The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
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International Atomic
Energy Agency

SMR/1882-9

Seismic Hazard in Asia

4 - 8 December 2006

Continental Deformation and Earthquake Hazard Models and Case Studies

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Continental Deformation and Earthquake Hazard:
Models and Case Studies

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ICTP Workshop 2006: Seismic Hazard in Asia

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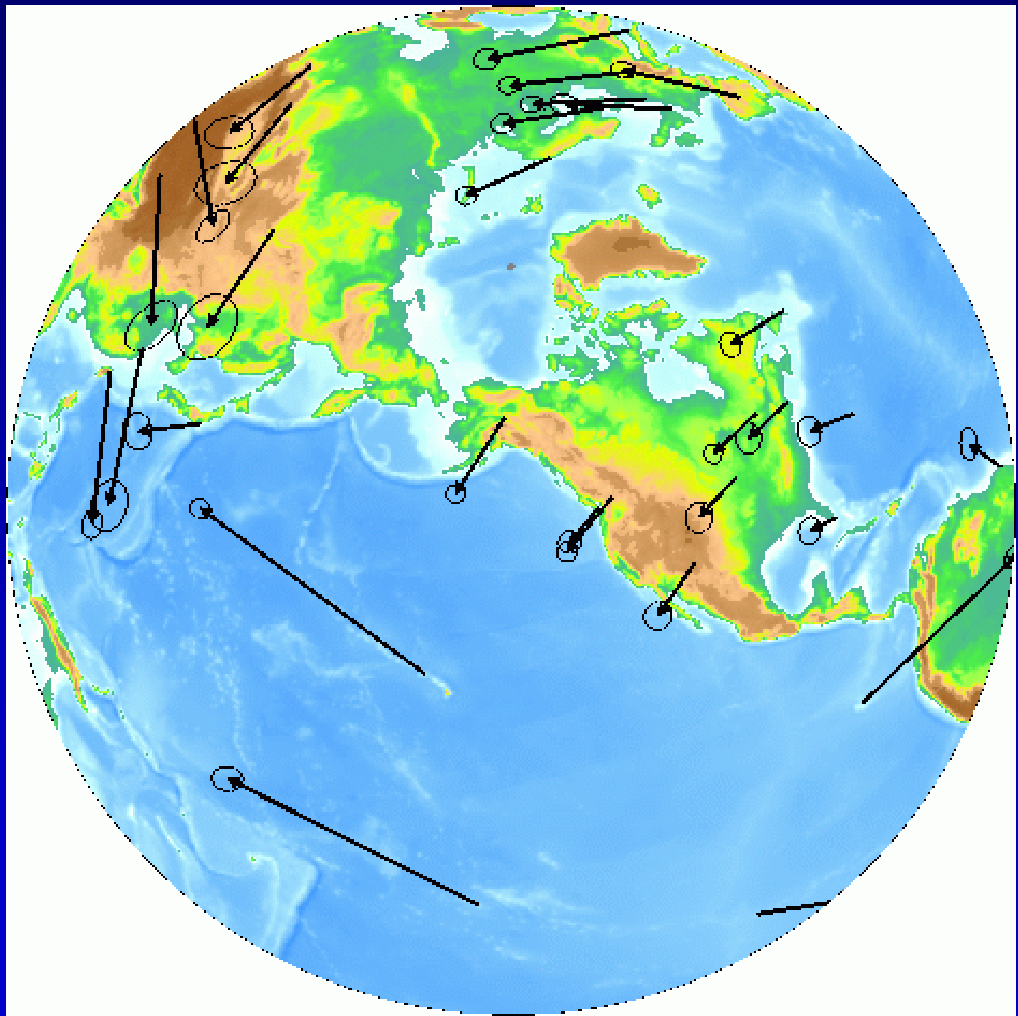
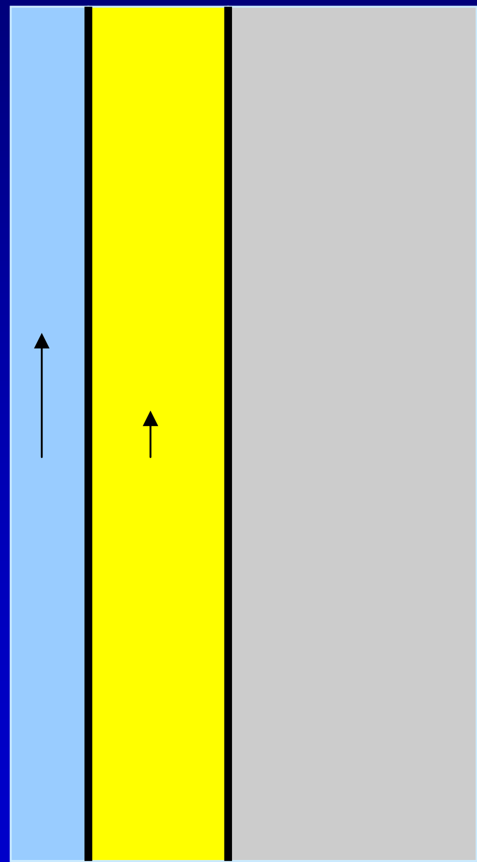
Block-like Motion





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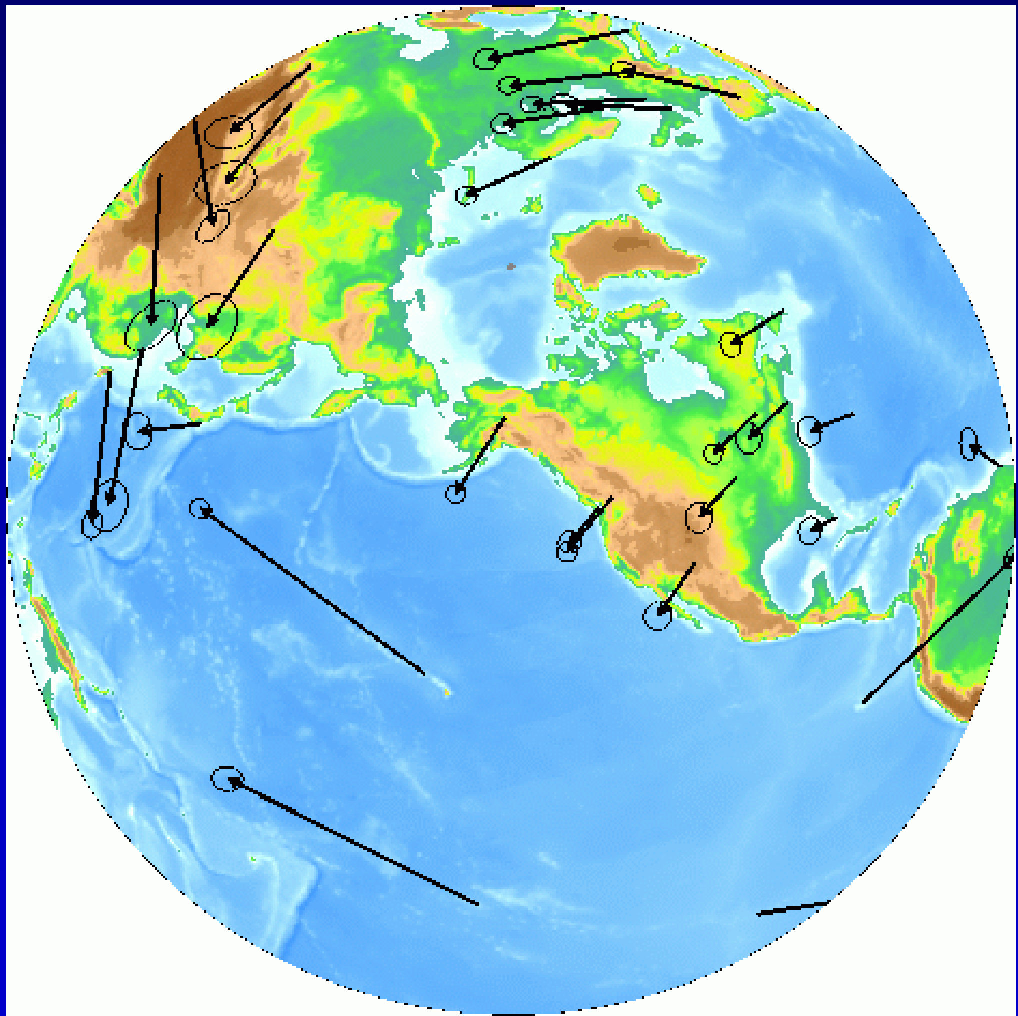
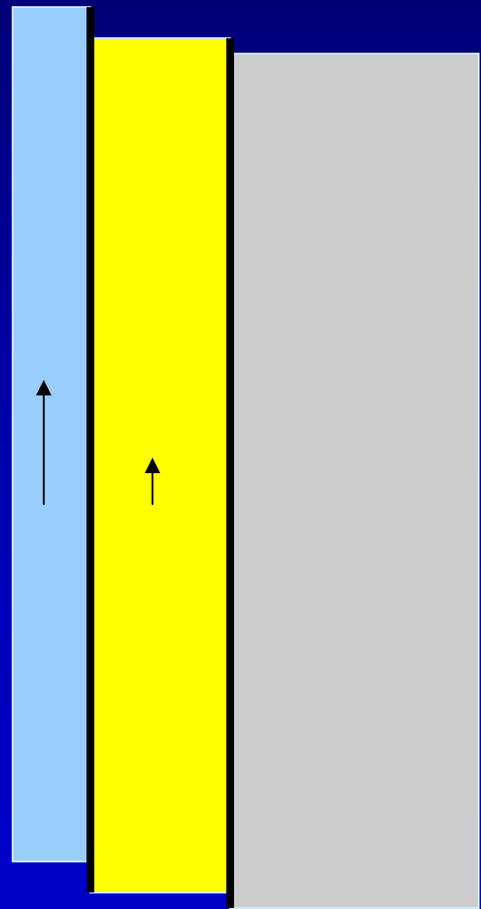
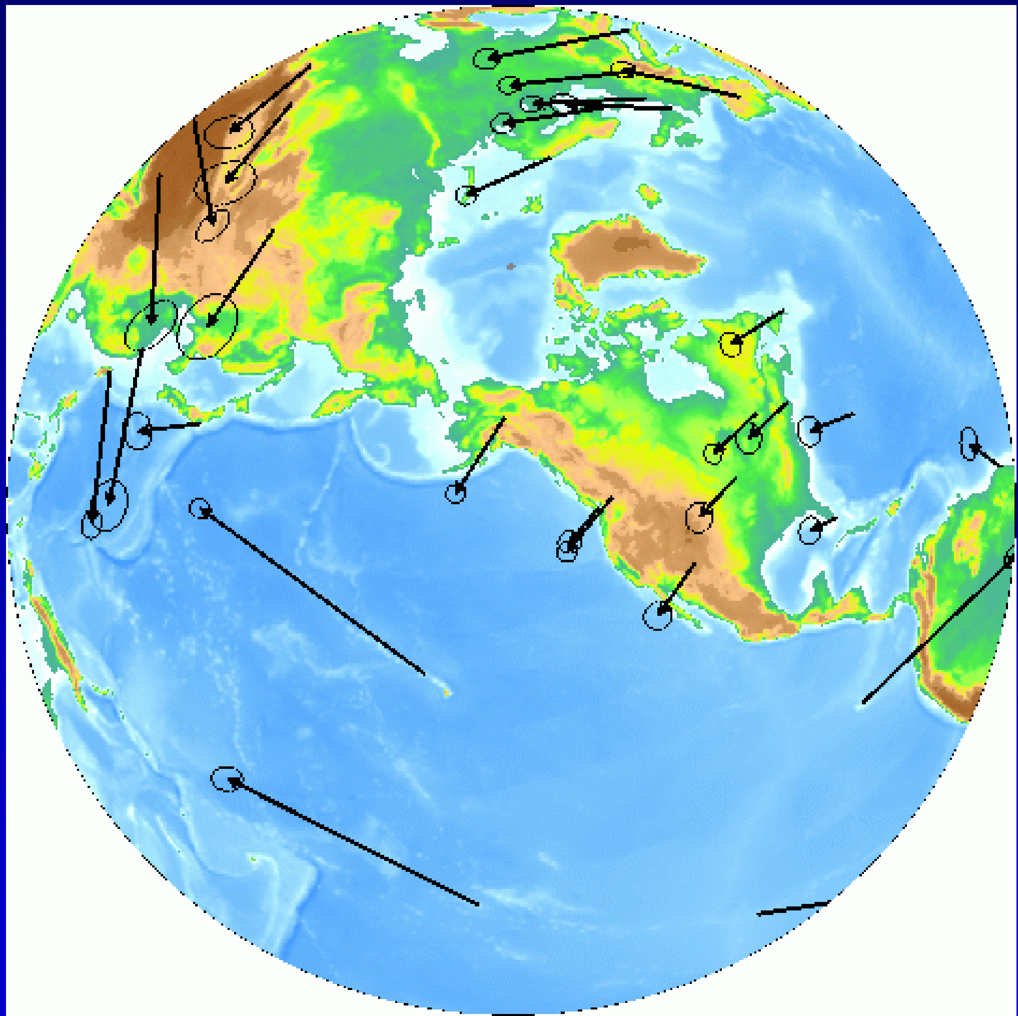
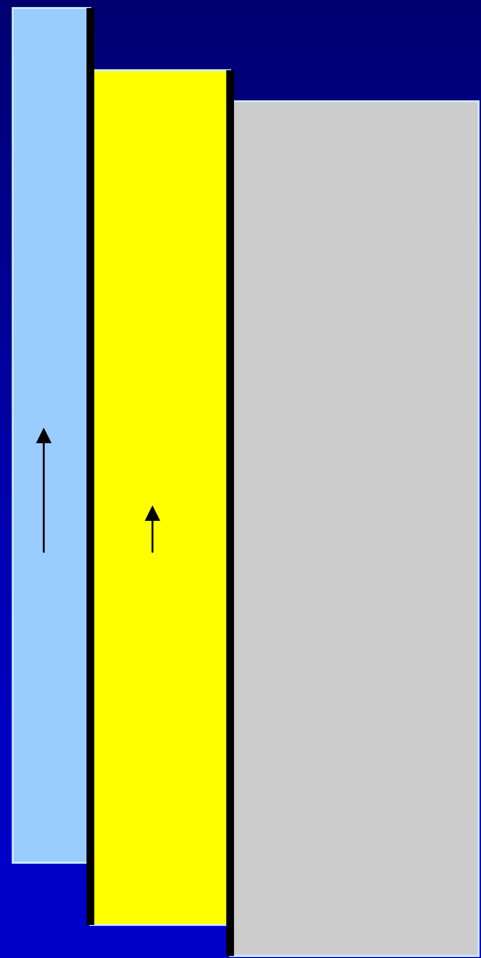




Block-like Motion





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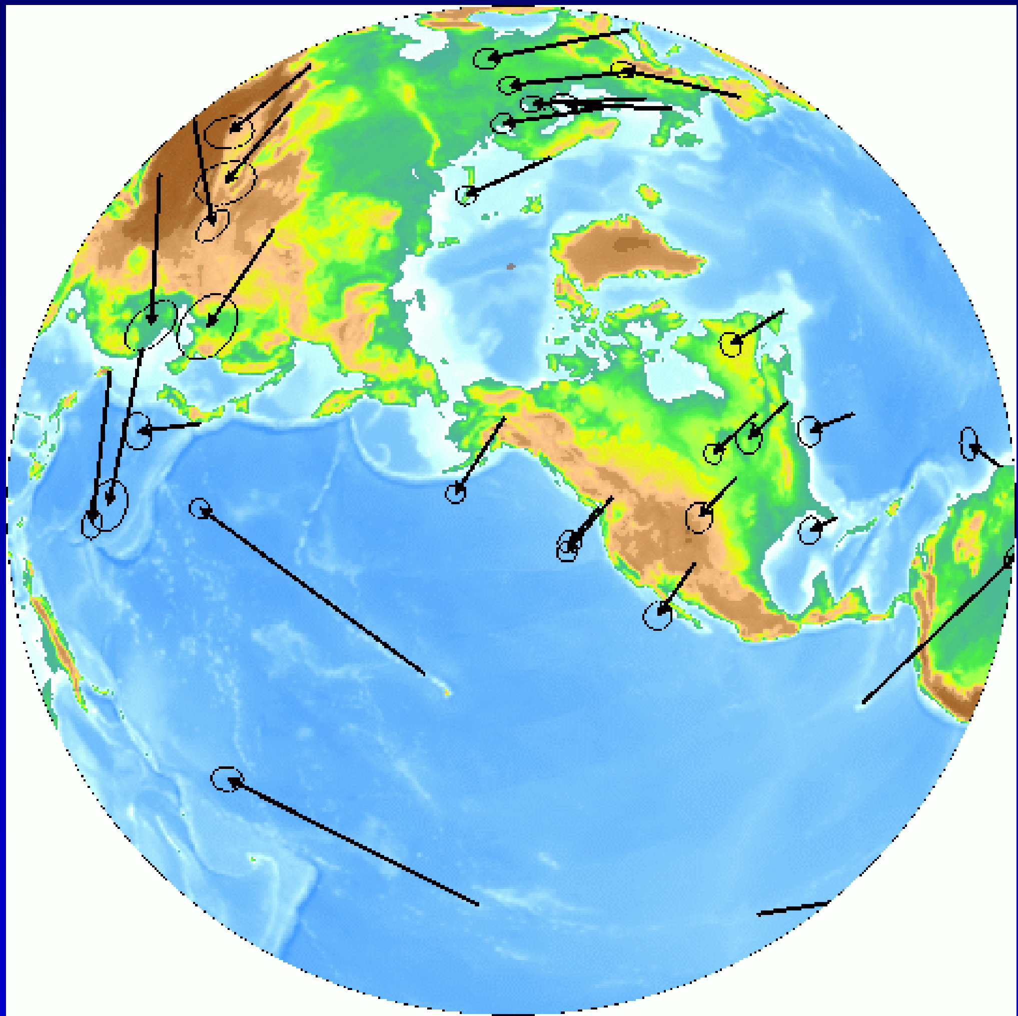
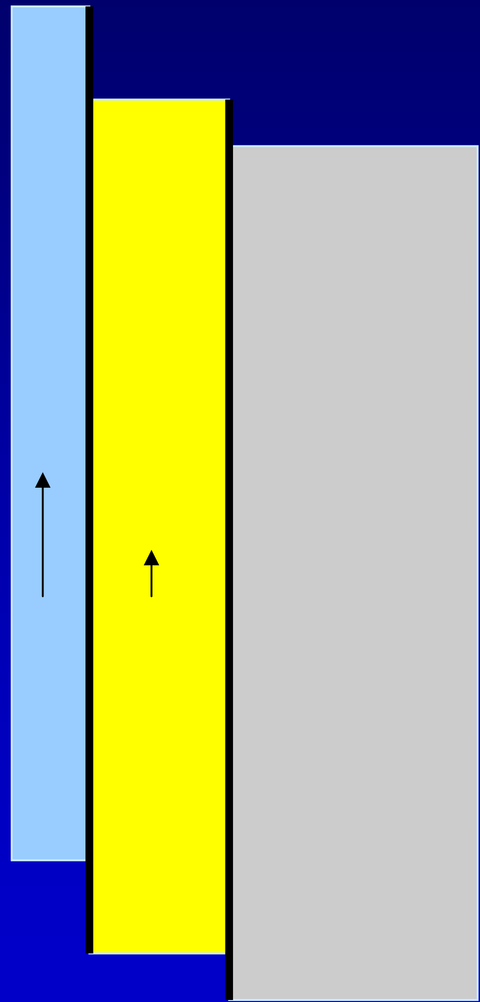
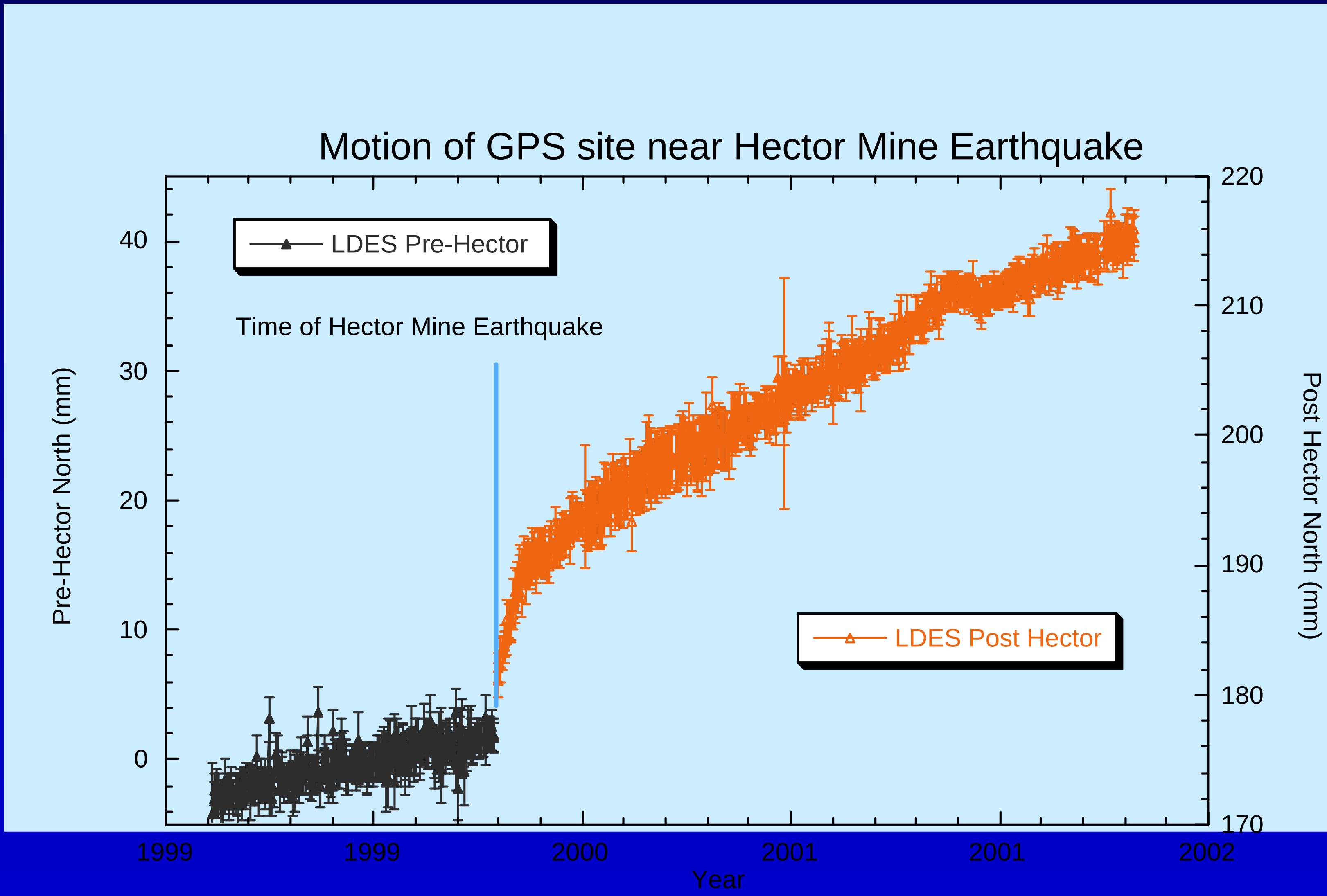


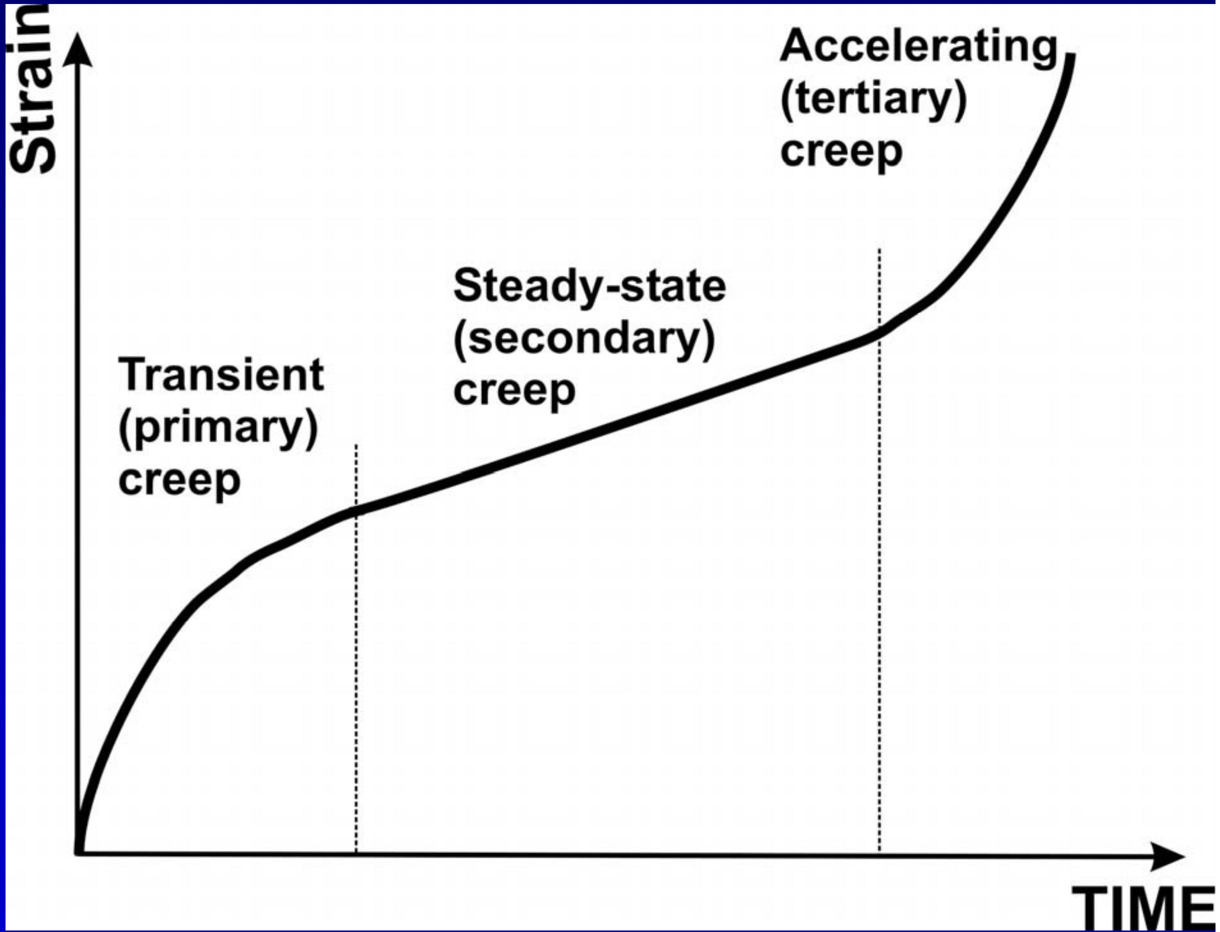


Motion before, during and after an Earthquake

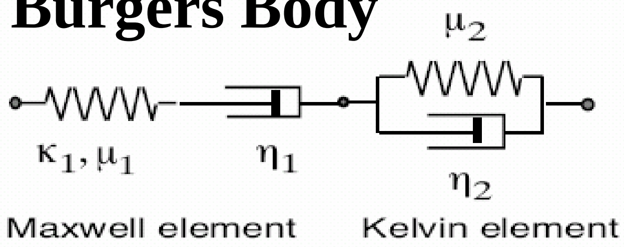


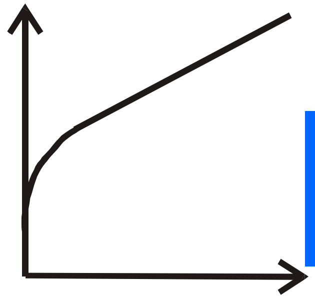
Creep cycle for constant loading from rock mechanics experiments

Frost and Ashby (1982)



Burgers Body

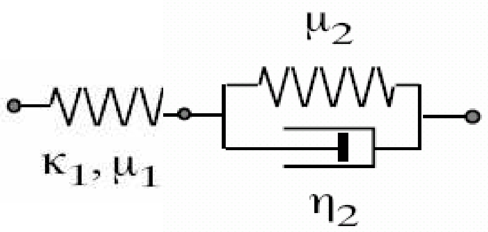


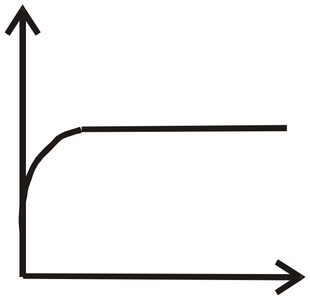


Transient

Non-recoverable + recoverable

Standard Linear Solid

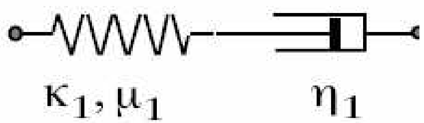


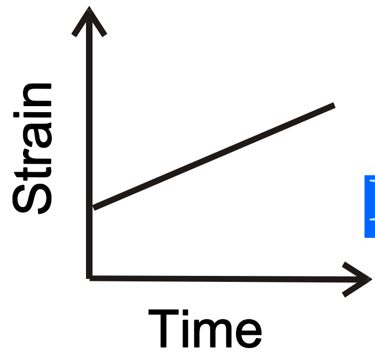


Transient

Recoverable

Maxwell Solid



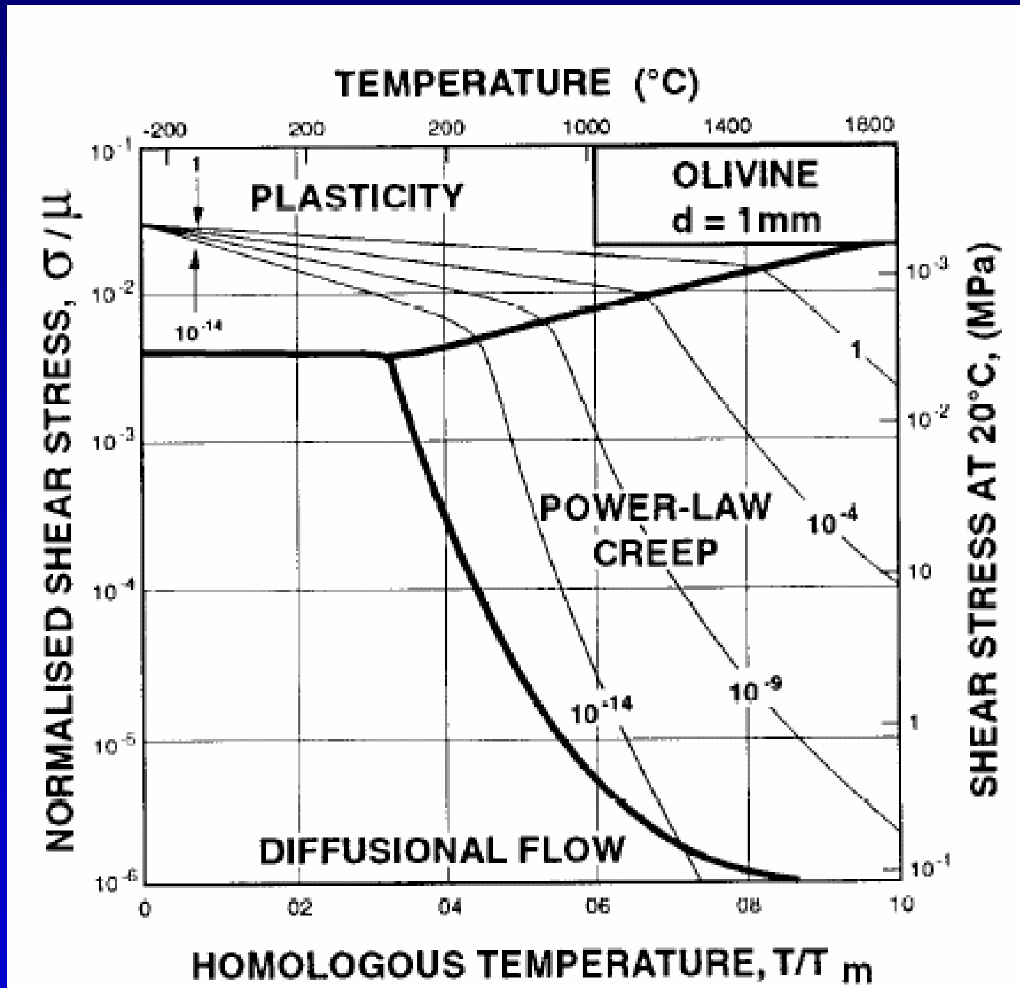


Steady-state

Non-recoverable

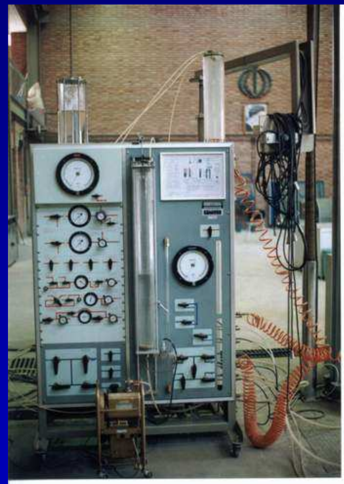
deformation mechanism map for Olivine

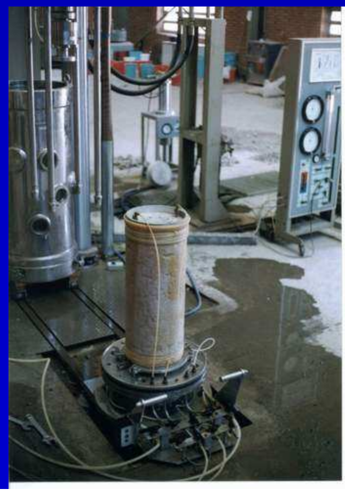
Frost and Ashby (1982)



From the laboratory ....

By necessity, rock and fault mechanics lab experiments have to be run on spatial and temporal scales and under conditions far from natural environment






an earthquake initiates a lithosphere-scale rock mechanics experiment:

- establish geometry, initial and boundary conditions:

  (e.g. surface geology and geomorphology, kinematic parameters of faulting, Earth structure through surface wave tomography and non-linear inversion)

- take relevant deformation measurments:

  (e.g. seismicity, continuous and campaign GPS, plaeoseismology)

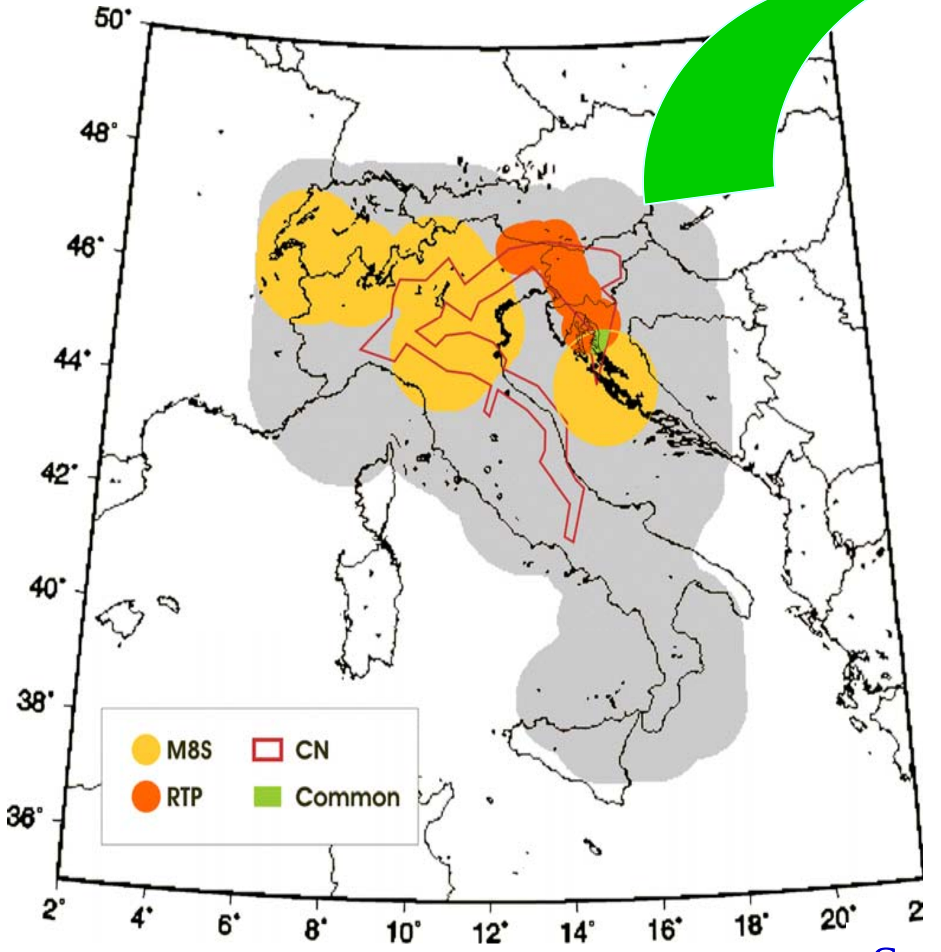
- use models to resolve fault/rock constitutive properties:

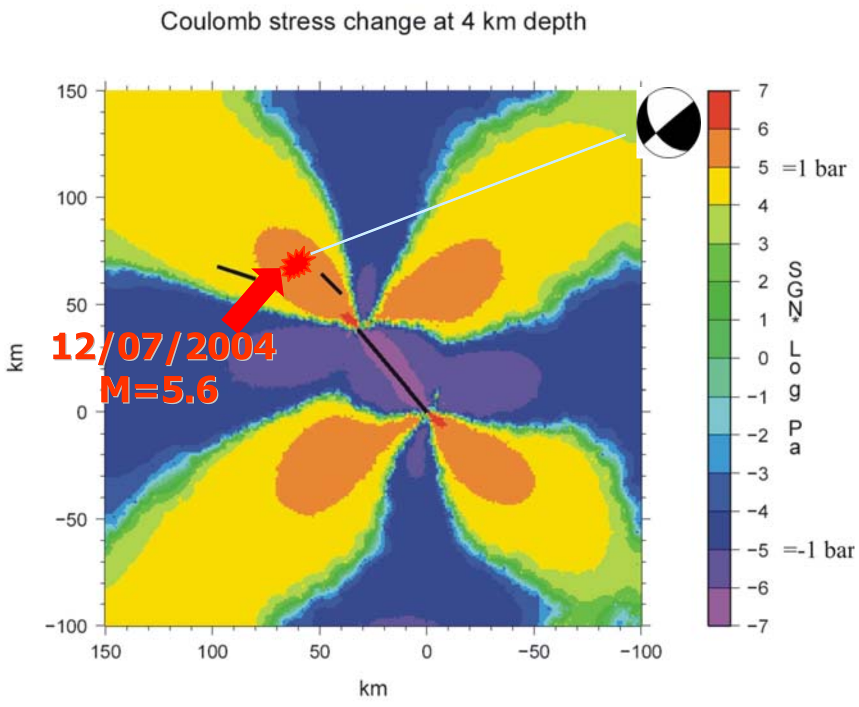
  (e.g. rate and state friction laws, visco-elastic modeling)

↓

A physical model for strain accumulation that carries predictive power for future stress patterns = future earthquakes

Statistics and Physics of Earthquake prediction





Stress evolution: the 1511-1976-1998 earthquake sequence and the 2004 event

Length scale

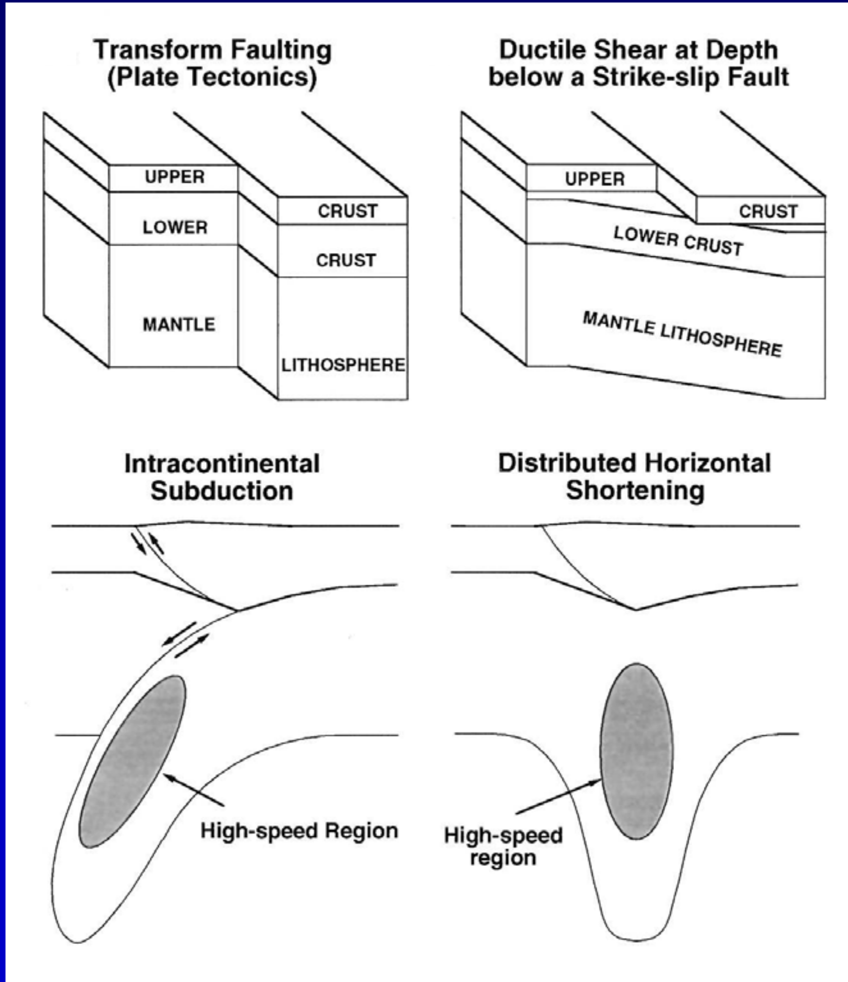
two end-member models of deformation:

1. **distributed deformation: creeping below mid-crust.**

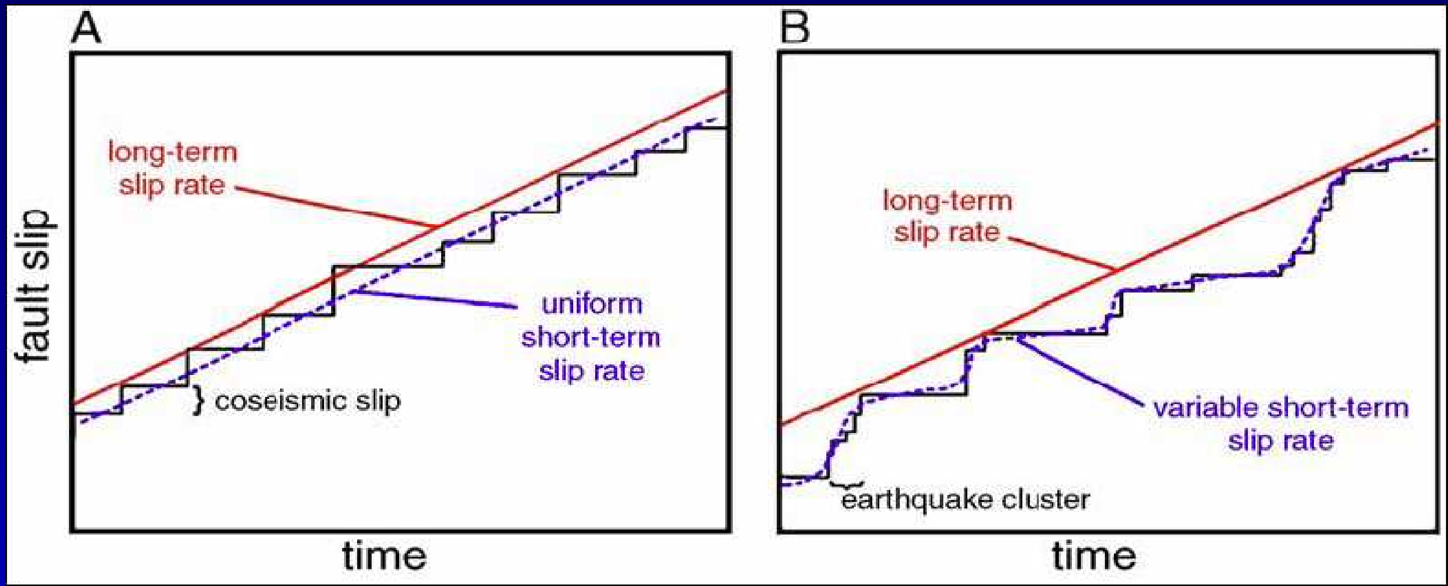
1. **localized shear zones: "rigid" down to mantle.**

↓

Differences are important for seismic hazard assessment



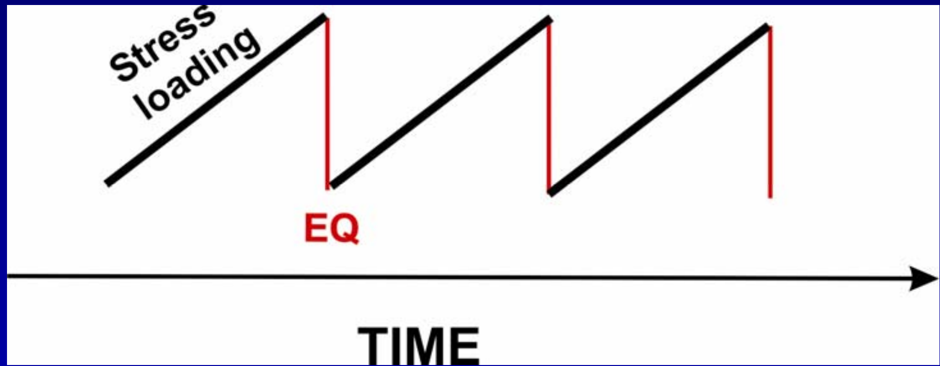
Time scale:
Two kind of seismic cycle models



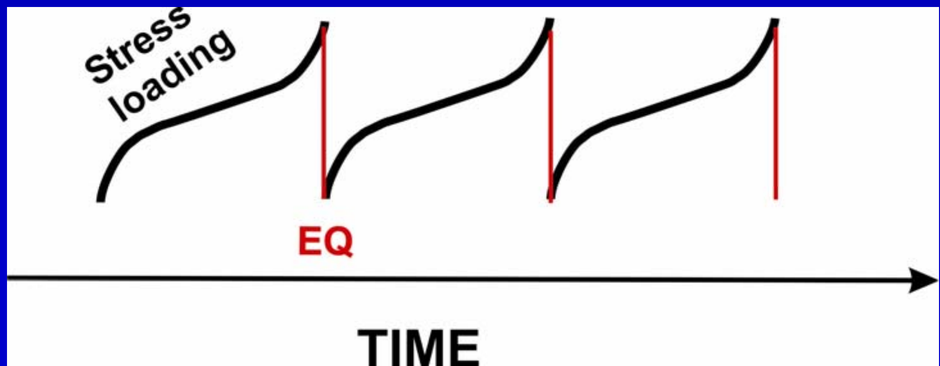
- A. **Quasi periodic earthquake occurrence (Shimazaki & Nakata's model)**
- B. **Clustered earthquake occurrence (wallace's model)**

Hypothetical stress evolution on the fault

... without transient deformation

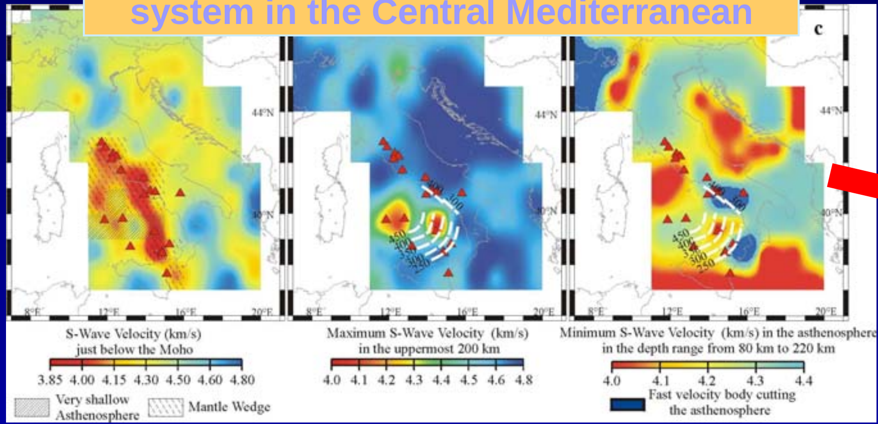


... with transient deformation

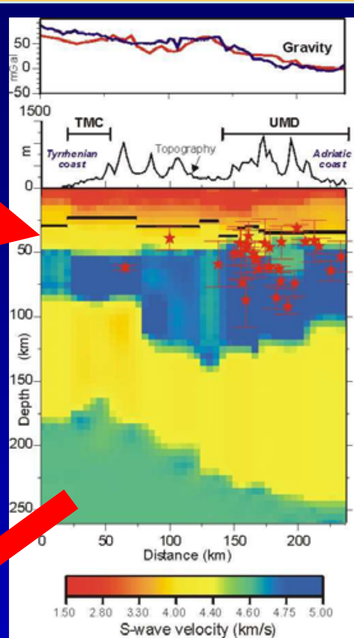


Earth Structure and Dynamics of the lithosphere

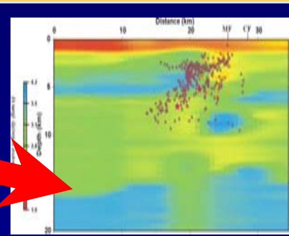
Earth crust and upper mantle system in the Central Mediterranean



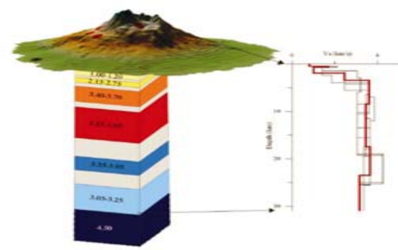
scale of the lithosphere



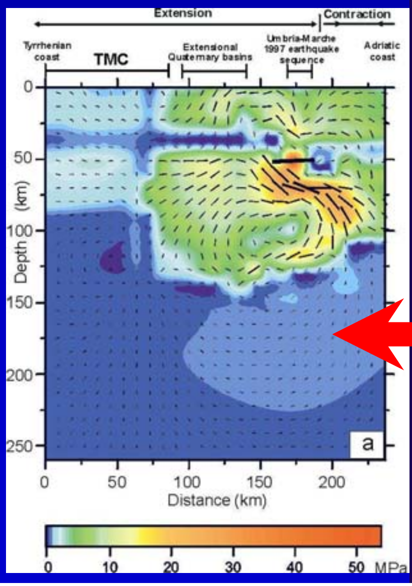
scale of a single fault

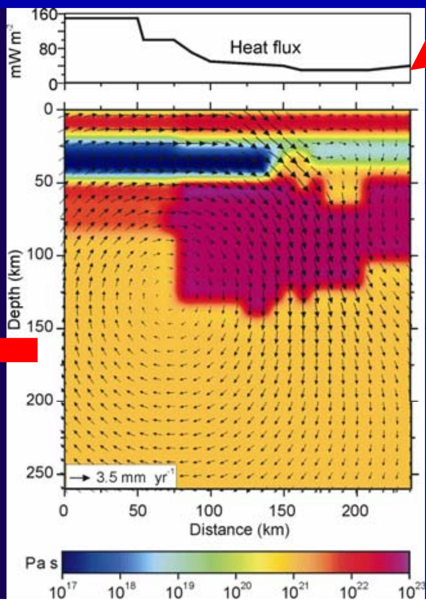


scale of a single volcano



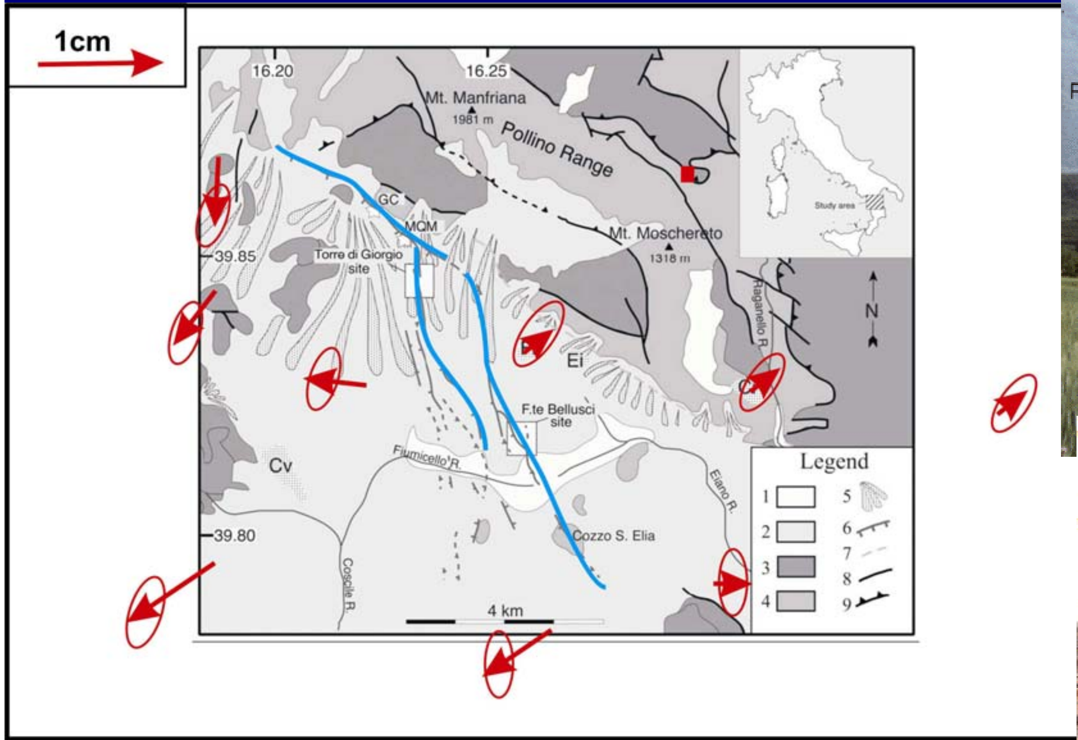
Flow and stresses in the lithosphere



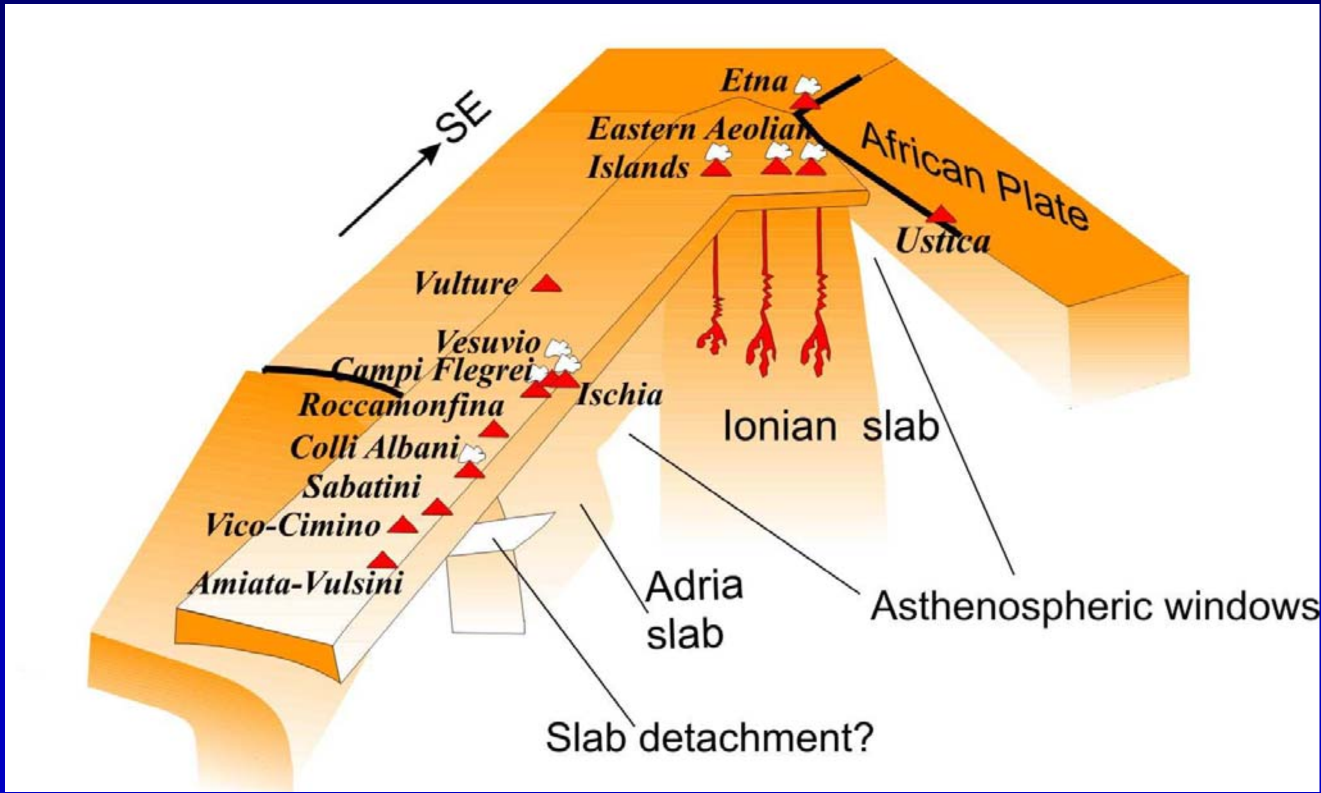


Multiscale tomography and non-linear linear inversion for the Earth structure retrieval & Dynamics of the flow and stresses in the lithosphere

GPS data are at least 4 times trenching data



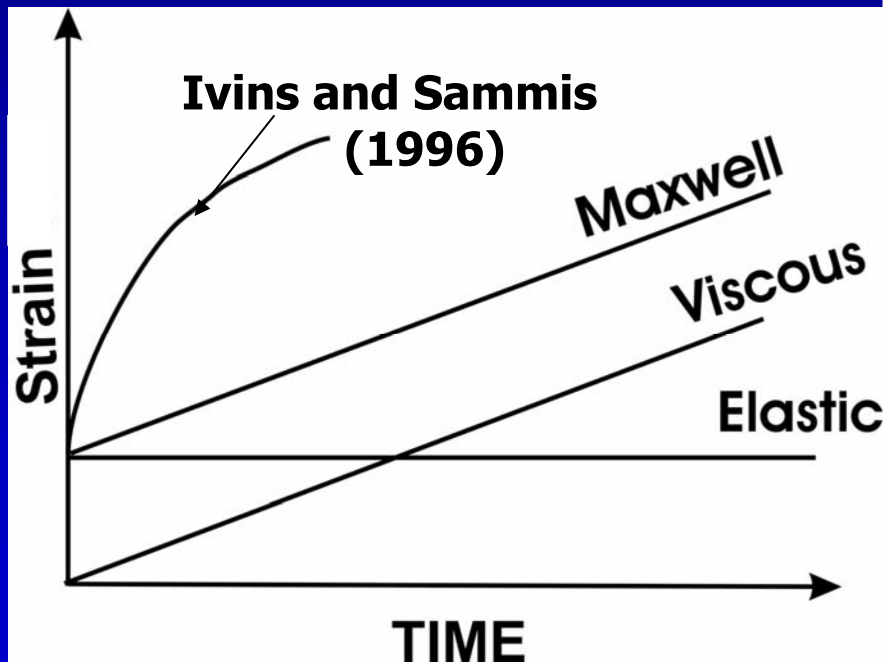
Schematic Earth model



Src: Panza, Peccerillo, Aoudia & Farina
in press – Earth Science Reviews

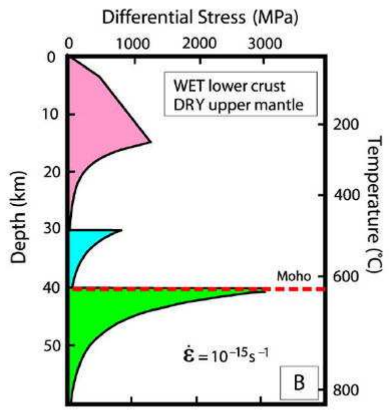
Distributed deformation:
Mechanics of the earthquake cycle

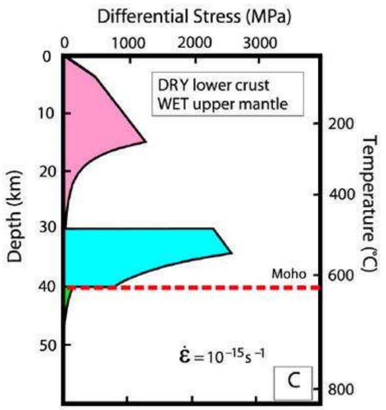
- transition from brittle to "ductile" deformation at mid-crustal depth
- the earthquake cycle is modeled as a system of interacting elastic and viscoelastic layers
- laboratory experiments suggest non-linear environment-and-lithology dependent rheology



Distributed deformation

Jackson, 2002





Where the deformation is accommodated?

Large vs. moderate size earthquakes

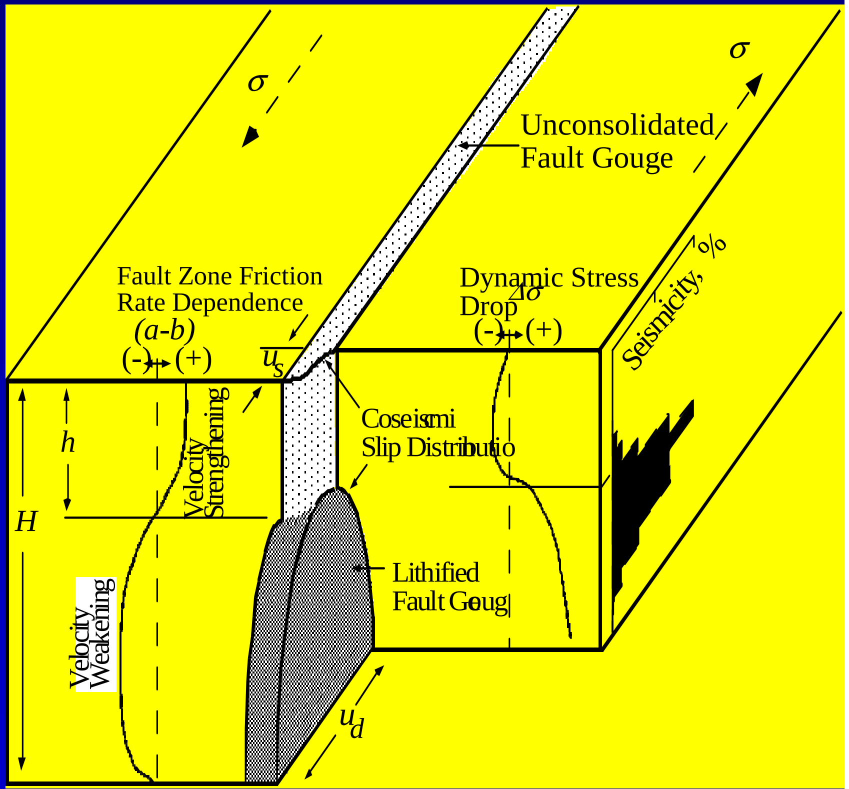
Seismogenic Crust: *Stick Slip*

Transitional Zone

Aseismic Crust: *Stable Sliding or plastic (flow) deformation*

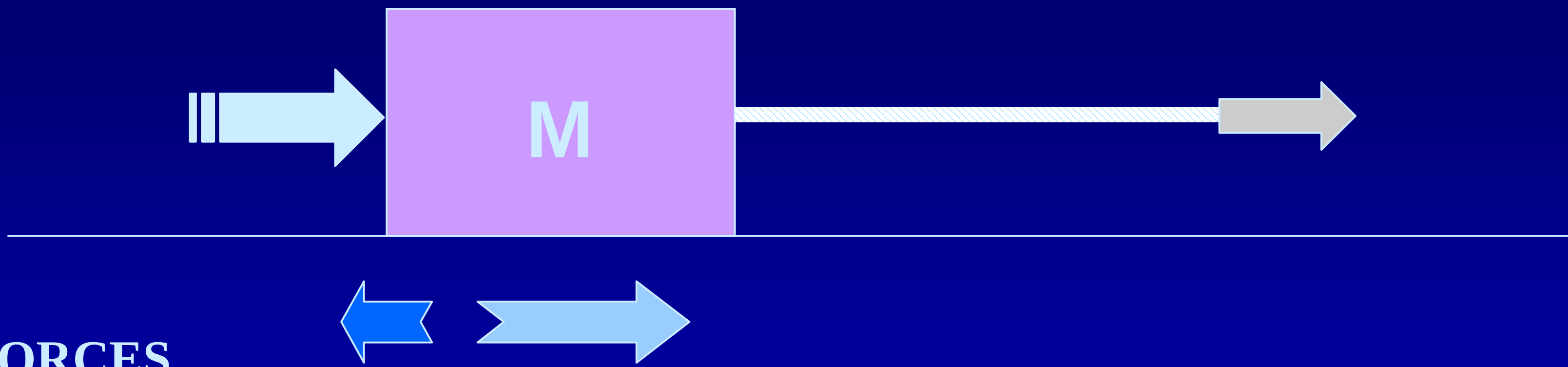
Localized deformation:
Mechanics of the earthquake cycle

- **transition from stick slip (velocity weakening) to stable (velocity strengthening) sliding at mid-crustal depth**
- **the earthquake cycle is modeled as a system of slipping fault patches (dislocations)**
- **laboratory experiments suggest complex depth, -environment-, scale- and material dependent rate-and-state dependent rheology with changes in strength and slip stability**



Frictional Instability

Velocity-weakening (dynamic < static friction)

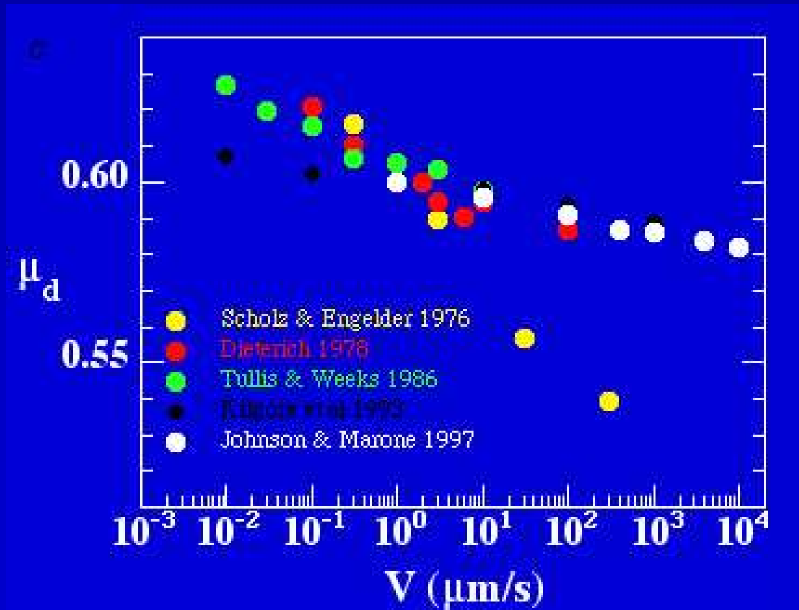


FORCES

Friction

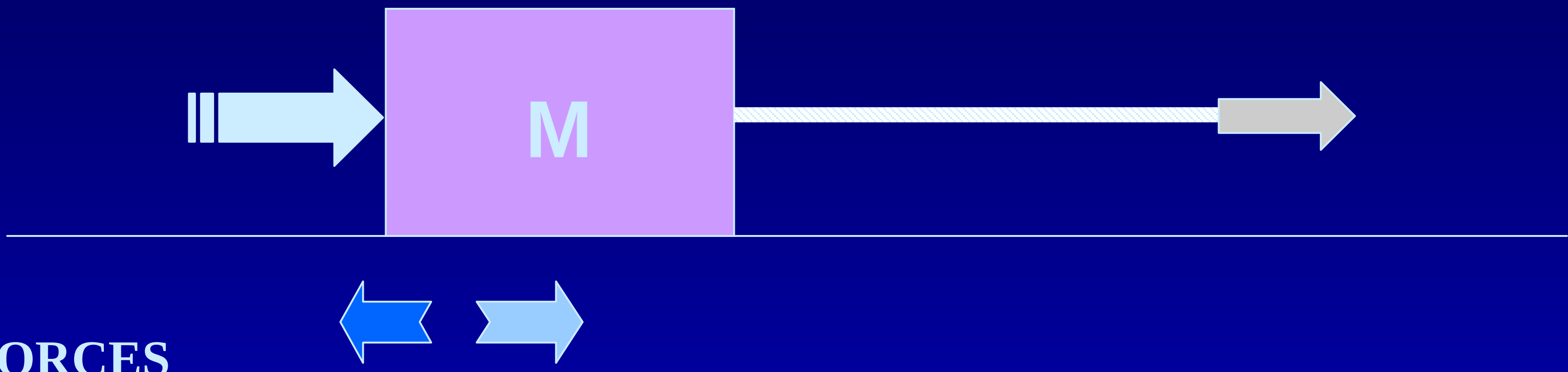
Elastic restoring force

Velocity (rate) dependence of friction.



Alternative: Stable Sliding

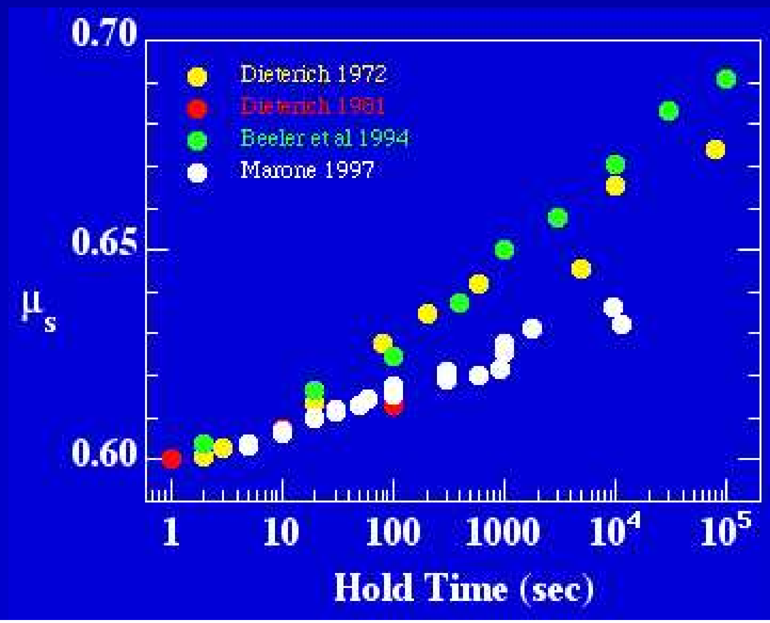
Velocity-strengthening (static friction)



FORCES

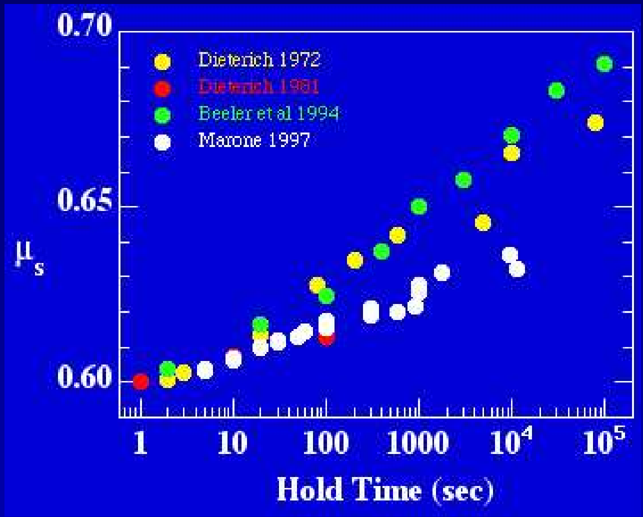
Friction Elastic restoring force

Time (state) dependence of friction:
Healing

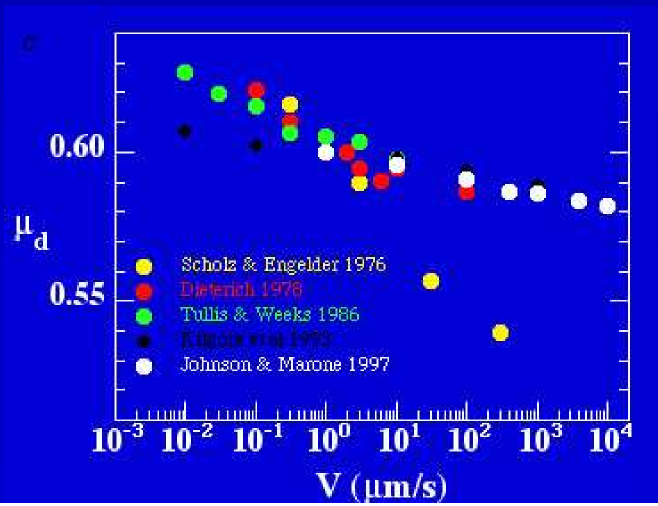


Laboratory studies

Time (state) dependence of friction: Healing



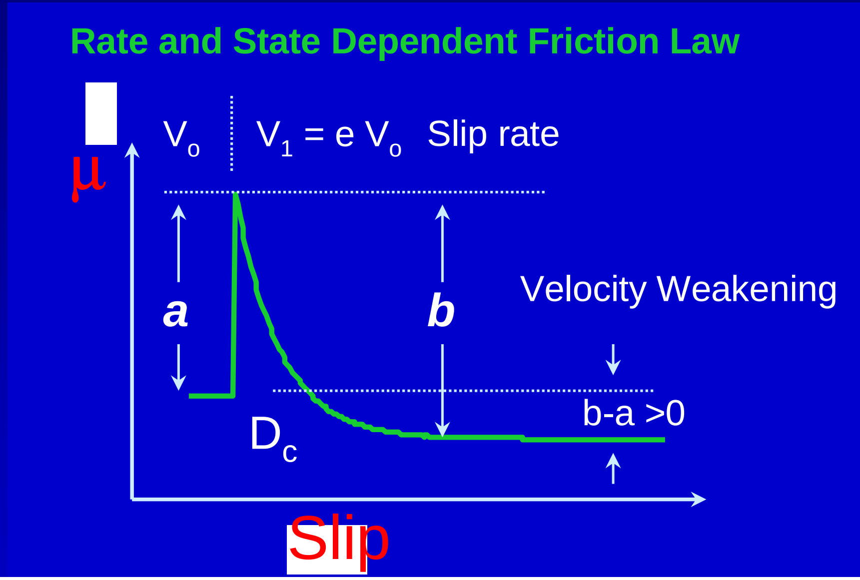
Velocity (rate) dependence of friction.



Plausible Mechanisms for Instability

Duality of time and displacement dependence of friction.

"Static" and "dynamic" friction are just special cases of a more general behavior called "rate and state friction"



$$\mu(\theta, v, \sigma) = \mu_0 + a\ln\left(\frac{v}{v_o}\right) + b\ln\left(\frac{v_o\theta}{D_c}\right)$$

$$ds = dt\, V_o \exp\left(\frac{\delta\tau}{(a-b)\sigma_n'}\right)$$

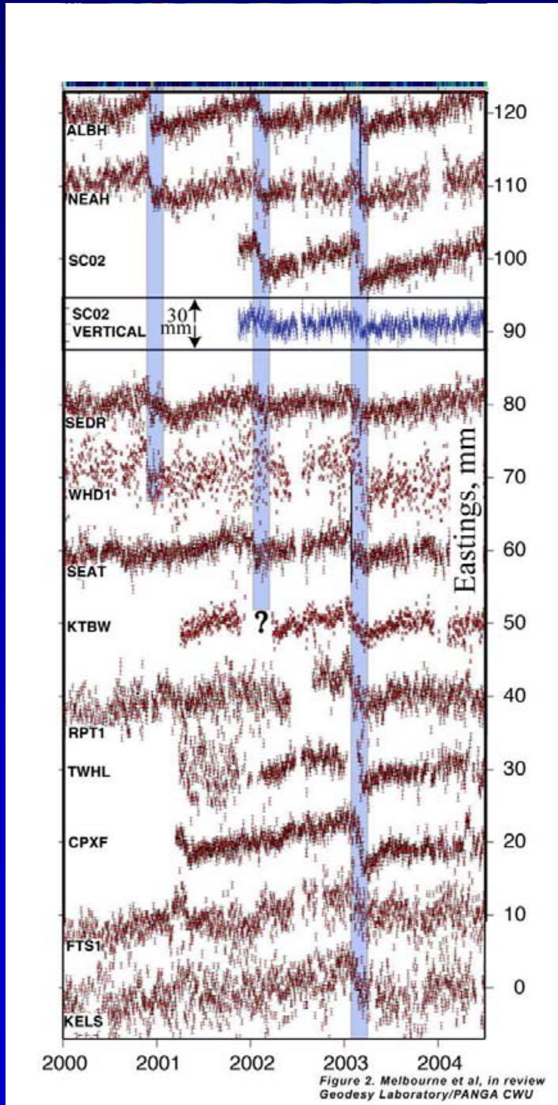
Fault Mechanics & Earthquake Physics

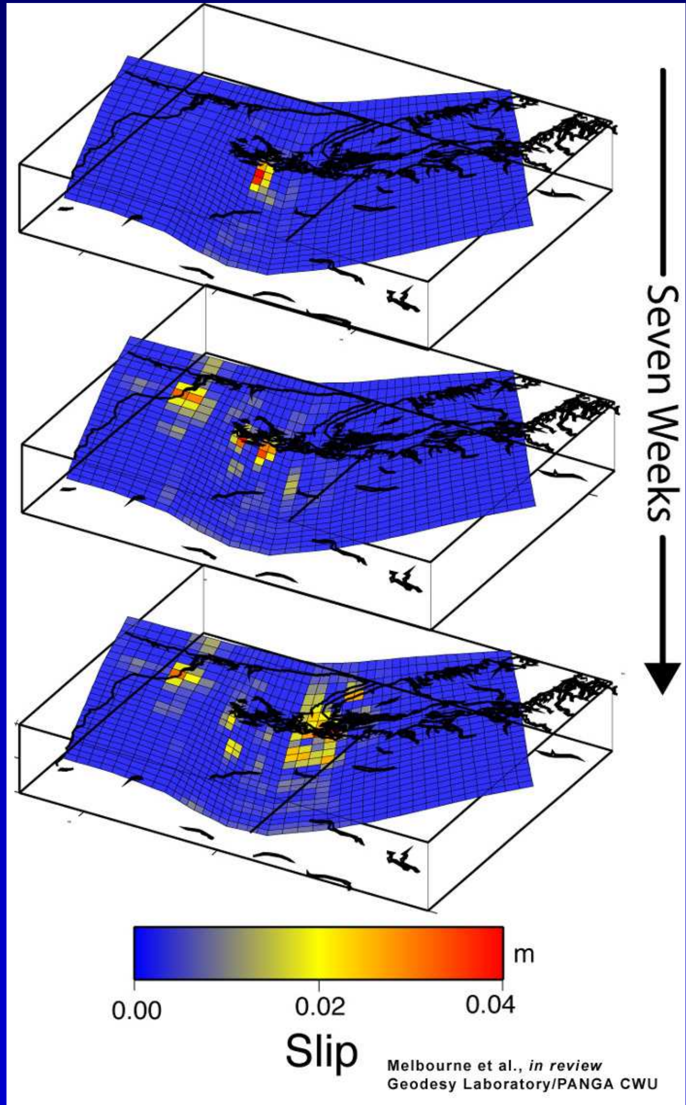
- Aseismic slip
- Creep events
- Strain transients
- Slow earthquakes
- Episodic tremor
- Silent earthquakes
- Afterslip and transient postseismic deformation
- Slow precursors to "normal" earthquakes
- Earthquakes with a distinct nucleation phase
- Normal (fast) earthquakes
- Earthquakes with supersonic rupture velocity

Seismic slip and aseismic faulting are **end members** of a **continuous spectrum** of behaviors

A single fault, and perhaps even a single fault patch, may exhibit both seismic and aseismic slip

Slow Slip Events: Displacement and Slip Model





Implications of Slow Slip

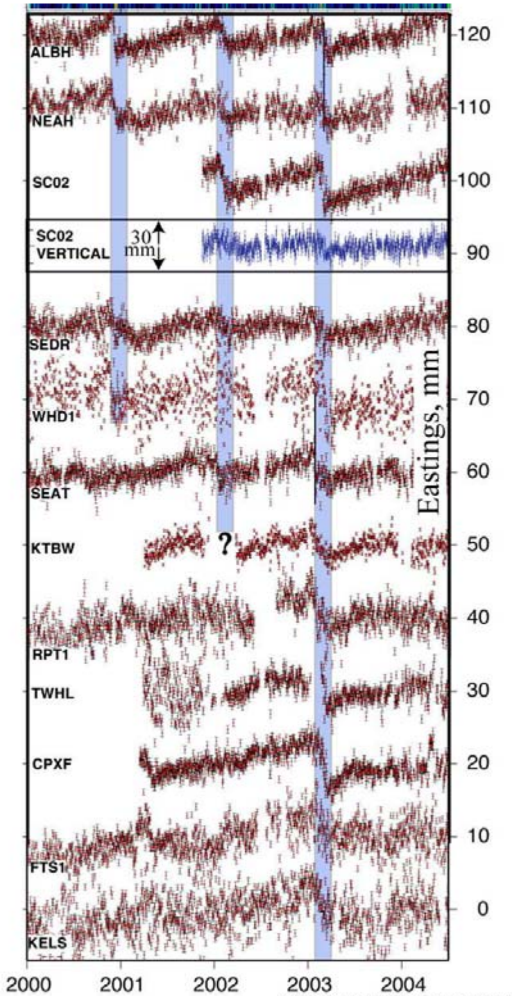
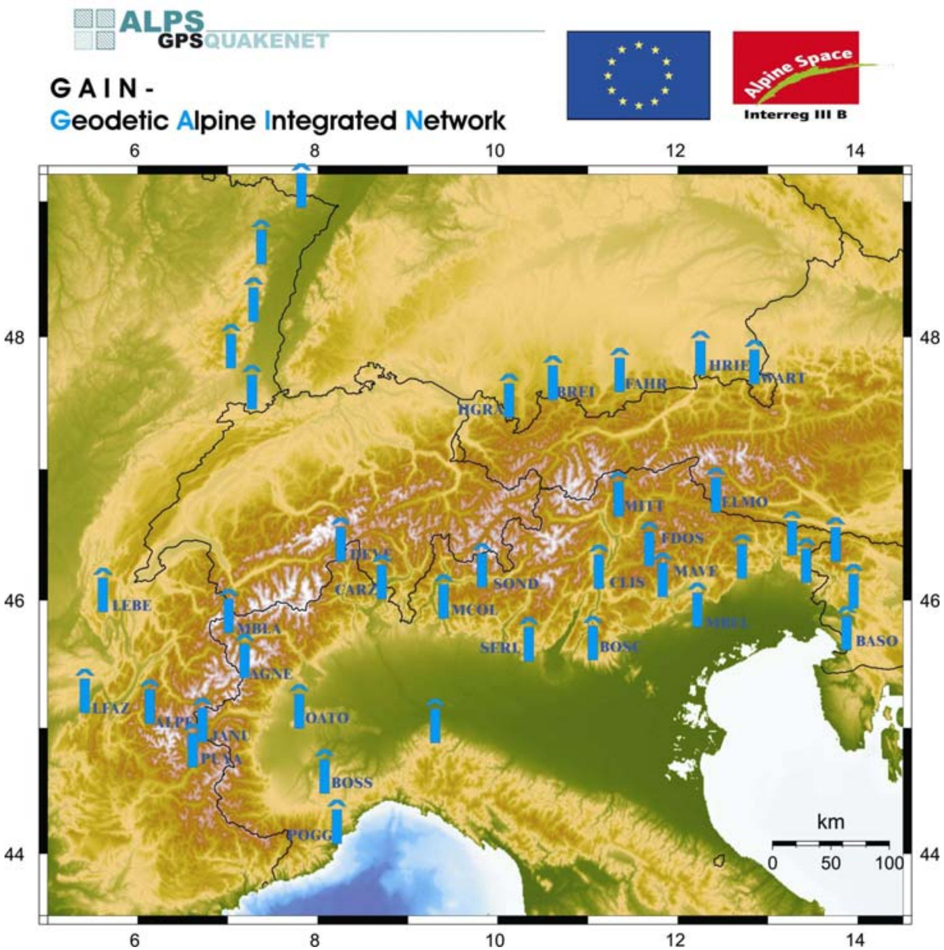


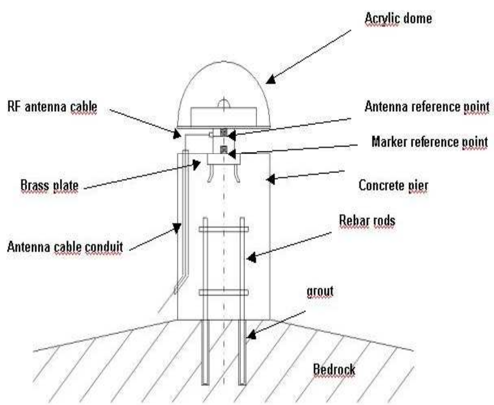
Figure 2. Melbourne et al, in review
Geodesy Laboratory/PANGA CWU

- Short-term average velocity not same as long-term average (months vs. years)
- Locking depth will depend on averaging time for velocities and interval of measurements



Need to monitor crustal deformation at a wide range of spatio-temporal scales

High gain GPS data will very likely revolutionize our understanding of crustal deformation, including fault friction and the *rheology* of deformation



GPS monitoring

- **monumentation on rock**

- **antenna forced centering with sub-millimetre repeatabiliy (*ad hoc* designed antenna mount, thoroidal level for vertical positioning)**

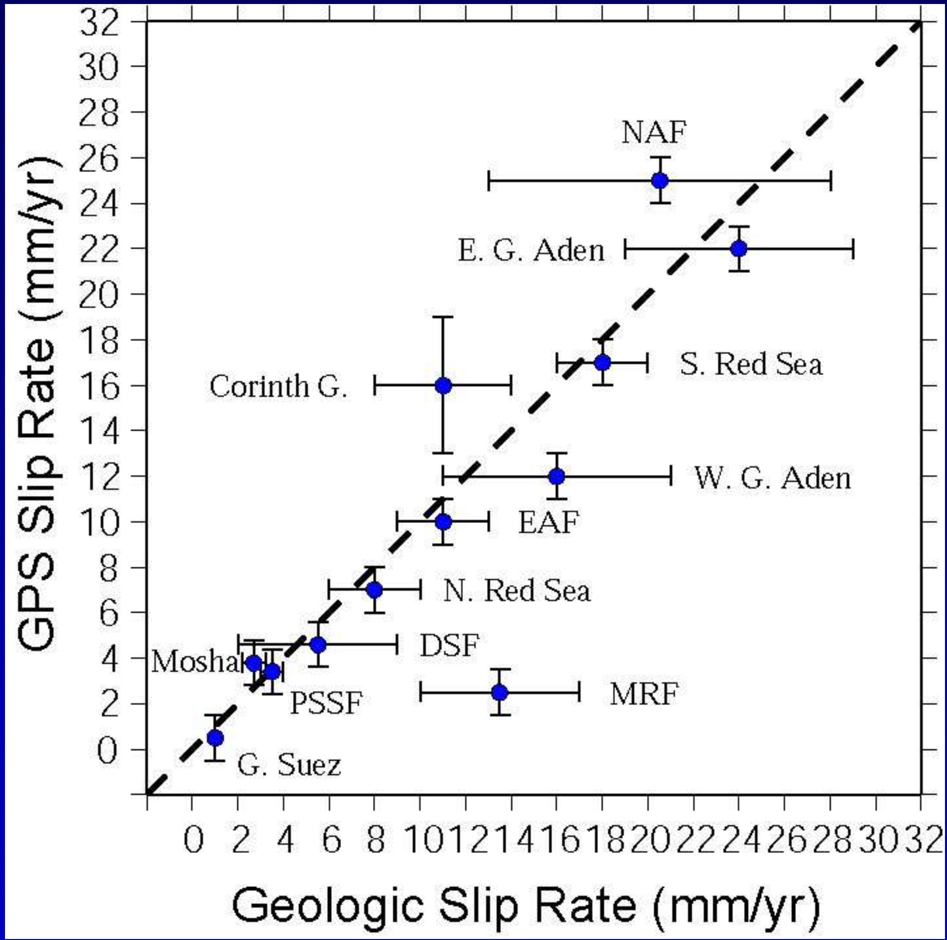
- **spirit levelling on each site to check for local vertical stability**

GPS is cool...
but there are many layers to the onion...

- ***Phase biases***
- ***Imperfect clocks***
- ***Indices of refraction***
- ***Satellite-Earth-GPS geometry***
- ***Other effects***
  - ***Loading (tidal, hydrological, ...)***
  - ***Electrical environment (satellite antennas, receiving antennas)***
  - ***Use of different antennas for the same monument***
  - ***Dome...***


POLLINO RANGE


A
B
C
E

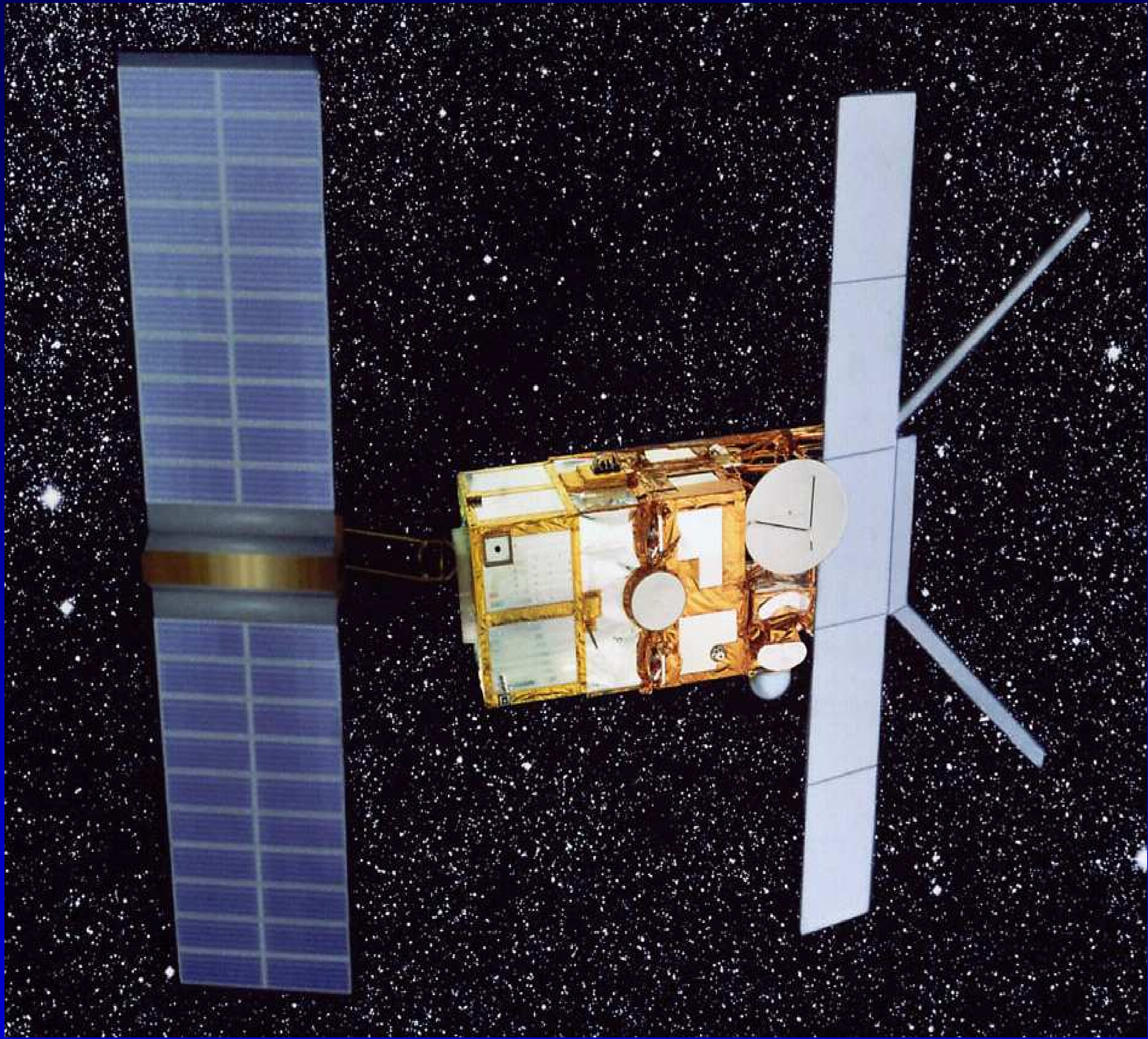


Vernant et al. 2004

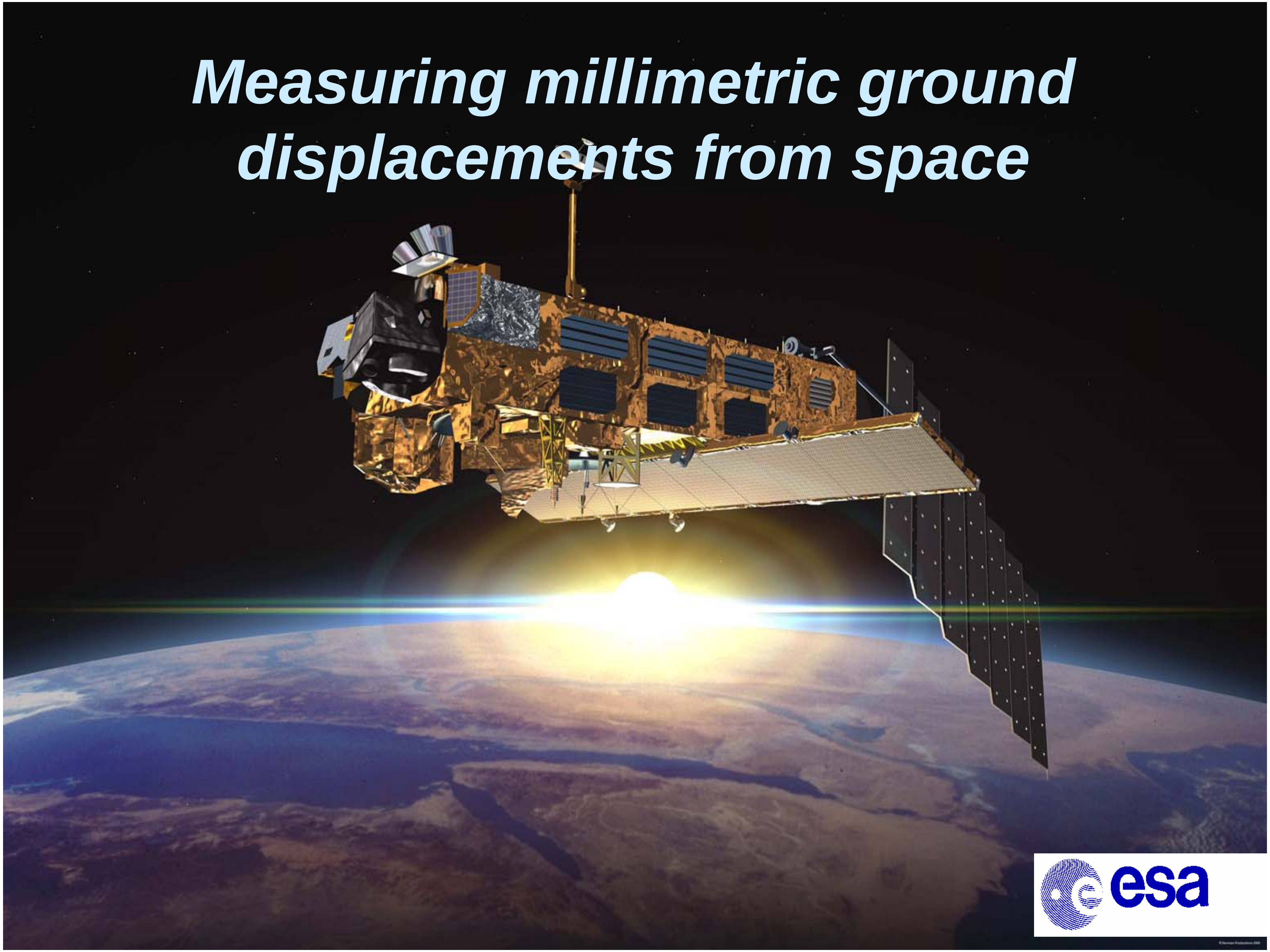

BORDER ROADS ORGANISATION
(GREF)
BREAK THE SPEED
THAT'S
THE NEED
753
SPEED
LIMIT:
3 MM/YR

ERS-1/2

1991 to 2002



Measuring millimetric ground displacements from space



Science Requires

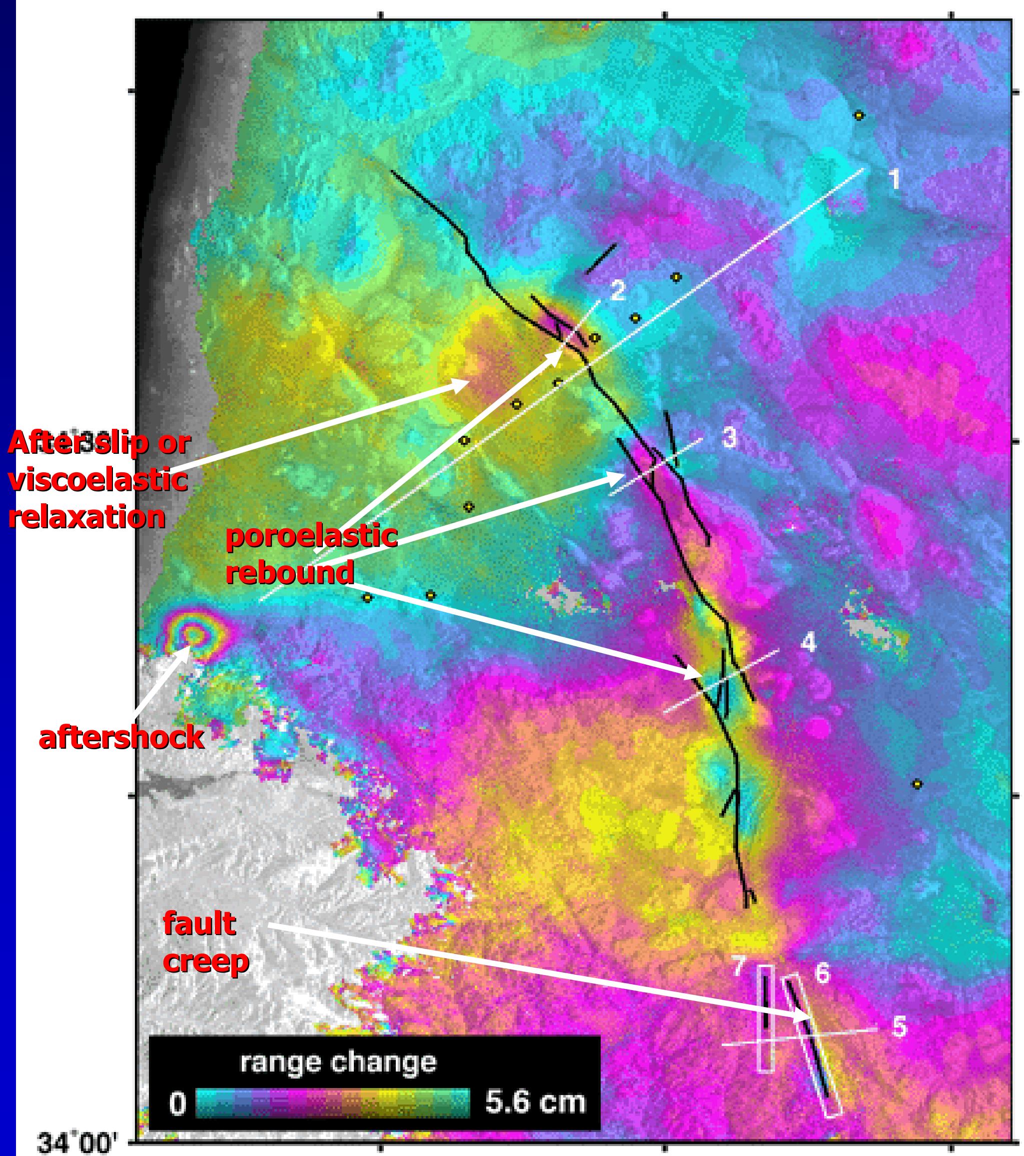
- 1 mm/yr velocity accuracy.
- 50 km spatial observational scales.
- Penetration of vegetation.

No International satellite is operating that meets these requirements.

... the Natural Laboratory

Challenges

- limited precision and space-time density of measurements
- limited modelling and computational ressources
- limited resolution and uniqueness in determining source of deformation
- limited ability to resolve multiple processes



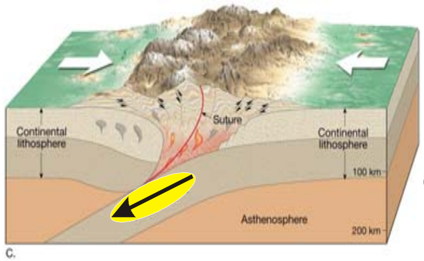
Peltzer et al, 1998

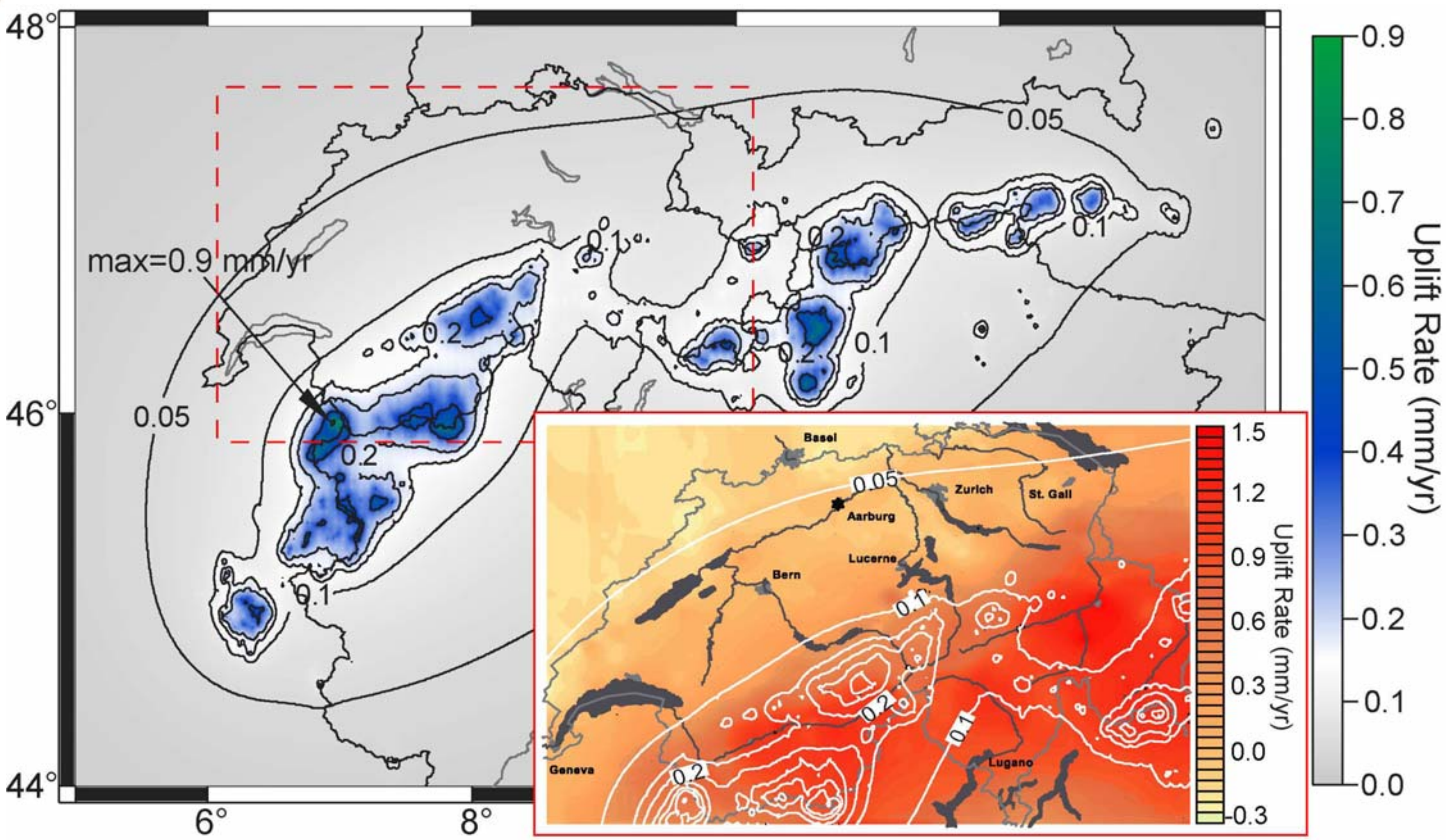
non-unique models

some solutions

- take geological reality into account
- require models to be consistent with deformation at all time scales, not just single snapshot of the velocity field

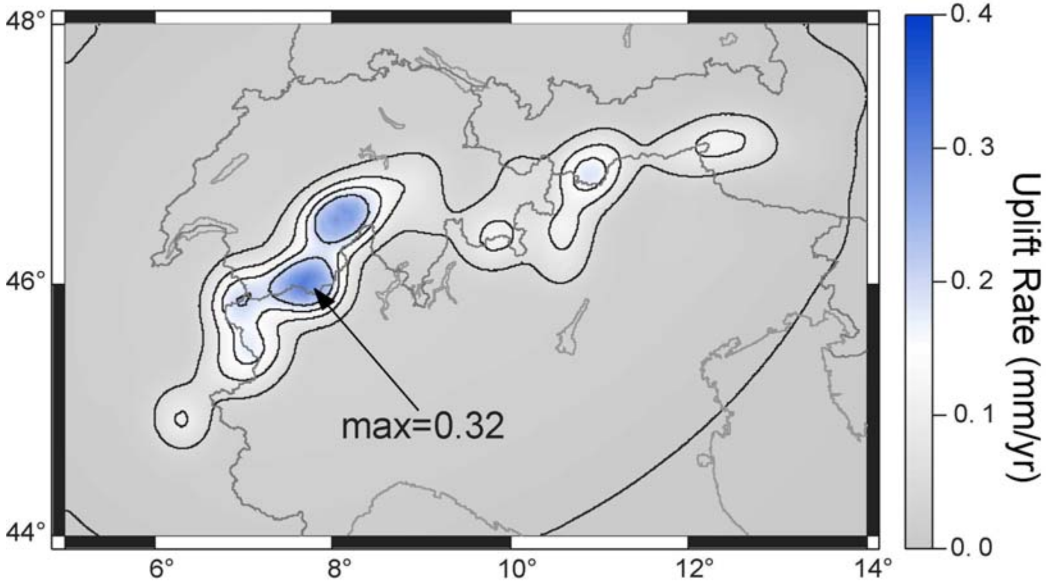
Glacier shrinkage and uplift of the Alps:elastic response





Computed high resolution <u>elastic response</u> to ice mass loss. In the inset (corresponding to the the dashed box in main figure), our white contour lines are superimposed to the vertical rates obtained from the new national height system (LHN95) of Switzerland [Schlatter et al., 1999], for comparison.

Glacier shrinkage and uplift of the Alps: Viscous contribution



Viscous contribution, for 155 Km^3 of ice volume loss since 1850 A.D.

Rheologic structure

Layer	r in Km	ρ in Kg/m^3	μ in Pa	ν in Pa s
1	6371.0	2650.0	2.97×10^{10}	1.00×10^{35}
2	6352.5	2750.0	5.58×10^{10}	2.15×10^{19}
3	6341.0	2900.0	6.81×10^{10}	5.00×10^{21}
4	6331.0	3439.3	7.27×10^{10}	4.64×10^{20}
5	5951.0	3882.3	1.09×10^{11}	4.64×10^{20}
6	5701.0	4890.6	2.21×10^{11}	1.000×10^{21}
7	3480.0	10932.	0.00	0.0