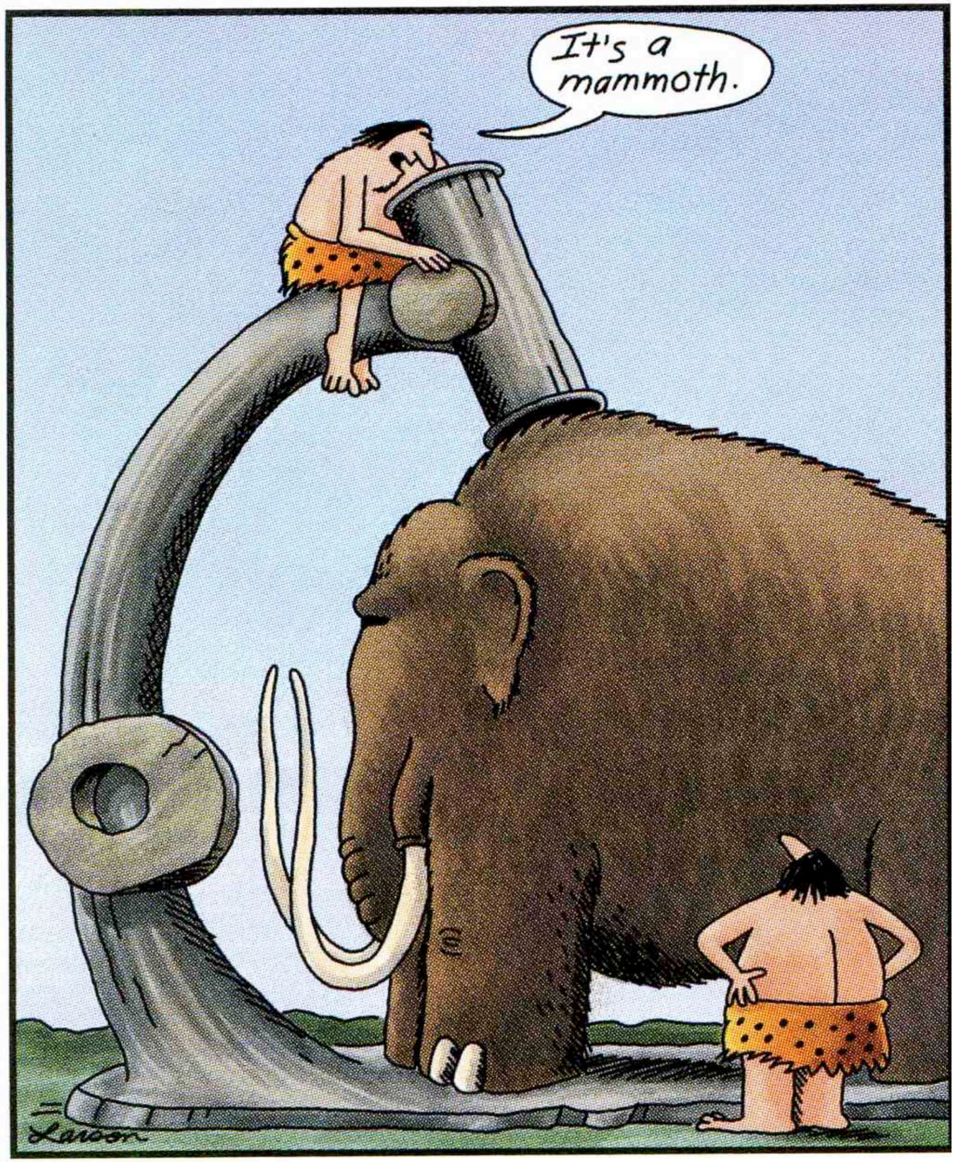
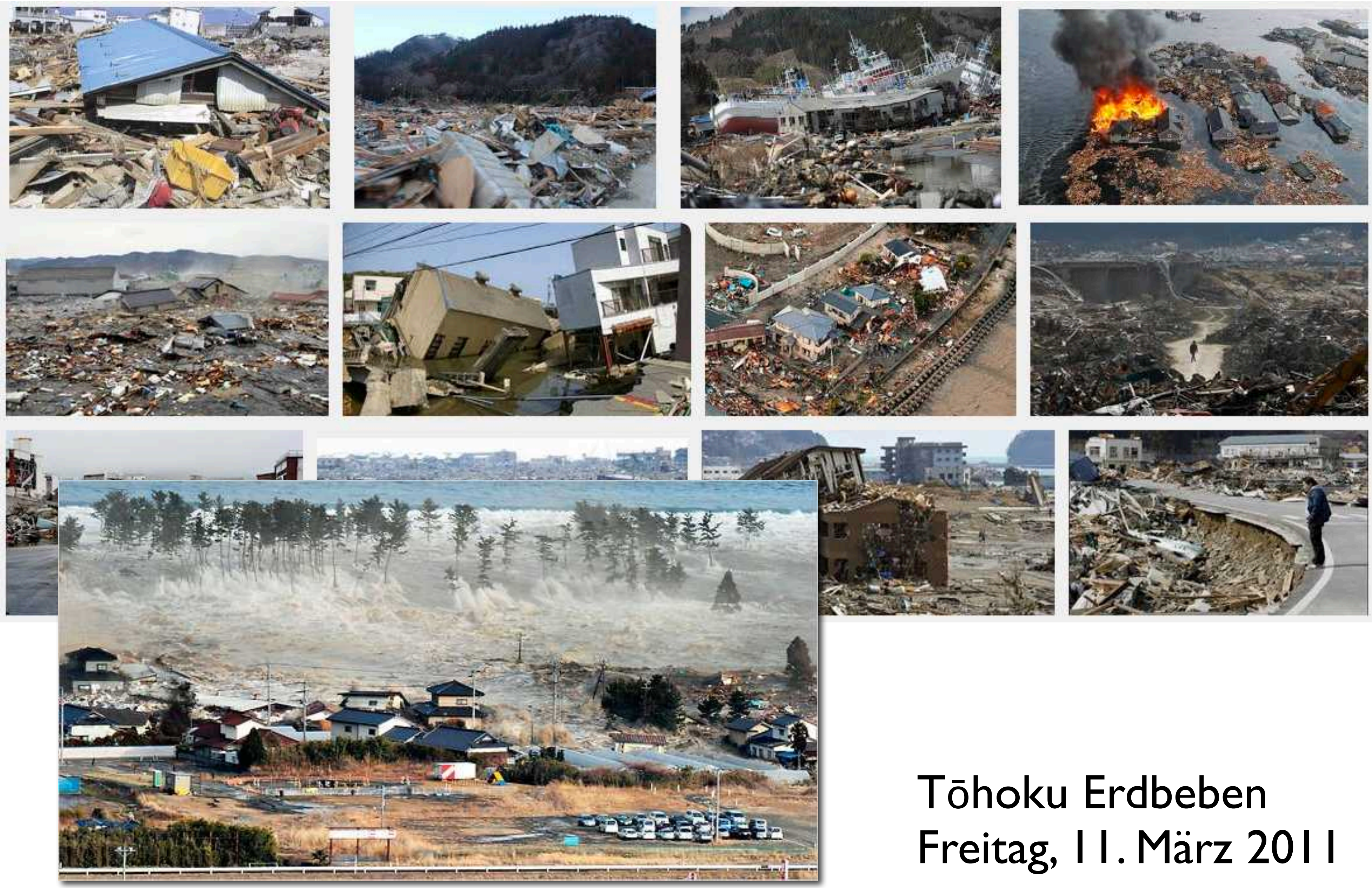
Senioren Universität
11. / 12. März 2015

Erdbeben unter dem Mikroskop

Prof. Dr. Renée Heilbronner
Departement
Umweltwissenschaften
Universität Basel



東北地方太平洋沖地震



Tōhoku Erdbeben
Freitag, 11. März 2011

Tohoku, Japan Earthquake, 03/11/2011, Mw 9.0

USGS

USGS ShakeMap : NEAR THE EAST COAST OF HONSHU, JAPAN

Fri Mar 11, 2011 05:46:23 GMT M 9.0 N38.32 E142.37 Depth: 32.0km ID:c0001xgp

Map Version 6 Processed Tue Mar 15, 2011 08:39:58 AM MDT -- NOT REVIEWED BY HUMAN

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

USGS science for a changing world

Earthquake Shaking Red Alert

GSN ANSS USAID FROM THE AMERICAN PEOPLE

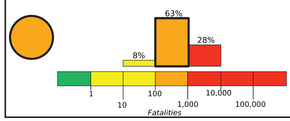
M 9.0, NEAR THE EAST COAST OF HONSHU, JAPAN

PAGER Version 7

Origin Time: Fri 2011-03-11 05:46:23 UTC (14:46:23 local)
Location: 38.32°N 142.37°E Depth: 32 km
FOR TSUNAMI INFORMATION, SEE: tsunami.noaa.gov

Created: 4 days, 9 hours after earthquake

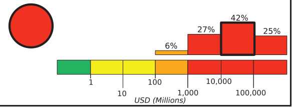
Estimated Fatalities



Red alert level for economic losses. Extensive damage is probable and the disaster is likely widespread. Estimated economic losses are 0-1% GDP of Japan. Past events with this alert level have required a national or international level response.

Orange alert level for shaking-related fatalities. Significant casualties are likely.

Estimated Economic Losses



Estimated Population Exposed to Earthquake Shaking

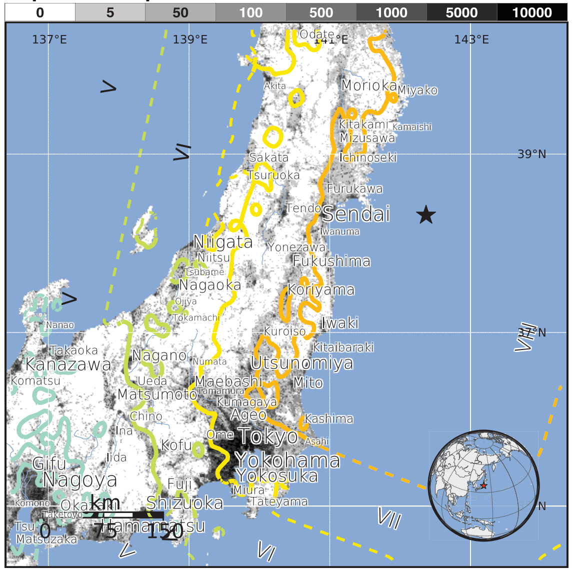
ESTIMATED POPULATION EXPOSURE (k = x1000)		- -*	6k*	2,483k*	15,269k*	10,864k*	36,088k*	6,781k*	66k	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
	Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure

population per ~1 sq. km from Landscan

0	5	50	100	500	1000	5000	10000



PAGER content is automatically generated, and only considers losses due to structural damage. Limitations of input data, shaking estimates, and loss models may add uncertainty.
http://earthquake.usgs.gov/pager

Structures:
Overall, the population in this region resides in structures that are resistant to earthquake shaking, though some vulnerable structures exist. The predominant vulnerable building types are non-ductile reinforced concrete frame and heavy wood frame construction.

Historical Earthquakes (with MMI levels):

Date (UTC)	Dist. (km)	Mag.	Max MMI(#)	Shaking Deaths
1998-06-14	363	5.7	VII(428k)	0
1994-12-28	263	7.7	VII(132k)	3
1983-05-26	369	7.7	VII(174k)	104

Recent earthquakes in this area have caused secondary hazards such as tsunamis, landslides, and fires that might have contributed to losses.

Selected City Exposure

from GeoNames.org

MMI	City	Population
IX	**Iwanuma**	**42k**
IX	Rifu	35k
IX	Shiogama	60k
IX	Hitachi	186k
VIII	Takahagi	34k
VIII	Ishinomaki	117k
VIII	**Sendai**	**1,038k**
VIII	Chiba	920k
VII	**Yokohama**	**3,574k**
VII	**Tokyo**	**8,337k**
V	**Nagoya**	**2,191k**

bold cities appear on map (k = x1000)

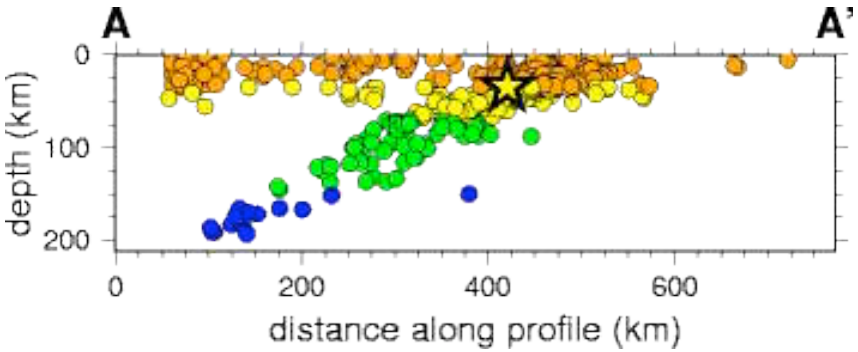
Event ID: usc0001xgp

IRIS Teachable Moments

Magnitude 9.0 NEAR THE EAST COAST OF HONSHU, JAPAN
Friday, March 11, 2011 at 05:46:23 UTC

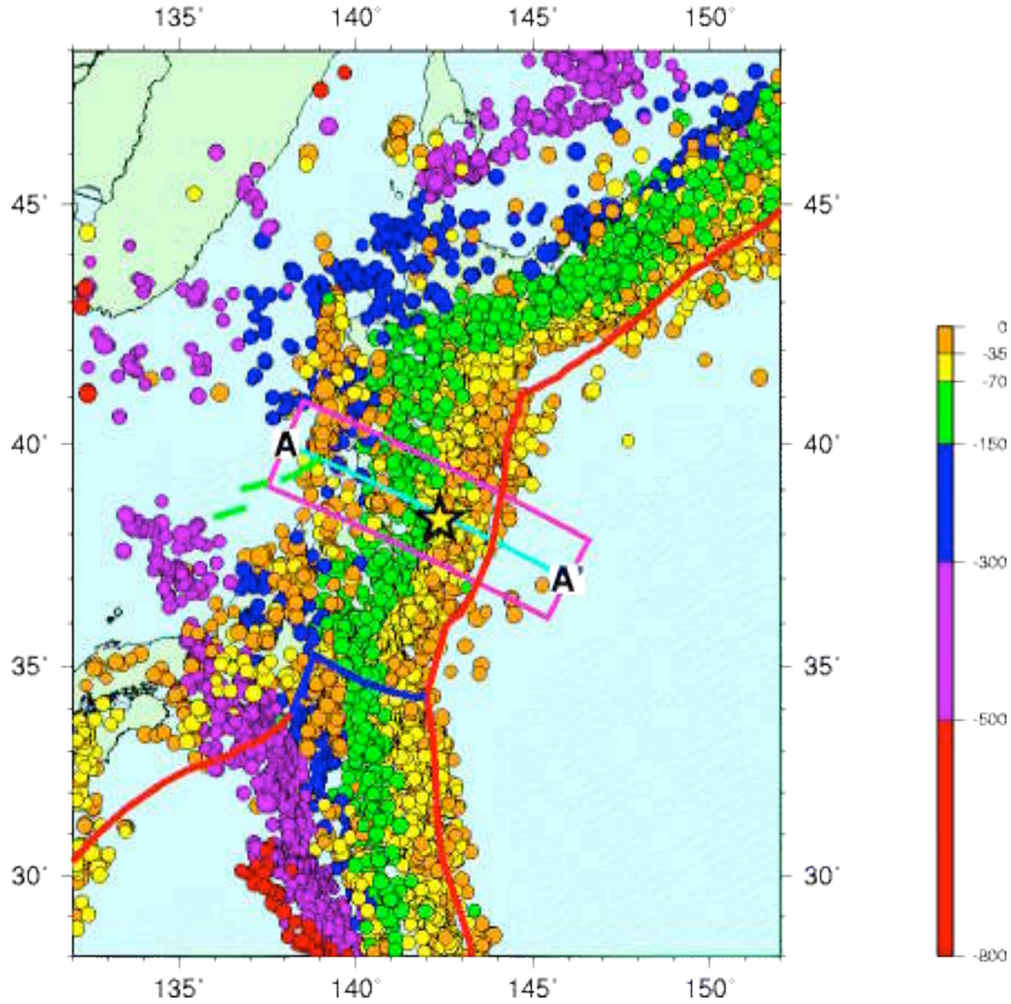
The map on the right shows historic earthquake activity near the epicenter (star) from 1990 to present.

As shown on the cross section, earthquakes are shallow (orange dots) at the Japan Trench and increase to 300 km depth (blue dots) towards the west as the Pacific Plate dives deeper beneath the Japan (Eurasian Plate or Ochotsk Plate).



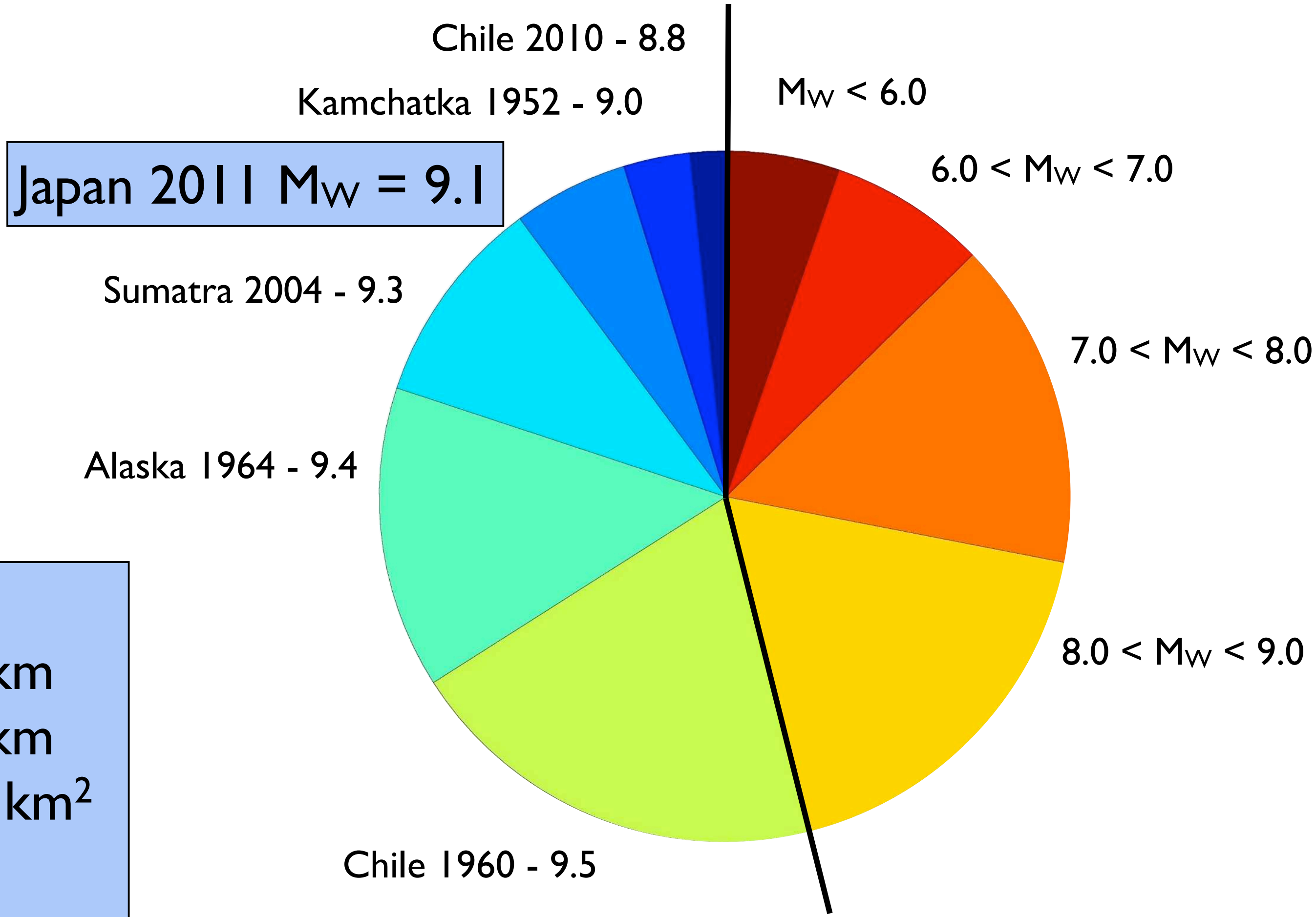
Seismicity Cross Section across the subduction zone showing the relationship between color and earthquake depth.

Seismicity Cross Section



Images courtesy of the US Geological Survey

eines der grössten Erdbeben

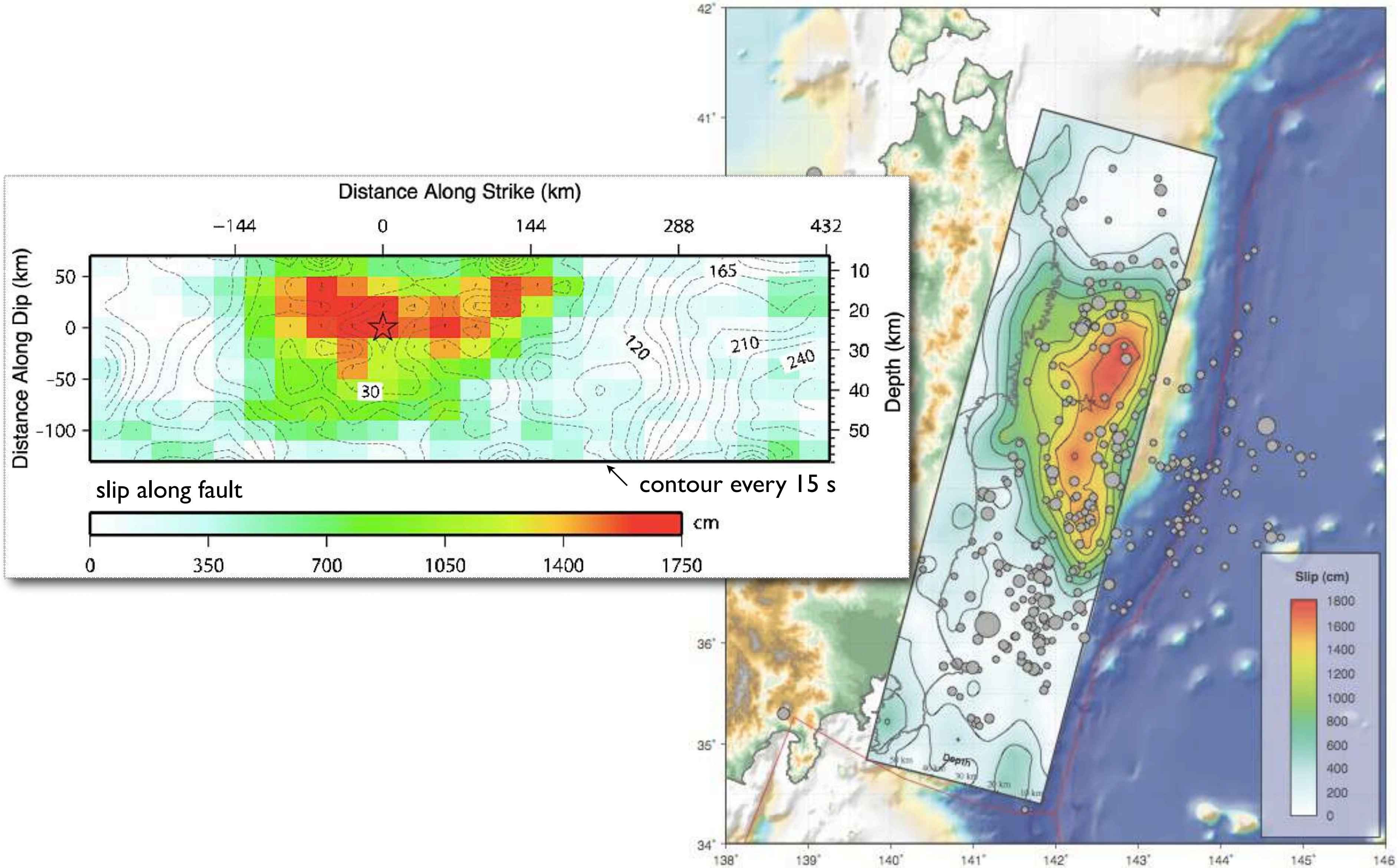


Verwerfung:	
Länge:	500 km
Breite:	200 km
Fläche:	100'000 km^2
Versatz:	20 m

Seismisches Moment M_0 = Fläche · Versatz · Schermodul

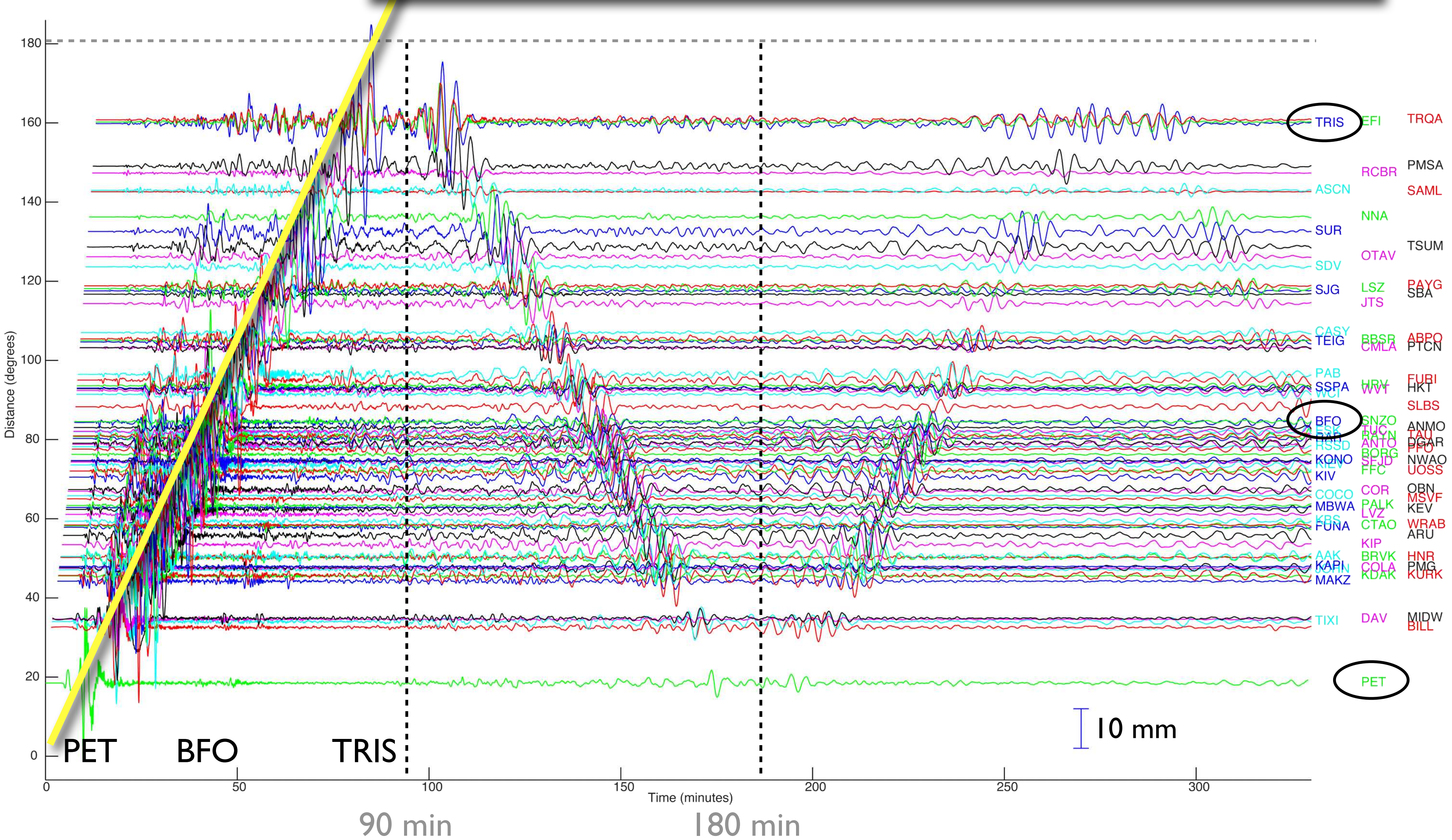
Momenten-Magnitude $M_W = {}^2/_3 \cdot \log(M_0) - 10.7$

was war geschehen ?

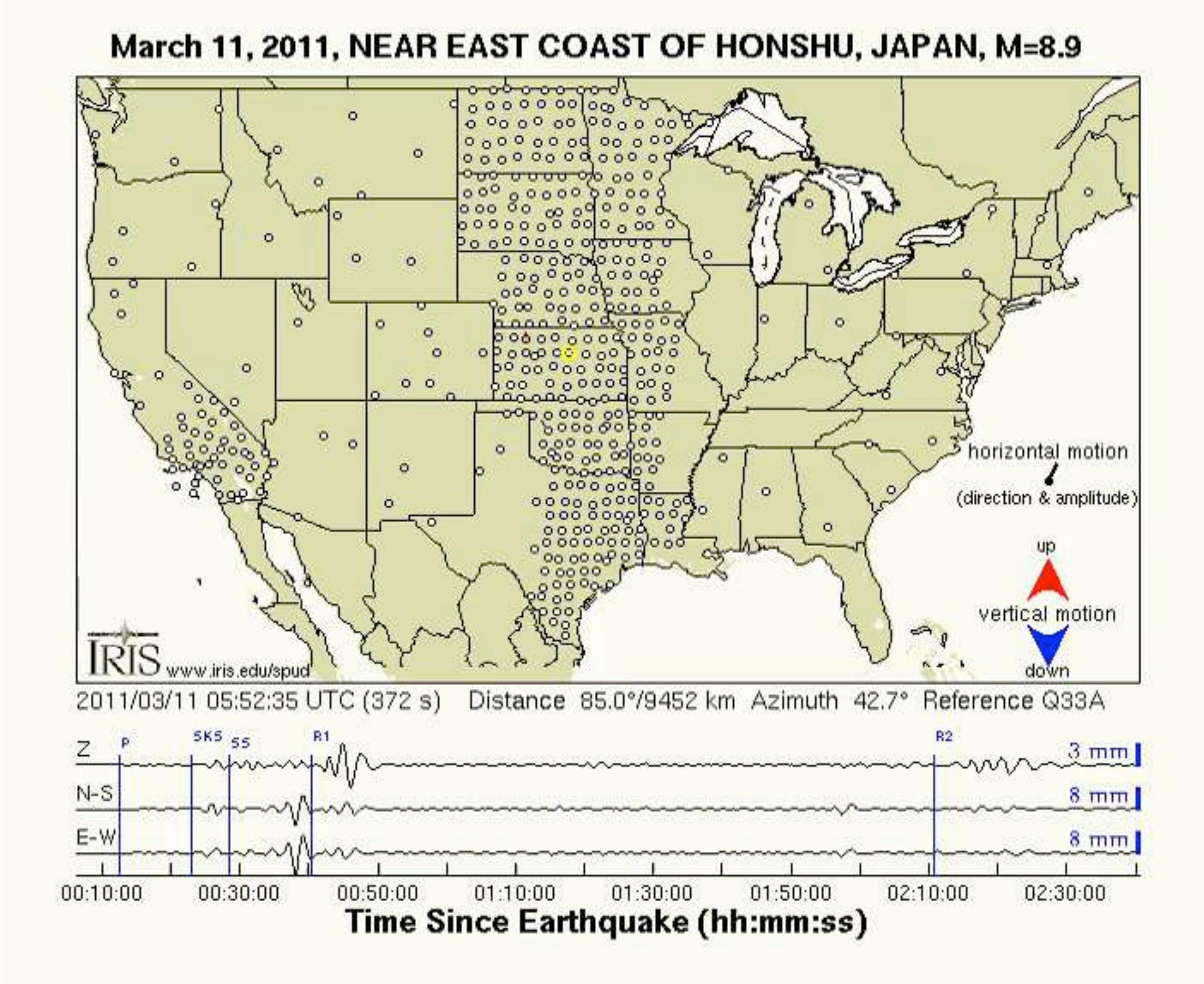


Ausbreitung seismischer Wellen

360° in 180 min ≈ 40'000 km in 10'800 s ≈ 4 km/s



Bodenbewegung in den USA



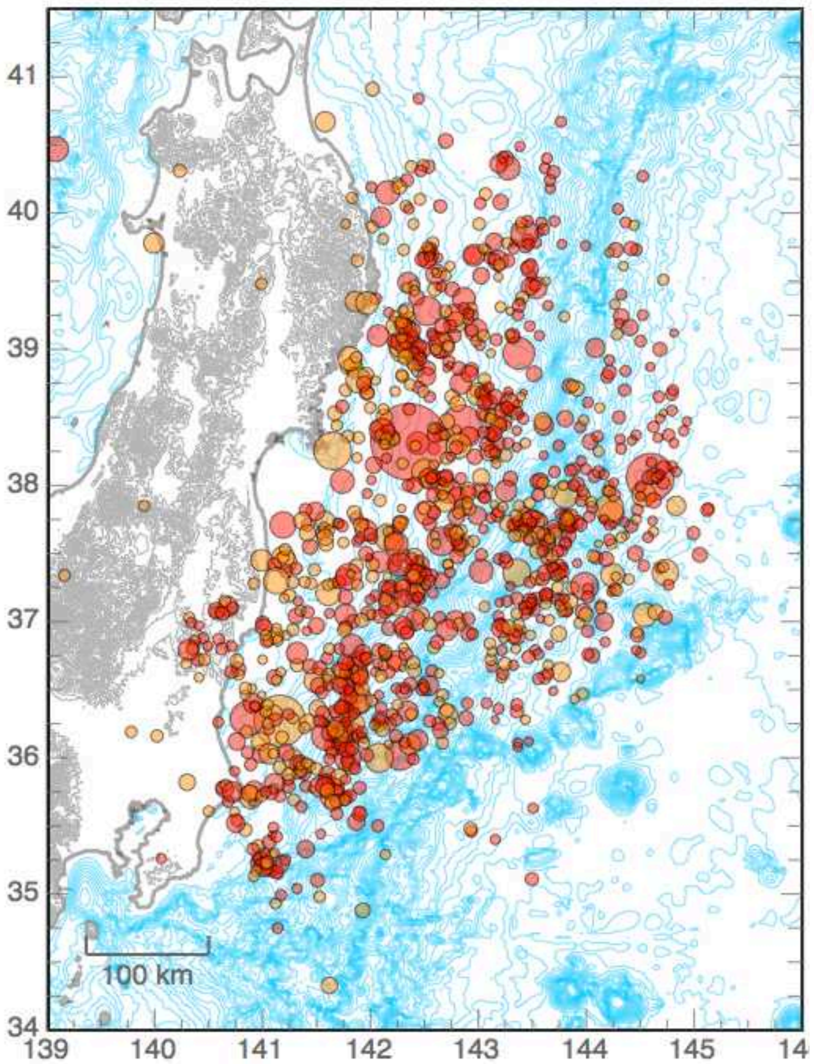
Ausbreitung eines Erdbebens

Intensität = 'gefühlte Magnitude'

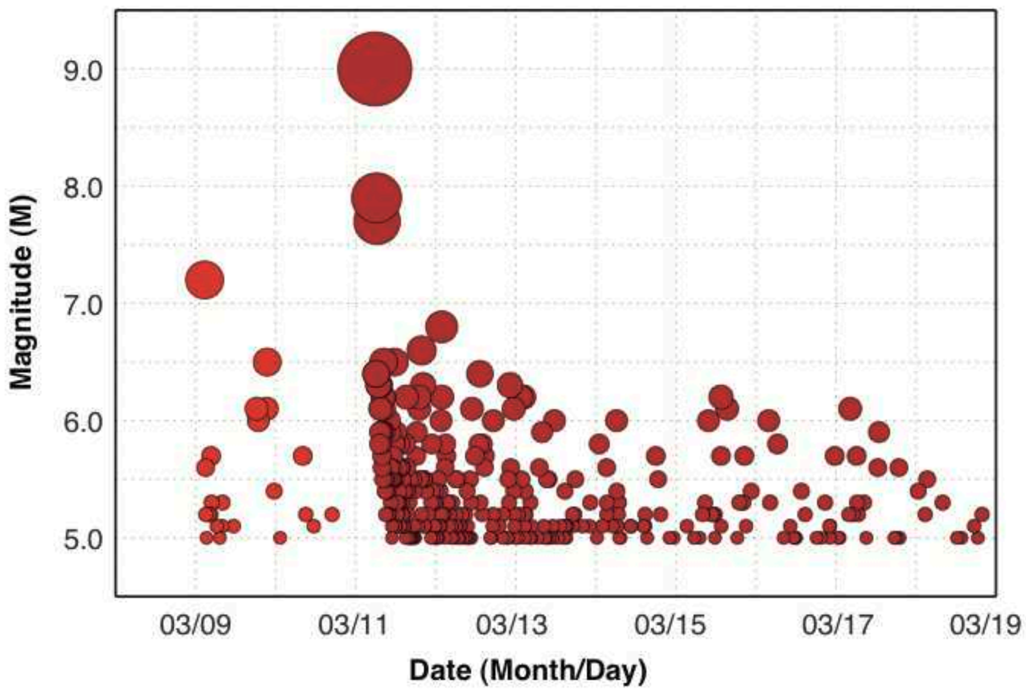
100 km

von pre-shock bis after-shock

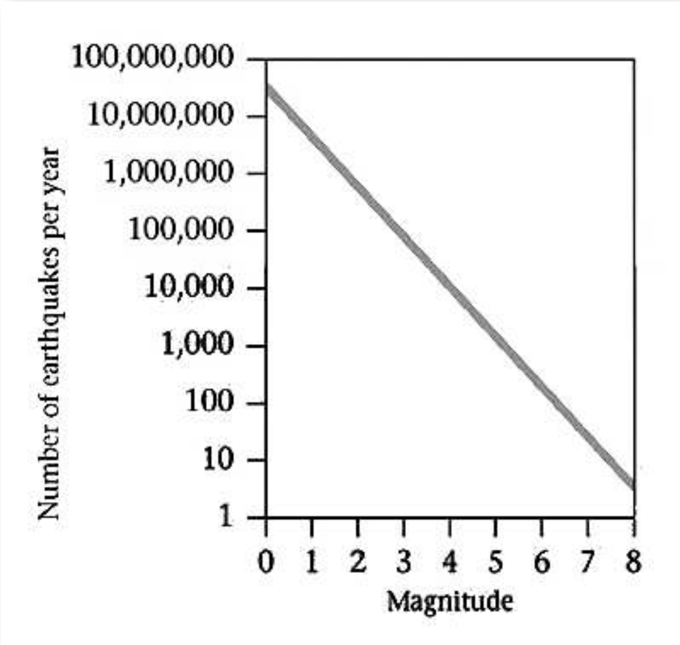
9. März - 4. April 2011



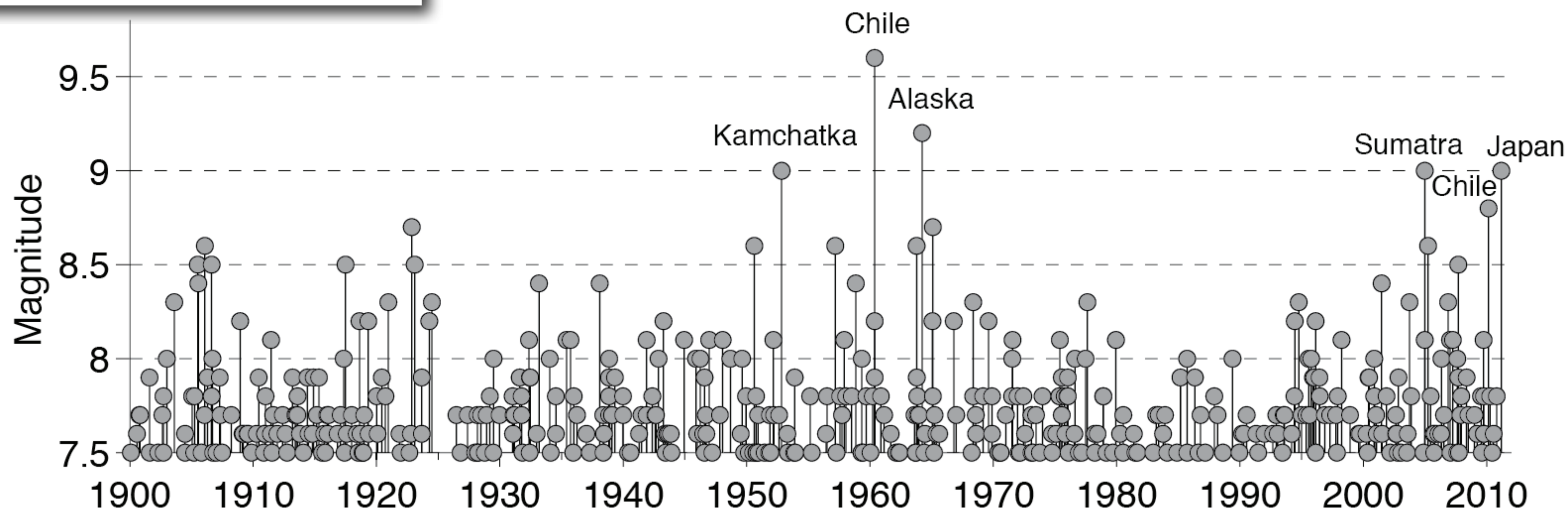
9. - 19. März 2011



Erdbeben - statistische Ereignisse



... grosse Erdbeben sind seltene Ereignisse



wie Erdbeben untersuchen ?

... und warum unter dem Mikroskop ?

was will man ansehen ?

- den slip selbst während des Erdbebens ?
- den aseismic creep dazwischen ?

wo gibt es Daten ?

Aktive Plattengrenzen:
- Bohrungen (SAFOD, Nojima)

Experimente
- high speed - für seismic slip
- creep - für interseismic creep

Feldarbeit
- fossile Erdbeben
- fossile creeping faults

Zusammenarbeit und Unterstützung

University of Wyoming

University of Tromsø

Brown University

MIT

Texas A&M Univerisity

University of Utrecht

University of Kyoto

Schweizerischer Nationalfonds

FNSNF
Swiss National Science Foundation

Geosciences

European Geosciences Union
General Assembly 2015

Vienna | Austria | 12 – 17 April 2015

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European Geosciences Union
General Assembly 2015
Vienna | Austria | 12 – 17 April 2015

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- ☐ Atmospheric Sciences (AS)
- ☐ Biogeosciences (BG)
- ☐ Climate: Past, Present, Future (CL)
- ☐ Cryospheric Sciences (CR)
- ☐ Earth Magnetism & Rock Physics (EMRP)
- ☐ Energy, Resources and the Environment (ERE)
- ☐ Earth & Space Science Informatics (ESSI)
- ☐ Geodesy (G)
- ☐ Geodynamics (GD)
- ☐ Geosciences Instrumentation & Data Systems (GI)
- ☐ Geomorphology (GM)
- ☐ Geochemistry, Mineralogy, Petrology & Volcanology (GMPV)
- ☐ Hydrological Sciences (HS)
- ☐ Natural Hazards (NH)
- ☐ Nonlinear Processes in Geophysics (NP)
- ☐ Ocean Sciences (OS)
- ☐ Planetary & Solar System Sciences (PS)
- ☑ Seismology (SM)
- ☐ Stratigraphy, Sedimentology & Palaeontology (SSP)
- ☐ Soil System Sciences (SSS)
- ☐ Solar-Terrestrial Sciences (ST)
- ☑ Tectonics & Structural Geology (TS)

TS – Tectonics & Structural Geology

- Programme Committee Login

- TS1 – Brittle Deformation and Fault-related Processes
- TS2 – Ductile Deformation, Metamorphism and Magmatism
- TS3 – Interplay between Tectonics and Surface Processes
- TS4 – Earthquakes and Tectonics
- TS5 – Extensional Tectonic Settings
- TS6 – Convergent Tectonic Settings
- TS7 – Plate-scale Tectonics
- TS8 – Methods and Techniques in Tectonics and Structural Geology
- TS9 – General Topics in Tectonics and Structural Geology
- TS10 – Workshops
- TS11 – Co-listed sessions

Geophysical Research Abstracts
Vol. 17, EGU2015-4698, 2015
EGU General Assembly 2015

The viscous and frictional strength of faults in experiment and nature

Renee Heilbronner (1), Matej Pec (2), and Holger Stunitz (3)
(1) Geological Institute, Basel University, Basel, Switzerland (renee.heilbronner@unibas.ch), (2) Matej Pec, University of Minnesota (mpec@umn.edu), (3) Department of Geology, Tromsø University, Tromsø, Norway (holger.stunitz@uit.no)

In an extended study of one of the authors (PhD thesis of Matej Pec), the deformational behaviour of granitoid fault rocks was explored using a Griggs solid medium deformation apparatus and a range of temperatures (T = 300˚C to 600˚C), confining pressures (Pc = 0.5 to 1.5 GPa) and strain rates ($d\gamma/dt \approx 10^{-3}$ to 10^{-5} s^{-1}). Layers of crushed and sieved material (1 mm thick) were deformed between alumina forcing blocks (on a 45˚ pre-cut) to finite shear strains of up to $\gamma = 5$.

The deformation within the fault rock layers is one of plane shear accompanied by considerable thinning. To a certain extent, extrusion occurs parallel to the displacement direction but not transverse to it. The fault rock material does not deform homogeneously, rather the microstructure develops from an initial Riedel fracture set into an SC' fabric at higher strains. Progressive comminution leads to strain partitioning with a microstructure that is characterized by a few survivor grains surrounded by a fine grained mantle (of the same mineral composition as the survivor grains) and an evolving network of slip zones consisting - at first - of nano-crystalline, partially amorphous and - at higher strains - of completely amorphous material.

The slip zones are approx. 10 μm thick - they are the site of highly localized shear strain. They form a percolating network from one end of the shear zone to the other and must be considerably weaker than the surrounding material as evidenced by turbulent flow structures and the occasional formation of apophyses. Yet, the fault rock layers as a whole support high shear stresses ($\tau \sim 570 – 1600$ MPa) and even in the presence of a fully connected network of slip zones (forming up to 20 vol% of the total fault rock material), they continue to deform at more or less steady state stress levels.

Within the range of experimental conditions, the flow stress sustained by the fault rock depends clearly on confining pressure (indicating a frictional components of flow) and temperature (indicating a viscous components) but only weakly on strain rate. Whether the fault rocks are comparatively strong or weak depends on which criterion is use to describe strength. For example, our experiments show that the flow stresses increase for increasing confining pressure. At the same time, the friction coefficient (τ / σ_n) decreases. In other words: with respect to the sustained flow stress, faults are 'Pc-strengthening' with respect to the friction coefficient, they are 'Pc-weakening'.

To extrapolate our experimental data to nature and to compare them to friction experiments, we present our results in terms of equivalent viscosity describing the deformation of a thin volume of material, and in terms of the friction coefficient describing the displacement along a 'thick' fault surface. We present a simple conceptual model for the temporal and spatial evolution of the geometry or topology of the weak slip zones, and the interplay between viscous and brittle behavior of faults at all scales.

Geophysical Research Abstracts
Vol. 17, EGU2015-13721, 2015
EGU General Assembly 2015

Mafic rocks at the brittle-viscous transition – interplay between fracturing, reaction and viscous deformation

Sina Marti (1), Holger Stünitz (2), and Renée Heilbronner (1)
(1) Geological Institute, Basel University, Switzerland (sina.marti@unibas.ch), (2) Department of Geology, Tromsø University, Norway

Deformation experiments have been performed on crushed Maryland Dibase (~ 55% Plg(An60-70), 42% Px, 3% accessories, 0.2 w.t.-% H_2O added) in a Griggs-type deformation apparatus in order to explore the brittle-viscous transition and the interplay between deformation and mineral reactions. Shear experiments at constant displacement rate of 1e-8 m/s (resulting shear strain rate ~ 1e-5 /s) are conducted at T=600 to 800°C and confining pressures of Pc = 1.0 and 1.5 GPa.

Below 700°C, the microstructure is dominated by brittle deformation processes. At 700°C, the steady state strength approaches the Goetze criterion. The microstructure shows less evidence of brittle deformation and the onset of mineral reactions and diffusive mass transport are observed. Samples deformed at 800°C sustain significantly lower stresses than the Goetze criterion and reaction products are far more abundant. For both, 700°C and 800°C experiments, the main reaction products are Amph, Plg(An45-50) and zoisite (Zo, at Pc=1.5).

Deformation localizes in all experiments. At 700°C, displacement takes place either along shear fractures or in shear bands formed by fine grained Plg and fibrous Amph. Reaction products such as Amph and Plg occur almost restricted along such zones of localized deformation. Strain energy introduced by early fracturing seems to be an important factor enhancing reaction kinetics.
At 800°C, strain localizes into broader shear bands formed by a mixture of Plg + Amph (+ Zo). Phases in shear bands are extremely fine grained with equivalent diameters between 0.1 – 0.4 μm for Plg. Px grains rarely show signs of deformation and mostly form porphyroclasts overgrown by Amph. Fracturing is largely absent.
The spatial distribution of Amph within the shear bands indicates material transport and precipitation of Amph between Plg-Plg boundaries. Thermodynamic modeling suggests that phases such as Grt + Cpx should grow abundantly but grow only in minor amounts (< 1 vol.-%). Amph and Plg have the highest nucleation rates. The reaction rate seems to limited by the nucleation rate of phases.
Minor partial melting (~ 1 vol.-%) occurs in the 800°C experiments. Localization of deformation occurs predominantly along favourable oriented grain- and phase-boundaries. At sites of incipient deformation cavities are observed, which are often filled by the melt phase.

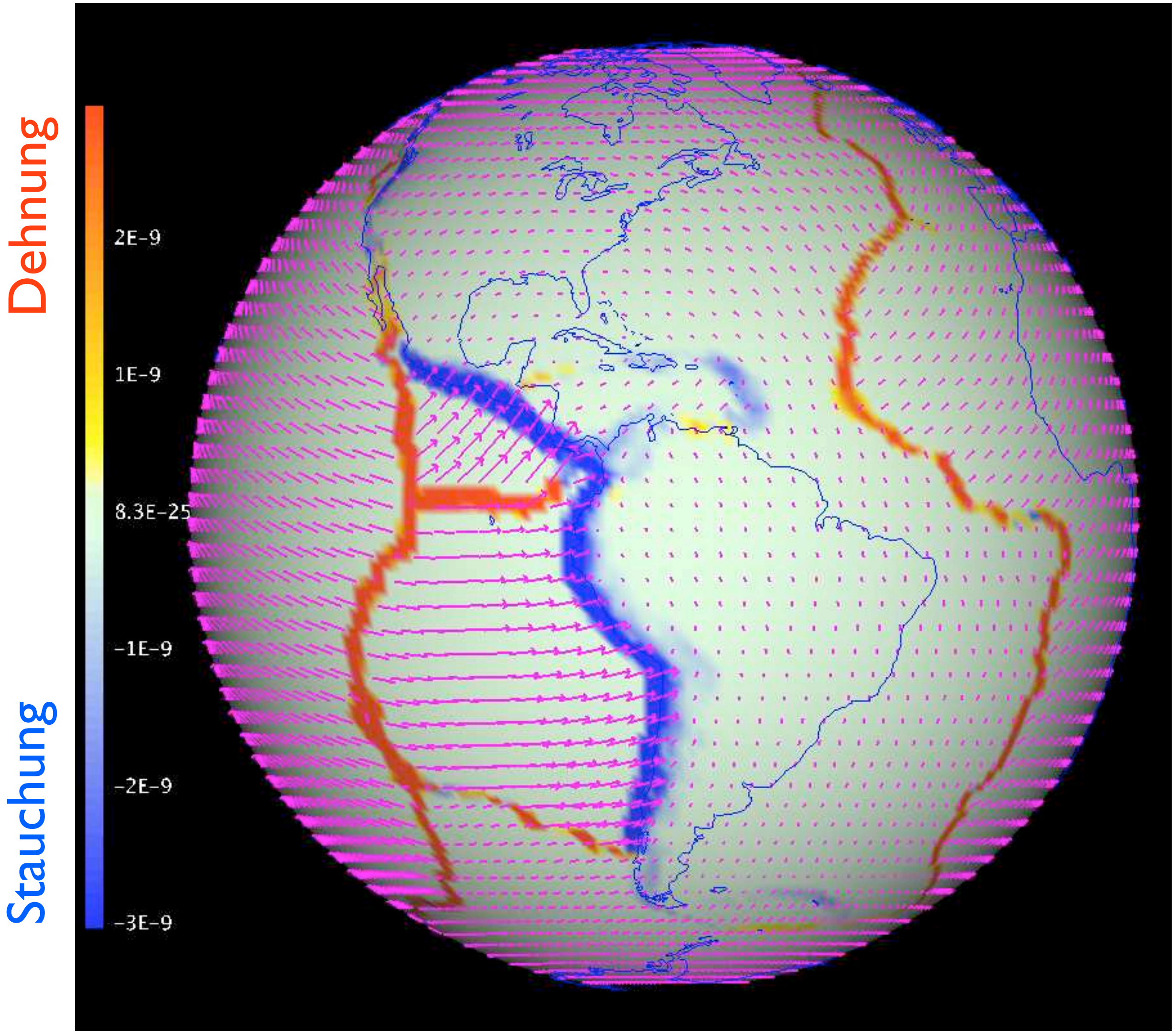
While in the 700°C experiments brittle processes kinematically contribute to deformation, fracturing is largely absent at 800°C. Diffusive mass transfer dominates. The absence of thermodynamically stable phases such as Grt and Cpx is explained by low nucleation rates. On the other hand, Amph and Plg are able to react sufficiently fast to keep up with the high experimental strain rates and the relatively low experimental T. The very small grain size within shear bands in the 700°C and 800°C experiments favours grain size sensitive deformation mechanisms. Due to the presence of water (and relatively high supported stresses), dissolution-precipitation creep is interpreted to be the dominant strain accommodating mechanism. Thus, viscous deformation takes place at comparatively low experimental temperatures, hence providing a realistic phase assemblage and likely deformation mechanism in a strong lower crust.

Vorbemerkung 1

spröde Verformung	≠	duktile Verformung:
diskontinuierlich schnell lokalisiert heterogen		kontinuierlich langsam penetrativ
typisch: Verwerfungen		typisch: Falten
nahe der Oberfläche tiefe Drucke hohe Spannungen tiefe Temperaturen		in grosser Tiefe hohe Drucke tiefe Spannungen hohe Temperaturen

Vorbemerkung II

Bewegung tektonischer Platten



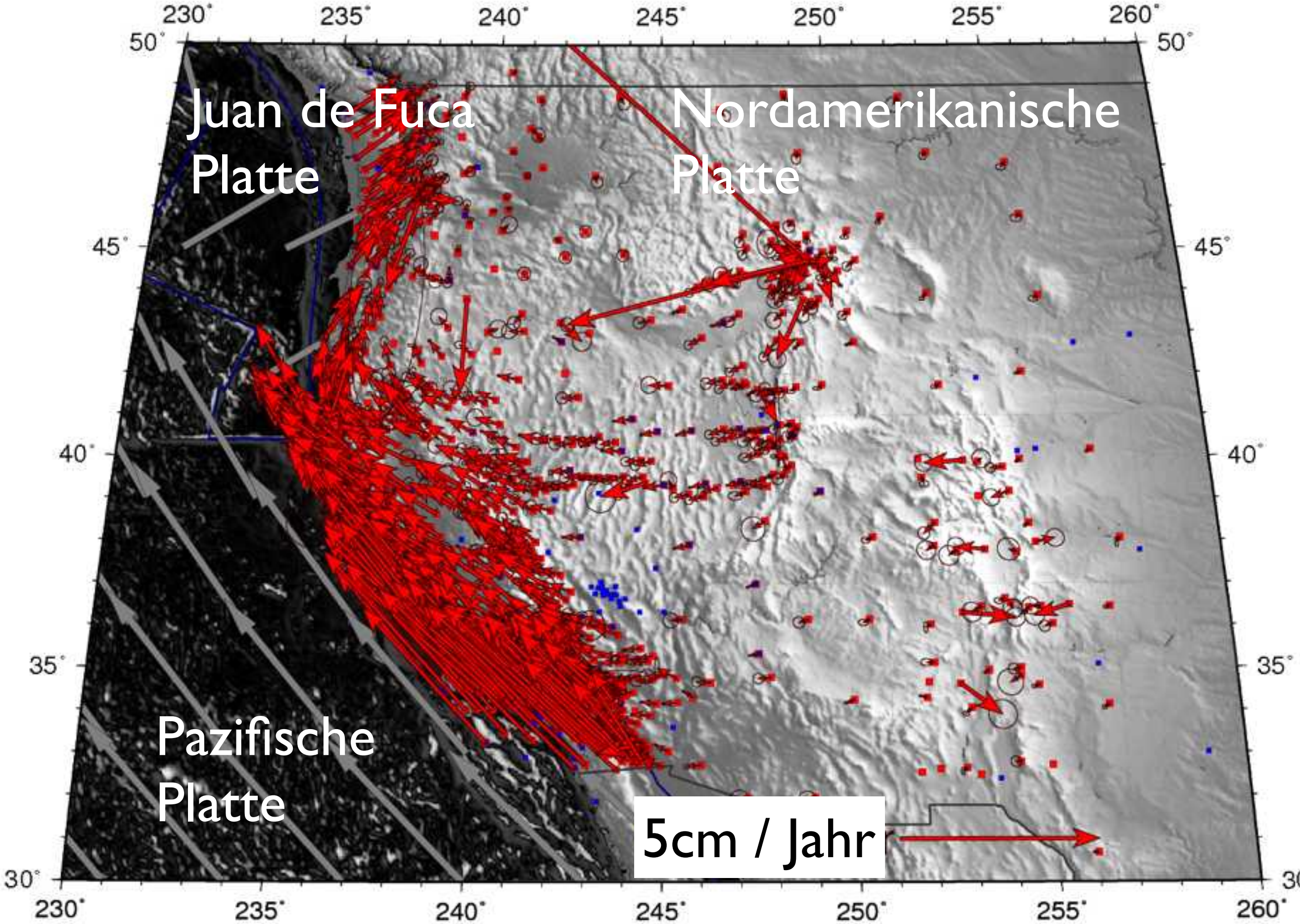
→ Absolutbewegung

1-10 cm / Jahr
kontinuierlich

aufgrund der
Mantelkonvektion
im Erdinnern

Vorbemerkung III

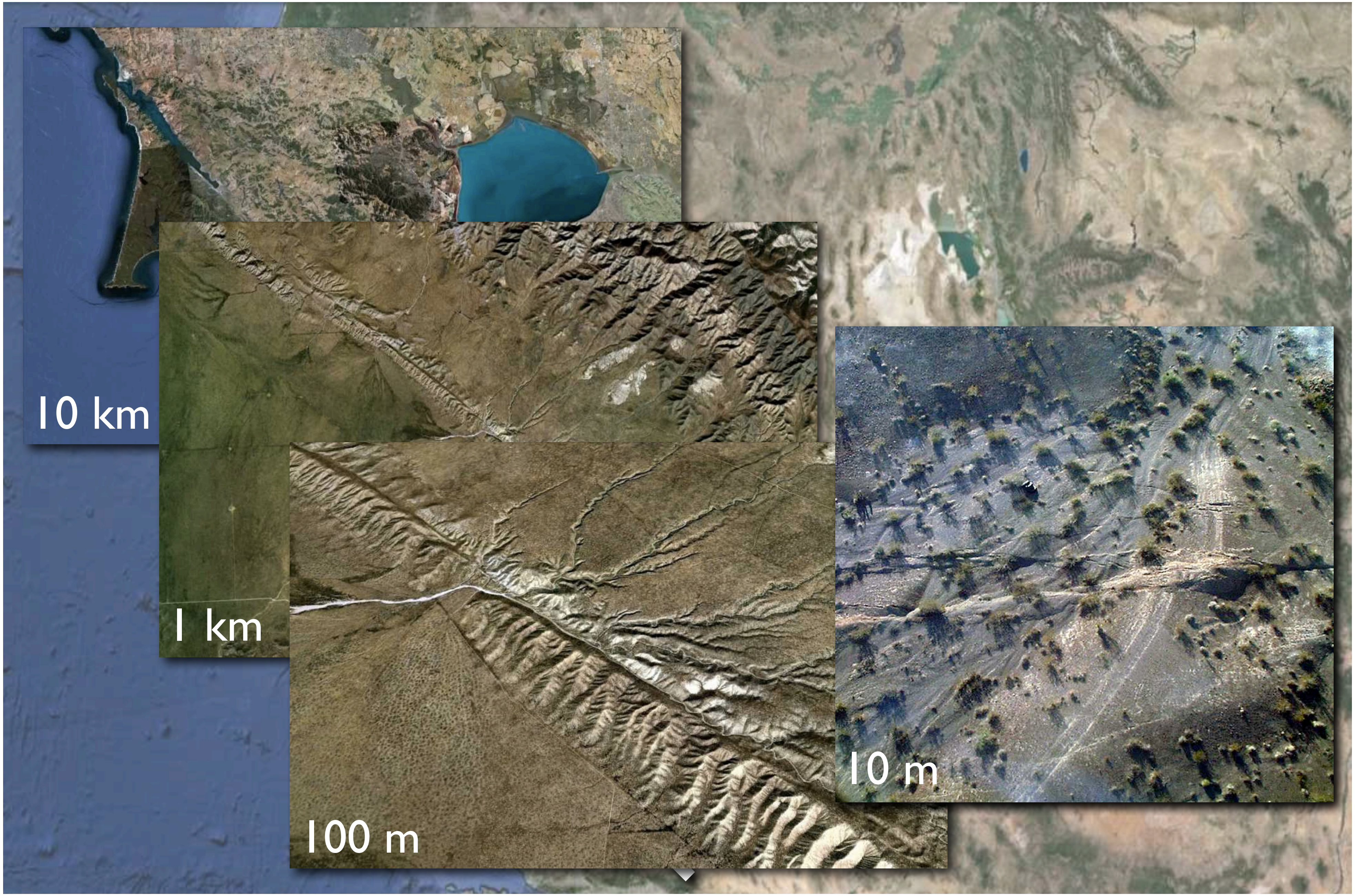
Bewegung an Plattengrenzen



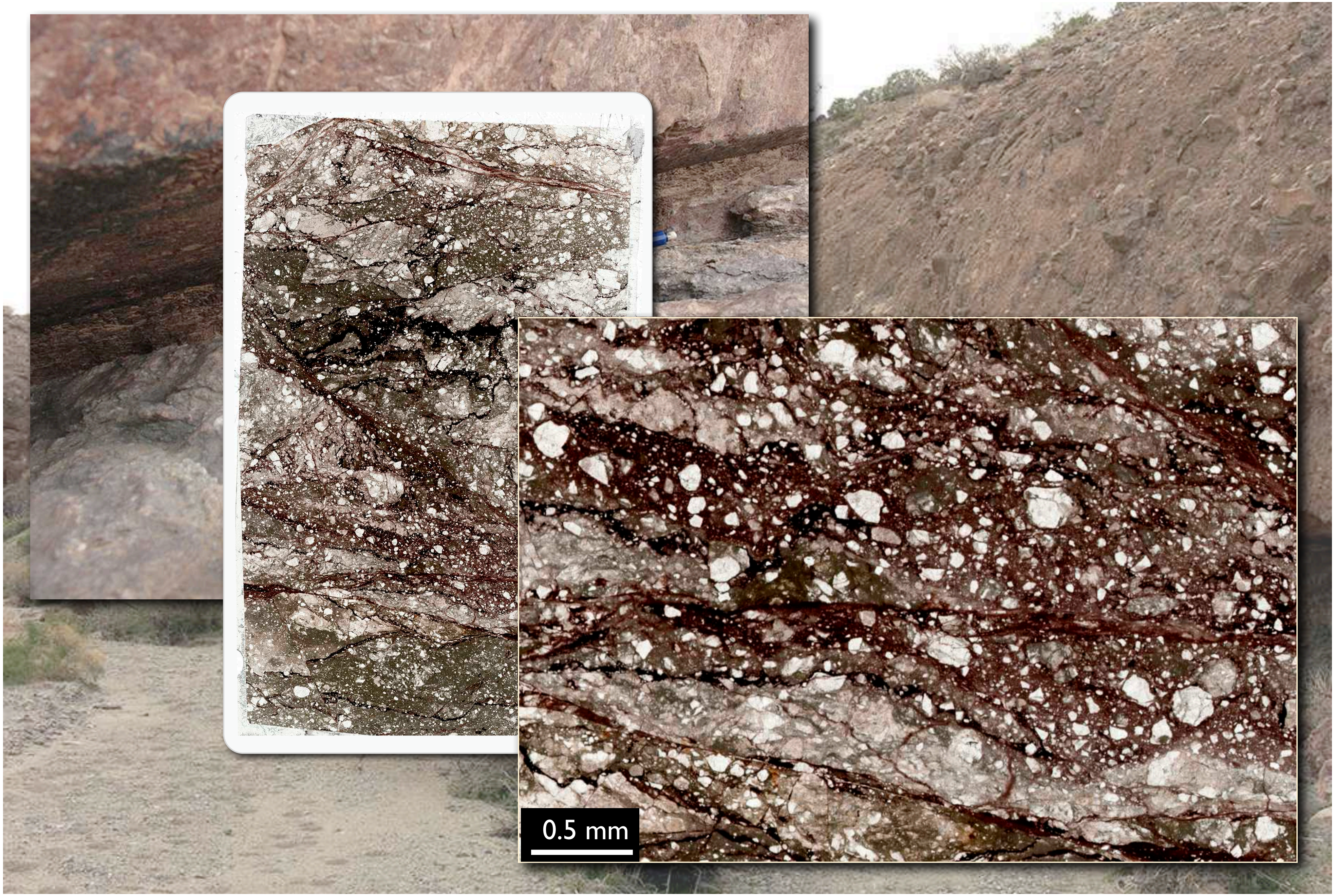
~5 cm / Jahr
kontinuierlich...

... gemittelt über
Hunderte km
Millionen Jahre

im Detail ...



... wird es diskontinuierlich



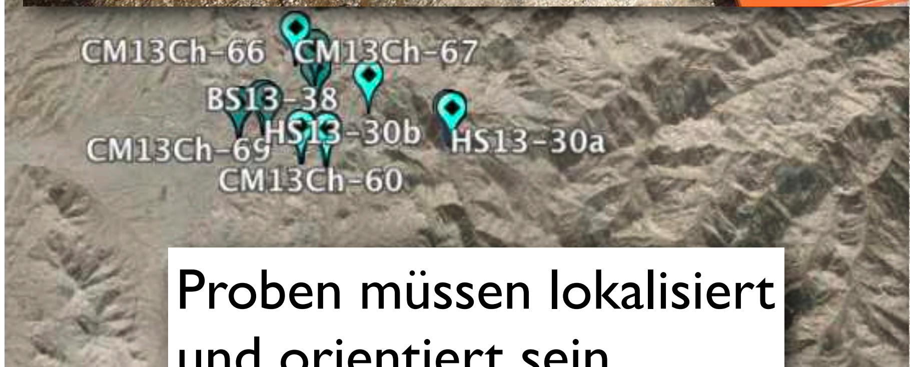
Feldarbeit

wie funktioniert eine Verwerfung ?

'low angle normal faults'
(= basal detachment)

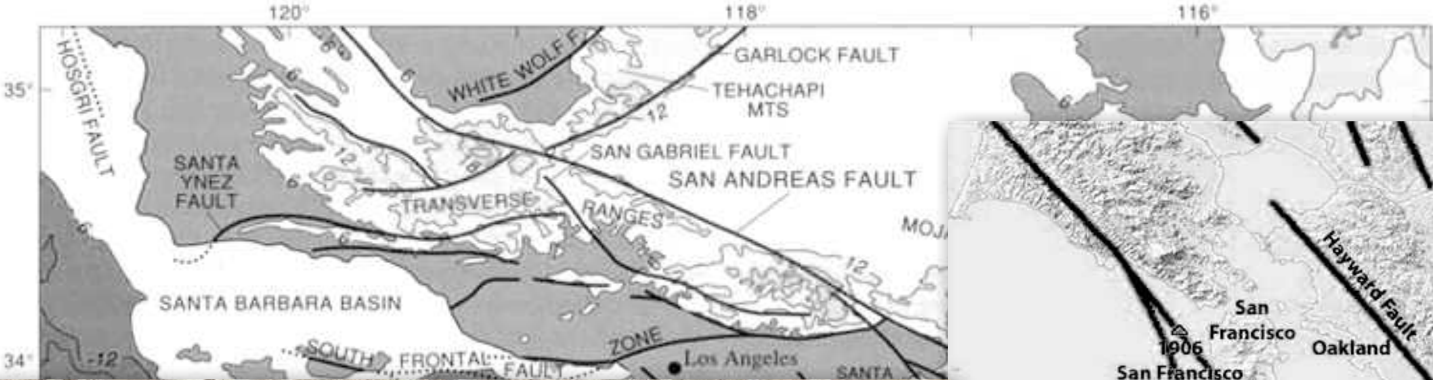
m - grosser Versatz findet an mm - dünnen Zonen statt

Probennahme



Proben müssen lokalisiert und orientiert sein

fault splays

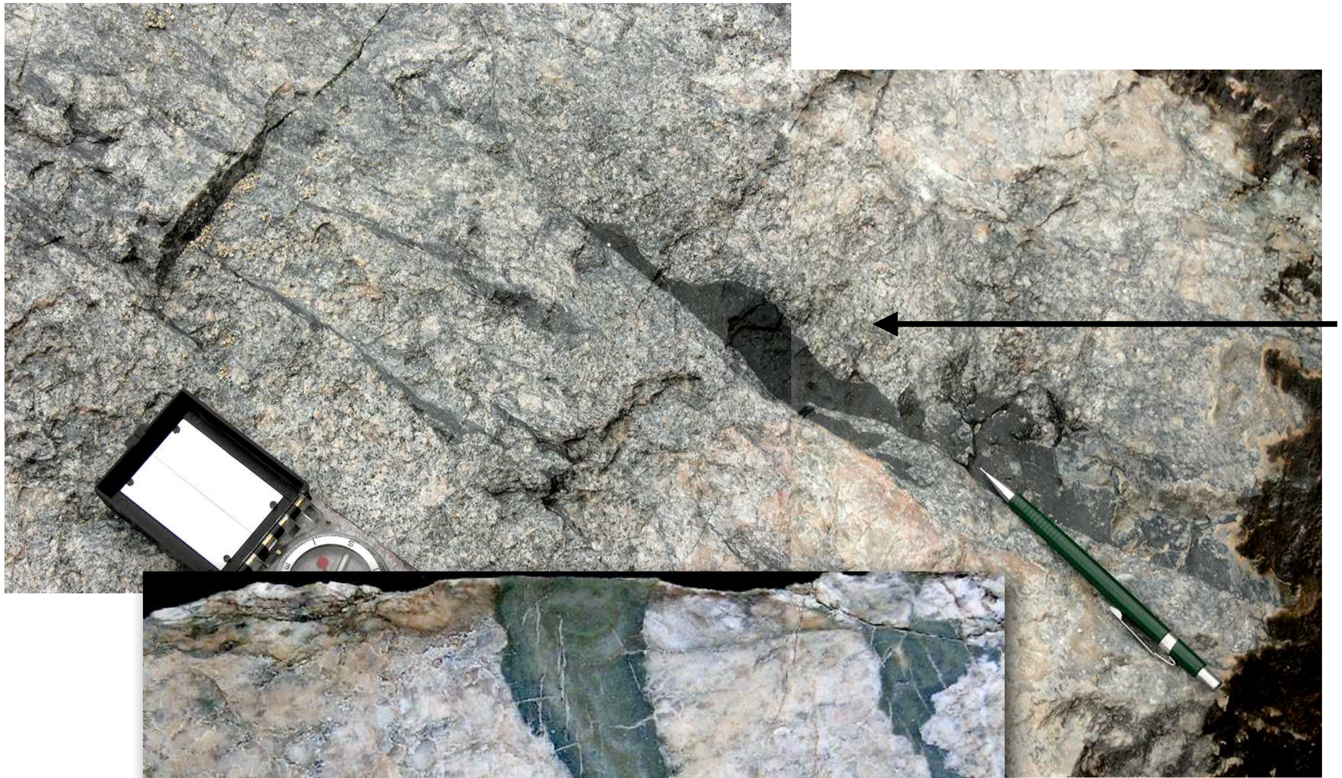


Versatz entlang zahlreicher
Verwerfungen ergibt riesige
Gesamt-Scherbeträge

Kornverkleinerung - comminution

zwischen den aneinander vorbeigleitenden Gesteinblöcken werden die Mineralkörner zunehmend verkleinert

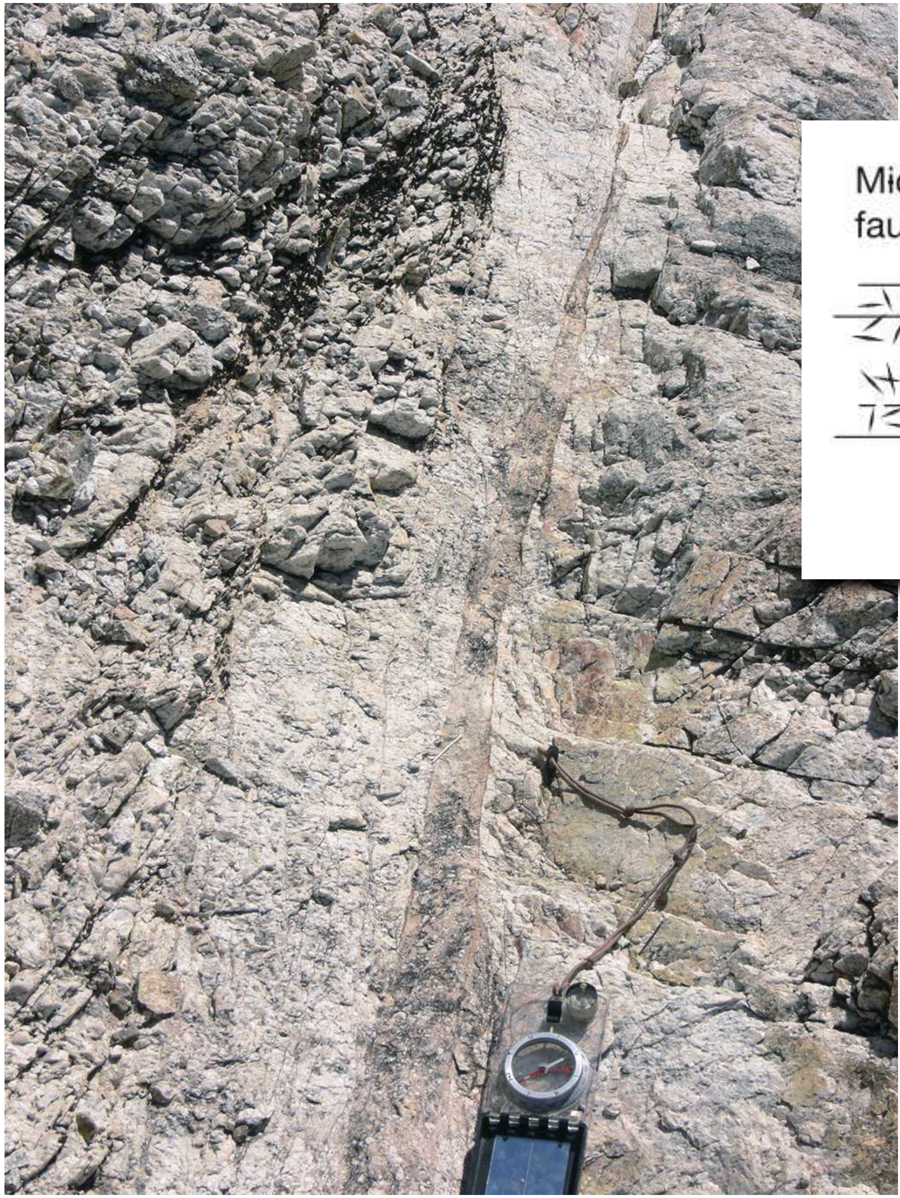
Ultrakataklasit

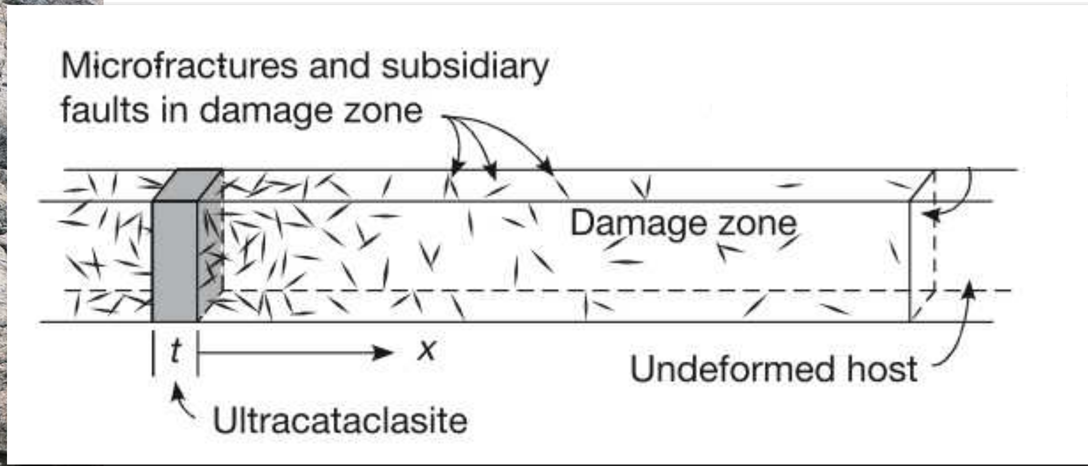


partiell amorph bis
vollständig amorph

... ≠ Pseudotachylite
(= Schmelze, mit Erdbeben assoziert)

von der 'damage zone' ...





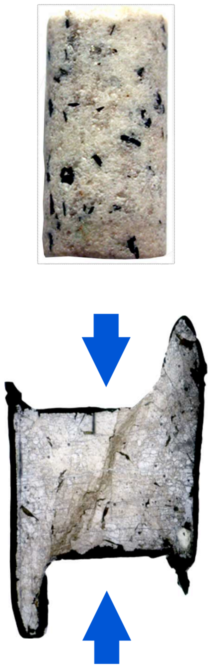
damage zone (m):
fragmentiertes Material

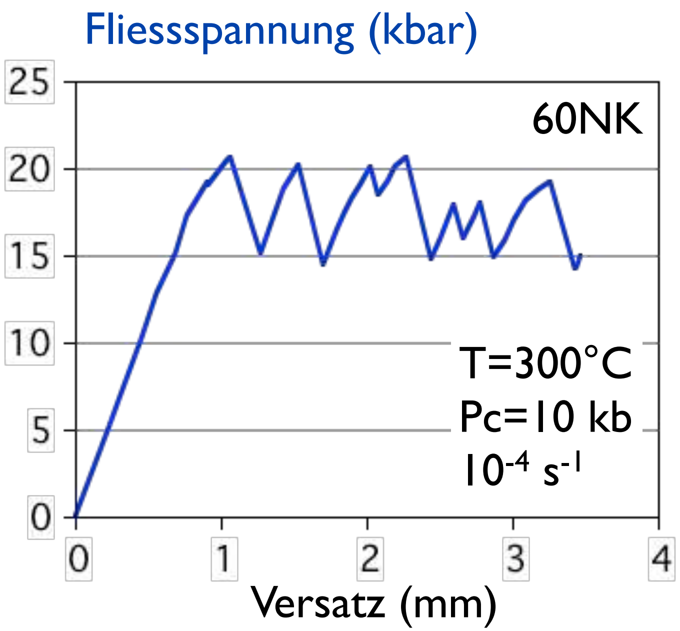
→ kaum Versatz

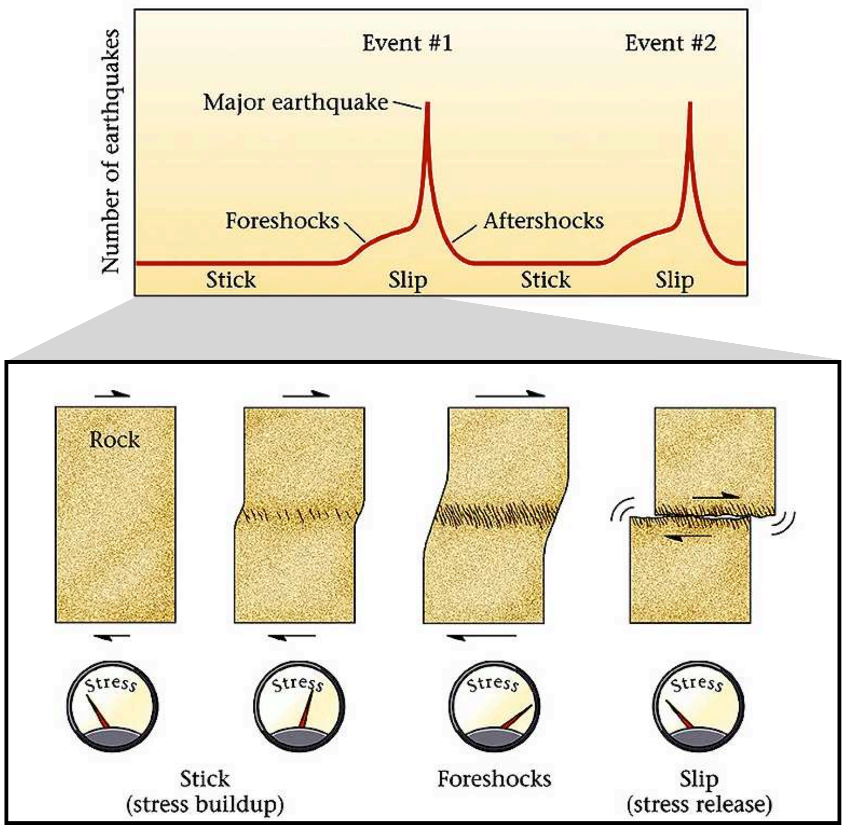
... zum 'fault core'

Deformationsexperimente: stick slip

Modell für Erdbeben





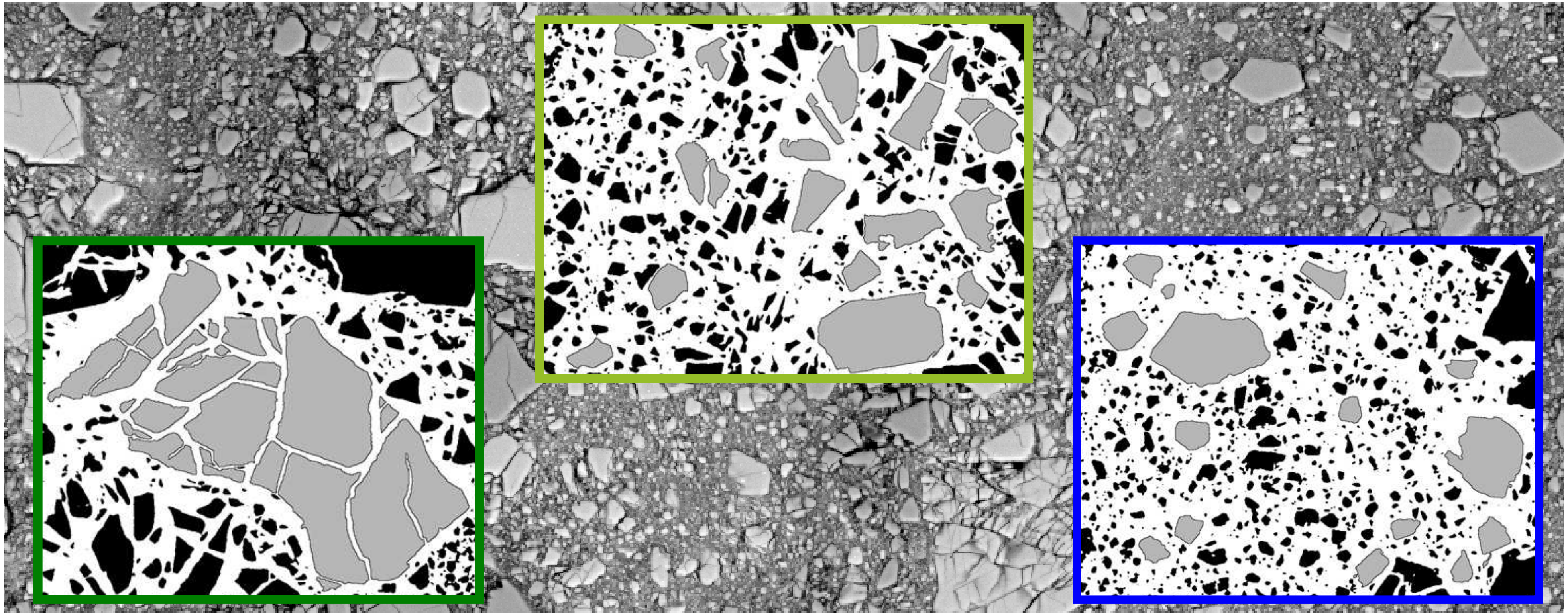


Experiment

Natur

Modellvorstellung

Entwicklung einer Verwerfung



intaktes Gestein - Bruchbildung / Verwerfung - intaktes Gestein

cracked in situ → cracked moved →→ gouge

Korngrössen - das Mass aller Dinge

(Protokataklasit) Ausgangsgestein

Kataklasit

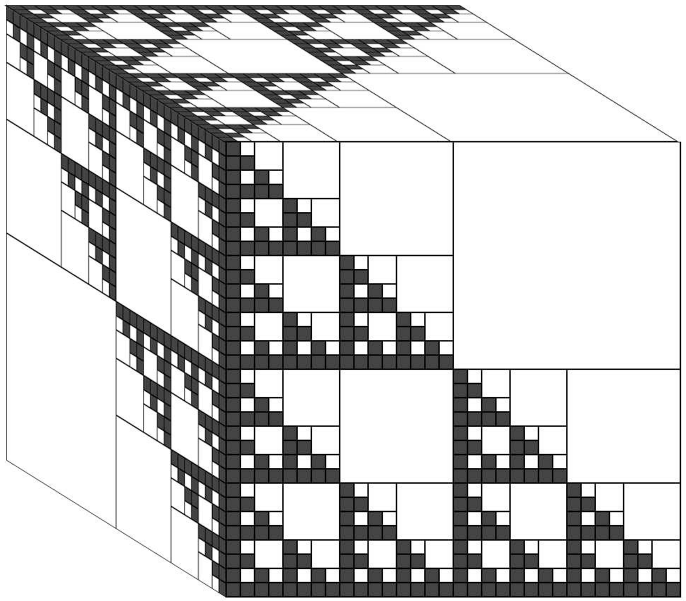
Ultrakataklasit

Partiell amoprh / amorph

Pseudotachylit

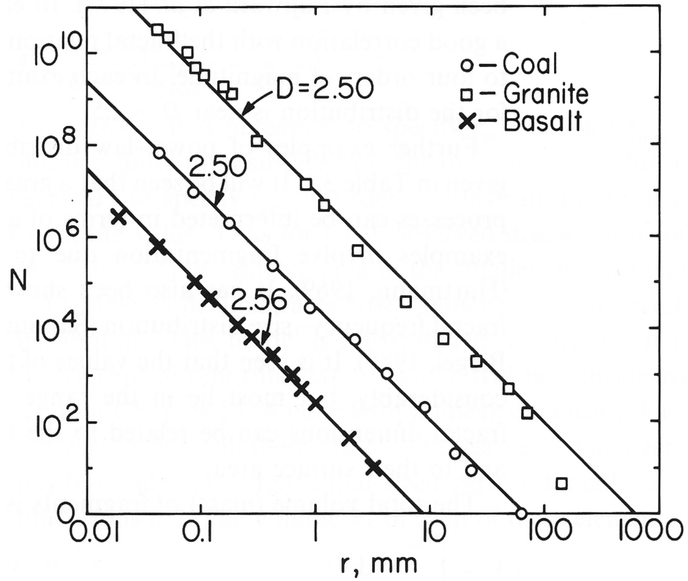
fraktale Aspekte

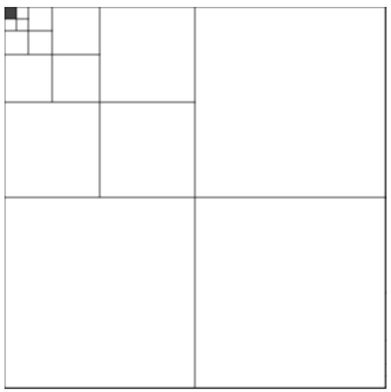
Fragmentierung



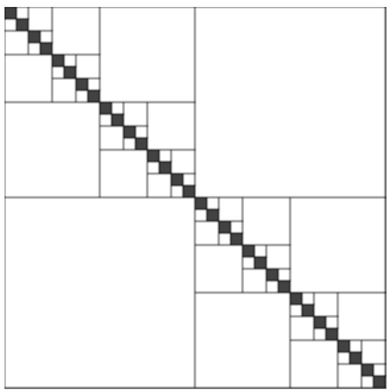
fraktale Dimension D

log - log plot

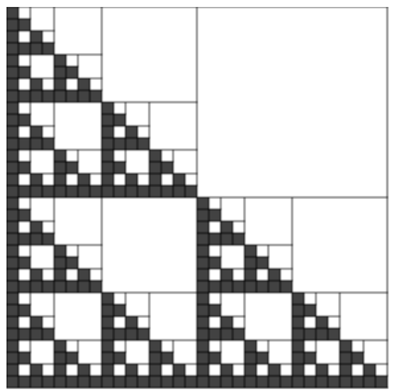




1/8 fragmented

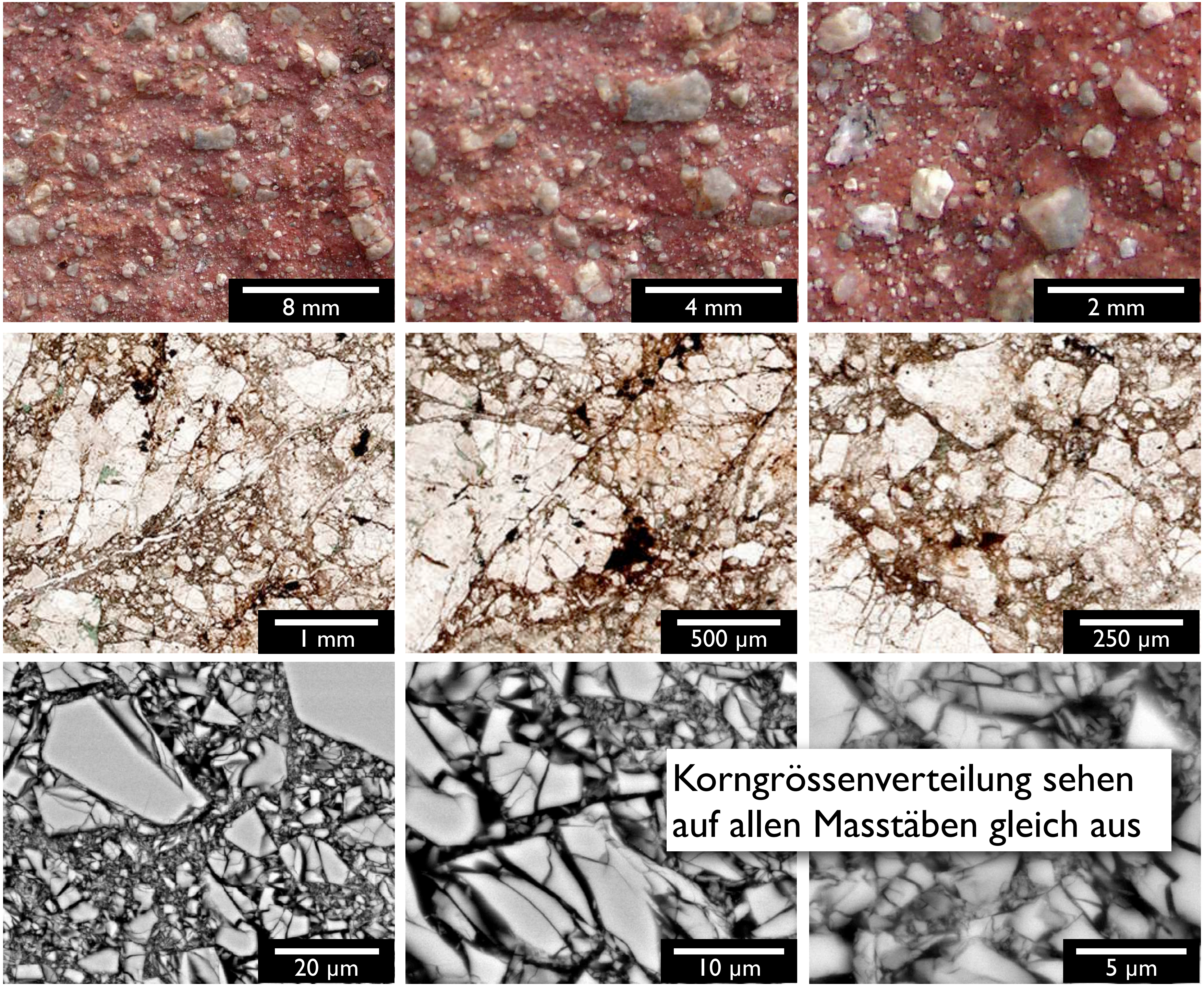


4/8 fragmented

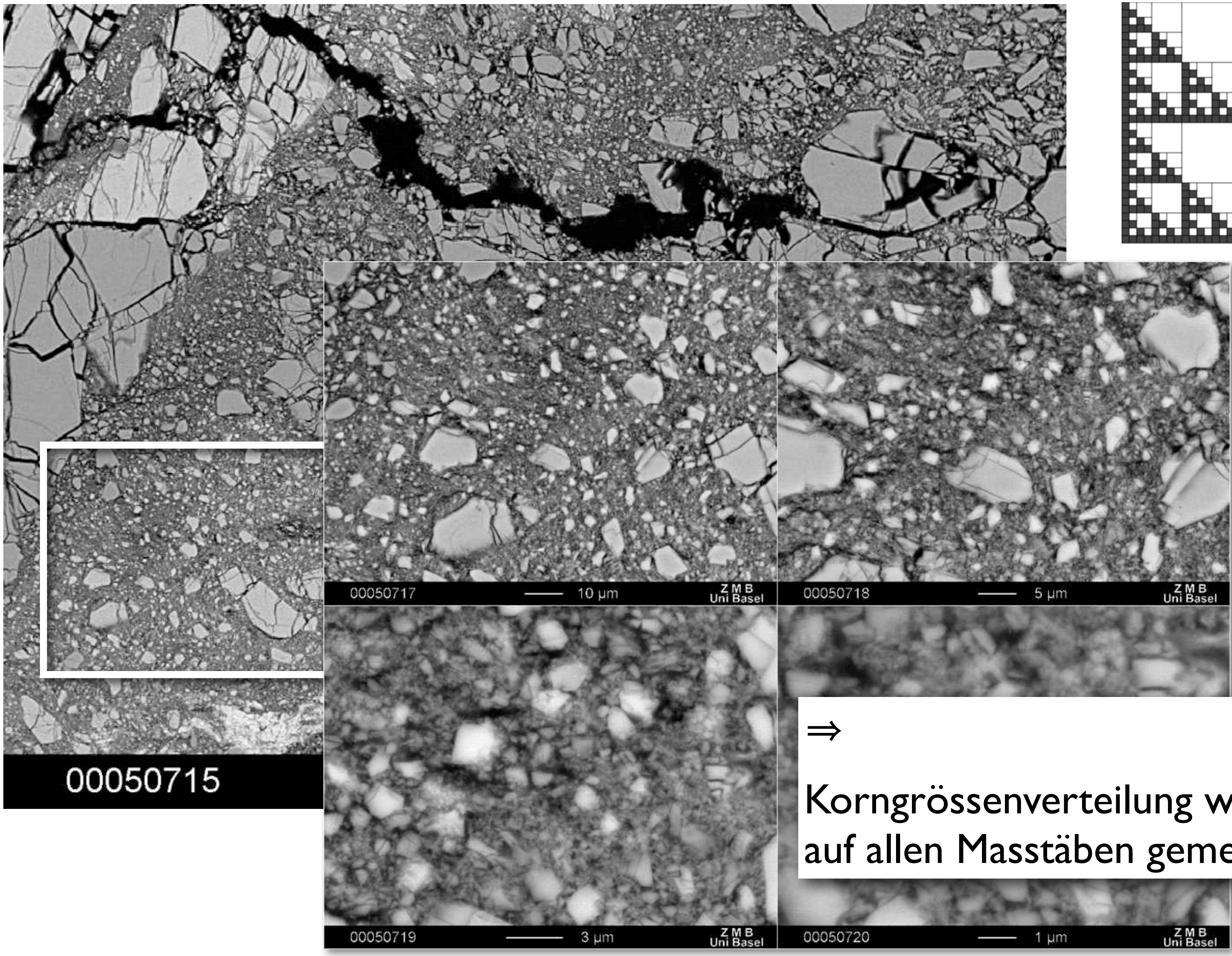


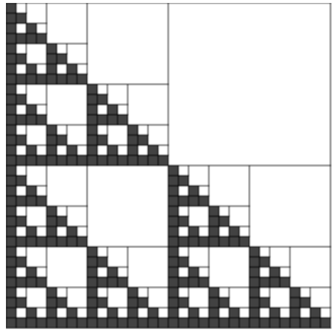
6/8 fragmented

je stärker fragmentiert desto höher D


8 mm
4 mm
2 mm
1 mm
500 µm
250 µm
20 µm
10 µm
5 µm
Korngrössenverteilung sehen auf allen Masstäben gleich aus

Kaskaden - Grössenordnungen



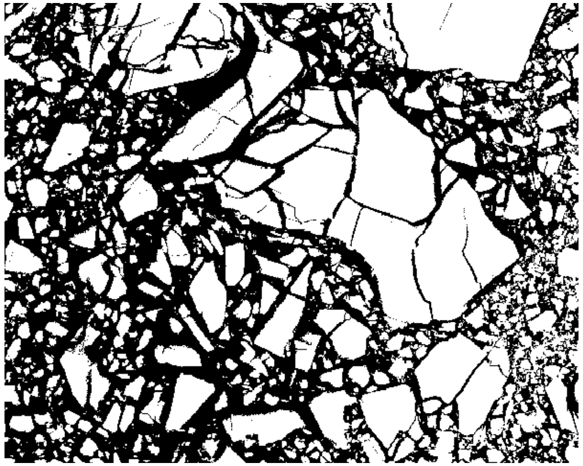


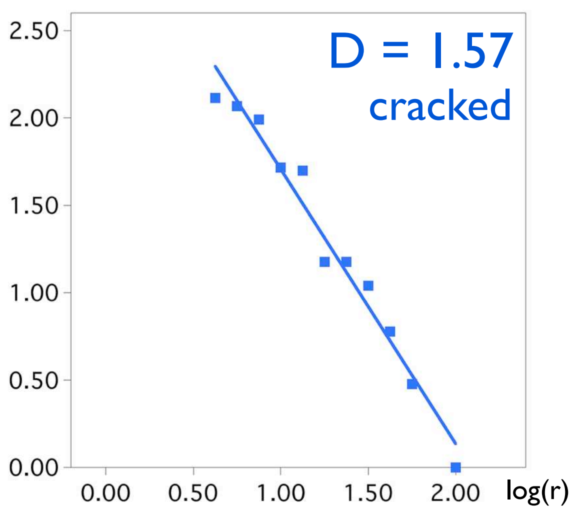
⇒

Korngrössenverteilung werden auf allen Masstäben gemessen

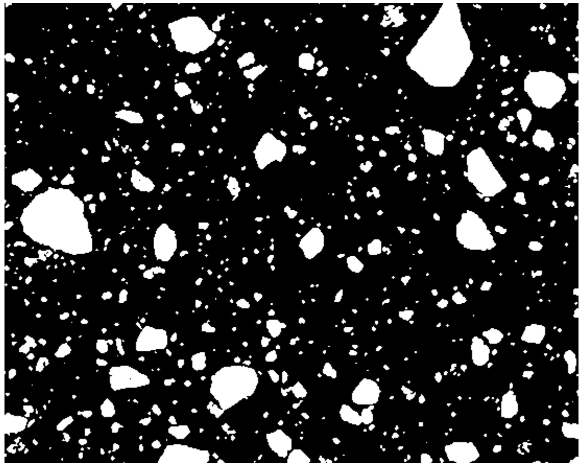
fraktale Korngrössenverteilung

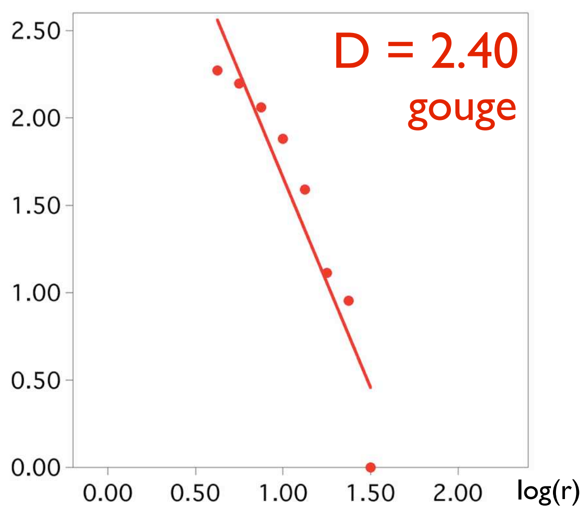
cracked
nur fragmentiert





gouge
fragmentiert und transportiert





cracked

fragmentiertes Material:

$D \approx 1.6$

gouge

feines Gesteinsmehl:

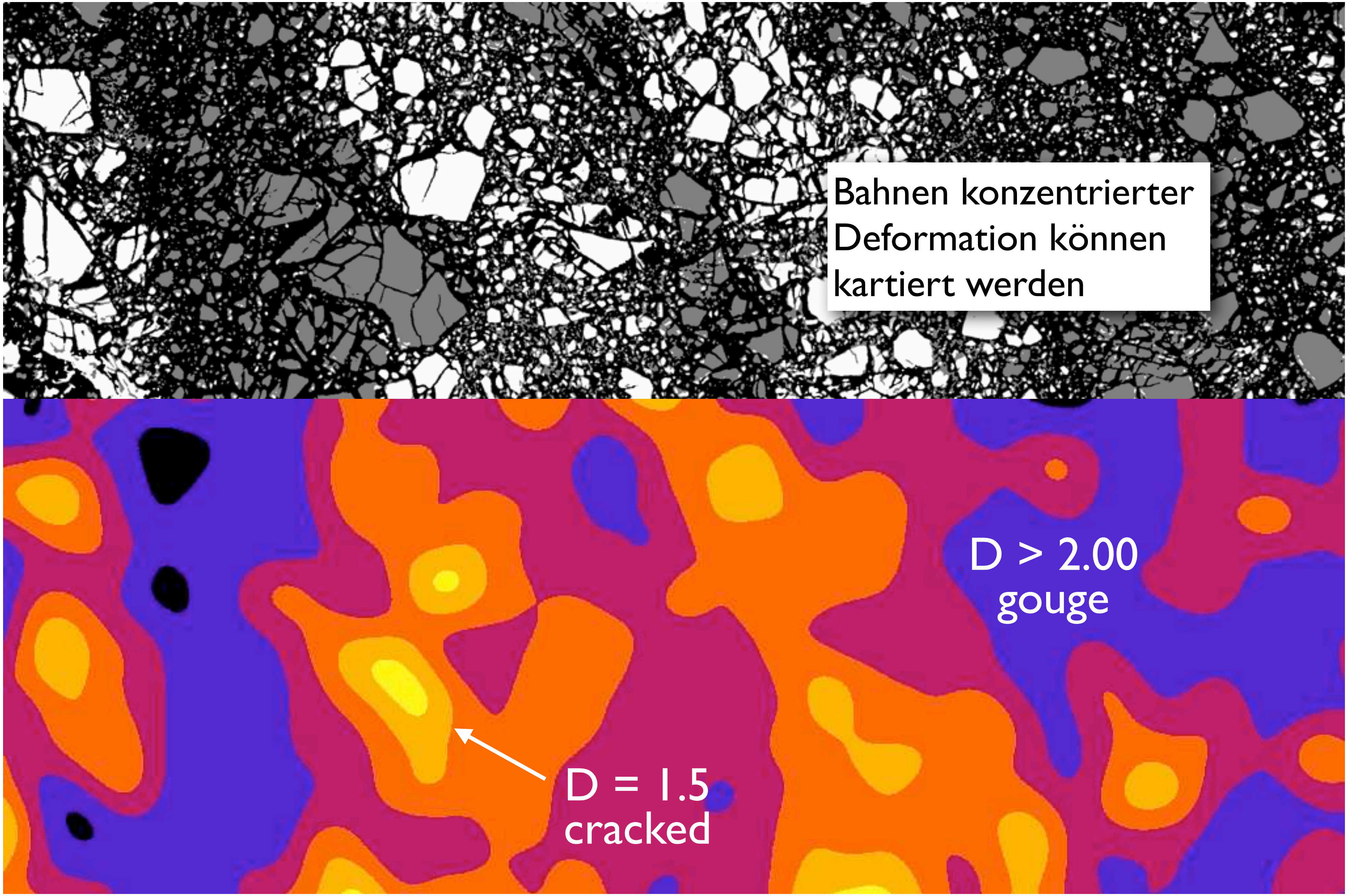
$D > 2.00$

$\Rightarrow$

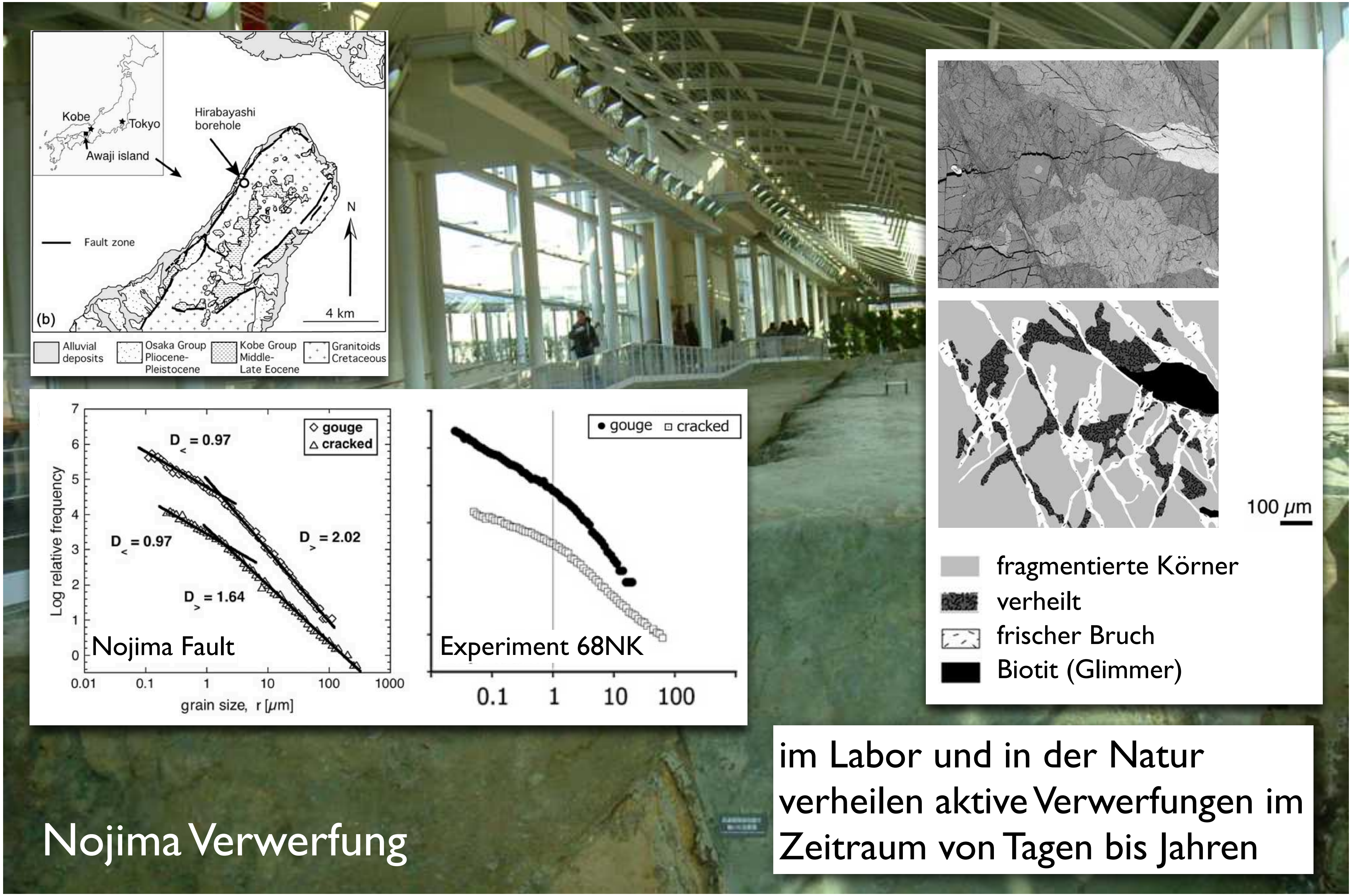
Zusammenhang

D - Versatz ??

D-maps

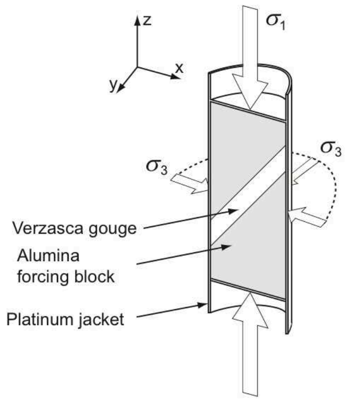

Bahnen konzentrierter Deformation können kartiert werden
D > 2.00
gouge
D = 1.5
cracked

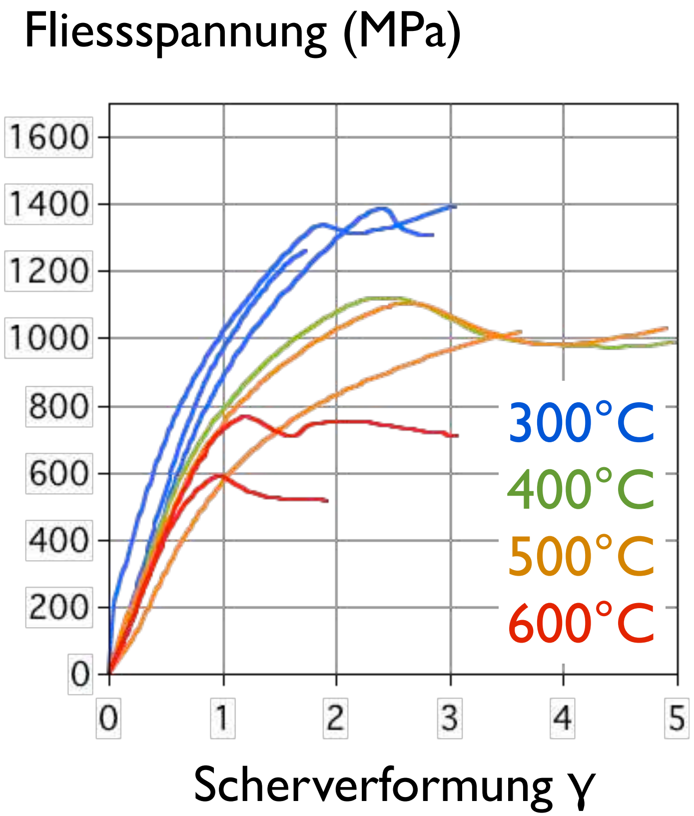
fault healing

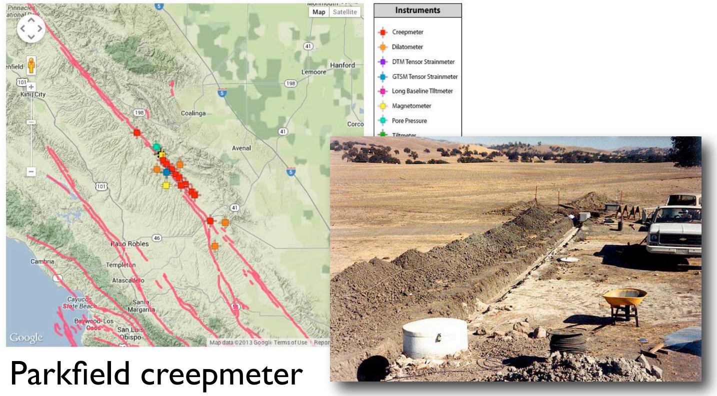


im Labor und in der Natur verheilen aktive Verwerfungen im Zeitraum von Tagen bis Jahren

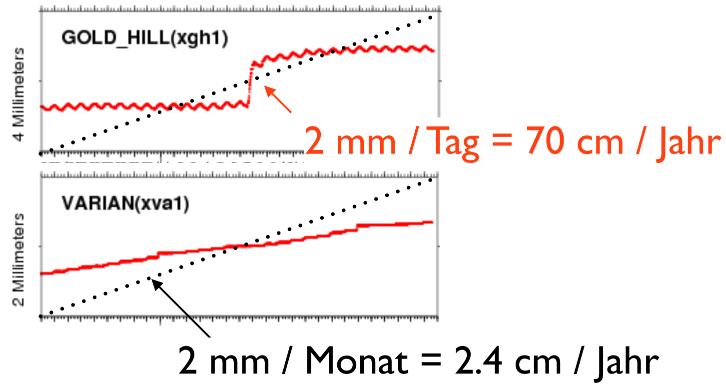
Deformationsexperimente: creep







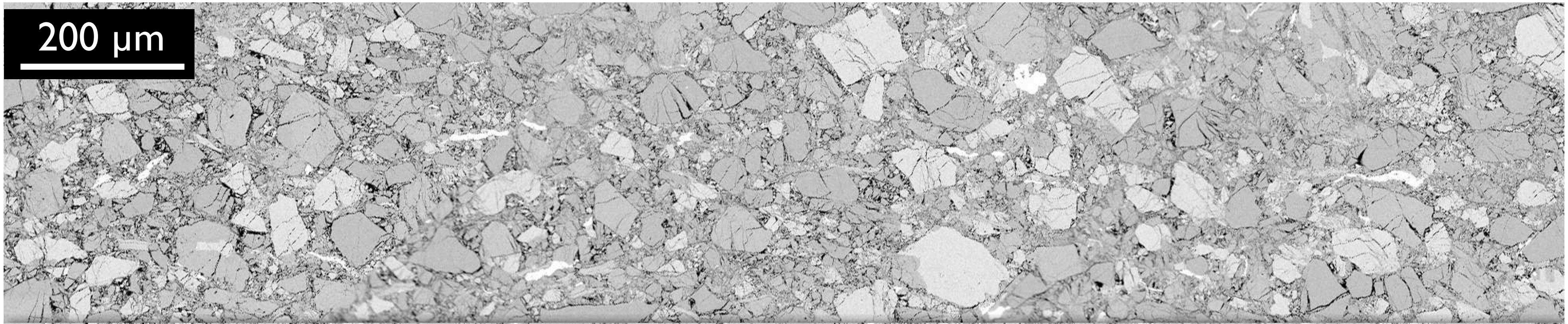
Parkfield creepmeter

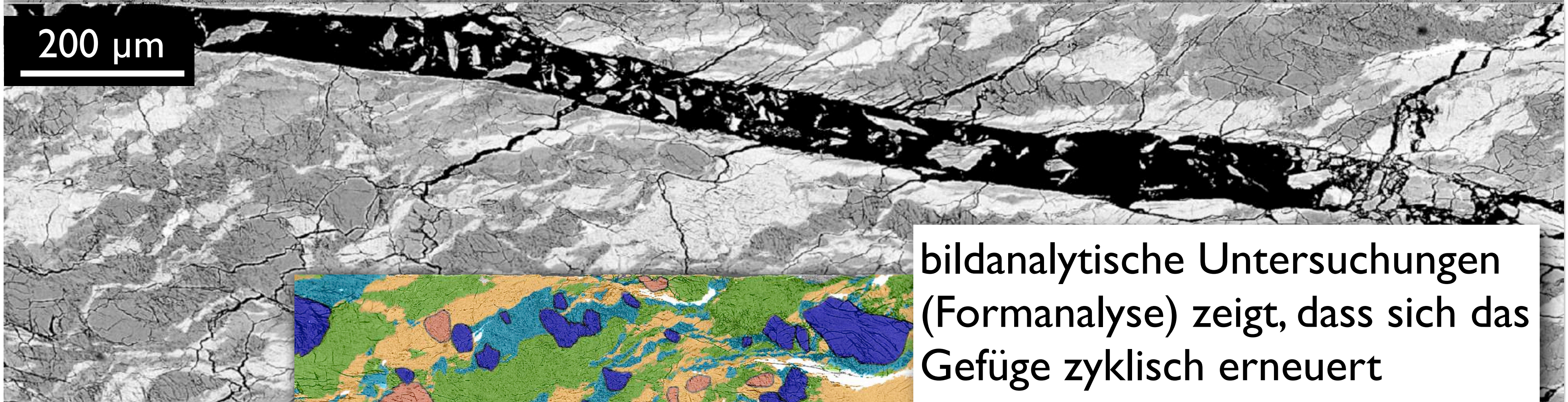


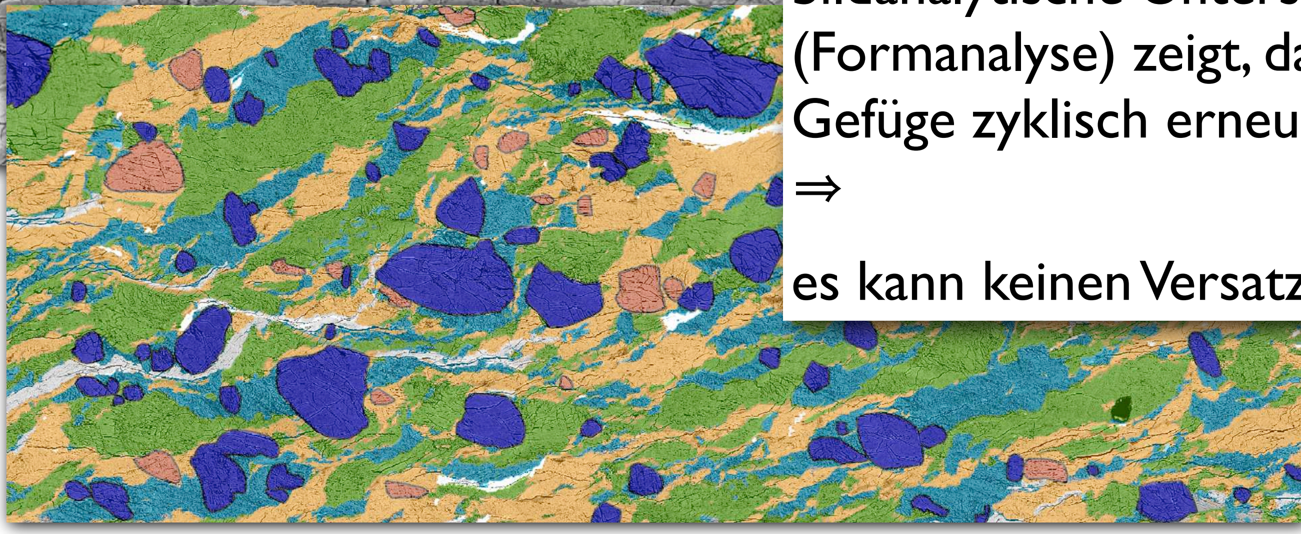
= 'live' Experimente

Experiment		Natur
Umschliessungsdruck = 500 MPa Verschiebungsrate = 10^{-8} ms^{-1}	=	15-20 km Tiefe 30 cm / Jahr

lokalisiert - stationär





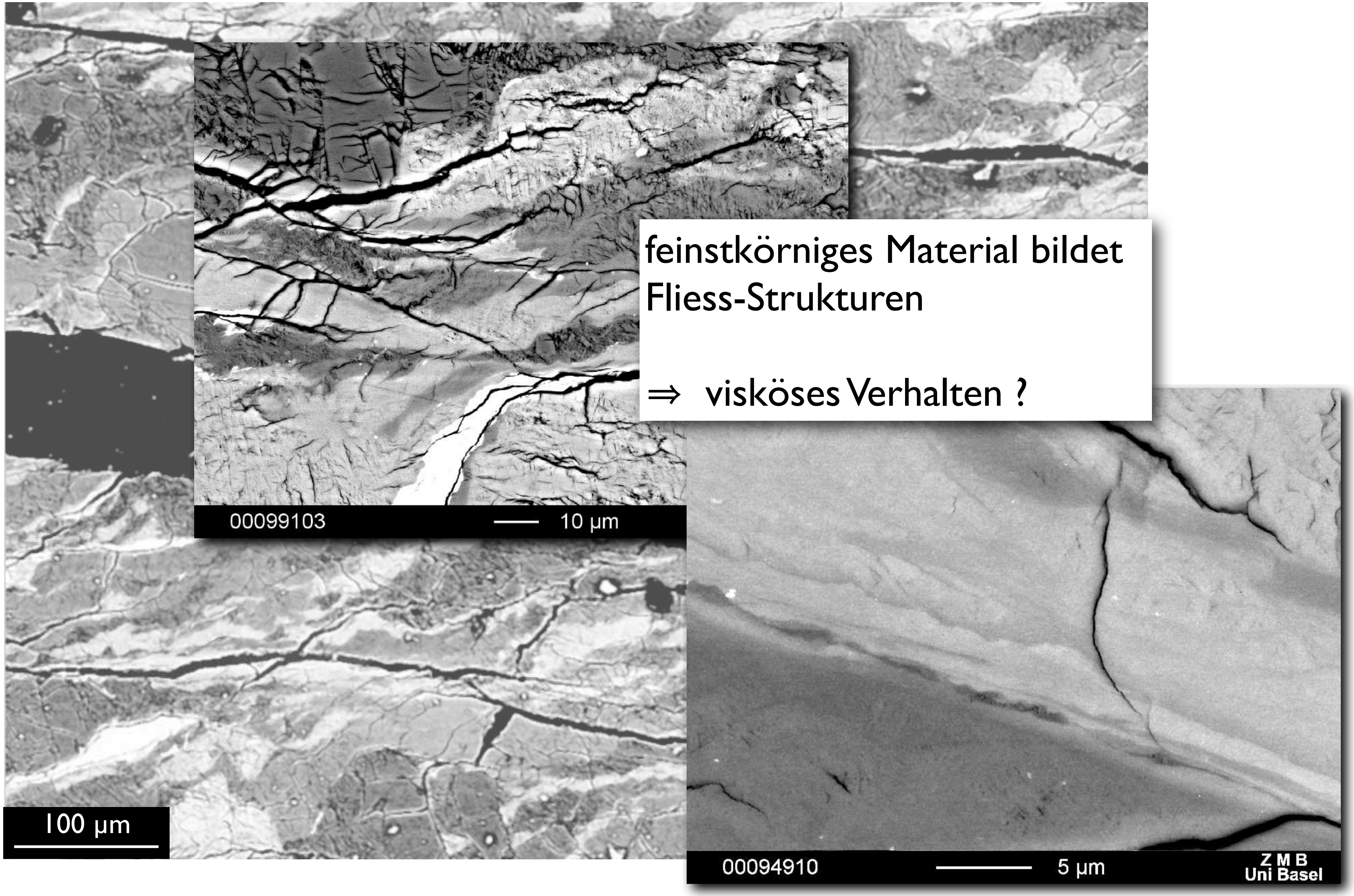


bildanalytische Untersuchungen (Formanalyse) zeigt, dass sich das Gefüge zyklisch erneuert

⇒

es kann keinen Versatz anzeigen

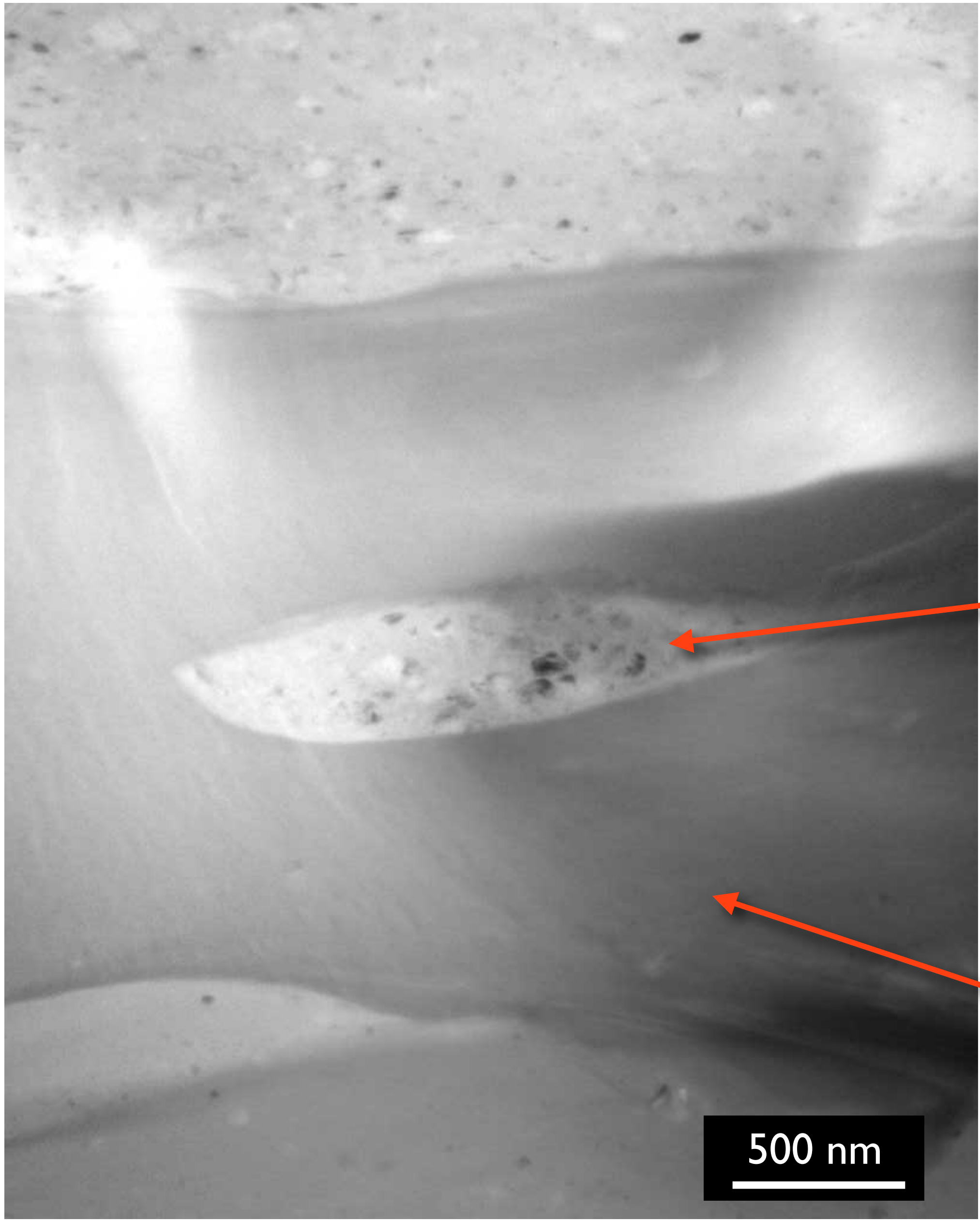
lokalisierte Verformung



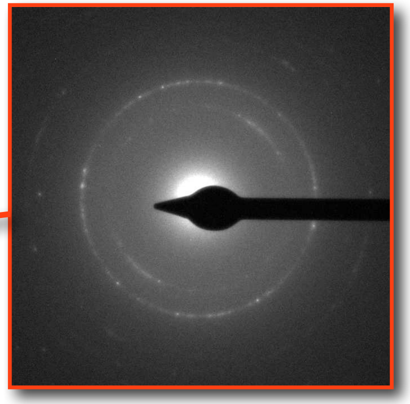
feinstkörniges Material bildet Fliess-Strukturen

⇒ visköses Verhalten ?

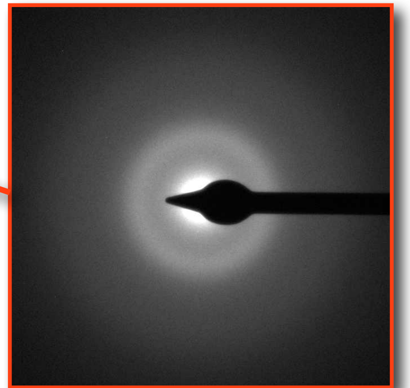
Amorphisierung



auf kleinstem Raum wird die Spannung so hoch, dass sich amorphes Material bilden kann - ohne dass die Schmelztemperatur erreicht wird

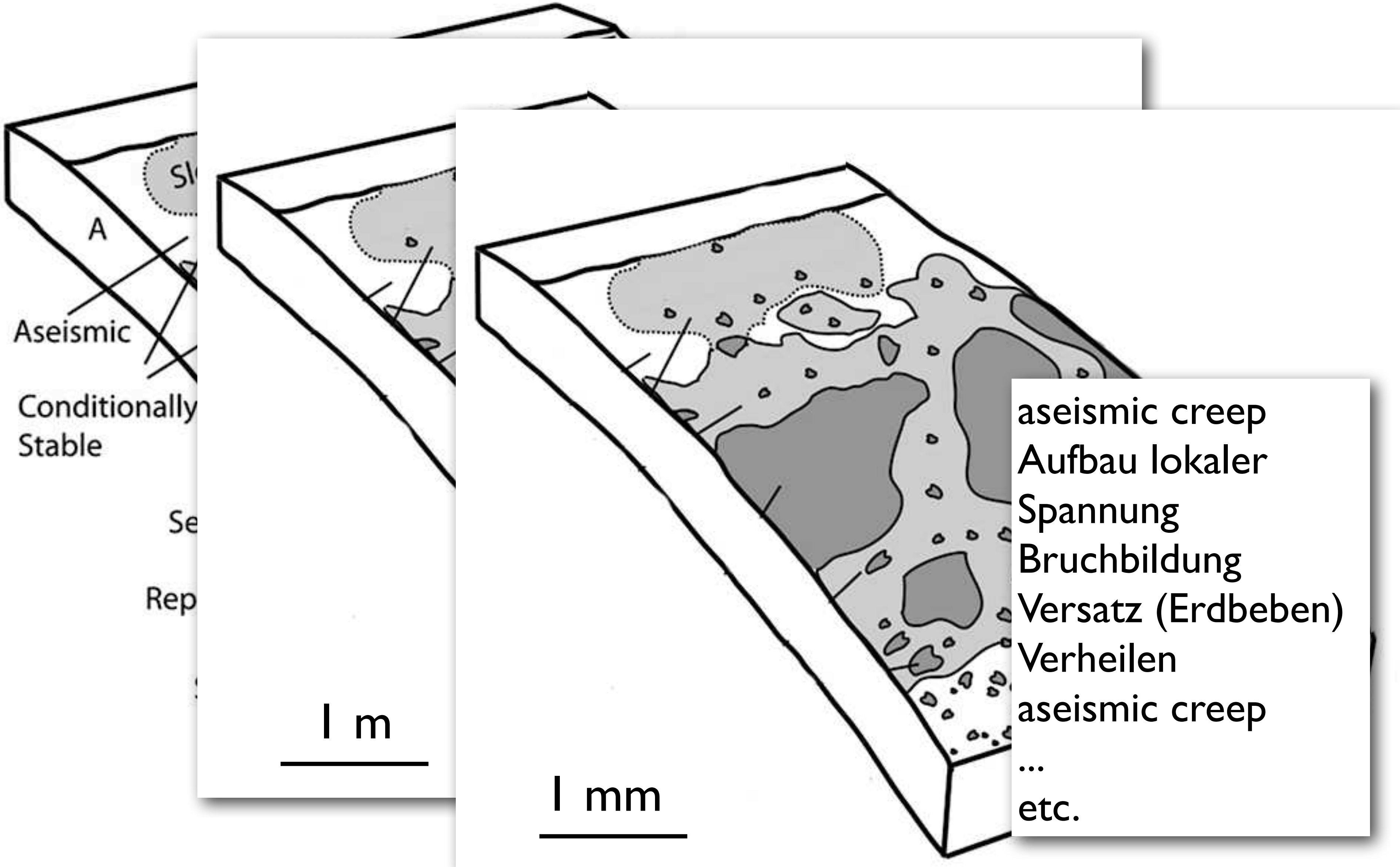


nano-
kristallin



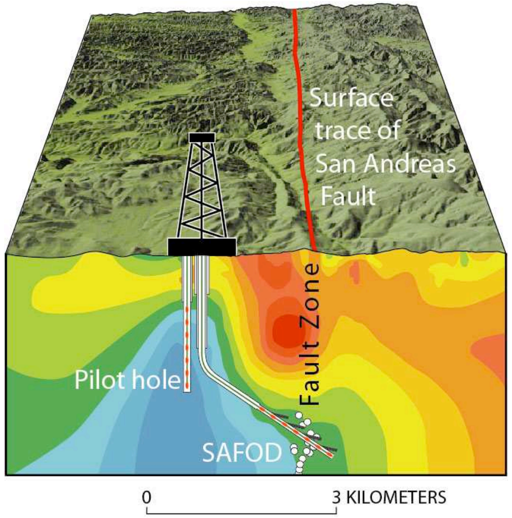
amorph

wie es funtionieren könnte



aseismic creep
Aufbau lokaler
Spannung
Bruchbildung
Versatz (Erdbeben)
Verheilen
aseismic creep
...
etc.

'seismic slip' in der Natur



aktiv

SAFOD
San Andreas Fault Observatory at Depth

lokale Bruchbildung
lokaler Versatz

fossil

Grøtfjord, Nordnorwegen

Fragen, die uns weiter beschäftigen

sind Verwerfungen stark oder schwach ?
ist die Reibung an der Verwerfung hoch oder tief ?
warum hält eine Verwerfung manchmal und manchmal nicht ?
unter welchen Bedingungen bricht sie (versagt sie) ?
welche Bedingung stabilisieren eine Verwerfung ?
kann eine Verwerfung verheilen ?
bis in welche Tiefe verhalten sich Verwerfungen bruchhaft ?
gehen alle Erdbeben von Verwerfungen aus ?
sind alle Erdbeben auf bruchhaftes Versagen zurückzuführen ?
....
kann man das Versagen (und damit Erdbeben) vorhersagen ?
....
kann man ein Versagen (und damit Erdbeben) verhindern ?


the end

Links

SED Schweizerischer Erdbebendienst

- www.seismo.ethz.ch

USGS - United States Geological Survey - Earthquake Hazard Program

- earthquake.usgs.gov/earthquakes/map/

IRIS - Incorporated Research Institutions for Seismology - Teachable Moments

- www.iris.edu/hq/retm

European-Mediterranean Seismological Centre

- www.emsc-csem.org/

Tohoku Erdbeben

- de.wikipedia.org/wiki/Tohoku-Erdbeben_2011
- www.iris.edu/hq/retm/event/1328
- www.iris.edu/hq/files/programs/education_and_outreach/retm/tm_110311_japan/Subduction_ElasticRebound_Tsunami_480.mov

Tsunami wave animation

- en.wikipedia.org/wiki/File:20110311Houshu.ogg

Earthquake Facts & Earthquake Fantasy

- earthquake.usgs.gov/learn/topics/megaqk_facts_fantasy.php