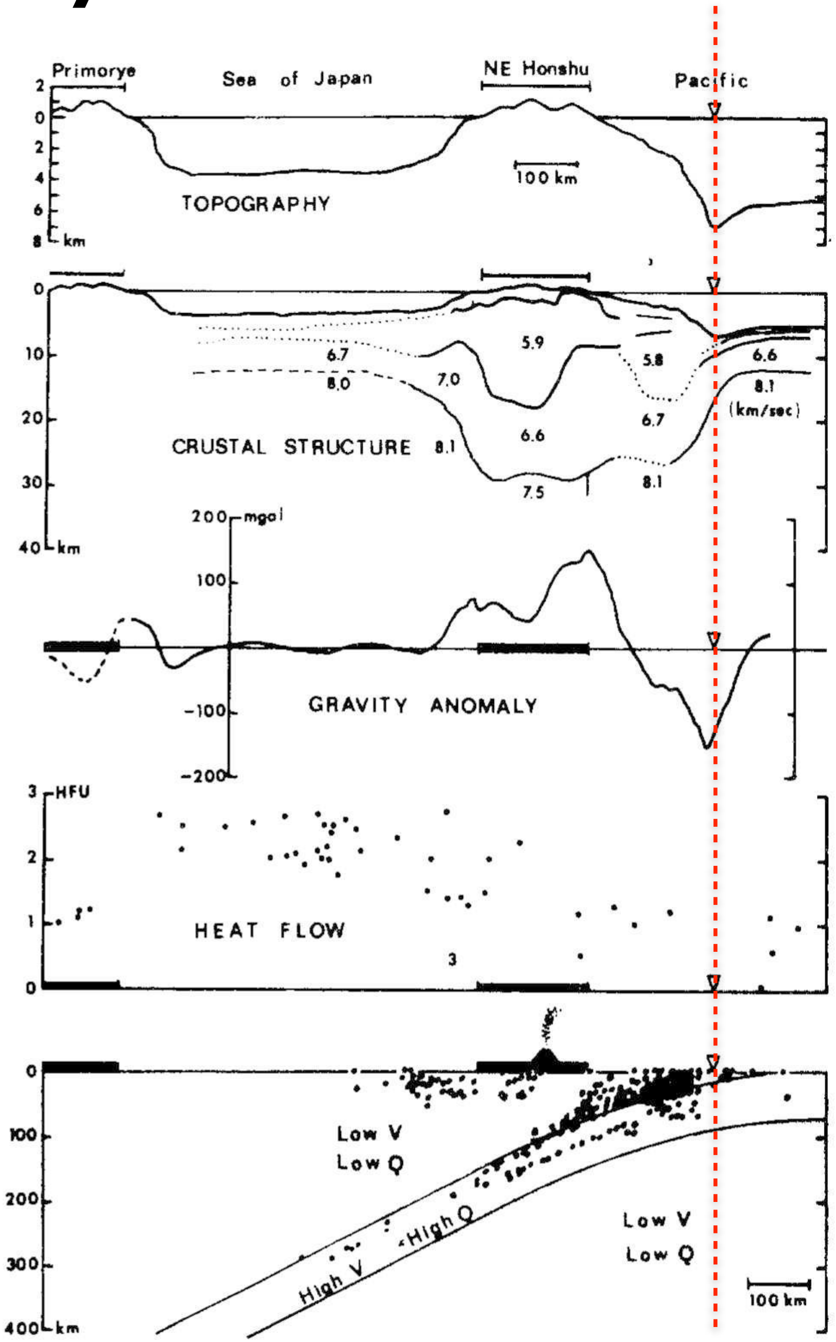


morphology of arc systems



Kearey et al. 2009

physical structure



Example Japan:

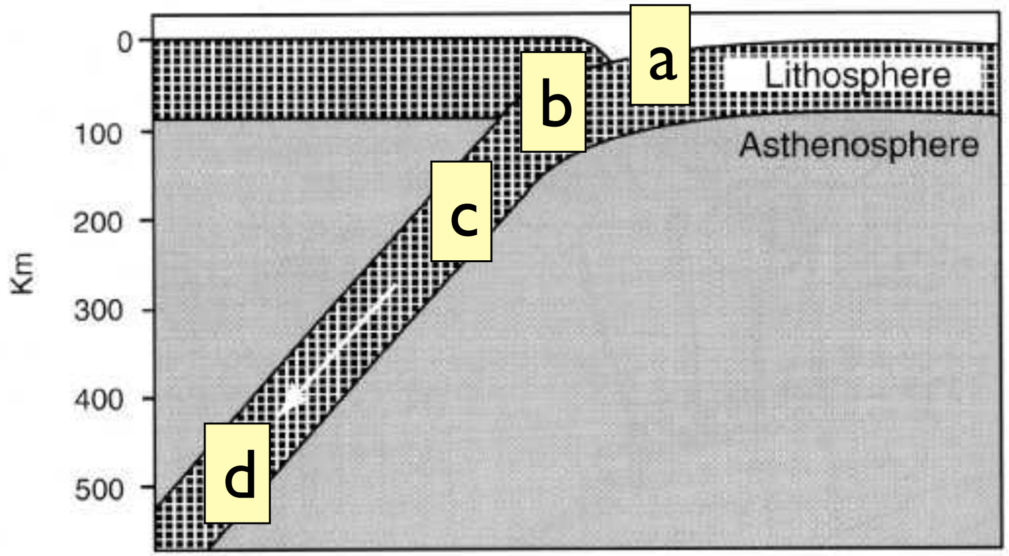
Low P-wave velocity in the uppermost mantle beneath the arc:
→ indicating thin lithosphere
→ high T asthenosphere elevated almost to Moho

Negative gravity anomaly
→ replacement of rock by water and low density sediments at the trench
Positive gravity anomaly at volcanic arc
→ replacement of water by high-density material.

Low heat flow at trench (here, Pacific Ocean)
high heat flow continentward of the volcanic front including backarc (here, Japan Sea)

Uyeda, 1984, Geojournal

earth quakes in bending slab

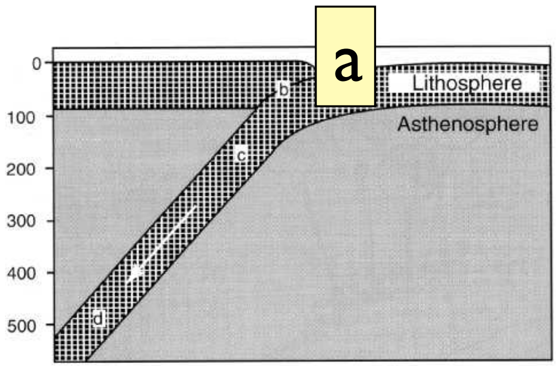


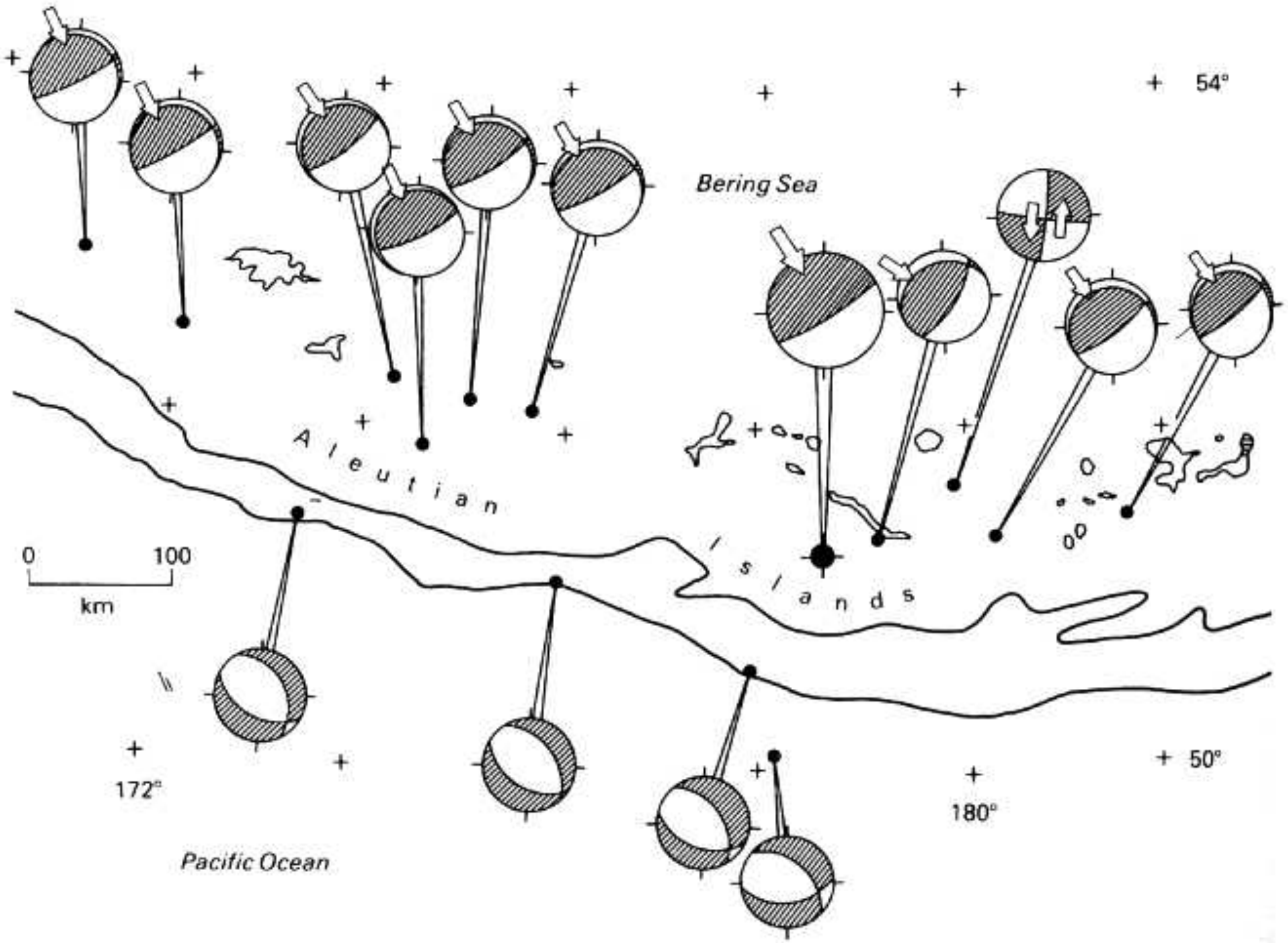
Depth of earthquakes and focal mechanism at downgoing slab

a. Extensional setting in bending slab
b. Frictional region in lithosphere
c. Internal deformation of slab below lithosphere depth
d. Deep earthquakes due to phase transformations

a. Extensional setting in bending slab

Focal solutions for Aleutian trench





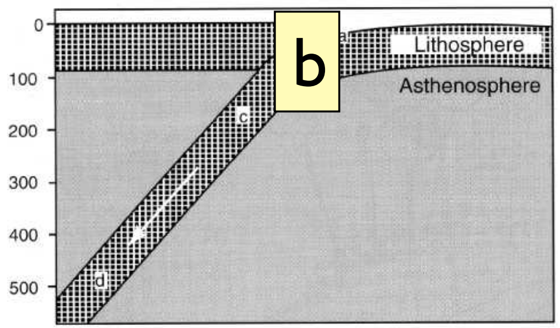
Kearey et al. 2009

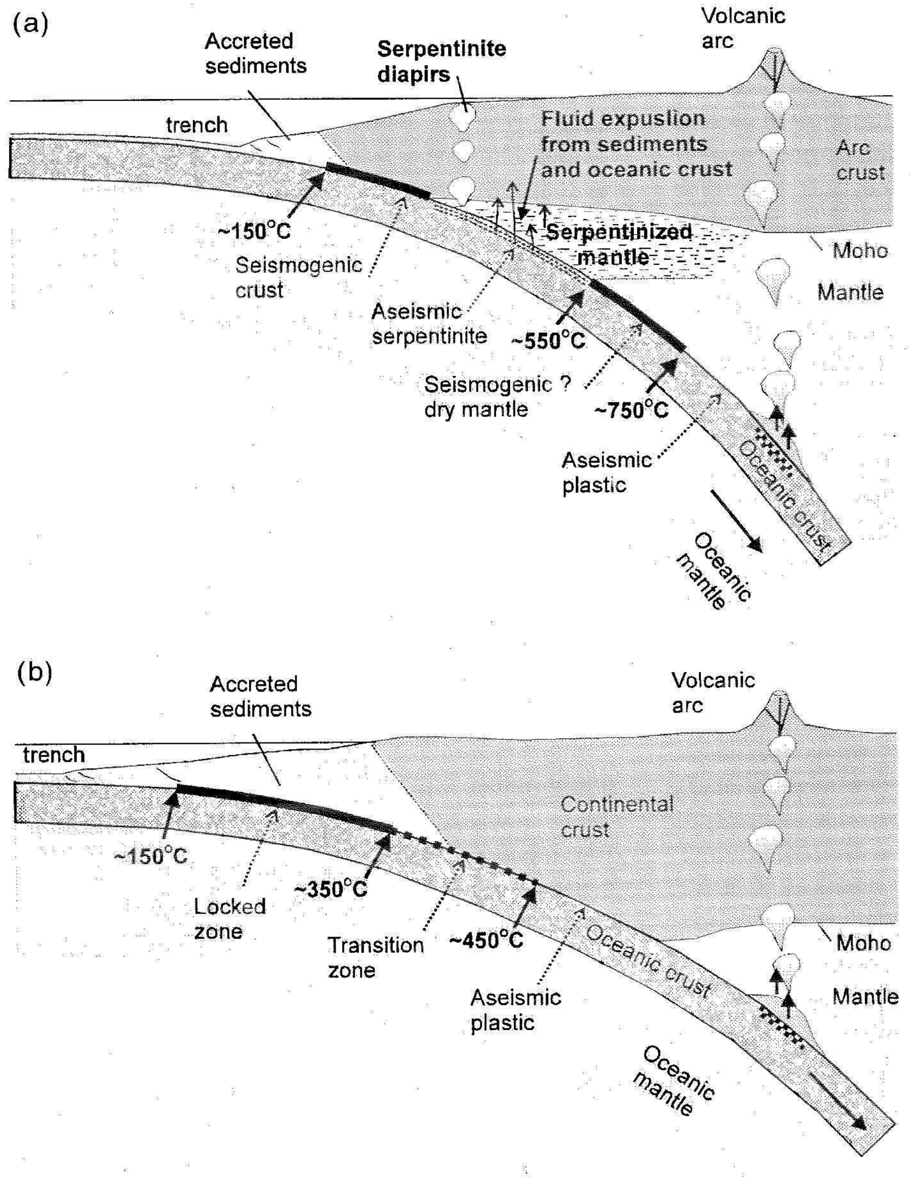
b. Frictional region in lithosphere

Large, shallow earthquakes in subduction zones contribute 90% of the total seismic moment released worldwide [Pacheco and Sykes, 1992].

These earthquakes have focal mechanisms indicating thrust faulting along the subduction interface by friction.

Only 2–5% of the total downdip length of the Wadati-Benioff Zone generates this kind of earthquake, and this segment is known as the main





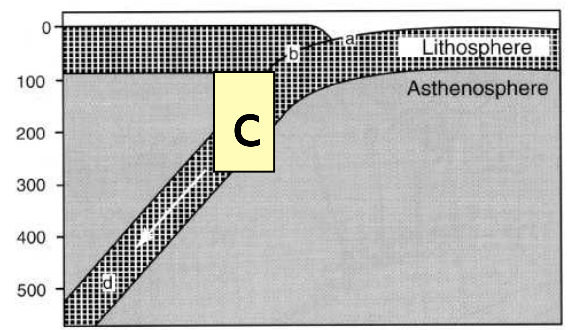
Hyndman et al., 1997

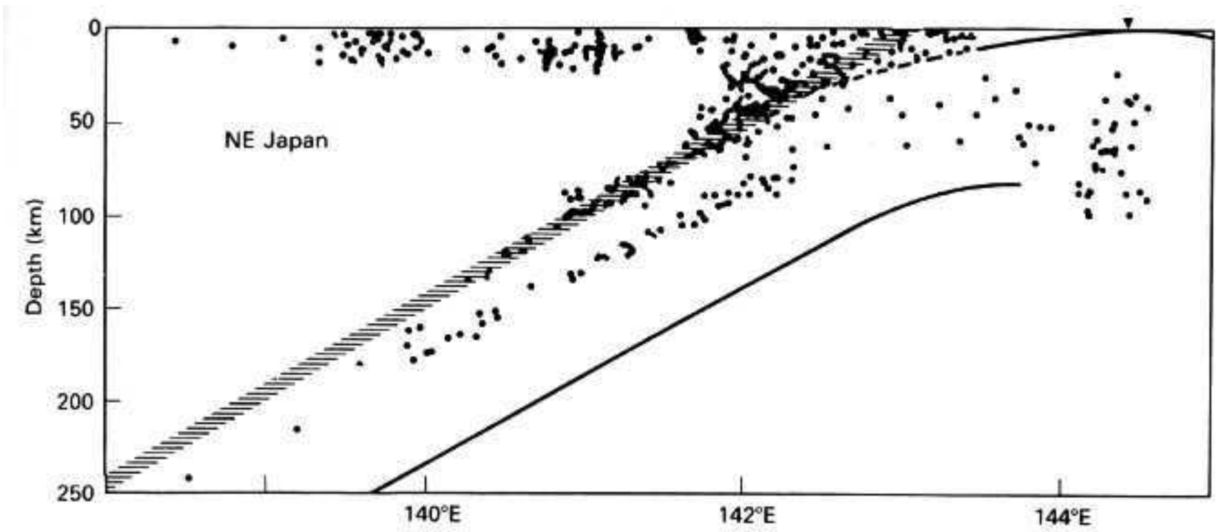
c. Internal deformation of slab

Different zones of earthquake sources in slab
=
different mechanisms for earthquakes

Upper zone:
Astenosphere too weak to cause earthquakes
→ eclogite formation ?

Lower zone:
→ serpentinite dehydration ?

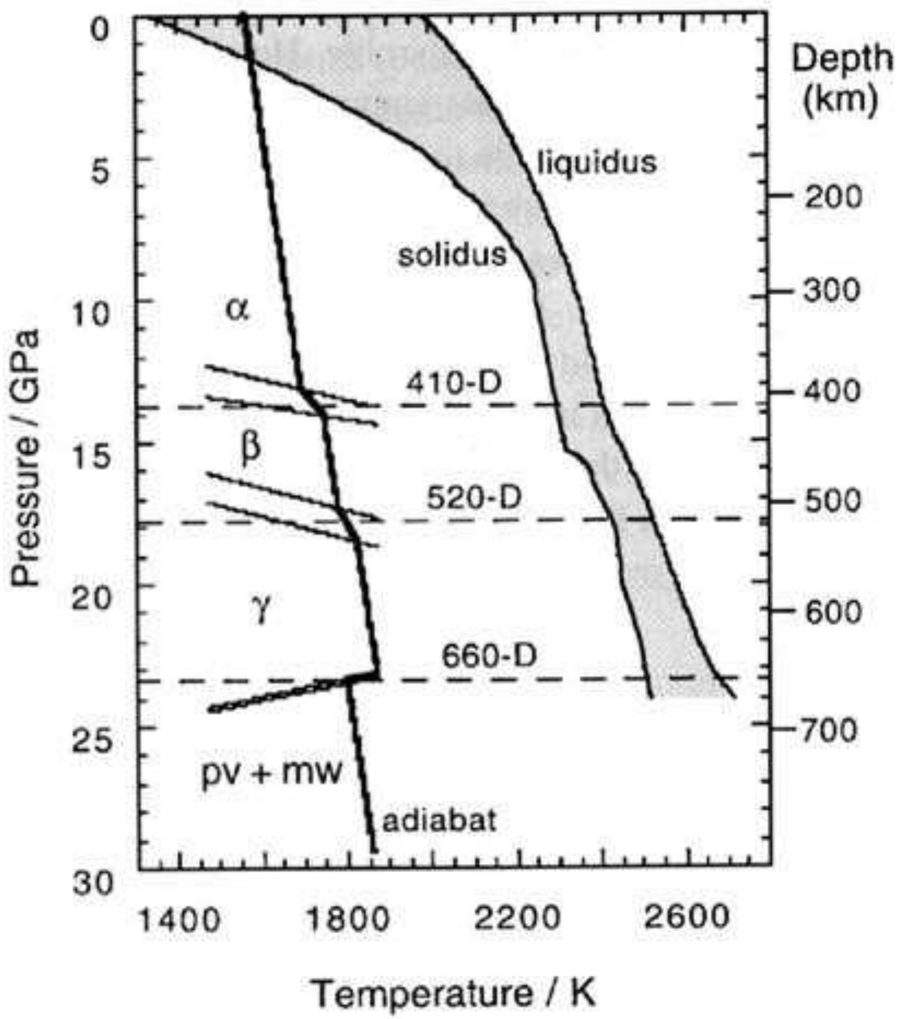




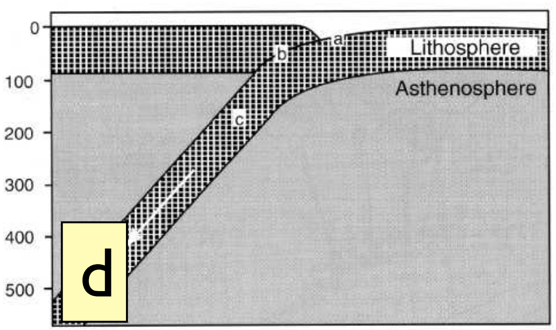
Kearey et al. 2009

d. Phase transformations

Phase transformations and seismic velocities fit very well in P,T-diagrams

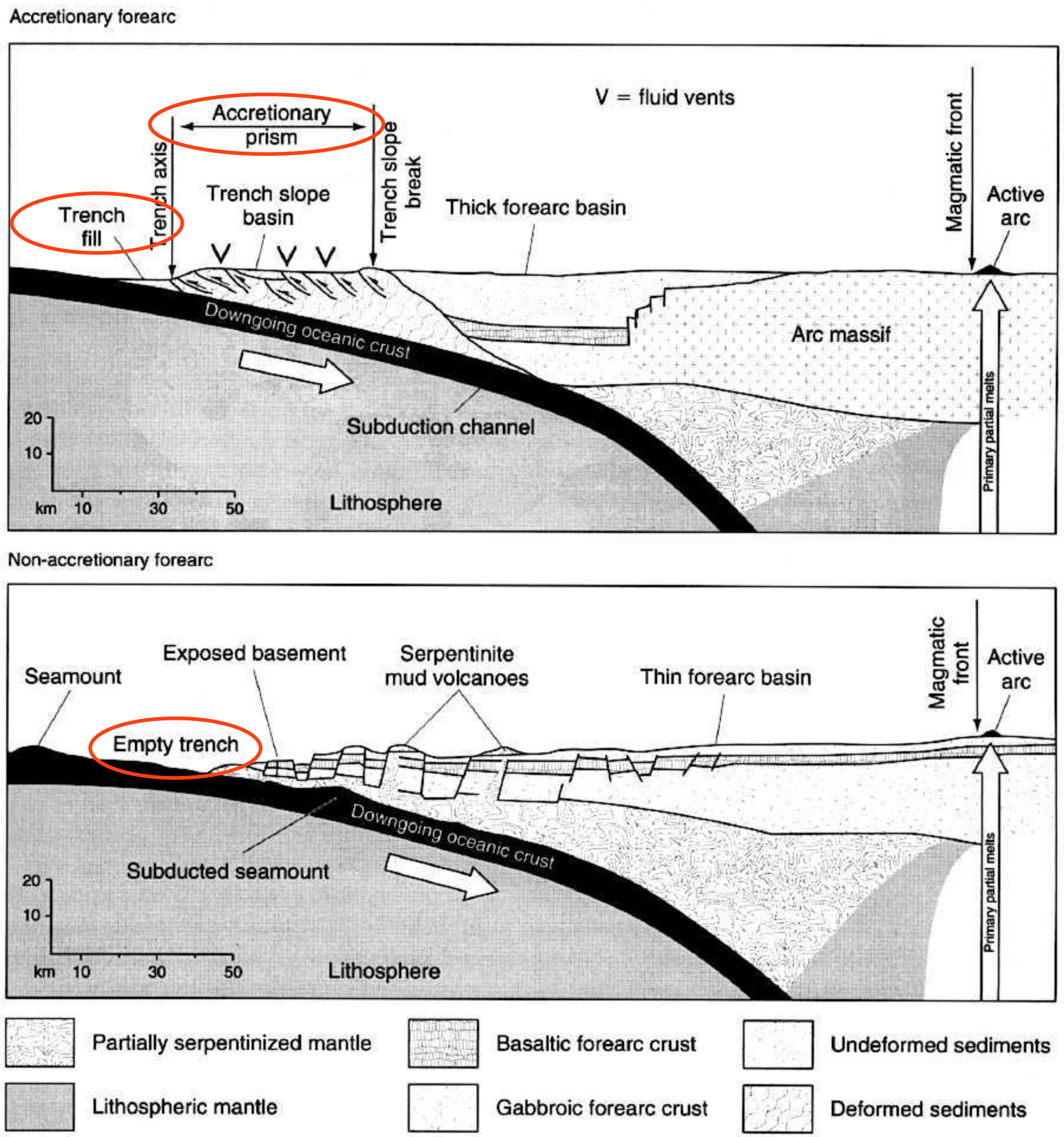


Bowfell, UCL



Akkretionskeil
Orogenkeil

accretionary wedge



Landward thickening wedge-shaped body of marine sediments scraped off from the downgoing slab and accreted onto the non-subducting plate.

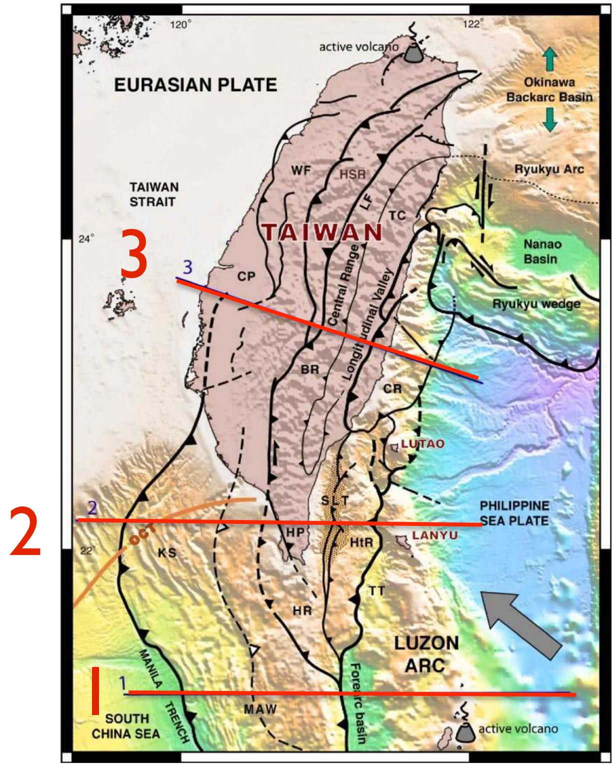
Material = marine sediments, may include erosional products of volcanic island arcs formed on the overriding plate.

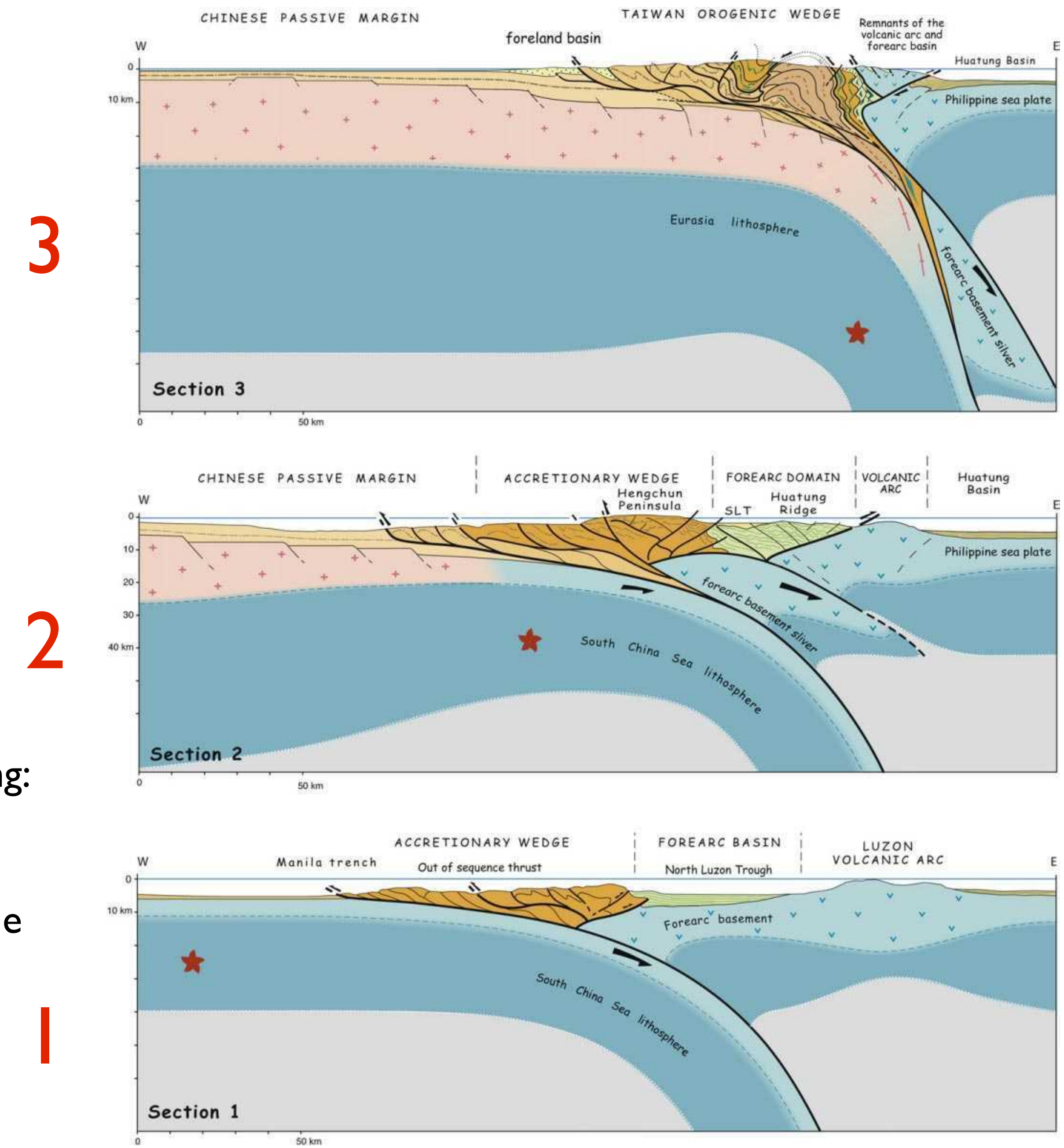
Thickness, t, of incoming sediment layers determines whether there is accretion or not

→ t > 400-1000m needed to accrete

Kearey et al. 2009

accretionary wedge - orogenic wedge



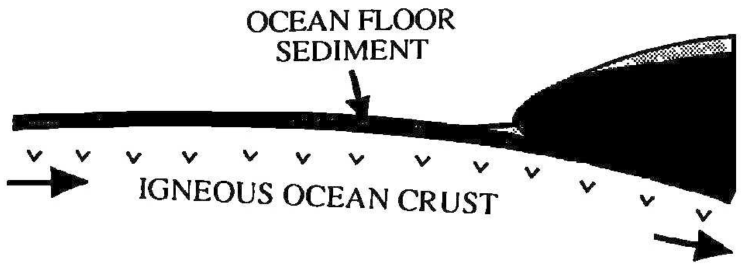


kontinuierlicher räumlicher Übergang:
Akkretionskeil → Orogenkeil

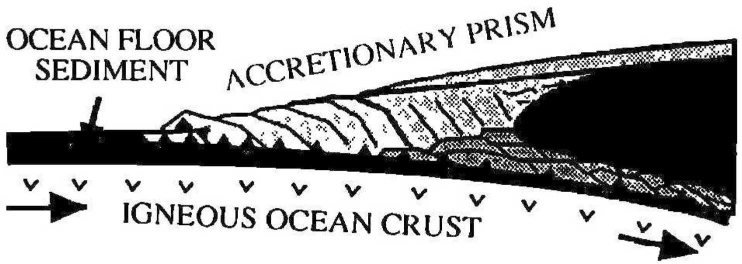
Orogenkeil = Keil, der sich über eine subduzierende Platte bildet
Material = hauptsächlich aus der unteren Platte.

accretionary non-accretionary

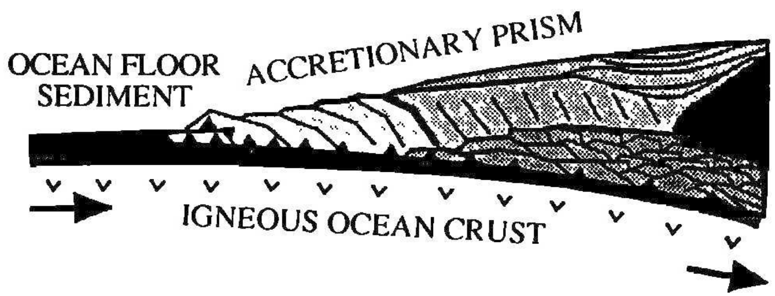
21000 km non-accretionary margin
(100% underthrusted)



16000 km semi-accretionary margin
(80% underthrusted)



7000 km typical accretionary margin
(70% underthrusted)



Non-accretionary wedges:

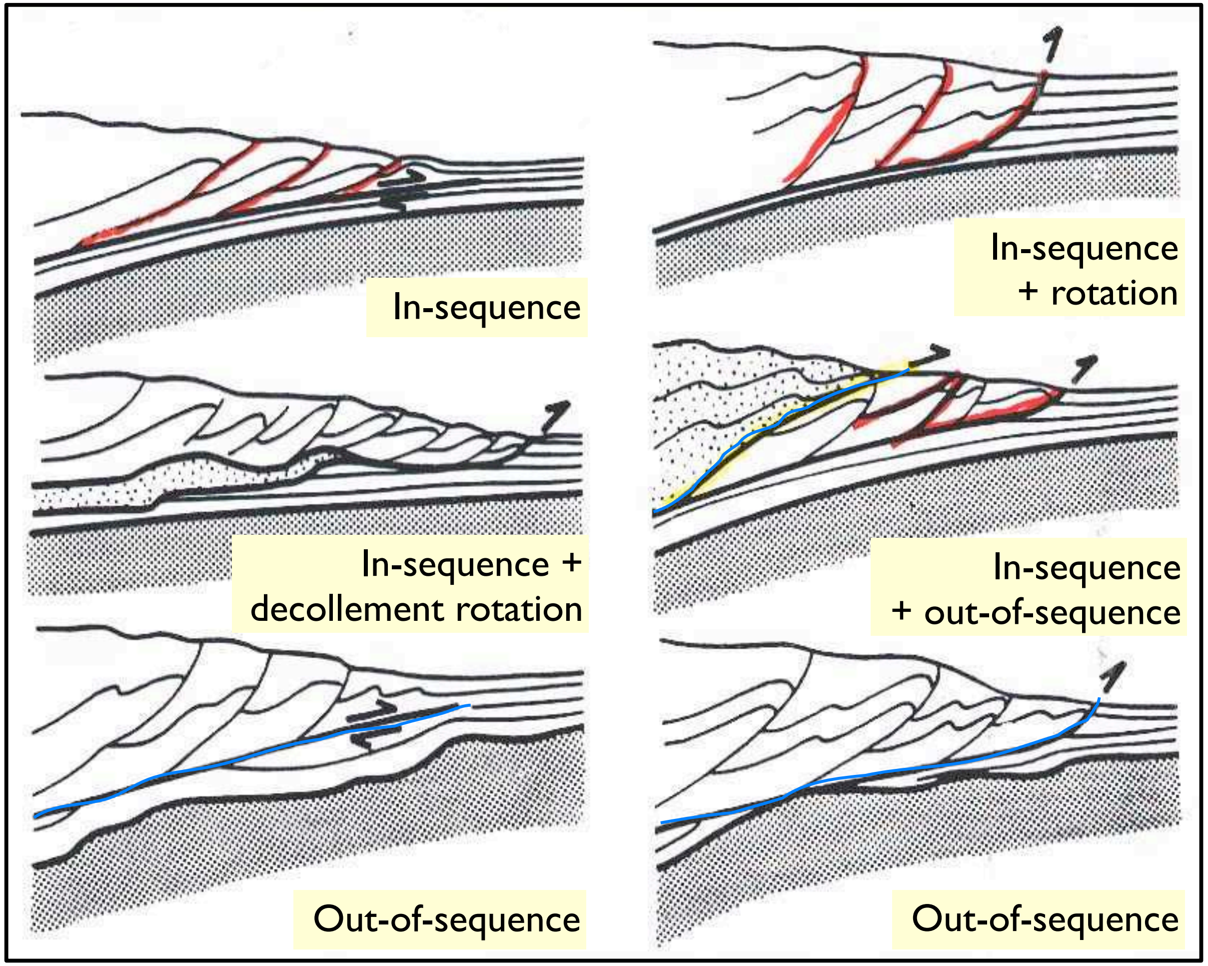
- larger slope angles (α)
- rougher surface of subducting plate
- high convergence rates
- almost no trench sediments

Typical Accretionary wedges:

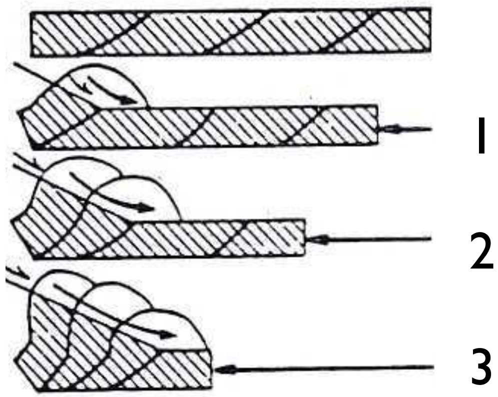
- small slope angles (α)
- smooth surfaces of subducting plate
- low convergence rates
- thick trench sediments

Lallemand et al., 1994, J. Geophys. Res.

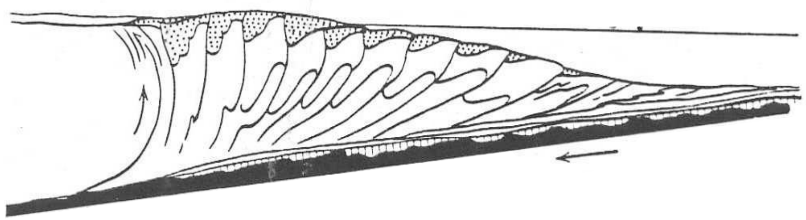
modes of accretion



Frontal accretion
Underplating &
telescoping



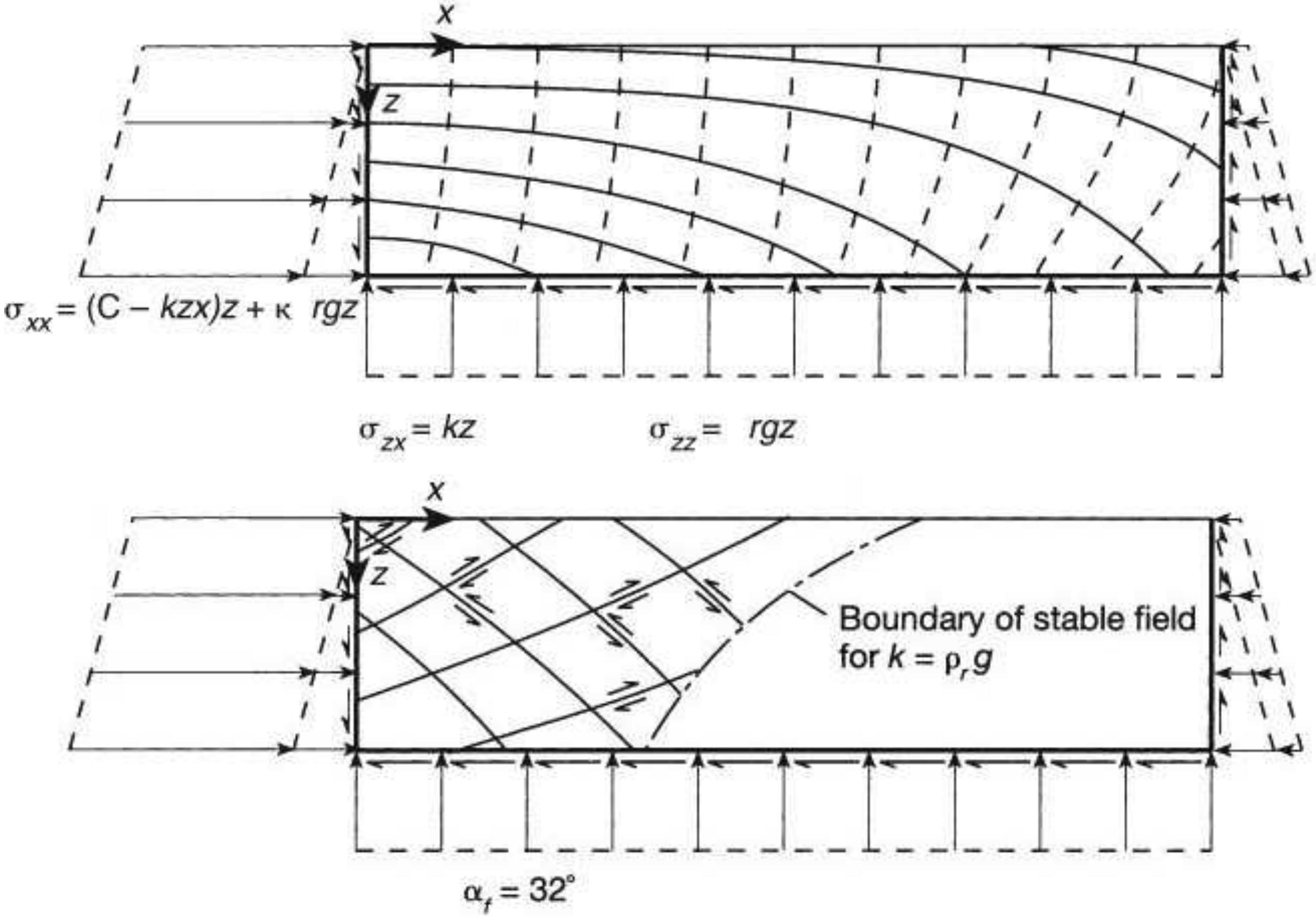
Rotation of older thrusts
in frontal part only



wedge

Hafner (1951)

Stress distribution in block



Hubbert & Rubey (1959)

Pore fluid pressure

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 70, PP. 115-166, 32 FIGS. FEBRUARY 1959

ROLE OF FLUID PRESSURE IN MECHANICS OF OVERTHRUST FAULTING

I. MECHANICS OF FLUID-FILLED POROUS SOLIDS AND ITS APPLICATION TO OVERTHRUST FAULTING

BY M. KING HUBBERT AND WILLIAM W. RUBEY

According to the Mohr-Coulomb law, slippage along any internal plane in the rock should occur when the shear stress along that plane reaches the critical value

$$\tau_{crit} = \tau_0 + \sigma \tan \phi; \quad (3)$$

where σ is the normal stress across the plane of slippage, τ_0 the shear strength of the material when σ is zero, and ϕ the angle of internal friction. However, once a fracture is started τ_0 is eliminated, and further slippage results when

$$\tau_{crit} = \sigma \tan \phi = (S - p) \tan \phi. \quad (4)$$

This can be further simplified by expressing p in terms of S by means of the equation

$$p = \lambda S, \quad (5)$$

which, when introduced into equation (4), gives

$$\tau_{crit} = \sigma \tan \phi = (1 - \lambda) S \tan \phi. \quad (6)$$

From equations (4) and (6) it follows that, without changing the coefficient of friction $\tan \phi$, the critical value of the shearing stress can be made arbitrarily small simply by increasing the fluid pressure p. In a horizontal block the total weight per unit area S_{zz} is jointly supported by the fluid pressure p and the residual solid stress σ_{zz}; as p is increased, σ_{zz} is correspondingly diminished until, as p approaches the limit S_{zz}, or λ approaches 1, σ_{zz} approaches 0.

Chapple (1978)

Wedge model

Mechanics of thin-skinned fold-and-thrust belts

WILLIAM M. CHAPPLE *Department of Geological Sciences, Brown University, Providence, Rhode Islana*

The essential characteristics of thin-skinned fold-and-thrust belts include the following: a wedge-shaped deforming region, thicker at the back end from which the thrusts come; a weak layer at the base of the wedge; and large amounts of shortening and thickening within the wedge. All these characteristics are incorporated into an analytical model of a perfectly plastic wedge, underlain by a weak basal layer and yielding in compressive flow.

Davis et al. (1983)

Critical taper

Mechanics of Fold-and-Thrust Belts and Accretionary Wedges

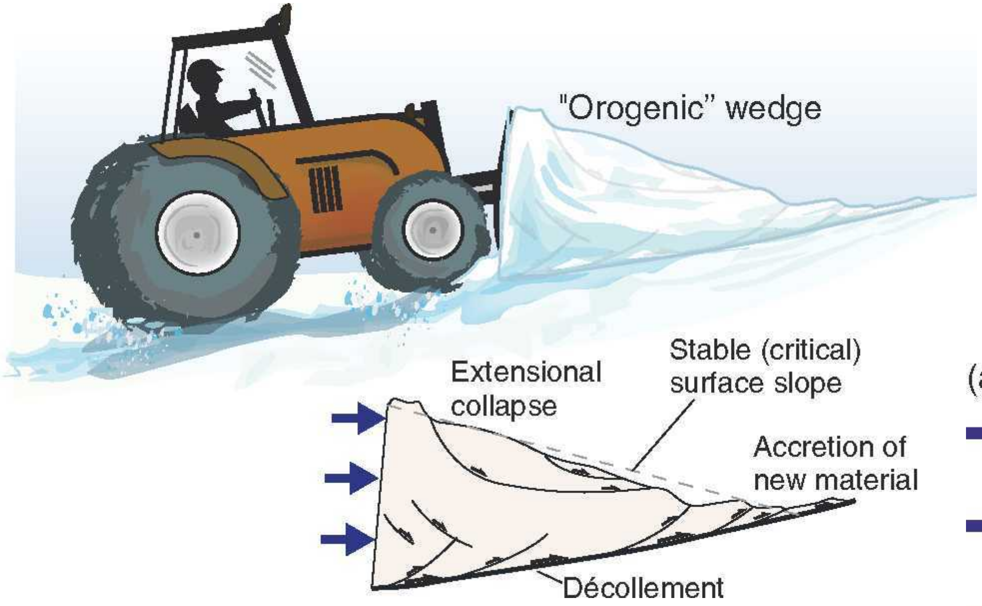
DAN DAVIS

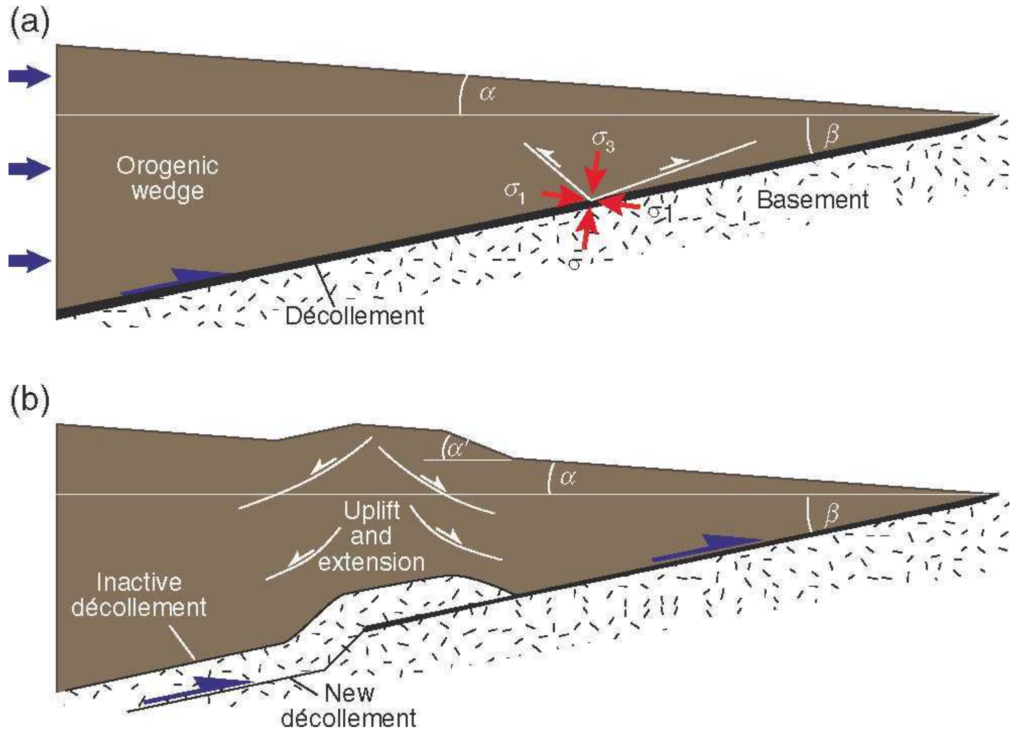
Department of Earth and Planetary Sciences, Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

JOHN SUPPE AND F. A. DAHLEN

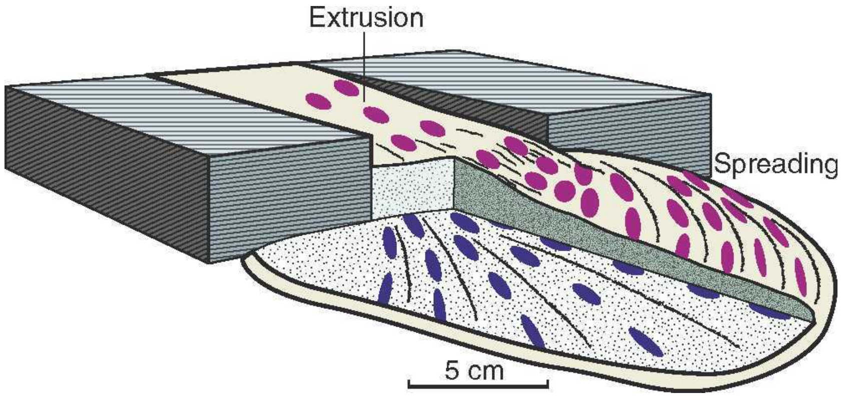
The overall mechanics of fold-and-thrust belts and accretionary wedges along compressive plate boundaries is considered to be analogous to that of a wedge of soil or snow in front of a moving bulldozer. The material within the wedge deforms until a critical taper is attained, after which it slides stably, continuing to grow at constant taper as additional material is encountered at the toe. The critical taper is the shape for which the wedge is on the verge of failure under horizontal compression everywhere, including the basal decollement. A wedge of less than critical taper will not slide when pushed but will deform internally, steepening its surface slope until the critical taper is attained. Common silicate sediments and rocks in the upper 10–15 km of the crust have pressure-dependent brittle compressive strengths which can be approximately represented by the empirical Coulomb failure criterion, modified to account for the weakening effects of pore fluid pressure. A simple

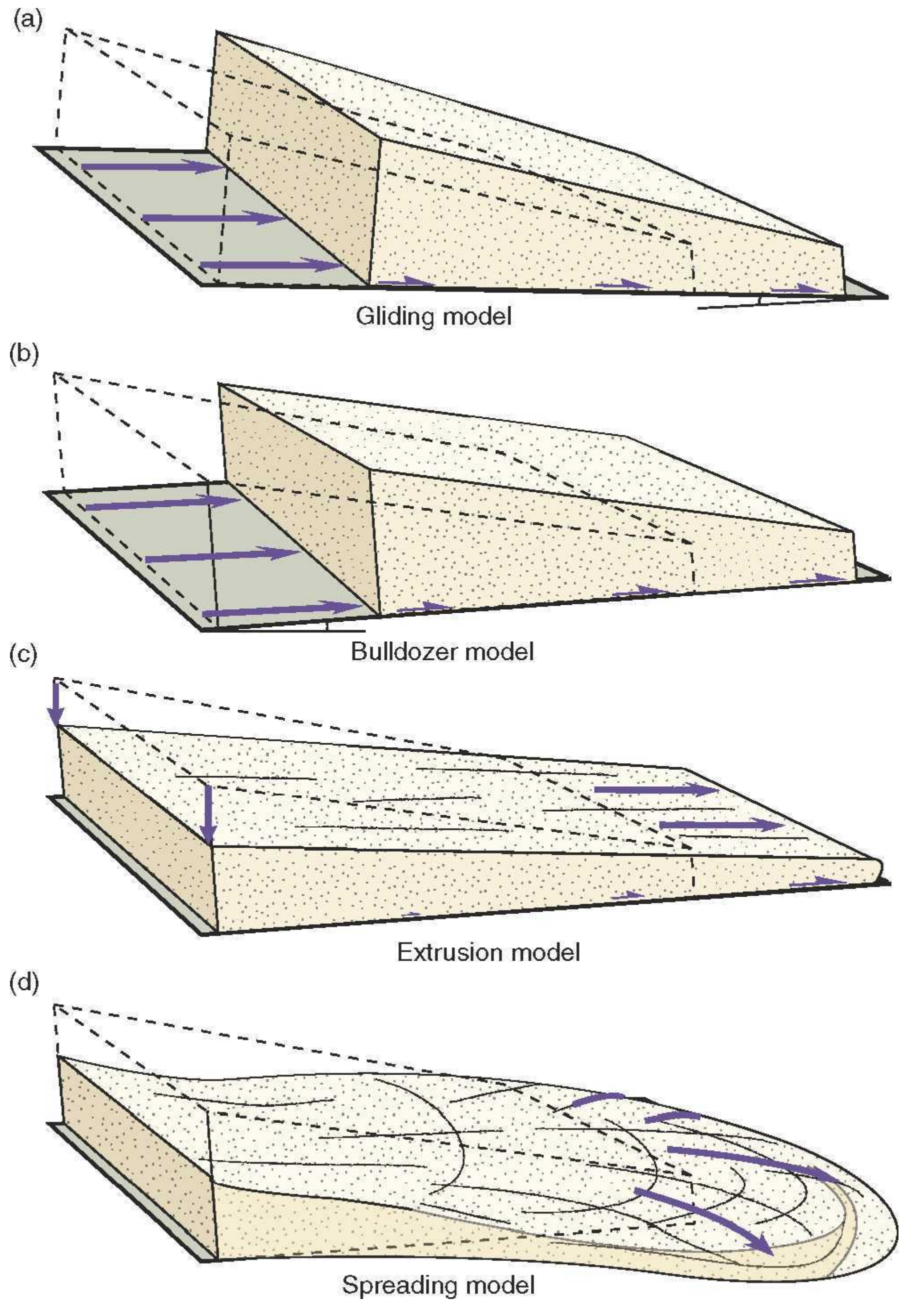
bulldozer model



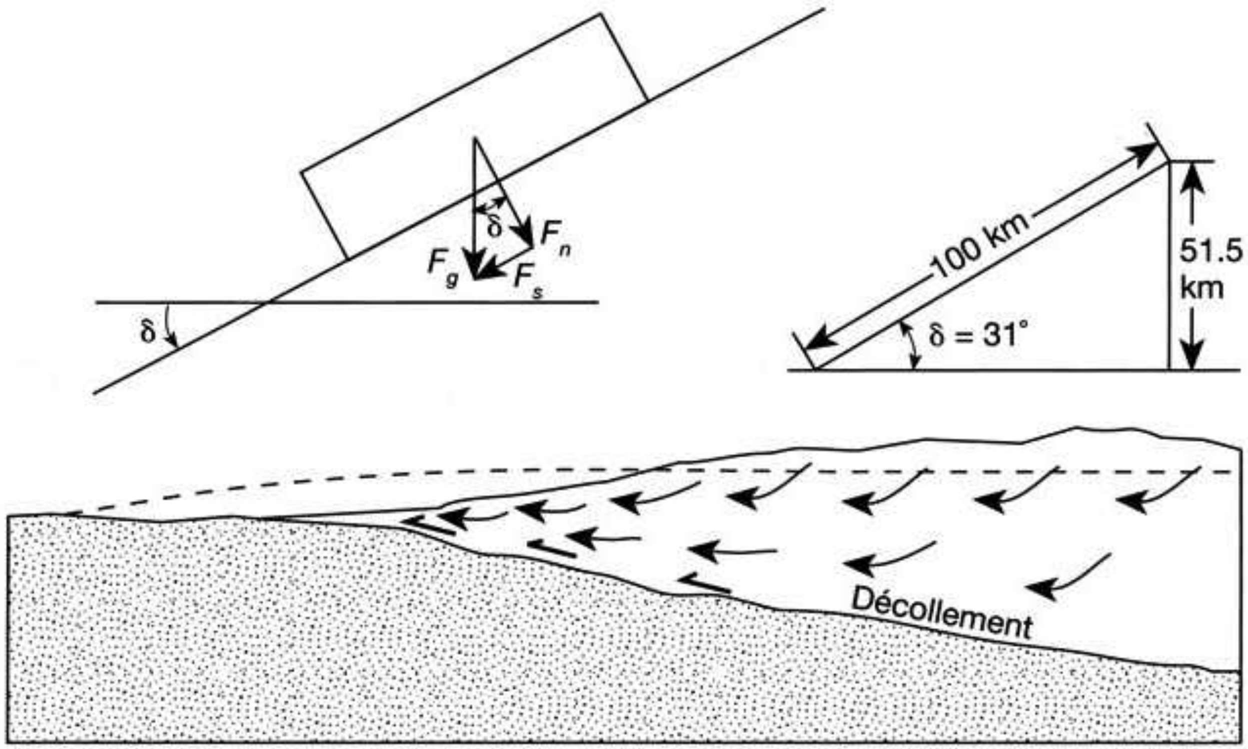


deformation of orogenic wedge

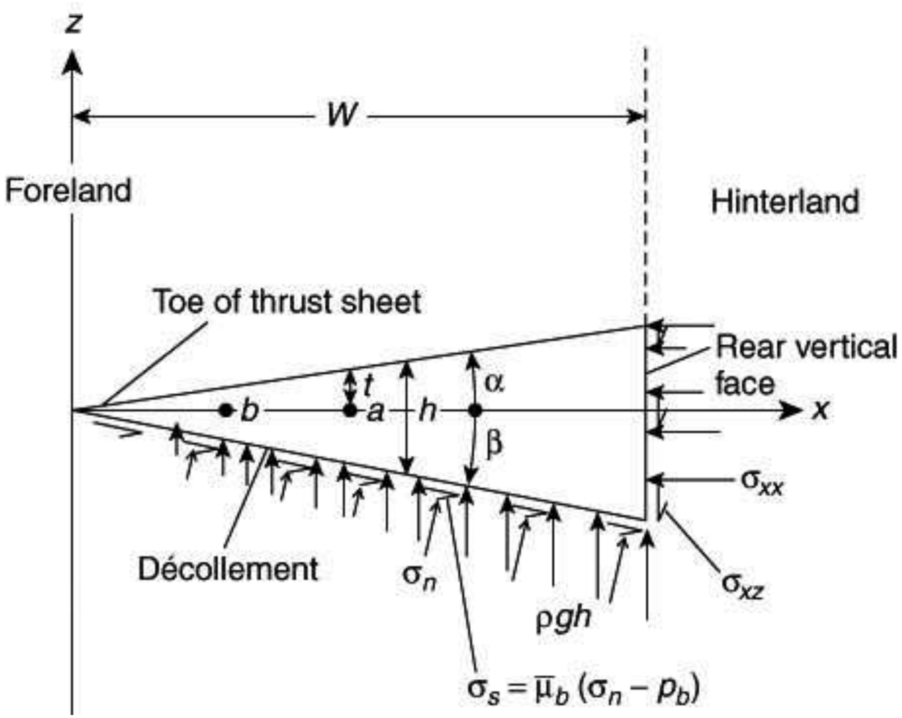




gravitationally driven thrust sheets

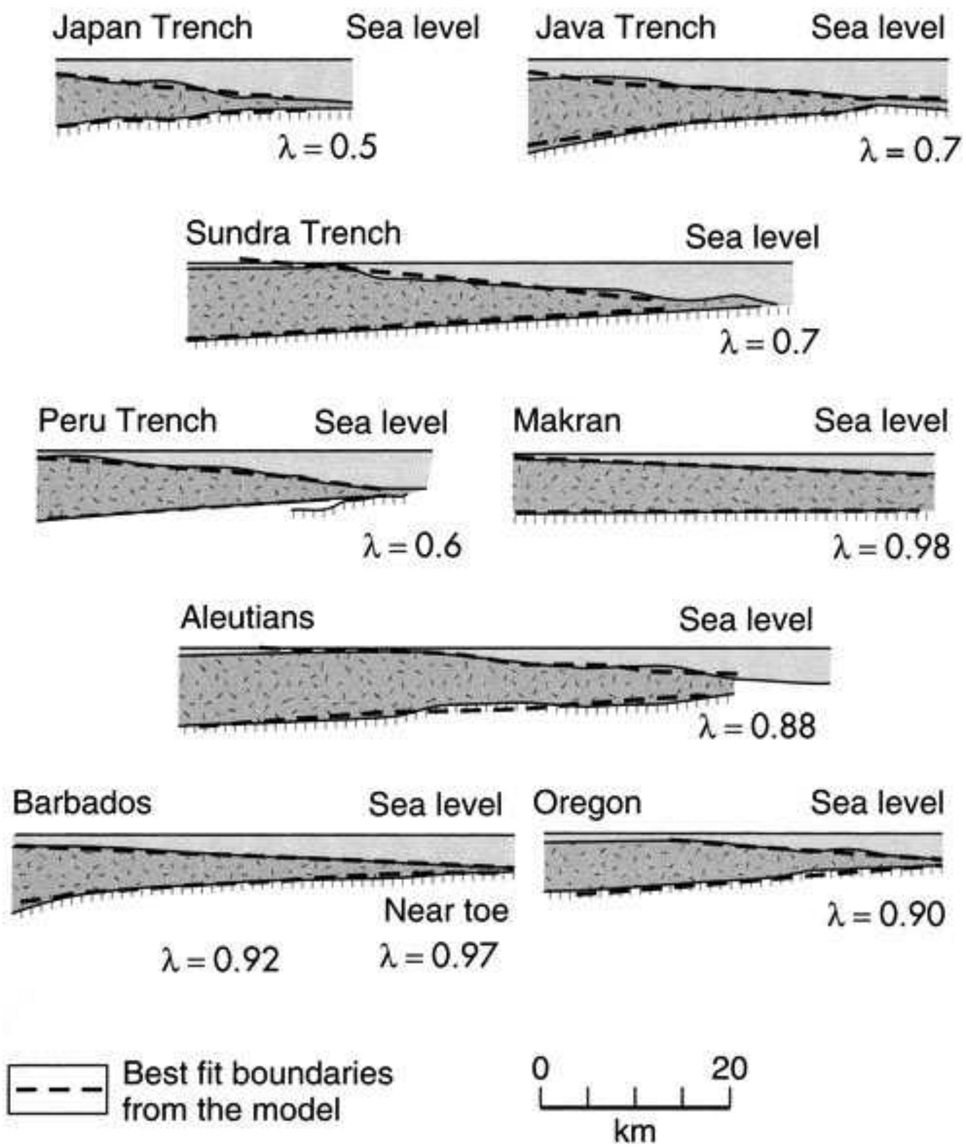


tapered thrust sheets

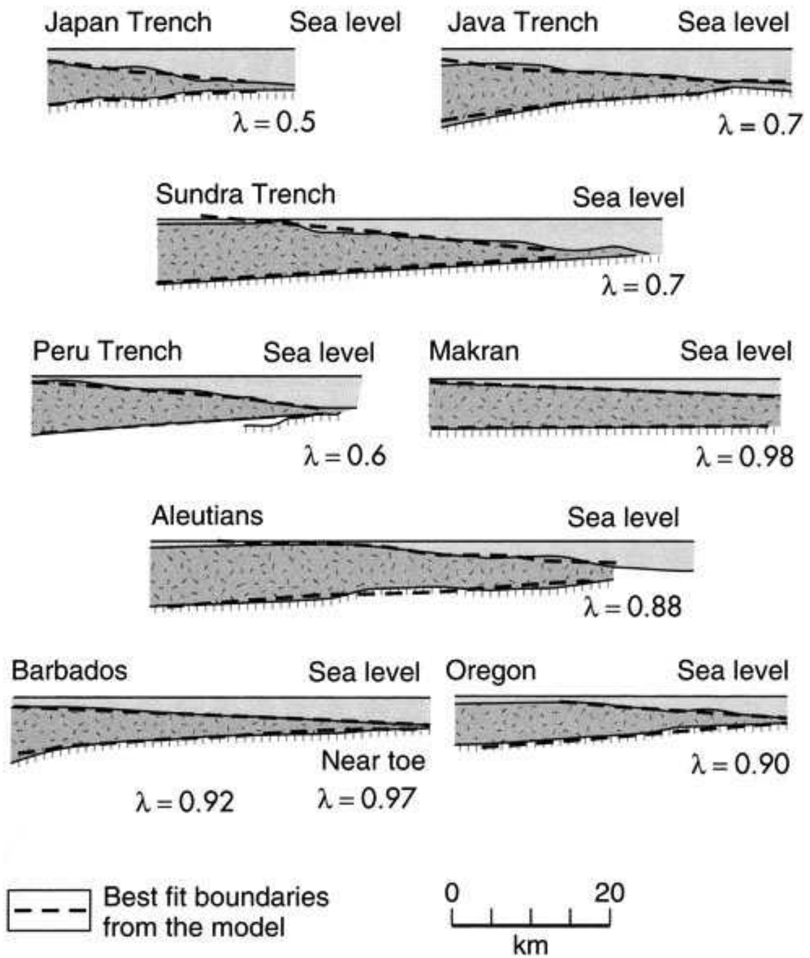


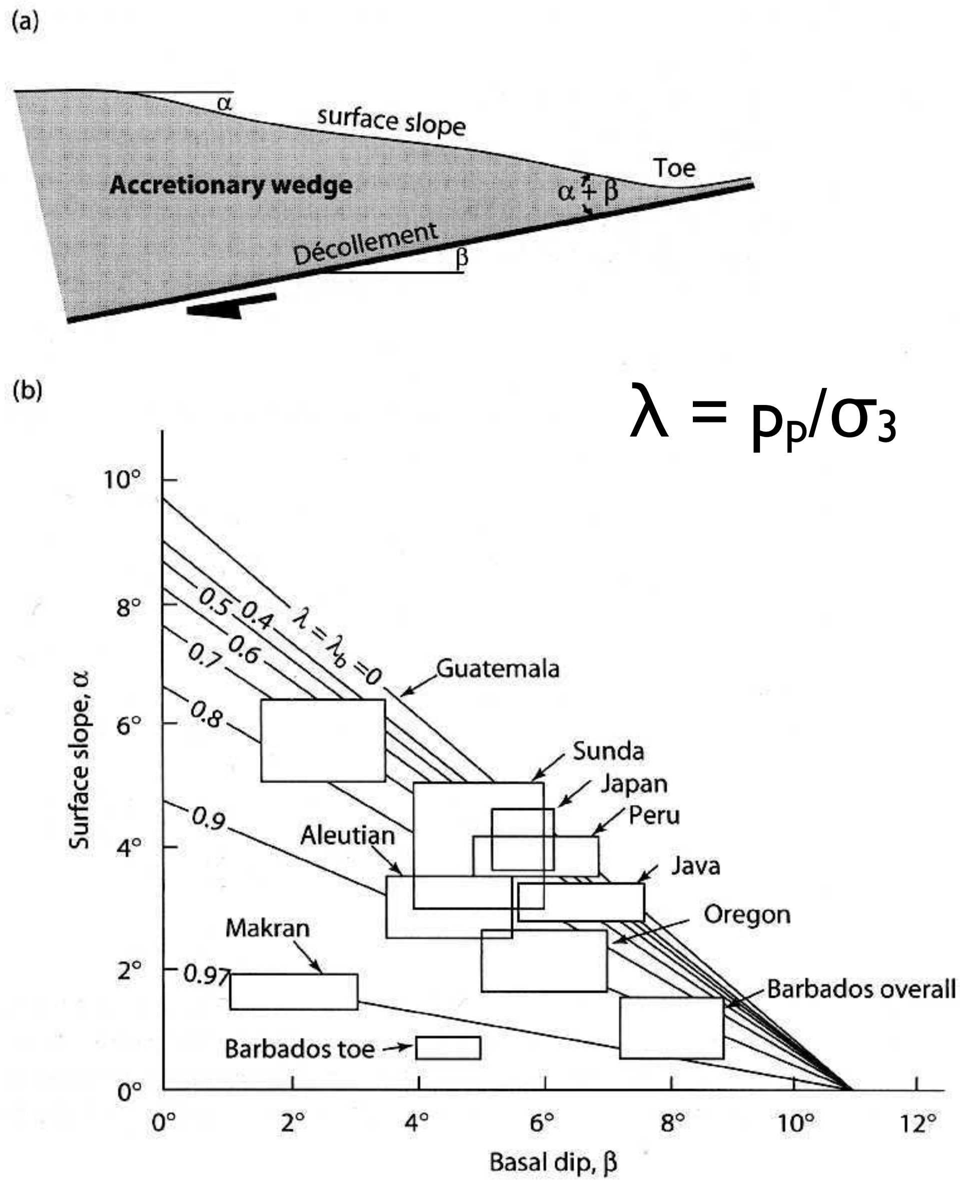
$$\sigma_{eff} = \sigma_3 - p_P$$

$$\lambda = p_P/\sigma_3$$



pore pressure effect



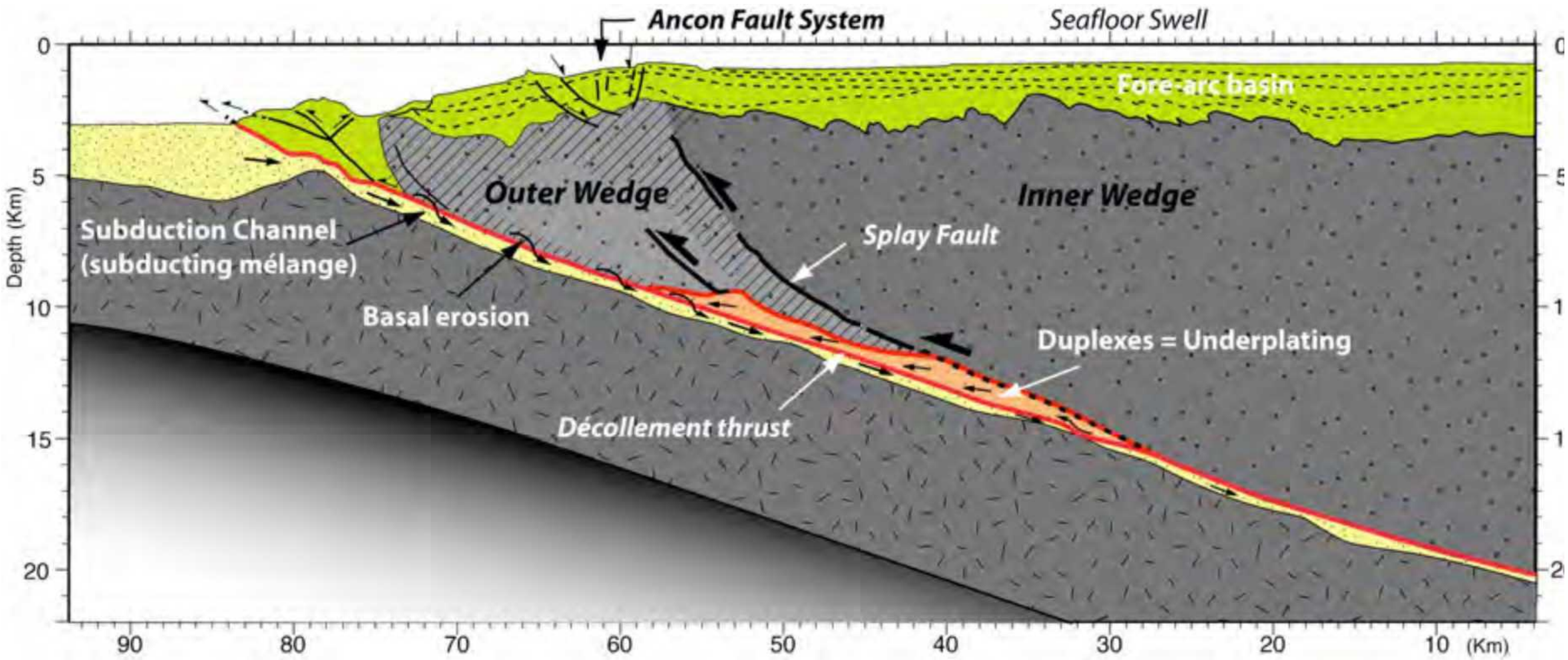


$\lambda = p_P/\sigma_3$

Kearey et al. 2009

subduction channel

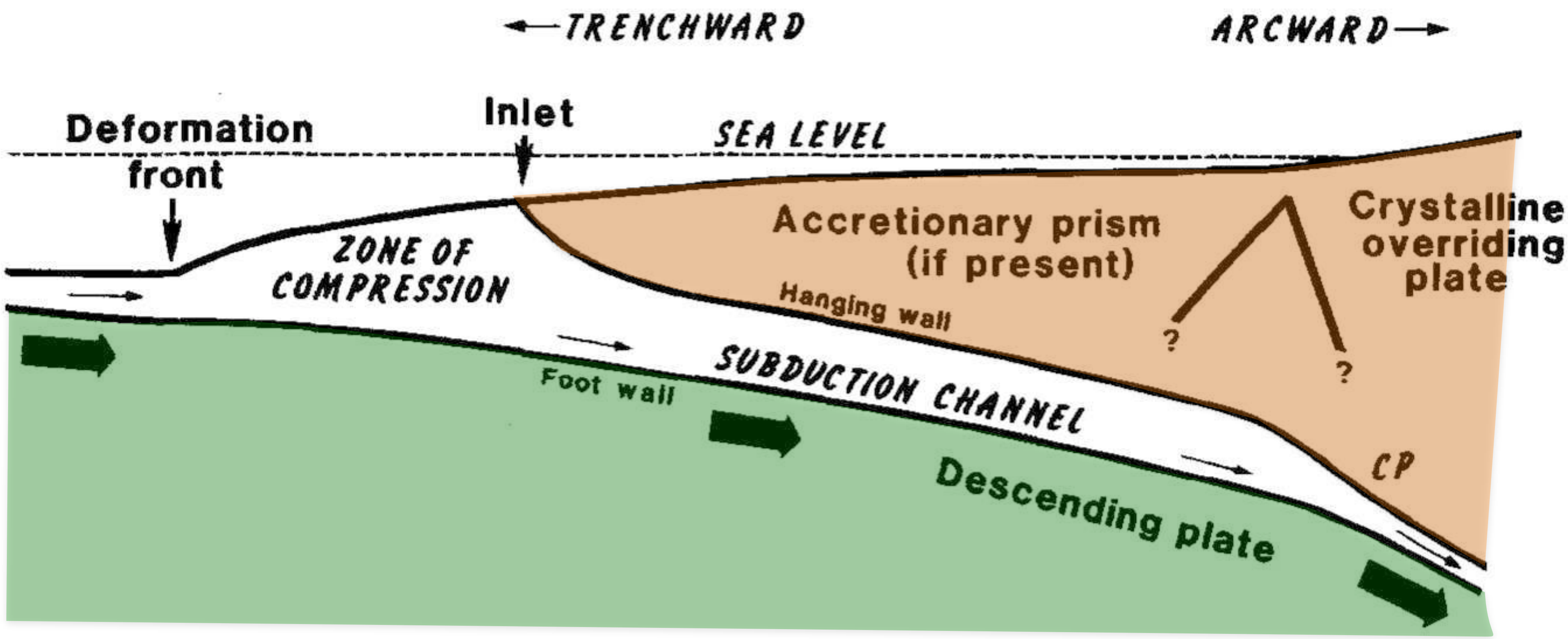
subduction channel



Collot et al., 2008, ISAG 2008, Nice

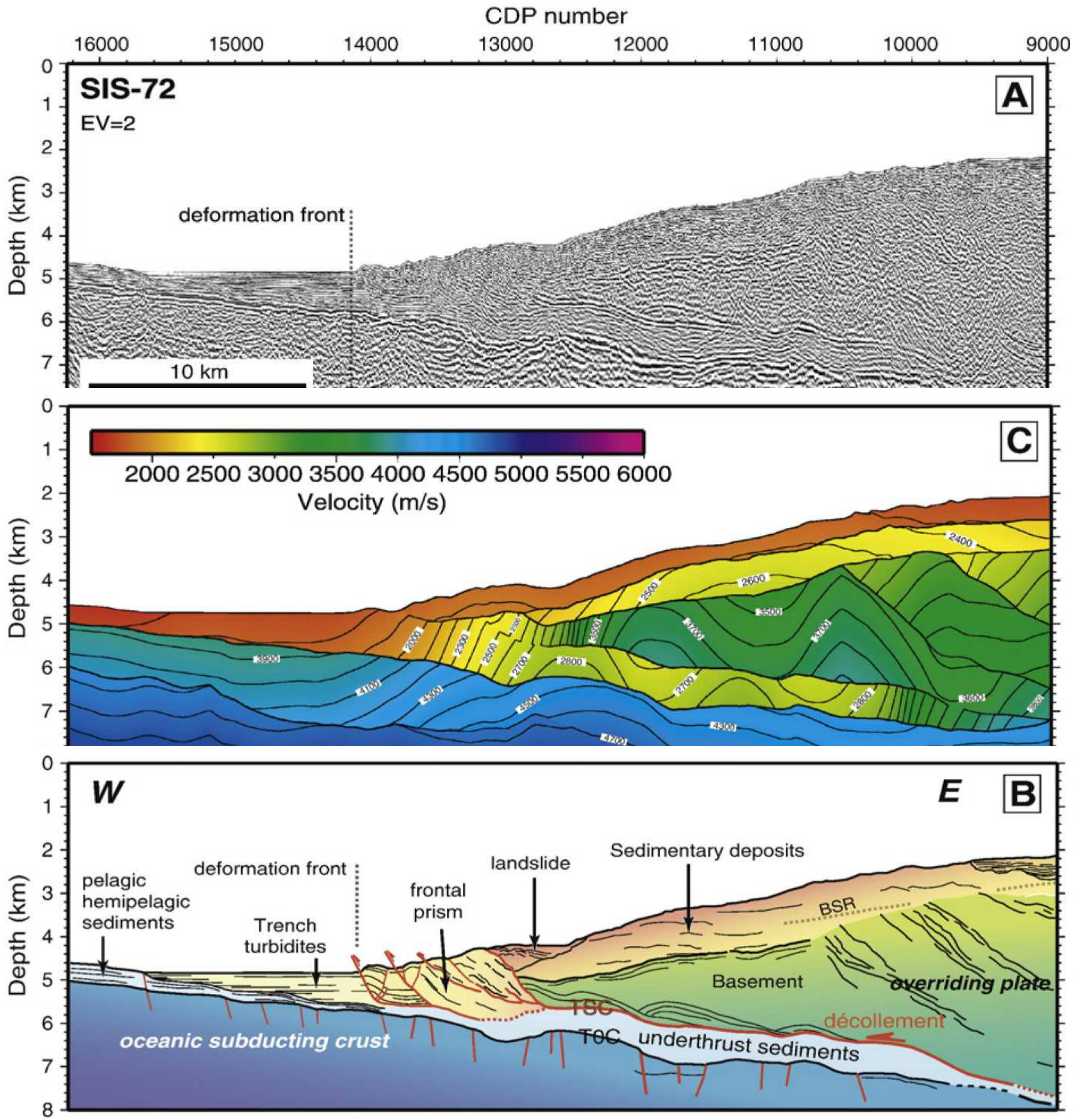
1- definition

Thin layer (less than 1 to several km) of poorly consolidated sediment dragged by the descending plate beneath the overriding one.



Cloos and Shreeve, 1988, Pageoph

2- seismic evidence



Calahorrano et al., 2008, EPSL

3- mass balance

Potential frontal mass (in 2D) : $h \cdot v_c \cdot t$

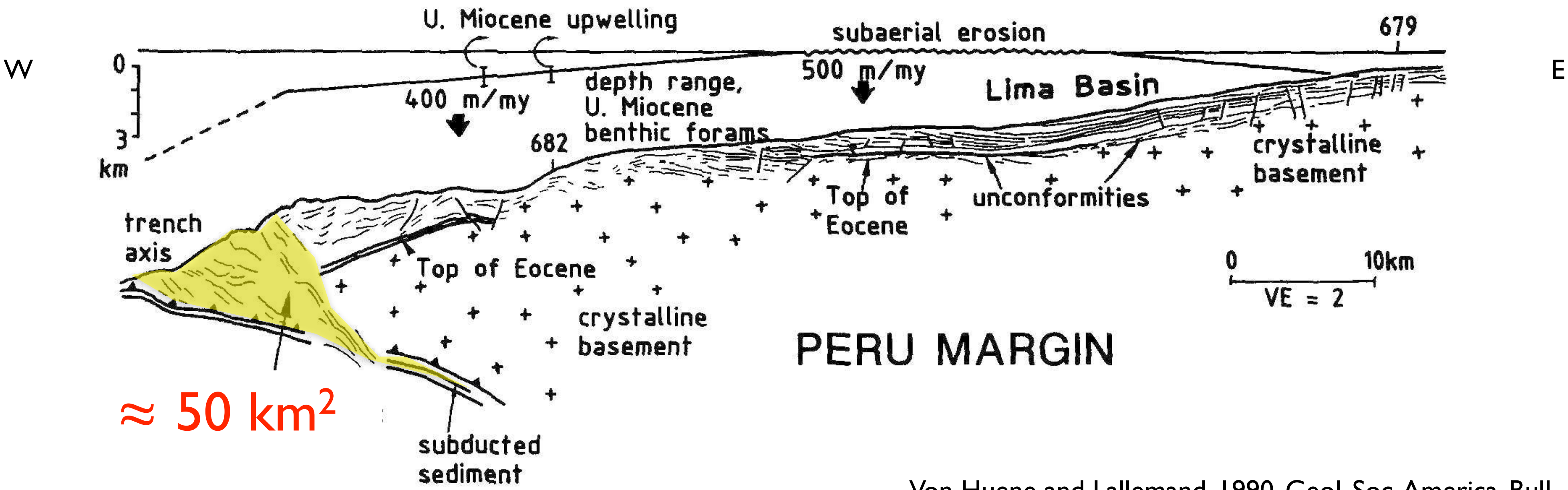
where h = incoming sediment thickness
v_c = convergence rate
t = time

Observed mass (in 2D): Surface of accreted sediment interpreted from seismic sections

$h = 1$km; $v_c = 10$ km/Ma (1cm/a); $t = 60$ Ma

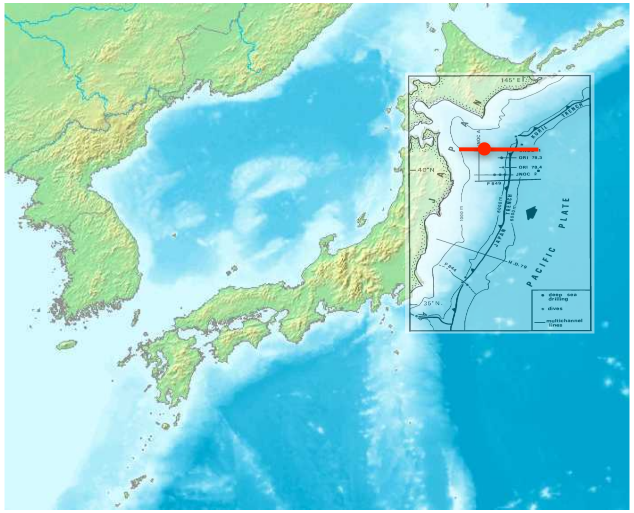
Expected cross section of prism: 600 km^2

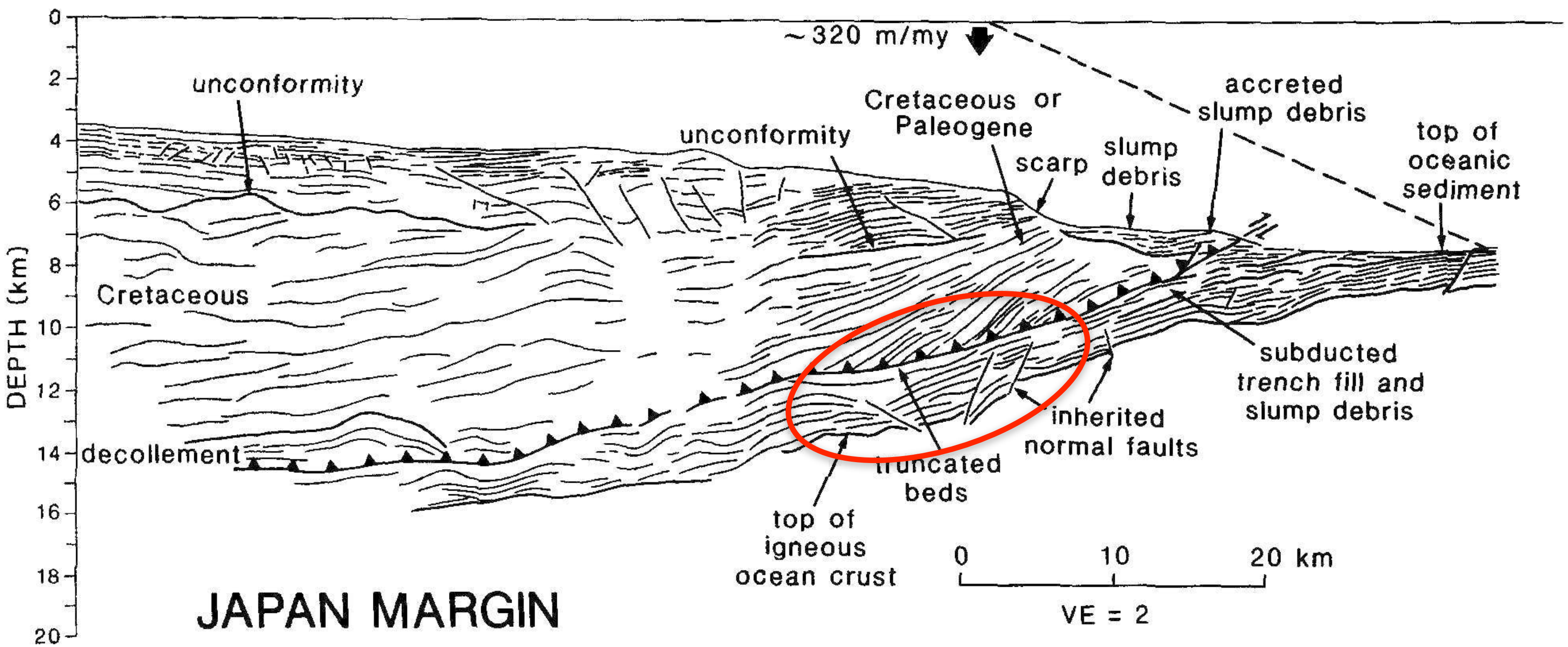
For $v_c = 100$ km/Ma (10cm/a); 6000 km^2



Von Huene and Lallemand, 1990, Geol. Soc. America, Bull

4- truncation of seismic reflector



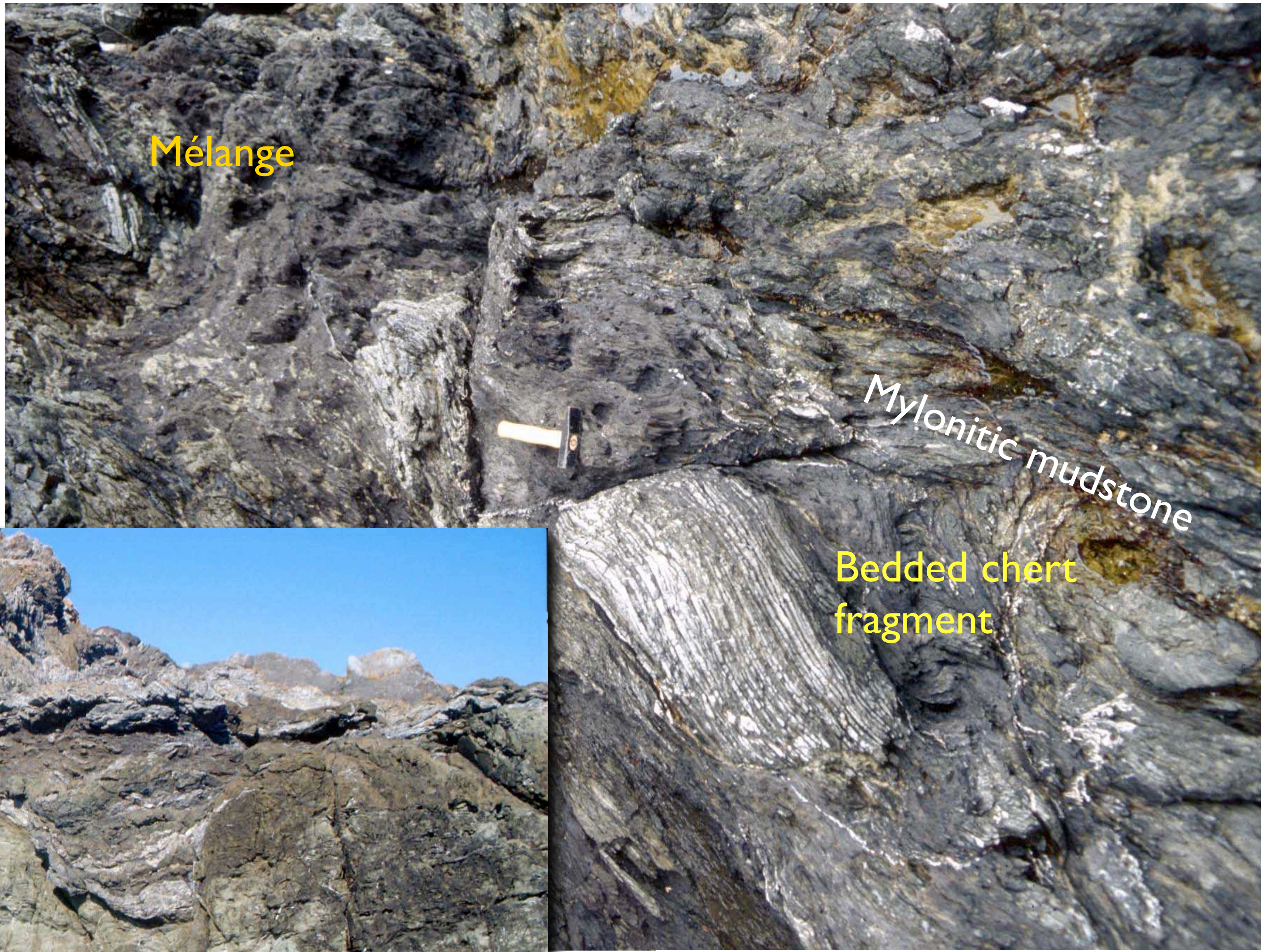


5- lithology


metasediment
serpentinite
http://complabs.nevada.edu/~jkula/Convergent/
crazy%2520melange

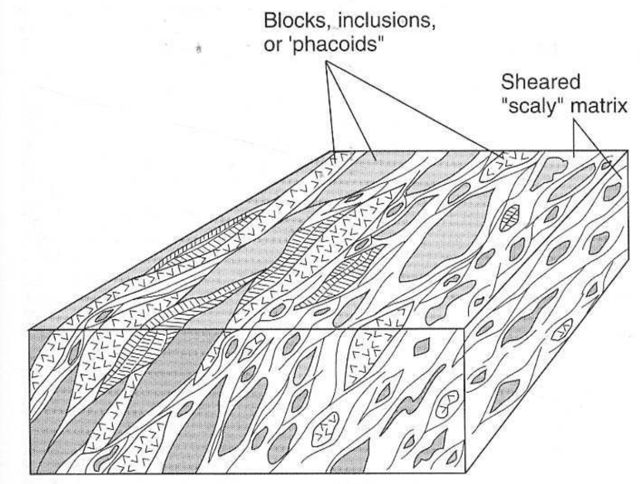

http://www.ugr.es/~agcasco/igcp546/Guate07/Guate_2007_Schedule.htm
#Stop_15:_Eclogites_and_blueschist_Belejey%C3%A1_

5- lithology



Mélange
Mylonitic mudstone
Bedded chert fragment

Mafic rock (ophiolite fragment)



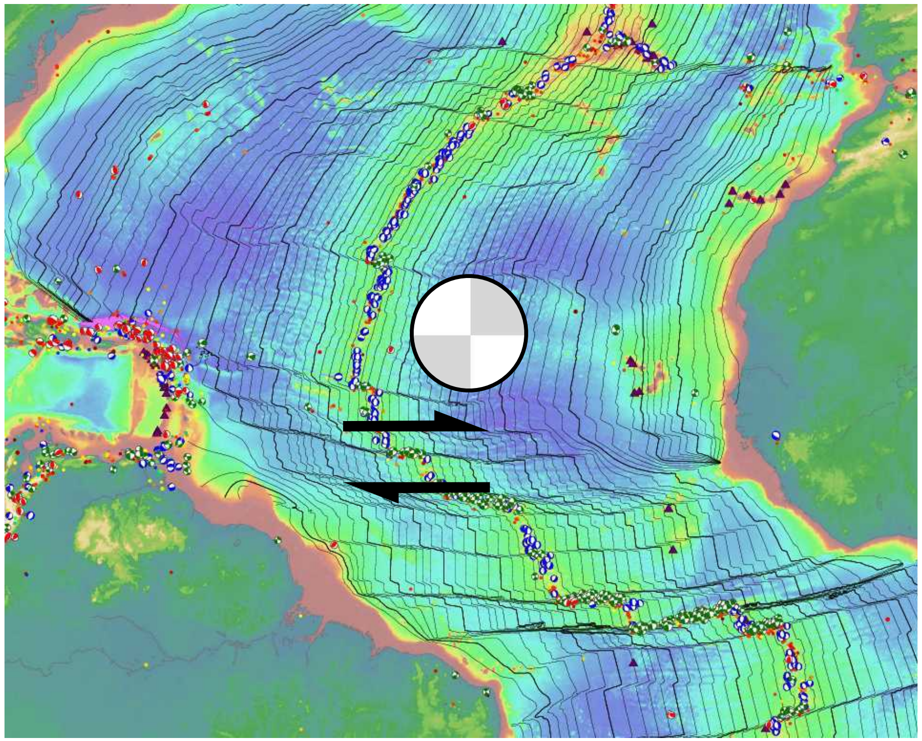
Blocks, inclusions, or 'phacoids'
Sheared "scaly" matrix

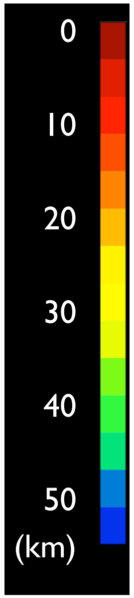
strike slip
geometry
kinematics

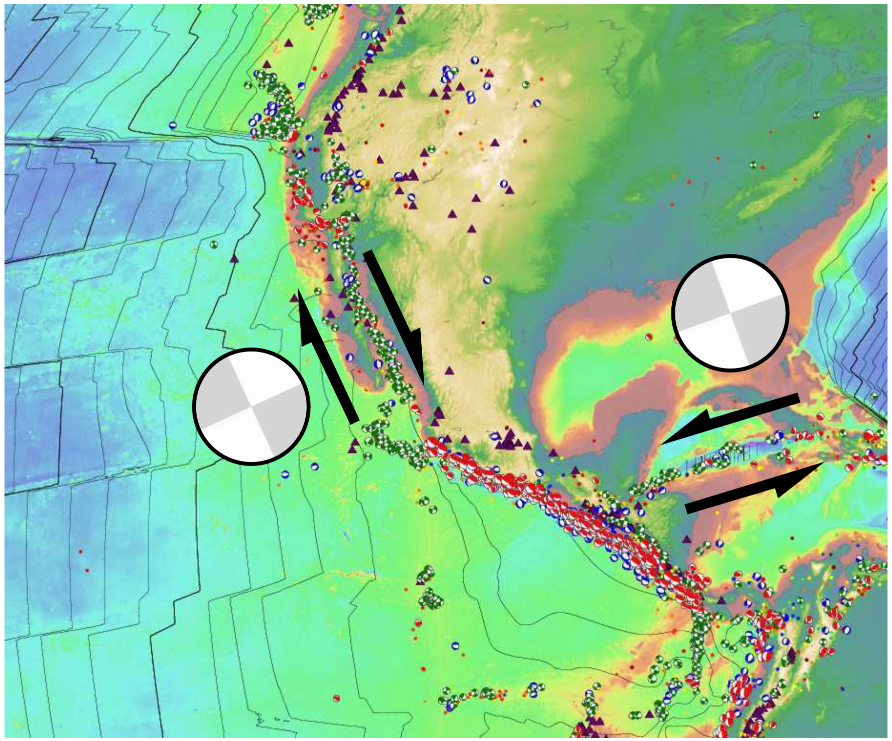
konservative Plattengrenze

Transform-Brüche:
Segmente von Platten-grenzen an mittelozeanischen Rücken

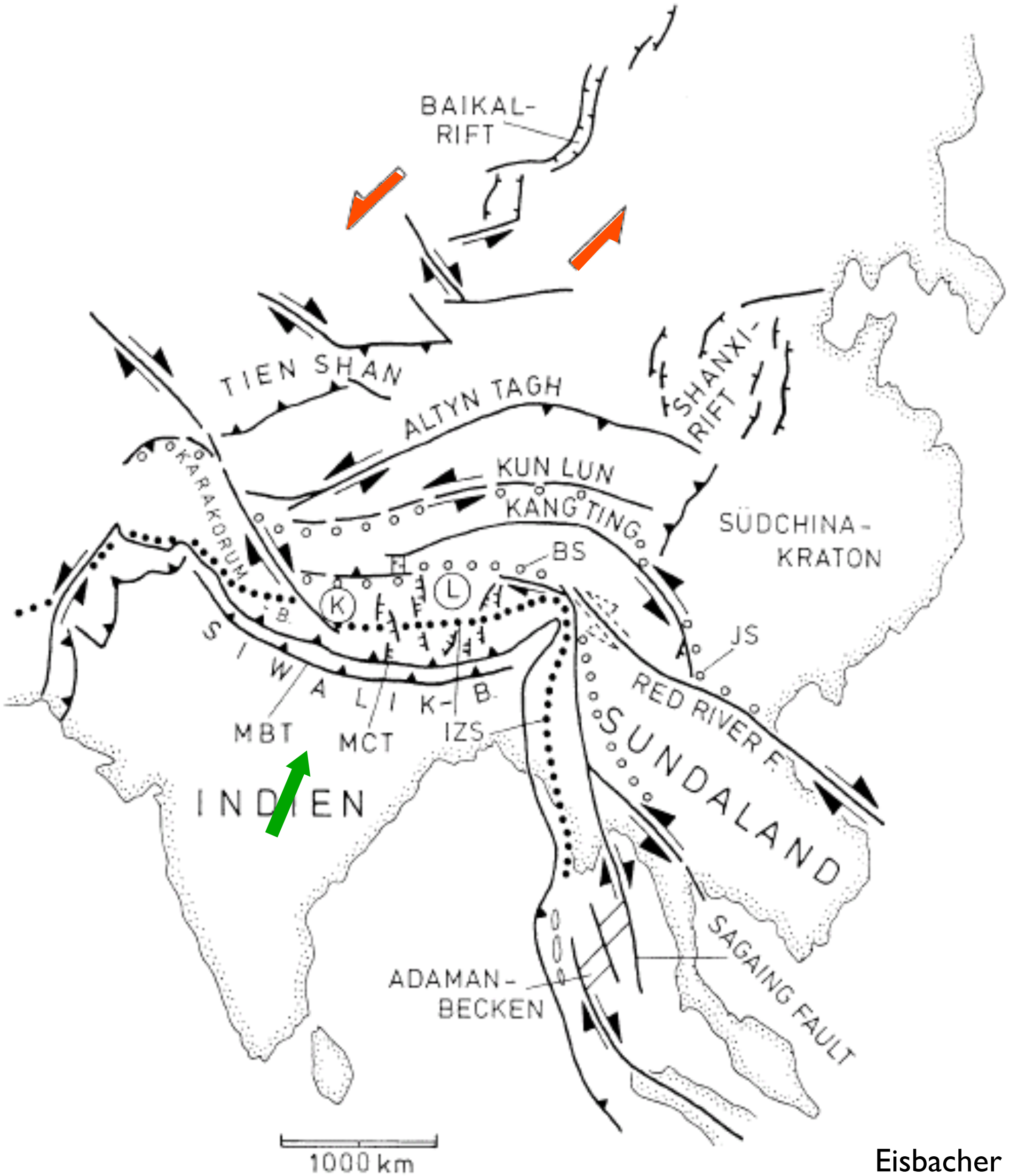
Transform Plattengrenzen:
Beispiel Kalifornien

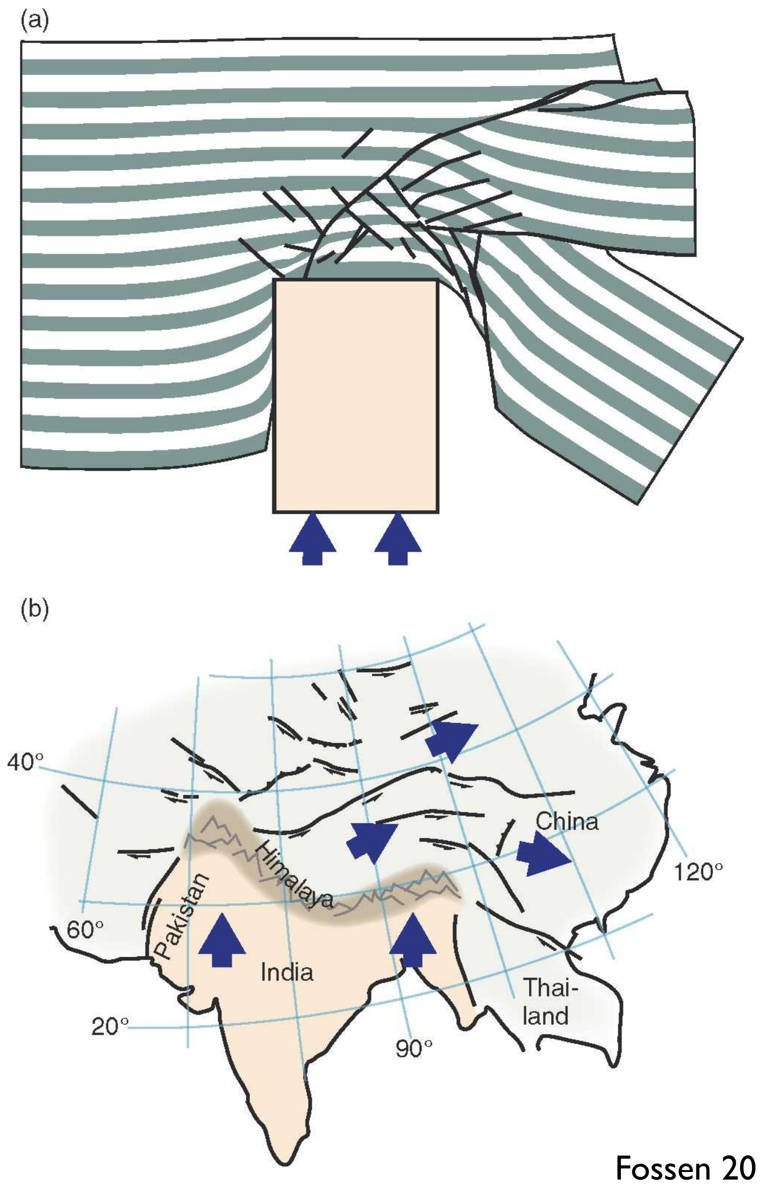






Intrakontinentale Blattverschiebungen





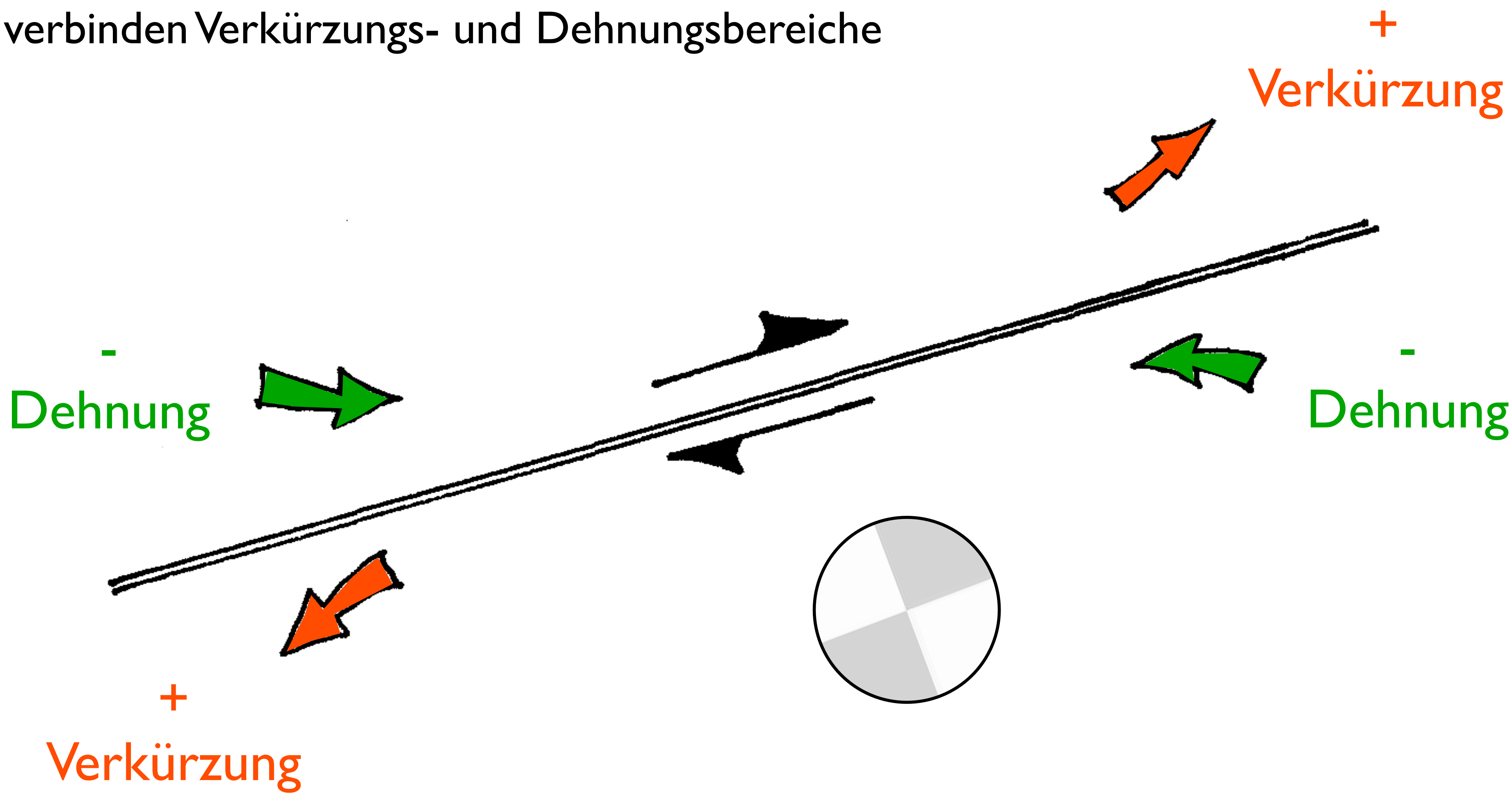
Fossen 2010

Eisbacher (1996) after Tapponnier et al. (1986)

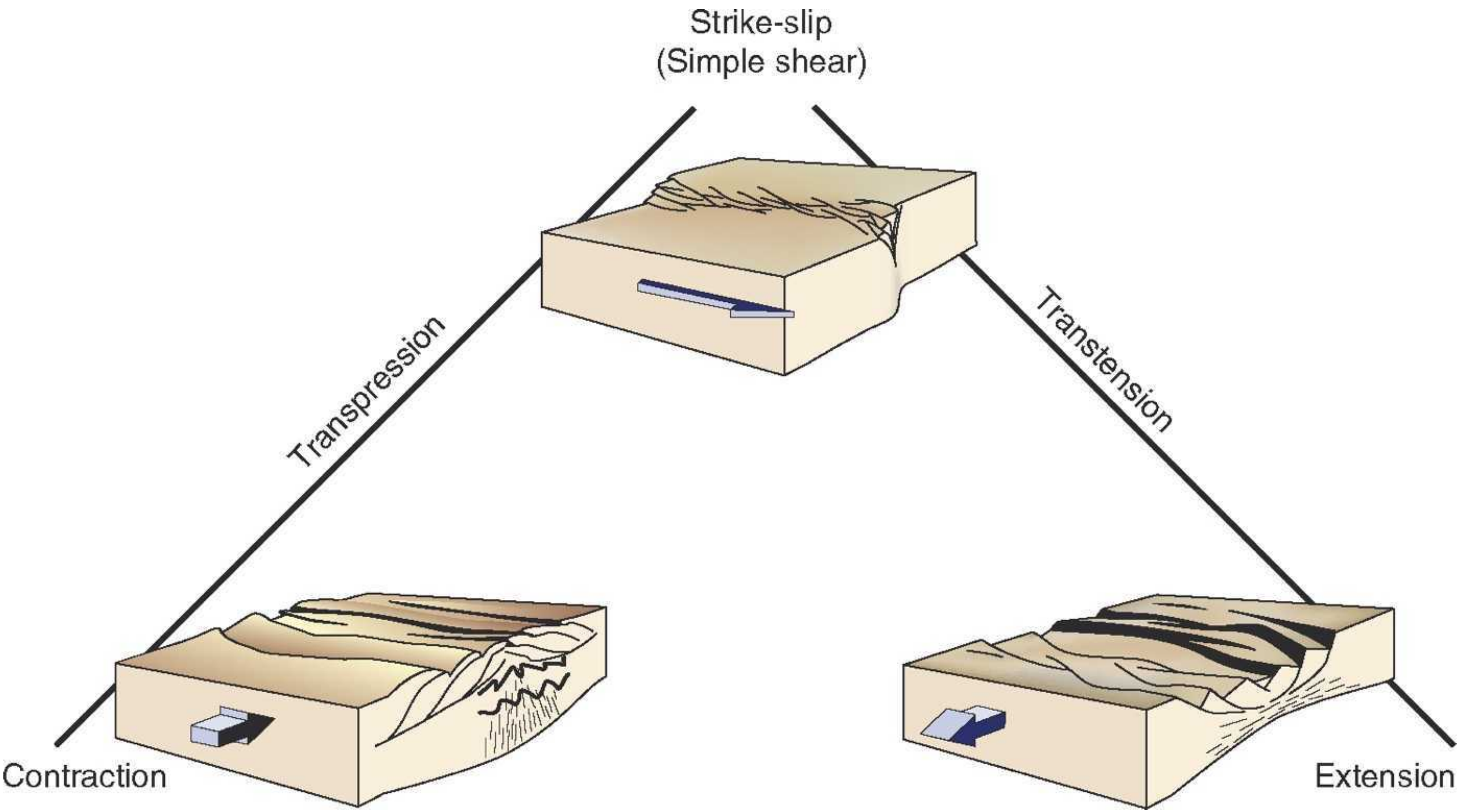
Transformsysteme

nehmen laterale Bewegungen parallel zu den Plattengrenzen auf
an Transformstörungen (transform faults)
an Blattverschiebungen (strike-slip faults, transcurrent faults)

verbinden Verkürzungs- und Dehnungsbereiche

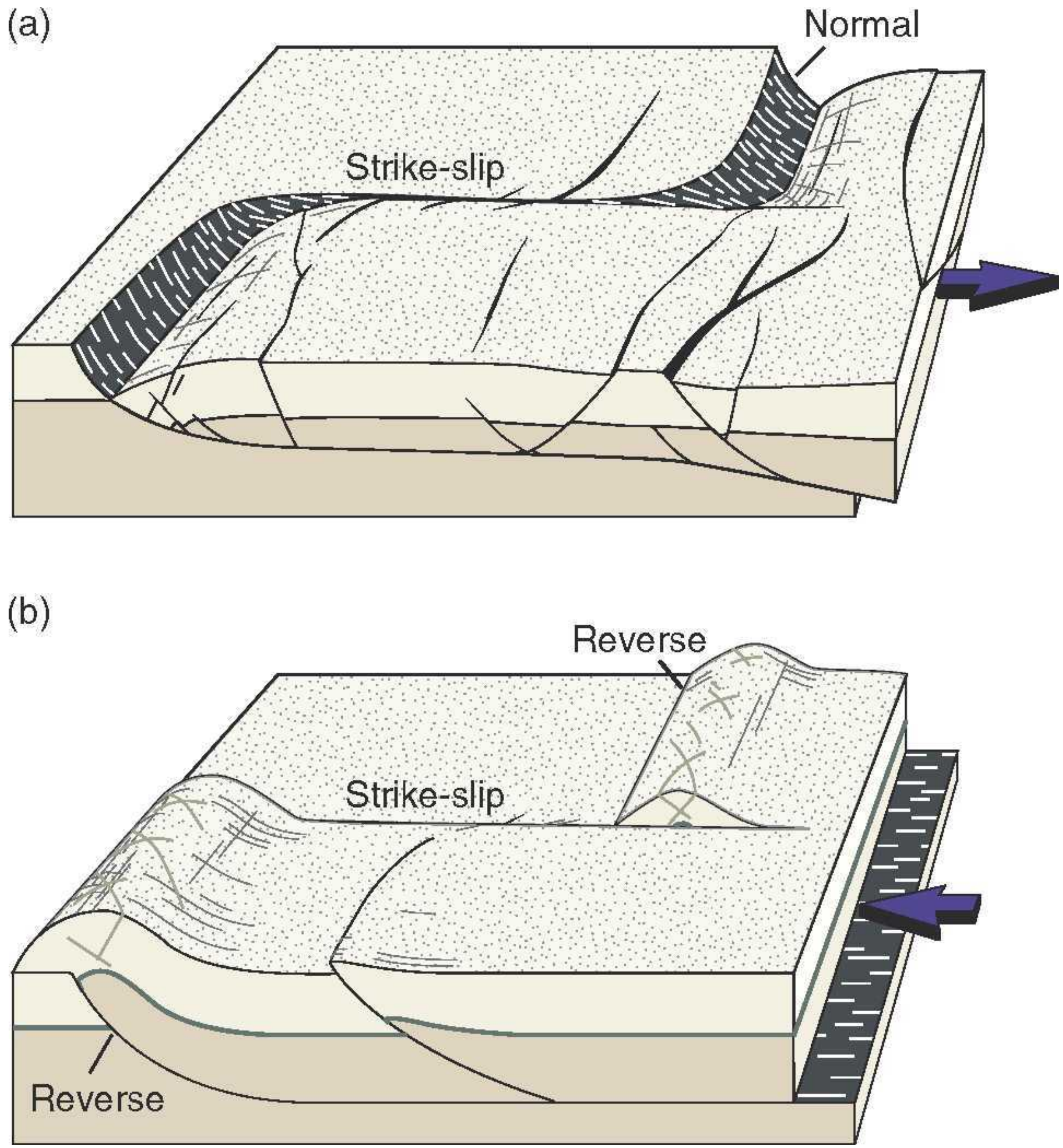


strike-slip & contaction / extension



Fossen 2010

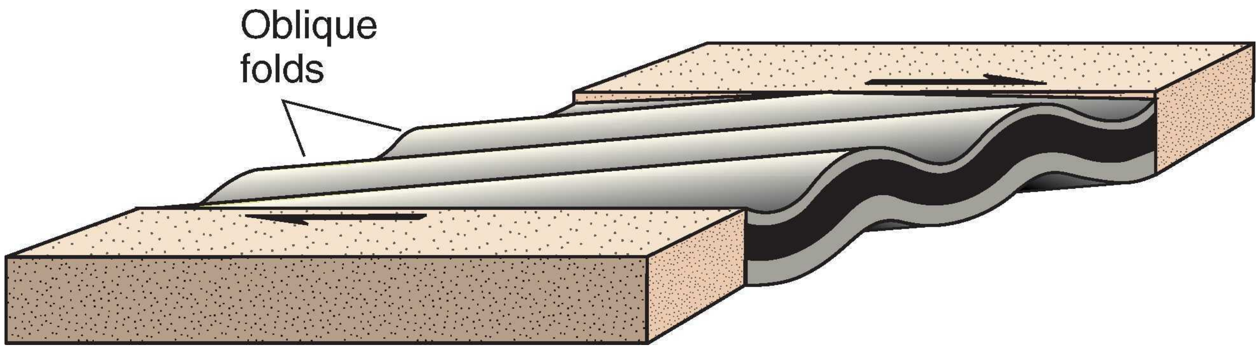
connecting strike-slip



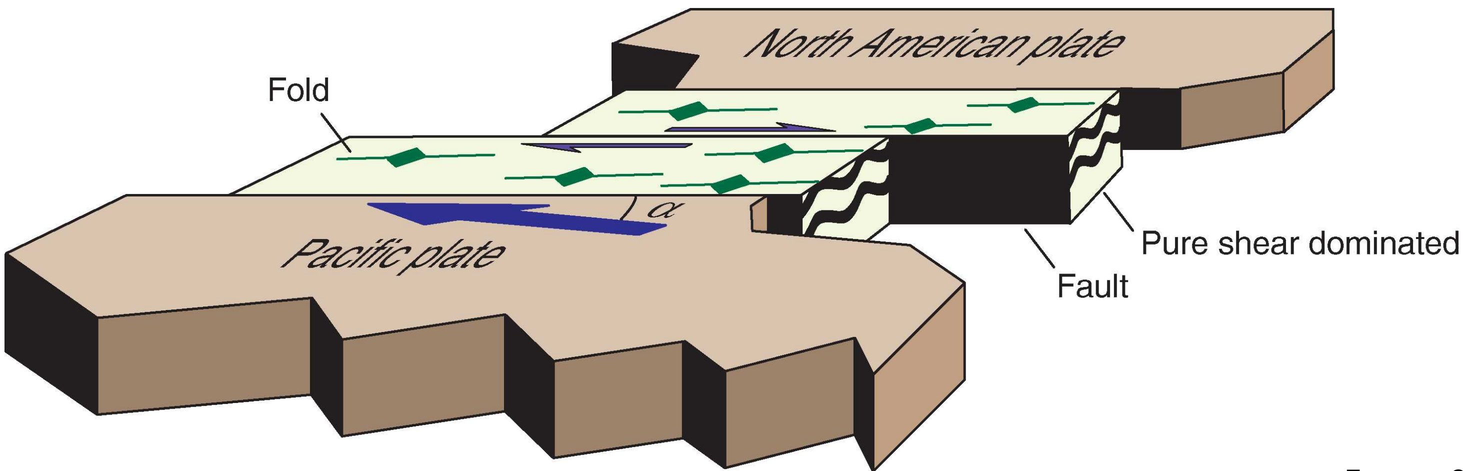
Fossen 2010

strike-slip & folding

If deformation occurs by non-brittle mechanisms, folding may accompany strike slip faulting

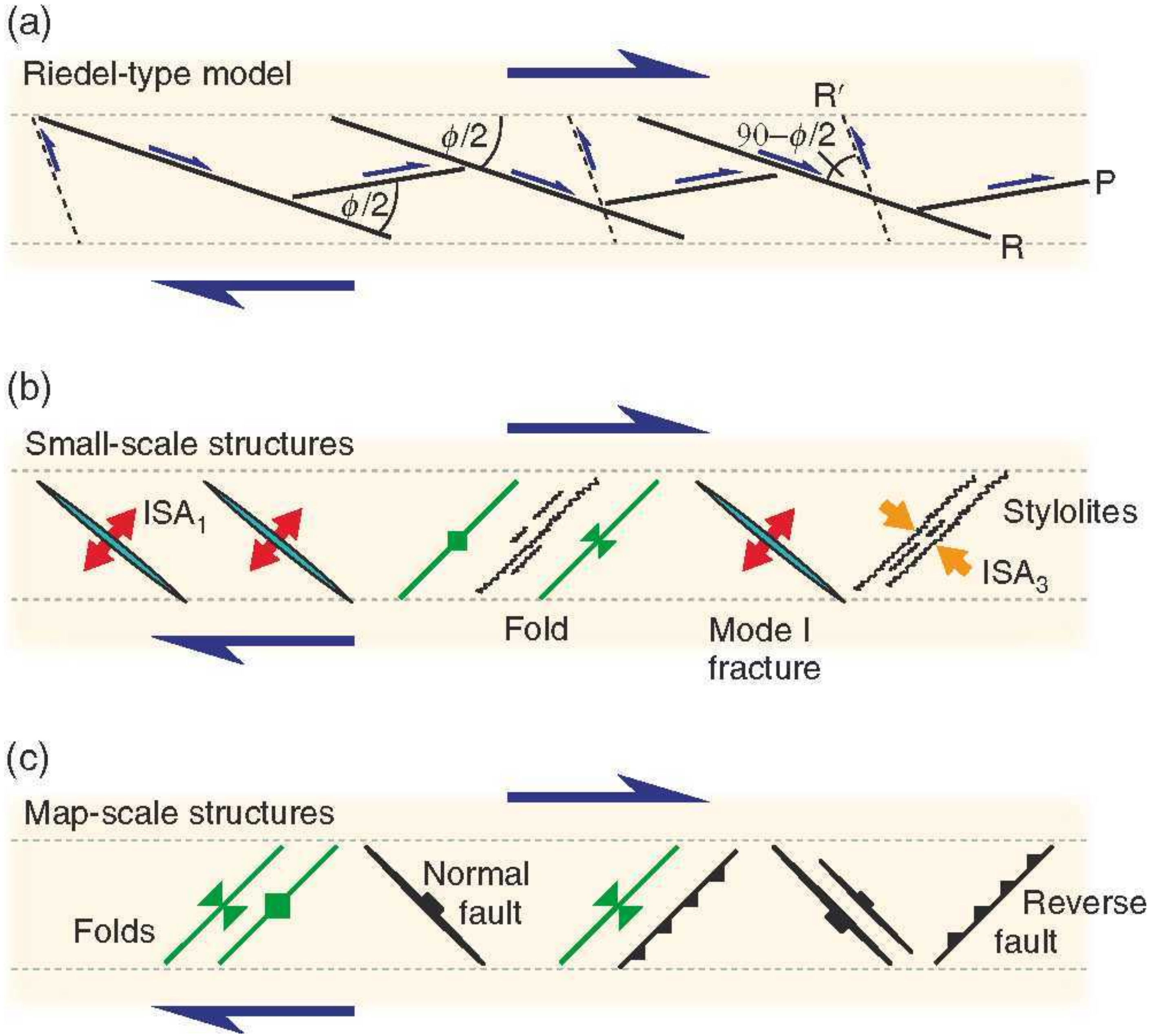


Strain partitioning can lead to fold patterns which are not oblique to simple shear zone boundaries



Fossen 2010

transfer system geometry

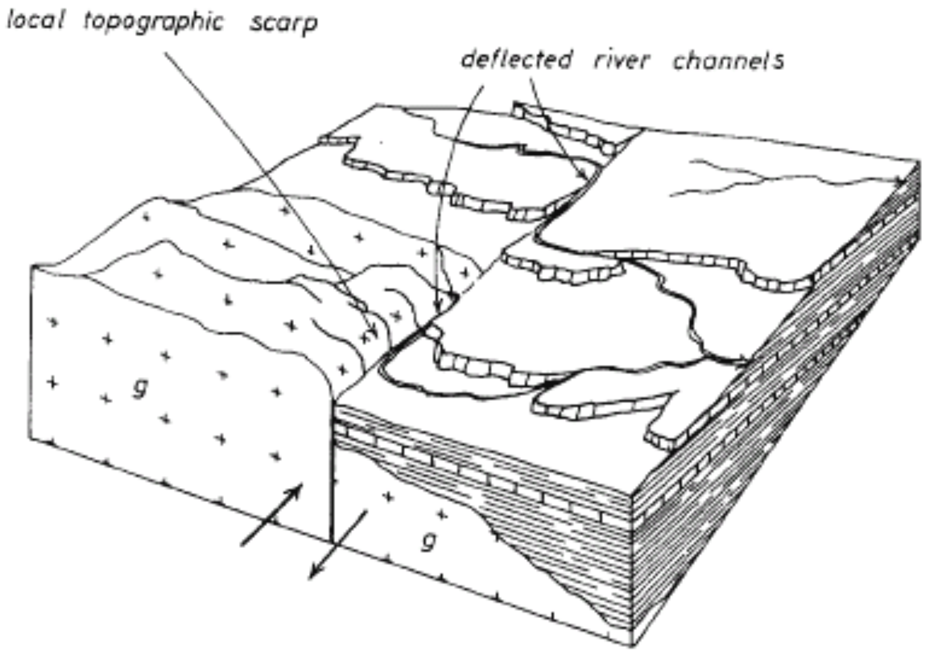


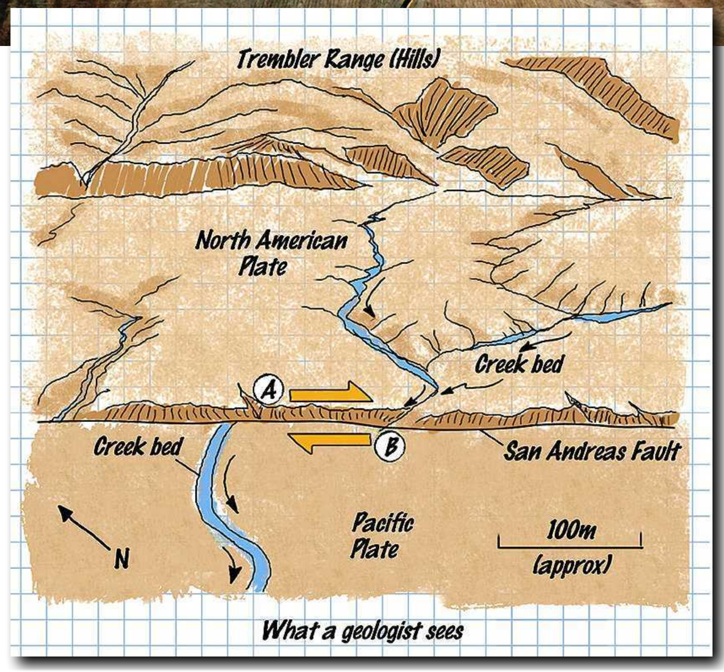
micro

meso

macro

Geomorphologie von strike-slip

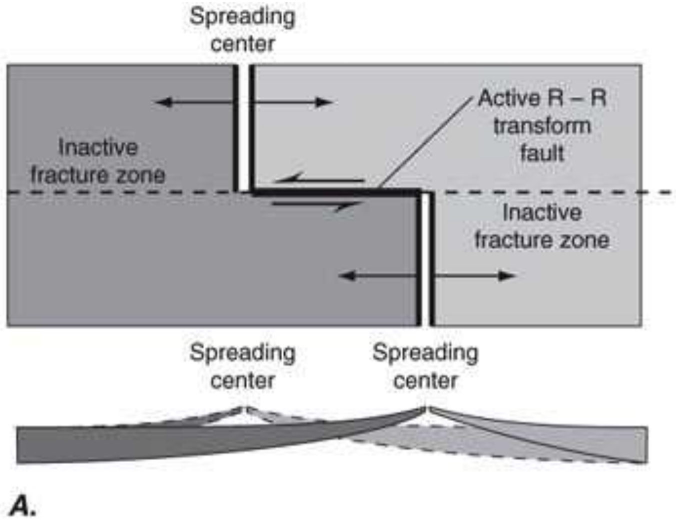




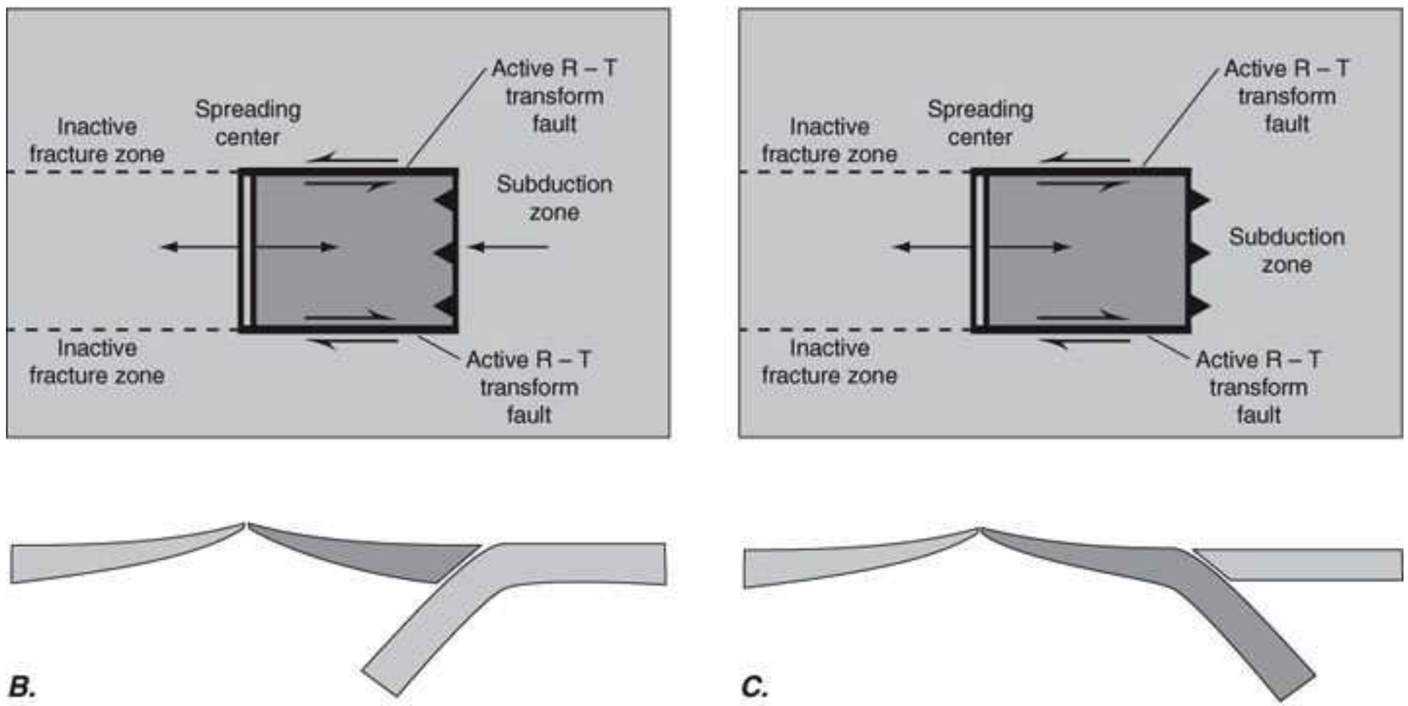
transform systems

Transformsysteme

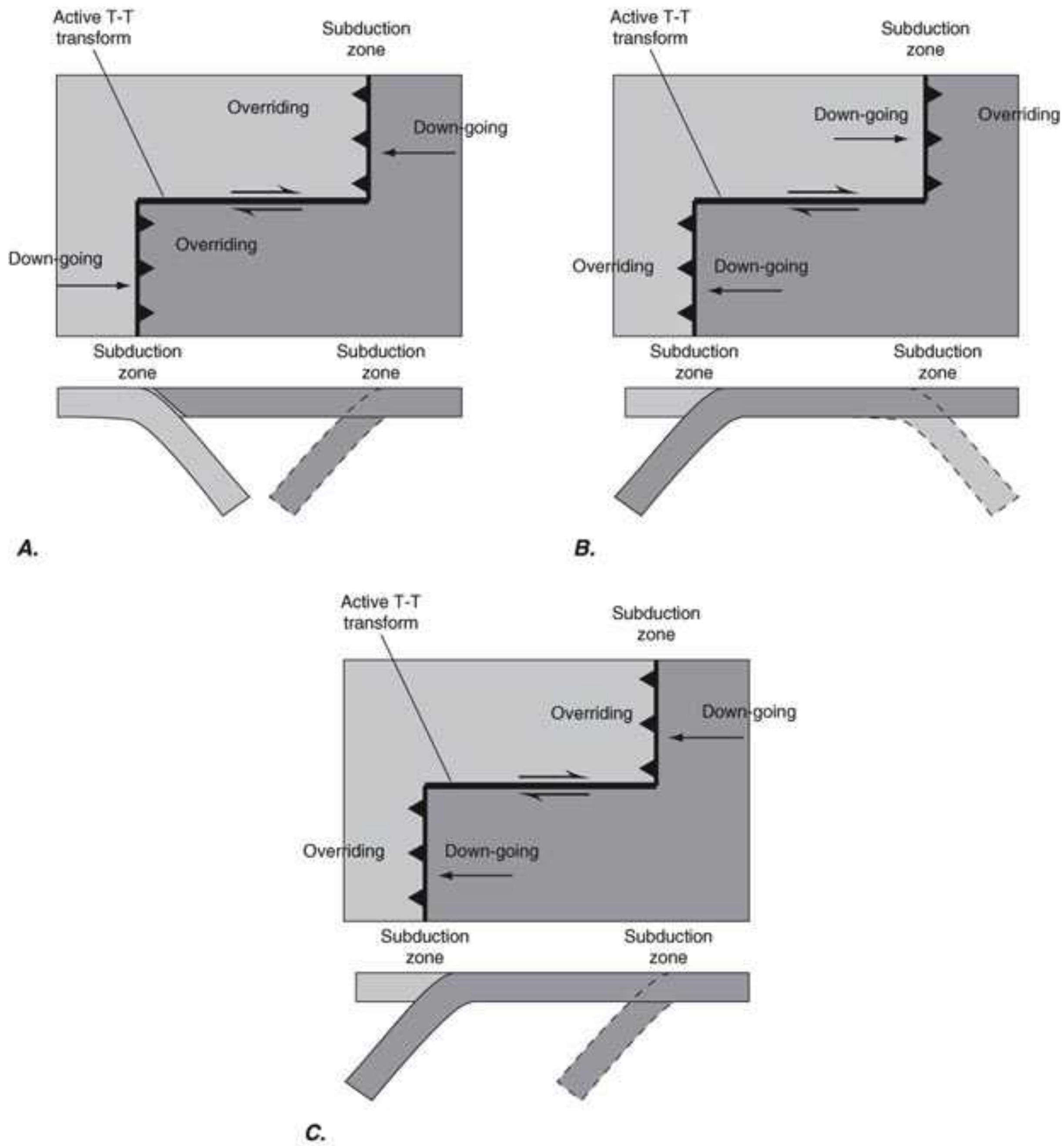
ridge-ridge



ridge-trench

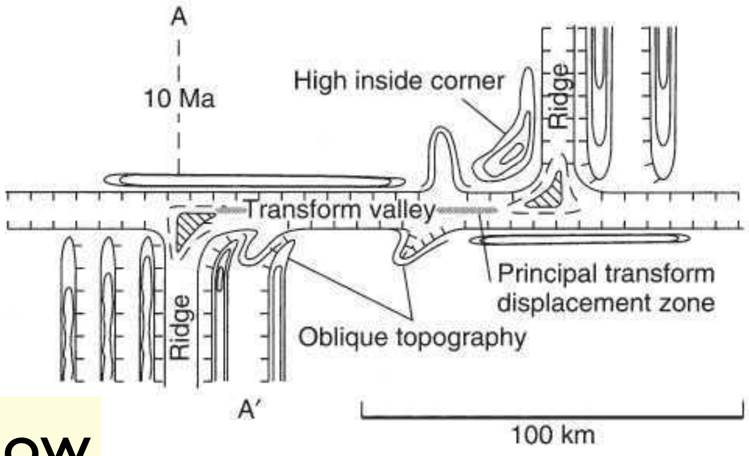


Transformsysteme



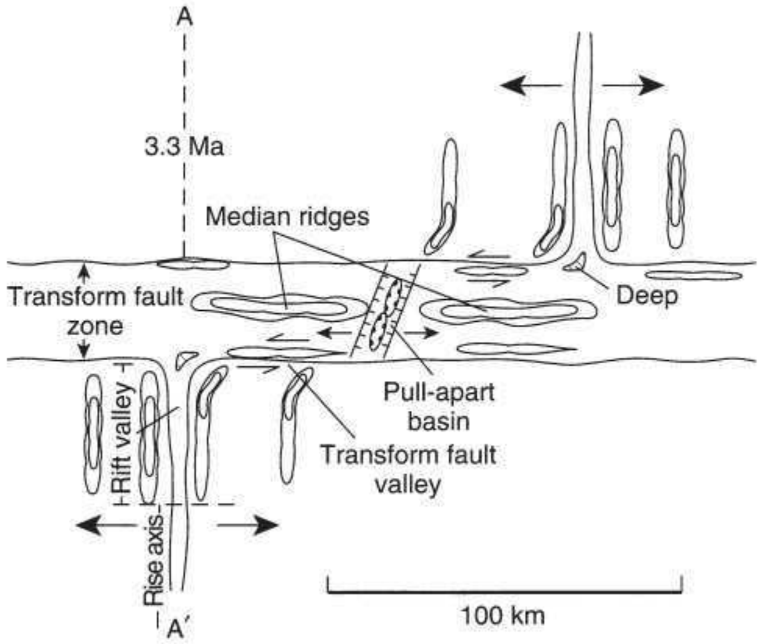
trench-trench

Transformsysteme



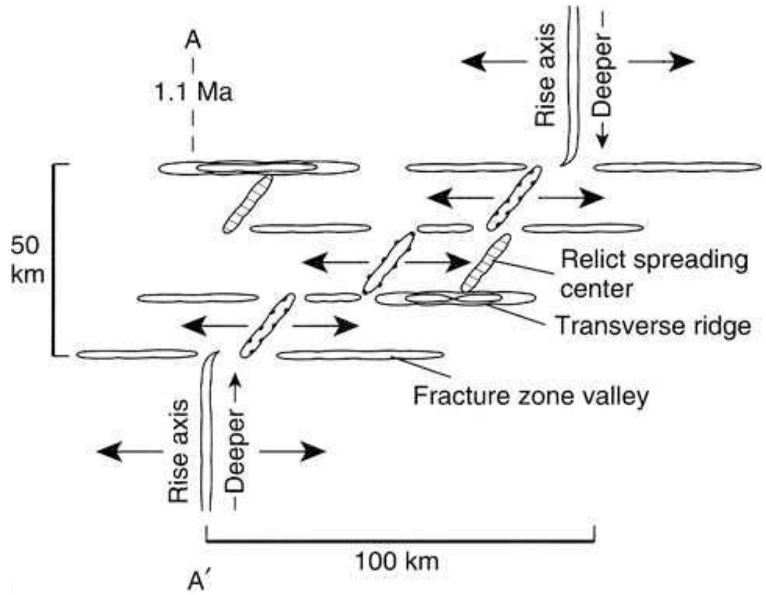
slow

< 5 cm / a



intermediate

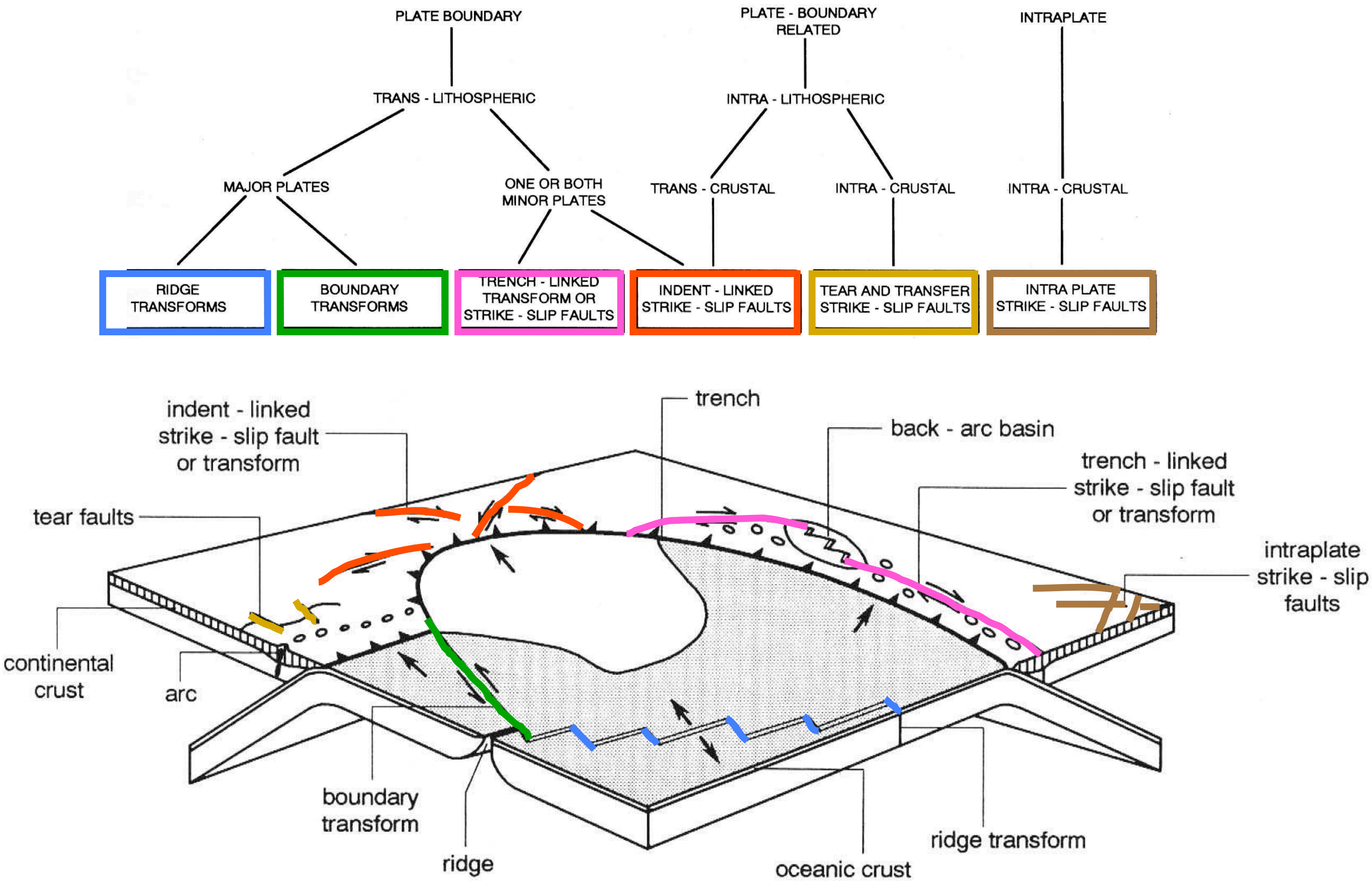
5 - 9 cm / a



fast

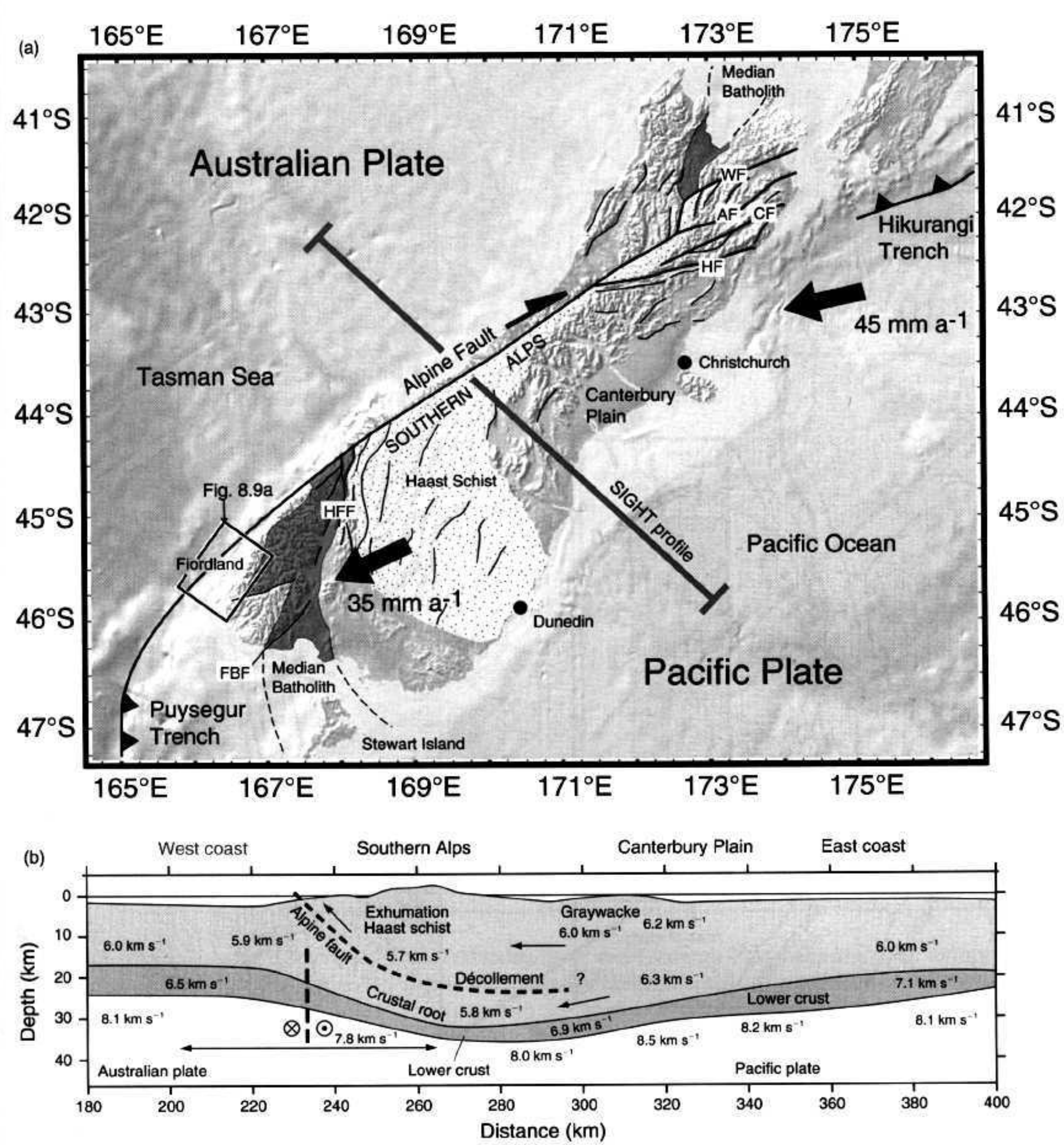
9 - 18 cm / a

Typen von Transformsystemen



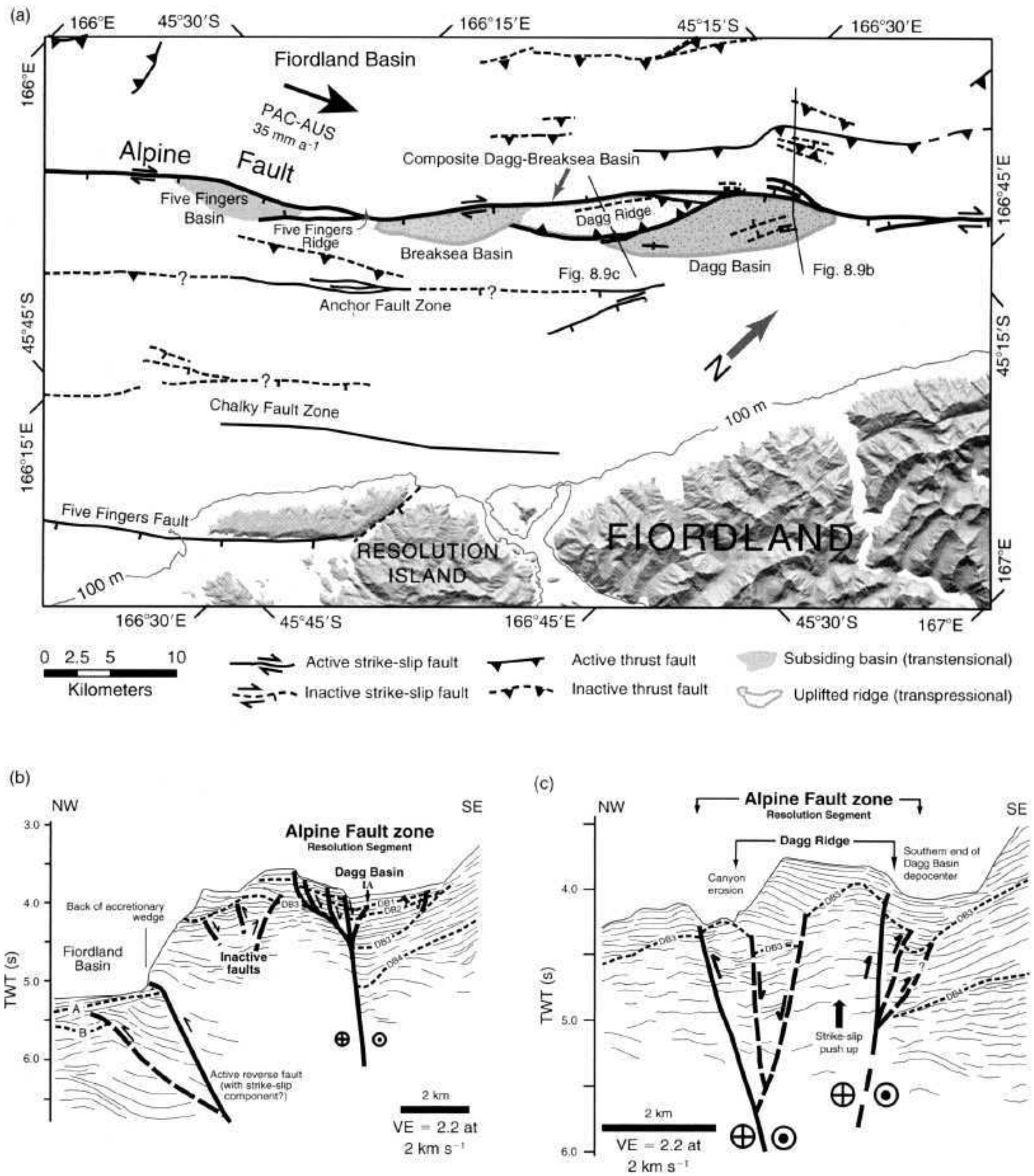
examples

Alpine Fault, New Zealand



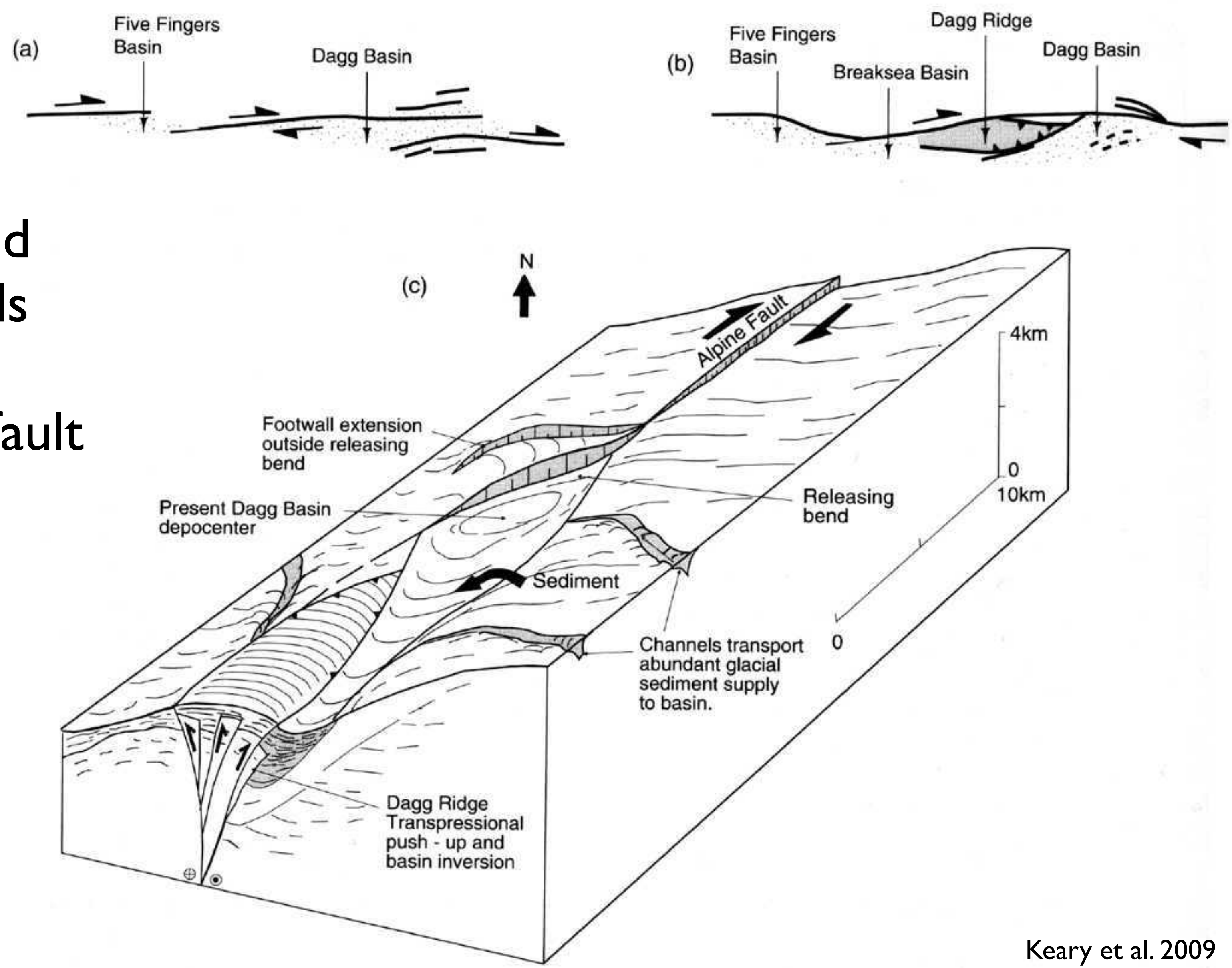
Keary et al. 2009

Alpine Fault, New Zealand



Keary et al. 2009

Alpine Fault, New Zealand

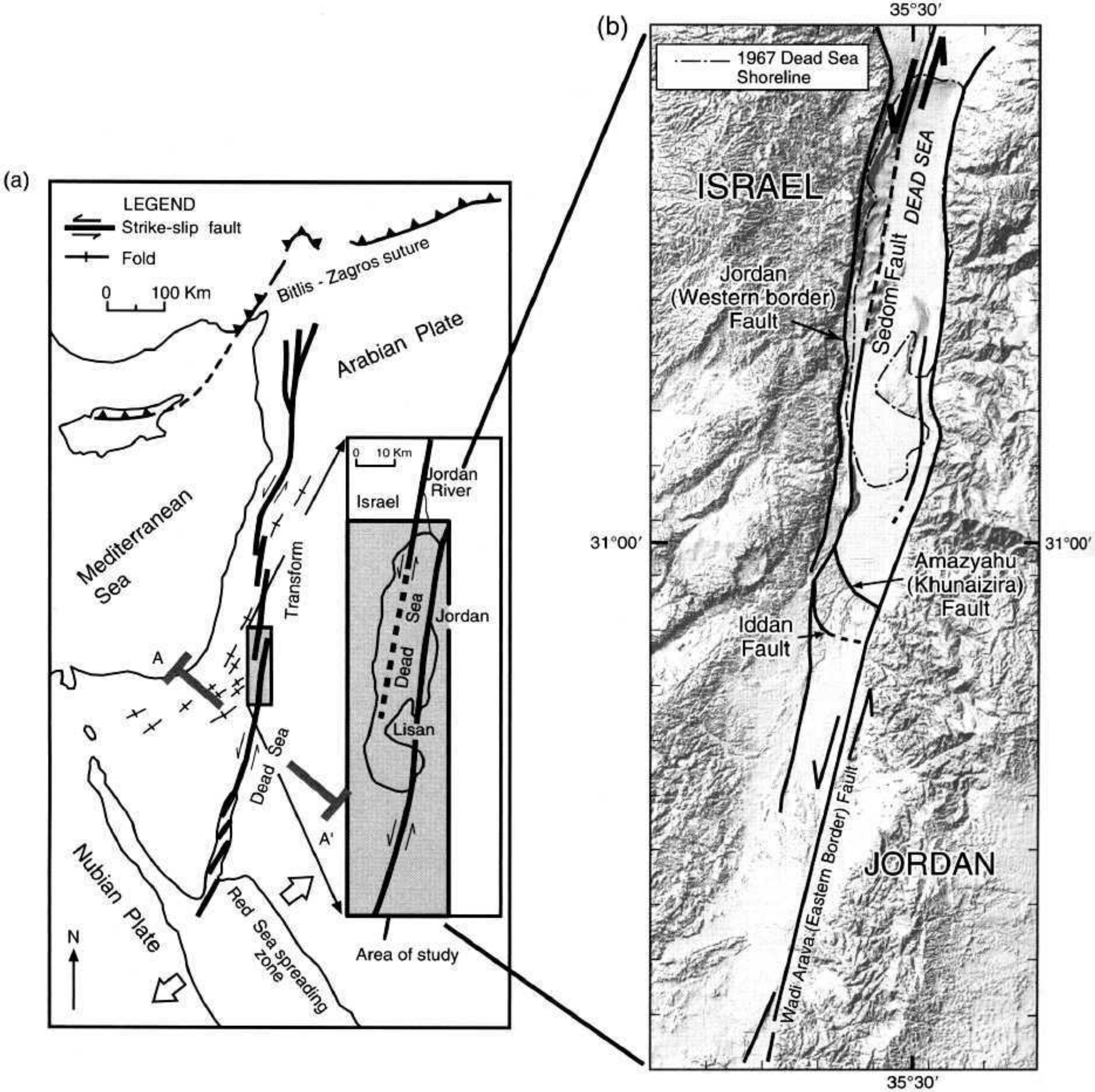


Restraining and releasing bends change along length of the fault

Keary et al. 2009

Dead Sea Transform

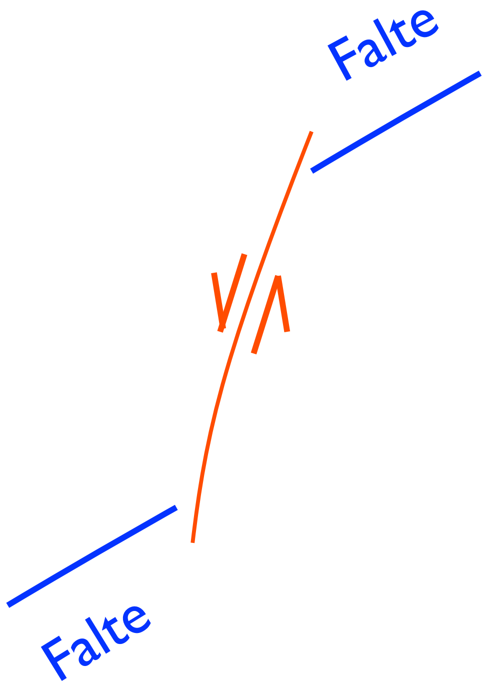
Dead Sea Transform, produces large depression (= Dead Sea) as a pull-apart-basin



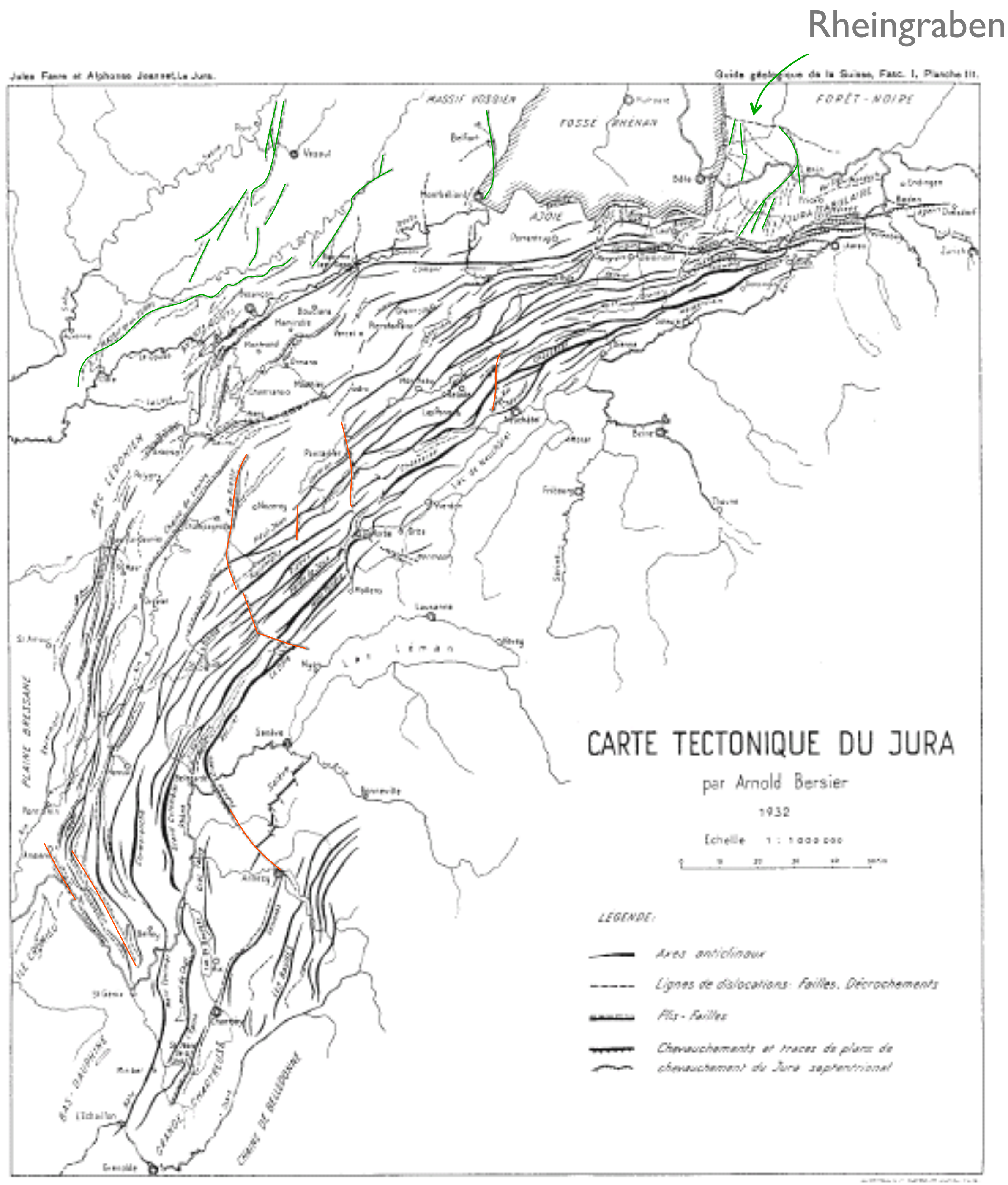
Rhein - Bressegraben Transferzone

transfer zone

Jura



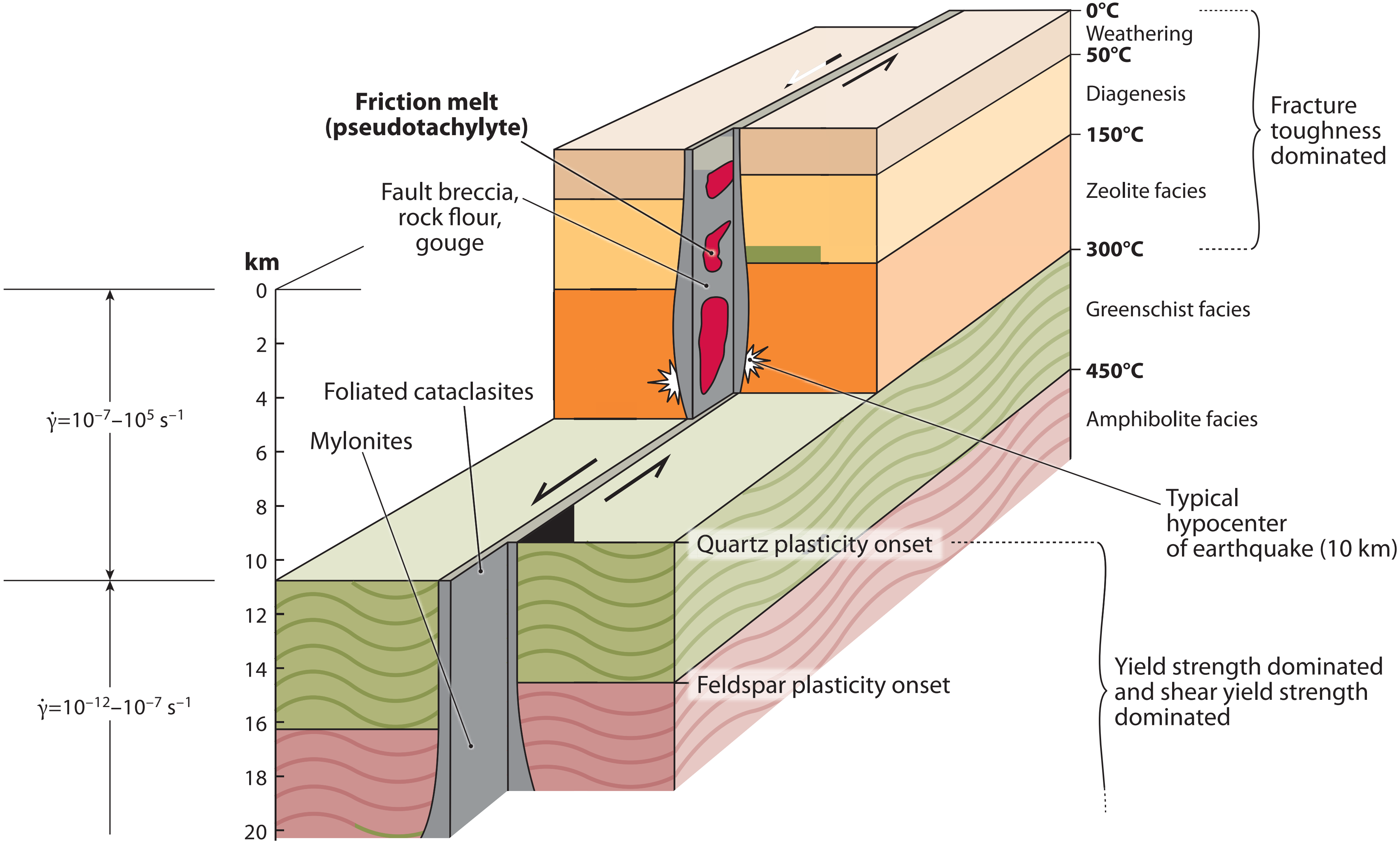
Falte
Falte



Rheingraben
Jules Favre et Alphonse Jeannet, Le Jura.
Guide géologique de la Suisse, Fasc. I, Planche III.
MASSIF VOSGIEN
FOSSE RHENAN
FORÊT - NOIRE
AJOIE
JURA TABULAIRE
ARC LEDONIEN
PLAINE BRESSANE
Lac Léman
CHAINE DE BELLEDONNE
CARTE TECTONIQUE DU JURA
par Arnold Bersier
1932
Echelle 1 : 1 000 000
LEGENDE:
Axes anticlinaux
Lignes de dislocations: Failles, Décrochements
Plis - Failles
Chevauchements et traces de plans de chevauchement du Jura septentrional

active faults

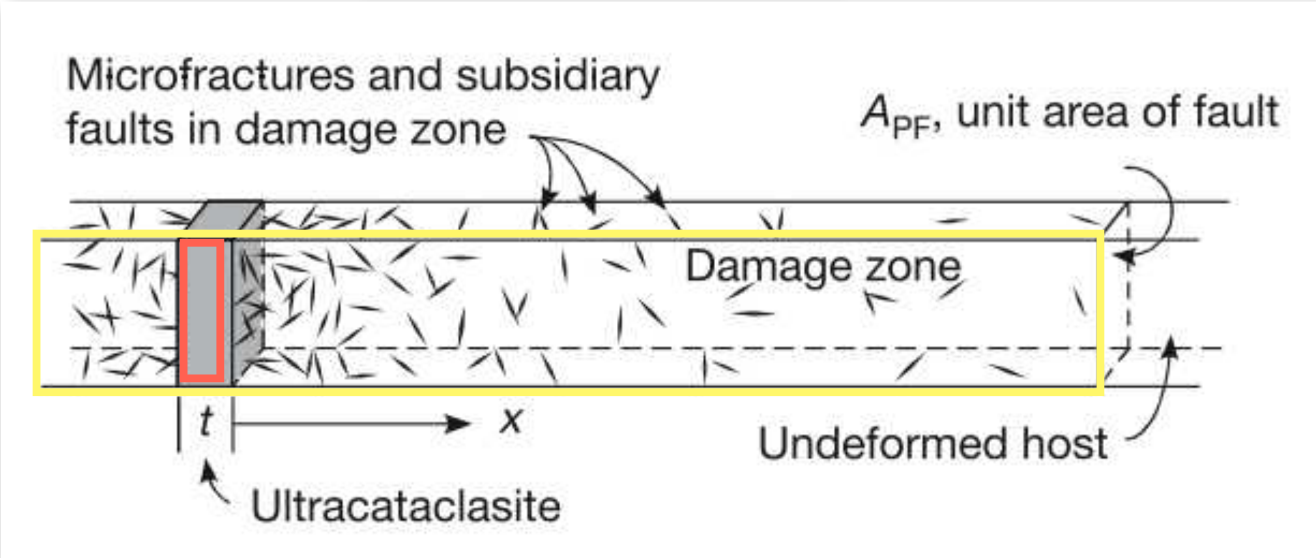
active faults



Spray, Ann.Rev. Earth Pl. Sci., 2010

fault architecture & spatial localization

$\dot{\gamma} \approx 10^{-14}\ s^{-1}$

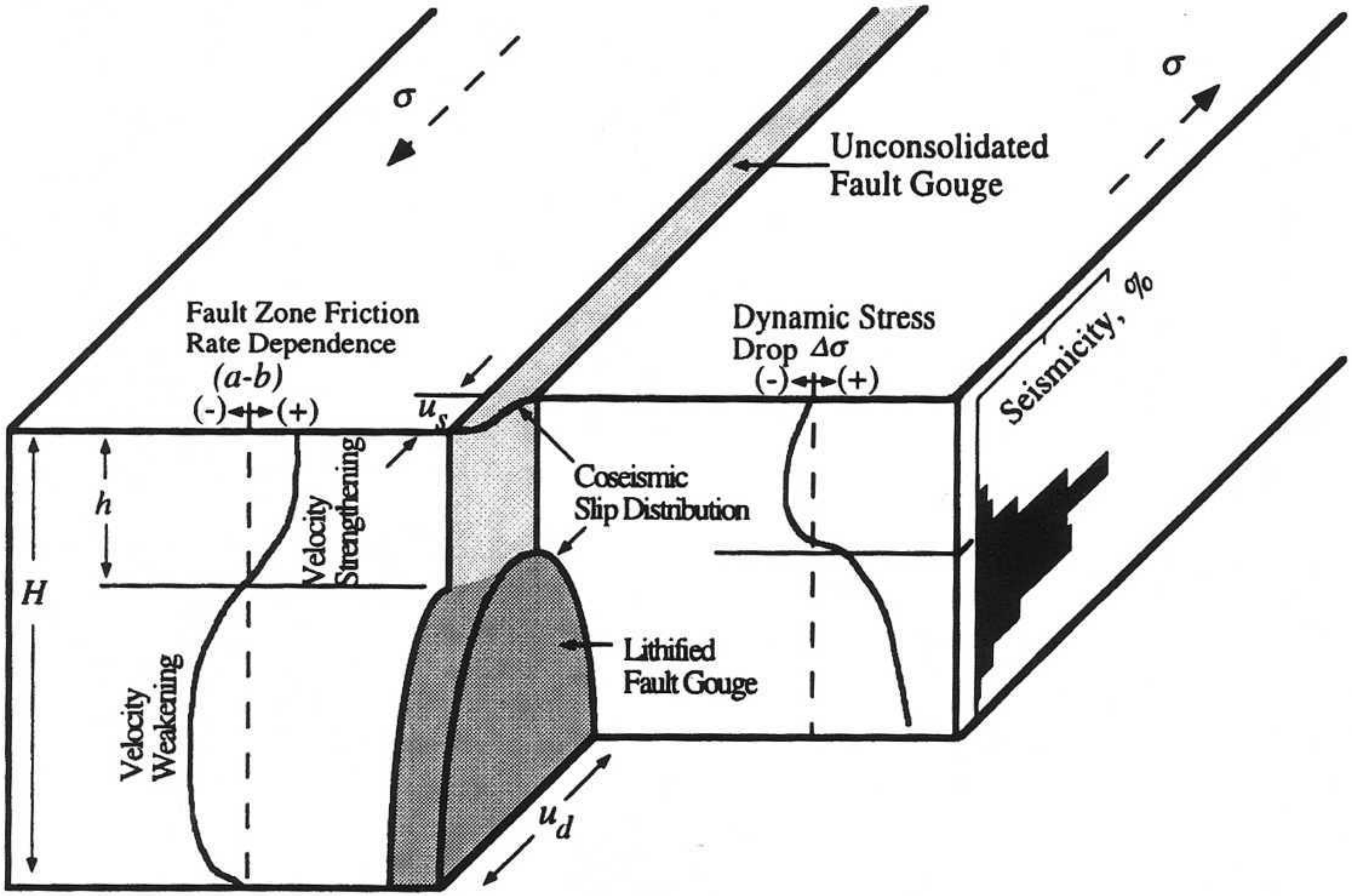


Chester et al. 2005, Nature 437, p.133

100km → 100m
(factor 10^3)
$\Rightarrow \dot{\Upsilon} = 10^{-11}\ s^{-1}$

100km → 1mm
(factor 10^8)
$\Rightarrow \dot{\Upsilon} = 10^{-6}\ s^{-1}$

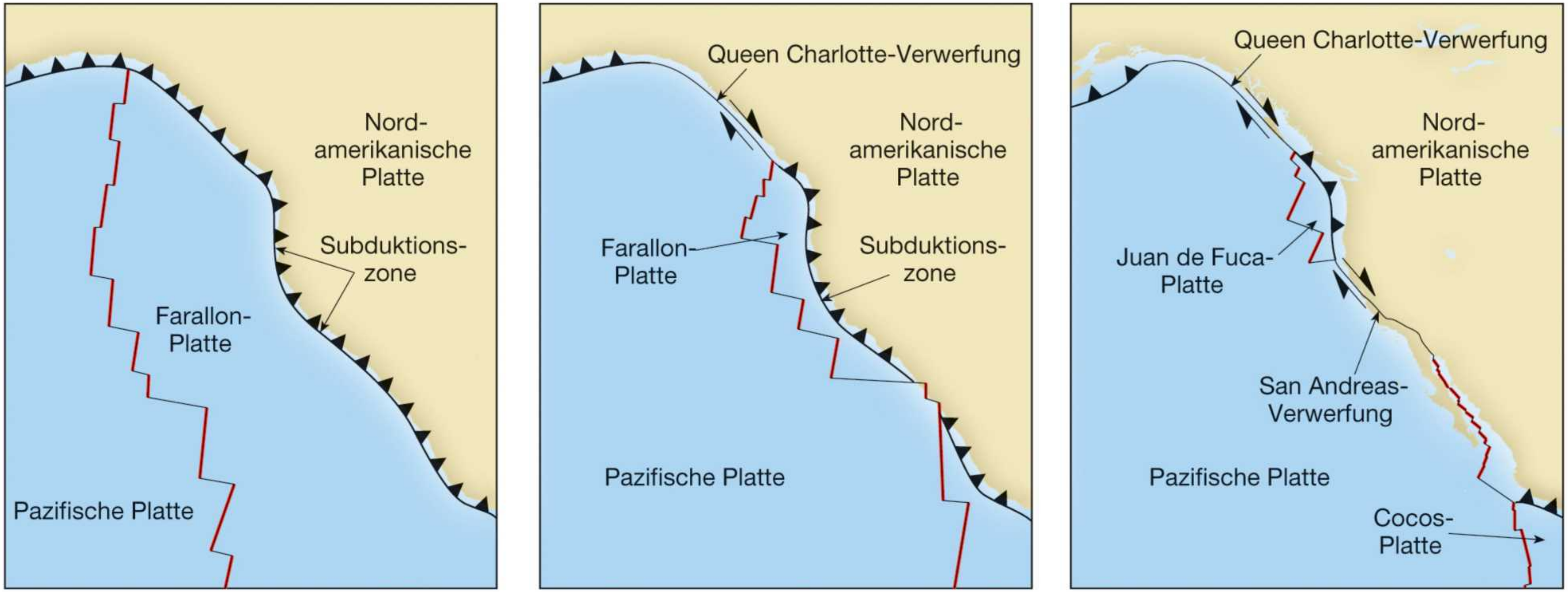
seismic fault model



Marone, AnnRev EPSL, 1998

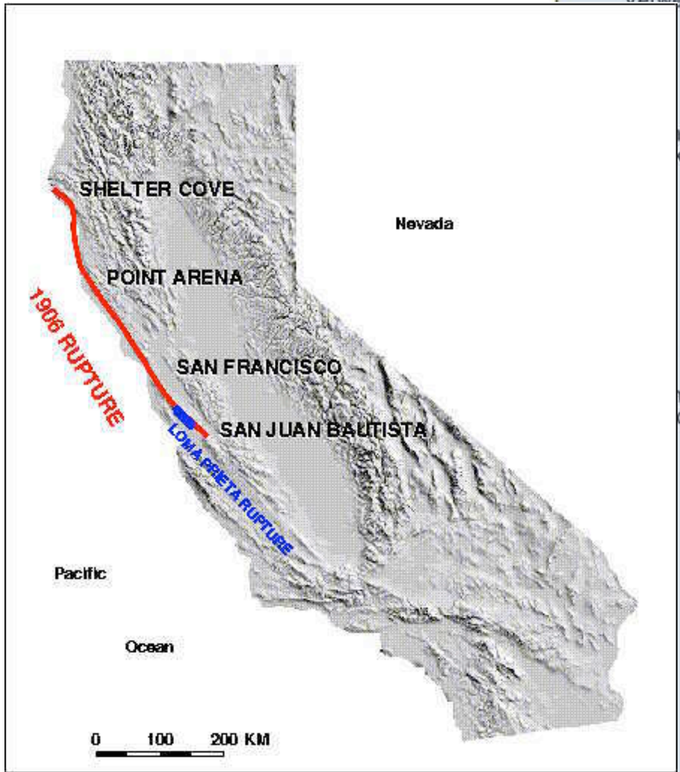
San Andreas Fault

San Andreas Fault



A. Vor 56 Millionen Jahren **B.** Vor 37 Millionen Jahren **C.** Heute

Average relative velocity between North American and Pacific plate = 48-50 mm/a


SHELTER COVE
Nevada
POINT ARENA
1906 RUPTURE
SAN FRANCISCO
SAN JUAN BAUTISTA
LOMA PRIETA RUPTURE
Pacific
Ocean
0 100 200 KM


Alaska
Kanada
Aleuten-Überschiebung
Queen
Charlotte-
Verwerfung
de Fuca-
ken
Nord-
amerikanische
Platte
ndocino-
chzone
San Andreas-Verwerfung
Pazifische
Platte
Vereinigte Staaten
Golf von
Kalifornien
Mexiko
Rivera-Verwerfung
Ostpazifischer
Rücken
Cocos-Platte
Motagua-
Verwerfung
Karibische
Platte
Mittelamerikanische
Überschiebung
Kalifornien
San
Francisco
Hayward-
Verwerfung
Calaveras-
Verwerfung
San
Andreas-
Verwerfung
Garlock-
Verwerfung
Los Angeles
San Jacinto-Verwerfung
Elsinore-Verwerfung
Coyote Cree-Verwerfung
Imperial-Verwerfung

San Andreas Fault

Heat flow

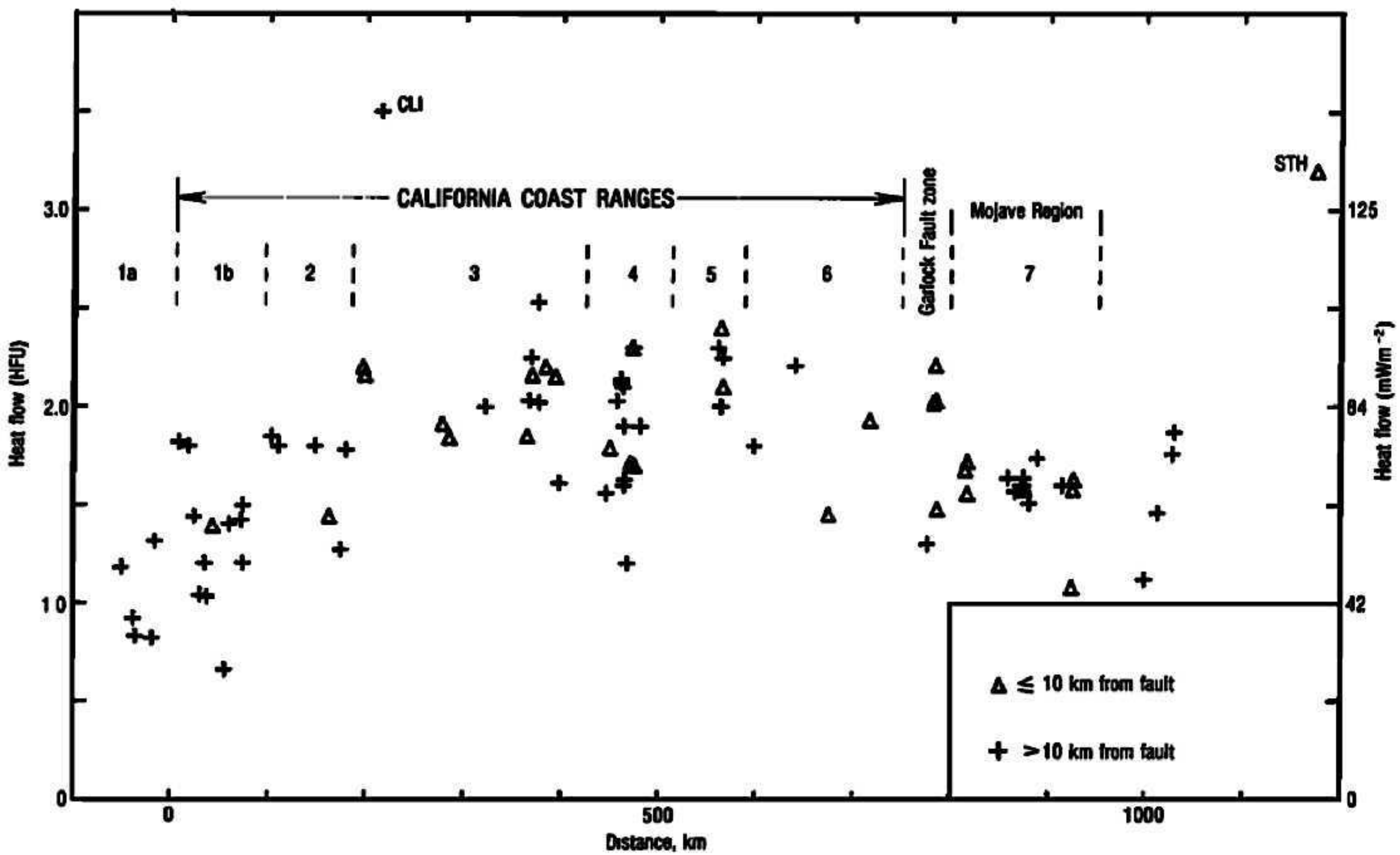


Fig. 12. Heat flow, projected on to the main trace of the San Andreas fault, as a function of distance from Cape Mendocino (CM, Figure 8). Regions are as defined in Figure 8. Points in Great Valley (stippled, Figure 8) were excluded.

Lachenbruch & Sass 1980

San Andreas Fault

Heat flow

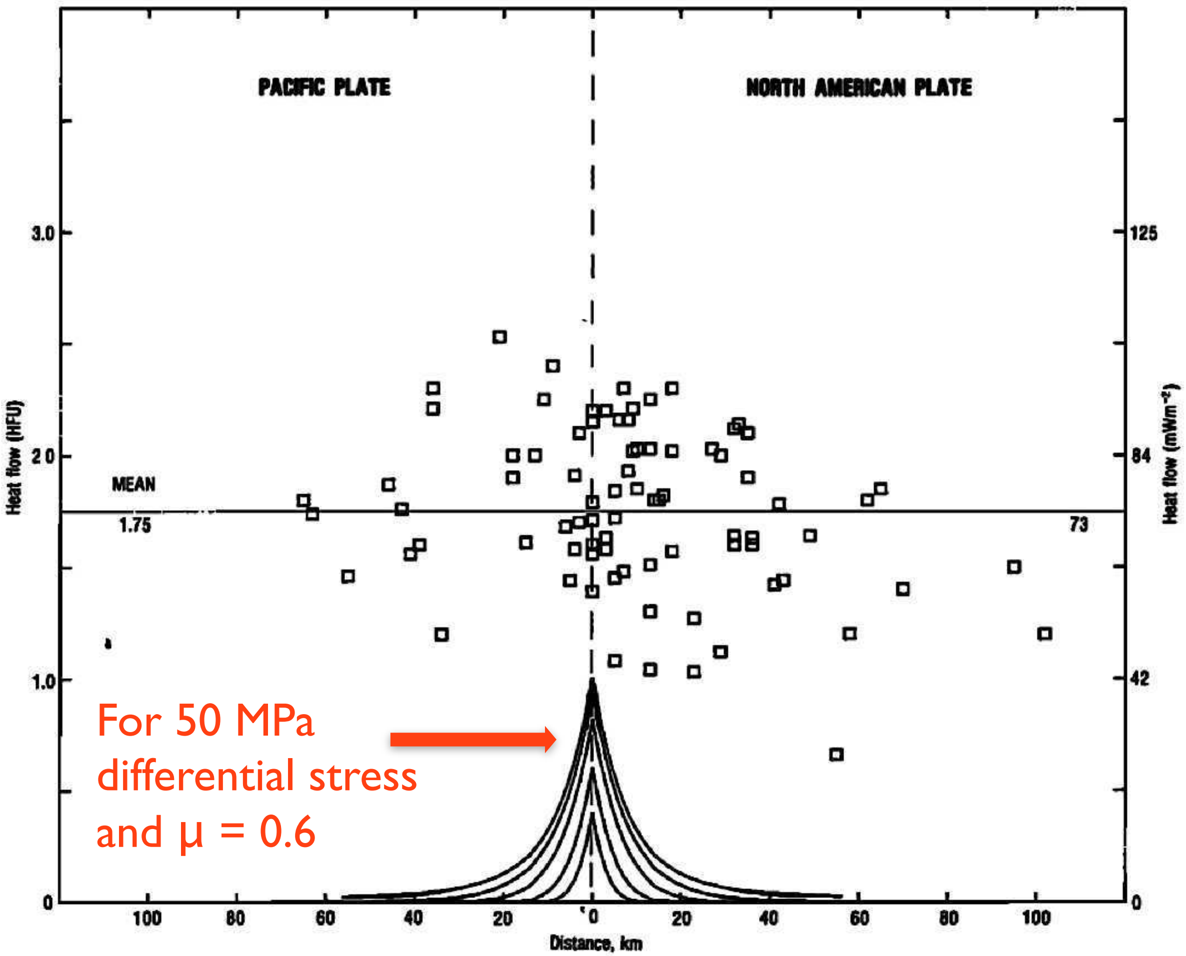


Fig. 11. Heat flow as a function of the distance from the main fault trace for 81 points of Figure 9. Pattern of curves is reference anomaly from Figure 2*a* (see (11) and (12)).

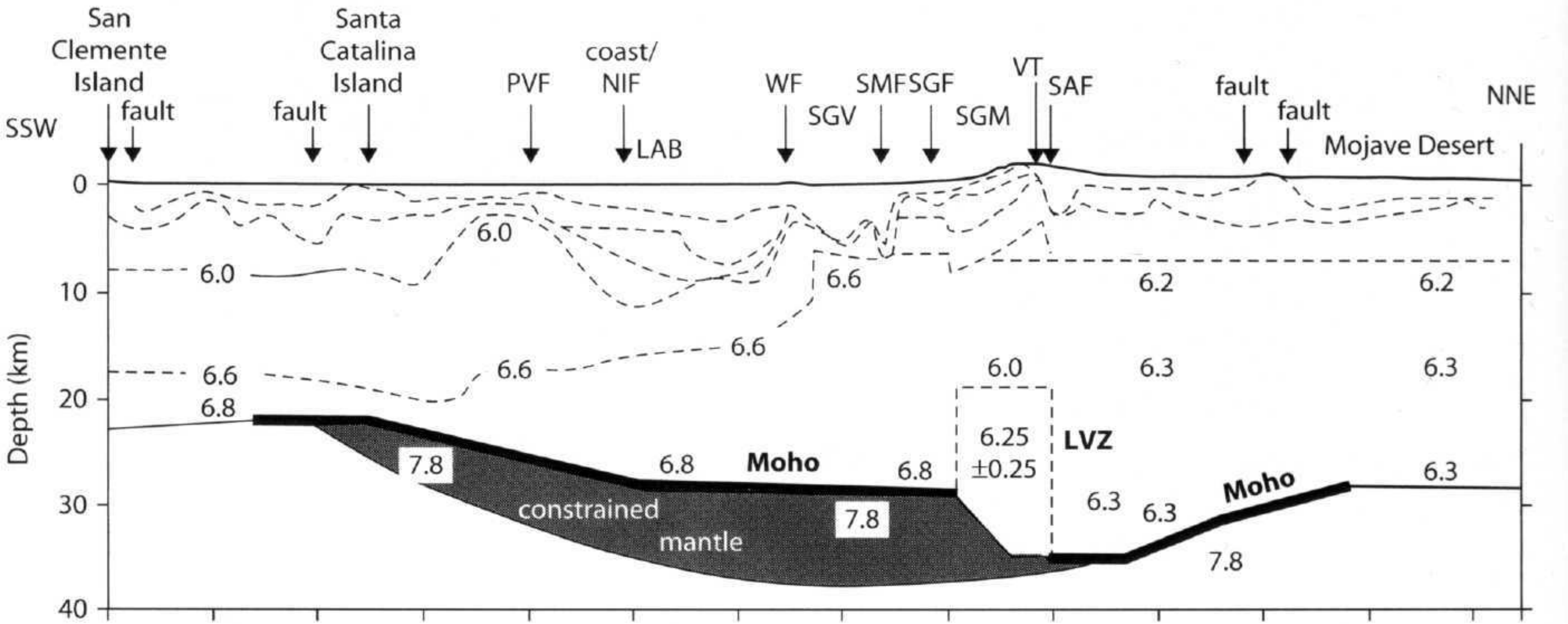
calculated anomaly for heat production by frictional heating, i.e., weak fault

Lachenbruch & Sass 1980

San Andreas Fault

Seismic Velocities:

- Show weak crust on top
- Moho offset of several kms^{-1}
- Fault reaches into mantle

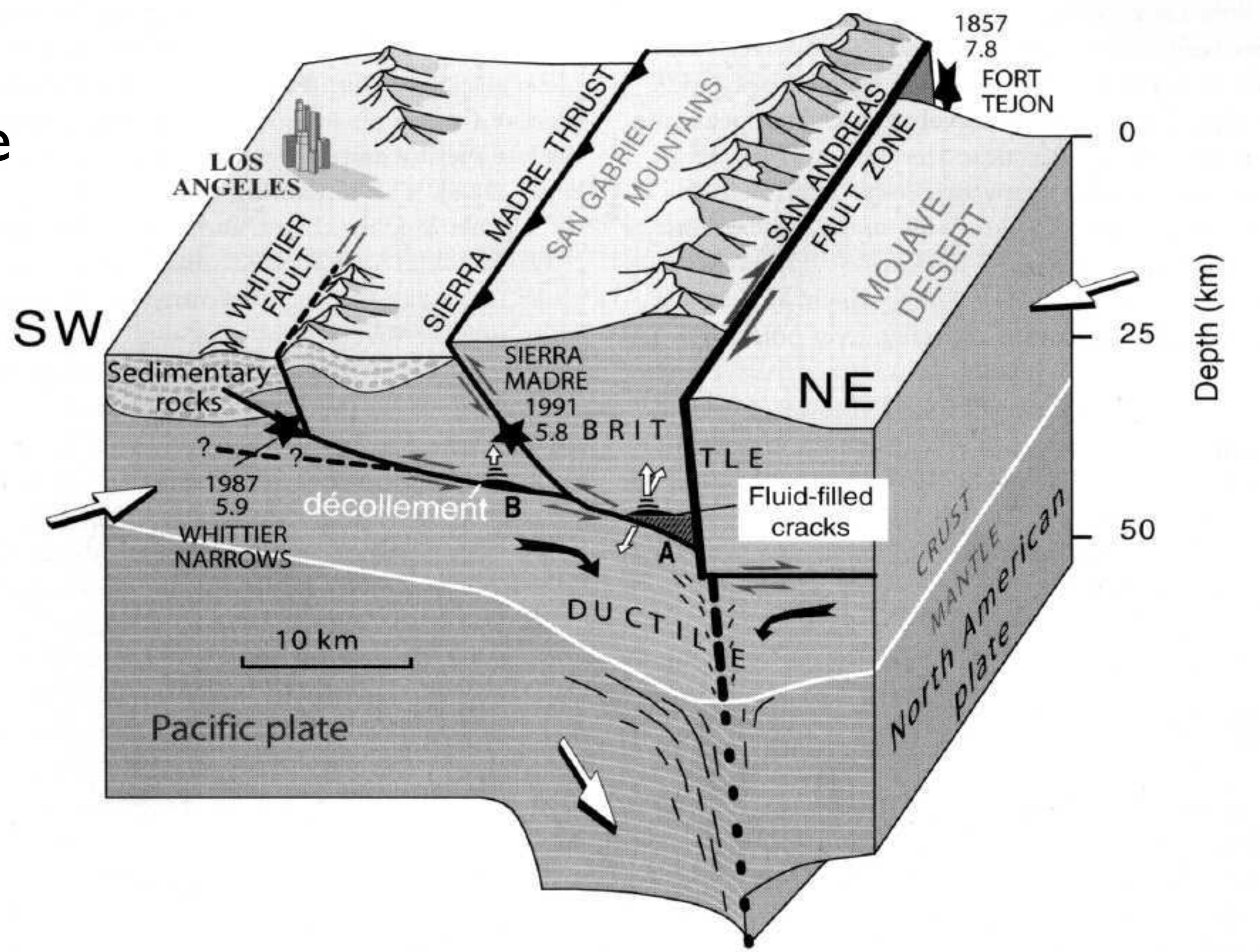


Keary et al. 2009

San Andreas Fault

Geologic interpretation:

- Decollement on the basis of weak crust constraints and seismic reflectors
- Deformation mechanisms must change with depth
- Earthquakes in upper part above decollement



Keary et al. 2009

9

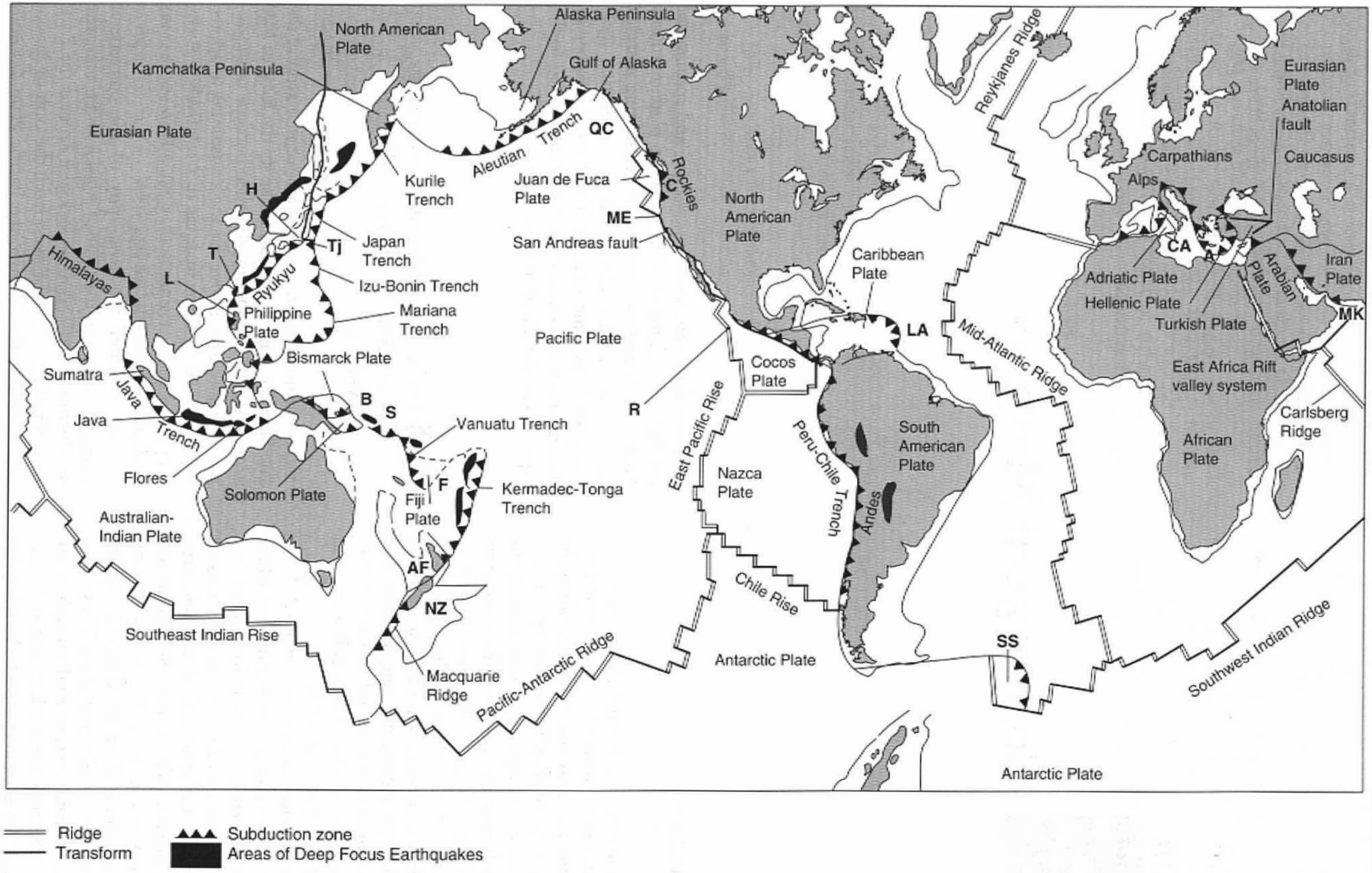
9 Extensionstektonik - rifting - MCCs - LANFs

VL-Themen:

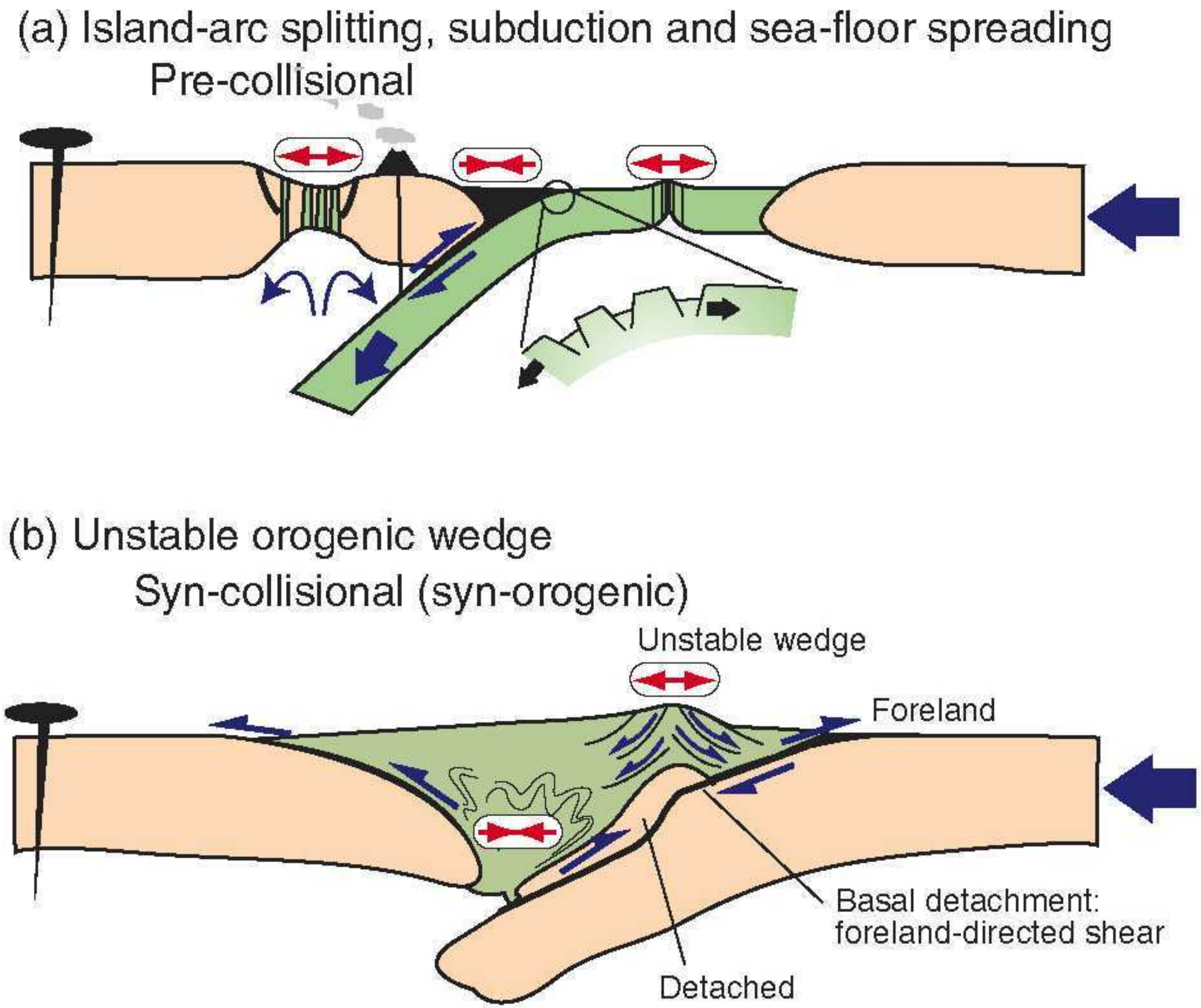
- Extensionsregimes
- Extensionsgeometrie
- Morphologie
- Krustenextension

- Ozeanische Rücken
- Graben Grabenbildung (rift - rifting)
- metamorphic core complexes MCC
- low angle normal faults LANF

extensional tectonics

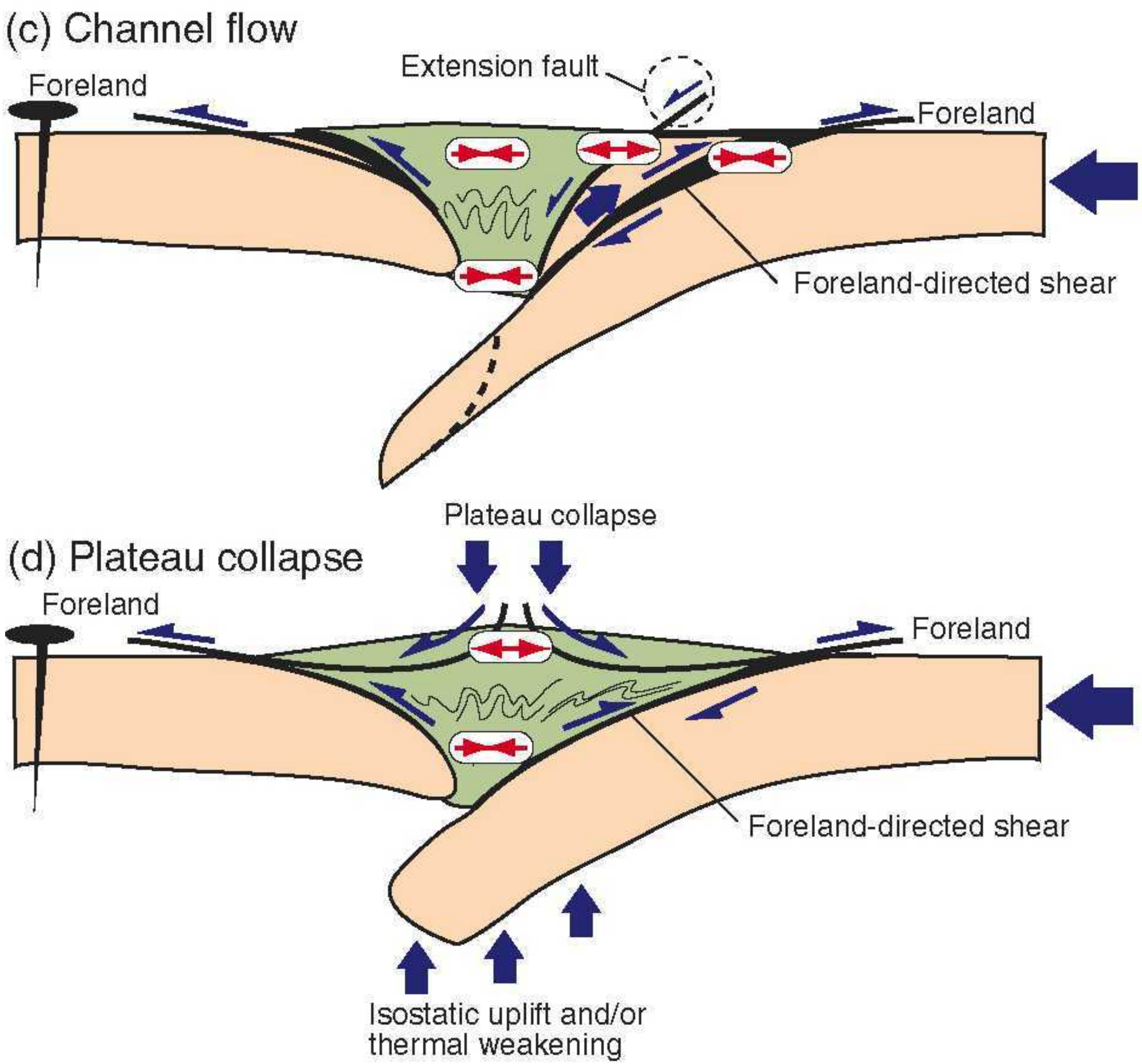


extensional settings



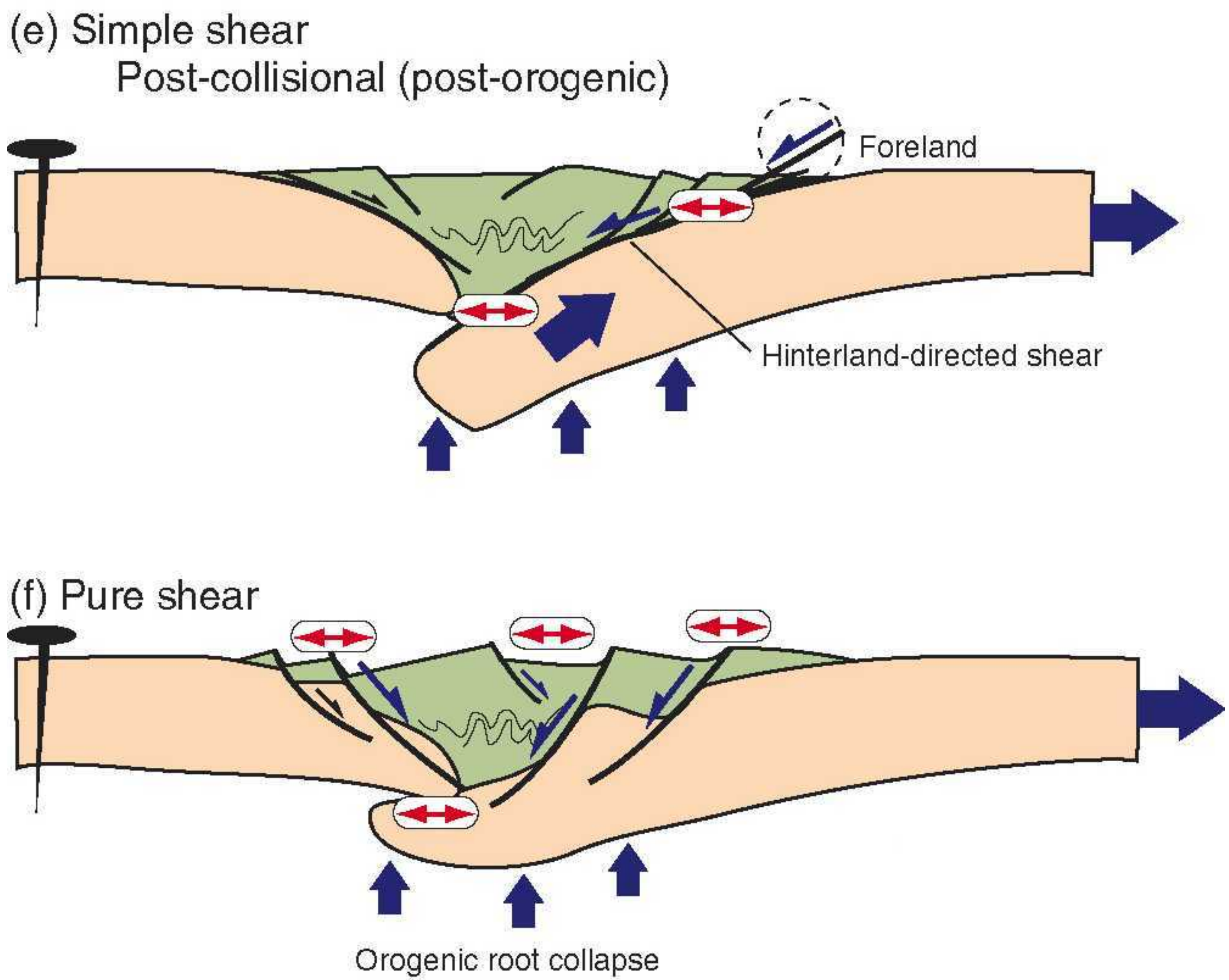
Håkon Fossen, 2012

extensional settings



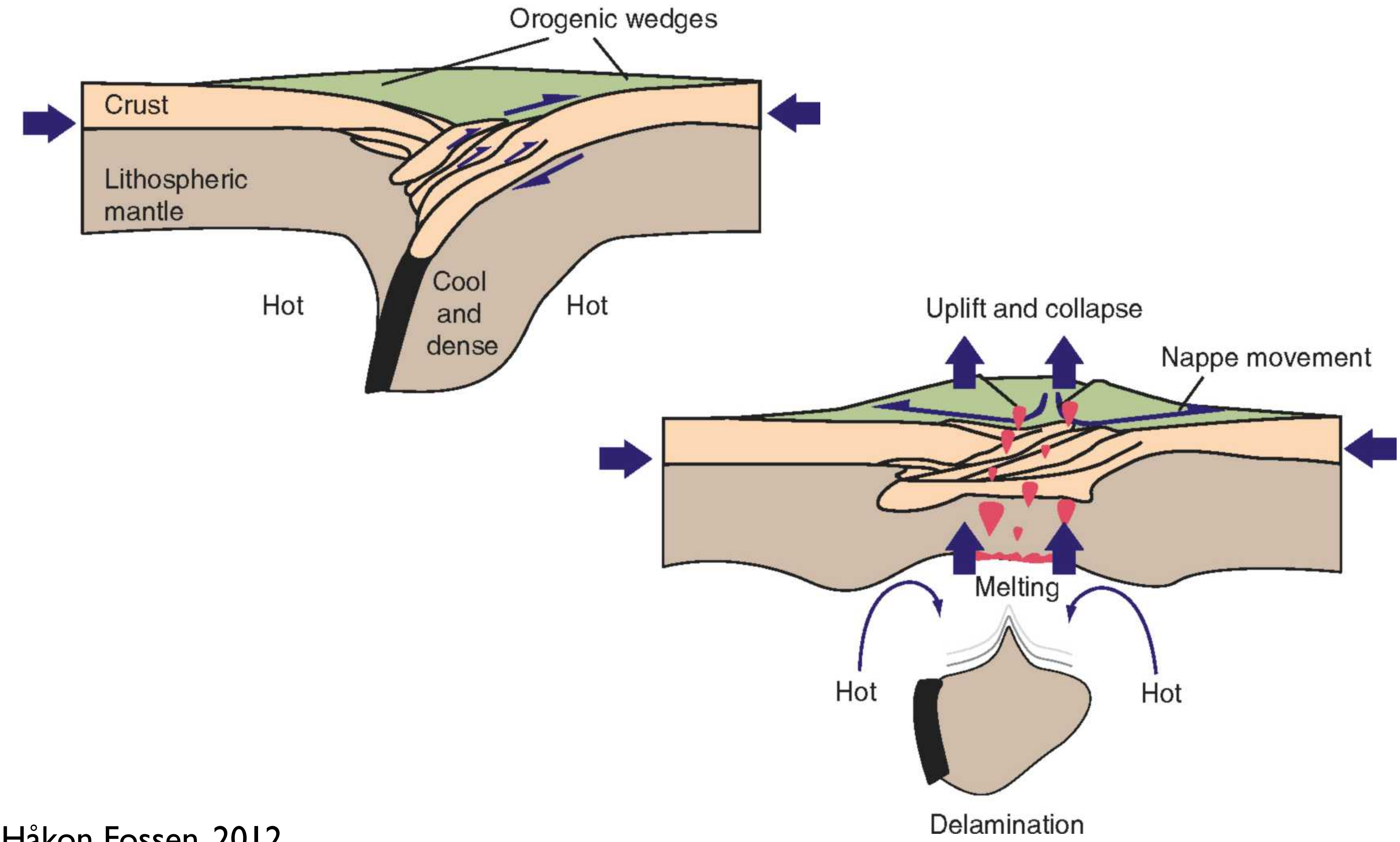
Håkon Fossen, 2012

extensional settings



Håkon Fossen, 2012

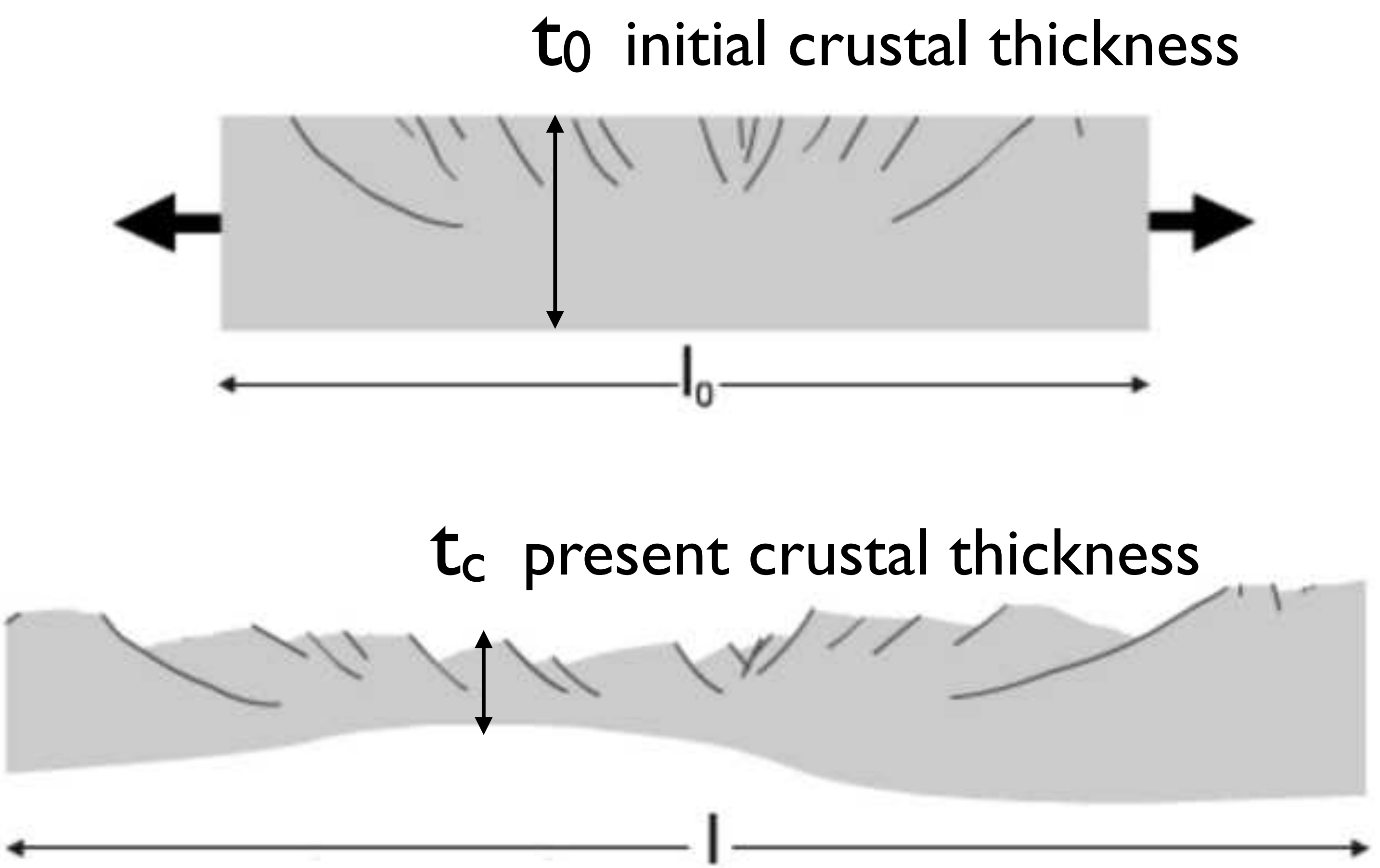
extensional settings



Håkon Fossen, 2012

geometry of extension

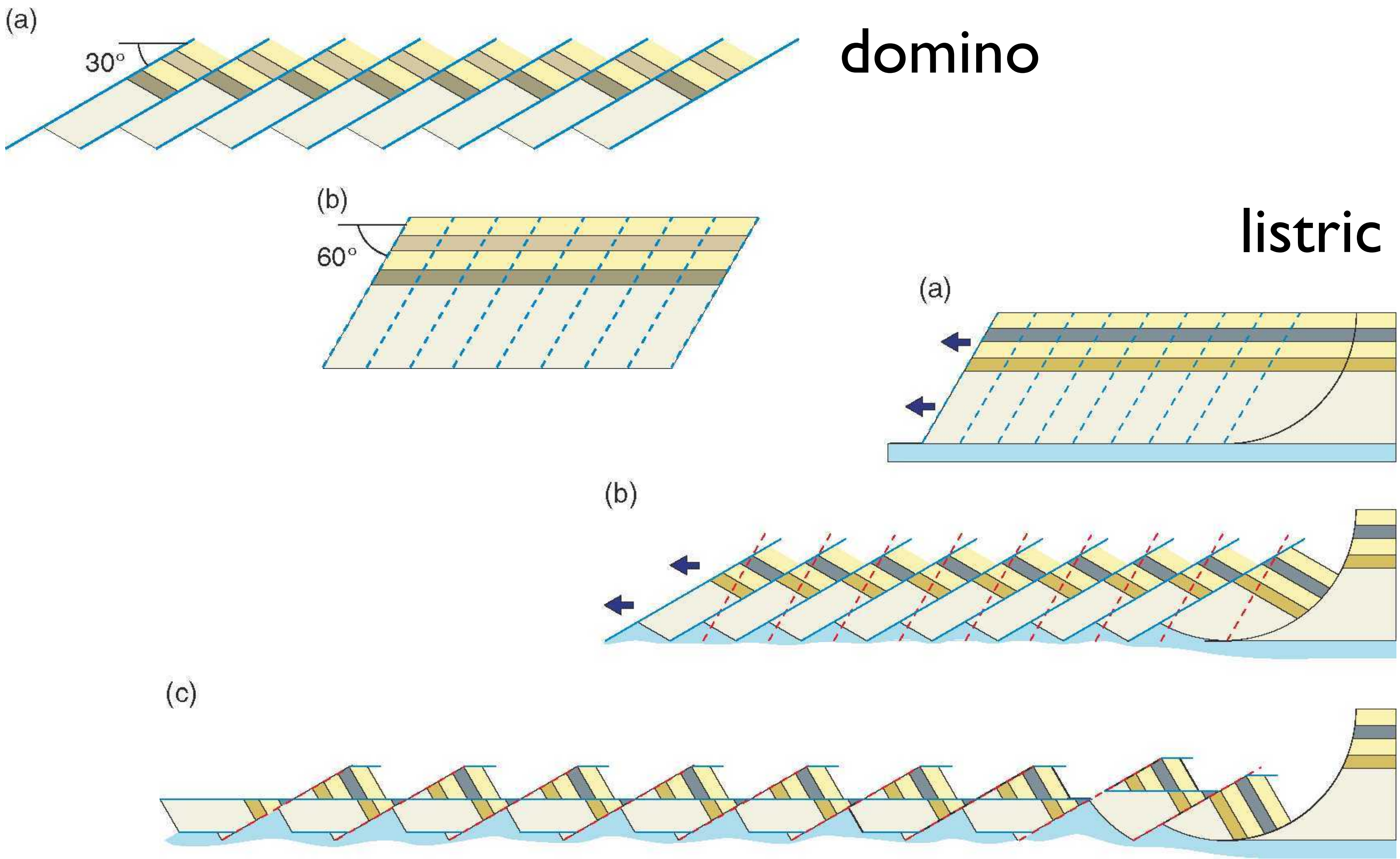
geometry of extension



$$\beta = \frac{t_0}{t_c}$$

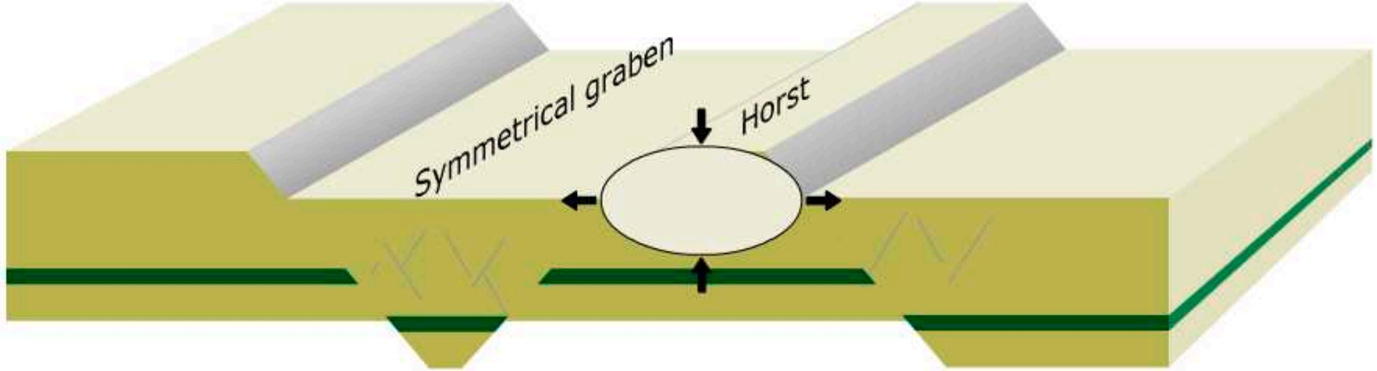
$$s = l / l_0 = (1 + e) = \text{stretching} = \text{extension}$$

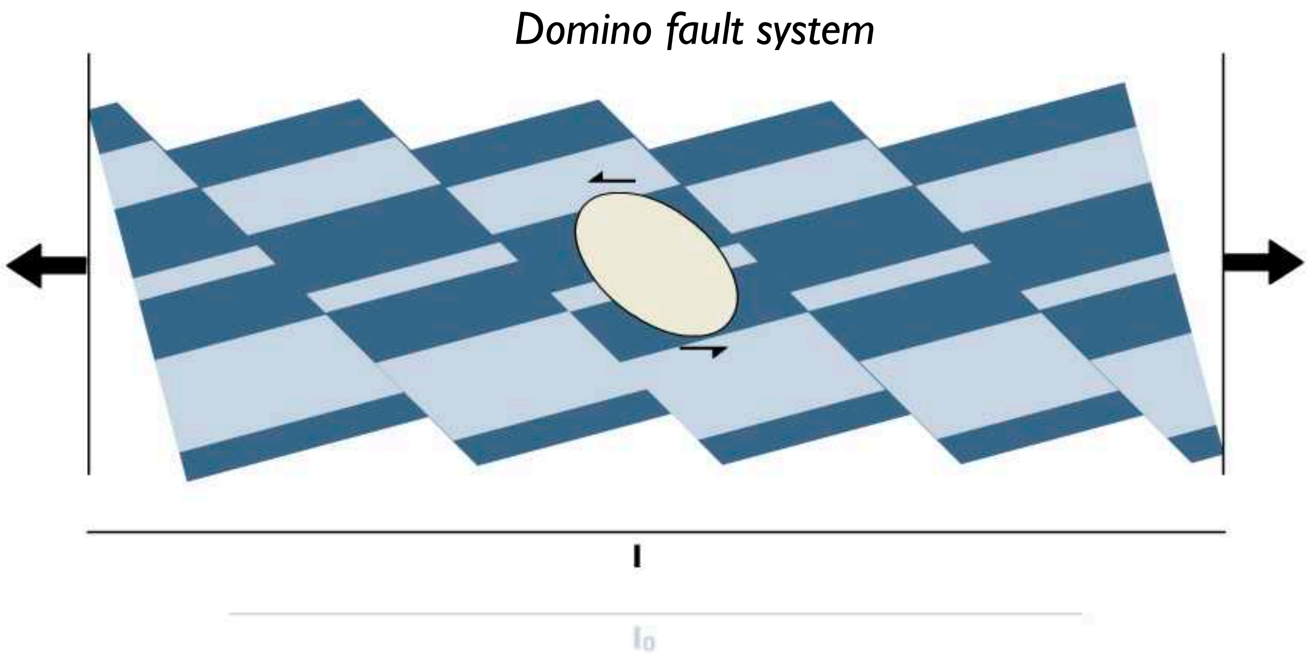
extensional faults



Håkon Fossen, 2012

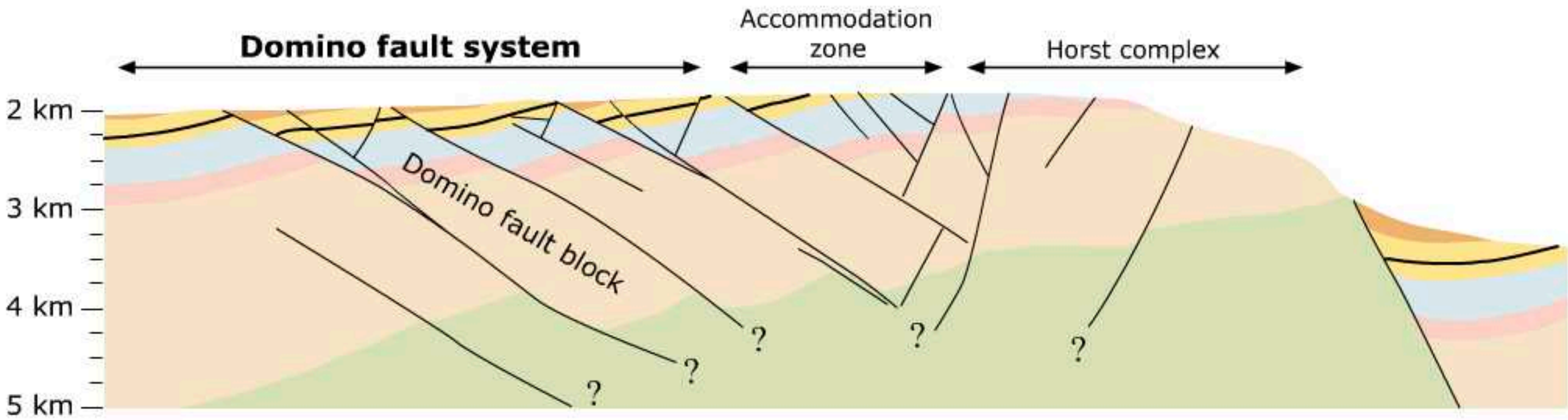
pure shear - simple shear   extension



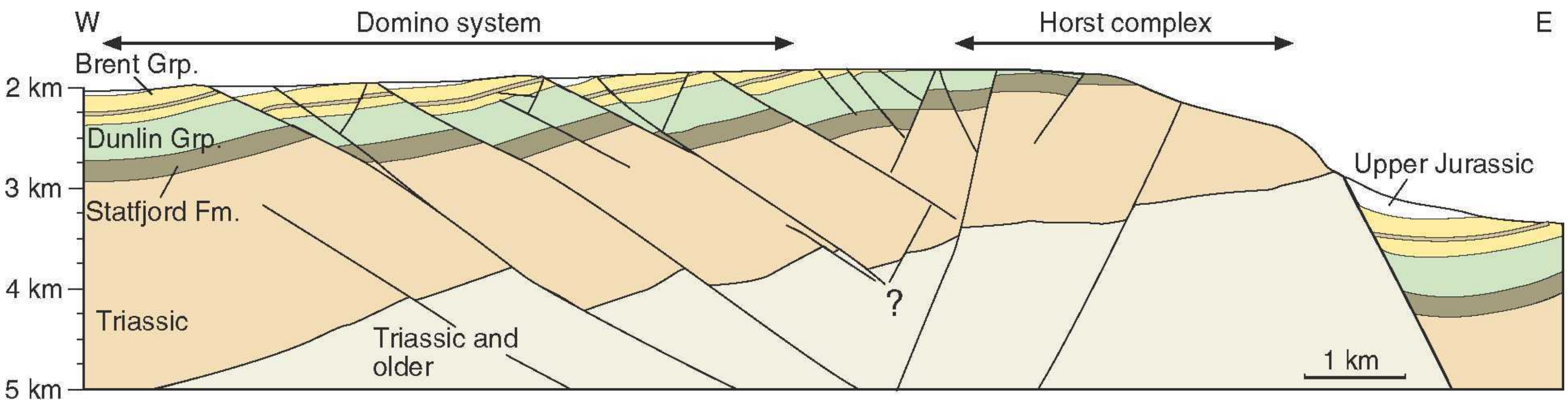


Håkon Fossen, 2012

Beispiel: Gullfaks Field, North Sea

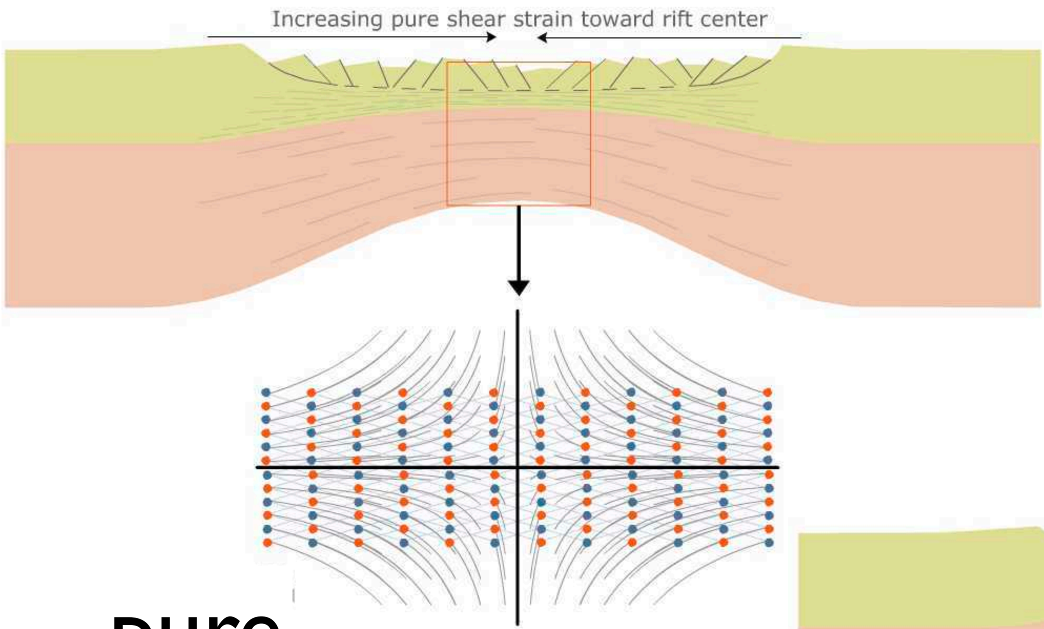


Domino faults on the Gullfaks Field, northern North Sea, based on seismic interpretation.

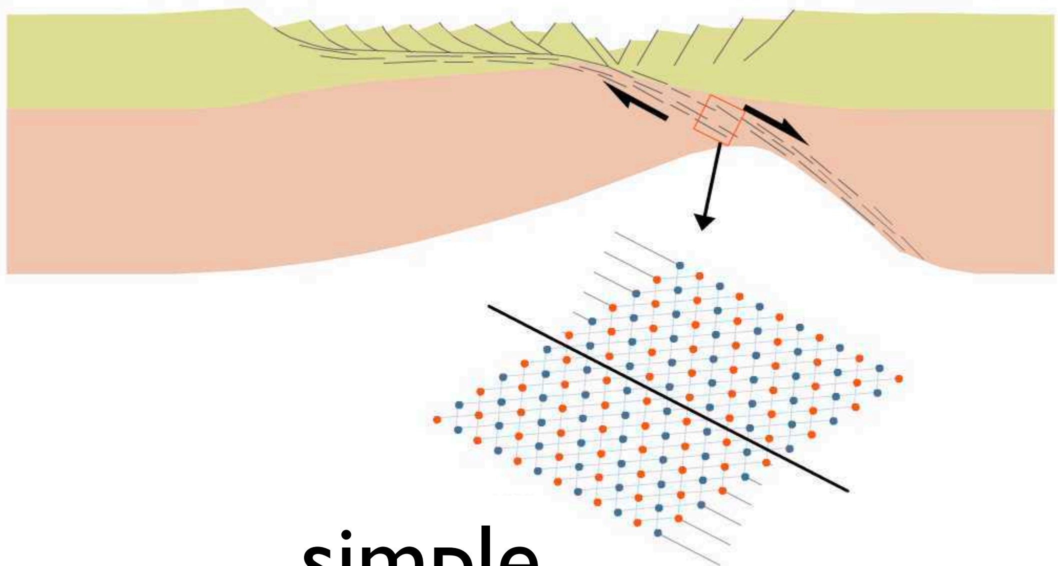


Håkon Fossen, 2012

strain during rifting



pure

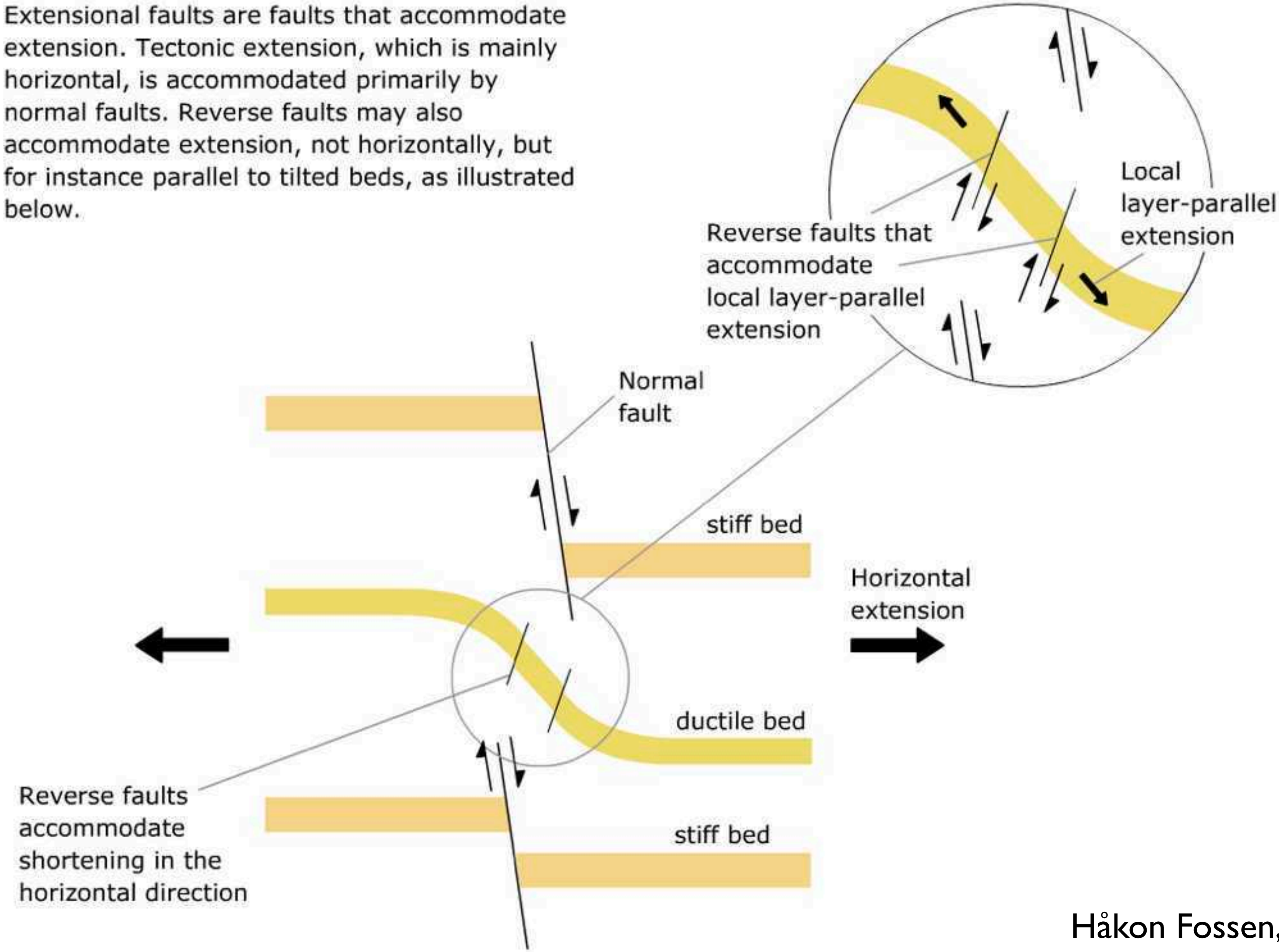


simple

Håkon Fossen, 2012, e-module 17

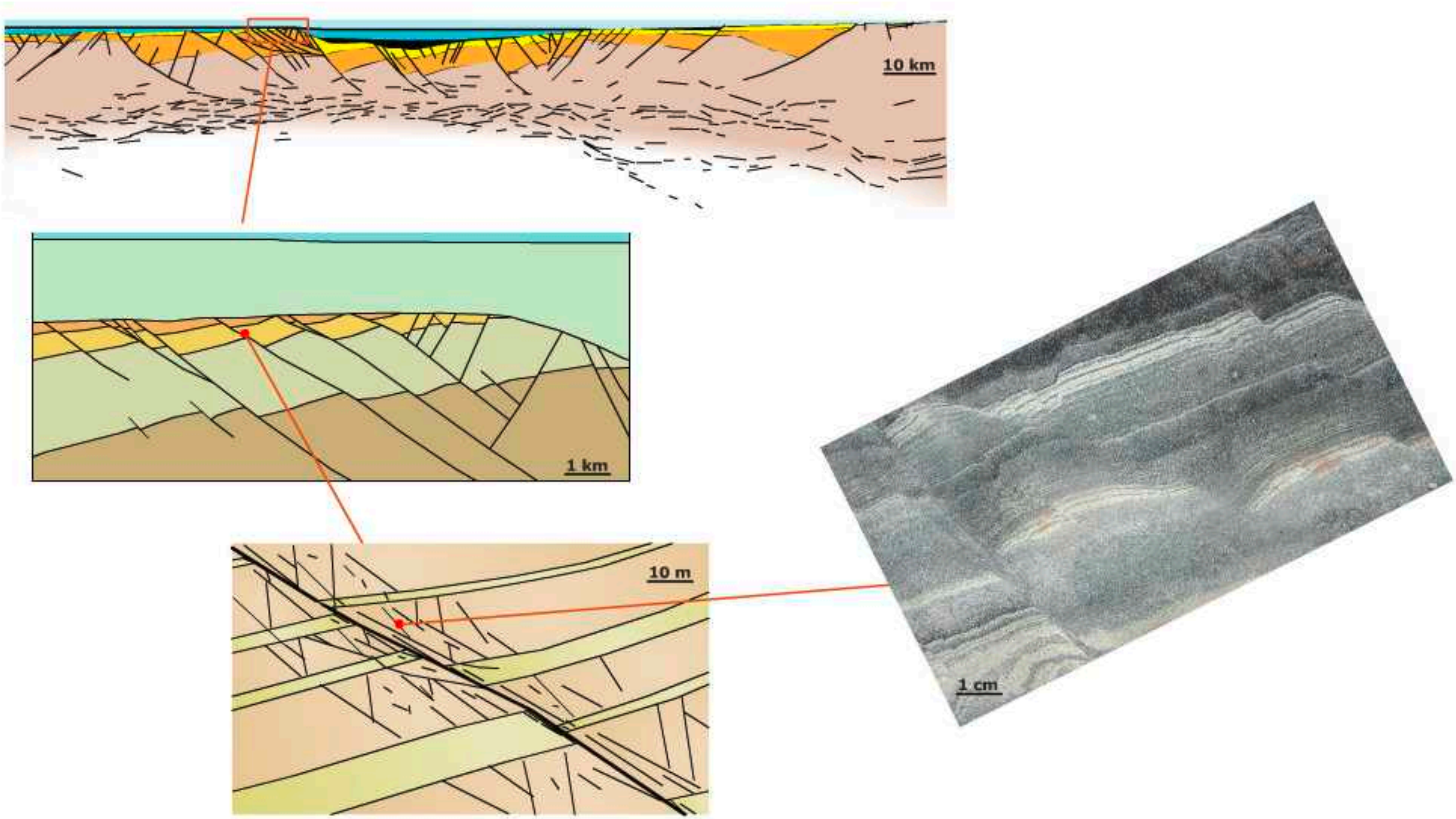
extensional faults

Extensional faults are faults that accommodate extension. Tectonic extension, which is mainly horizontal, is accommodated primarily by normal faults. Reverse faults may also accommodate extension, not horizontally, but for instance parallel to tilted beds, as illustrated below.



Håkon Fossen, 2012

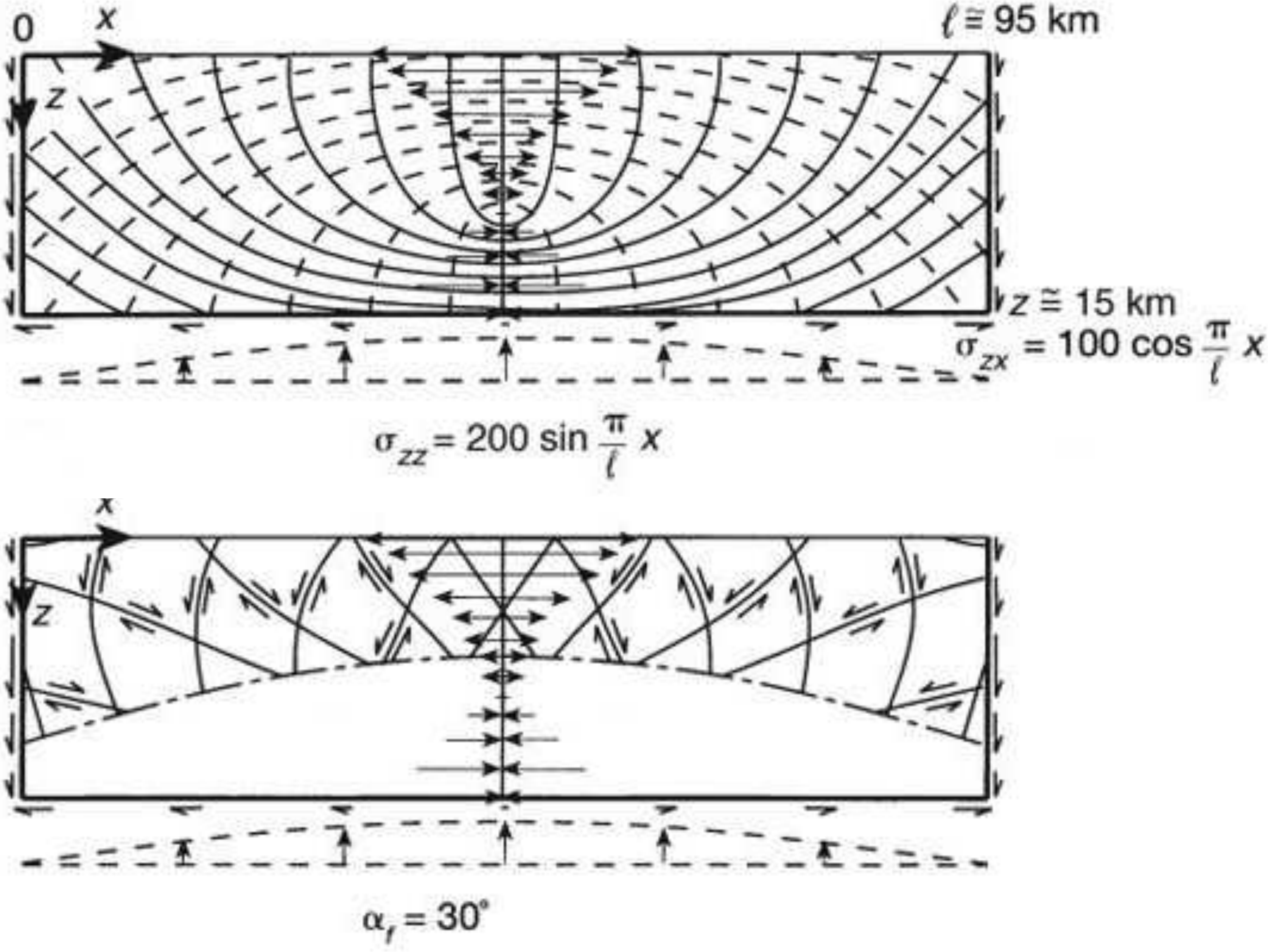
fractal aspects



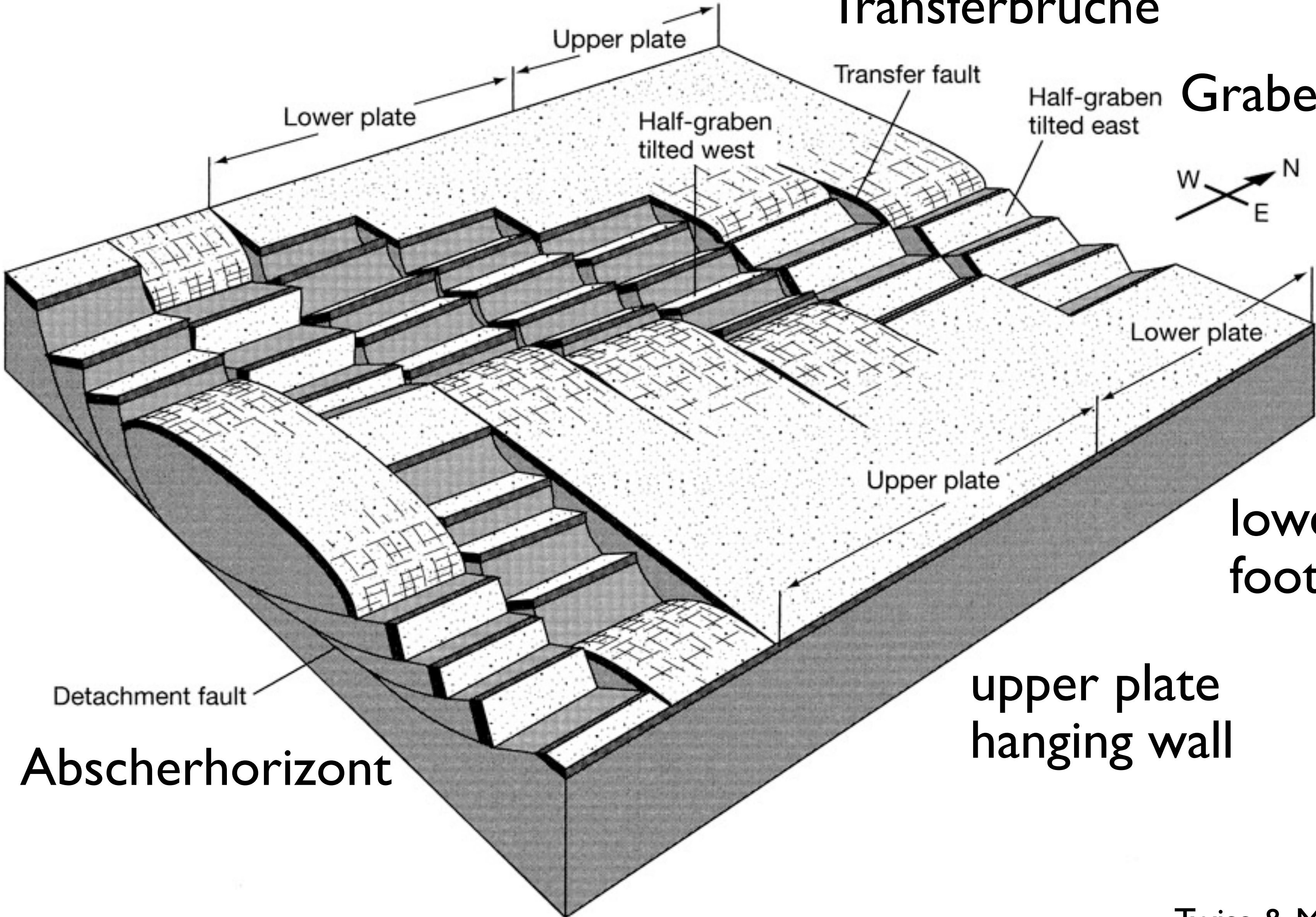
Håkon Fossen, 2012, e-module 17

morphology of extension

Hafner: extension



crustal extension



Transferbrüche

Grabenbrüche

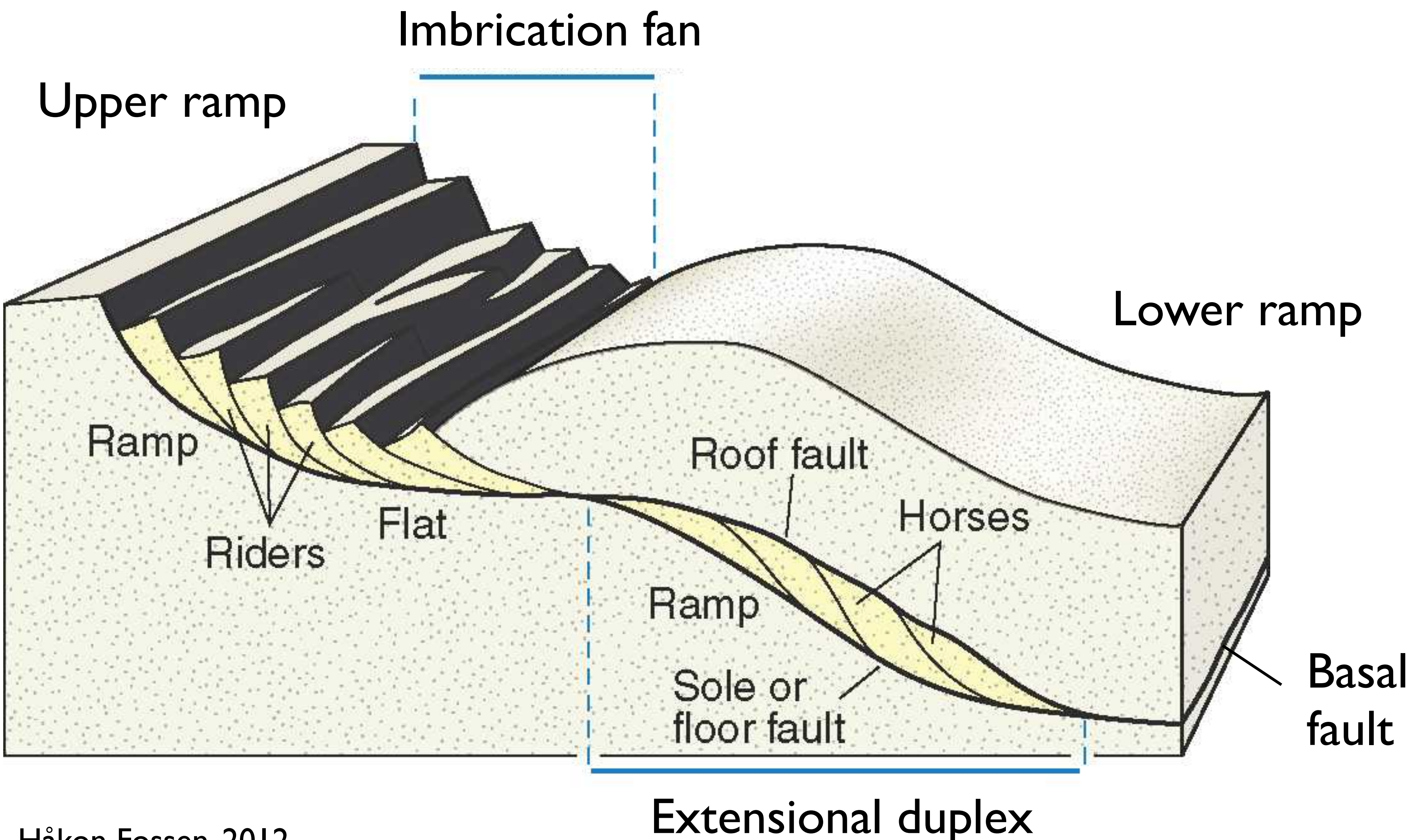
lower plate
footwall

upper plate
hanging wall

Abscherhorizont

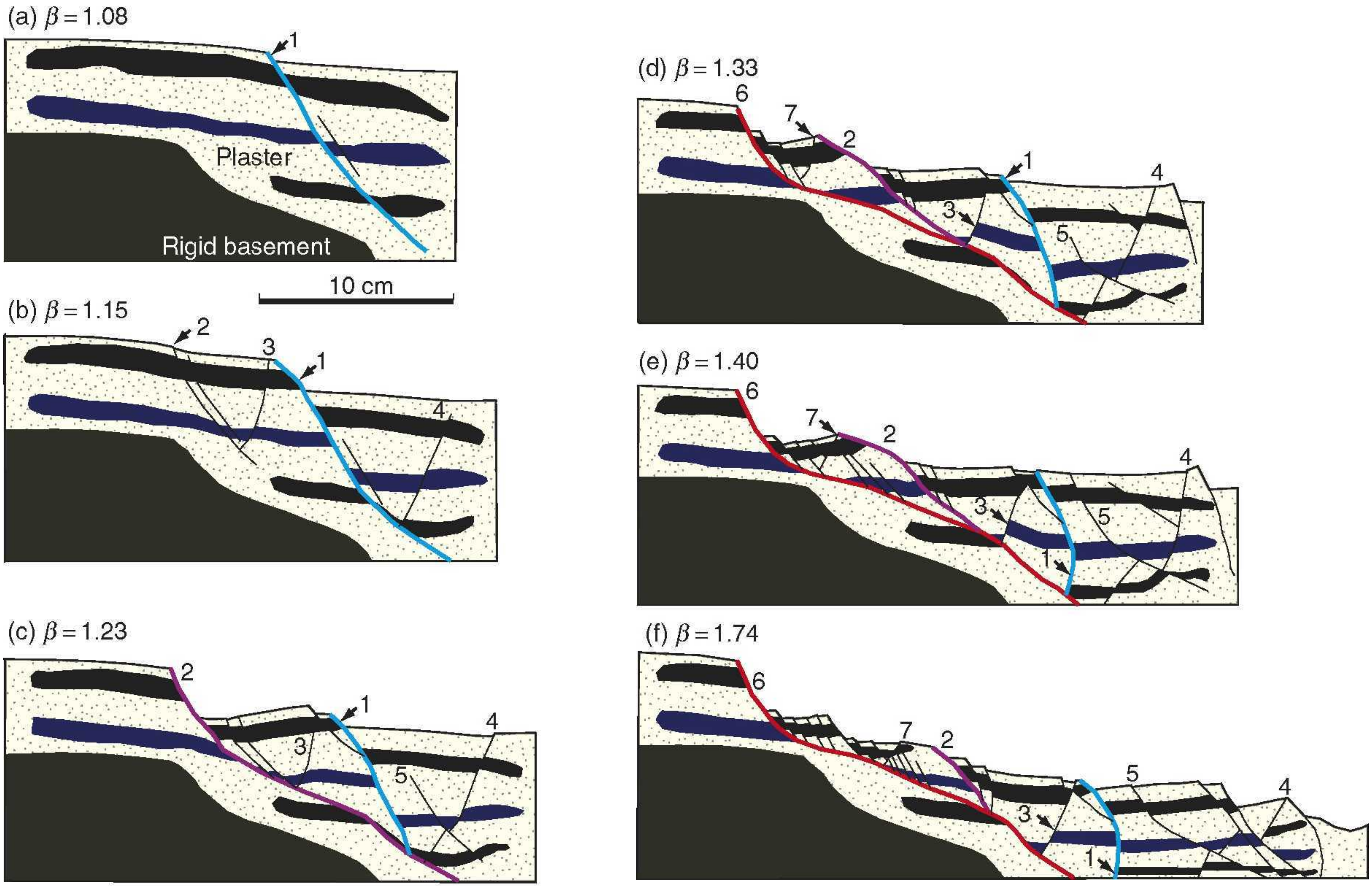
Twiss & Moores, 2007

ramp-flat-ramp faults



Håkon Fossen, 2012

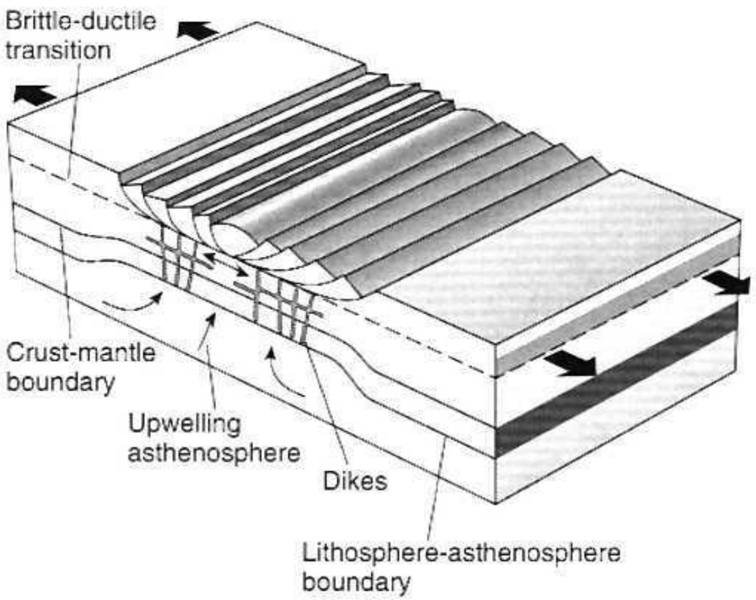
ramp-flat-ramp fault evolution

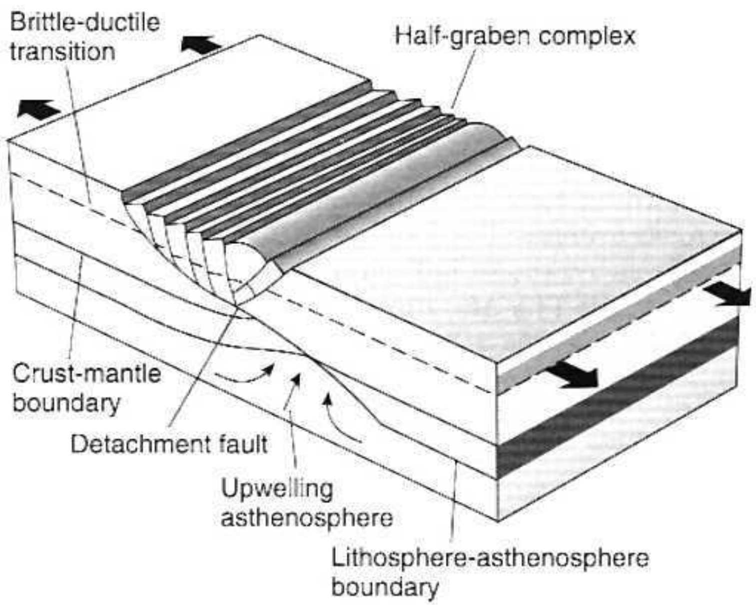


Håkon Fossen, 2012

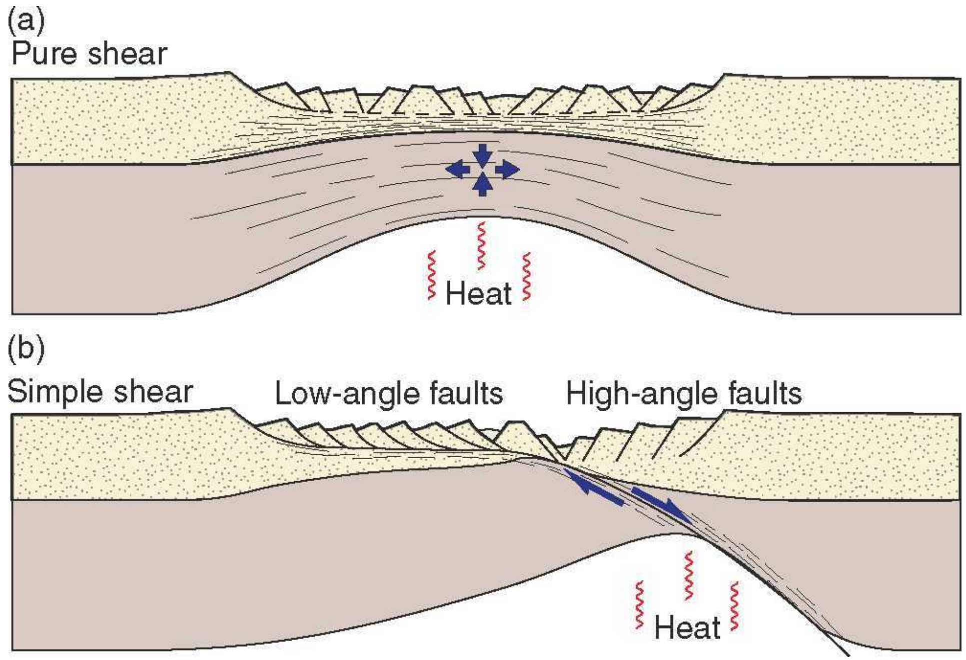
crustal extension models

symmetry of extension





Twiss & Moores



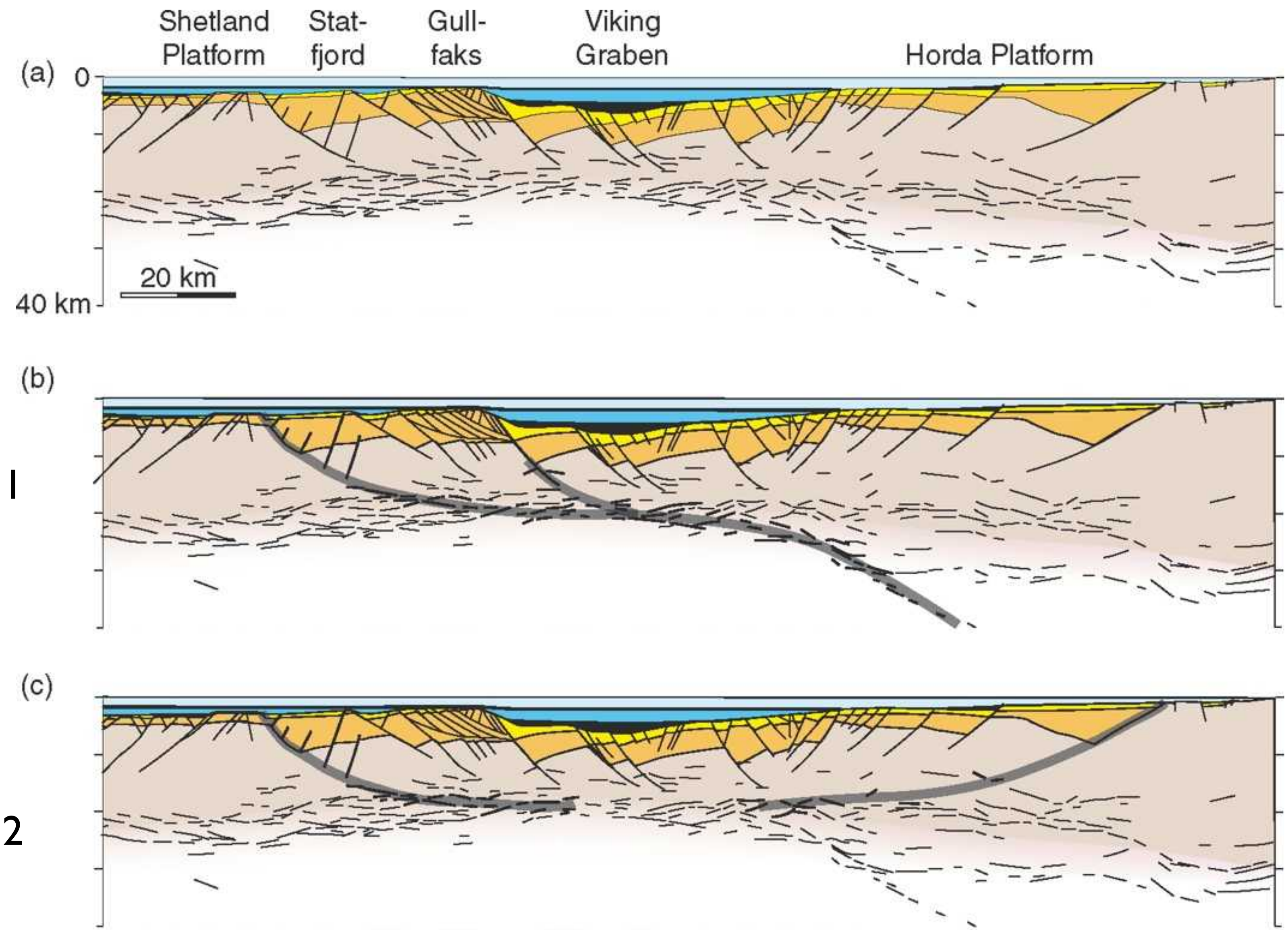
Håkon Fossen, 2012

symmetry (?) of extension

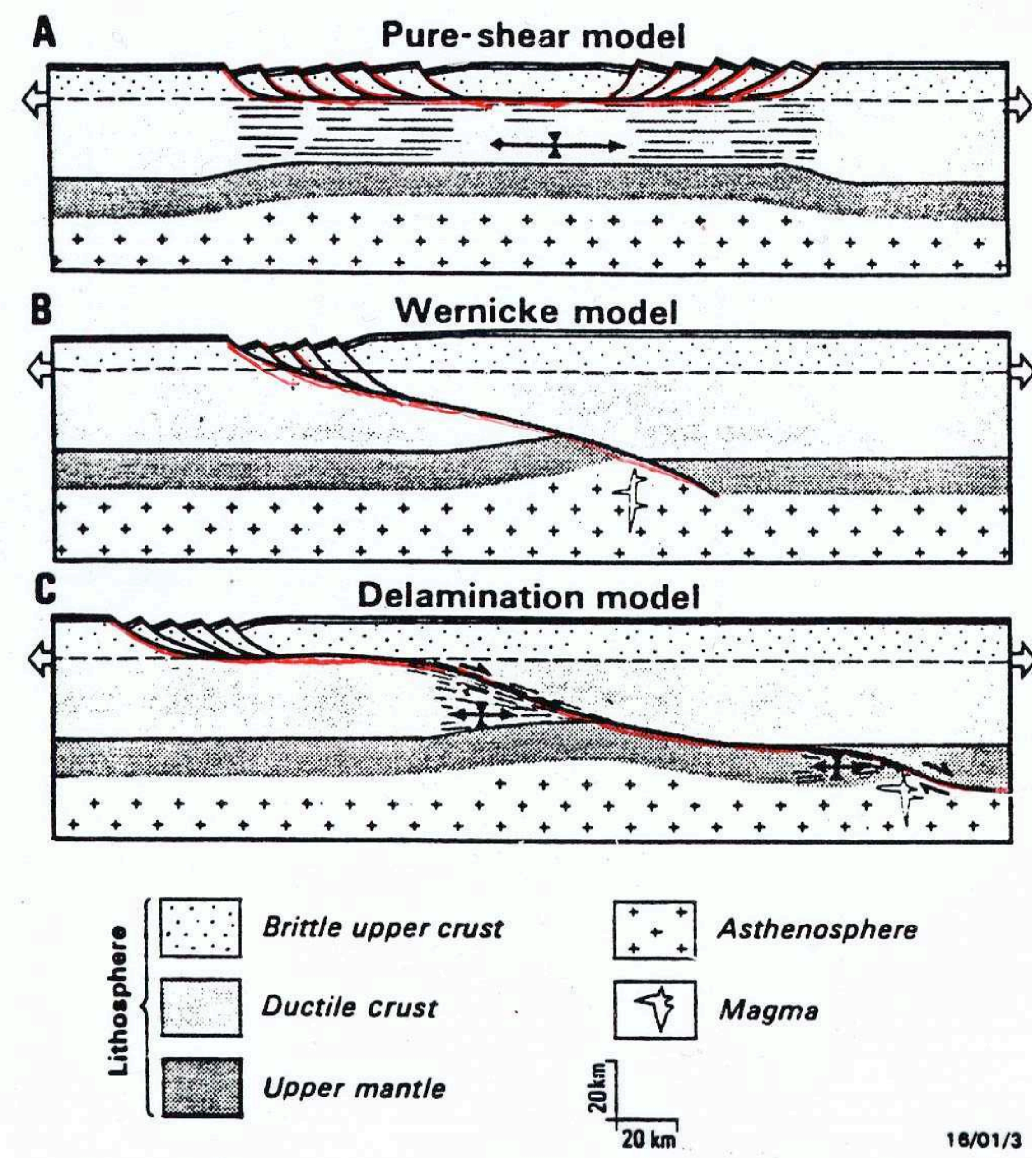
seismic data

interpretation 1
asymmetric

interpretation 2
symmetric



models for stretched lithosphere



- symmetric extension and graben
- listric normal faults
- detachment between upper and lower crust
- brittle extension (upper part)
- ductile extension (lower part)

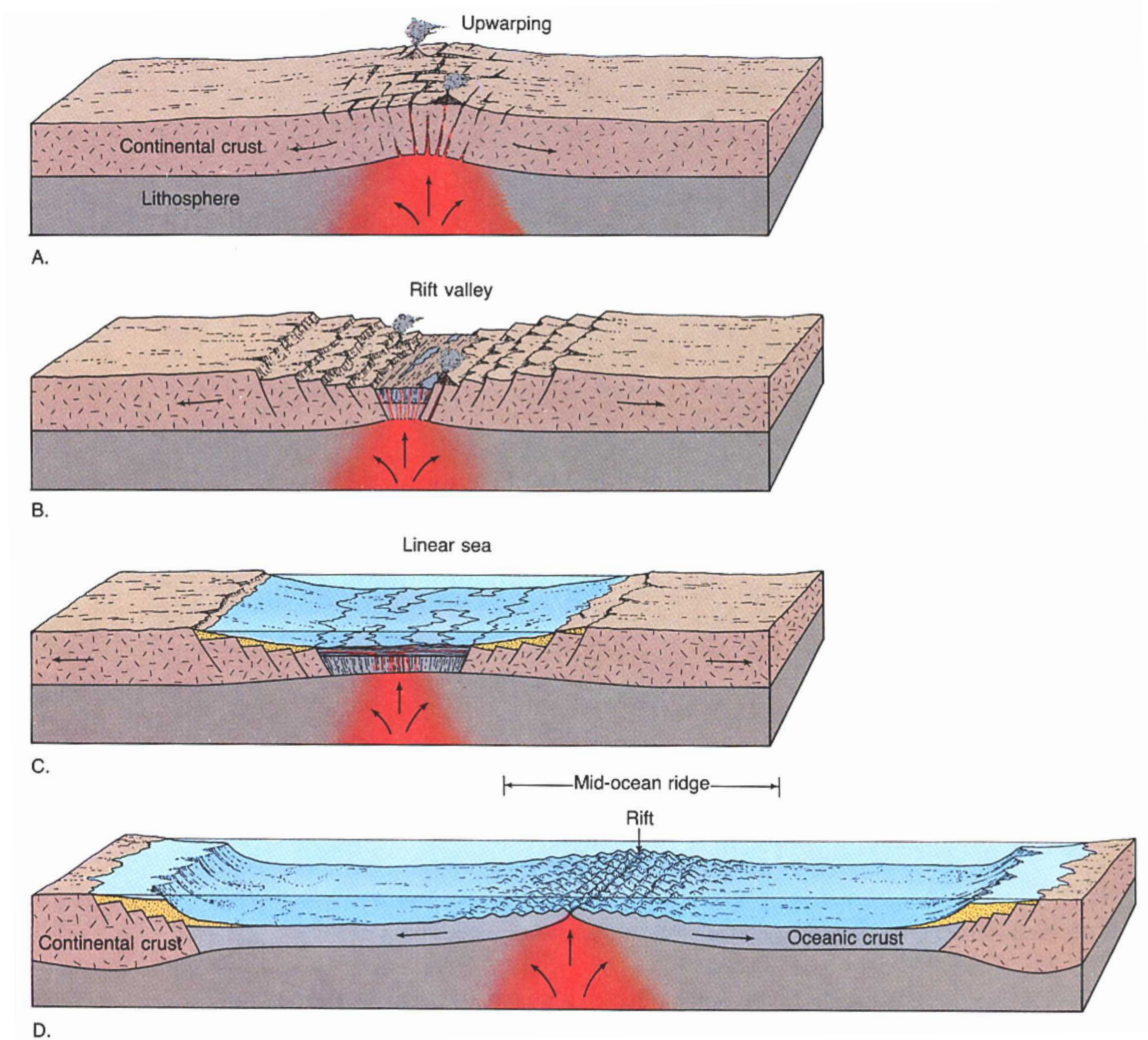
- asymmetric extension (also in graben)
- low-angle listric detachment cutting into the astenosphere

- Low-angle detachment that flattens in different crustal levels
- regional flat-ramp geometry

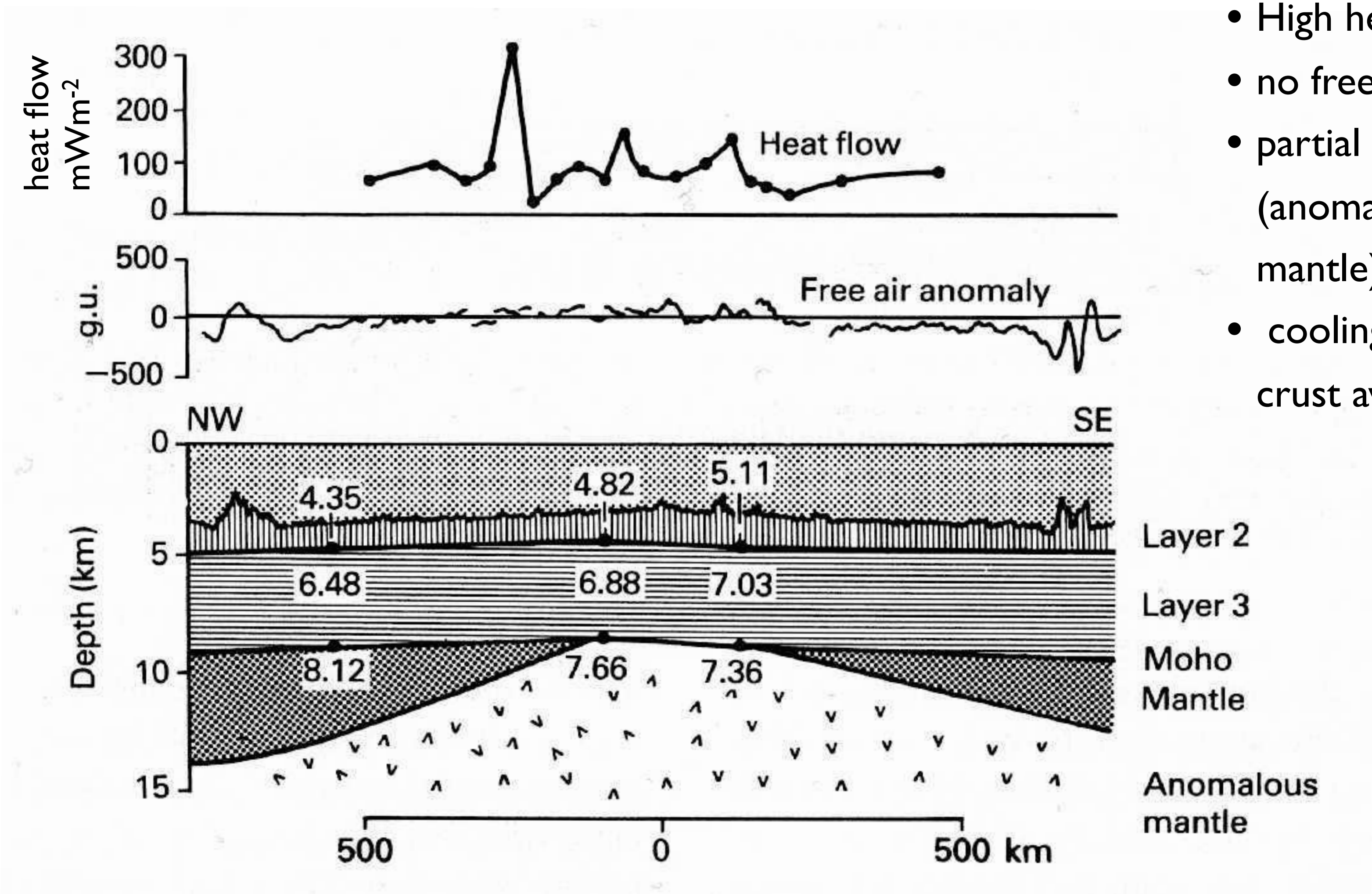
mid ocean ridges

(Beilagen z.T. modifiziert nach Claudio Rosenberg)

extensional regimes

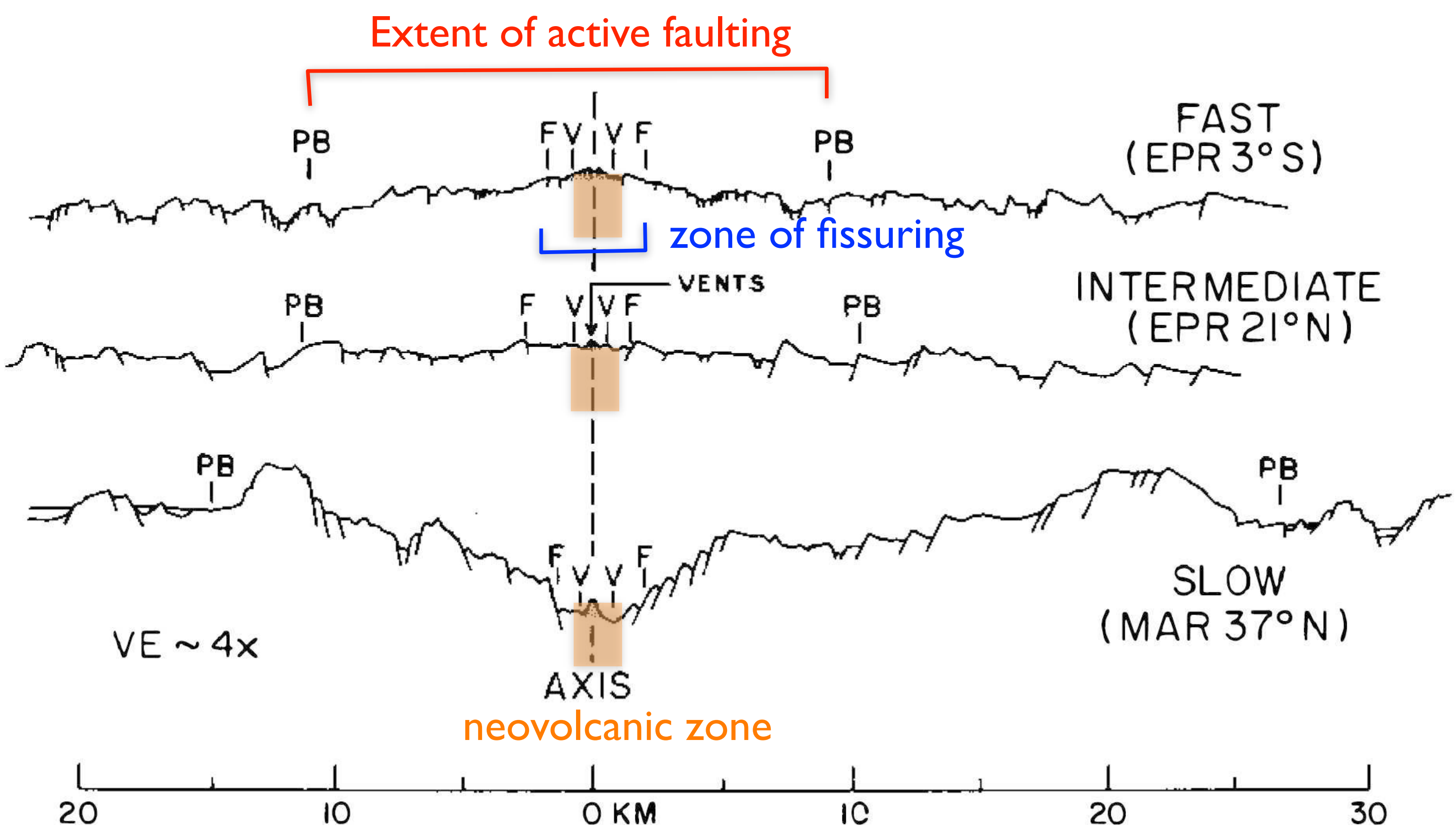


heat flow and gravity at ridges



- High heat flow under ridge
- no free air anomaly
- partial melt under ridge (anomalous mantle)supports elevation
- cooling leads to sinking of crust away from ridge

fast- and slow-spreading ridges

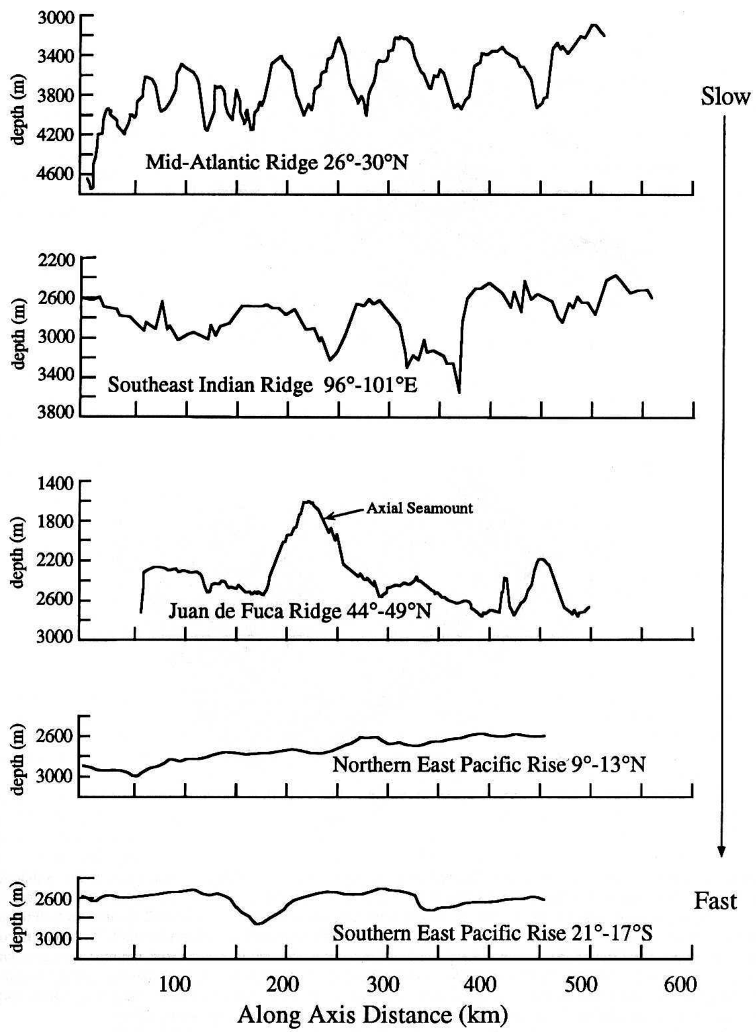


EPR East Pacific Rise
MAR mid Atlantic ridge

Real topography of ridges:
Fast Ridges not much relief at ridge
Slow Ridges 30-50 km wide, much deeper
V = Neovolcanic activity, F = fissures, P = zone of active faulting

fast - slow ridges topography

Profile parallel zum Rücken



Profile senkrecht zum Rücken

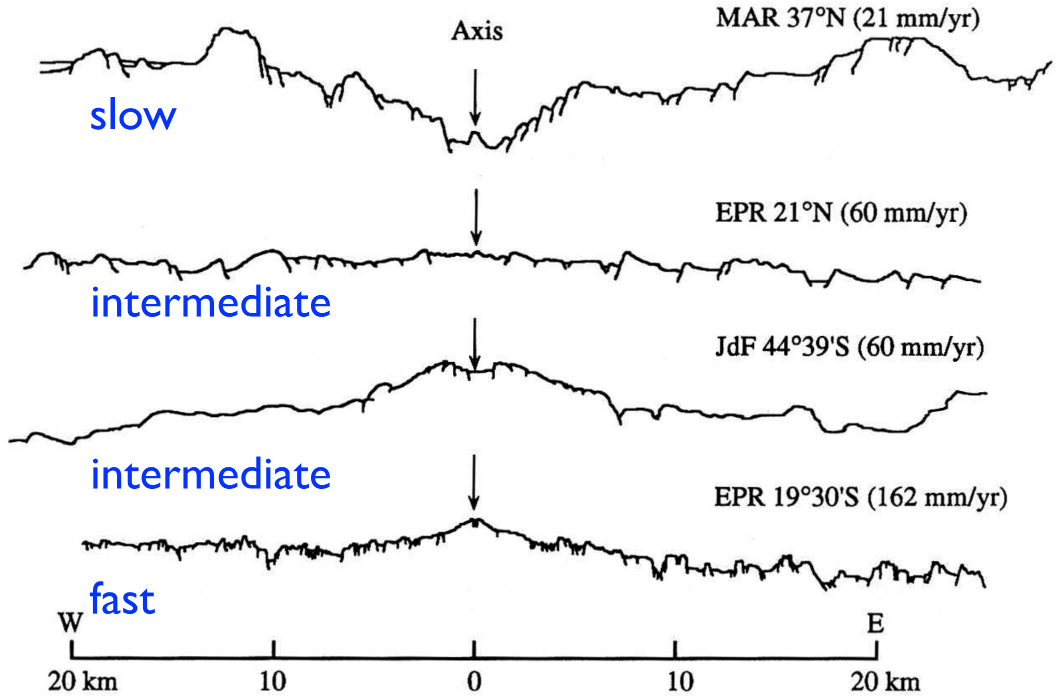
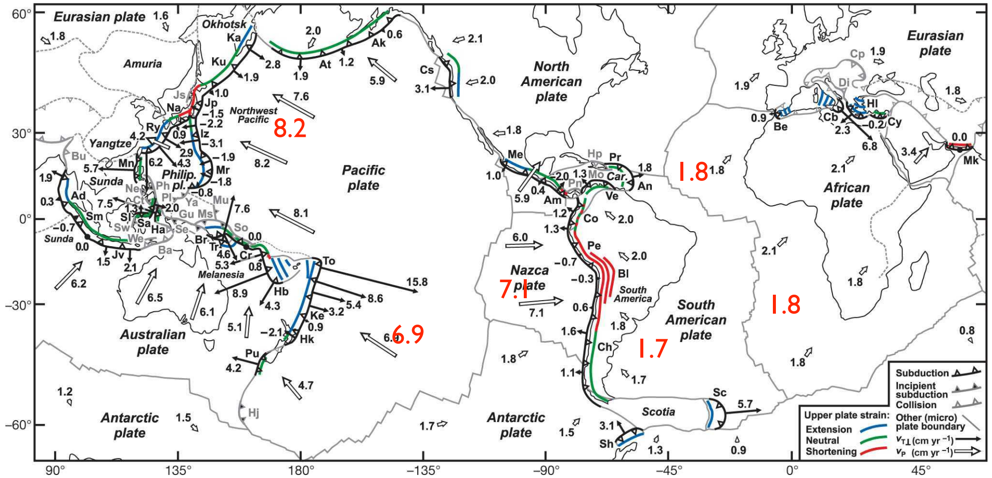
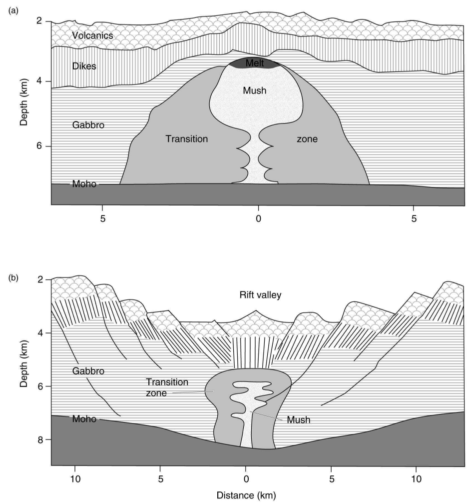


Figure 1. Cross-axis bathymetric profiles of selected mid-ocean ridges with different spreading rates. Profiles across fast-spreading (Southern East Pacific Rise) and slow-spreading (Northern Mid-Atlantic Ridge) ridges show the morphologic contrast between an axial high and a rift valley whereas intermediate spreading rate ridges (Juan de Fuca Ridge) have transitional features. Profiles are modified from Macdonald [1986].

MacDonald, 1982, Annual Review of Earth and Planetary Sciences

fast- and slow-spreading ridges





EAST PACIFIC RISE, fast spreading

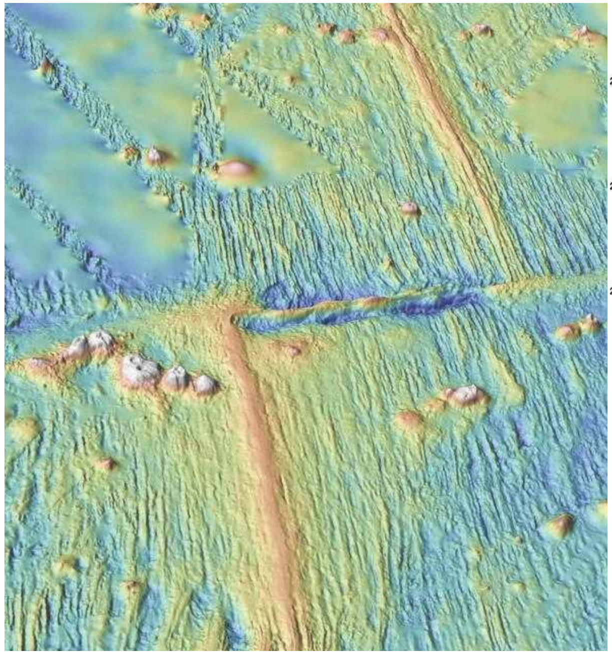
- presence of axial topographic high of up to 400 m height and 1-2 km width
- within this high, small graben < 100m wide and 10 m deep. High may result from buoyancy of hot rocks at shallow depth.
- faulting is more prevalent than on SSR and it accounts for the vast majority of relief
- low seismic velocities in a 4-8 km wide region in the lower crust, 1-2 km below sea-floor, interpreted as the top of magma chamber

MID-ATLANTIC RIDGE, slow spreading

- median valley, 30-50 km width and 500 to 2500 m depth.
- Inner valley bounded by normal fault scarps, ca. 100 m height
- Axial topographic high, 1-5 km width with 100´s m relief, extending only for 10‘s of km along axis. Formed by the coalescence of volcanoes.
- low seismic velocities the lower crust, but no convincing evidence for magma chambers => probably magma chambers are transient below SSR

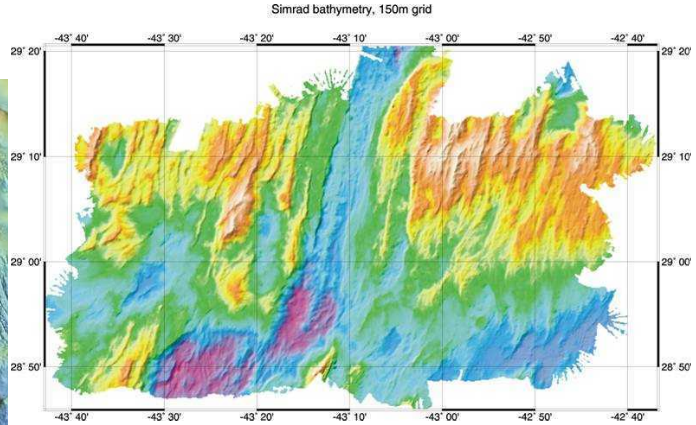
fast- and slow-spreading ridges

Perspective view looking north along the East Pacific Rise at 9° to 11°. Prominent (dark blue = deeper) transform fault running to the east.

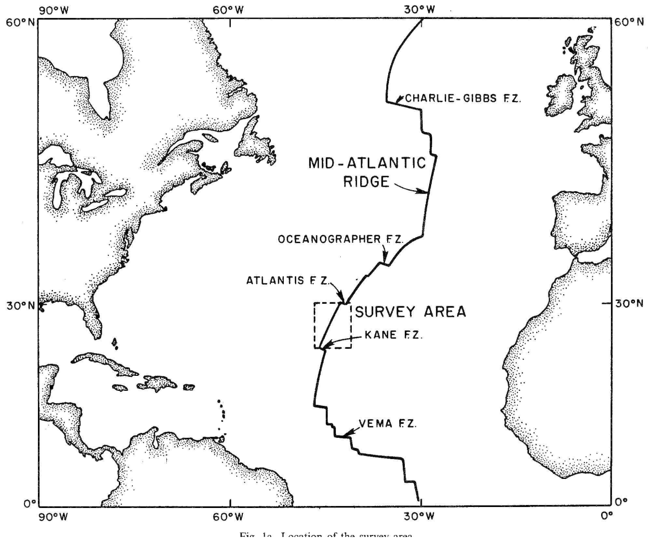


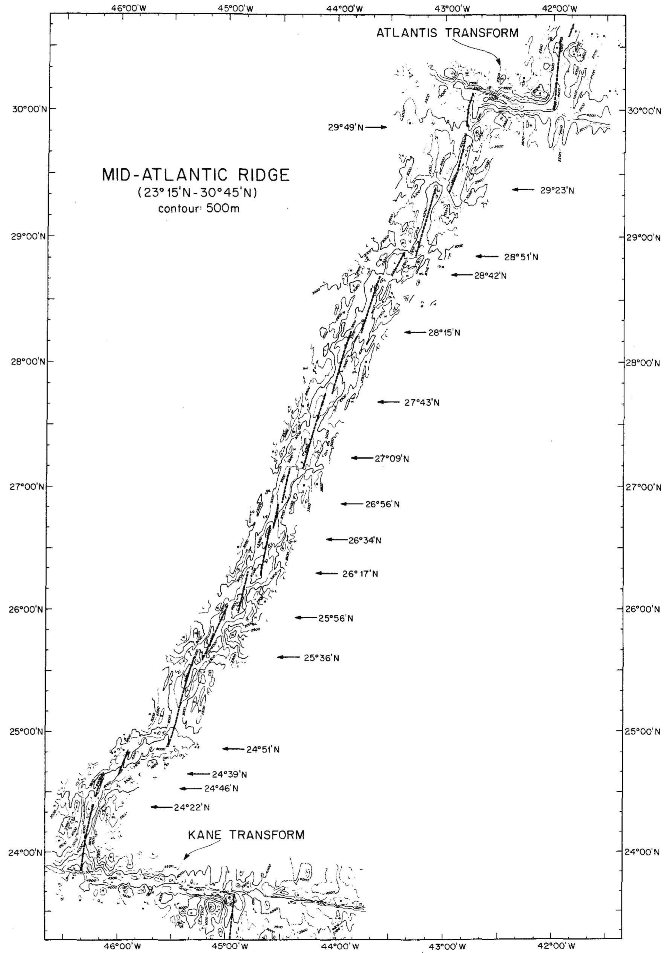
http://media.marine-geo.org/image/east-pacific-rise-9°-to-11°-n-3d-view-2008

Mid-Atlantic Ridge axis near 29°N, illuminated from the NW.



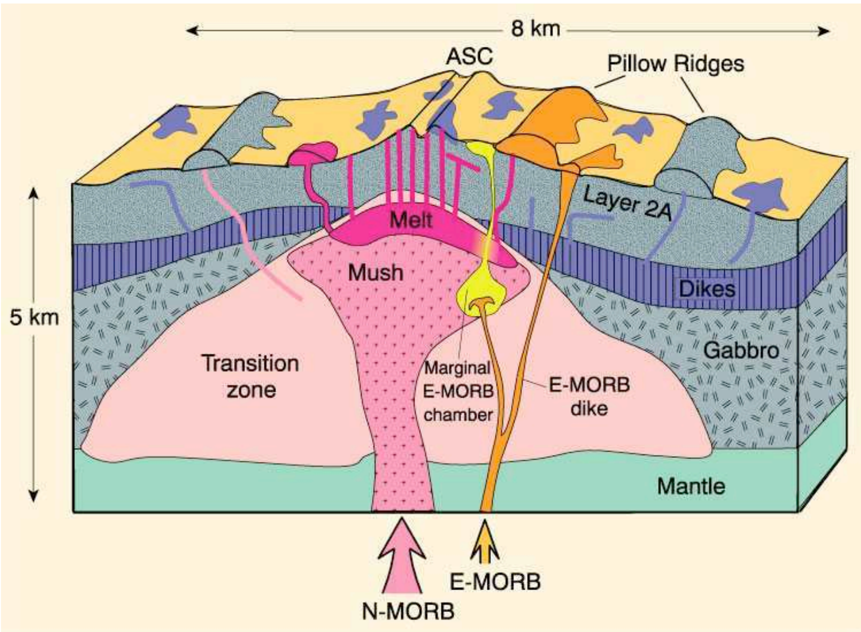
Searle et al., 1998





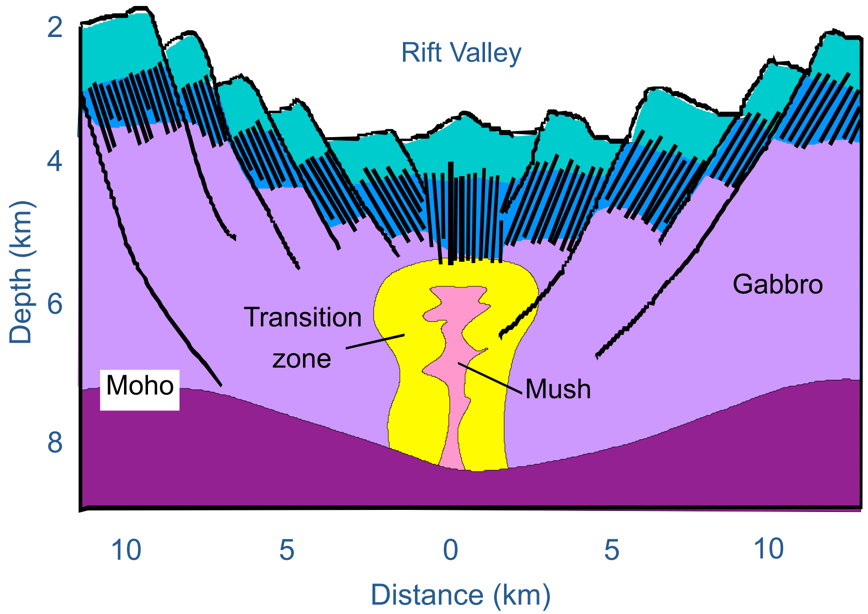
Sempéré et al., 1993, Marine Geophysical Researches

magma chambers



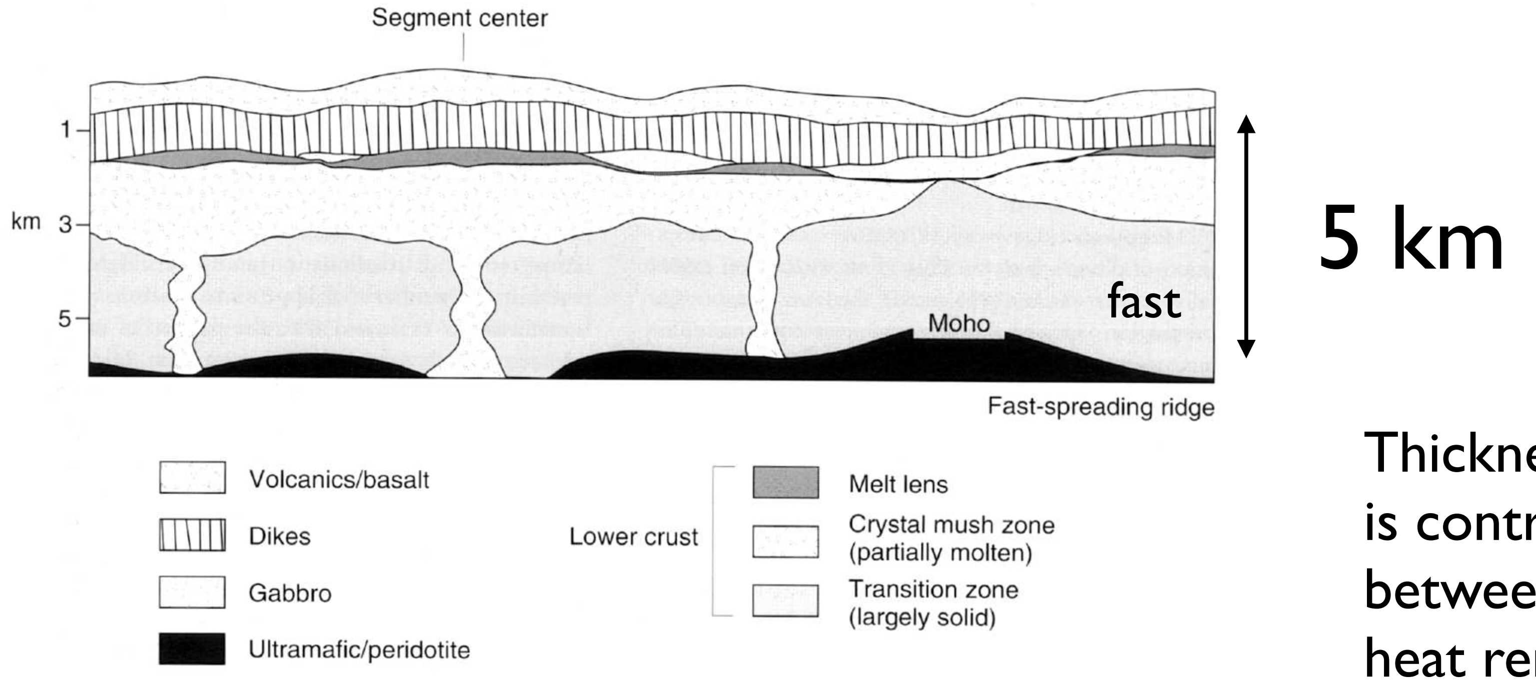
axial magma chamber beneath fast-spreading ridge

After Perfit et al. (1994) Geology, 22, 375-379.
After Sinton and Detrick (1992) J. Geophys. Res., 97, 197-216.

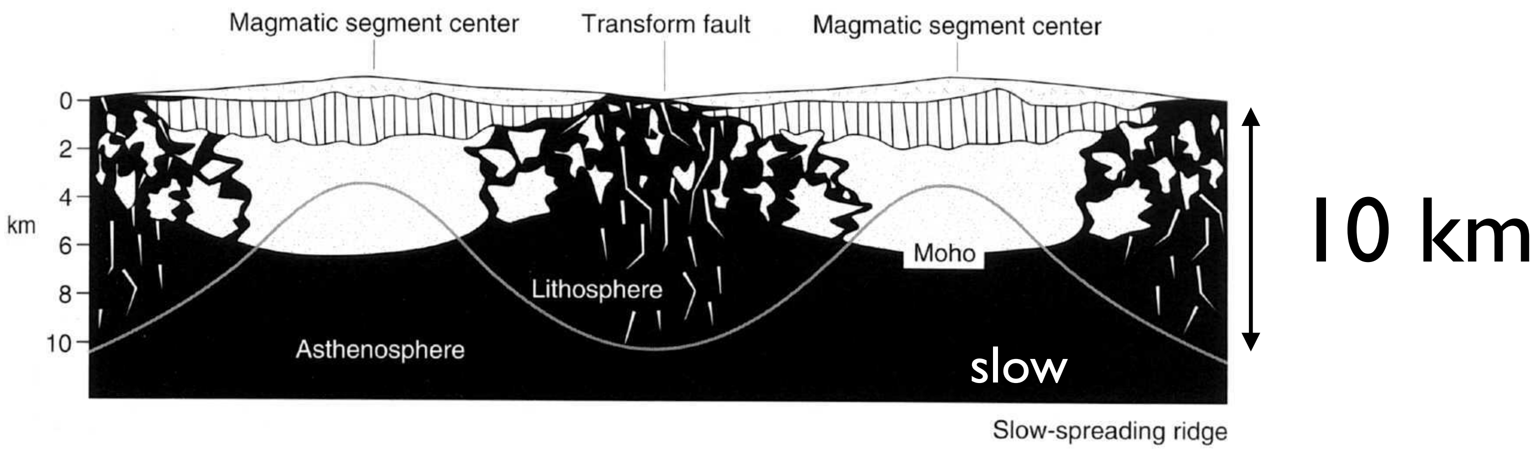


axial magma chamber beneath slow-spreading ridge

profiles along ridges



Thickness of lithosphere is controlled by balance between heat input and heat removal



Keary et al. 2009

ridge morphology

Two processes control ridge morphology:

1. Stretching of mechanically strong lithosphere makes median valley at spreading center
2. Thickness of lithosphere is controlled by balance between heat input and heat removal

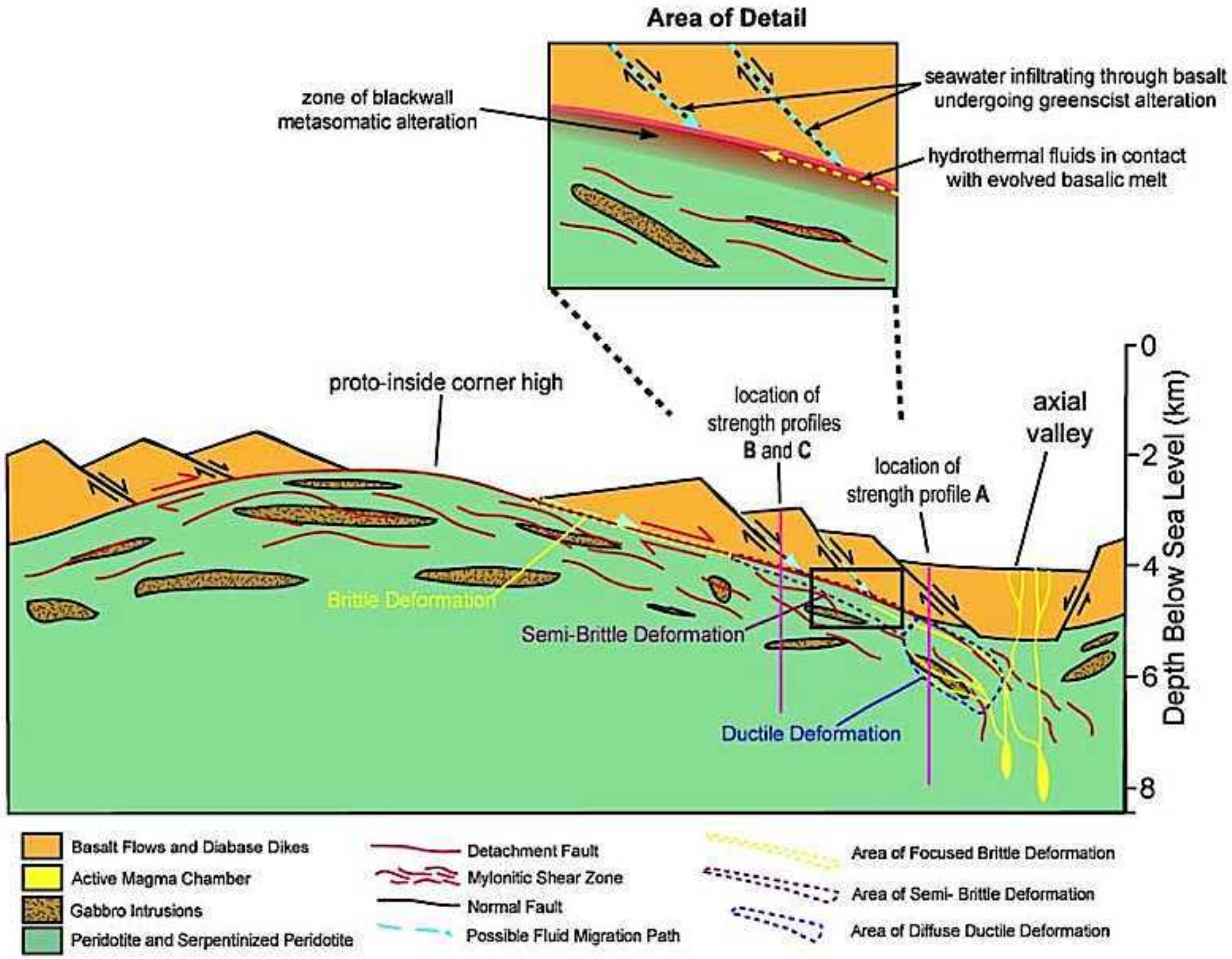
⇒ Ridge morphology is a consequence of thermal structure

Thermal structure is determined by two factors:

1. Rate and geometry of magma supply
2. Efficiency of heat removal by hydrothermal circulation (cracking / normal faulting at $T < 600°C$).

Magma ascent by buoyancy – stopped by freezing at top of magma chamber (solidus at 1200°C)

low angles faults at ridges



Asymmetric ridges because of low angle normal faults denuding mantle at ridges

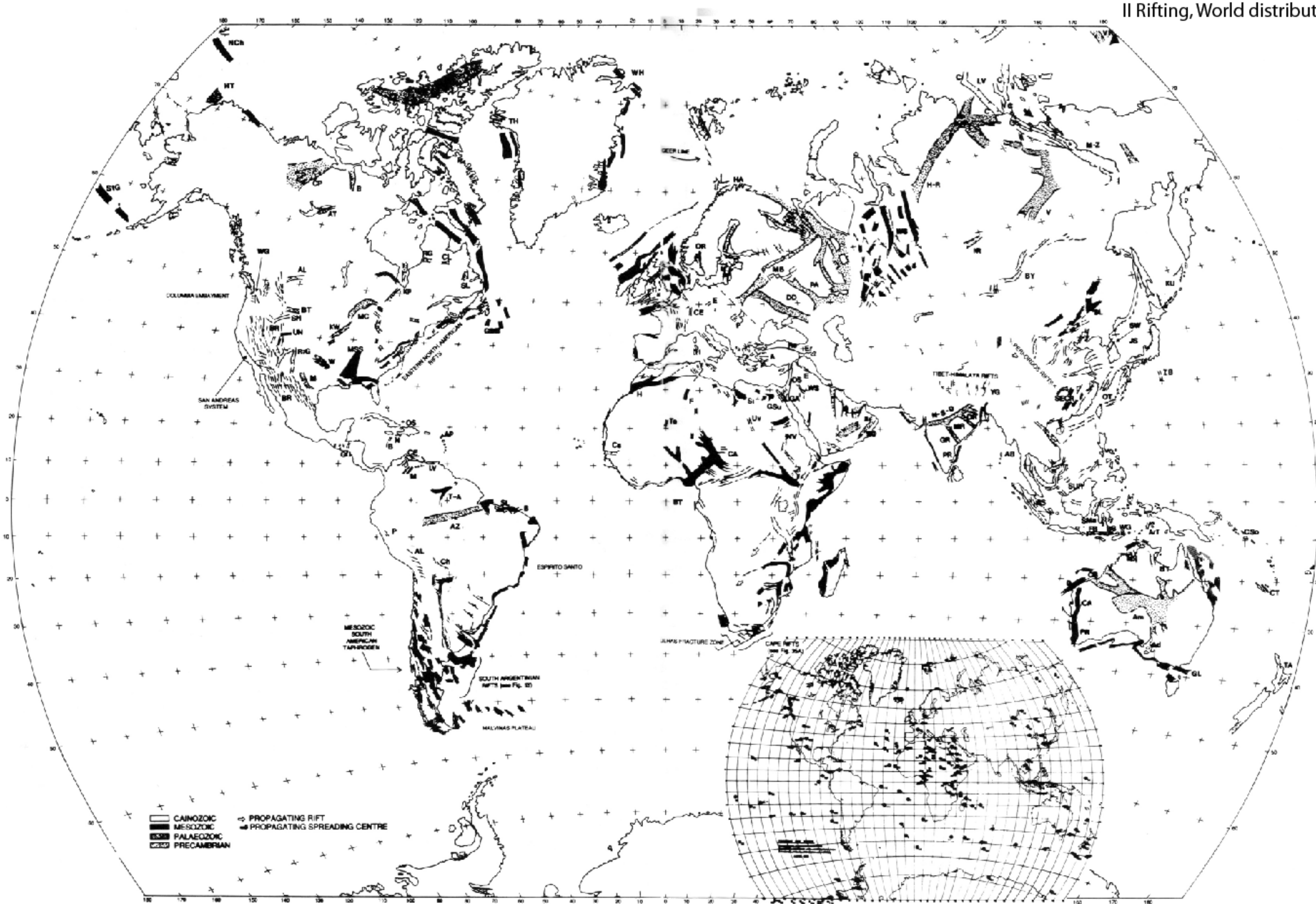
- low angle normal faults at ocean ridges
- similar to metamorphic core complexes
- deformation localized through reactions from viscous to semi-brittle

rifts

(Beilagen z.T. modifiziert nach Claudio Rosenberg)

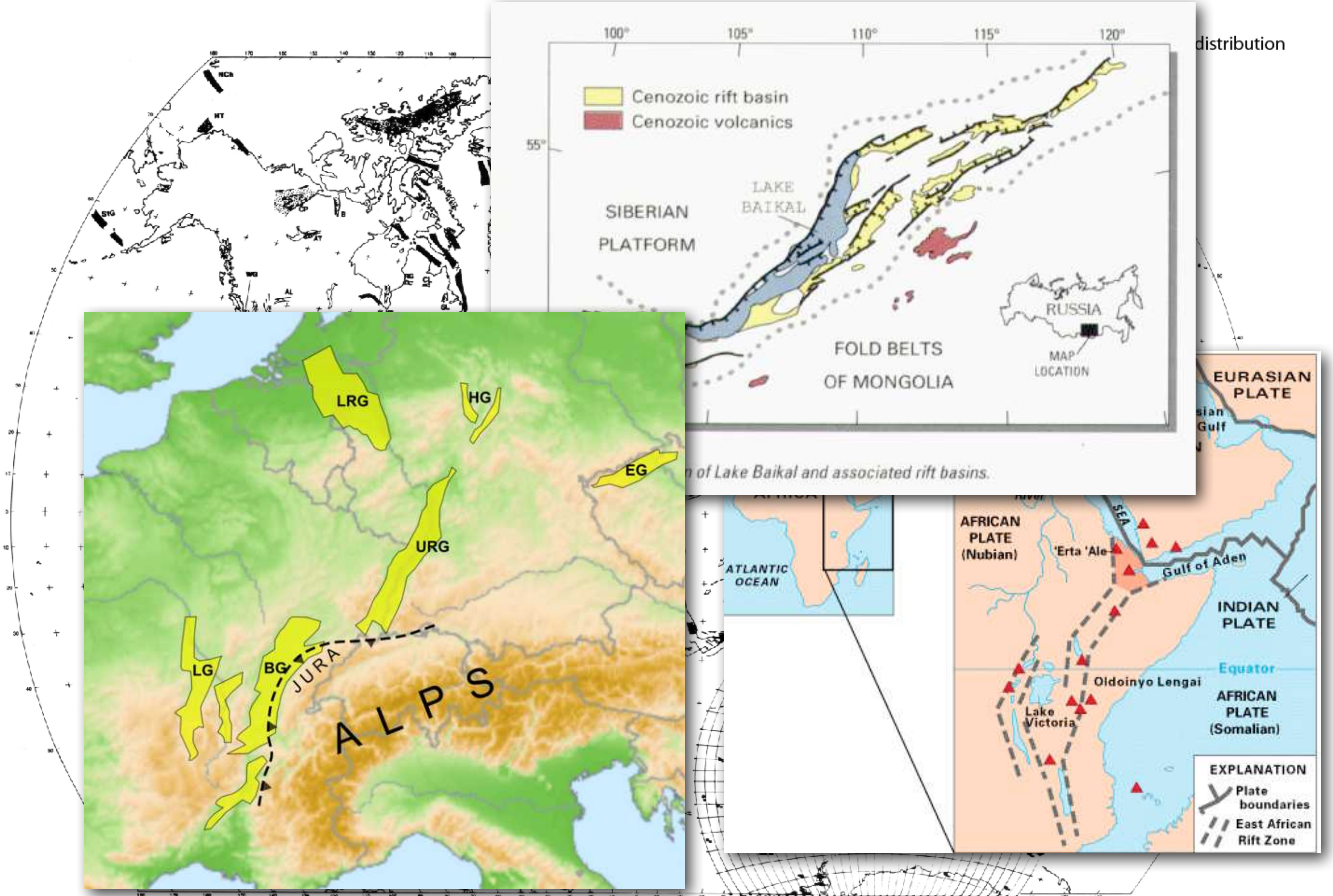
distribution of rifts worldwide

II Rifting, World distribution



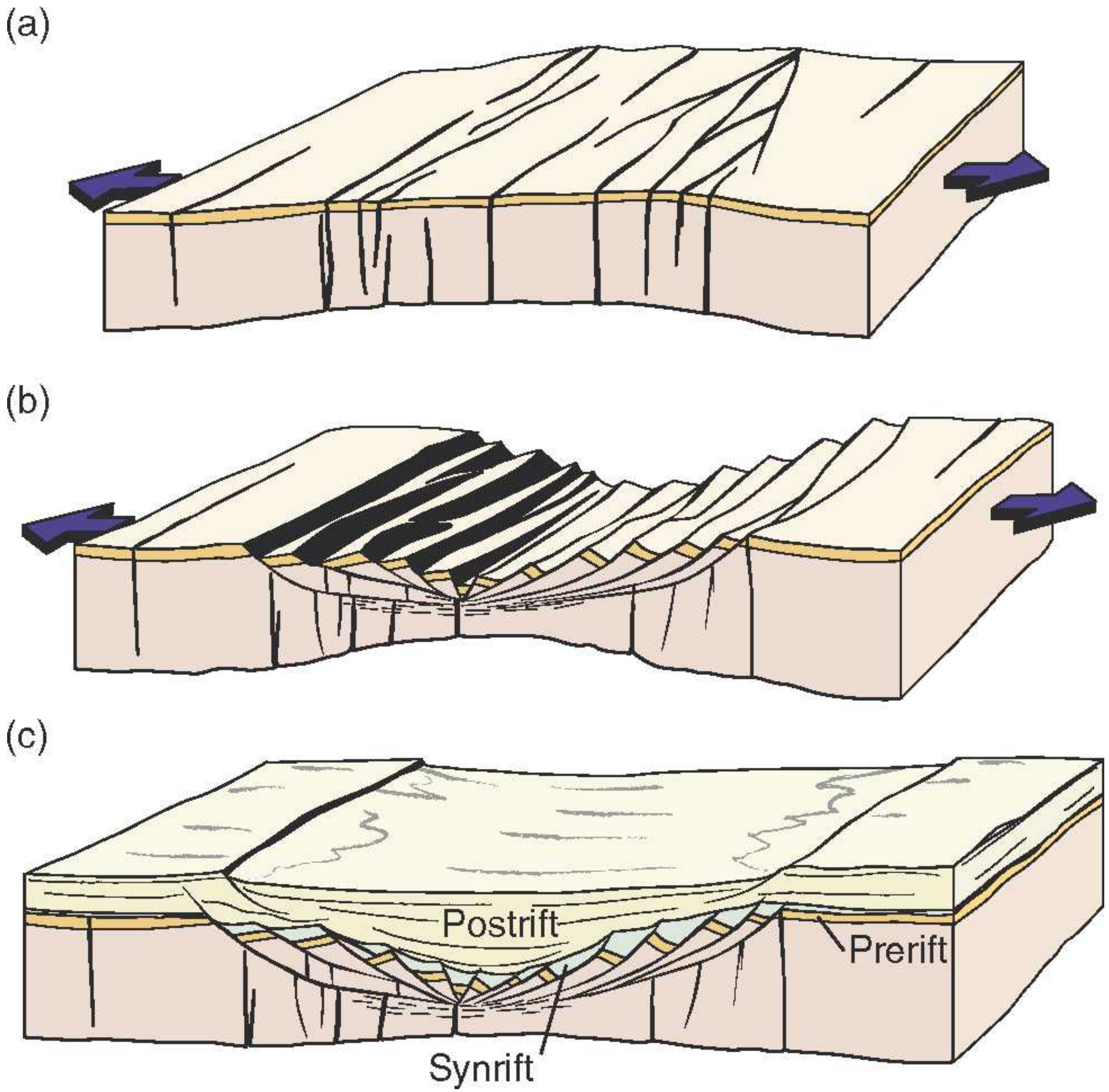
Sengör, 1995

distribution of rifts worldwide



Sengör,1995

rifting



rifts - definition

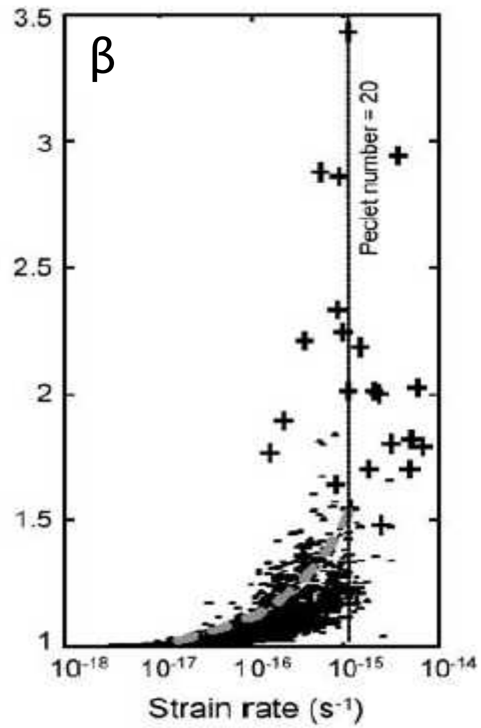
RIFT: region where the crust has split apart.
GRABEN: depression or trough, which is much longer than it is wide.

"Rift" comes from the root "reve", meaning to tear apart, or to pull asunder.
"Graben" is purely descriptive, rift is genetic (extensional rupture).
(A.M. Sengör, 1995)

Commonly, if the stretching factor β exceeds 3, sea-floor spreading starts, opening an ocean and destroying the rift.

$\beta = t_0/t_c$ t_0: initial crustal thickness
t_c: present crustal thickness

Rifts, which do not attain the oceanic stage are termed "failed rifts". This term should better be replaced with "fossil rifts", because these structures are not failed rifts, but rather failed oceans.

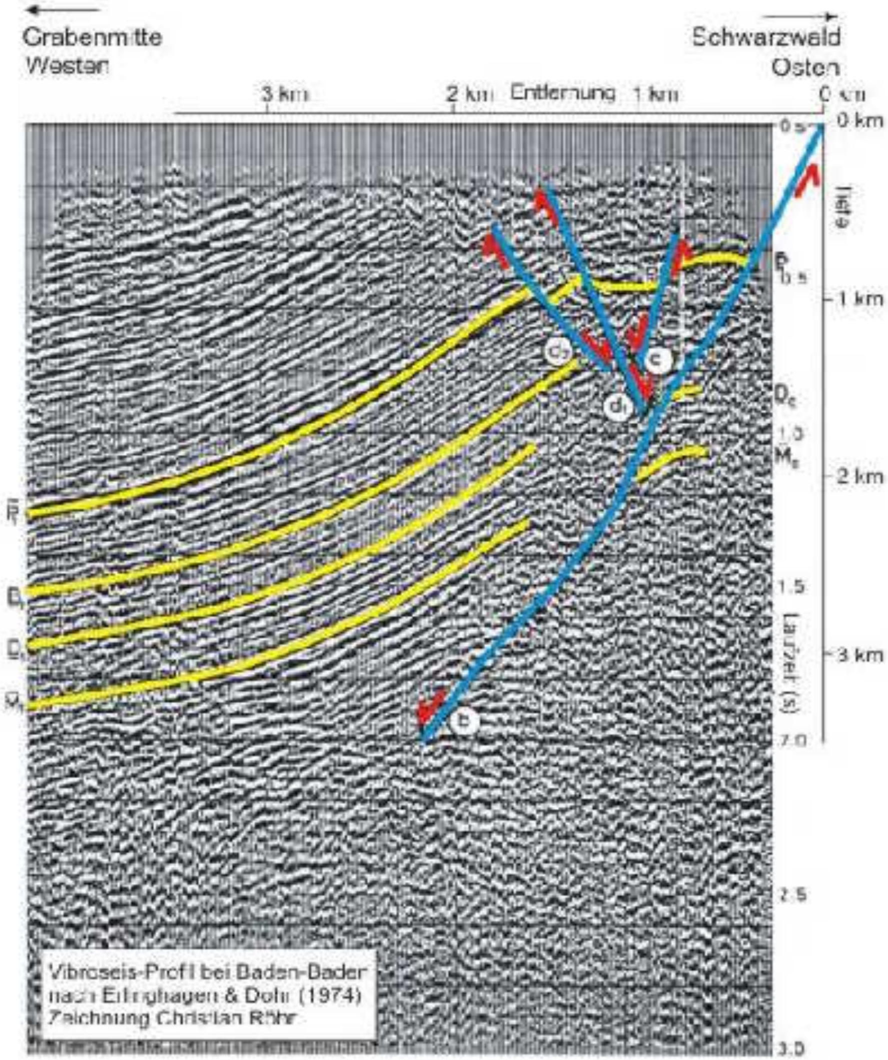


+ Rift basins of the Atlantic margins
· sedimentary basins

common chracteristics of rifts

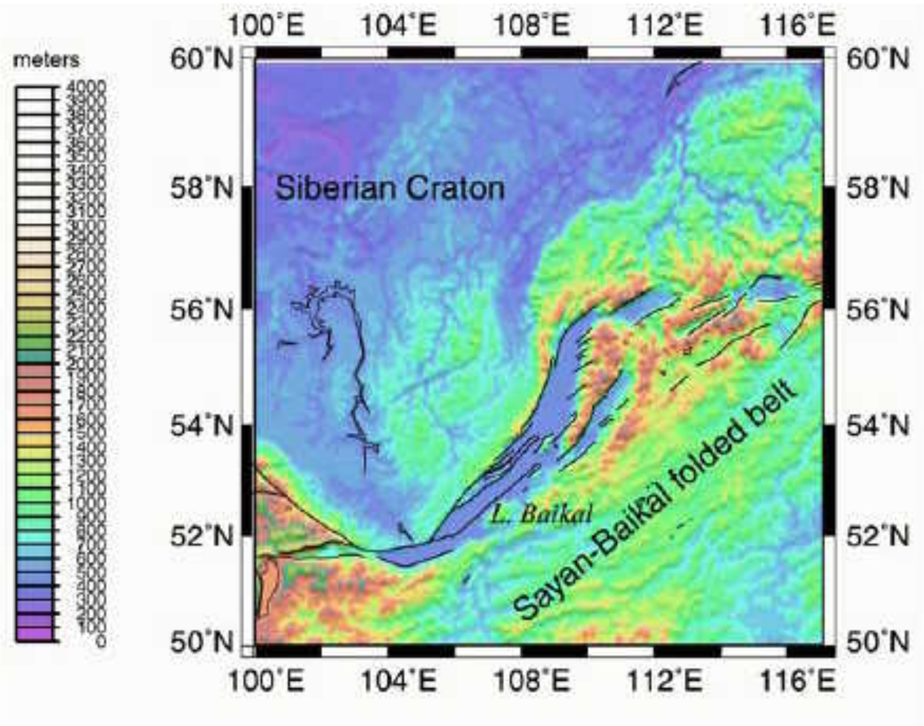
1. A rift or Graben structure with a rift valley flanked by normal faults

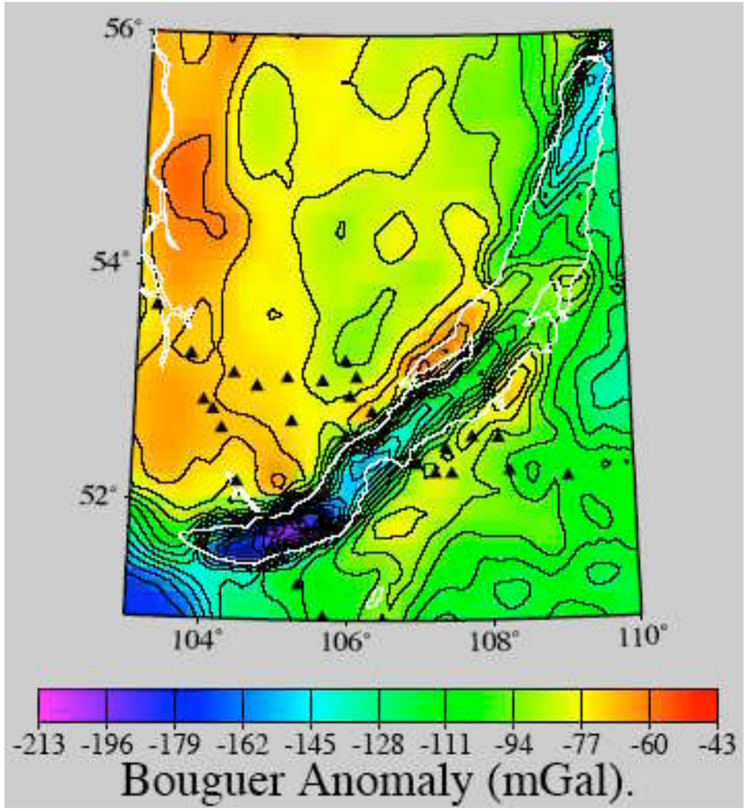
View of the Dabbahu rift, Afar region of Ethiopia. Recent lava flows are cut by subvertical normal faults.



common chracteristics of rifts

2. Negative Bouguer gravity anomalies (mass deficit)

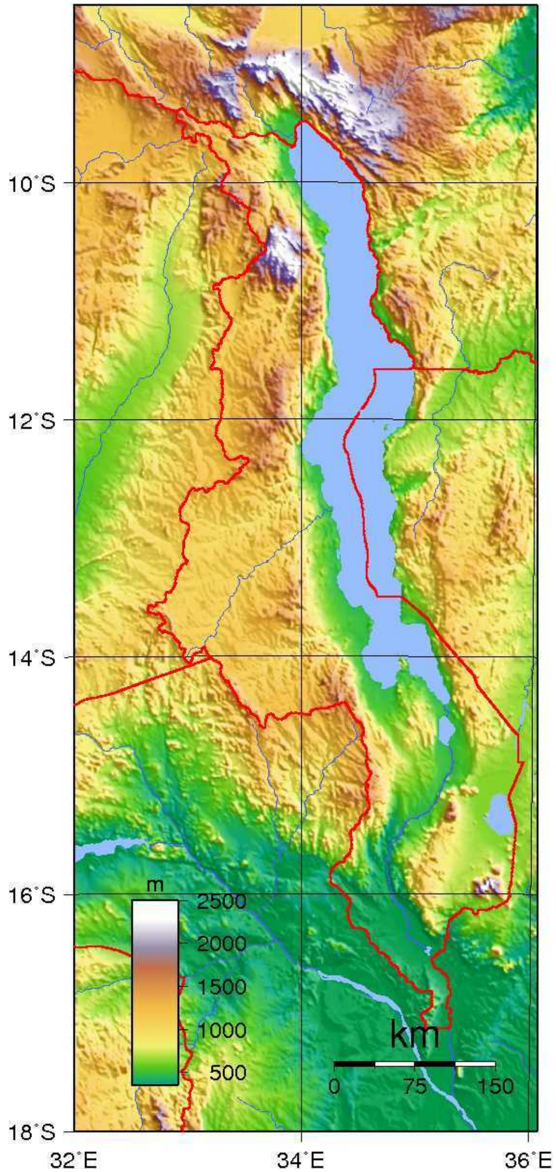




www.ipgp.jussieu.fr/files_lib/
307_2001_AGU_insights%20into%20baikal.pdf

common chracteristics of rifts

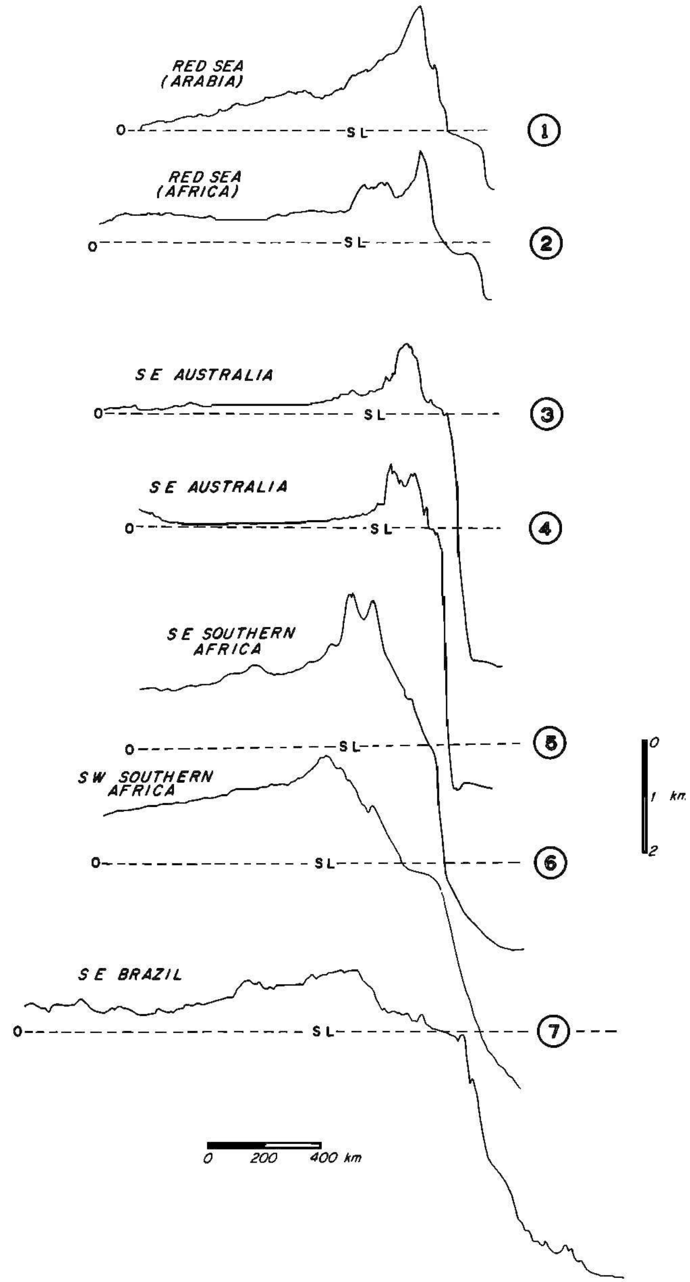
3. Uplifted rift shoulders



Lake Malawi

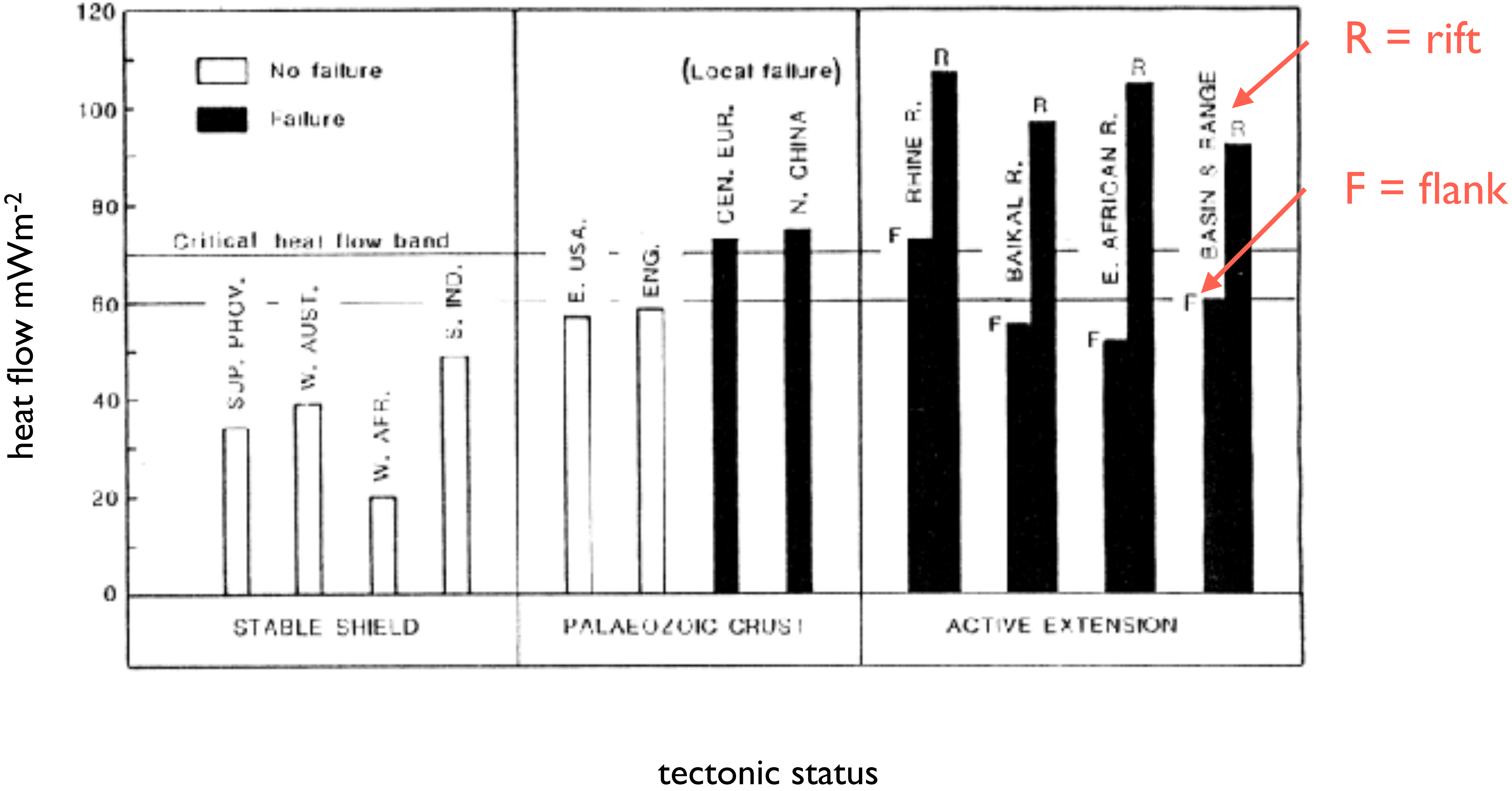
Rift flank uplifts are permanent structures. In SE-Brazil and S-Africa extension terminated in the Late Jurassic/early Cretaceous. Therefore, thermal support should have ended long time ago.

These structures can be explained by mechanical unloading during extension and consequent isostatic rebound, provided the lithosphere retains flexural rigidity, i.e. no local, but flexural (regional) isostatic response takes place.



common chracteristics of rifts

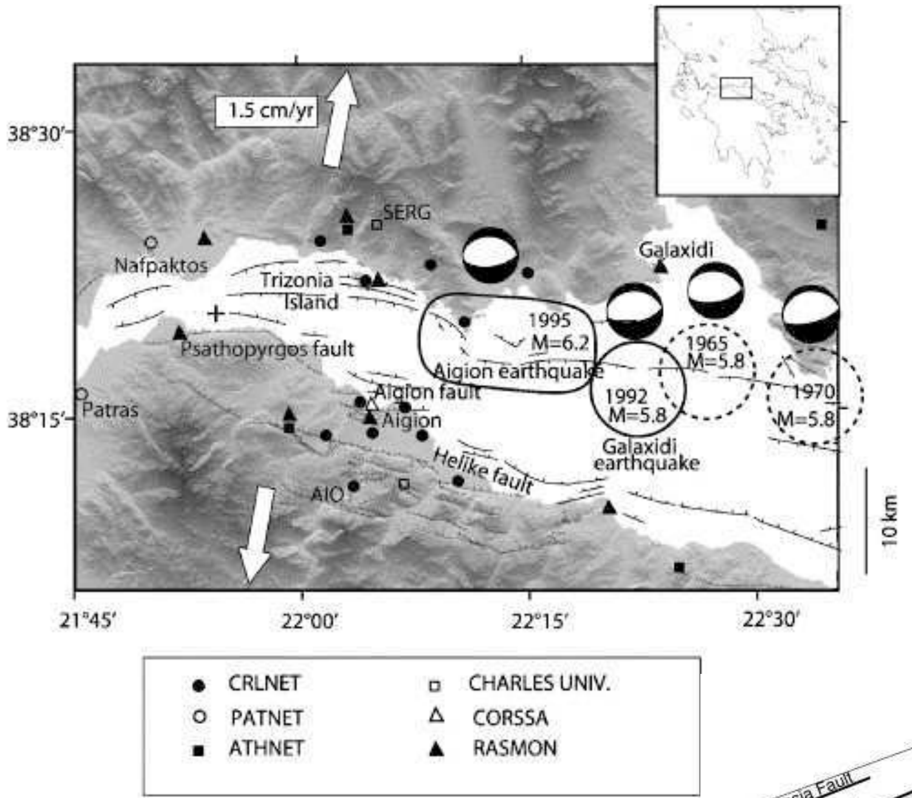
4. Higher than normal surface heat flow

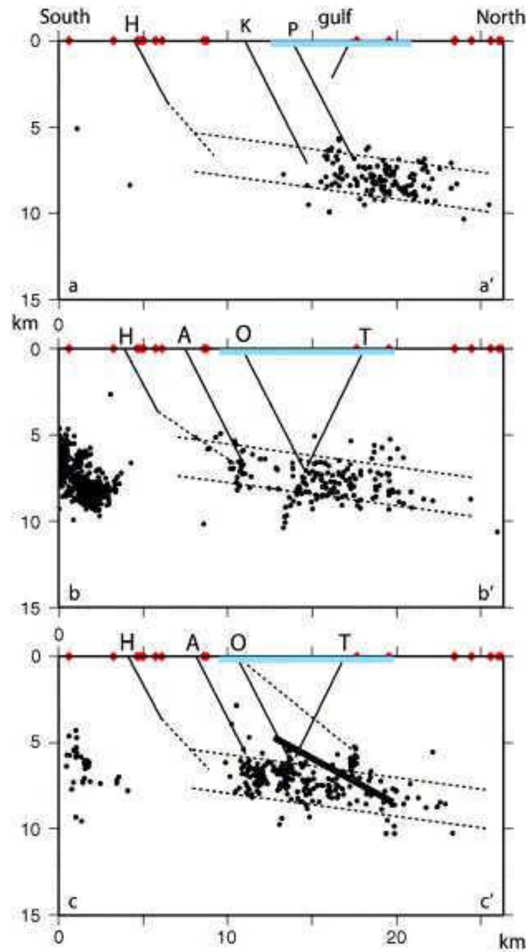


Kusznir and Park, Geological Society of London, Special Publication, 28.

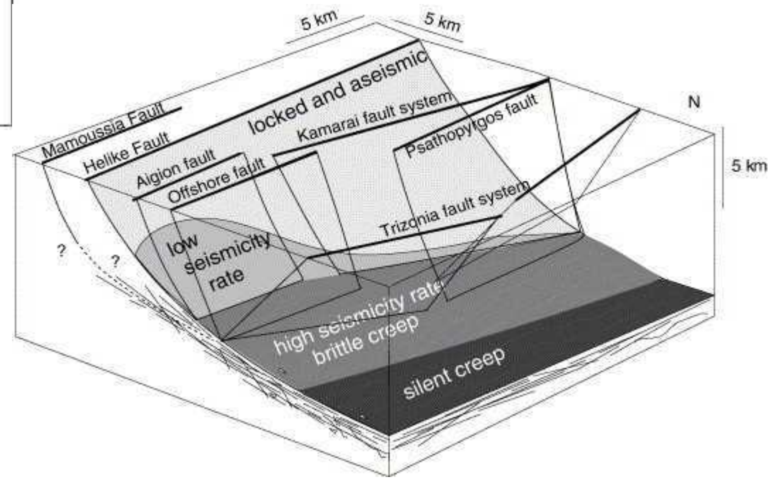
common chracteristics of rifts

5. Shallow, tensional seismicity





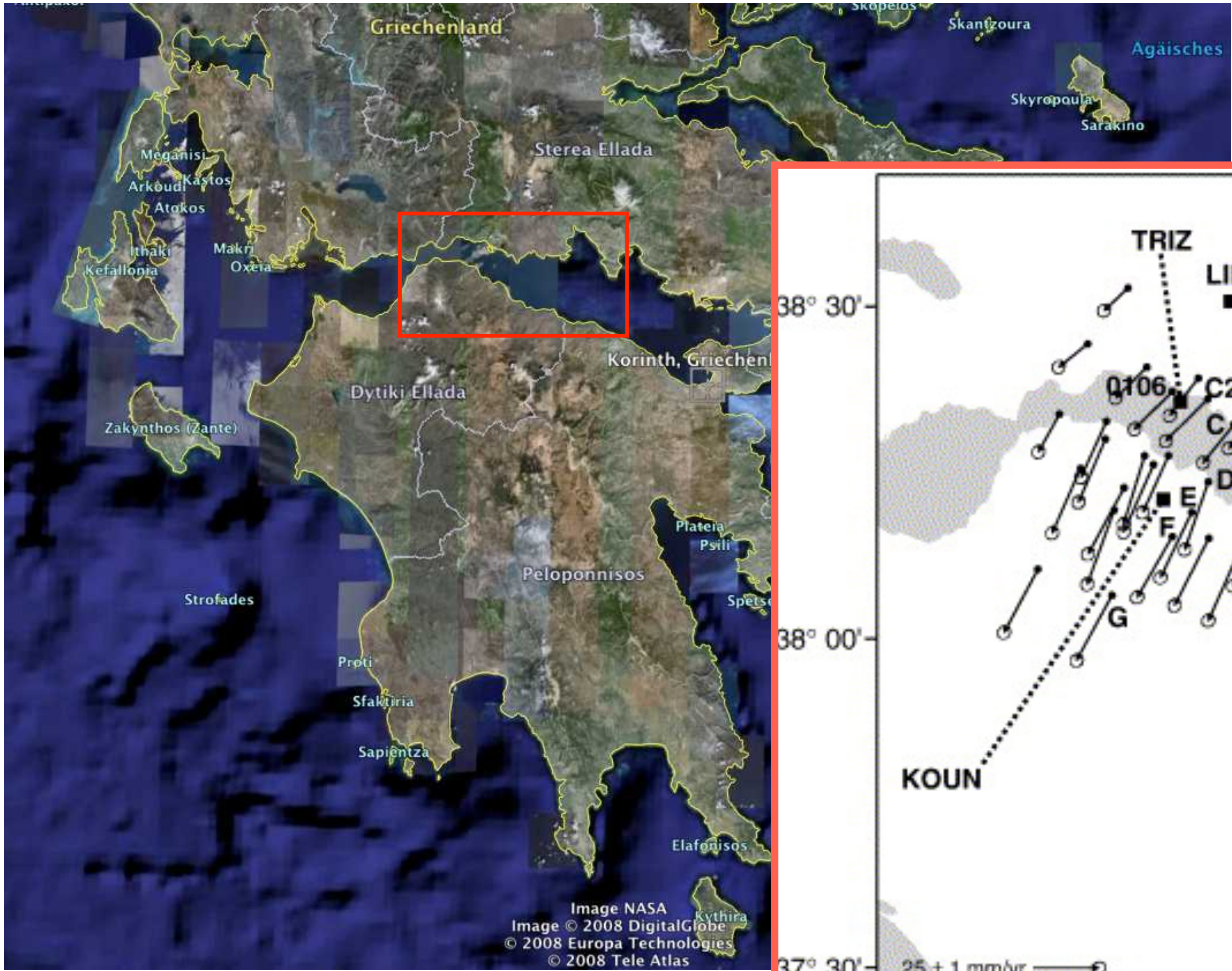
Gulf of Corinth

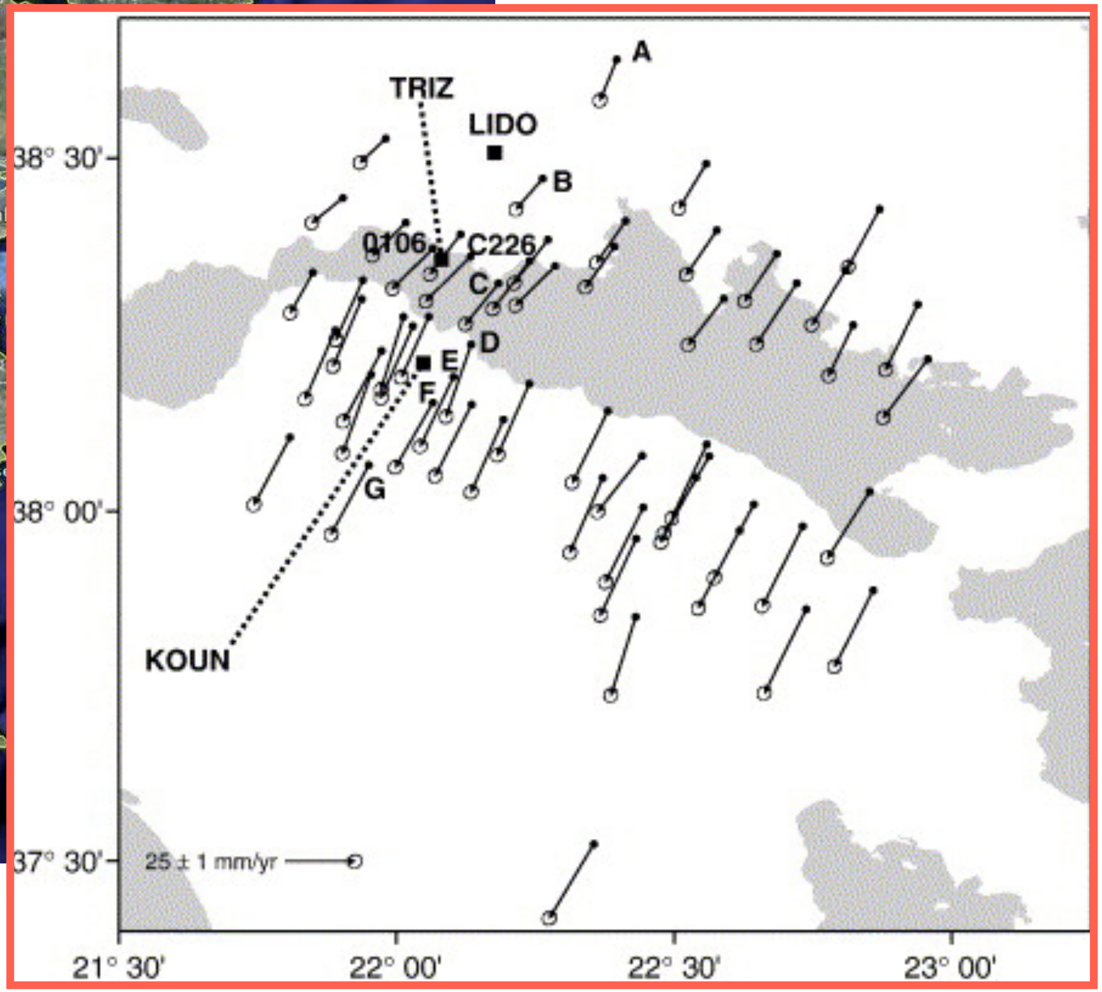


Bernard et al., 2006, Tectonophysics

common chracteristics of rifts

6. Differential motion of both rift flanks during activity

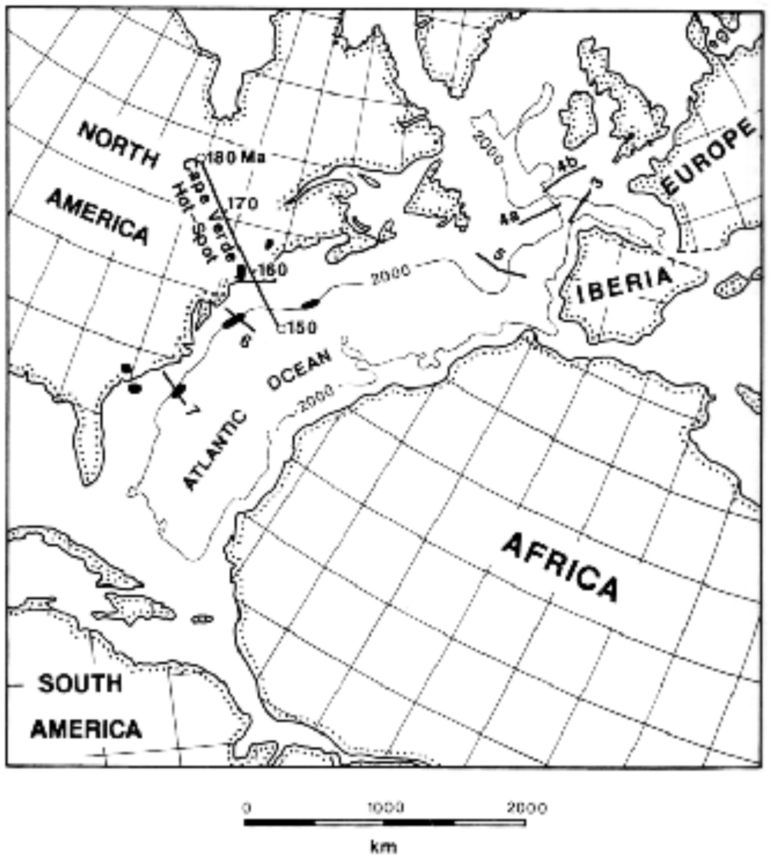




Bernard et al., 2006, Tectonophysics

common chracteristics of rifts

7. Thinning of the crust beneath the rift valley



White and McKenzie, 1989, J. Geophys. Res

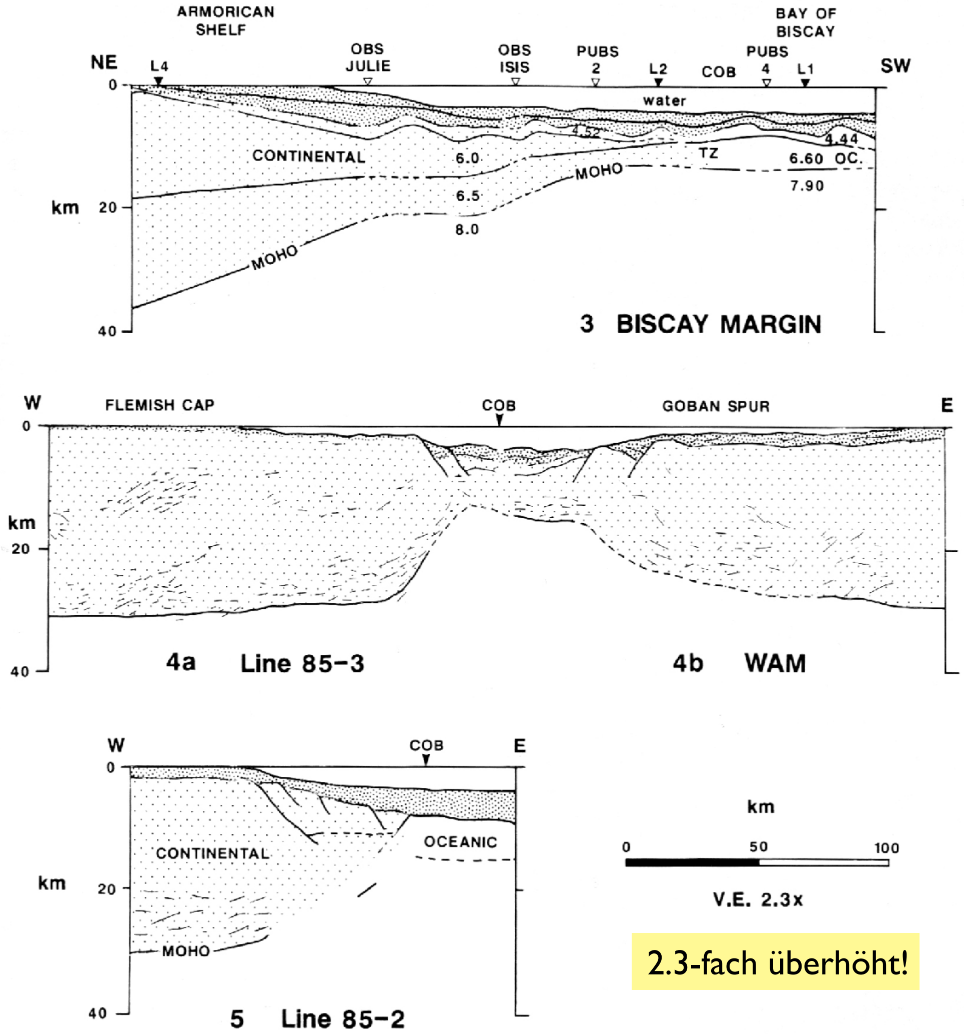
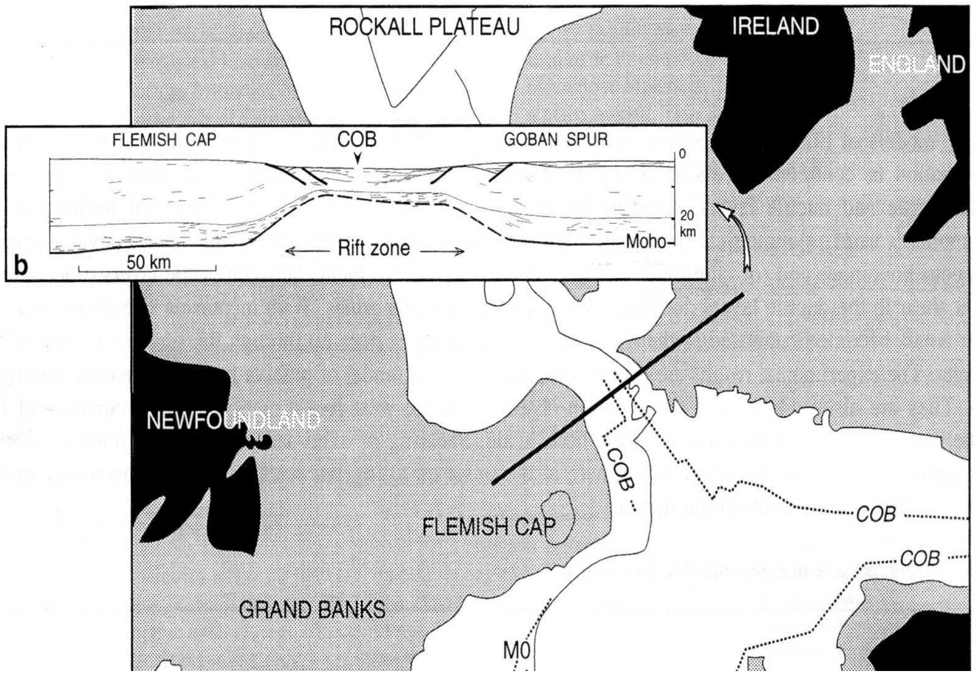


Fig. 12. Cross sections showing deep structure of the Biscay margin, the Western Approaches margin and Newfoundland margins. For locations see Figure 13. Biscay margin (profile 3) is redrawn from *Ginzburg et al.* [1985]. Western Approaches–Flemish Cap composite line (profile 4) is redrawn from *Keen et al.* [1989] Newfoundland margin (profile 5) is from *Keen and de Voogd* [1988] line 85-2. Key to symbols and scales are the same as for Figure 9.

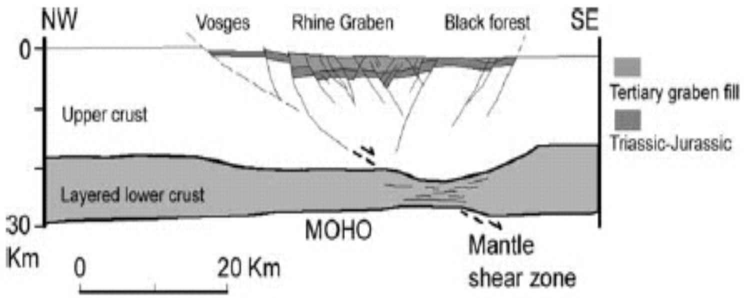
rifting

(Beilagen z.T. modifiziert nach Claudio Rosenberg)

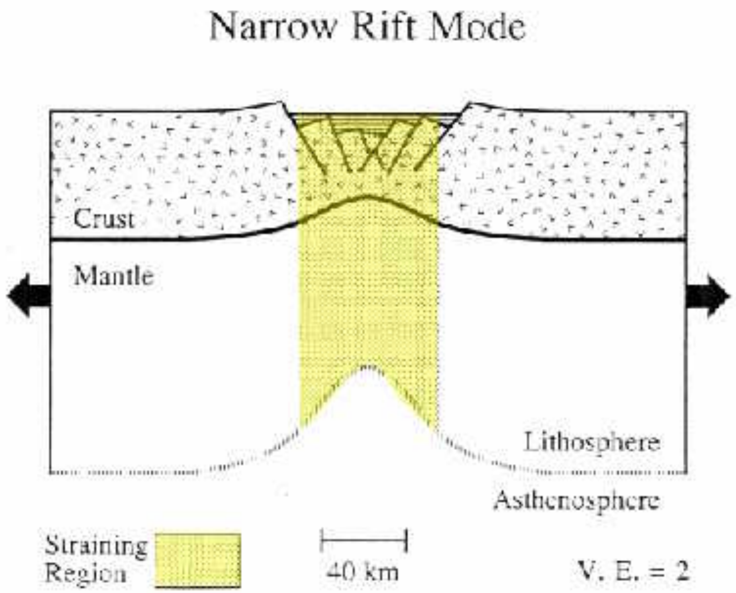
narrow rifts



Brun and Beslier, 1996, Tectonophysics



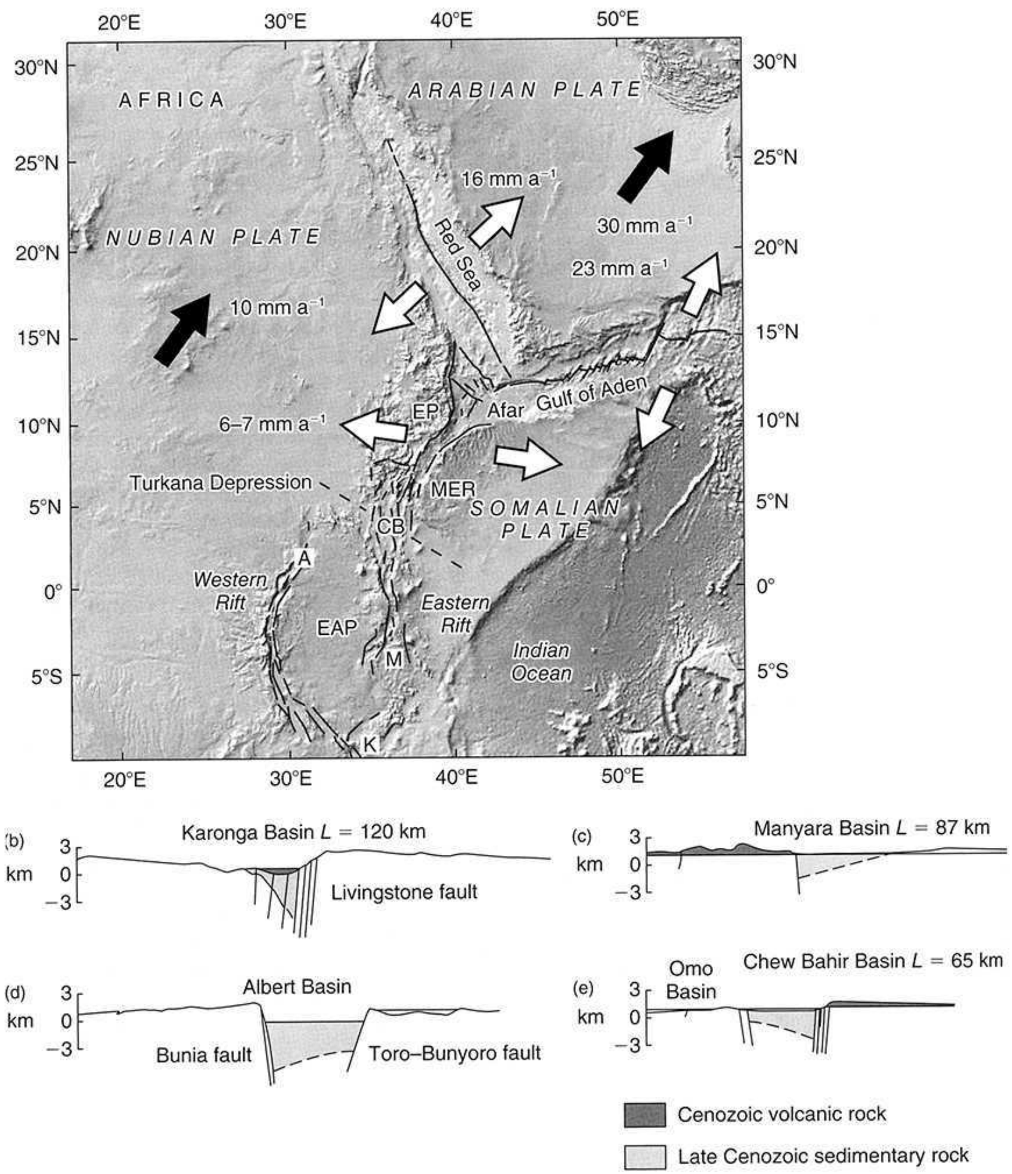
DECORP-ECORS deep seismic profile
modified after Brun et al., 1992



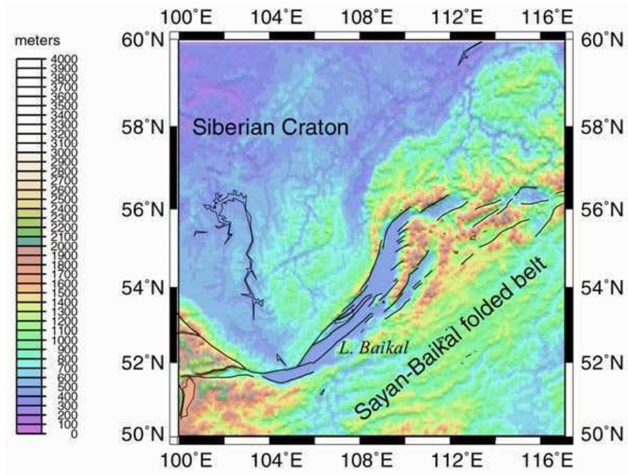
Die Verformung (gelbe Fläche) ist stark lokalisiert und reicht bis in den Mantel hinein. Die Moho und die Basis der Lithosphäre bilden eine „Antiform“

Buck, 1991, J. Geophys. Res.

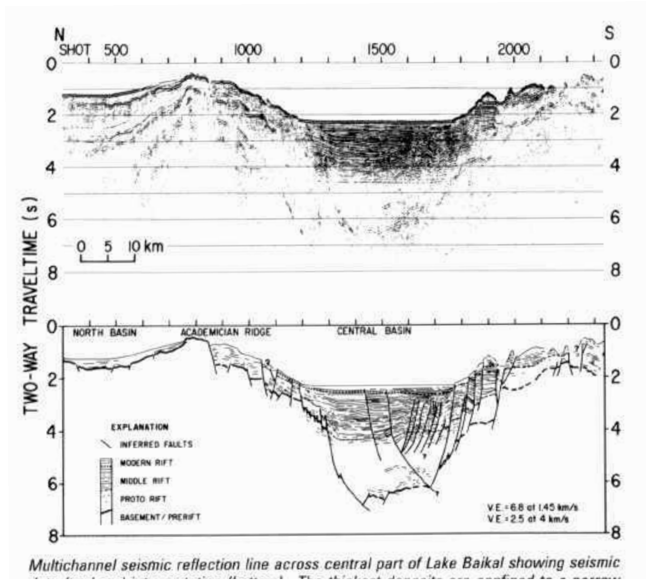
Red Sea   Lake Baikal



Kearey, Klepeis and Vine, 2009, Global Tectonics, Wiley-Blackwell

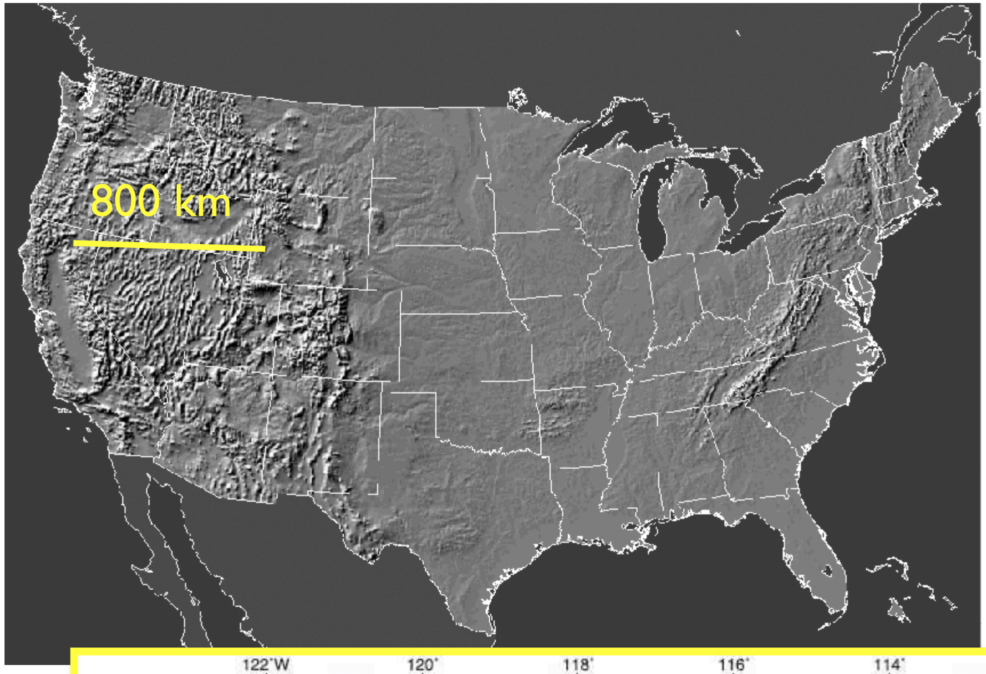


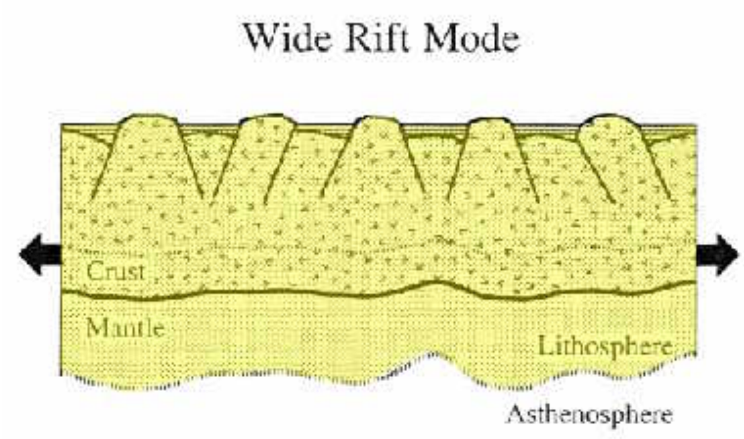
www.ipgp.jussieu.fr/files_lib/307_2001_AGU_insights%20into%20baikal.pdf

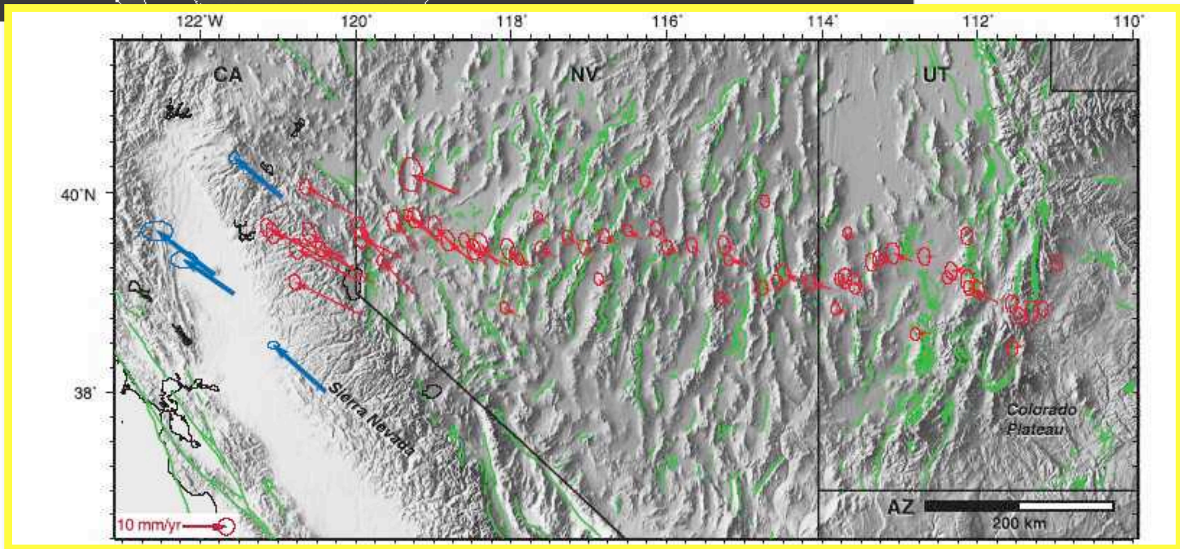


http://marine.usgs.gov/fact-sheets/baikal/baikal-2.gif

wider rifts







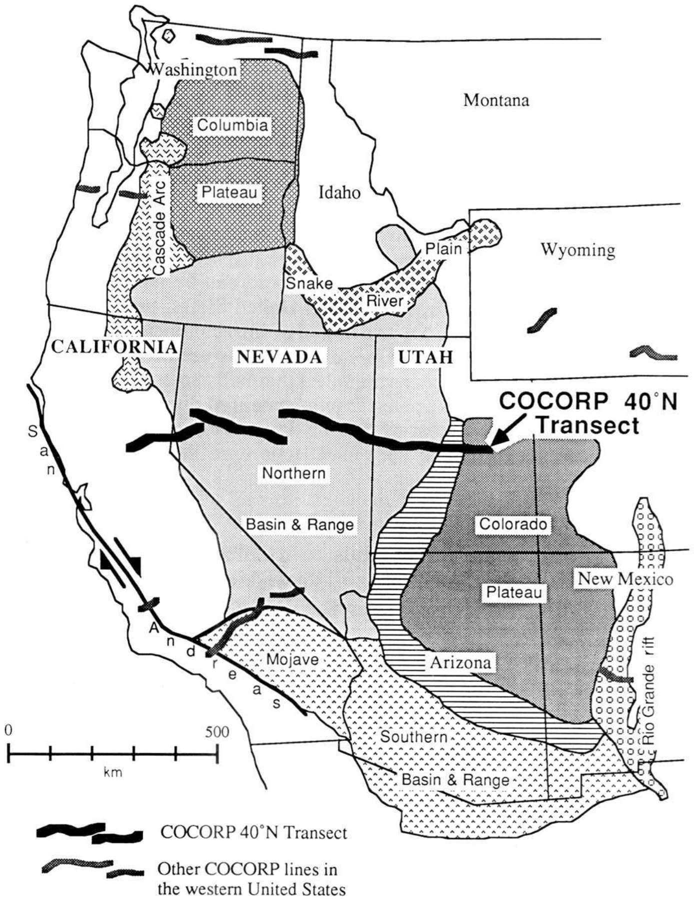
Thatcher et al., 1999, Science

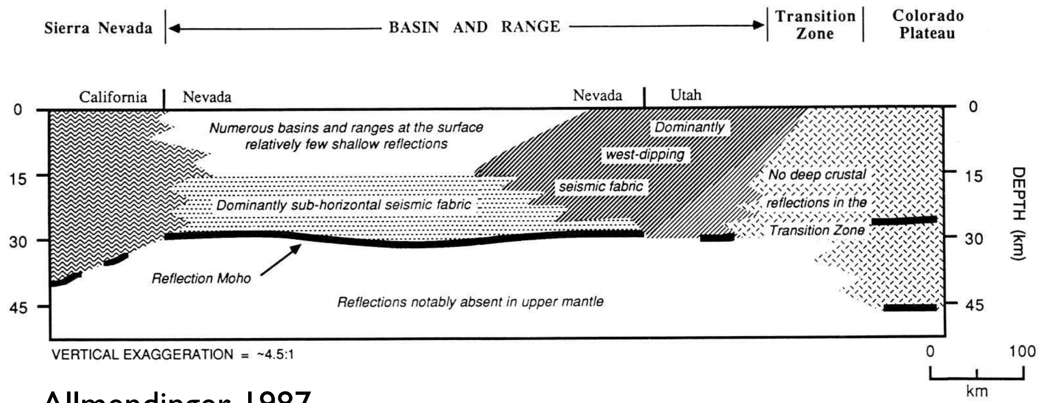
Die Verformung (gelbe Fläche) ist „delokalisiert“ (homogen verteilt) und reicht bis in den Mantel hinein

Buck, 1991, J. Geophys. Res.

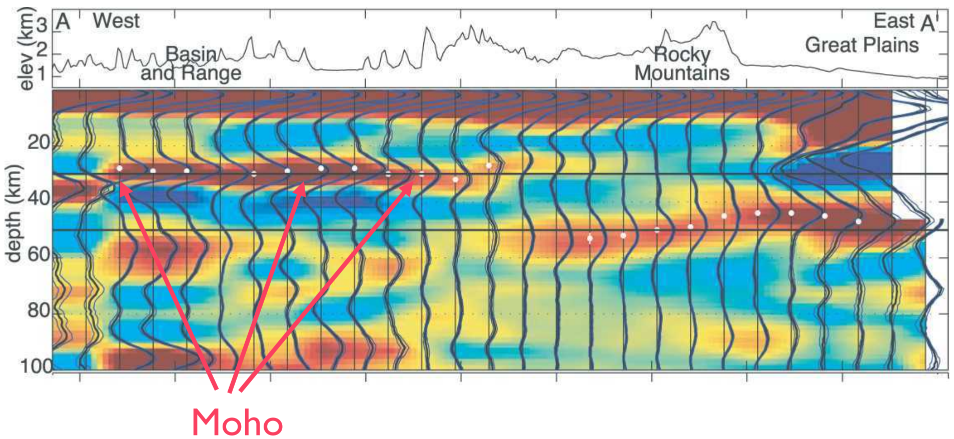
Flachliegende Moho

unterhalb der Basin and Range





Allmendinger, 1987

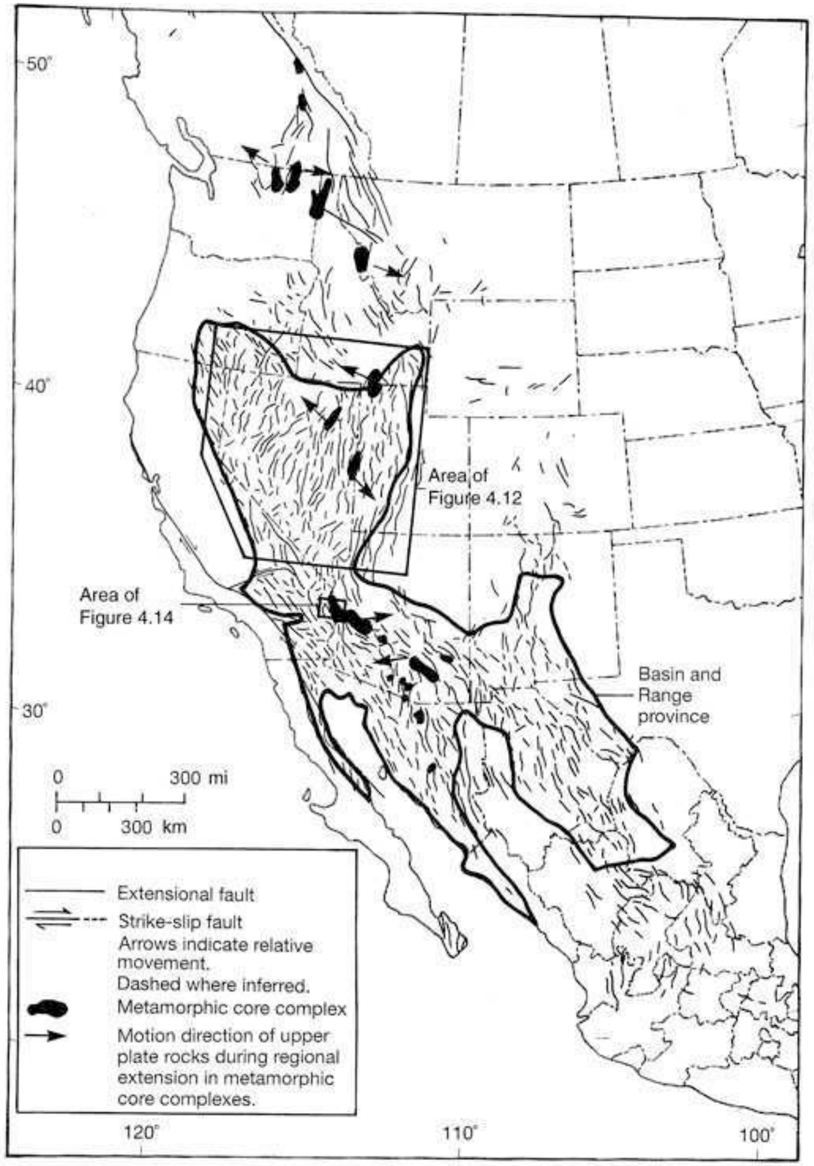


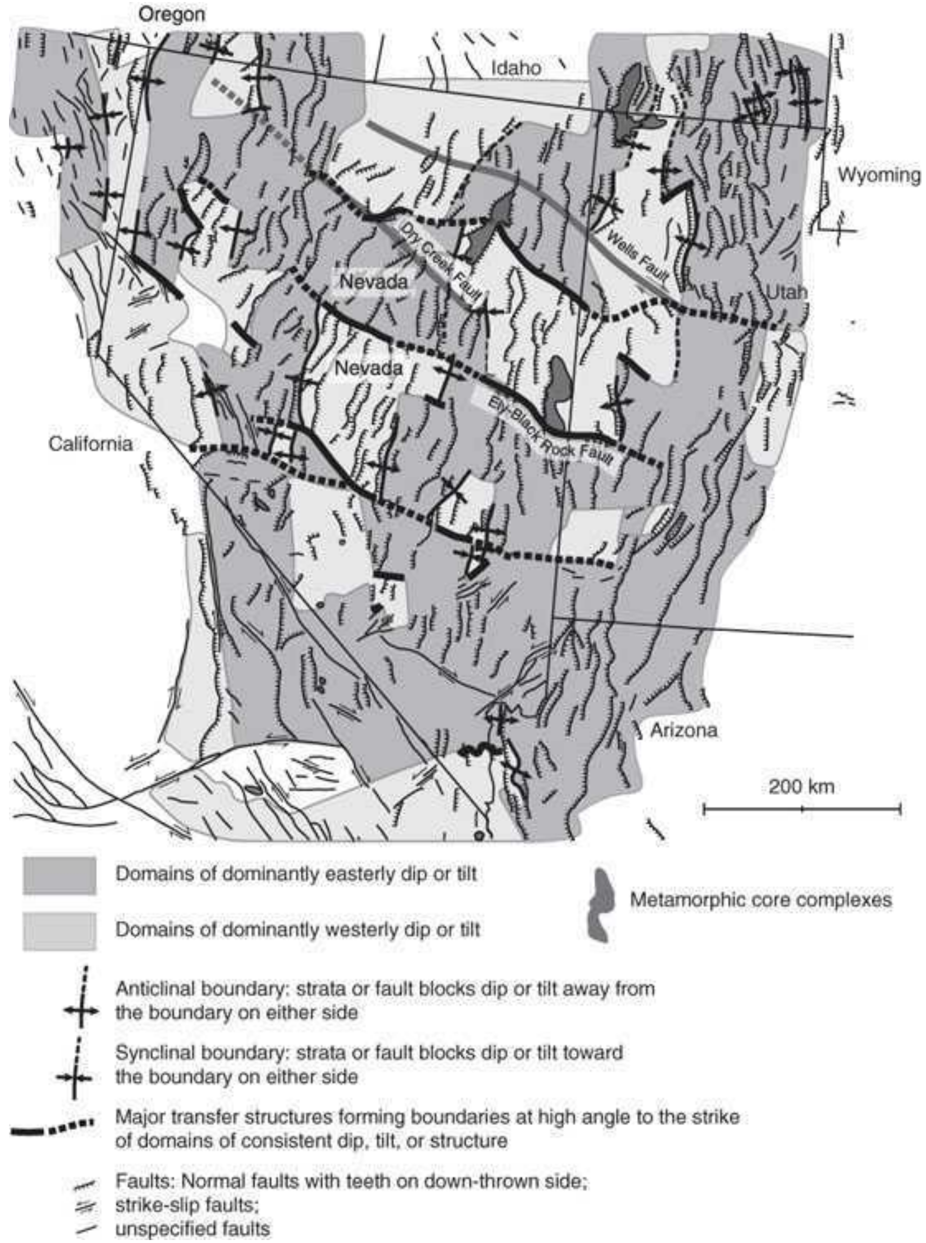
Gilbert and Shehaan, 2004, J. Geophys. Res.

metamorphic core complexes (MCC)

(Beilagen z.T. modifiziert nach Claudio Rosenberg)

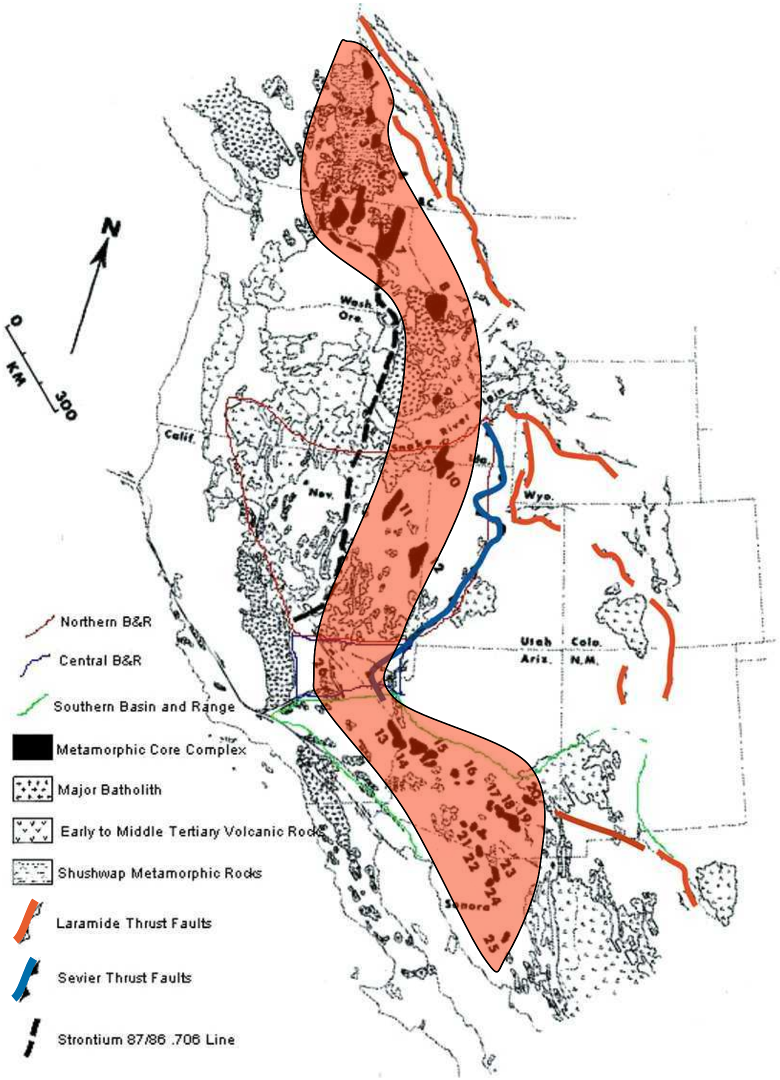
Beispiel: Western USA





Twiss & Moores, 2007

Geschichte und Definition



Davis and Coney, 1979, Geology

Mitte des 20. Jahrhunderts wurden hochmetamorphe Gebiete westlich der N-Amerikanische Kordillere, mit Durchmesser von bis > 100 km auskartiert.

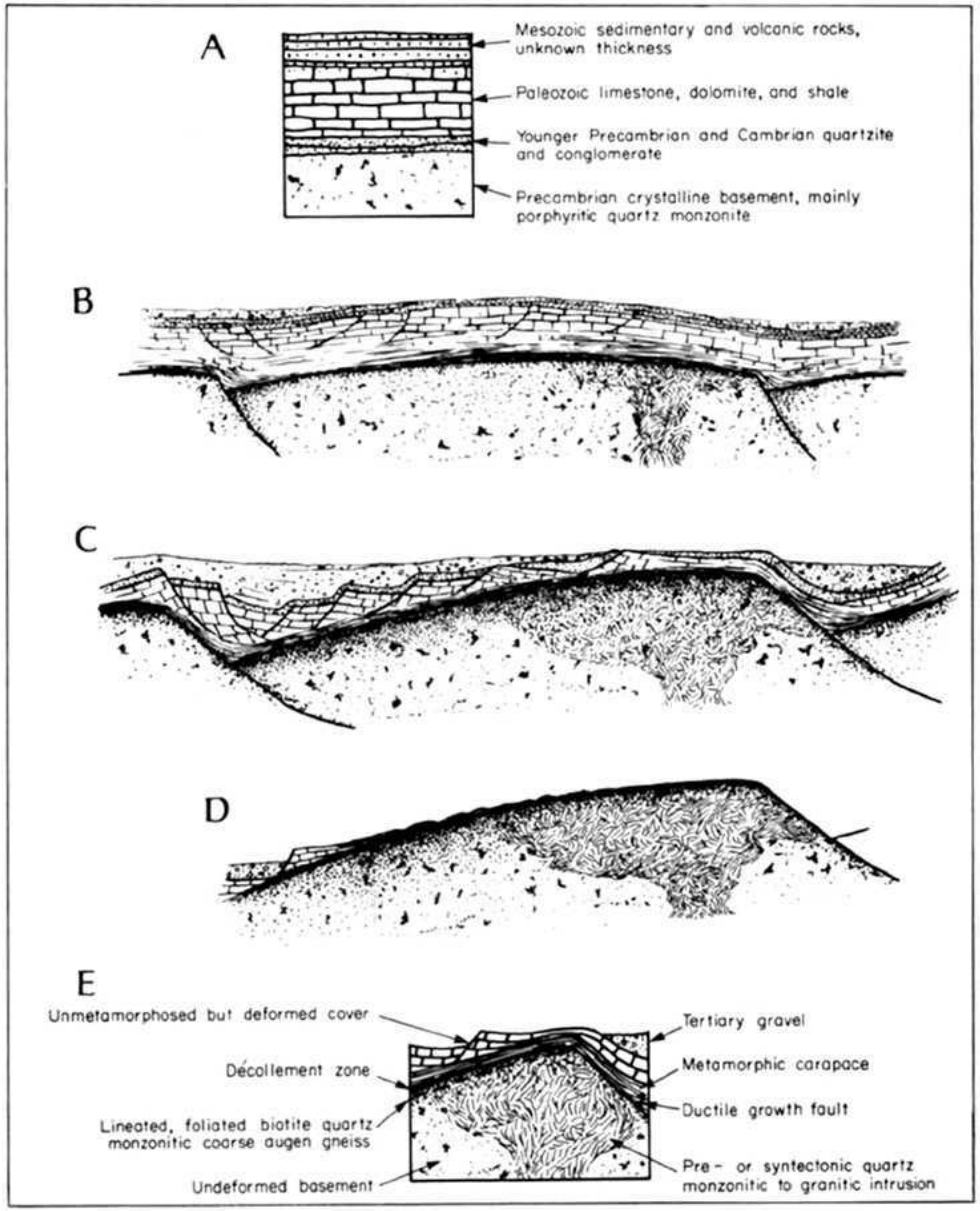
Typisch:
- Domartige Aufwölbung der Hochmet. Einheit
- Scharfe Grenze zur darüberliegende unmet. Einheit
- Grenze fällt zusammen mit flachliegende Störung(Detachment, Décollment)

→ Allgemeiner Begriff: Metamorphic Core Complex.

- von Canada bis Mexico, westlich der Vorlands-überschiebungen der Laramiden/Sevier Orogenese
- tiefste strukturelle Niveaus sind in der Axialzone aufgeschlossen, manchmal als Gneissdome

Frage: MCC Gürtel = Axialzone des Laramiden/Sevier Orogens ?

→ man versuchte EIN tektonisches Bild zu enwerfen der die Core Complexes UND die Vorlandüberschiebungen miteinschliesst



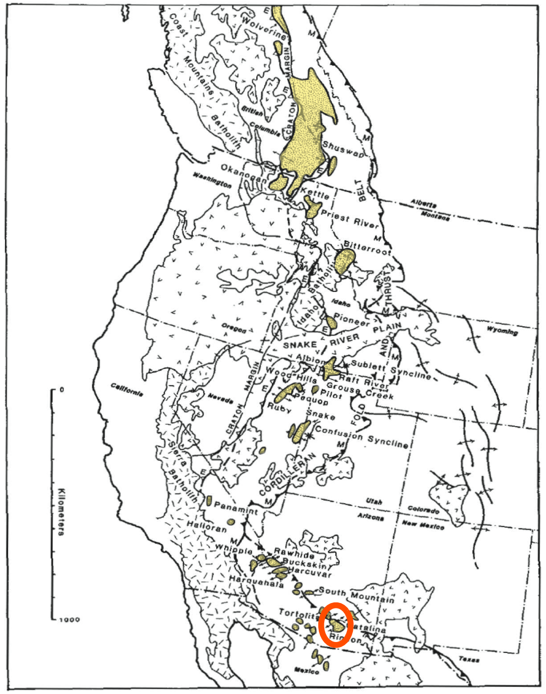
Ende der `70er Jahre konnten Entwicklungsmodelle gezeichnet werden, die sich kaum von den heutigen unterscheiden.

Die obere Einheit wird durch Abschiebungen progressiv ausgedünnt.

Dabei findet die Hebung und Exhumation der unteren, hoch metamorphen Einheit statt.

Davis and Coney, 1979, Geology

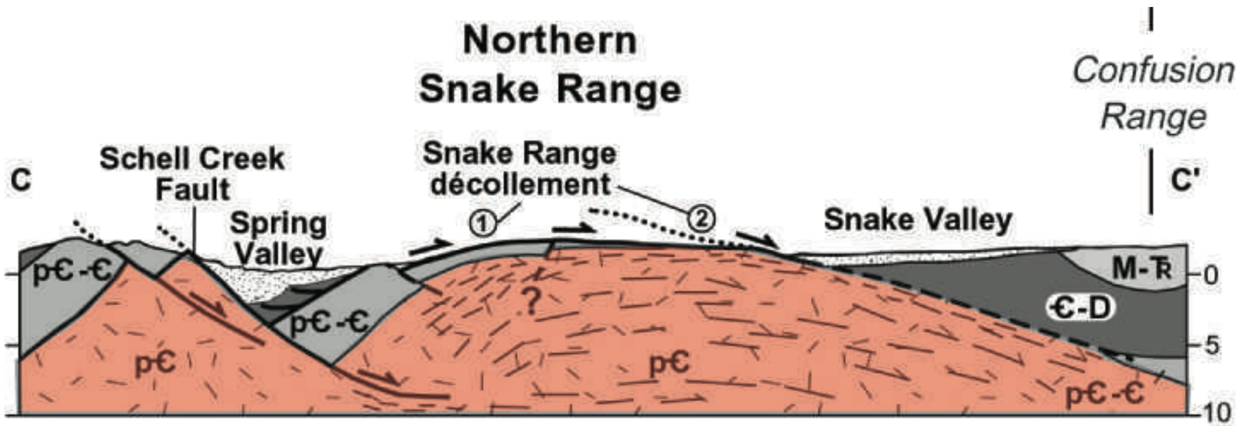
Geometrie, Struktur, Metamorphose



Asymmetrischer Dom der hochmetamorphen unteren Einheit.

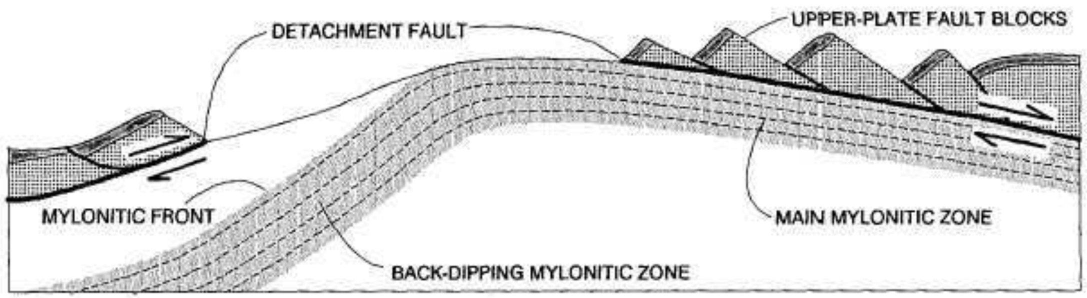
Ein Schenkel ist flacher und länger. Dieser ist vom Detachment überprägt.

Der zweite Schenkel ist kürzer, steiler, nicht vom Detachment überprägt.



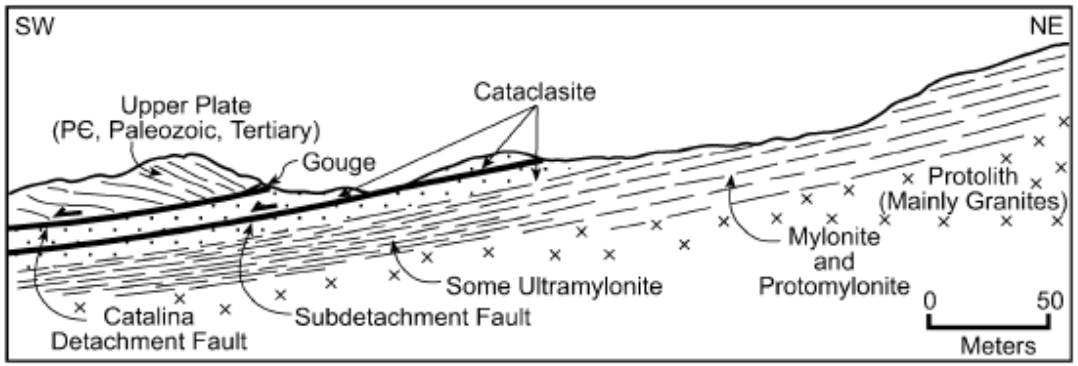
Miller et al., 1999, GSA Bull

Geometrie, Struktur, Metamorphose



South Mountain, Arizona, U.S.A. , Reynolds and Lister, 1990, Geology

Wenn beide Seiten des Doms durch Scherzonen begrenzt sind kann die eine Seite eine scheinbare Überschiebung darstellen.
→ ursprüngliche Abschiebung wurde während der Hebung der unteren Einheit verfaltet
→ scheinbare Überschiebung



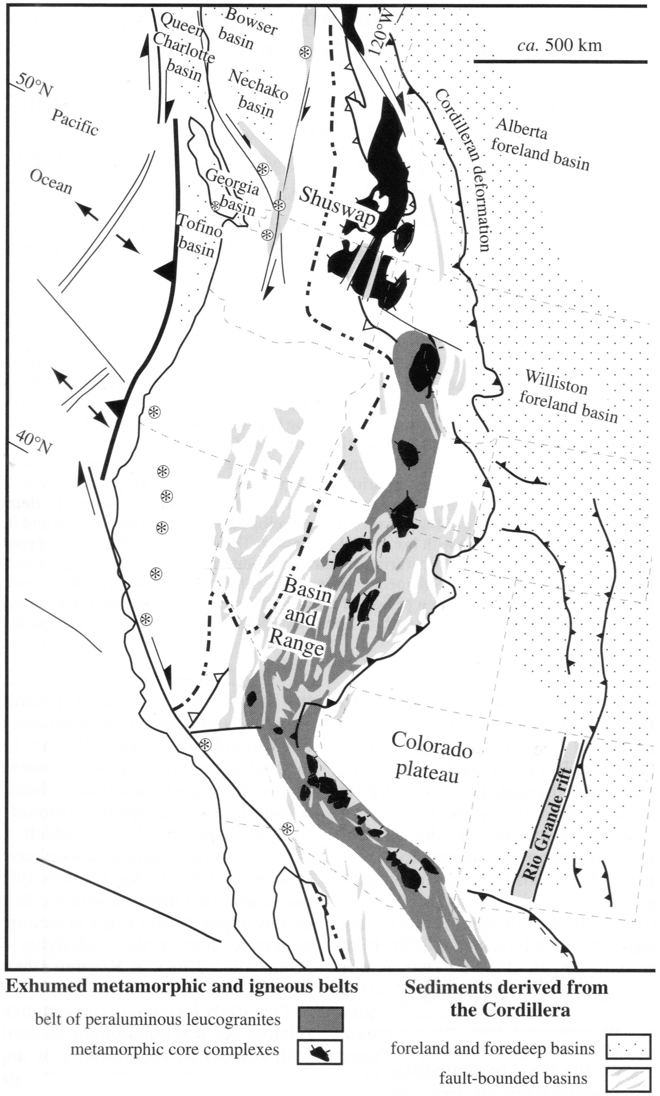
Davies et al. 2004, GSA Bull.

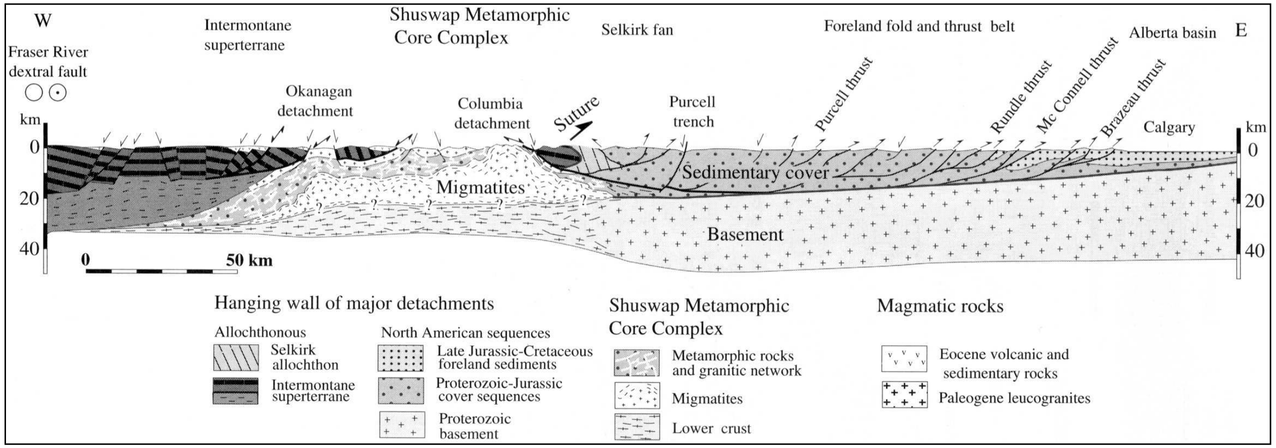
Detachment

Zunahme der Verformungsintensität
- Kaum verformter Granitoid
- Mylonite
- Ultramylonite

Spröd-duktiler Übergang
- Mylonite
- Kataklasite

Beispiel Nordamerikanische Kordilliere





Verformung ist stark lokalisiert, reicht aber nicht bis in den Mantel

die entstehenden Mächtigkeitsunterschiede der oberen Kruste werden durch das Fliessen der unteren Kruste komplett ausgeglichen

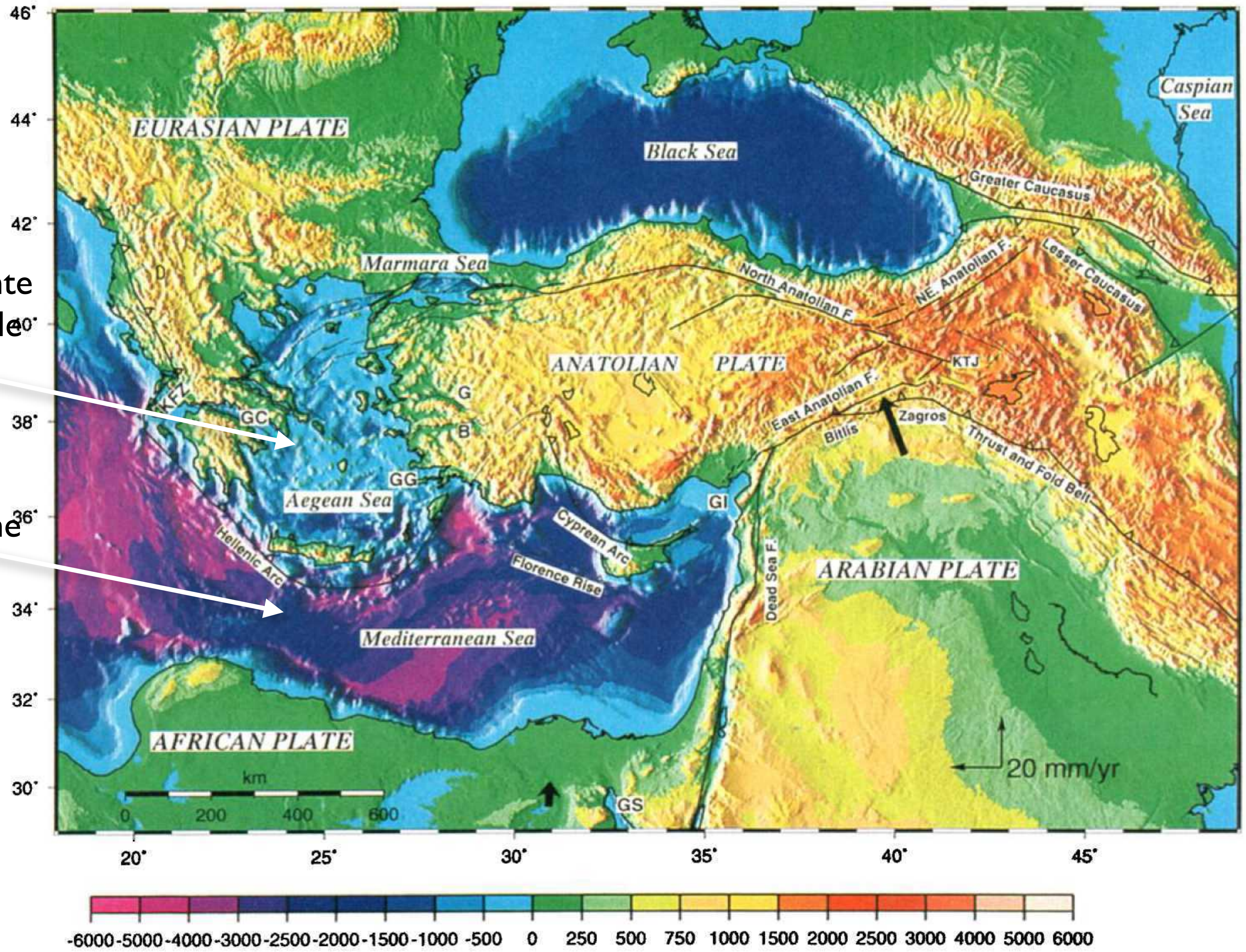
→ MOHO ist flach

Vanderhaeghe et al., 1999, J. Geol. Soc. Spec. Publ.

Beispiel Ägäis

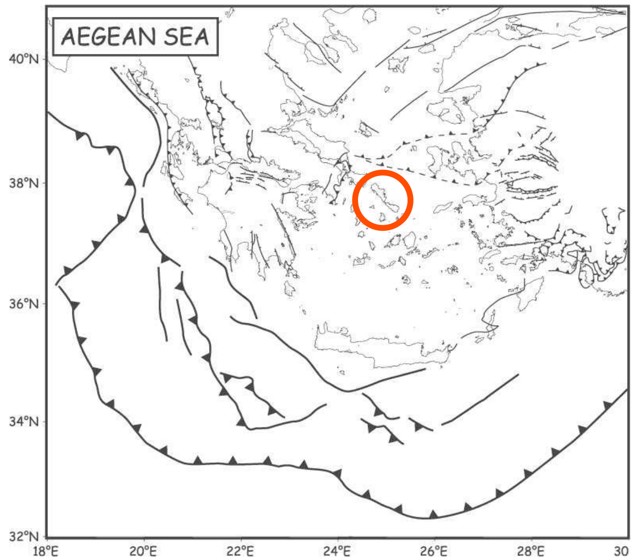
Ausgedünnte kontinentale Kruste

Ozeanische Kruste



McClusky et al., 2000. JGR

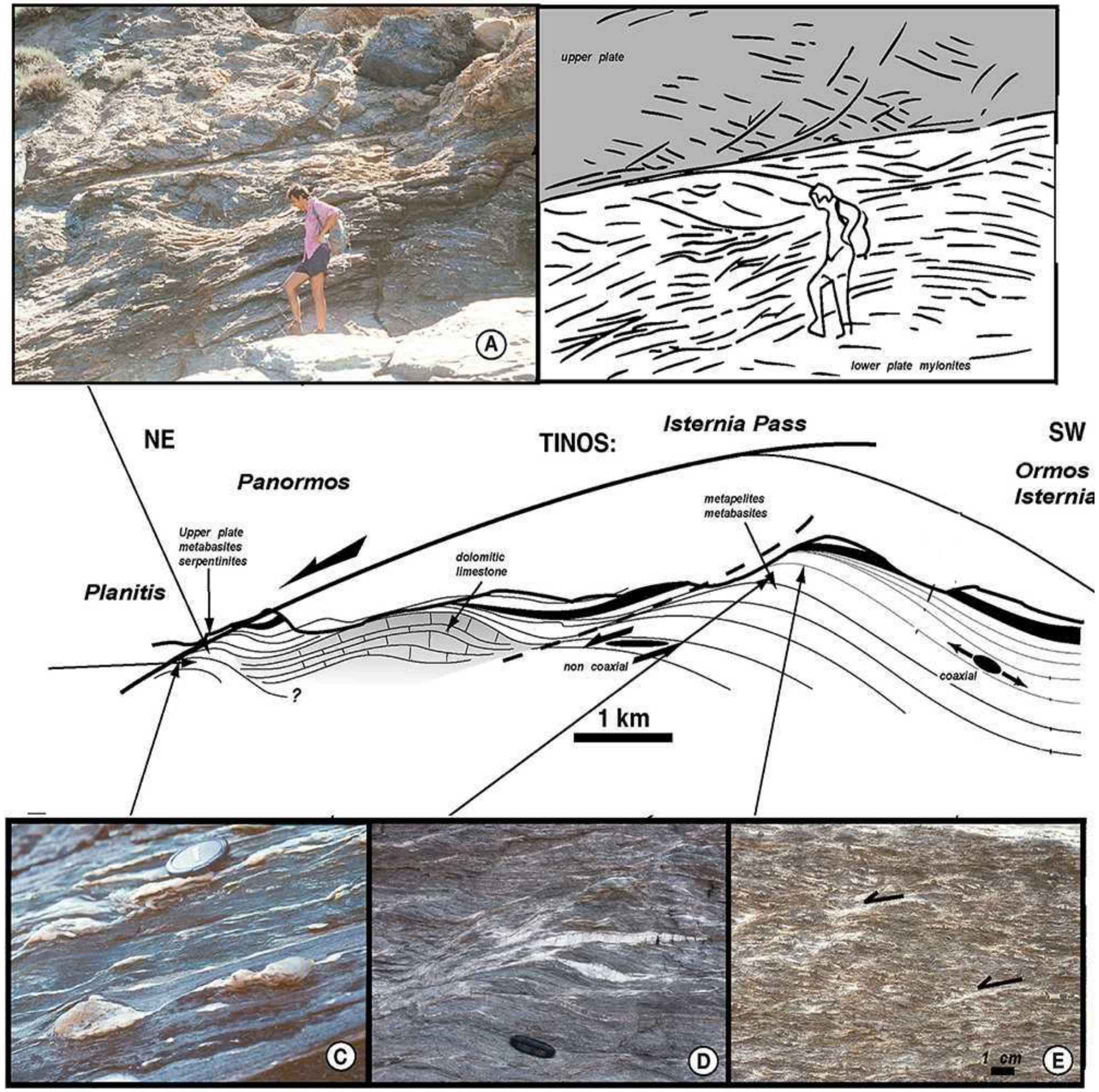
Beispiel Tinos

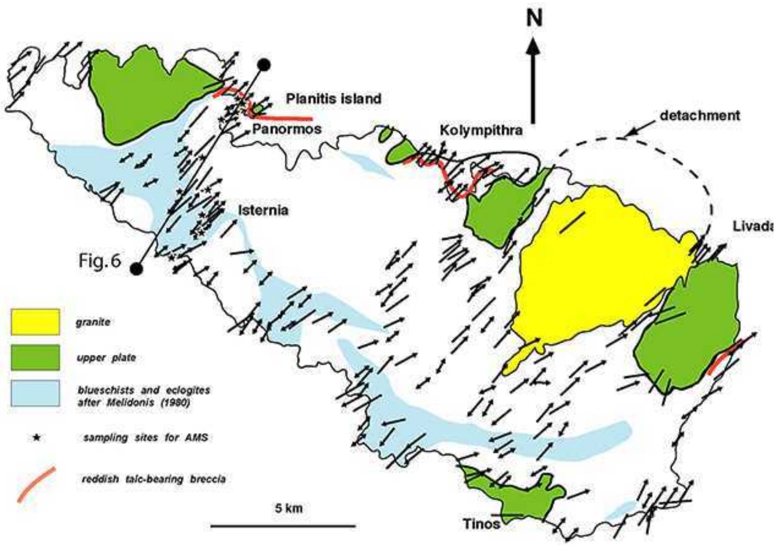


Jolivet et al., 2004, *GSA Spec. Paper*

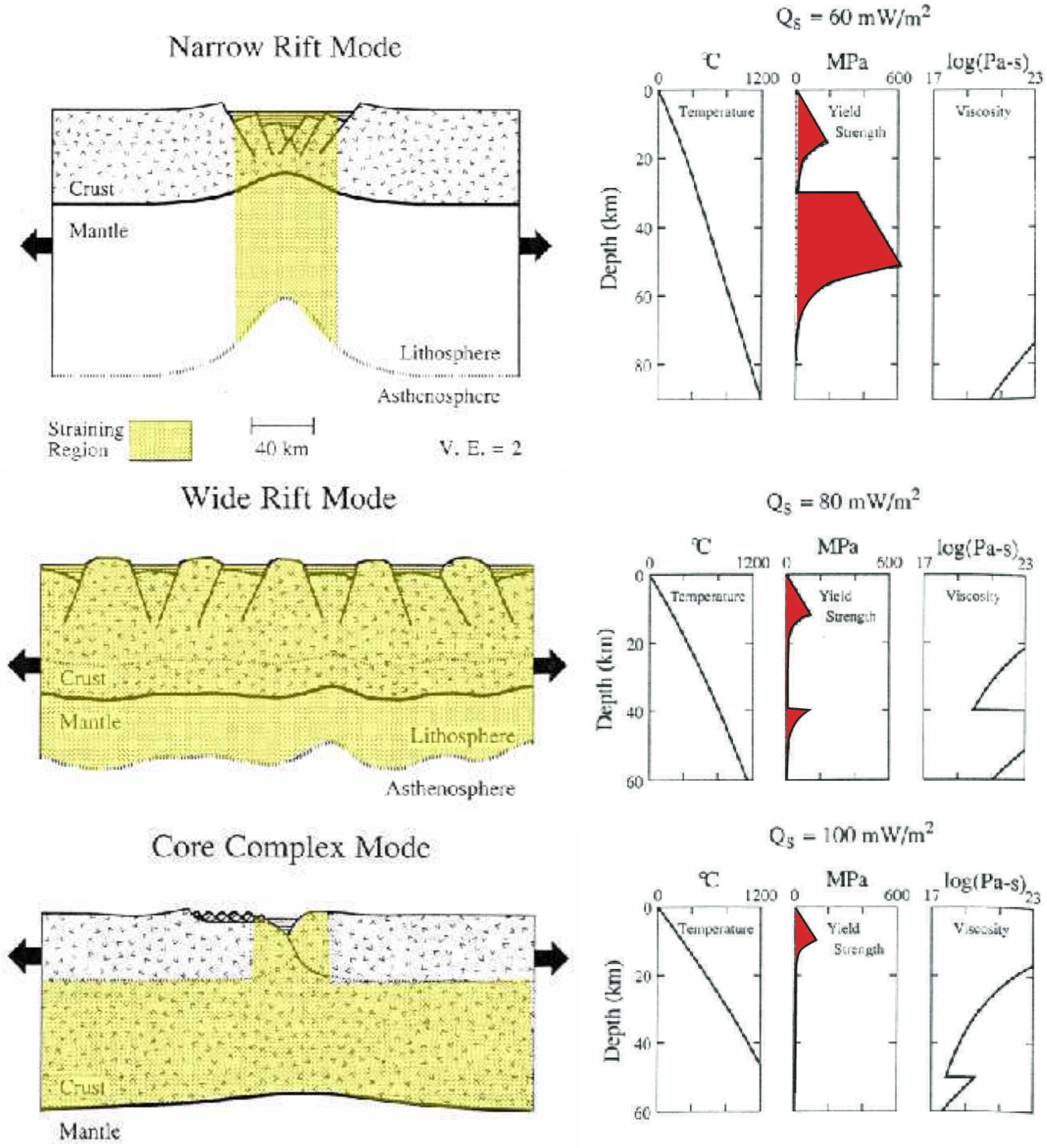
Die Brekzien und die Mylonite zeigen den selben Schersinn:

→EINE Deformationsgeschichte, die sowohl im duktilen als auch im spröden Bereich der Kruste aktiv ist





Entstehung eines MCC



Niedriger geothermischer Gradient: die Festigkeit der Kruste dominiert über die gravitativen Gradienten

→narrow rift

Höherer geothermischer Gradienten: gravitative Kräfte nehmen relativ zur Festigkeit zu

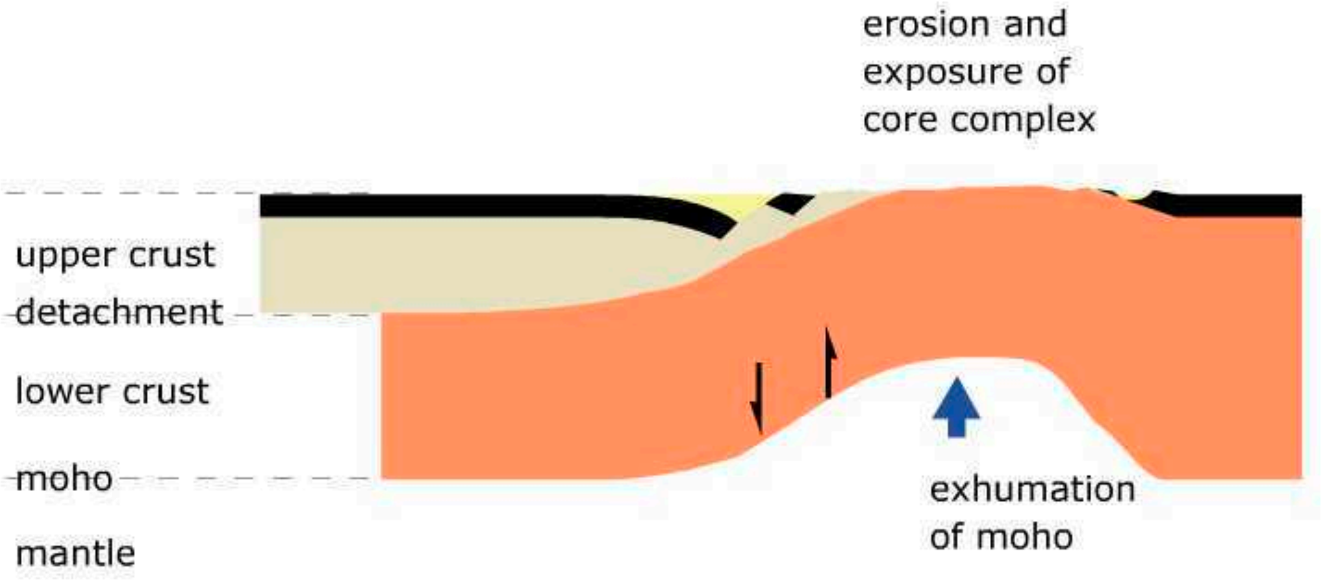
→wide rift

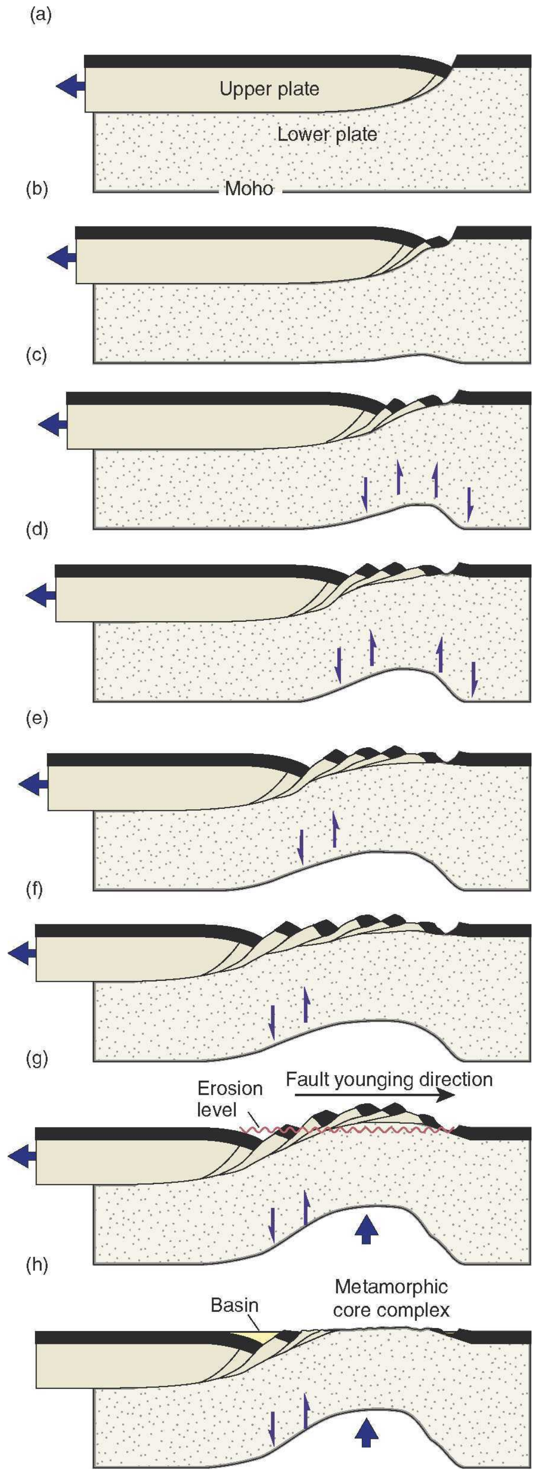
Sehr hoher geothermischer Gradienten: schnelles Fliessen der unteren Kruste reduziert die Gradienten der gravitativen Kräfte, in der oberen Kruste kann die Extension lokalisiert bleiben, während die untere Kruste homogen ausgedünnt wird

→core complex

Buck, 1991, J. Geophys. Res.

development of MCC

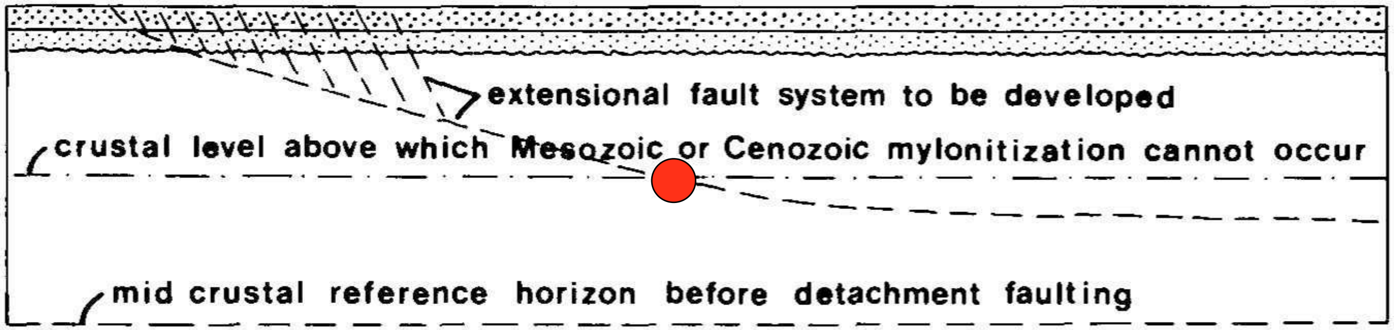


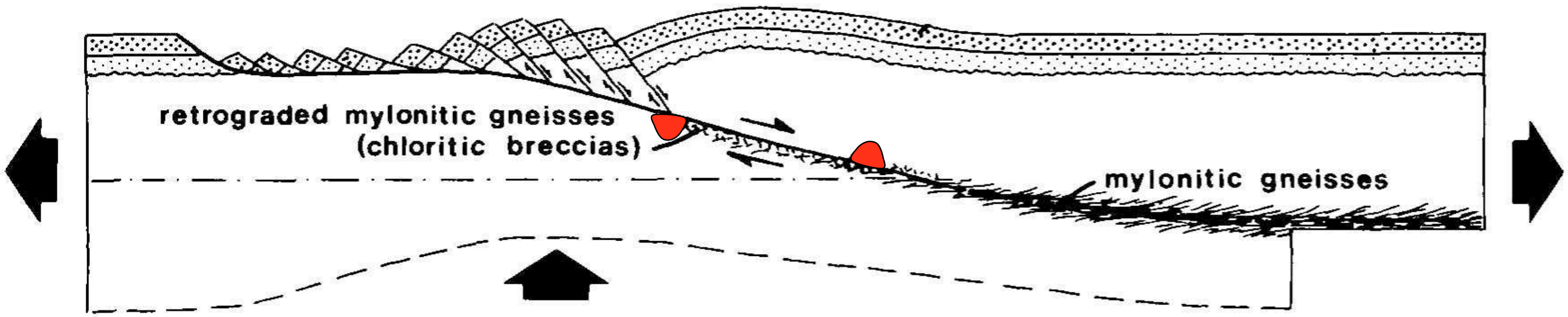


Håkon Fossen, 2012

development of MCC

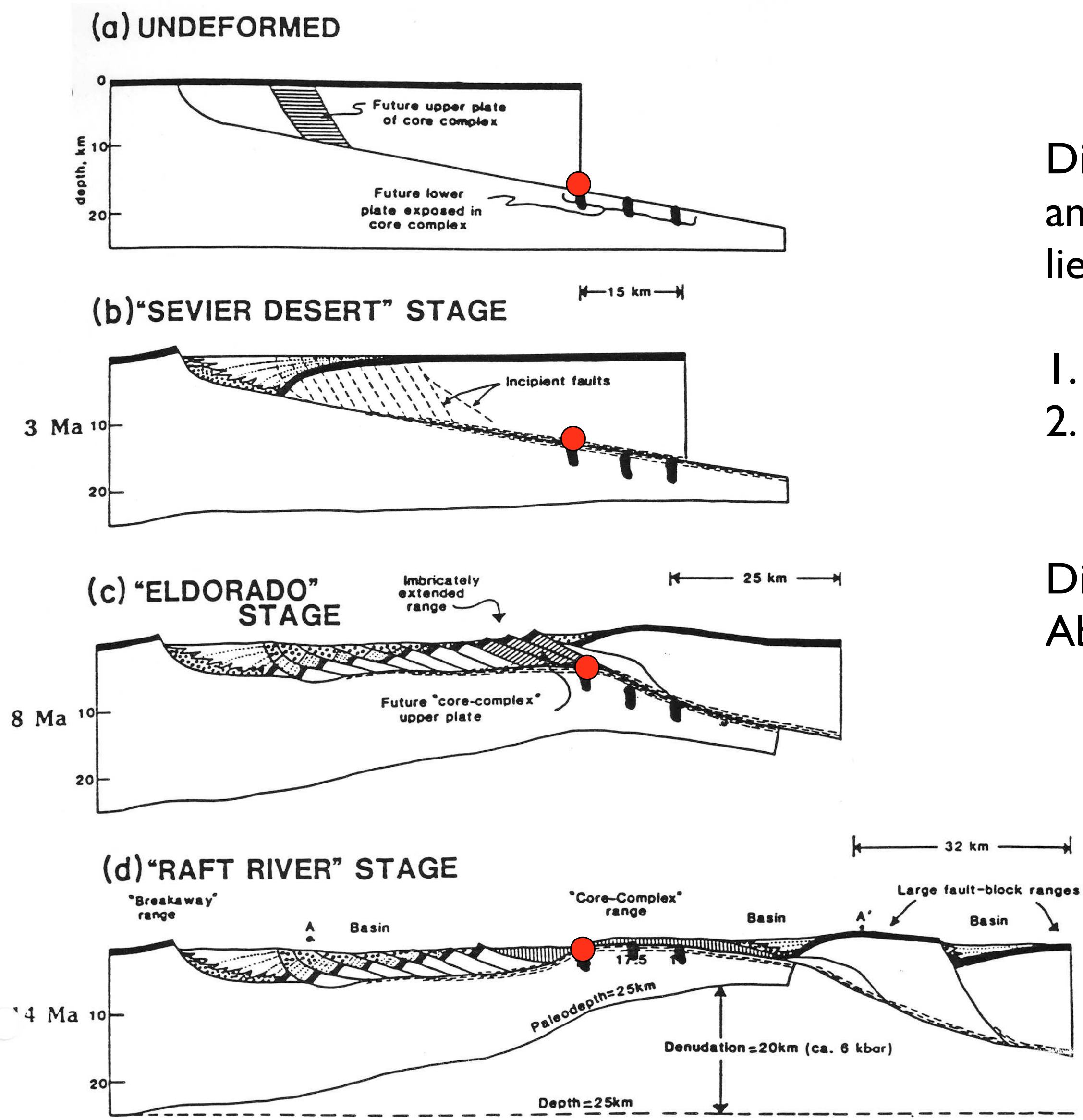
Unterhalb der spröd-duktilen Grenze bilden sich Mylonite. Ein Teil dieser Mylonite wird mit der unteren Platte exhumiert und kataklastisch übeprägt.





Davis et al. 1986, Geology

development of MCC



Die Materialpunkte, die an der Oberfläche am nächsten zur Abschiebungsfläche liegen, sind diejenigen die

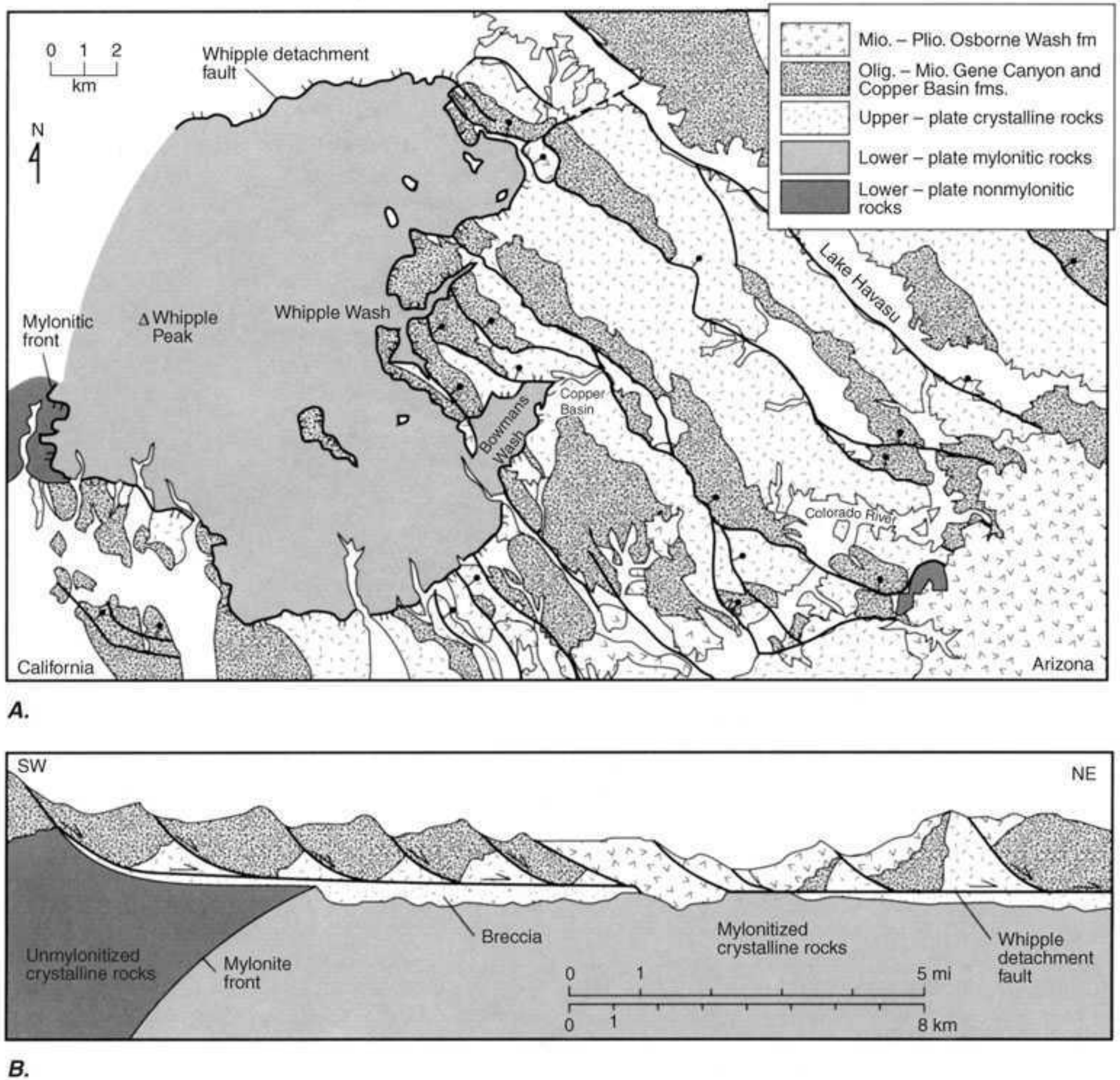
1. zuletzt exhumiert worden sind
2. aus dem tiefsten Strukturniveau stammen (roter Punkt)

Diese Interpretation lässt sich anhand von Abkühlungsalter erhärten

Wernicke, 1985

low angle detachment faults (LANF)

low angle detachment faults

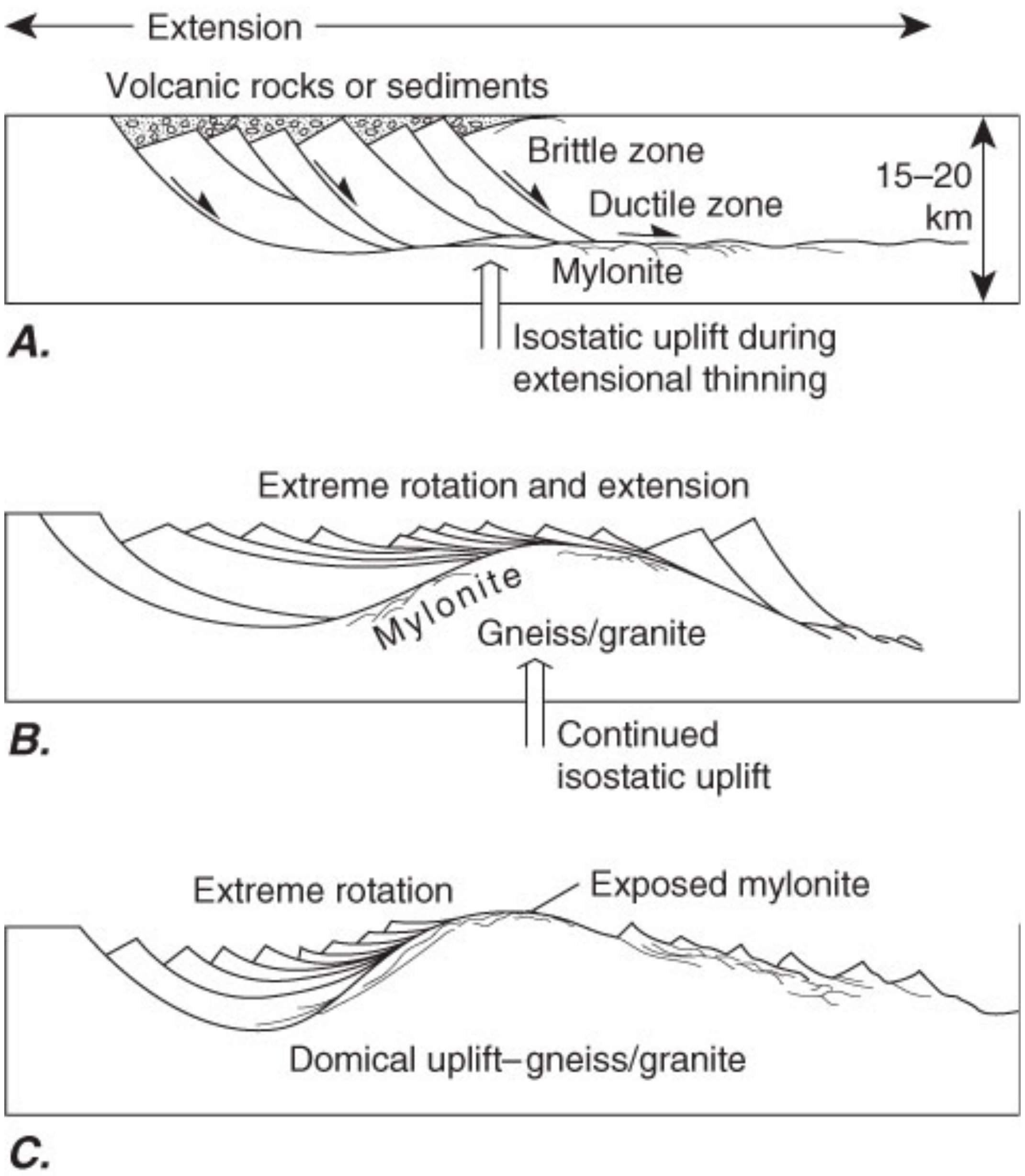


low angle detachment faults

Example: Whip

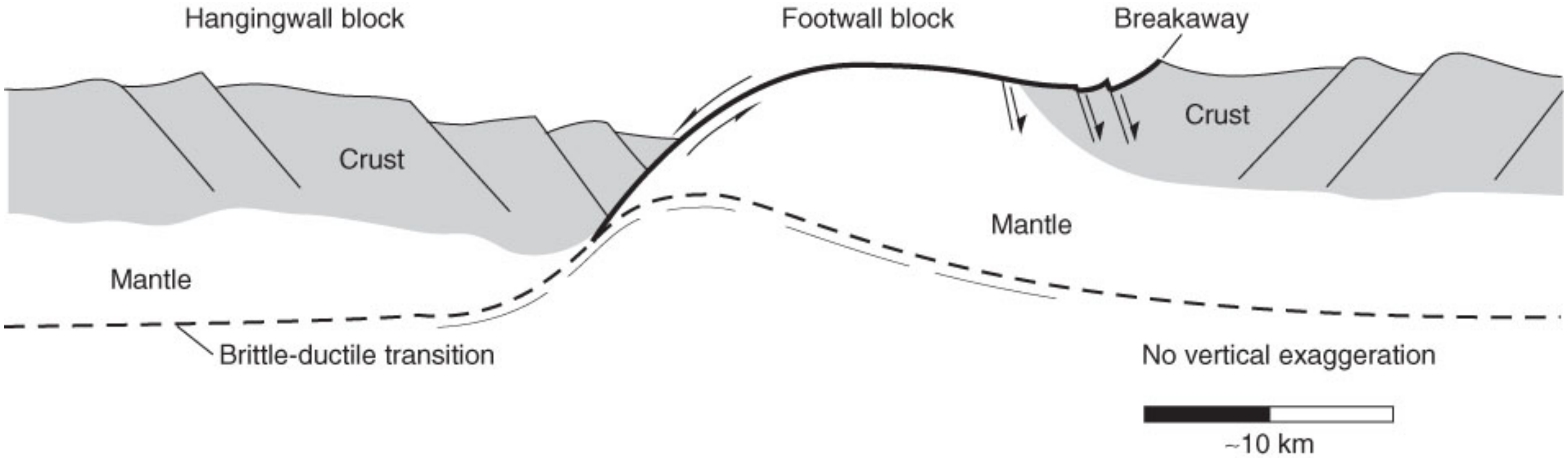
Example: Western Chemihuevi Mountains

low angle detachment faults

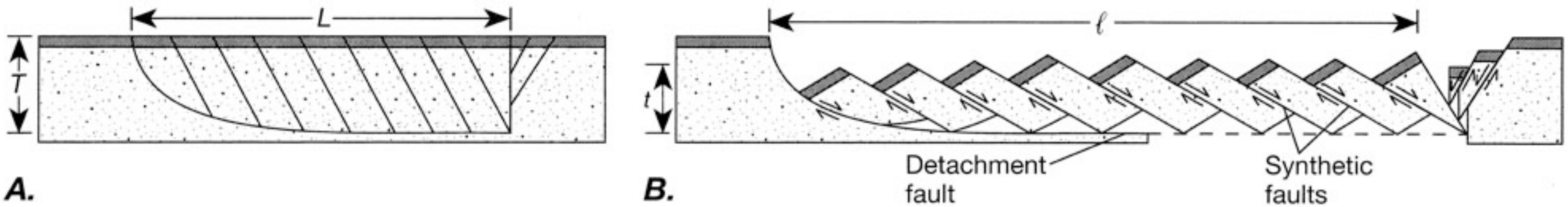


may unroof metamorphic core complexes
due to isostatic uplift
→
cataclasites and mylonites may form

low angle detachment faults



B.



A. B.