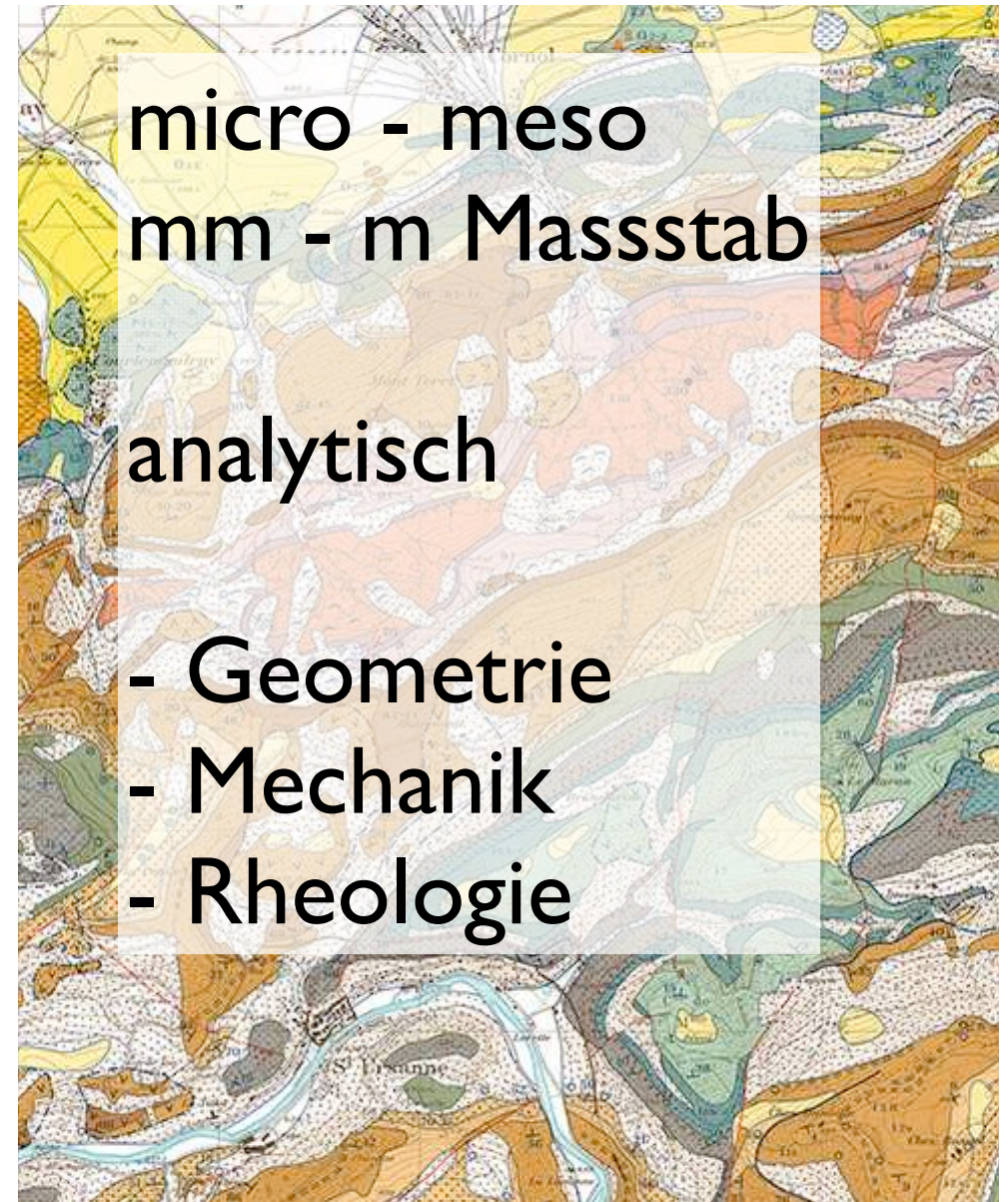
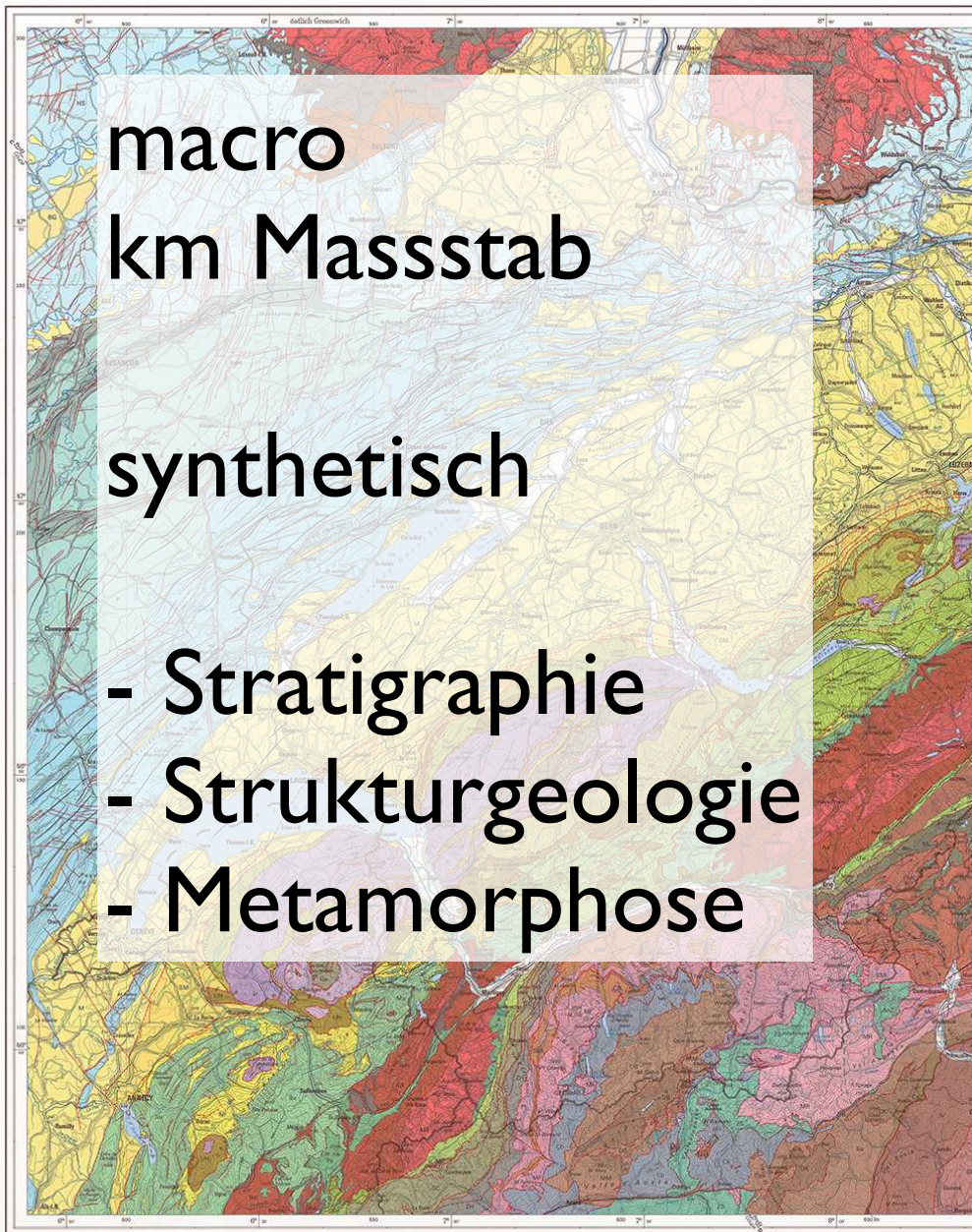


# System Erde Entwicklung & Dynamik



Dumasfjellet (Nordnorwegen)

# Tektonik - Strukturgeologie



# I Geologie im Kartenbild

## Einfache Grosstrukturen

- Flachliegende Schichten
- Steilstehende Schichten, Intrusionen

## Interpretation

- Superpositionsprinzip
- Schichtlücke: Diskordanz
- Deformation: Winkeldiskordanz
- Überschneidungskriterien
- Relative Alter
- zeitliche Abfolge

## Karten

- Tektonische
- Geologische

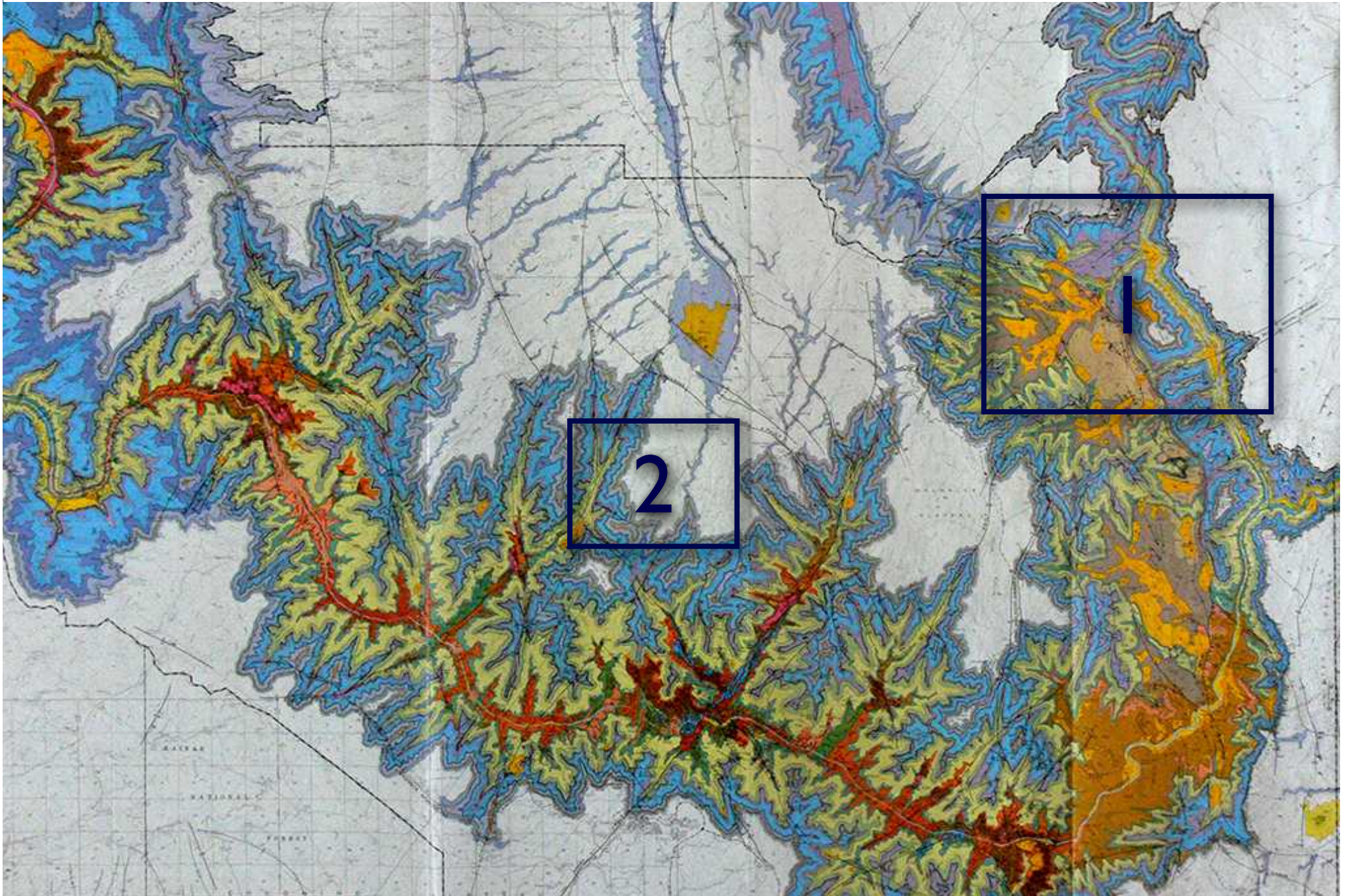
# Flachliegende Schichten

# Flachliegende Schichten

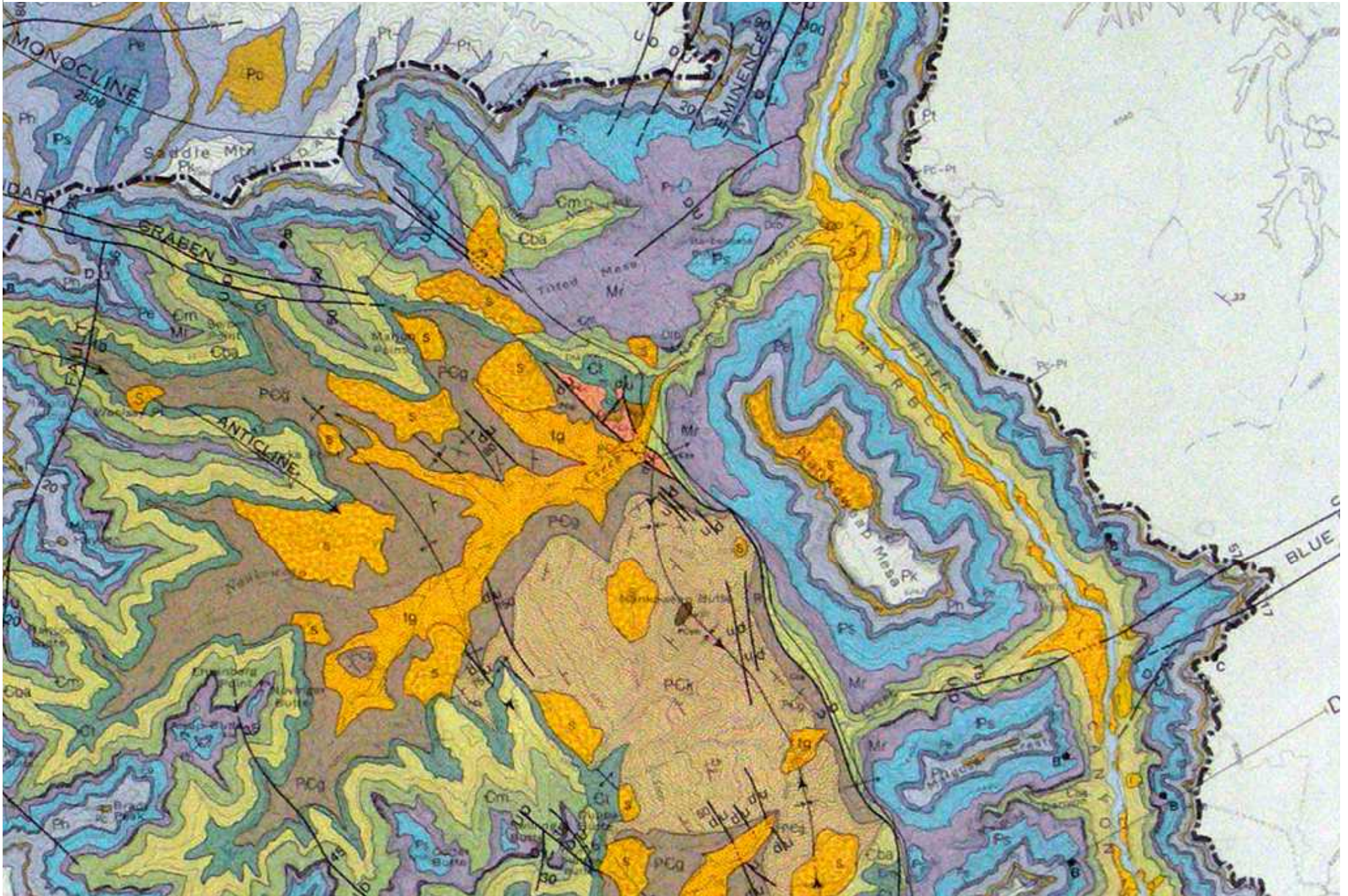


Beispiel: Grand Canyon

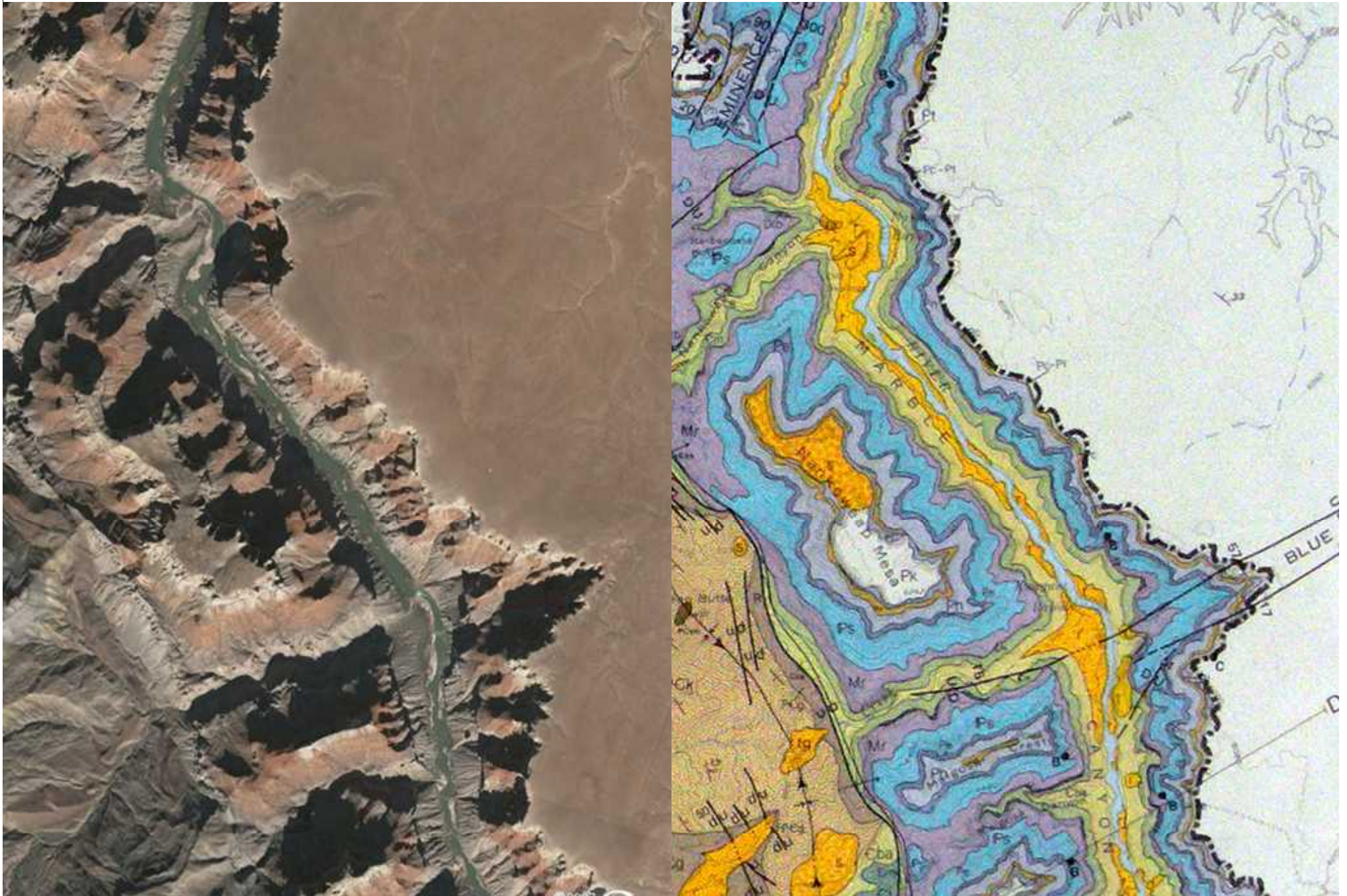
# Flachliegende Schichten



# Flachliegende Schichten - Stelle I



# Flachliegende Schichten - Stelle I

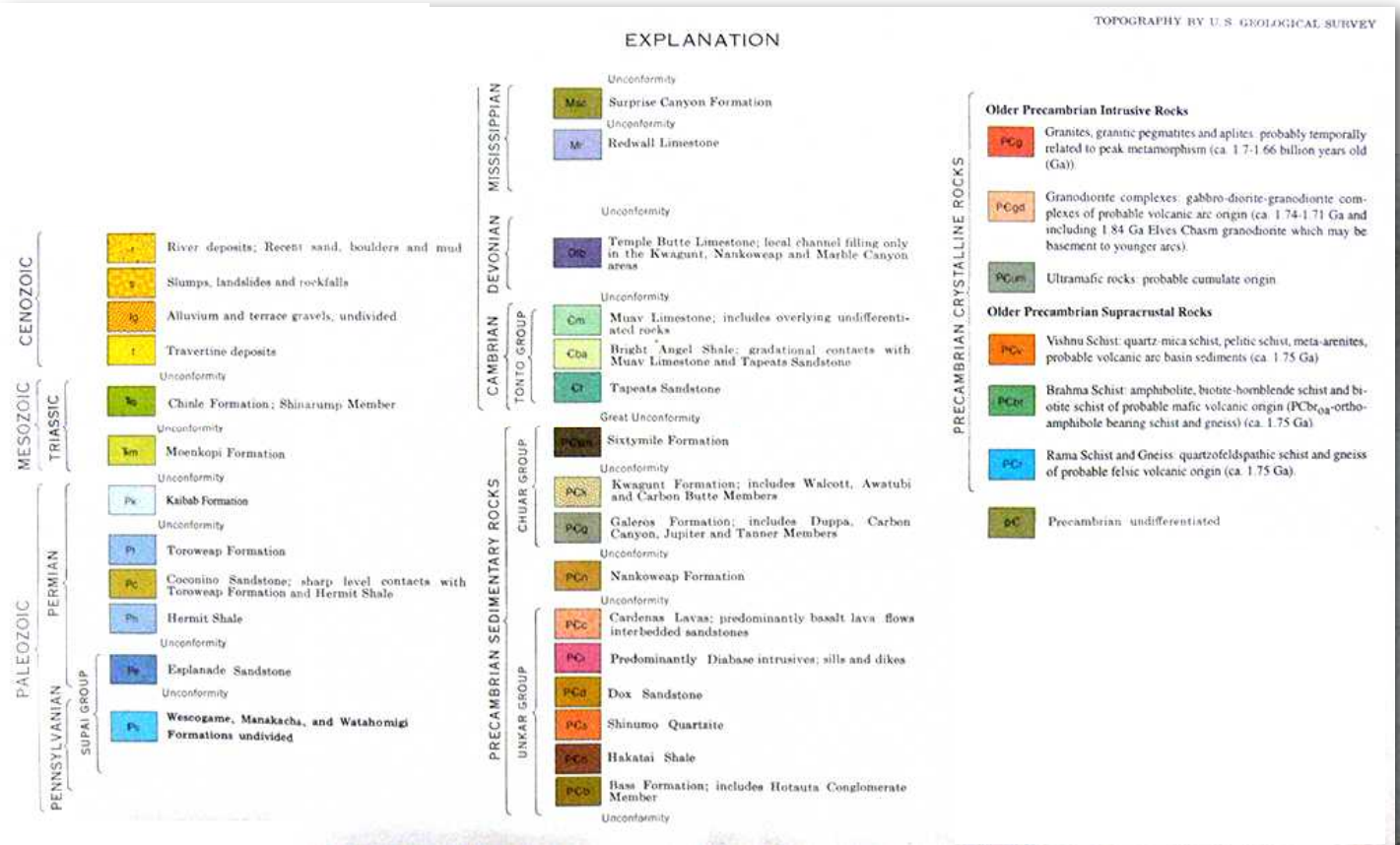
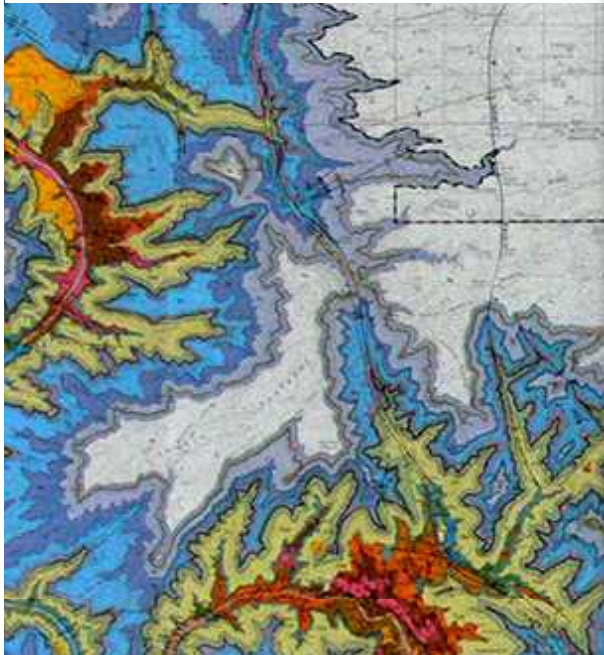




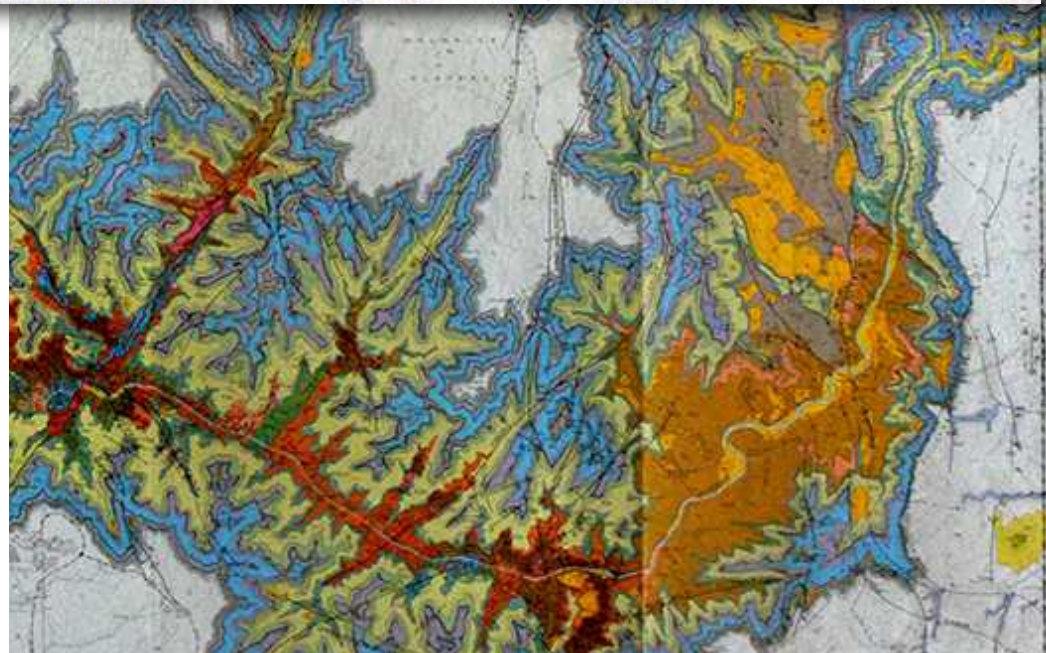
# Flachliegende Schichten - Stelle 2



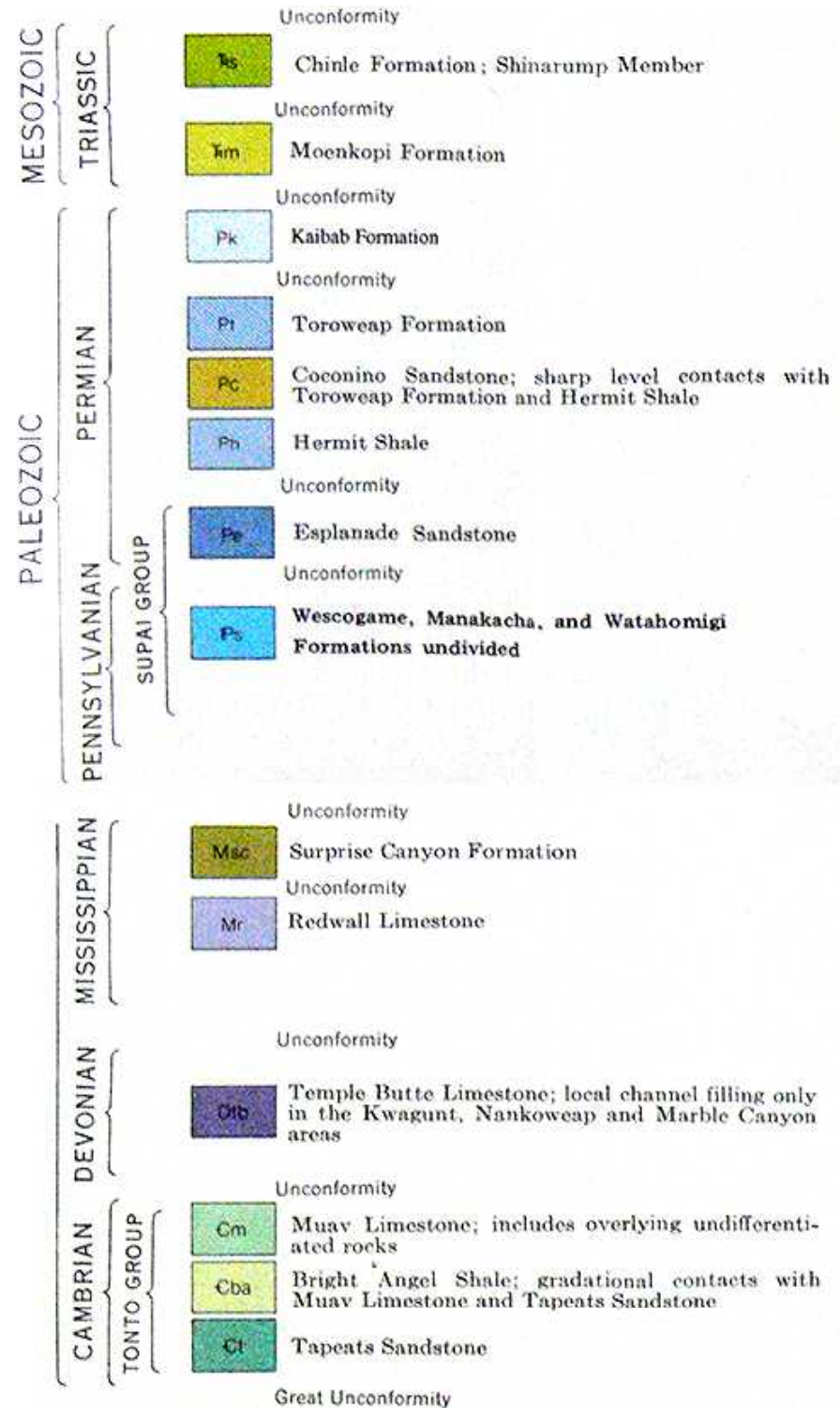
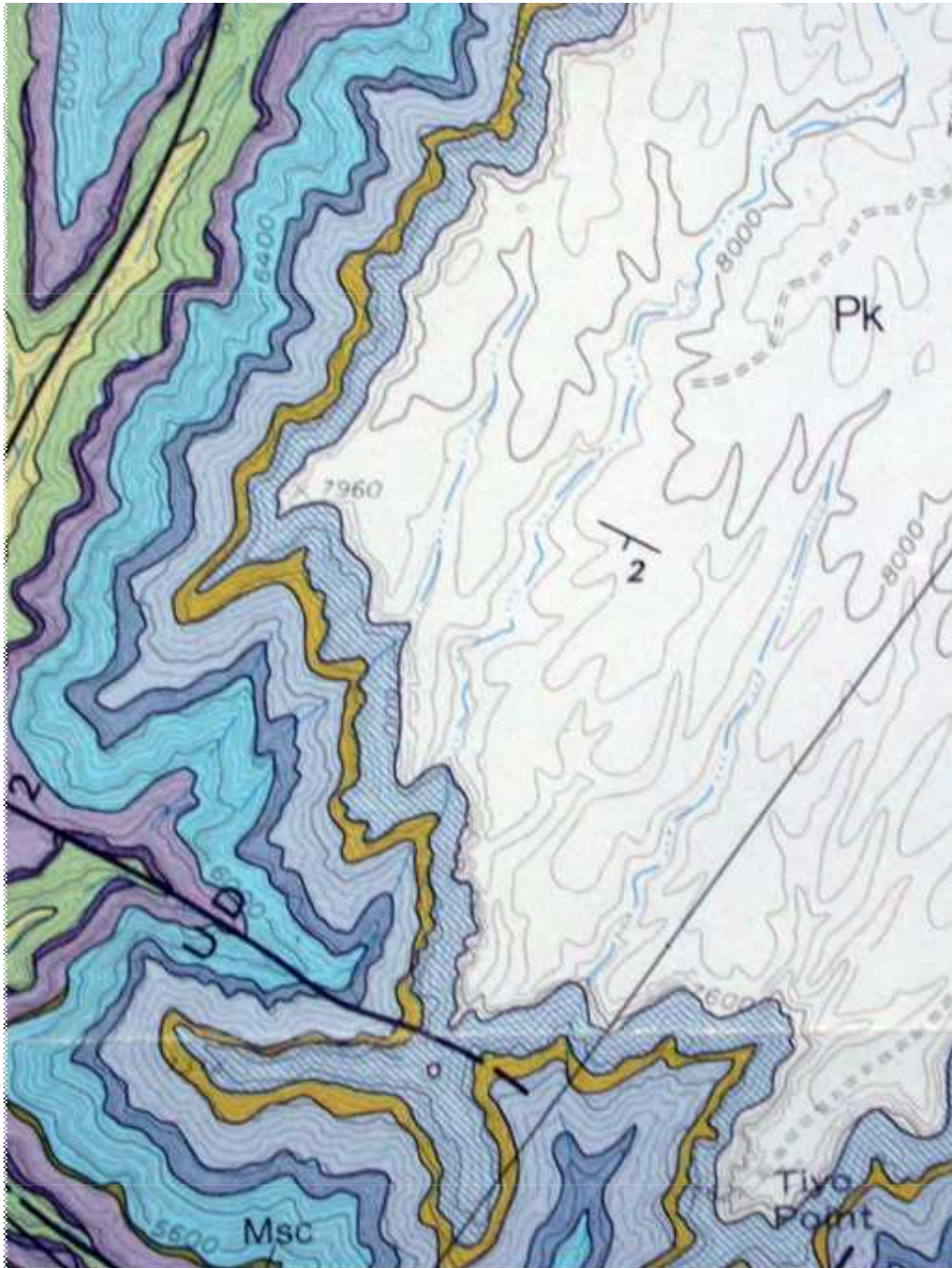
# Stratigraph



Epoch	Series	Stage	Age (Ma)	GSSP		
Phanerozoic	Cenozoic	Holocene	Upper	0.0117		
			Lower			
		Quaternary	Upper	0.126		
			Middle	0.781		
			Lower	1.806		
		Neogene	Pliocene	Upper	2.588	
				Lower	3.600	
			Miocene	Upper	5.332	
				Middle	7.246	
				Lower	11.608	
	Upper			13.82		
	Lower			15.97		
	Paleogene	Oligocene	Upper	23.03		
			Lower	28.4 ± 0.1		
		Eocene	Upper	33.9 ± 0.1		
			Middle	37.2 ± 0.1		
			Lower	40.4 ± 0.2		
			Upper	48.6 ± 0.2		
			Middle	55.8 ± 0.2		
			Lower	58.7 ± 0.2		
Upper			~ 61.1			
Lower			65.5 ± 0.3			
Mesozoic	Cretaceous	Upper	70.6 ± 0.6			
		Middle	83.5 ± 0.7			
		Lower	85.8 ± 0.7			
		Upper	~ 88.6			
		Lower	93.6 ± 0.8			
	Paleozoic	Permian	Upper	99.6 ± 0.9		
			Lower	112.0 ± 1.0		
		Triassic	Upper	125.0 ± 1.0		
			Middle	130.0 ± 1.5		
			Lower	~ 133.9		
Paleozoic	Permian	Upper	140.2 ± 3.0			
		Middle	145.5 ± 4.0			
		Lower				
		Upper				
		Lower				
	Carboniferous	Upper	Upper			
			Lower			
		Lower	Upper			
			Middle			
			Lower			
Paleozoic	Devonian	Upper	359.2 ± 2.5			
		Middle	374.5 ± 2.6			
		Lower	385.3 ± 2.6			
		Upper	391.8 ± 2.7			
		Lower	397.5 ± 2.7			
	Silurian	Upper	Upper	407.0 ± 2.8		
			Lower	412.2 ± 2.8		
		Lower	Upper	416.0 ± 2.8		
			Middle	418.7 ± 2.7		
			Lower	421.3 ± 2.6		
Ordovician	Upper	Upper	422.9 ± 2.5			
		Lower	428.2 ± 2.4			
	Lower	Upper	428.2 ± 2.3			
		Middle	436.0 ± 1.9			
		Lower	439.0 ± 1.8			
Paleozoic	Cambrian	Upper	443.7 ± 1.5			
		Middle	445.8 ± 1.5			
		Lower	455.8 ± 1.6			
		Upper	460.9 ± 1.6			
		Lower	468.1 ± 1.6			
	Precambrian	Sturion	Upper	471.8 ± 1.6		
			Lower	478.6 ± 1.7		
		Furongian	Upper	488.3 ± 1.7		
			Middle	~ 492		
			Lower	~ 496		
Precambrian	Ediacaran	Upper	~ 499			
		Lower	~ 503			
	Neoproterozoic	Upper	~ 506.5			
		Middle	~ 510			
		Lower	~ 515			
Precambrian	Tonian	Upper	~ 521			
		Lower	~ 521			
	Cryogenian	Upper	~ 528			
		Middle	~ 528			
		Lower	~ 528			
Precambrian	Stenian	Upper	~ 542			
		Lower	~ 542			
	Ectasian	Upper	~ 635			
		Middle	~ 635			
		Lower	~ 635			
Precambrian	Calymnian	Upper	~ 635			
		Lower	~ 635			
	Orosirian	Upper	~ 635			
		Middle	~ 635			
		Lower	~ 635			
Precambrian	Rhyacian	Upper	~ 635			
		Lower	~ 635			
	Siderian	Upper	~ 635			
		Middle	~ 635			
		Lower	~ 635			
Precambrian	Neoproterozoic	Upper	~ 635			
		Lower	~ 635			
	Mesoproterozoic	Upper	~ 635			
		Middle	~ 635			
		Lower	~ 635			
Precambrian	Paleoproterozoic	Upper	~ 635			
		Lower	~ 635			
	Archean	Upper	~ 635			
		Middle	~ 635			
		Lower	~ 635			
Precambrian	Hadean (informal)	Upper	~ 635			
		Lower	~ 635			
	Hadean (informal)	Upper	~ 635			
		Middle	~ 635			
		Lower	~ 635			



# Stratigraphie



**zeitliche Abfolge**

# Superpositionsprinzip



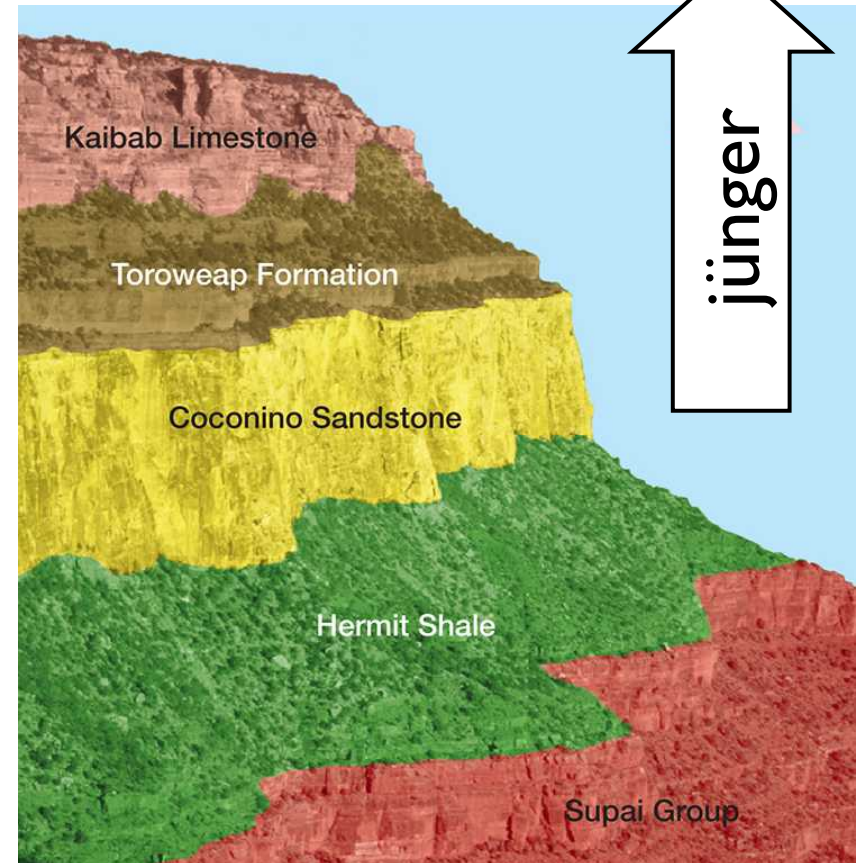
Nikolaus Steno (1669): "De solido intra solidum"

1. Horizontbeständigkeit (Lateral konstant)

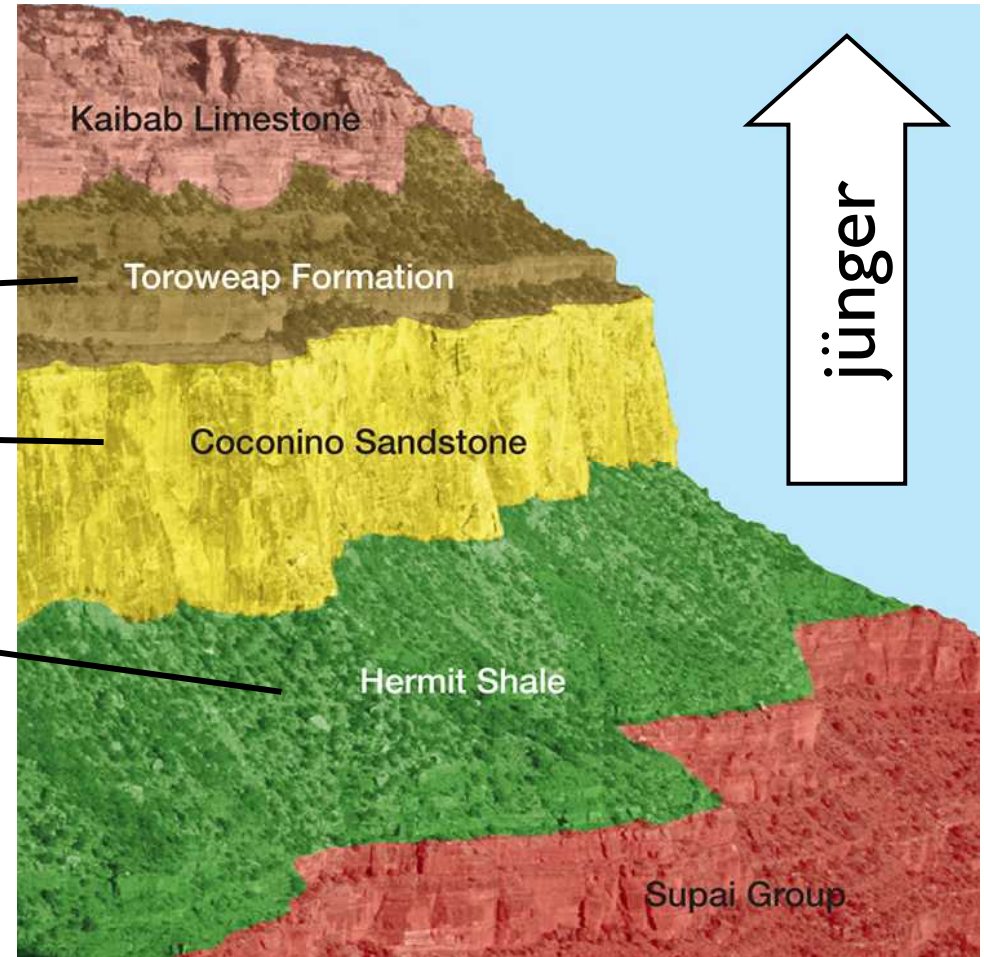
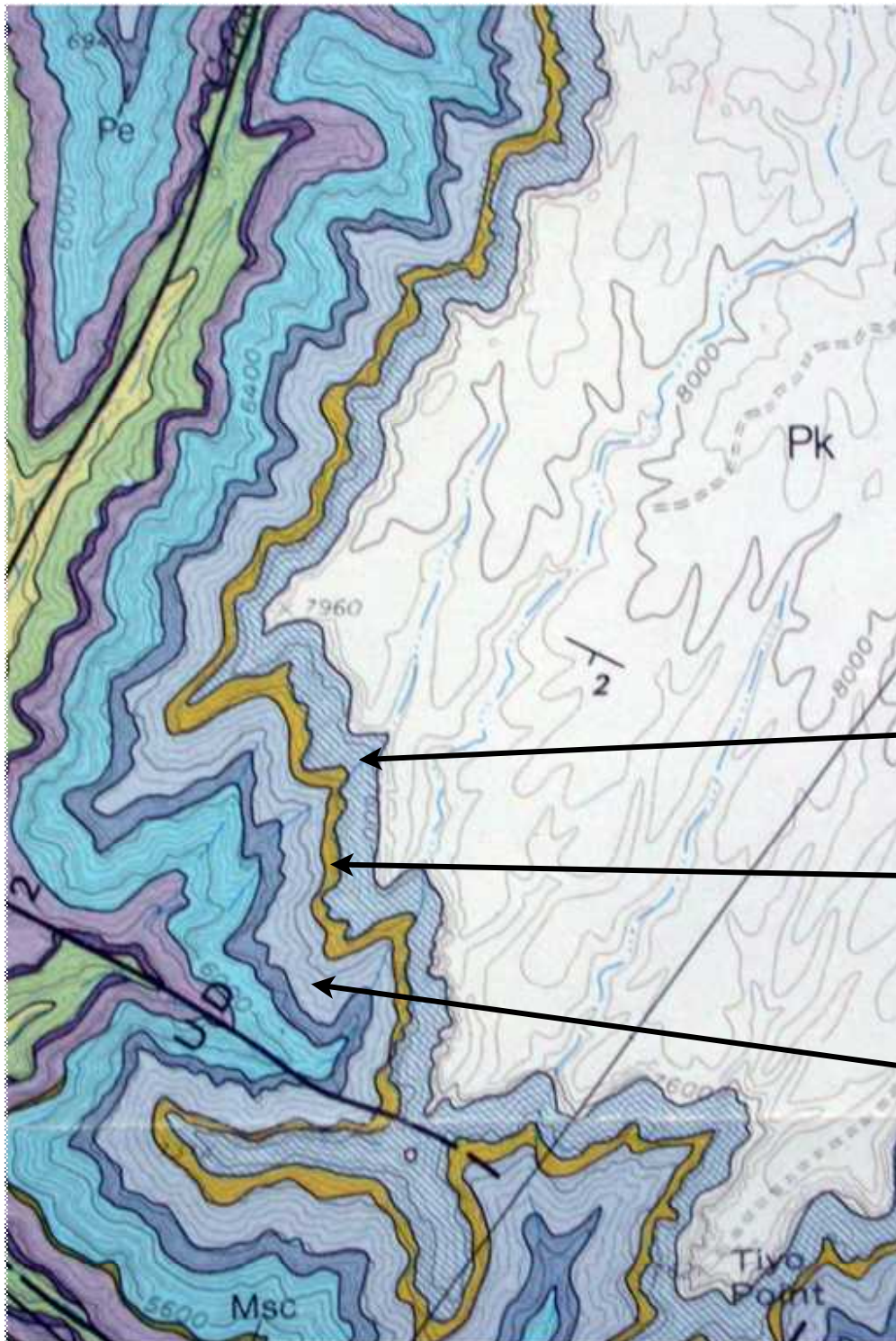
2. Horizontale Ablagerung

3. Lagerungsabfolge (Superpositionsprinzip):

Altersabfolge bei undeformierten Sedimenten:  
unten (Liegendes) alt - oben (Hangendes) jung



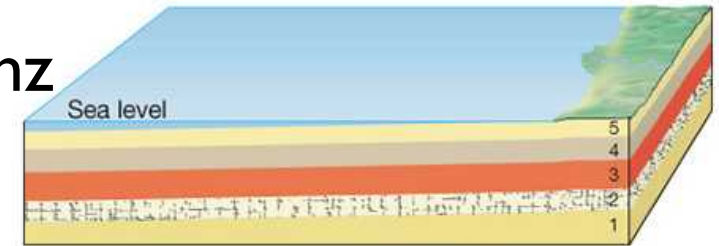
# Schichtdicke Verwitterung Kartenbild



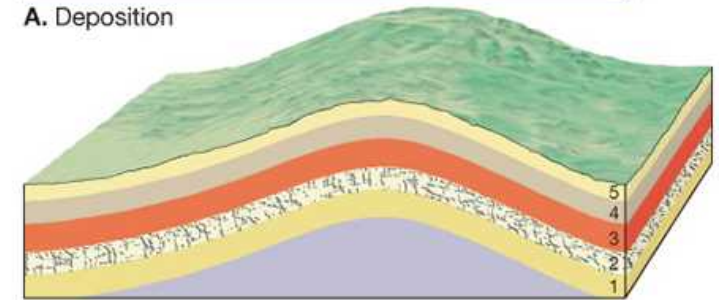
# Diskordanz



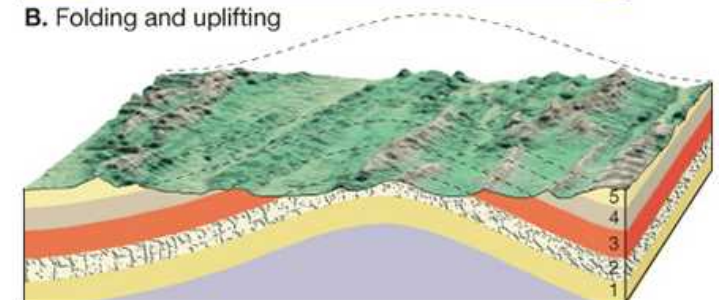
James Hutton (1726-1797)  
entdeckt 1788 Winkeldiskordanz  
bei Siccar Point (Schottland)



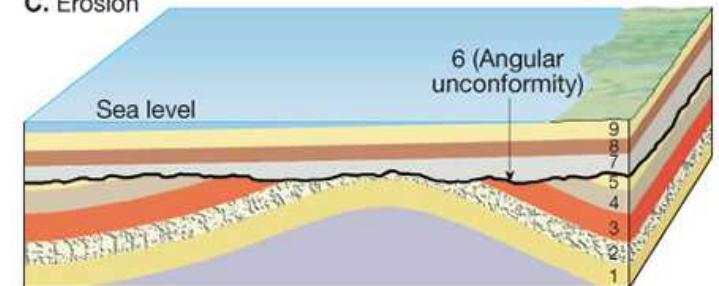
A. Deposition



B. Folding and uplifting



C. Erosion



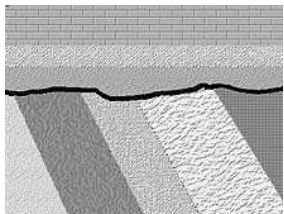
D. Subsidence and renewed deposition

Old Red Sandstein  
Stratheden Group (Devon)

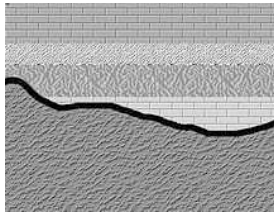


Grauwacken Tonschiefer  
Gala Group (Silur)

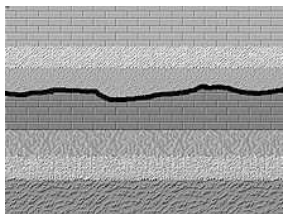
# Diskordanz - Schichtlücke



**Winkeldiskordanz**  
= angular unconformity\*)

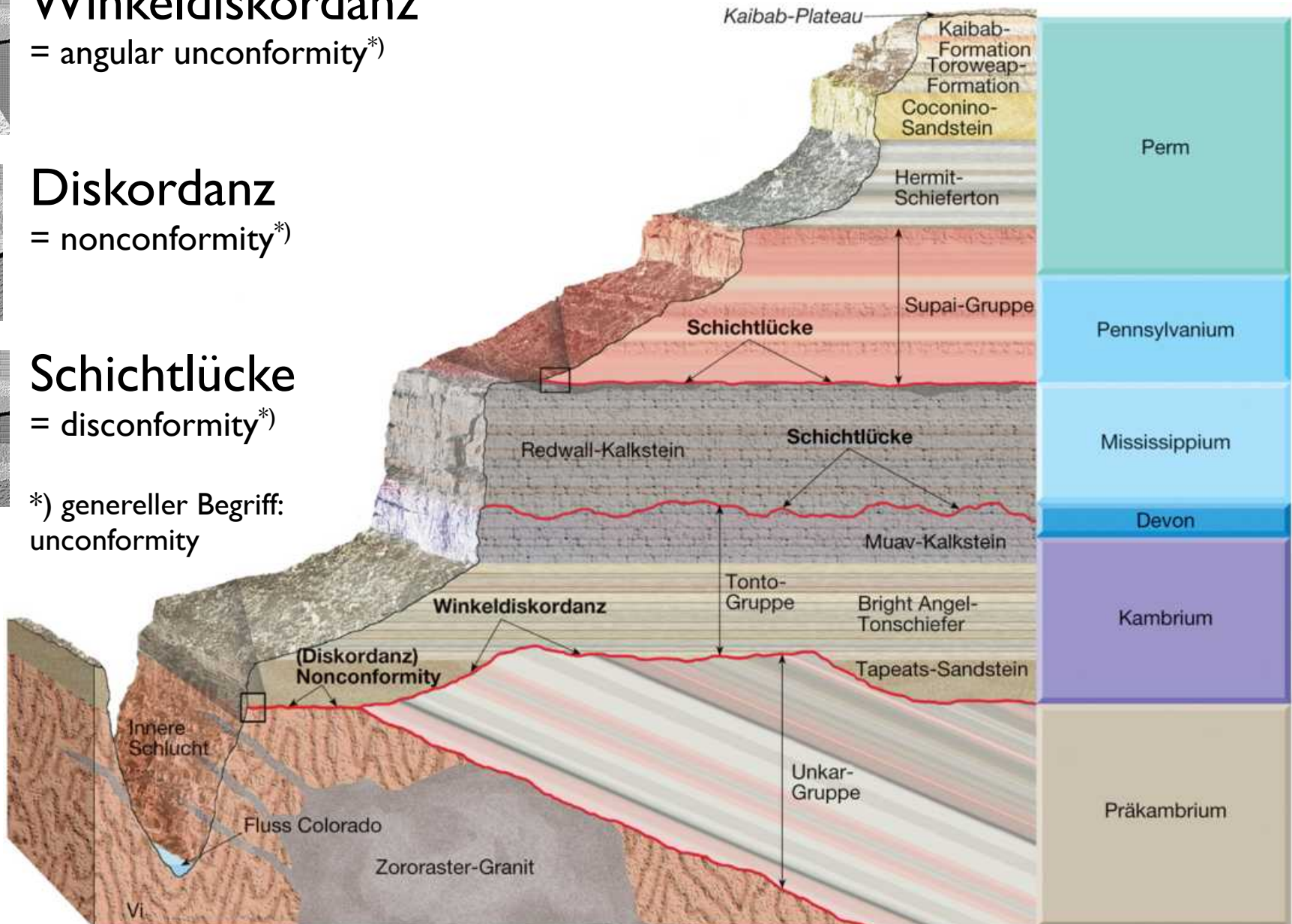


**Diskordanz**  
= nonconformity\*)



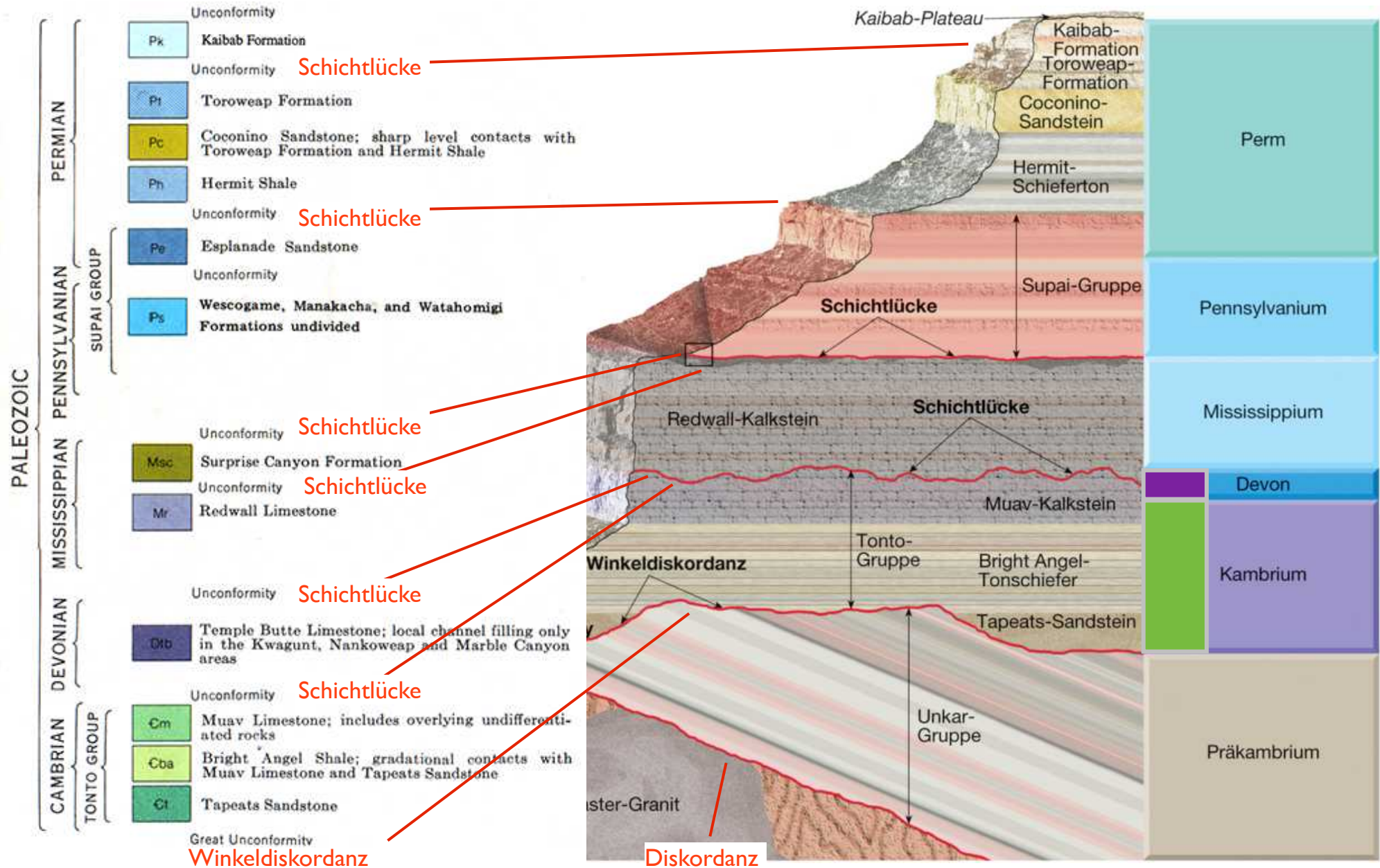
**Schichtlücke**  
= disconformity\*)

\*) genereller Begriff:  
unconformity





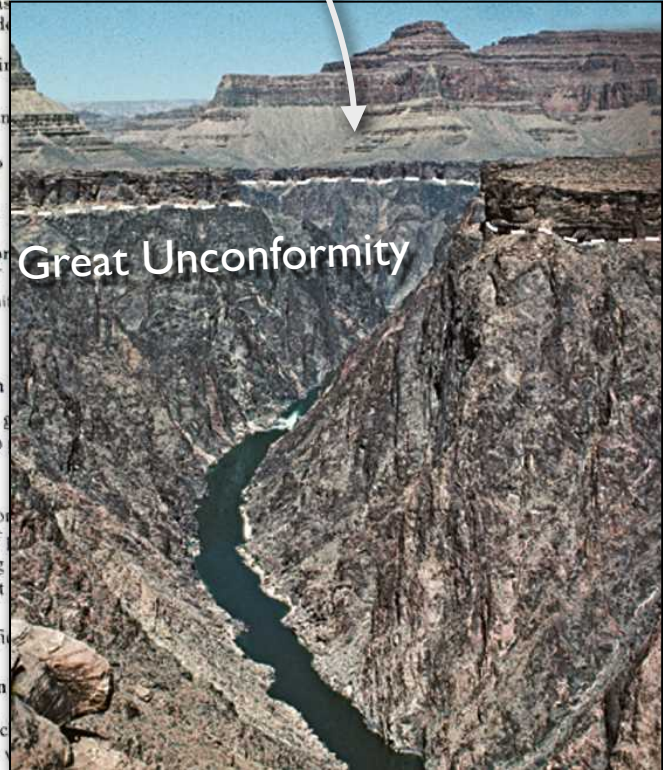
# Relative Alter



**Steilstehende  
Schichten,  
Intrusionen**

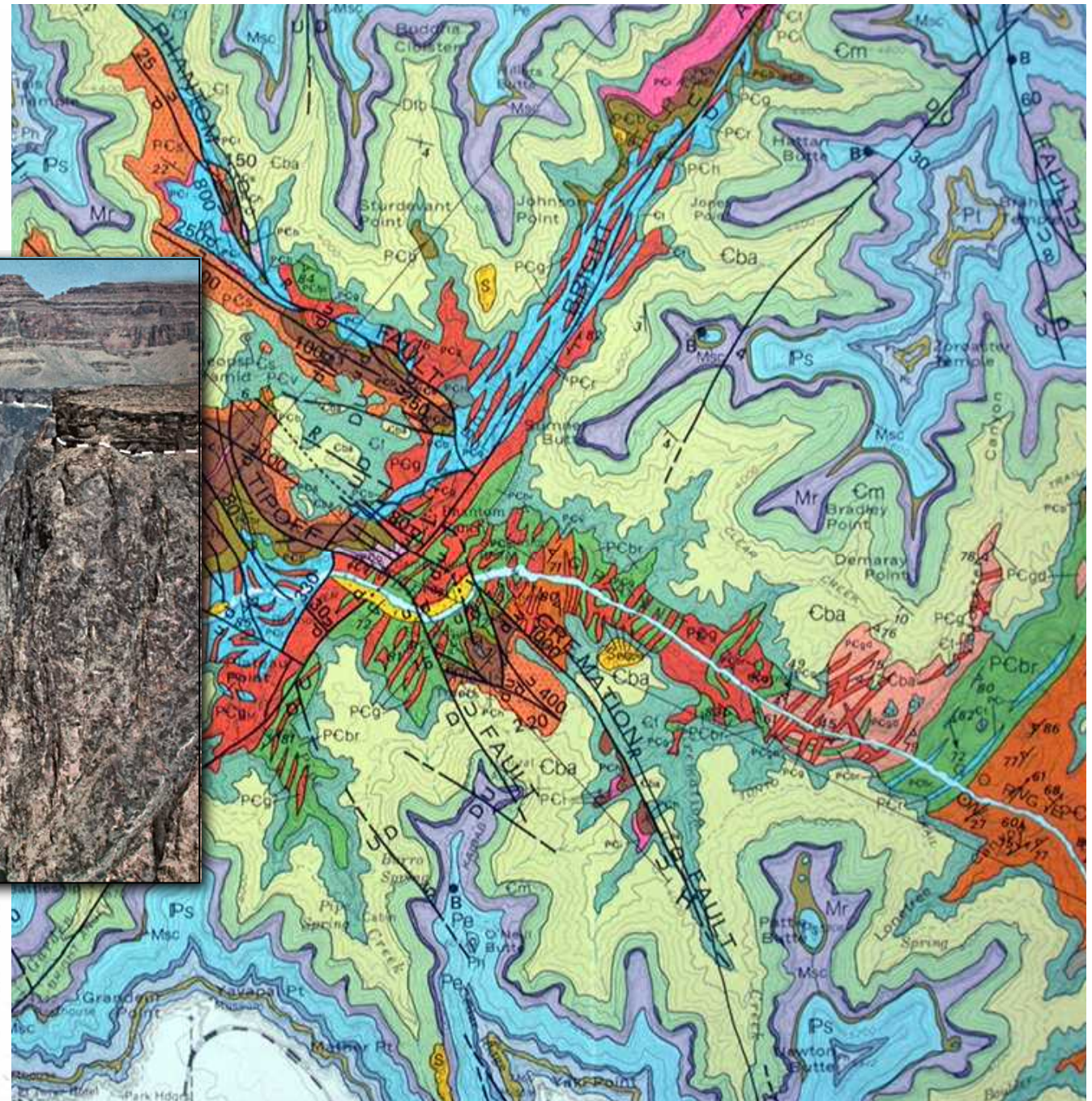
# Steilstehende Schichten

- PRECAMBRIAN SEDIMENTARY ROCKS**
- CHUAR GROUP**
    - PC6 Sixtymile Formation
    - Unconformity
    - PC5 Kwagunt Formation; includes Walcott, Awatubi and Carbon Butte Members
    - PCg Galeros Formation; includes Dopa, Carbon Canyon, Jupiter and Tanner Members
    - Unconformity
    - PCn Nankowep Formation
    - Unconformity
  - UNKAR GROUP**
    - PCc Cardenas interbeds
    - PCi Predominant
    - PCd Dox Sandstone
    - PCs Shinumo
    - PCv Hakatai
    - PCb Bass Formation
    - Unconformity



Great Unconformity

- PRECAMBRIAN CRYSTALLINE ROCKS**
- Older Precambrian**
    - PCg Granites, gneisses related to (Ga).
    - PCgd Granodioritic complexes of including basement
    - PCun Ultramafic
  - Older Precambrian**
    - PCv Vishnu Schist probable
    - PCbr Brahma Schist: amphibolite, biotite-hornblende schist and biotite schist of probable mafic volcanic origin (PCbr<sub>0a</sub>-ortho-amphibole bearing schist and gneiss) (ca. 1.75 Ga).
    - PCs Rama Schist and Gneiss: quartzofeldspathic schist and gneiss of probable felsic volcanic origin (ca. 1.75 Ga).
    - PC Precambrian undifferentiated

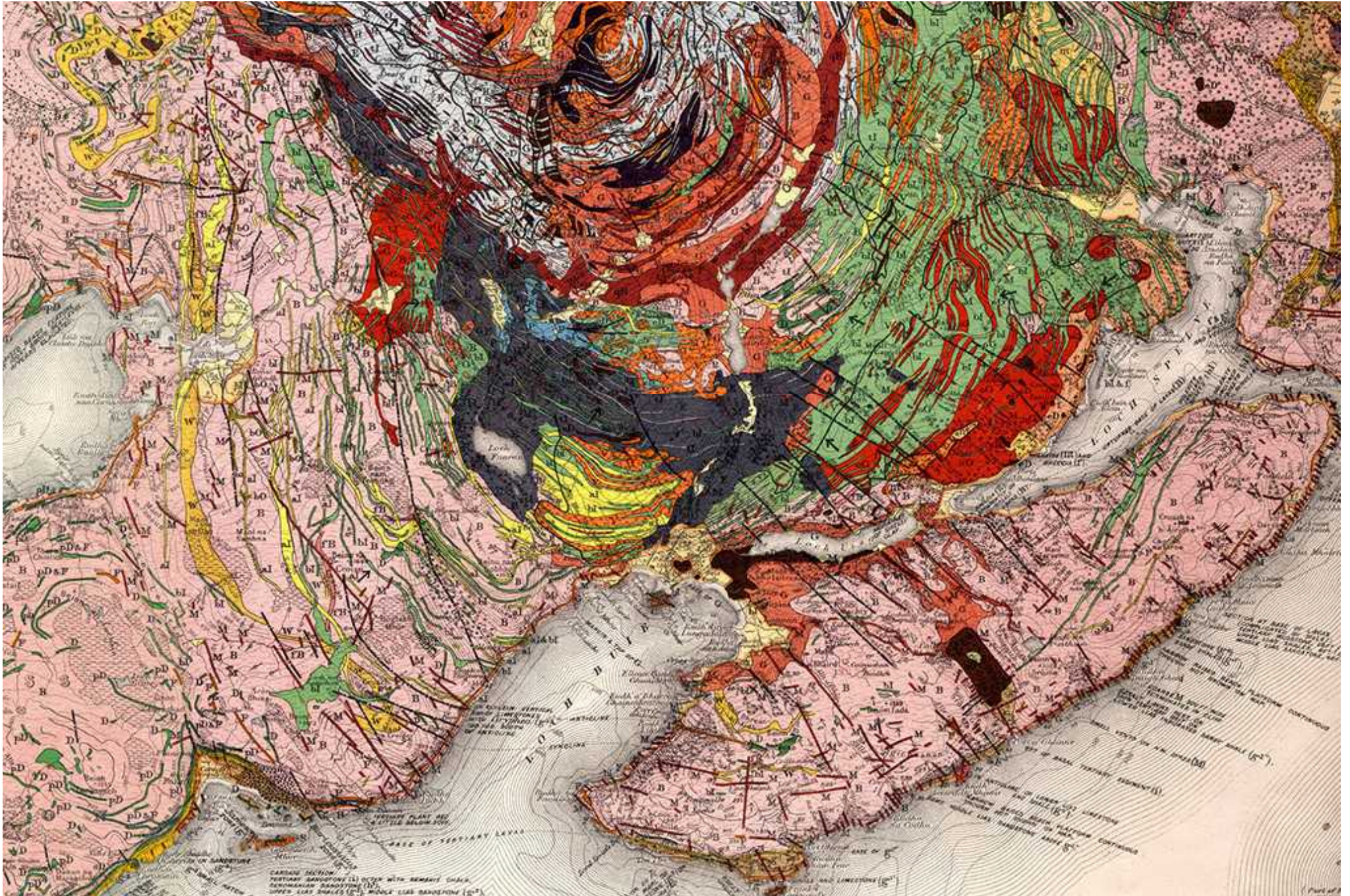


# Intrusion



**Beispiel: Isles of Mull, Schottland**

# Intrusion

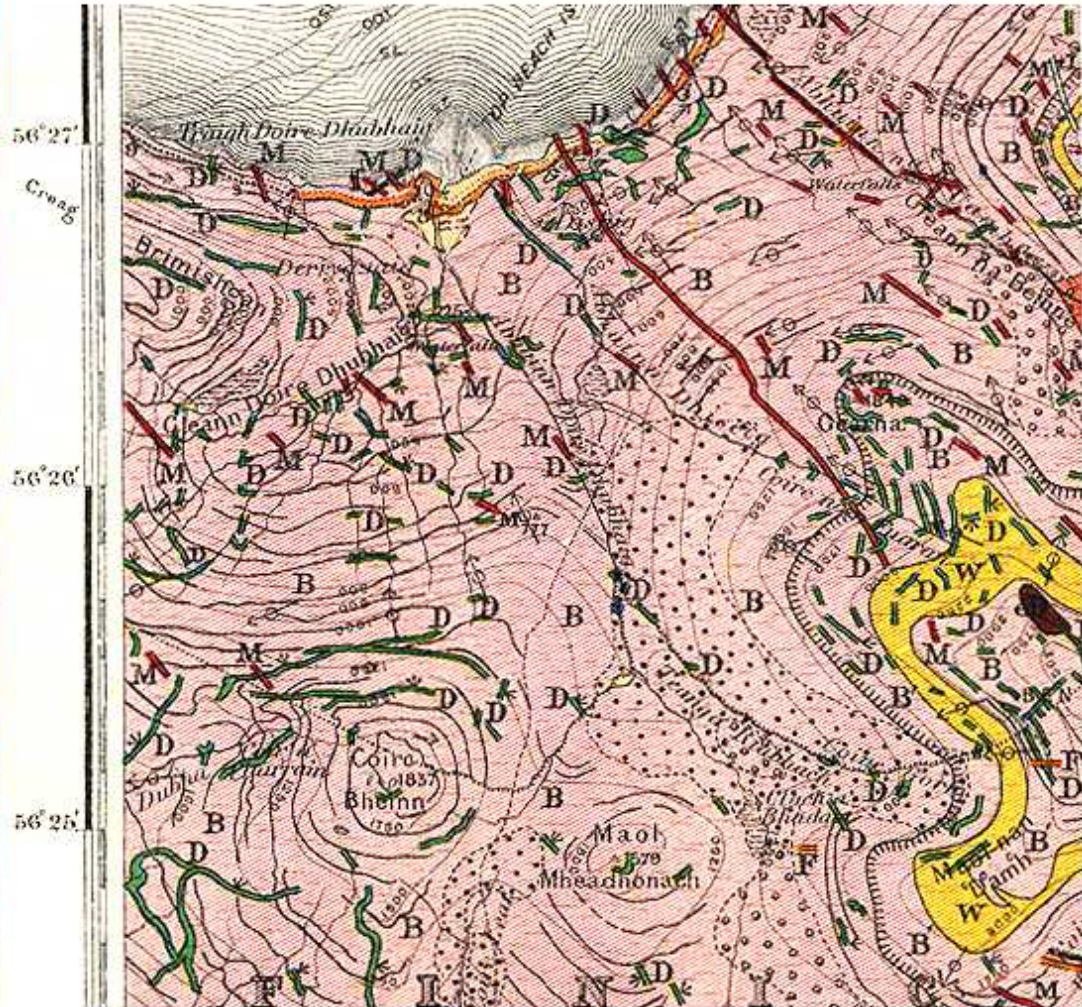


# Gänge - Lagergänge (dikes - sills)

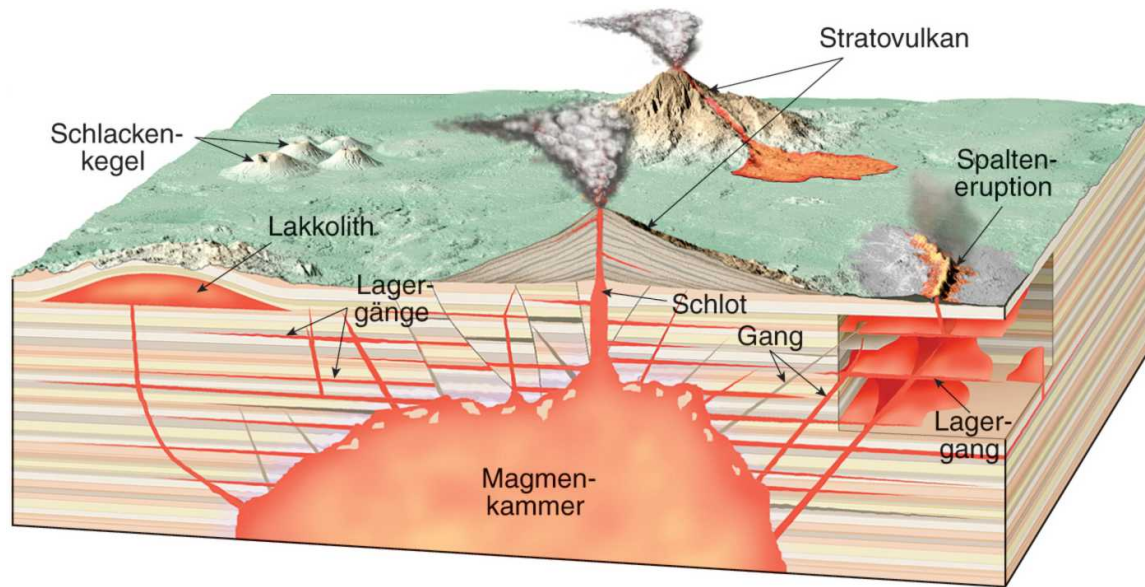
Gänge  
(dikes)

Lager-  
gänge  
(sills)

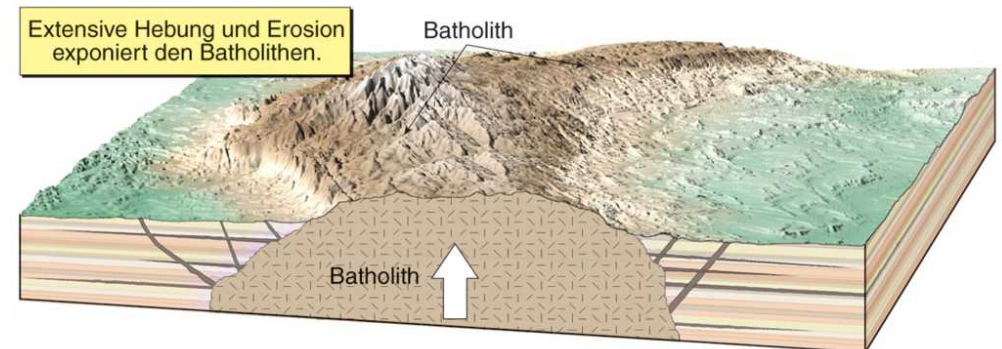
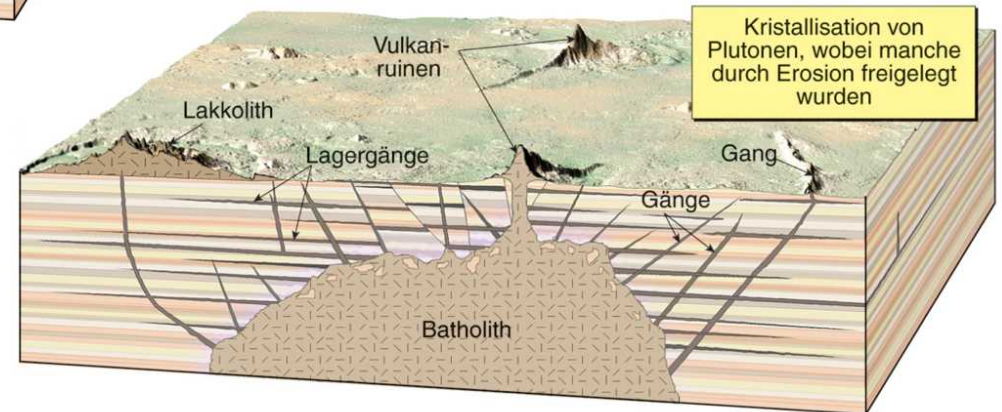
<i>Dolerite, Basalt, and Augite Andesite Dykes</i>	M
<i>Camptonite Dykes (perhaps Pre-Tertiary)</i>	C
<i>Late Basic (mainly Olivine-free Talaidh Type)</i>	tI
<i>Early Basic (mainly Olivine Dolerite)</i>	bI
<i>Acid (mainly Craignurite and earlier than bI)</i>	aI
<i>Dolerite and Basalt of Creag na h-Iolair Complex</i>	cD
<i>Dolerite, Basalt, and Augite Andesite sills and sheets not included as cD, bI, or tI</i>	D
<i>p indicates Basic Pitchstone in D</i>	pD
<i>s indicates xenolithic sapphire or its normal associates</i>	sD
	spD
<i>Mugearite</i>	W
<i>Basalt with large Felspar phenocrysts</i>	fB
<i>B Basalt of Pale Group of Ben More, where separated (base ornamented)</i>	B
<i>B Basalt where not separated as B' or fB</i>	B



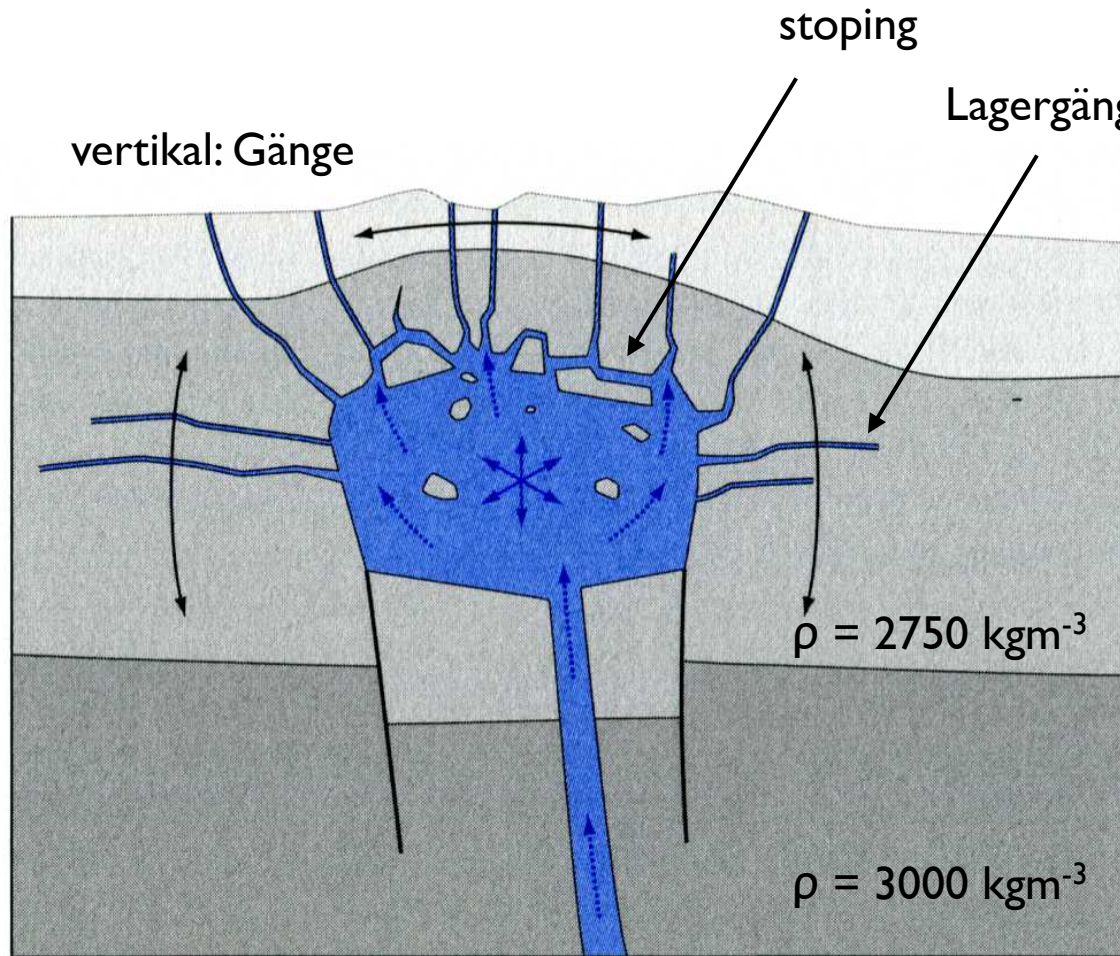
# Intrusion










Gänge (dikes) = diskordant  
Lagergänge (sills) = konkordant



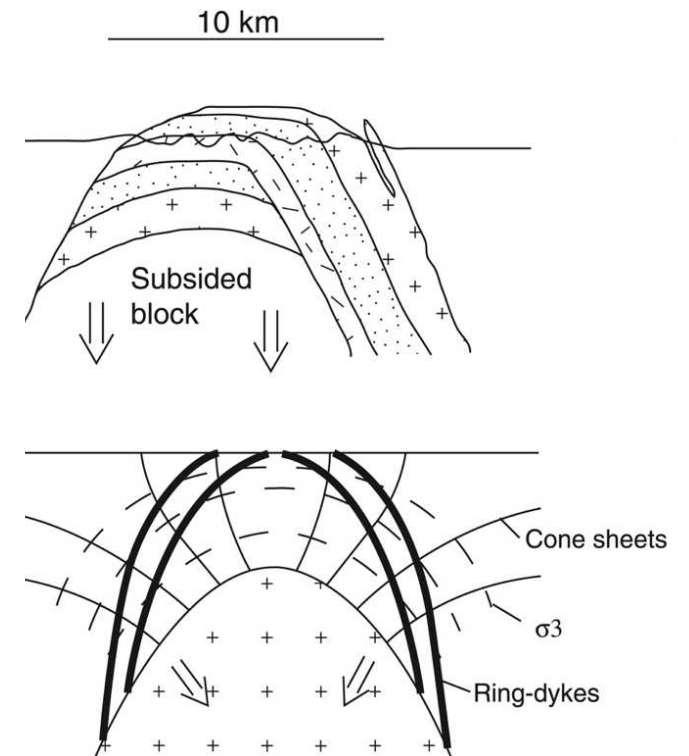
# Platznahme von Plutonen



-  Sedimente
-  Metamorphe Sedimente oder Kristallingesteine
-  Kristallingesteine
-  Schmelze/Intrusivgesteine

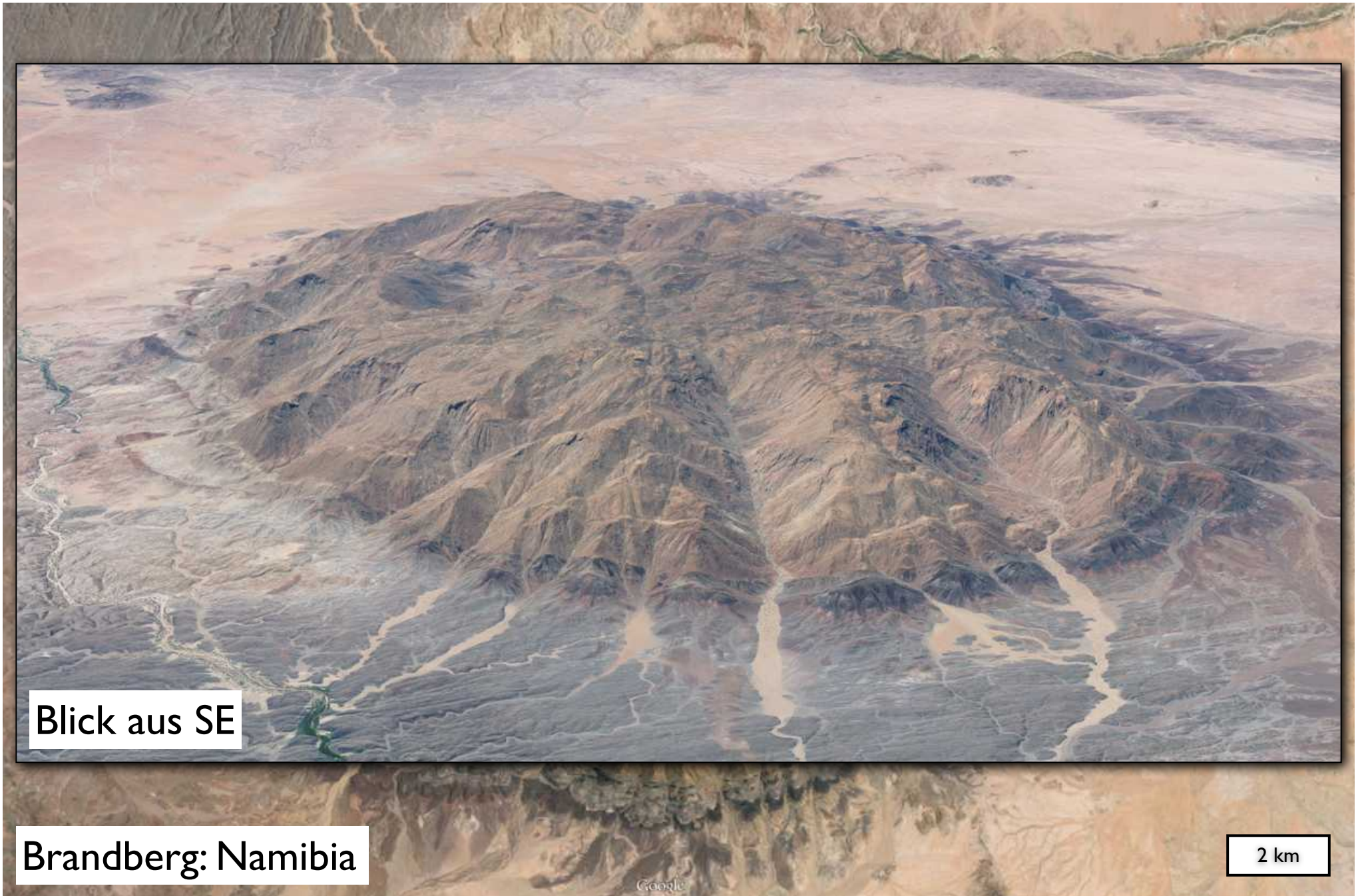
-  Dehnung
-  Allseitiger Magmadruck
-  Aufsteigende Schmelze

1. cone sheets
2. ring dykes





# Intrusion



Blick aus SE

Brandberg: Namibia

2 km

Google

# Vulkanischer Stock + Gänge



Blick aus S

Shiprock: New Mexico

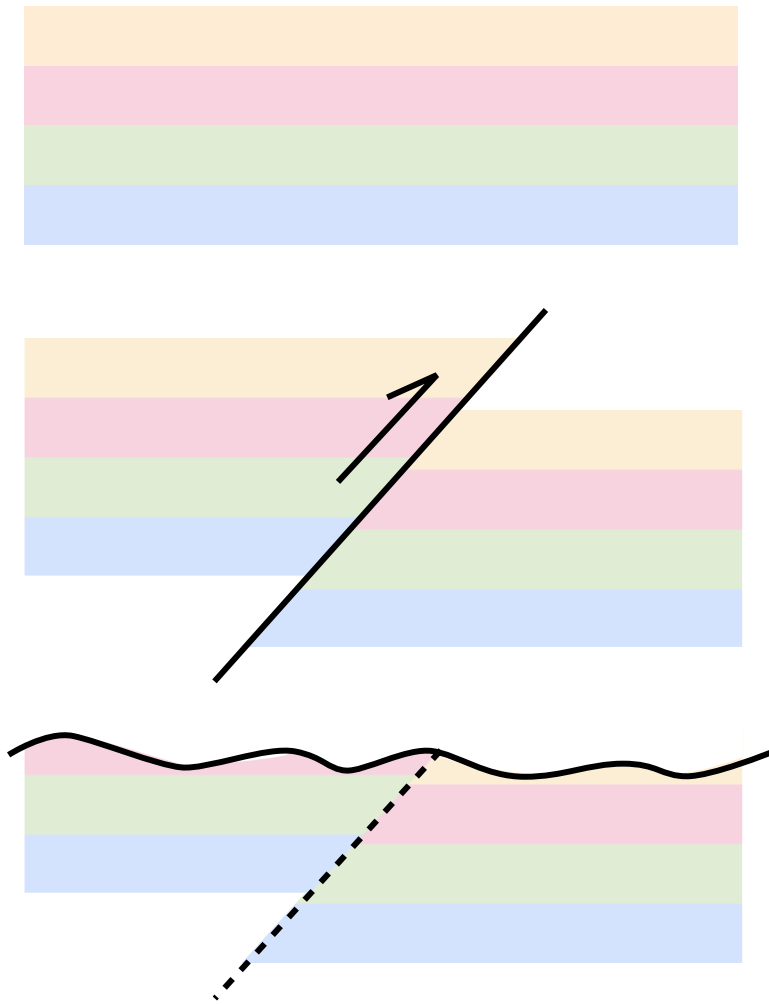
1 km

**Interpretation**

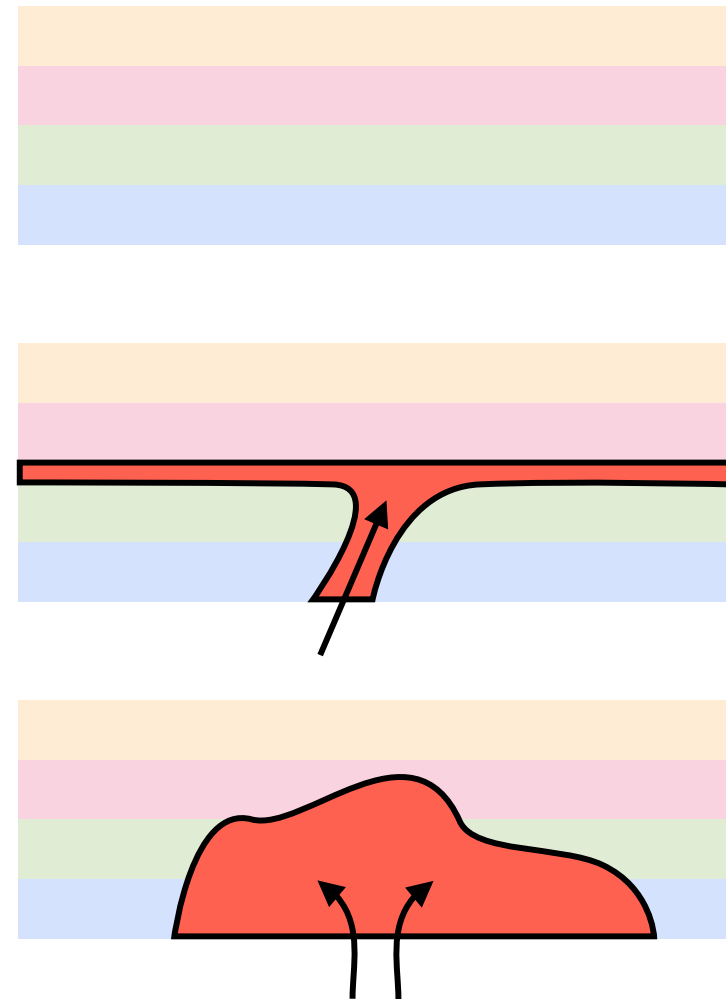
# Überschneidungskriterien

Jüngeres durchschlägt / schneidet Älteres

Verwerfung und Erosion



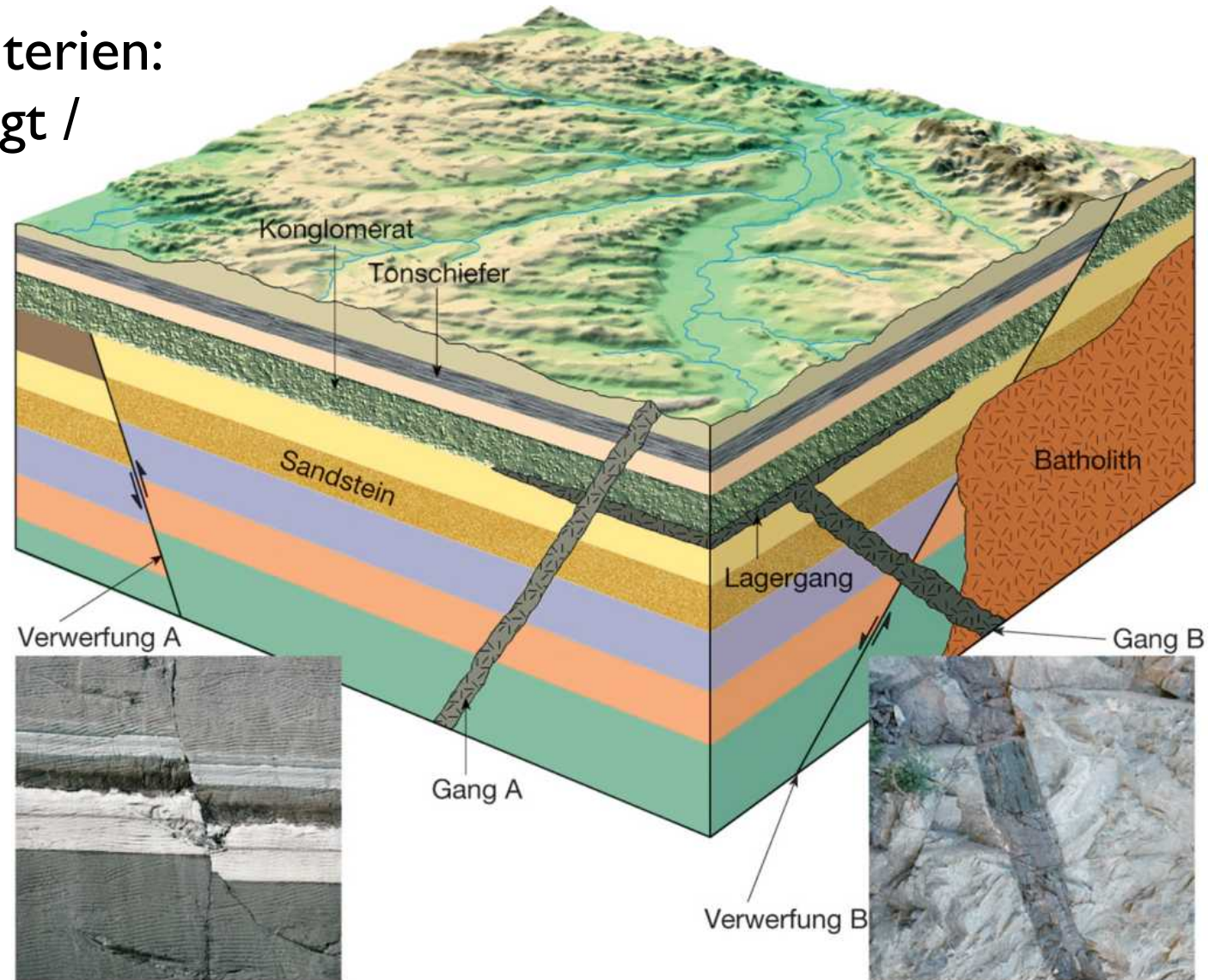
Intrusion



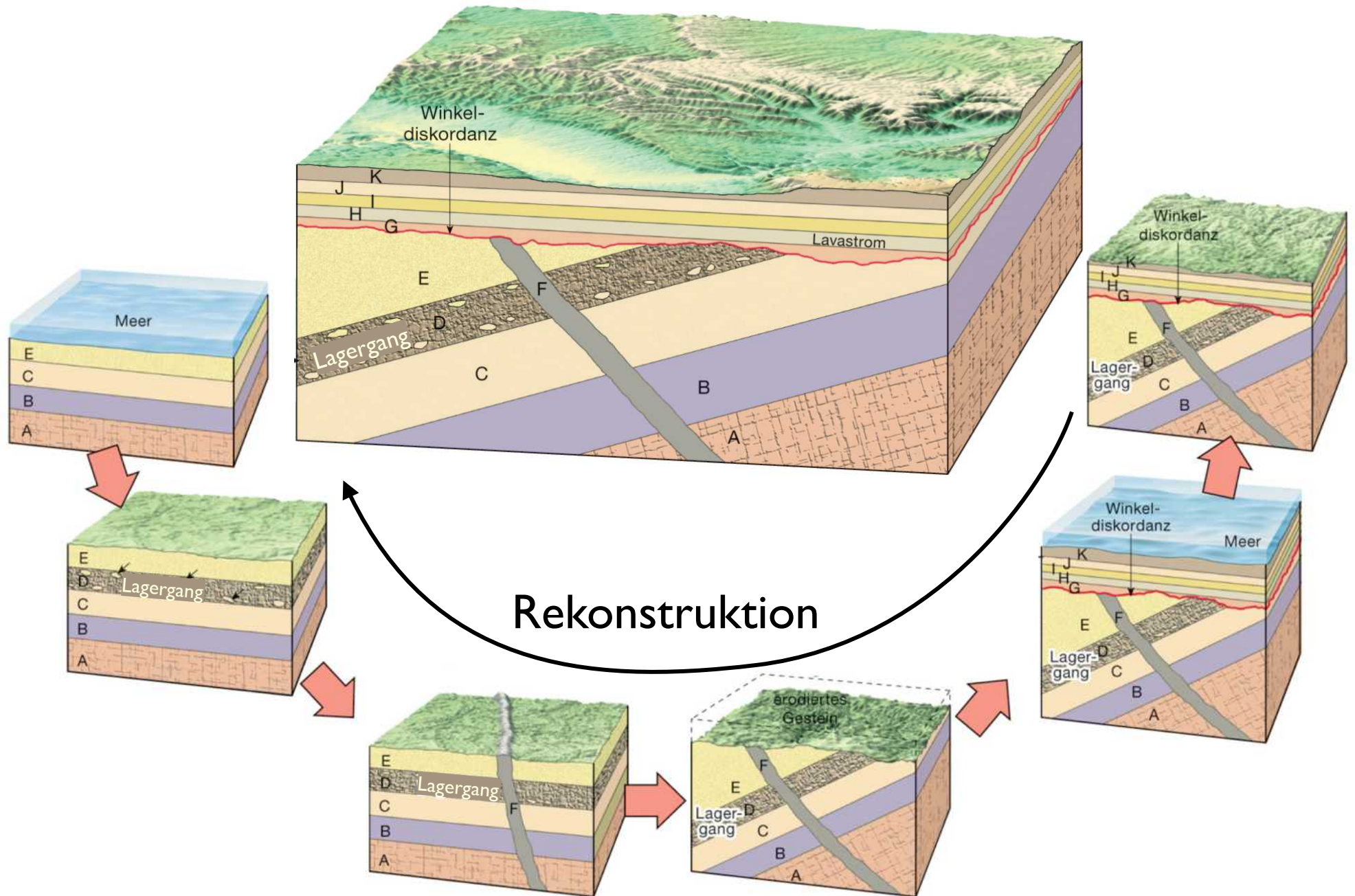
# Relative Alter

Superpositionsprinzip: unten alt - oben jung  
flachliegende Schichten sind undeformiert

Überschneidungskriterien:  
Jüngeres durchschlägt /  
schneidet Älteres

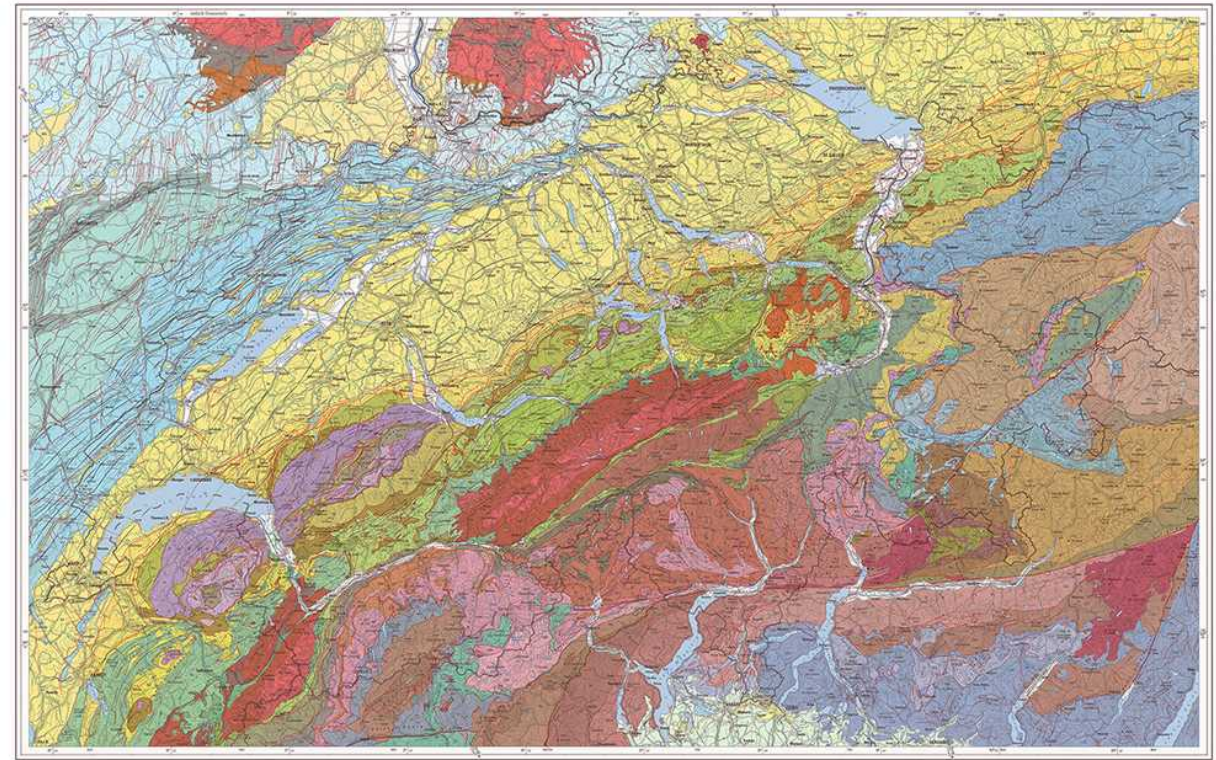
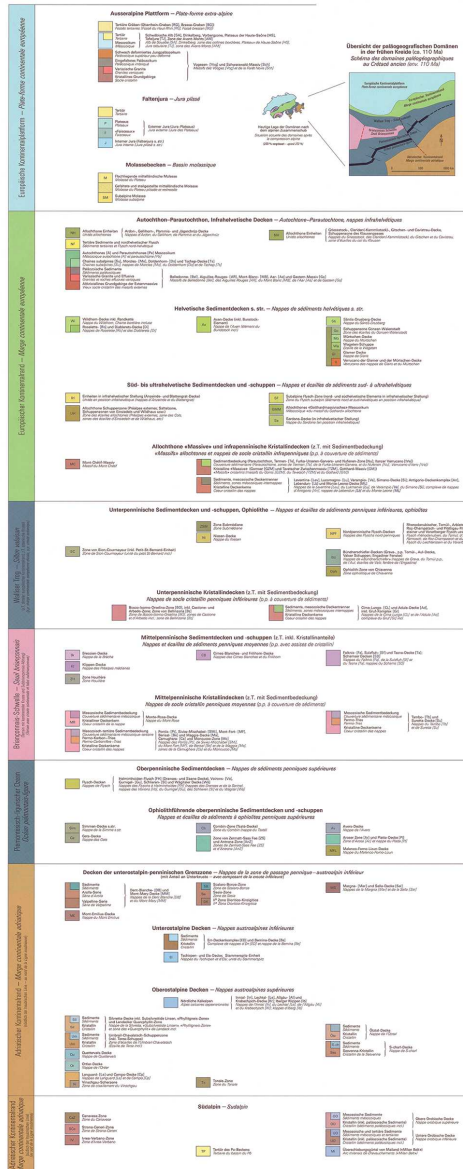


# Zeitliche Abfolge



# Geologische - Tektonische Karten

# Tektonische Karte

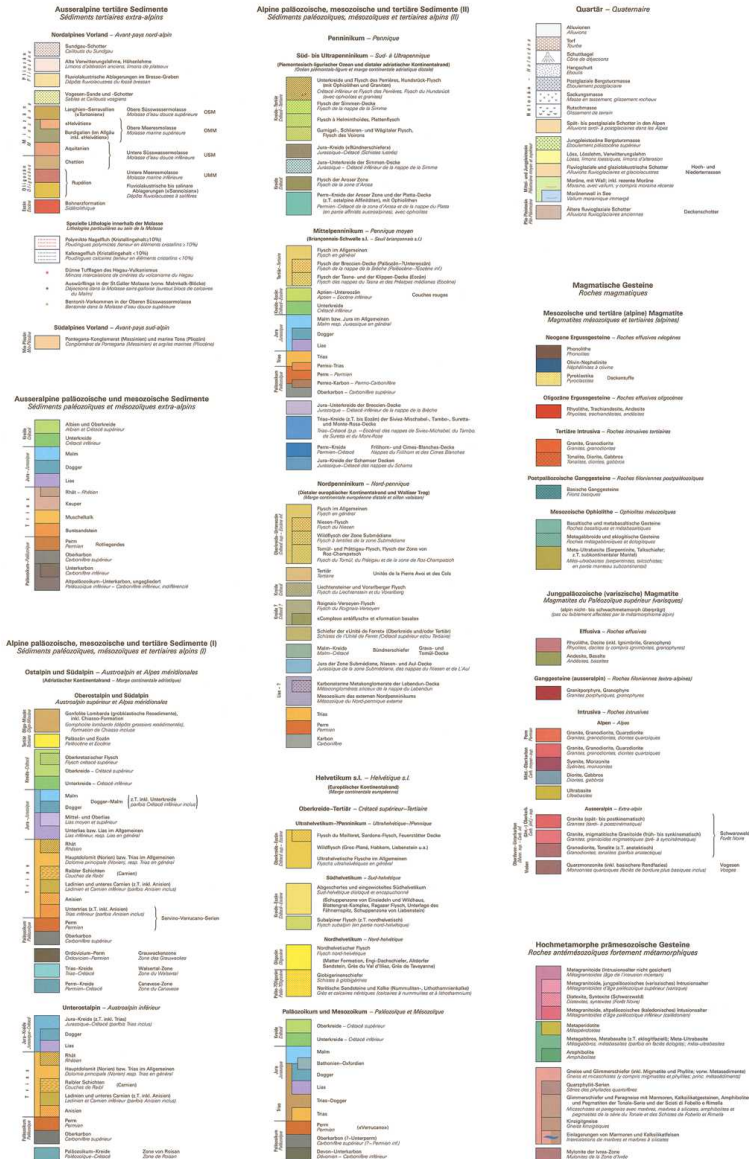


Tektonische Einheiten:  
 (gemeinsam bewegt)  
 Kristallin- Sedimentdecken  
 Paläogeographische Zuordnung

paläogeographisch gruppiert



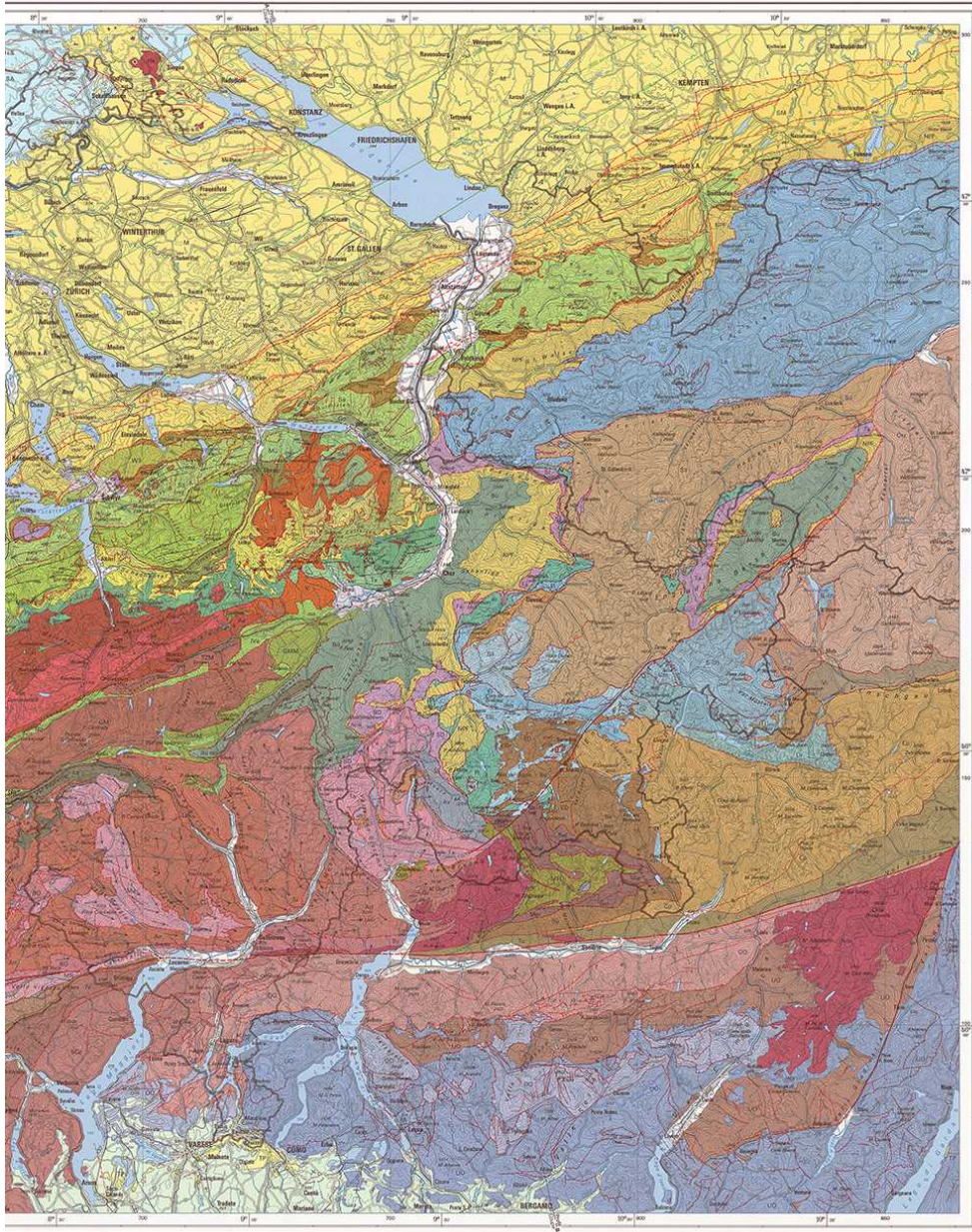
# Geologische Karte



Geologische Einheiten:  
 Sedimente (Sedimentgesteine)  
 Magmatische, metamorphe Gesteine  
 Stratigraphische (Alters-) Zuordnung

tektonisch gruppiert

# Tektonische

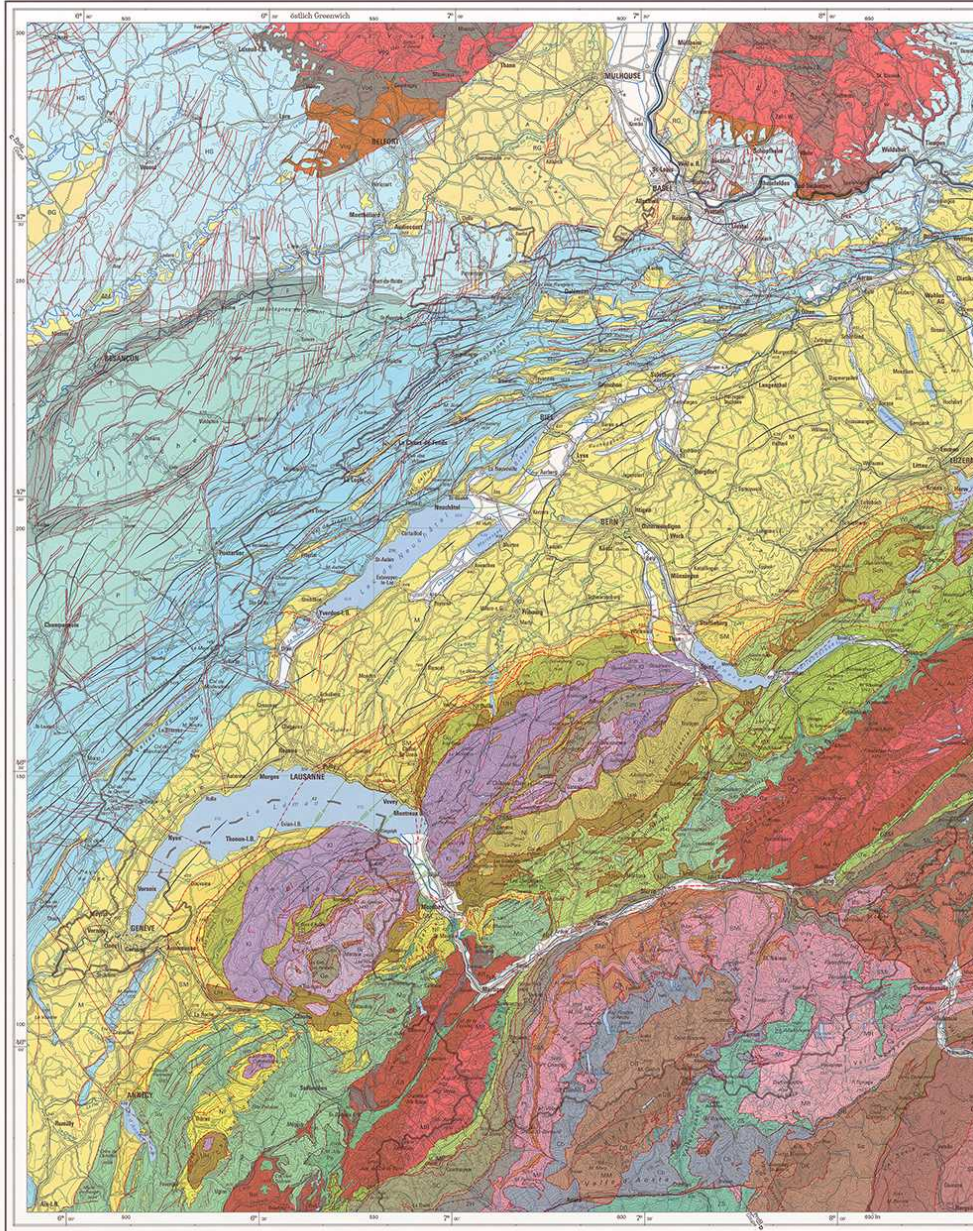


# Geologische

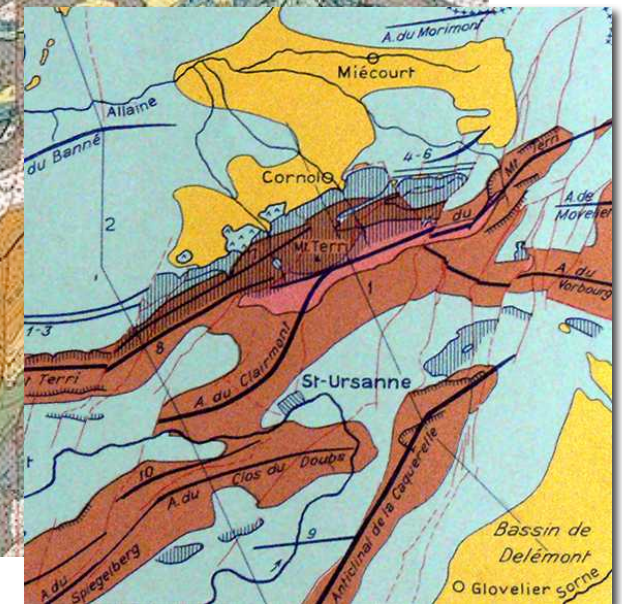
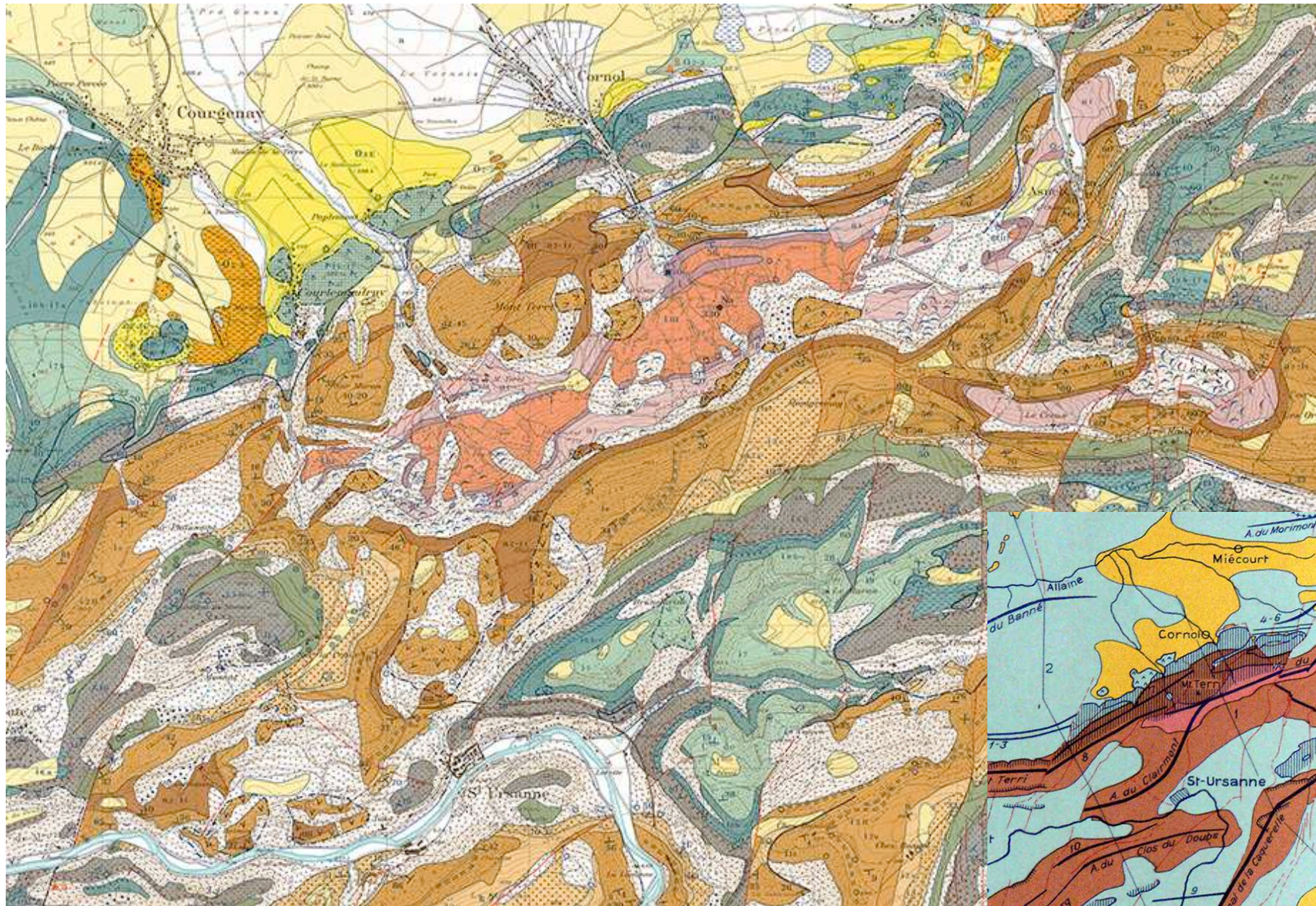


# Tektonische

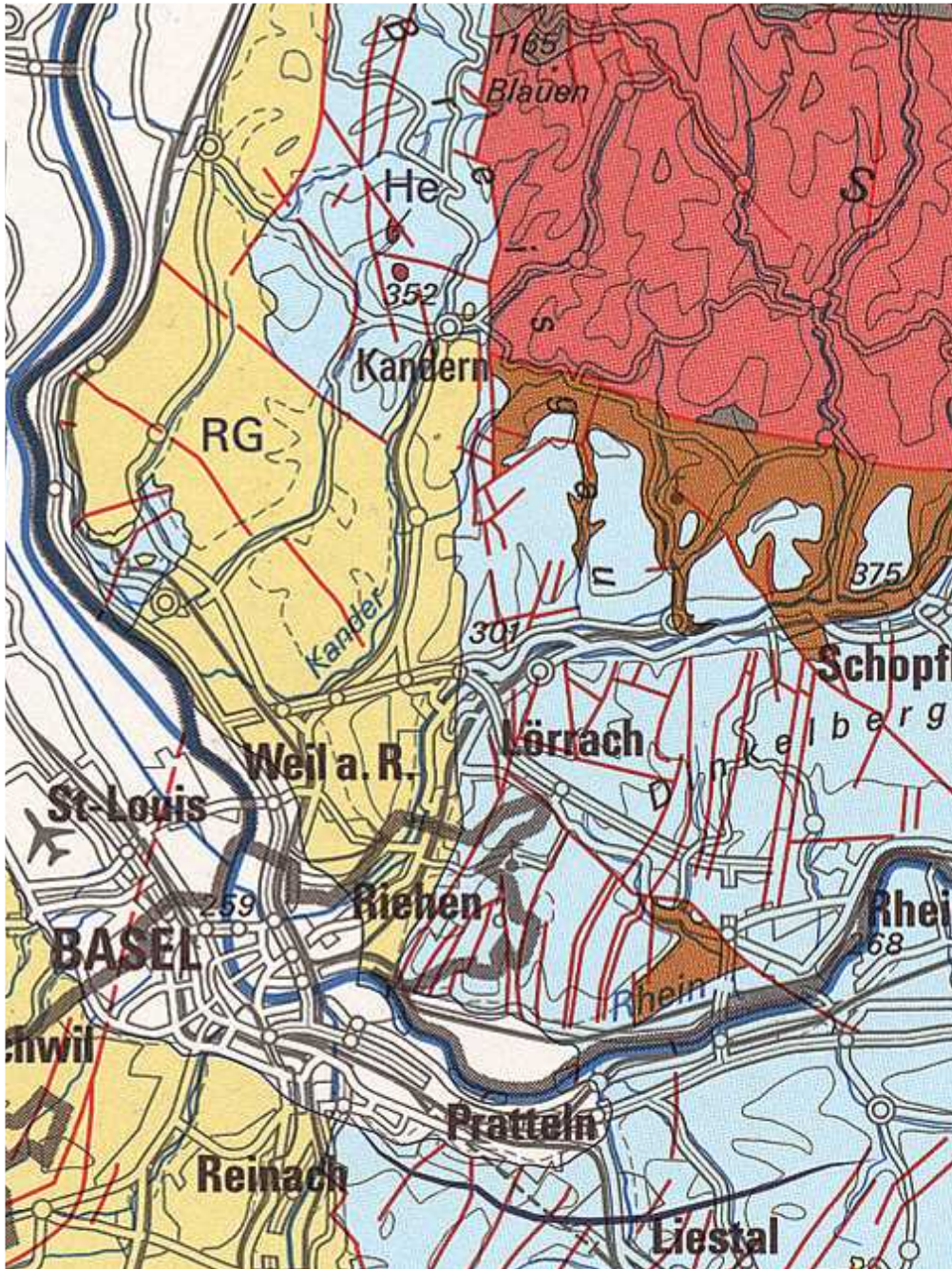
# Geologische



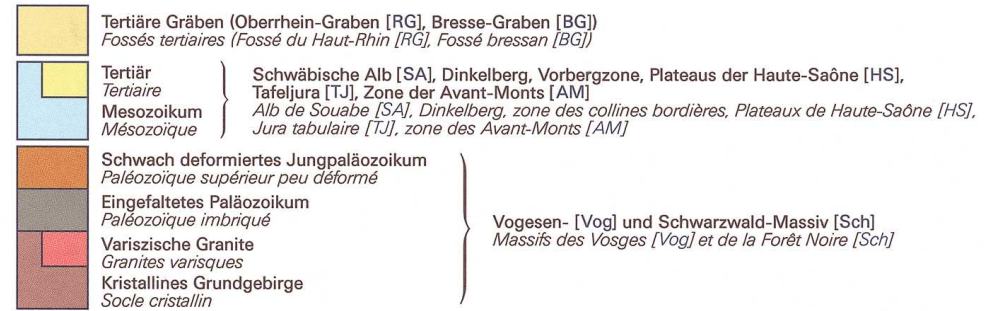
# Mont Terri Antiklinale



# Tektonik



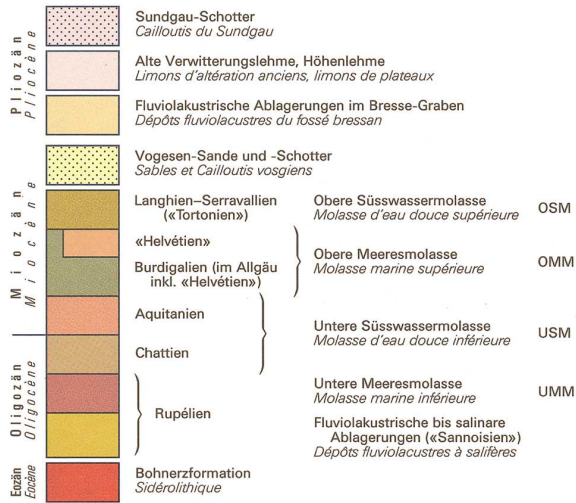
## Auseralpine Plattform – Plate-forme extra-alpine



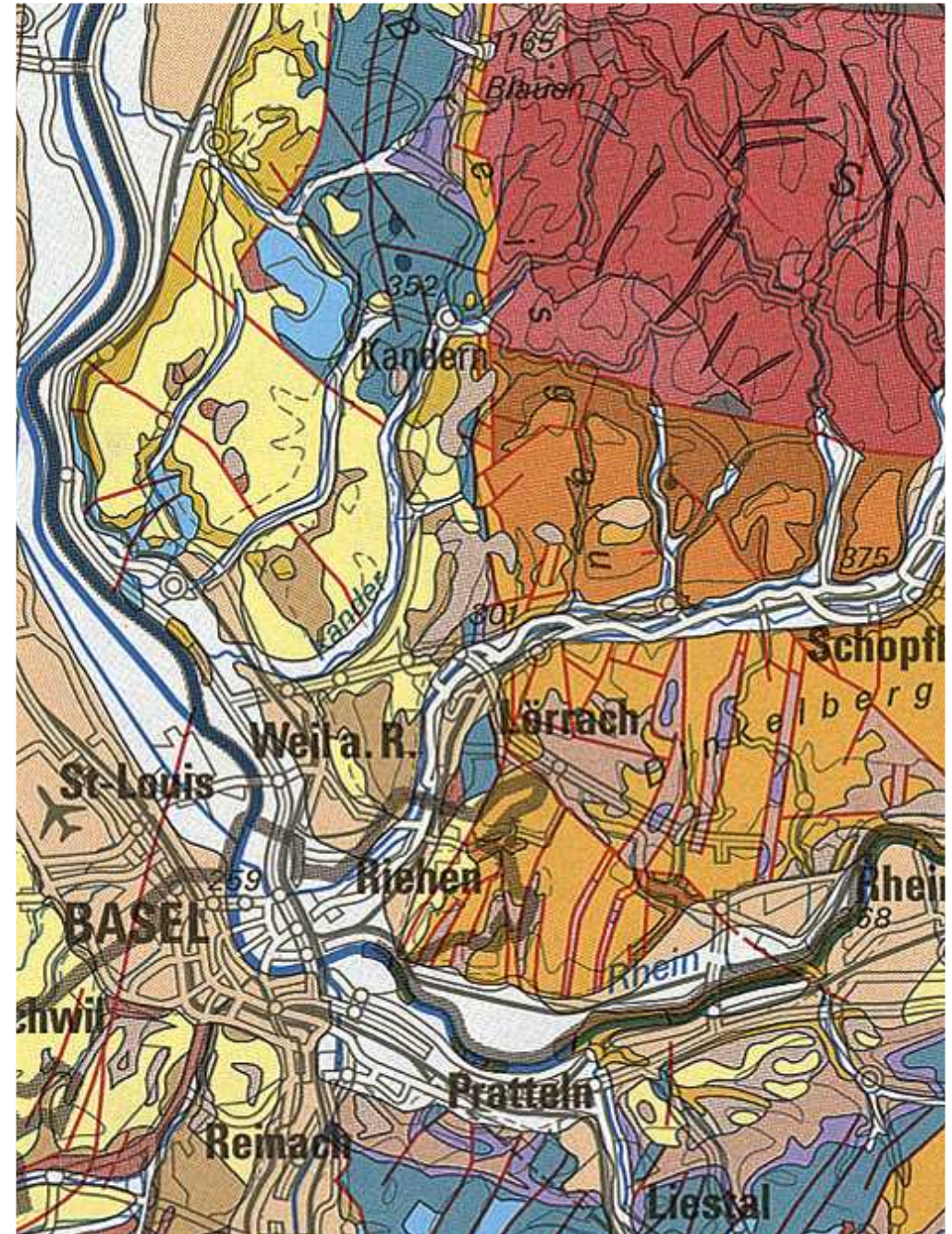
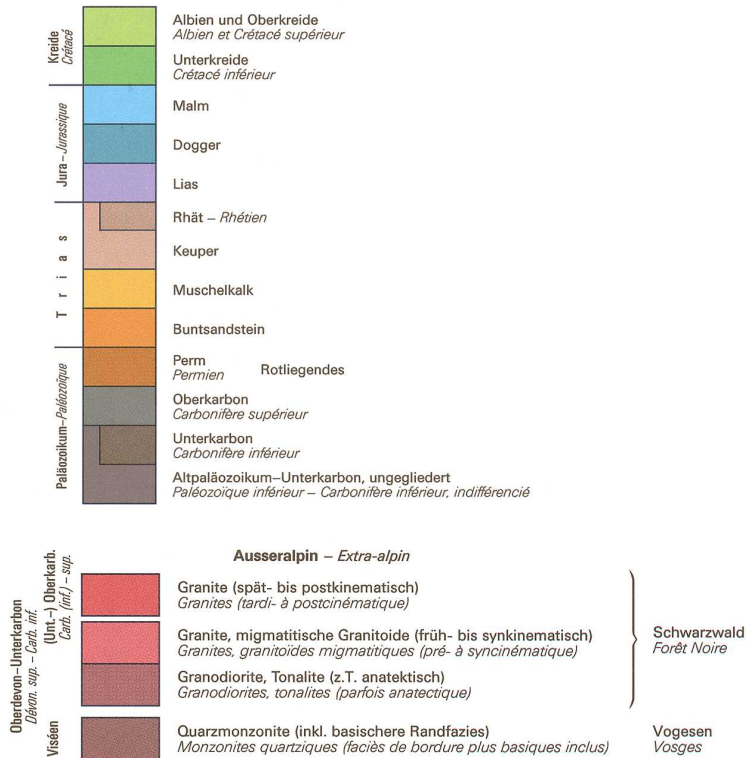
# Geologie

## Ausseralpine tertiäre Sedimente Sédiments tertiaires extra-alpins

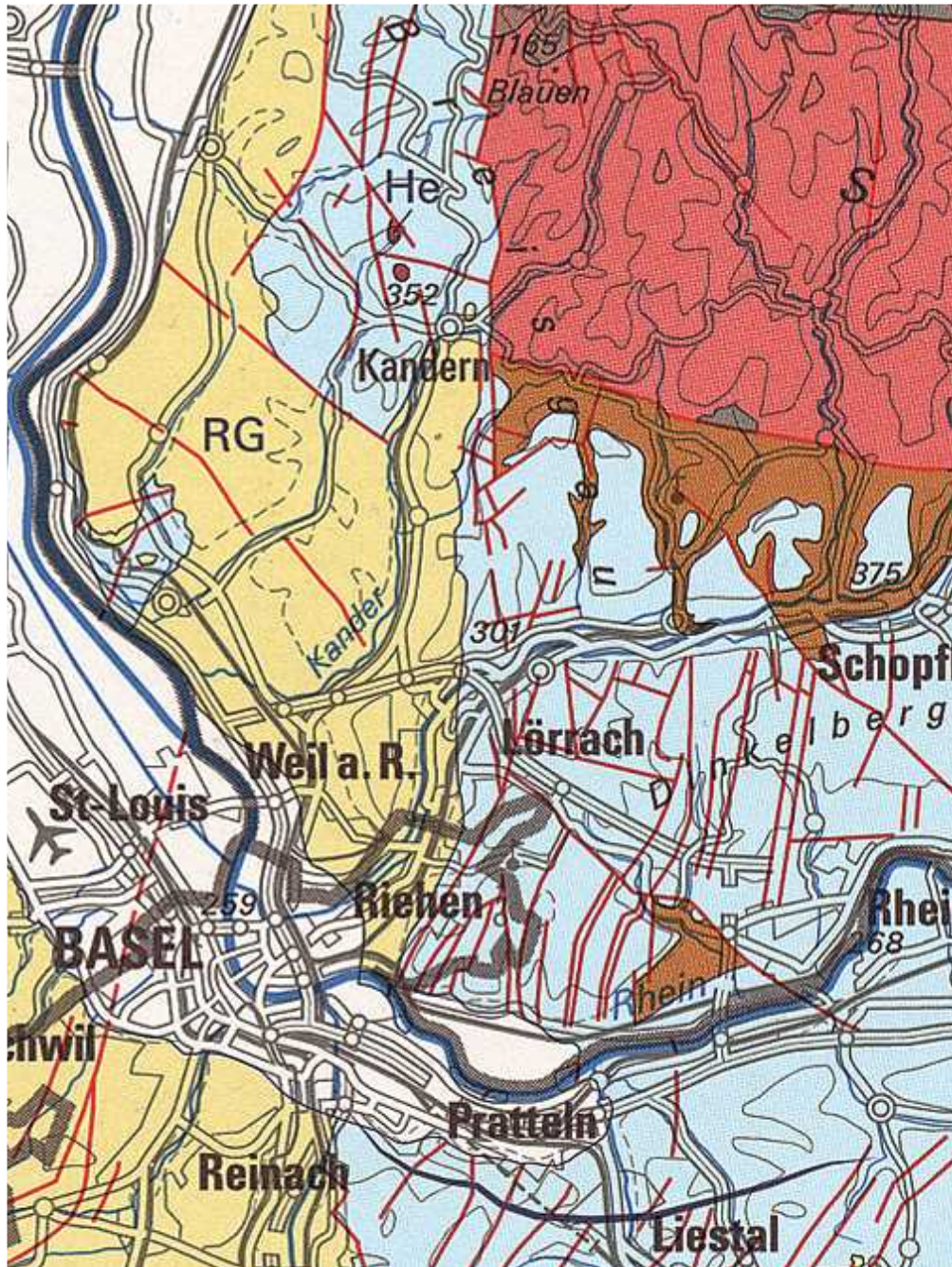
### Nordalpines Vorland – Avant-pays nord-alpin



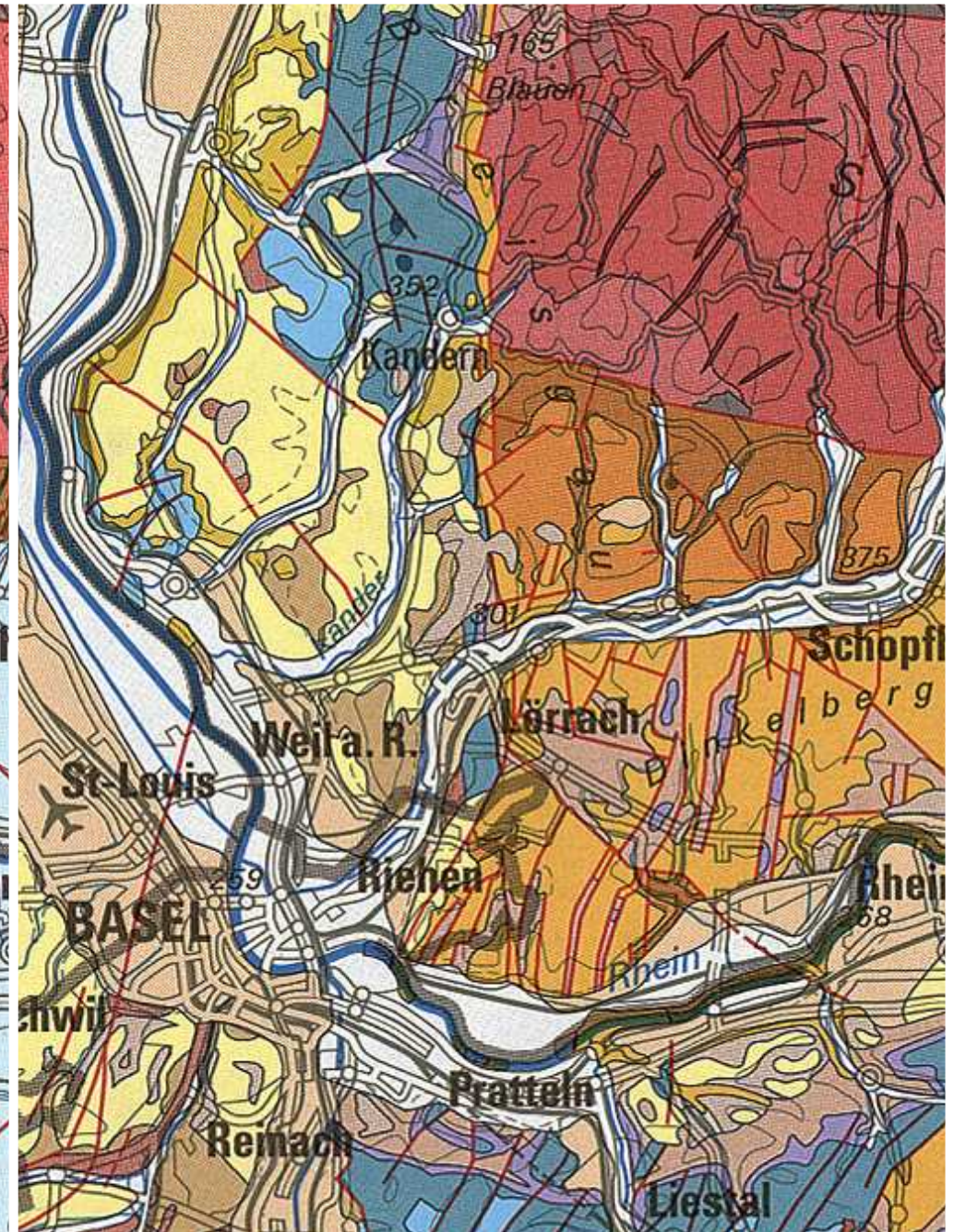
## Ausseralpine paläozoische und mesozoische Sedimente Sédiments paléozoïques et mésozoïques extra-alpins



# Tektonik



# Geologie



# 2 Strukturengelogeologisch kartieren

## Messung und Darstellung von Strukturen

- Strukturgeologische Karten
- Orientierung von Flächen im Raum
- Signaturen

## Stereographische Projektion

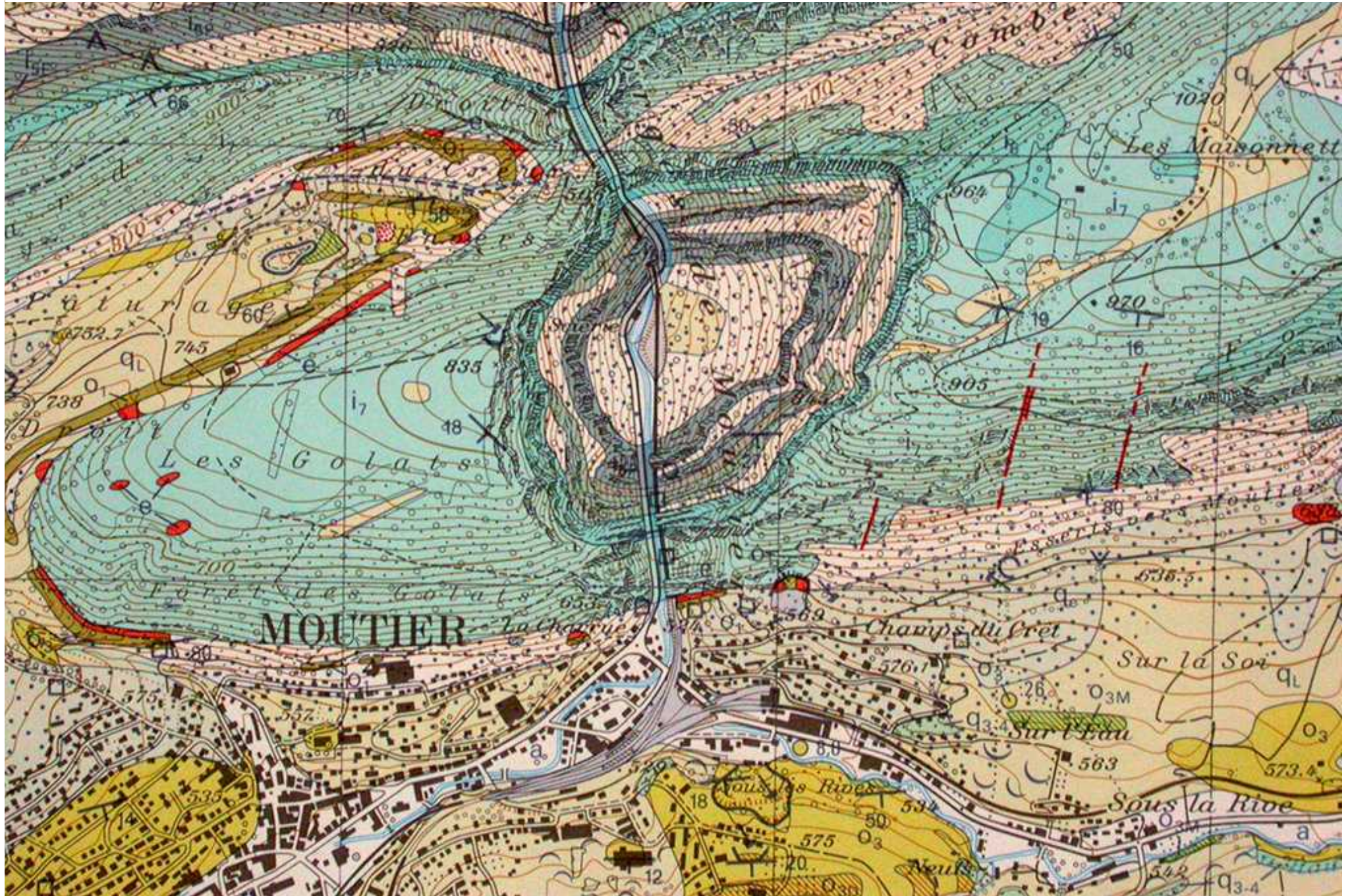
- Fallazimuth (Einfallrichtung) - Fallwinkel (Einfallswinkel)
- Flächen und Pole



# Beispiel: Jura (Klus bei Moutier)



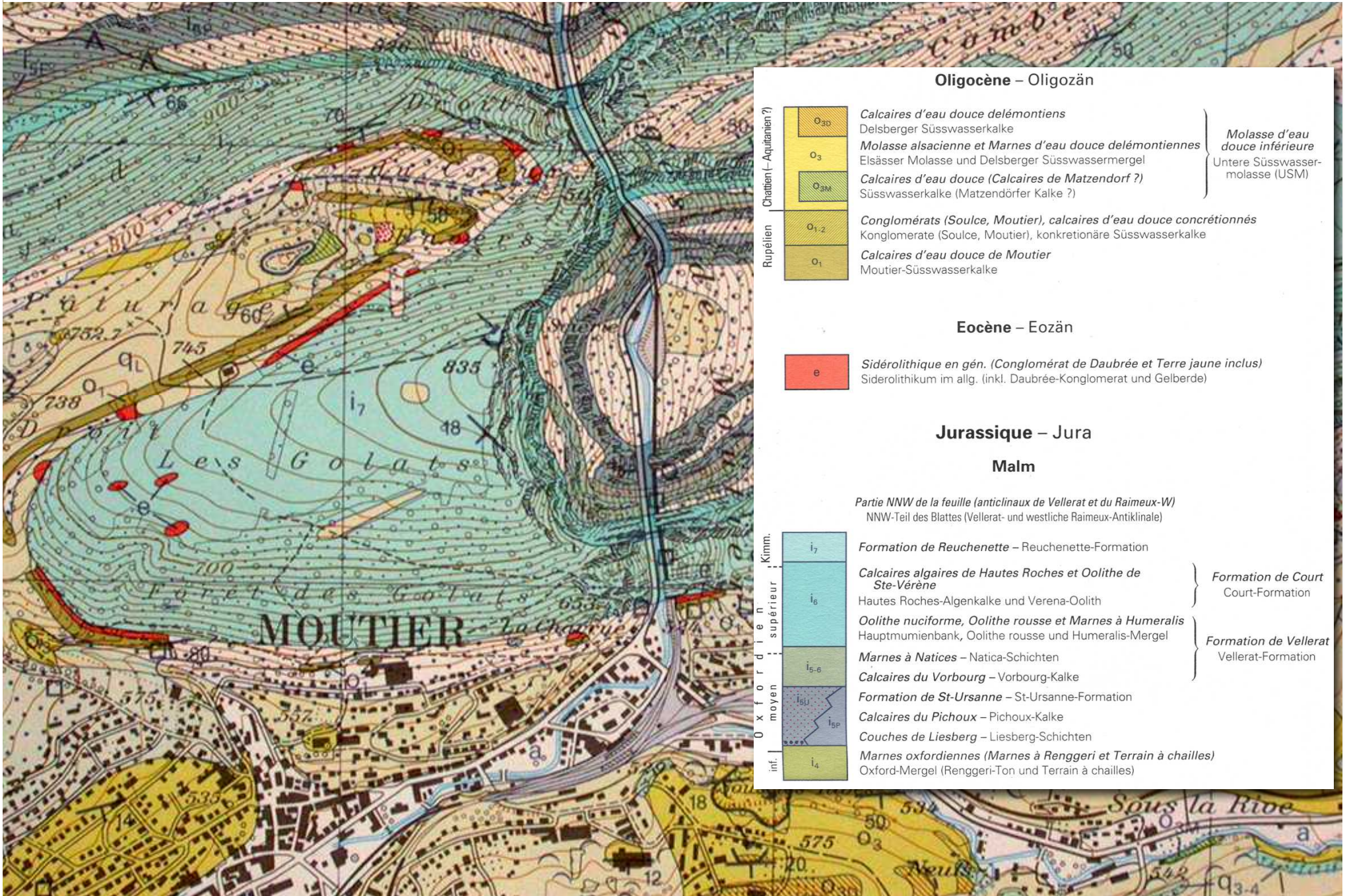
# Geologische Karte



# Luftbild



# Falte im Kartenbild



## Oligocène – Oligozän

Chatain (= Aquitanien?)	O <sub>3D</sub>	Calcaires d'eau douce delémontiens Delsberger Süßwasserkalke	} Molasse d'eau douce inférieure Untere Süßwassermolasse (USM)
	O <sub>3</sub>	Molasse alsacienne et Marnes d'eau douce delémontiennes Elsässer Molasse und Delsberger Süßwassermergel	
	O <sub>3M</sub>	Calcaires d'eau douce (Calcaires de Matzendorf ?) Süßwasserkalke (Matzendorfer Kalke ?)	
Rupélien	O <sub>1,2</sub>	Conglomérats (Soulece, Moutier), calcaires d'eau douce concrétionnés Konglomerate (Soulece, Moutier), konkretionäre Süßwasserkalke	
	O <sub>1</sub>	Calcaires d'eau douce de Moutier Moutier-Süßwasserkalke	

## Eocène – Eozän

e	Sidérolithique en gén. (Conglomérat de Daubrée et Terre jaune inclus) Siderolithikum im allg. (inkl. Daubrée-Konglomerat und Gelberde)
---	---

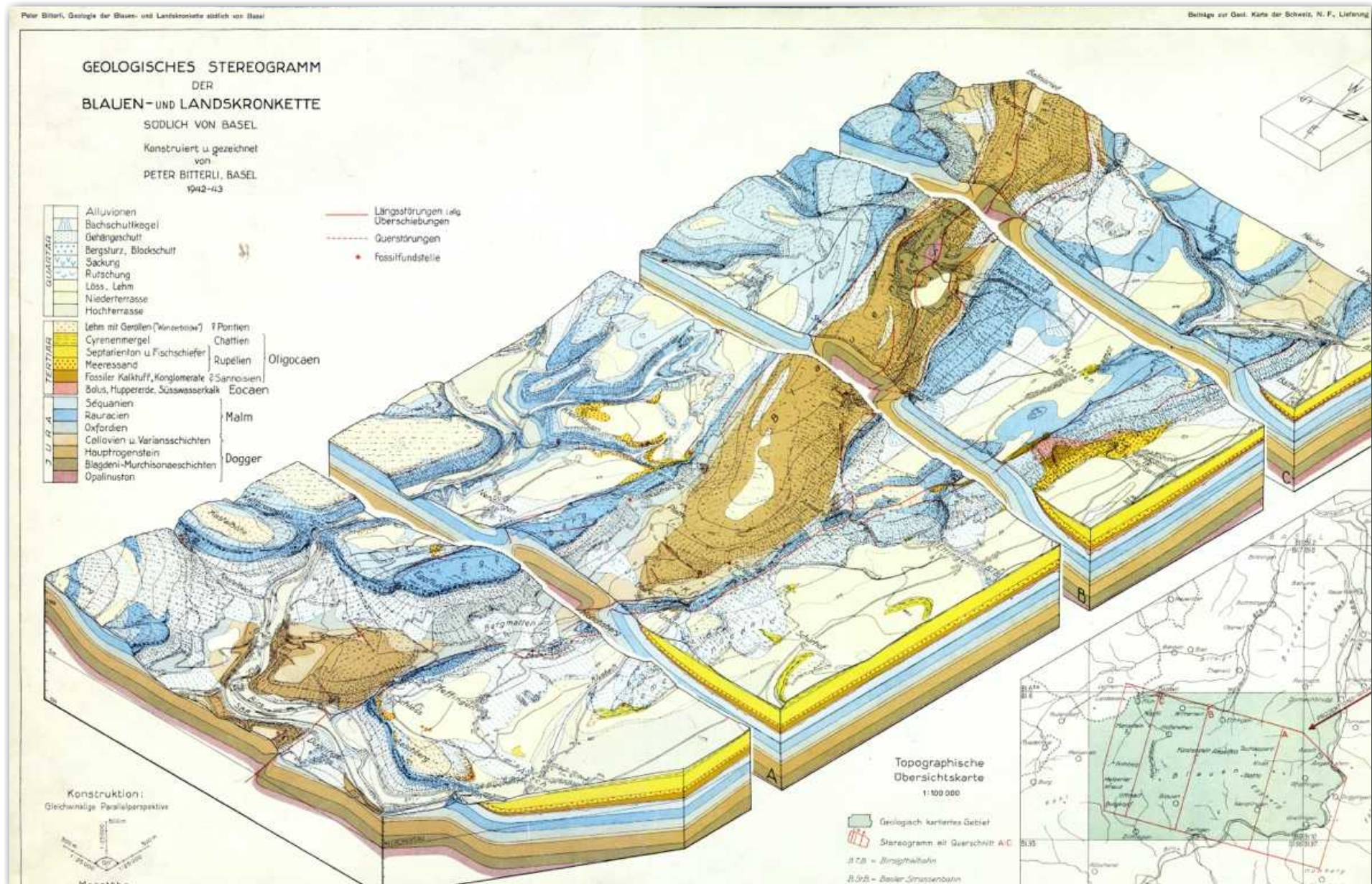
## Jurassique – Jura

### Malm

Partie NNW de la feuille (anticlinaux de Vellerat et du Raimeux-W)  
NNW-Teil des Blattes (Vellerat- und westliche Raimeux-Antiklinale)

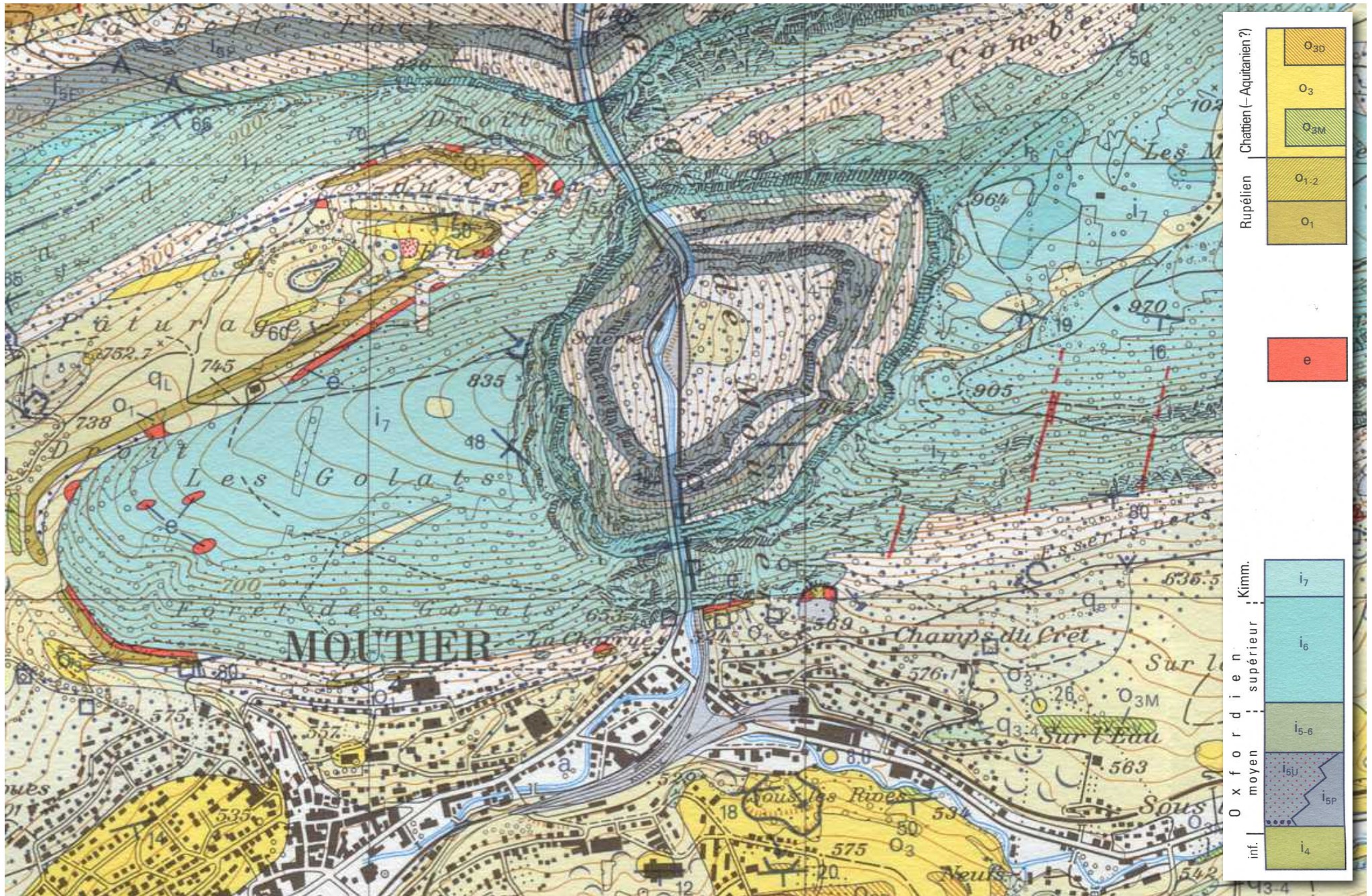
O x f o r d i e n m o y e n s u p é r i e u r K i m m.	i <sub>7</sub>	Formation de Reuchenette – Reuchenette-Formation	} Formation de Court Court-Formation
	i <sub>6</sub>	Calcaires algaires de Hautes Roches et Oolithe de Ste-Vérène Hautes Roches-Algenkalke und Verena-Oolithe	
	i <sub>5,6</sub>	Oolithe nuciforme, Oolithe rousse et Marnes à Humeralis Hauptmurnienbank, Oolithe rousse und Humeralis-Mergel	} Formation de Vellerat Vellerat-Formation
	i <sub>5U</sub>	Marnes à Natices – Natica-Schichten	
	i <sub>5P</sub>	Calcaires du Vorbourg – Vorbourg-Kalke	
	i <sub>4</sub>	Formation de St-Ursanne – St-Ursanne-Formation	
	inf.	Calcaires du Pichoux – Pichoux-Kalke Couches de Liesberg – Liesberg-Schichten Marnes oxfordiennes (Marnes à Renggeri et Terrain à chailles) Oxford-Mergel (Renggeri-Ton und Terrain à chailles)	

# 3D Darstellung: Karte mit Profilen

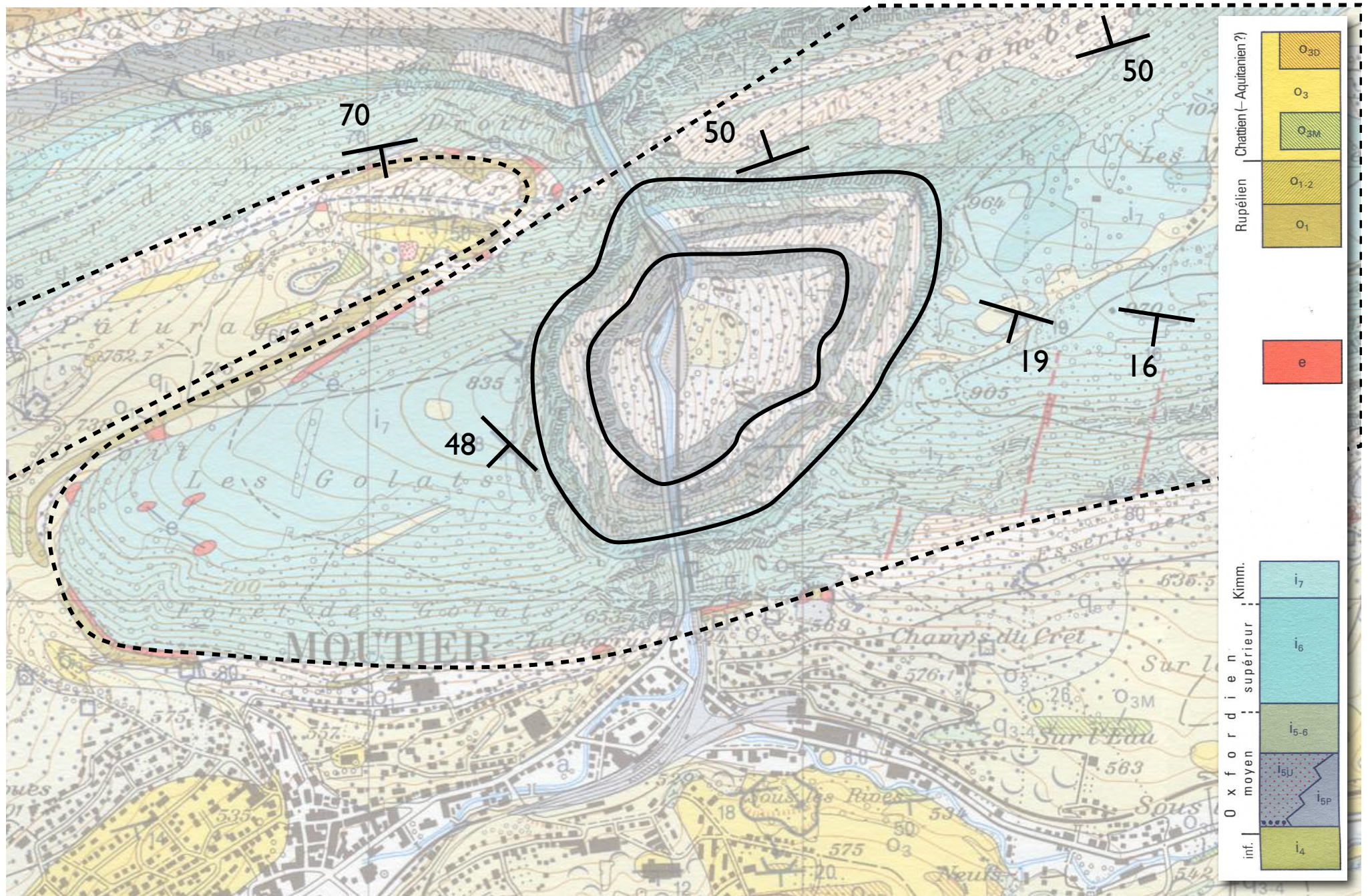


# Strukturen in der Karte

# Einfallsrichtung /-winkel    Streichen / Fallen



# Einfallsrichtung /-winkel    Streichen / Fallen





# Orientierung einer Ebene im Raum

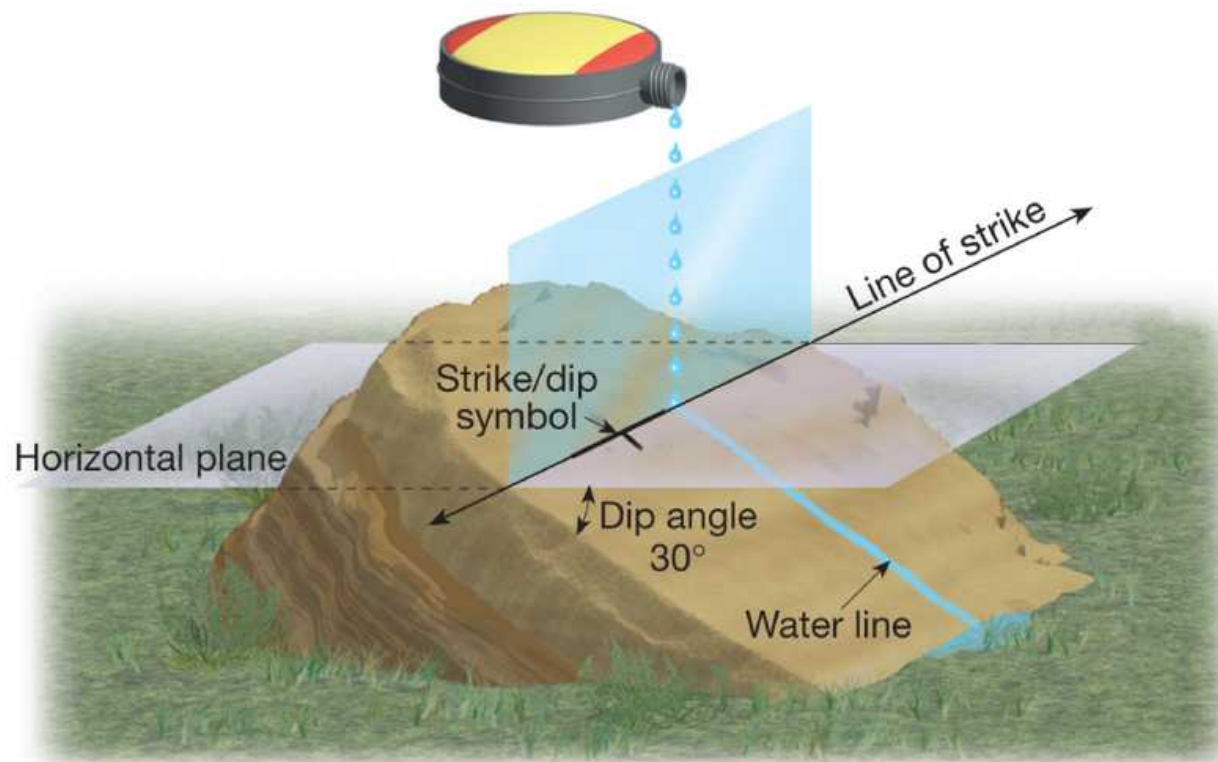
Darstellung von Flächen:

1. Streichen ( $0^\circ - 180^\circ$ ) - Fallen ( $0^\circ - 90^\circ$ )

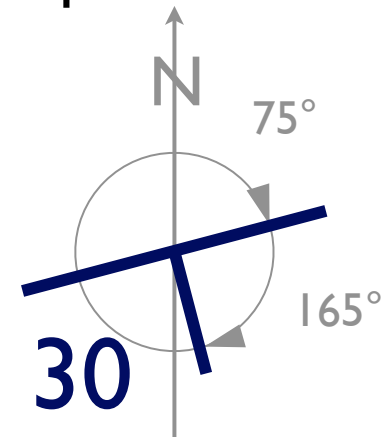
2. Einfallsrichtung ( $0^\circ - 360^\circ$ ) - Einfallswinkel ( $0^\circ - 90^\circ$ ), auch:  
Fallazimuth (*dip direction*) ( $0^\circ - 360^\circ$ ) - Fallwinkel (*dip*) ( $0^\circ - 90^\circ$ )

Darstellung von Linien:

Abtauchrichtung (*plunge direction*) / Abtauchen (*plunge*)



Beispiel:

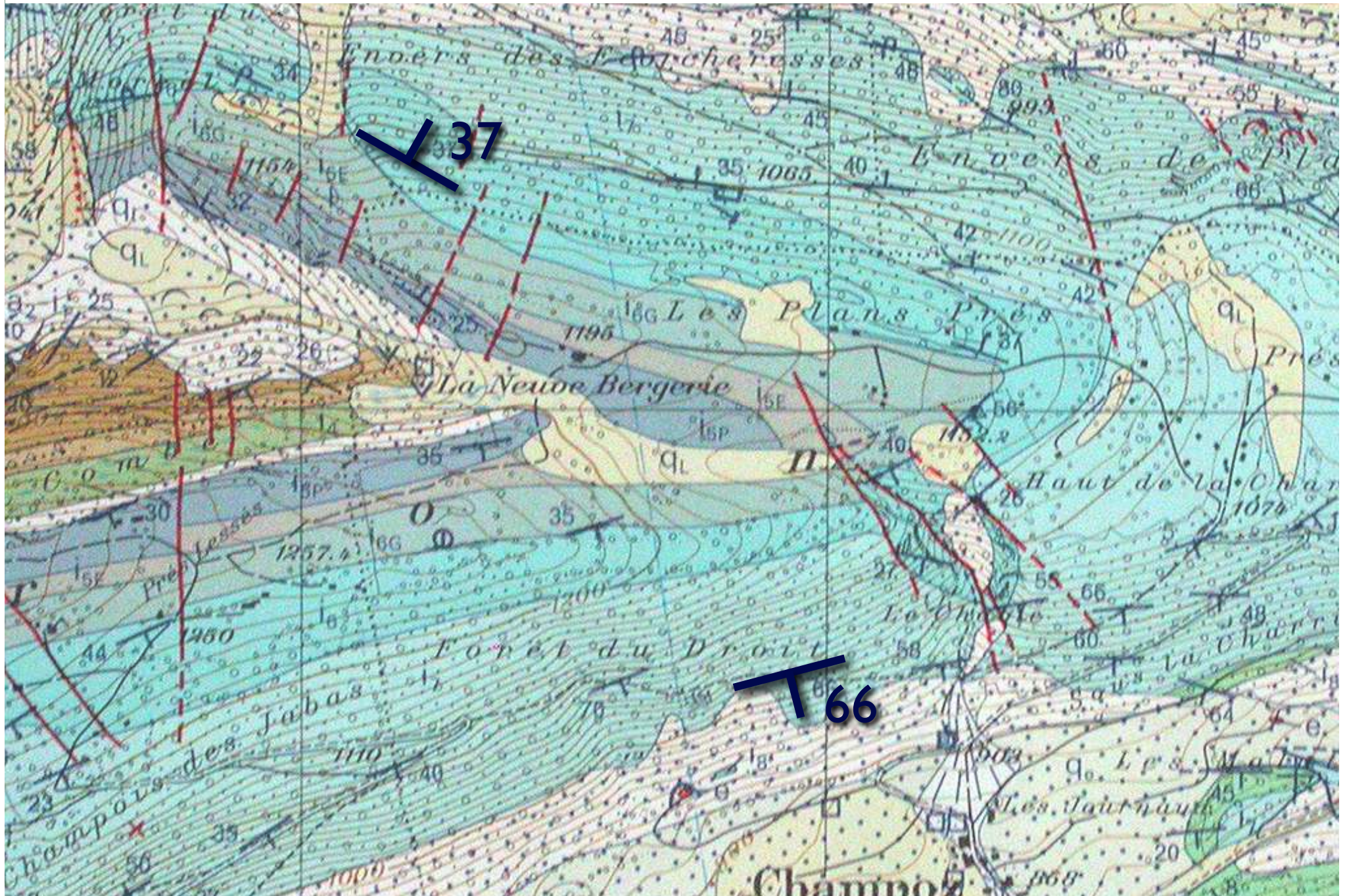


Einfallsrichtung:  $165^\circ$

Einfallswinkel:  $30^\circ$

Streichen:  $75^\circ$

# Faltenstruktur



# Falten



Einfallsrichtung / Einfallswinkel  
030 / 37  
Streichen / Fallen  
N120E / 37N

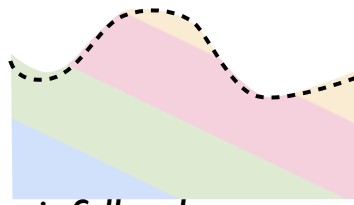
Einfallsrichtung / Einfallswinkel  
175 / 66  
Streichen / Fallen  
N85E / 66S

T 66

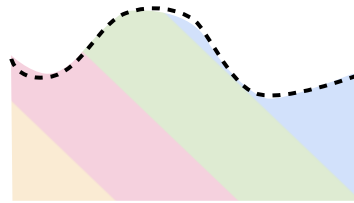
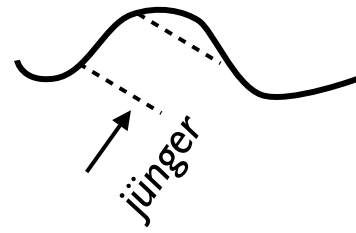
# Signaturen

Karte

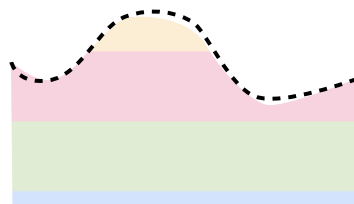
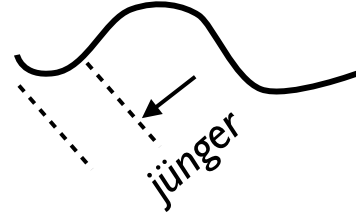
N-S-Profil



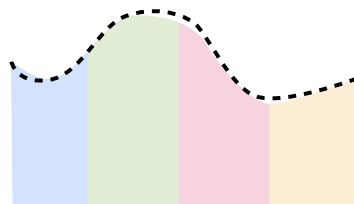
*einfallend*



*überkippt*



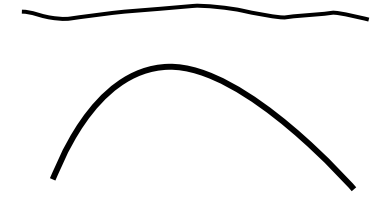
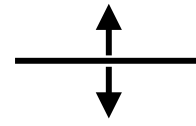
*flach liegend*



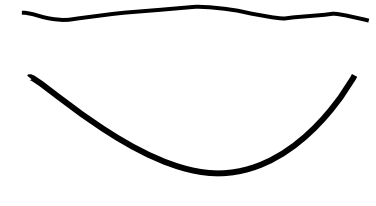
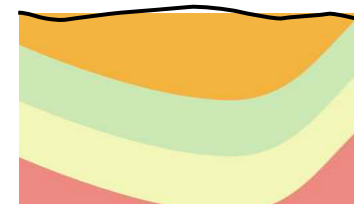
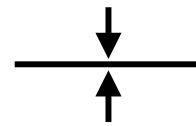
*vertikal stehend*

Karte

N-S-Profil

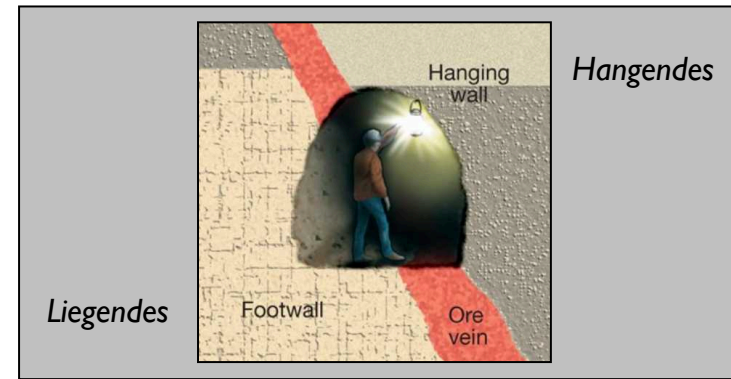


*Antiklinale*

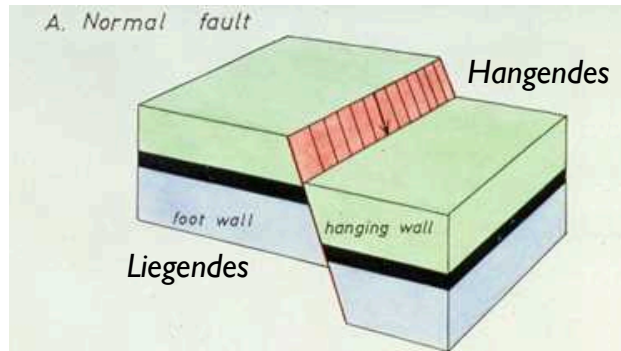


*Synklinale*

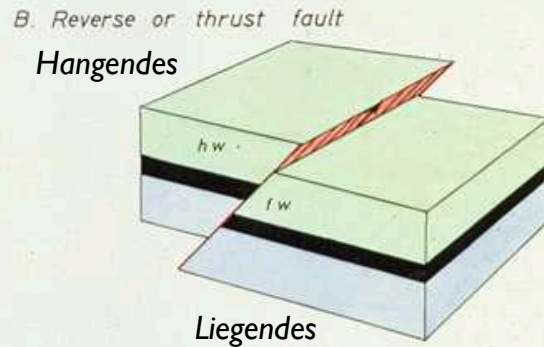
# Verwerfungen



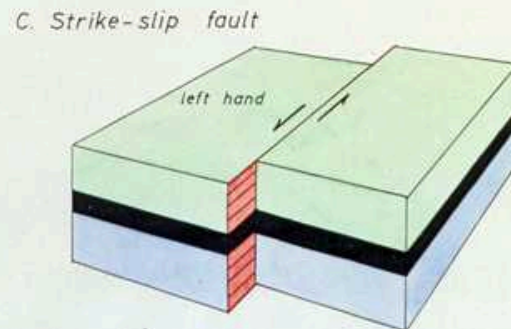
Extension  
(länger)



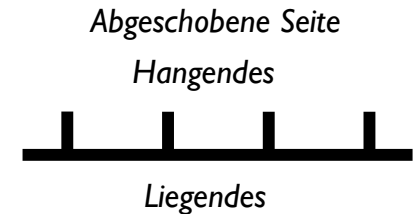
Kompression  
(kürzer)



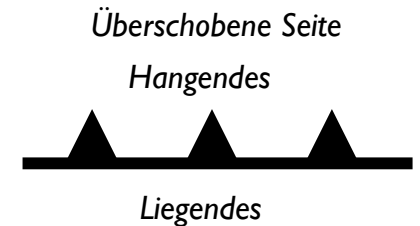
Translation  
(neutral)



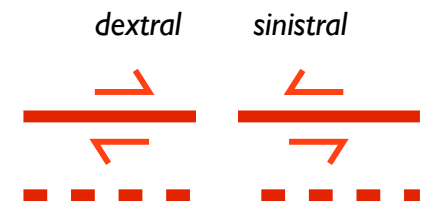
Abschiebung  
(Einfallen typisch 60°)



Überschiebung  
(Einfallen typisch 30°)

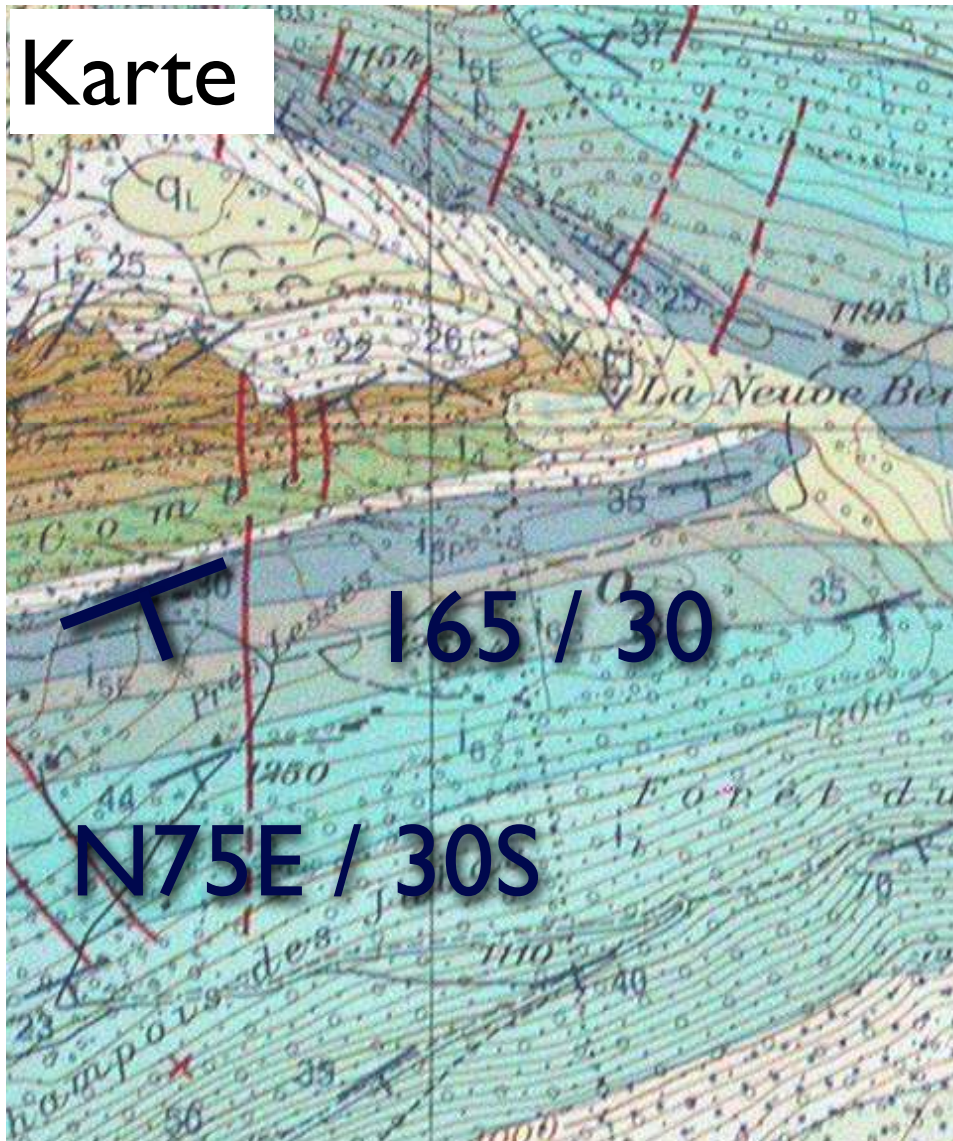


Blattverschiebung  
(Einfallen typisch 90°)

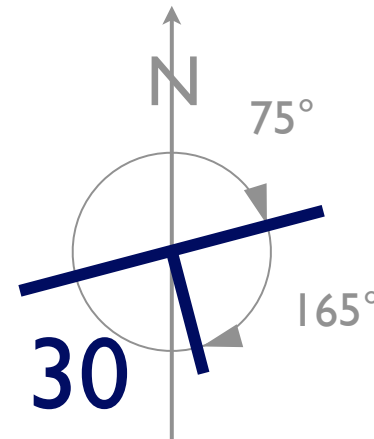


# Stereographische Projektion

# Orientierung von Flächen im Raum



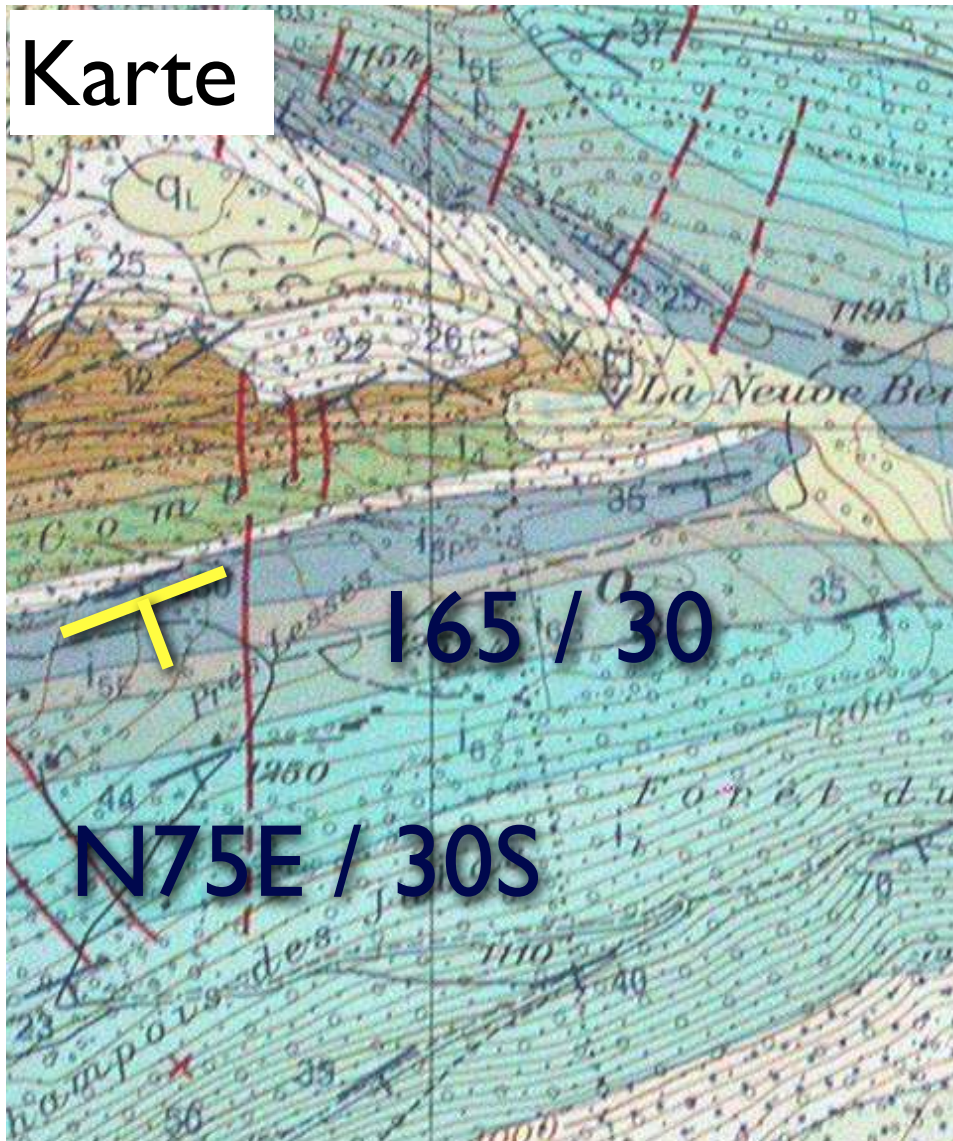
use this !



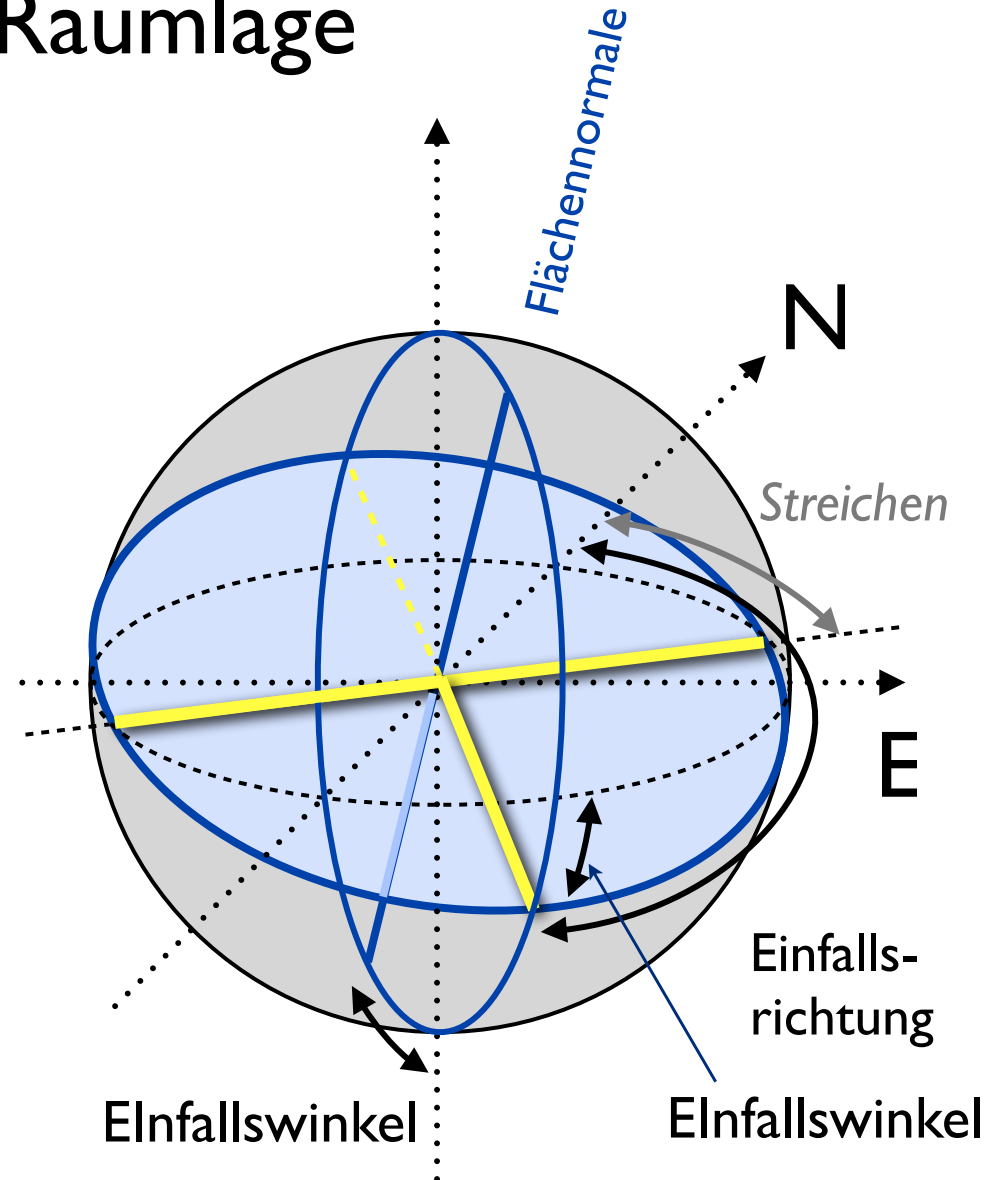
Beispiel:  
Einfallsrichtung:  $165^\circ$   
Einfallswinkel:  $30^\circ$   
bzw.  
Fallazimuth:  $165^\circ$   
Fallwinkel:  $30^\circ$

veraltet:  
Streichen:  $75^\circ$   
Fallen:  $30^\circ$  Süd

# Orientierung von Flächen im Raum



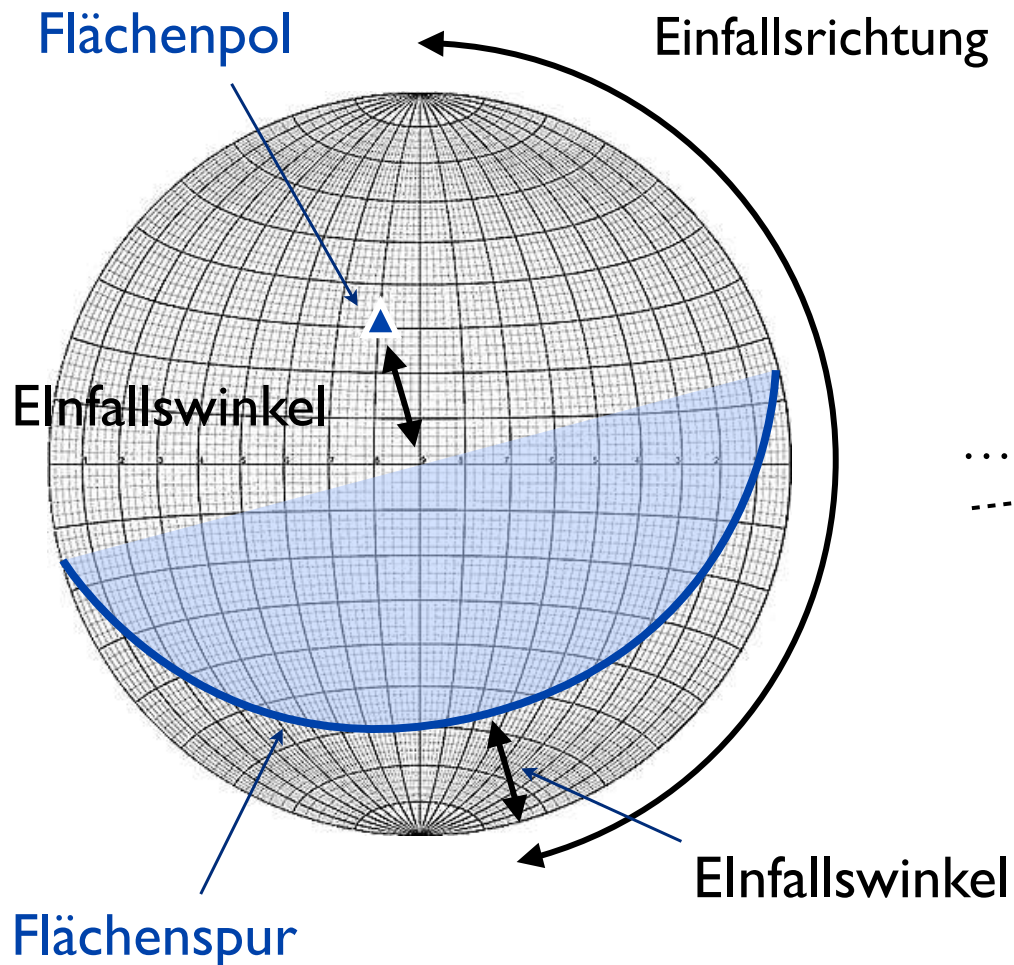
## Raumlage





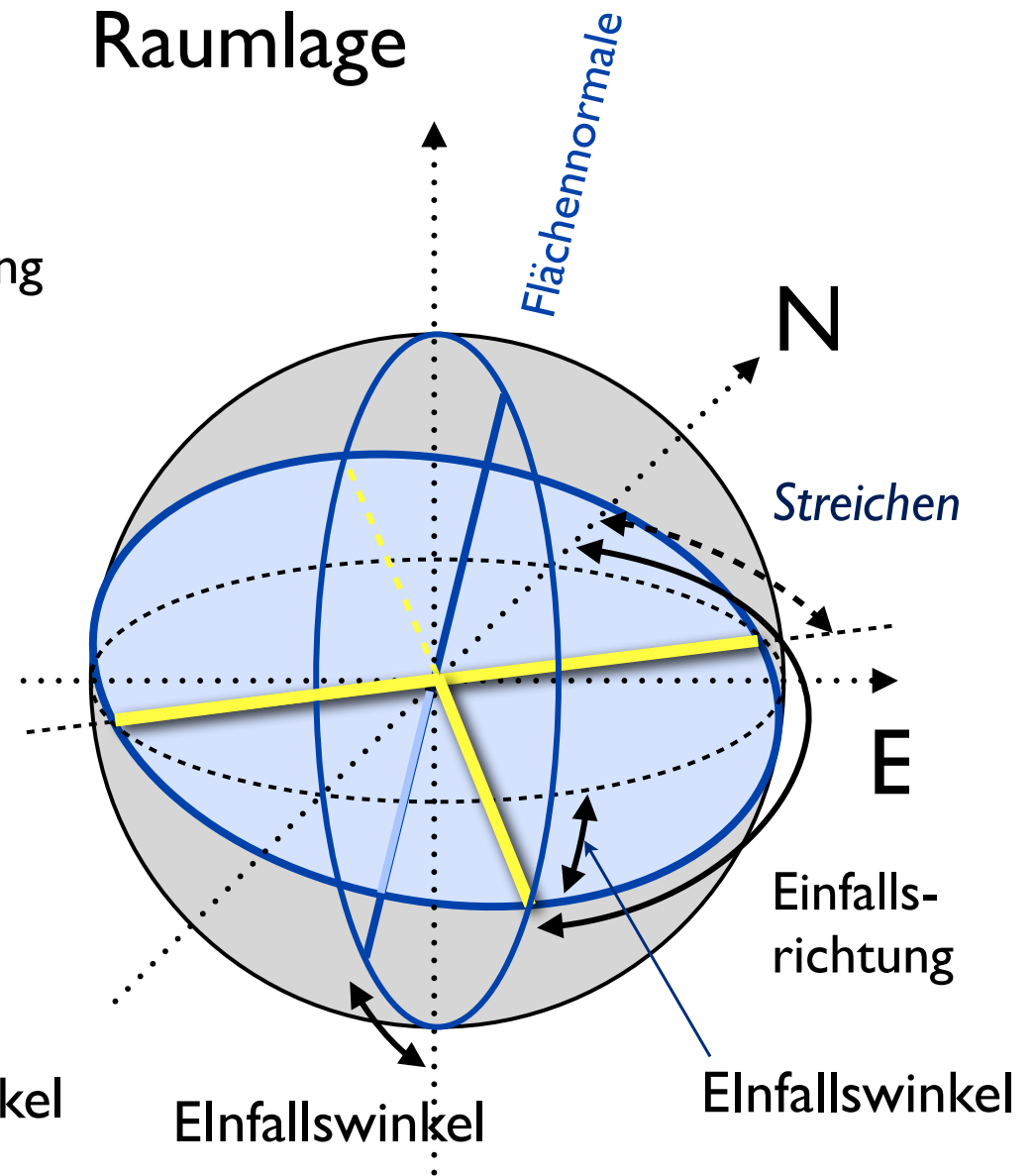
# Flächen im Stereonetz

Projektion  
untere Halbkugel:



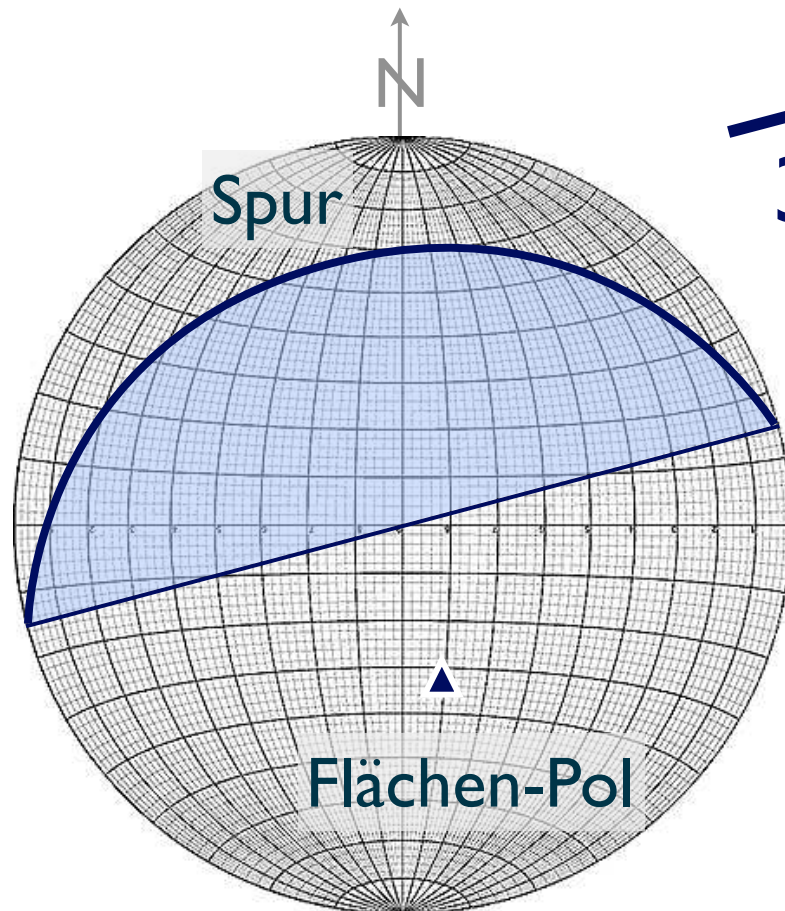
Schmidt Netz = flächentreu

Raumlage

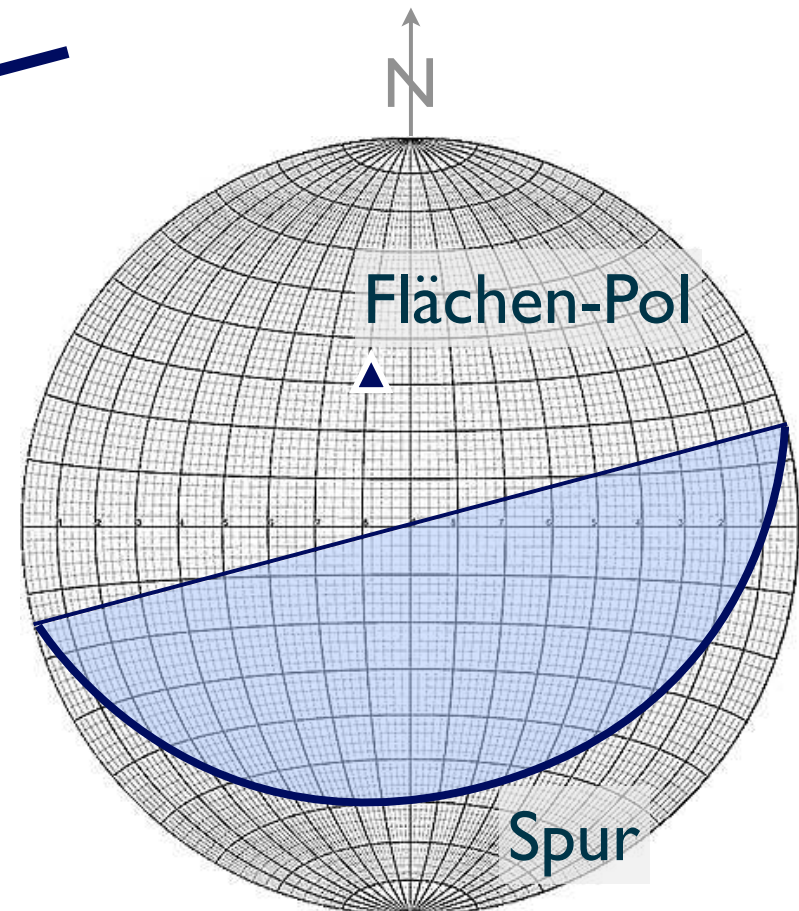


# Orientierung einer Fläche im Raum

Projektion:  
obere Halbkugel



untere Halbkugel

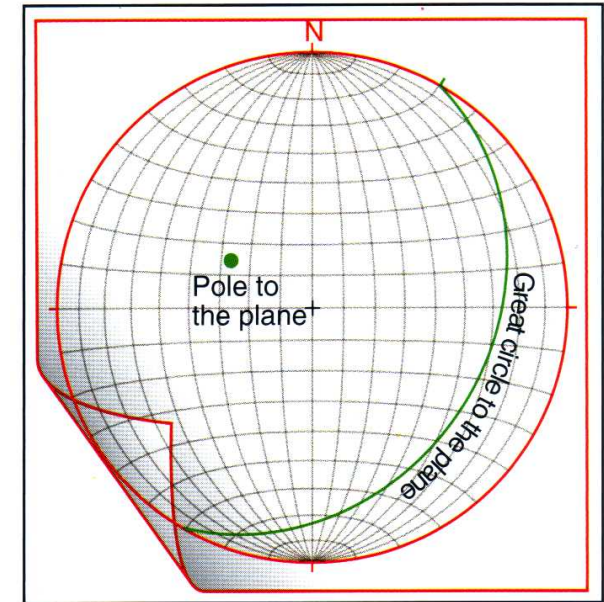
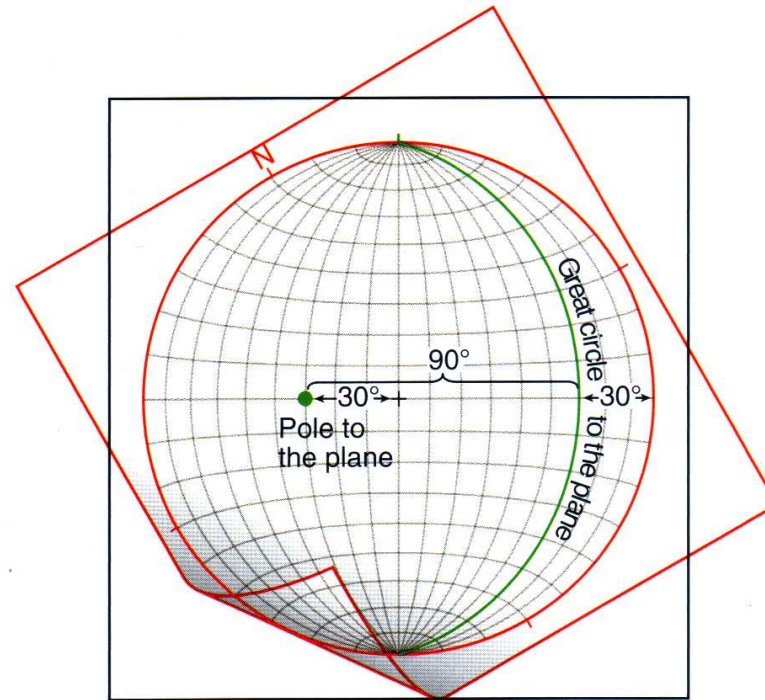
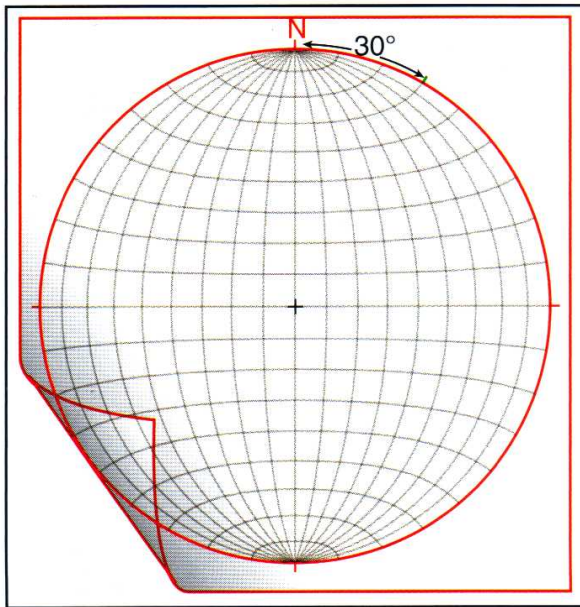


30

# Fläche im Stereonetz: Spur und Pol

geg: Fläche mit  $120 / 30$

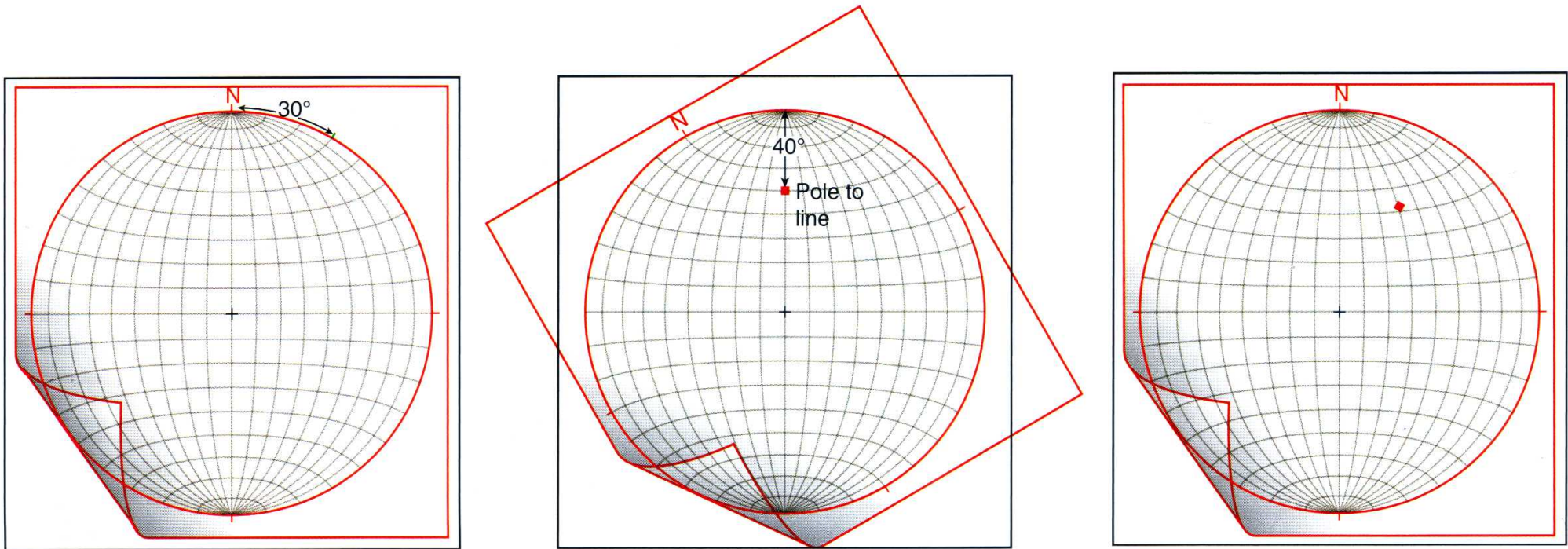
$\swarrow$  30



1. Kreis markieren, N,S,W,E eintragen, Einfallsrichtung von N aus markieren (Uhrzeigersinn).
2. Markierung auf E oder W rotieren. Einfallswinkel auf E-W Gerade ab der Peripherie abzählen, Spur des Grosskreises durchpausen, Pol vom Zentrum aus ( $90^\circ$  von Spur) eintragen.
3. Blatt zurückrotieren.

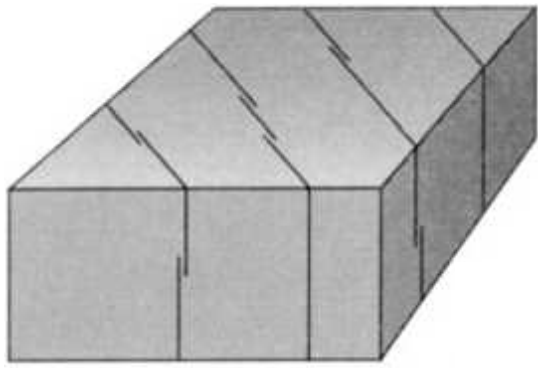
# Richtung im Stereonetz

geg: Linear mit 030 / 40

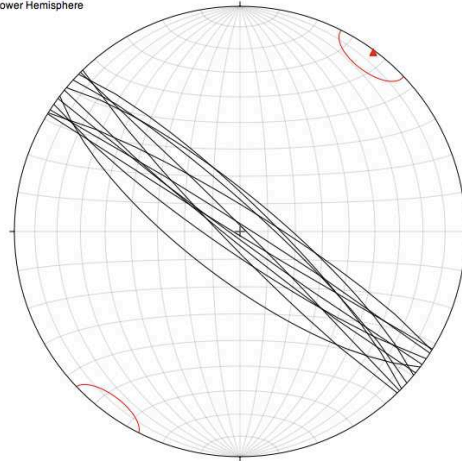


1. Kreis markieren, N,S,W,E eintragen, Abtauchrichtung von N aus markieren (Uhrzeigersinn).
2. Markierung auf N, S, E oder W rotieren. Abtauchen auf N-S bzw. E-W Gerade ab der Peripherie abzählen, markieren.
3. Blatt zurückrotieren.

# Klüfte und Brüche im Stereonetz

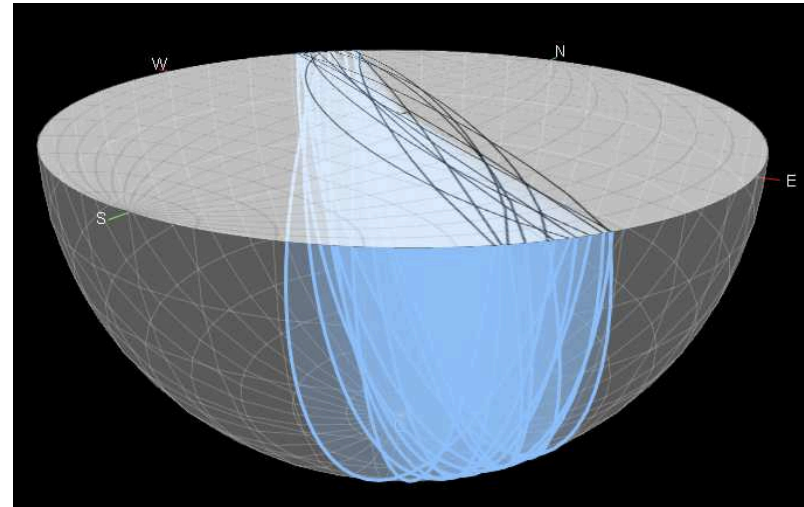


Equal Area  
Lower Hemisphere

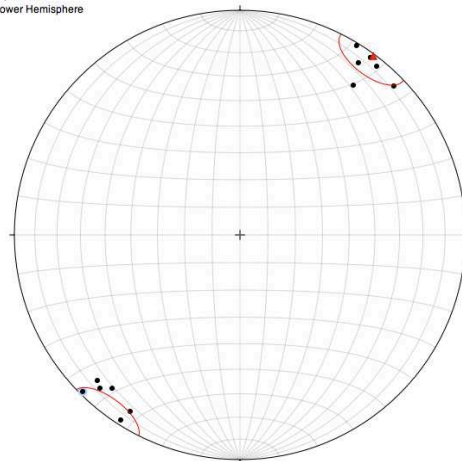


N = 12

## Flächenspuren



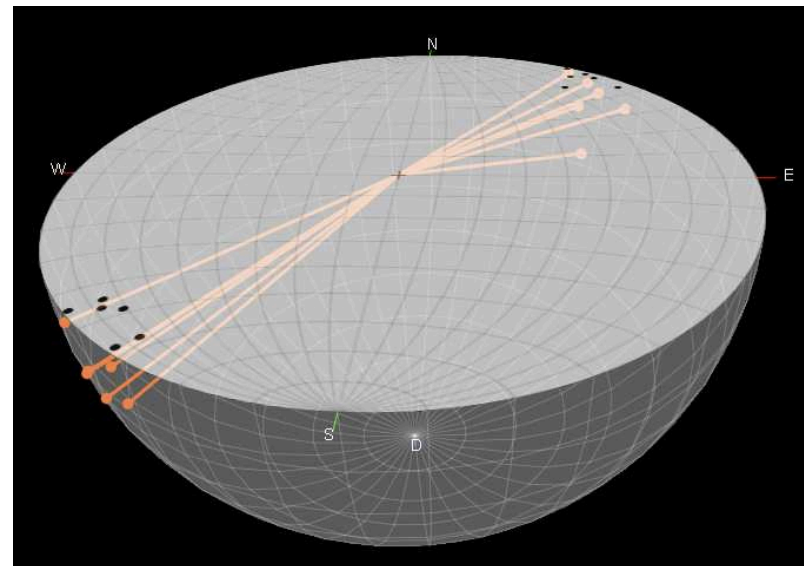
Equal Area  
Lower Hemisphere



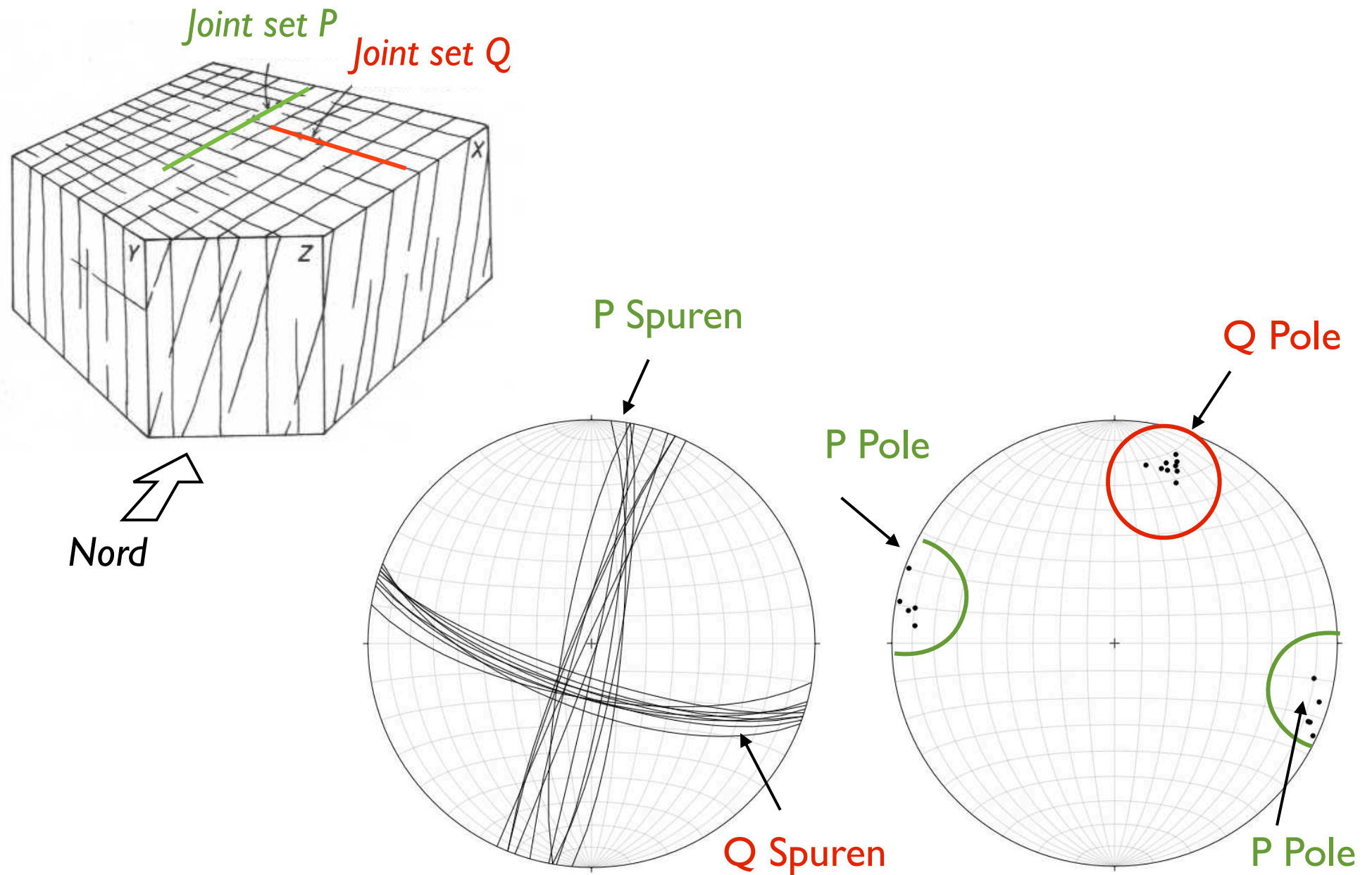
Trend = 315, Plunge = 15

N = 12

## Flächenpole

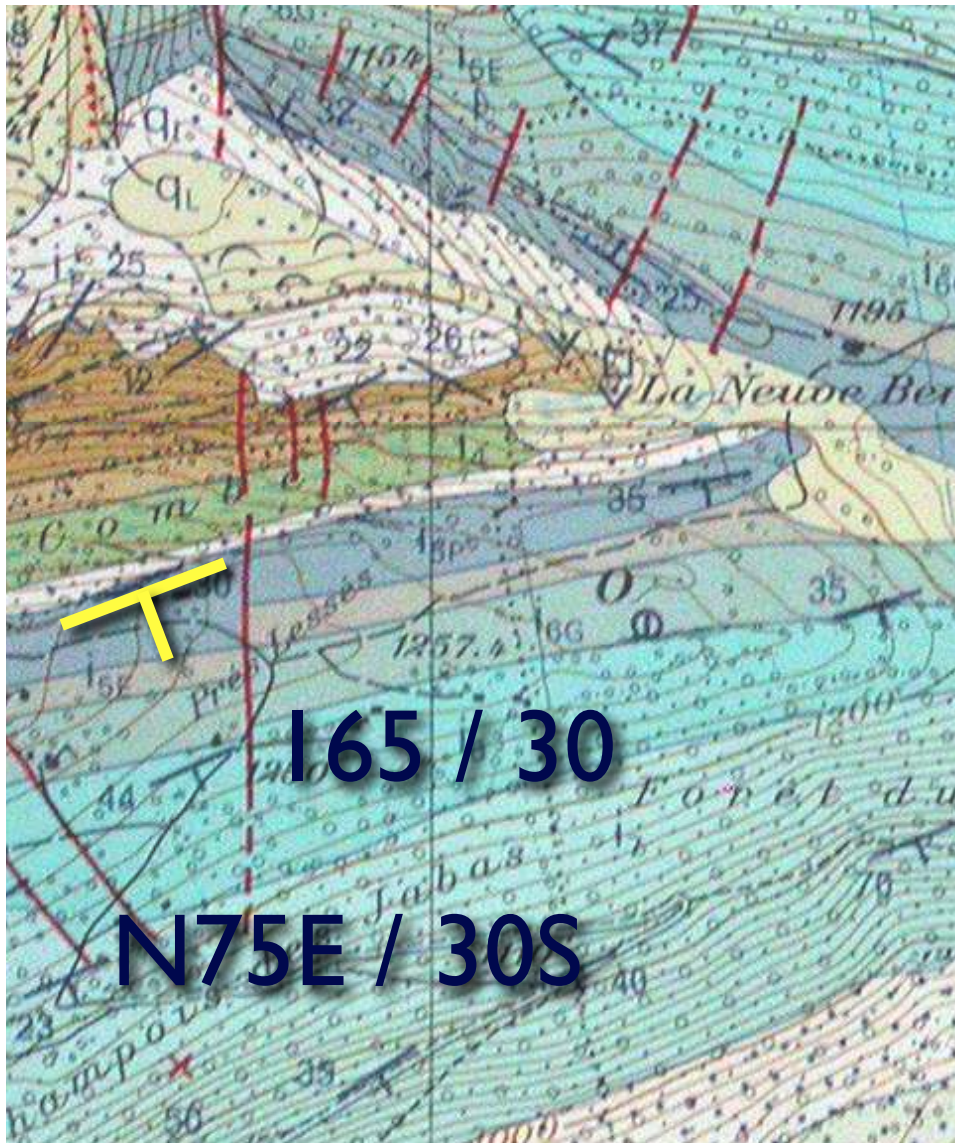


# Klüfte und Brüche im Stereonetz

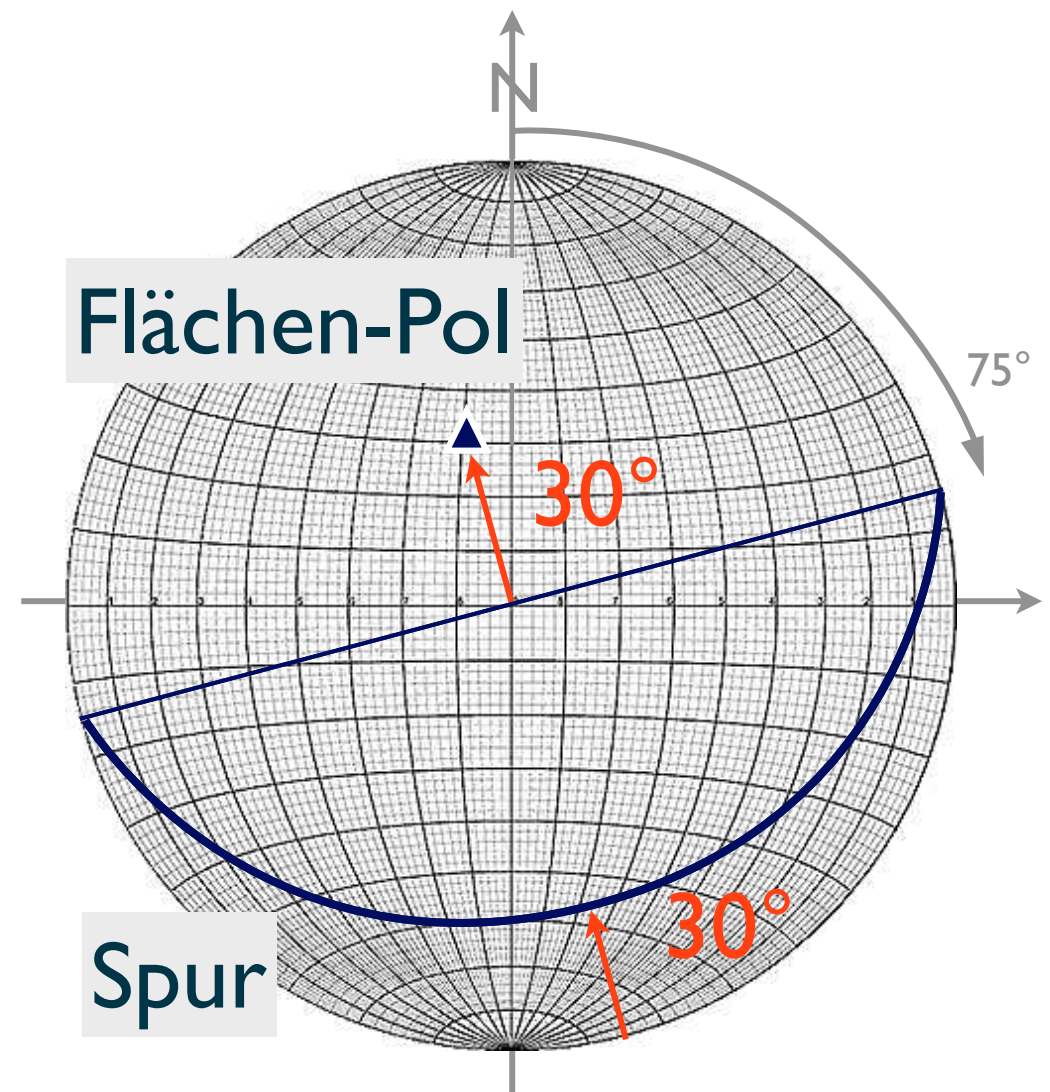


# Falten im Stereonetz

## I. Fläche: Südschenkel

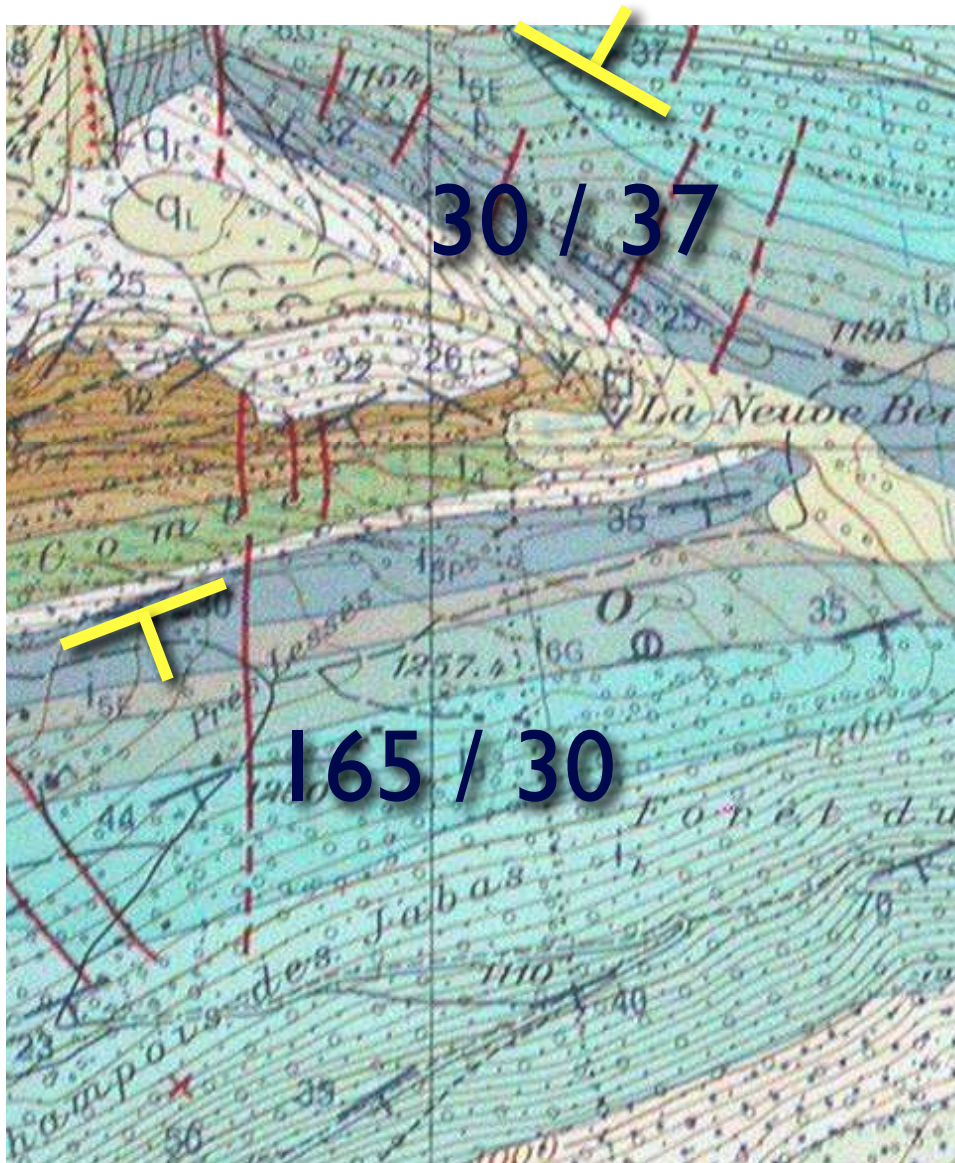


## Stereonetz

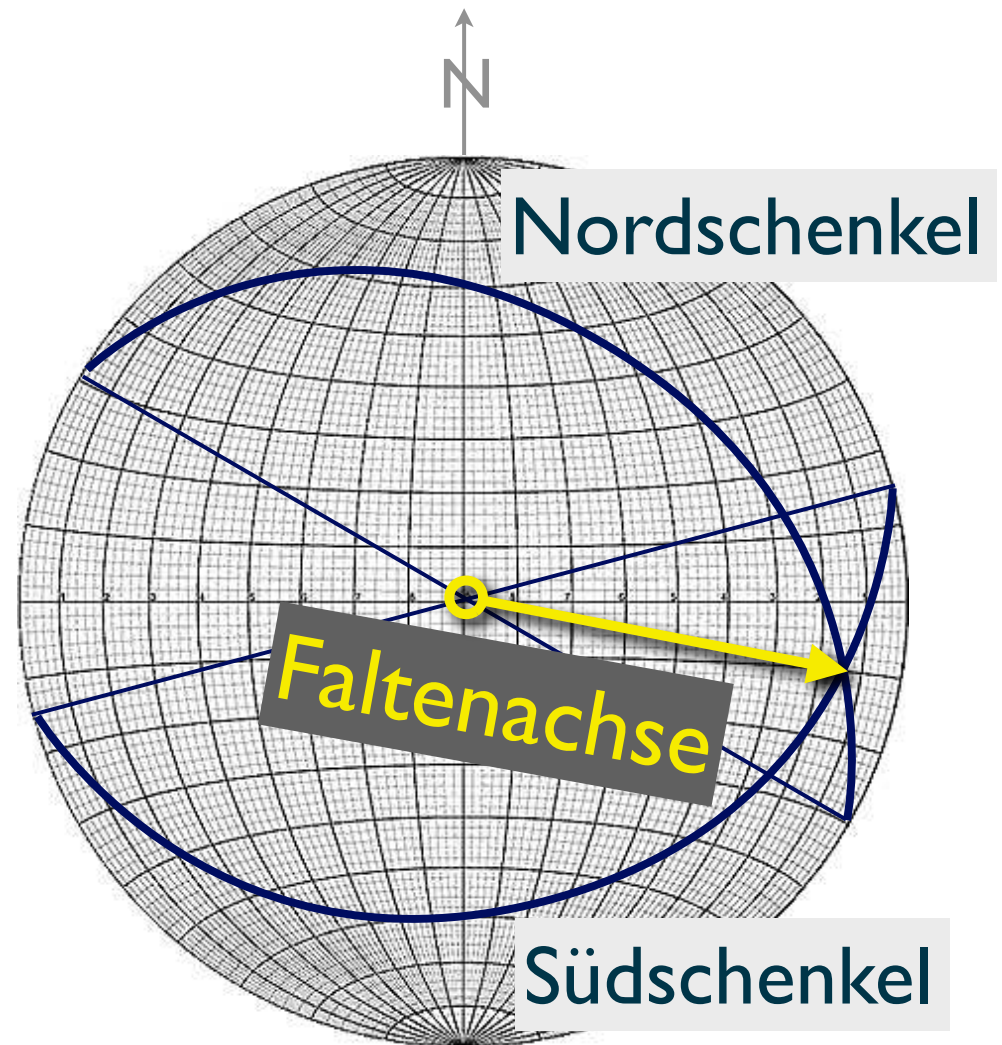


# Faltenachsen - Konstruktion

## 2. Fläche: Nordschenkel



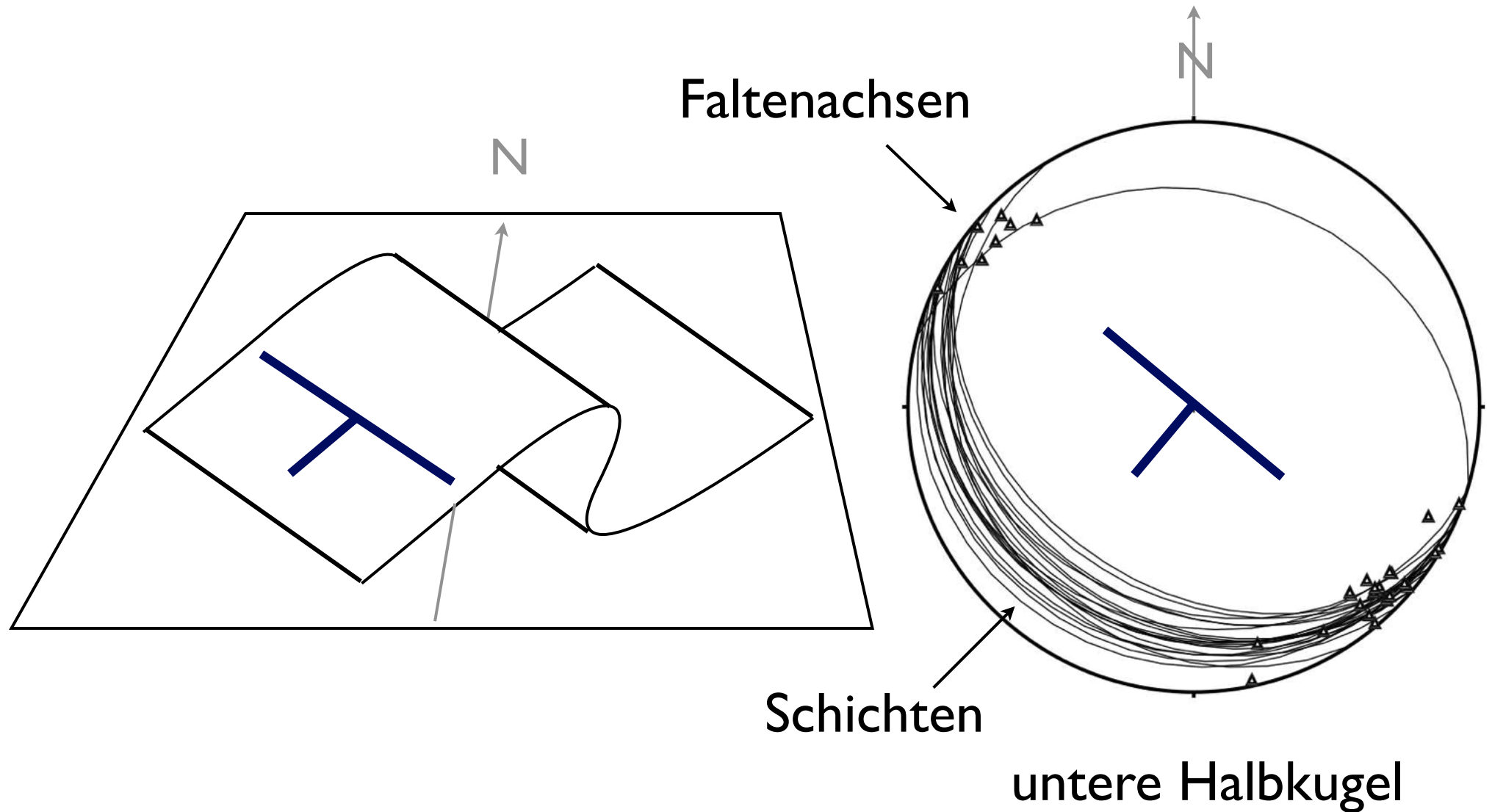
## Stereonet





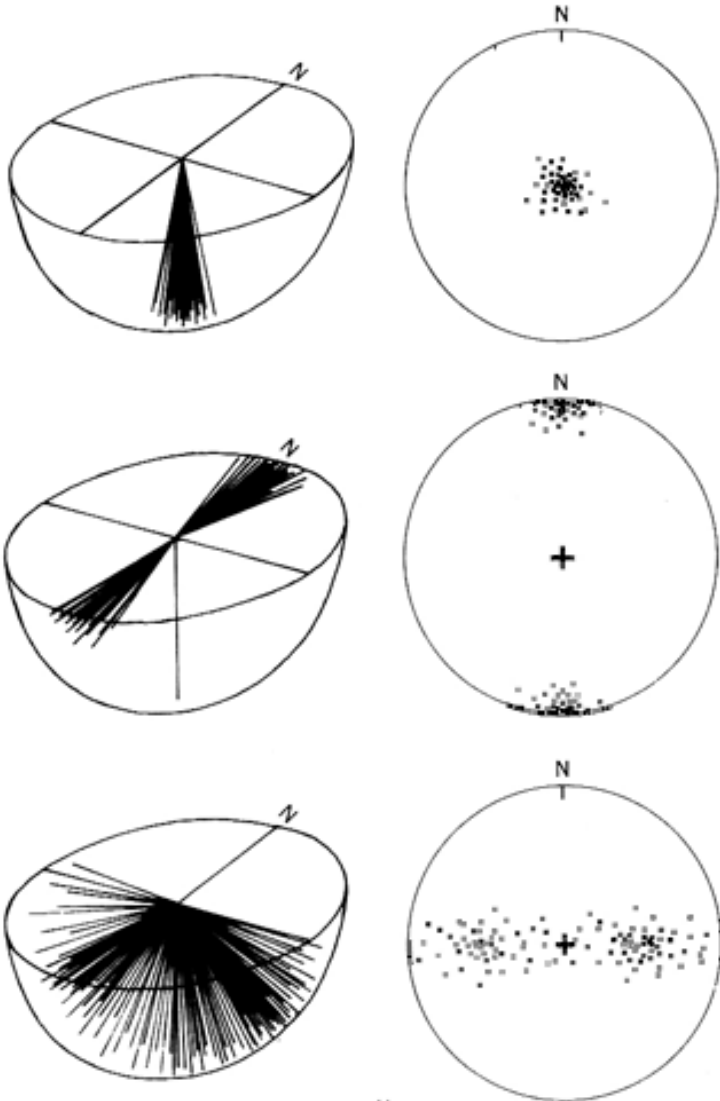
# Isoklinalfalten im Stereonetz

## Stereographische Projektion



# Konzentrationen im Stereonetz

Stereographische Projektion von  
Flächenpolen (Flächennormalen)



± parallele Schichten

⇒ ein Maximum

← horizontale Schichten

← vertikale Schichten, E-W  
streichend

gefaltete Schichten  
⇒ Gürtelverteilung

← Faltenachse N-S streichend

# 3 Geologische Strukturen

## Extensions-Strukturen

- Abschiebung, Horst-Graben
- Listrische Dehnungsbrüche

## Kontraktions-Strukturen

- Überschiebung
- Falten

## Strike-Slip-Strukturen

- Blattverschiebung
- Transpression / Transtension

## weitere Strukturen

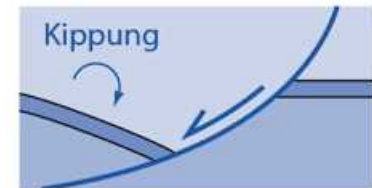
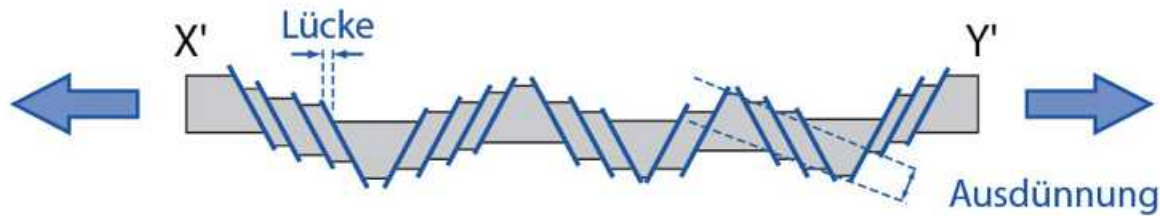
## Intersektion Struktur - Topographie

- Fenster - Klippe
- Morphologie  $\neq$  Struktur

# EXTENSION versus KONTRAKTION



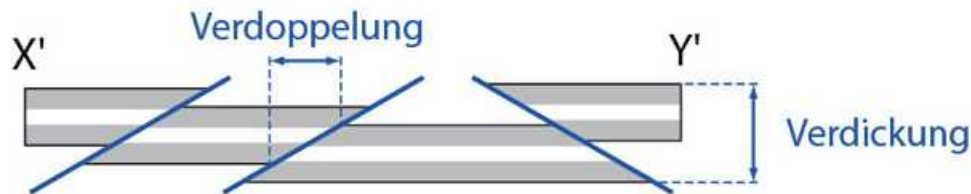
Abschiebungen:  
Streckung & Ausdünnung



Listrische Verwerfung



Aufschiebungen:  
Verkürzung & Verdickung

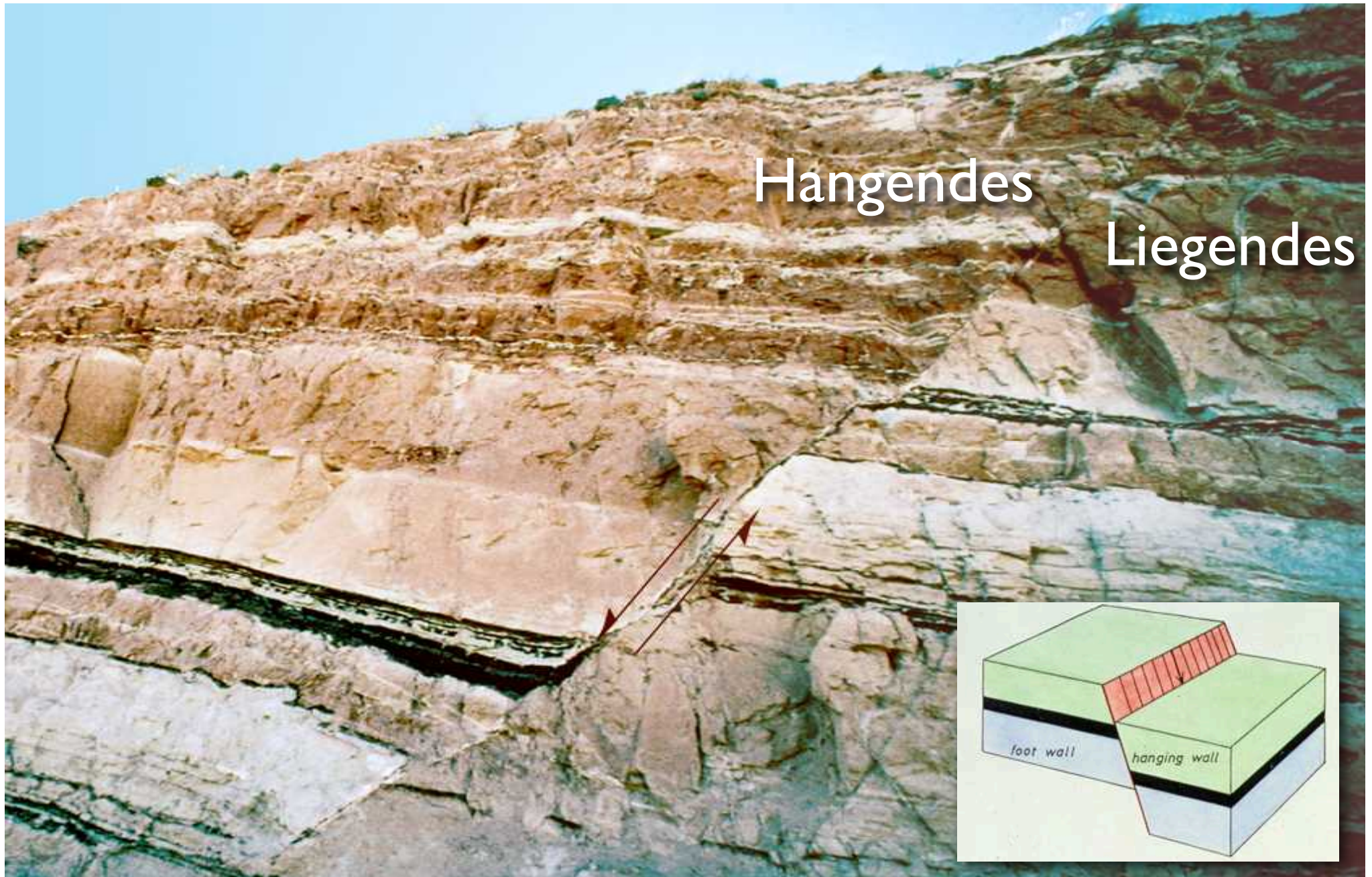


Überschiebung

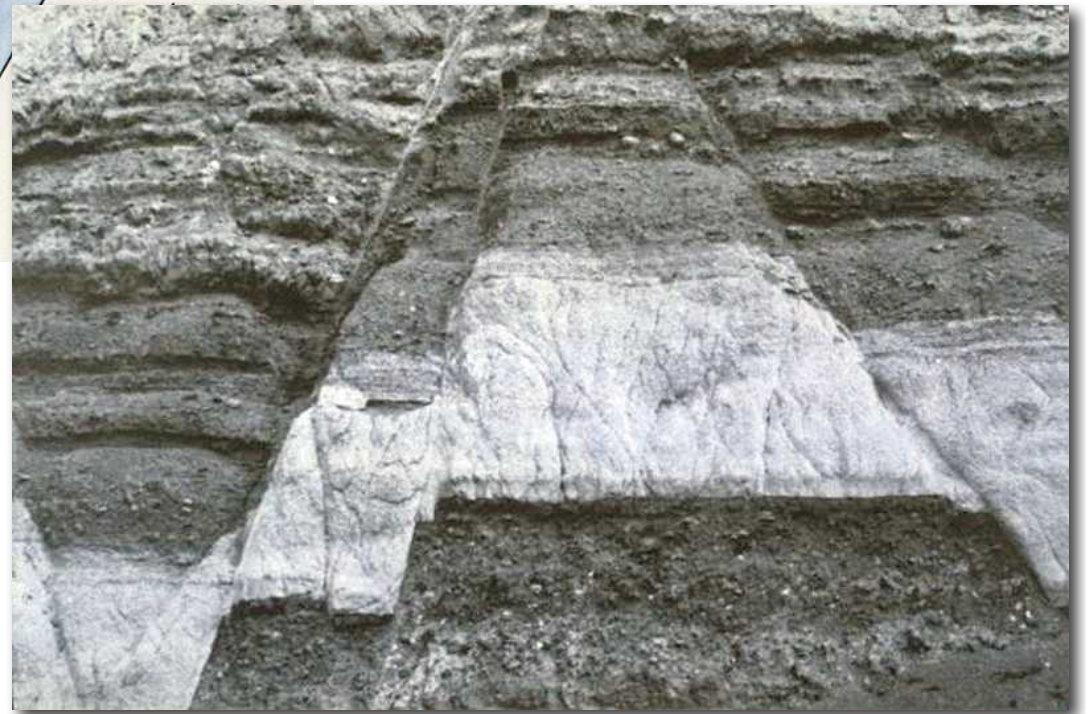
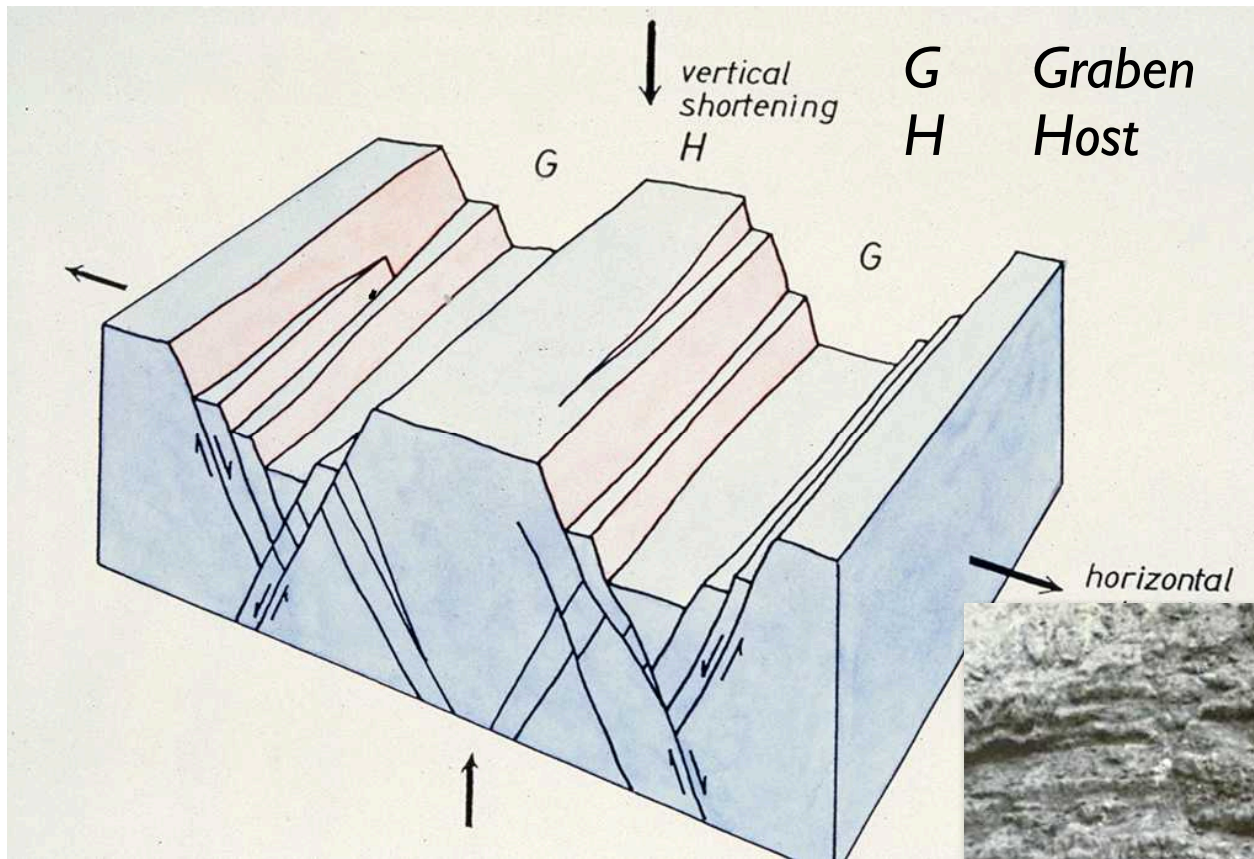
# Extensions- Strukturen

# Abschiebung

10 m

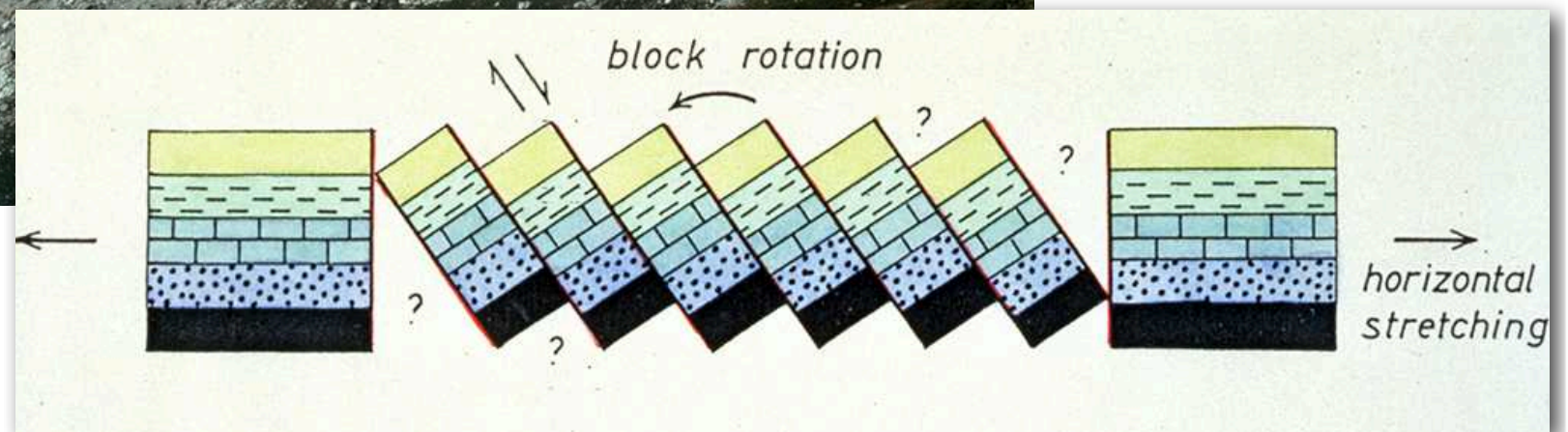
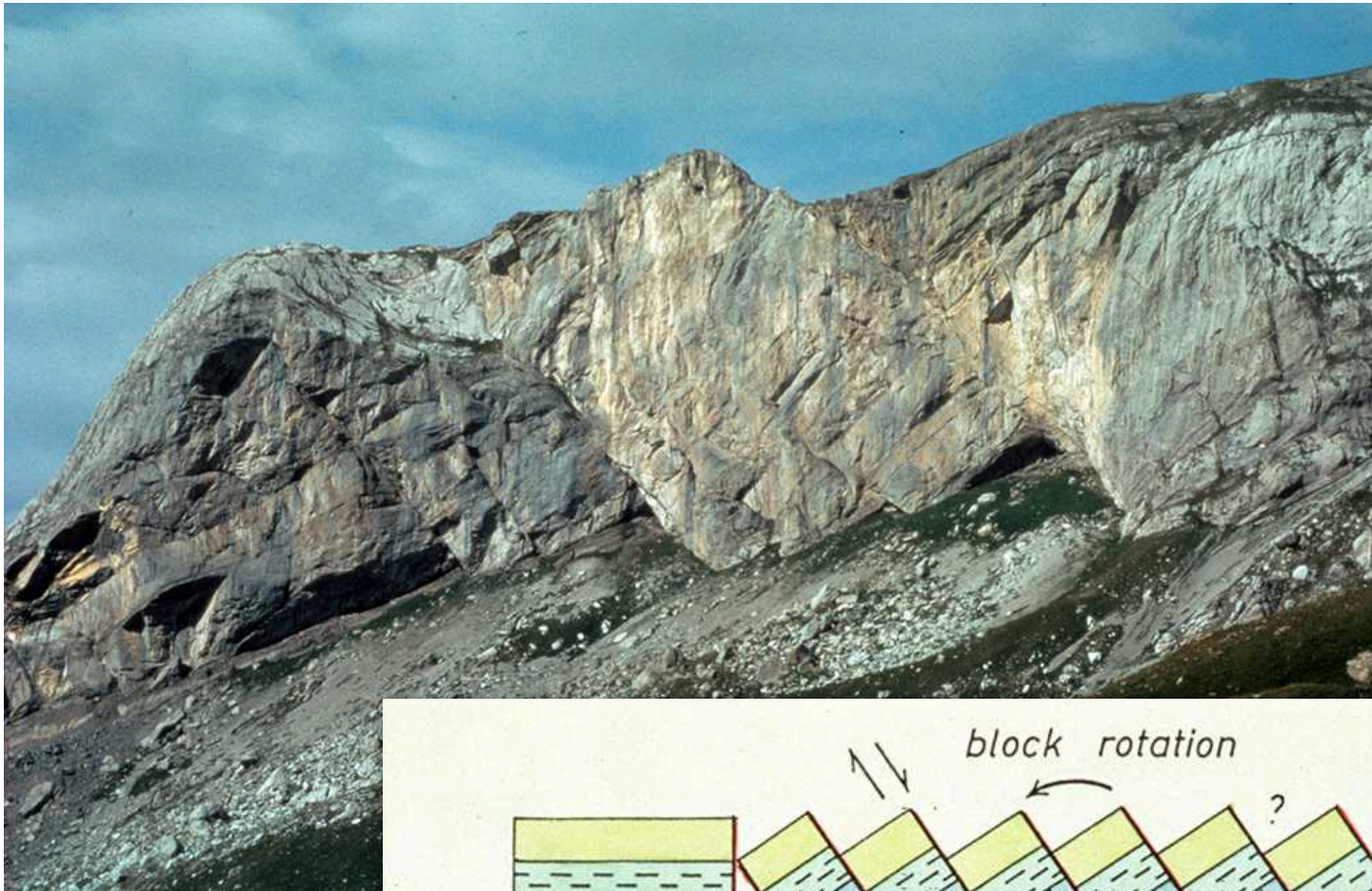


# Graben - Horst



# Domino-Brüche (block faulting)

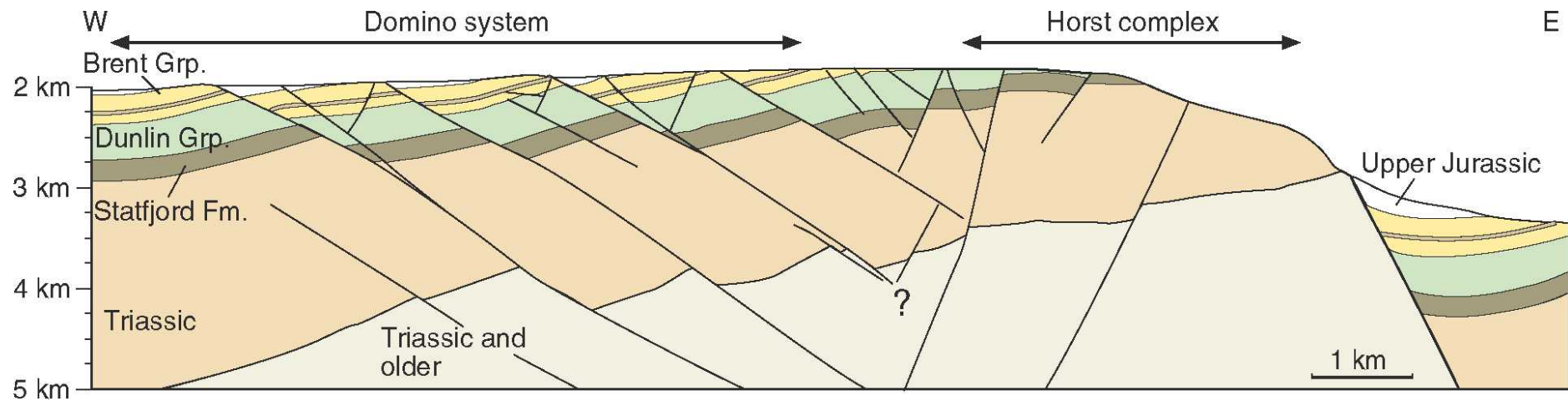
100 m





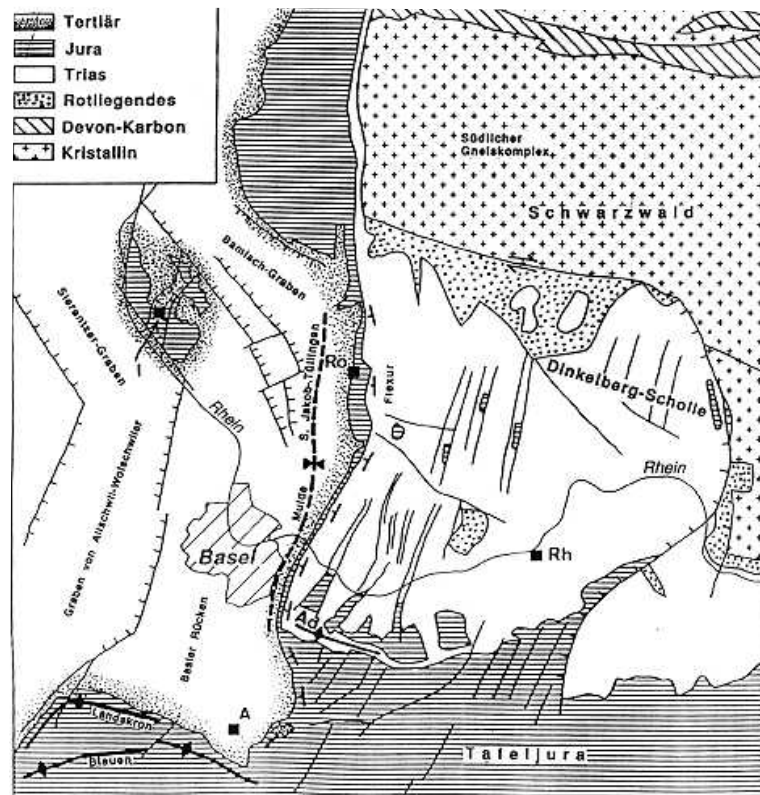
# Horst-Graben Domino

1 km

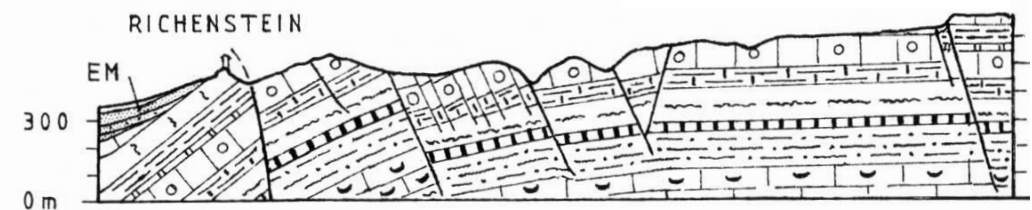


## Gulfaks Domino System

Haakon Fossen: Structural Geology



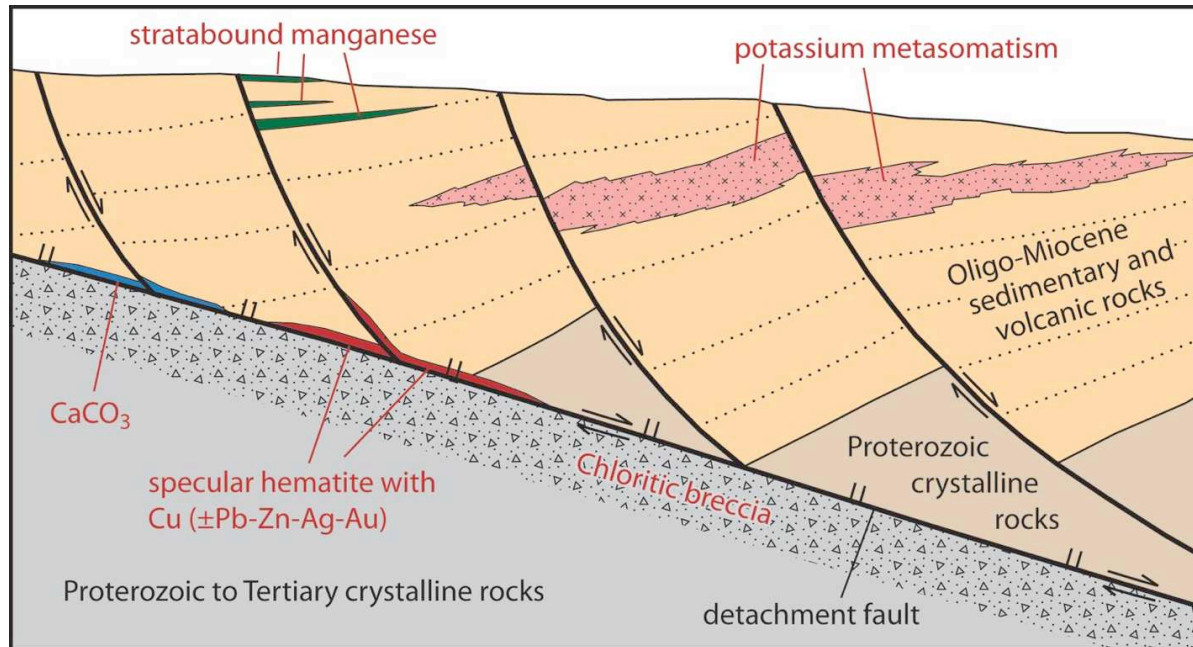
## Tafeljura



## Rheintalgraben

# Listrische Dehnungsbrüche

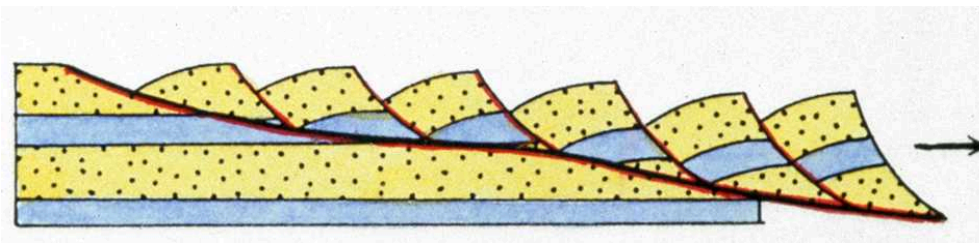
1 km



Harcuvar metamorphic core complex (Artillery Mts., Western Arizona)

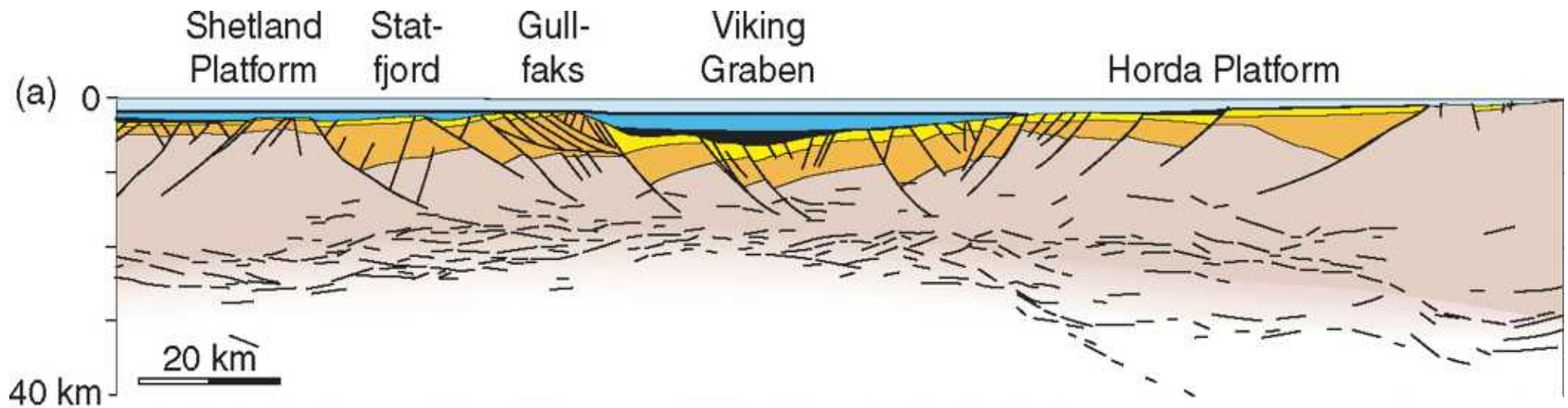
Listrische Brüche verbinden sich zu Detachment Faults

Flach einfallender Detachment Fault



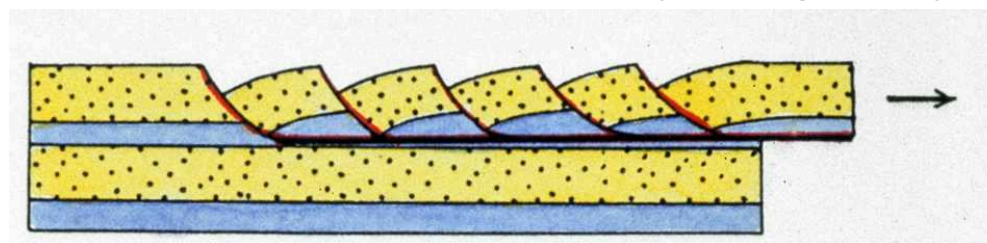
# Detachment

10 km



Listrische Brüche verbinden sich zu Detachment Faults

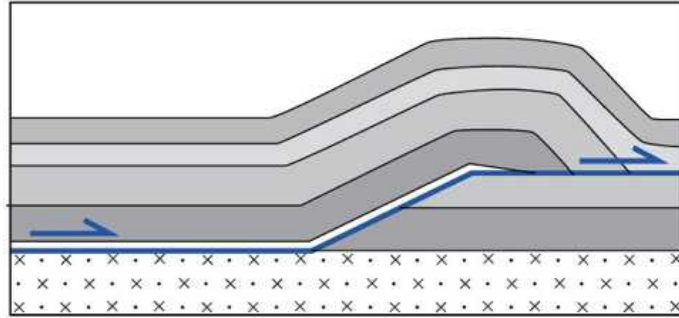
Horizontaler Detachment Fault (schichtparallel)



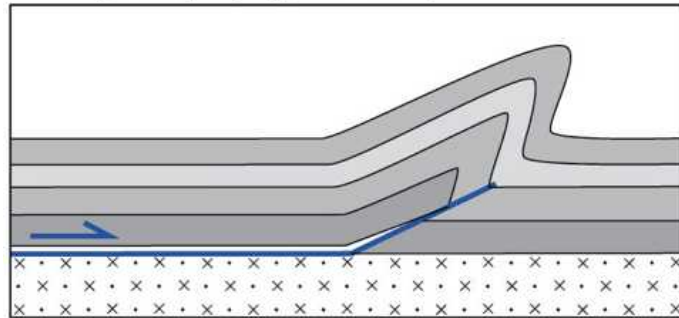
# Kontraktions - Strukturen

# Falten und Überschiebungen

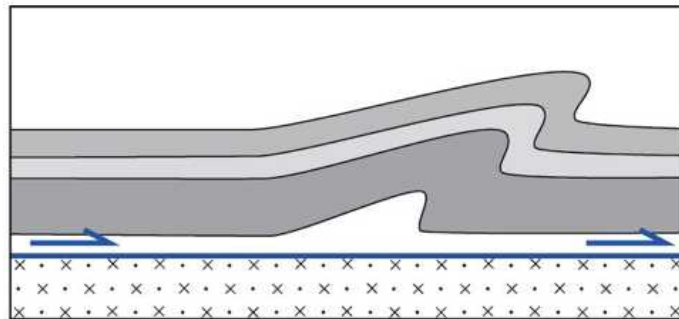
A Rampenfalte (fault bend fold)



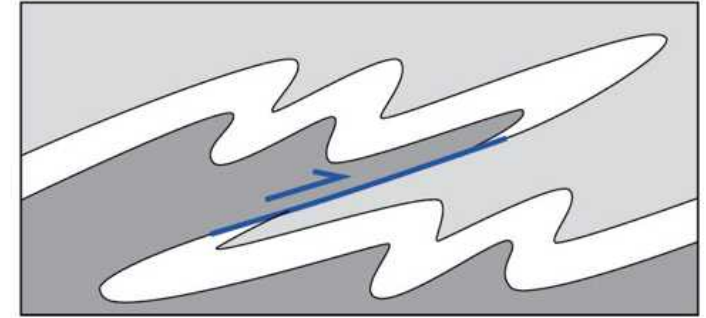
B Falte mit Überschiebung (fault-propagation fold)



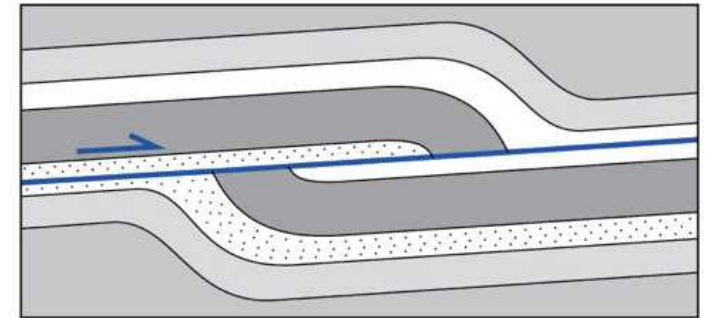
C Abscherfalte (detachment fold)



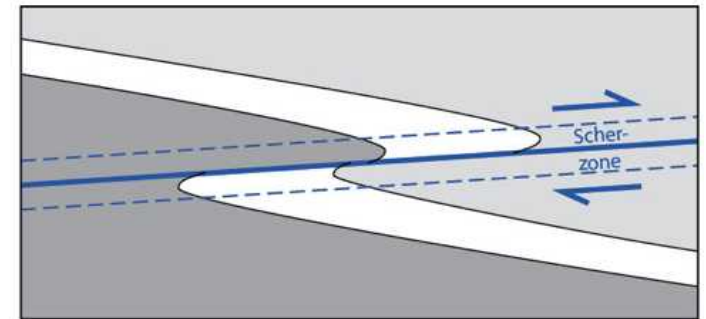
D Falte mit zerschertem Schenkel (stretched fold limb)



E Zerschnittene Falte (dissected fold)

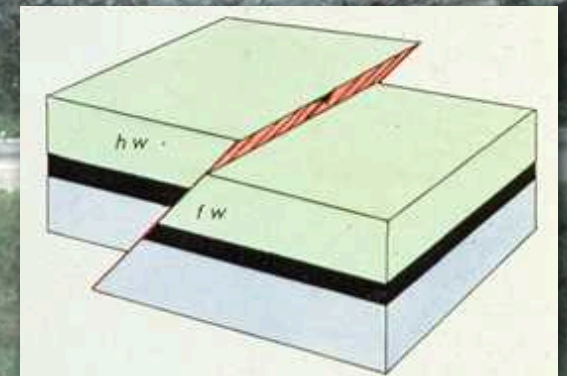
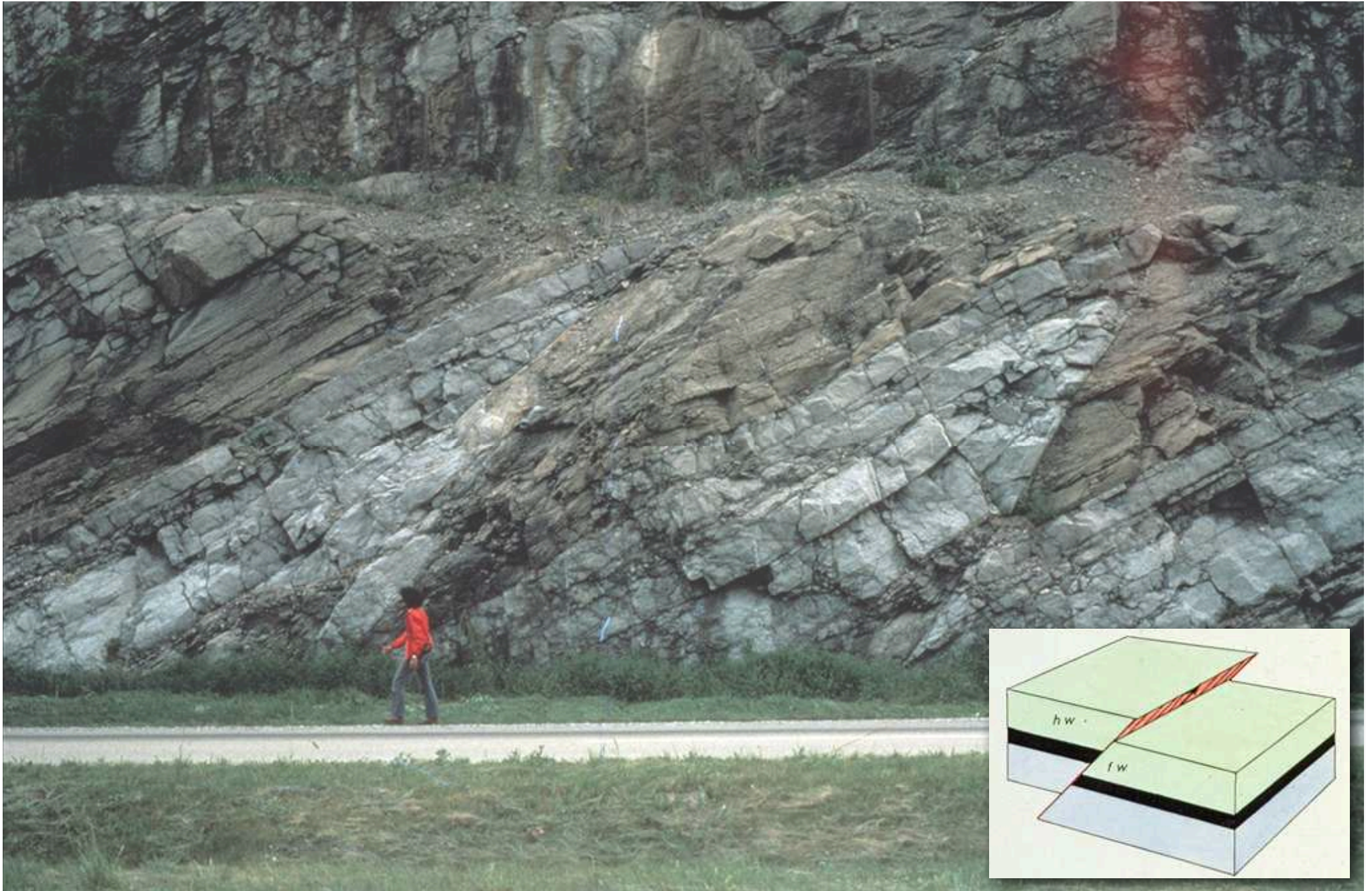


F Scherfalte (drag fold)



# Auf- / Überschiebung

10 m



# Überschiebung

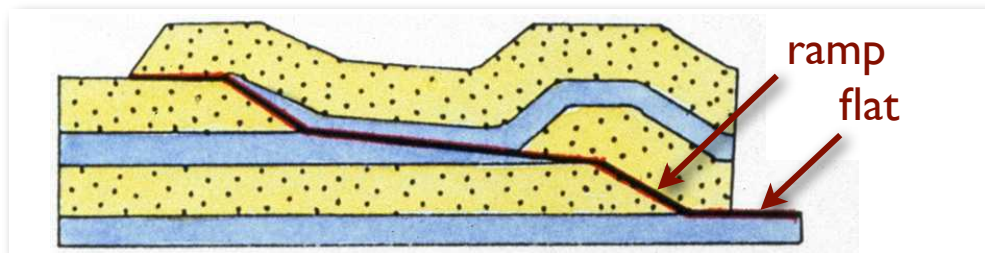
100 m



Thrust fault in the Chilean Andes  
Photo credit Constantino Mpodozis.



Seneca Stone Quarry  
Located in Seneca County  
Image courtesy of Richard W. Allmendinger

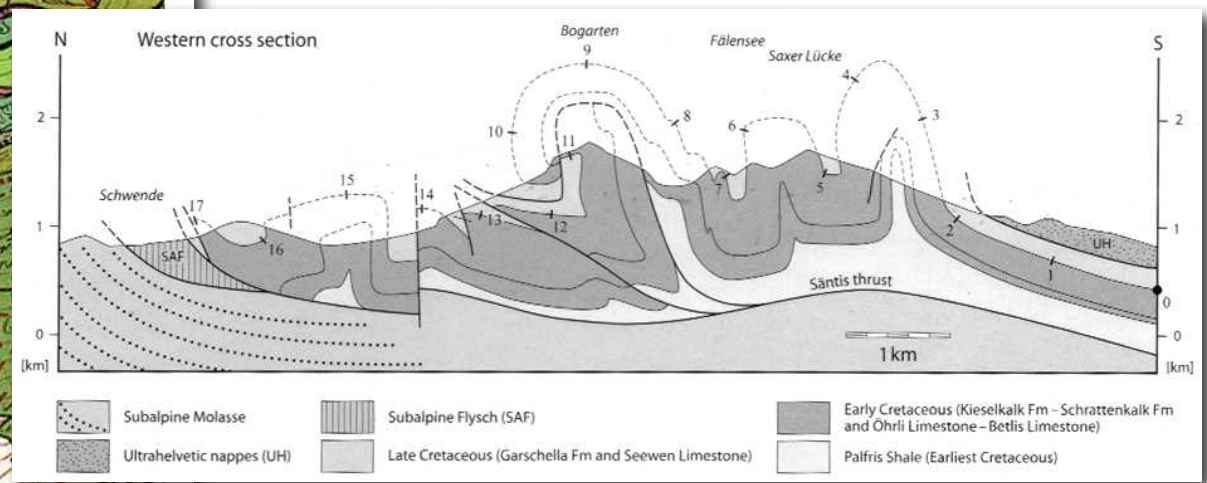
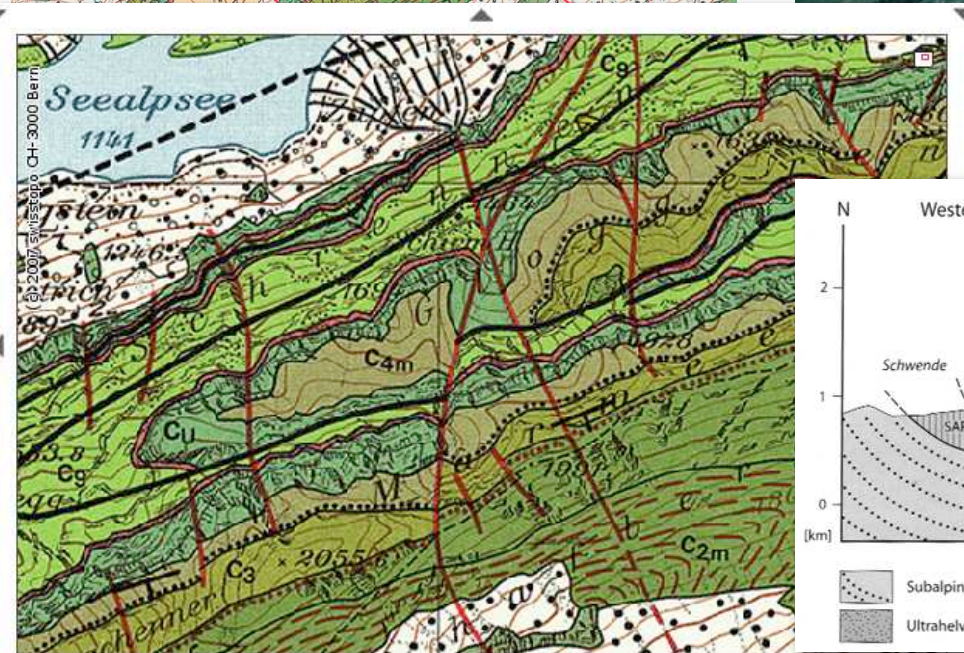
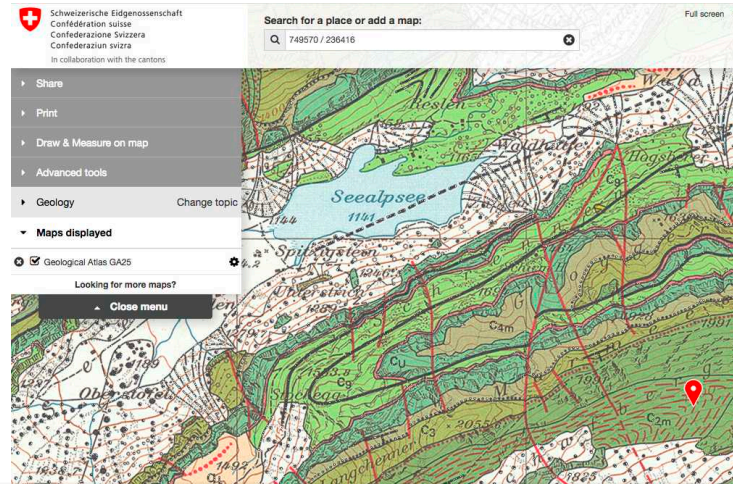


flat schichtparallel  
ramp schicht durchschneidend

# Gefaltete Überschiebung ...

1 km

<http://www.geologieviewer.ch/ga.php#>

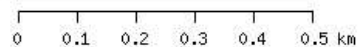


Coords (m): 749570 / 236416

1:10'000

Massstab 1:10'000

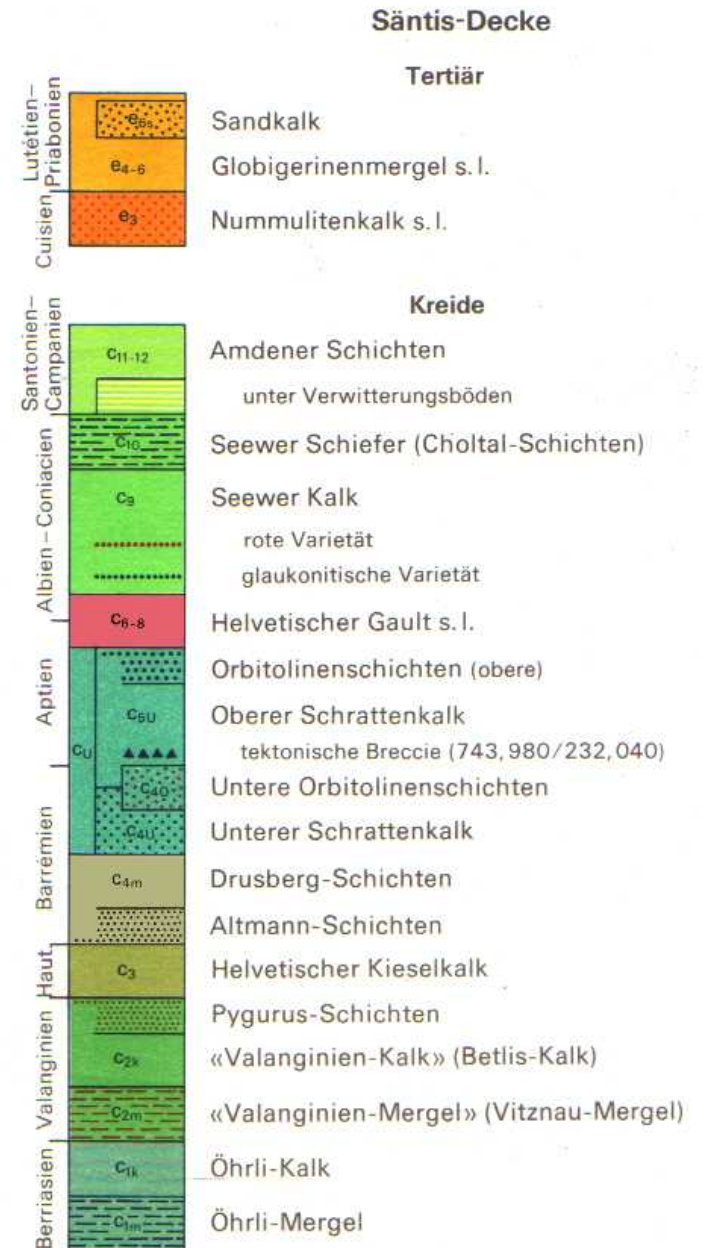
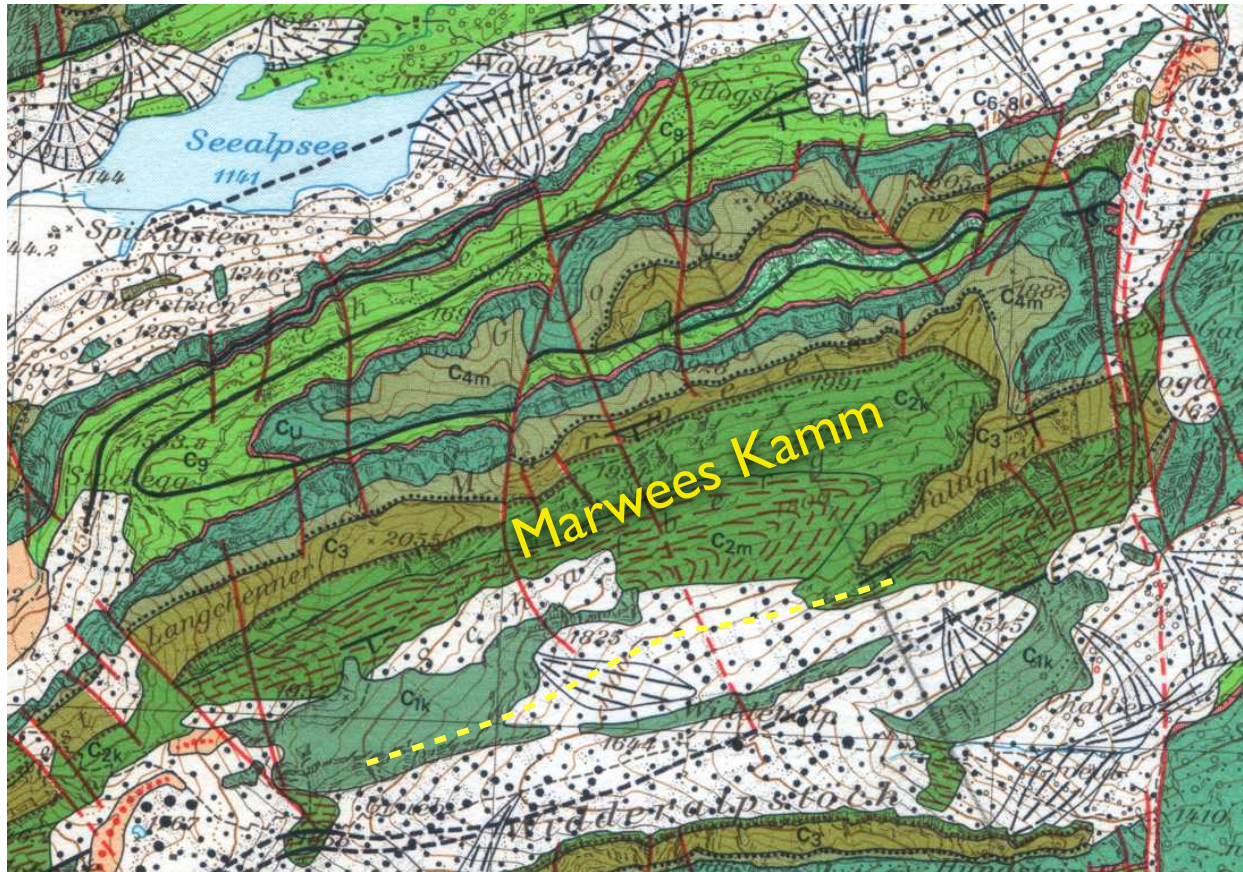
Kartengrösse: 600x400



Struktural Map of the Helvetic Zone of the Swiss Alps,  
1:100'000, swisstopo, 2011

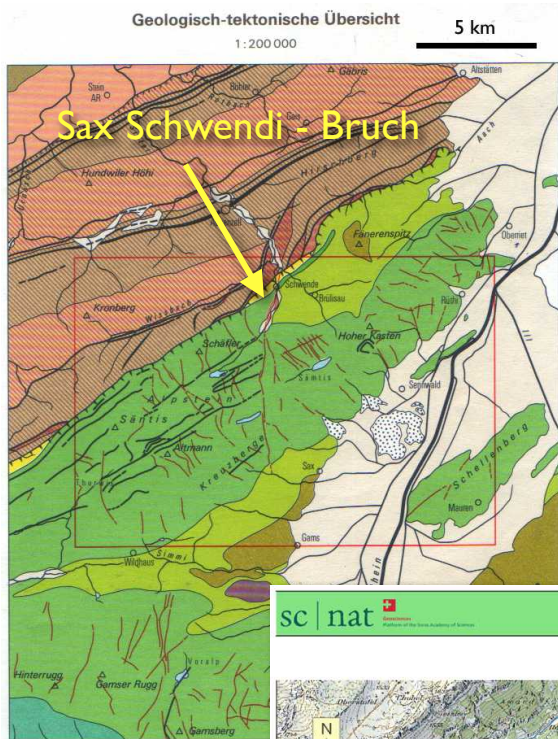
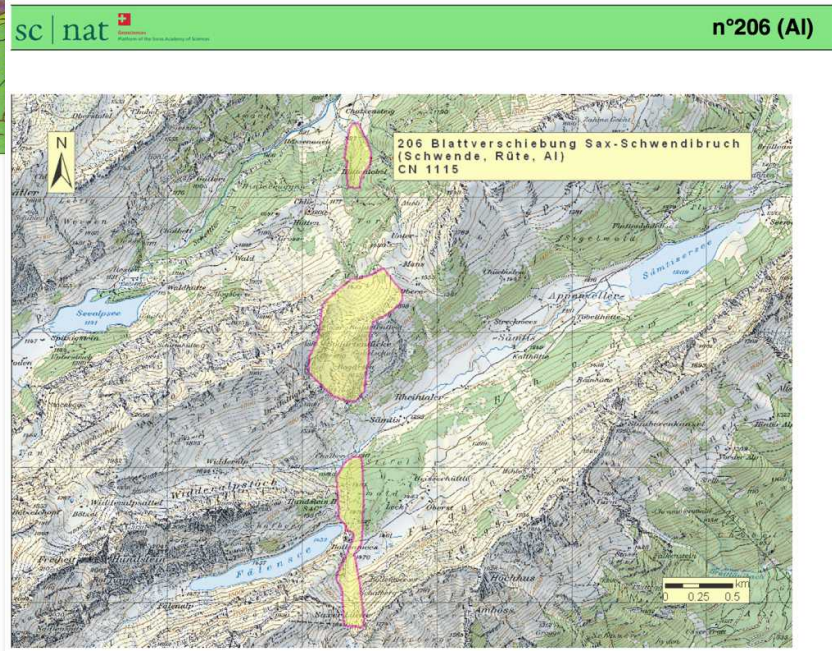


# ... und erst noch auf dem Kopf



Geologische Karte der Schweiz 1:25'000, Blatt Säntis

# Geologie Portal - Geotope

# Falten

100 m



Beispiel: Ugab (Namibia)

# Falten

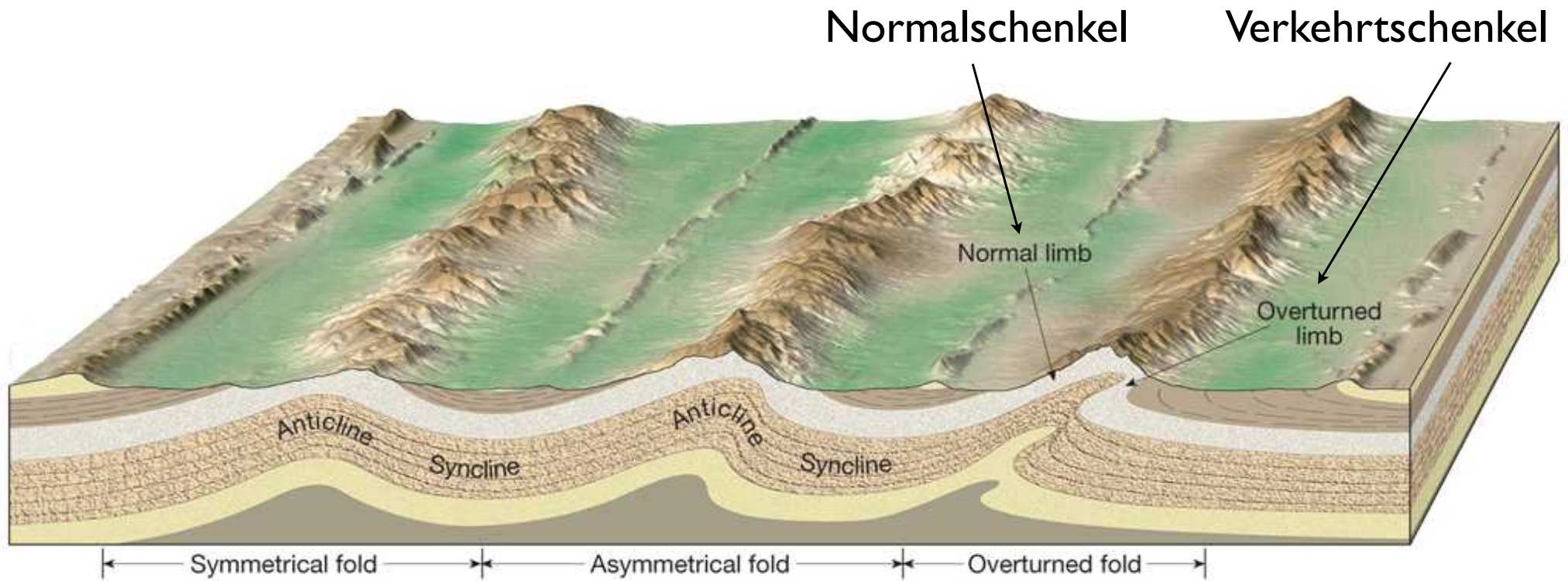
10 km



0.5 km

## Beispiel: Ugab (Namibia)

# Falten



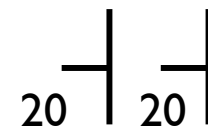
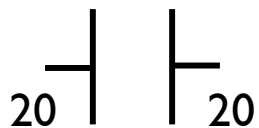
W

symmetrische Falte

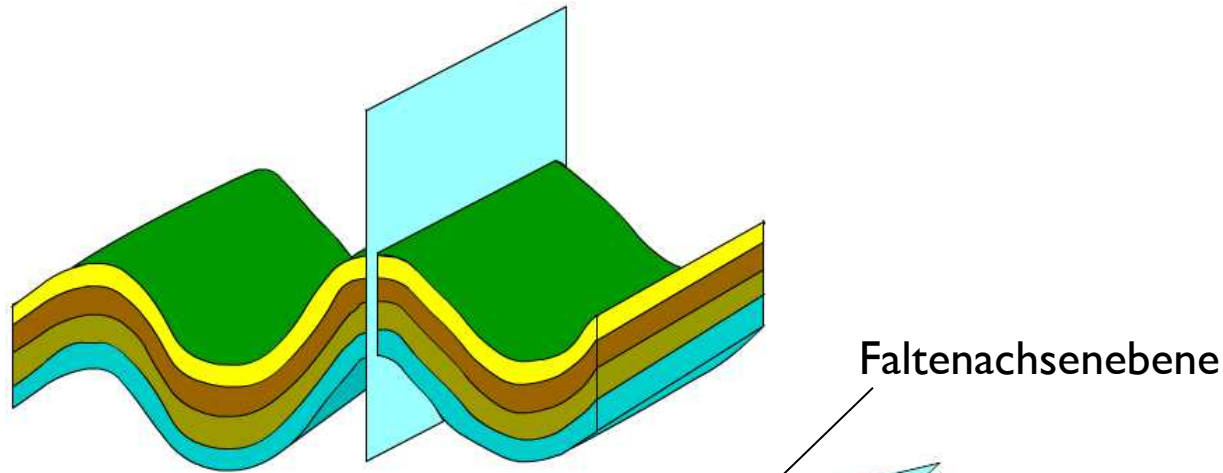
asymmetrische Falte

überkippte Falte

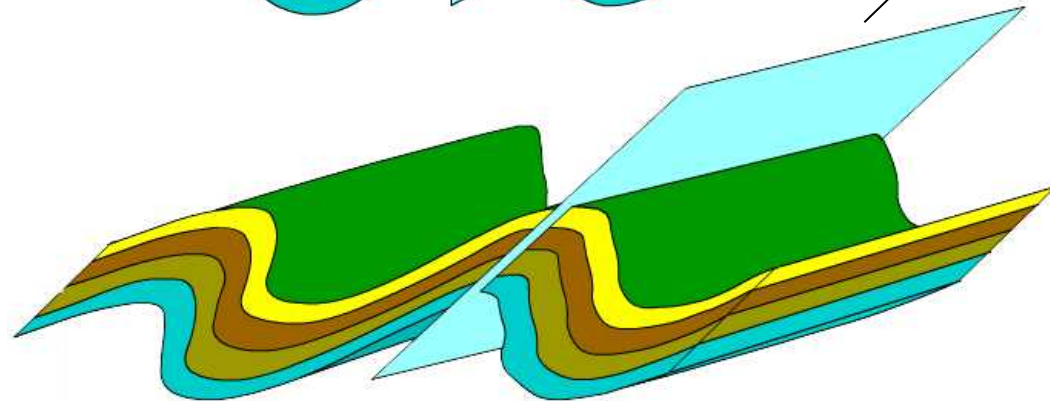
E



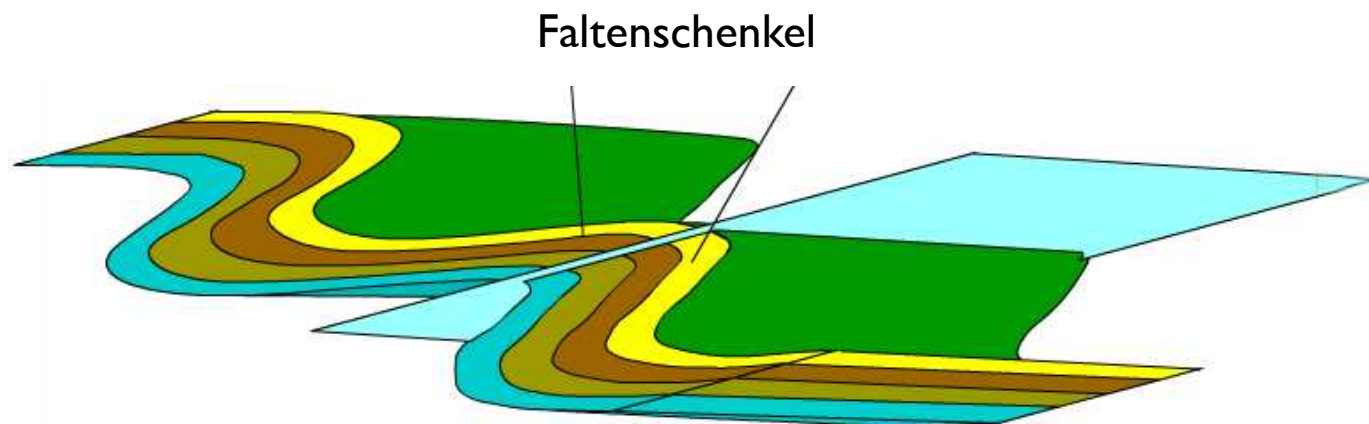
# Falten: Achsenebenen



aufrecht  
stehend



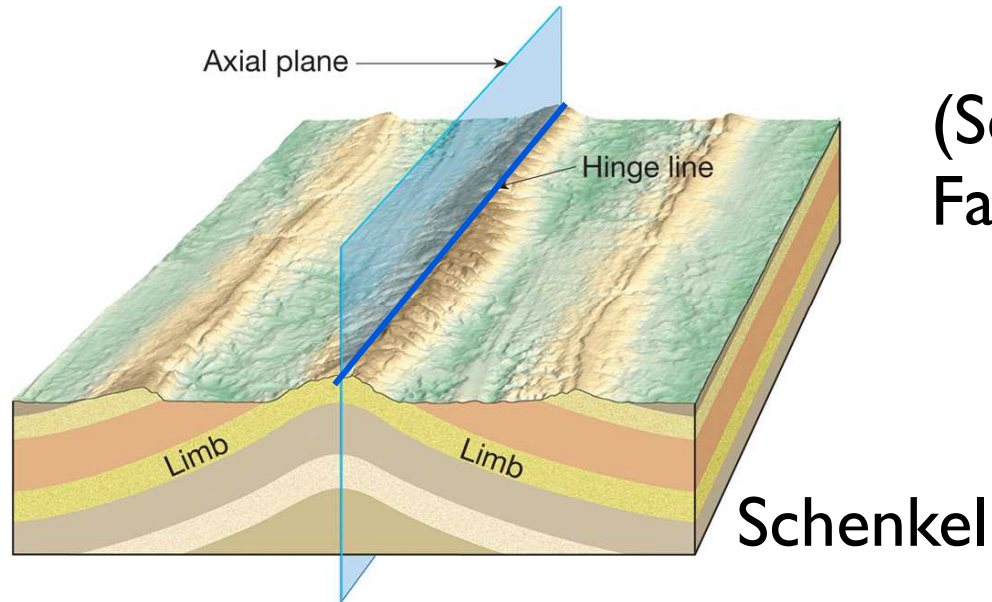
schräg  
geneigt



überkippt  
liegend

# Falten: Faltenachsen

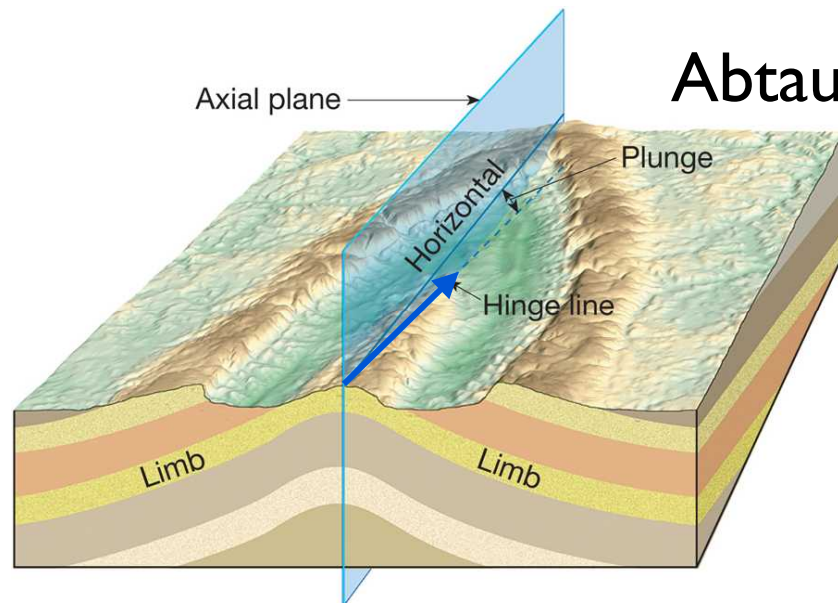
## Achsenebene (Fläche)



(Scharnierlinie)  
Faltenachse (Linear)

horizontale Falte  
horizontale Faltenachse  
vertikale Achsenebene

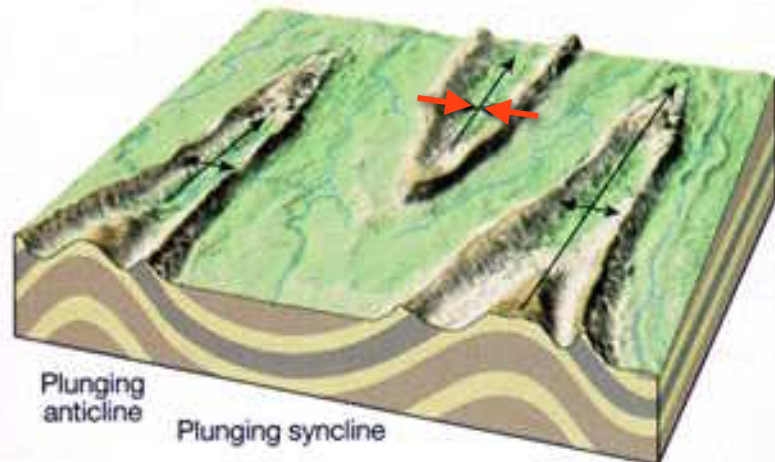
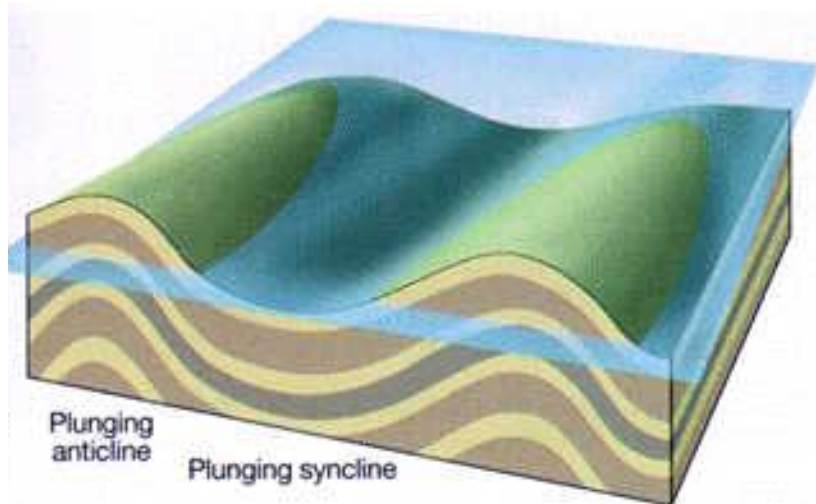
## Abtauchen



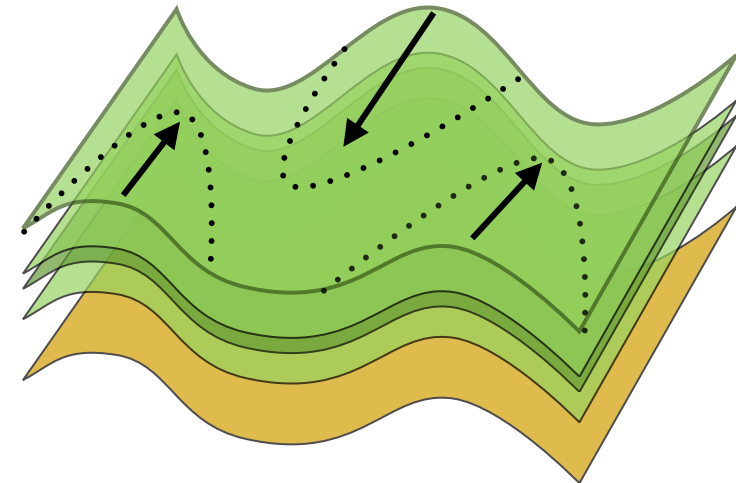
abtauchende Falte  
abtauchende Faltenachse  
vertikale Achsenebene

# Falten: tauchende Faltenachsen

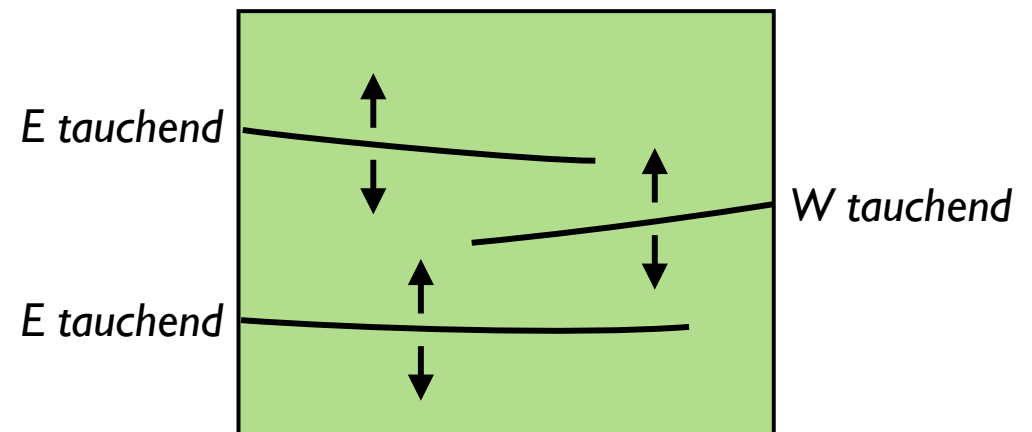
tauchende Antiklinalen  
und Synklinalen



tauchende Antiklinalen:  
Kernaustausch

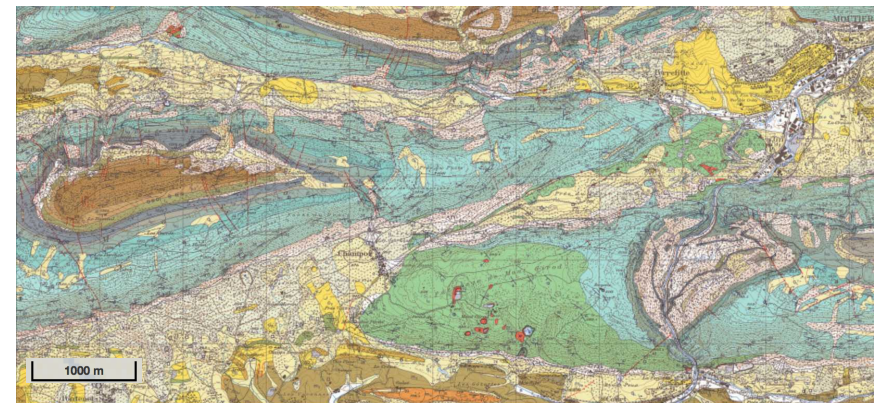
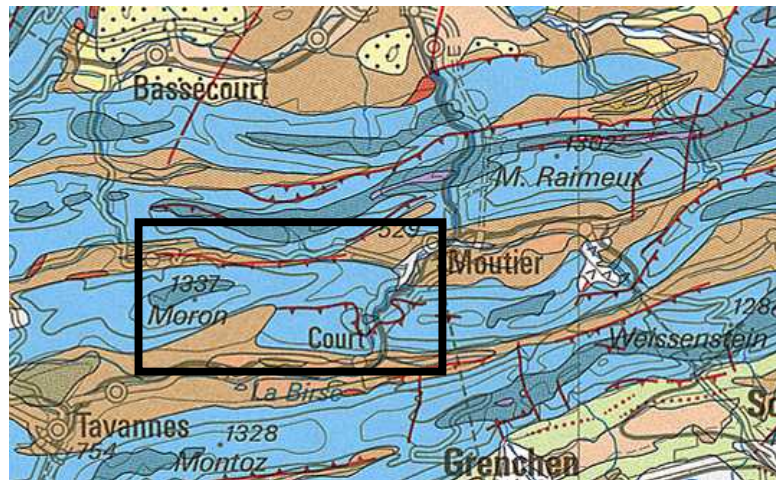
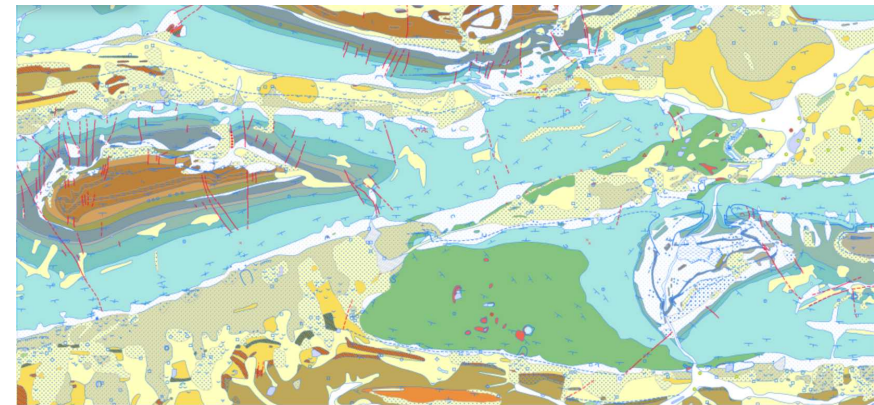
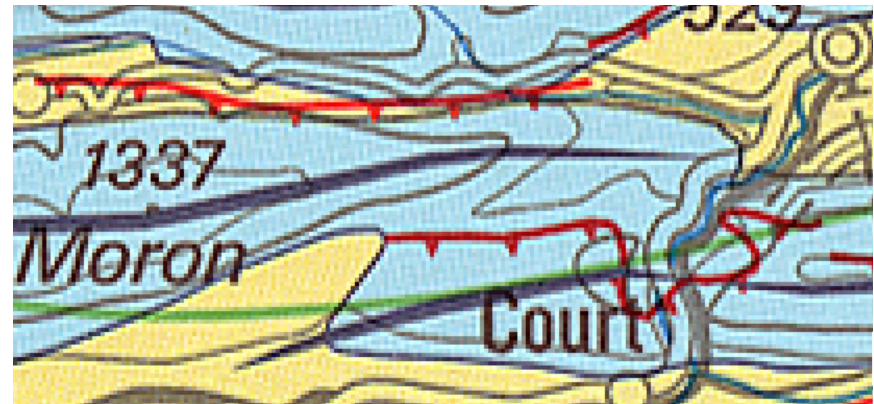
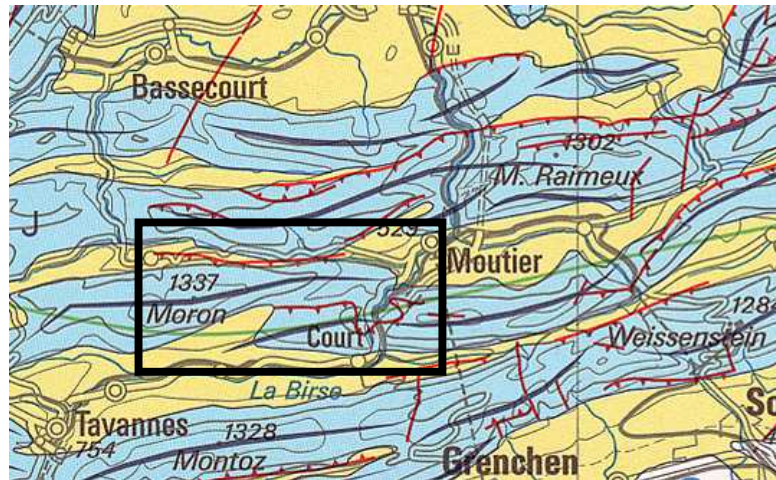


≠



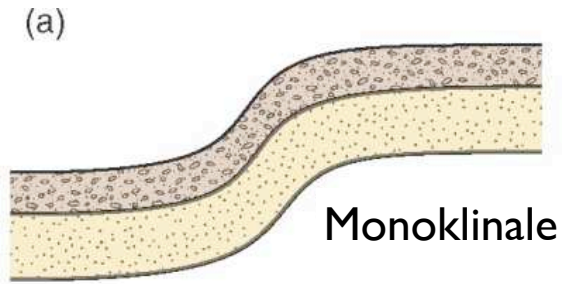


# Falten: Kernaustausch

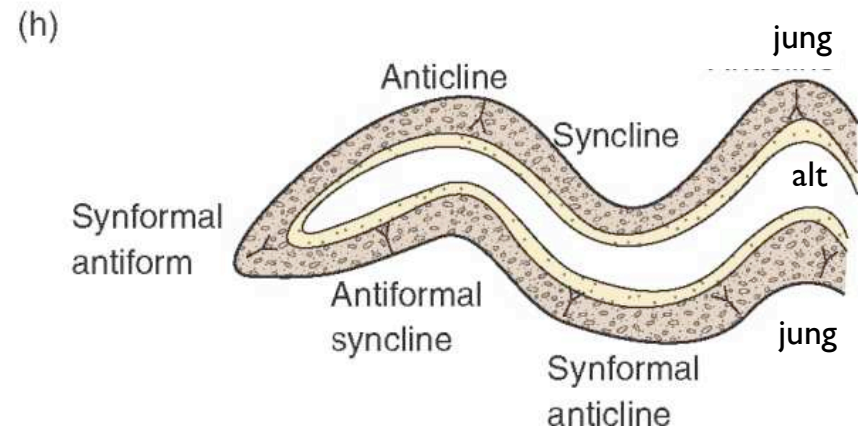
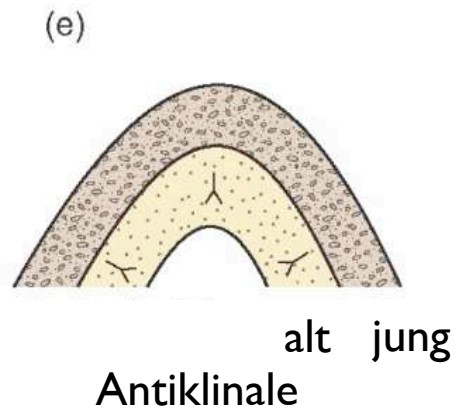
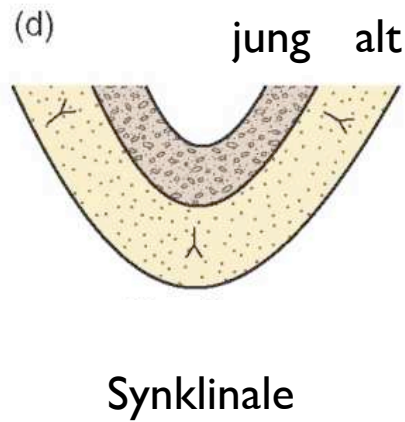
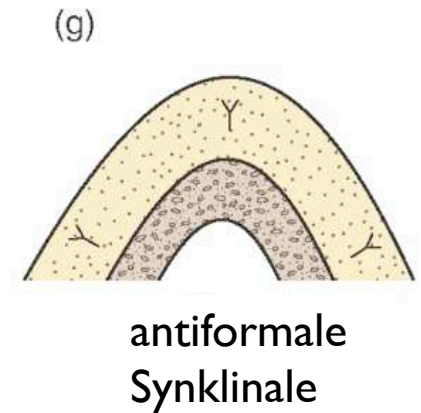
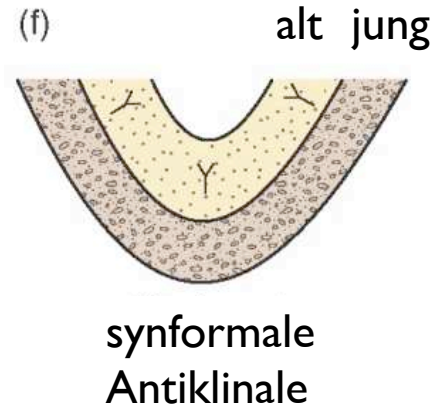
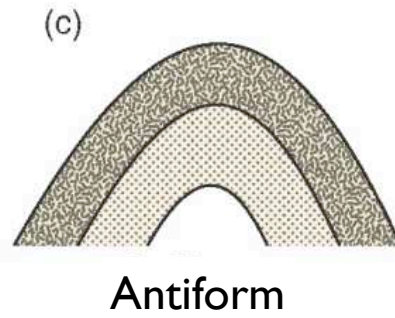
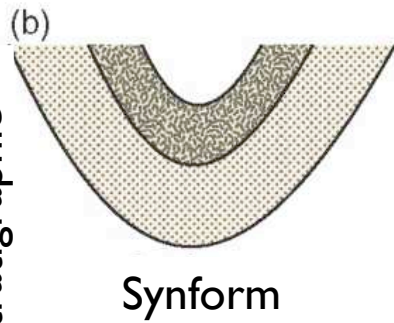


<https://map.geo.admin.ch/>

# Synform - Antiform



Unbekannte  
Stratigraphie

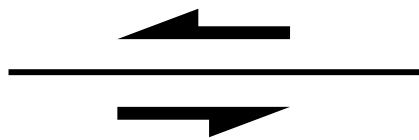
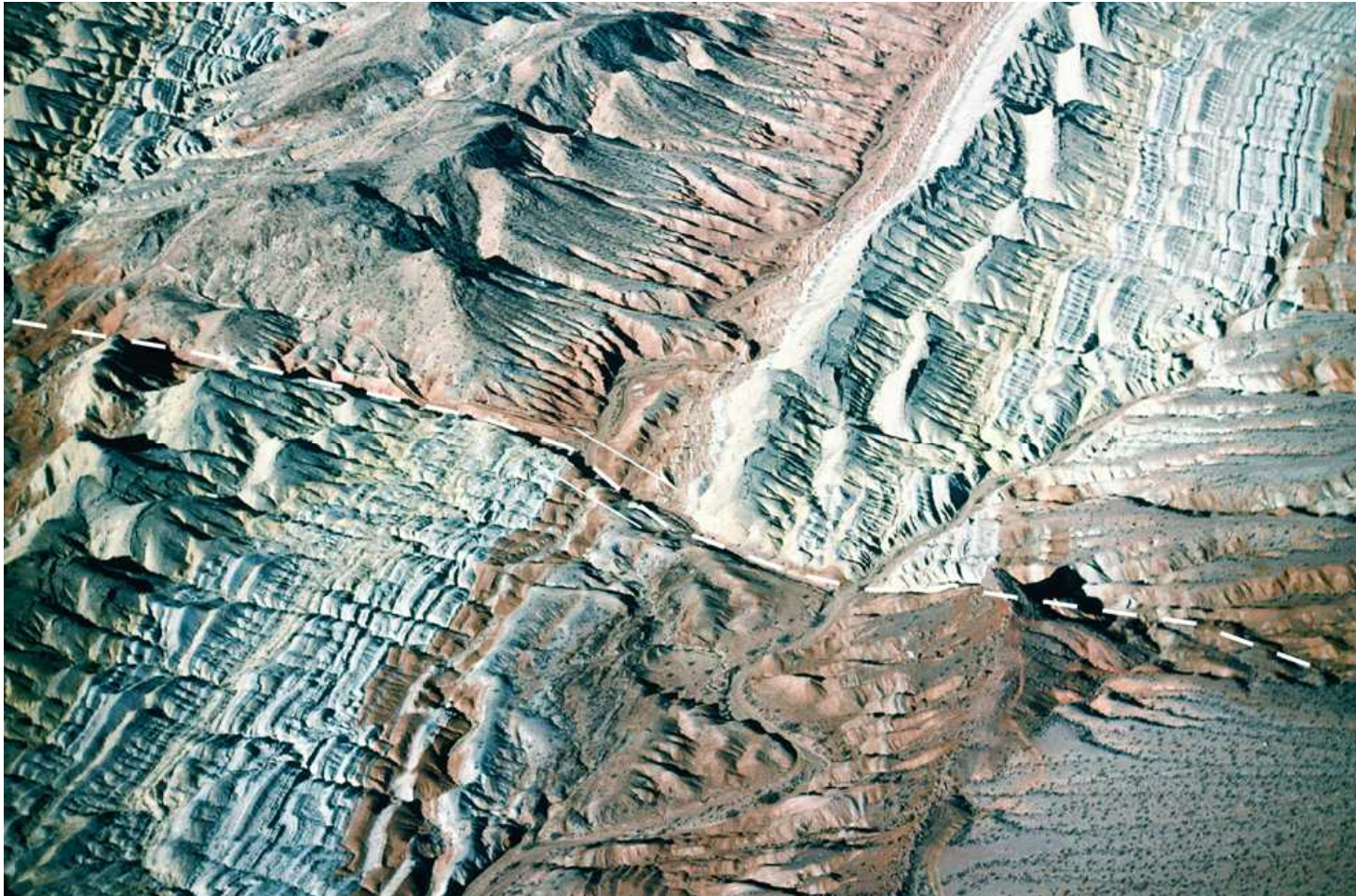


λ “younging direction”

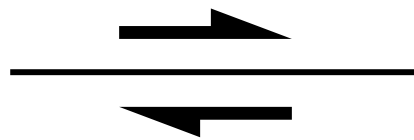
# Strike-Slip - Strukturen

# Blattverschiebung

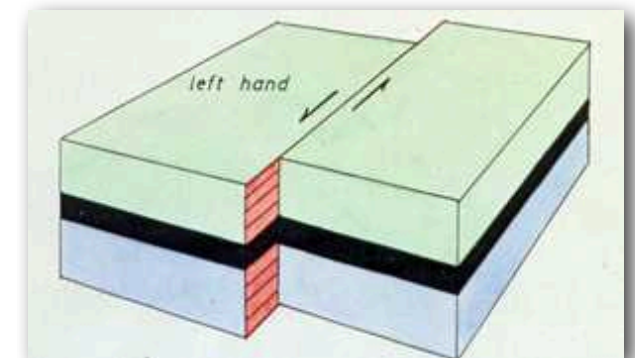
1 km



sinistral

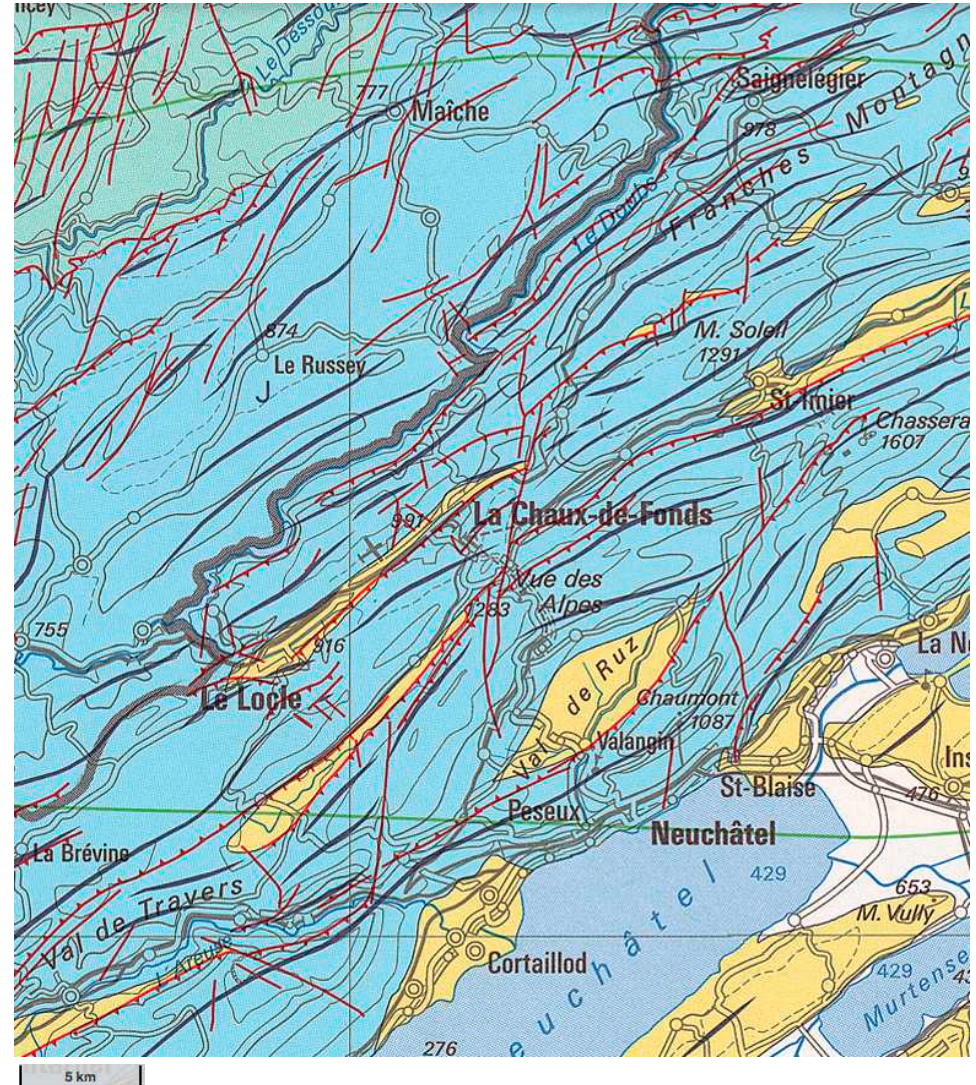


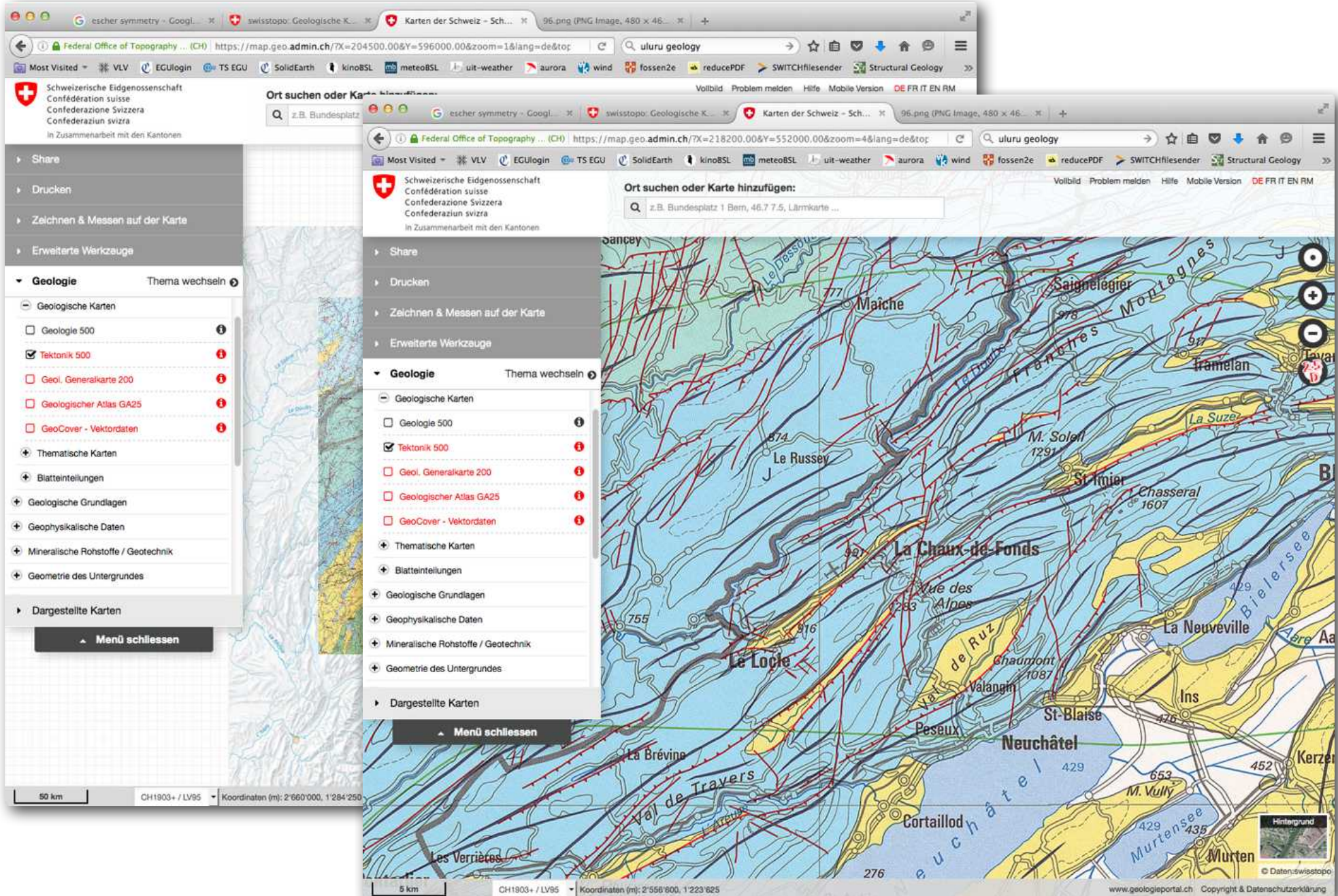
dextral



# Sinistrale Blattverschiebung

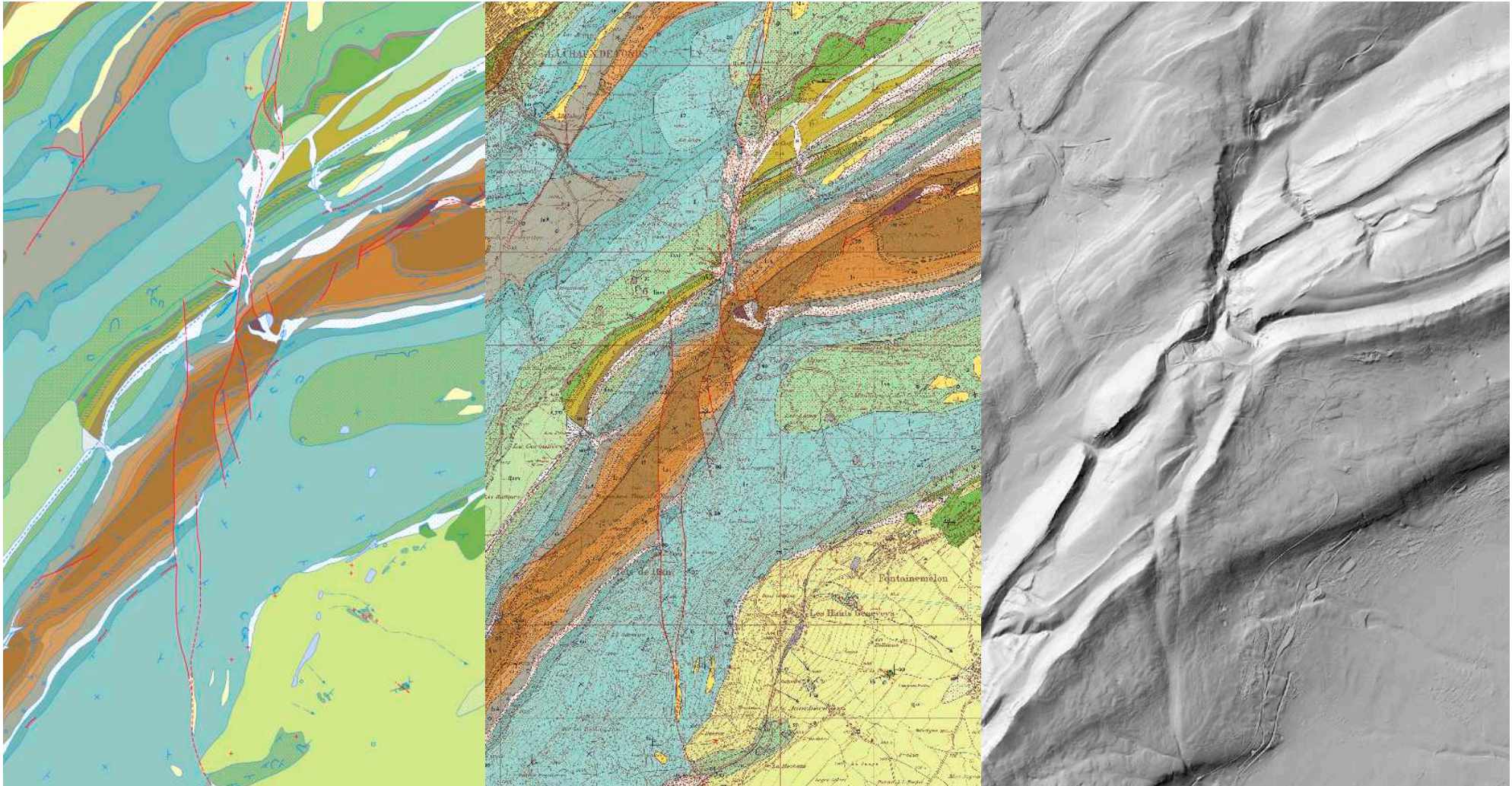
<https://map.geo.admin.ch>





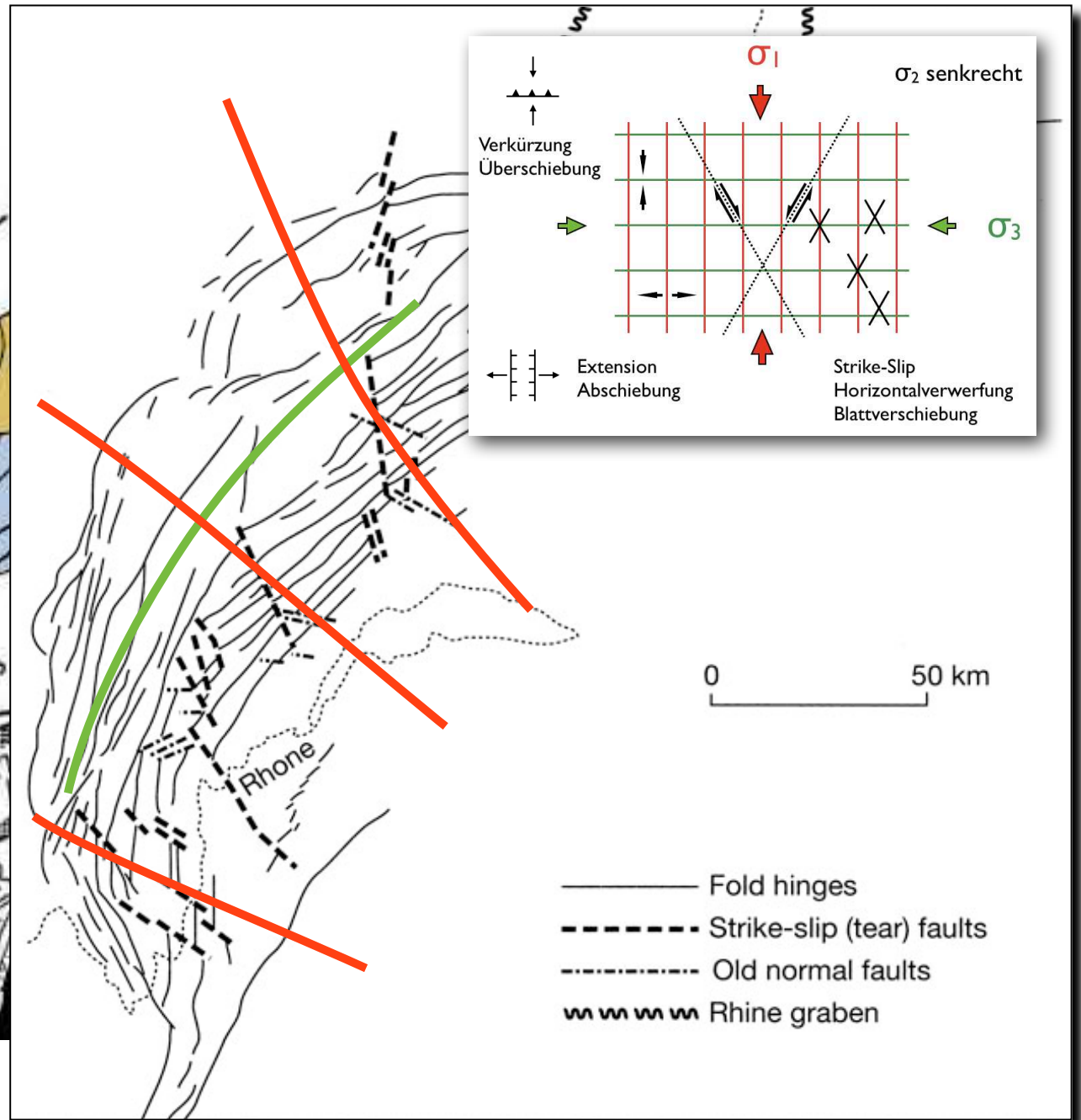
# swisstopo

<https://map.geo.admin.ch>



1000 m

# recap: Transversalstörungen im Jura

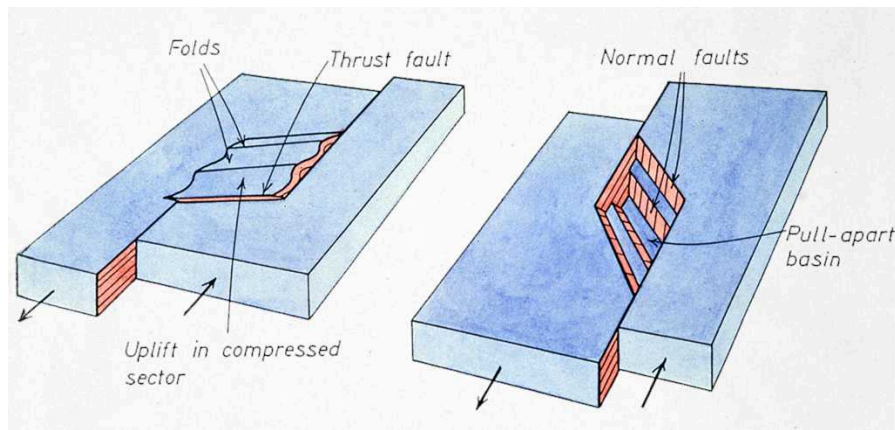
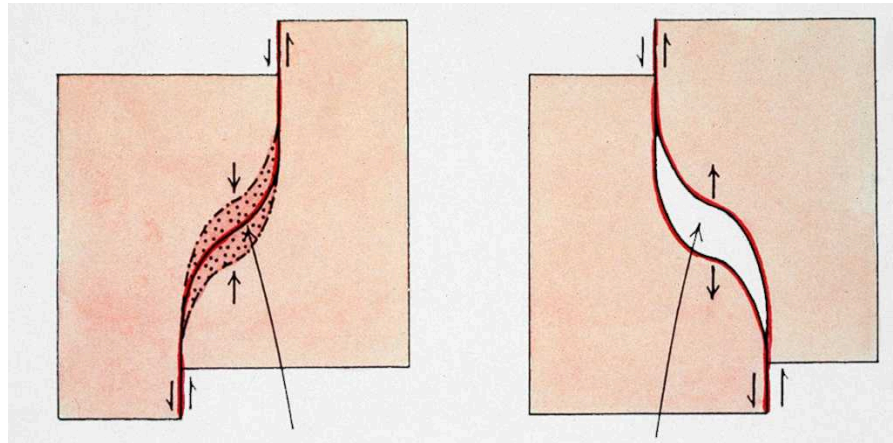




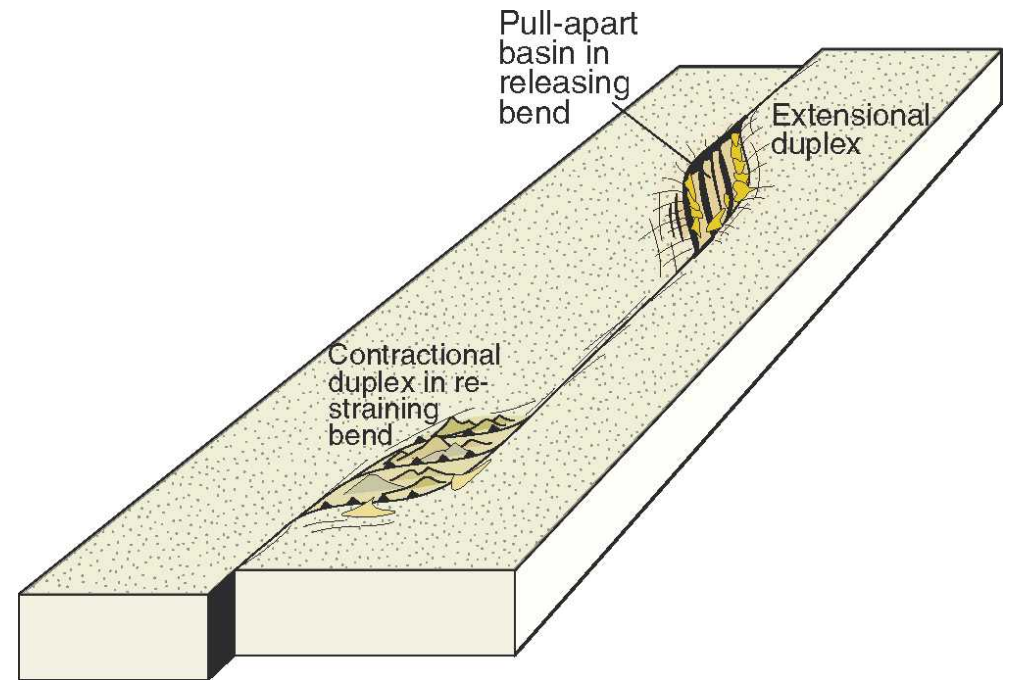
# Transpression Transtension

restraining bend

releasing bend

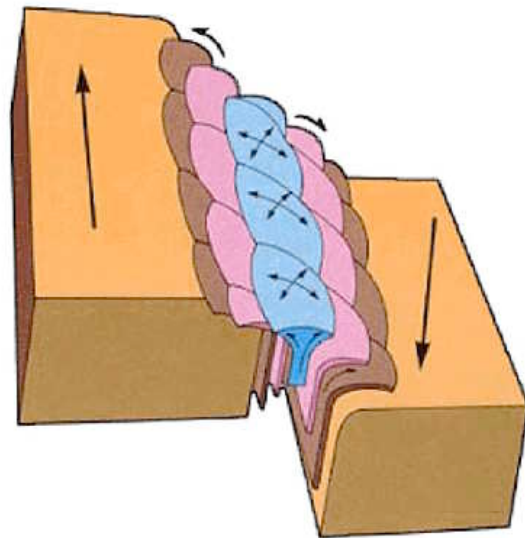
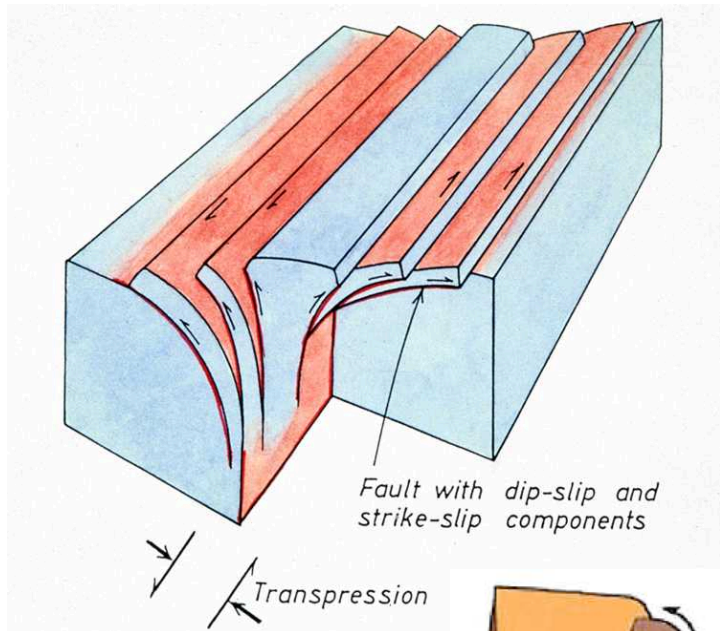


Ramsay

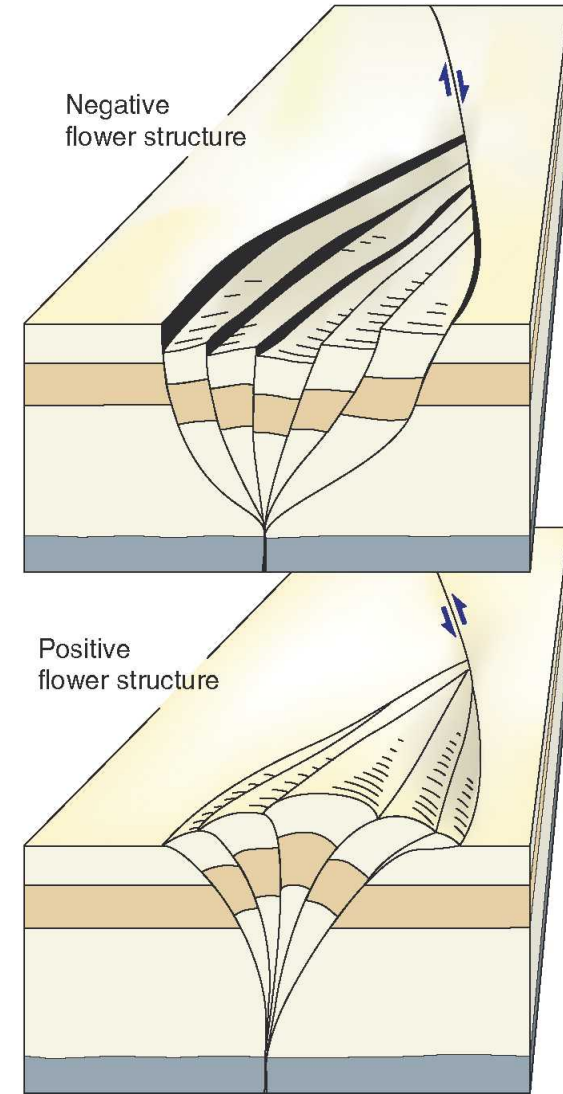


Fossen

# Flower structures



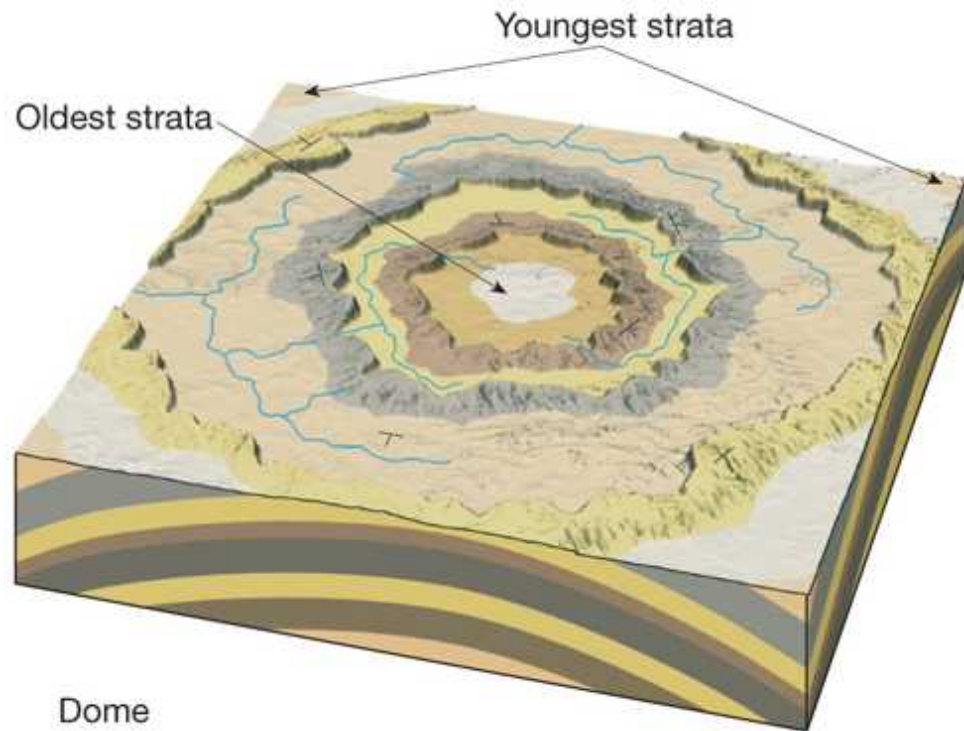
Ramsay



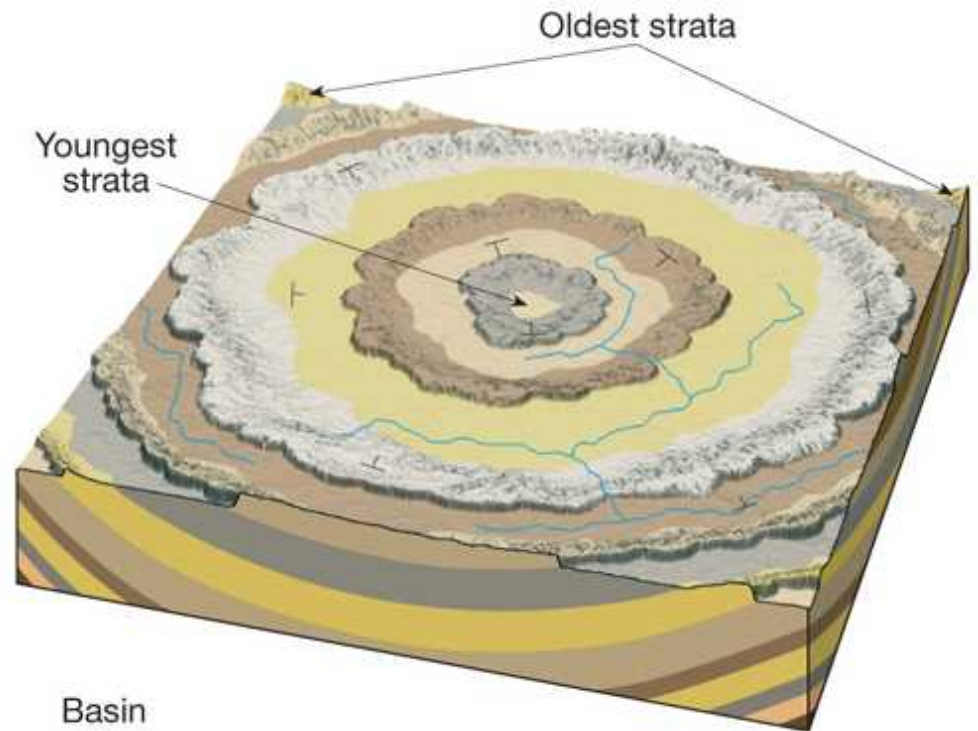
Fossen

# Vertikalbewegungen

# Dom

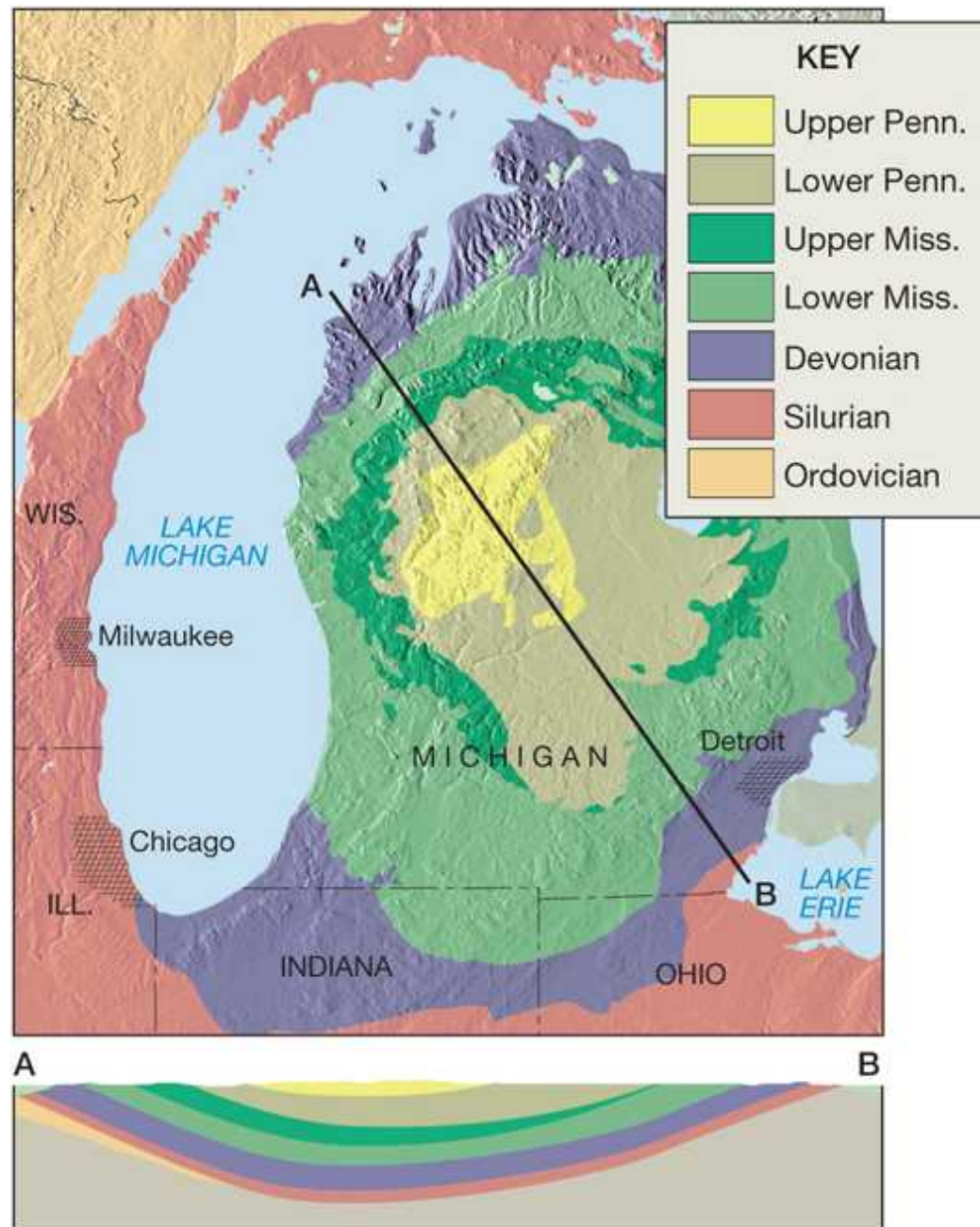


# Becken



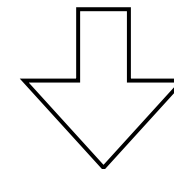
Morphologie  $\neq$  Struktur

# Beispiel: Becken

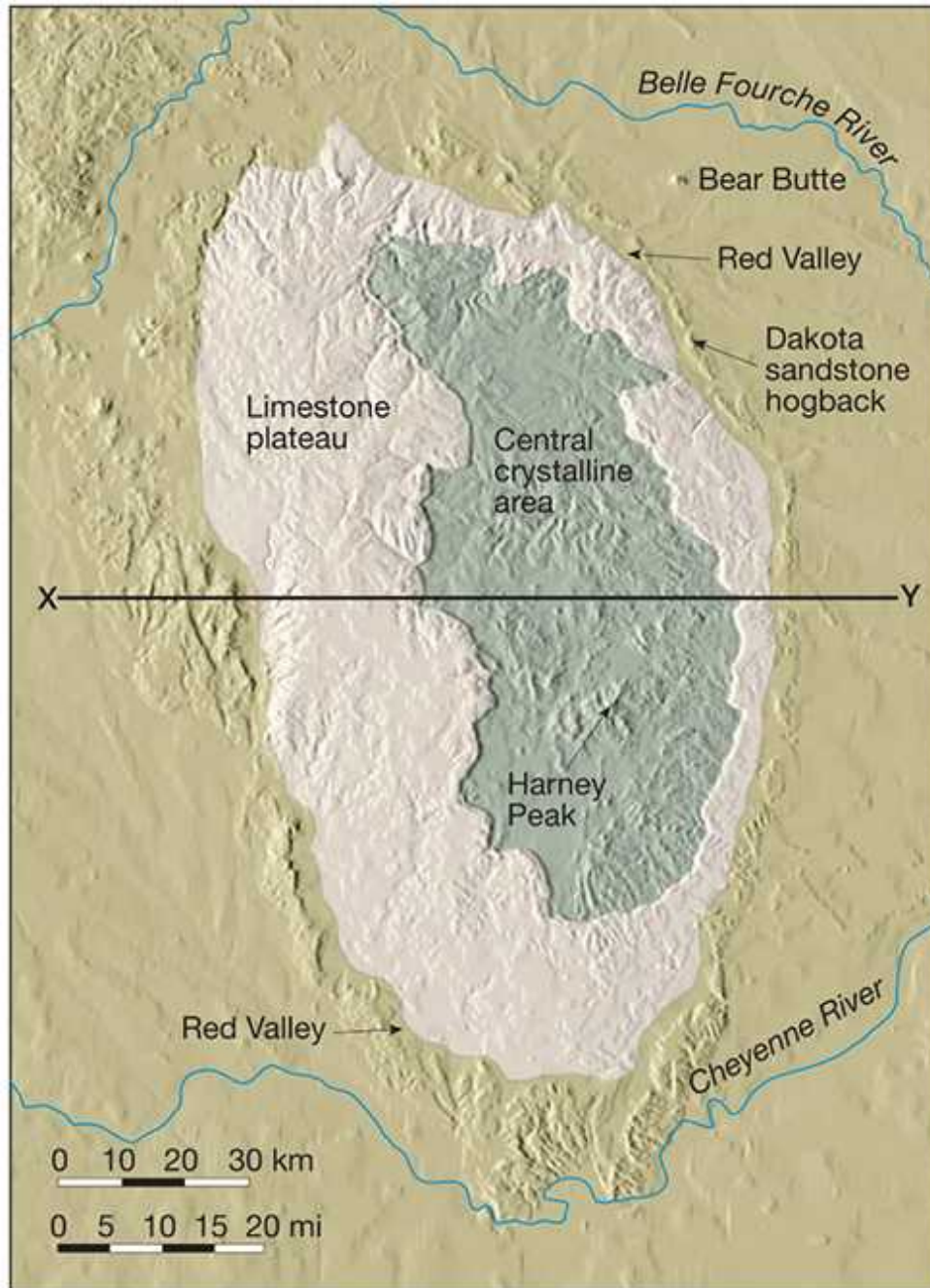


## Michigan Basin

Isostatische  
Absenkung  
während  
Sedimentation

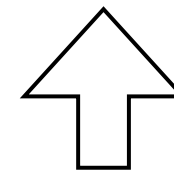


# Beispiel: Dom

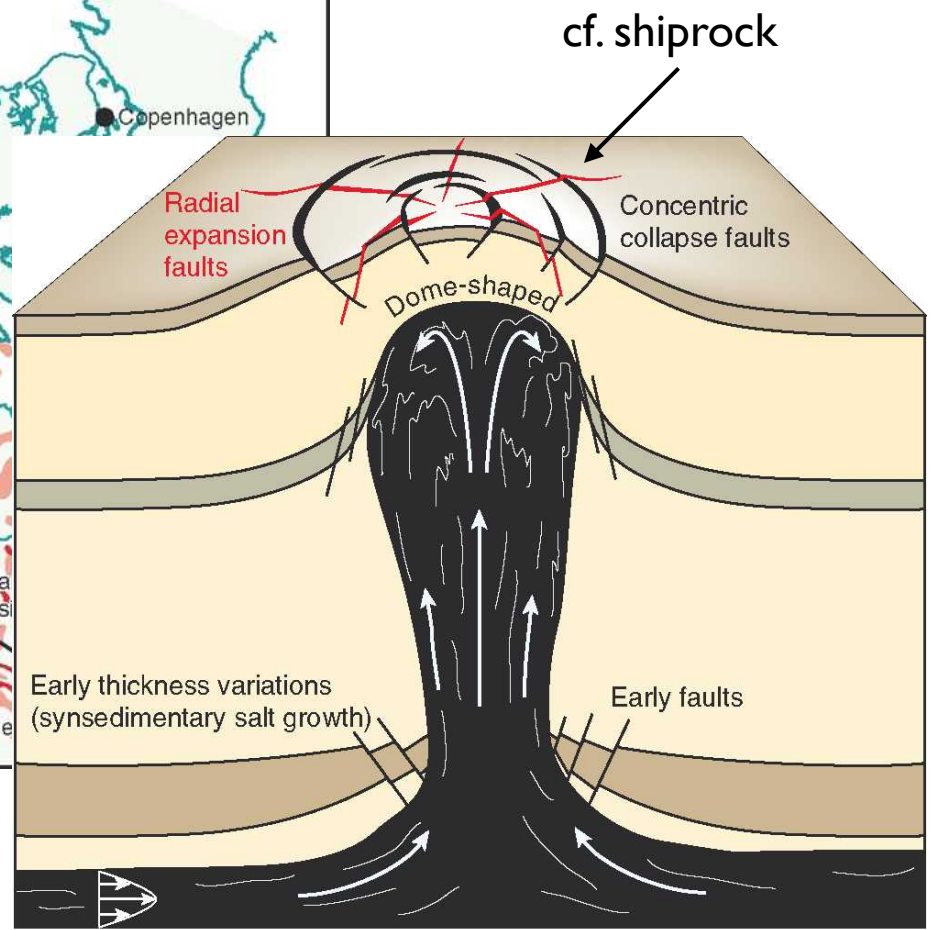
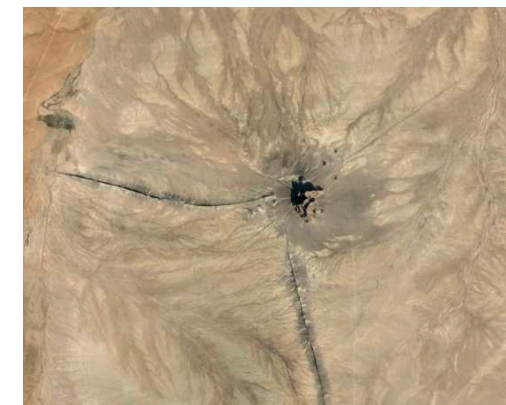
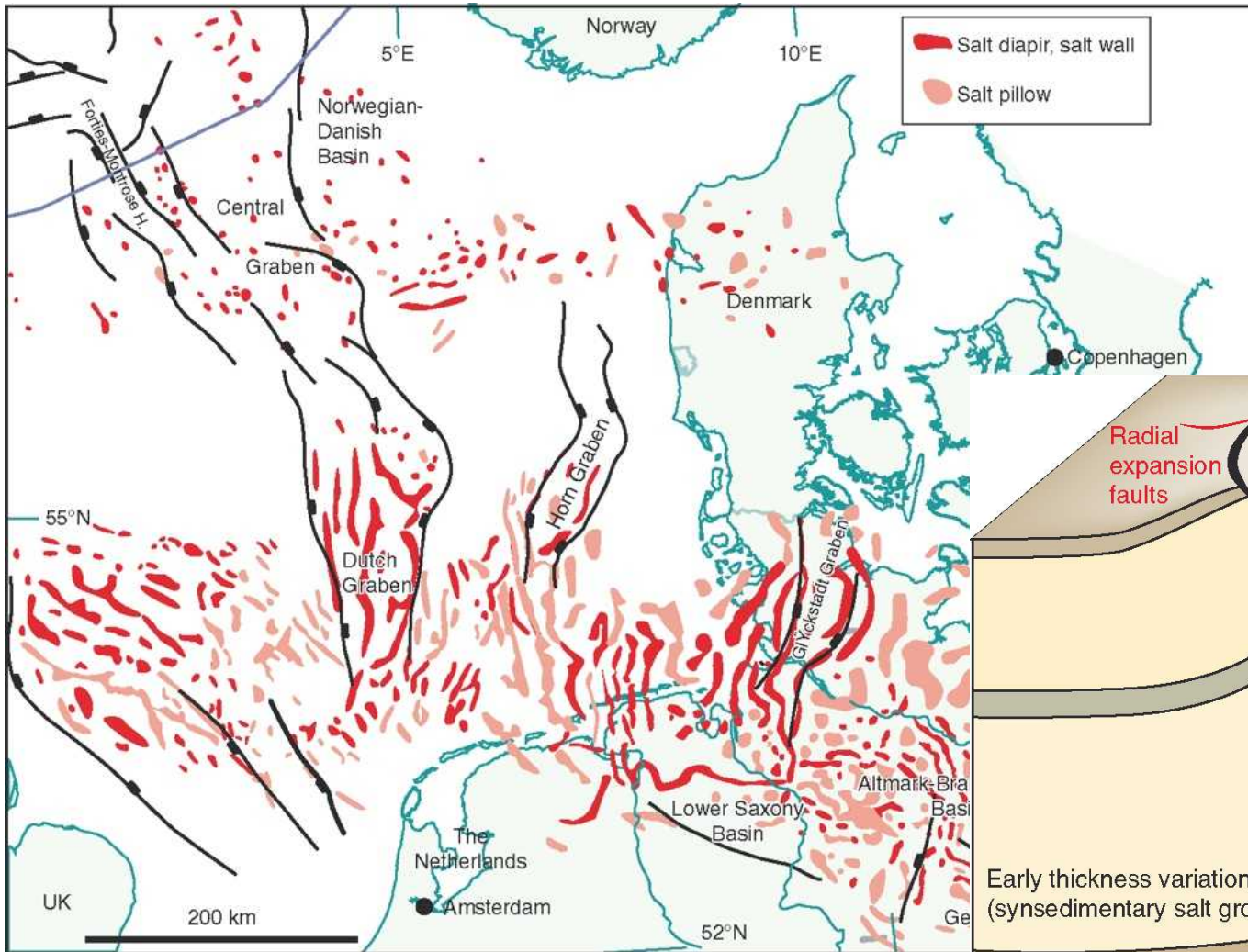


Black Hills South  
Dakota

Aufwölbung  
durch  
Intrusion



# Salzstöcke (Diapire)

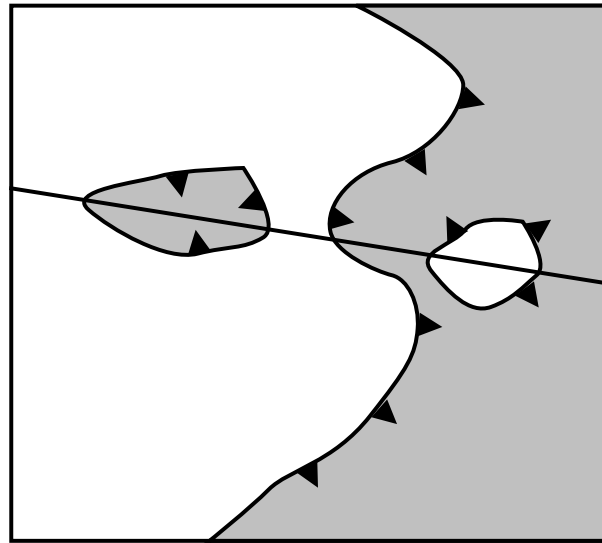
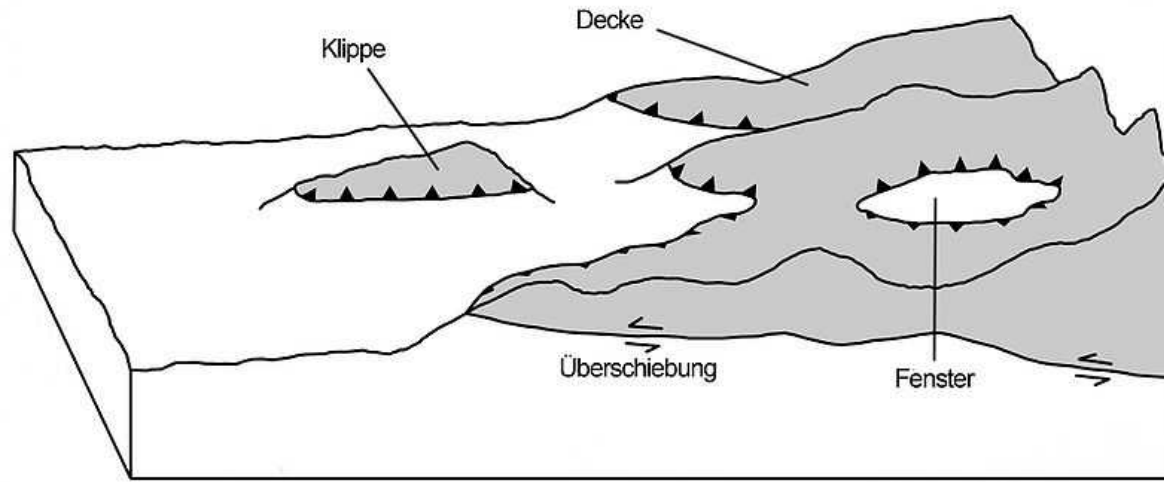


Velocity profile

# Intersektion: Struktur - Topographie

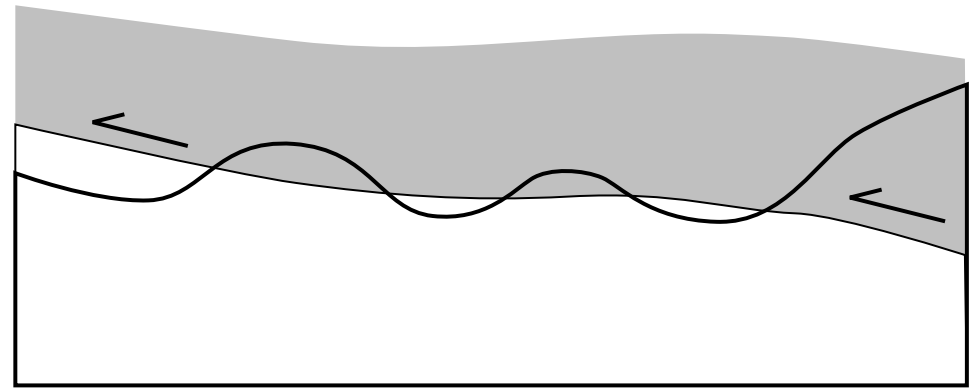


# Klippe - Fenster



Karte

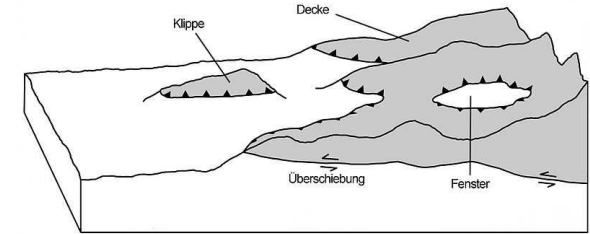
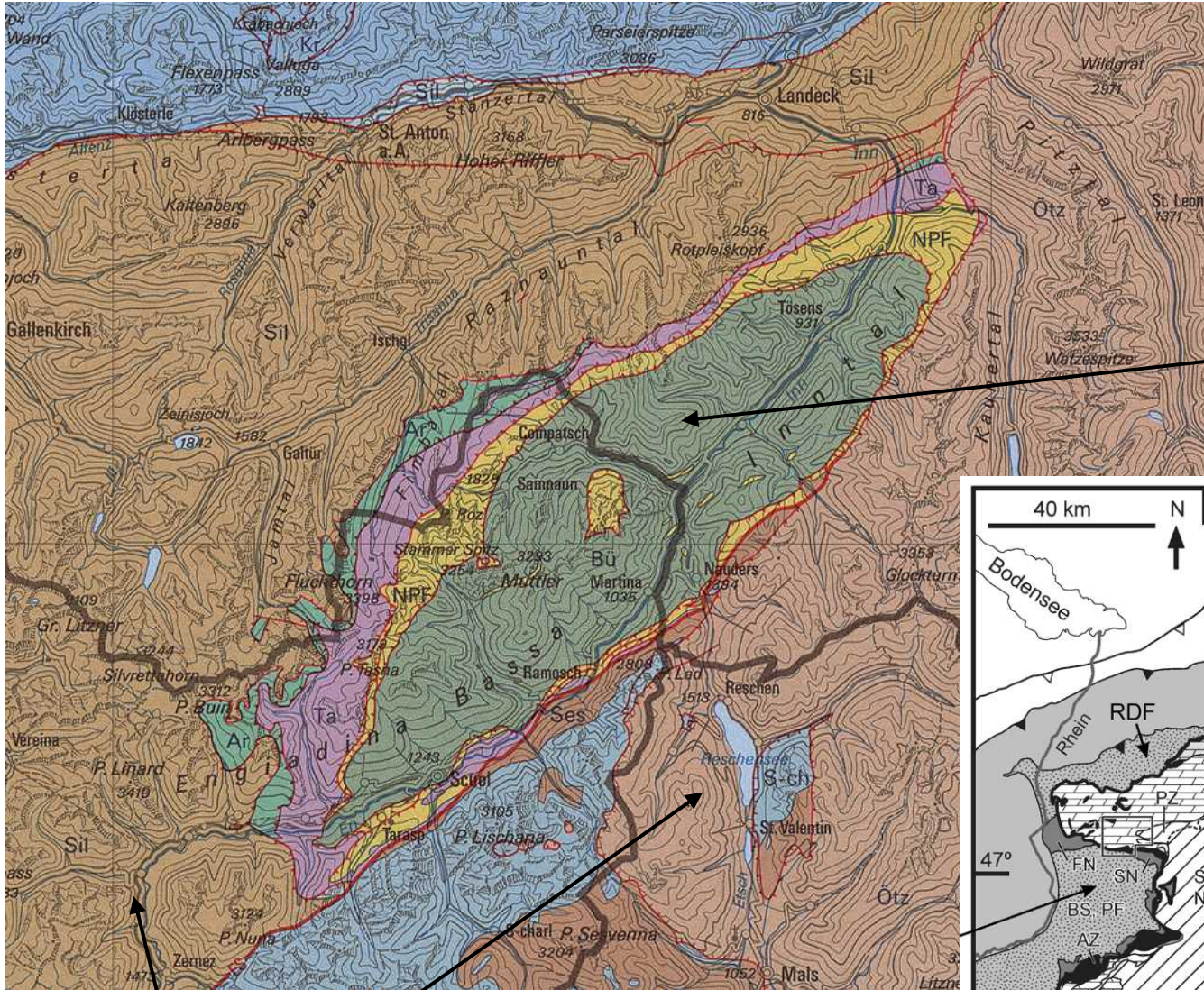
Profilspur



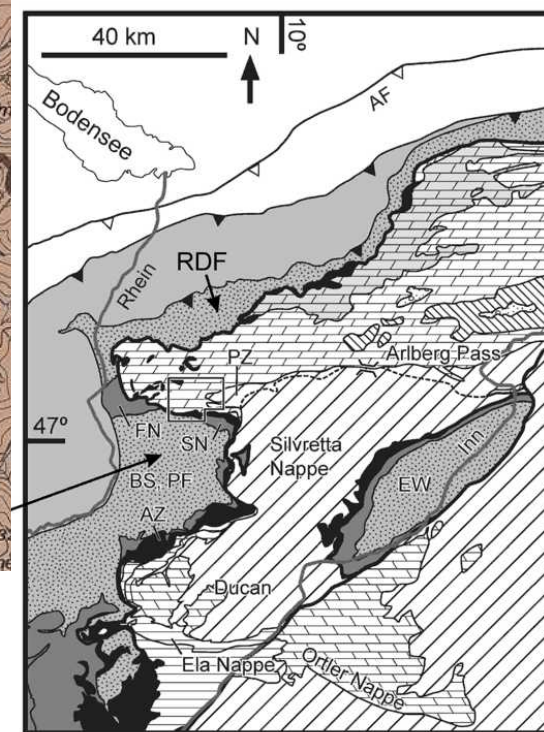
Profil

# Beispiel: Engadiner Fenster

Nördliche Kalkalpen = Ostalpine Decken



Fenster =  
Penninikum



## Ostalpin

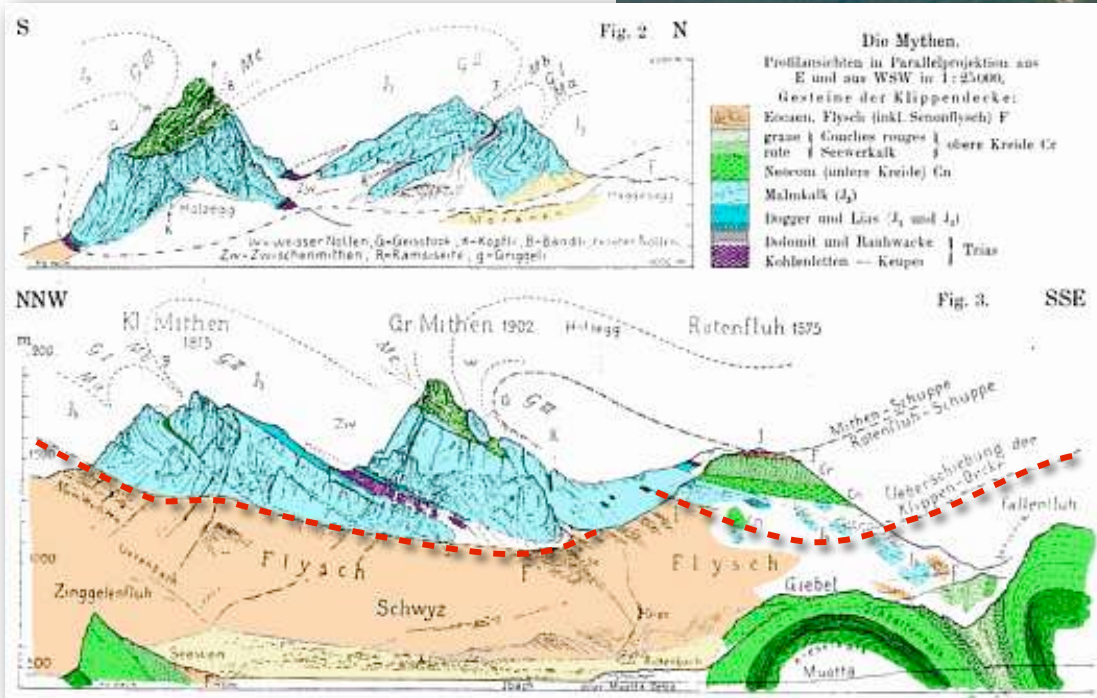
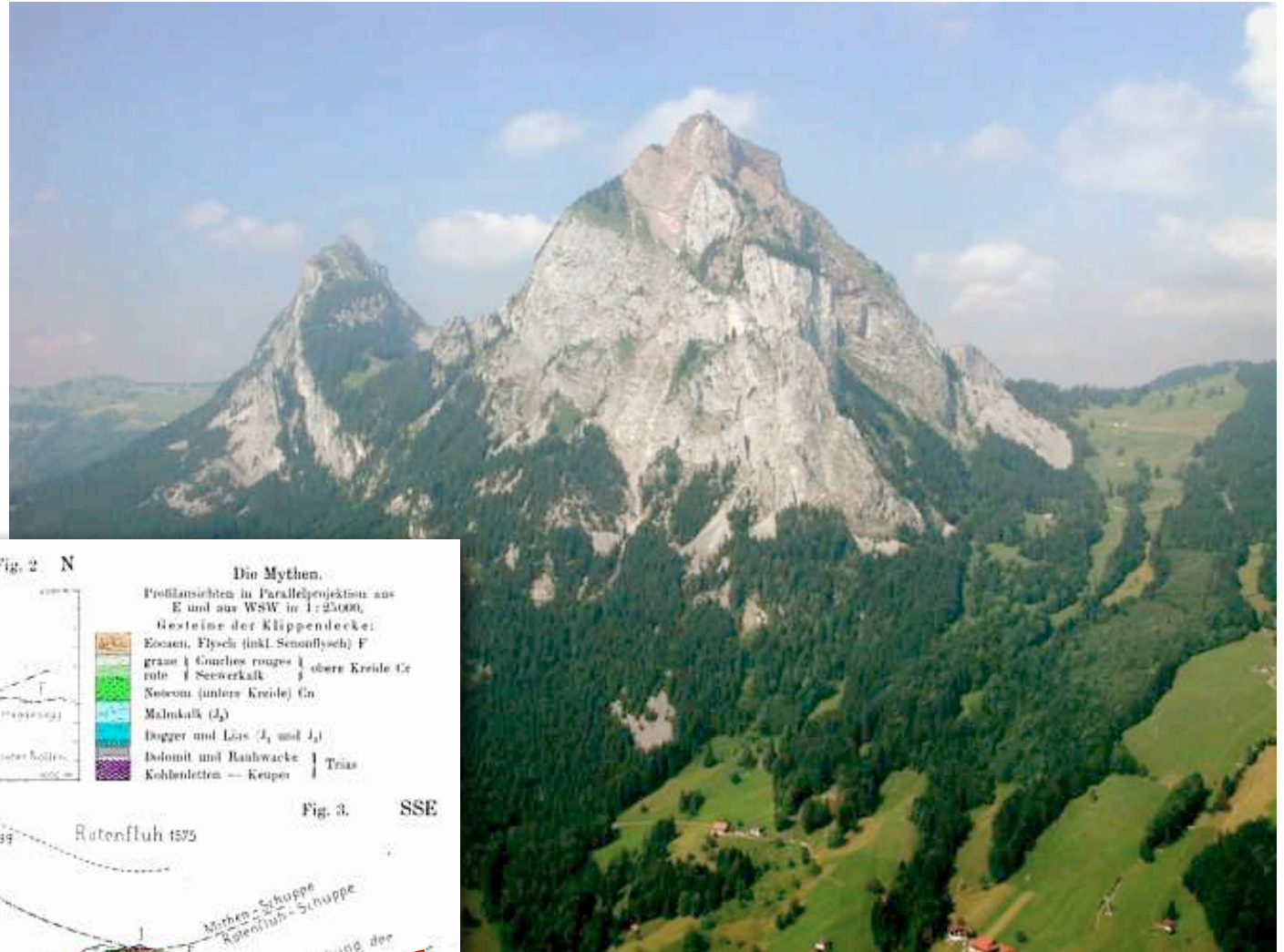
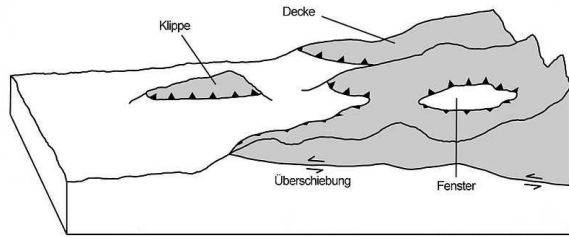
- Northern Calcareous Alps**
  - Gosau group
  - Inntal Nappe
  - Lechtal Nappe
  - Allgäu Nappe
- Central Austroalpine Nappes**
  - Mesozoic Cover
  - Basement
  - Lower Austroalpine Nappes

- Upper Penninic Nappes**
- Middle Penninic Nappes**
- Lower Penninic Nappes**

## Penninikum

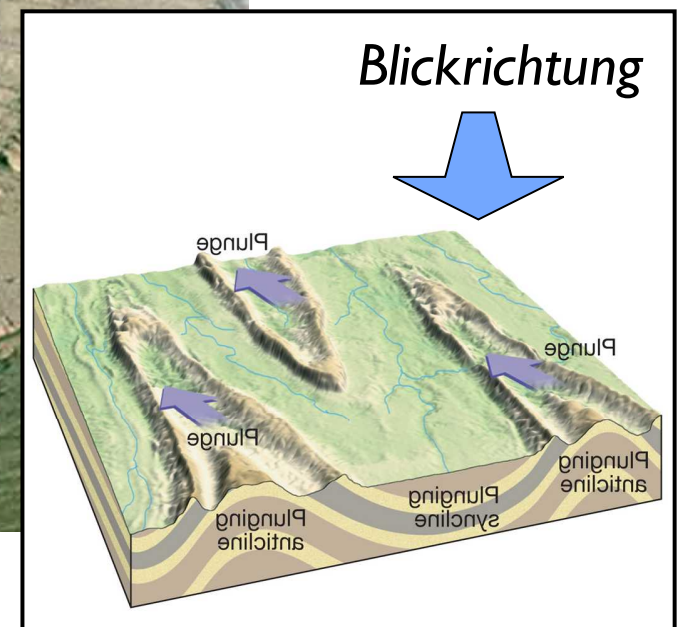
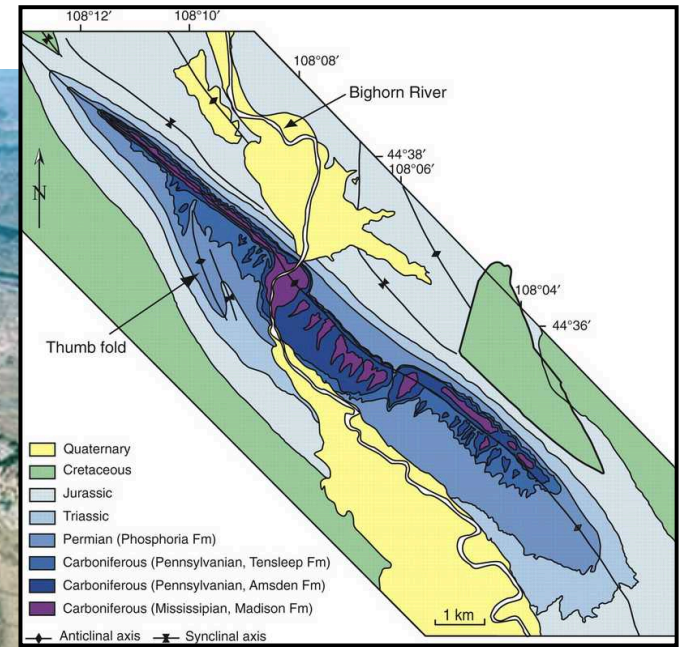
Ostalpines Basement

# Beispiel: Klippendecke

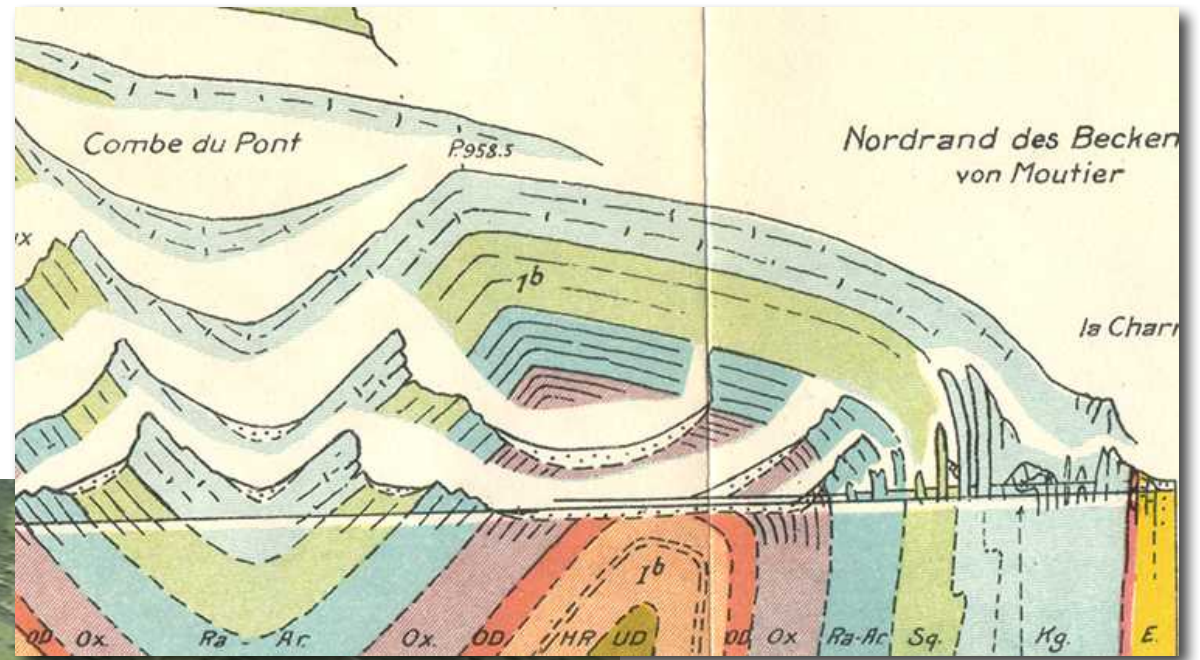


Grosser und kleiner Mythen

# Morphologie $\neq$ Struktur

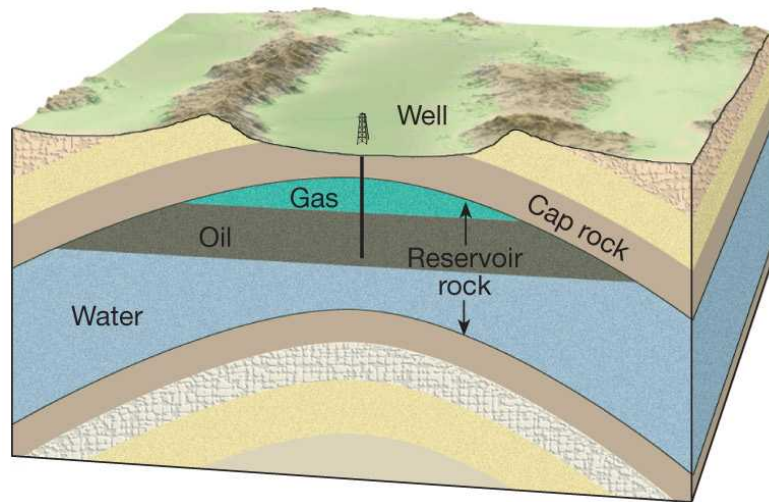


# Morphologie $\neq$ Struktur

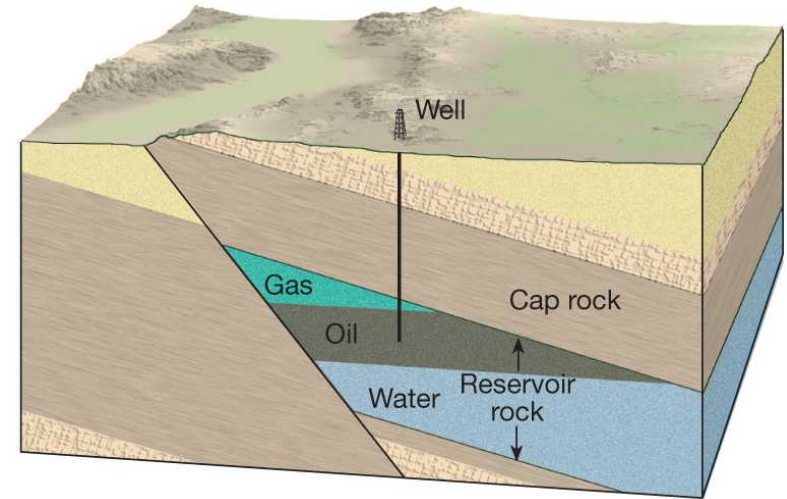


# Bedeutung von Strukturen für Rohstoffe

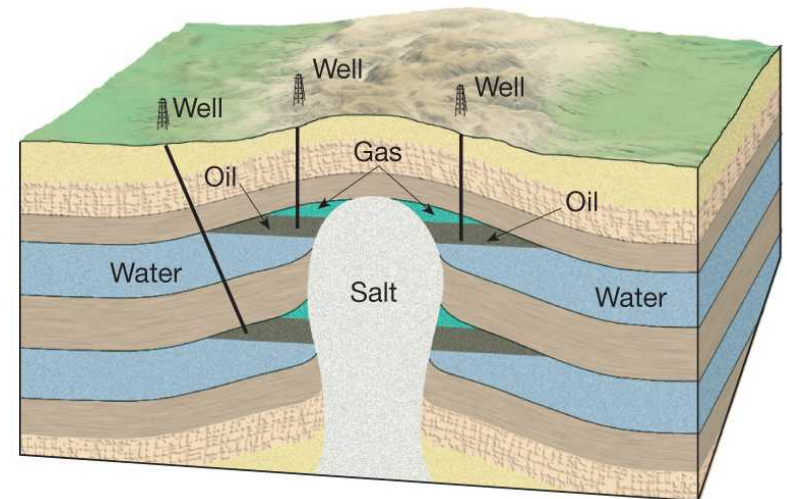
## Antiklinale



## Verwerfung



## Salzstock (→ Dom)



= structural traps

# 4 Strain (Deformation als Zustand)

## Geometrie der Deformation: Strain

- Strain ellipse
- 2-D 3-D strain
- Reine Scherung - einfache Scherung (pure shear - simple shear)

## Strain - Messung

- Strain marker
- Längenänderung, Formänderung
- überlagerte Verformung
- heterogene Verformung

# Deformation

## 1 Deformations - Zustand:

finite Verformung:  $e_1, e_2, e_3, \lambda_1, \lambda_2, \lambda_3$   
verformter Zustand relativ zum unverformten Zustand

Geometrie

## 2 Deformations - Bewegung:

Veränderung der Form durch die Zeit  
displacement rate:  $\dot{d}$  (m/s, km/Ma,...)  
strain rate:  $\dot{\epsilon}$  ( $s^{-1}$ )

Kinematik

## 3 Deformations - Prozess:

Elastisches, visköses Verhalten (Kristallplastizität, Fließgesetze) als Reaktion auf Druck, Spannung, Temperatur, Plattenbewegungen:  $\dot{\epsilon} = f(T, \Delta\sigma, \dots)$

Dynamik

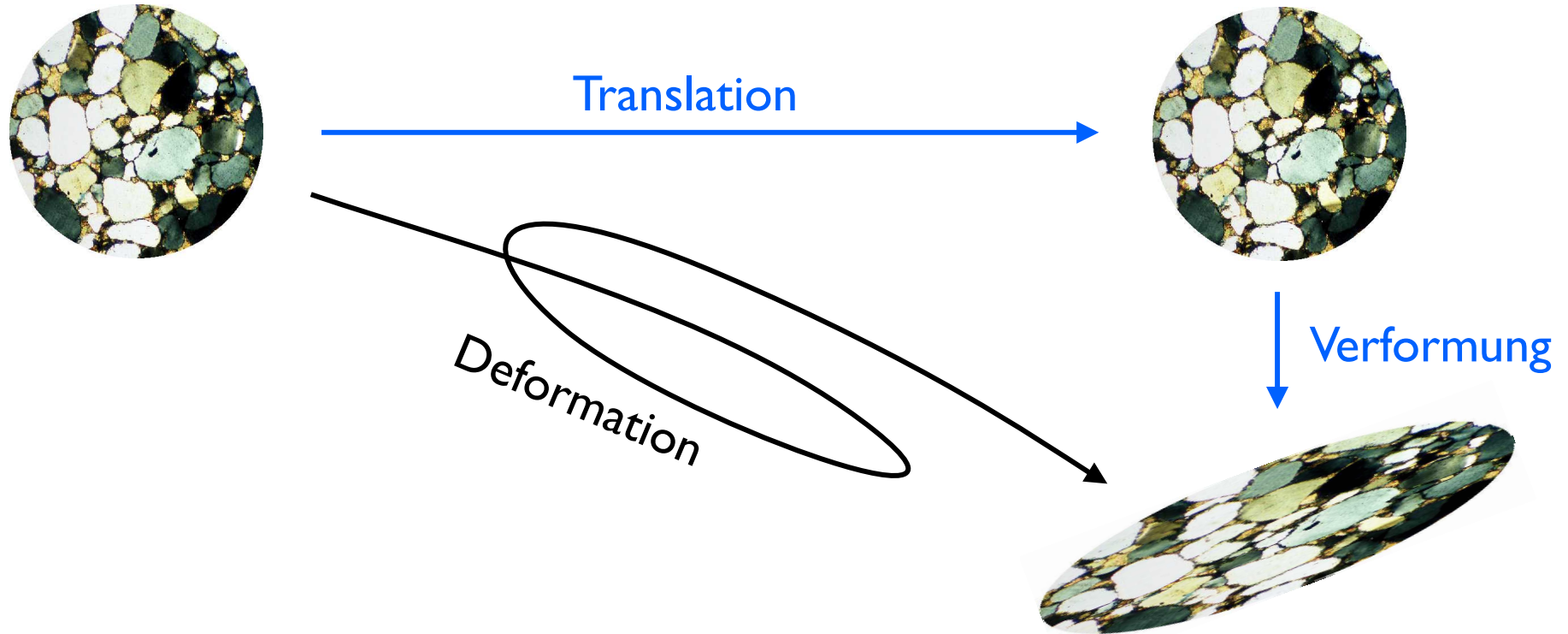
siehe Teil I der Vorlesung



**Strain**

# Deformations - Zustand

Deformation: Translation + Verformung (displacement + strain)



Strain: Dehnung / Verkürzung  
Rotation (CLW - CCLW)  
Scherung (sinistral - dextral)

Dimension: Länge / Länge = dimensionslos

# Strain ID

$L_0$  unverformt

$L'$  verformt

Längenänderung

$$\Delta L = L' - L_0$$

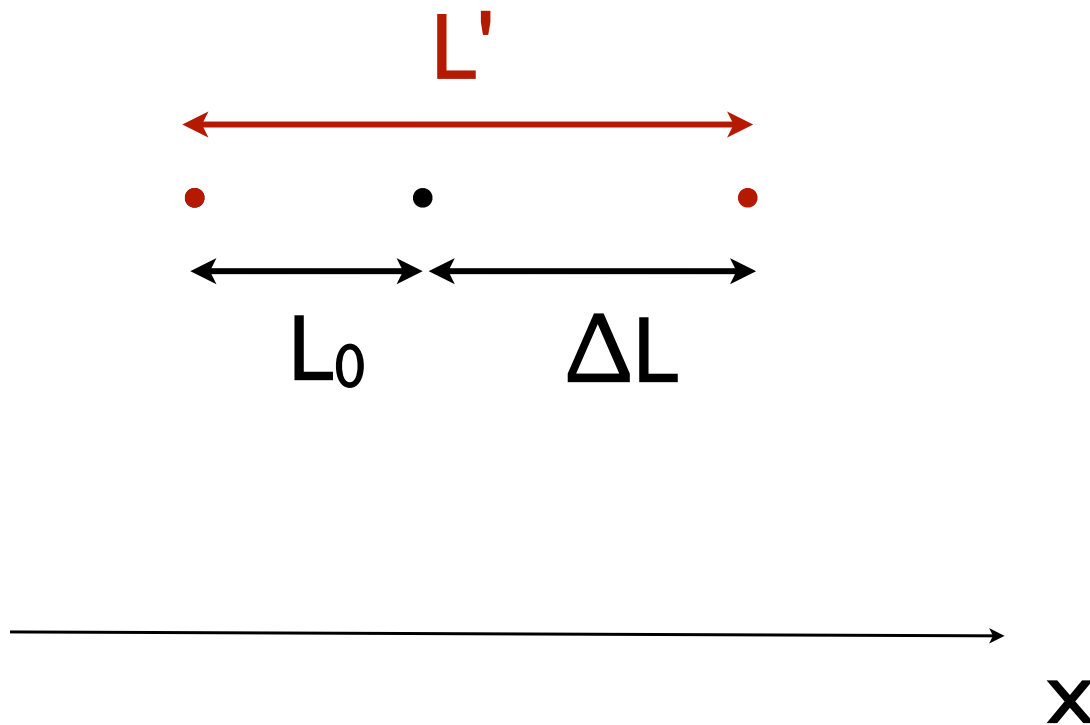
Extension

$$\varepsilon = \Delta L / L_0$$

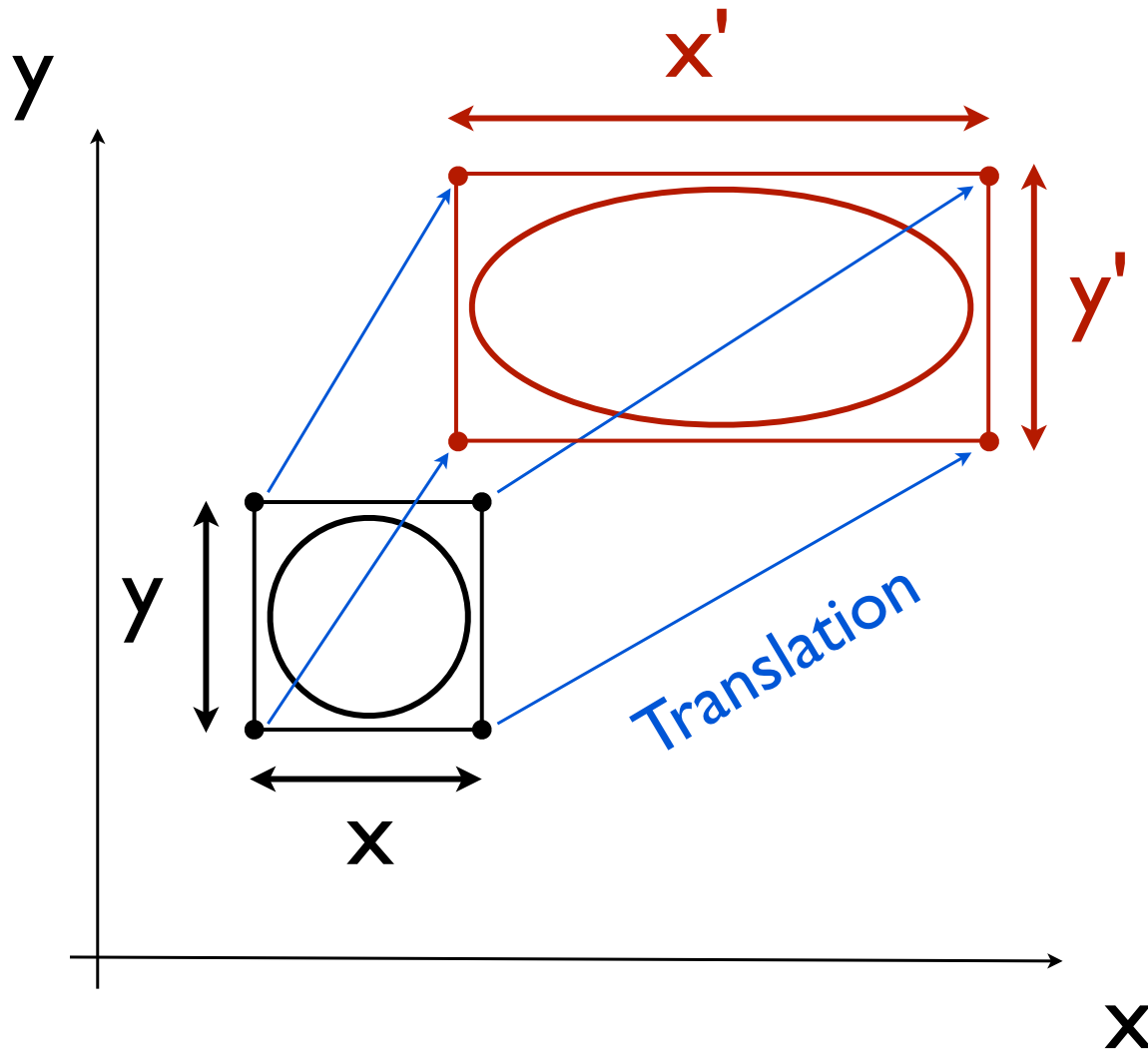
(dimensionslos)

$\varepsilon > 0$  Streckung

$\varepsilon < 0$  Verkürzung



# Strain 2D



$x, y$  unverformt  
 $x', y'$  verformt

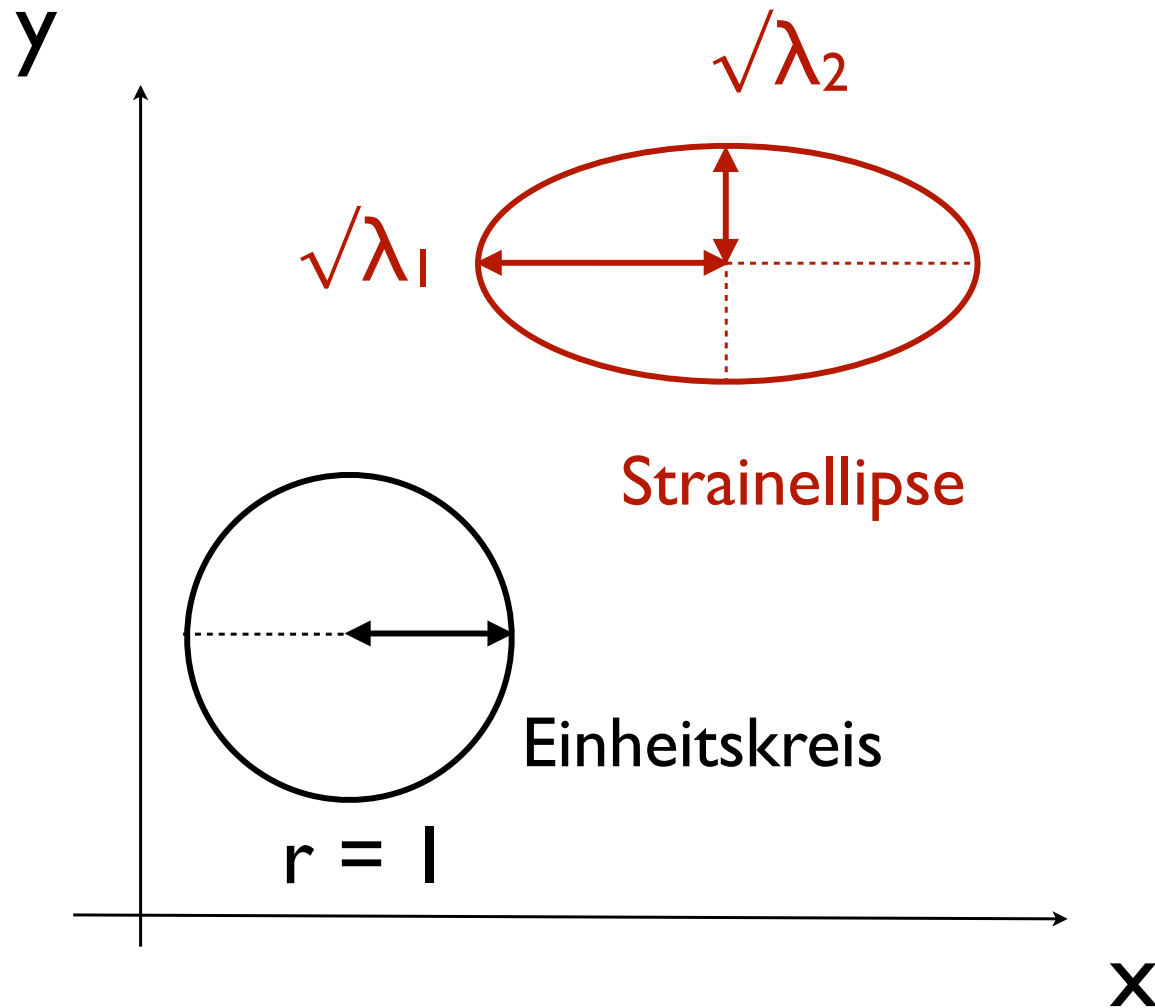
Extension

$$\epsilon_x = \Delta x / x$$

$$\epsilon_y = \Delta y / y$$

Translation ist in der Regel nicht messbar - Längenänderungen sind messbar

# Strain 2D - Strainellipse



Extension

$$\varepsilon = \Delta L / L_0$$

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

quadratische Elongation

$$\lambda_1 = (1 + \varepsilon_1)^2$$

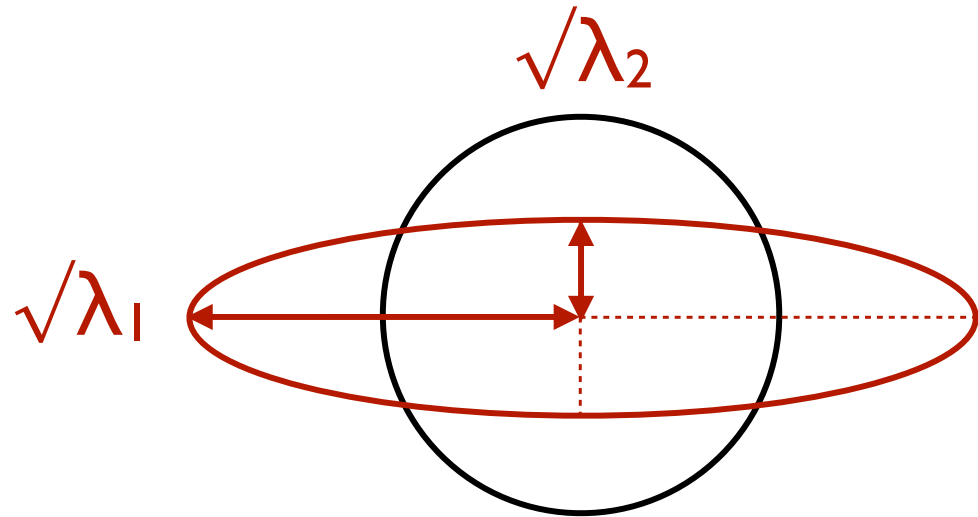
$$\lambda_2 = (1 + \varepsilon_2)^2$$

$$\lambda_1 > \lambda_2$$

$\lambda > 1$  Streckung

$\lambda < 1$  Verkürzung

# Achsenverhältnis $R_f$ (long/short)



Beispiel:

$$\sqrt{\lambda_1} = 2.0$$

$$\sqrt{\lambda_2} = 0.5$$

$$R_f = a/b = 4.0$$

$R_f$  finite strain ratio

Ellipsenachsen

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

Achsenverhältnis

$$R_f = \sqrt{\lambda_1} / \sqrt{\lambda_2} = a / b$$

$a, b$  = lange, kurze Achse

$$R_f \geq 1.00$$

flächenkonstante Verformung

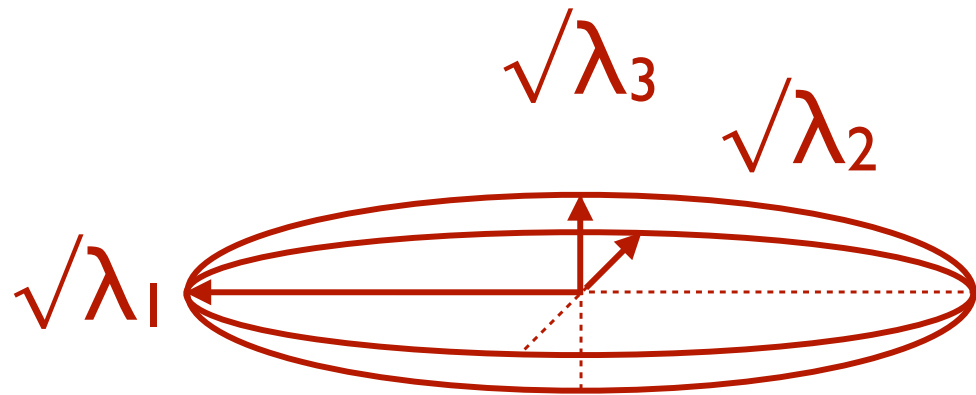
$$\Delta A = 0:$$

$$\sqrt{\lambda_1} \cdot \sqrt{\lambda_2} = 1$$

$$\sqrt{\lambda_2} = 1 / \sqrt{\lambda_1}$$

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

# Strain 3D - Strainellipsoid



Beispiel:

$$\sqrt{\lambda_1} = 2.0$$

$$\sqrt{\lambda_2} = 1.0$$

$$\sqrt{\lambda_3} = 0.5$$

$$R_f = a/b = 4.0$$

$R_f$  finite strain ratio

Ellipsenachsen

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

Plain strain

$$\sqrt{\lambda_2} = 1$$

volumenkonstante Verformung

$$\Delta V = 0$$

$$R_f = \sqrt{\lambda_1} / \sqrt{\lambda_3}$$

$$\sqrt{\lambda_1} \cdot \sqrt{\lambda_3} = 1$$

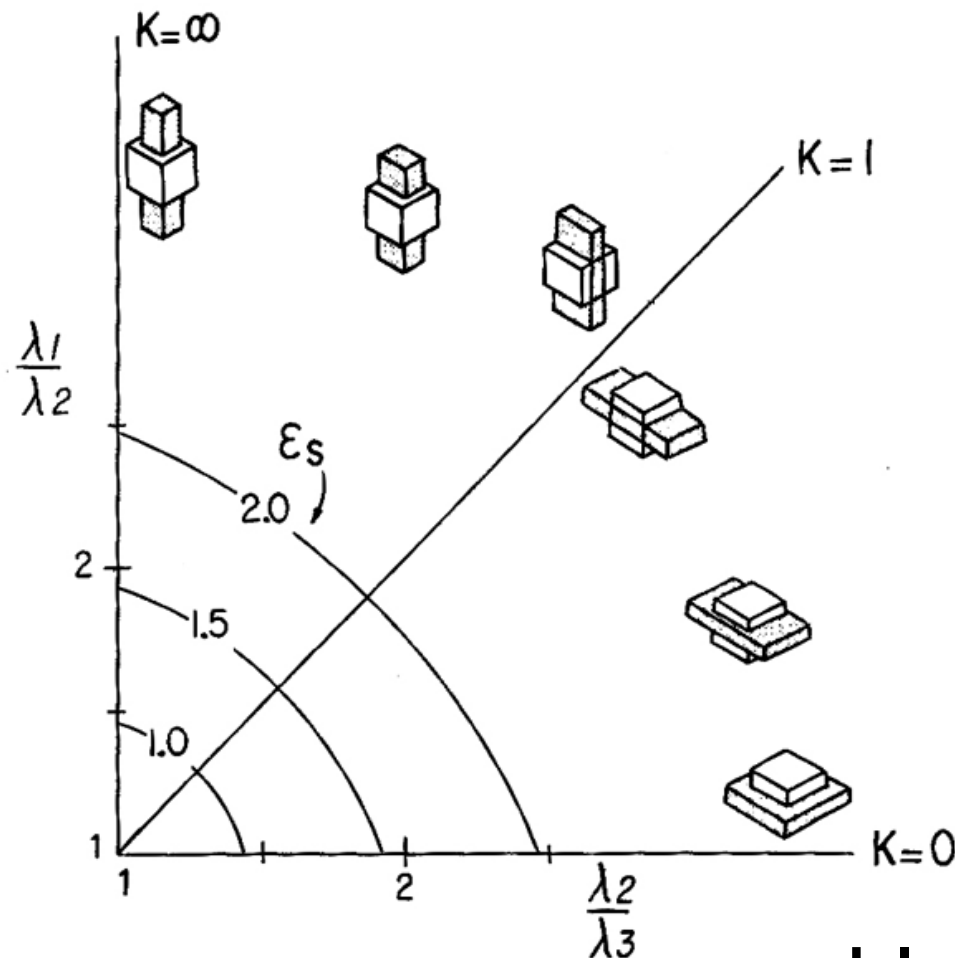
$$\sqrt{\lambda_3} = 1 / \sqrt{\lambda_1}$$

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

# Strain 3D Flinn - Diagram finite strain

prolate "Zigarren"

symmetrische Streckung  
constrictional strain  
 $k = \infty \Rightarrow l + e_2 = l + e_3$



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

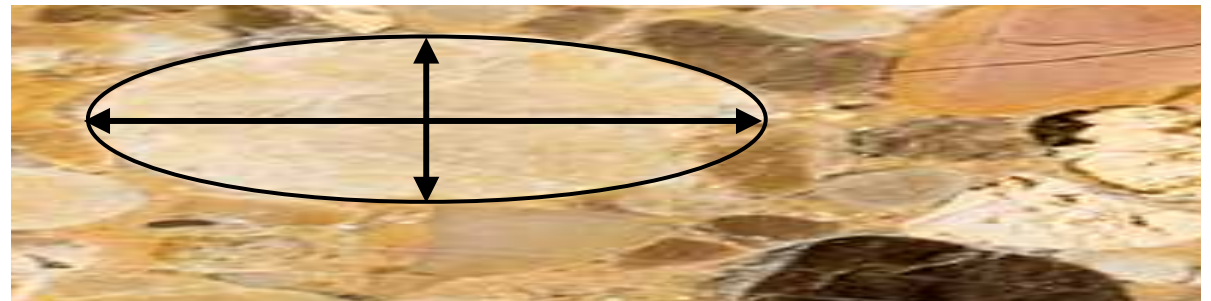
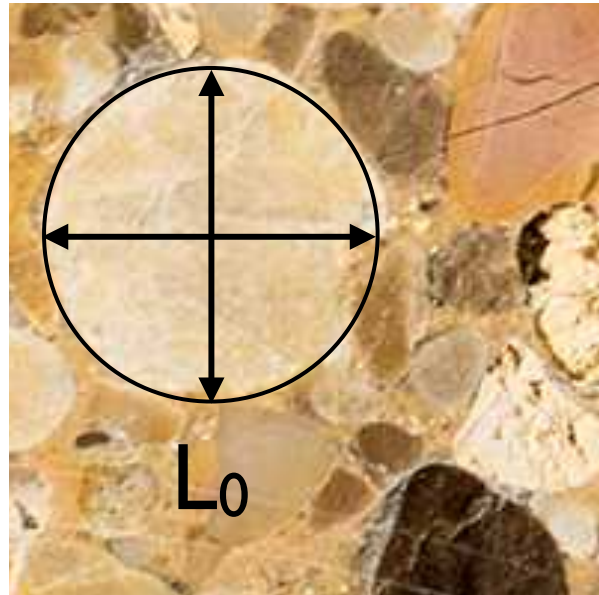
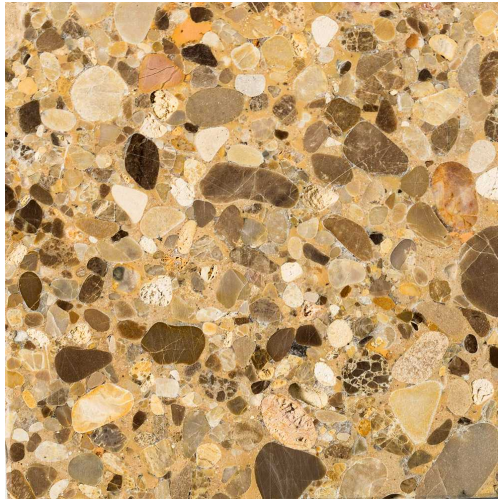
symmetrische Plättung  
flattening strain  
 $k = 0 \Rightarrow l + e_1 = l + e_2$

$\epsilon_s$  = strain magnitude

oblate "Pfannkuchen"

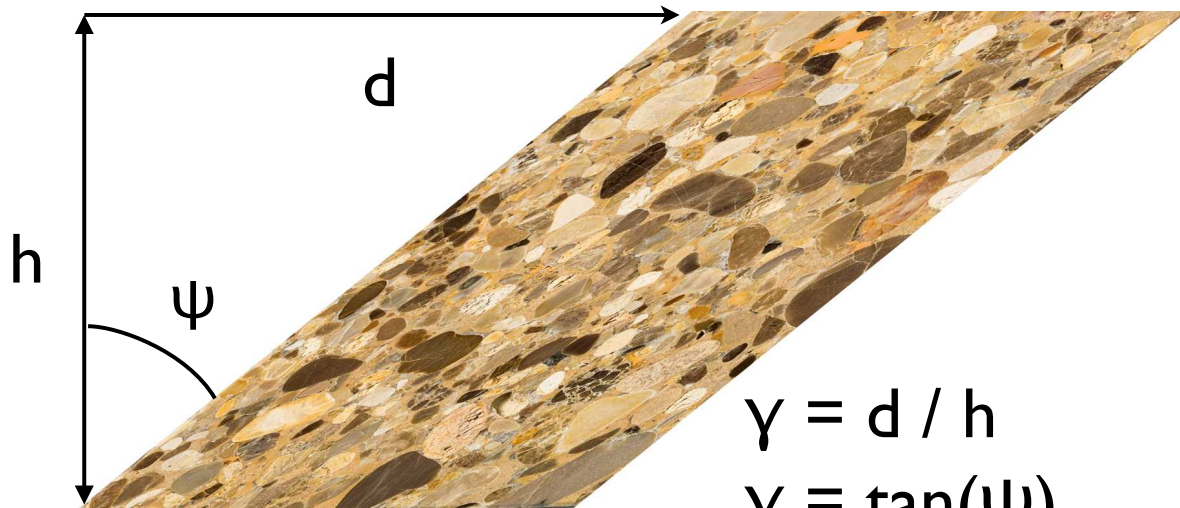
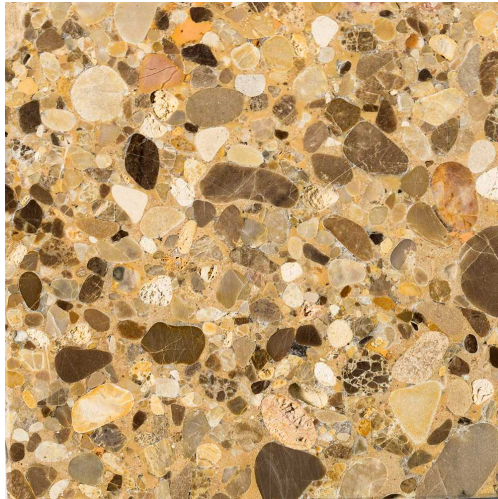


# Reine Scherung - pure shear

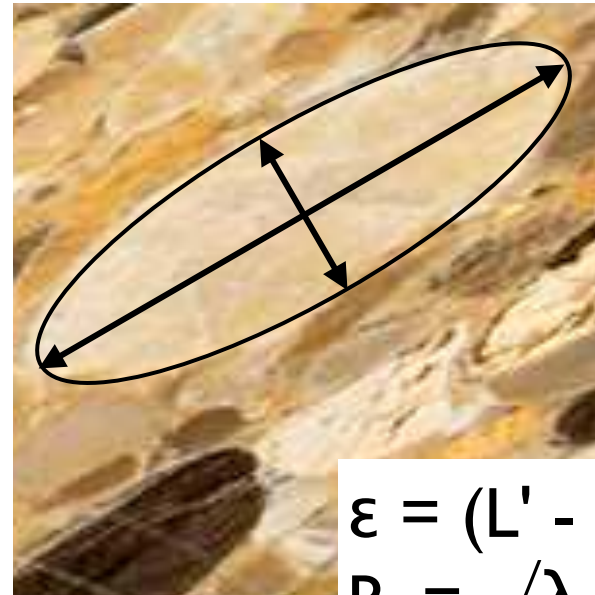
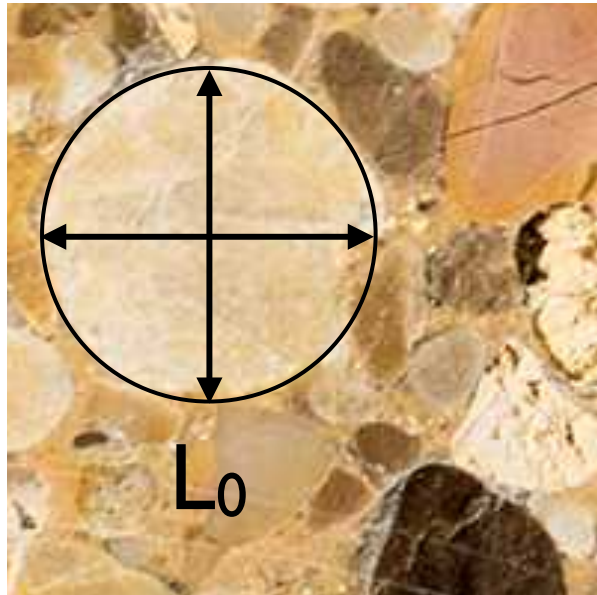


$$\varepsilon = (L' - L_0) / L_0 = \Delta L / L_0$$
$$R_f = \sqrt{\lambda_1} / \sqrt{\lambda_2} = a / b$$

# Einfache Scherung - simple shear

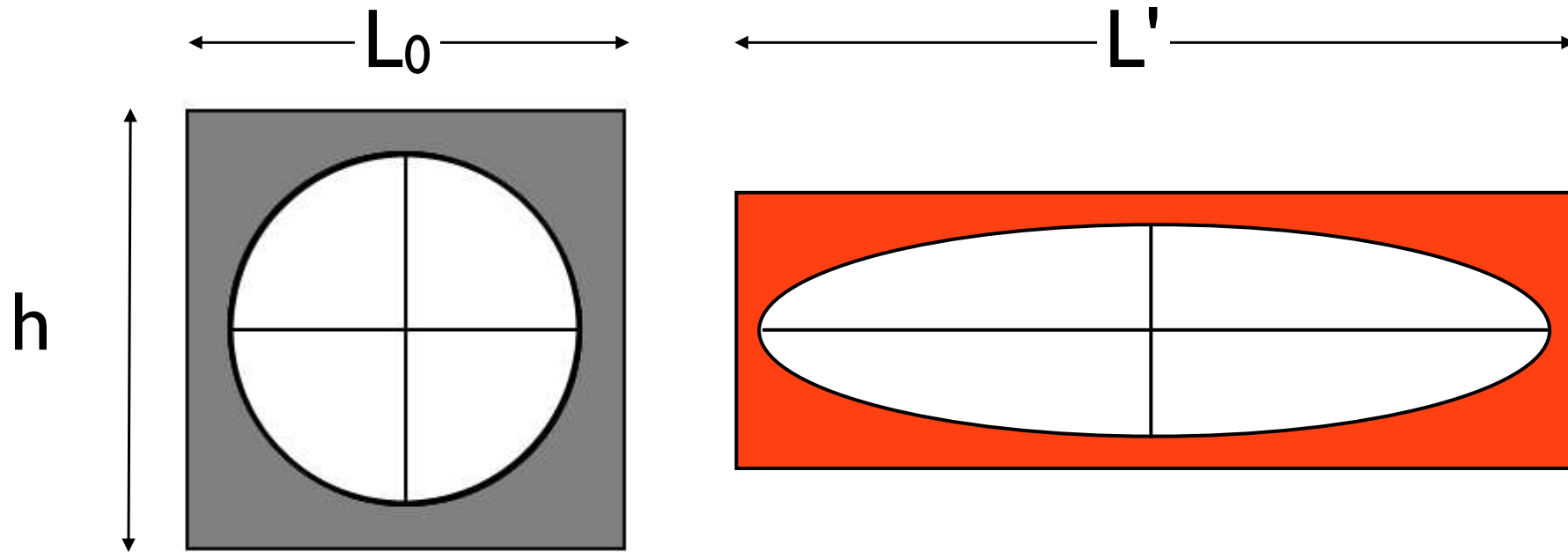


$$\gamma = d / h$$
$$\gamma = \tan(\psi)$$



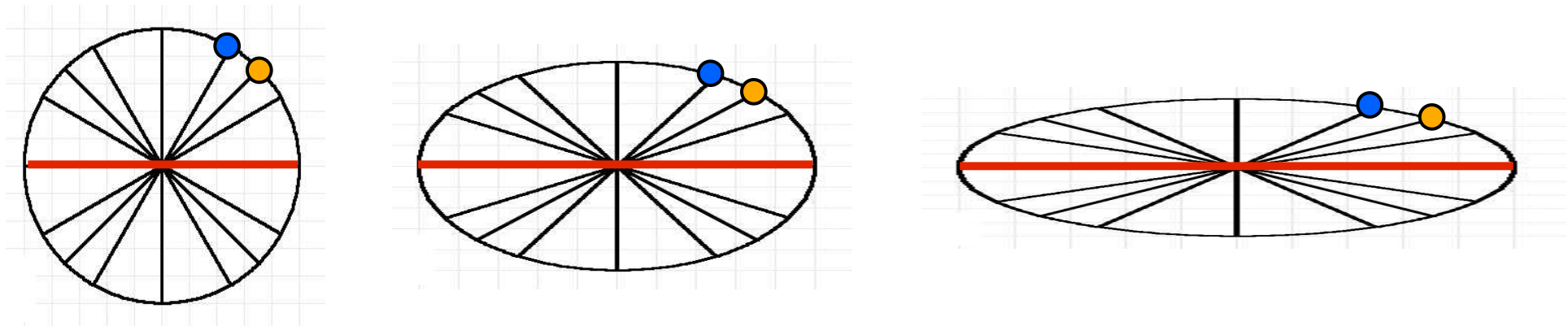
$$\epsilon = (L' - L_0) / L_0 = \Delta L / L_0$$
$$R_f = \sqrt{\lambda_1} / \sqrt{\lambda_2} = a / b$$

# Reine Scherung - koaxial



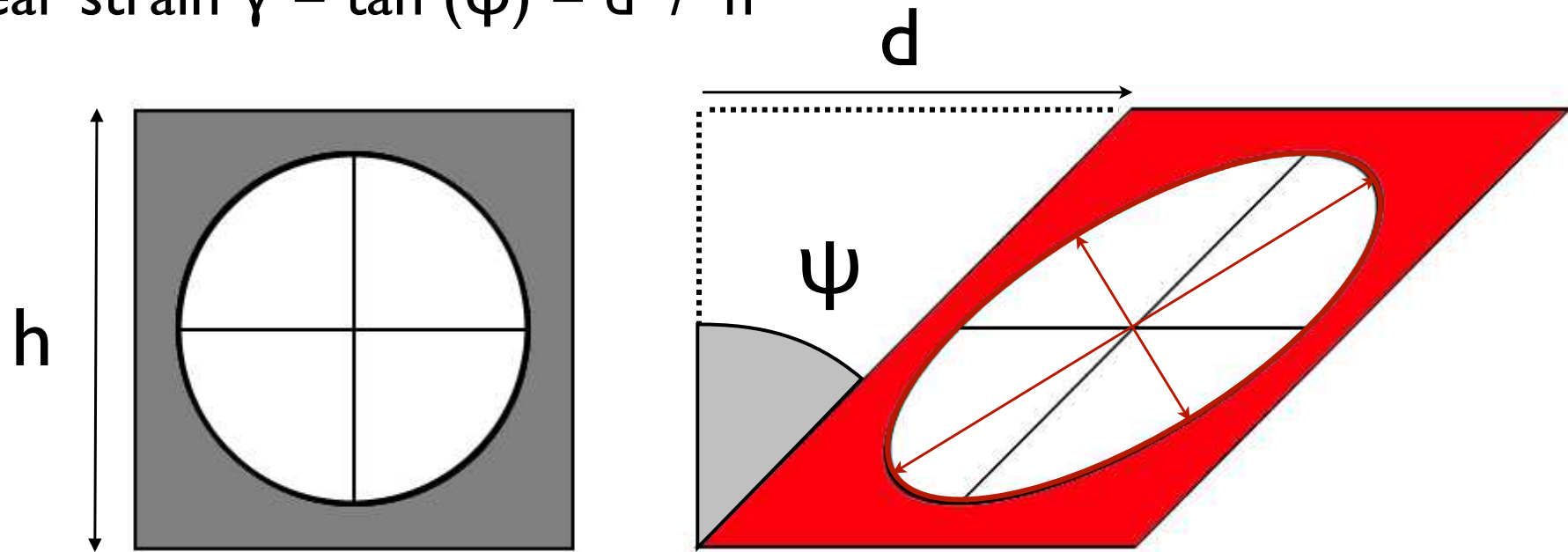
Achsen der Strainellipse

- rotieren nicht
- sind Materiallinien

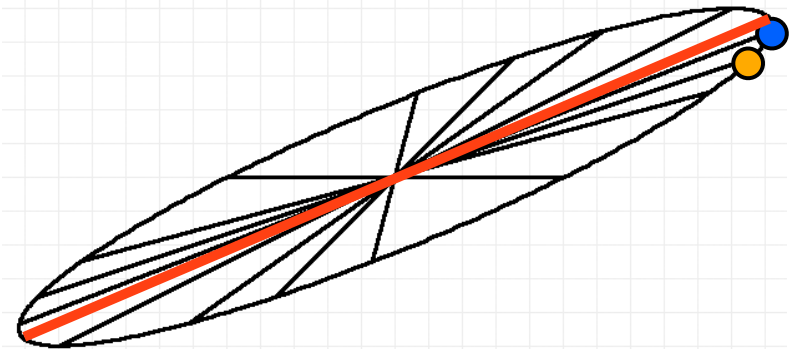
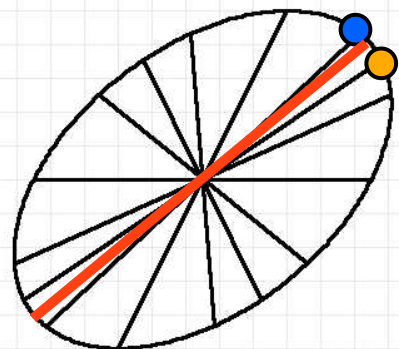
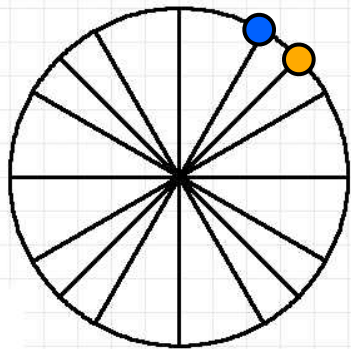


# Einfache Scherung - rotational

shear strain  $\gamma = \tan(\psi) = d / h$

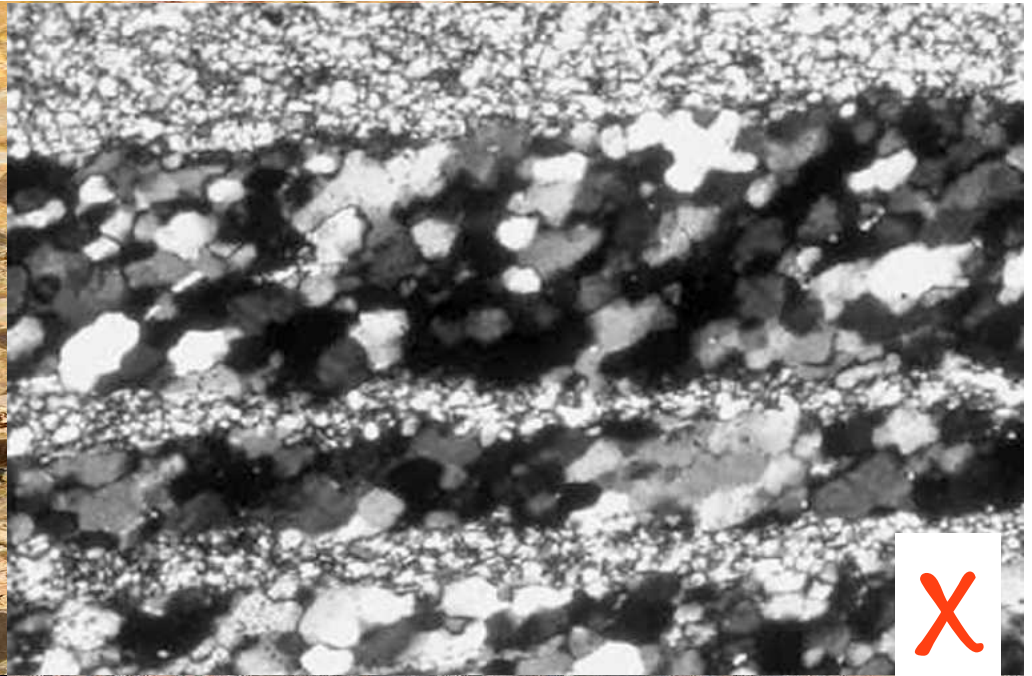


Achsen der Strainellipse • rotieren langsamer als Materiallinien  
• sind keine Materiallinien

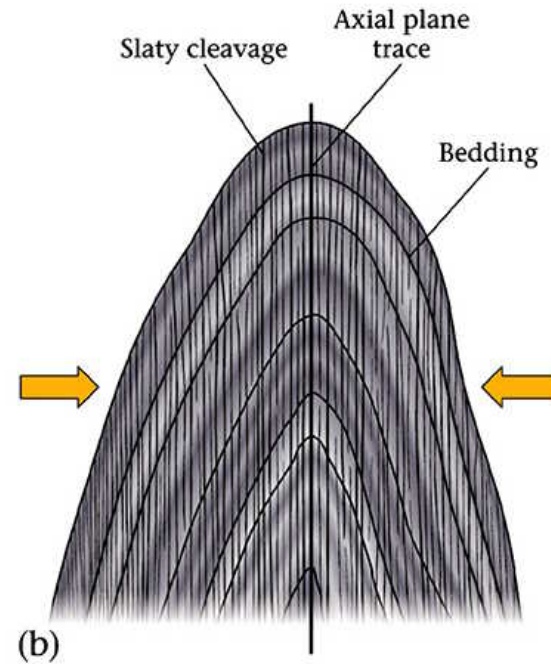
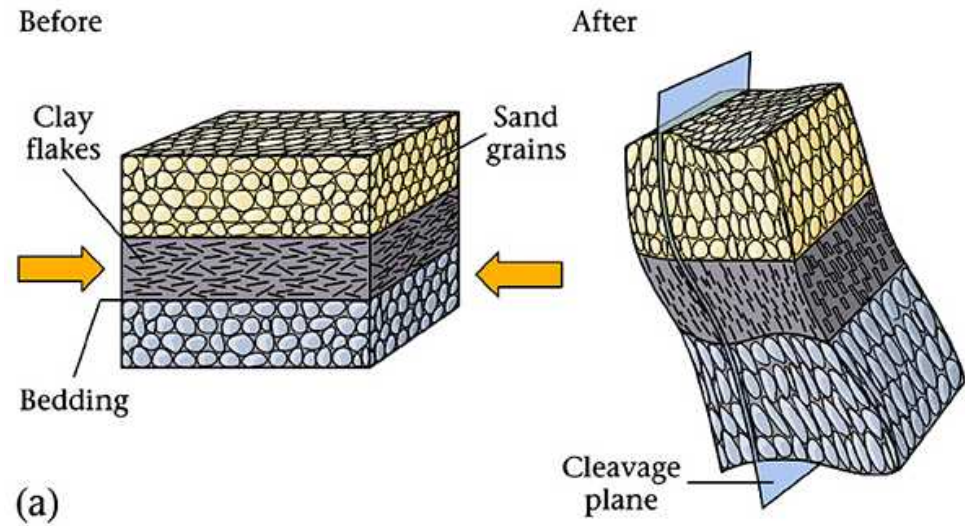
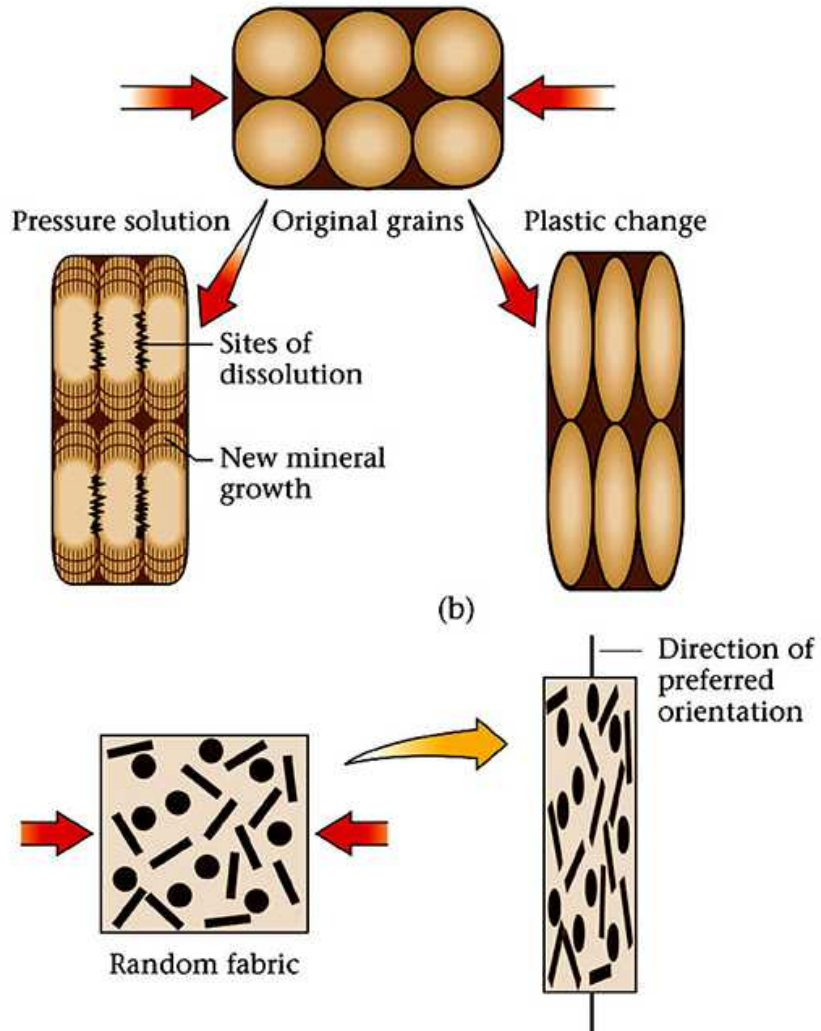


# Strainmessung

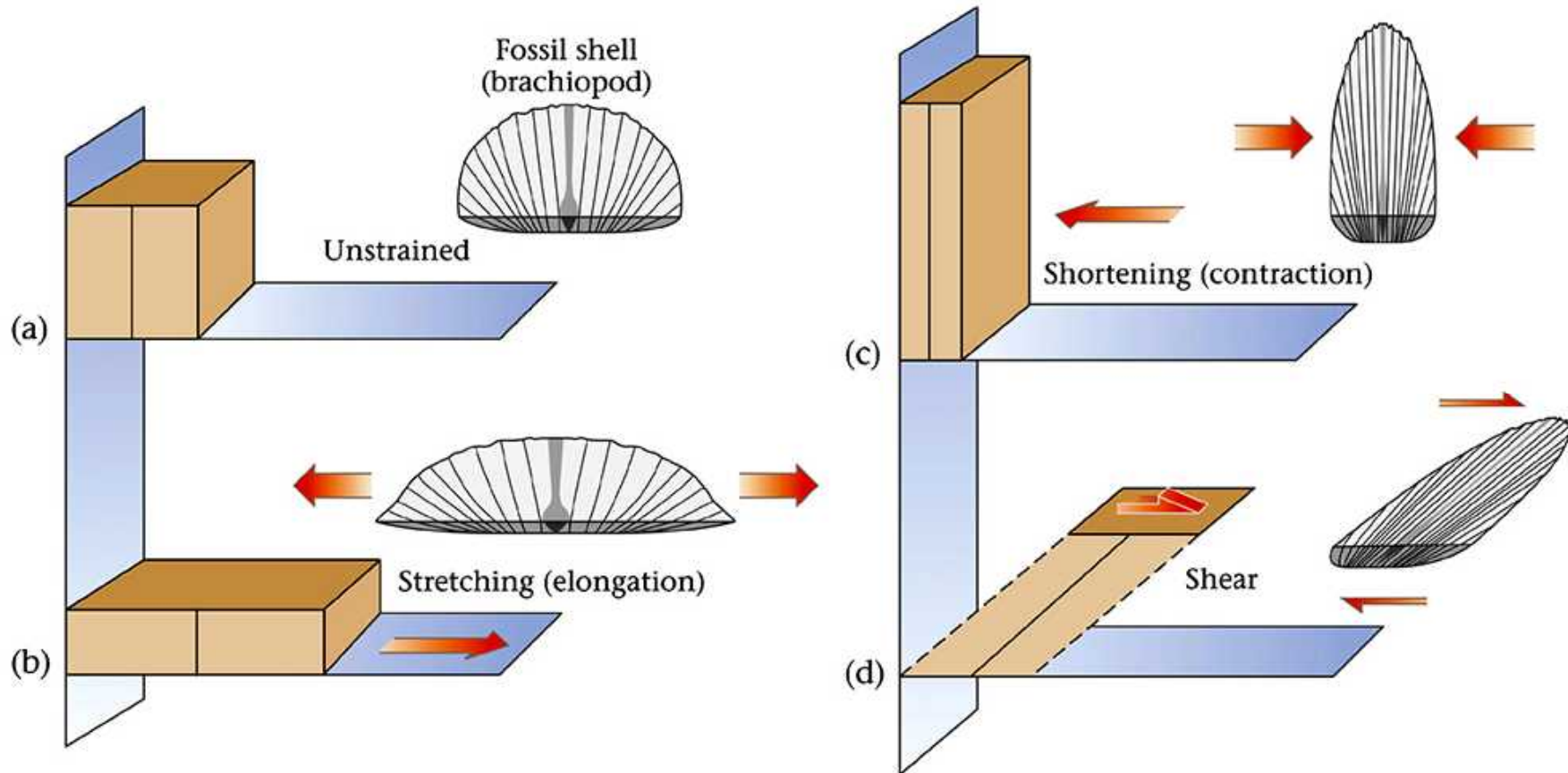
# Strain marker ?



# Strain marker



# Strainmessung

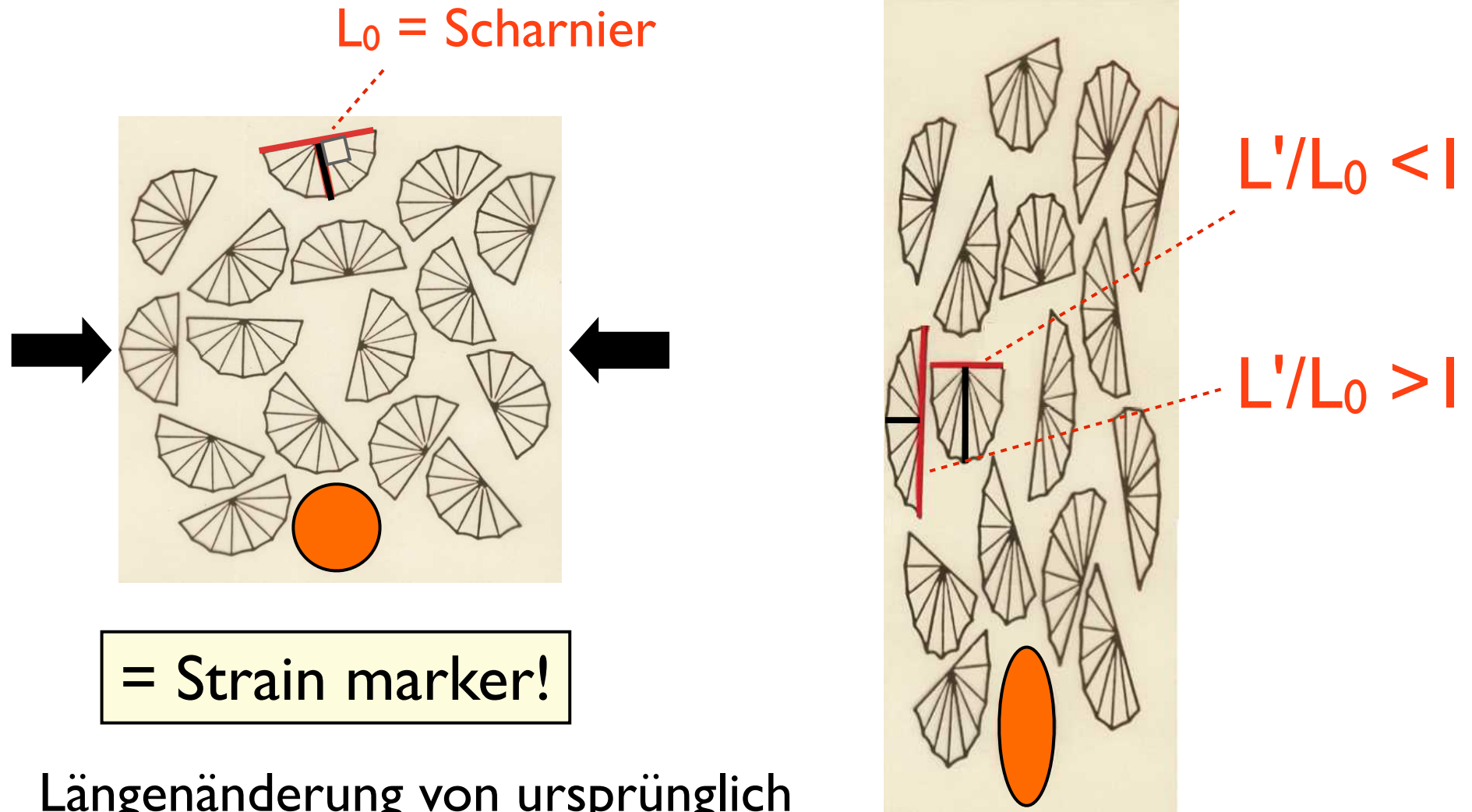


Was ist messbar?  
Längenänderung  
Winkeländerung  
⇒ Strainellipse

Im allgemeinen nicht messbar ist,  
ob Verformung durch  
reine Scherung oder  
einfache Scherung !



# Achsen verformter Objekte messen

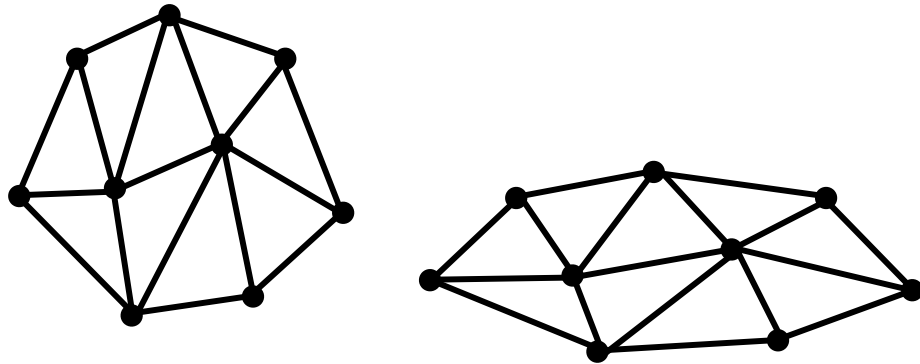


= Strain marker!

Längenänderung von ursprünglich zueinander senkrechten Linien, die wieder senkrecht sind.

# Abstandsänderung messen

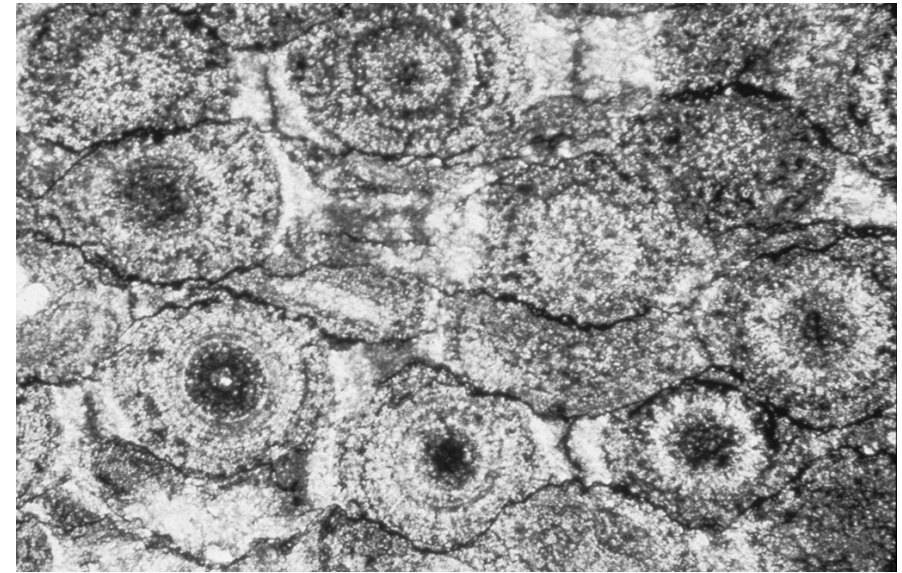
im Feld / Handstück / Dünnschliff  
Mittelpunktgerüst wird geplättet



= Strain marker!

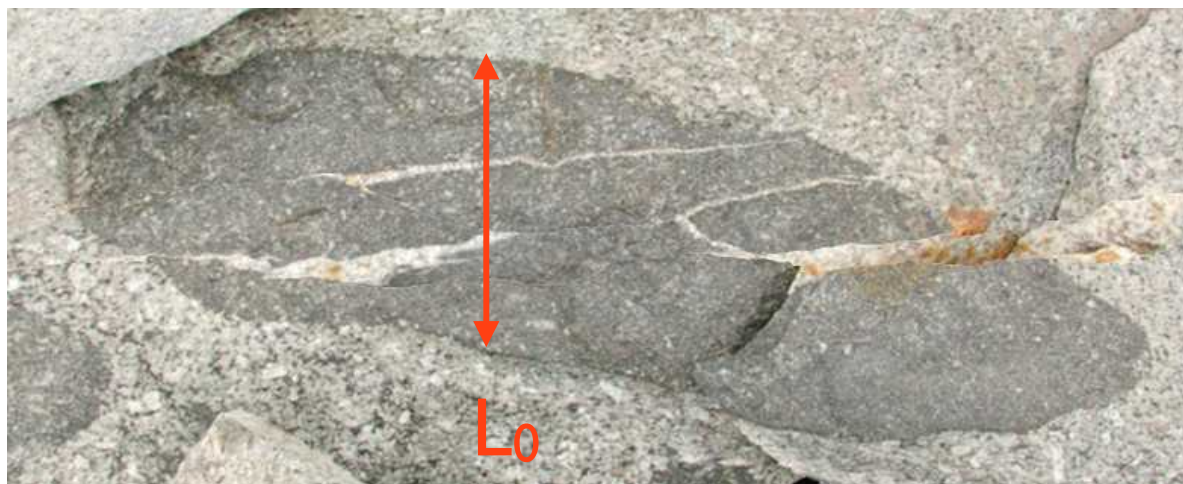
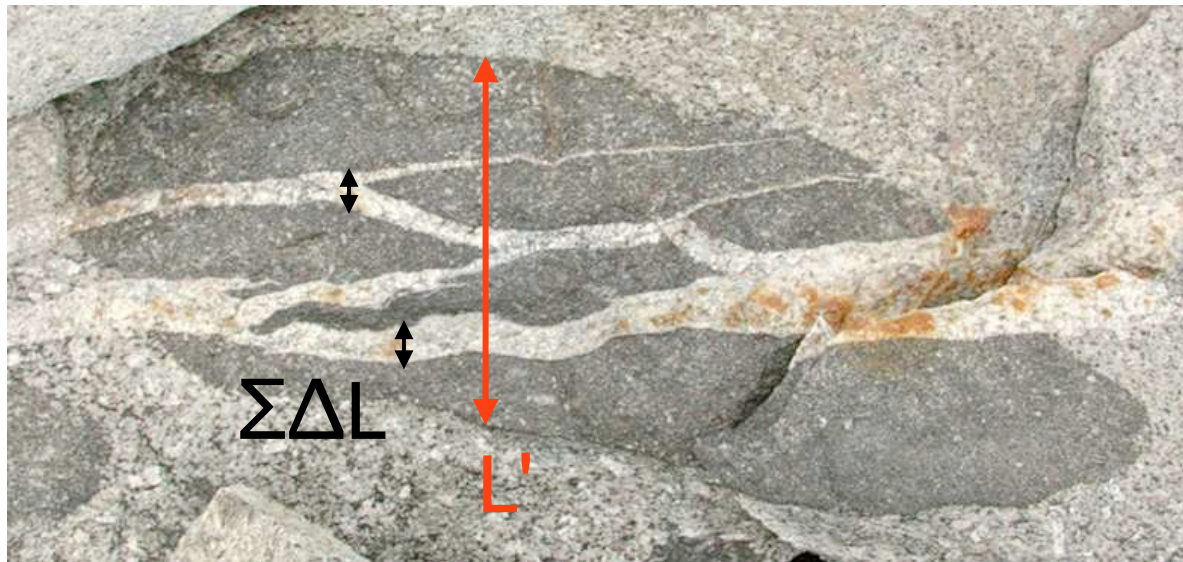
Ursprüngliches Gitter ist bekannt  
Mittelpunkte nachher erkennbar

Vorgehen:  
verformte Mittelpunkte plotten  
Strain Ellipse berechnen



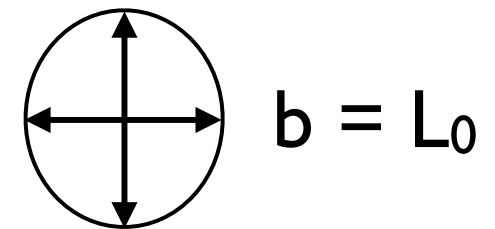
# überlagerte Verformung

1. Plättung
2. Streckung durch Zerbrechen



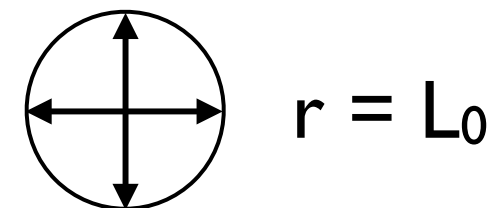
Letzte Deformation  
zuerst

$$a = L'$$



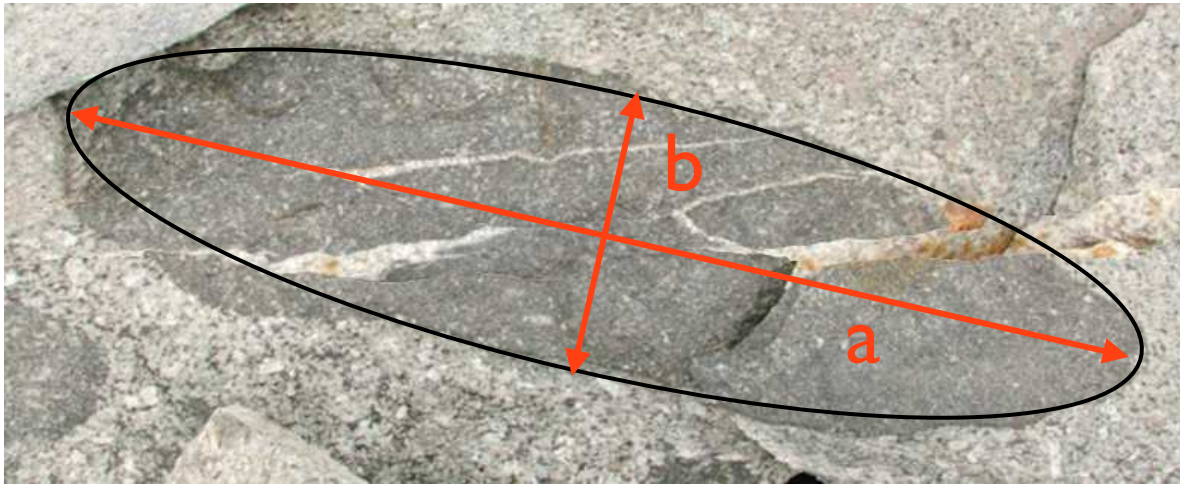
Längenänderung  
 $\Delta L$  messbar

Schliessen der  
Klüfte

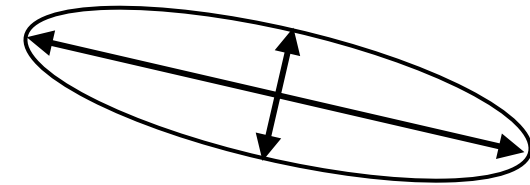


# überlagerte Verformung

geplätteter Kiesel vor Zerbrechen:

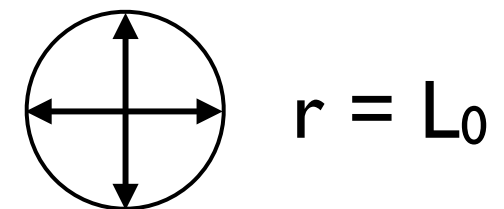


$$R_f = a/b$$



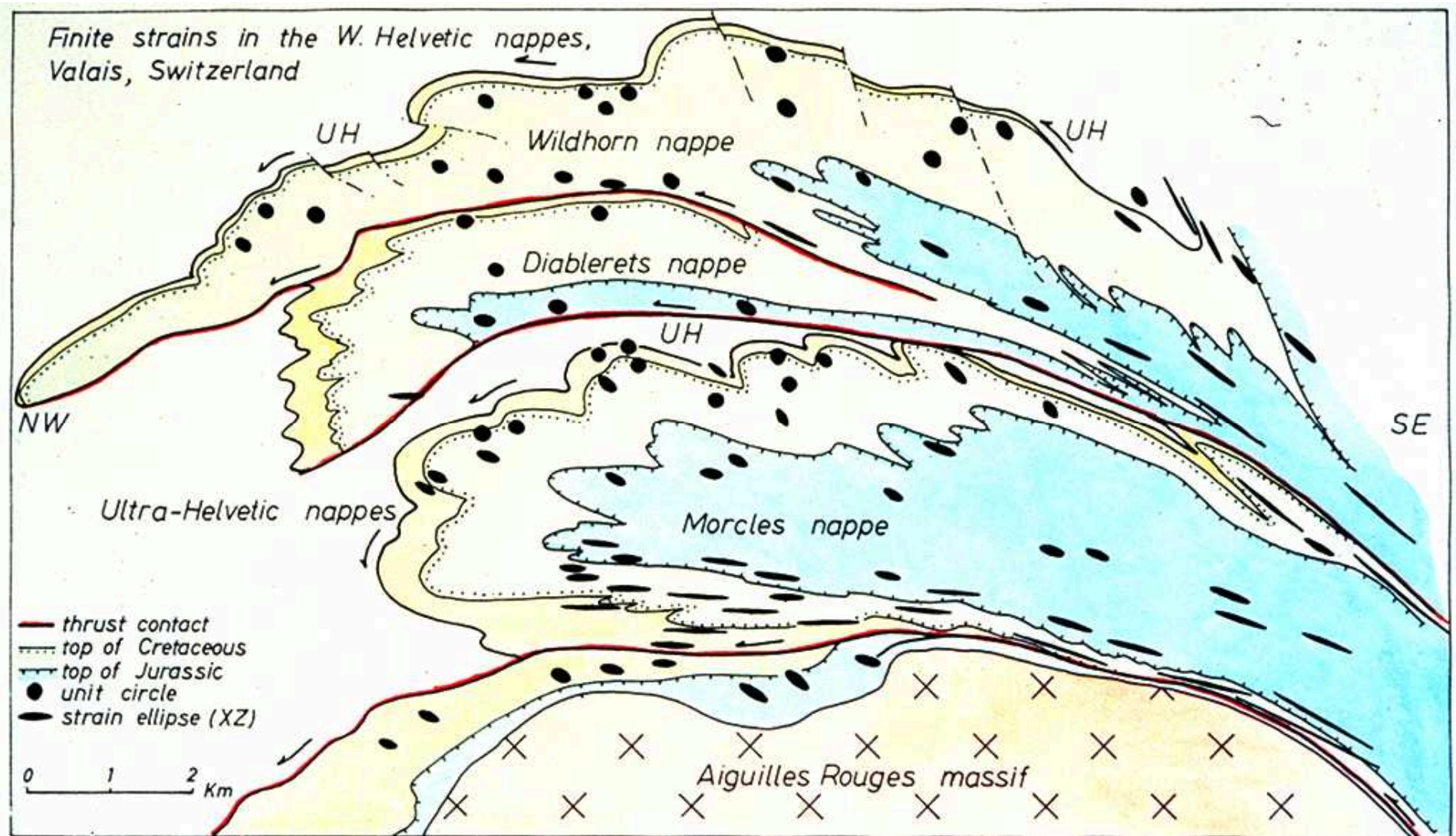
Formänderung  
a/b messbar

Volumenkonstanz  
& runde Form  
angenommen



$$r = L_0$$

# Heterogene Verformung



Strainmessung an Ooiden in Helvetischen Decken

# Geologischer Atlas 1: 25'000



# Morcles - Decke

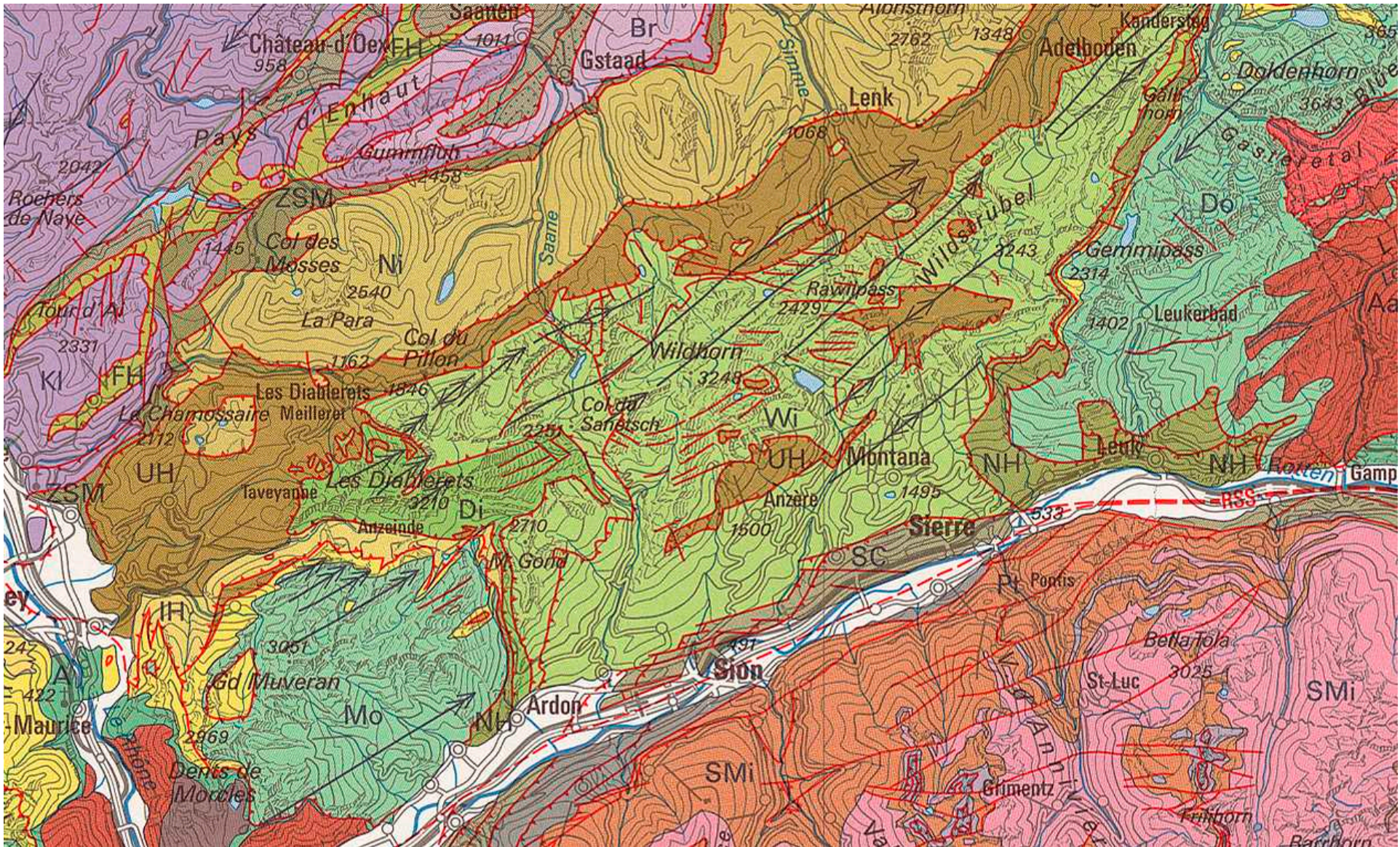
swisstopo <https://map.geo.admin.ch/>



**Helvétique**  
(Autochtones; nappe de Morcles et ses racines)

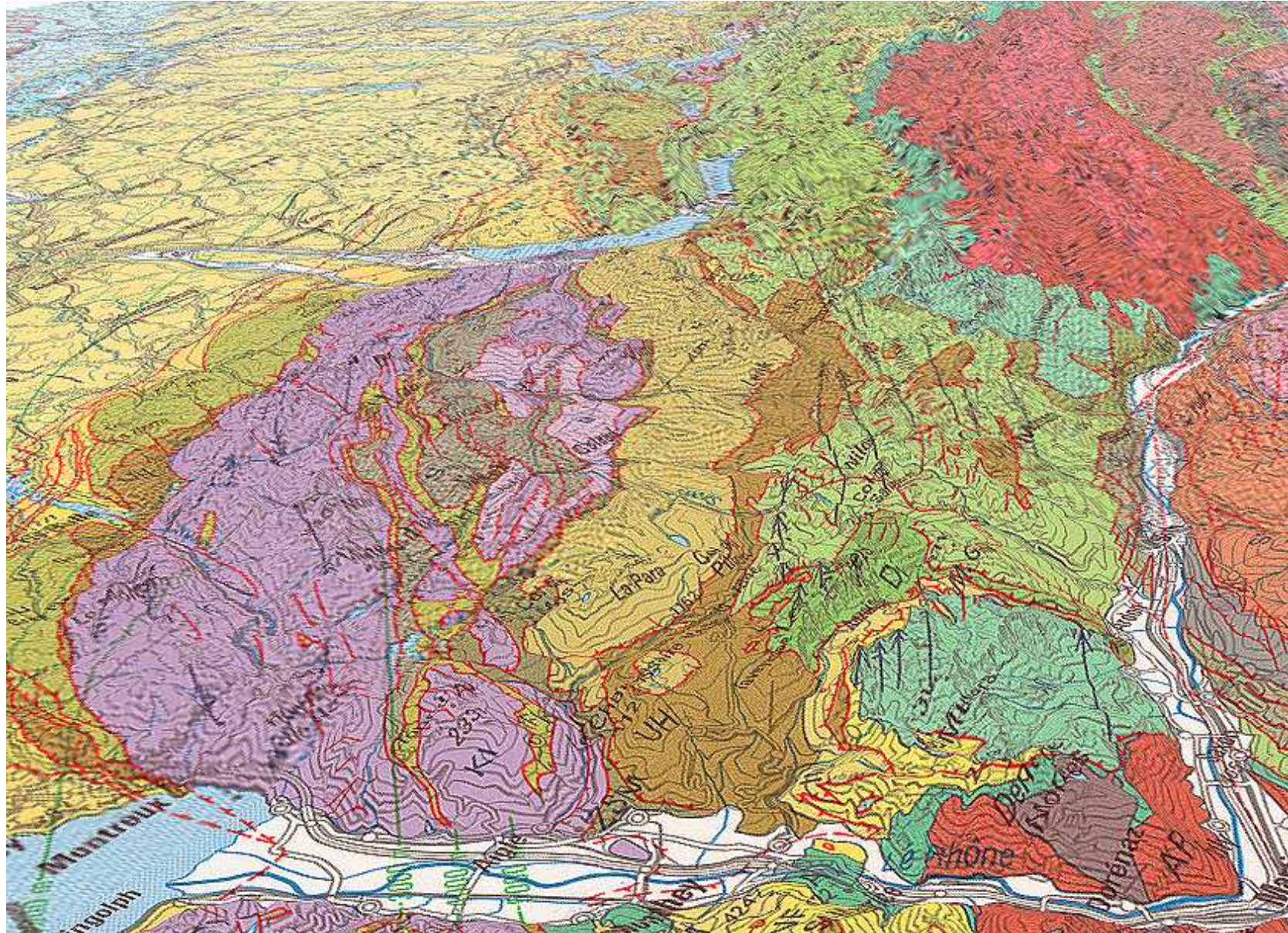
Stratigraphic Unit	Description
Tertiaire (Nummulitique)	(?) Eocène sup. – Oligocène inf.: Flysch paraautochtone Principaux niveaux de grès
	Priabonien: Marnes à Globigérines
	Priabonien: Calcaire à petites Nummulites Avec blocs et lentilles de: <ul style="list-style-type: none"> <li>Crétacé</li> <li>Trias</li> <li>Malm</li> </ul>
Crétacé	Priabonien: Couches à Vivipares et à Corithos
	(?) Priabonien inf. («Auversien»): Couches du Roc Champion
	Albien – Cénomannien; Crétacé sup.: Schistes gréseux; alternance de schistes et de calcaires
	Aptien supérieur: Schistes gréseux et calcaires
	«Urgonien» (Barrémien sup. – Aptien inf.): Calcaires massifs clairs
	Barrémien inférieur: Alternance de marnes et de calcaires
	Hauteriviens: Calcaire siliceux
	Valanginien (calcaire): Calcaires massifs prédominants
	Portlandien sup. – Valanginien (Valanginien schisteux): Alternance de marnes et de calcaires argileux
	Malm
Argovien: Calcaires gris lites	
Callovo-Oxfordien: Marnes schisteuses Doitha ferrugineuse calcaire	
Bathonien: Calcaires et schistes sombres	
Dogger	Bajocien – Bathonien (?) [autochtones]: Calcaire massif transgressif
	Bajocien supérieur [nappe de Morcles]: Calcaires siliceux
	Bajocien inférieur [nappe de Morcles]: Alternance de schistes marneux et de calcaires siliceux
Lias	Aalénien: Schistes argileux sombres
	Toarcien (partie supérieure): Schistes foncés
	Toarcien: Schistes avec bancs calcaires
	Lias moyen: Alternance de calcaires et de marnes
	Lotharingien: Grès siliceux
Trias	Hettangien – Sinémurien: Schistes et calcaires à <i>Schabheimia</i> et à <i>Arietites</i>
	Rhétien: Alternance de quartzites, schistes et calcaires
	Trias supérieur: Calcaire dolomitique
	Trias supérieur: Argilles ou schistes bigarrés
	Trias supérieur: Grès à claires
Trias moyen (?): Cornouais	
Trias inférieur: Quartzites, arkoses	

# Tektonische Karte 1:500'000





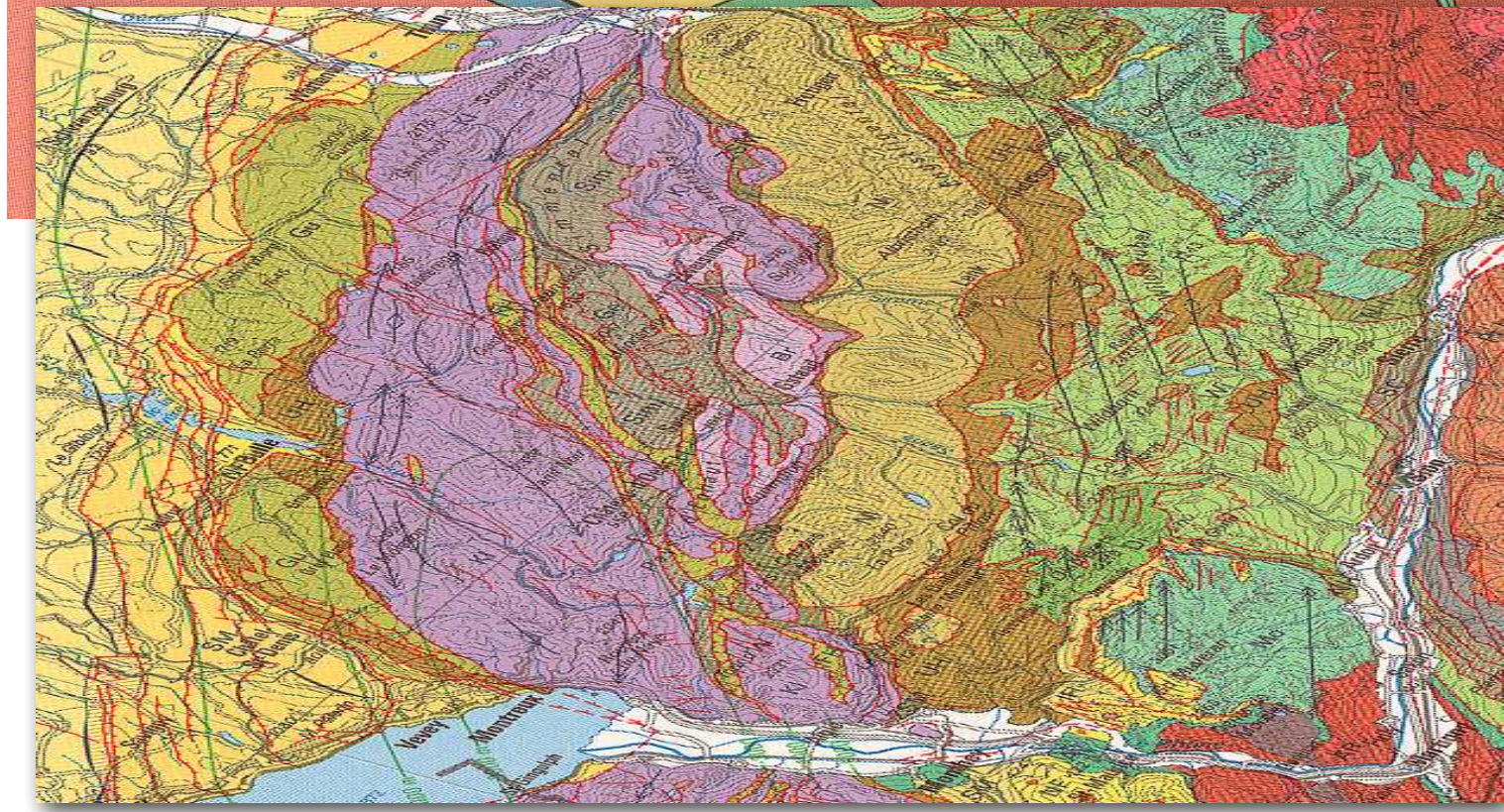
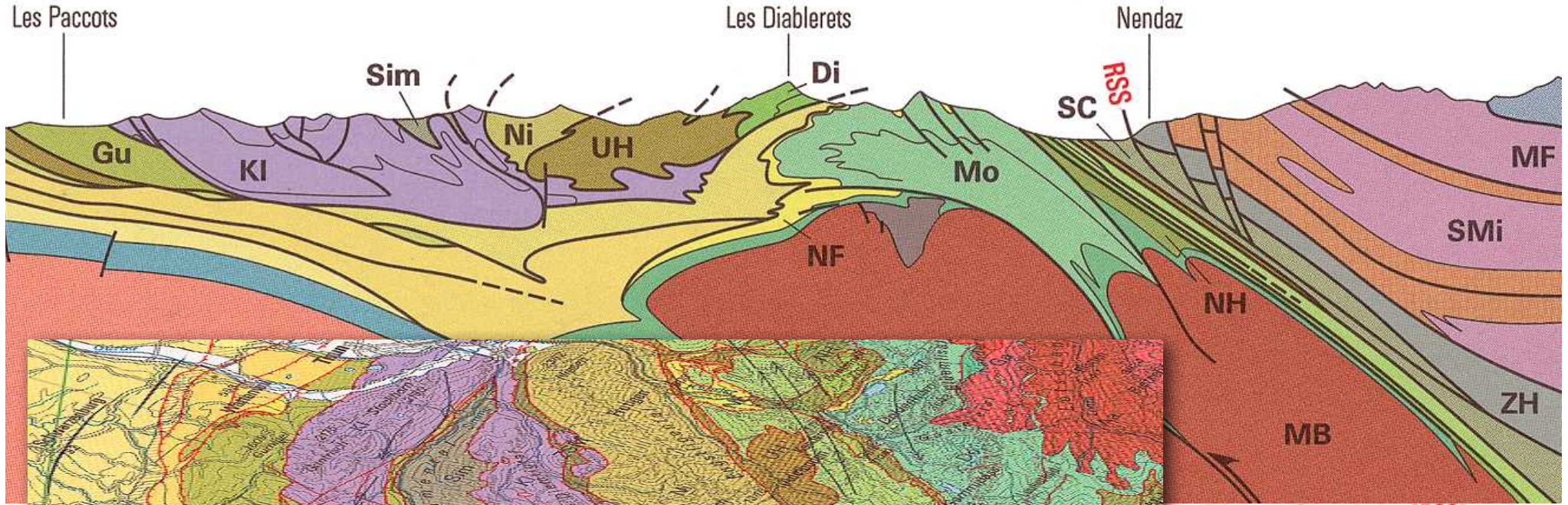
# Tektonische Karte 1:500'000



**Penninische Sedimentdecken**  
*Nappes de sédiments penniques*

**Helvetische Sedimentdecken**  
*Nappes de sédiments helvétiques*

**Penninische Sediment-  
und Kristalldecken**  
*Nappes de sédiments et  
de cristallin penniques*









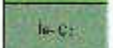
Rhone-Simplon- [RSS]

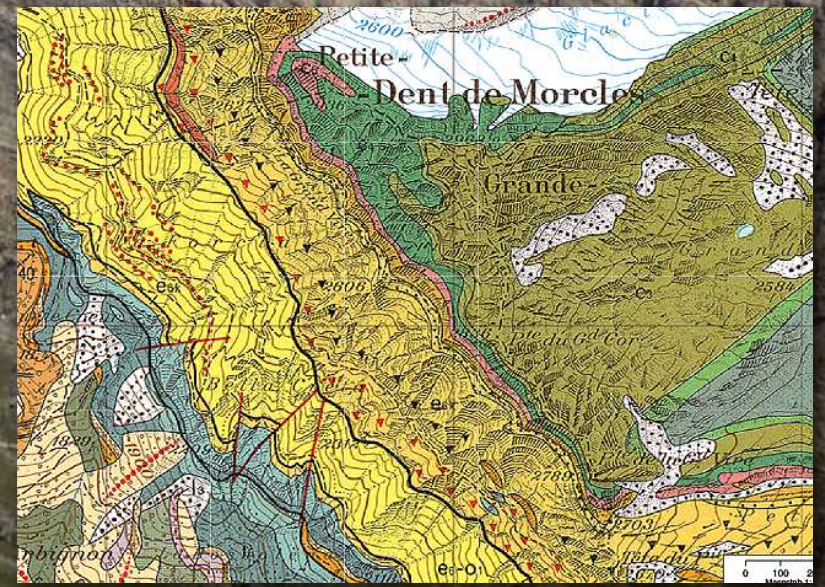
# Dent de Morcles



Aptian

Urgon

Crétacé		Albien – Cénomaniens; Crétacé sup.: Schistes gréseux; alternance de schistes et de calcaires
		Aptien supérieur: Schistes gréseux et calcaires
		«Urgonien» (Barrémien sup. – Aptien inf.): Calcaires massifs clairs
		Barrémien inférieur: Alternance de marnes et de calcaires
		Hauterivien: Calcaire siliceux
		Valanginien (calcaire): Calcaires massifs prédominants
		Portlandien sup. – Valanginien (Valanginien schisteux): Alternance de marnes et de calcaires argileux



# 5 Kinematik (Deformation als Bewegung)

## Deformationsanzeiger

- Spöddeformation
- plastische Deformation

## Mikrostrukturen

- typisch für Extension
- typisch für strike slip
- Scherzonen
- typisch für Verkürzung

## Geol. Geschwindigkeiten / Verformungsraten

- Berechnung
- Lokalisierung

# Deformation

## 1 Deformations - Zustand:

finite Verformung:  $e_1, e_2, e_3, \lambda_1, \lambda_2, \lambda_3$

verformter Zustand relativ zum unverformten Zustand

Geometrie

## 2 Deformations - Bewegung:

Veränderung der Form durch die Zeit

displacement rate:  $\dot{d}$  (m/s, km/Ma,...)

strain rate:  $\dot{\epsilon}$  ( $s^{-1}$ )

Kinematik

## 3 Deformations - Prozess:

Elastisches, visköses Verhalten (Kristallplastizität, Fließgesetze) als Reaktion auf Druck, Spannung, Temperatur, Plattenbewegungen:  $\dot{\epsilon} = f(T, \Delta\sigma, \dots)$

Dynamik

siehe Teil I der Vorlesung

# allgemeine Deformationsanzeiger

## spröd - kalt - schnell

- Zerr- Dehnungsklüfte
- Abkühlungsklüfte
- Bruchflächen: Besenstrukturen
- Bruchharnisch
- Mikrobrüche
- Stylolite

Spannungsrichtung  
Abkühlungsgradient  
Fortpflanzungsrichtung  
Relativbewegung  
Dilatanz, Extension  
Verkürzungsrichtung

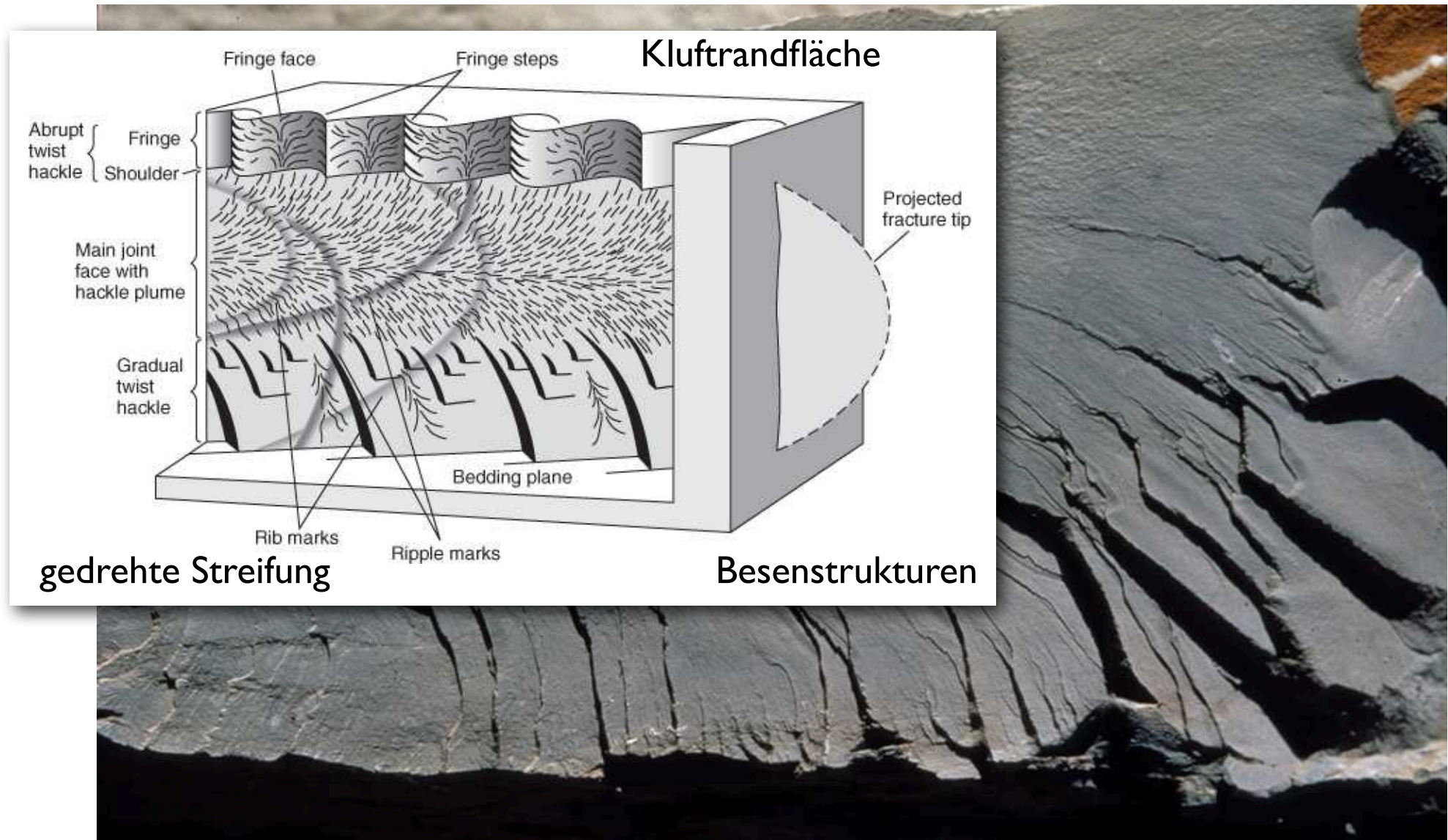
## duktil - warm - langsam

- Falten
- Boudinage
- Schieferung
- duktile Scherzone

Verkürzung  
Dehnung  
Plättung  
Schersinn

# Mikrostrukturen der Extension

# Bruchfläche • Besenstrukturen Fortpflanzungsrichtung



→ Ausbreitungsrichtung

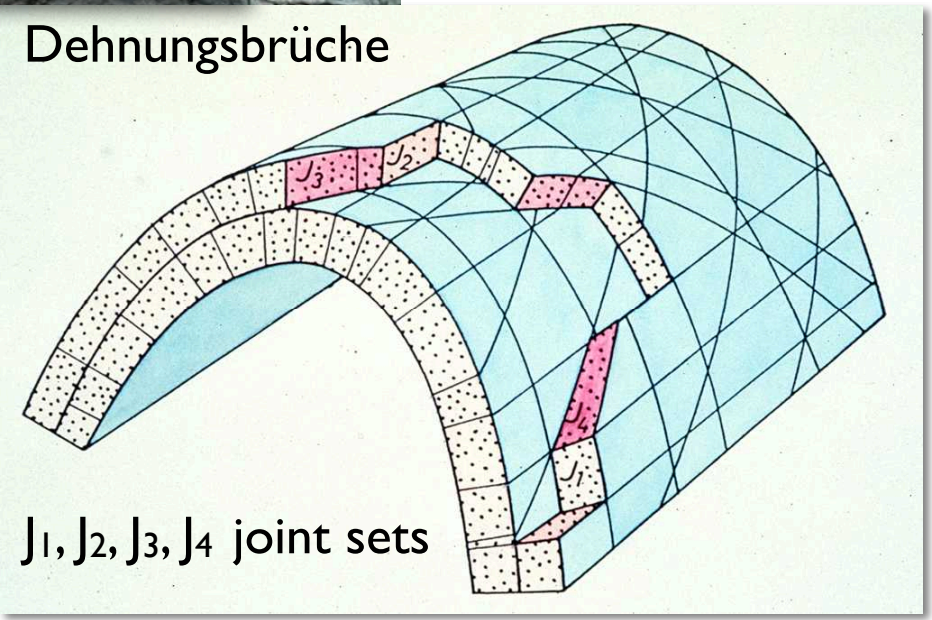
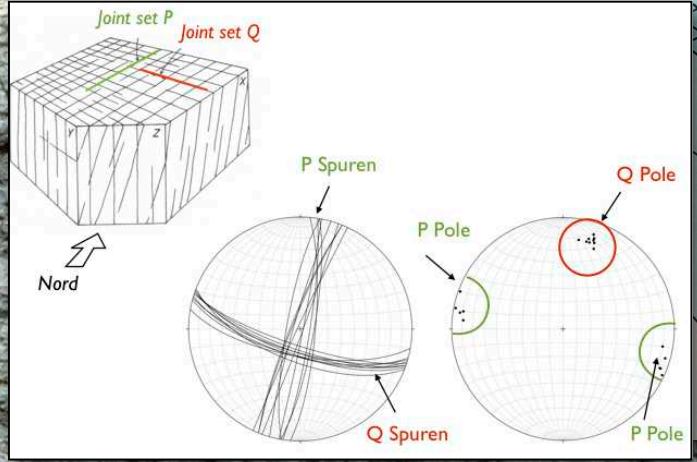
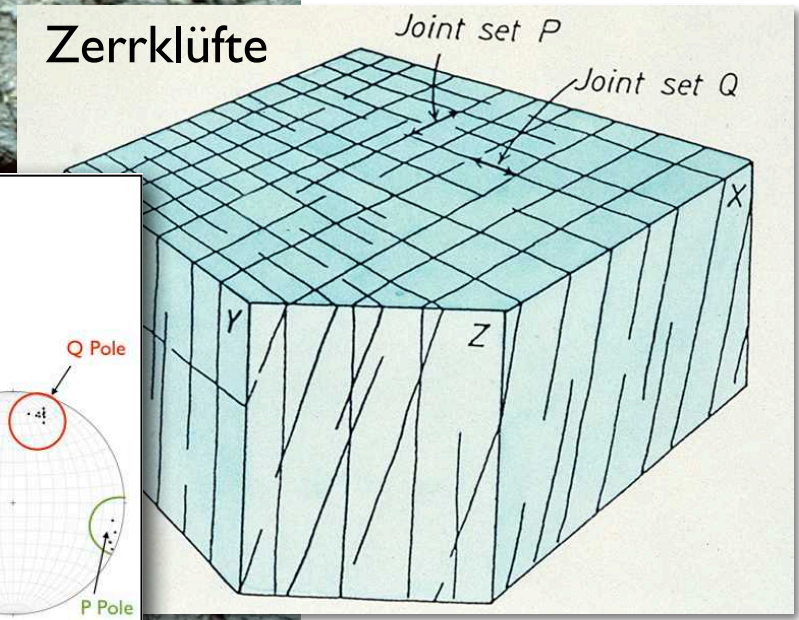
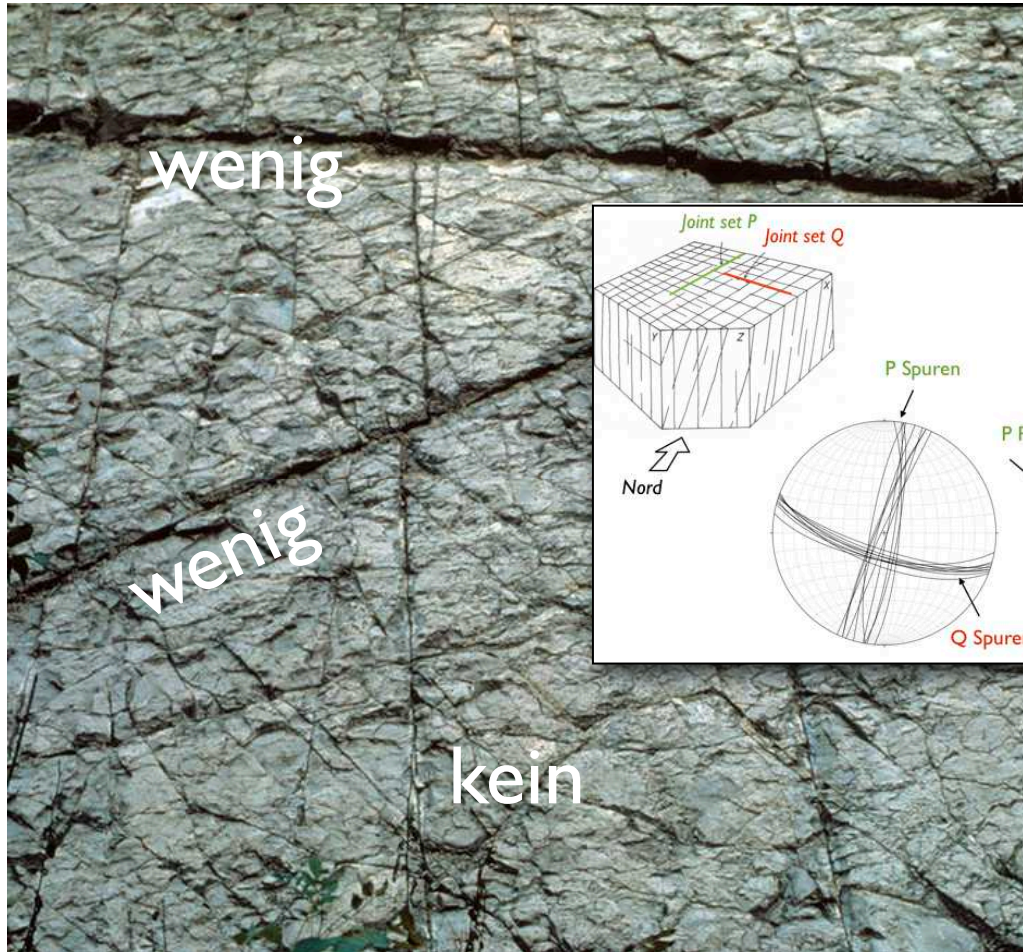




# Klüfte

• Zerr- Dehnungsklüfte

Spannungsrichtung

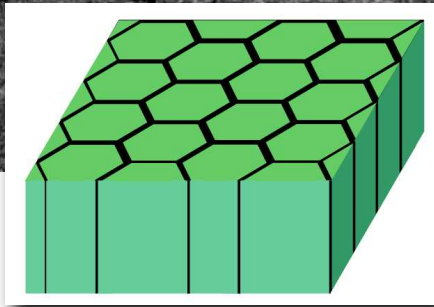
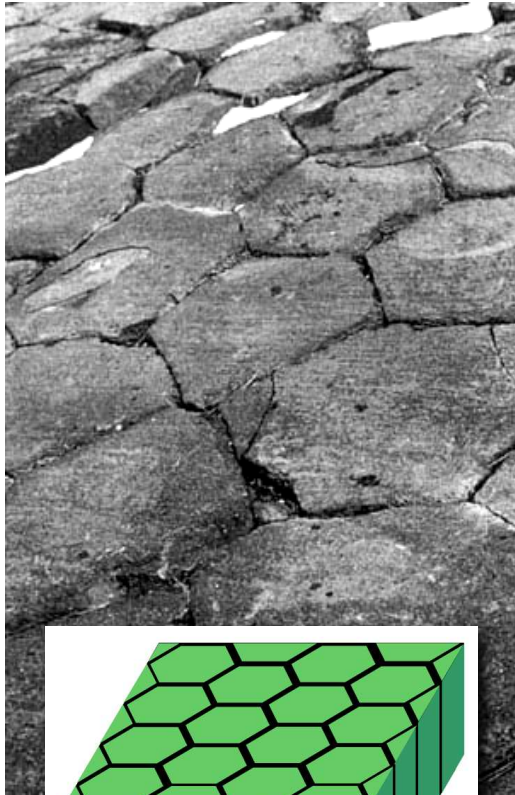


Klüfte =  
Brüche ohne (mit wenig) Versatz  
→ Spannungsrichtungen

# Klüfte

- Abkühlungsklüfte

Abkühlungsgradient



Säulenbasalt

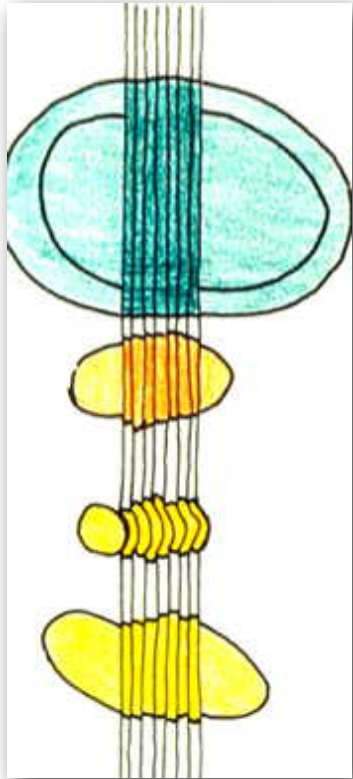


→ Kontraktion  
(Abkühlung)

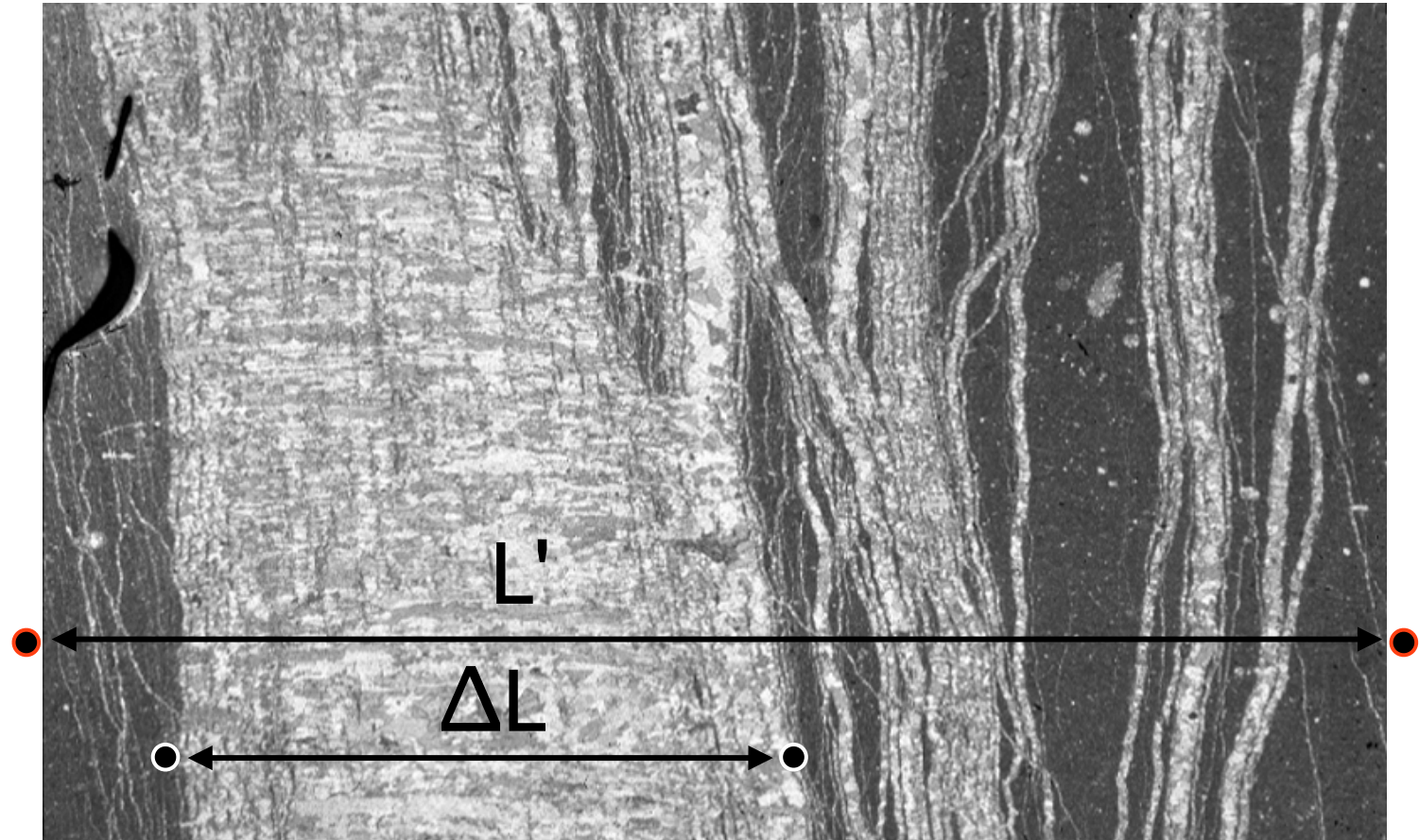
# Mikrobrüche

- Mikrobrüche Dilatanz, Extension

crack - seal



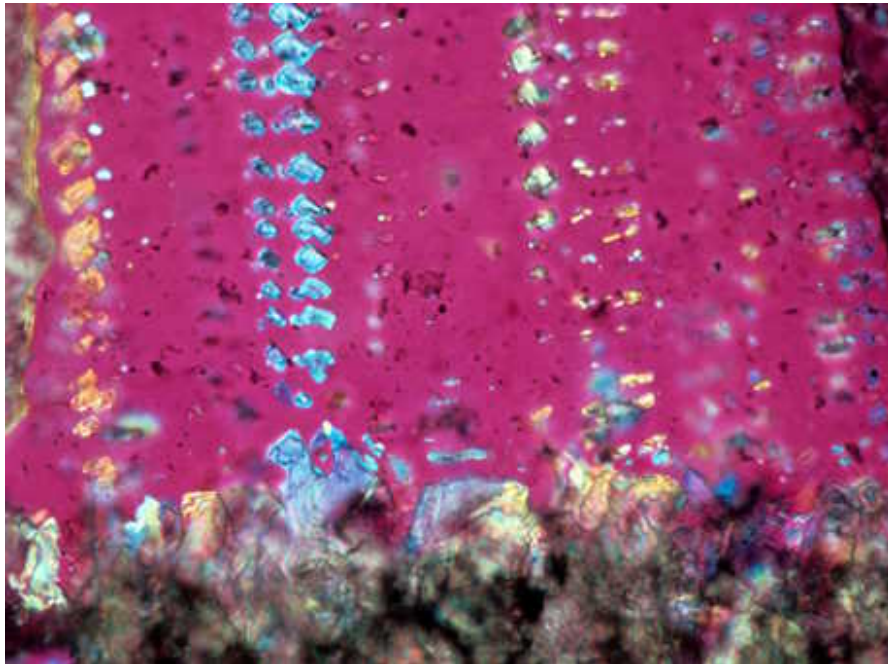
microcracks



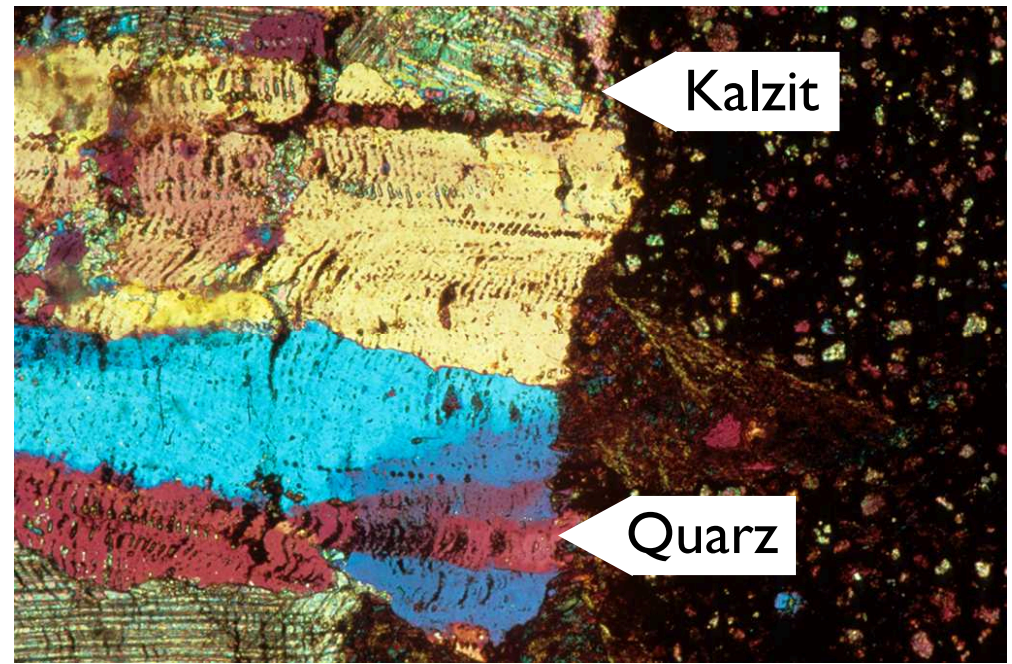
→ Längenänderung (mm)

$$L_0 = L' - \Delta L$$

# crack seal



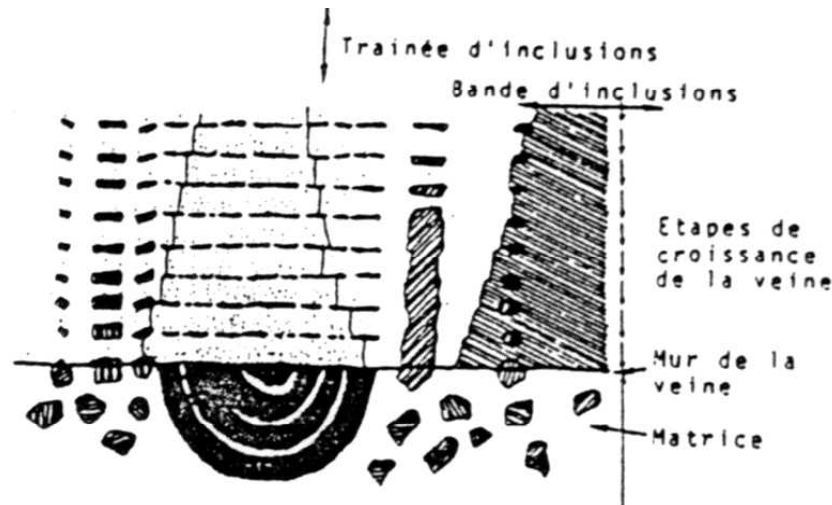
gelb / blau (Farben I. Ordnung von Quarz):  
optische Kontinuität  
gleiche Orientierung  
der Kristallachsen



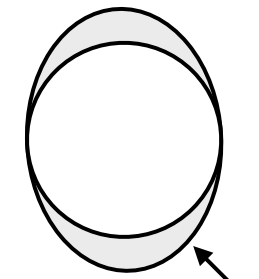
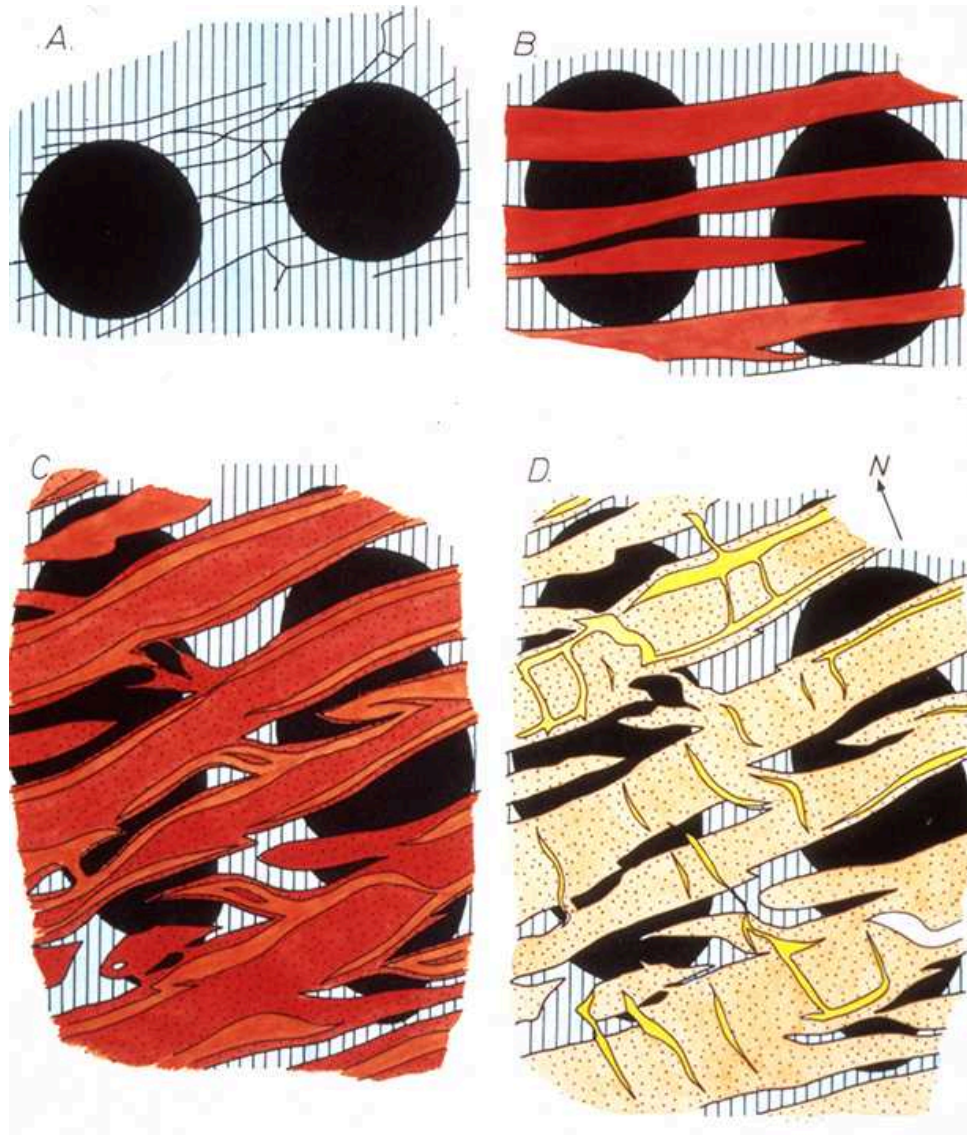
gelb / blau  
Quarz, niedere Doppelbrechung

bunt  
Kalzit, hohe Doppelbrechung

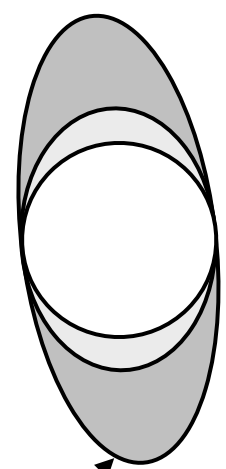
dunkel  
Einschlüsse



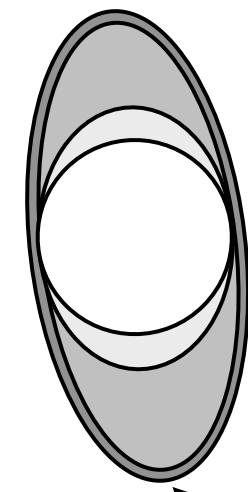
# bulk strain durch crack seal



strain ellipse



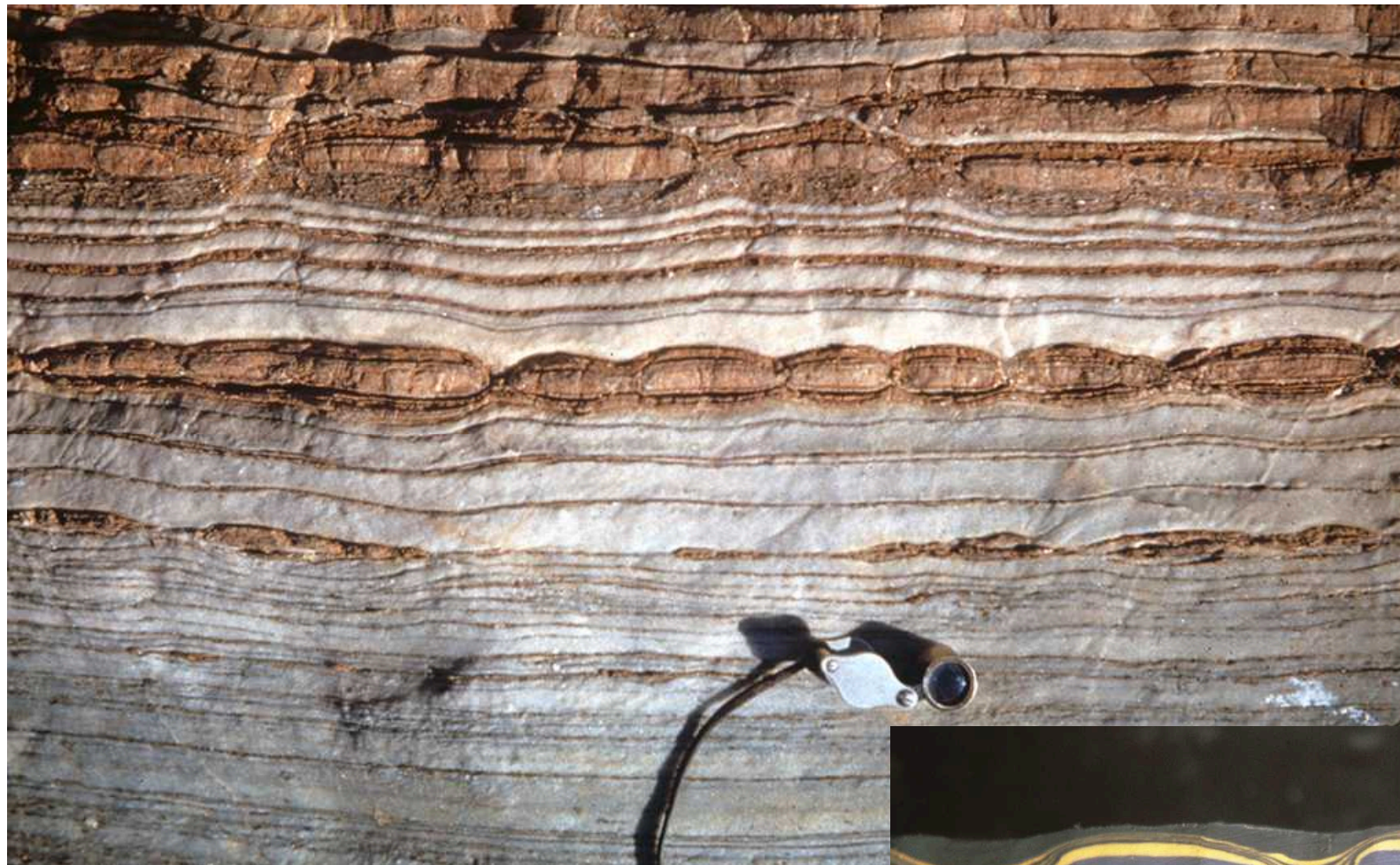
strain ellipse



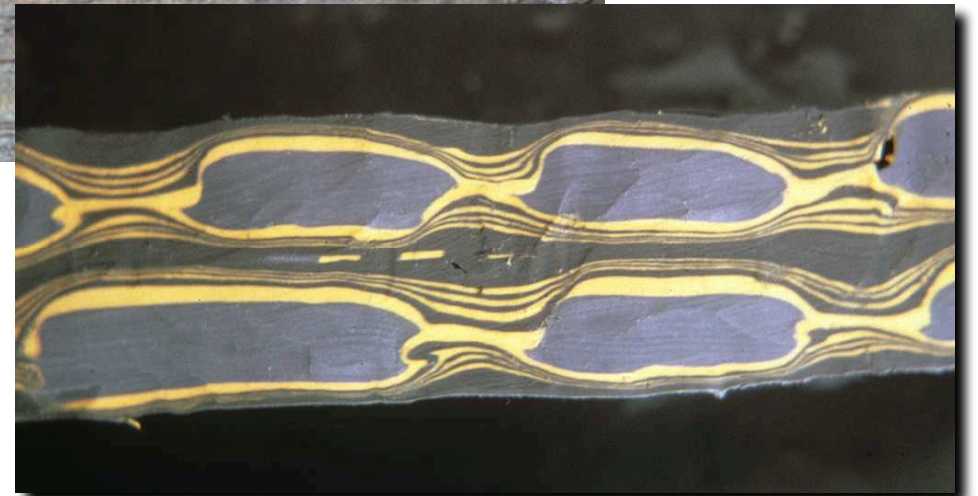
strain ellipse  
finite Verformung

progressive Verformung

# Boudinage



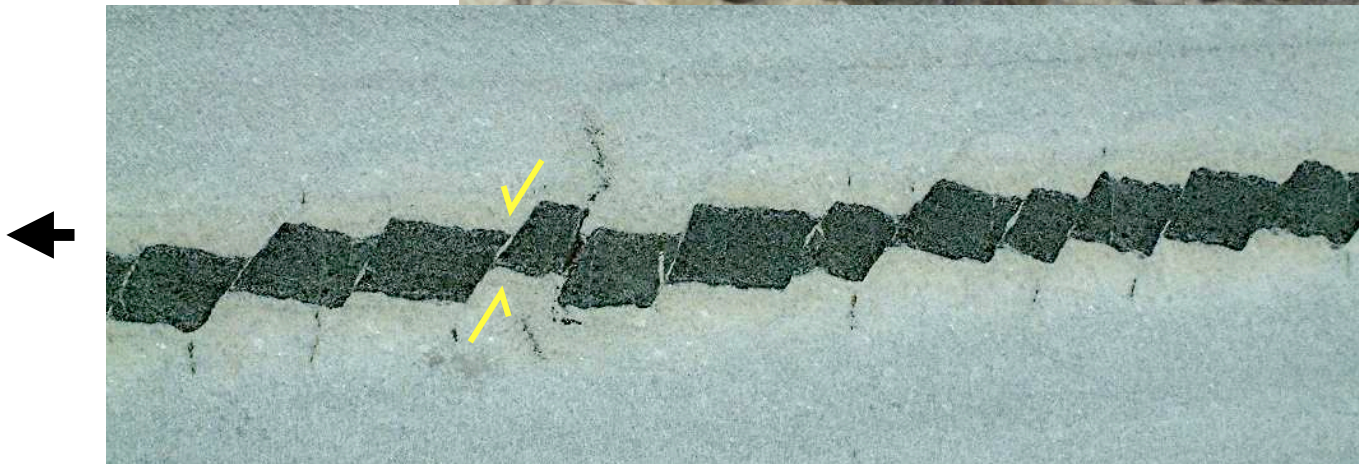
duktil



→ Dehnung, Extension

# book shelf boudinage

spröd



→ Dehnung, Extension

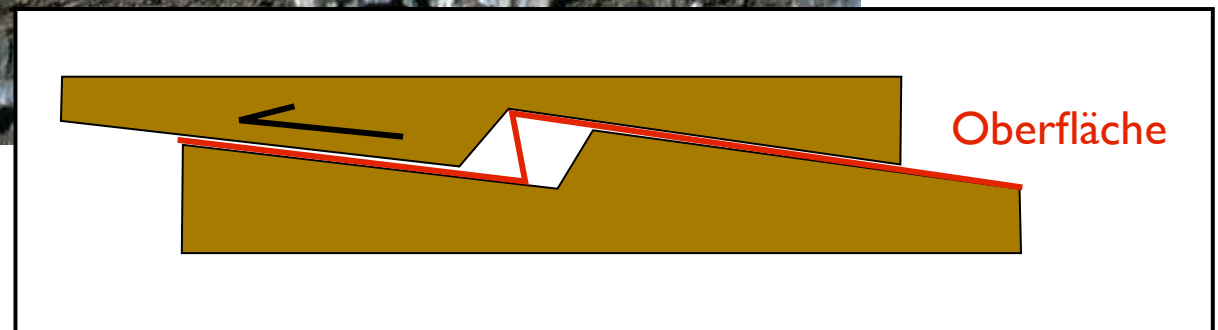
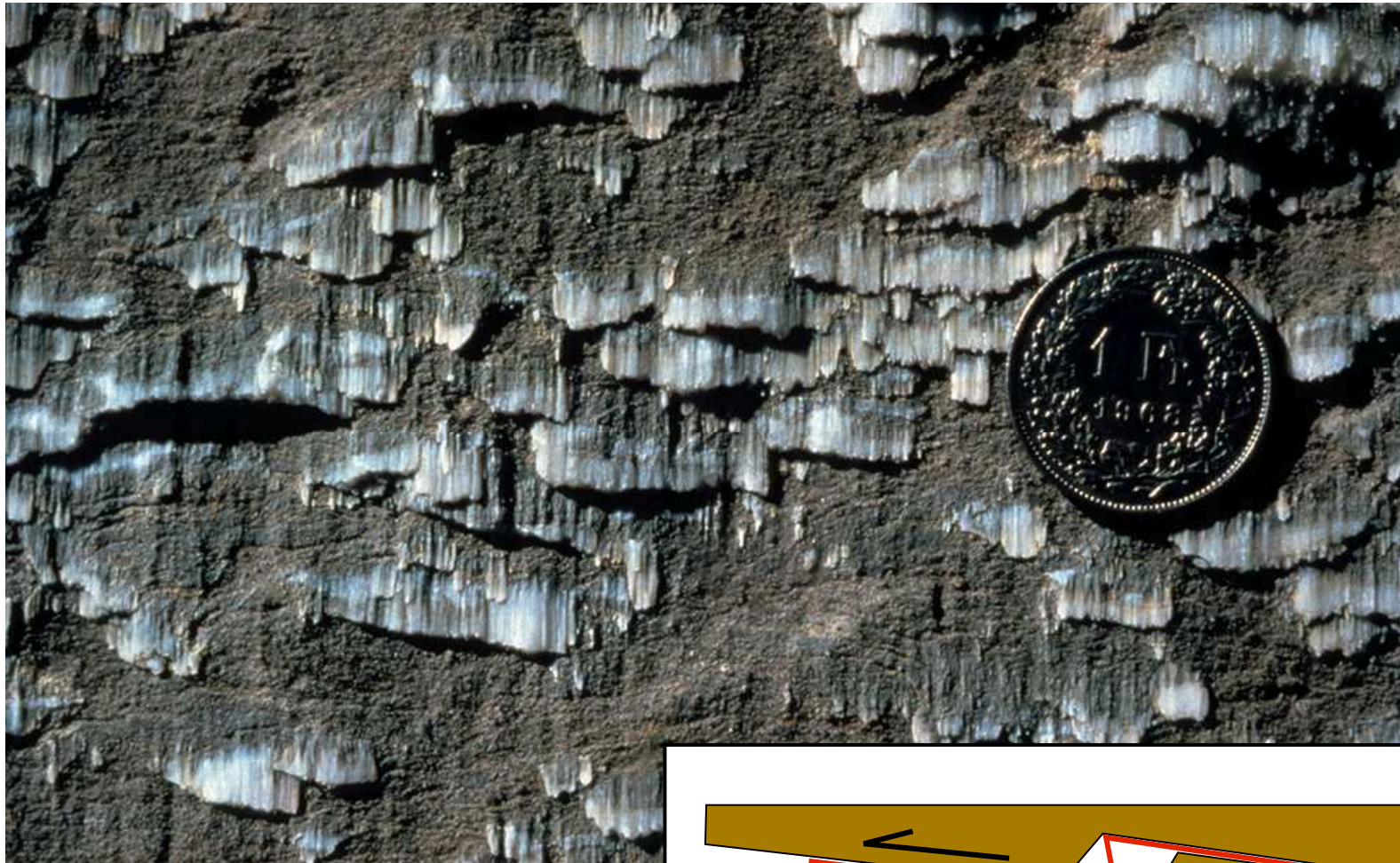
strike slip

Mikrostrukturen



# Bruchharnisch

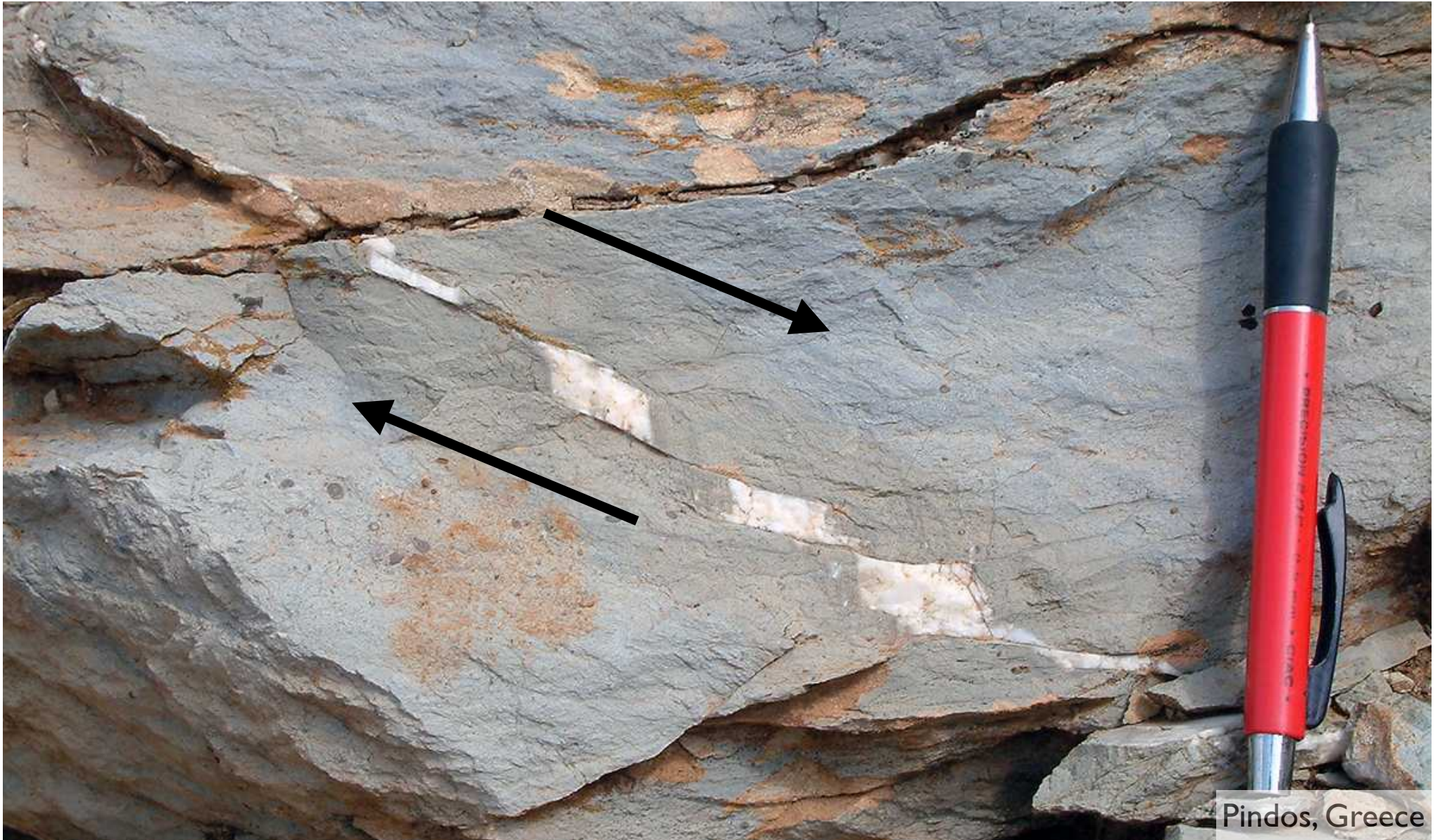
- Bruchharnisch    Relativbewegung



→ Faltenvorschub - Versetzungsrichtung

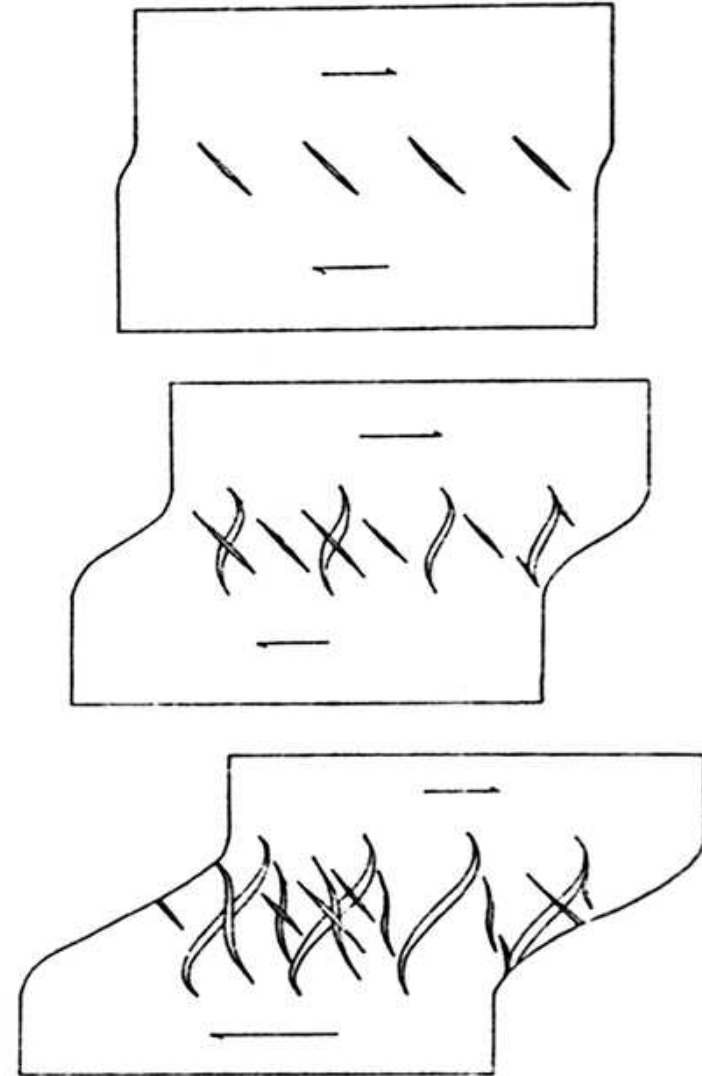
# dehnender Übertritt extensional bridge

STRIKE - SLIP



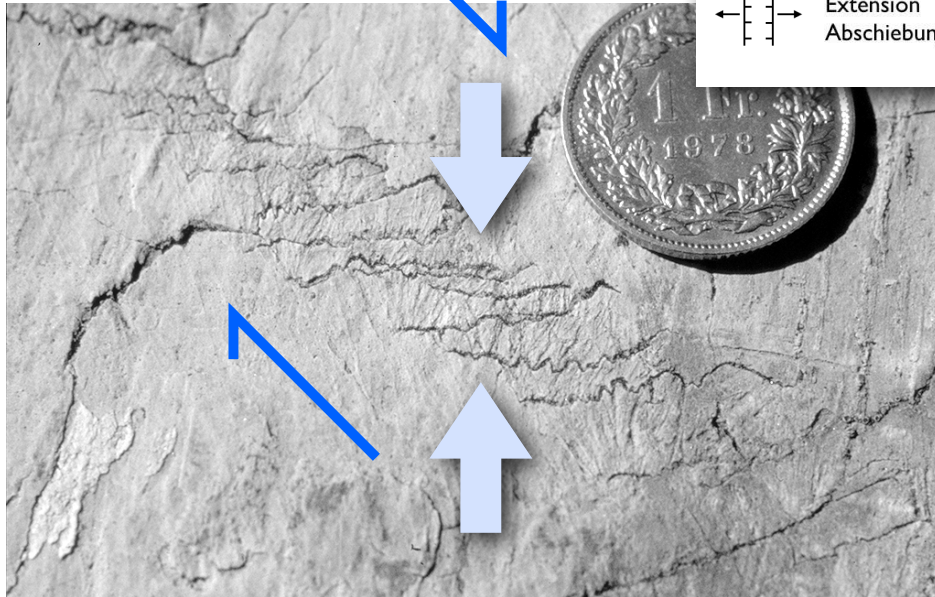
Pindos, Greece

# Zerrklüfte - Fiederklüfte



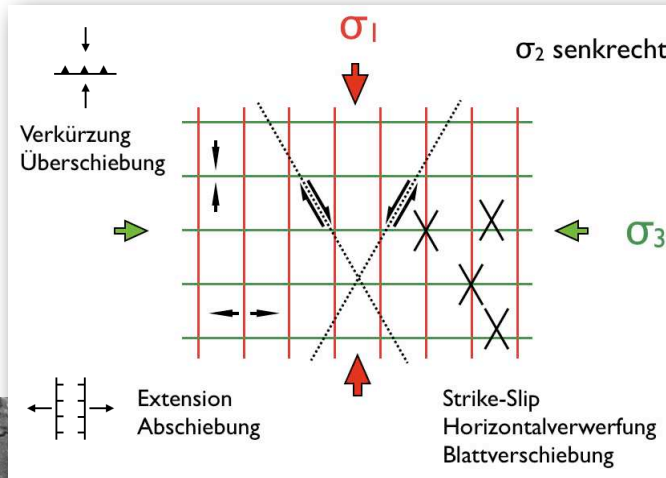
# Transpression & Transtension

en echelon Stylolithe

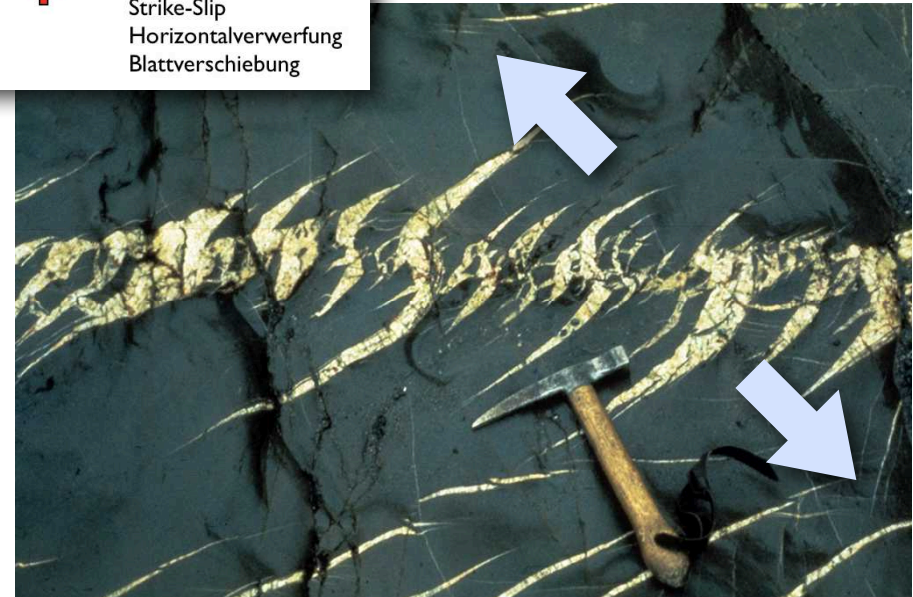


zone = source

$$\Delta V_{\text{zone}} > 0$$



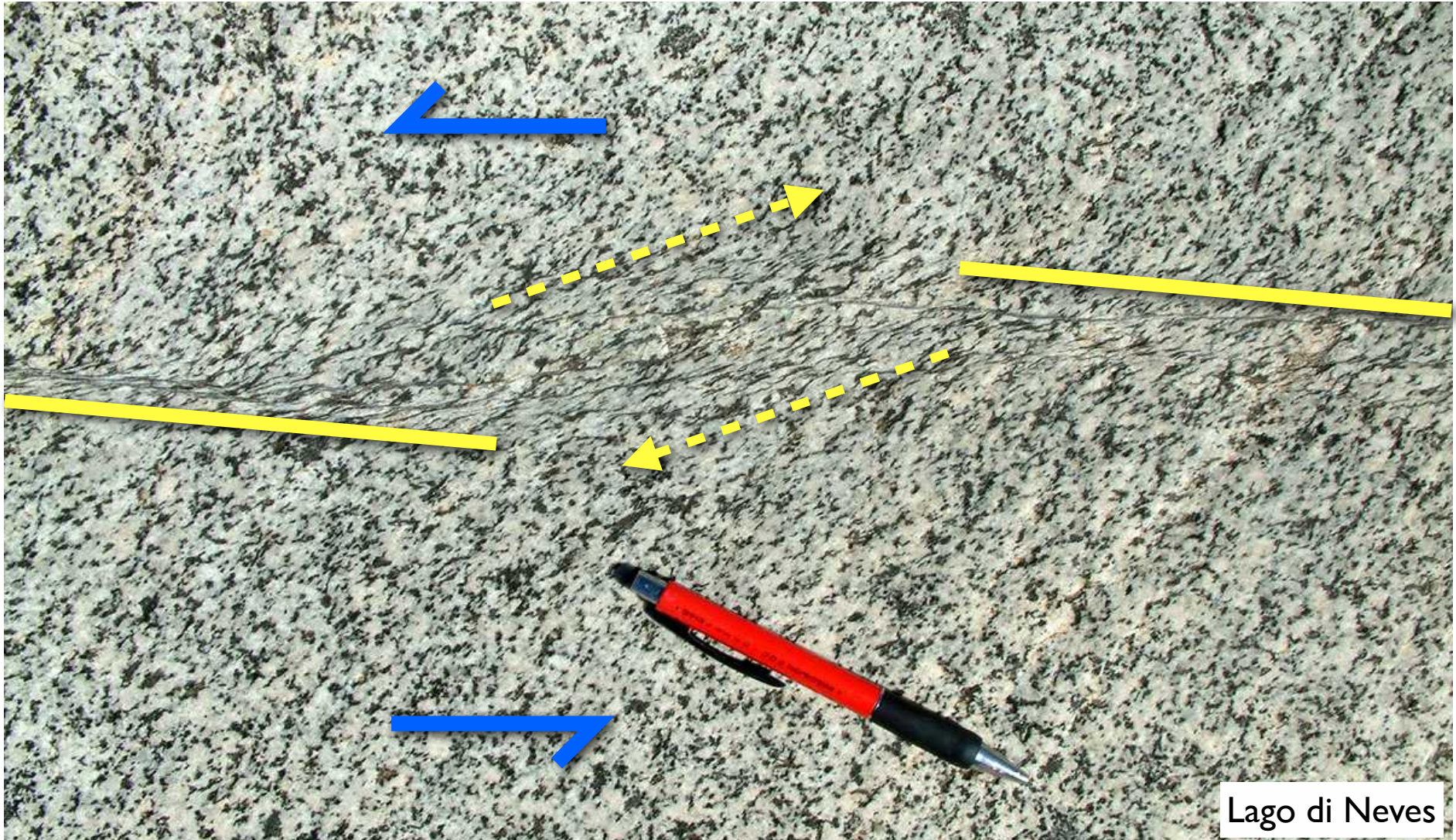
Fiederklüfte



zone = sink

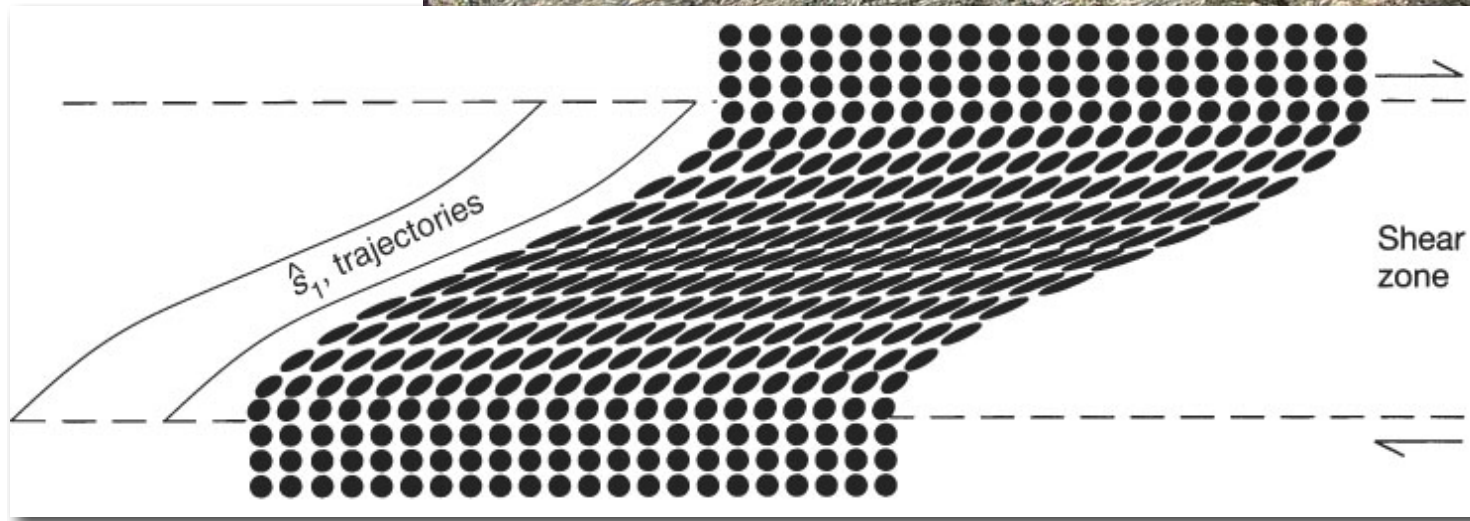
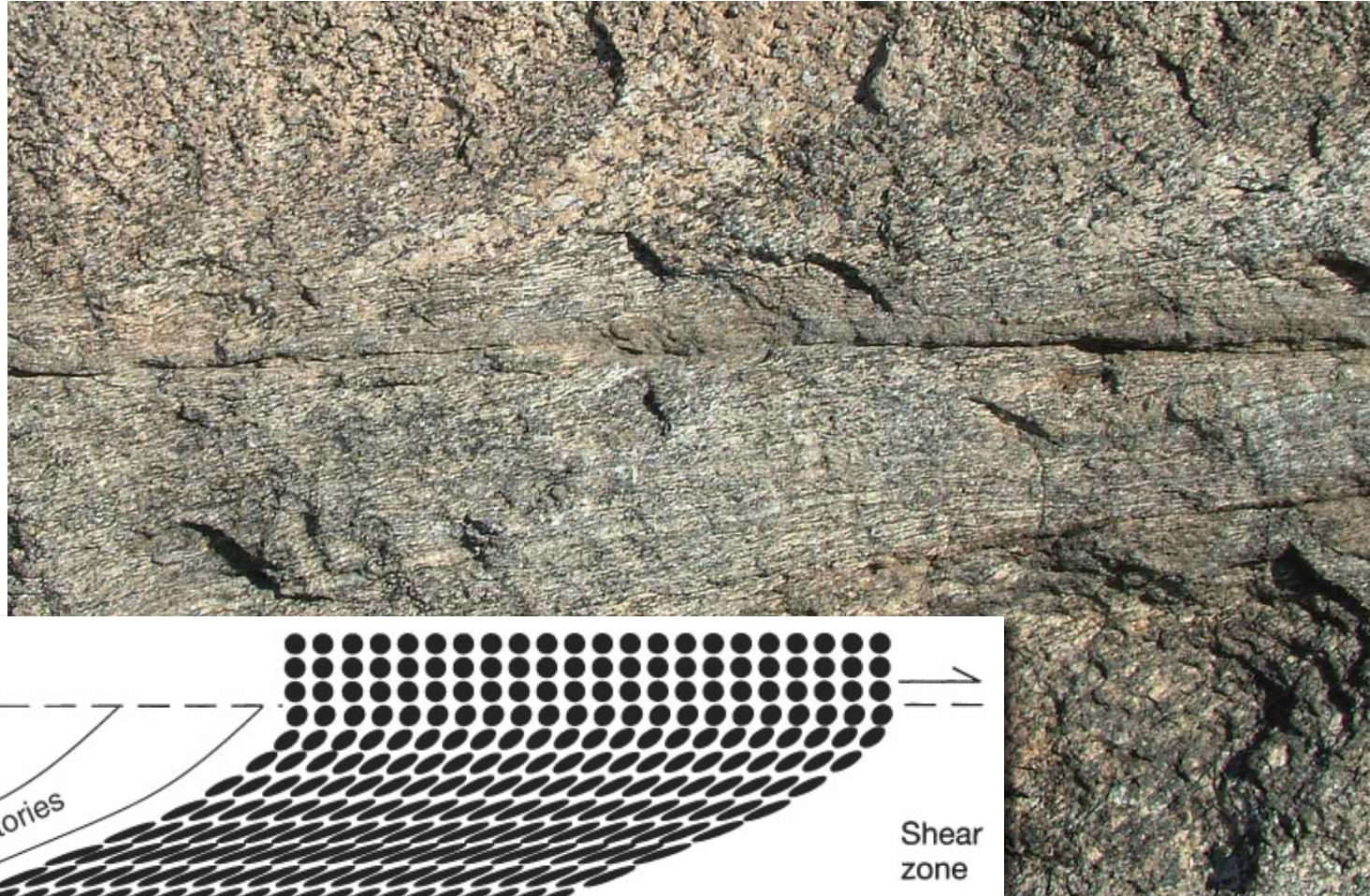
$$\Delta V_{\text{zone}} < 0$$

# kompressiver Übertritt compressional bridge



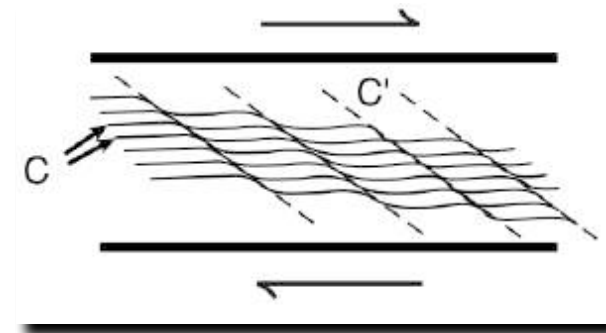
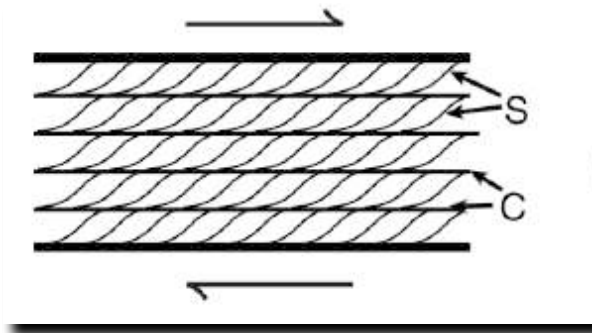
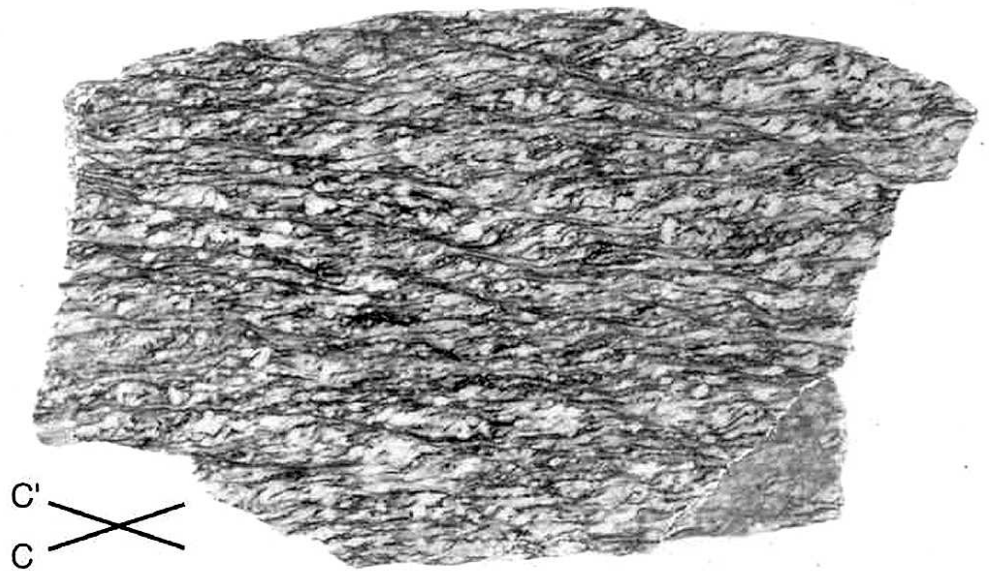
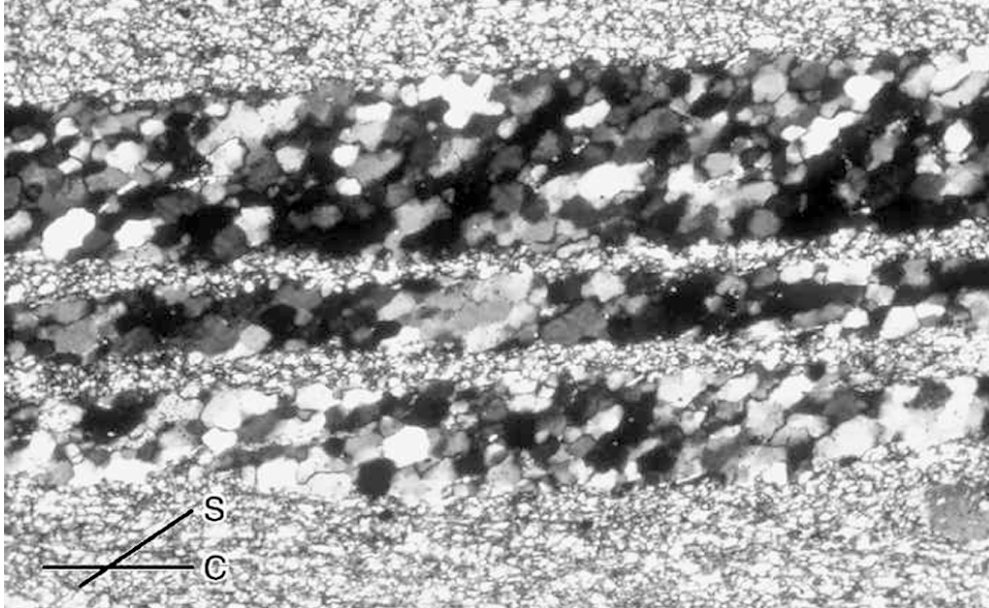
# Scherzonen

# Duktile Scherzonen



→ Schersinn

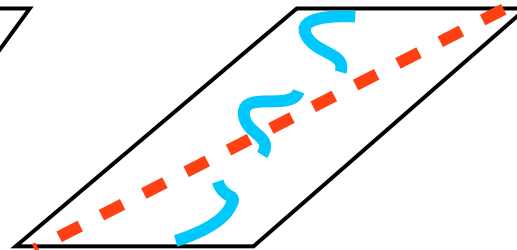
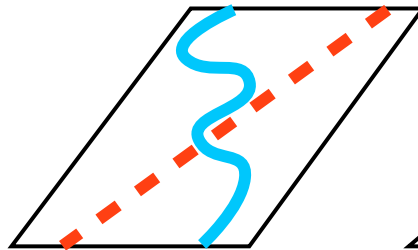
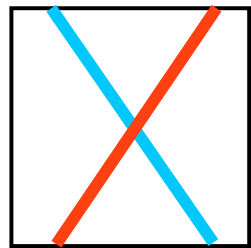
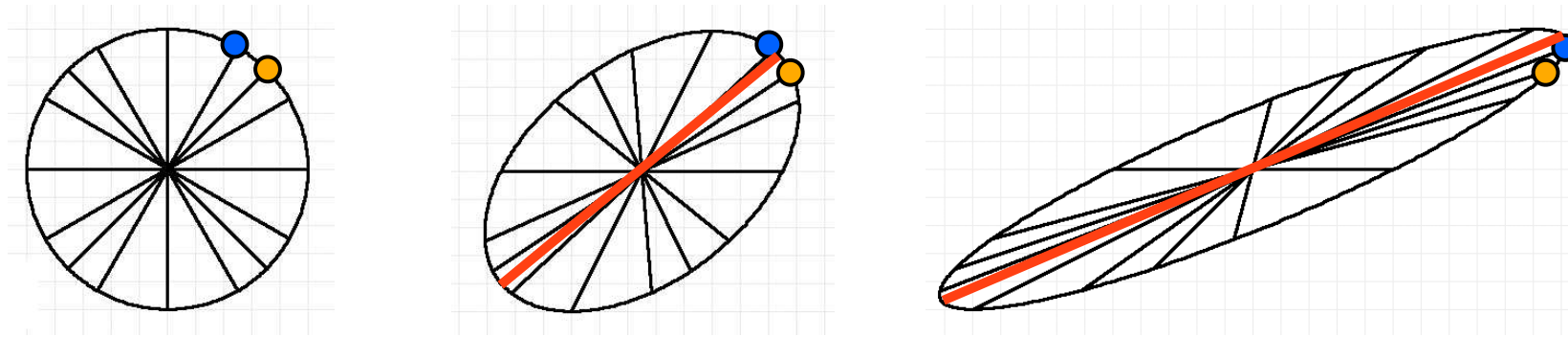
# S-C und C-C' - Gefüge



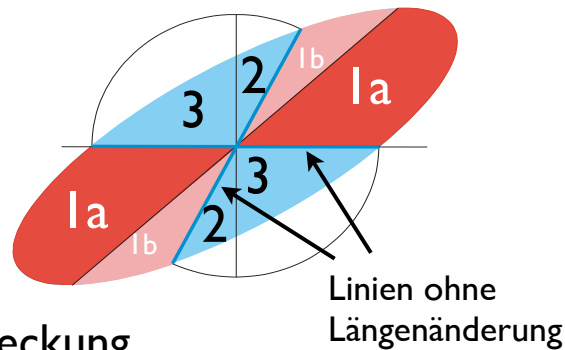
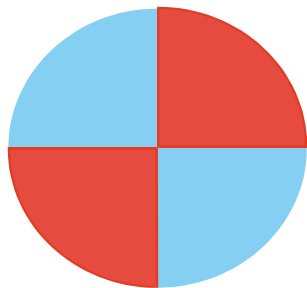
S = schistosité  
C = cisaillement



# finite Verformung - strain history



progressive  
simple shear



Feld 1a immer Streckung  
 Feld 1b Stauchung Streckung (total gestreckt)  
 Feld 2 Stauchung Streckung (total gestaucht)  
 Feld 3 Stauchung

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

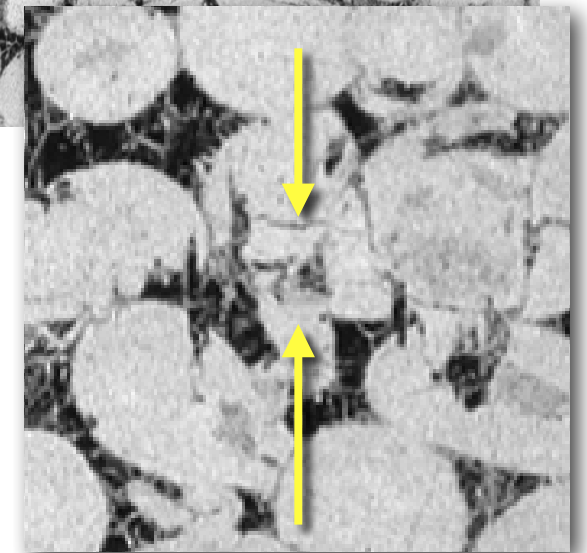
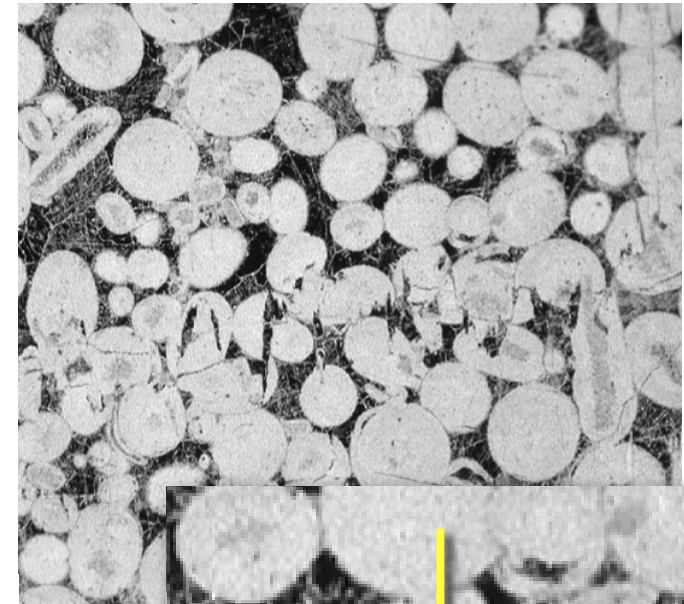
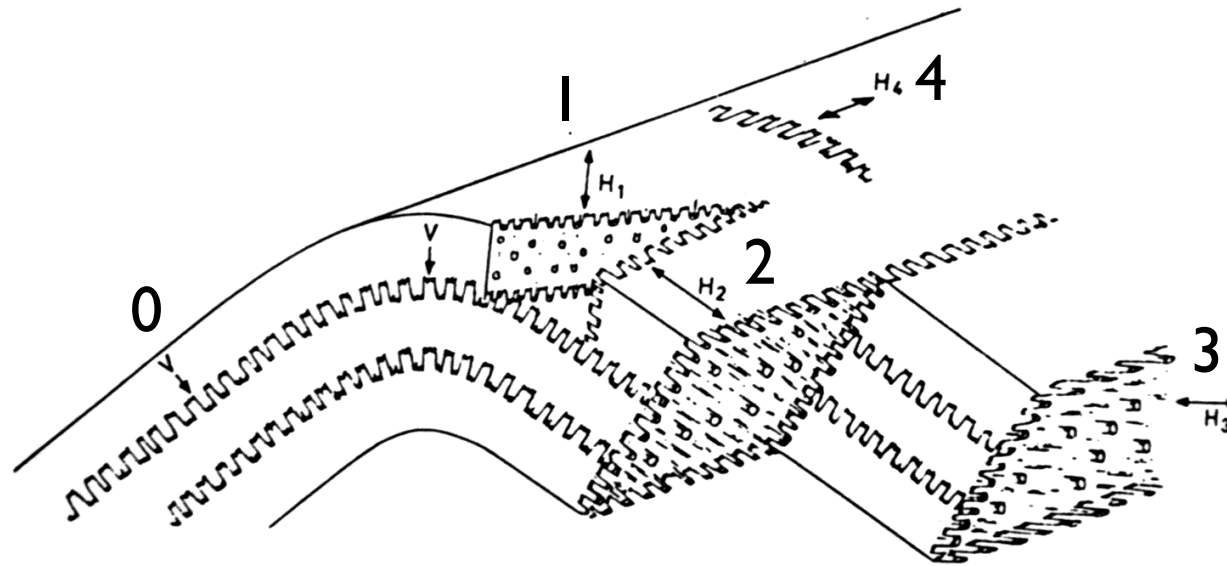
Stauchung dann Dehnung ✓  
 Dehnung dann ~~Stauchung~~

# Mikrostrukturen der Verkürzung

# Stylolithe

• Stylolite

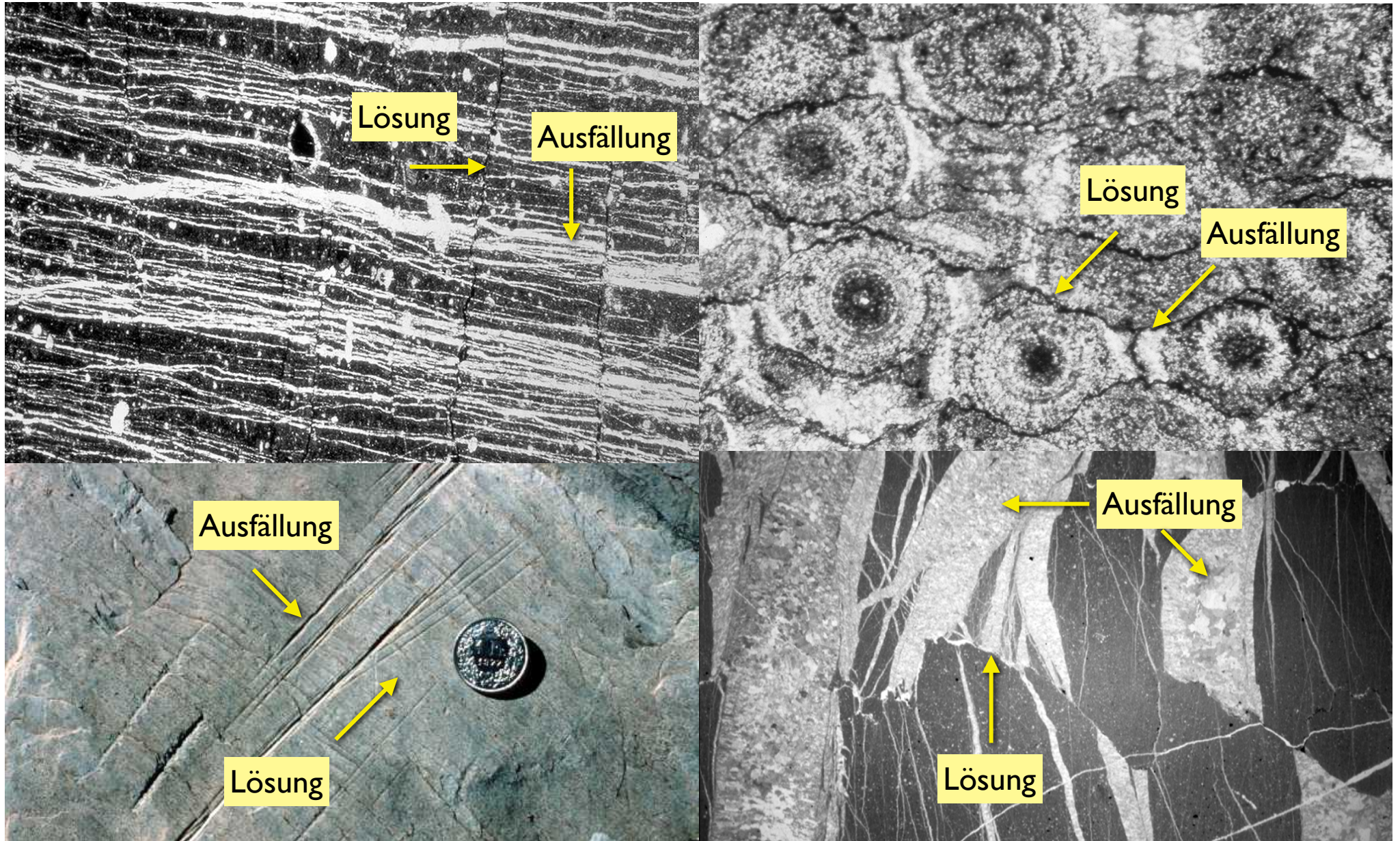
Verkürzungsrichtung



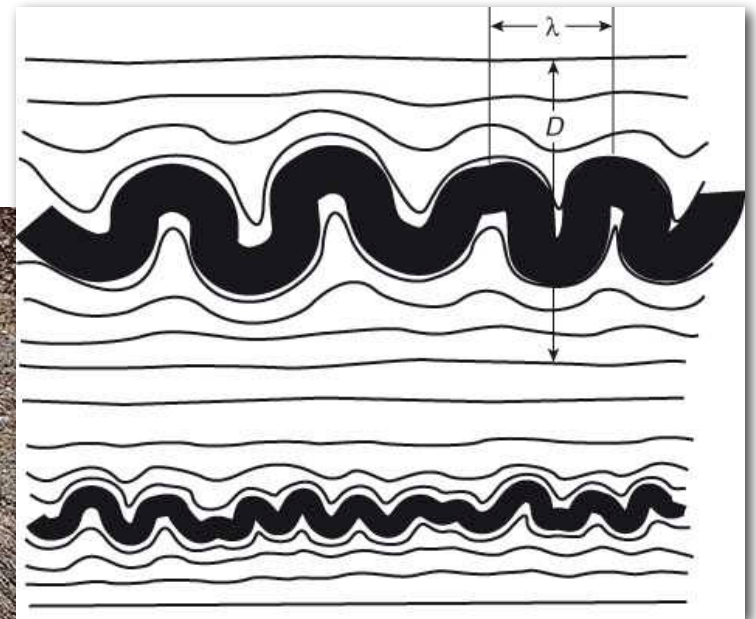
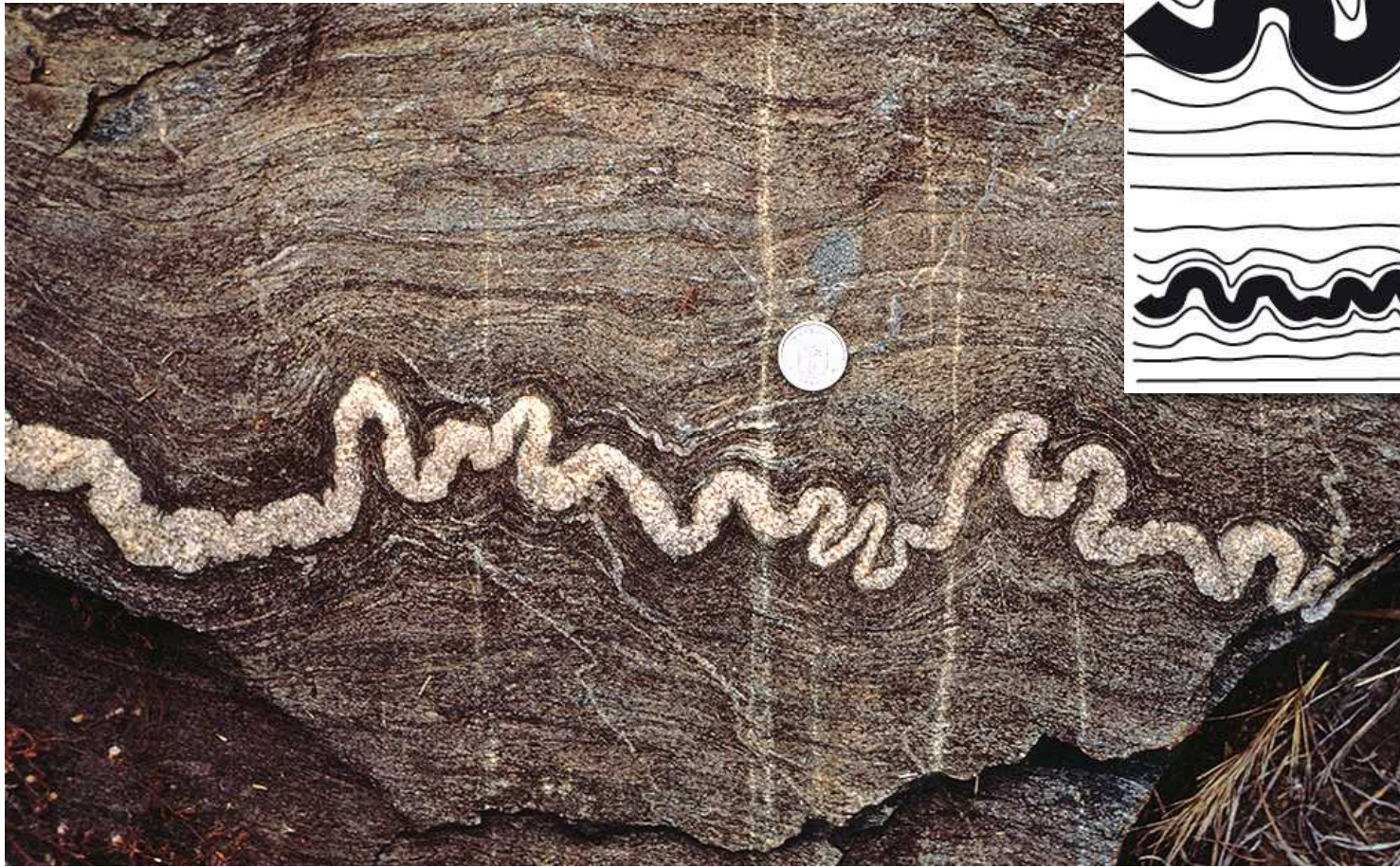
- 0, 1 diagenetische Stylolithe
- 2 tektonische Stylolithe: senkrecht zur Faltenachse
- 3 Schrägstylolithe: horizontale Scherung
- 4 tektonische Stylolithe: ('blockierte Querdehnung')

→ Versetzungsrichtung (nicht -betrag)

# source - sink



# Ptygmatische Faltung



→ Verkürzung

→ Viskositätskontrast

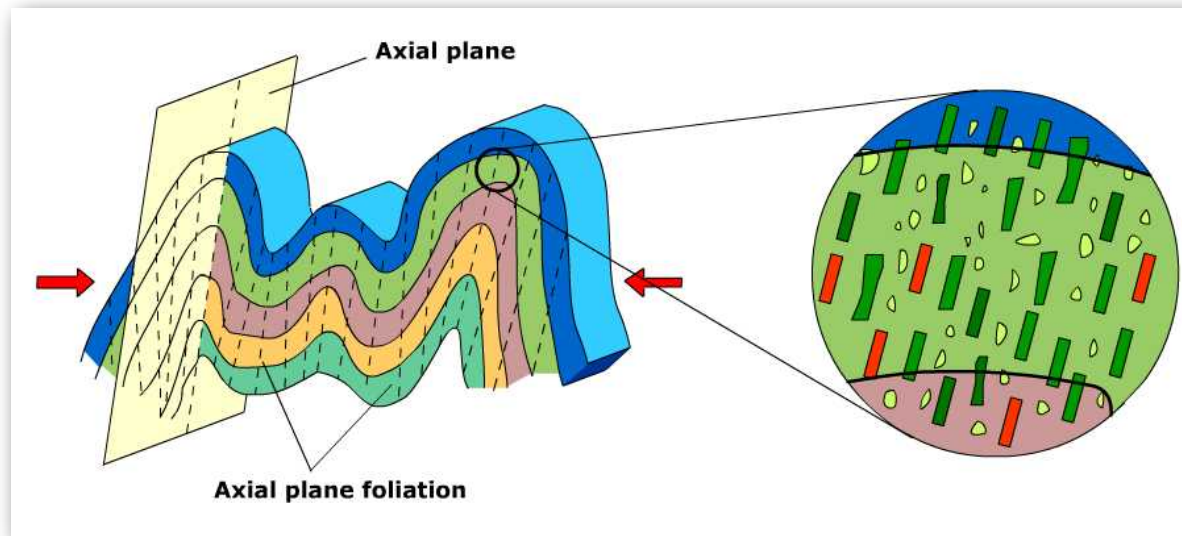
# Überschiebung

Verkürzung



Pindos, Greece

# Schieferung



→ Verkürzung

(Metamorphose)

geologische  
Geschwindigkeiten,  
Verformungsraten  
(strain rates)

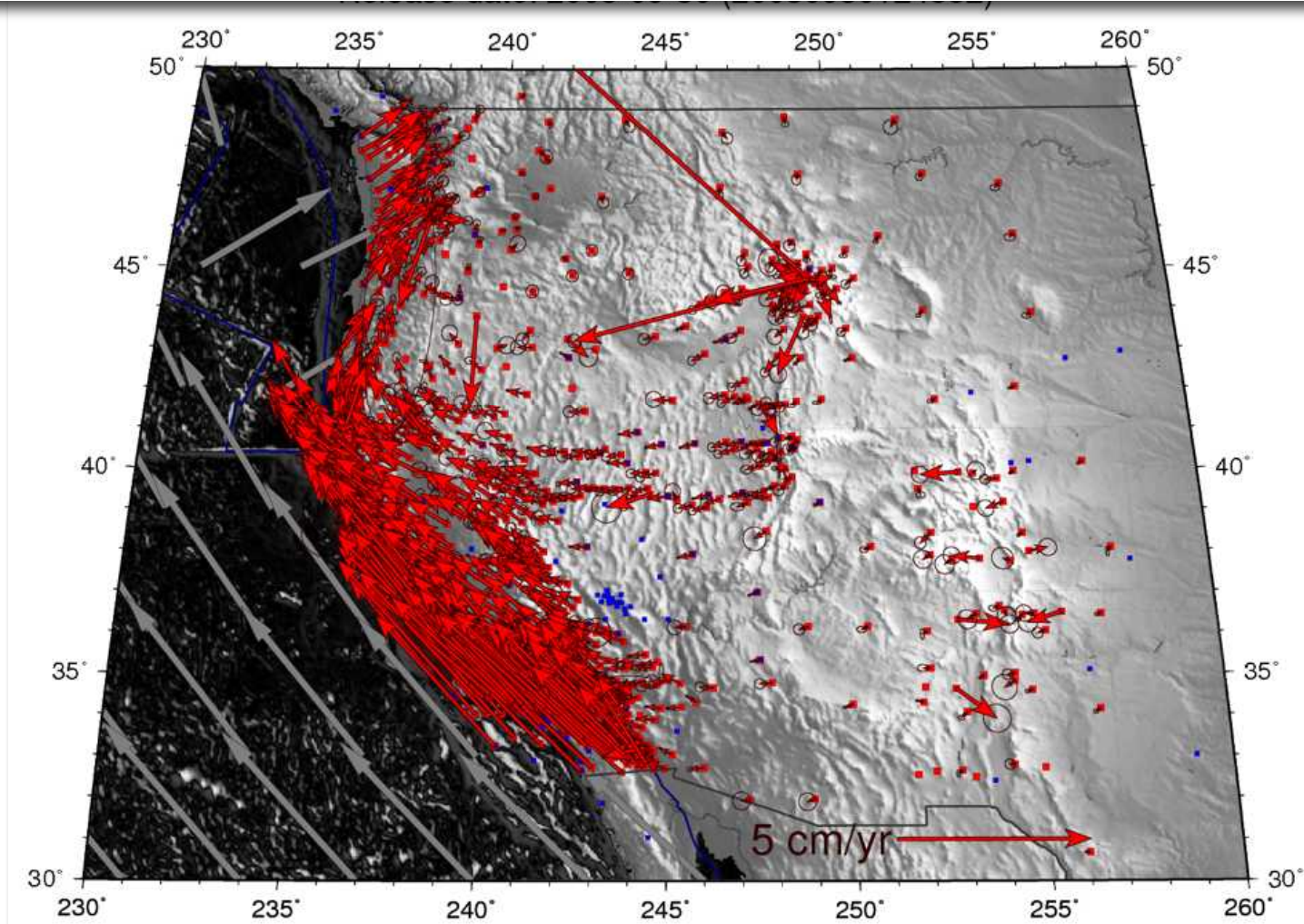


# Geologische Geschwindigkeiten

Momentane Plattengeschwindigkeit:

**1 bis 10 cm / Jahr**

$= 10^{-2} - 10^{-1} \text{ m} / 31'536'000 \text{ s} \approx 10^{-9} - 10^{-8} \text{ ms}^{-1}$

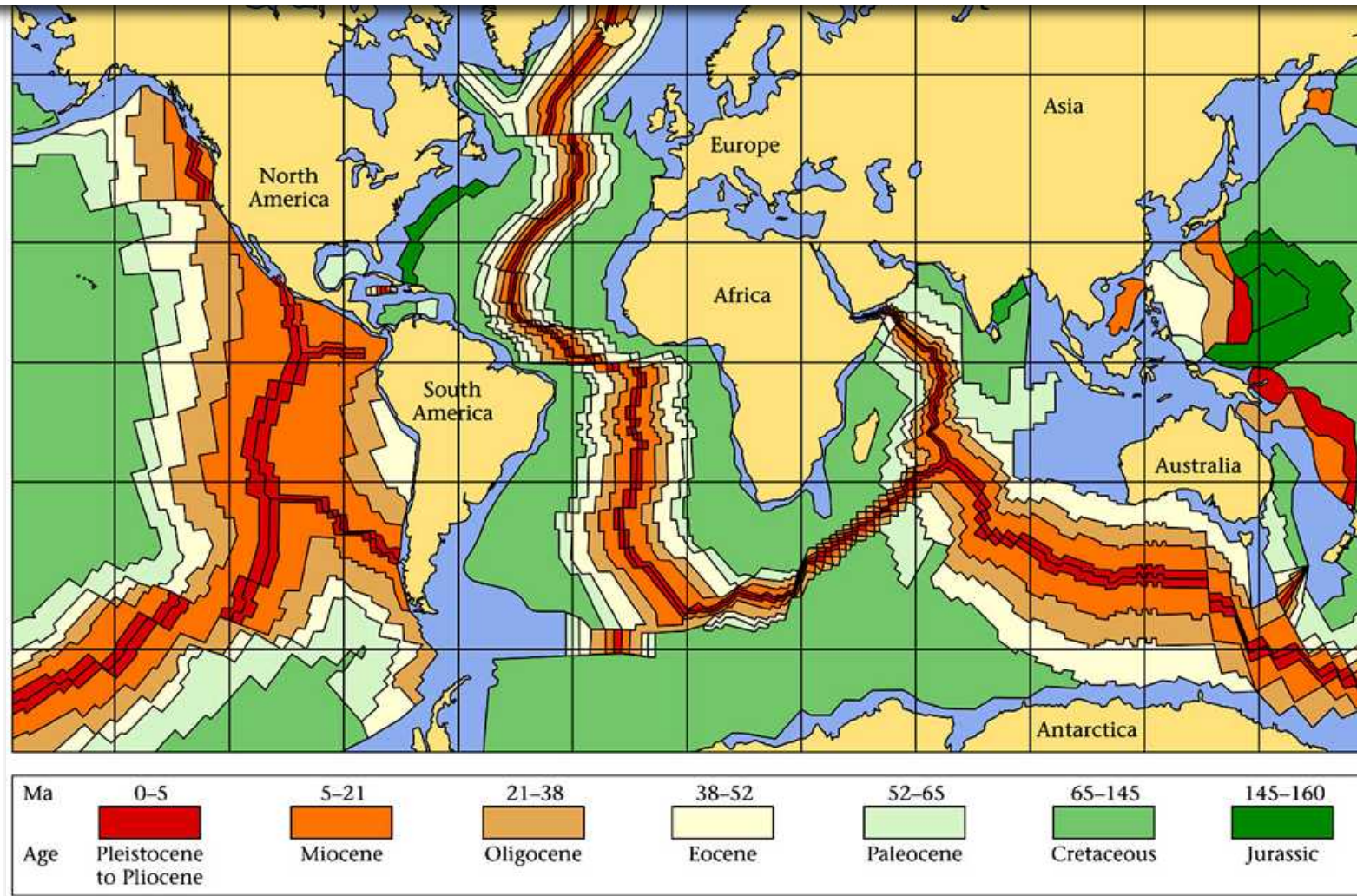


# Geologische Geschwindigkeiten

im Durchschnitt : **3000 km / 150 Ma**

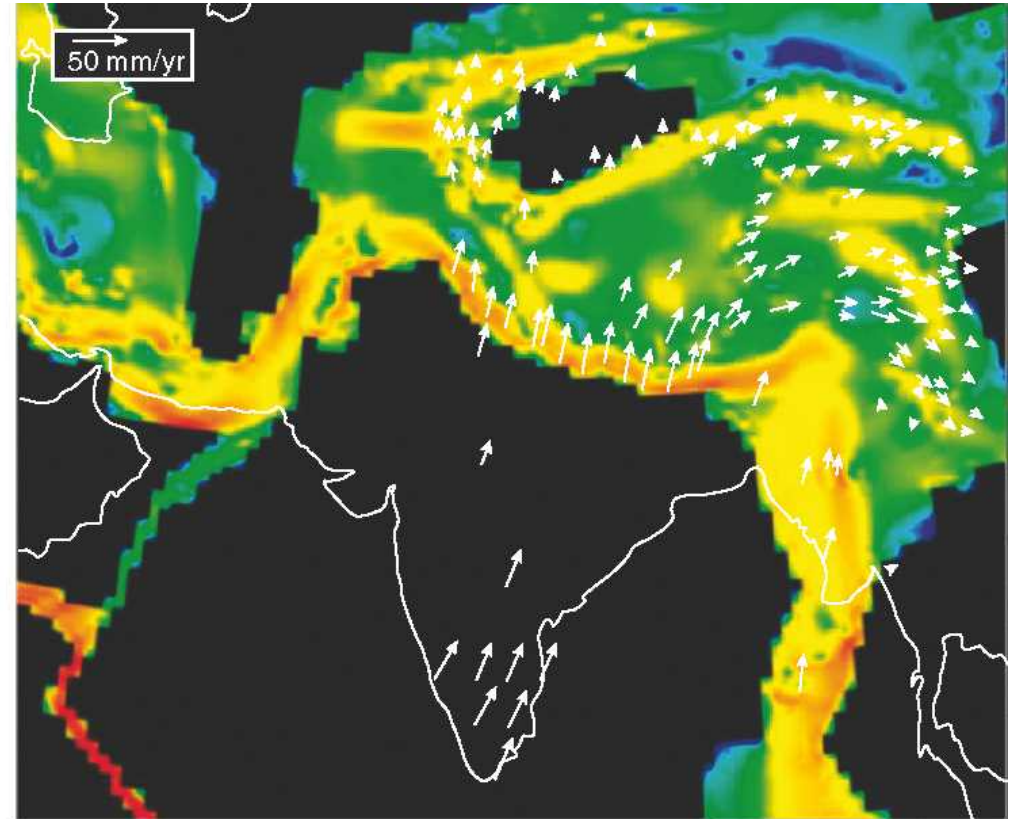
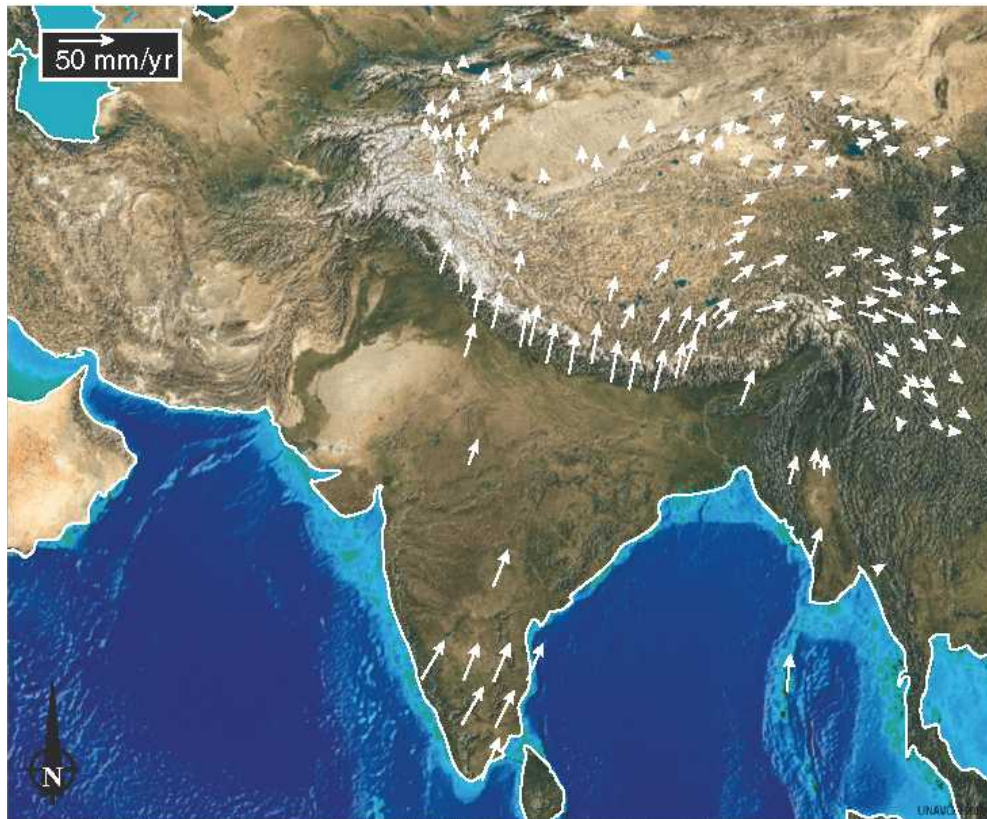
$$= 3 \cdot 10^3 \cdot 10^3 \text{ m} / 150 \cdot 10^6 \cdot 3 \cdot 10^7 \text{ s}$$

$$= 3 \cdot 10^6 / 4.5 \cdot 10^2 \cdot 10^{13} \quad \approx 10^{-9} \text{ ms}^{-1}$$



# Geologische Geschwindigkeiten

zeitlich variable Plattengeschwindigkeit



kann auch örtlich variabel sein

# Verformungsraten

## Geschwindigkeit

= Länge / Zeit

$\text{ms}^{-1}$  Meter / Sekunde

tektonische Platten:

3 cm / Jahr

$\sim 10^{-9} \text{ms}^{-1}$

zu Fuss:

3.6 km / h

1  $\text{ms}^{-1}$

Faktor  $10^{-9}$

## Verformungsrate (strain rate)

= Strain / Zeit

$\text{s}^{-1}$  strain / Sekunde

= (Länge / Länge) / Zeit

(strain: dimensionslos)

(1) = ( Längenänderung / Länge ) / Zeit

(2) = Geschwindigkeit / Länge

woher kommen die 'magischen'  $10^{-14} \text{s}^{-1}$  ???

# Rate als Strain / Zeit

Beispiel: Alpen

Verkürzung während Kollision

Hunderte von km in Millionen Jahren

$$t: 3 \text{ Ma} \approx 3 \cdot 10^6 \cdot 3 \cdot 10^7 \text{ s} \approx 10^{14} \text{ s}$$

$L_0$ : z.B. 100 km

$\Delta L$ : z.B. 100 km

$$\Rightarrow \Delta L / L_0 = x \cdot 10^5 \text{ m} / x \cdot 10^5 \text{ m} \Rightarrow e \approx 1$$

$$\dot{e} = e / t = 1 / 10^{14} \text{ s}^{-1} = 1 \cdot 10^{-14} \text{ s}^{-1}$$

# Rate als Geschwindigkeit / Länge

Beispiel: San Andreas Fault

$$D = 10 \text{ cm} = 10^{-1} \text{ m}$$

$$B = 100 \text{ km} = 10^5 \text{ m}$$

$$t = 1 \text{ a} = 3 \cdot 10^7 \text{ s}$$

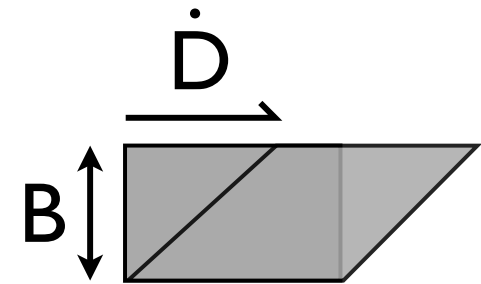
Plattengeschwindigkeit:

$$\dot{D} = 3.3 \cdot 10^{-9} \text{ ms}^{-1} \approx 10^{-9} \text{ ms}^{-1}$$

Verformungsrate:

$$\dot{\gamma} = \dot{D} / B \approx 10^{-9} / 10^5 \text{ m} \approx 10^{-14} \text{ s}^{-1}$$

$$\text{oder: } \dot{\gamma} = (D / B) / t = 10^{-6} / 3 \cdot 10^7 \approx 10^{-14} \text{ s}^{-1}$$



$$\dot{\gamma} = \frac{\dot{D}}{B}$$

# Lokalisierung: räumlich & zeitlich

für 100 km Breite:

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

räumlich

für Damage zone  $\approx 100$  m:

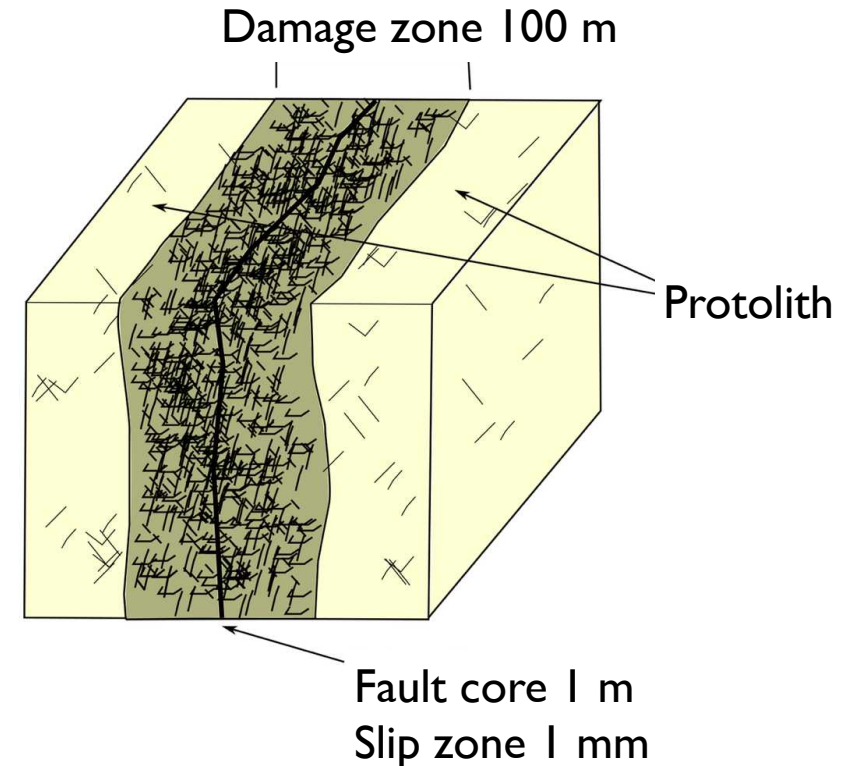
$$\text{Faktor} = 100 \text{ km} / 100 \text{ m} = 10^3$$

$$\Rightarrow \dot{\gamma} \approx 10^{-11} \text{ s}^{-1}$$

für Slip zone  $\approx 1$  mm:

$$\text{Faktor} = 100 \text{ km} / 1 \text{ mm} = 10^8$$

$$\Rightarrow \dot{\gamma} \approx 10^{-6} \text{ s}^{-1}$$



zeitlich

für kurzzeitige Bewegung (Erdbeben):

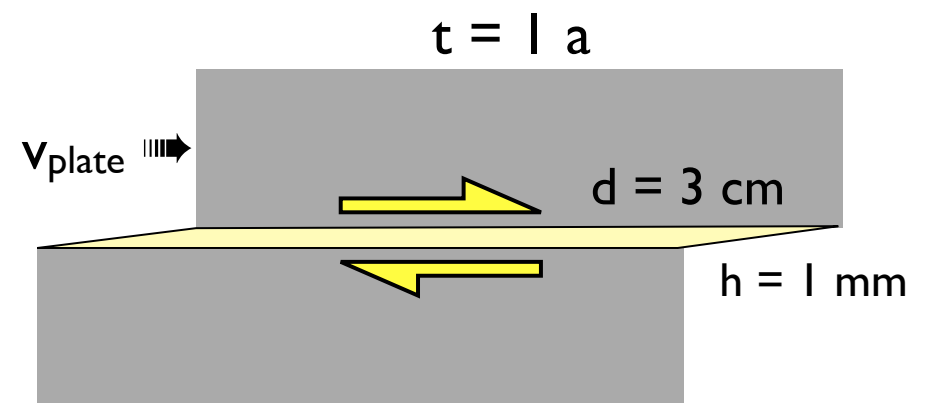
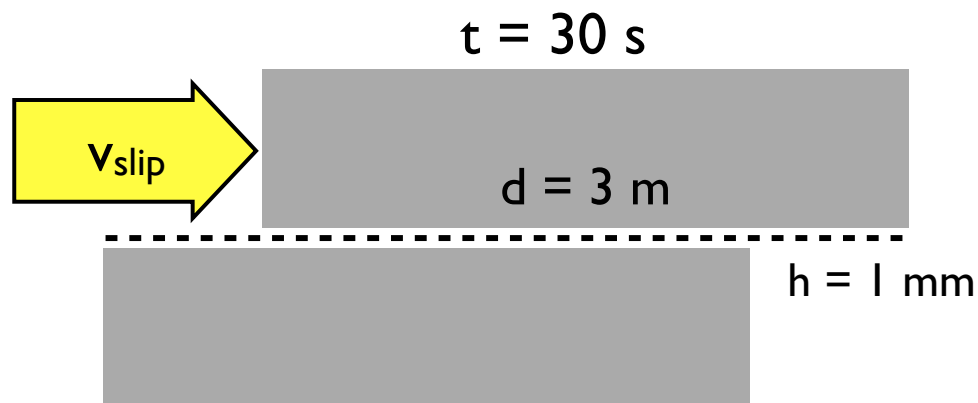
$$\text{Faktor Zeit} = 3 \cdot 10^7 \text{ s} / 30 \text{ s} = 10^6$$

$$\Rightarrow \dot{\gamma} \approx 1 \text{ s}^{-1}$$

bzw.  $\dot{\gamma} \approx 100\text{-}1000 \text{ s}^{-1}$ , da grösserer Versatz berücksichtigt werden muss

# Geschwindigkeit $\neq$ Verformungsrate

	Erdbeben	Creeping fault
Zeit	$t = 30 \text{ s}$	$t = 3 \cdot 10^7 \text{ s}$ (1 Jahr)
Distanz	$d = 3 \text{ m}$	$d = 3 \text{ cm}$
Bruchfläche	$h = 1 \text{ mm}$	$h_{\text{slip}} = 1 \text{ mm}$ $h_{\text{core}} = 10 \text{ cm}$
Verformung	$\gamma = d / h = 3000$	$\gamma = d / h = 30$ bzw. $0.3$
Geschwindigkeit (typisch für Erdbeben)	$v_{\text{slip}} = 10^{-1} \text{ ms}^{-1}$ (max $\approx 1 \text{ ms}^{-1}$ )	$v_{\text{plate}} = 10^{-9} \text{ ms}^{-1}$
Verformungsrate (typisch für creeping faults)	$\dot{\gamma}_{\text{EQ}} = \gamma / t \approx 100 \text{ s}^{-1}$	$\dot{\gamma}_{\text{slip}} = \gamma / t \approx 10^{-6} \text{ s}^{-1}$ $\dot{\gamma}_{\text{core}} = \gamma / t \approx 10^{-9} \text{ s}^{-1}$





# Zusammenfassung: Kinematik

## Deformationsmarker ( $\neq$ strain marker)

Bewegungsrichtung:	Bruchflächen, Harnisch, Stylolithe
Bewegungsbetrag:	crack seal
Bewegungssinn:	Falten, Schieferung (komp), Boudinage (ext)
Schersinn:	en echelon Klüfte, duktile Scherzone

## Geologische Geschwindigkeiten

tektonische Platten:	$\sim 10^{-9} \text{ ms}^{-1}$
seismic slip	$\sim 1 \text{ ms}^{-1}$
pro memoria: Seismische Wellen	$\sim 4-6 \cdot 10^3 \text{ ms}^{-1}$

## Geologische Verformungsraten (strain rate)

Gebirge "typisch geologisch"	$10^{-14} \text{ s}^{-1}$
schnell, z.B. Scherzonen	$10^{-10} - 10^{-12} \text{ s}^{-1}$
lokalisiert (creeping faults)	bis zu $10^{-6} \text{ s}^{-1}$

# 6 Extensions-Tektonik

## Rifting

- stages of rifting
- active / passive rifting

## Geophysikalische Merkmale

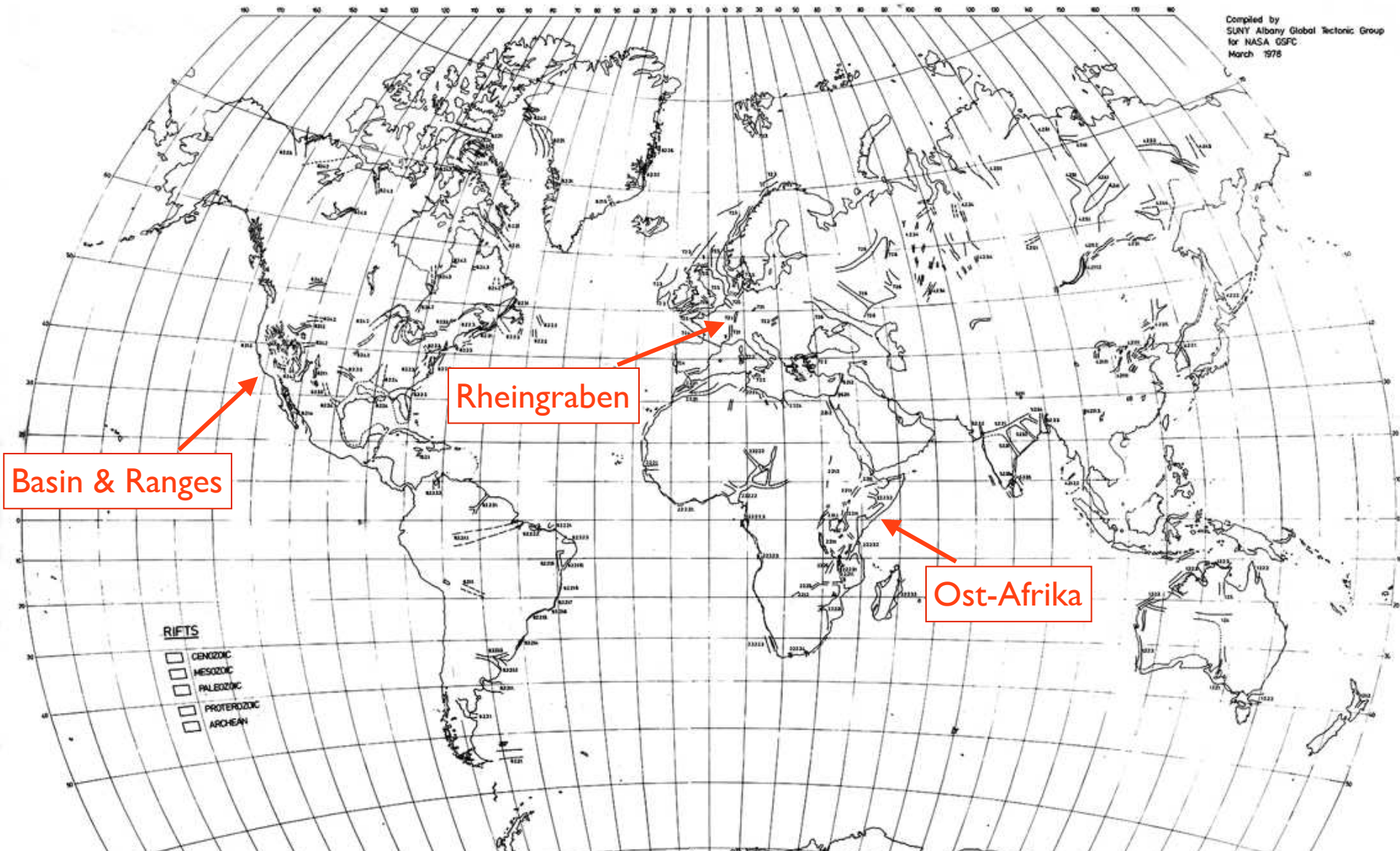
- Geometrie - Topographie
- Schwereanomalie
- Relativbewegung
- Wärmefluss
- Krustenausdünnung

## Verschiedene Rifts - Typen

- narrow rift
- wide rift
- metamorphic core complex
- rheology of detachment faults

# Rifting

# Rifts - aktiv und fossil



K.C. Burke, L. Delano, J.F. Dewey, A. Edelstein, W.S.F. Kidd, K.D. Nelson, A.M.C. Sengor and J. Stroup, 1979. Rifts and Sutures of the World. Contract Report NAS 5-24094. Geophysics Branch, ESA Division, Goddard Space Flight Center, Greenbelt, Maryland, 238 pp.

# fossile Rifts

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.

## Nord-Atlantik Öffnung:

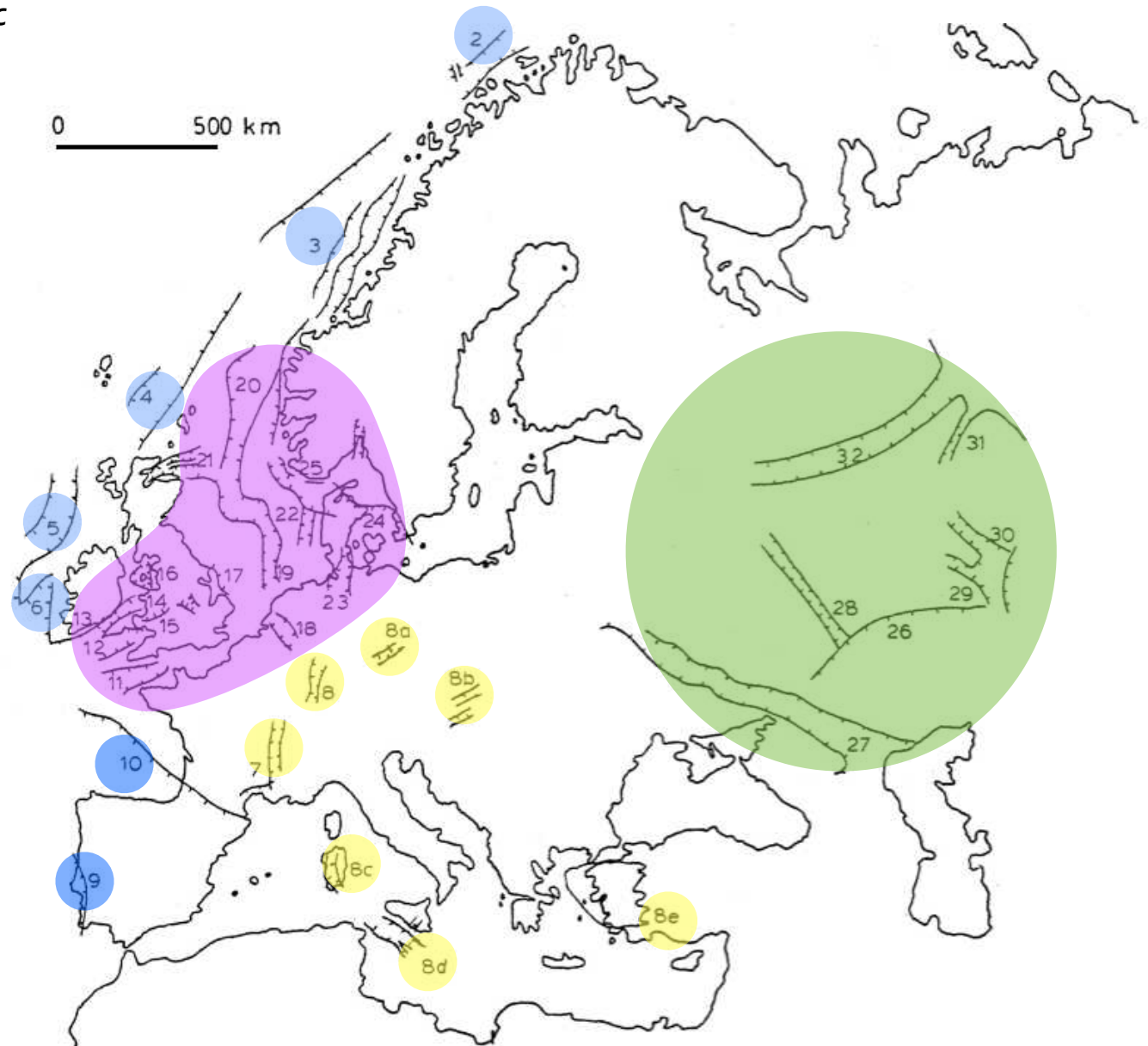
- ▶ Paläozän / Eozän
- ▶ Jura / Kreide
- ▶ Trias / Jura

## Bresse Rhein Graben:

- ▶ Paläogen

## Ural - Ozean:

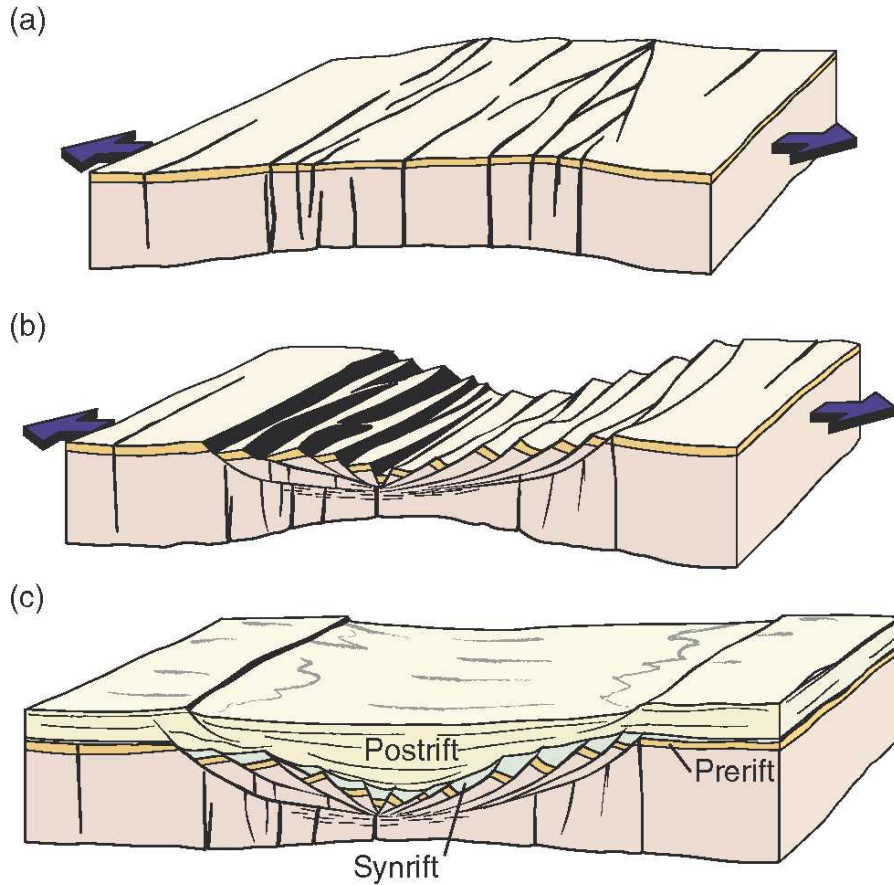
- ▶ Präkambrium



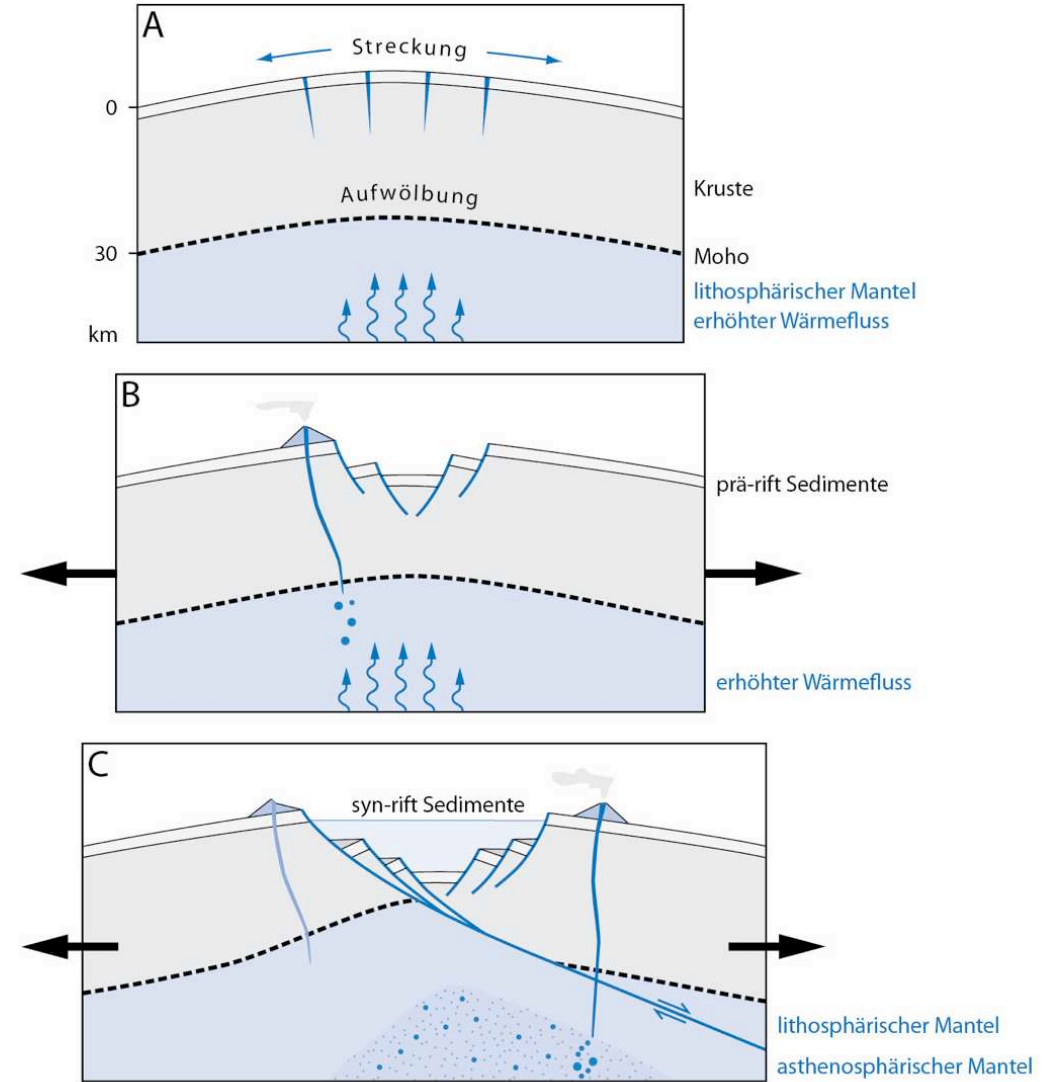
# Rifting

**RIFT** (genetic) region where the crust has split apart.

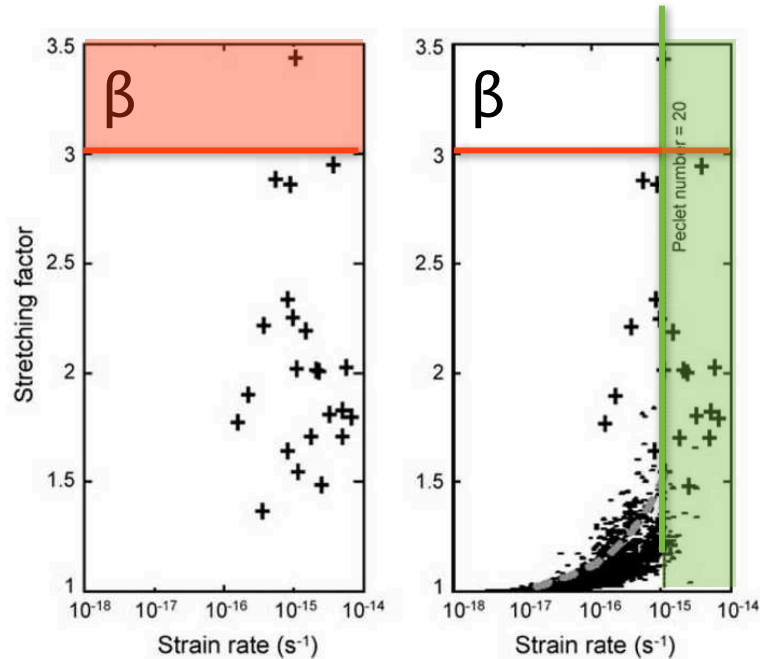
**GRABEN** (descriptive) trough, much longer than wide.



Haakon Fossen: Structural Geology



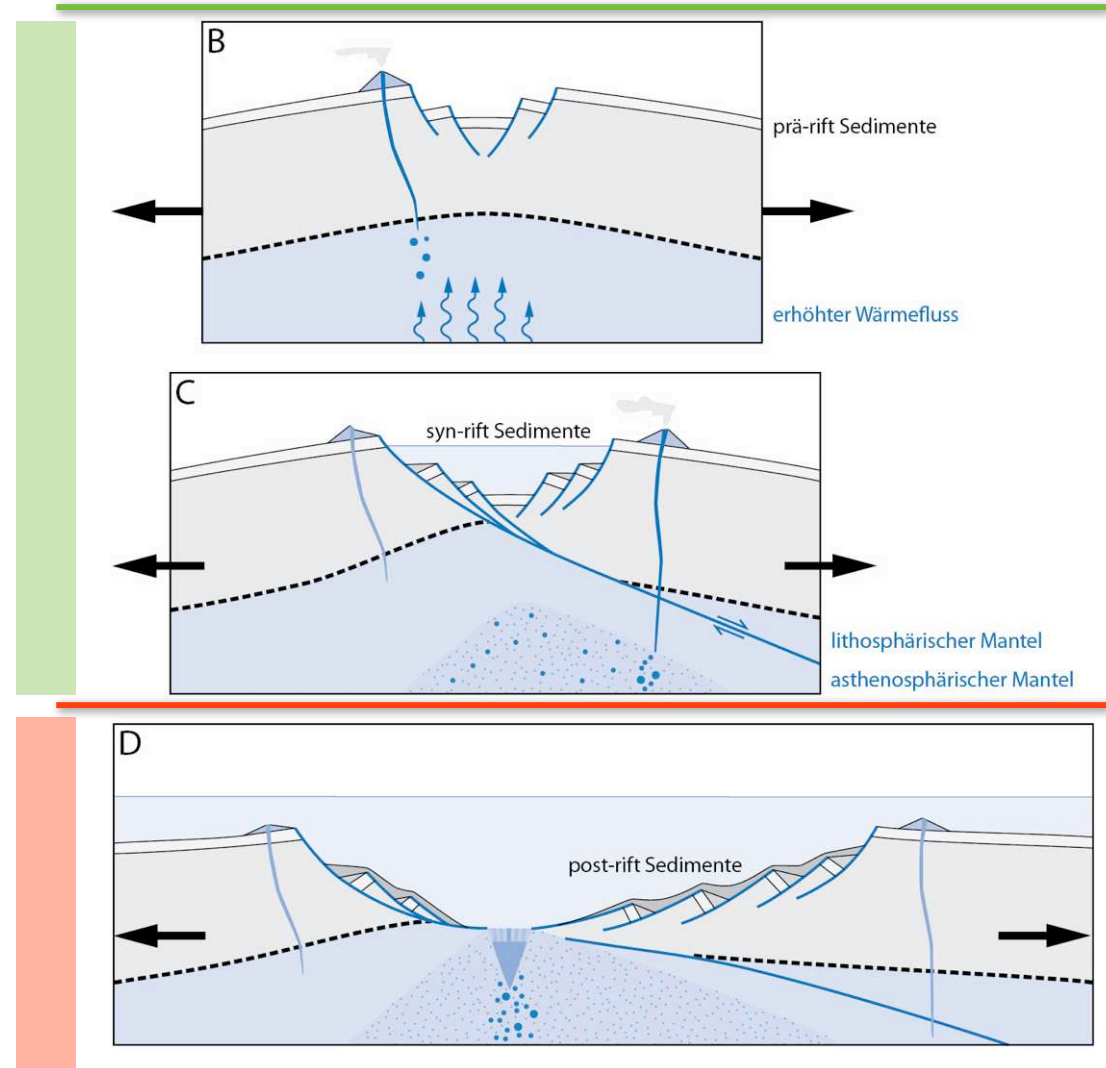
# rifting → seafloor spreading



+ rift basins (Atlantic margins)  
 - sedimentary basins  
 Davis and Kusznr, 2002, Geophys J Int, 149, 524-533

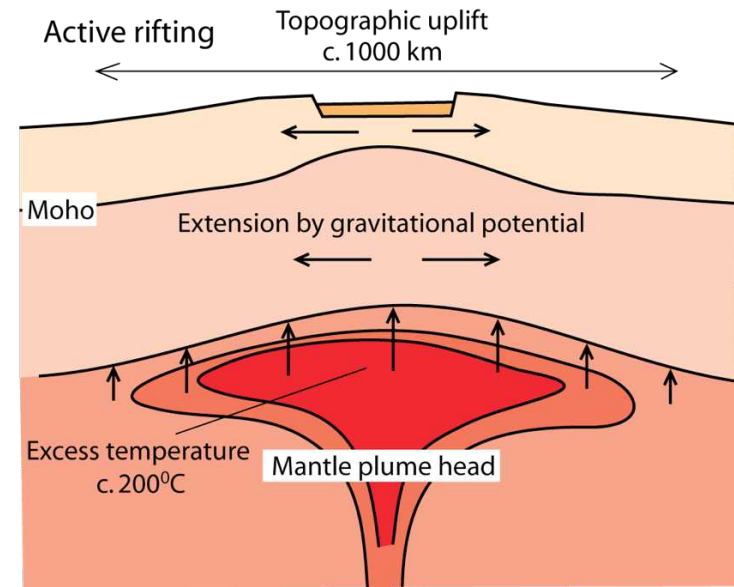
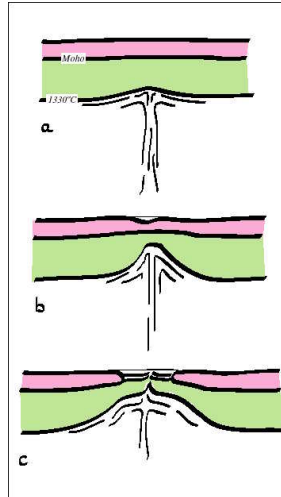
$\beta = t_o/t_c$  stretching factor  
 $t_o$  initial crustal thickness  
 $t_c$  present crustal thickness  
 wenn  $\beta > 3 \Rightarrow$  seafloor spreading

$Pe = f(\xi, \dots)$   
 wenn  $Pe > 20 \Rightarrow$  rift basins

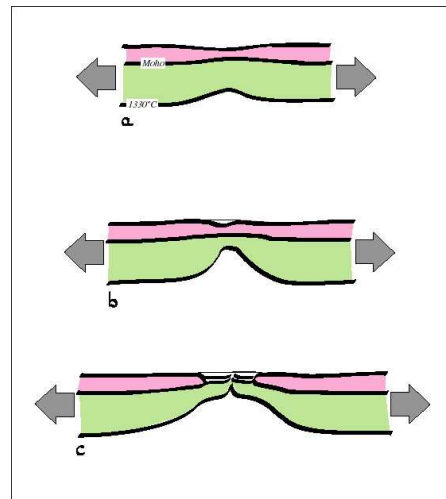


# active - passive rifting

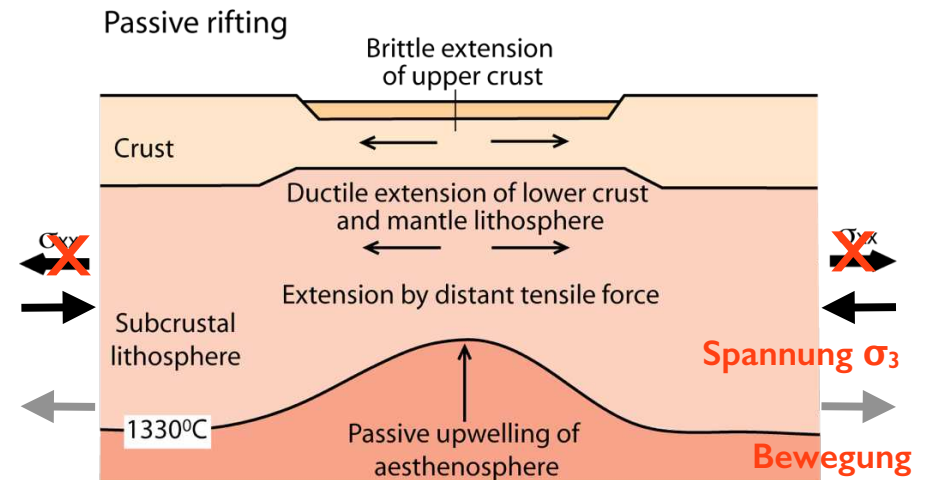
active rifting:  
Mantel Plume initiiert  
isostatischen Uplift  
Vulkanismus und  
“Doming” früh



passive rifting:  
Dehnung der  
Lithosphäre gefolgt  
von Mantel-Aufstieg  
Vulkanismus und  
“Doming” spät in  
Riftentwicklung

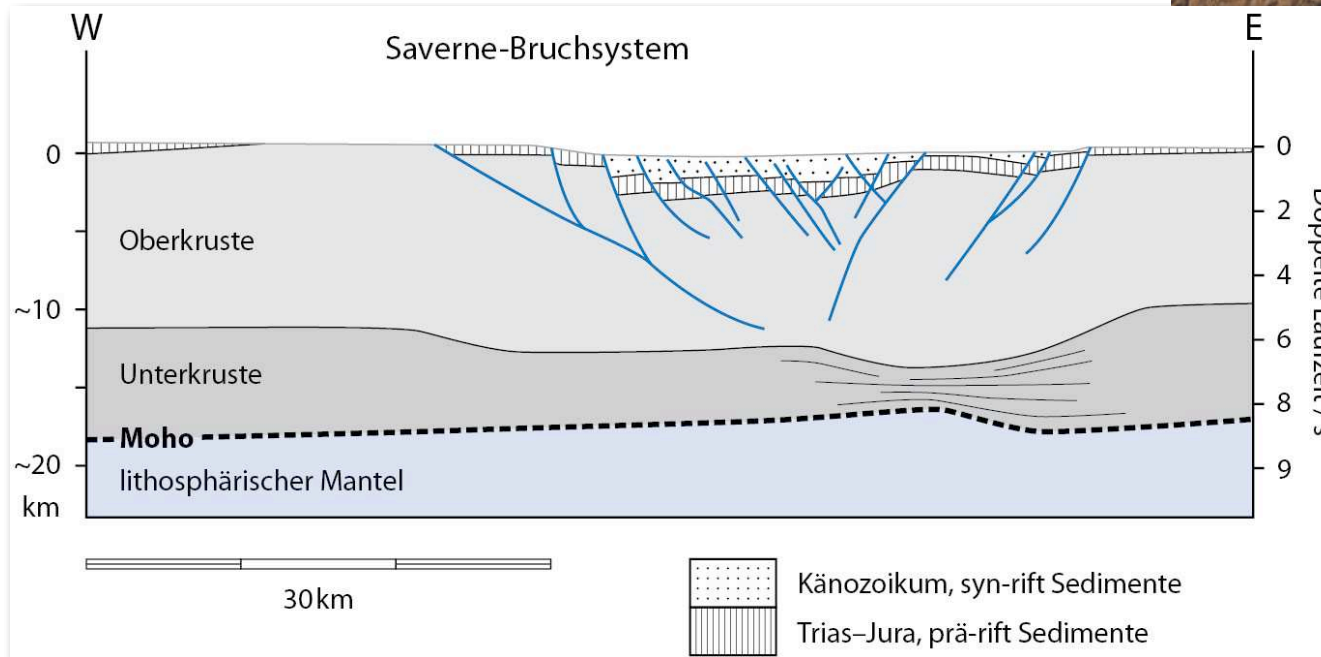


Bewegungsrichtung





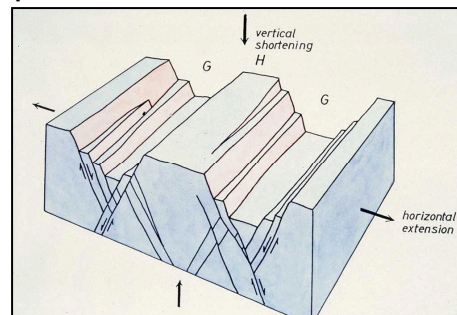
# Fossile rift: Rheingraben



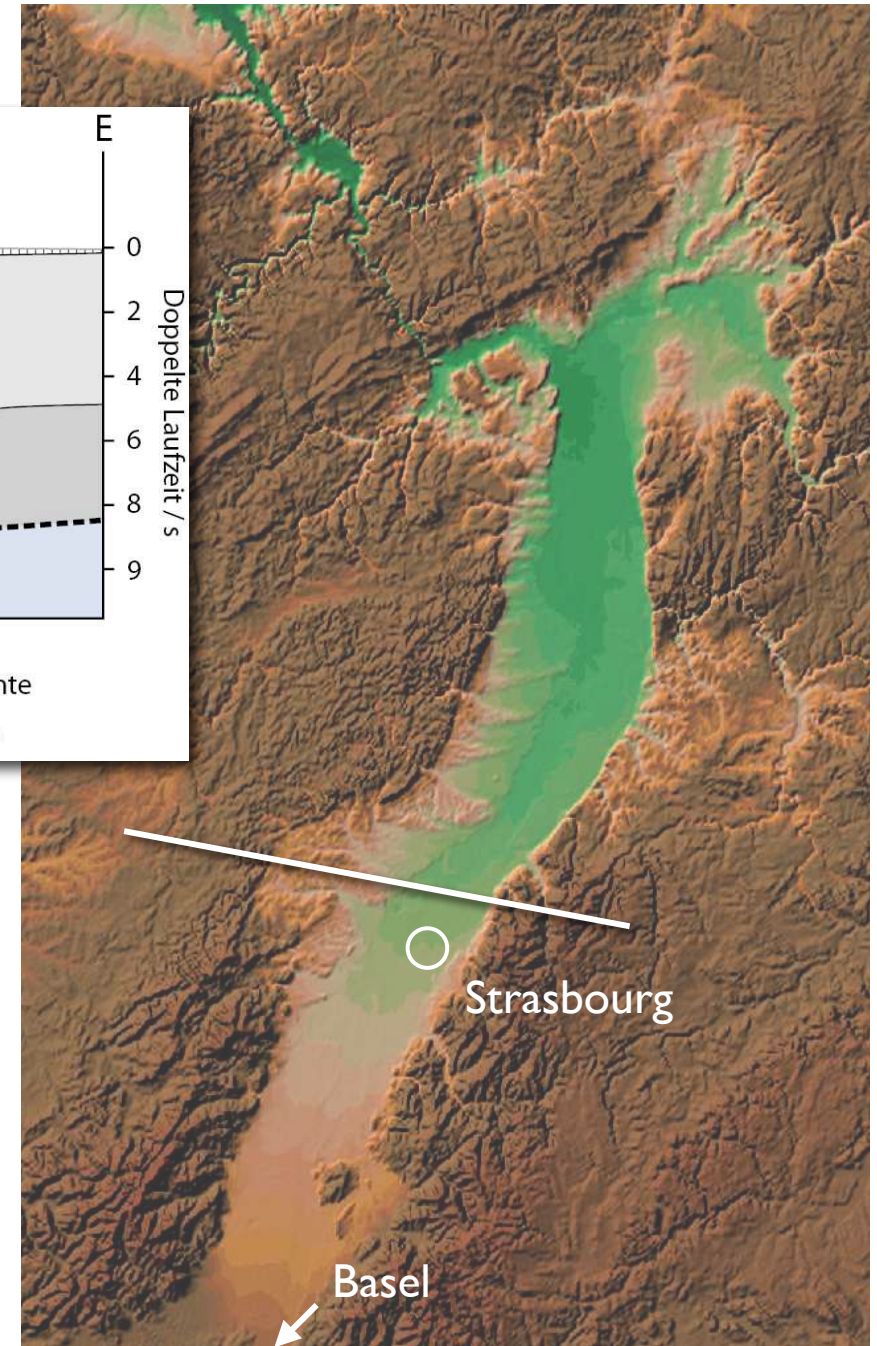
Pfiffner et al. Erdwissenschaften

narrow rift  
30 - 80 Ma

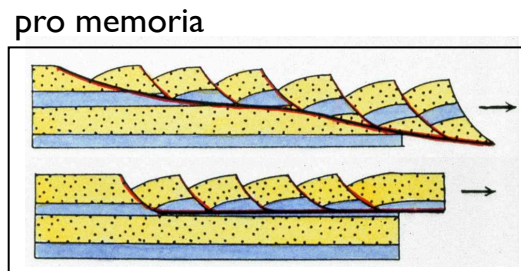
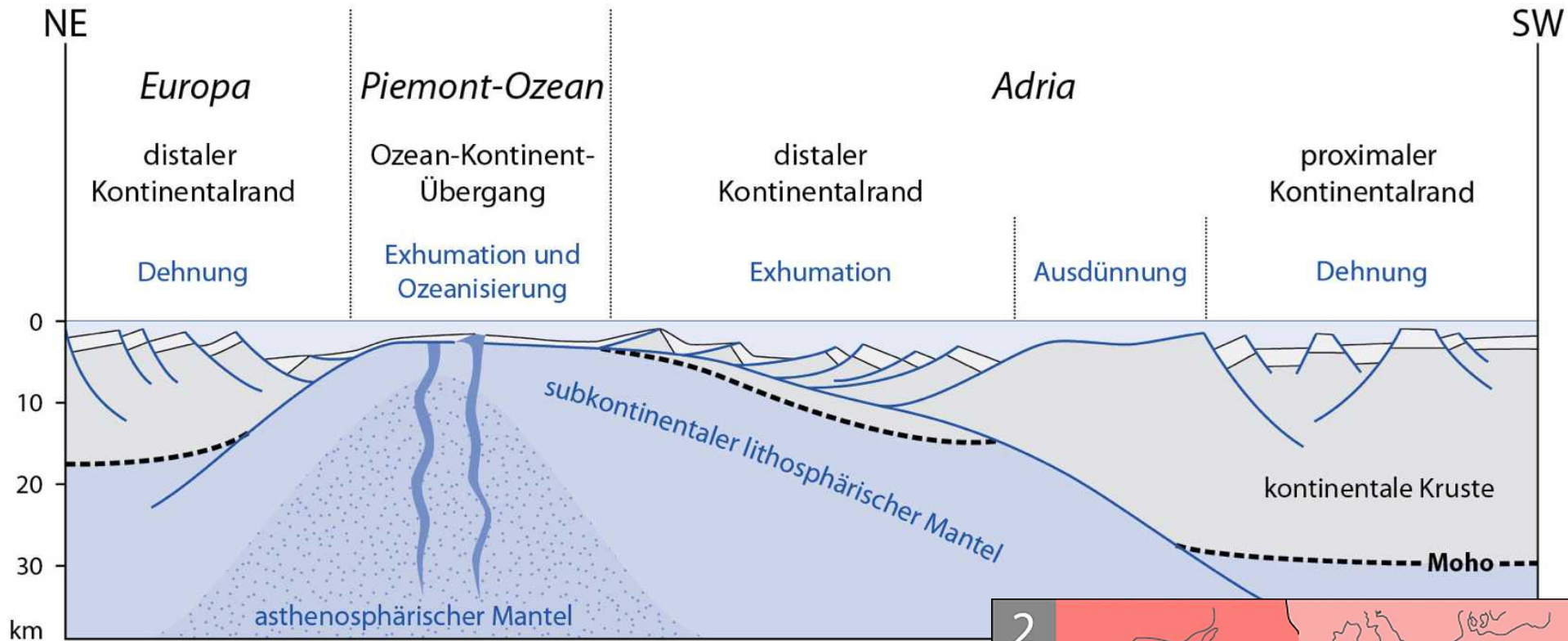
pro memoria



Rhine Graben = fossil rift  
(failed rift, aborted rift)

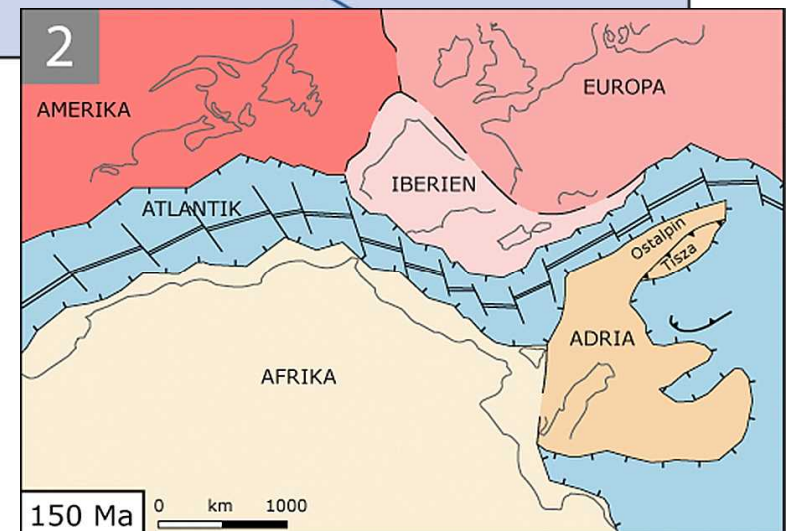


# Fossil ocean: Piemont-Ozean



190-120 Ma

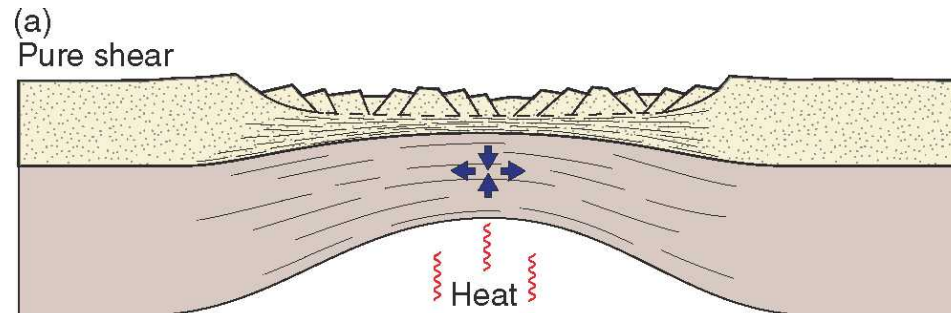
voll entwickelt → Ozeanisierung



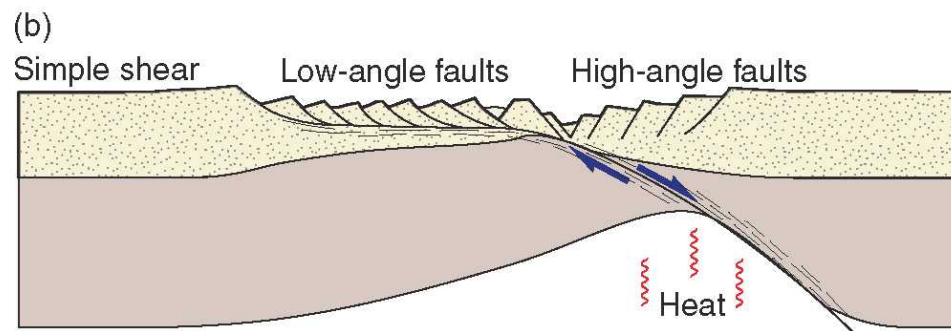
# Geophysikalische Merkmale

# Rift - Geometrie - Charakteristika

symmetrisch



asymmetrisch



Haakon Fossen:  
Structural Geology

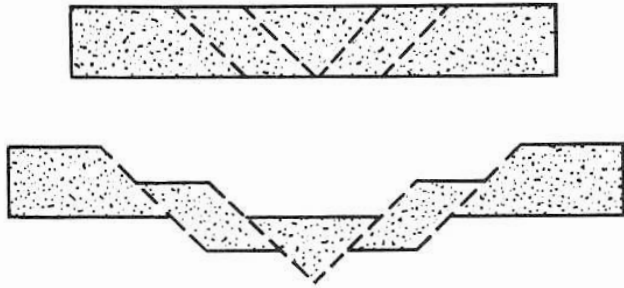
Characteristics of rifts:	1- normal faults flanks	Abschiebungen,
	2- uplifted shoulders	gehobene Schultern
	3- negative Bouguer Anomaly	negative Bouguer Anomalie
	4- differential motion of flanks	differenziell Bewegung
	5- shallow (tensional) seismicity	shallow Seismizität
	6- higher heat flow	hoher Wärmefluss
	7- crustal thinning	ausgedünnte Kruste

sieh auch: <http://earth-literally.blogspot.ch/2012/01/basin-analysis-flog.html>

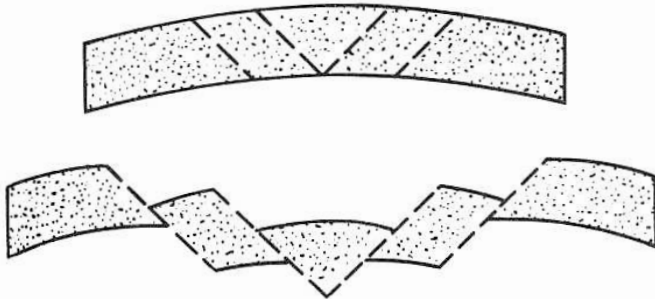
# Block faulting

## PLANAR NORMAL FAULTS

(a) Normal faults without folding



(b) Normal faults with folding



Allen and Allen, 1990

## Normal faults – rotation of fault blocks

(c)

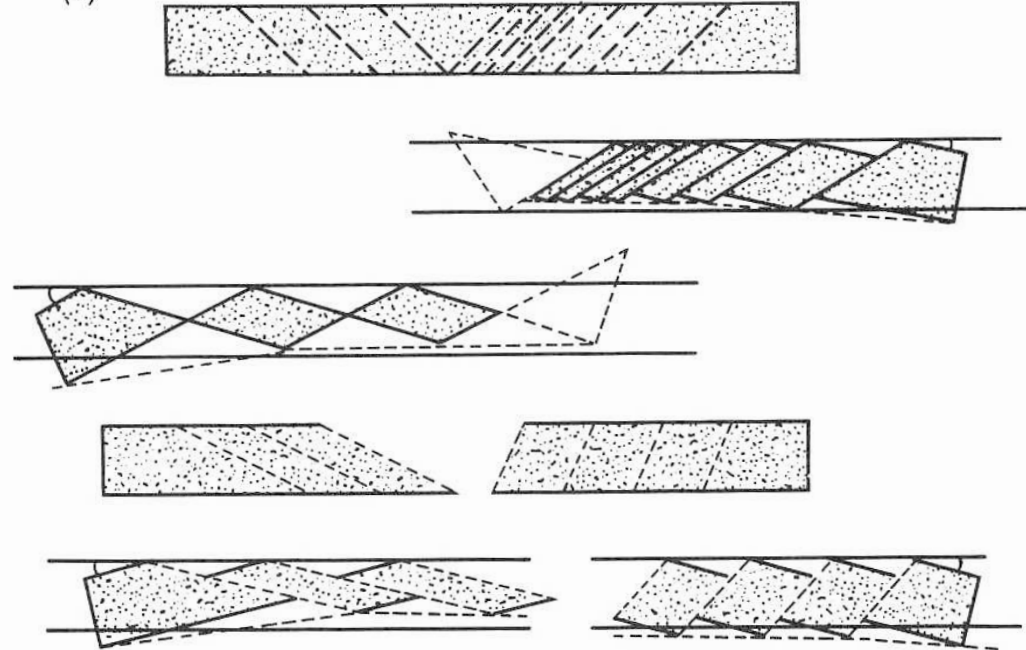
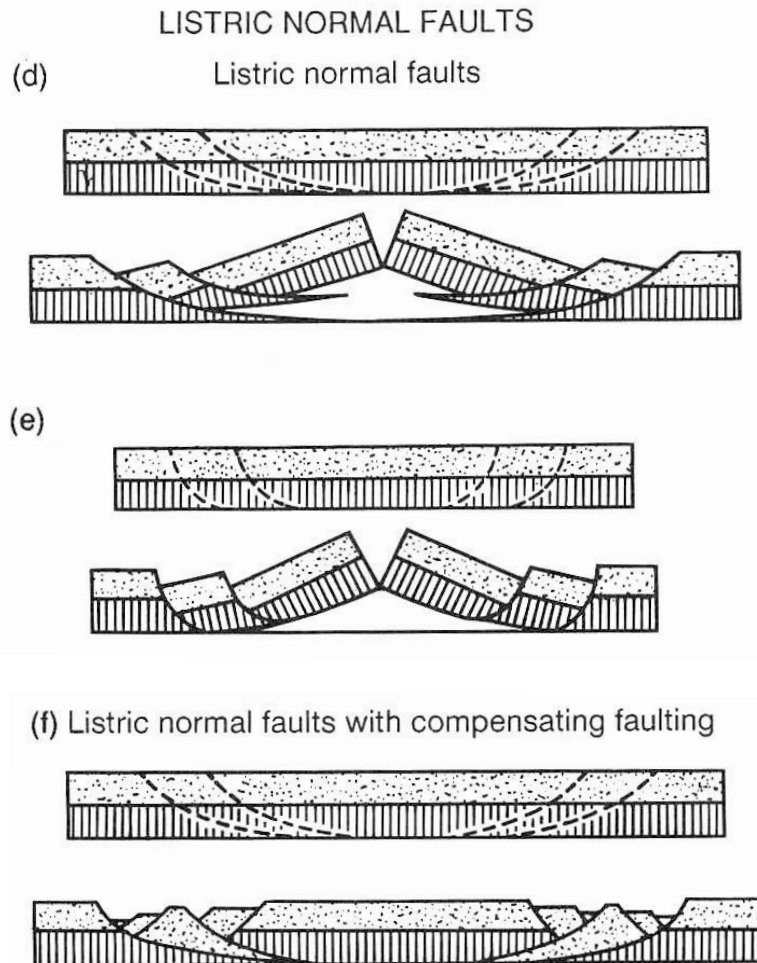


Photo Claudio Rosenberg

# Listric faults



Allen and Allen, 1990

## Kompatibilitätsprobleme

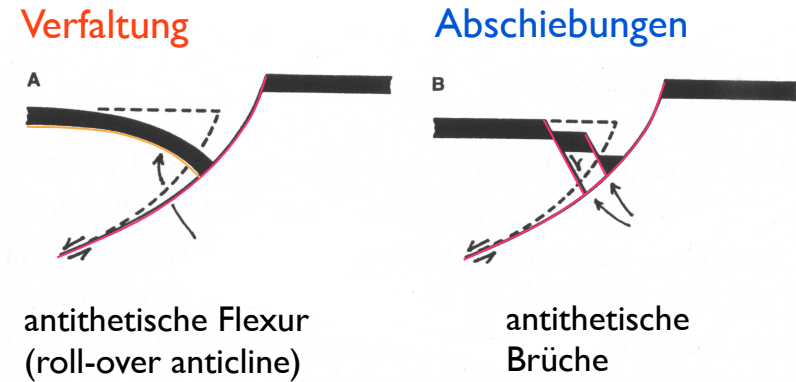
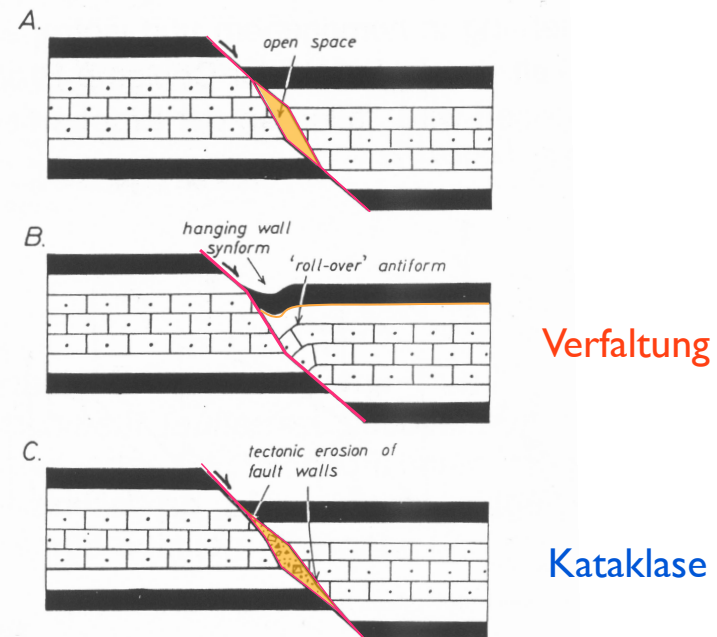


Fig. 9.4 Davis (1984)



Ramsay & Huber (1987, vol.2)

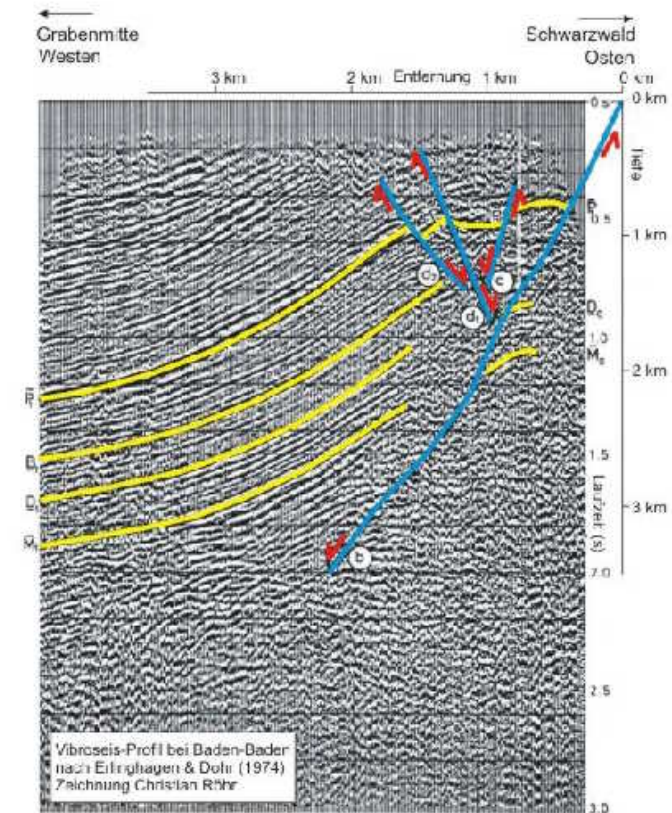
# Rift - Flanken

I- normal faults flanks

Beispiel: Afar



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

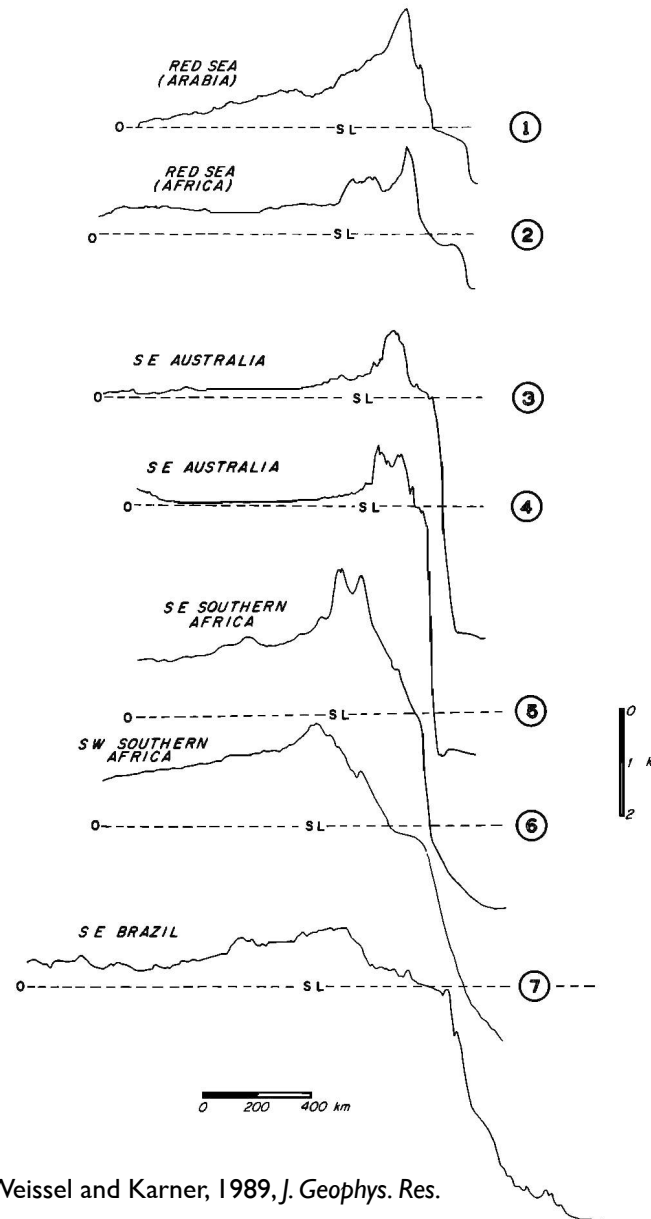
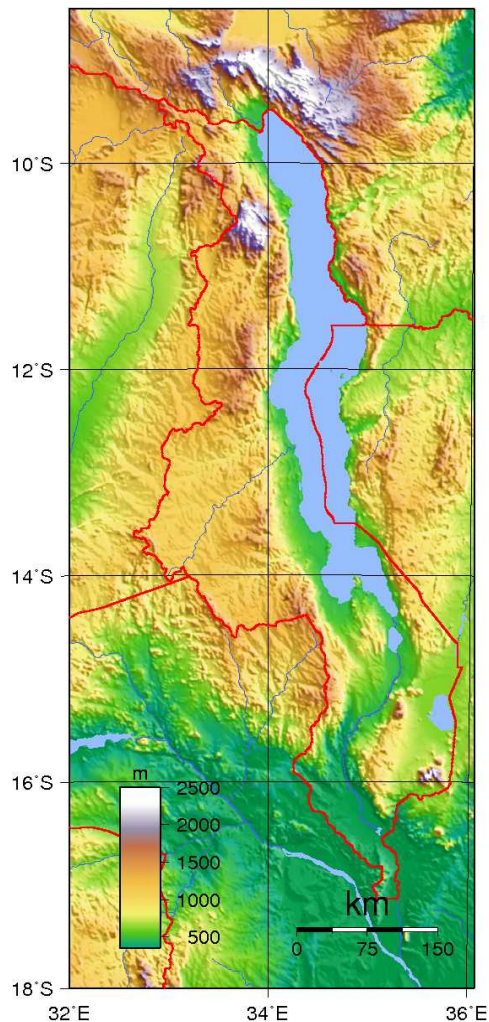


Rheingraben

# Rift - Topographie

2- uplifted shoulders

Beispiel: Lake Malawi



Rift flank uplifts  
= permanent structures

Caused by:  
mechanical unloading  
during extension  
→ isostatic rebound

≠ thermal structures  
(In fossil rifts, thermal support  
ended long time ago)

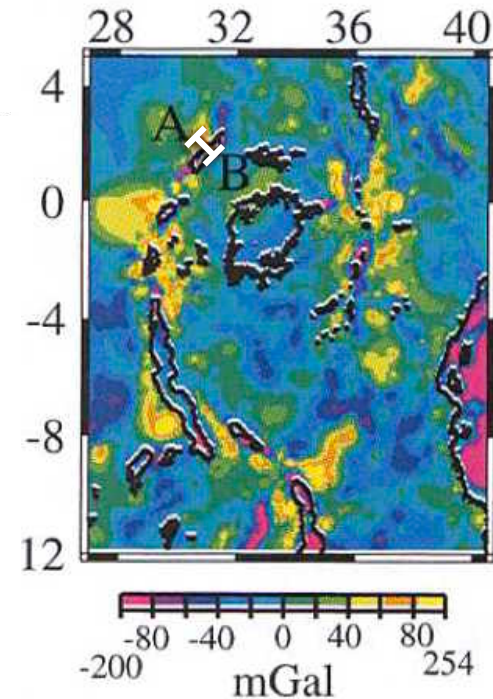
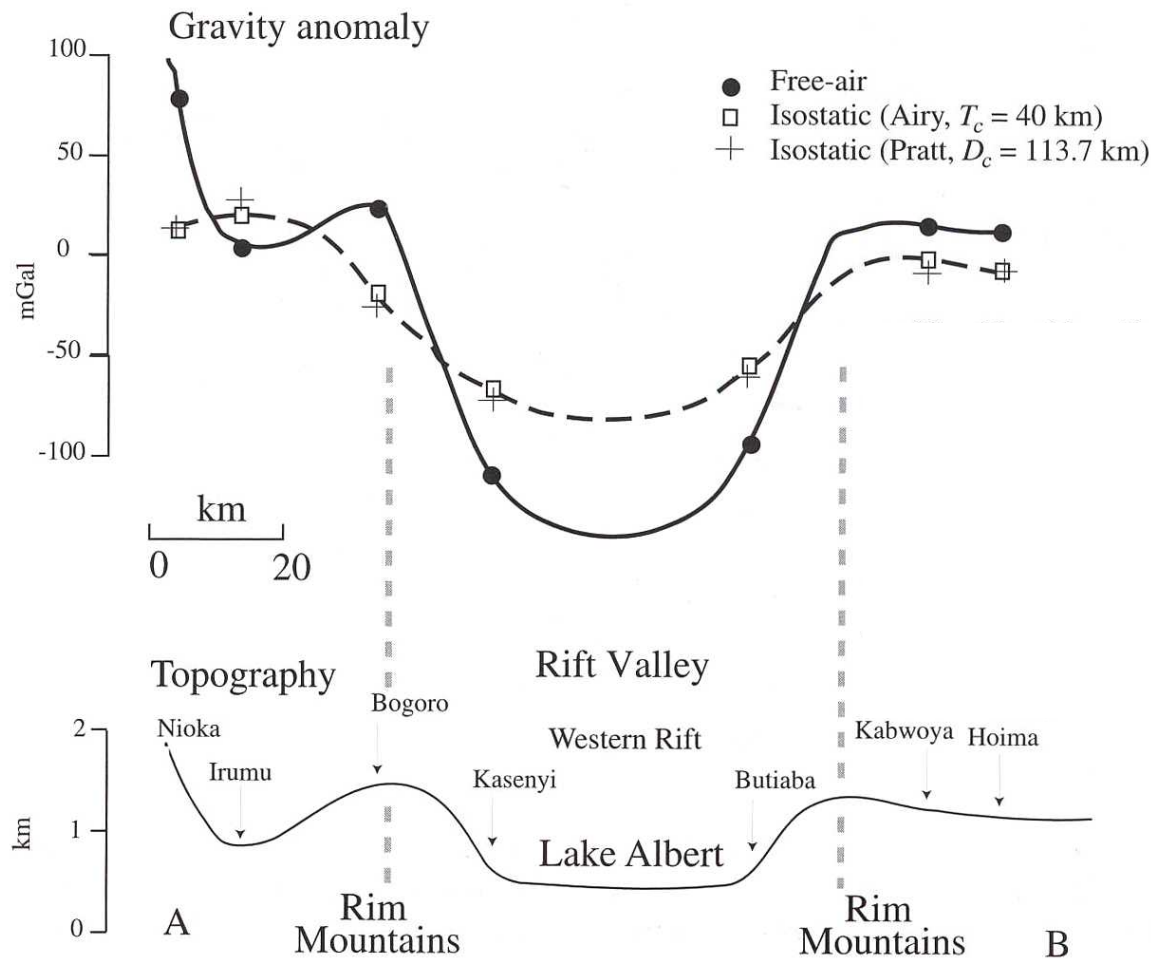
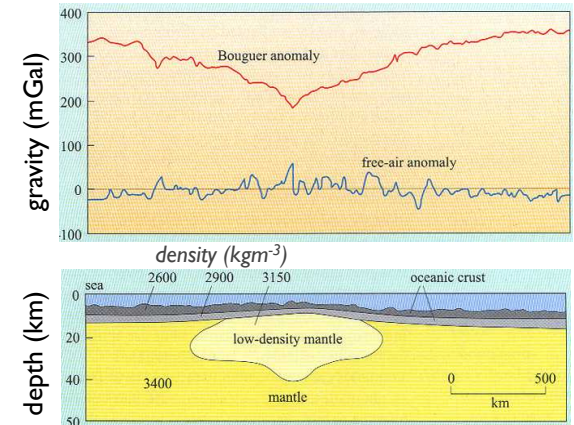


# Rift - Schwere-Anomalie

3- negative Bouguer Anomaly

Beispiel: East African Rift

pro memoria

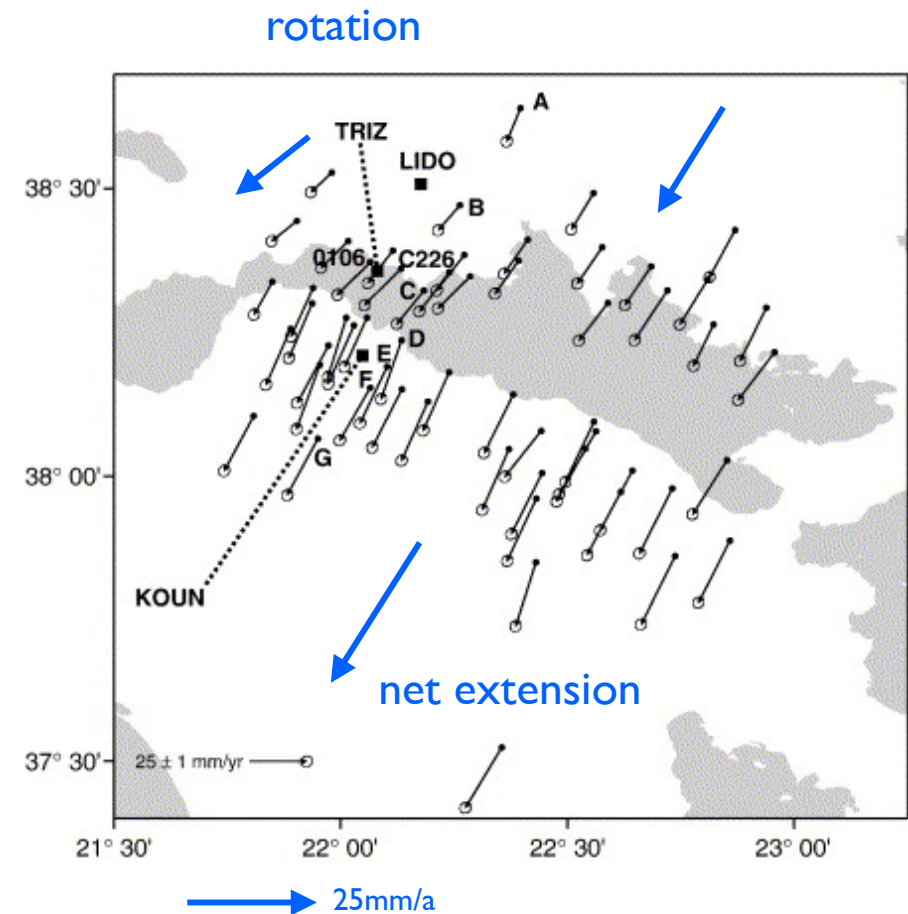


Watts, 2001

# Rift - Öffnungsbewegung

4- differential motion of flanks

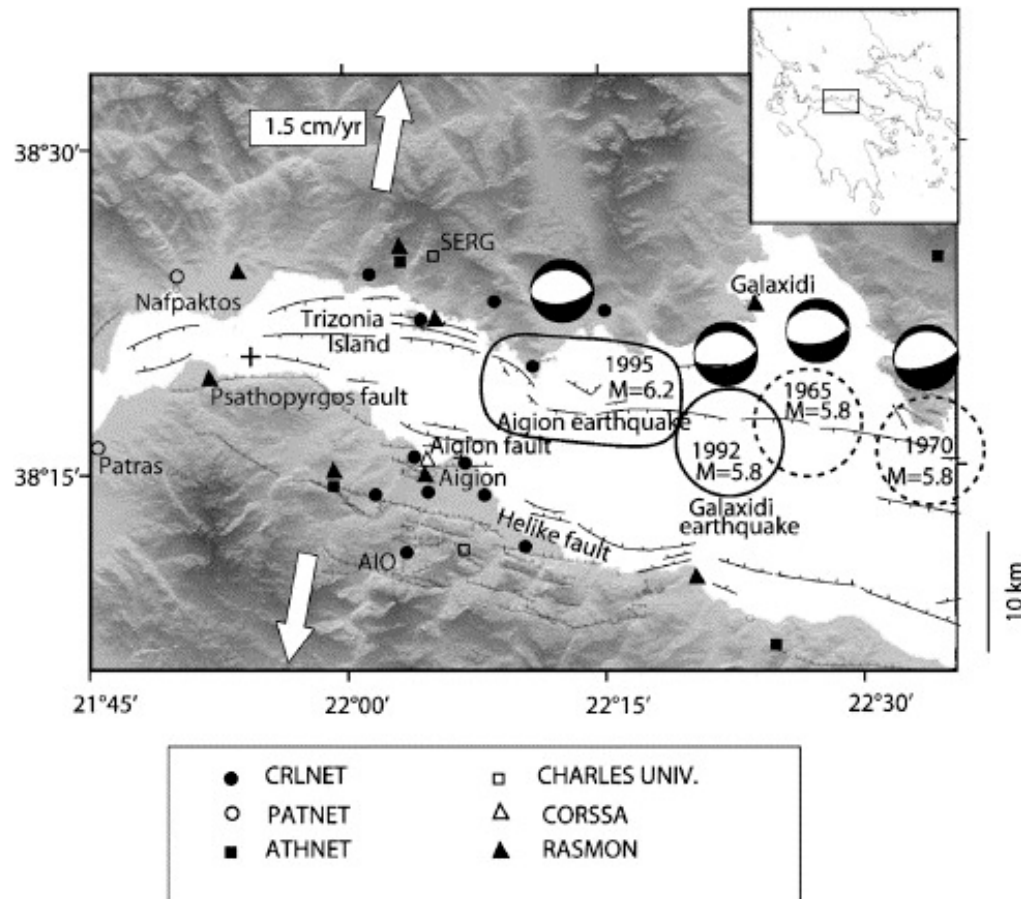
Beispiel: Golf von Korinth



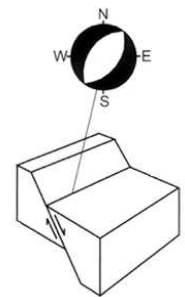
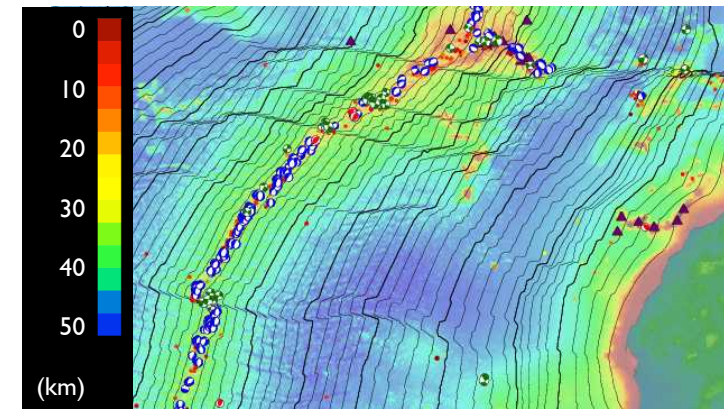
# Rift - Seismizität

5- shallow (tensional) seismicity

Beispiel: Golf von Korinth



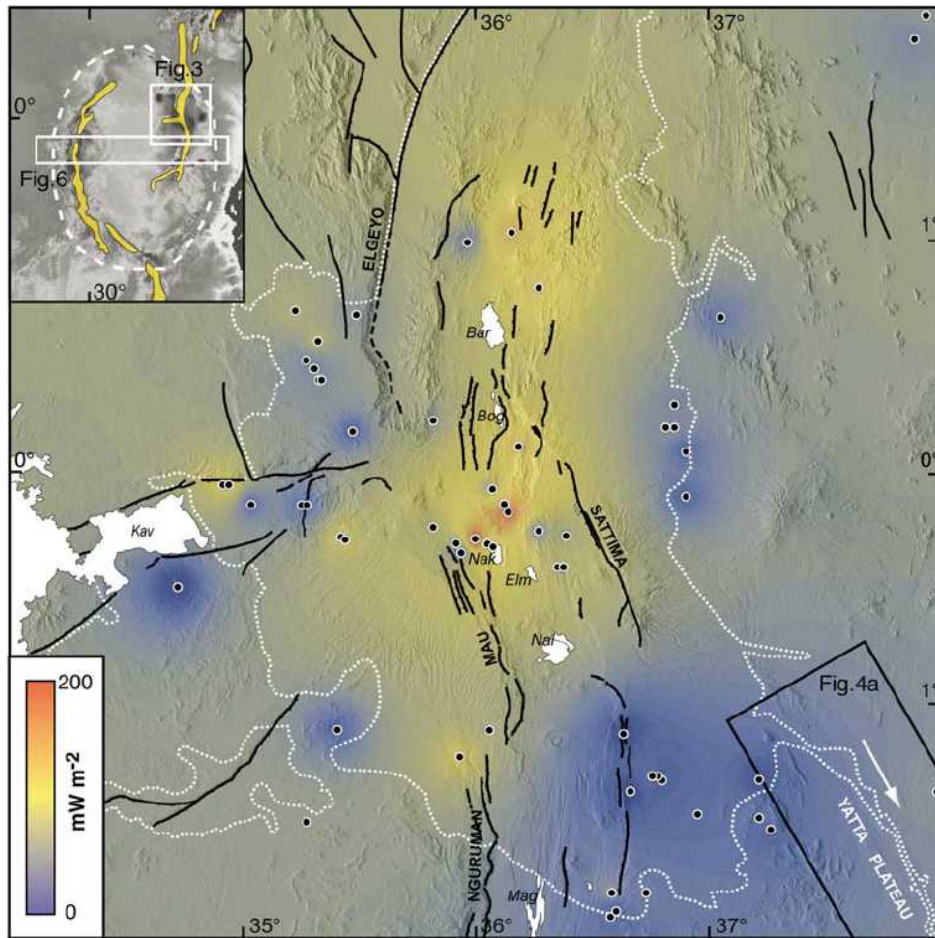
pro memoria



# Rift - Wärmefluss

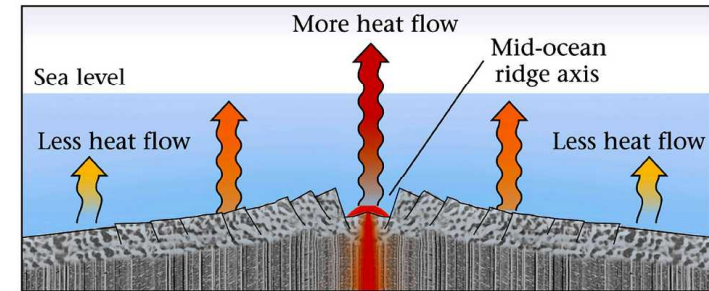
6- higher heat flow

Beispiel: Kenya



Wichura, Bousquet, Oberhänsli, et al. 2011  
Geol.Soc.Lond.Spec.Pub.

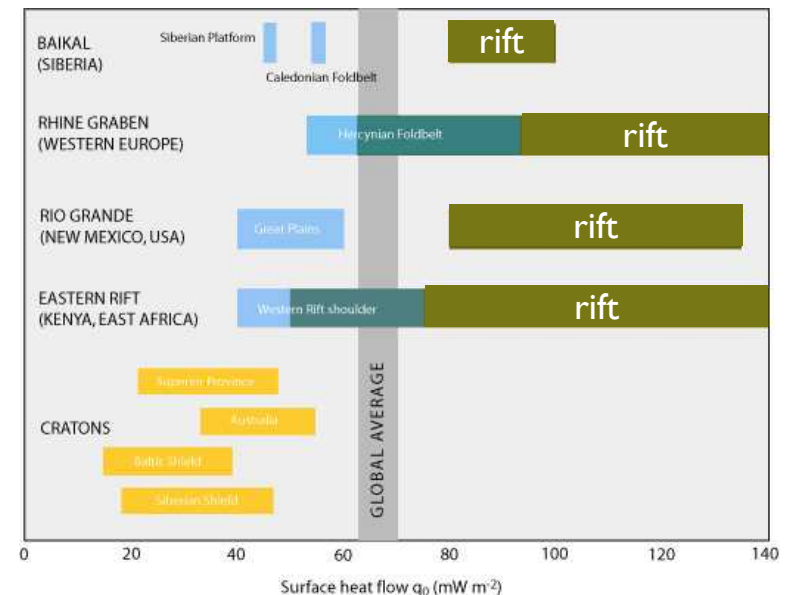
pro memoria



$$Q_{\text{rift}} = 100 - 200 \text{ mWm}^{-2}$$

$$Q_{\text{average}} = 100 \text{ mWm}^{-2}$$

- old cratons  $< 40 \text{ mWm}^{-2}$
- old oceanic crust  $\sim 50 \text{ mWm}^{-2}$
- young mountain belts  $60-75 \text{ mWm}^{-2}$

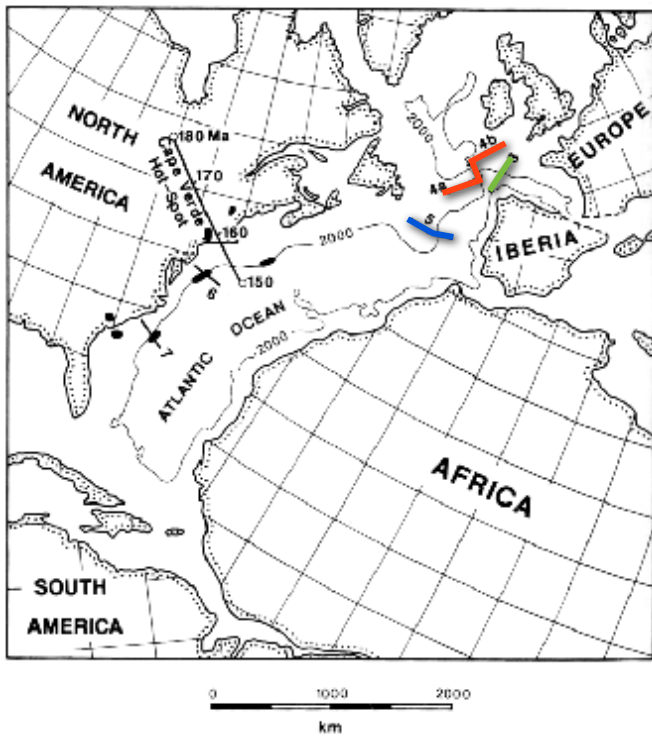


<http://earth-literally.blogspot.ch/2012/01/basin-analysis-flog.html>

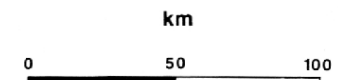
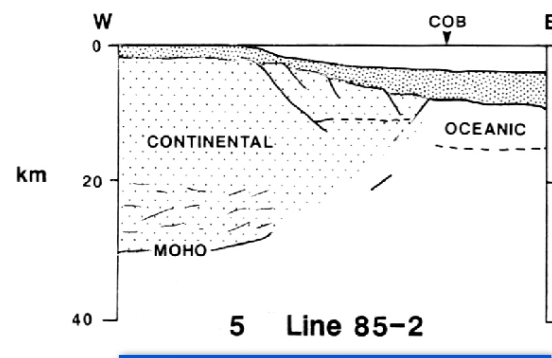
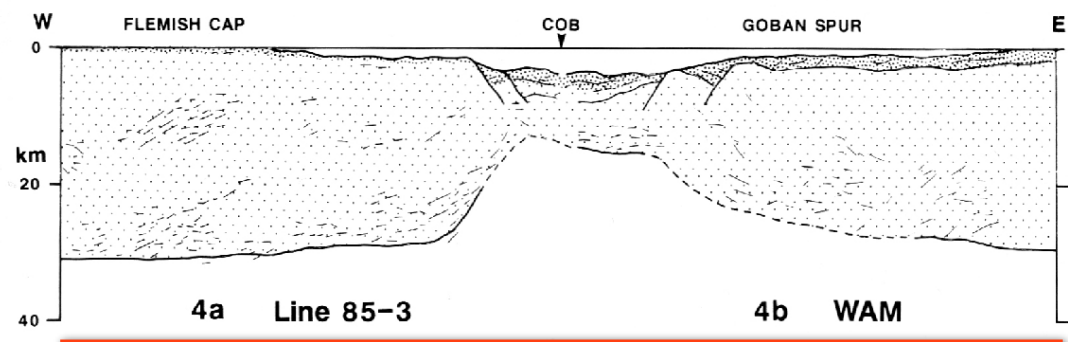
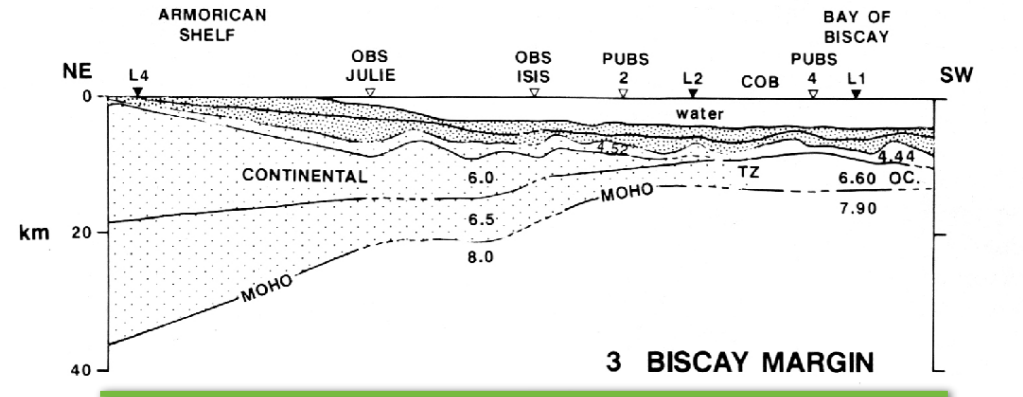
# Rift - Krustenausdünnung

7- crustal thinning

Beispiel: Golf von Biscaya



Biscay margin  
 Western Approaches margin (WAM)  
 Newfoundland margin



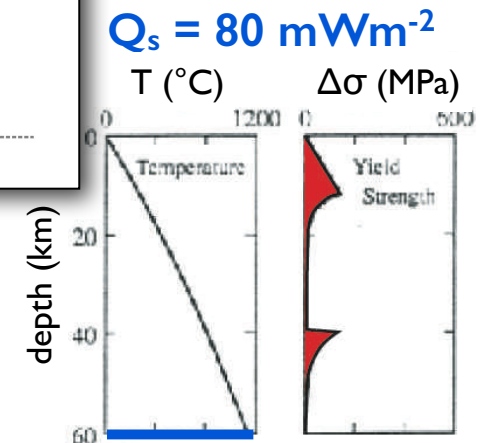
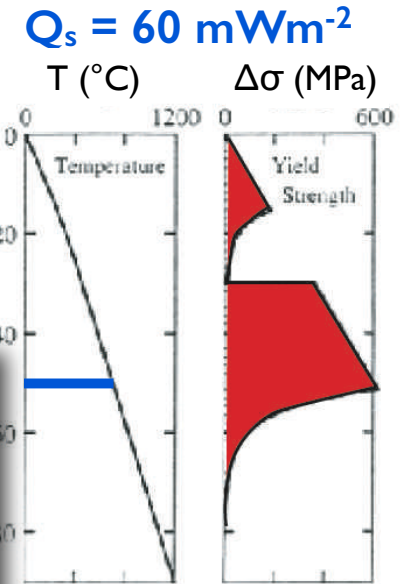
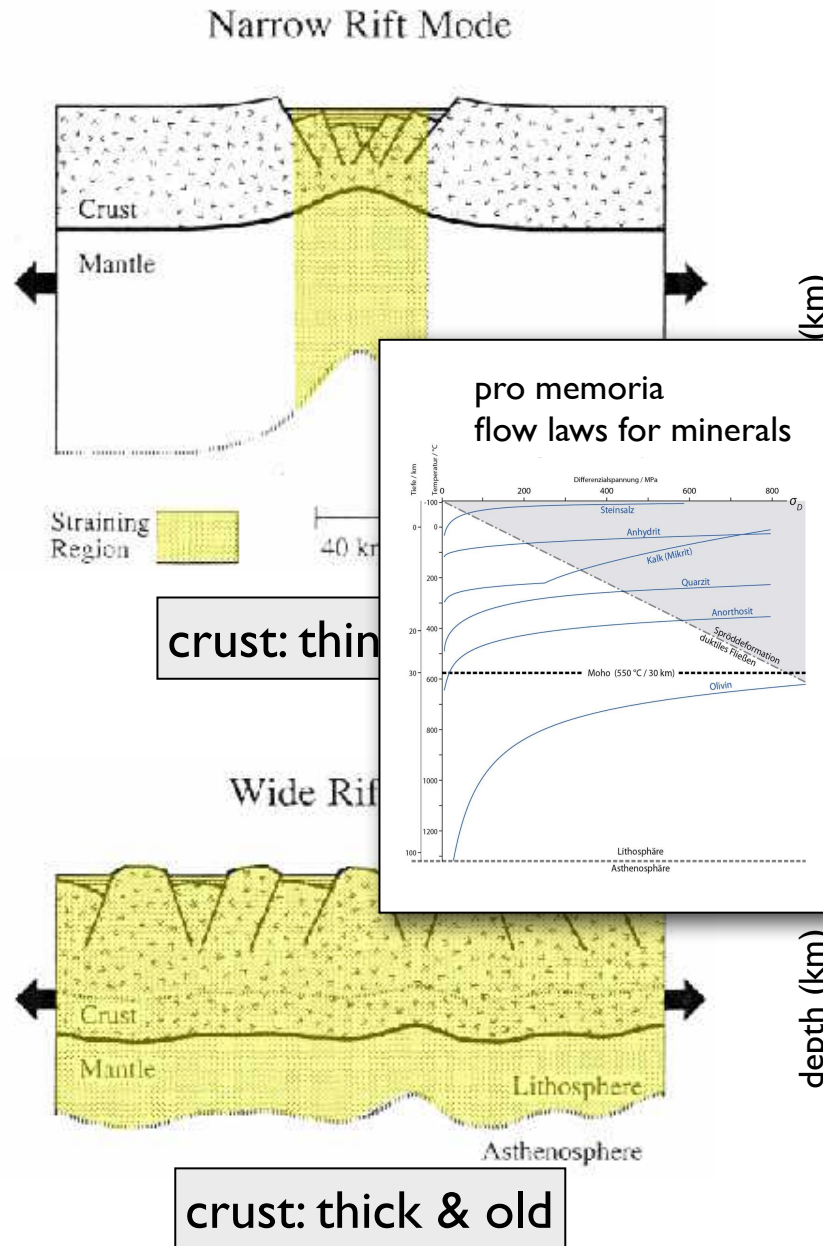
V.E. 2.3x  
 2.3x überhöht!

different rift types

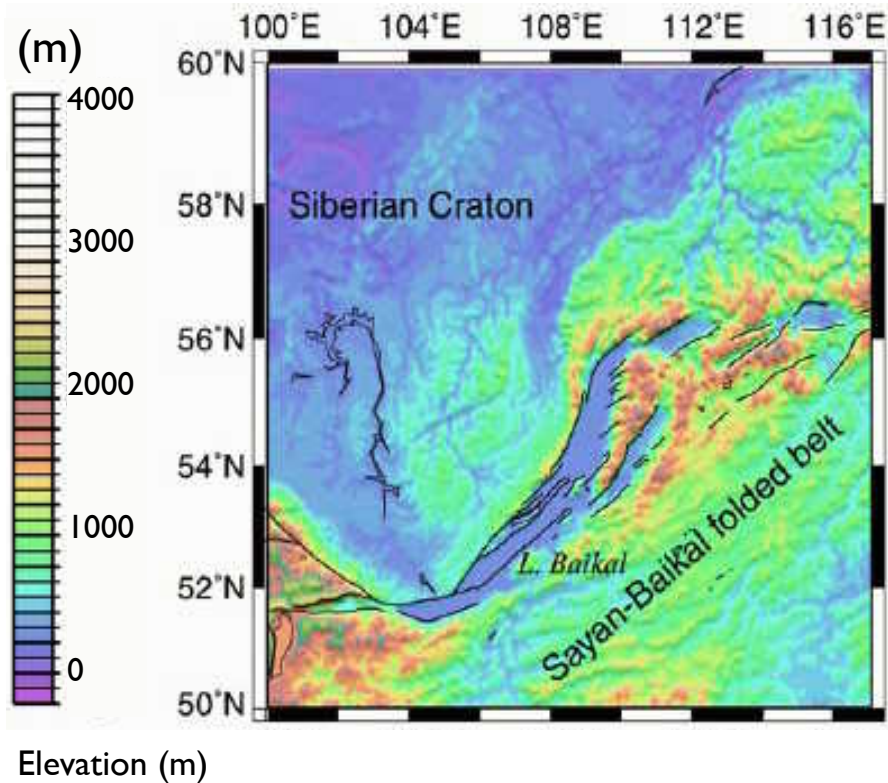
# narrow - wide rift

Narrow rift (localized):  
 Niedriger **geothermischer Gradient**: die **Festigkeit** von Kruste und Mantel ist relativ hoch - kein gravitativer Kollaps

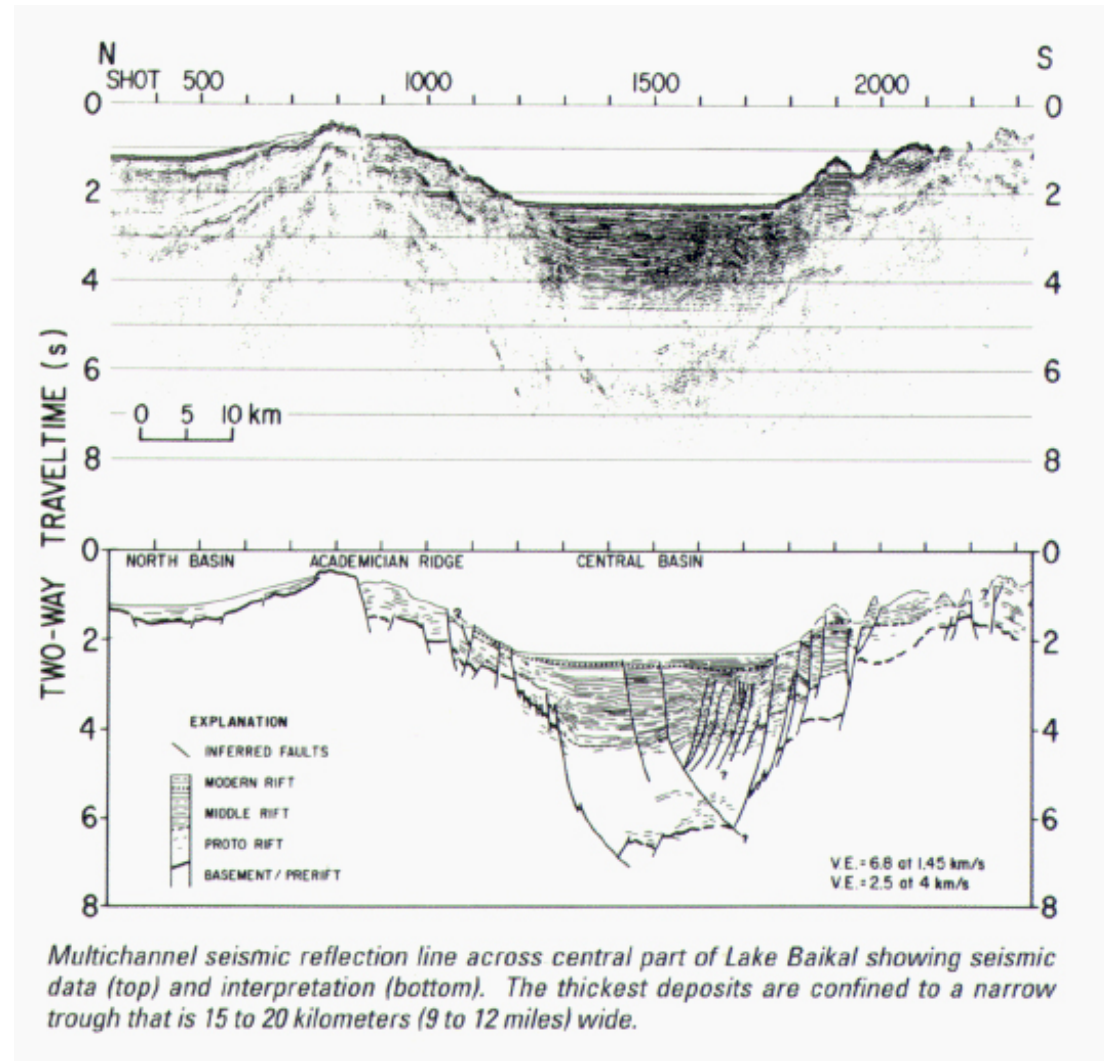
Wide rift (distributed):  
 Höherer **geothermischer Gradient**: die **Festigkeit** von (Kruste und) Mantel nimmt ab - weiträumiger Kollaps der Lithosphäre



# narrow rift: Bsp. Baikal Rift



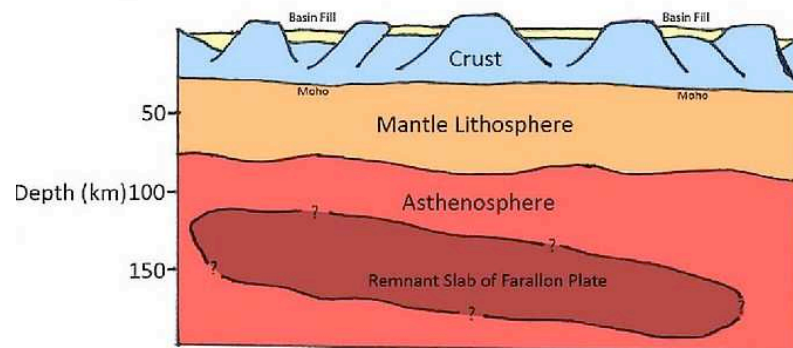
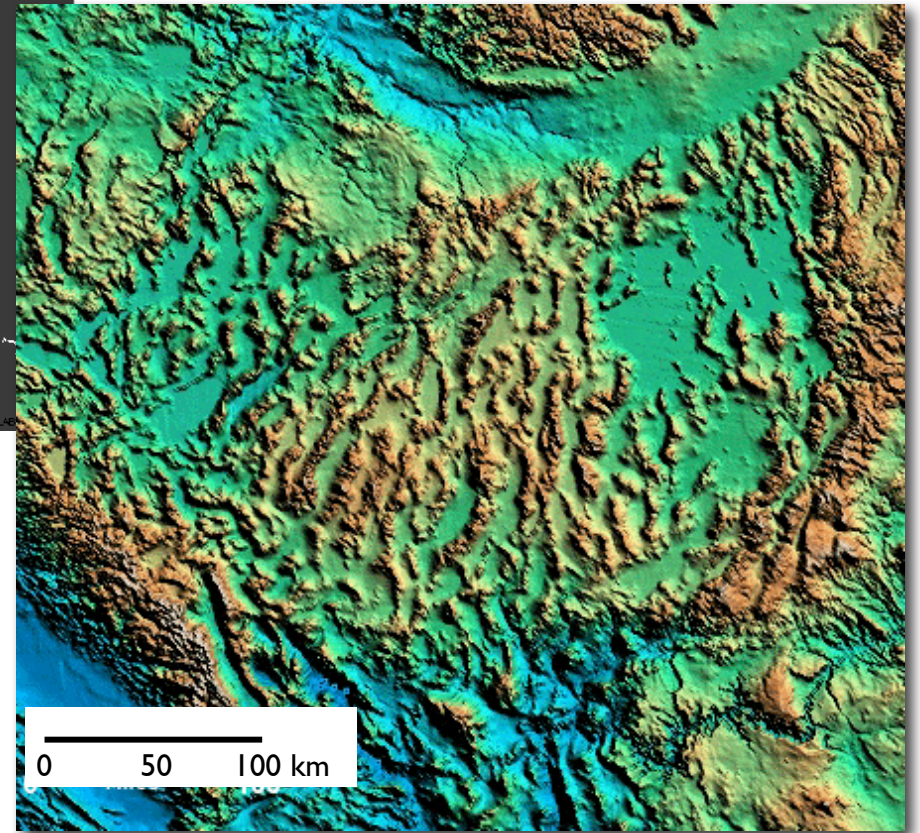
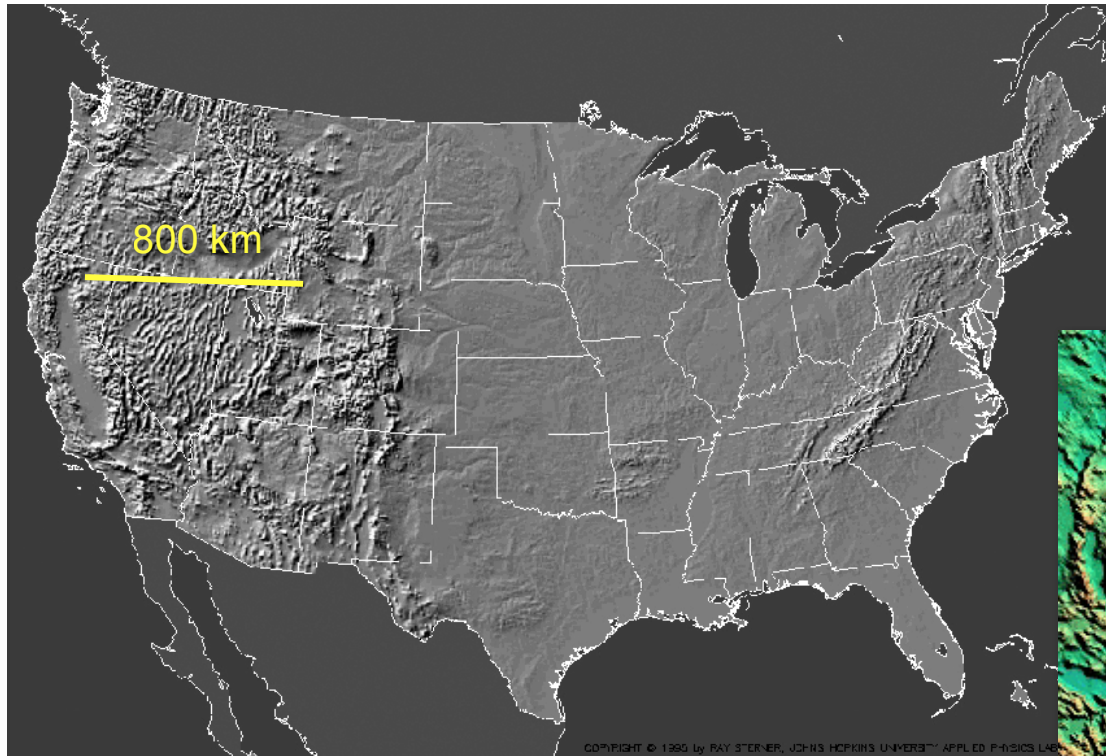
Topographie



Seismisches Profil  
Interpretation

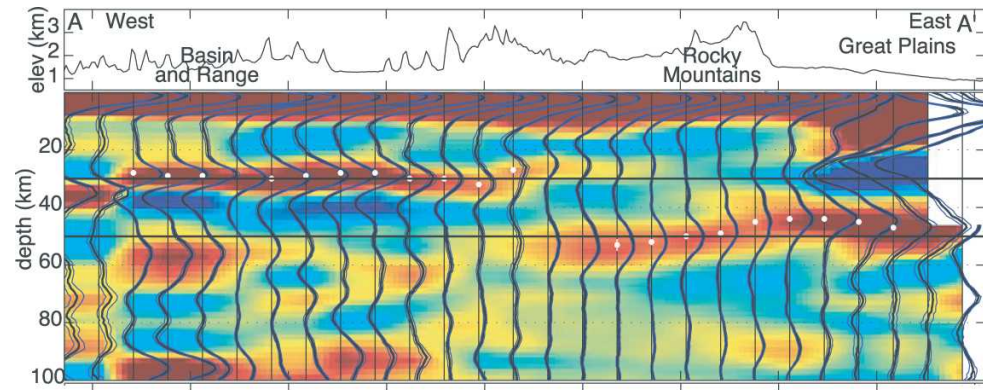
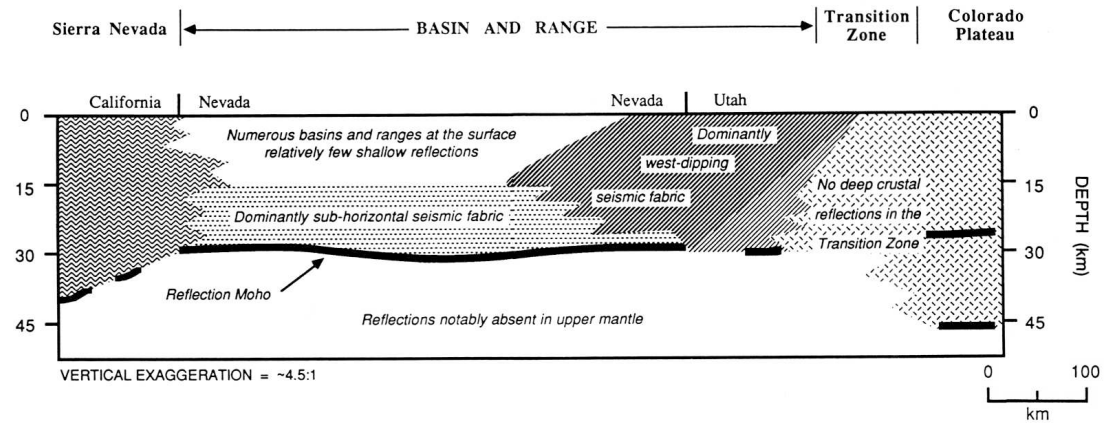
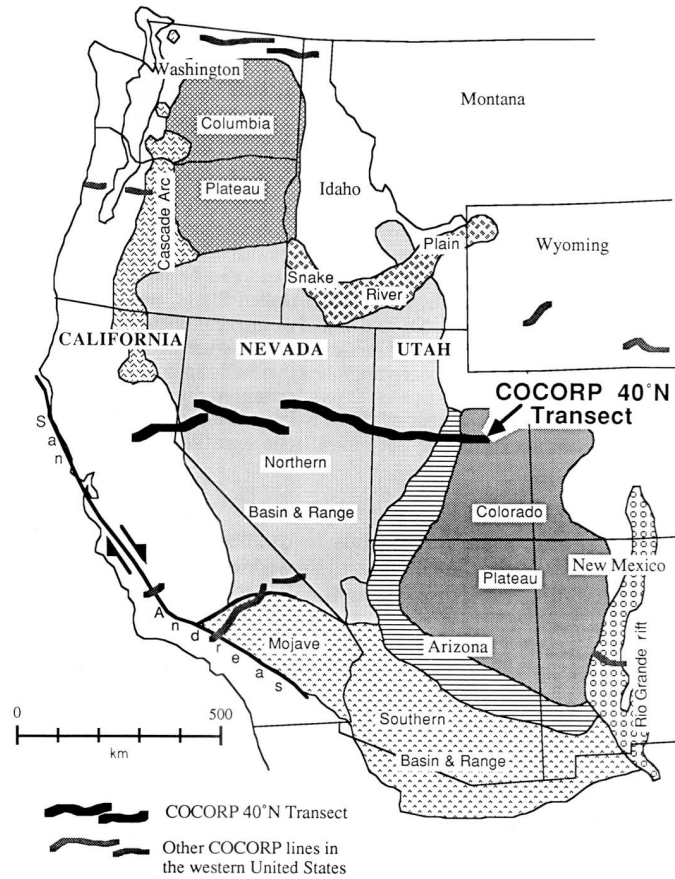


# wide rift: Bsp. Basin and Ranges

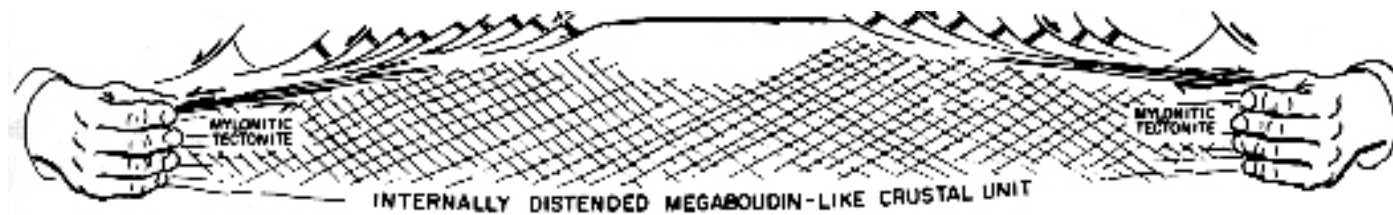


crustal thickening

# flache Moho



# metamorphic core complexes

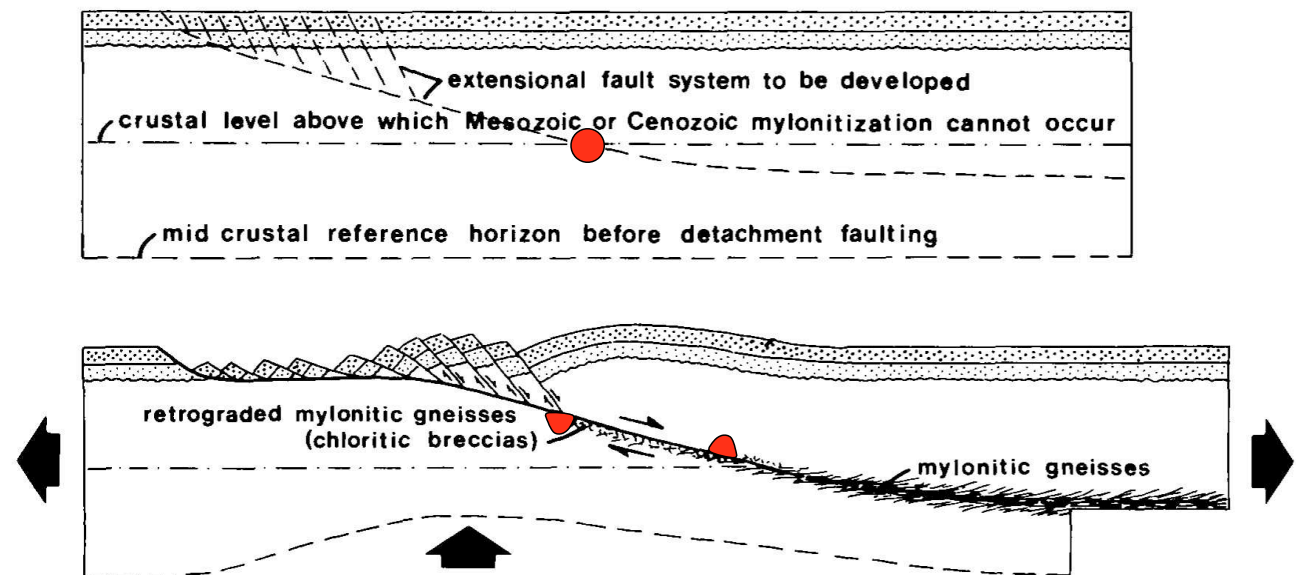
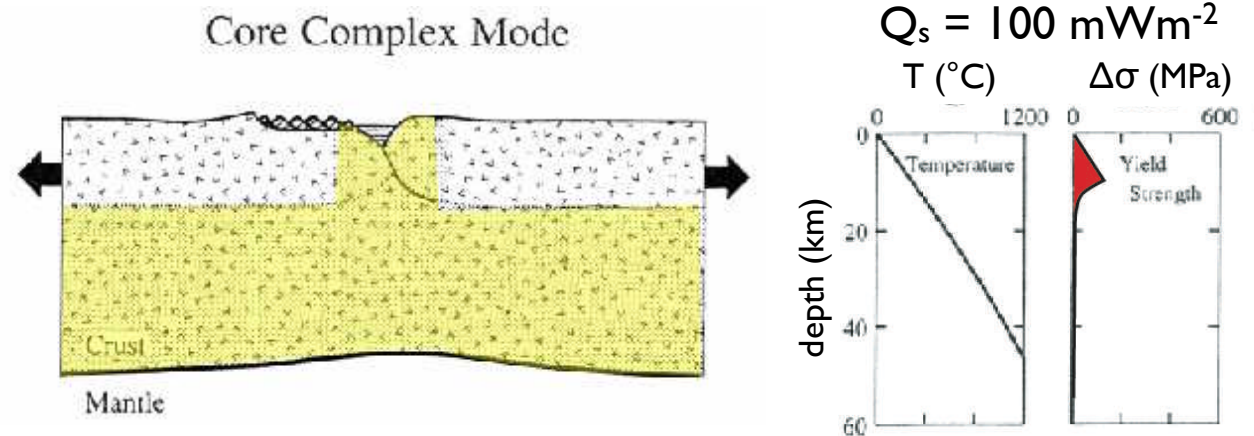


# Metamorphic Core Complex

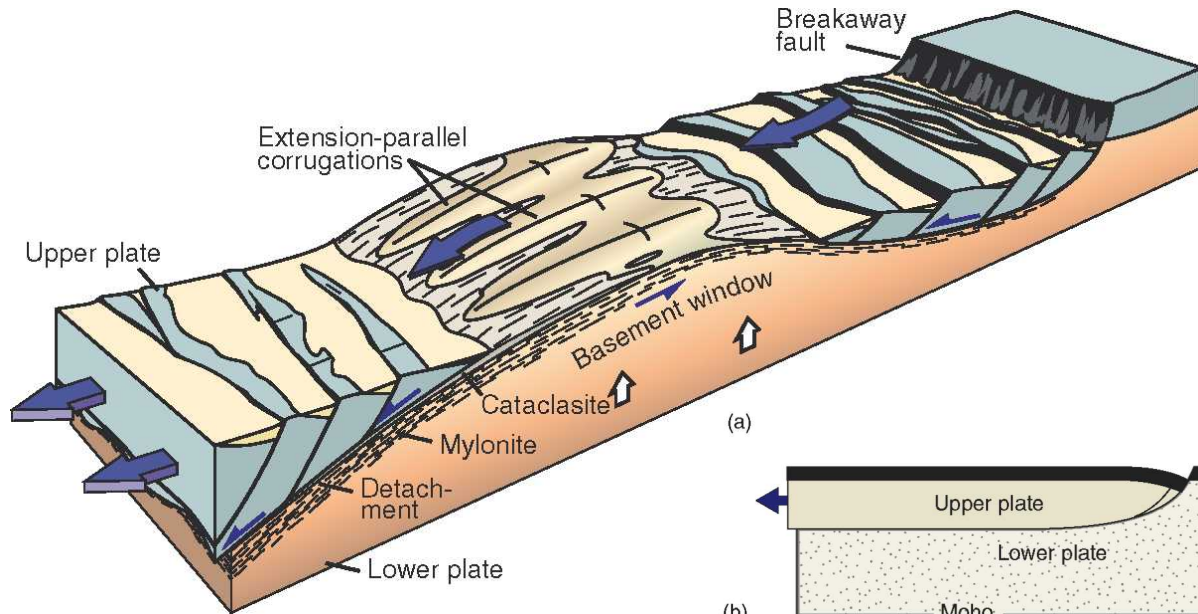
Wide rift (localized):

Sehr hoher geothermischer Gradient: im unteren Teil der verdickten Kruste nimmt die Festigkeit stark ab

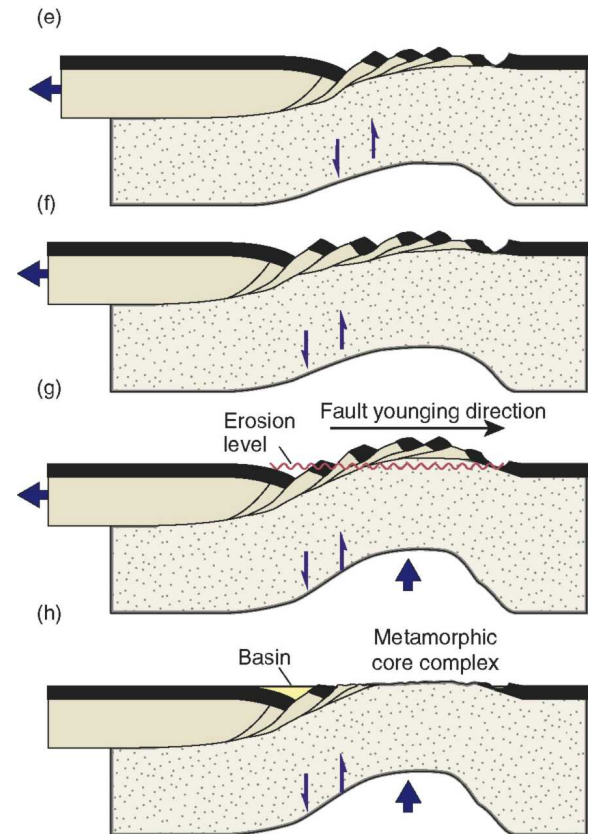
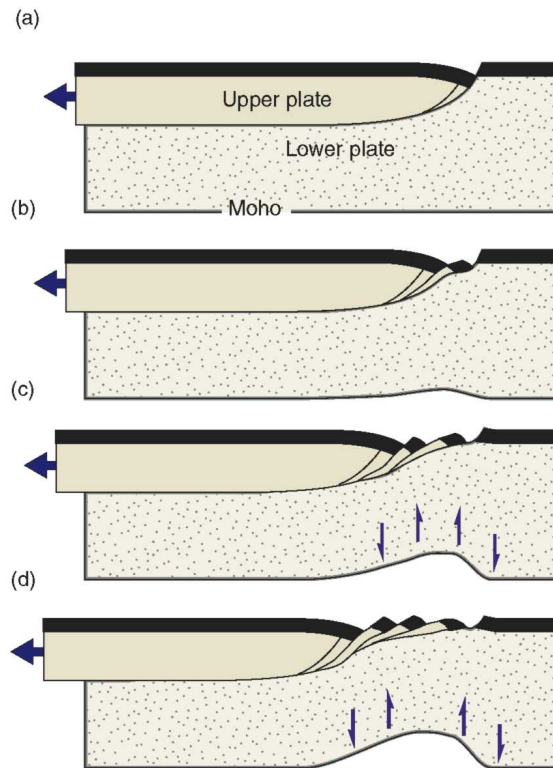
→ in der oberen (relativ stärkeren) Kruste bleibt die Extension lokalisiert, während die untere Kruste homogen ausgedünnt wird



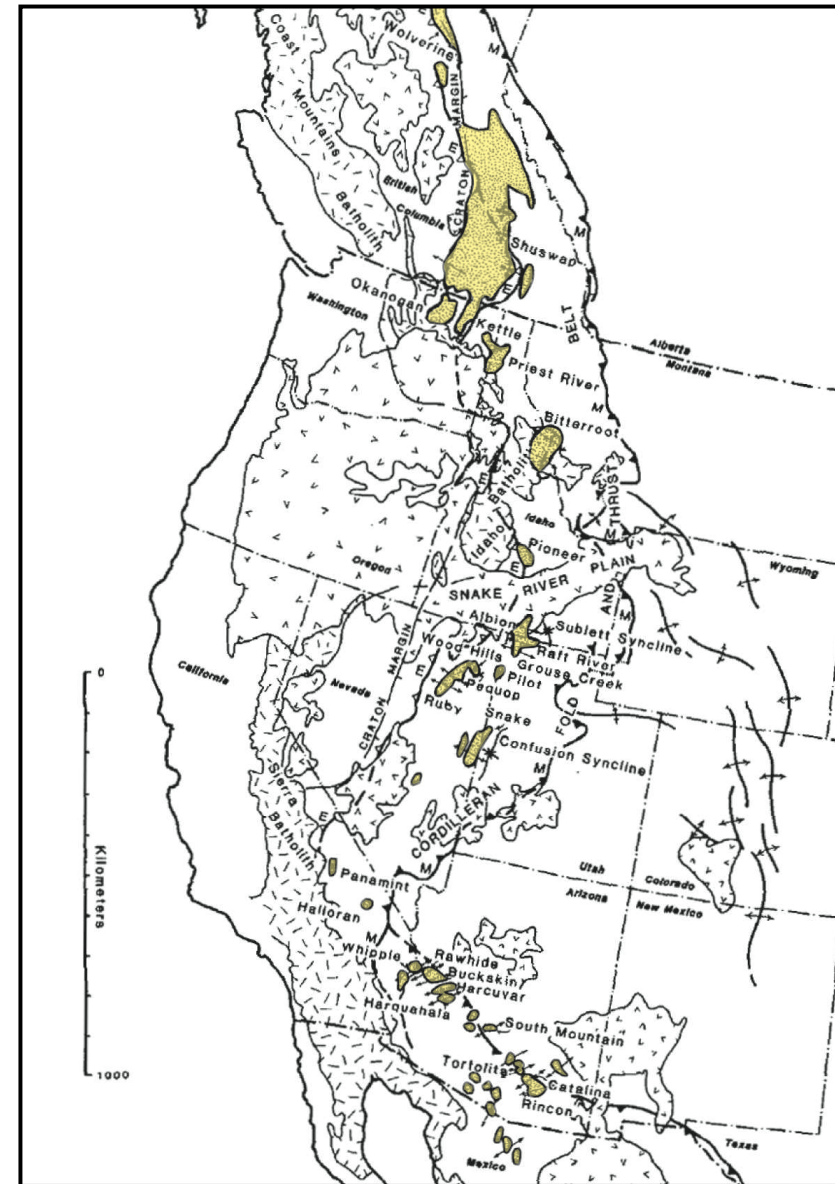
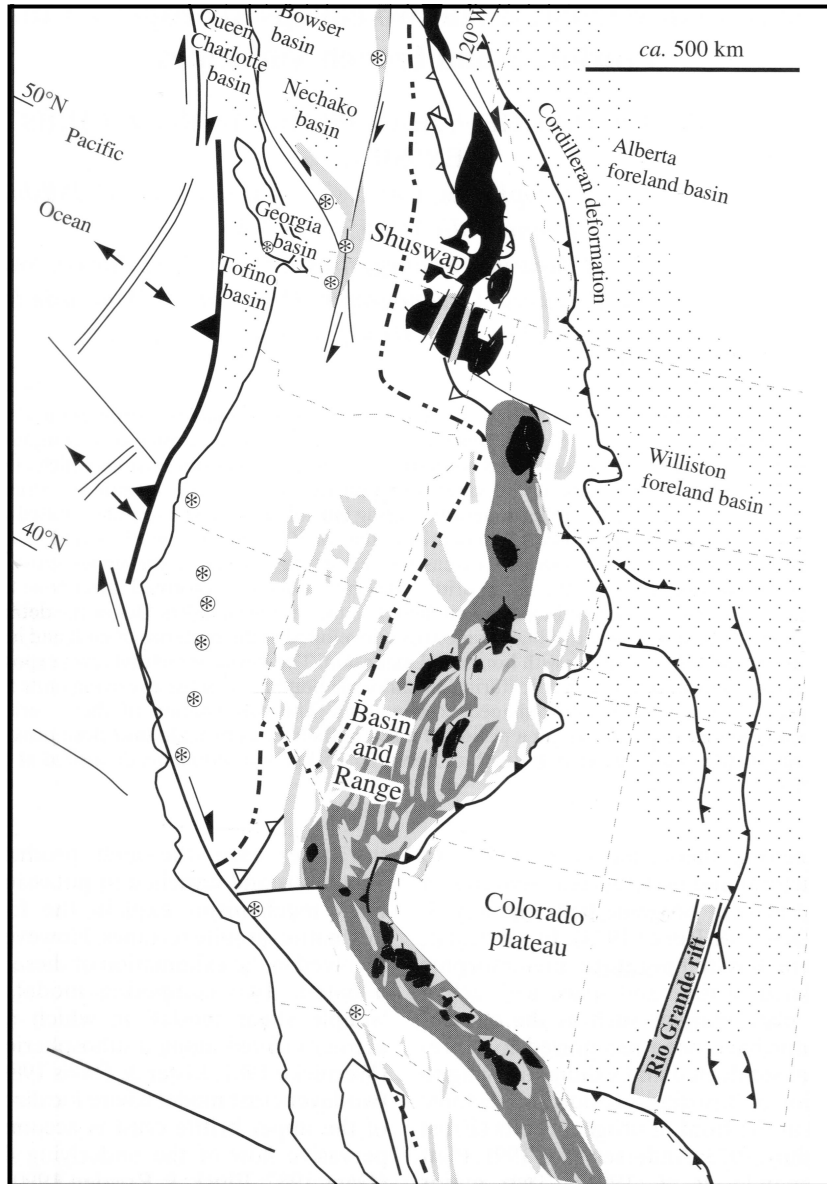
# metamorphic core complex features







Haakon Fossen: Structural Geology



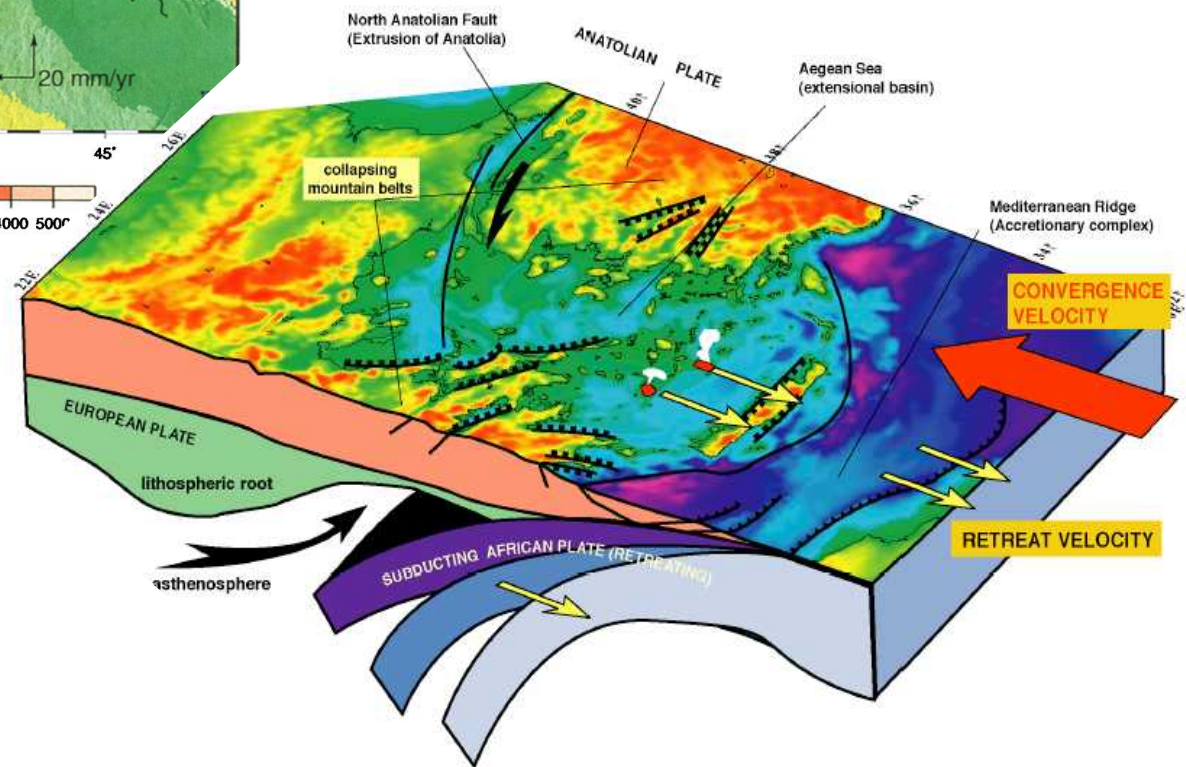
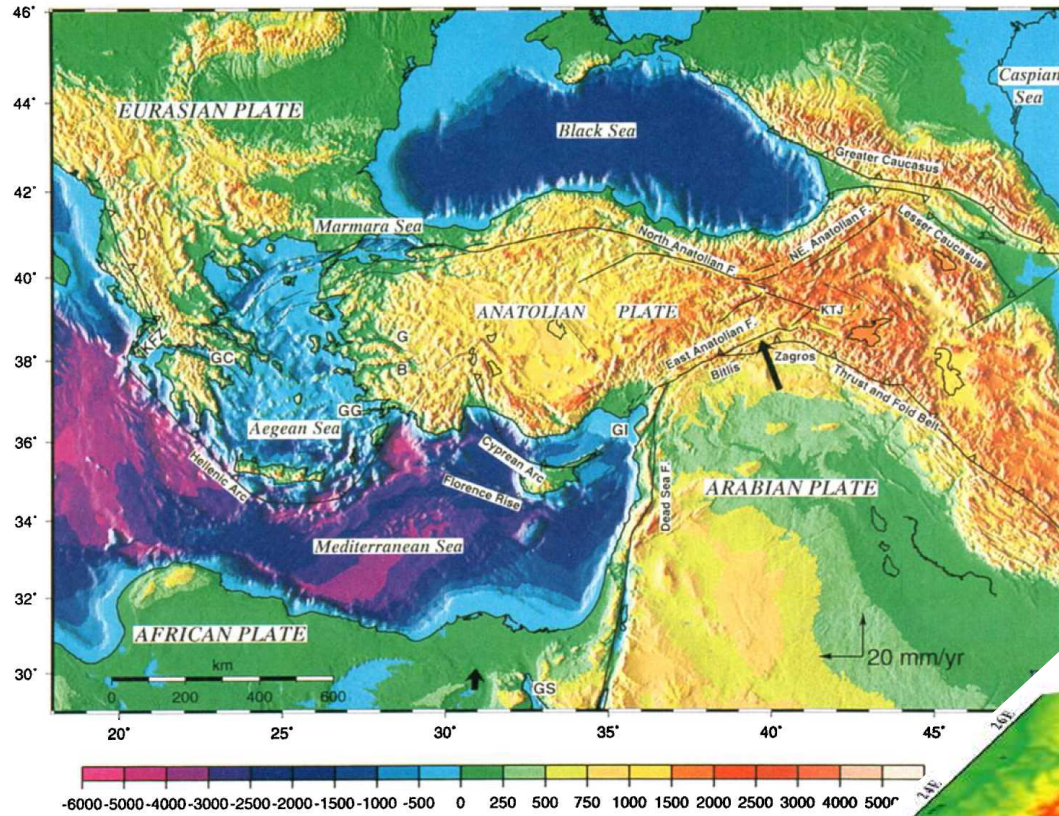
# MCC: Bsp. Western North America



- |  |   |
|--|---|
| <b>Exhumed metamorphic and igneous belts</b>   | <b>Sediments derived from the Cordillera</b>  |
| belt of peraluminous leucogranites  | foreland and foredeep basins  |
| metamorphic core complexes          | fault-bounded basins          |



# MCC: Bsp. Ägäis

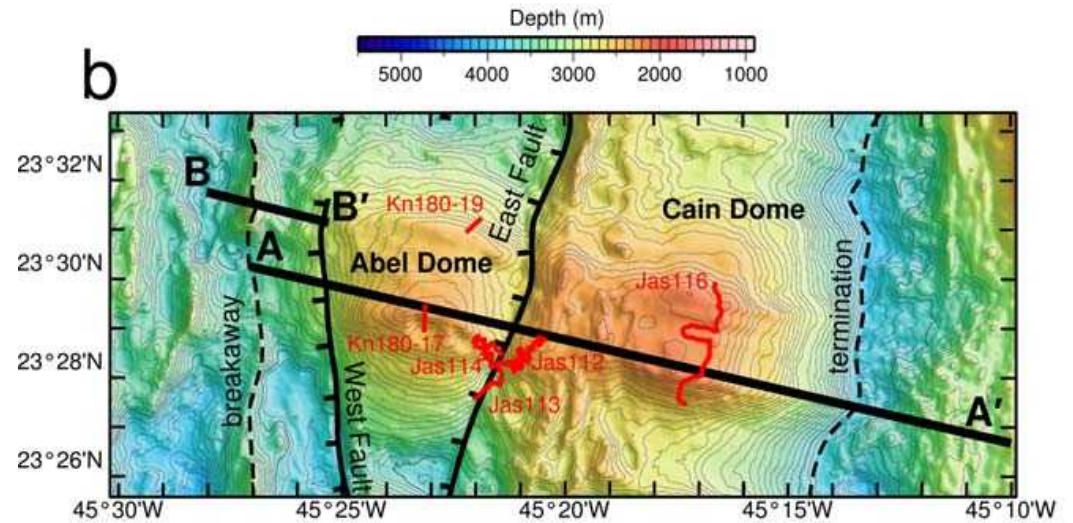


Krusteverdickung &  
Erhitzung  
(Helleniden 45Ma)

# Problem mit den detachment faults



Detachment Fault, Western Chemihuevi Mountains



Kane Fracture Zone (Hansen et al. 2013, G<sup>3</sup>)

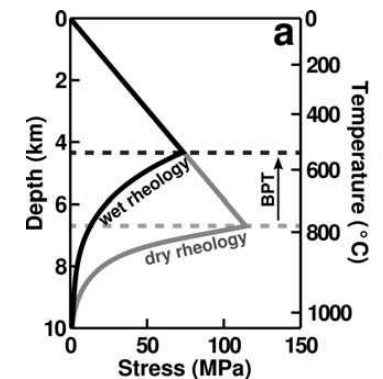
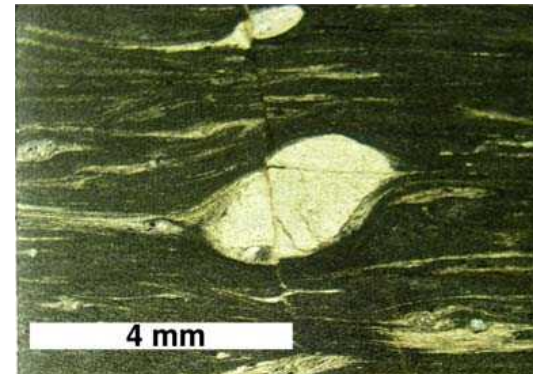
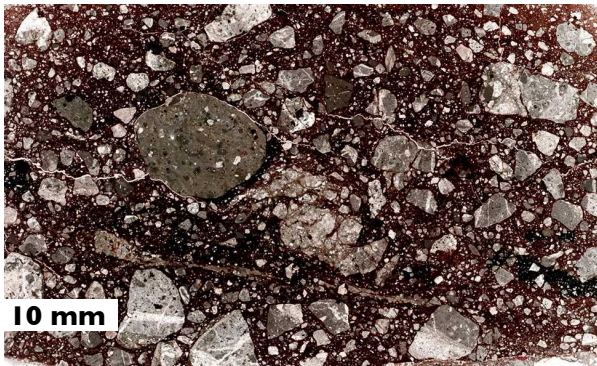
Low-T deformation: Cataclasis

Grain size sensitive.  
Small grain sizes.

High-T deformation: Dislocation creep.

Grain boundary sliding. Diffusion creep.

Grain size sensitive.  
Small grain sizes.





# 7 Gebirgsbildung

## Kompressive Plattengrenzen

- Subduktion
- Akkretion
- Orogenese

## Gebirgstypen

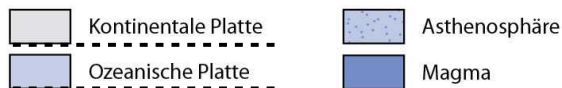
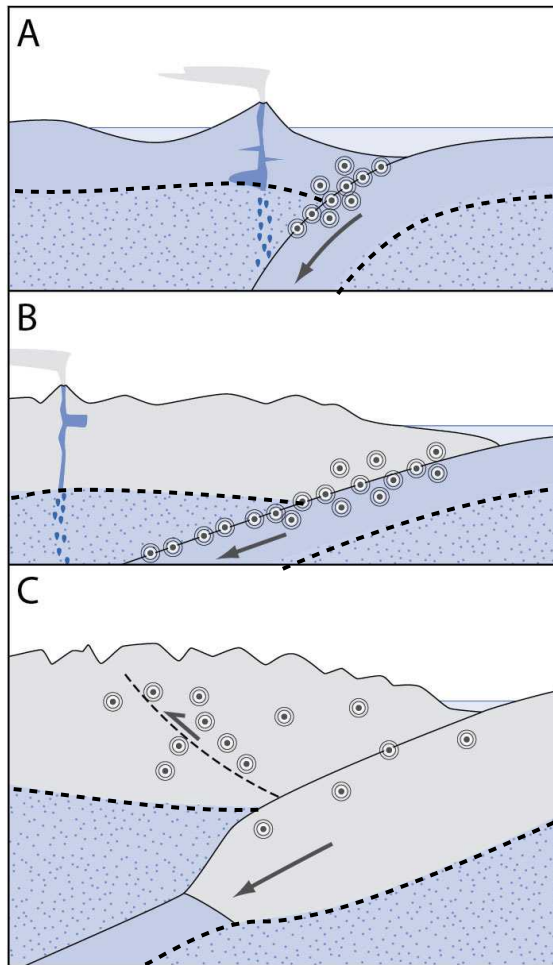
- Inselbogen
- Andiner Typ
- Kollisionsgebirge (Kontinent-Kontinent)

## Alpen

- Tektonischer Aufbau
- Verkürzung

# Kompressions- Tektonik

# Kompressive Plattengrenzen



Ozean - Ozean  
Inselbogen

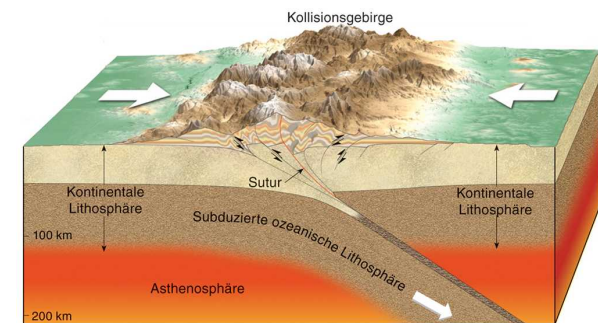
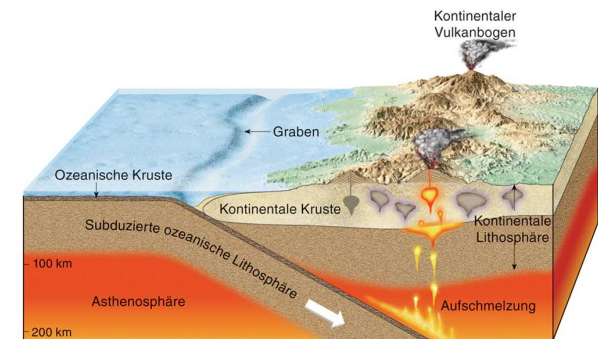
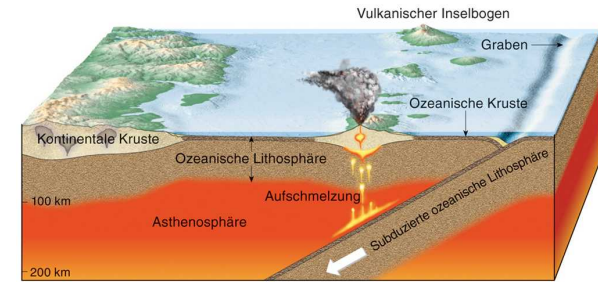


$\sigma_3$

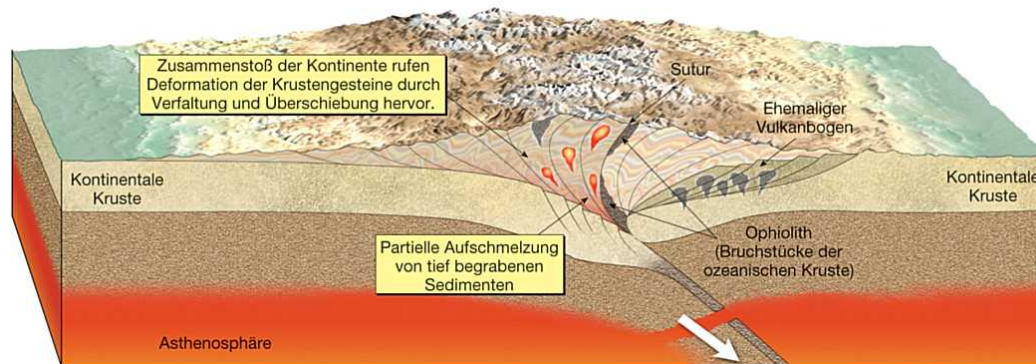
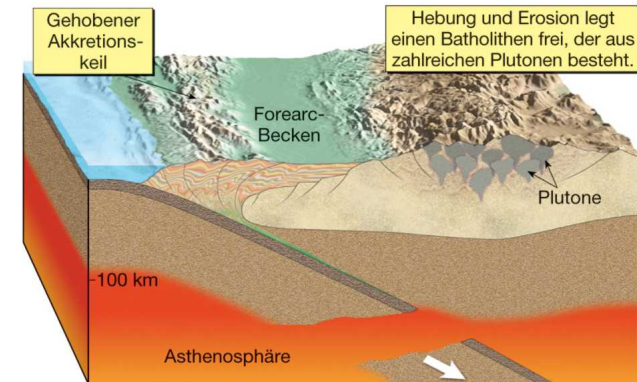
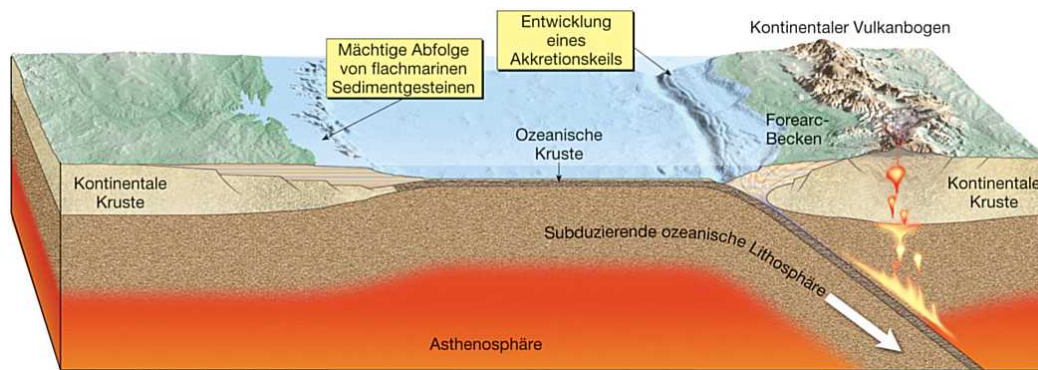
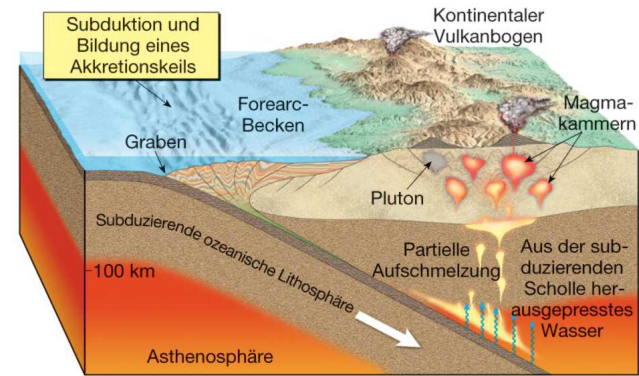
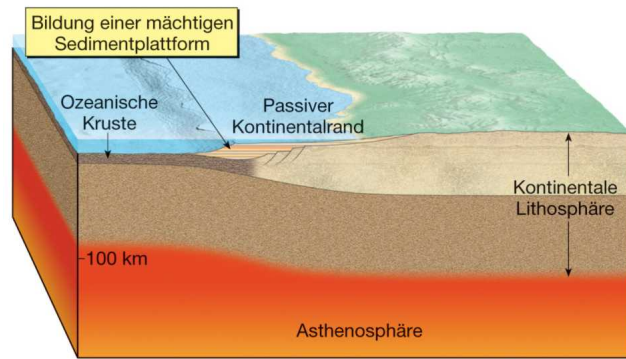
Ozean - Kontinent  
Andiner Typ



Kontinent - Kontinent  
Kollisionsgebirge



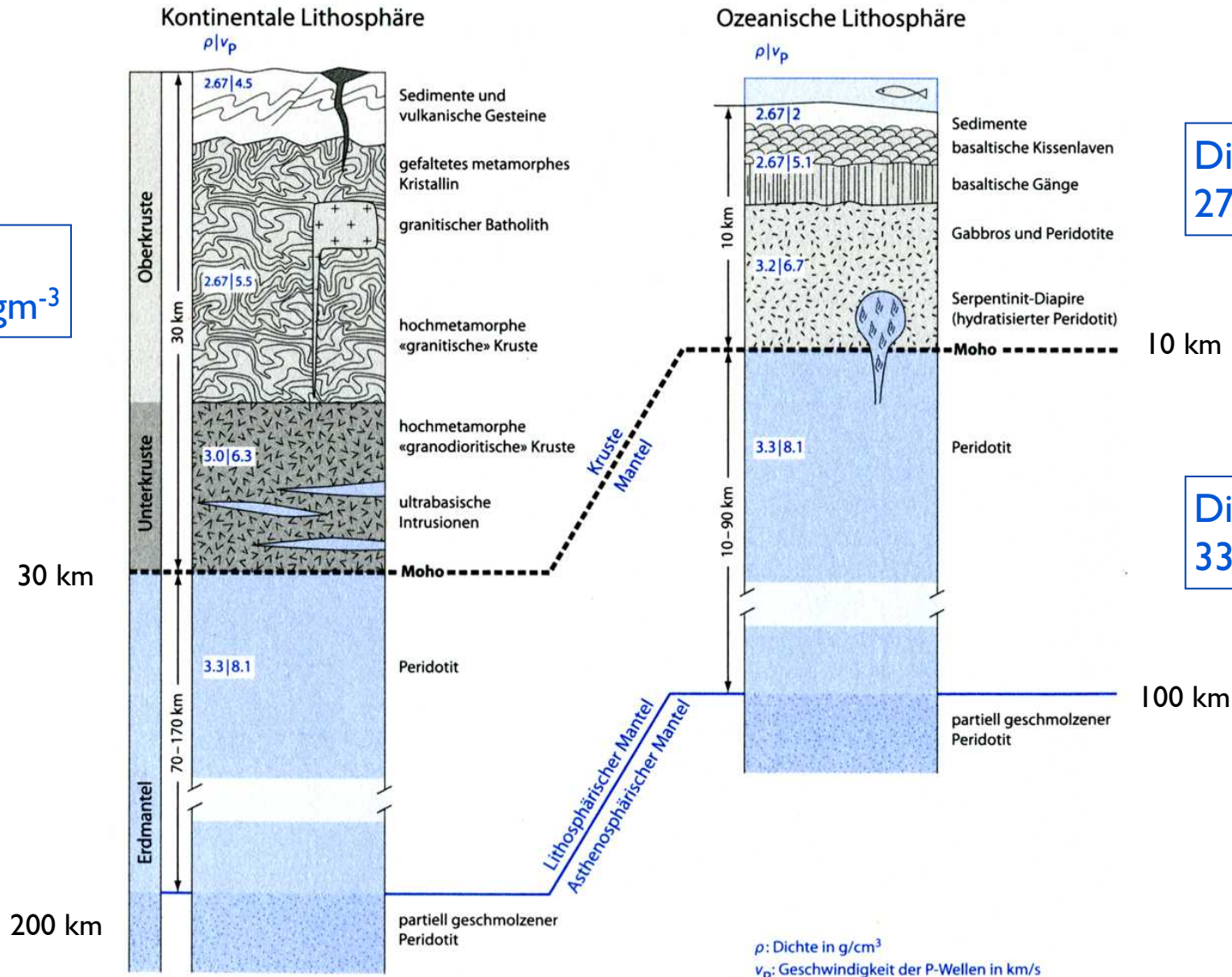
# pro memoria



# Lithosphäre

Dichte:  
2700-3000 kgm<sup>-3</sup>

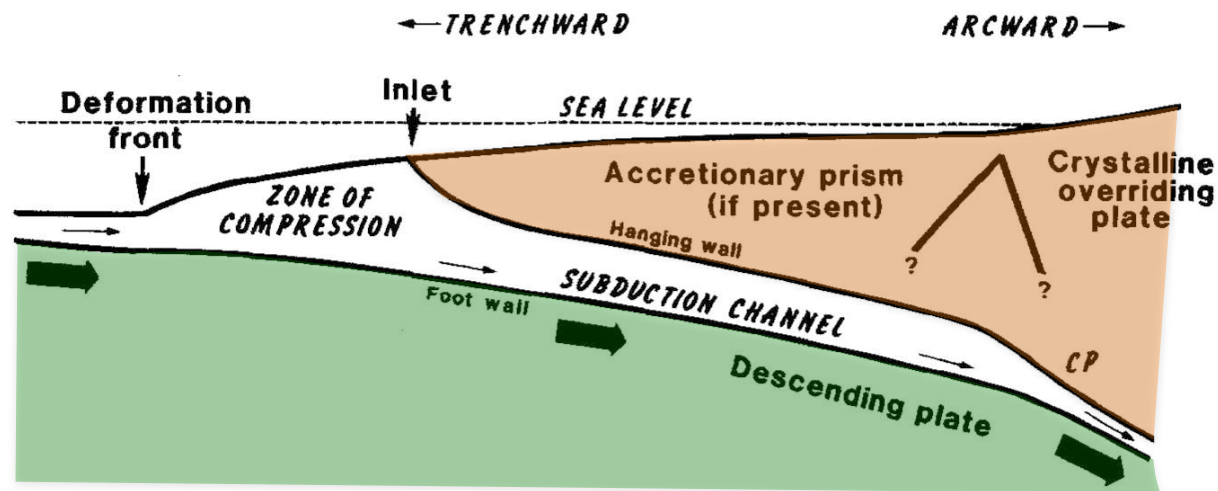
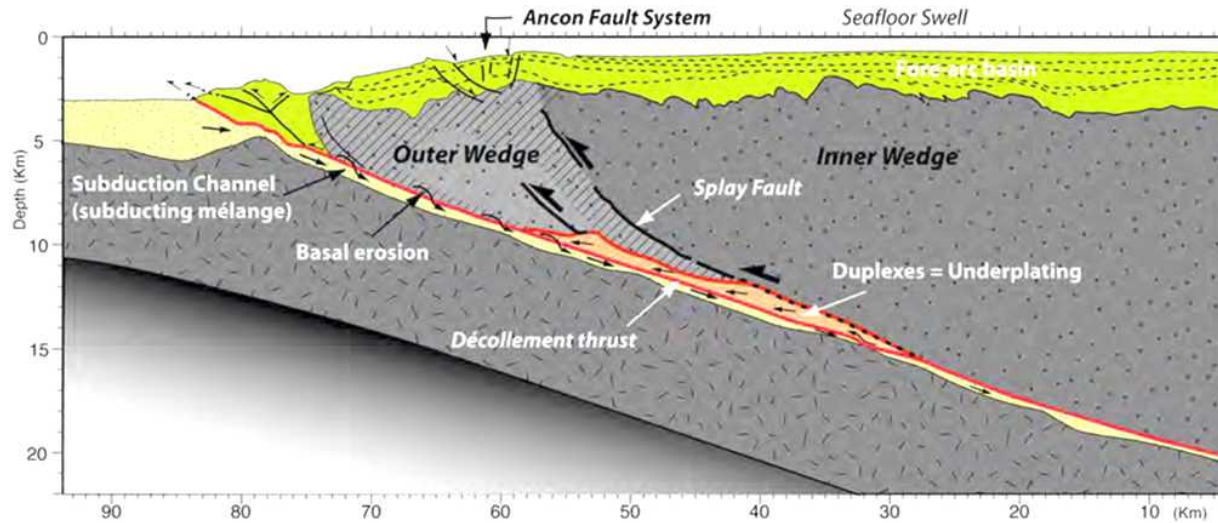
Dichte:  
3300 kgm<sup>-3</sup>



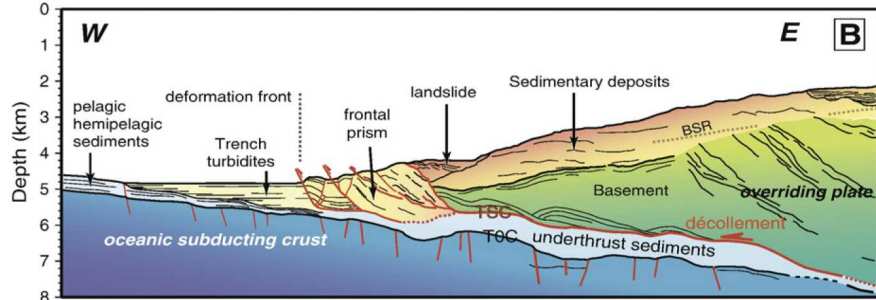
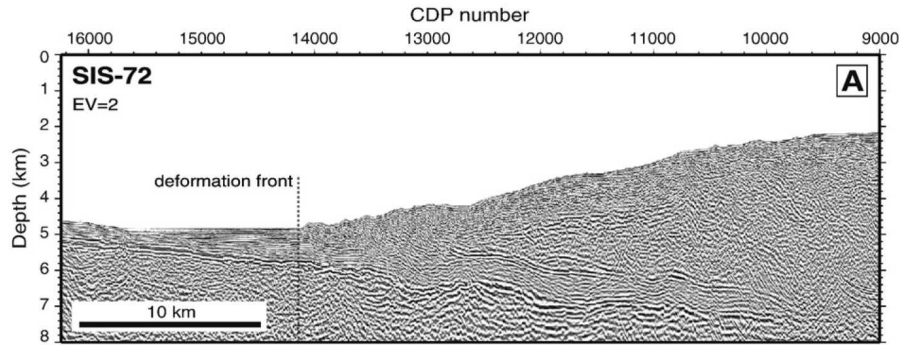
Dichte:  
2700-3200 kgm<sup>-3</sup>

Dichte:  
3300 kgm<sup>-3</sup>

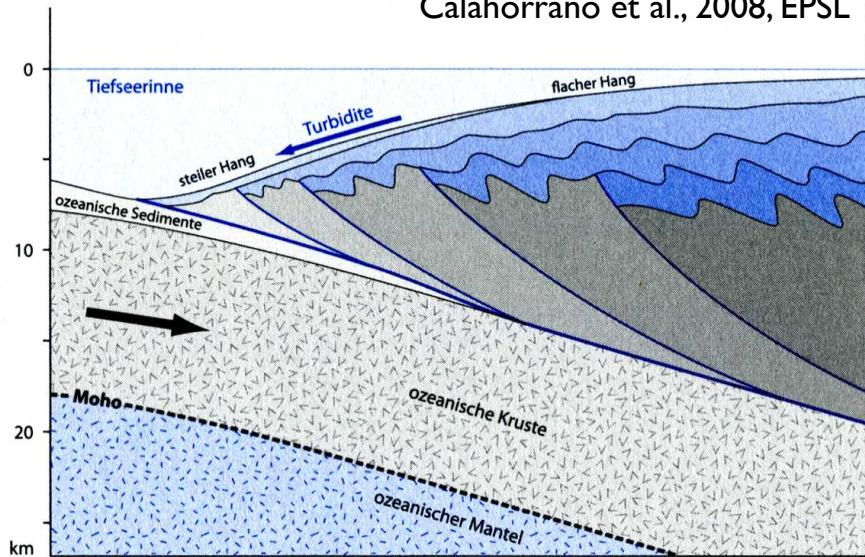
# Subduktion - Subduktionskanal



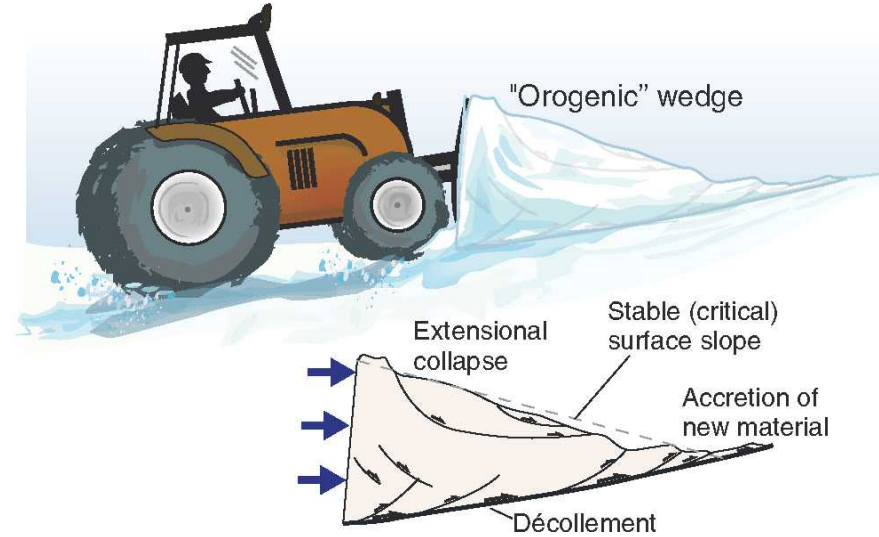
# Akkretionskeil (Akkretionskomplex)



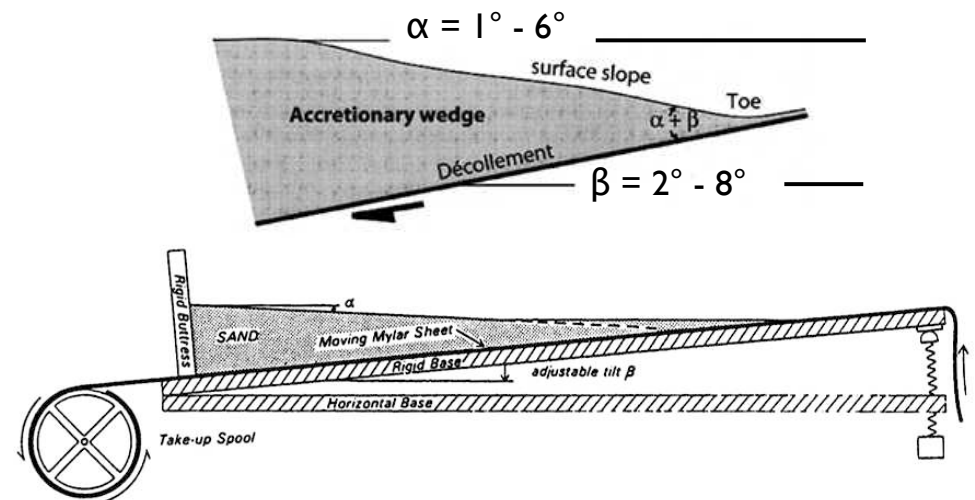
Calahorrano et al., 2008, EPSL



Pfiffner et al., 2012

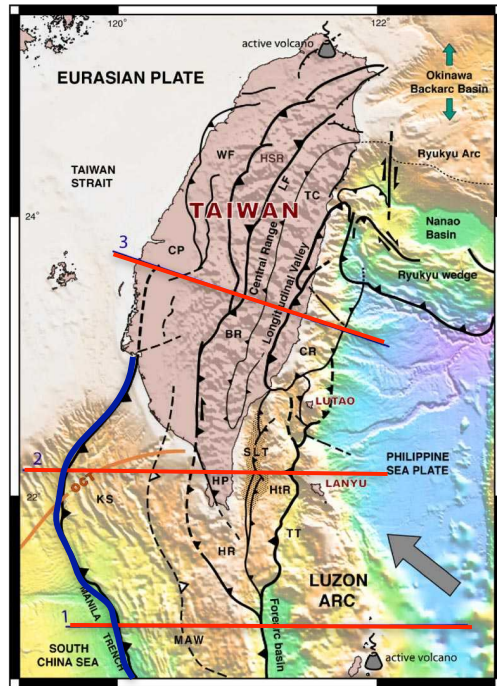


Haakon Fossen: Structural Geology



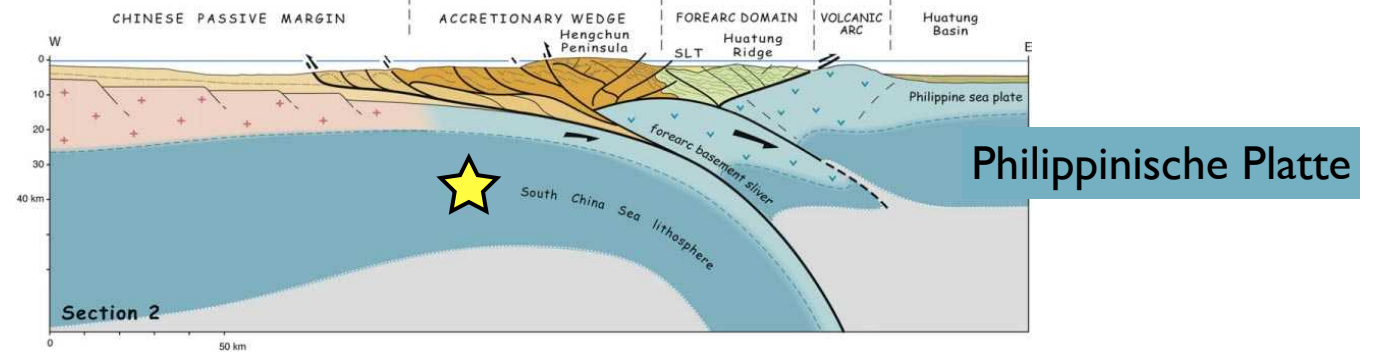
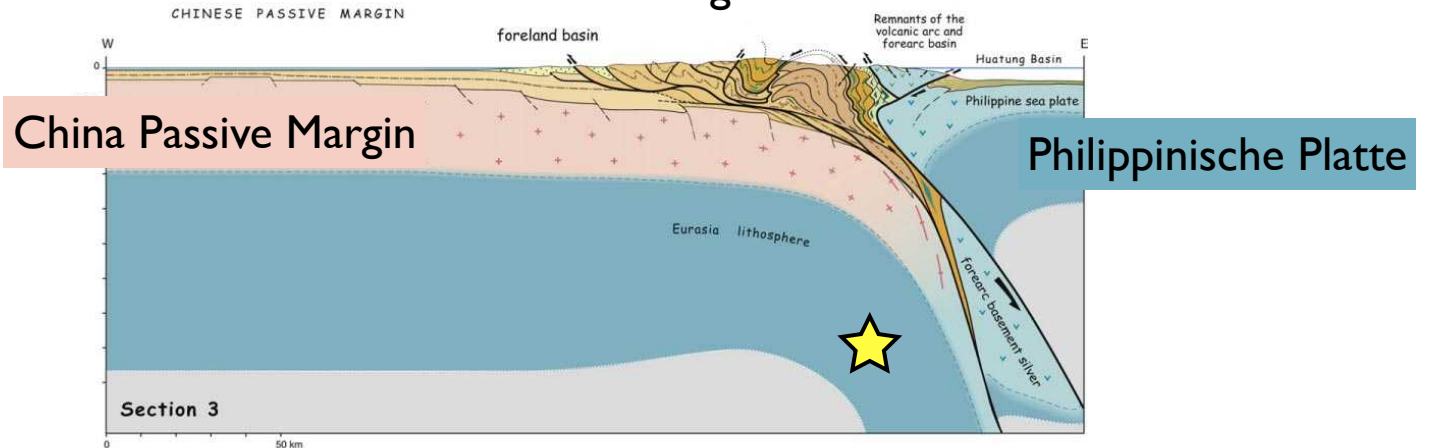
Davies et al., 1983

# Subduktion → Akkretionskeil → Orogenkeil

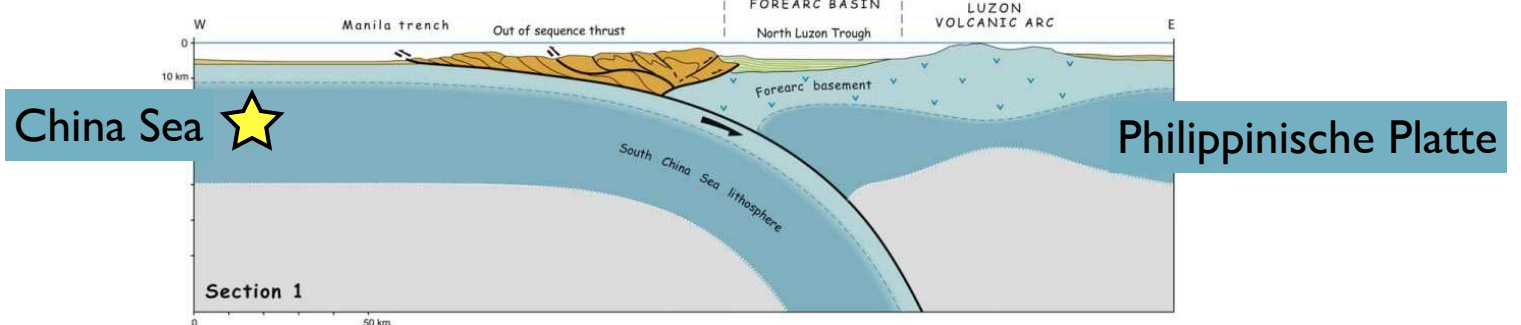


Malavielle & Trullenque, 2009, *Tectonophysics*

## Orogenkeil



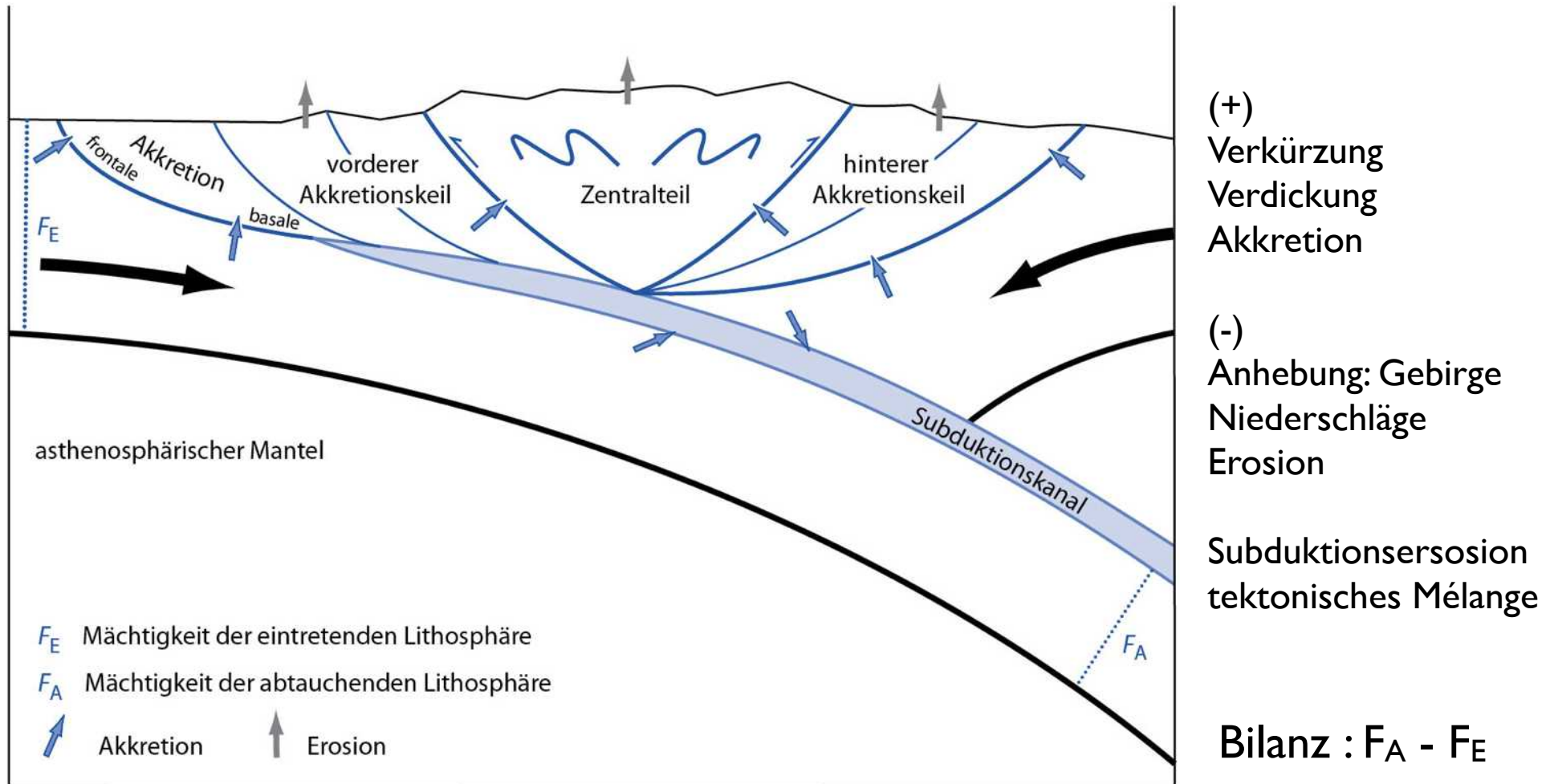
## Akkretionskeil



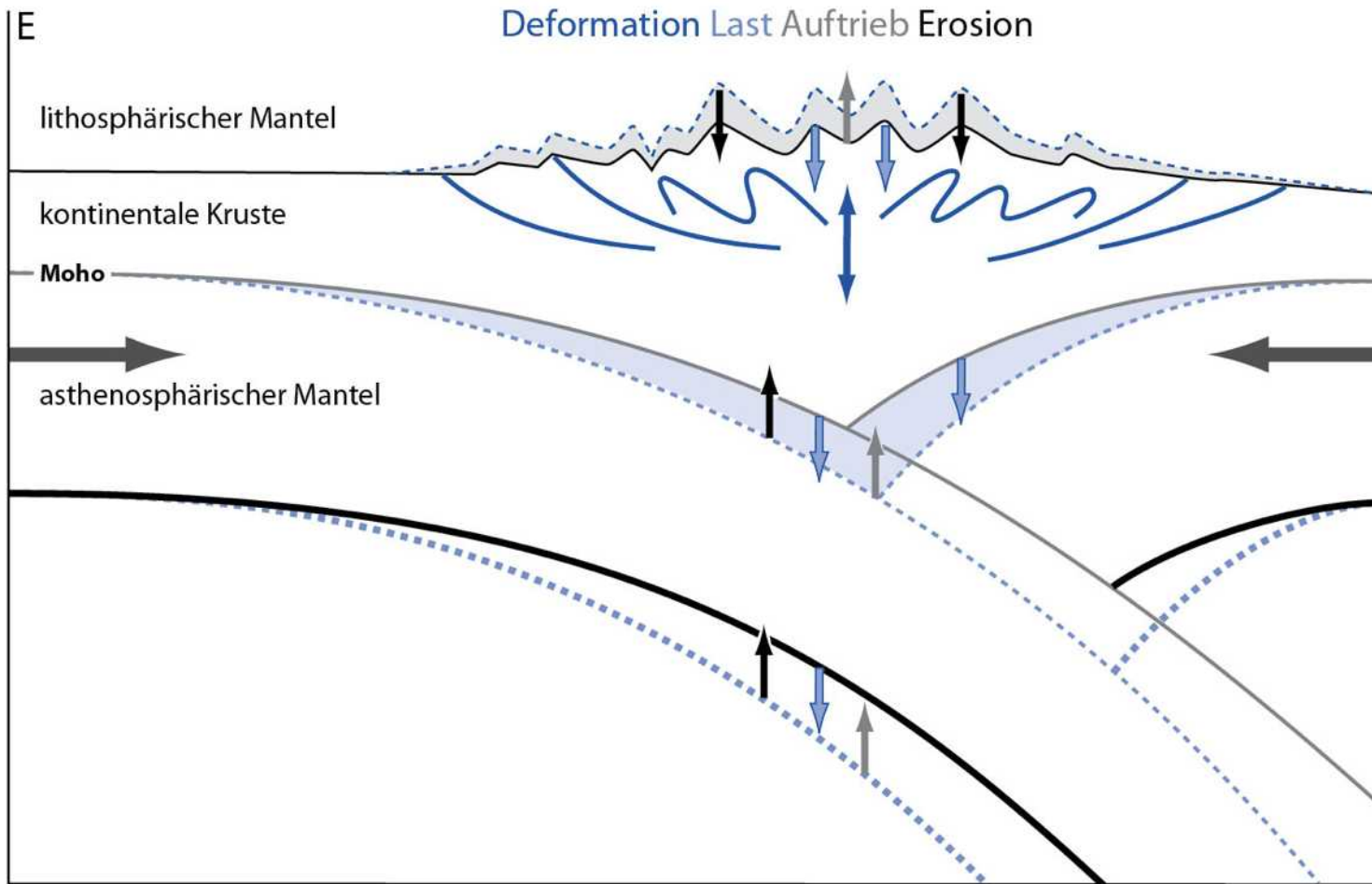
★ fortschreitende Subduktion



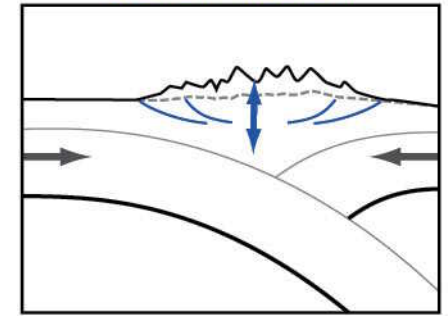
# Massenbilanz im Orogen



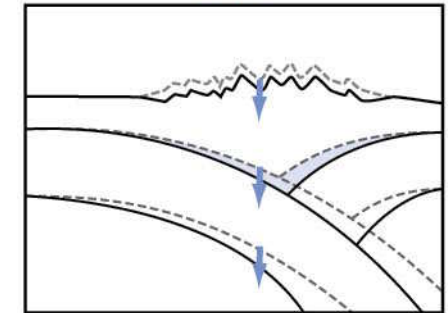
# Isostasie und Erosion



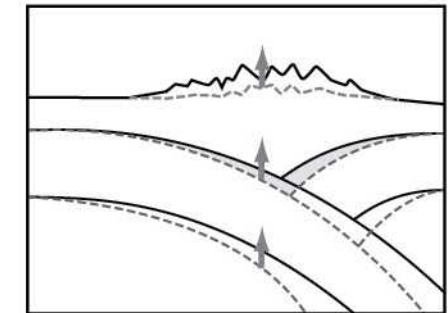
A Deformation



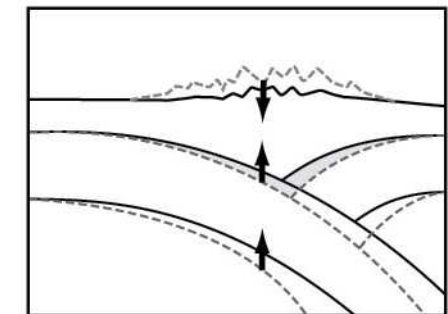
B Last



C Auftrieb

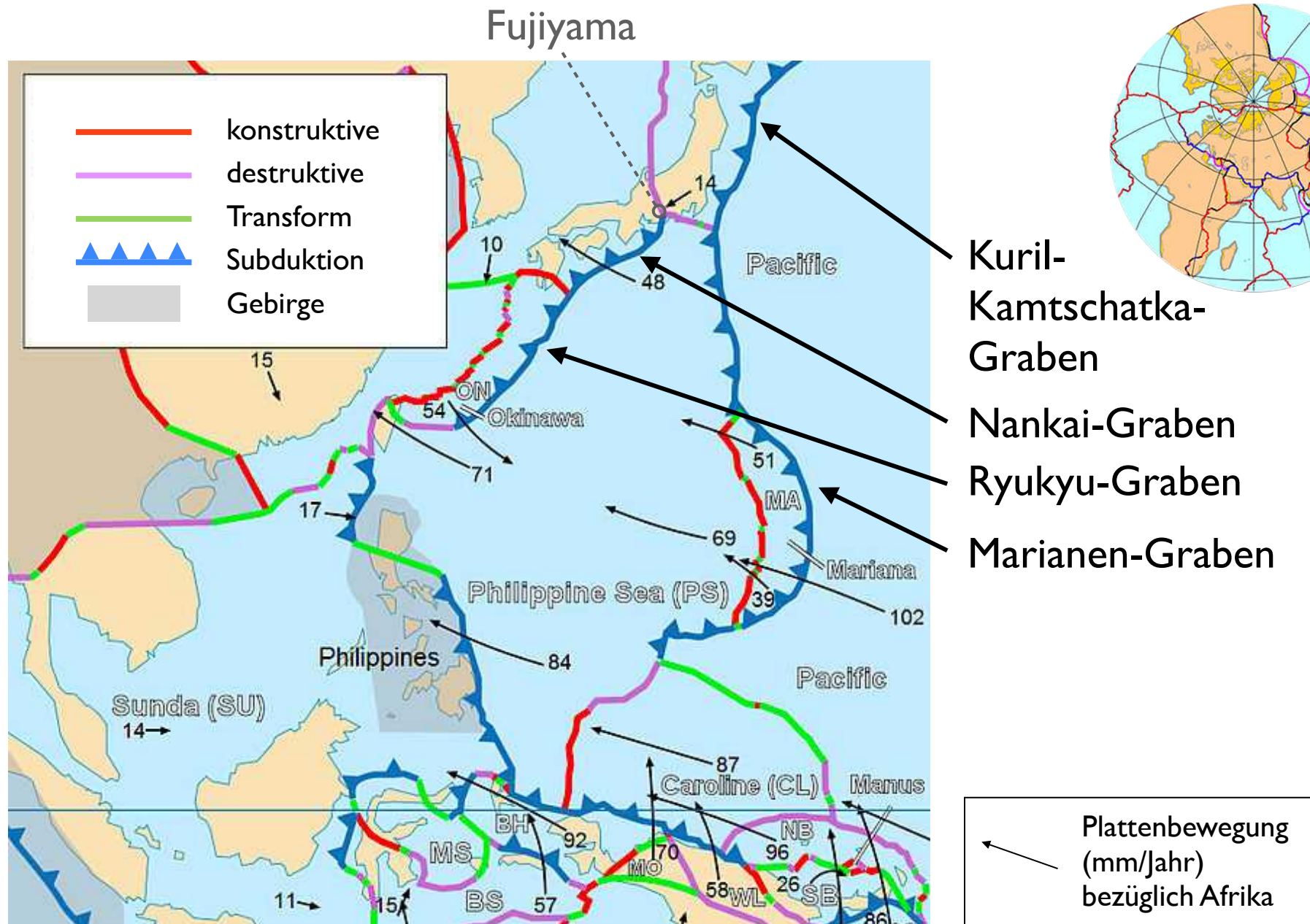


D Erosion



# Gebirgstypen

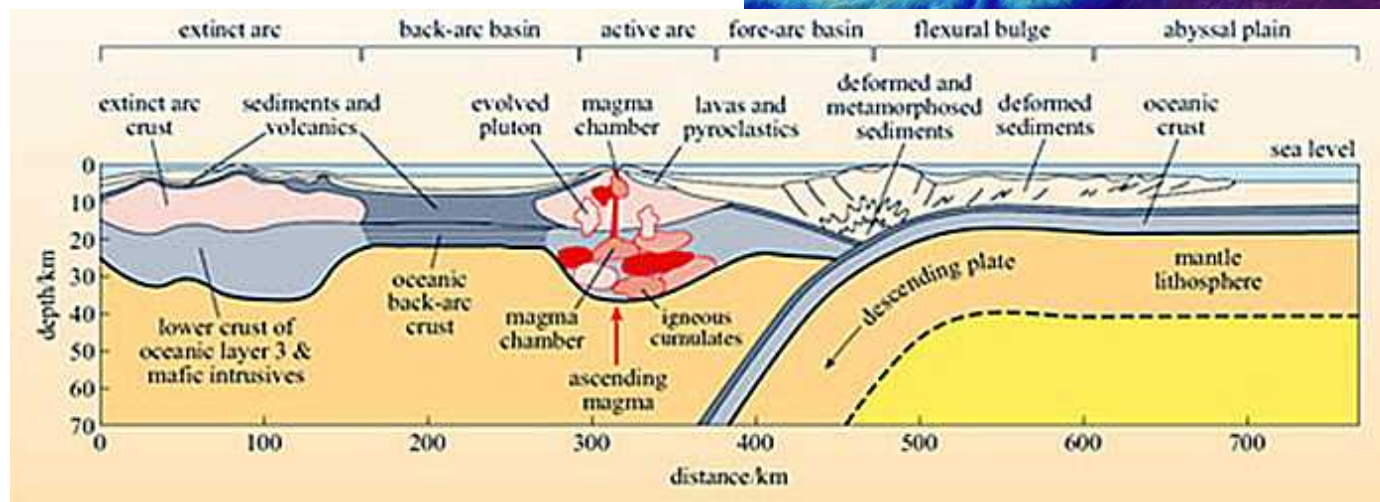
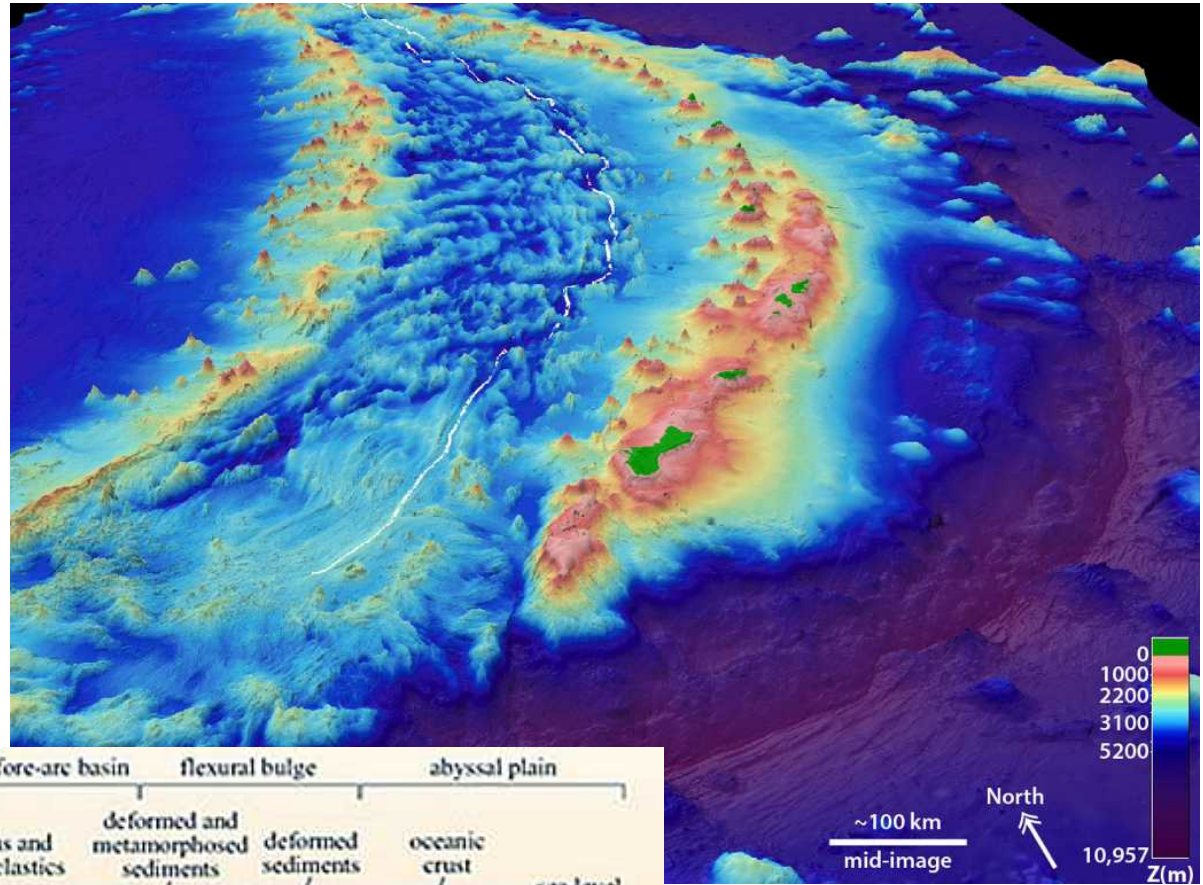
# (I) Kollision Eurasien - Philippinen



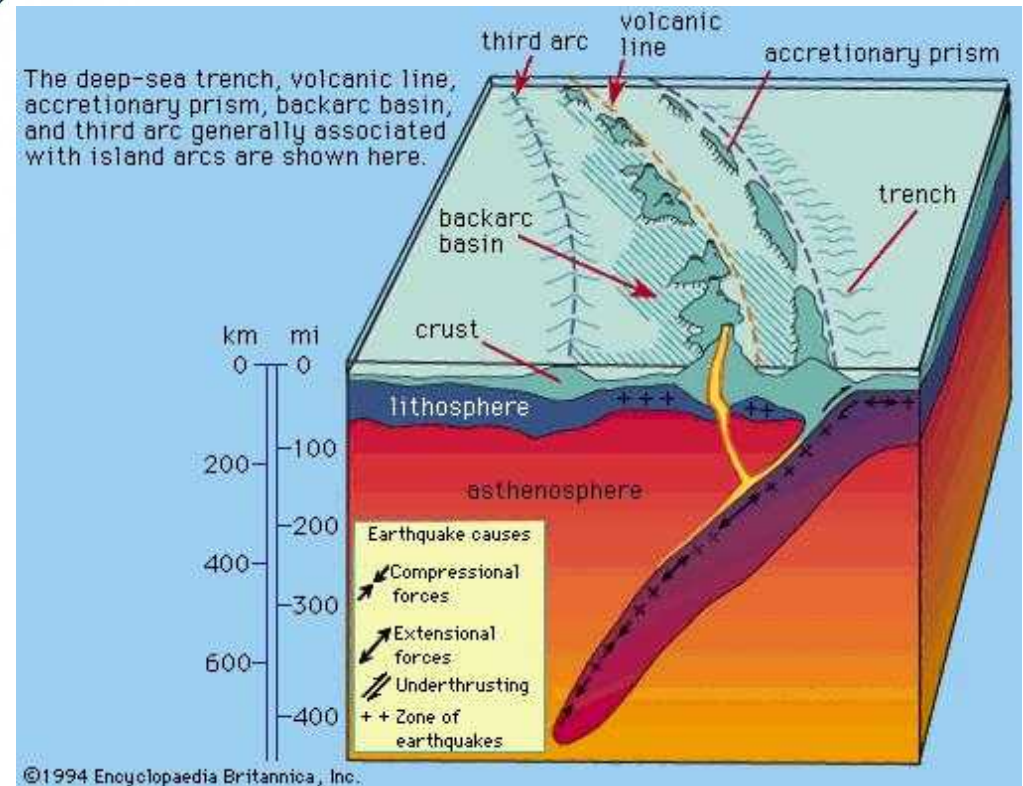
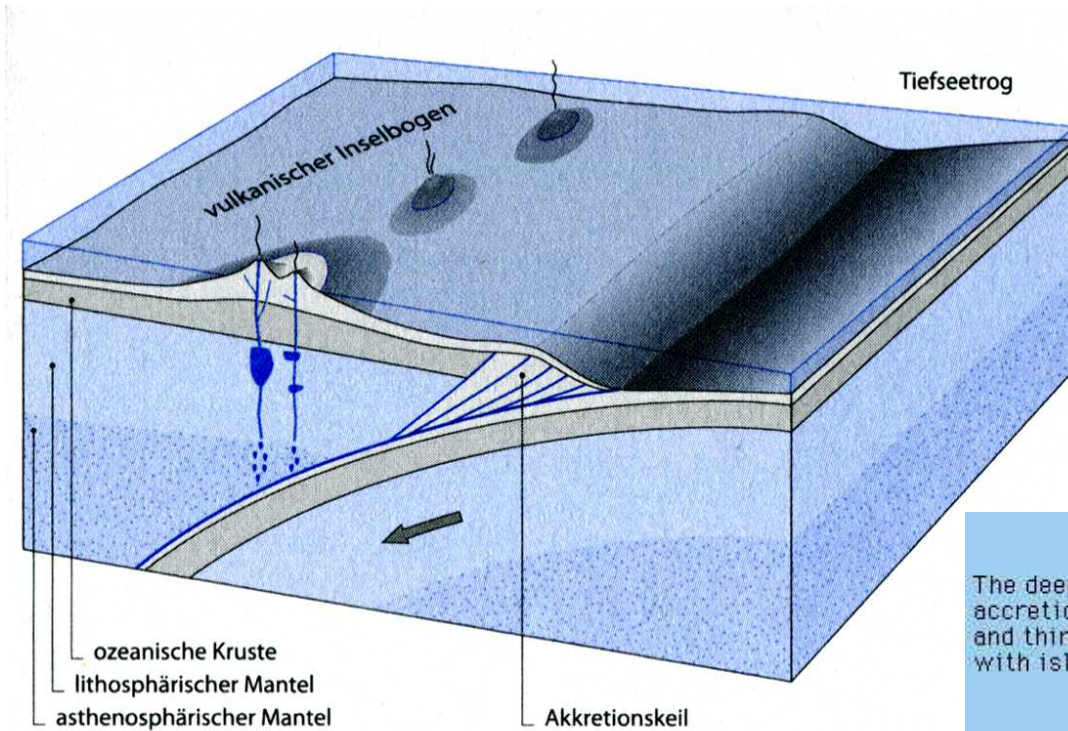
# Ozean - Ozean: Marianen

[https://www.pmel.noaa.gov/eoi/marianas\\_site.html](https://www.pmel.noaa.gov/eoi/marianas_site.html)

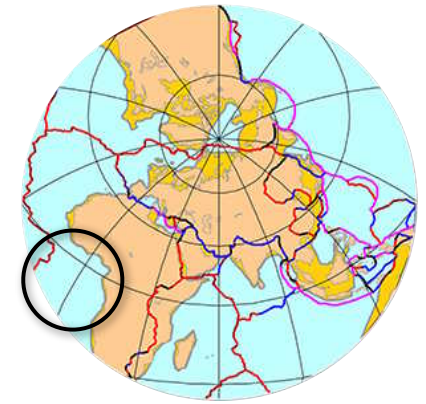
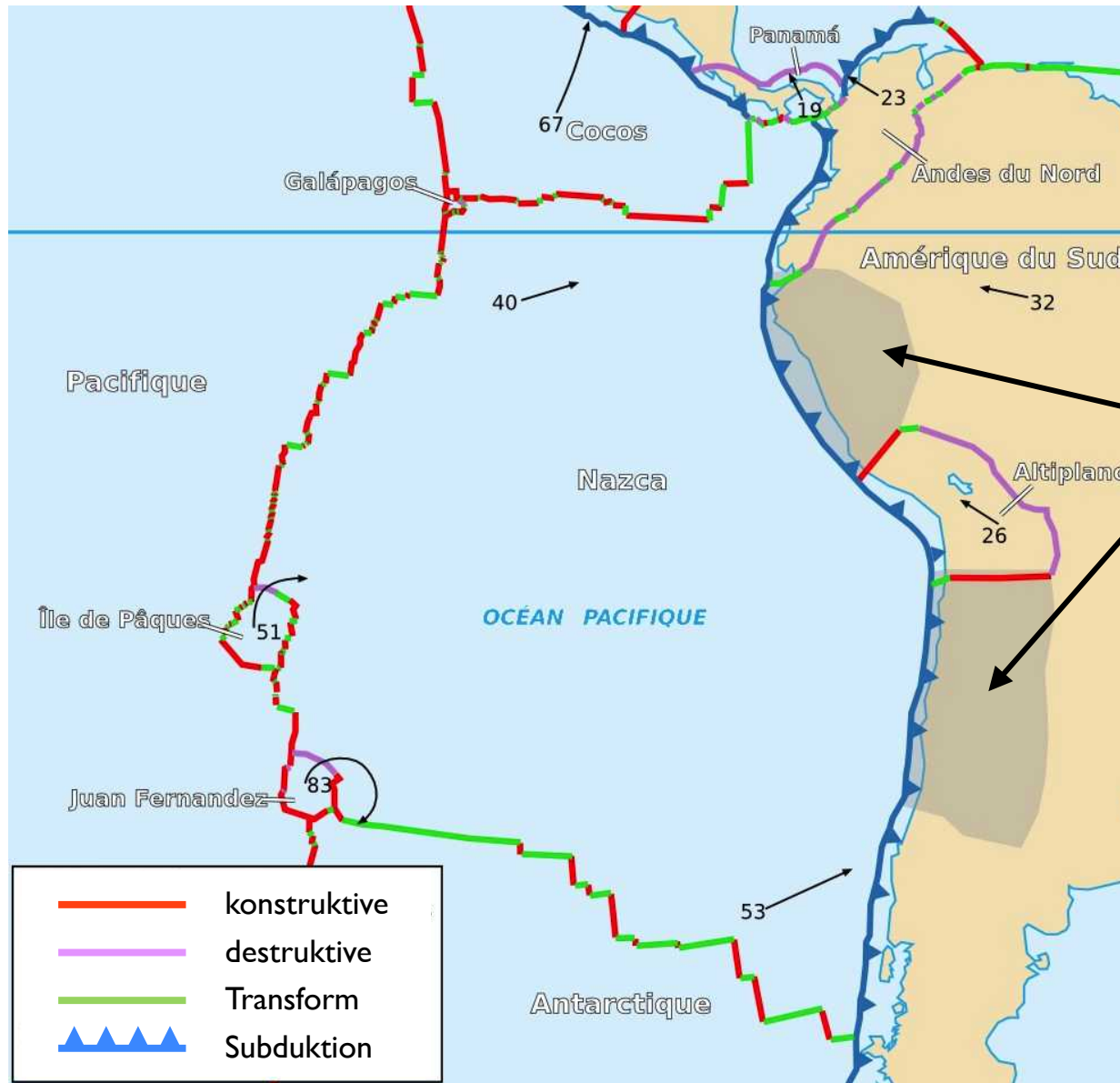
open.edu



# Vulkanischer Inselbogen



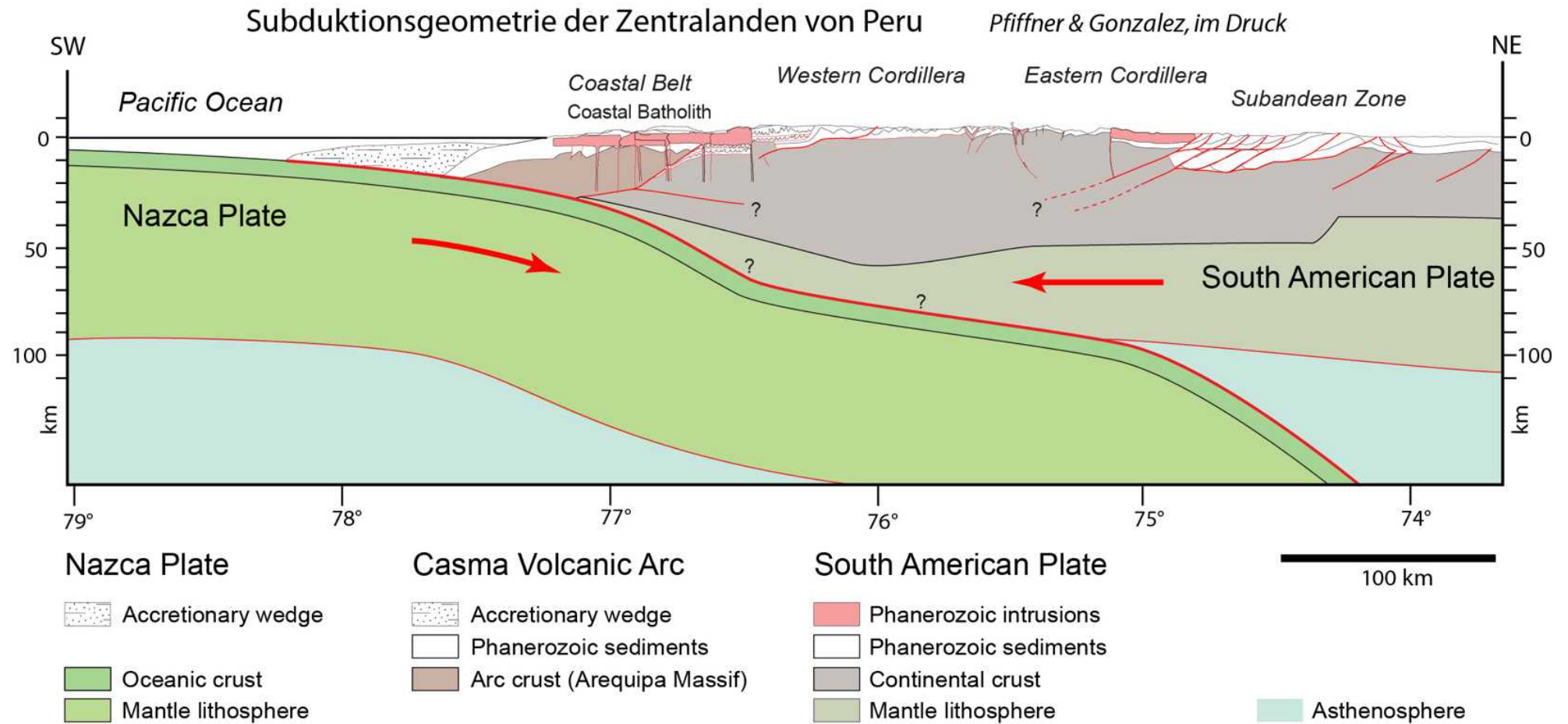
# (2) Kollision Nazca-Platte - S-Amerika



Orogenese

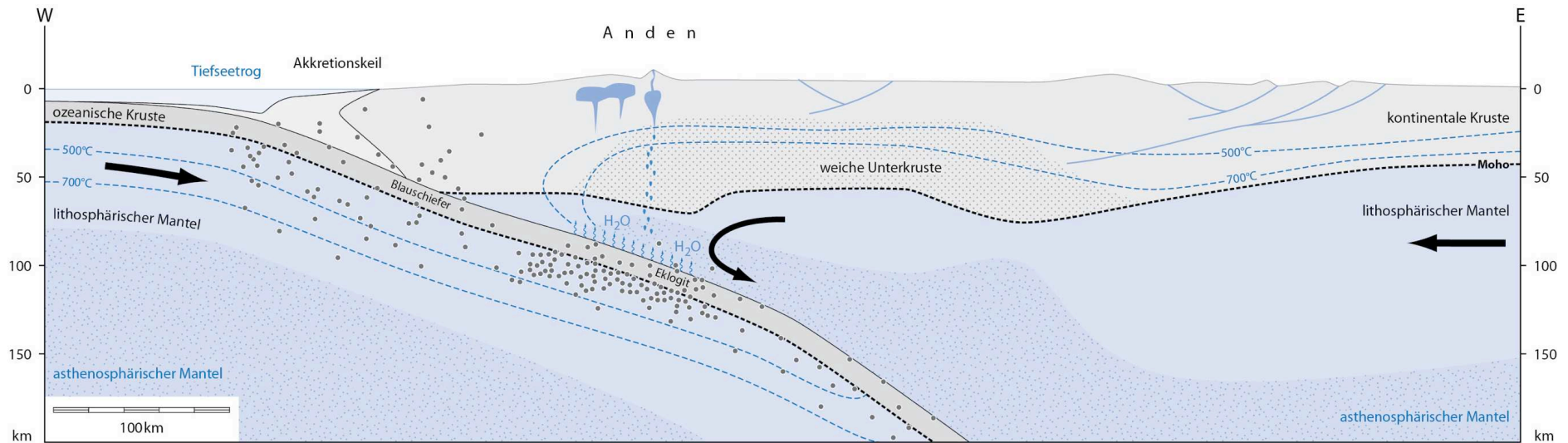
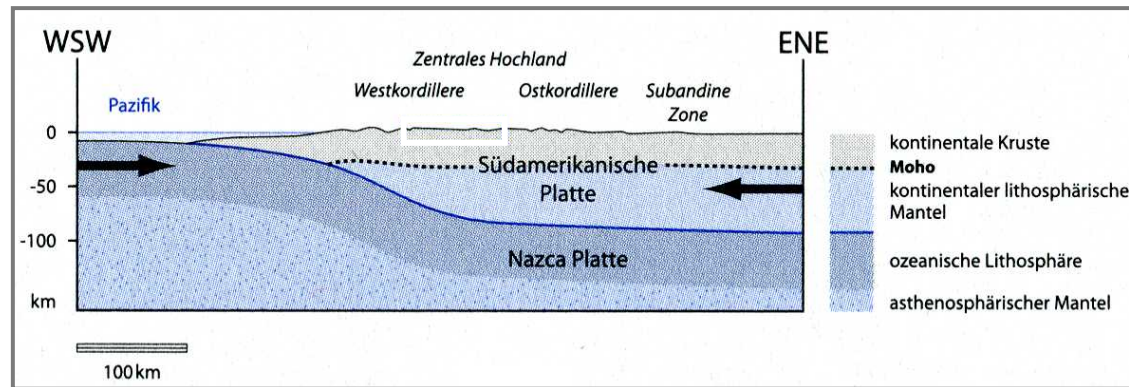
Plattenbewegung  
(mm/Jahr)  
bezüglich Afrika

# Ozean - Kontinent: Anden

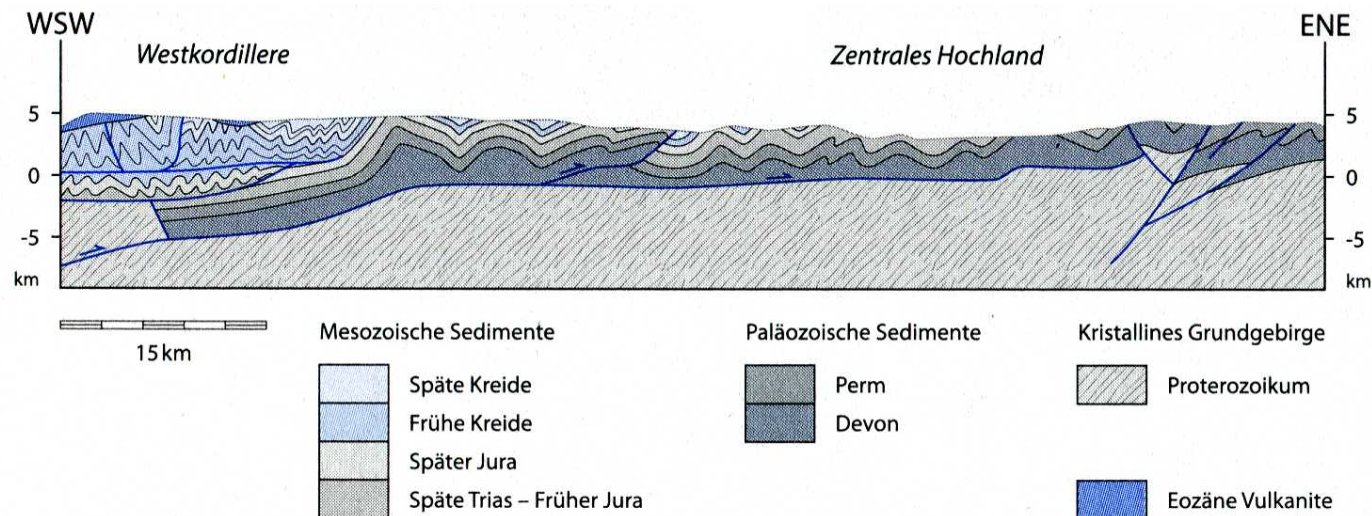
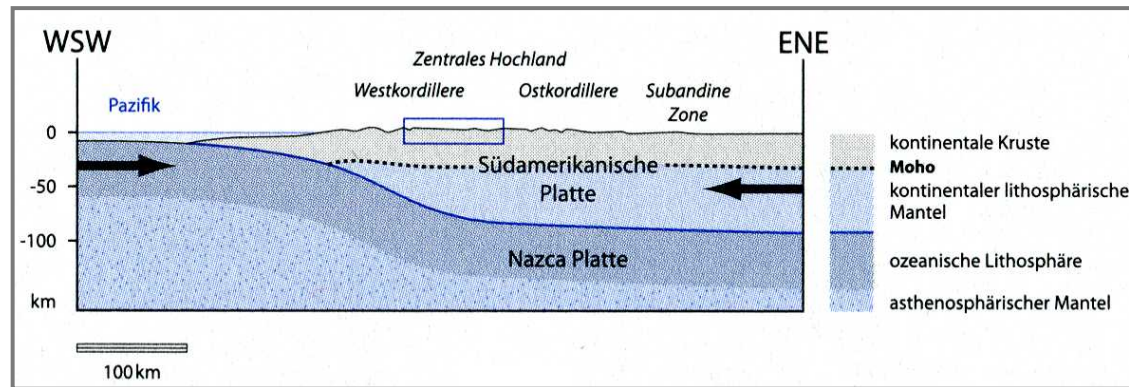




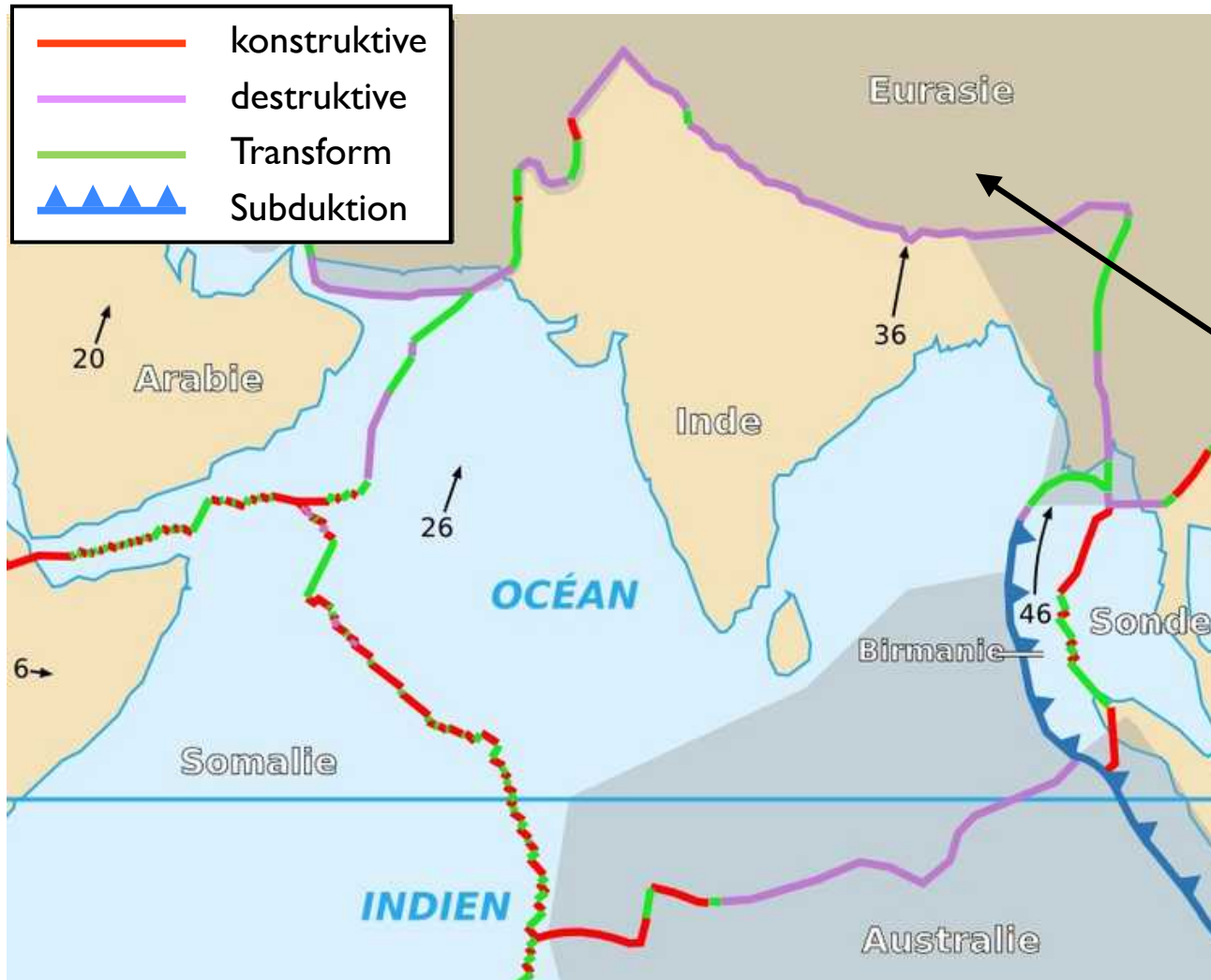
# Tiefenstruktur der Anden



# Tiefenstruktur der Anden



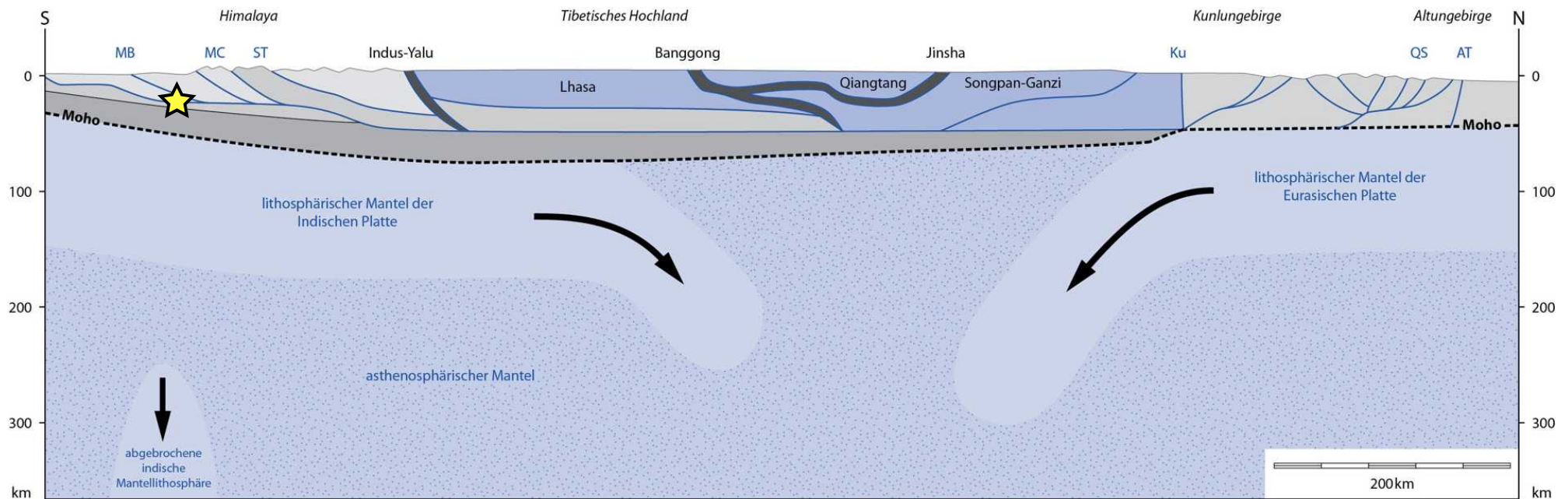
# (3) Kollision Eurasien - Indien



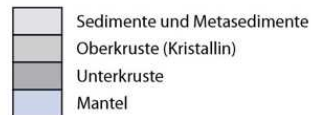
Orogenese

Plattenbewegung  
(mm/Jahr)  
bezüglich Afrika

# Kontinent - Kontinent: Himalaya



## Indische Platte



## Wichtige Störungen

- MB «Main Boundary» Überschiebung
- MC «Main Central» Überschiebung
- ST Süd-Tibetische Abschiebung

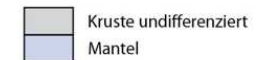
## Suturen

- Relikte subduzierter ozeanischer Platten
- Terrane**
- Kruste angedockter Mikrokontinente

## Wichtige Störungen

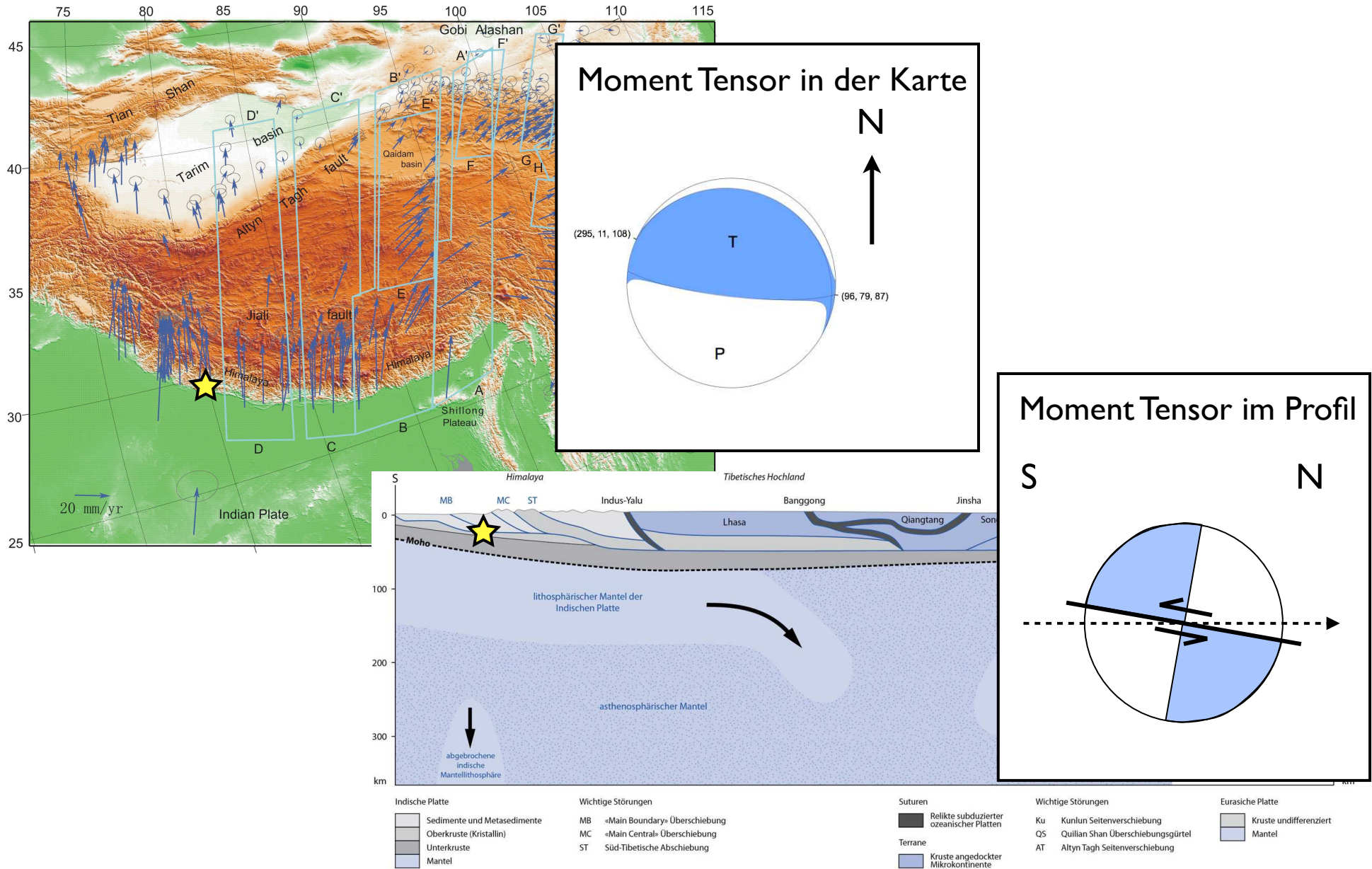
- Ku Kunlun Seitenverschiebung
- QS Quilian Shan Überschiebungsgürtel
- AT Altyn Tagh Seitenverschiebung

## Eurasische Platte



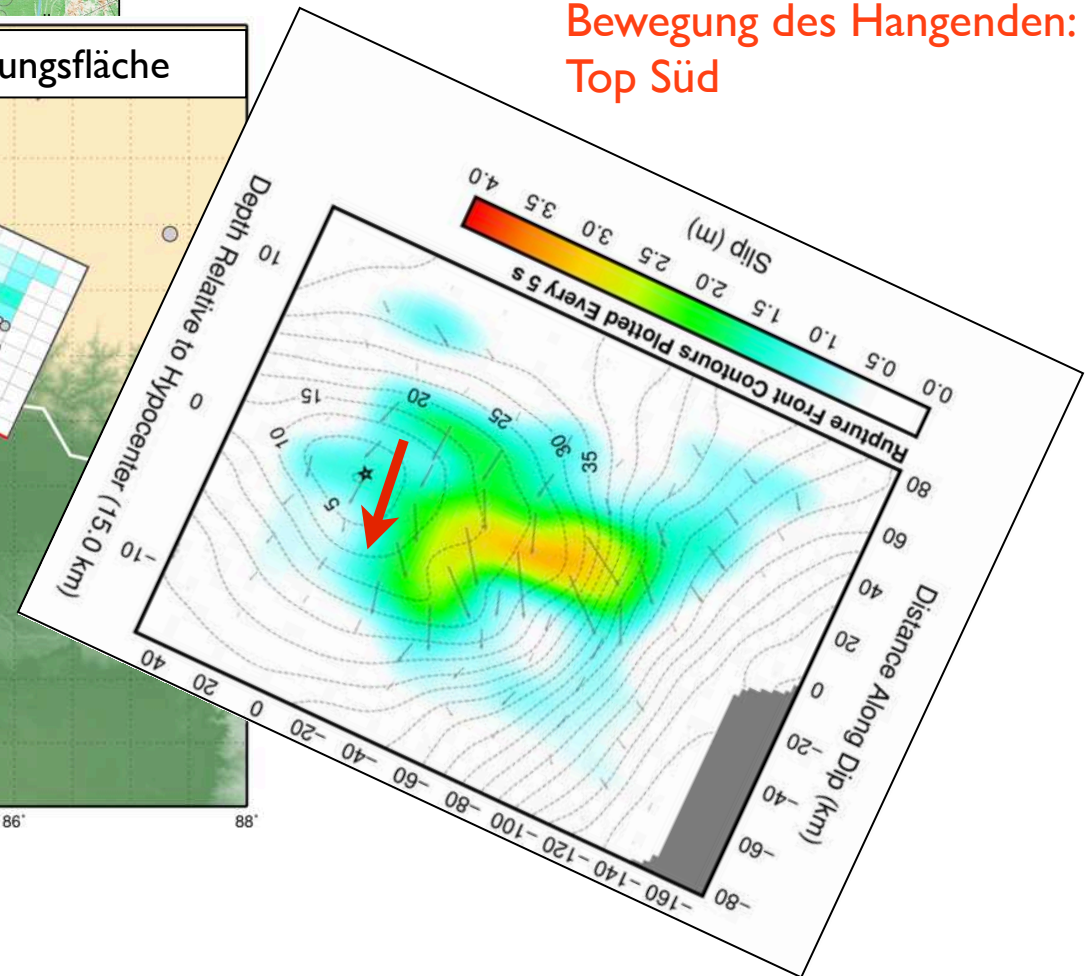
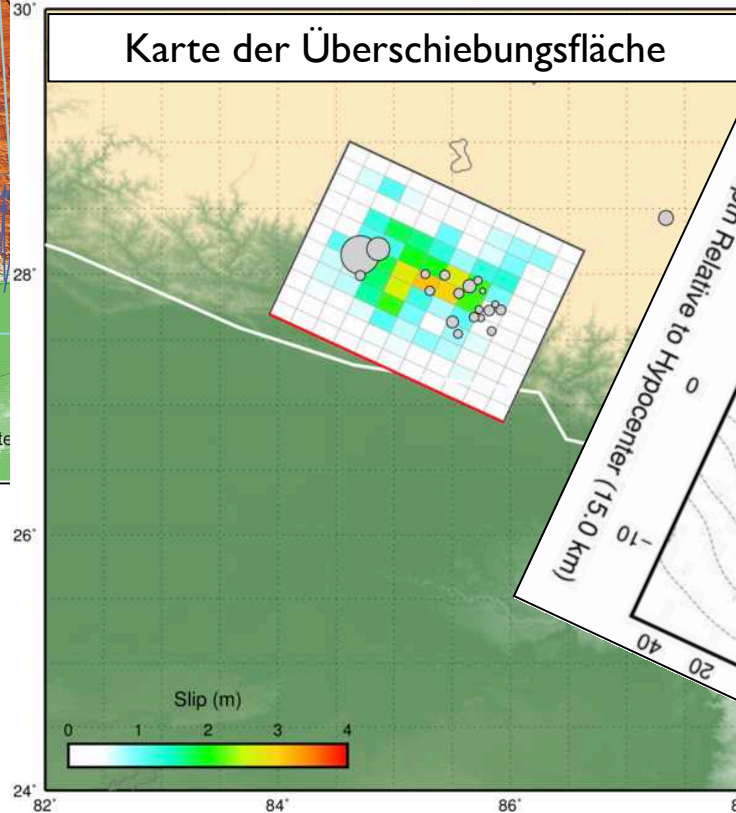
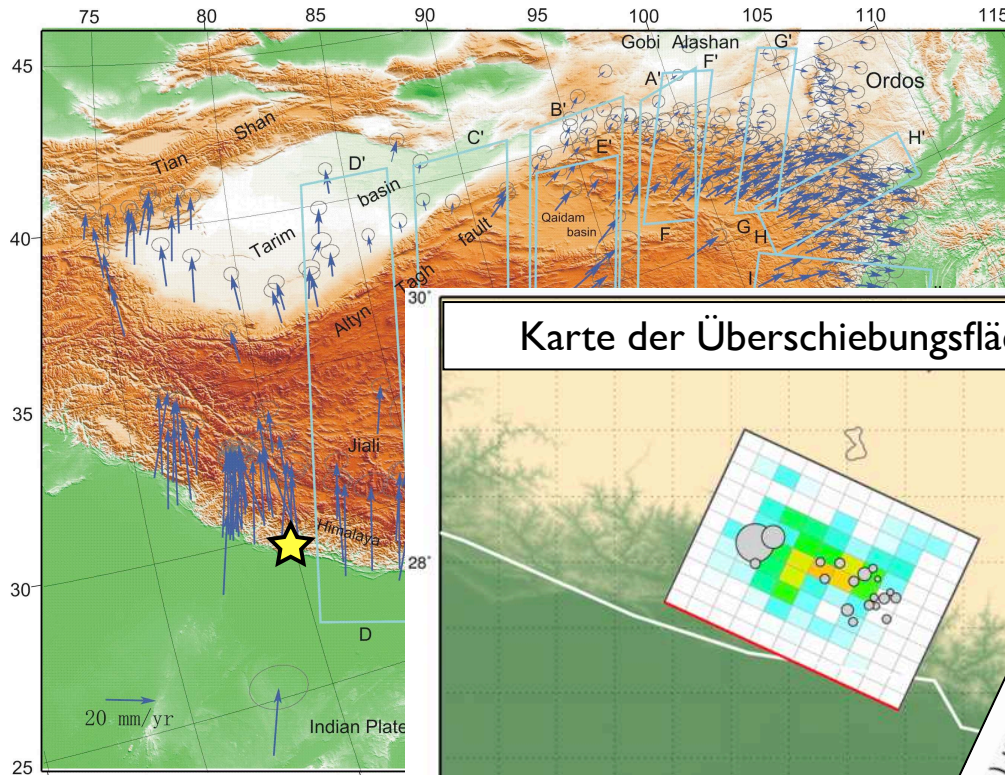
# Himalaya (aktuell)

Erdbeben 25. 4. 2015: Frontale Hauptüberschiebung (Main Frontal Thrust)



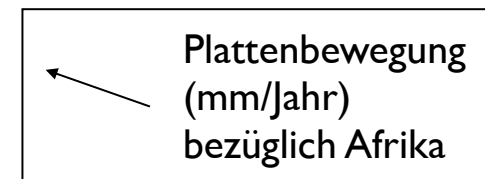
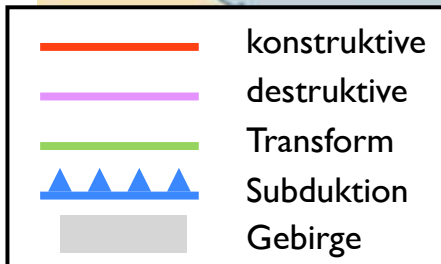
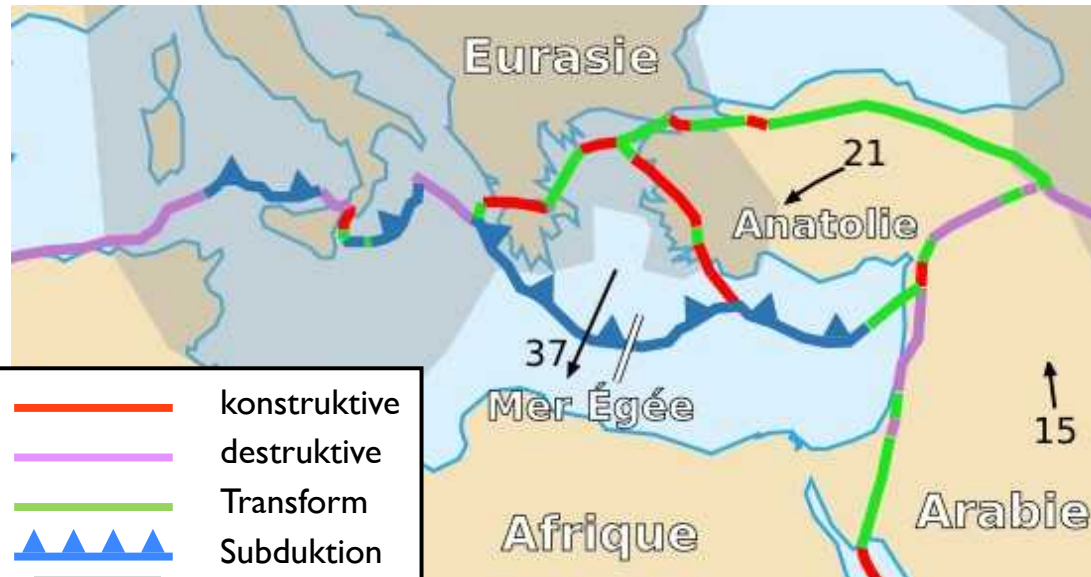
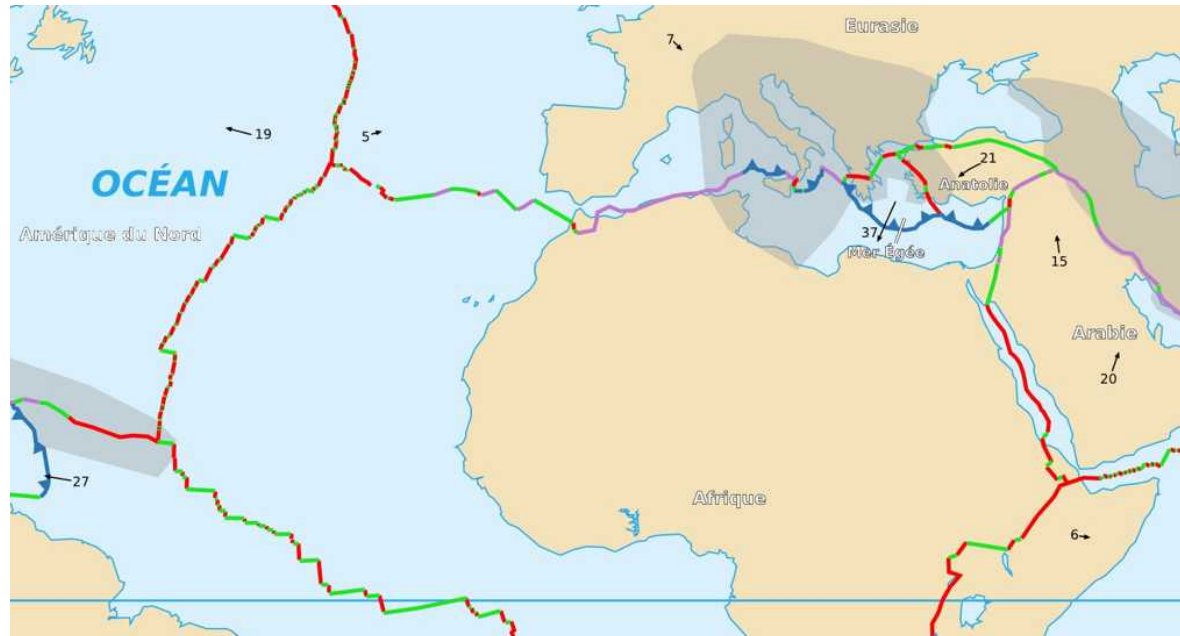
# Himalaya (aktuell)

Erdbeben 25. 4. 2015: Frontale Hauptüberschiebung (Main Frontal Thrust)

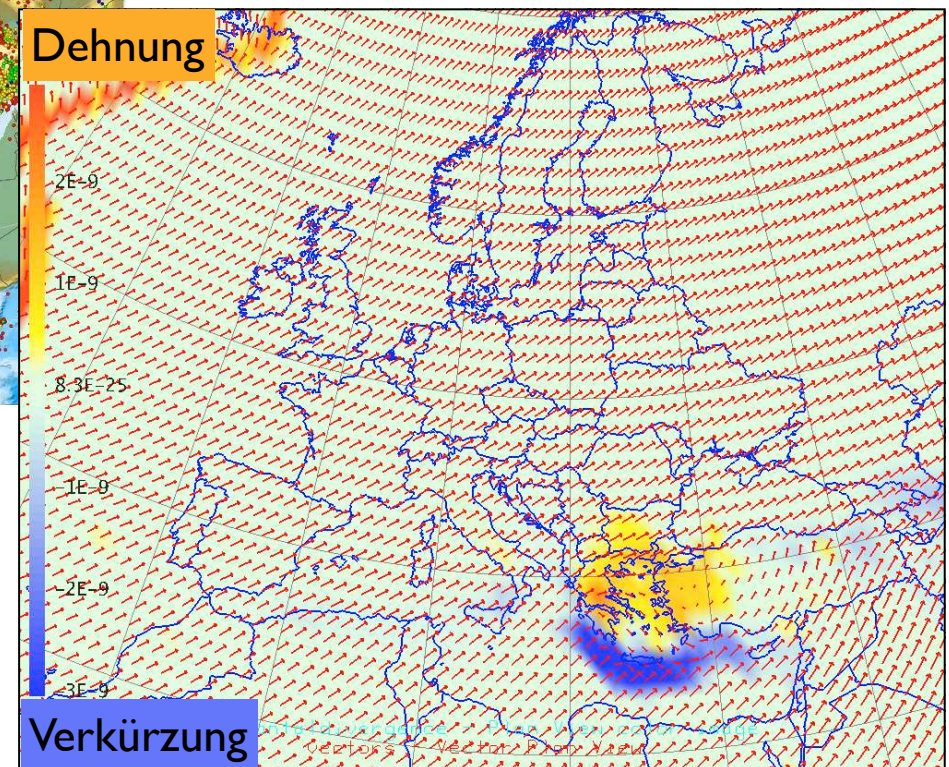
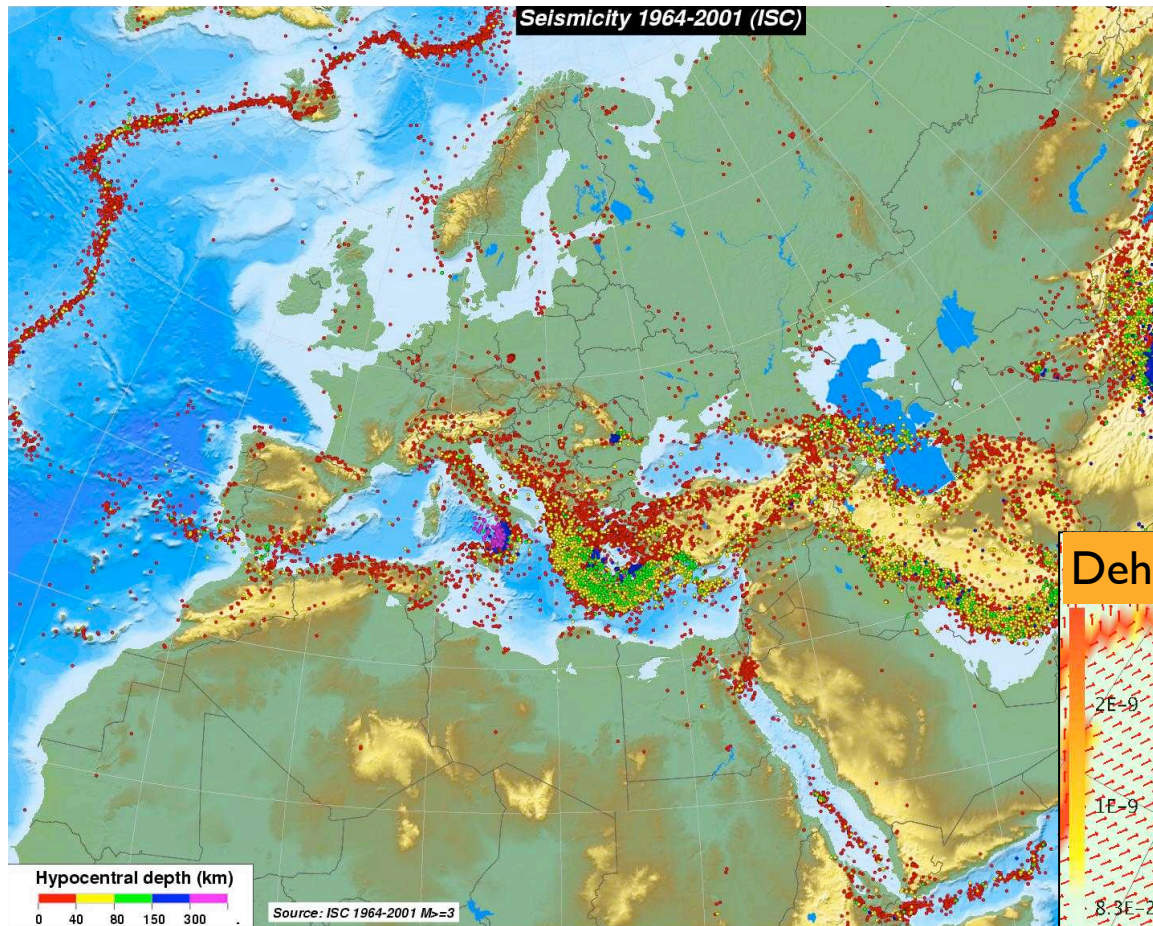


Bewegung des Hangenden:  
Top Süd

# (4) Plattengrenze Europa - Afrika



# aktuelle (abgeklingende) Bewegung





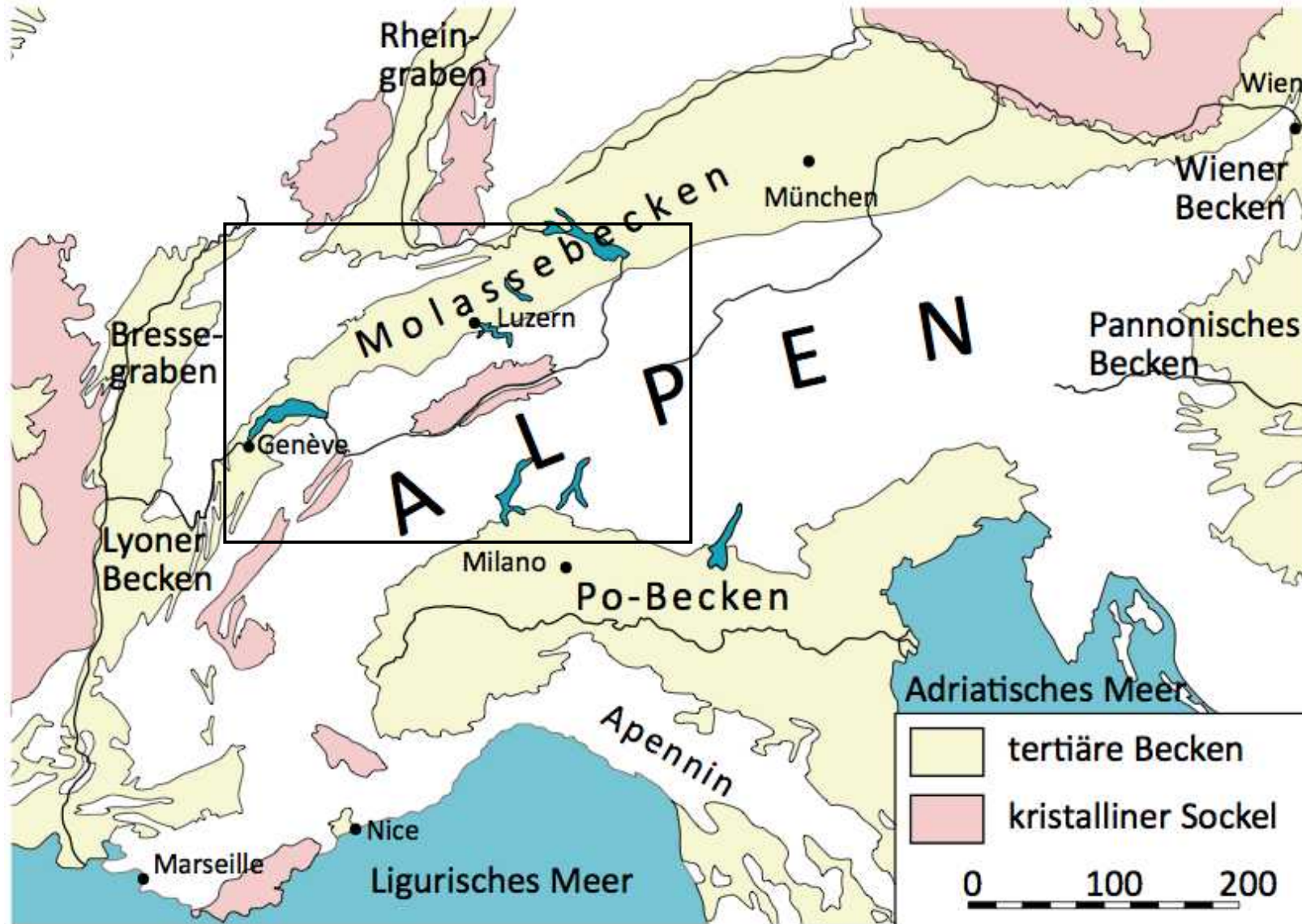
Alpen

# Alpenbogen

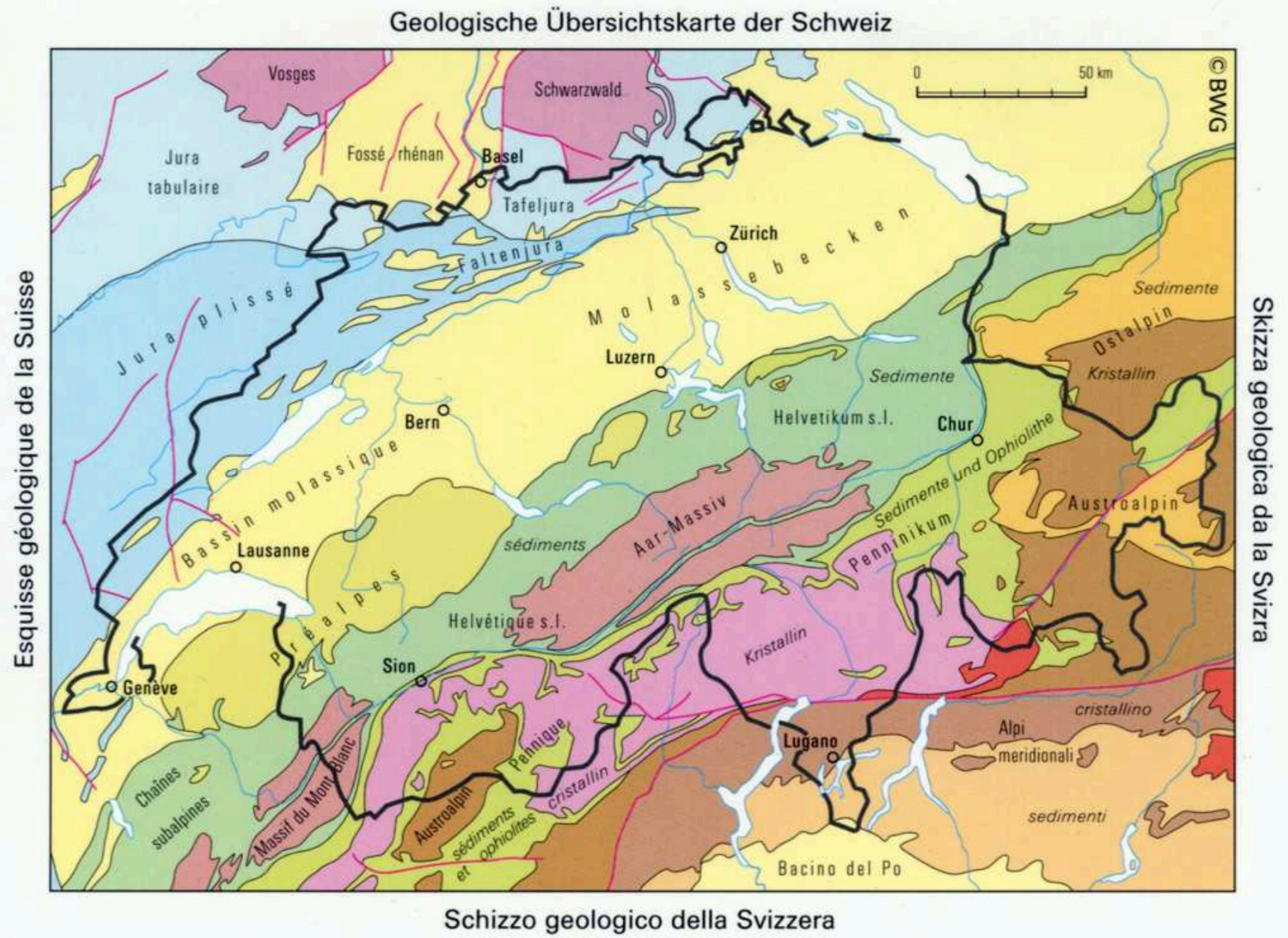


<https://upload.wikimedia.org/wikipedia/commons/4/4a/Alpenbogen.jpg>

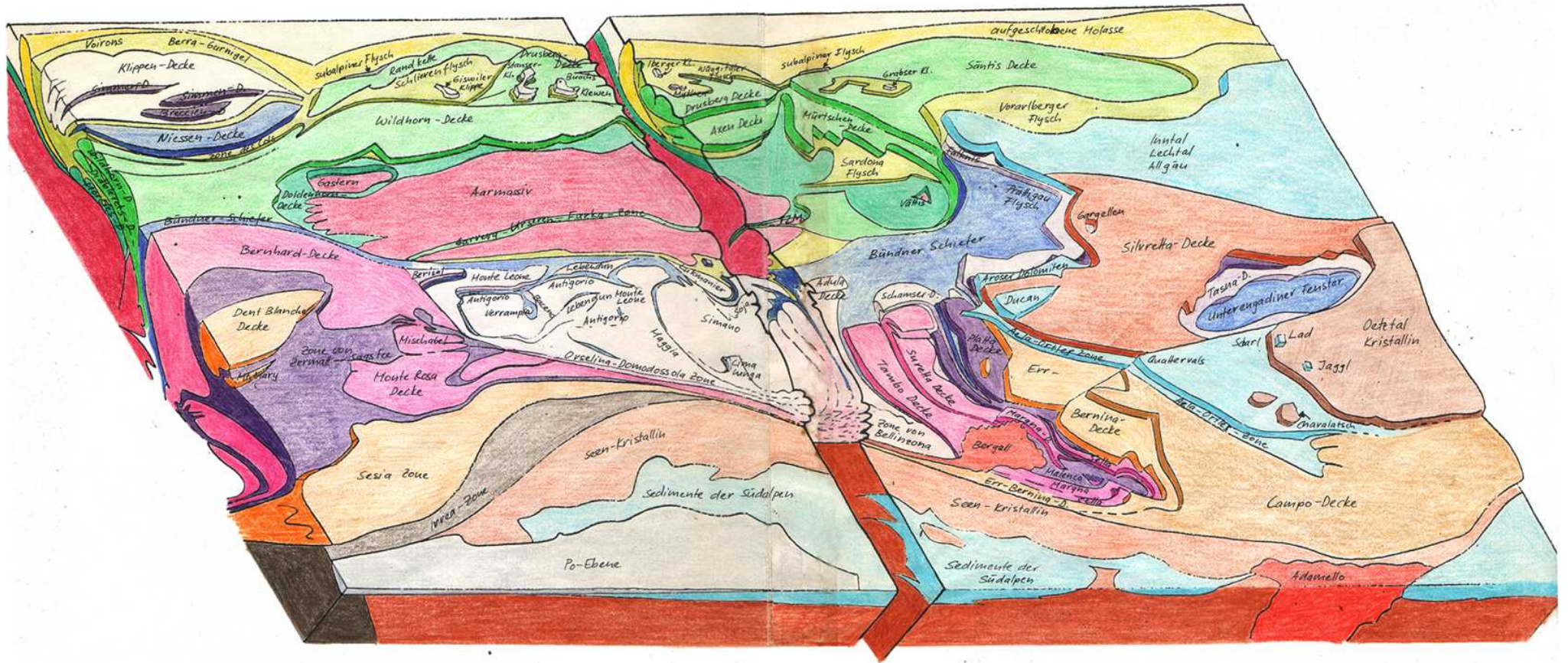
# Schweizer Alpen



# Tektonische Postkarte

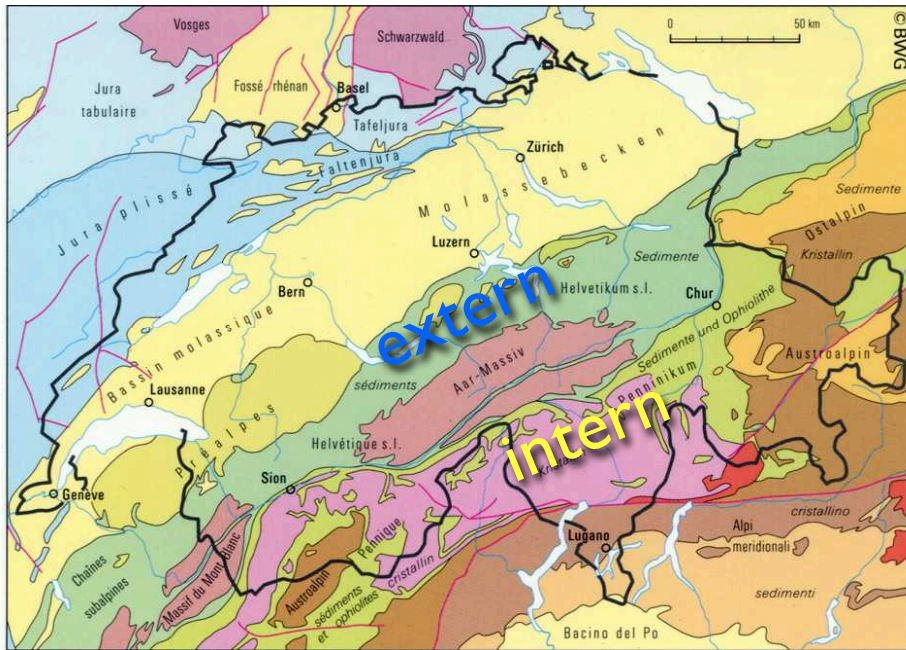


# Blockdiagram



# Tektonische Stellung

Nordkontinent



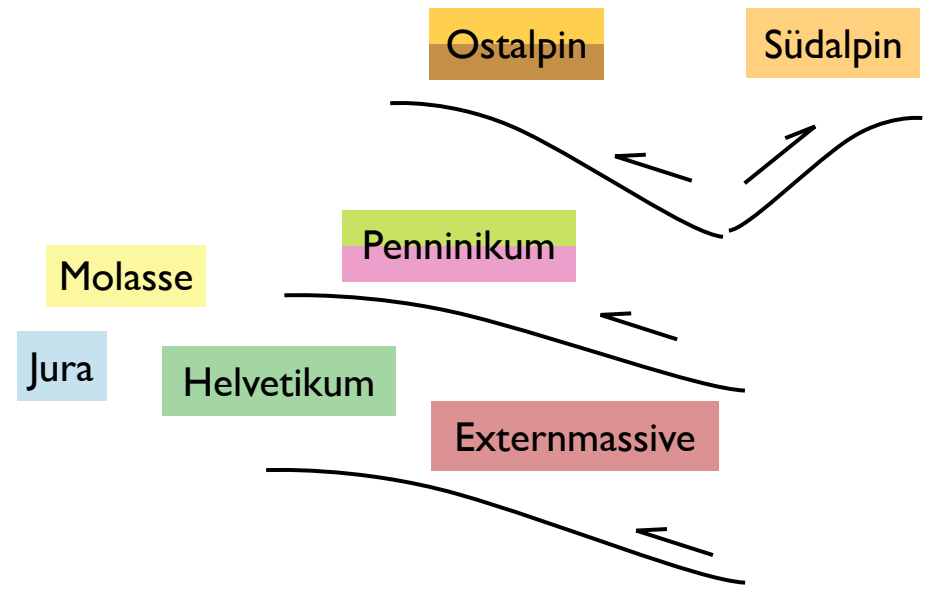
Südkontinent

extern: helvetisch  
intern: penninisch

N

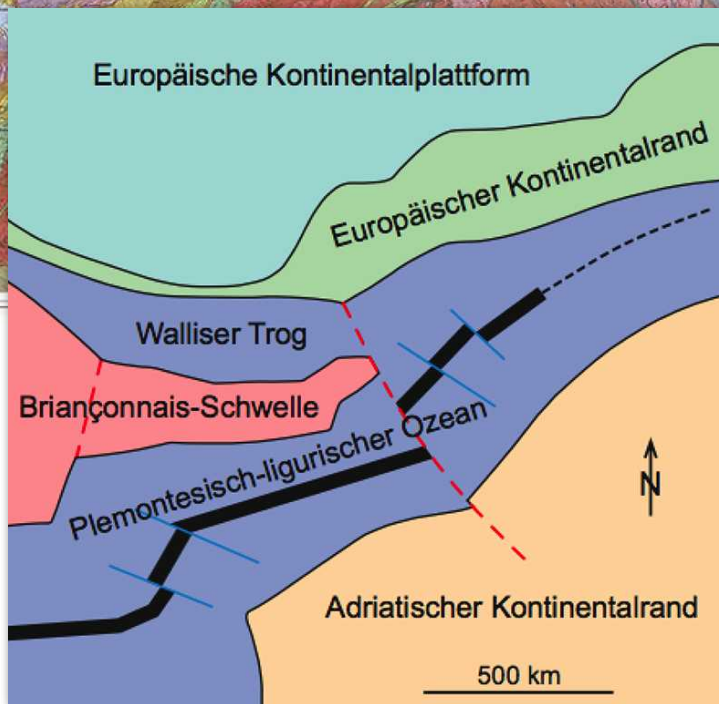
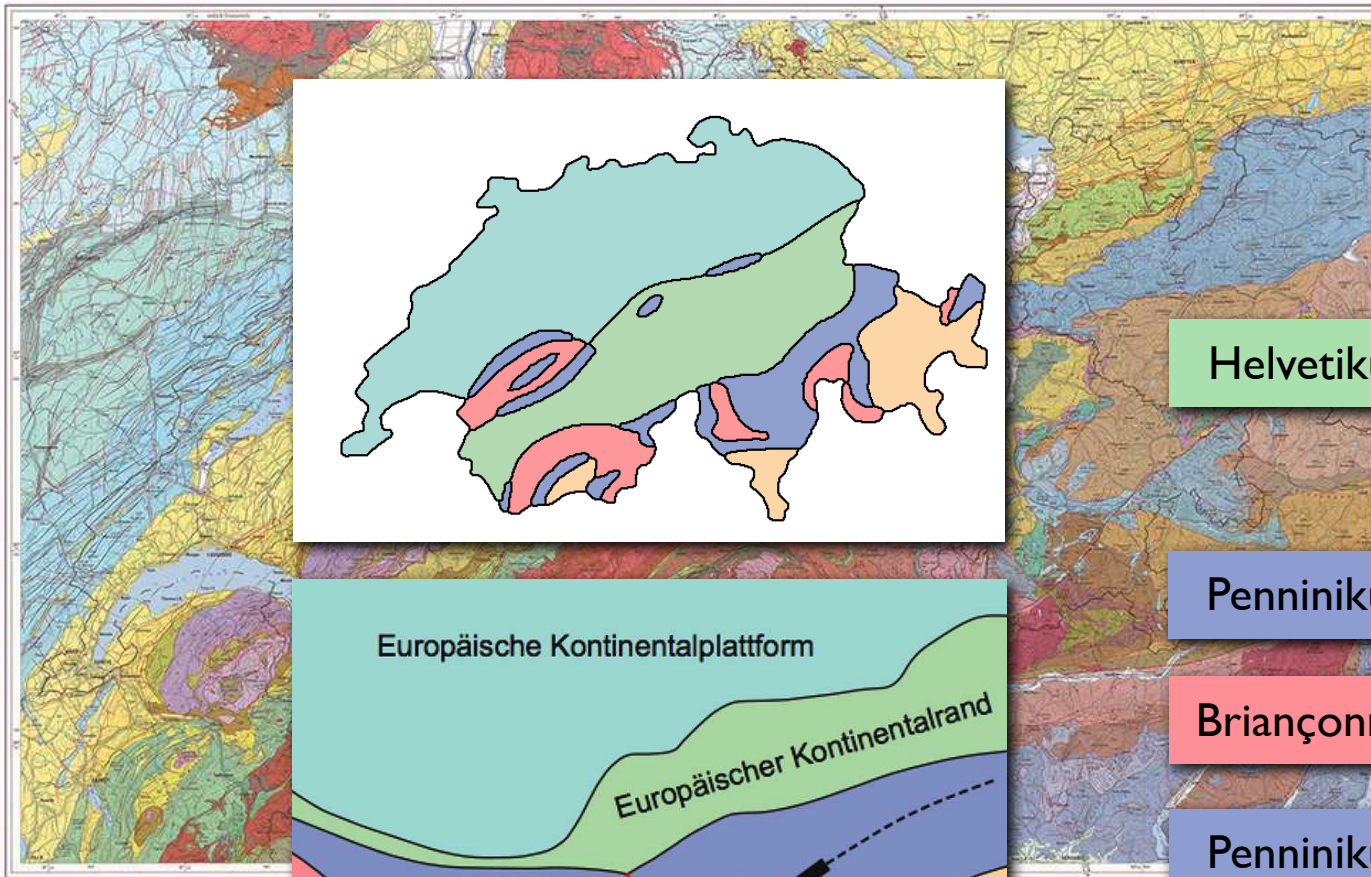
tektonisch höher

S



tektonisch tiefer

# Tektonische Karte



Helvetikum

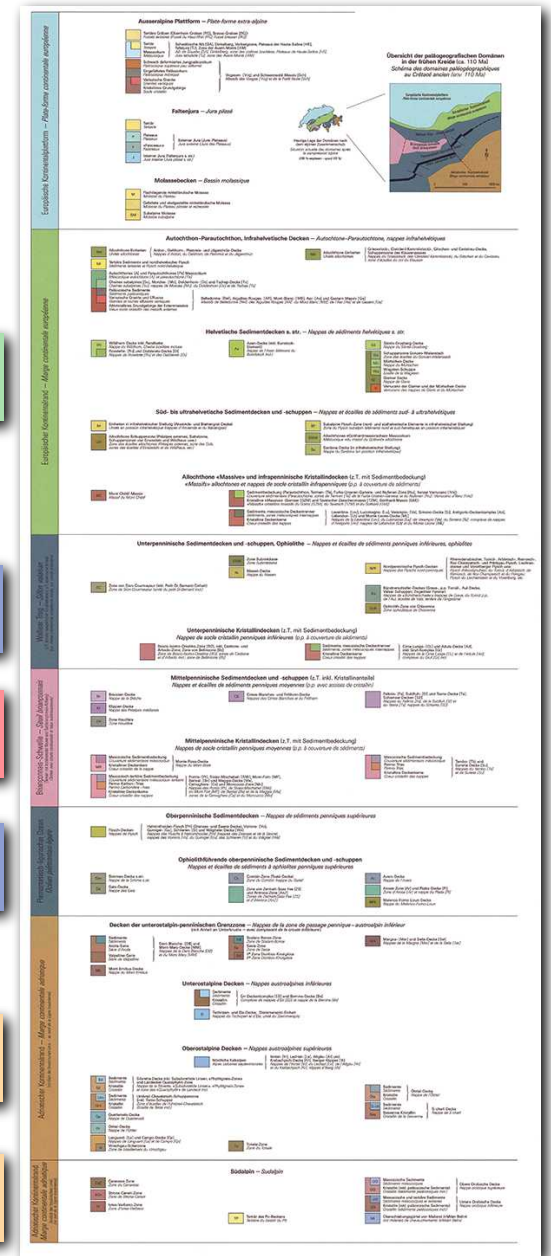
Penninikum

Briançonnais

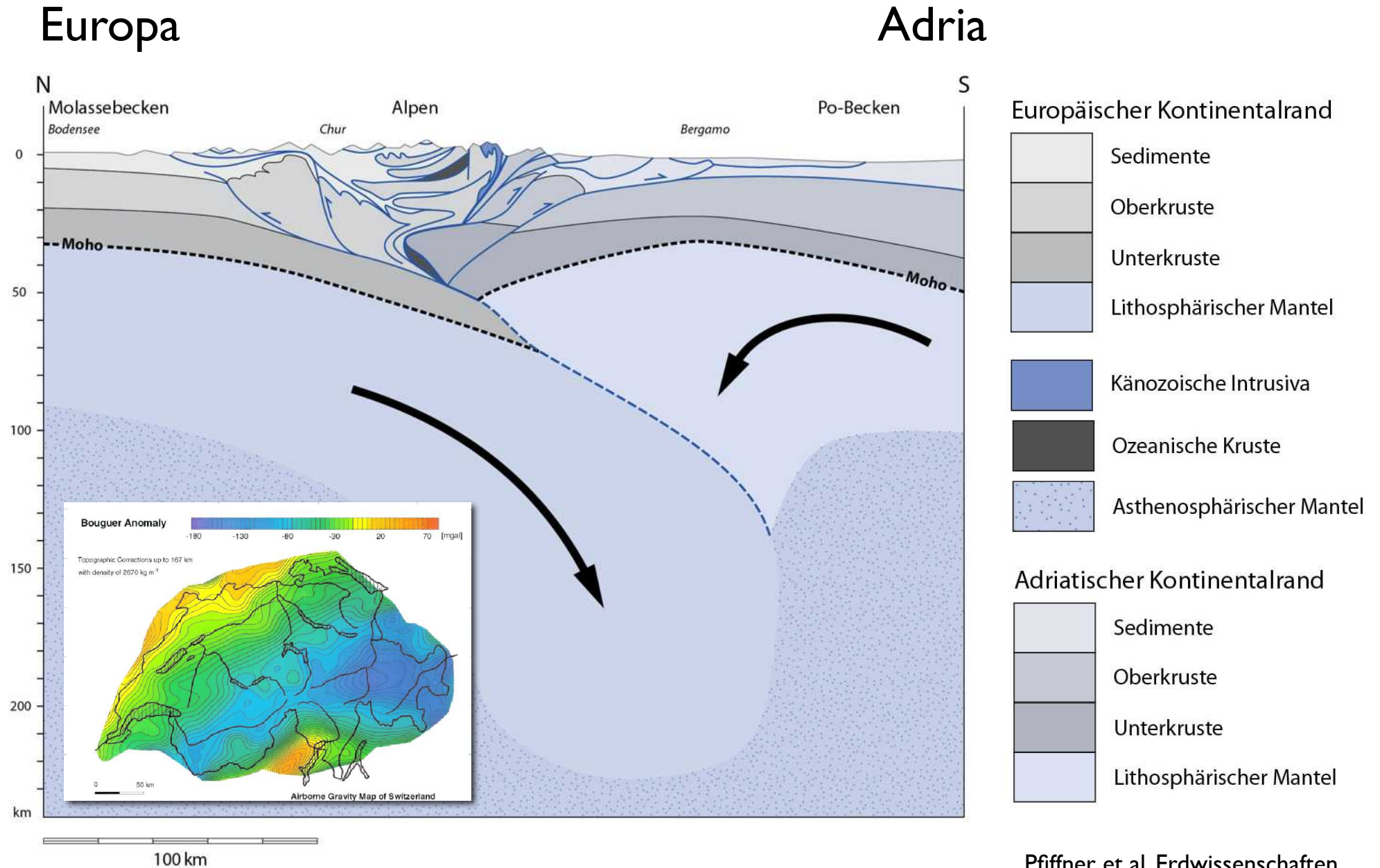
Penninikum

Ostalpin

Südalpin

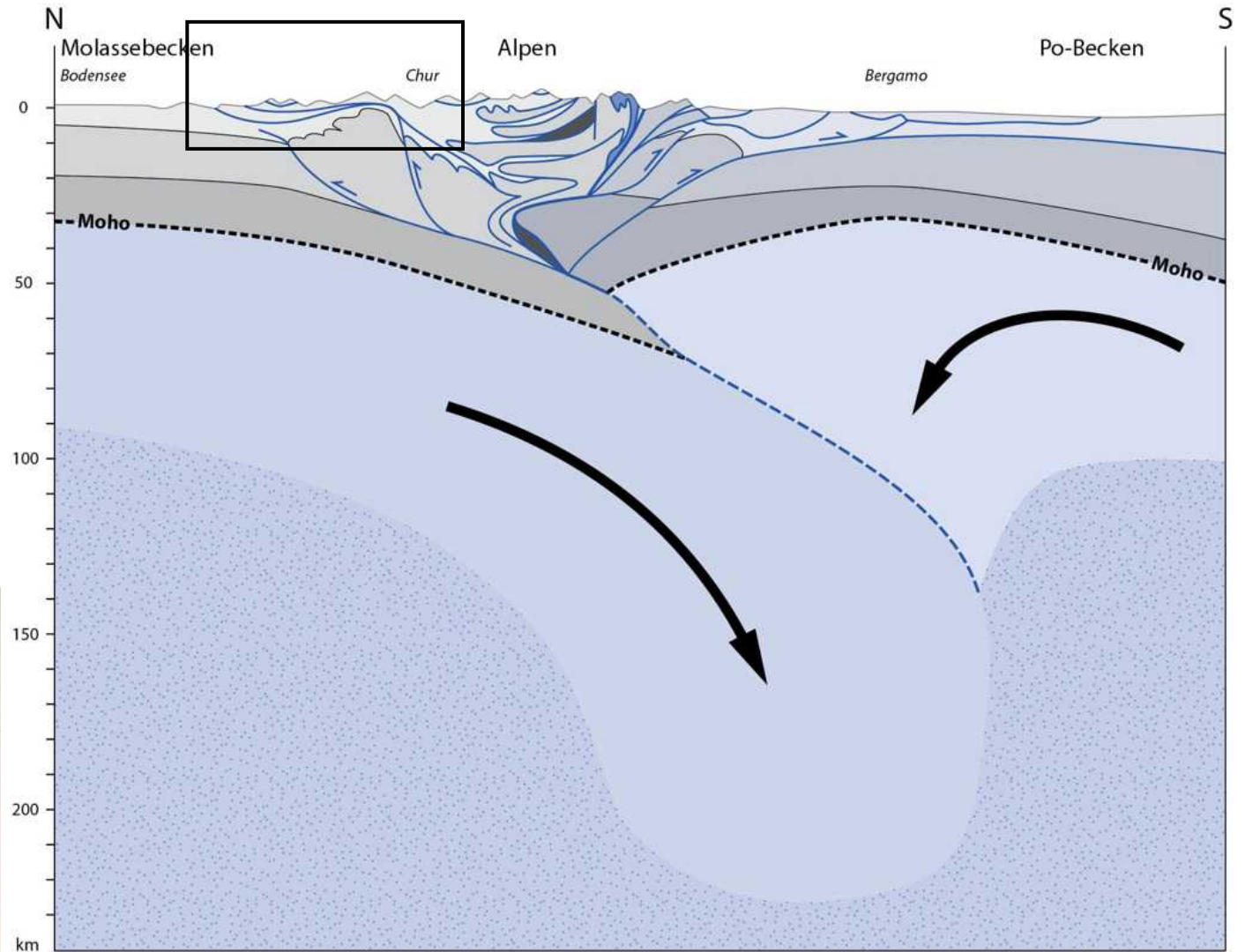
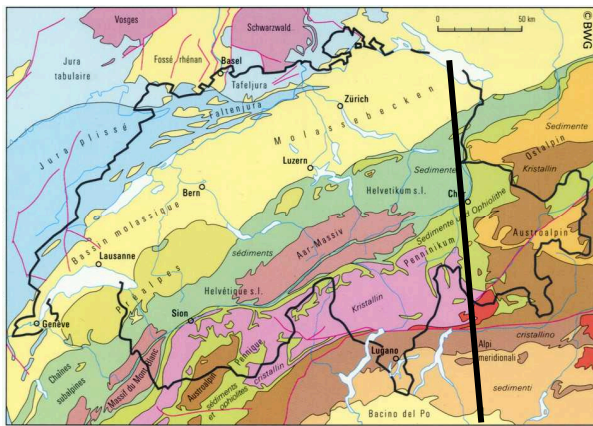


# Tiefenstruktur der Alpen

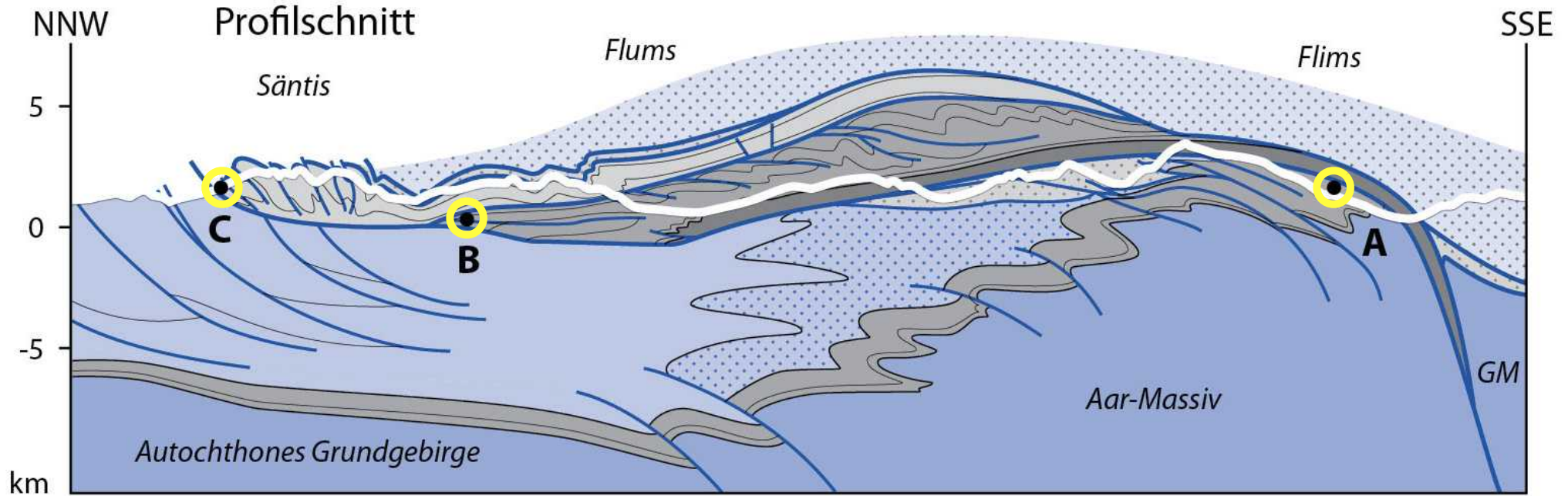




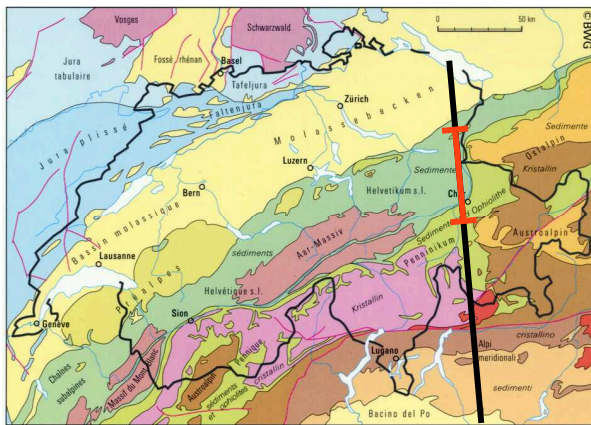
# Verkürzung



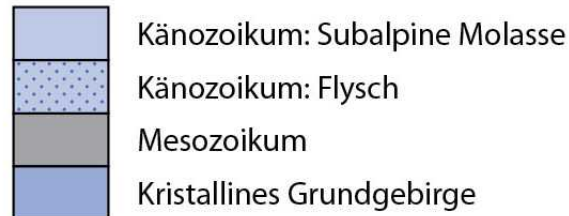
# Verkürzung



Pfiffner et al. Erdwissenschaften



## Autochthon, Infrahelvetikum



## Penninische Decken



## Ultrahelvetikum

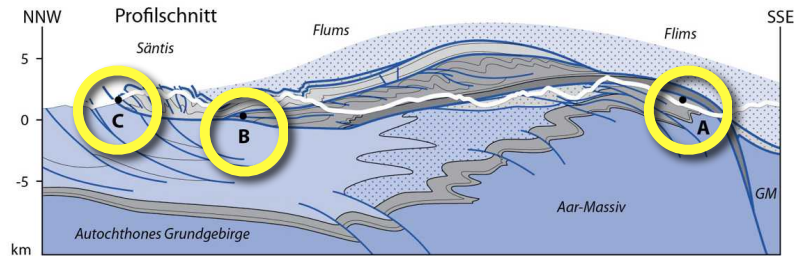


## Säntis-, Glarner-Decke

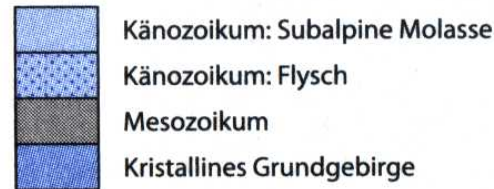


# Abgewickeltes Profil

C Kreide  
B Jura  
A Trias



## Autochthon, Infrahelvetikum



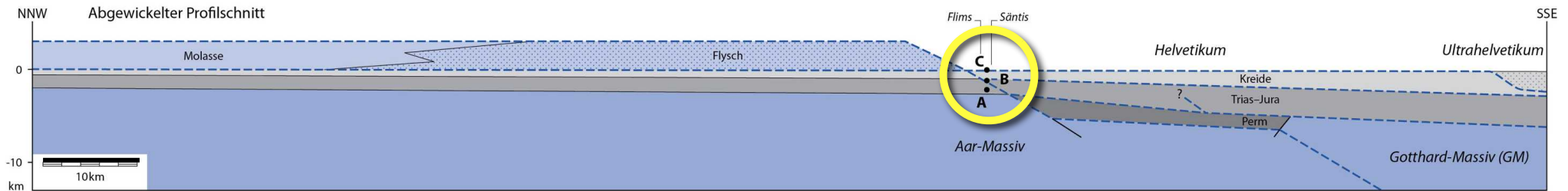
## Penninische Decken



## Ultrahelvetikum



## Säntis-, Glarner-Decke



Pfiffner et al. Erdwissenschaften

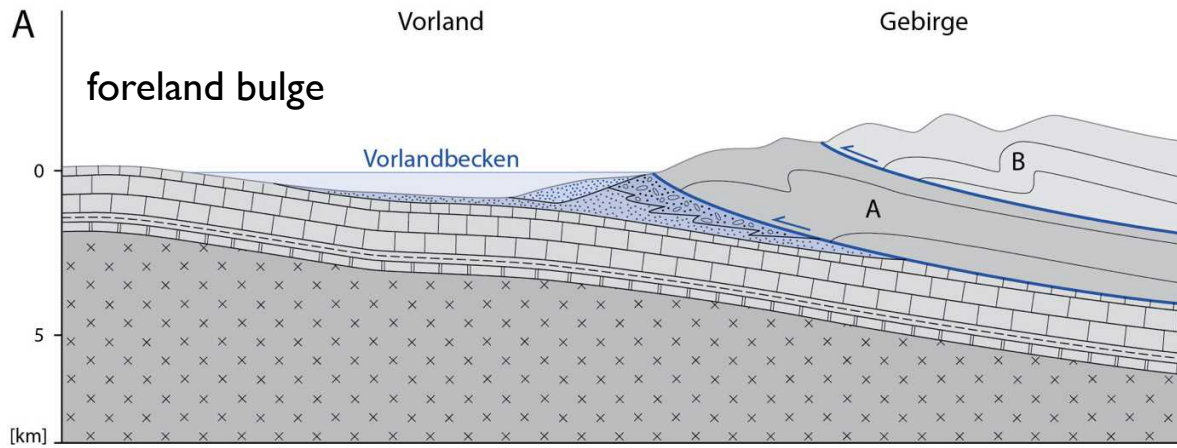
$$L' = 58 \text{ km}$$

$$L_0 = 155 \text{ km}$$

$$\Delta L = L' - L_0 = 97 \text{ km}$$

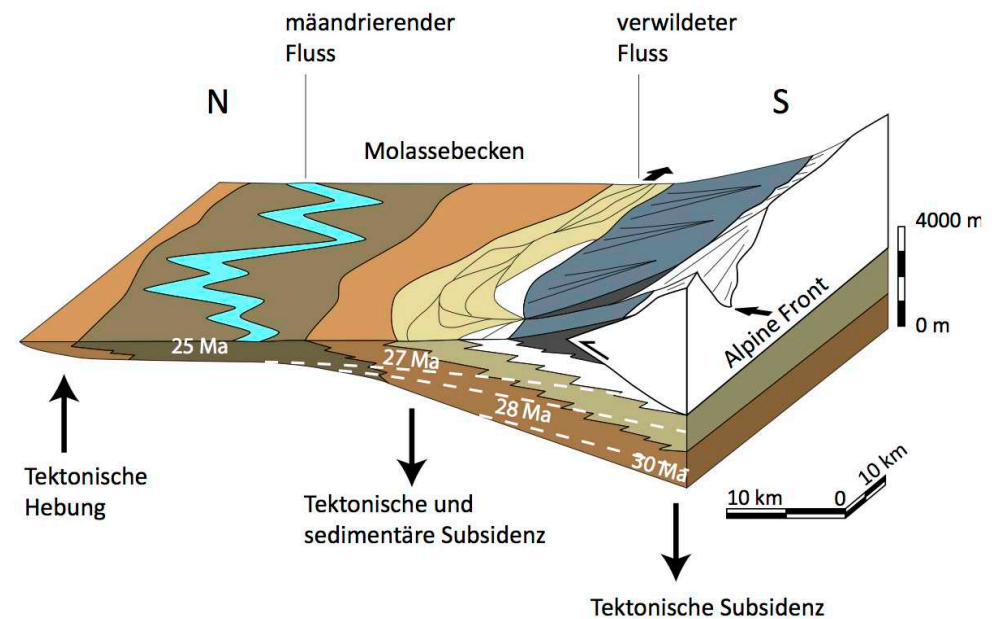
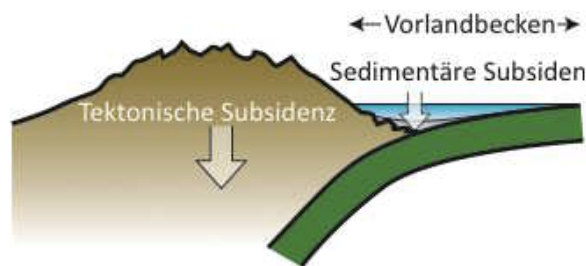
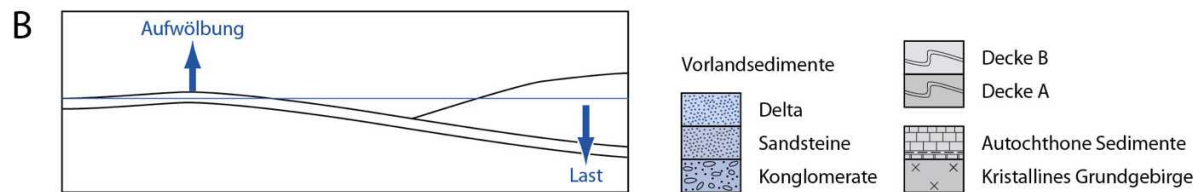
horizontale Verkürzung  $\Delta L / L_0 = 0.63 = 63\%$

# Vorlandbecken



Trogfüllung im Vorlandbecken:  
 marin: Turbidite  
 terrestrisch: fluviatile Sedimente

Pfiffner et al. Erdwissenschaften



# 8 Entstehung der Alpen

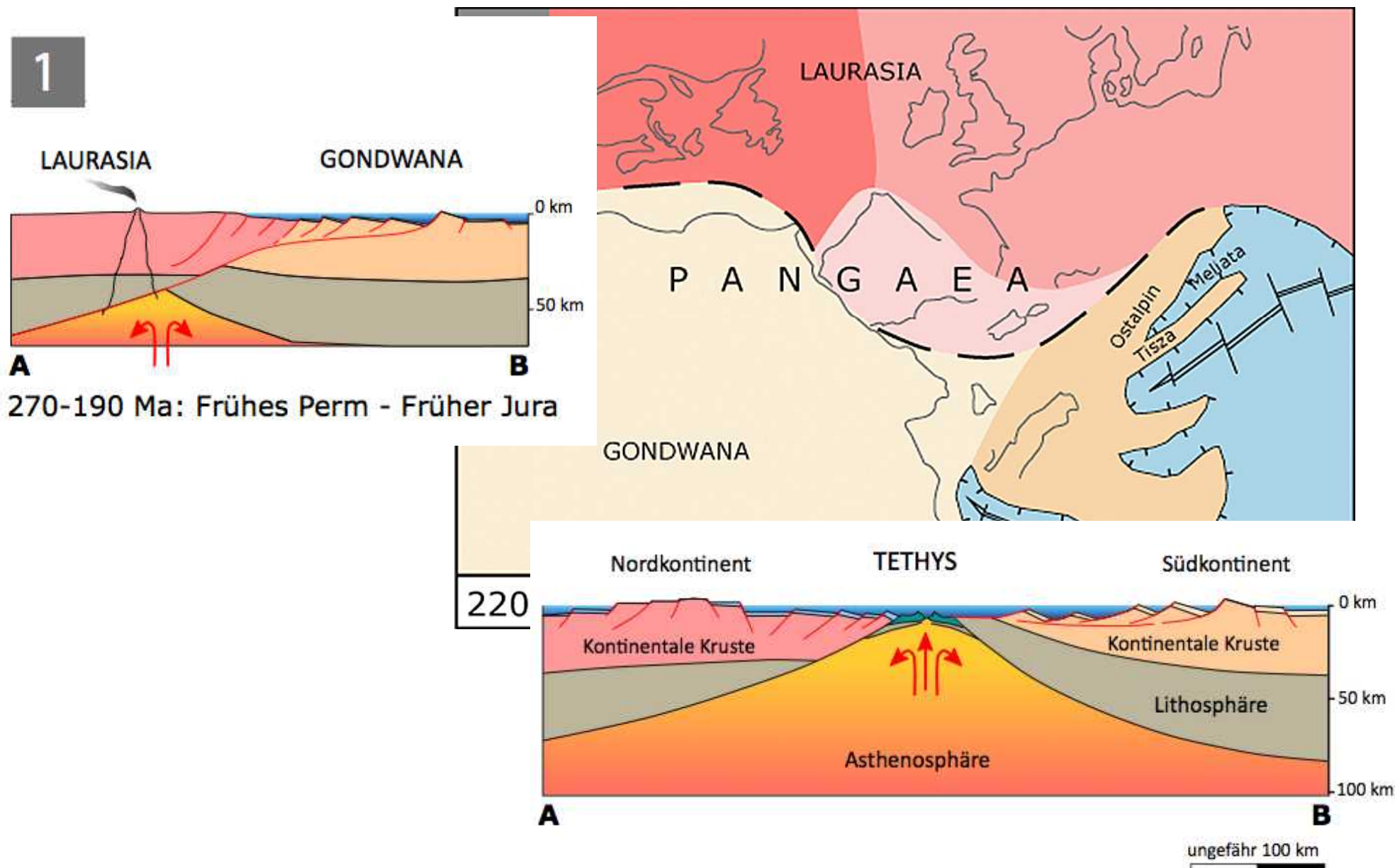
Abriss der plattentektonischen Entwicklung

## Geologisches Signalement

- Tafeljura
- Faltenjura
- Helvetikum
- Externe Massive
- Molasse
- Penninikum
- Ostalpin
- Südalpin

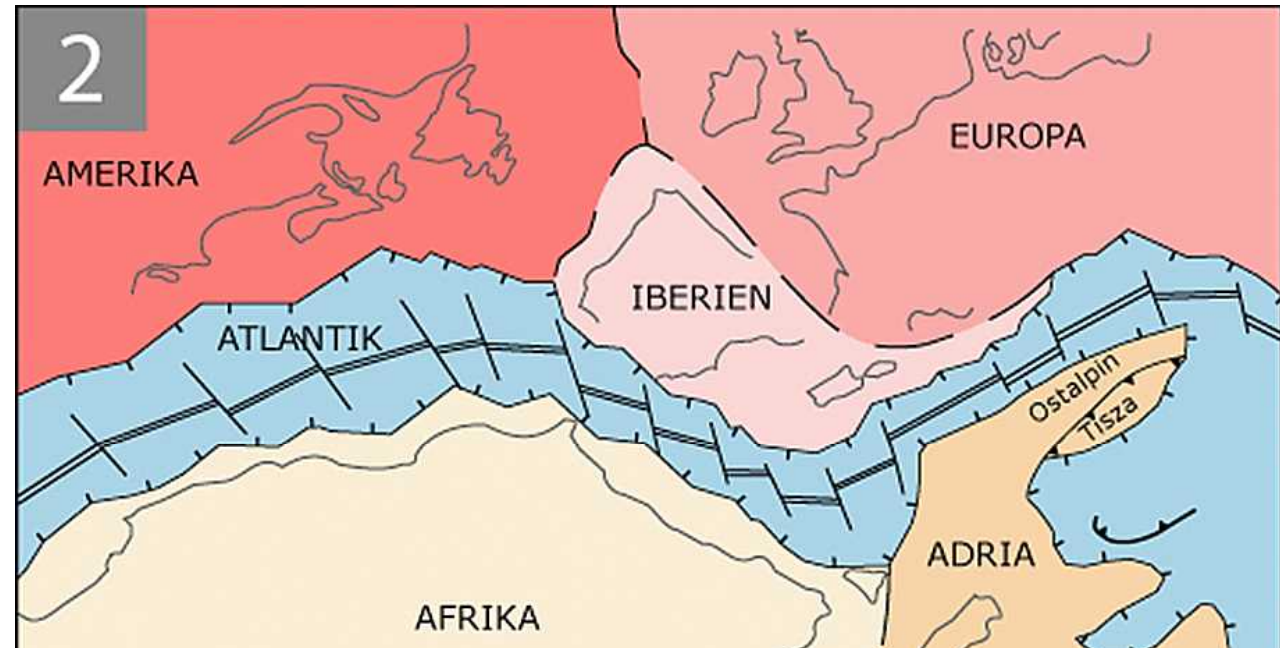
# Entstehung der Alpen

# Phase I: Neuer Raum wird geschaffen ("Rifting Phase")

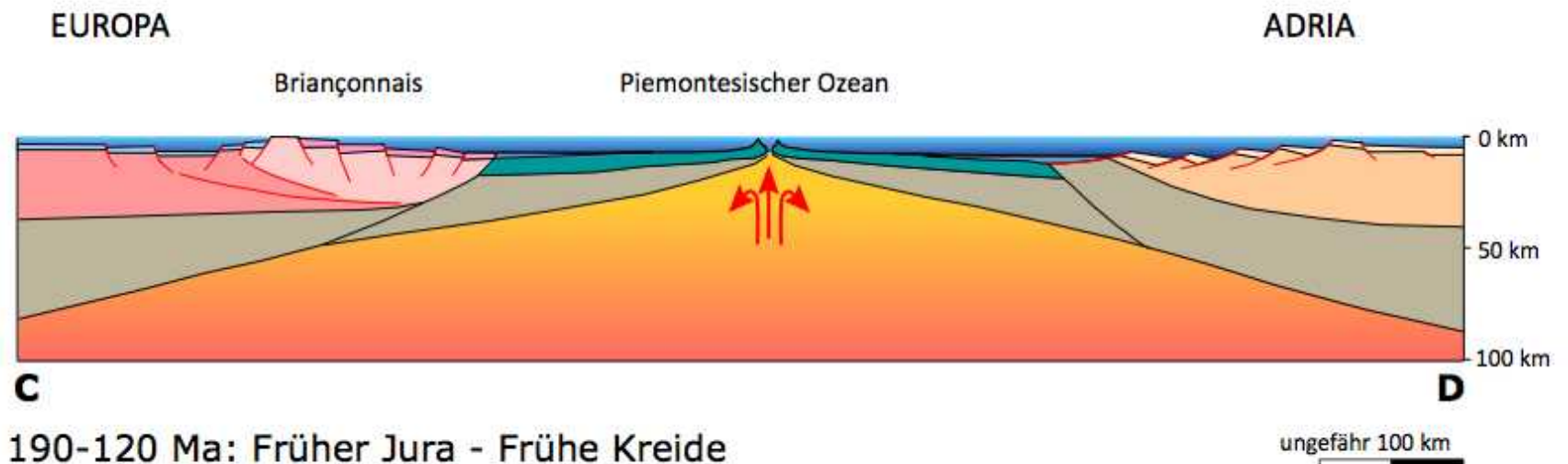


## Phase 2:

Neue ozean. Kruste wird gebildet ("Drifting Phase")



2

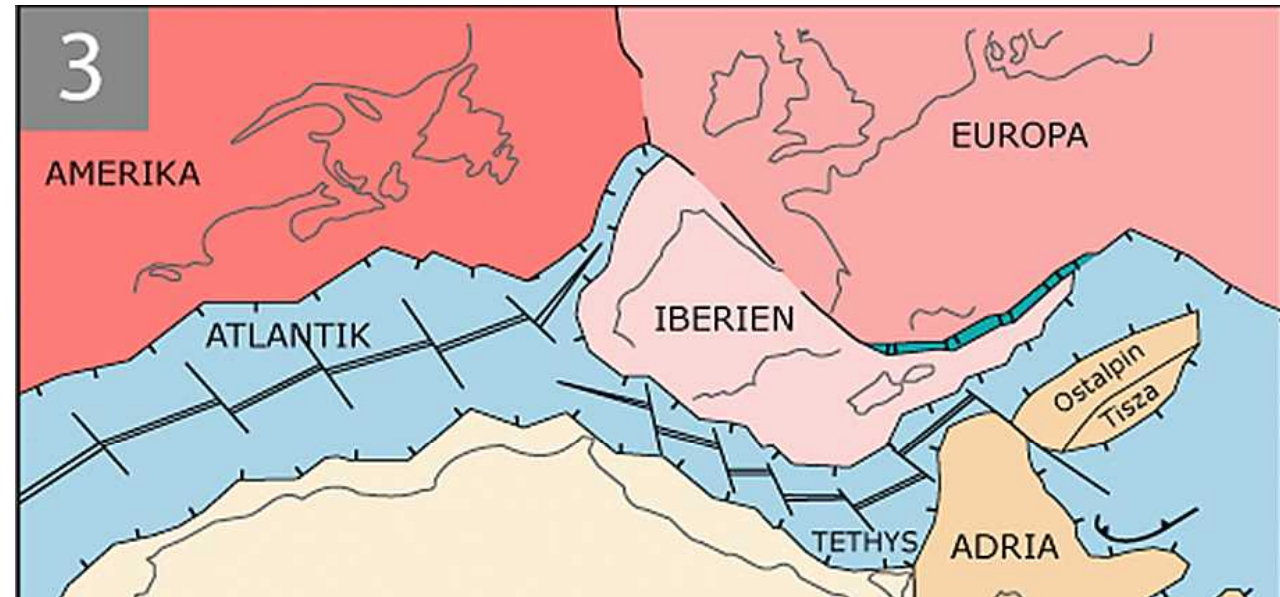


190-120 Ma: Früher Jura - Frühe Kreide

ungefähr 100 km



# Phase 3: Ozeanische Kruste und Transform-Brüche



3

EUROPA

ADRIA

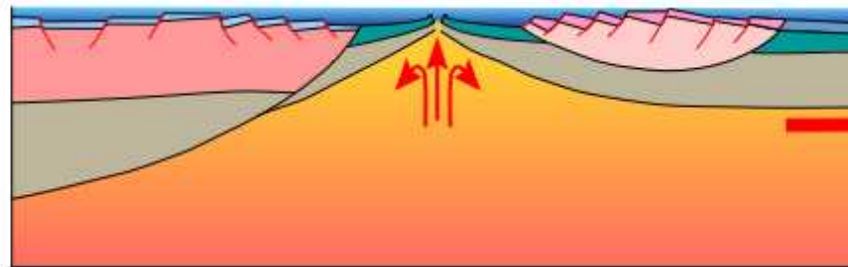
Helvetikum

Walliser Trog

Piemontesischer Ozean

Ostalpin / Südalpin

Briançonnais

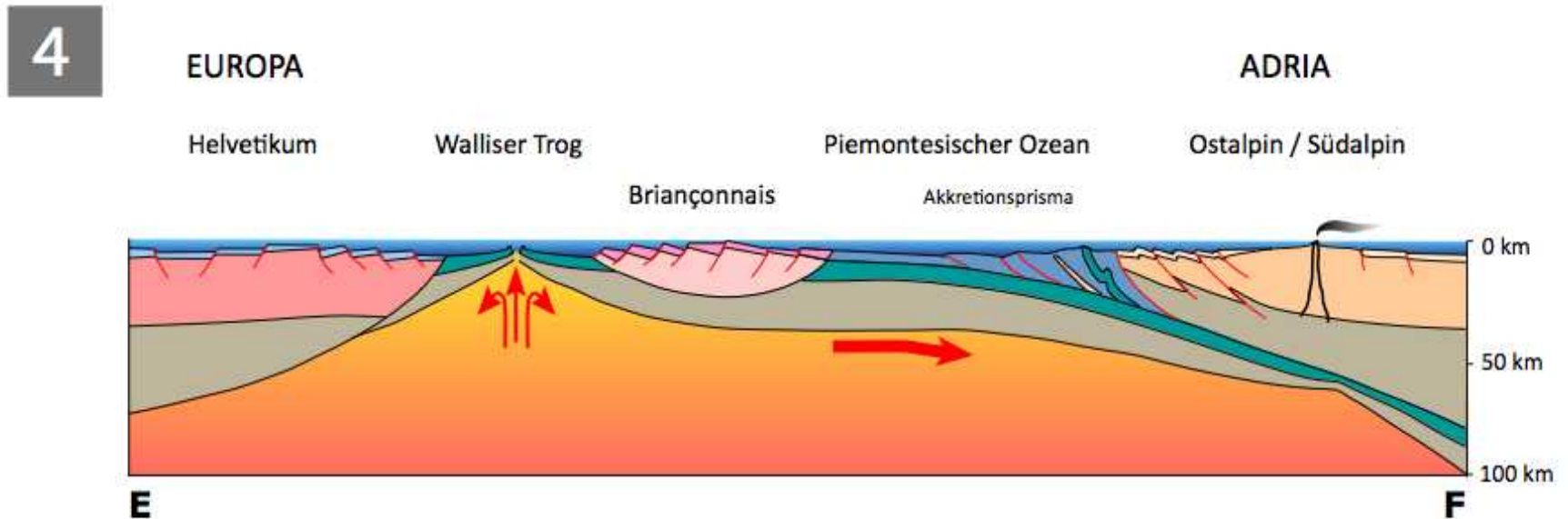
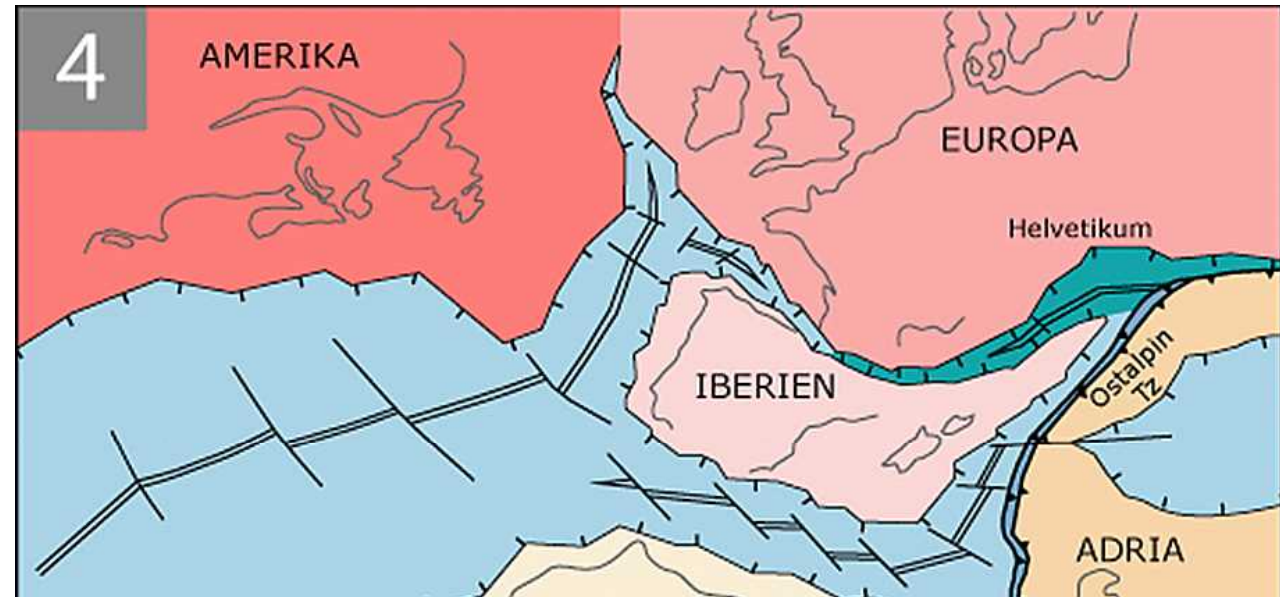


E

F

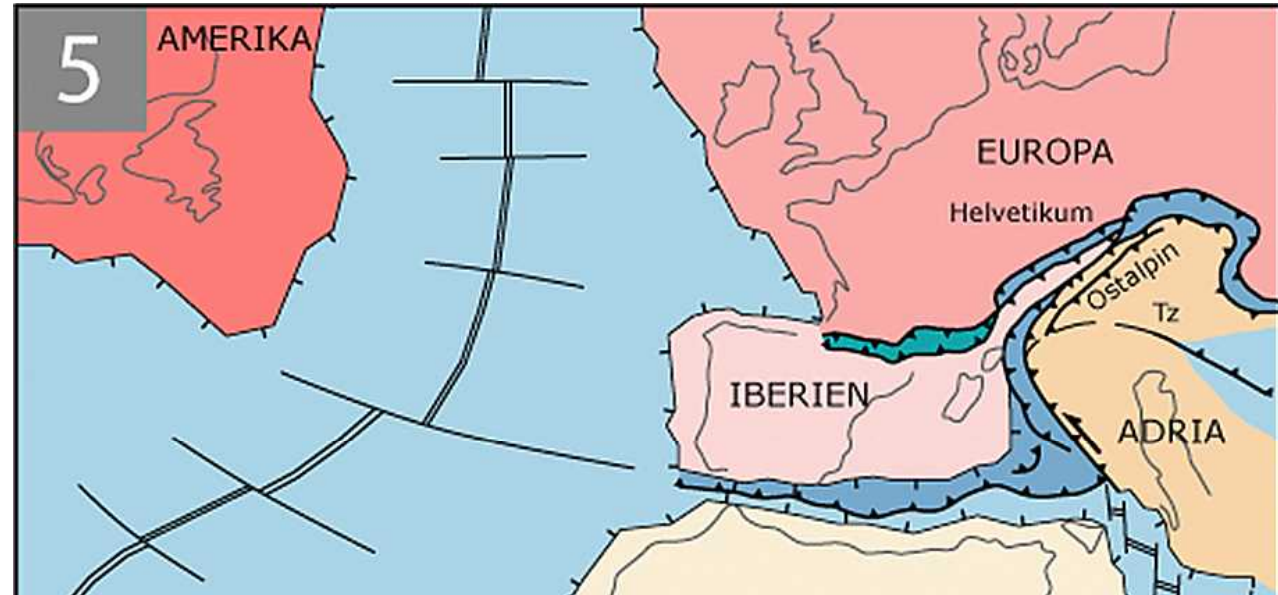
120-60 Ma: Frühe Kreide - Paläozän

# Phase 4: Subduktion

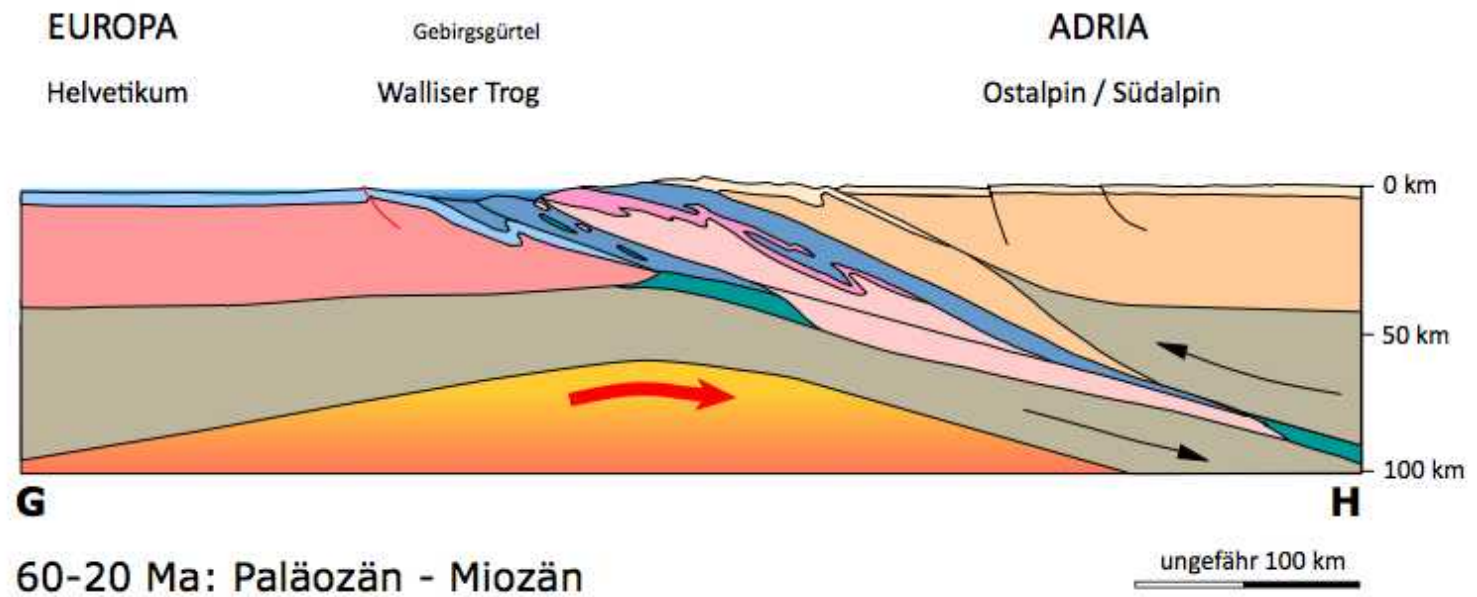


120-60 Ma: Frühe Kreide - Paläozän

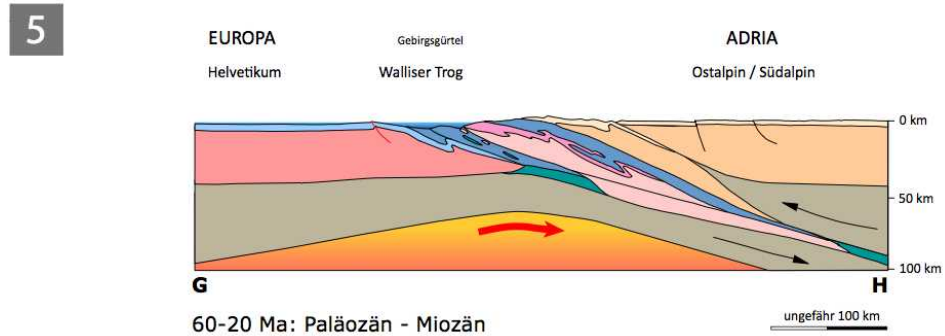
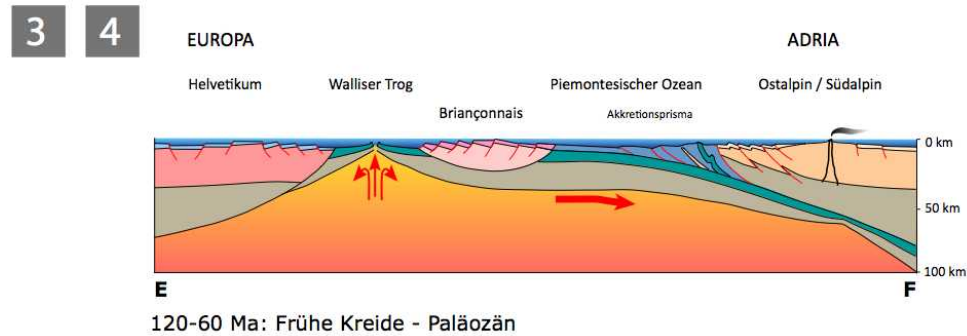
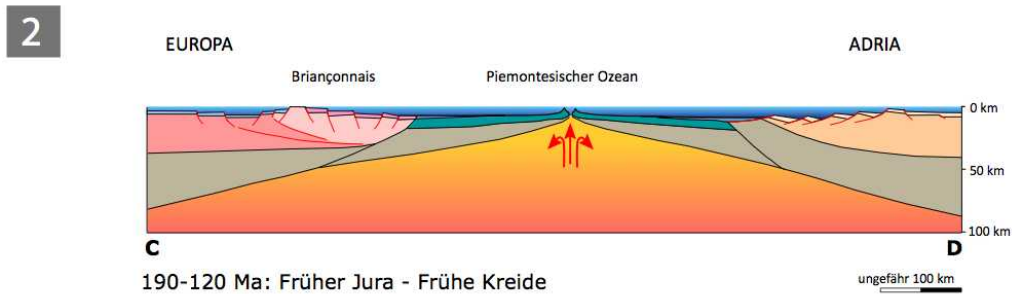
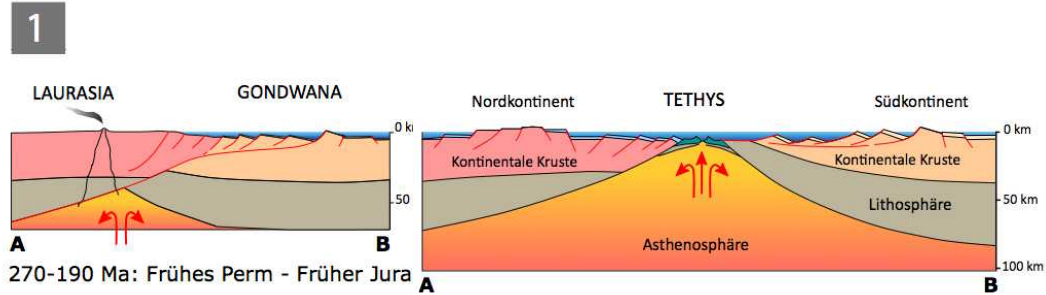
# Phase 5: Kollision der Kontinente



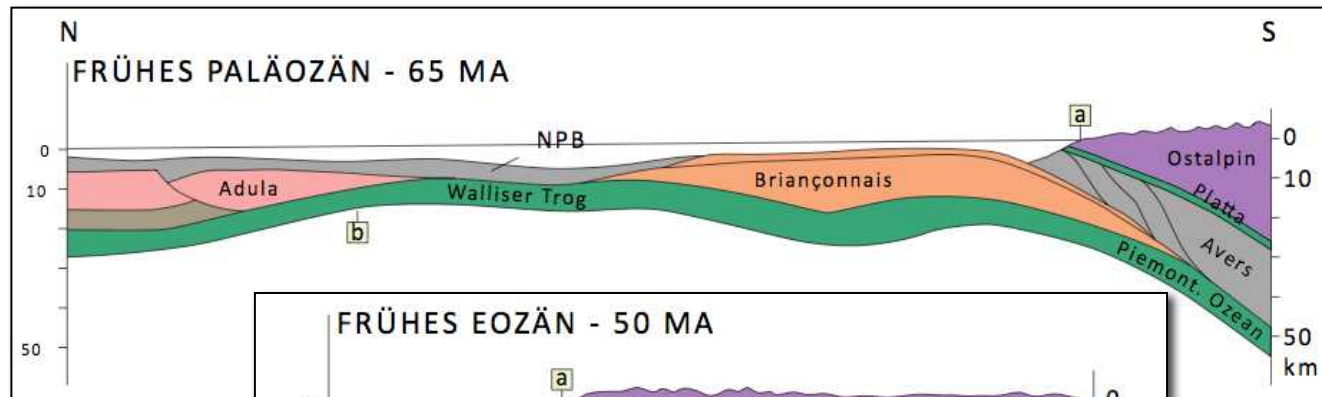
5



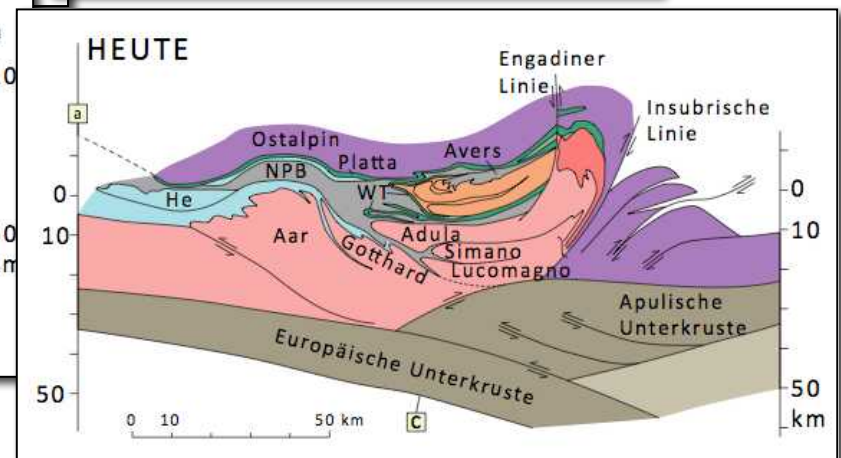
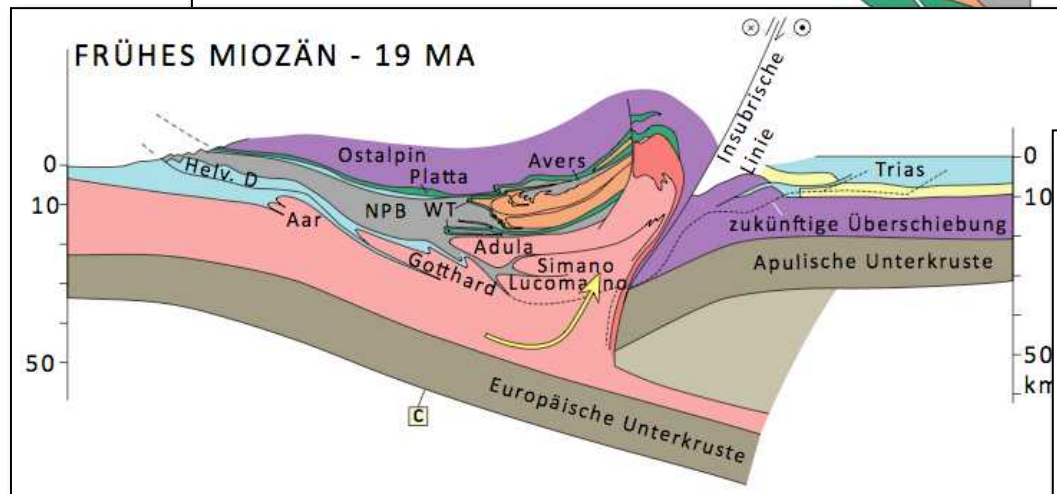
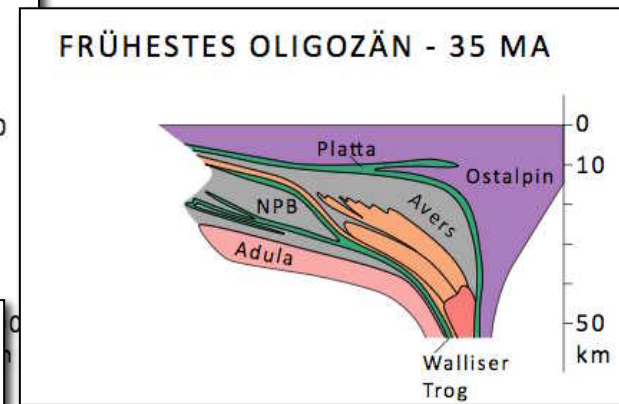
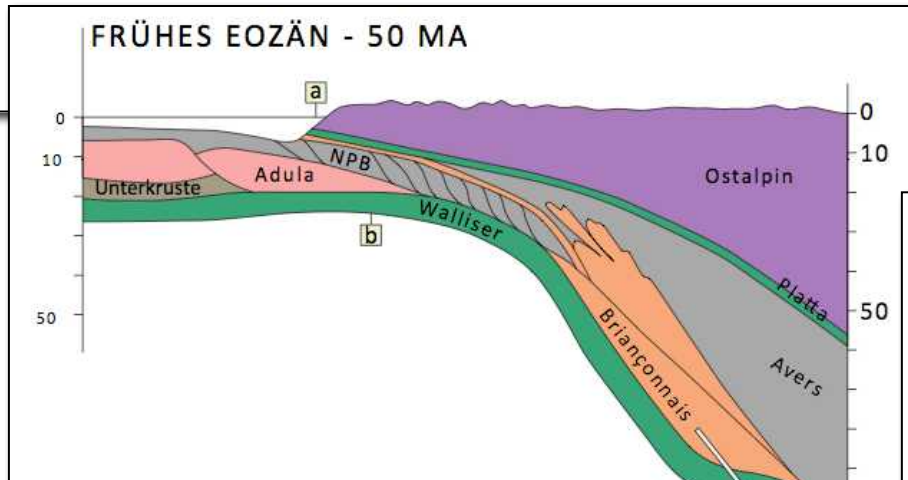
# Synopsis Perm - Kreide



# Synopsis Kreide - Heute



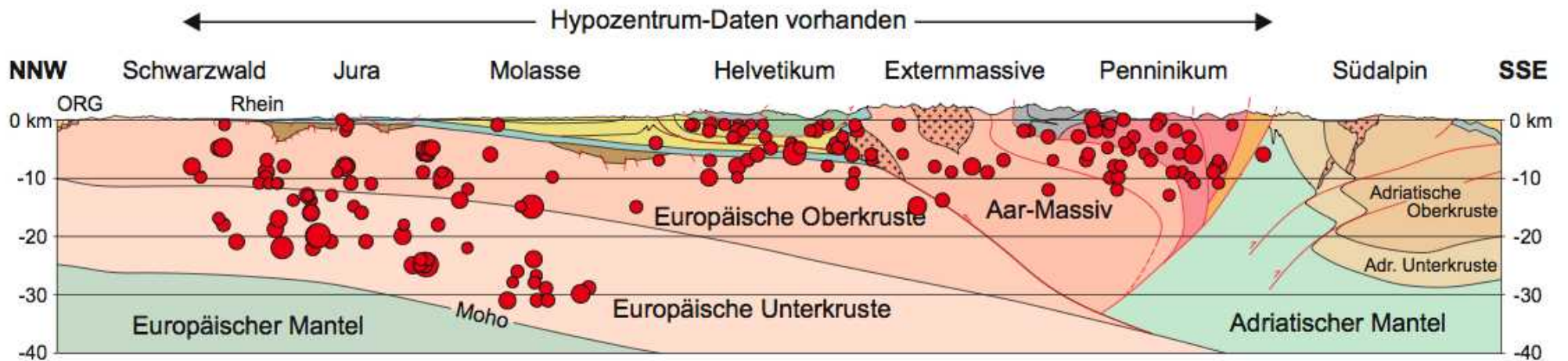
Subduktion  
Kollision  
Postkollisionale Verkürzung  
Exhumation



# Geophysikalische Aspekte

## Seismizität

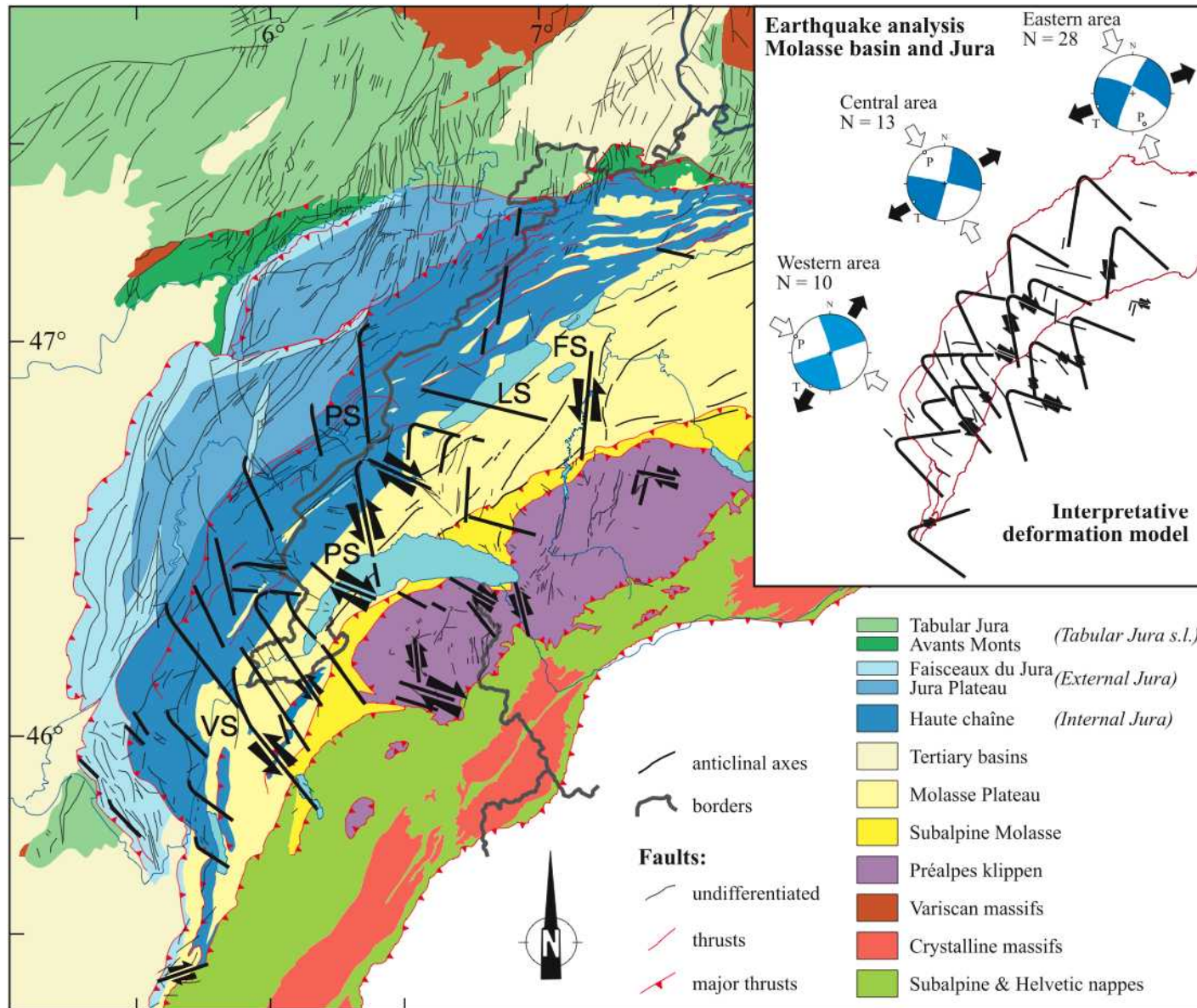
(NAGRA Bericht)



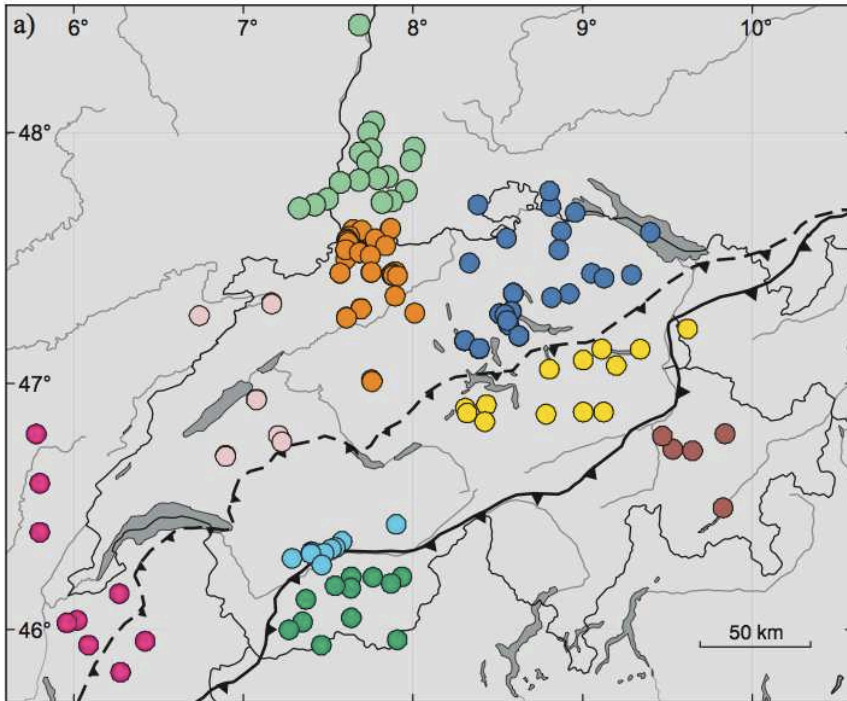
Erdbeben 1975 - 2007:  
Magnitude  $M_j$



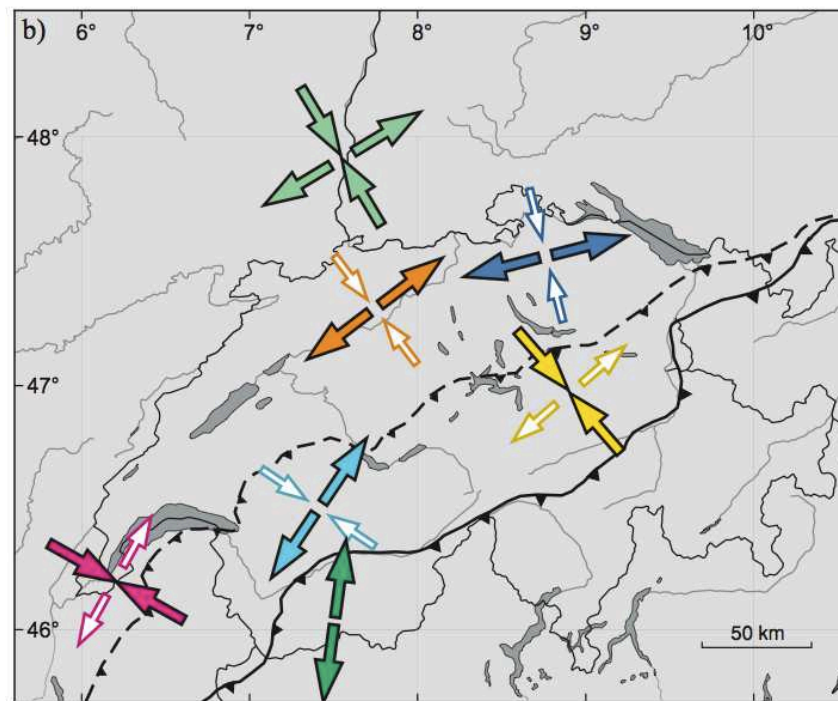
# Herdflächenlösungen Neotektonik



# Spannungsfeld Neotektonik



Lage der Erdbeben



Regionalen Spannungszustände  
(horizontale Hauptspannungsrichtungen).

Spannungszustand

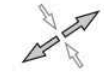
Blattverschiebung



Blattverschiebung  
bis Überschiebung



Blattverschiebung  
bis Abschiebung



Abschiebung



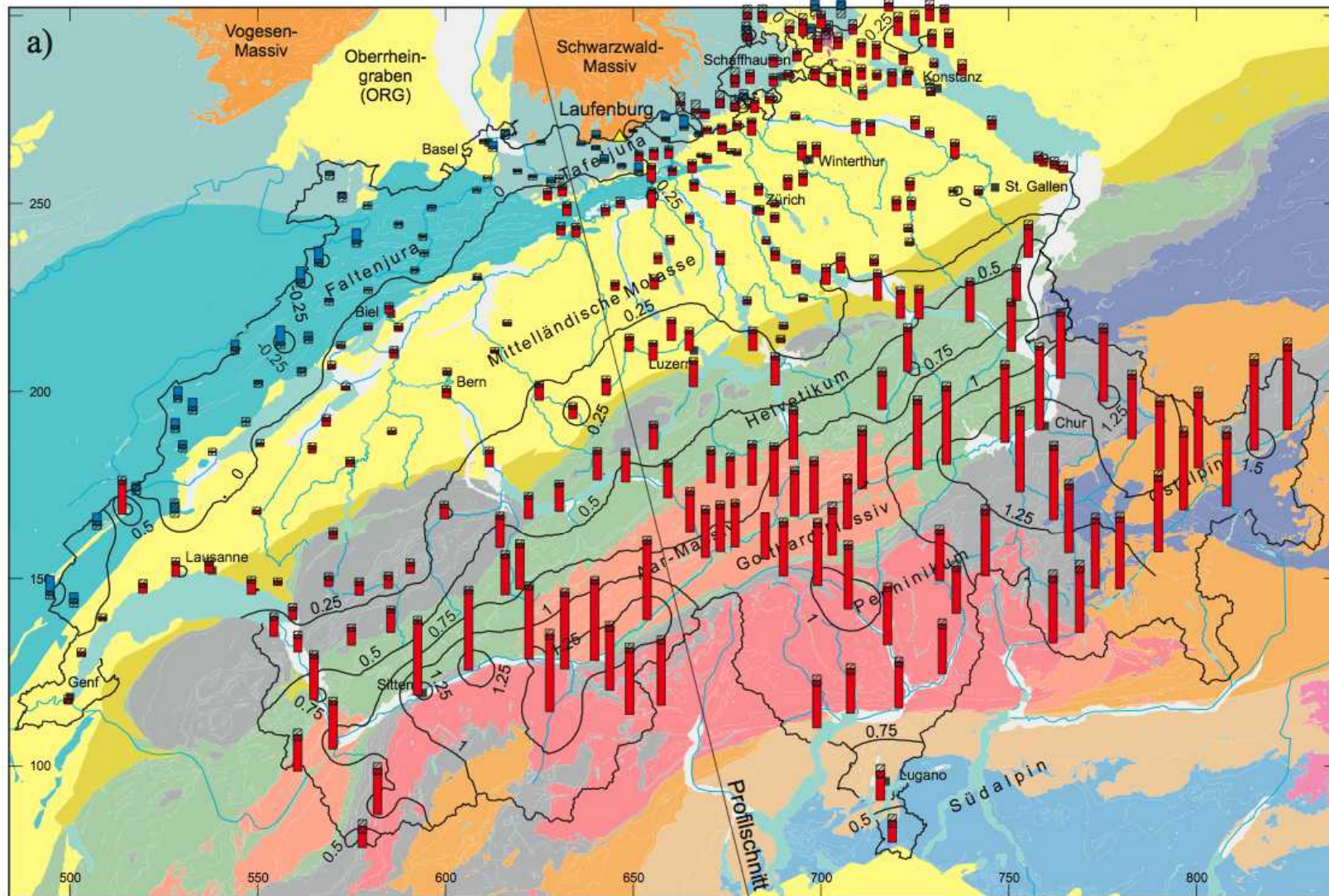
Front der Helvetischen Decken.



Front der Penninischen Decken (ohne Klippen-Decke).



# Vertikalbewegungen



Vergleichsmassstab Vertikalbewegung:

Hebungs-/Senkungsgeschwindigkeit = 1 mm/a



Hebung



Senkung



▲ Referenzpunkt Laufenburg

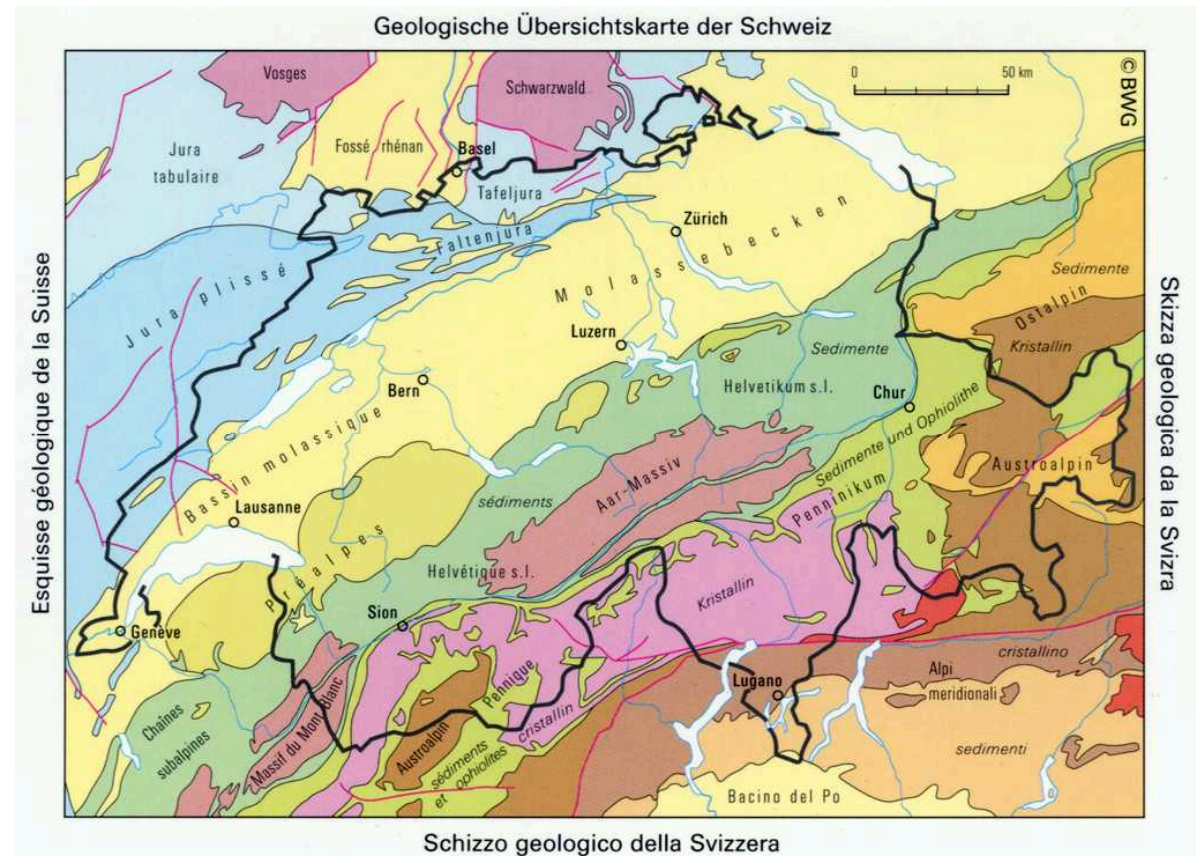
Mittlerer Fehler  
(Einfache Standard-  
abweichung)



# Gelogisches Signalement der Schweiz

Jura  
Helvetikum  
externe Massive  
Molasse  
Penninikum  
Südalpin

frei nach: Helmut Weissert  
frei nach: NTB 08-04



# Tafeljura

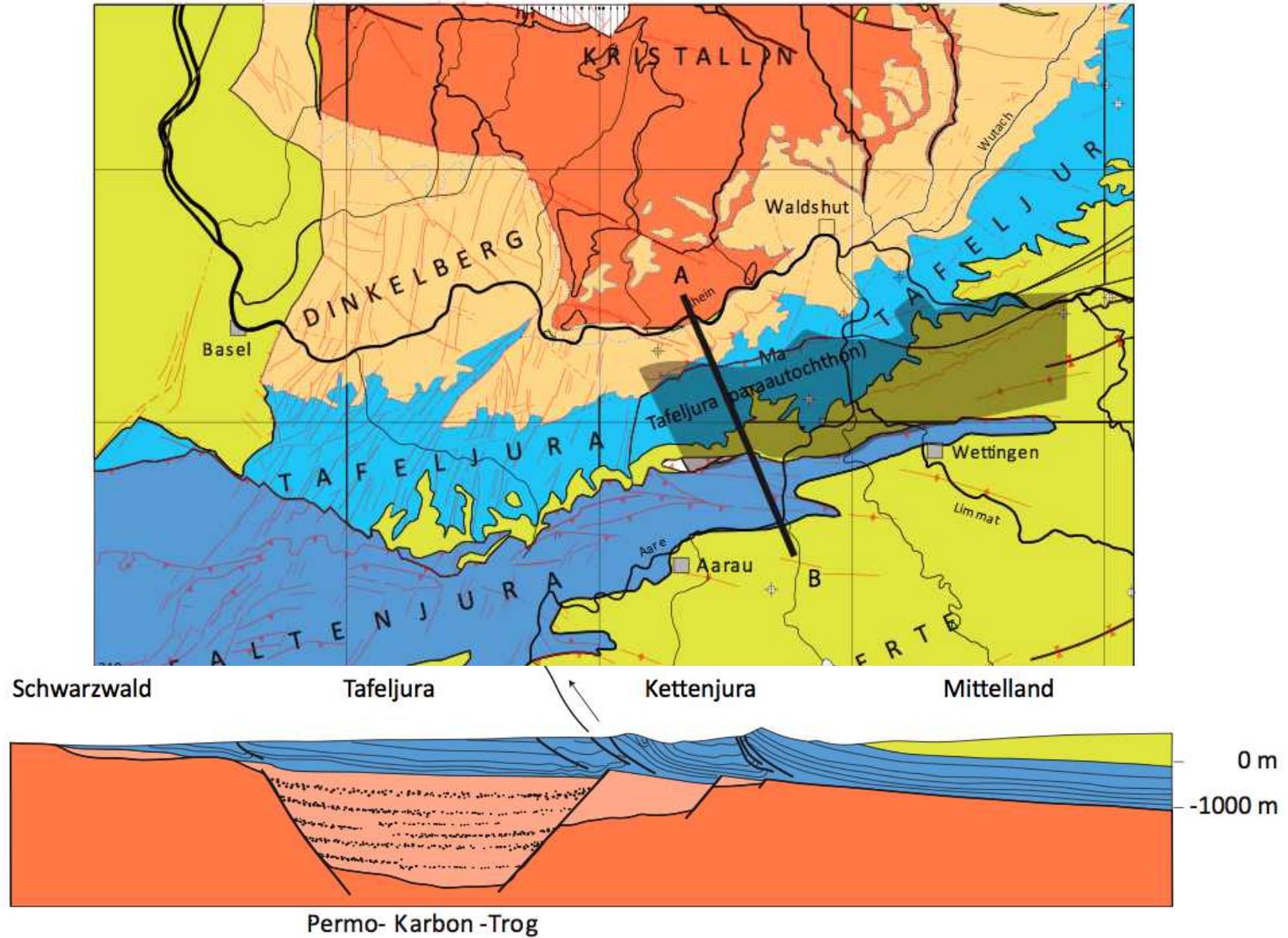
Ost: Tafeljura  
Sedimente autochthon, Blocktektonik

West: Faltenjura  
Sedimente abgeschert, gefaltet

Sedimente: Kalke, Mergel, Tone, Evaporite  
Alter: Ost: Trias - später Jura  
West: Trias - Kreide

Tafeljura (inkl. Schwäbische Alb)  
Autochthone mesozoische und tertiäre Sedimente der Europäischen Kontinentalplattform über Kristallin und Permokarbontrögen. Vor allem im Westen ist der Tafeljura von engständigen rheinischen Brüchen durchsetzt und in verschiedene sich in die Morphologie durchpausende Schollen zerlegt.

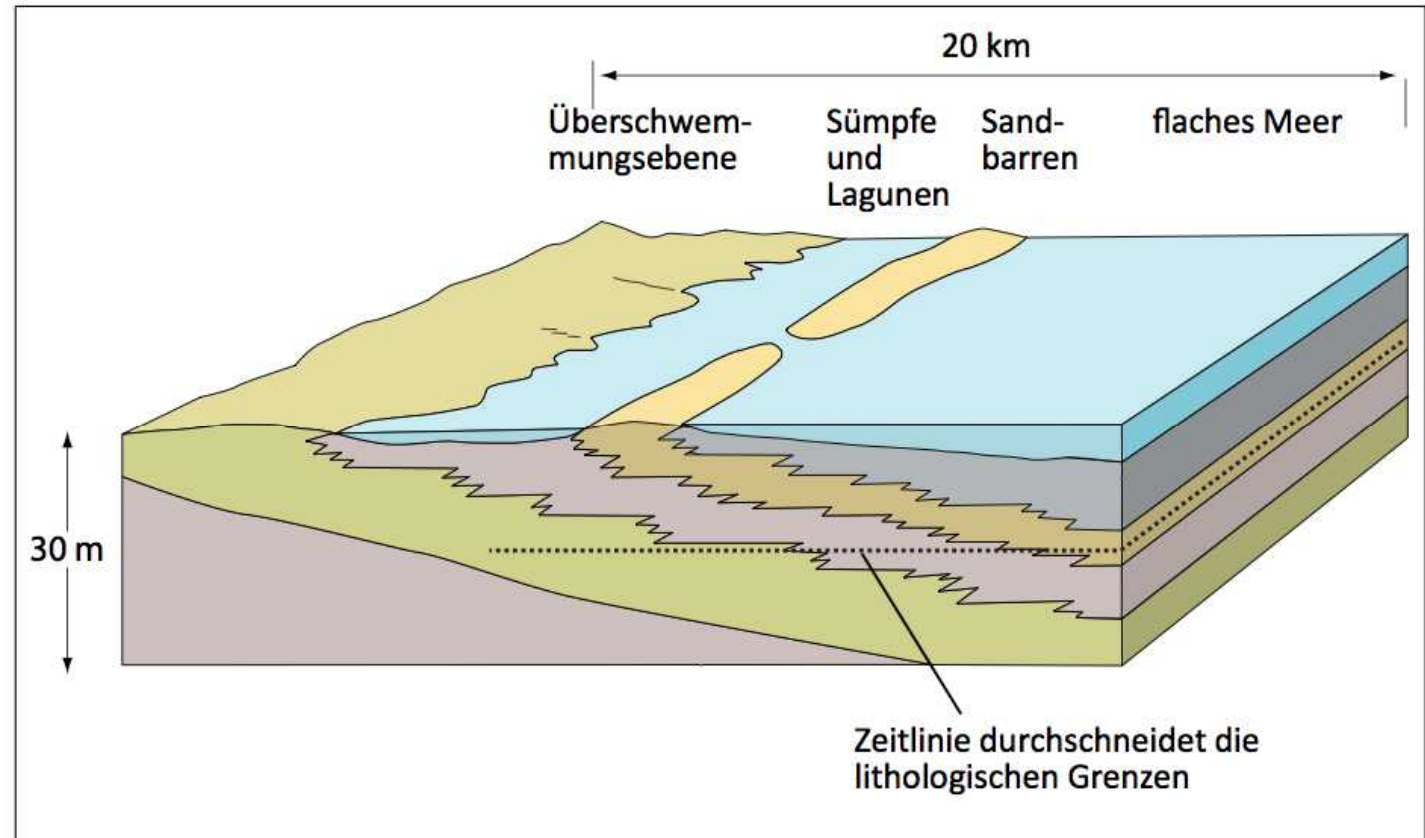
# Tafeljura - Schabische Alb



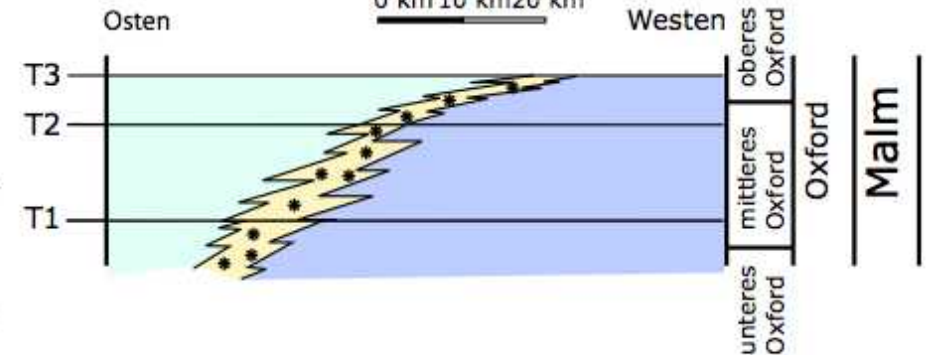
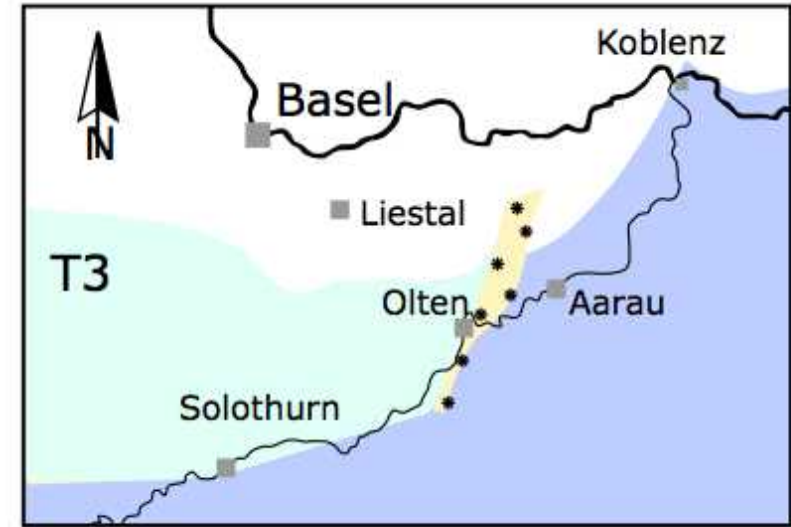
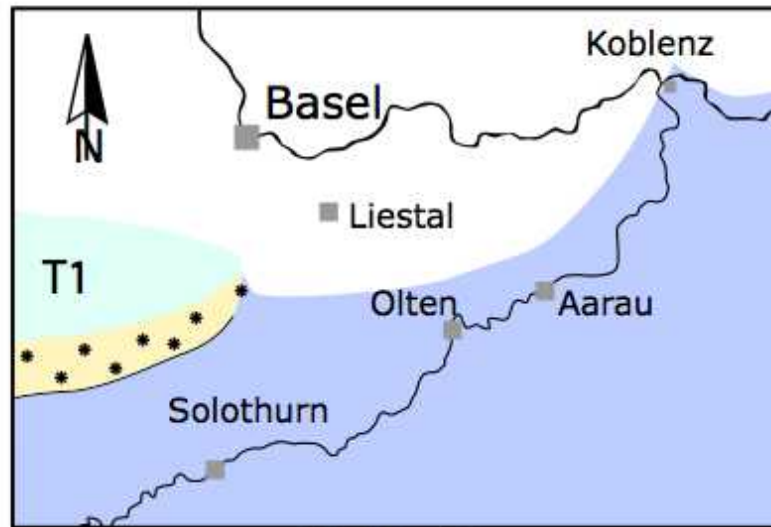
# Amanz Gressli: Facies - Konzept



Amanz Gressli  
(1814 - 1865)



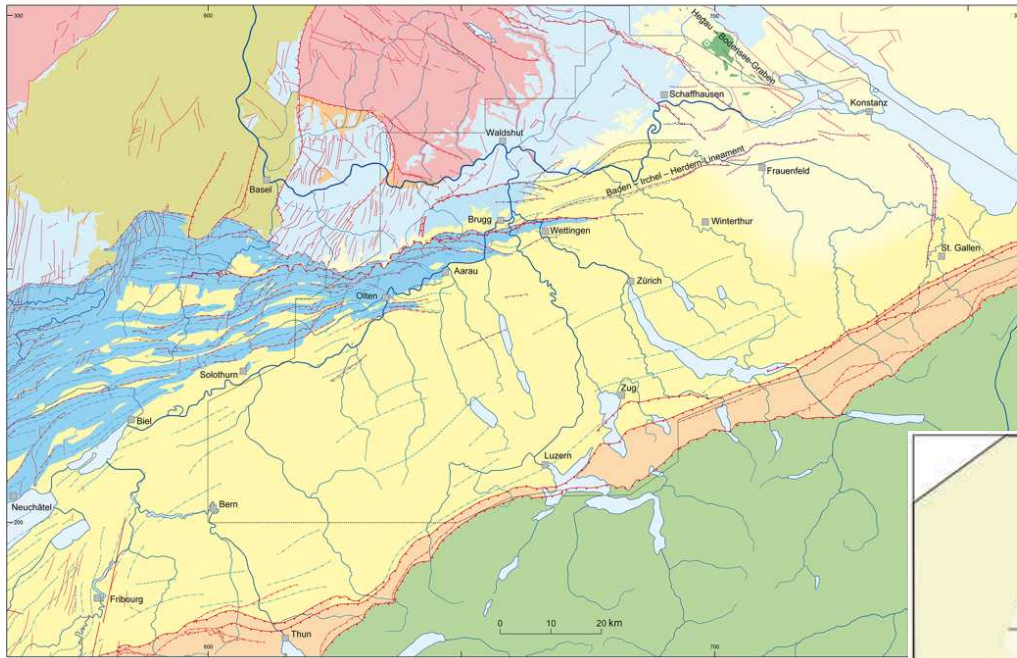
# Fazieswechsel - Riffprogradation



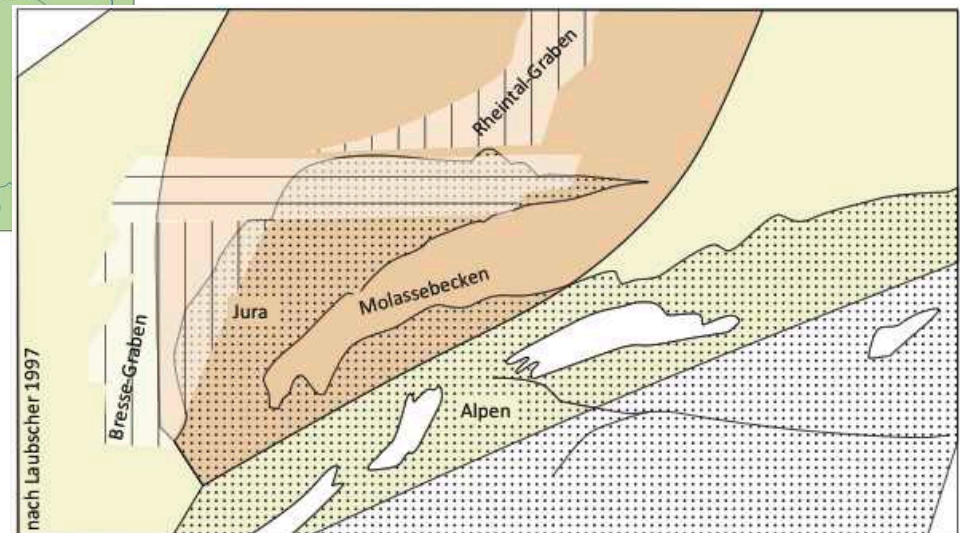
- Ablagerungen einer Karbonatplattform
- Ablagerungen eines Riffgürtels
- Ablagerungen eines Beckens

- Ablagerungen einer Karbonatplattform
- Ablagerungen eines Riffgürtels
- Ablagerungen eines Beckens

# Rheingraben Jura Molasse Abscherhorizont









- Ausseralpine Plattform**
- Miocäne Vulkanite des Hegaus
  - Tertiär des Oberrheingrabens
  - Mittelländische Molasse
  - Mesozoikum
  - Piem
  - Kristallin / Grundgebirge
- Alpenvorland (vom Fernschub deformiert)**
- Abgescherzte Molasse und Tertiär des Faltenjuras
  - Mesozoikum der Voralpenzone
  - Mesozoikum des Faltenjuras
- Alpen**
- Subalpine Molasse
  - Alpine Decken (undifferenziert)
- Strukturen aus Oberflächengeologie**
- Hauptabschiebungen
  - Hauptüberschiebungen
  - Weitere wichtige Überschiebungen
  - Weitere wichtige Abschiebungen
  - Weitere Störungen i. allg., z.T. vermutet
  - Antiklinalen
  - Synklinalen
  - Flexuren

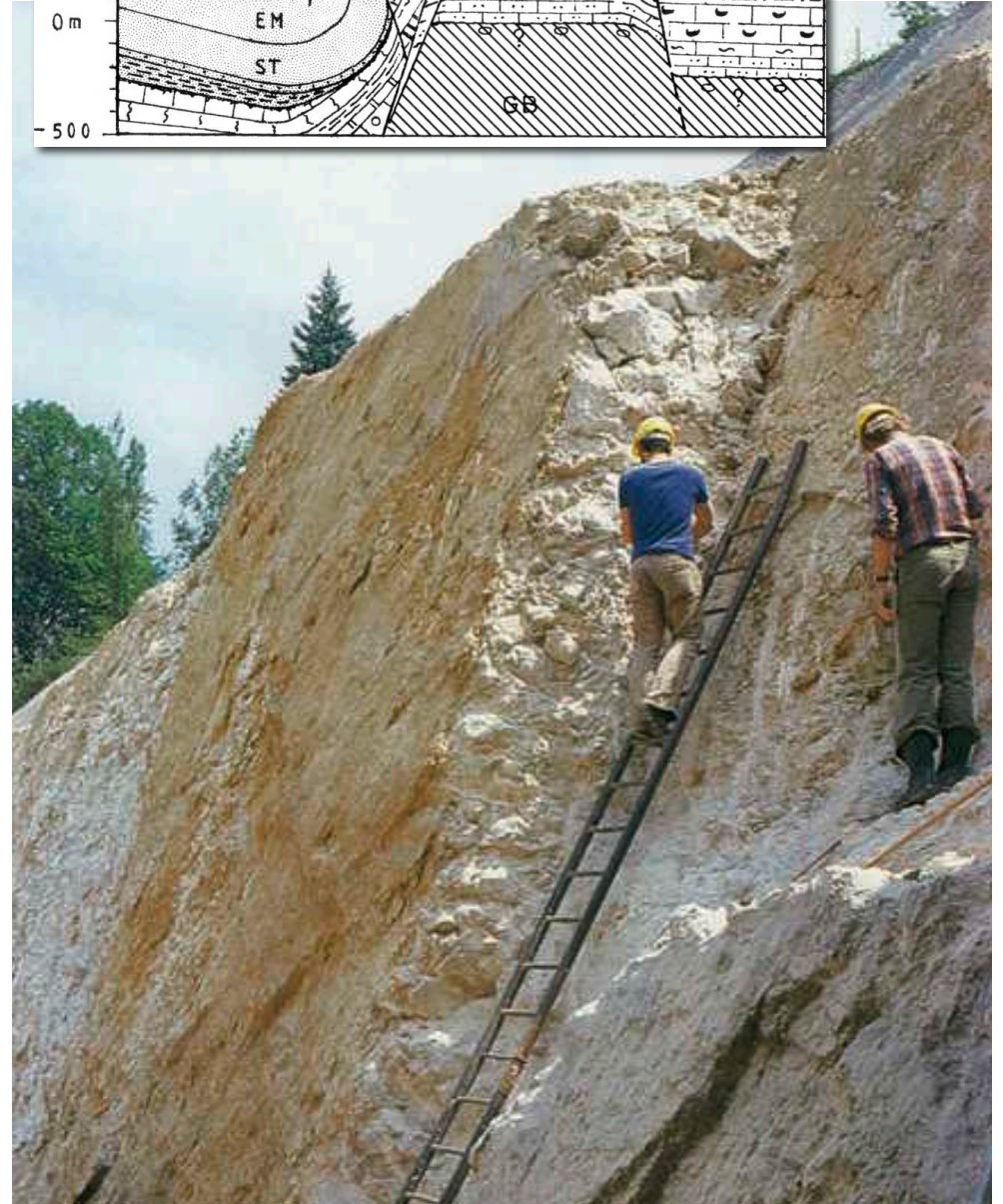
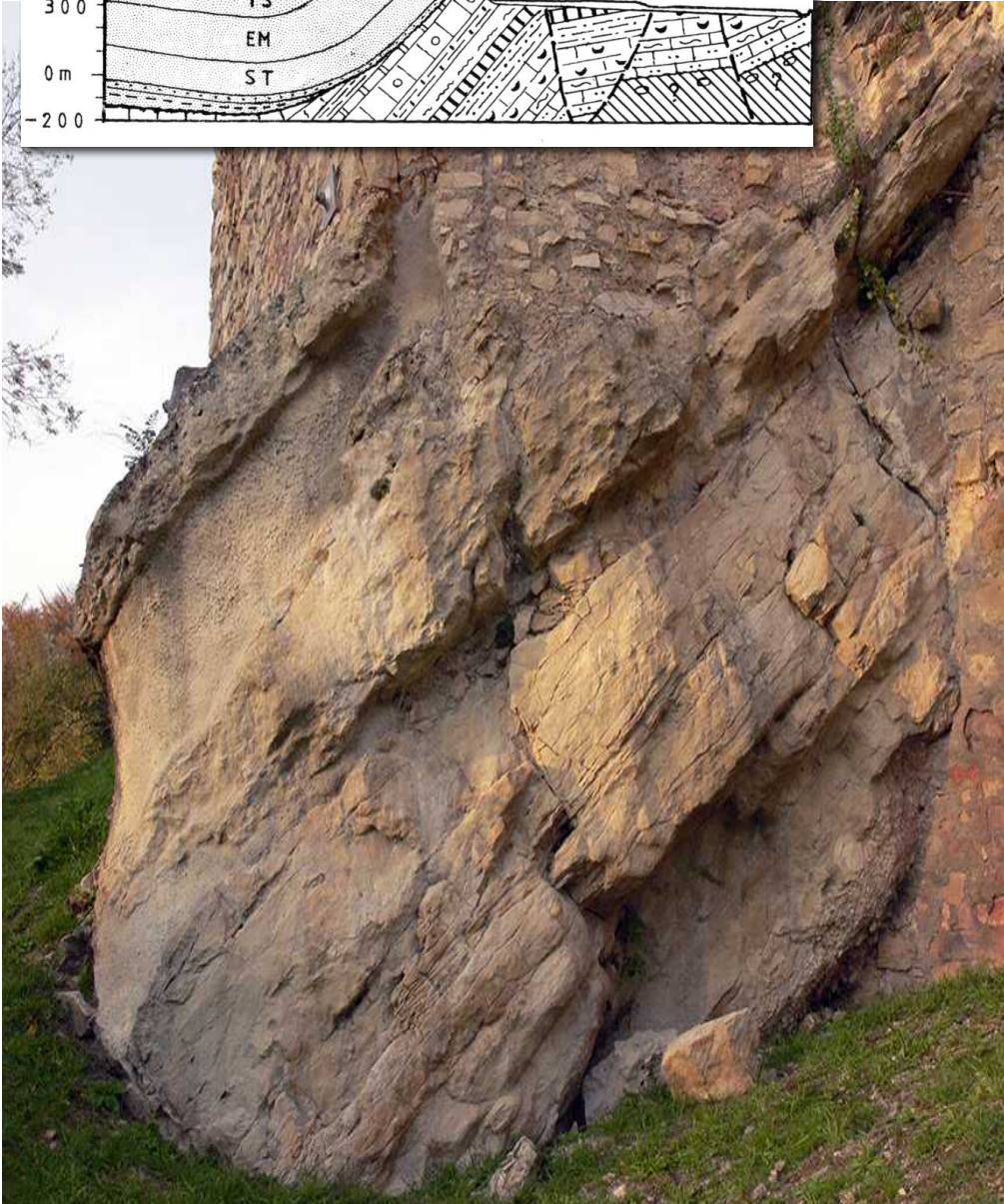
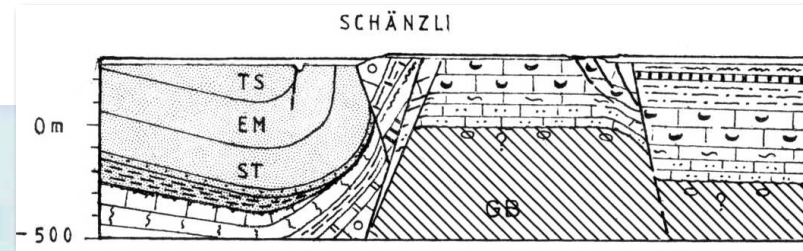
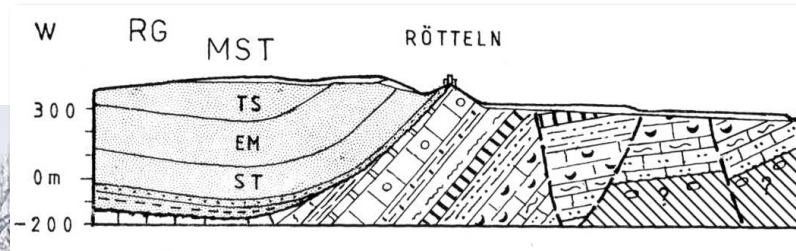


nach Laubscher 1997

200 km

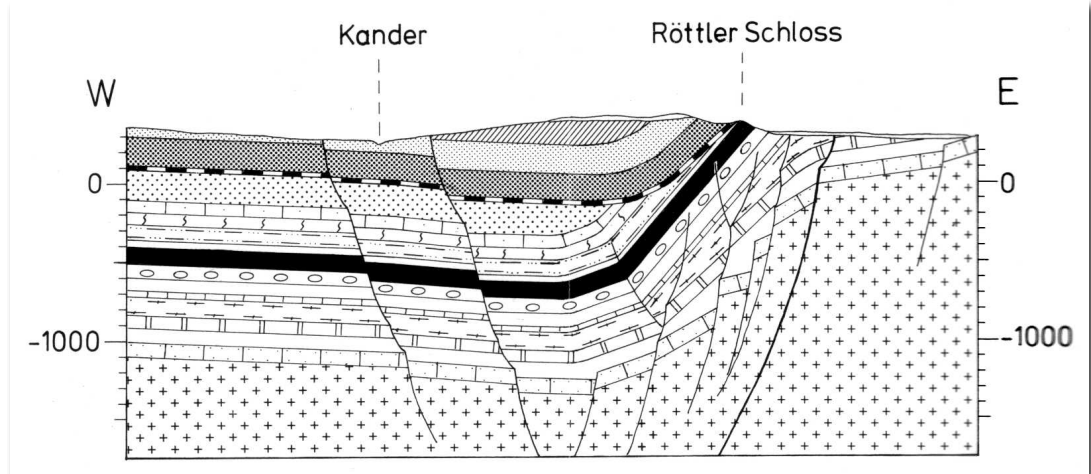
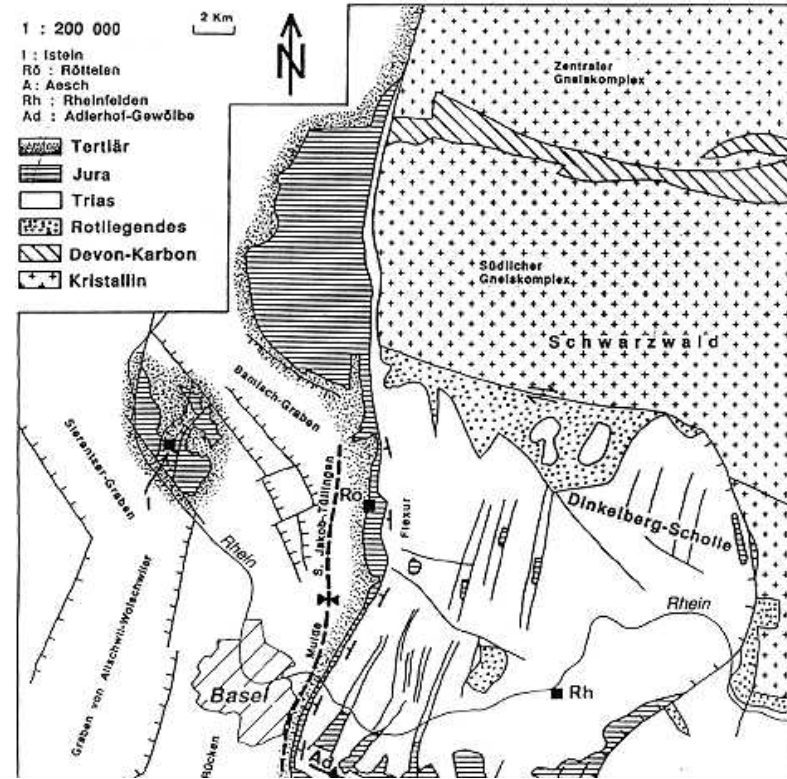
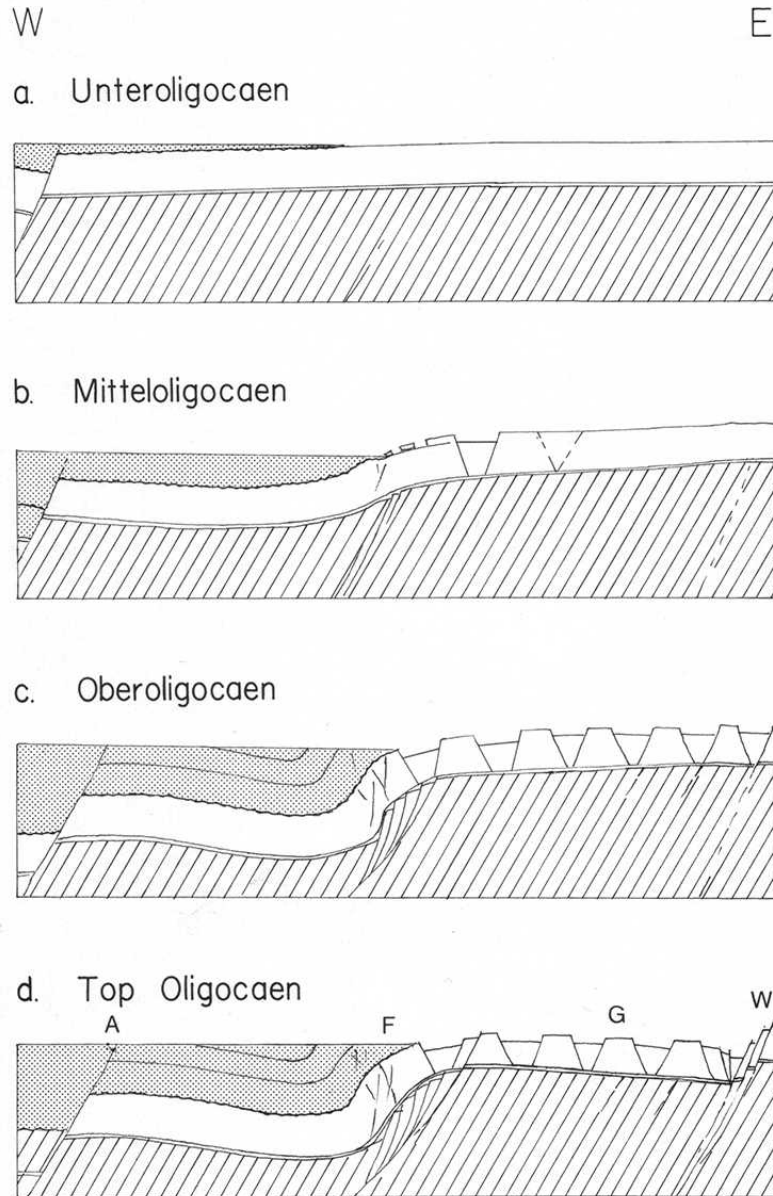
- |   |  |   |   |
|---|--|---|---|
|  | Bereich der alpinen Deformation                |  | Bereich mit wenigen oder keinen triassischen Evaporiten |
|  | Paläogene Grabenstrukturen                     |  | Bereich mächtiger triassischer Evaporite                |
|  | Transfer-Zone zwischen Rhein und Bresse-Graben |  | Zentralmassive  |

# Rheintalflexur: Schänzli, Rötteln





# Entstehung der Flexur



# Faltenjura

Ost: Tafeljura  
Sedimente autochthon, Blocktektonik

West: Faltenjura  
Sedimente abgeschert, gefaltet

Sedimente: Kalke, Mergel, Tone, Evaporite  
Alter: Ost: Trias - später Jura  
West: Trias - Kreide

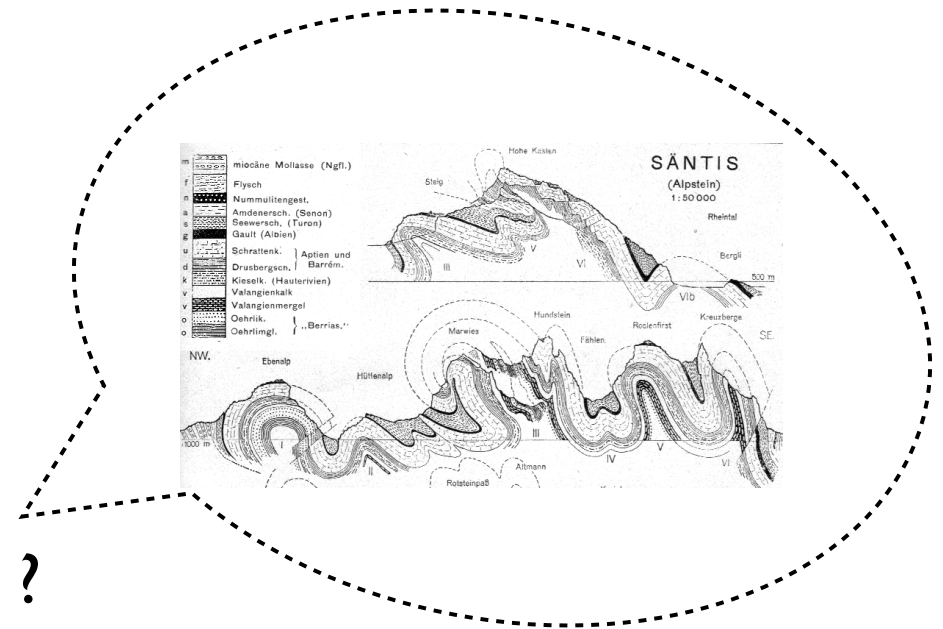
Deformation: Überschiebung, Faltung  
Alter: Miozän, Pliozän

## Faltenjura:

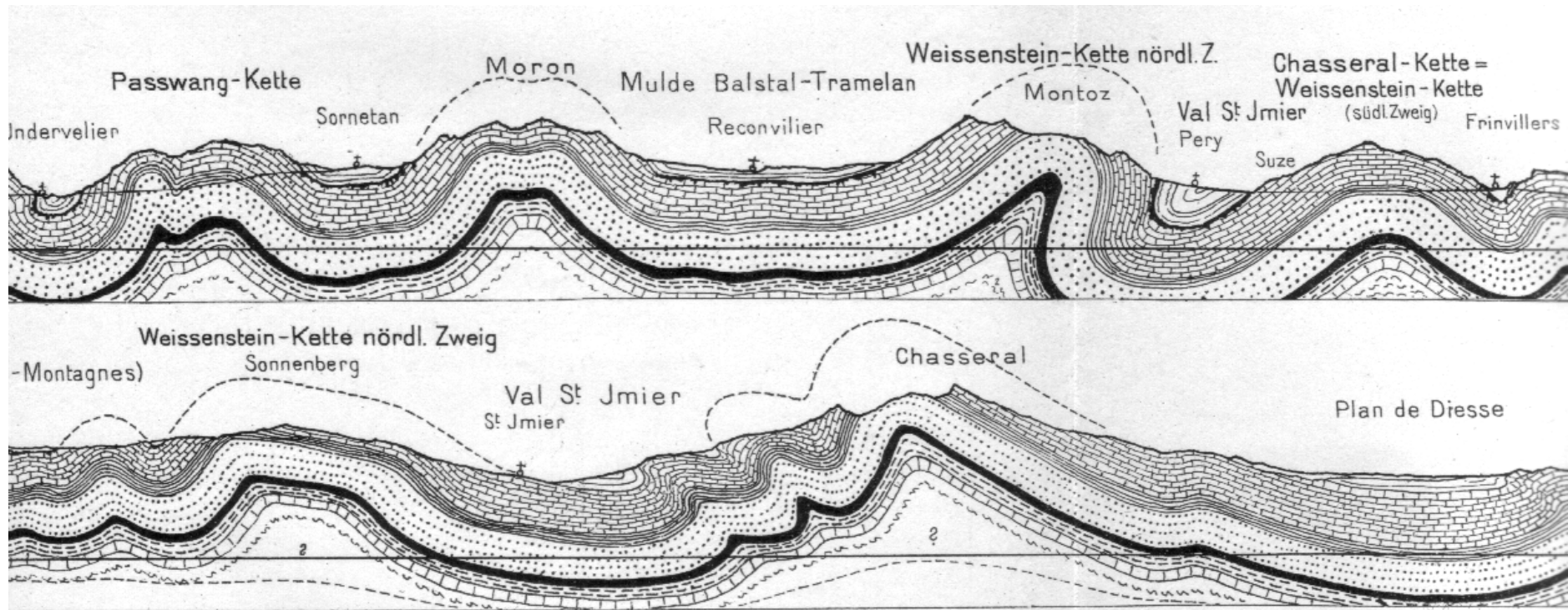
Mesozoische und tertiäre Sedimente der Europäischen Kontinentalplattform, welche in der Spätphase der alpinen Gebirgsbildung von ihrer Unterlage abgeschert, nach Norden transportiert und dünnhäutig verfault wurden (Hauptabscherungshorizont = Evaporite der Trias). Im Liegenden frühtriadische Sedimente über Kristallin mit Permokarbontrögen.

Stallfluh, Obergrenchenberg

# Falten im Jura ...



... wie im Helvetikum ?



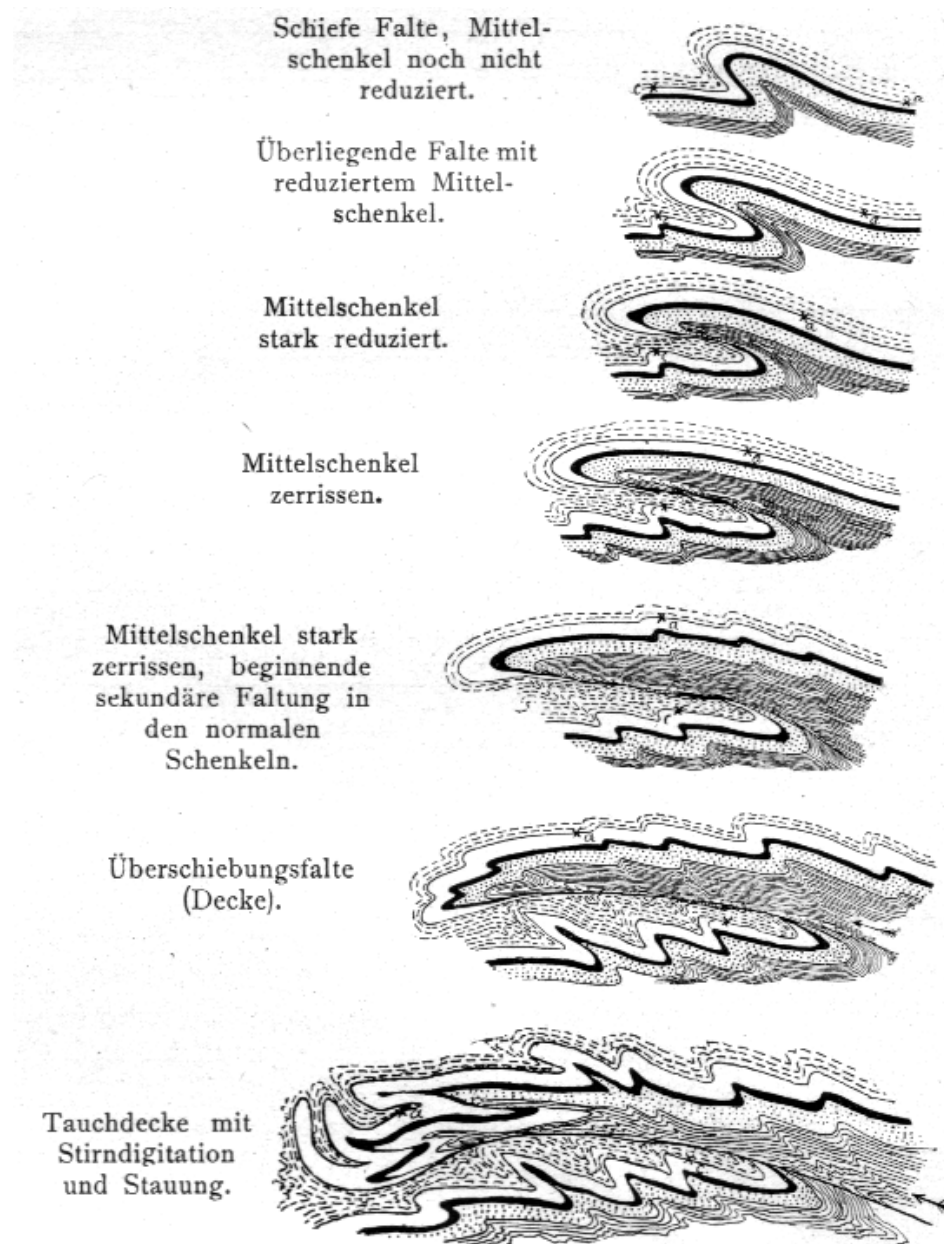
Profil A. Heim

# Albert Heim: Überschiebungsfalten

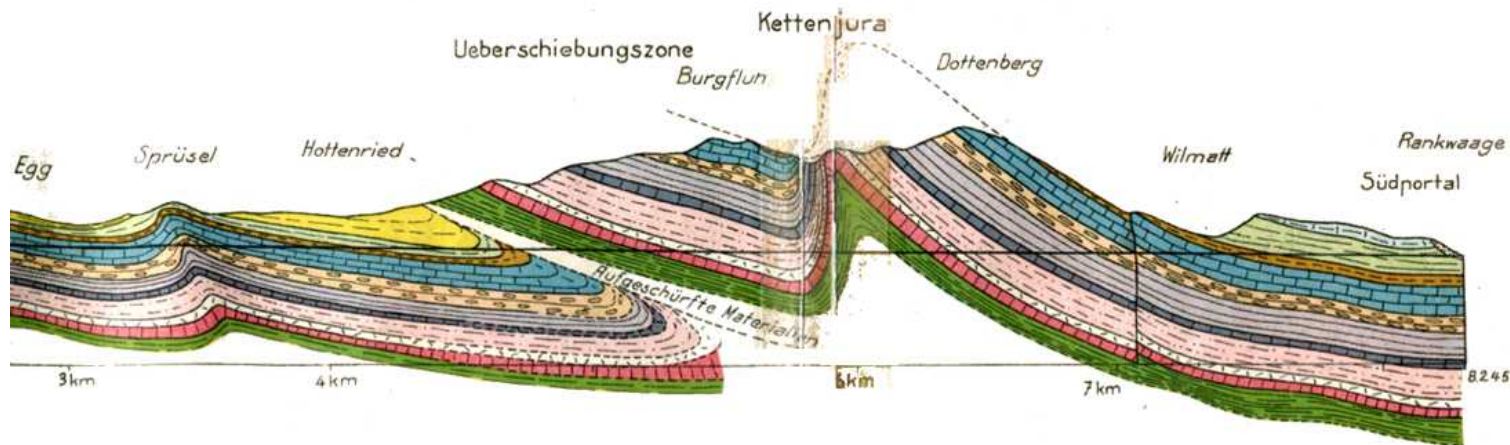
Falten werden zu  
Überschiebungen



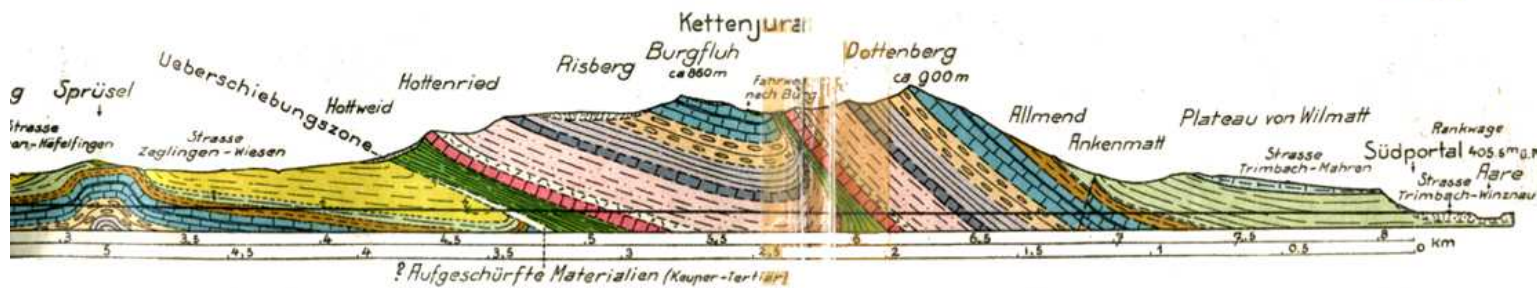
Albert Heim  
(1849-1937)



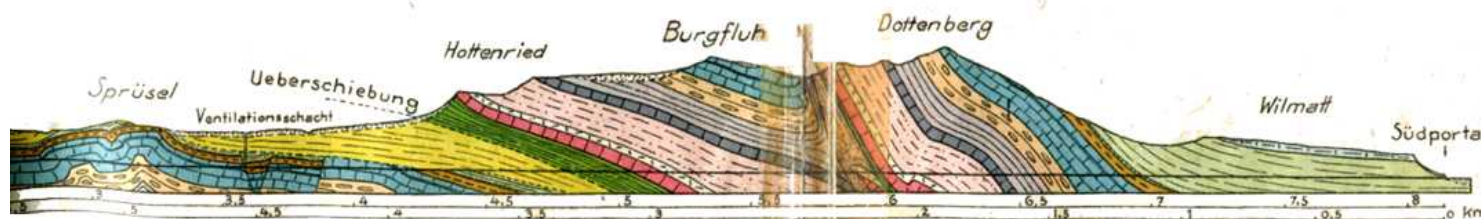
# August Buxtorf: Prognosen und Befunde ...



Prognostisches Profil Mühlberg 1910



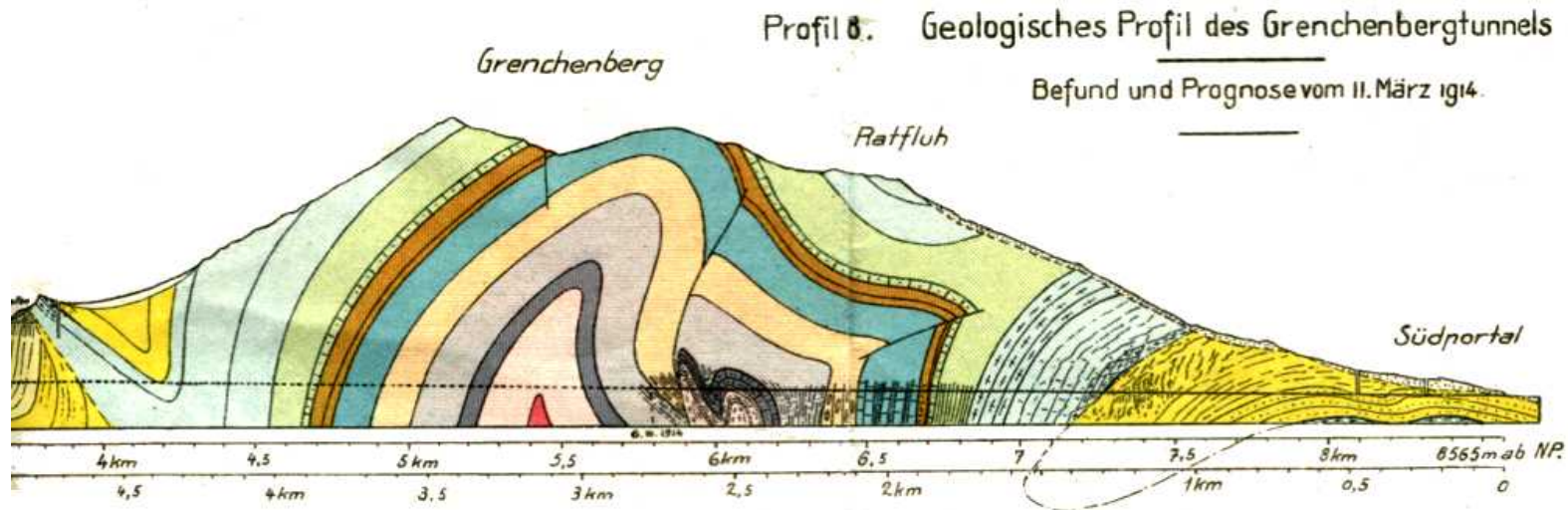
Prognostisches Profil Buxtorf 1911



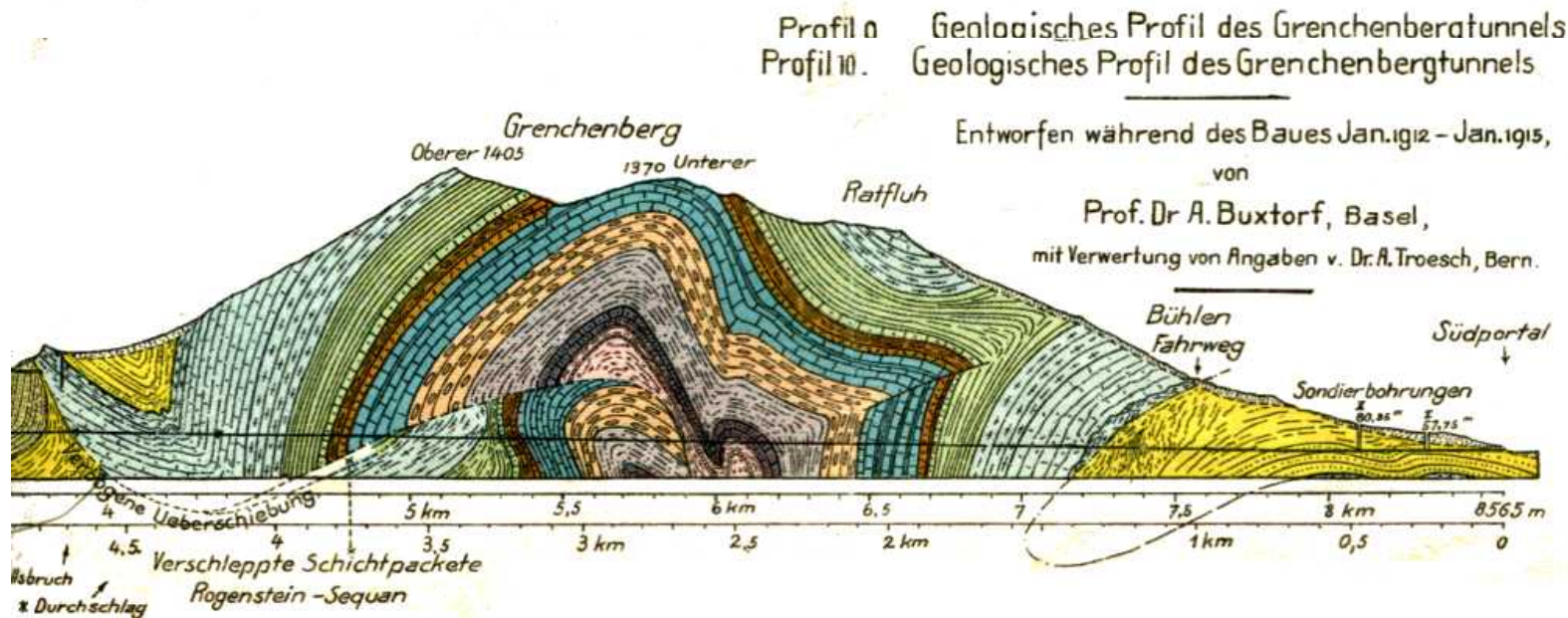
Befund Buxtorf 1914

# August Buxtorf: Prognosen und Befunde ...

März  
1914



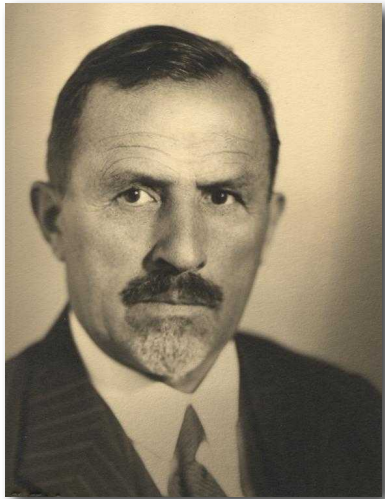
Januar  
1915



# August Buxtorf

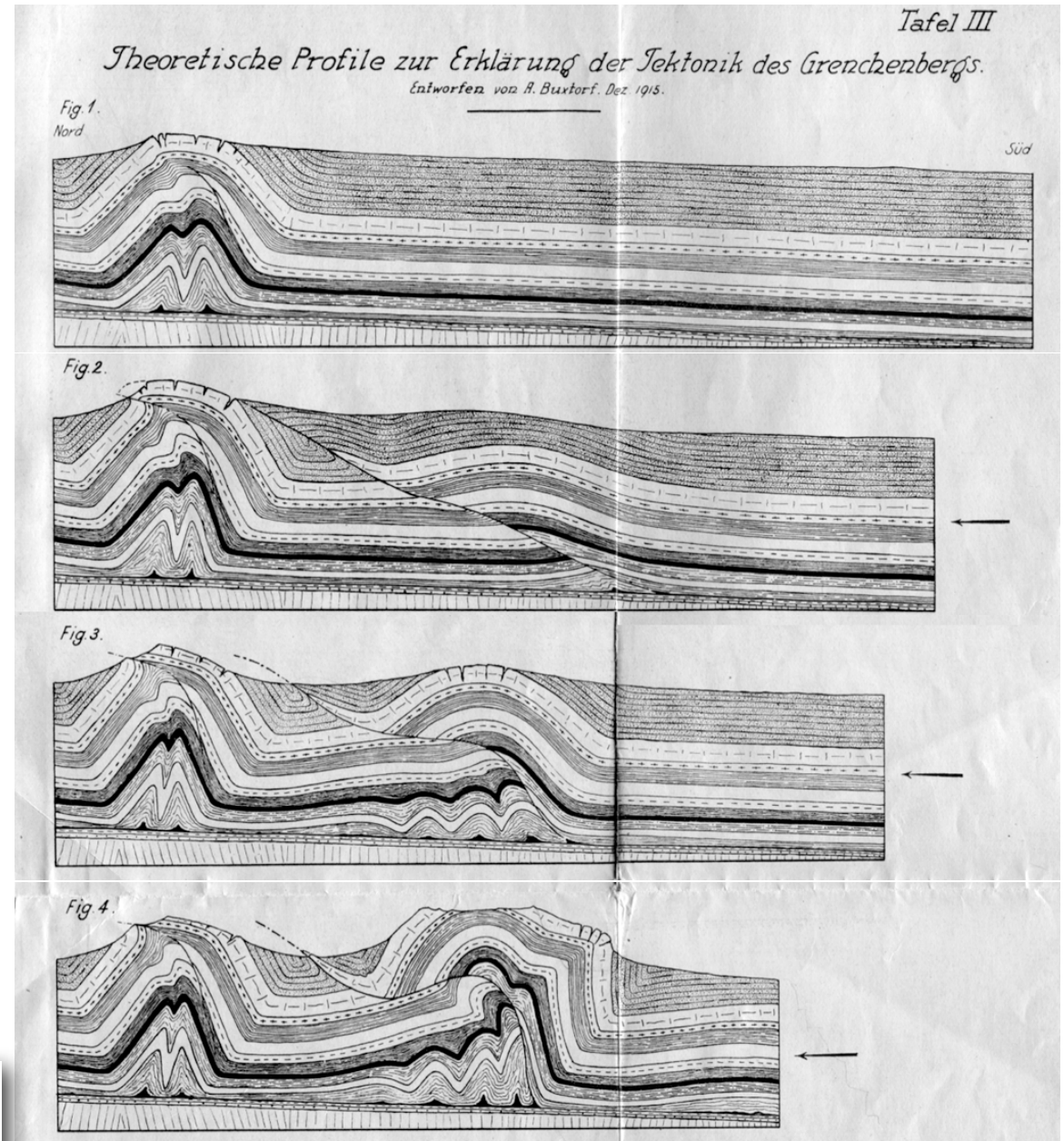
## Überschiebungen entstehen zuerst

Überschiebungen  
werden gefaltet



August Buxtorf  
(1877-1969)

⇒ Fernschub - Hypothese



# Helvetikum

Alpstein

Säntis

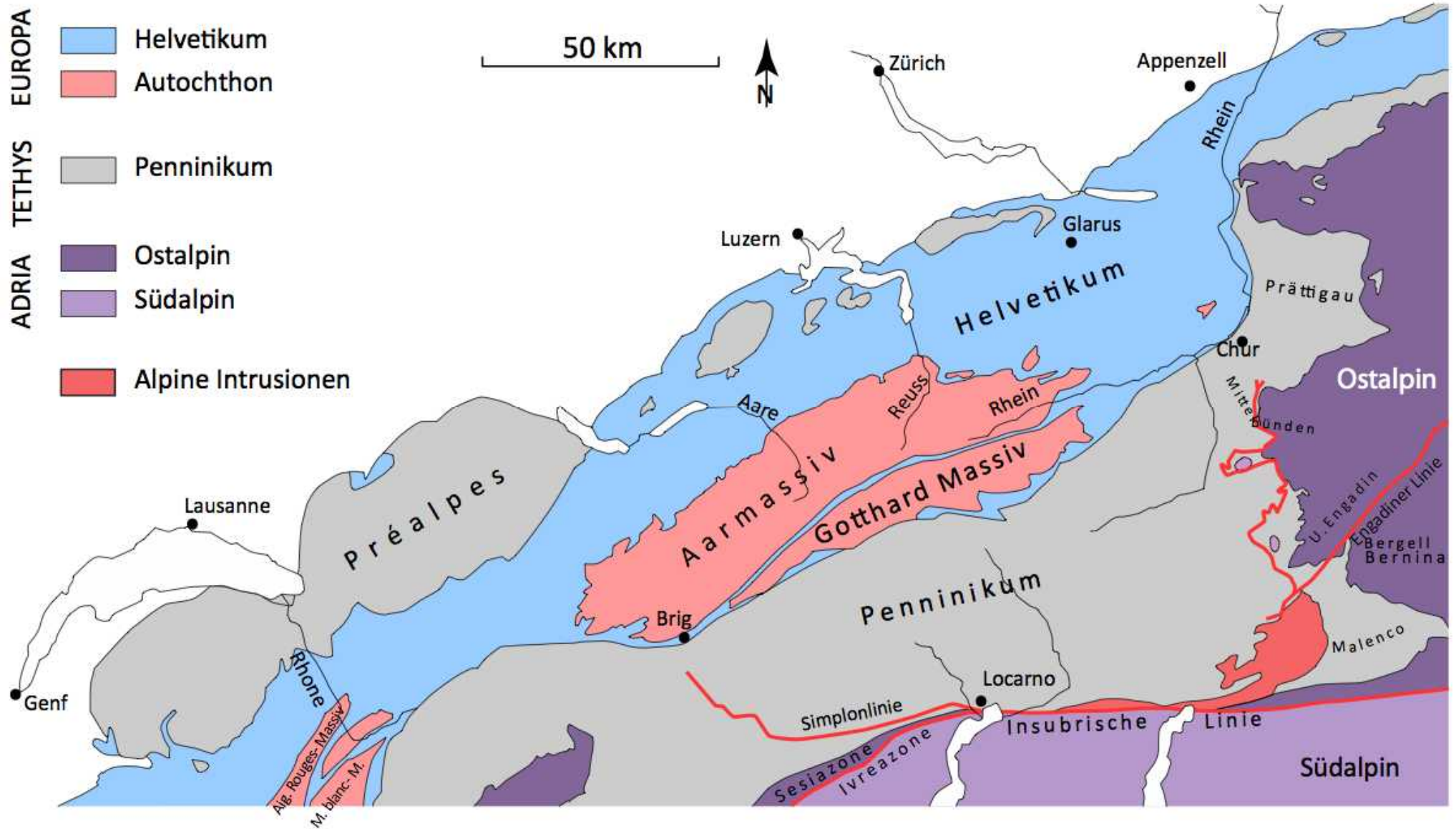
Churfirsten

## Helvetikum

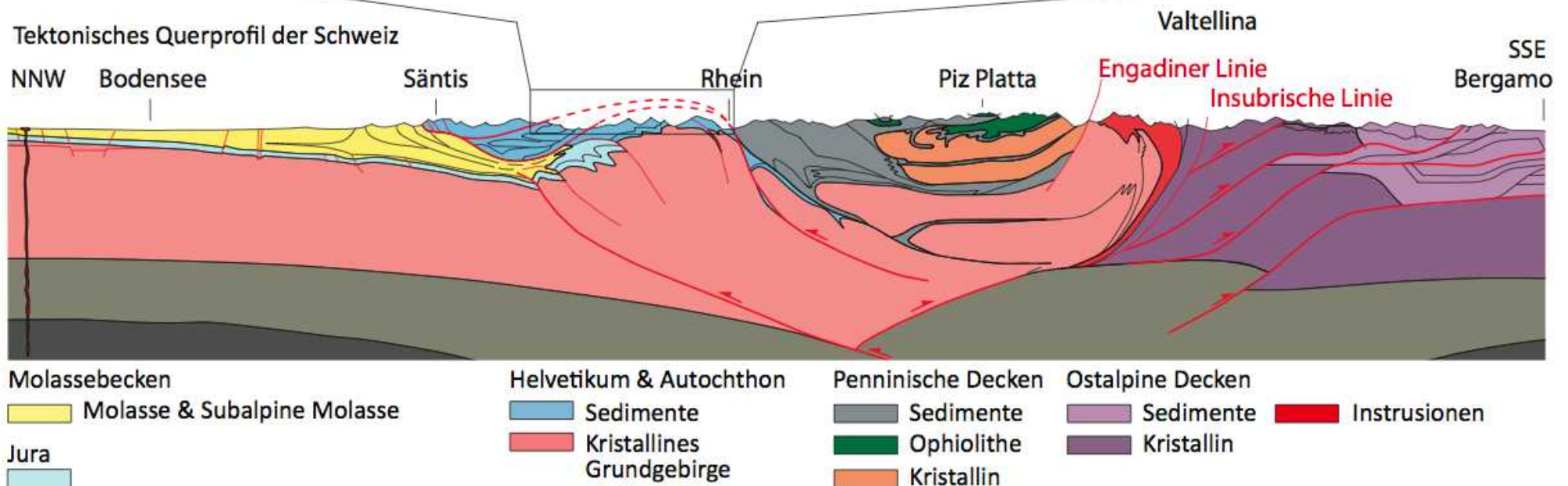
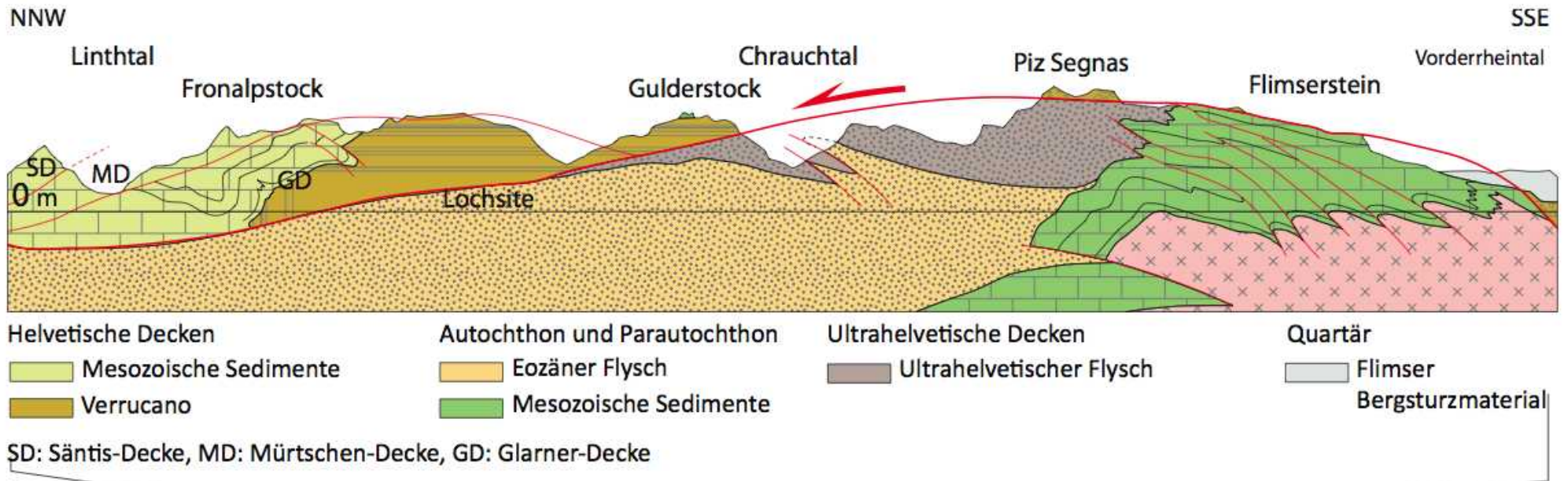
Als Decken nach Norden verfrachtete paläozoische, mesozoische und frühtertiäre Sedimente des Europäischen Kontinentalrands. In mehrere, intern komplex deformierte Decken gegliedert.



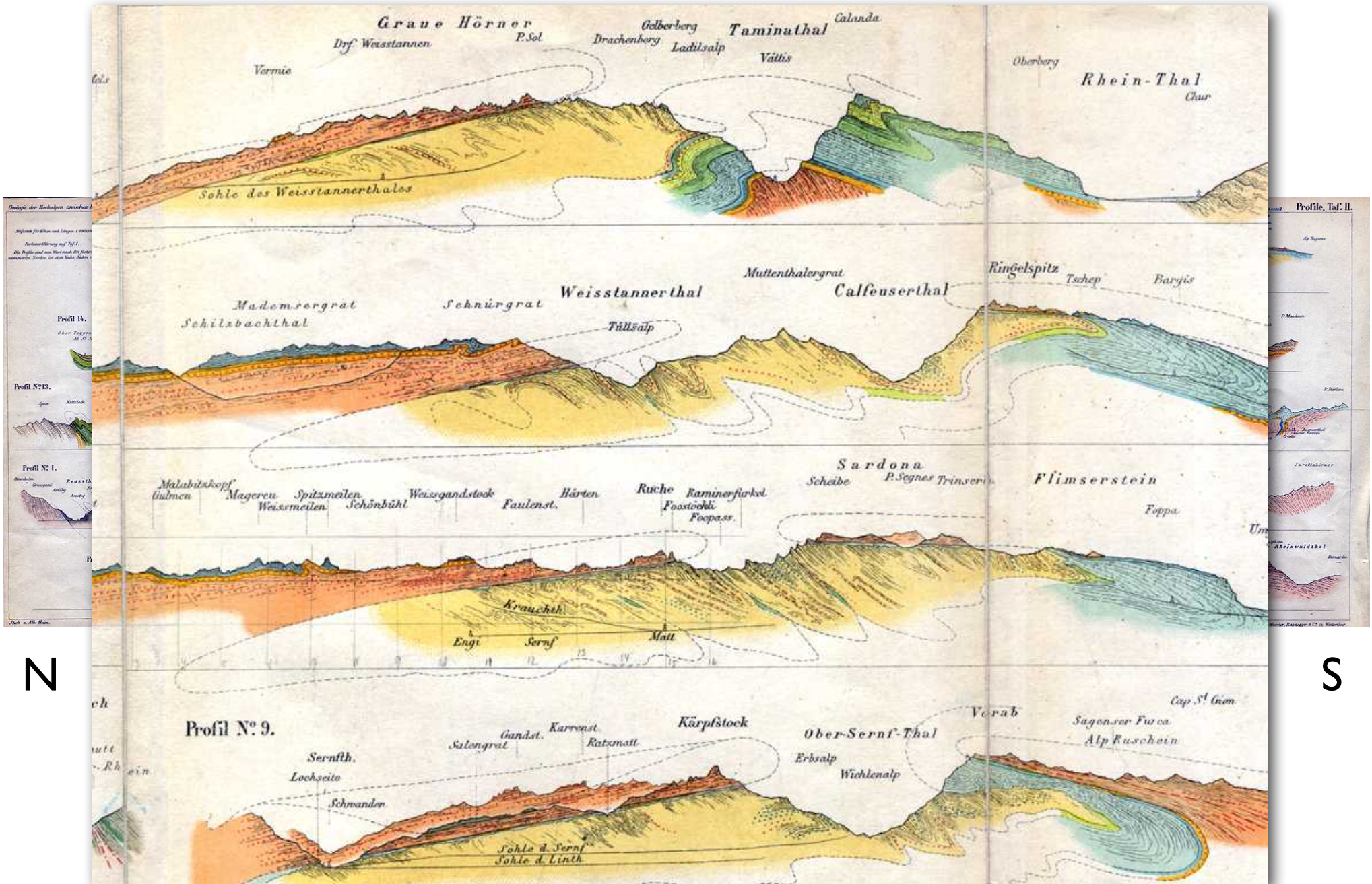
# Helvetikum



# Helvetikum



# Heim'sche Doppelfalte



# Externe Massive

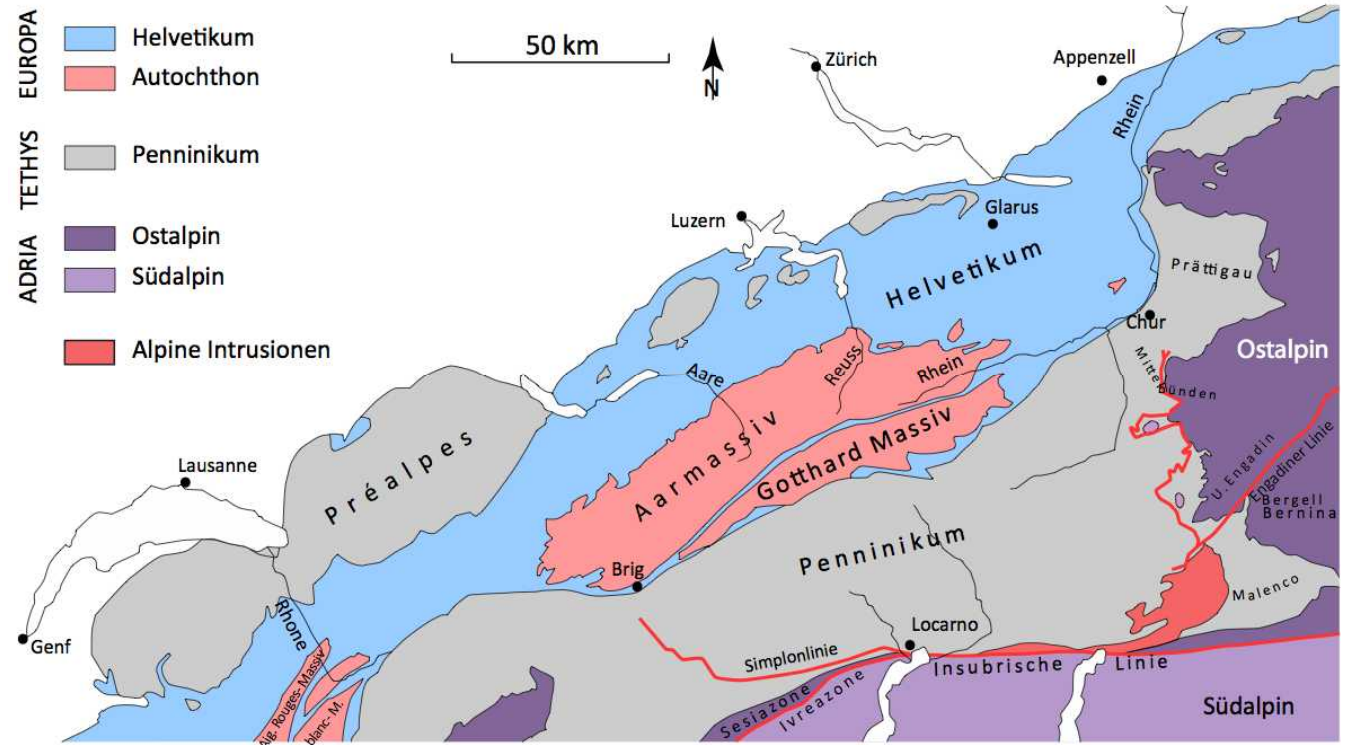


Externmassive

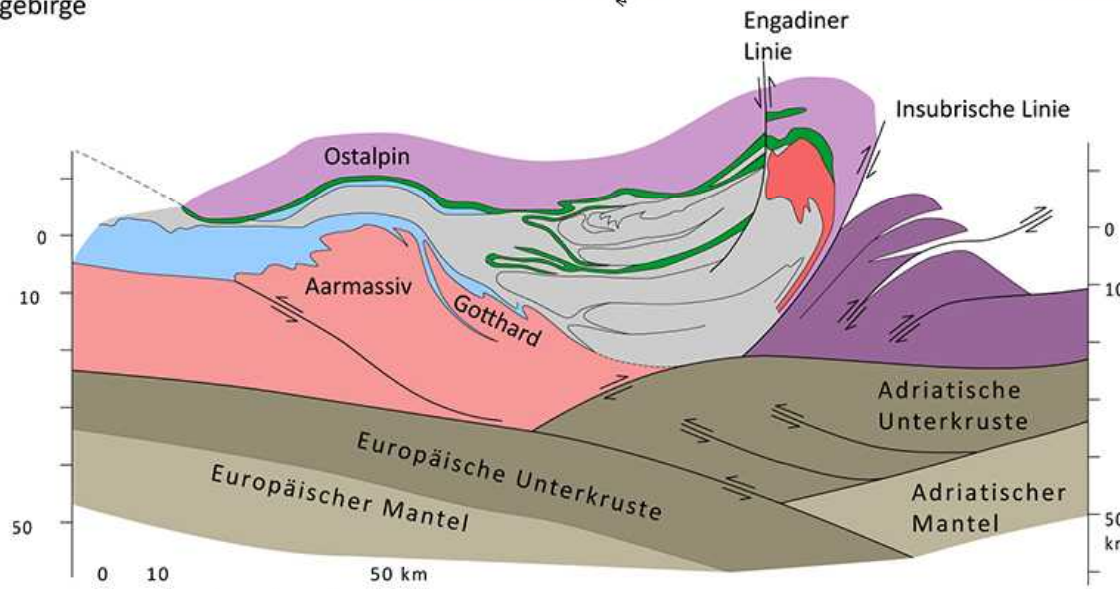
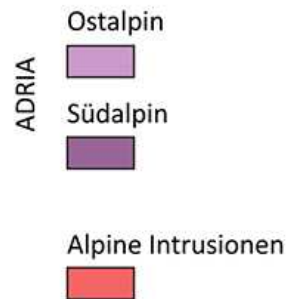
(Aar, Gotthard, Aiguilles Rouges, Mont Blanc)

Kristalline Oberkruste des Europäischen Kontinentalrands, nach Norden und Nordwesten überschoben, zerschert und in der Spätphase der alpinen Gebirgsbildung herausgehoben. Enthalten Reste von Permokarbontrögen.

# Externe Massive



Der alpine Deckenstapel



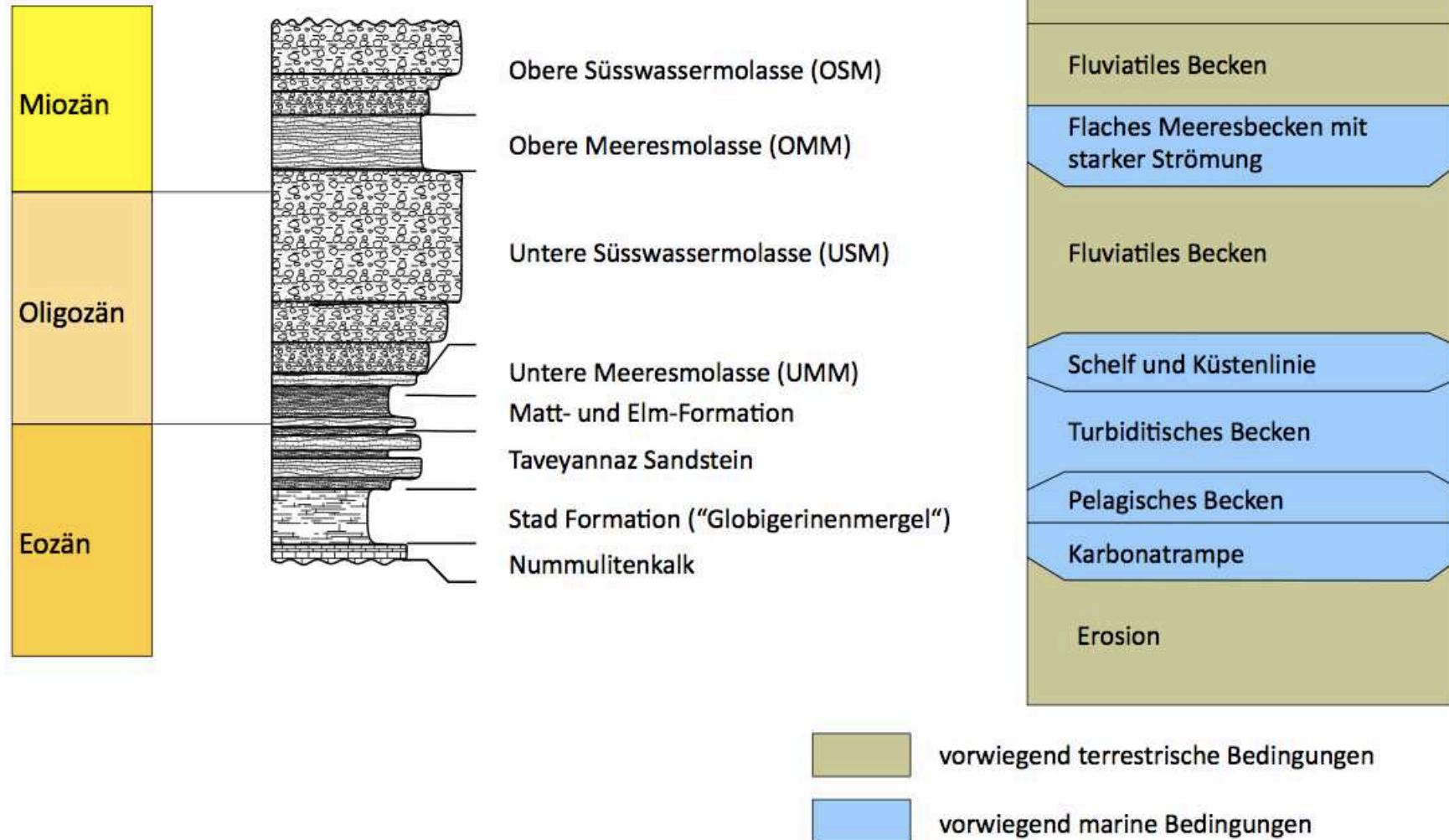
Aarmassiv  
 Gotthard  
 Mont Blanc  
 Aiguilles Rouges

# Molasse

## Mittelländische Molasse

Im nördlichen Vorlandbecken der Alpen im Oligozän und Miozän abgelagerte Sedimente, welche sich ganz im Osten in autochthoner Lage befinden und im Westen in der Spätphase der alpinen Orogenese mitsamt ihrer mesozoischen Unterlage abgeschert, nach Norden transportiert und leicht deformiert wurden. Im Liegenden frühtriadische Sedimente über Kristallin mit Permokarbontrögen.

# Molasse - Stratigraphie



# Subalpine (aufgeschobene) Molasse



USM am Rigi

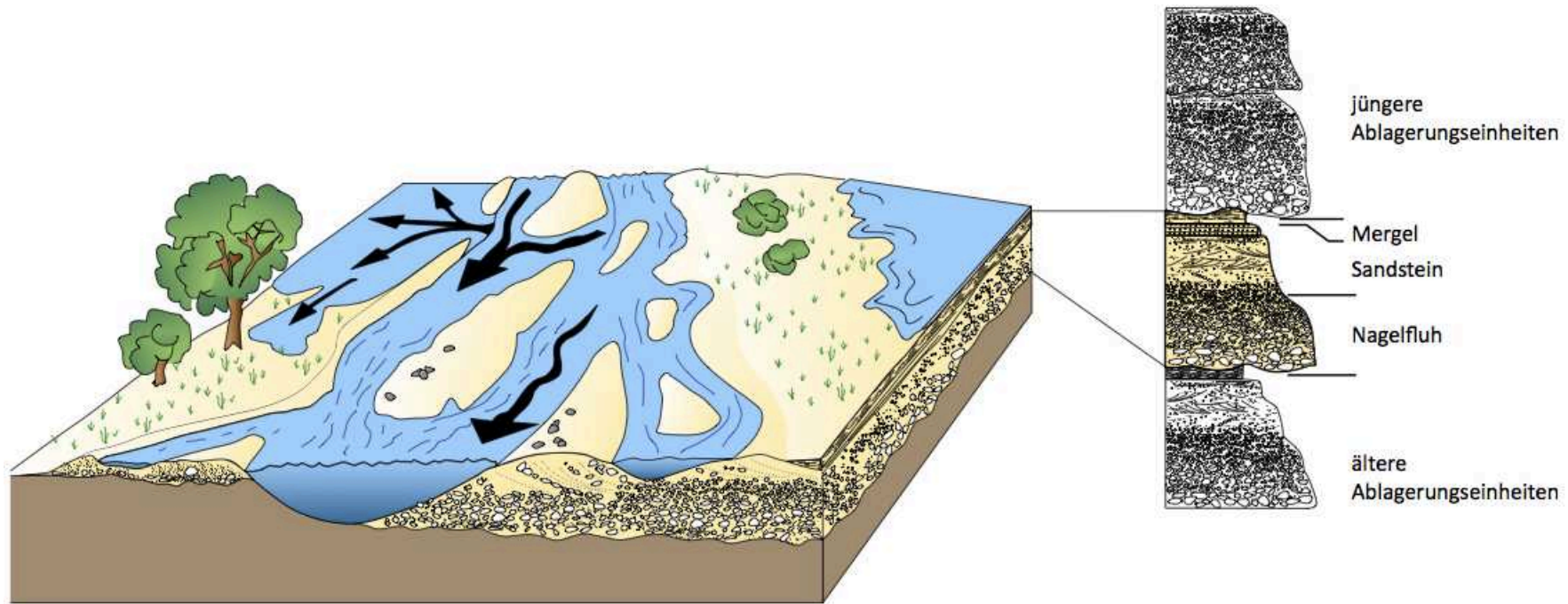
Subalpine Molasse (aufgeschobene Molasse)

Am Südrand des nördlichen Vorlandbeckens der Alpen im Oligozän und Miozän abgelagerte tertiäre Sedimente, welche in der Spätphase der alpinen Gebirgsbildung von der Deformation erfasst und verschuppt wurden.

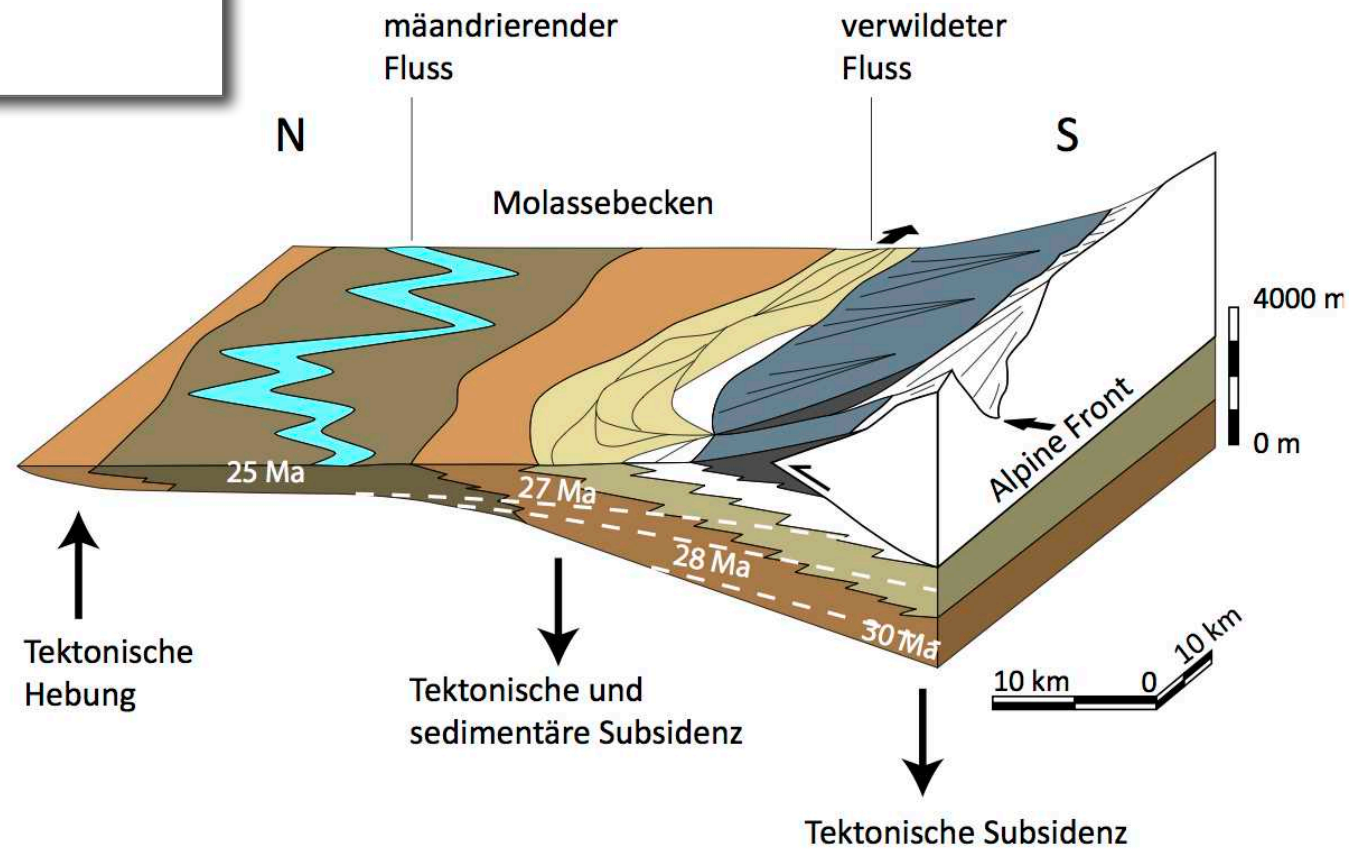
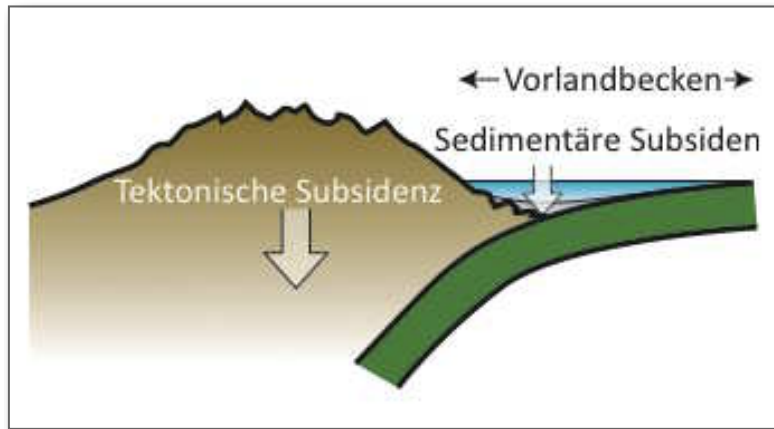
USM am Speer



# Ablagerungsregime



# tektonische Subsidenz und Sedimentation



# Penninikum

## Penninikum

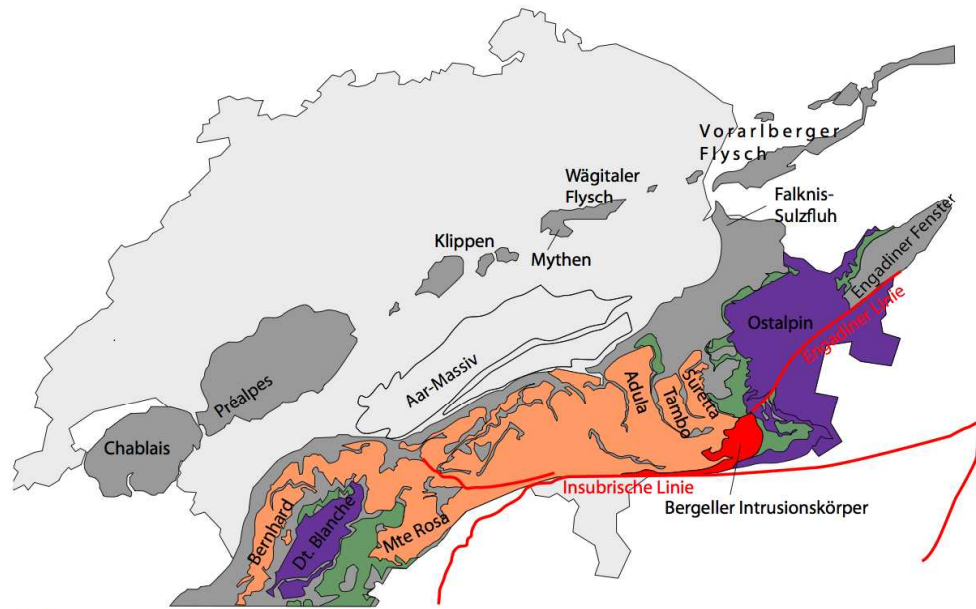
Kontinentale Kruste und paläozoische, mesozoische sowie frühtertiäre Sedimente des Walliser Trogs und der Briançonnais-Schwelle sowie Kruste und Sedimente des zwischen der Europäischen und der Adriatischen Platte gelegenen Piemontesisch-ligurischen Ozeans.

Ein grosser Teil der Sedimente wurde vom kristallinen Grundgebirge abgeschert und nach Norden auf das Helvetikum aufgeschoben. Später wurden das Penninische Kristallin mit der übrigbleibenden Sedimentbedeckung in Decken zerlegt und aufeinander gestapelt. Bilden in den nördlichen Voralpen Klippen (z.B. Préalpes).



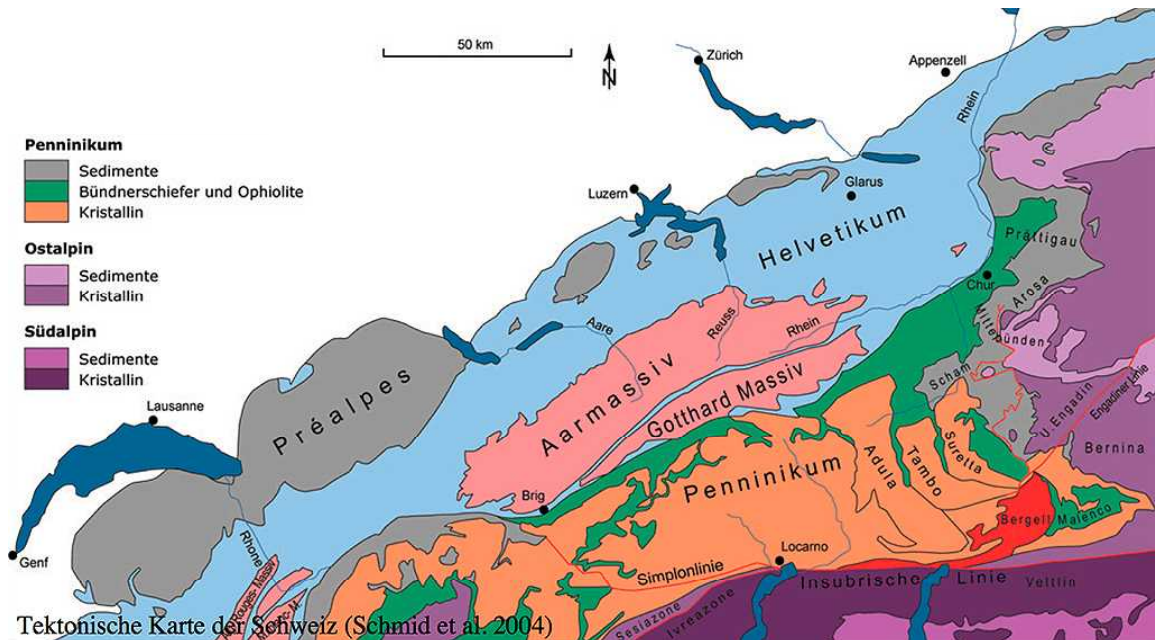
Dent de Savigny Dent de Ruth Zuckerspitz

# Penninikum



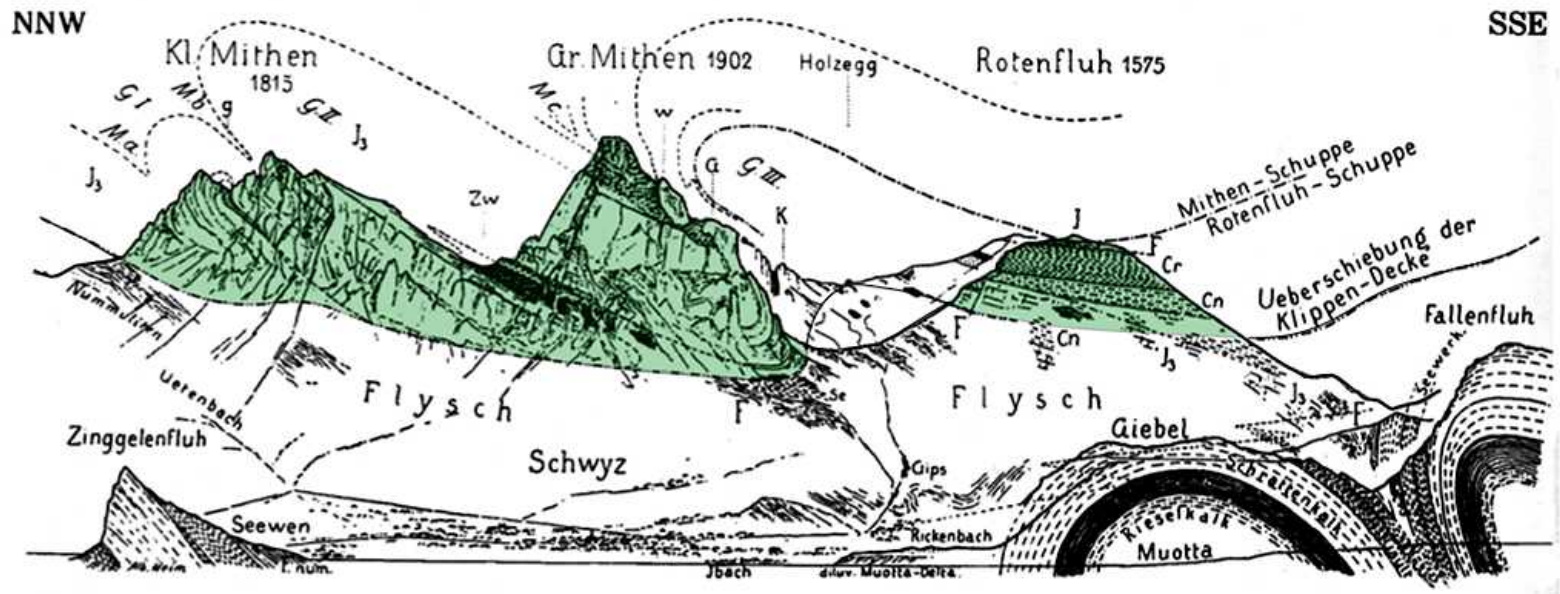
- |                                      |                              |
|--------------------------------------|------------------------------|
| <b>Südpenninikum</b>                 | <b>Ostalpin</b>              |
| Sedimentdecken mit Ophiolithen       | Kristallin- & Sedimentdecken |
| <b>Nord- &amp; Mittelpenninikum</b>  |                              |
| mehrheitlich Sedimentdecken          | Tertiäre Intrusiva           |
| Kristallindecken z.T. mit Sedimenten | Störungszonen                |

Sediment - Decken  
 Kristallin - Decken  
 Ophiolit - führende Decken

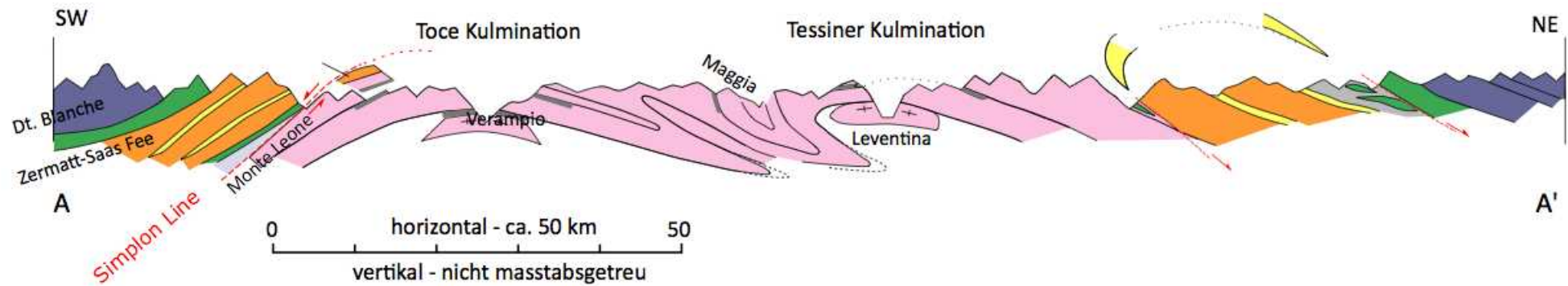


Tektonische Karte der Schweiz (Schmid et al. 2004)

# Klippendecke (Penninikum)



# Penninische Decken - Tessiner Kulmination



## Legende zum Profil

### Ostalpin - Südalpin

Adriatischer Kontinentalrand

### Penninikum

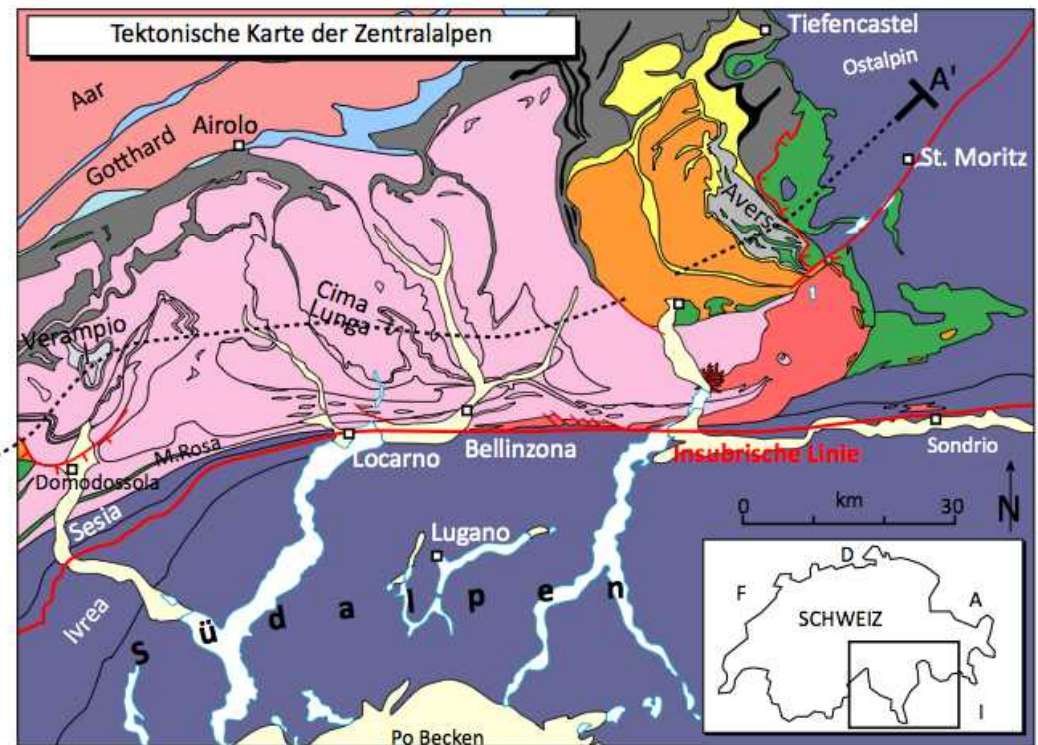
O S Süd penninikum (Piemont-Ligurischer Ozean)

S G Mittelpenninikum (Briançonnais)

S/O Nordpenninikum (Walliser Trog)

S G Nordpenninikum (Europäischer Kontinentalrand)

S Sedimente, G Grundgebirge, O Ophiolithe



diverse Quellen

# Ostalpin



Penninikum

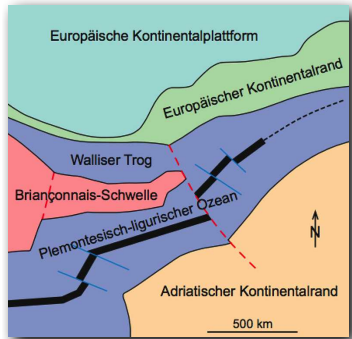
Ostalpin

*Engadiner Linie*

Ostalpin  
Kristalline Oberkruste und paläozoische sowie mesozoische Sedimente der Adriatischen Platte, in mehrere Decken gegliedert und nach Norden auf die Penninischen Decken überschoben.

Engadin von Süden

# Ocean-Continent Transition (OCT)



Ostalpin

Adriatischer Kontinentalrand

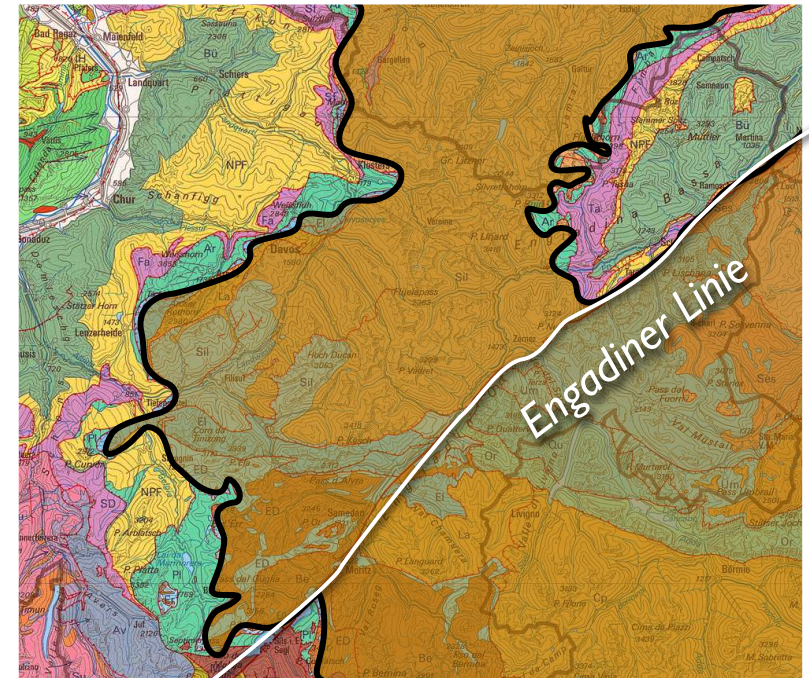
Penninikum

Piemont Ozean

Briançonnais

Walliser Trog

Walliser Trog



Walliser Trog

Briançonnais

Piemont Ozean

Futur external part of the Alps

Futur internal part of the Alps

Futur external part of the Alps

Dauphiné and Helvetic nappes

North Penninic nappes

Middle Penninic nappes

South Penninic nappes

Southern Alps, Upper and Lower Austroalpine nappes

European proximal margin

European distal margin

Valais domain

Briançonnais domain

Ocean-Continent Transition and Piemontese-Liguria domain

Adriatic distal margin

Adriatic proximal margin

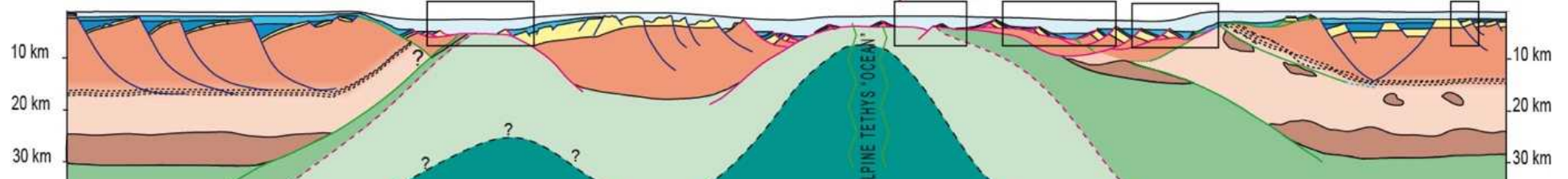
Day 1  
Tasna  
OCT

Day 3  
Platta  
OCT/  
embryonic ocean

Day 2  
Bardella  
distal margin

Day 2  
Piz Alv-Diavolezza  
distal/necking zone

Day 2  
Il Motto  
proximal margin





# Engadiner Fenster

Silvretta-Decke Ober-Ostalpin (adriatischer Kontinentalrand)

Aroser Schuppenzone Ober-Penninikum (Piemont Ozean)

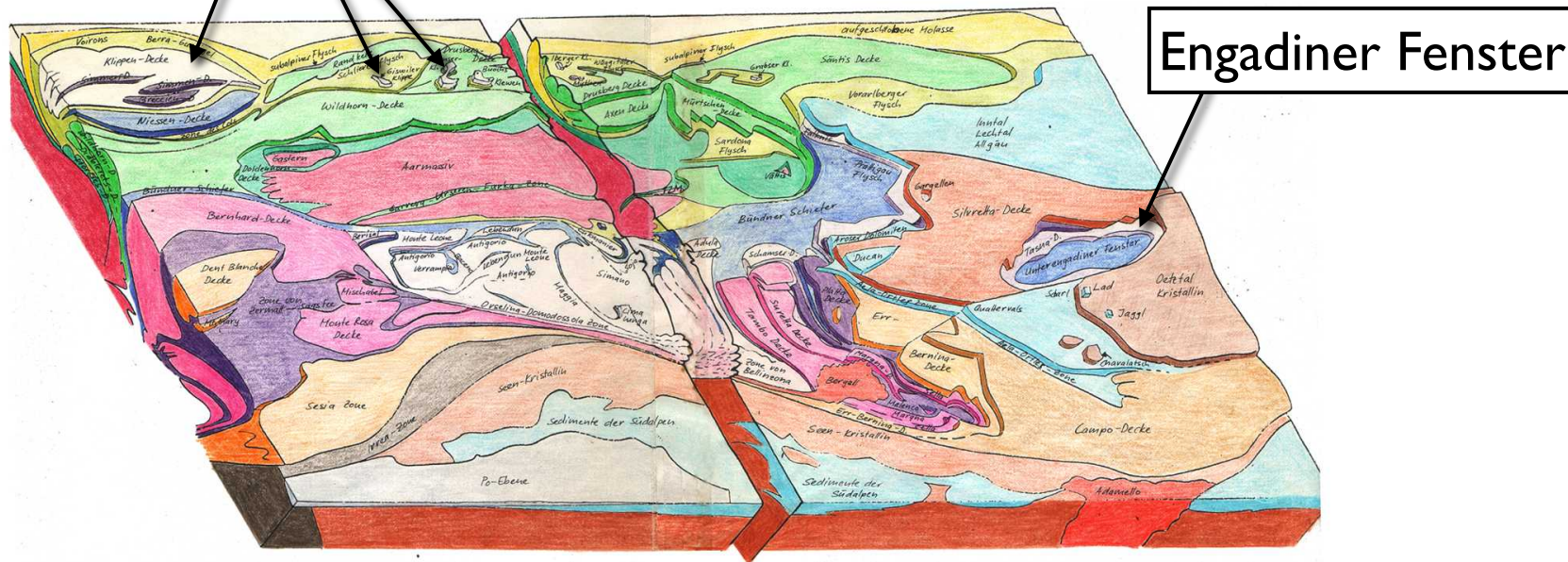
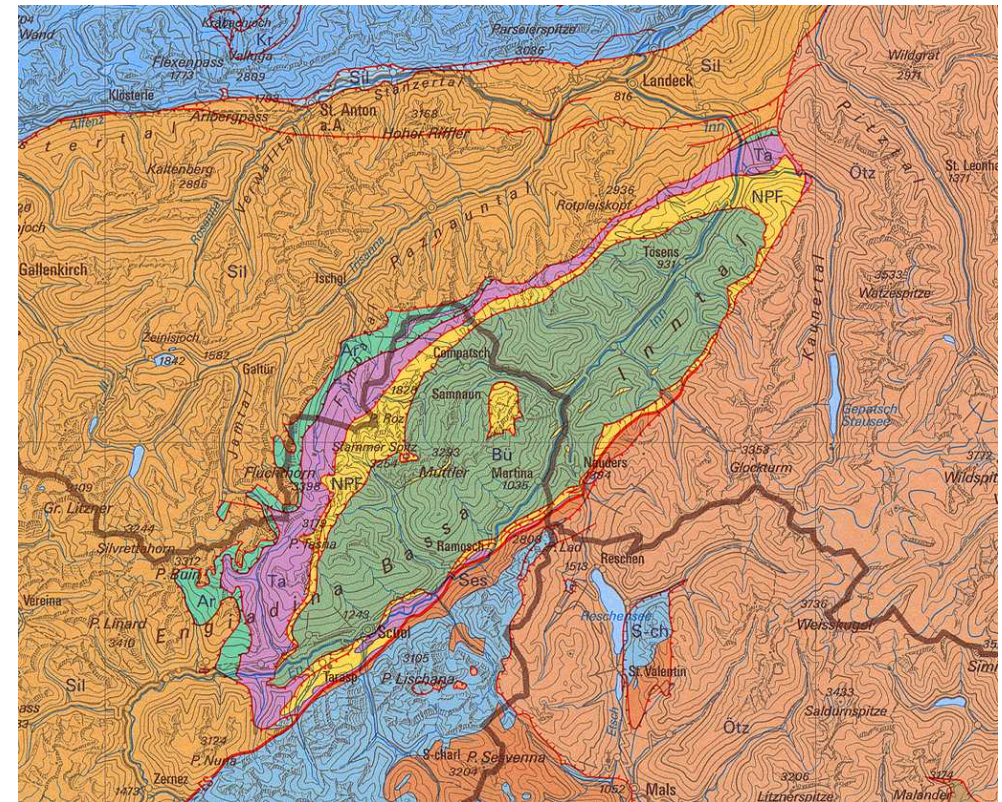
Tasna-Decke Mittel-Penninikum (Briançonnais)

Nordpenninischer Flysch Unter-Penninikum (Walliser Trog)

Bündnerschiefer Unter-Penninikum (Walliser Trog)

pro memoria...

Klippendecke



Engadiner Fenster

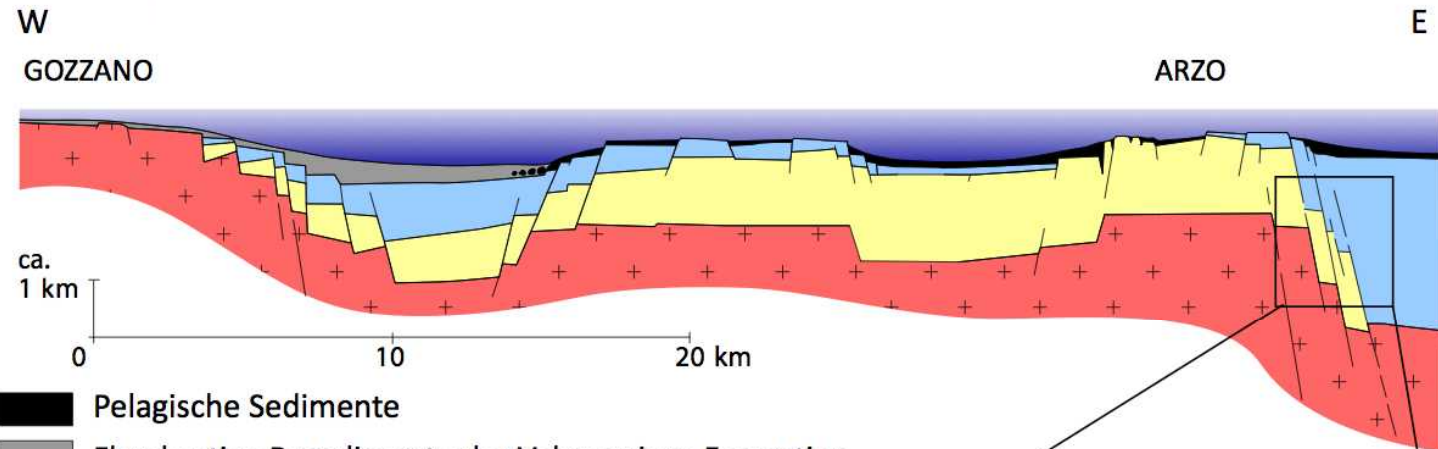
# Südalpin



Südalpin  
Kristalline Unterkruste, Oberkruste und paläozoische, mesozoische und frühtertiäre Sedimente der Adriatischen Platte. Nach Süden überschoben. Bei Chiasso und südlich davon überlagert vom Tertiär des Po-Beckens.

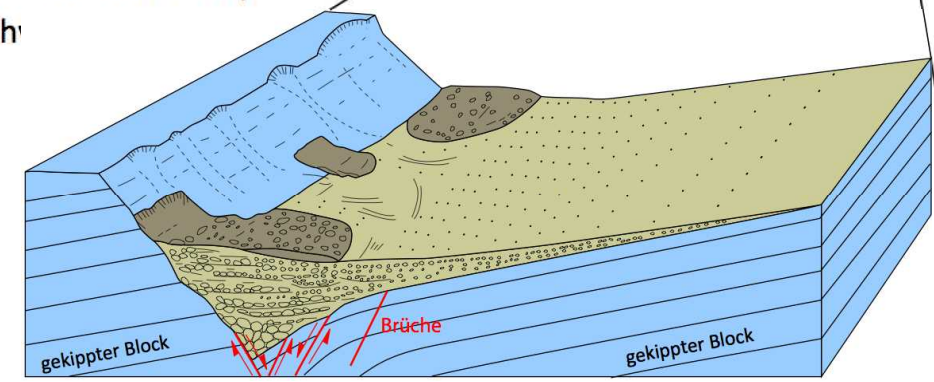
Monte Tamaro

# Südalpin - Rifting



- Pelagische Sedimente
- Flyschartige Resedimente der Valmaggiore-Formation
- Früh- und mittelliasische Beckensedimente (inkl. hemipelagische Sedimente des Domerian)
- Mittel- und spätriasische Flach
- Permische Vulkanite

modifiziert nach Kälin und Trümpy (1977)



Brekzie von Arzo

# pro memoria

## Lehrbuch

Pfiffner, O.A., Diamond, L., Engi, M., Mezger, K., Schlunegger, F., Baumeler, A. (Illustration) (2016)  
Erdwissenschaften. UTB basics 3632, Haupt Verlag, ISBN: 978-3-8252-4381-4

## Weitere Literaturempfehlung (deutsch)

- Tarbuck, E.J. and Lutgens, F. K., 2009. Allgemeine Geologie. Pearson Studium
- Siever, R., 2003. Allgemeine Geologie. 3.Aufl., Spektrum, Heidelberg
- Bahlburg, H. und Breitzkreuz, C., 2008. Grundlagen der Geologie, 3.Aufl., Spektrum, Heidelberg
- Weissert H., Stössel, I. (2015) Der Ozean im Gebirge. vdf Hochschulverlag. ISBN: 978-3-7281-3606-0

## Weitere Literaturempfehlung (englisch)

- Tarbuck, E.J. and Lutgens, F. K., 2008. Earth, 9th ed., Prentice Hall, Upper Saddle River, NJ
- Marshak, S., 2008. Earth: Portrait of a Planet. Norton & Co., New York
- Rogers, N., editor, 2008. Our Dynamic Planet. Cambridge Univ. Press, Cambridge

## Web sites

<http://de.wikipedia.org>

<http://en.wikipedia.org>

<http://ansatte.uit.no/kare.kullerud/webgeology/>

<http://www.seismo.ethz.ch/>

<http://earthquake.usgs.gov/earthquakes/>

# Ende

... fast ... was noch kommt:

auf ADAM:

- korrigierte / vervollständigte slides
- Prüfungsfragen

Prüfungsstoff:

Vorlesungs(-slides, -notizen) & Übungen

Lehrbuch: Pfiffner et al.

im Herbst:

- Prüfung 25 % =

Plattentektonik & Geophysik  
Strukturgeologie & Tektonik

*trotzdem ... schöne Sommerferien !*