Convergent Margins and Mega-Earthquakes

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with the contribution of the Laboratory of Experimental Tectonics, the EURYI crew and colleagues who have shared info about the Tohoku-Oki earthquake

PRESENTATION OUTLINE

- ☞ **The earthquake phenomenon (in a nut-shell)**
- ☞ **Geodynamic framework of global seismicity**
- ☞ **Mega-Earthquakes**
- ☞ **Subduction and Mega-Earthquakes @ Roma TRE**

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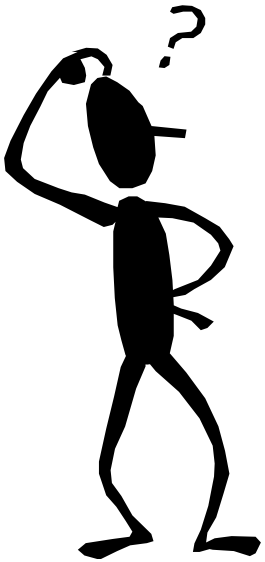
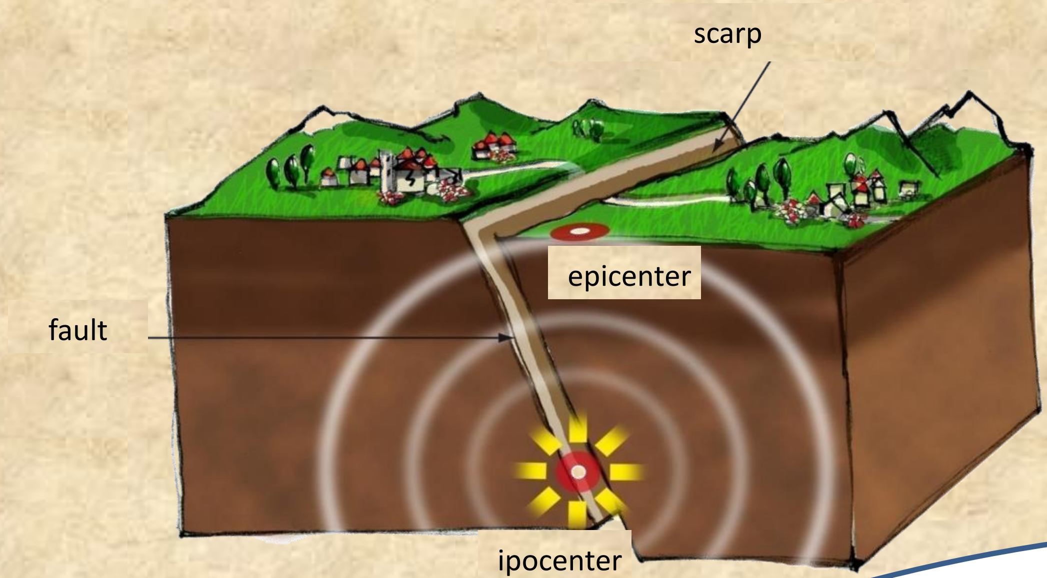


WHAT is an earthquake and HOW does it occur?

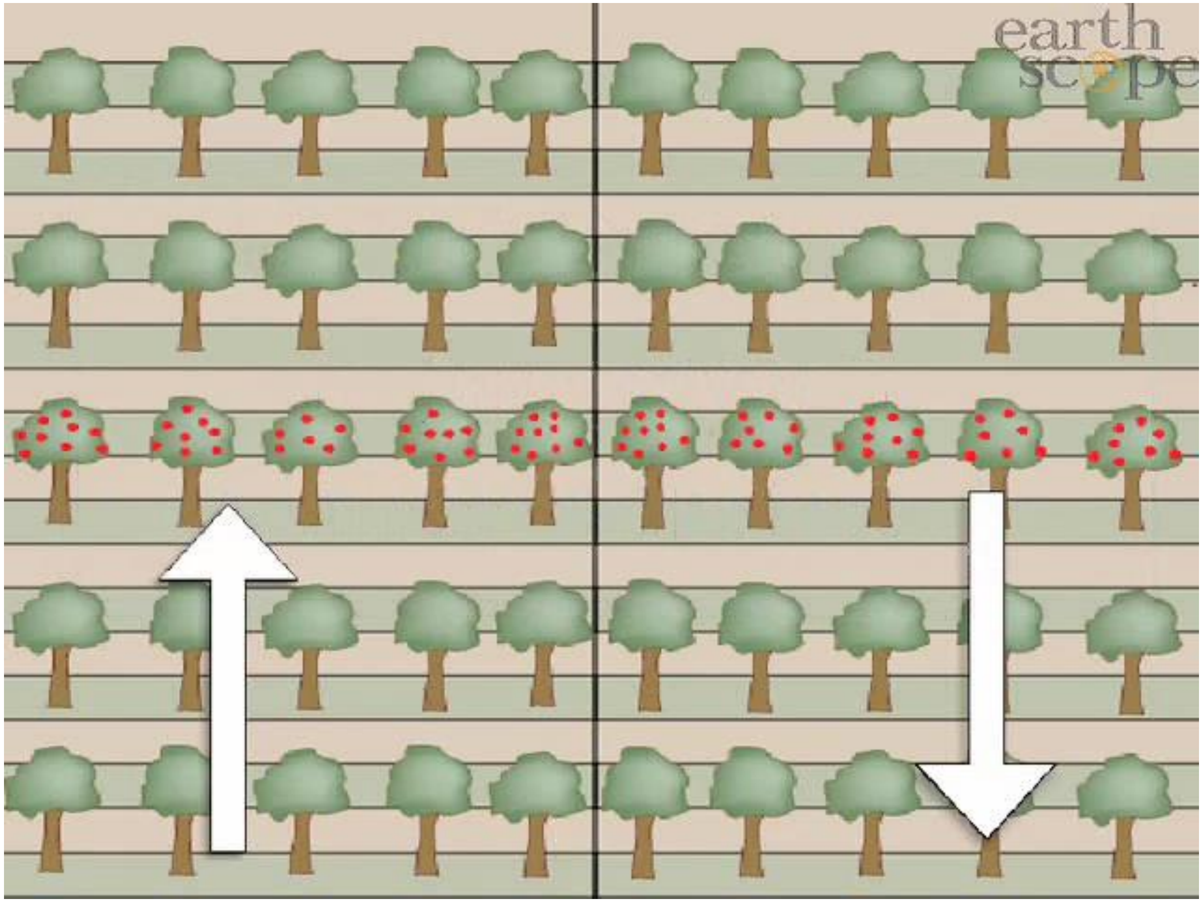
DEFINITION

"A sudden movement of the earth's lithosphere caused by the release of stress accumulated along a fault"



ELASTIC REBOUND THEORY

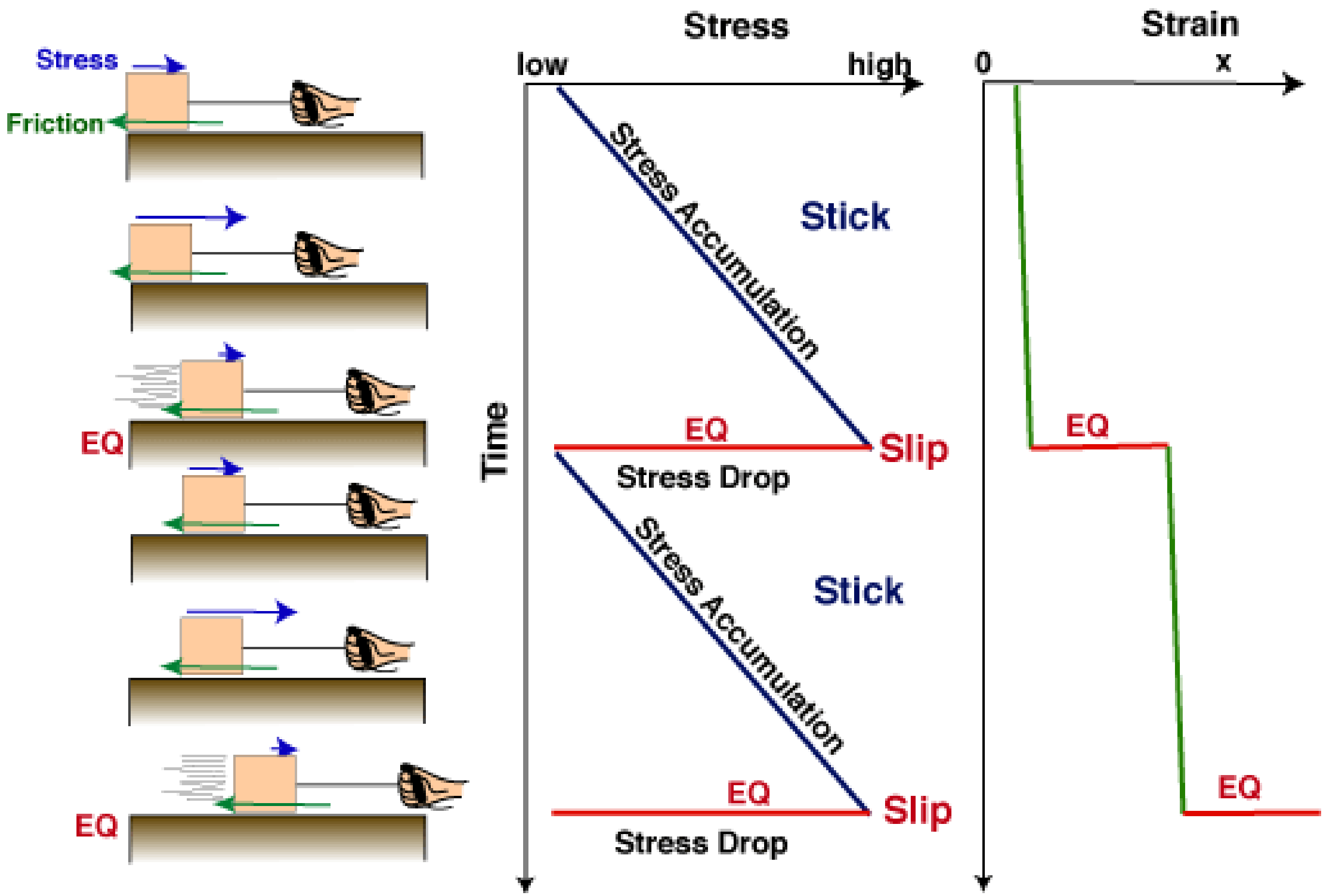
«How energy is spread during an earthquake»



$$\Delta U_e = U_s + U_f + U_k$$

ΔU_e = change in elastic strain energy
U_s = surface energy (to create new crack surface area)
U_f = frictional energy (heat)
U_k = kinetic energy (seismic)

ELASTIC REBOUND & STICK- SLIP BEHAVIOR



http://www.iris.edu/

SEISMIC CYCLE

years — Inter-seismic

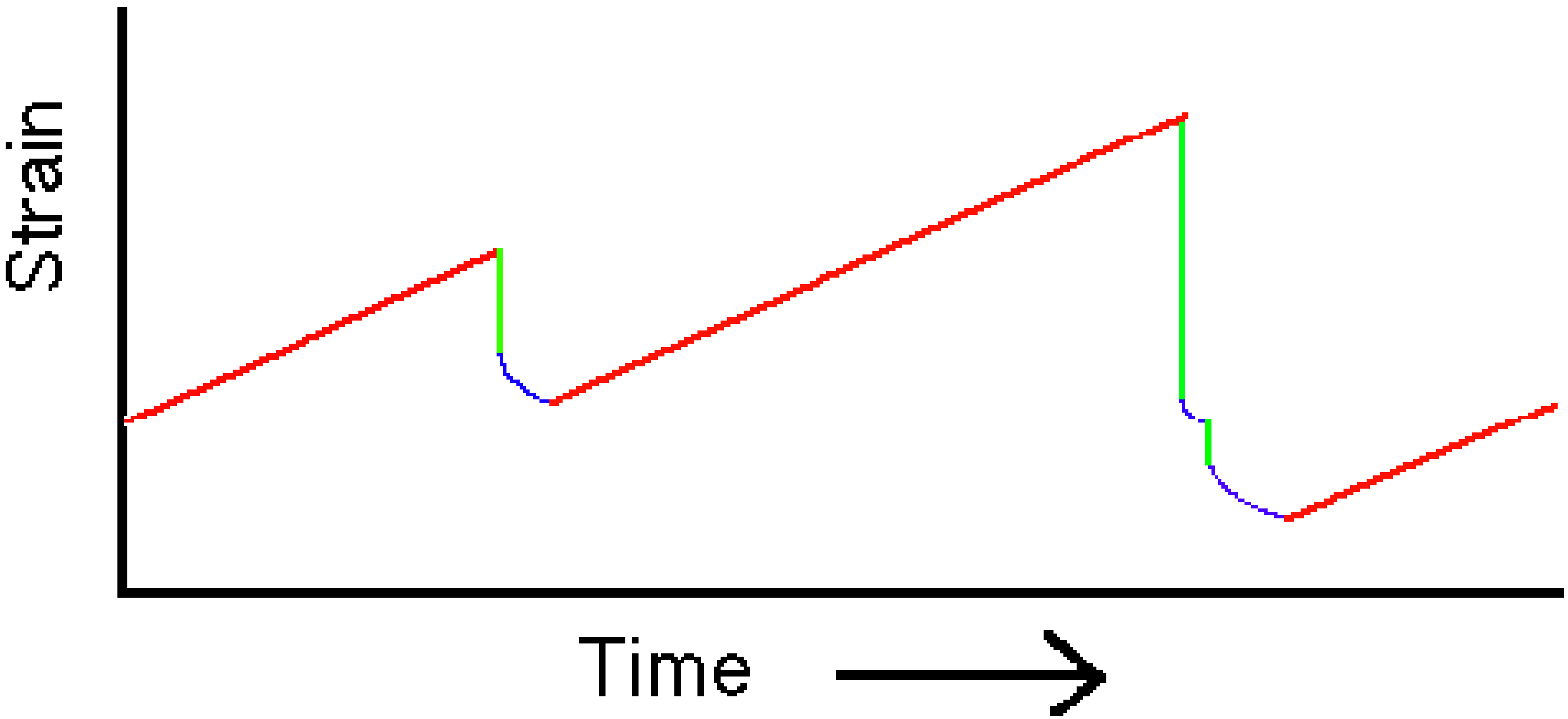
Elastic deformation on rocks

seconds — Co-seismic

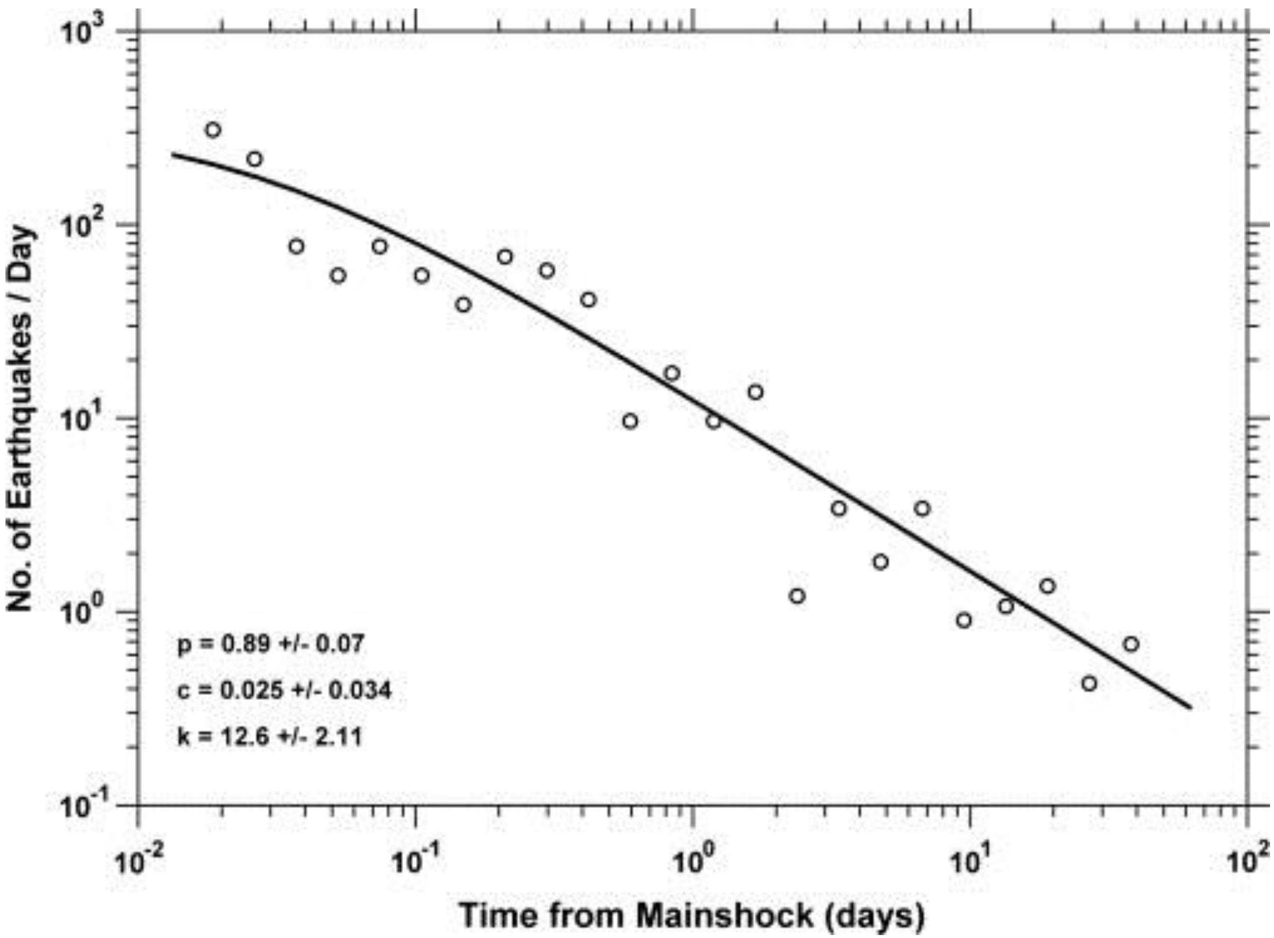
Earthquake

days/year — Post-seismic

Towards a new phase of equilibrium by means of aftershocks



OMORI'S LAW

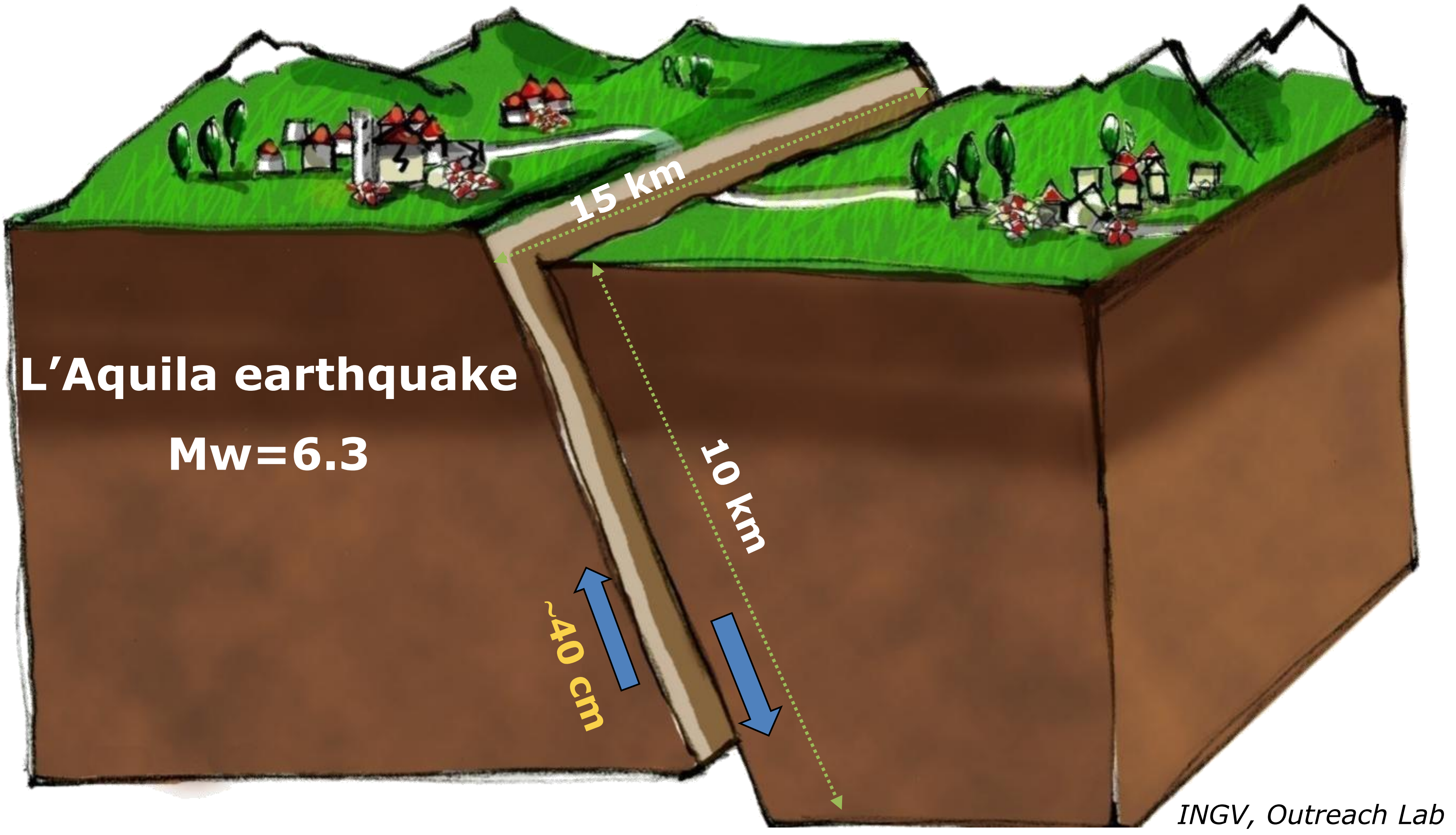


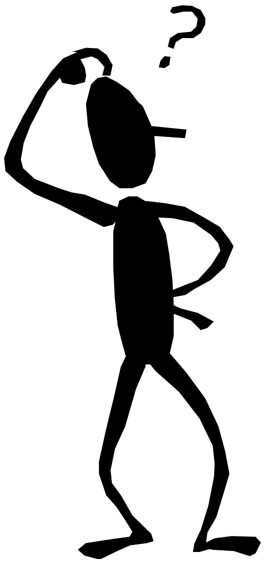
Yadav et al., 2012

MOMENT MAGNITUDE

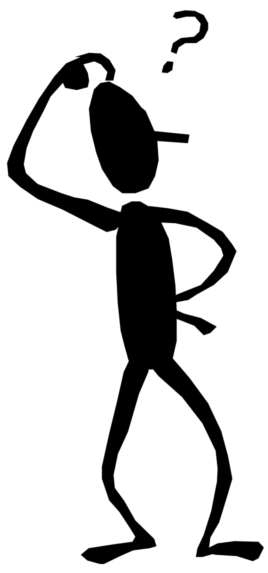
used by seismologist to measure the size of earthquakes in terms of the energy released

$M_w \propto M_o = \mu A u$ (μ rigidity, *A rupture area*, *u* slip)





Are earthquakes RARE events?



Frequency of earthquakes (i.e., M>4) in the last 30 days?

about 550

http://earthquake.usgs.gov/

http://www.iris.edu

http://www.ingv.it/

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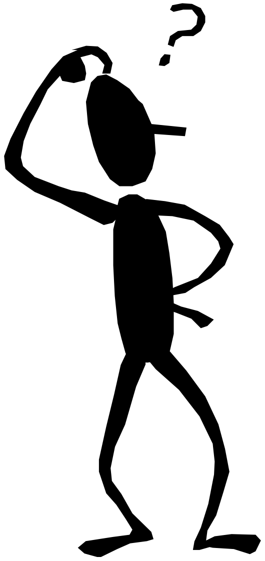
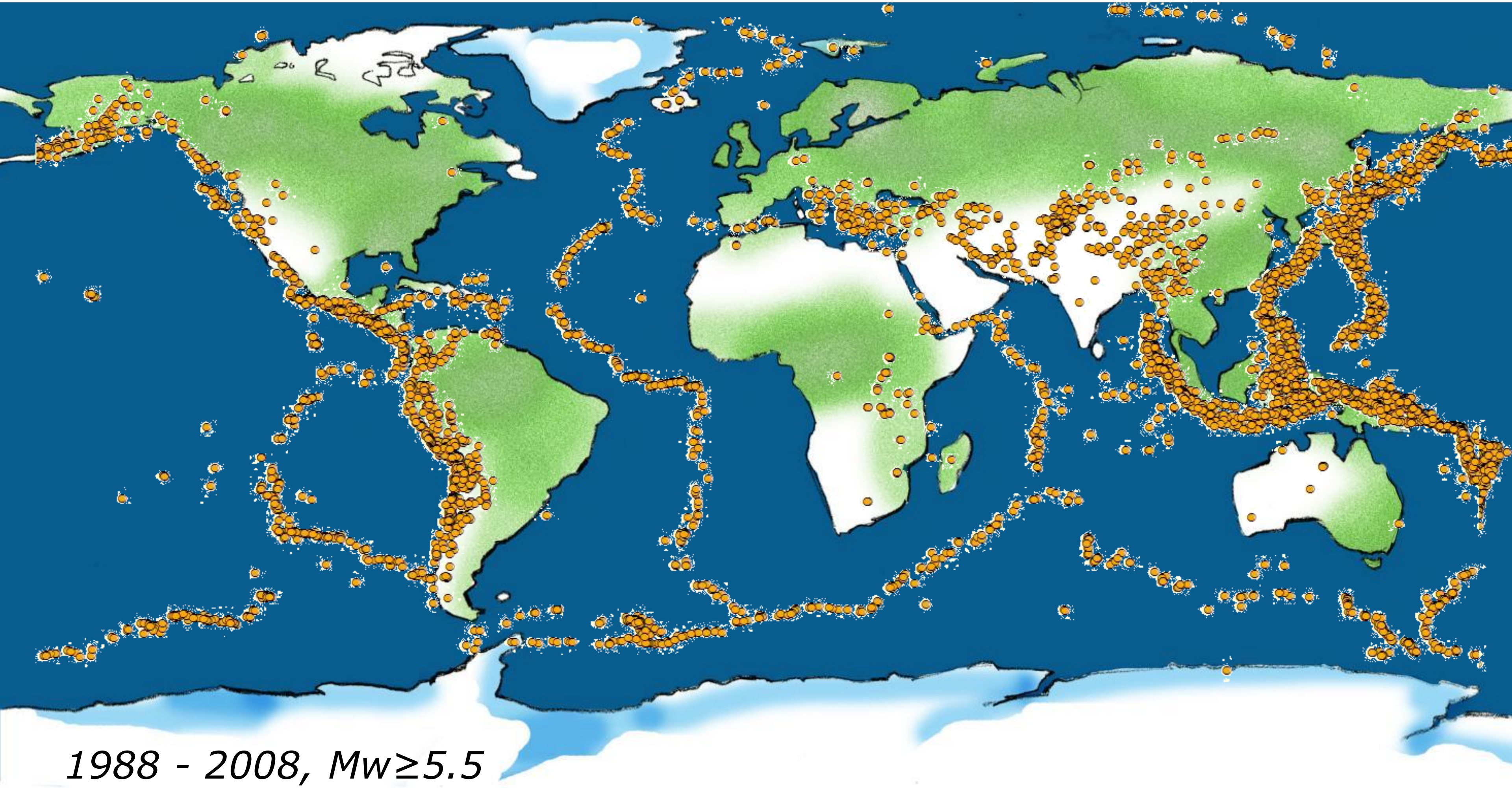


WHERE do earthquakes occur?

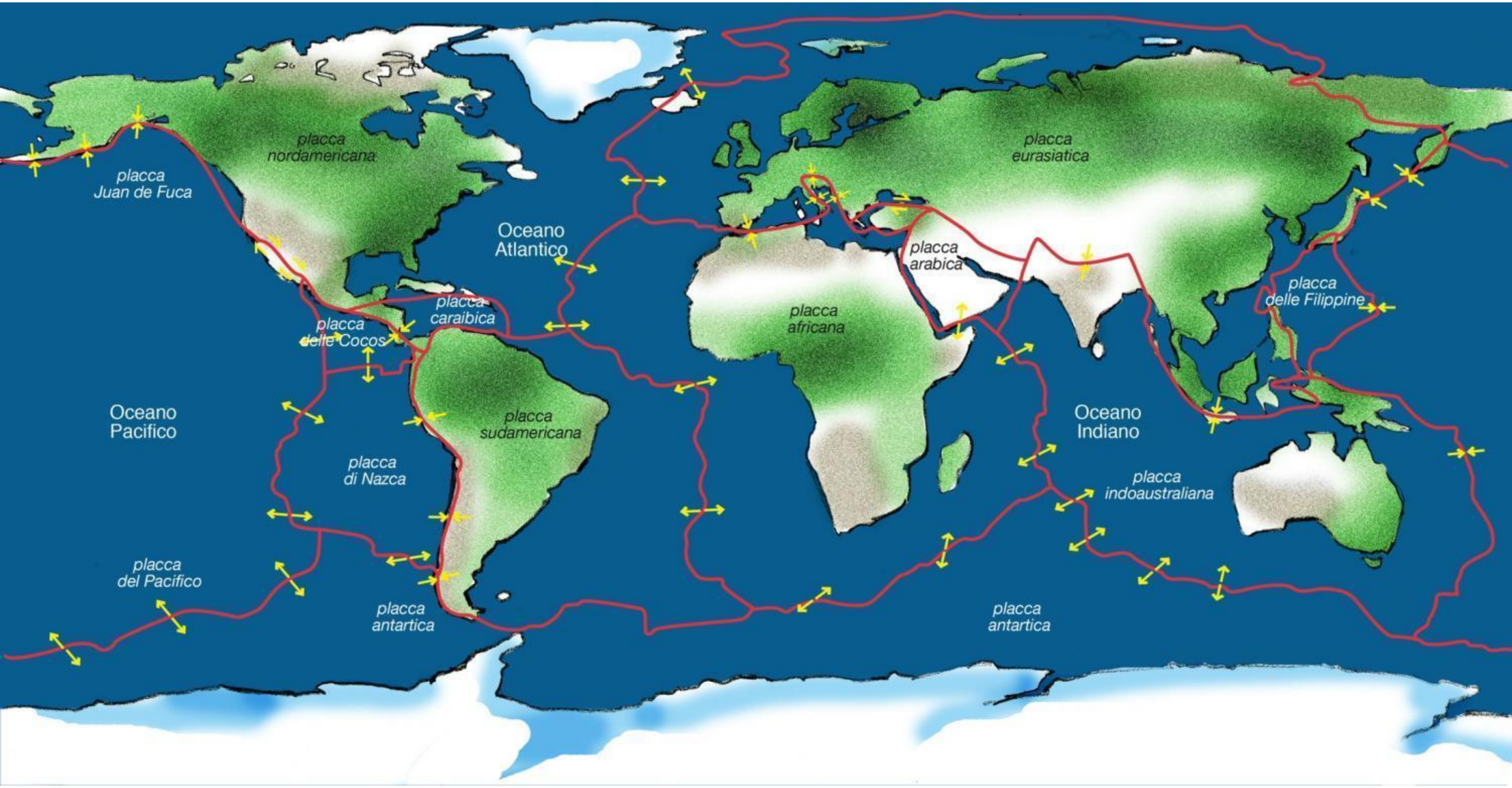
distribution earthquakes …



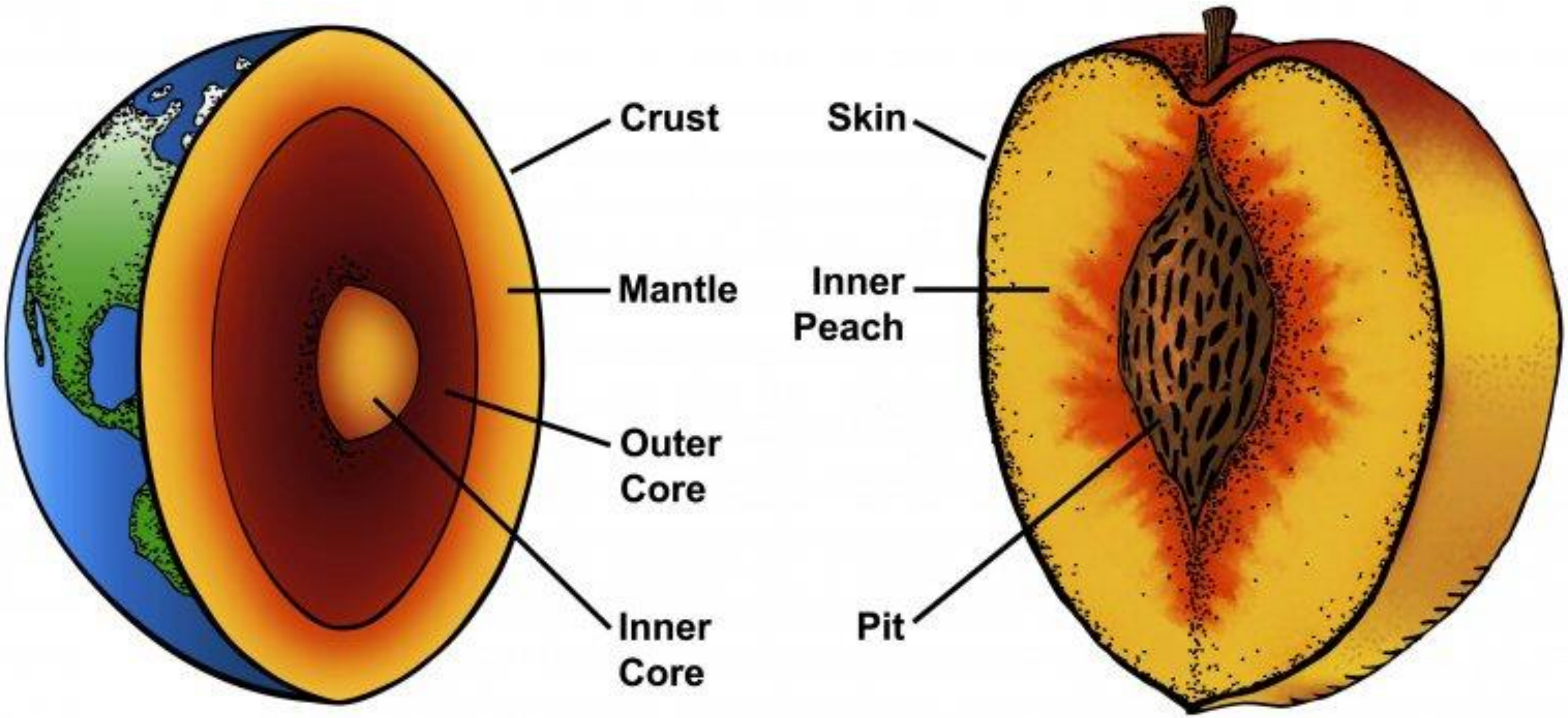
…not by chance!

INGV, Outreach Lab

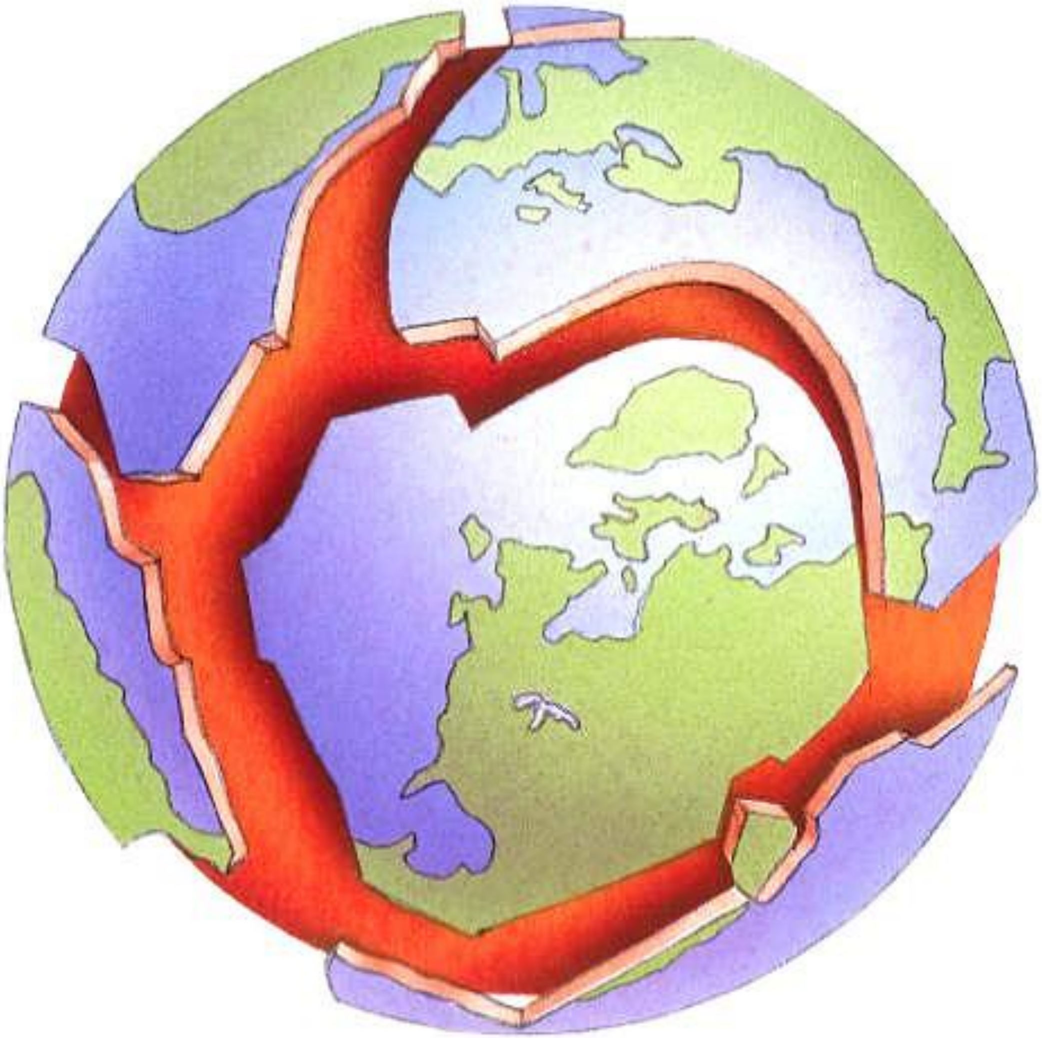
Along plate margins!



INGV, Outreach Lab

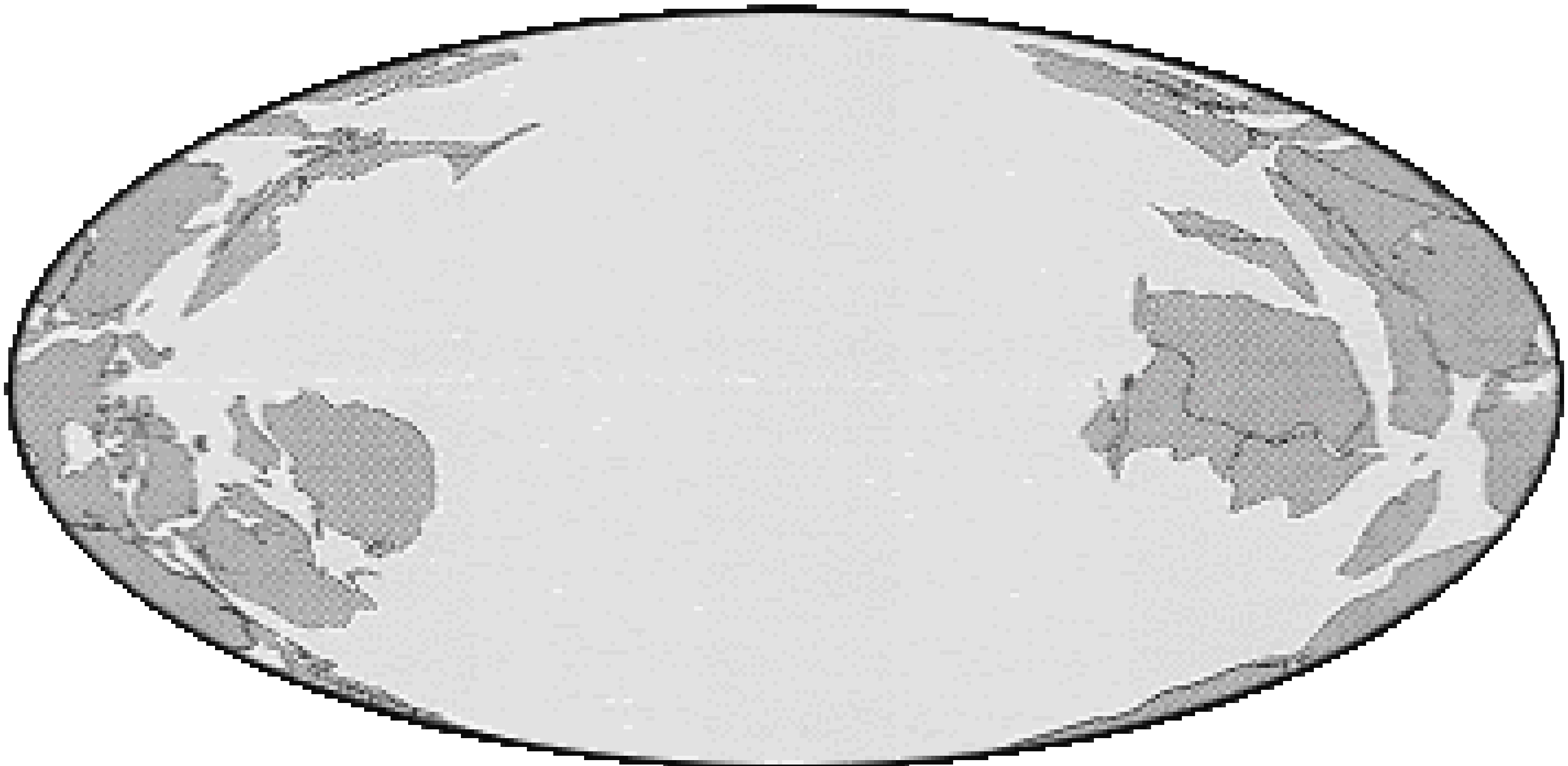

Crust
Mantle
Outer Core
Inner Core
Skin
Inner Peach
Pit

JIGSAW PUZZLE LITHOSPHERIC STRUCTURE



THE «DANCING» PLATES

today

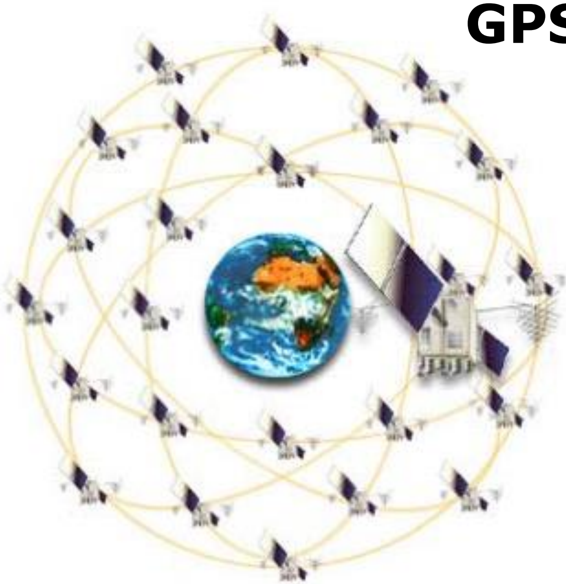


660 Ma

http://www.scotese.com

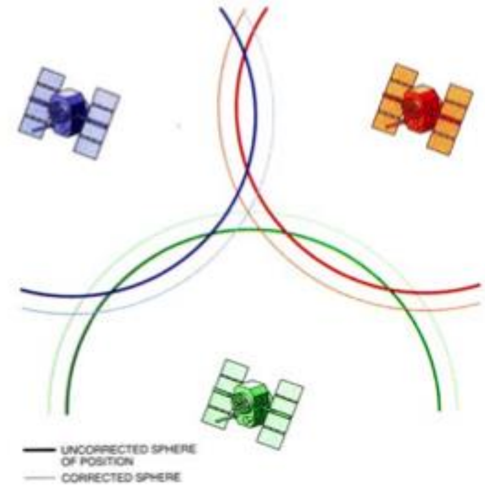
THE «DANCING» PLATES

GPS – Global Positioning System



30 satellites orbiting at ~20,000 km, period ~24h, 6-12 satellites simultaneously visible

Receivers and GPS antennas decode the satellite-antenna signals

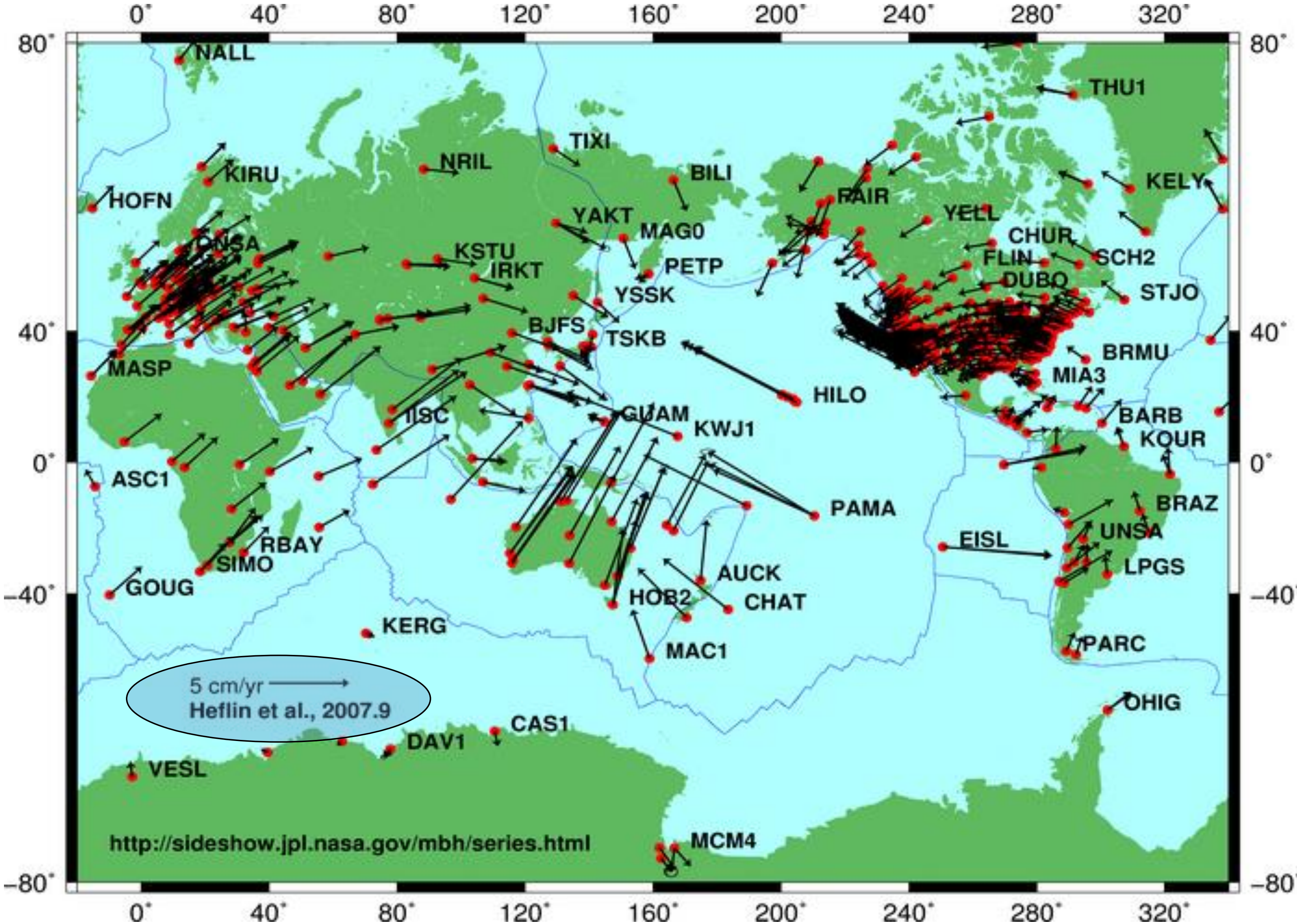


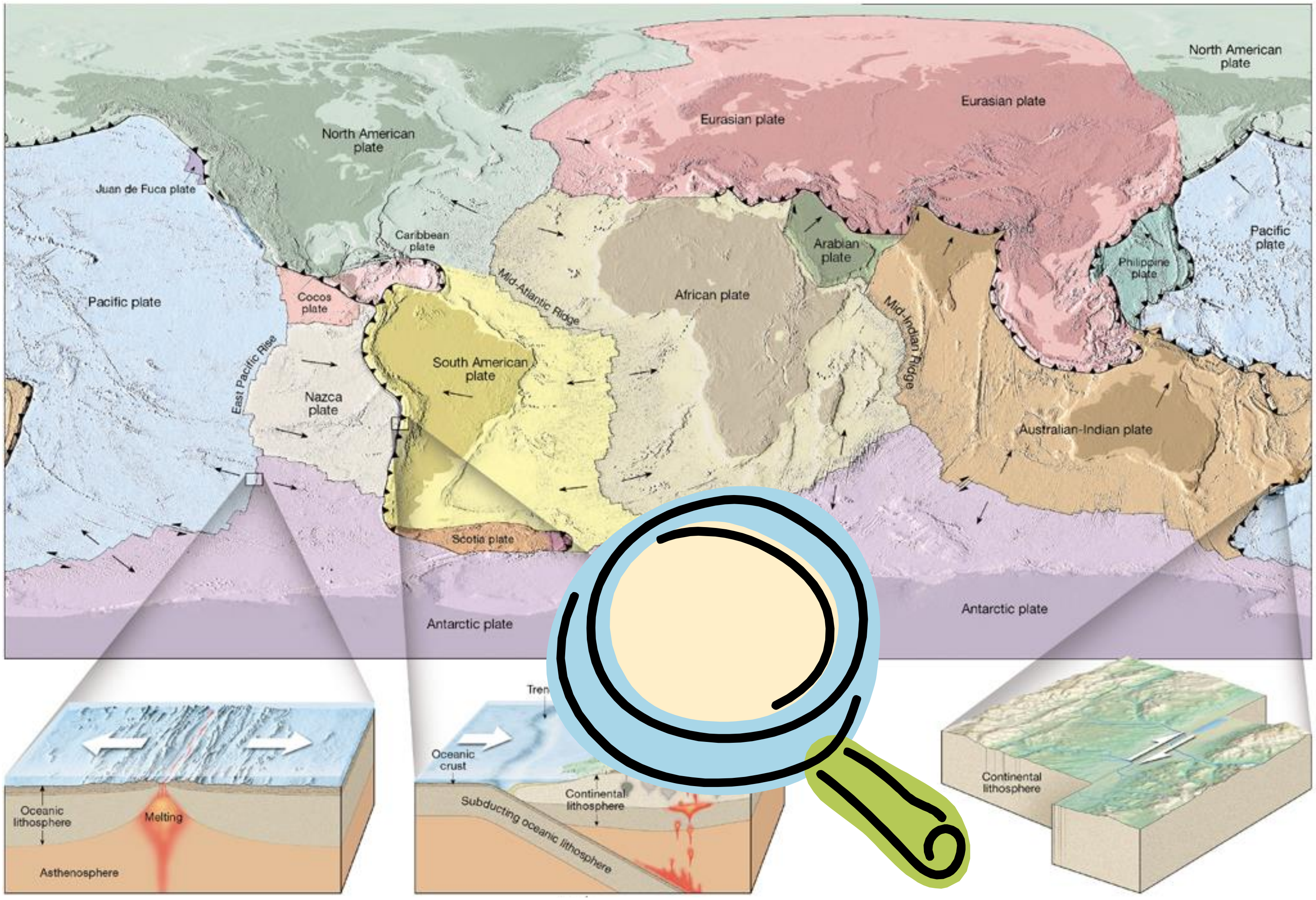
Precision:
1-10 m => 100 euro
1 mm => 10,000 euro
(with data post-processing)

APPLICATIONS

Military, positioning (aircrafts, boats, cars),
geophyiscs (measuring deformations)

THE «DANCING» PLATES





DIVERGENT MARGINS
(constructive)

CONVERGENT MARGINS
(destructive)

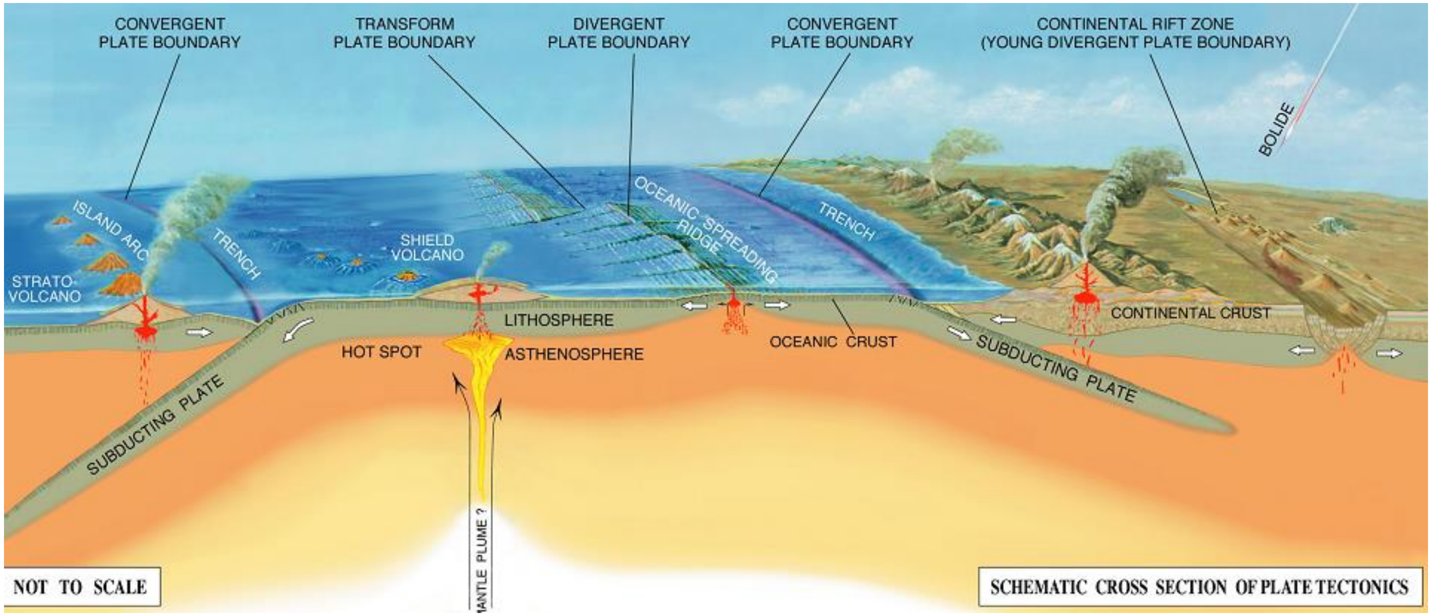
TRANSFORM MARGINS
(conservative)

SUBDUCTION

"the process of consumption of lithosphere

at convergent plate margins"

(Oxford Dictionary)



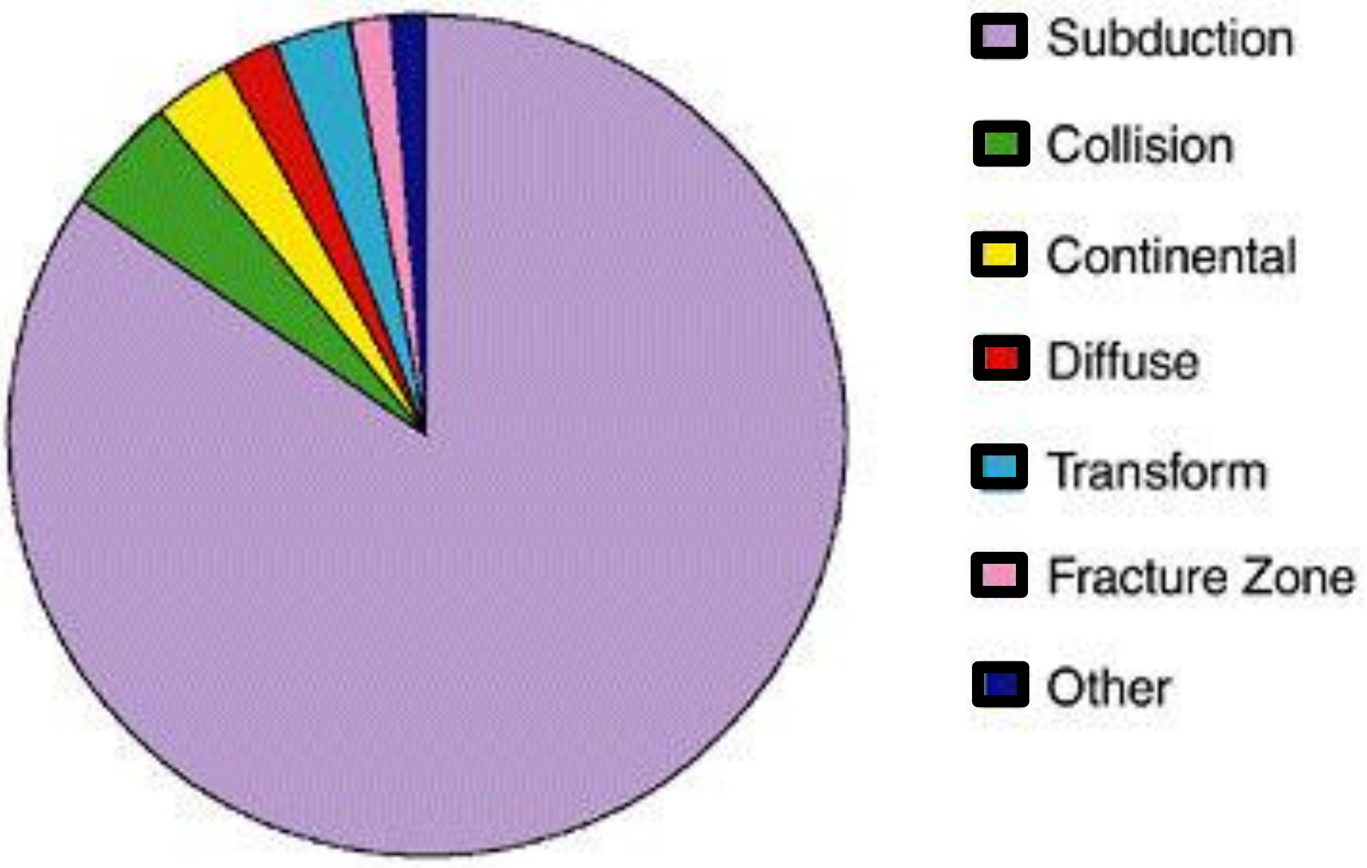
USGS

- earthquakes
- volcanism
- phase transformations

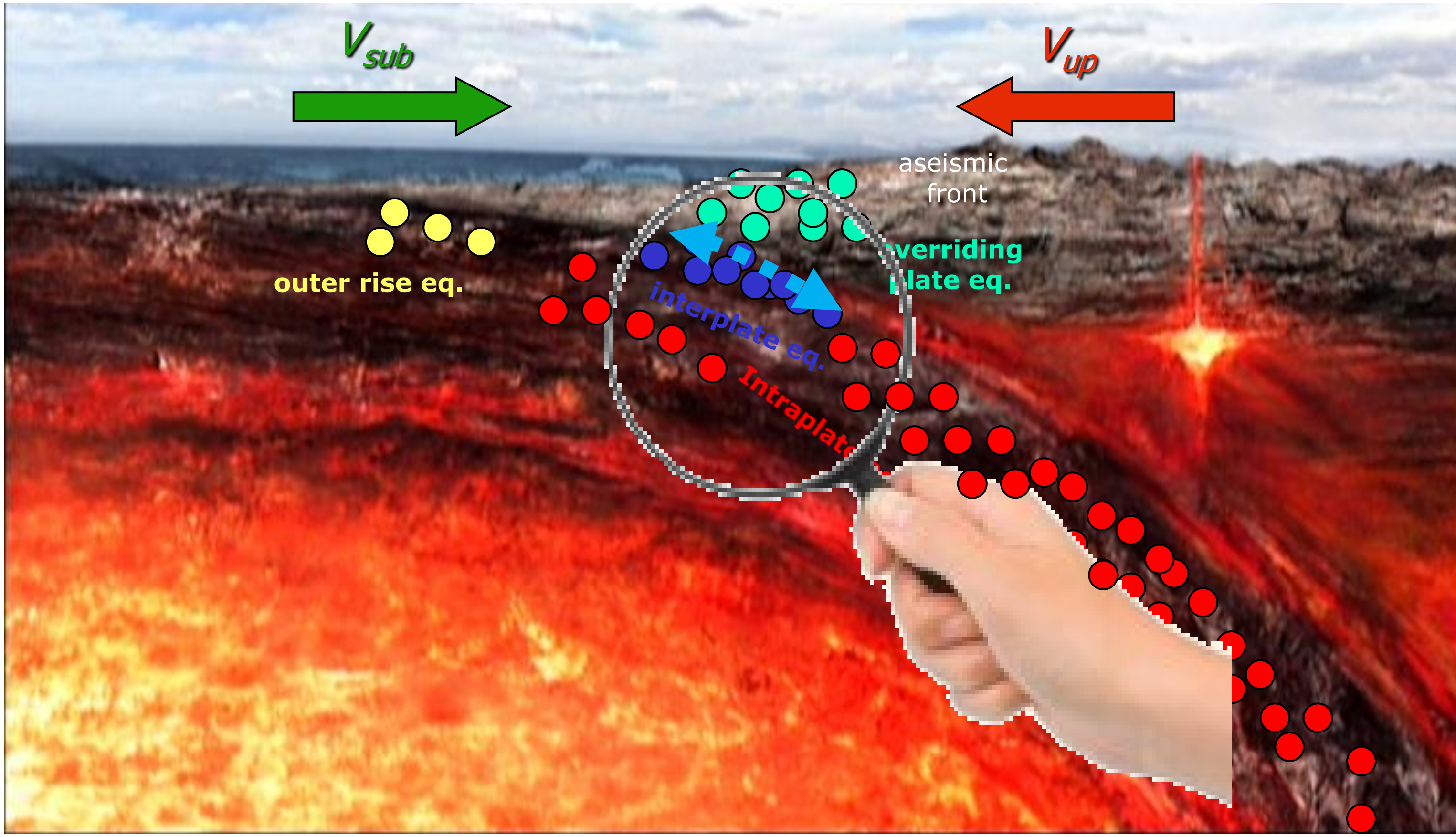
- thermal effects
- mantle circulation
- plate motion

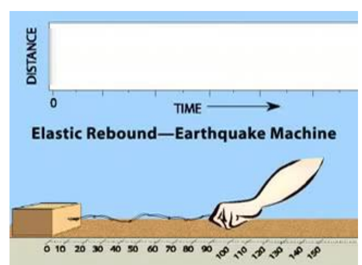
CUMULATED SEISMIC MOMENT (1900-1989)

4.0×10^{23} Nm



Pacheco and Skyes, 1989

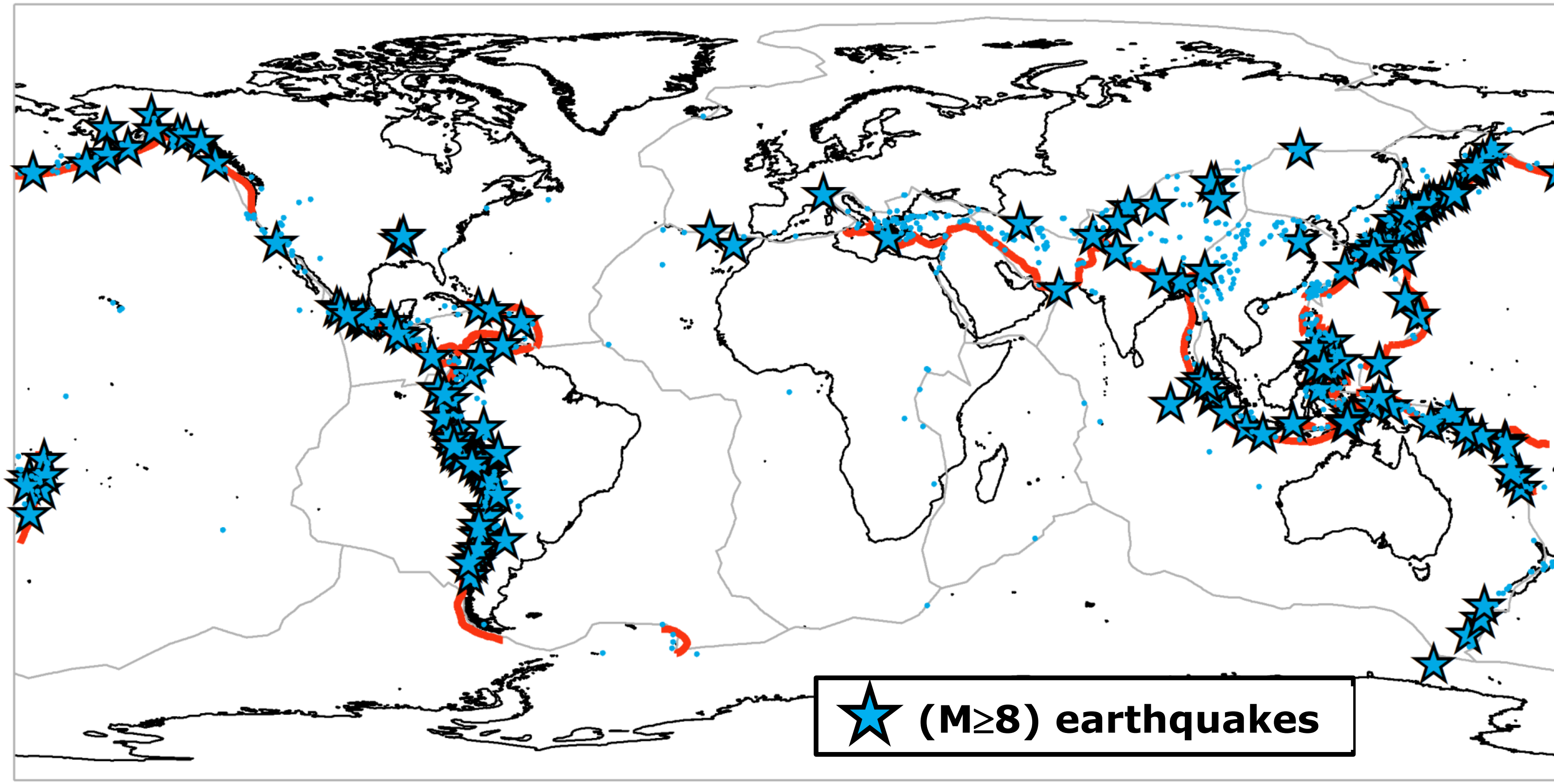




= frictional laws

= solid-solid phase transitions, dehydration

INTERPLATE SUBDUCTION EARTHQUAKES



Global Significant Earthquake Database – NGDC

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Tohoku-Oki earthquake, M_w 9.0

11 March 2011

INTERPLATE EARTHQUAKES OCCURRED ALONG SUBDUCTION THRUST FAULTS

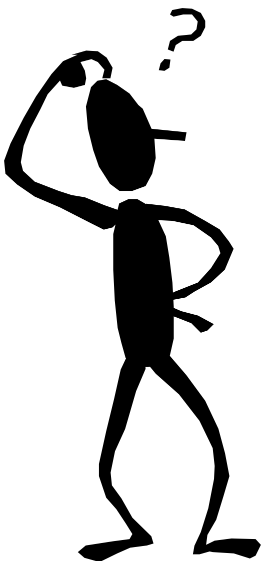
Chile earthquake, M

27 Febr

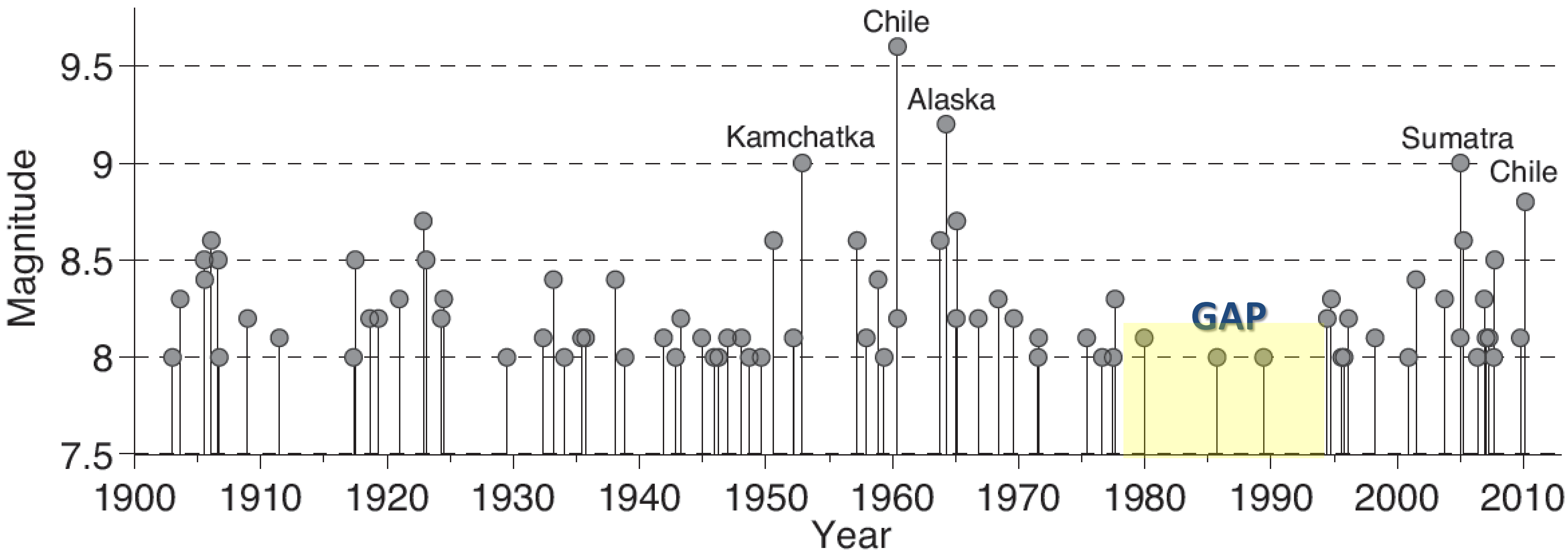
, M_w 9.1

ember.2004

Are mega-earthquakes RARE events?



TIME LINE OF MEGA-EARTHQUAKES

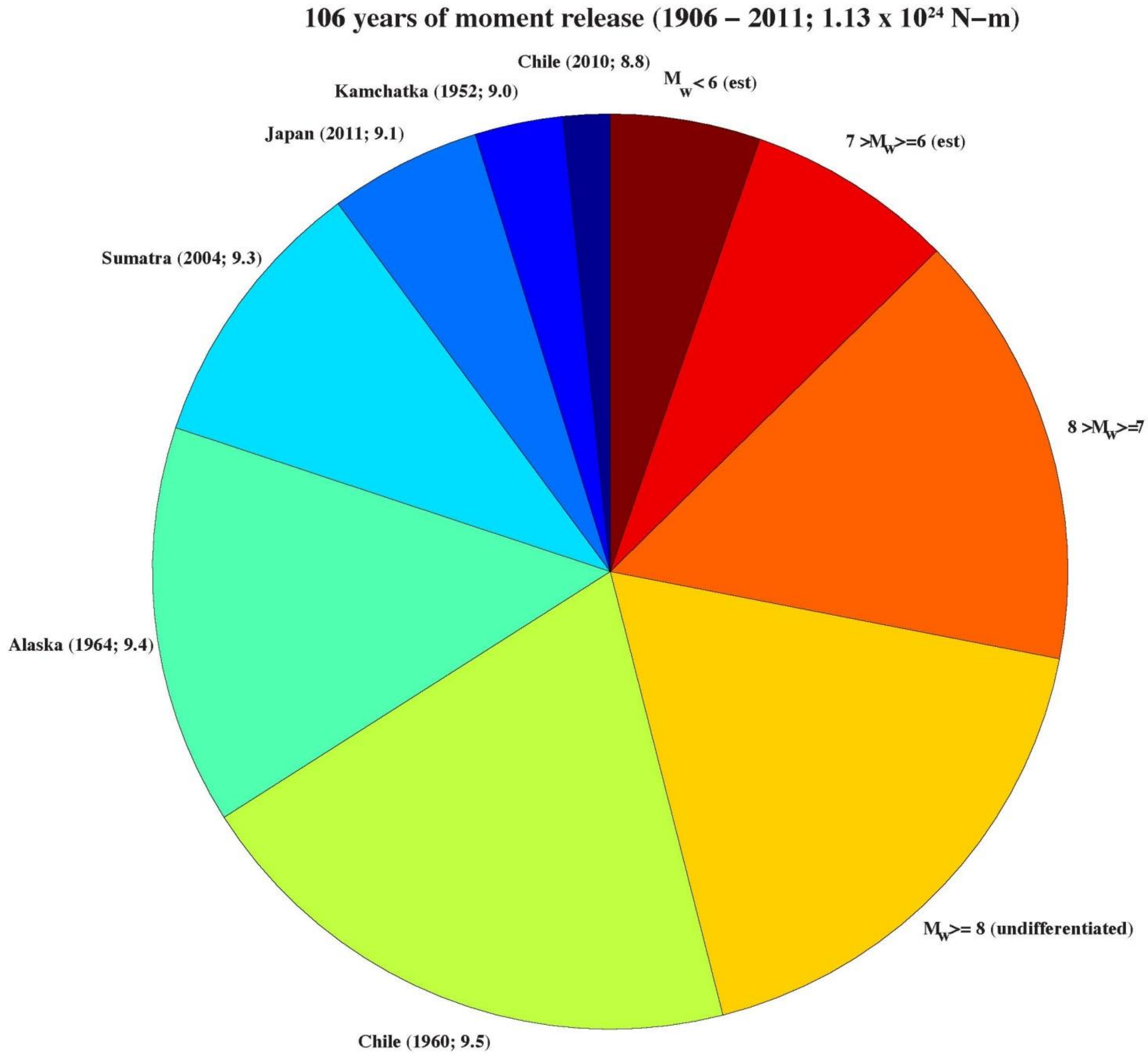


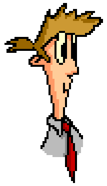
magnitude 8.0-8.9 → yearly avarage **1**

magnitude > 9.0 → yearly avarage **0.1**

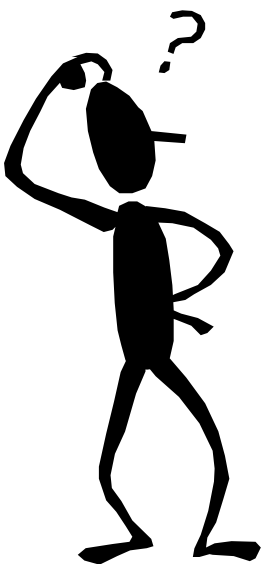
Ammon et al., 2010

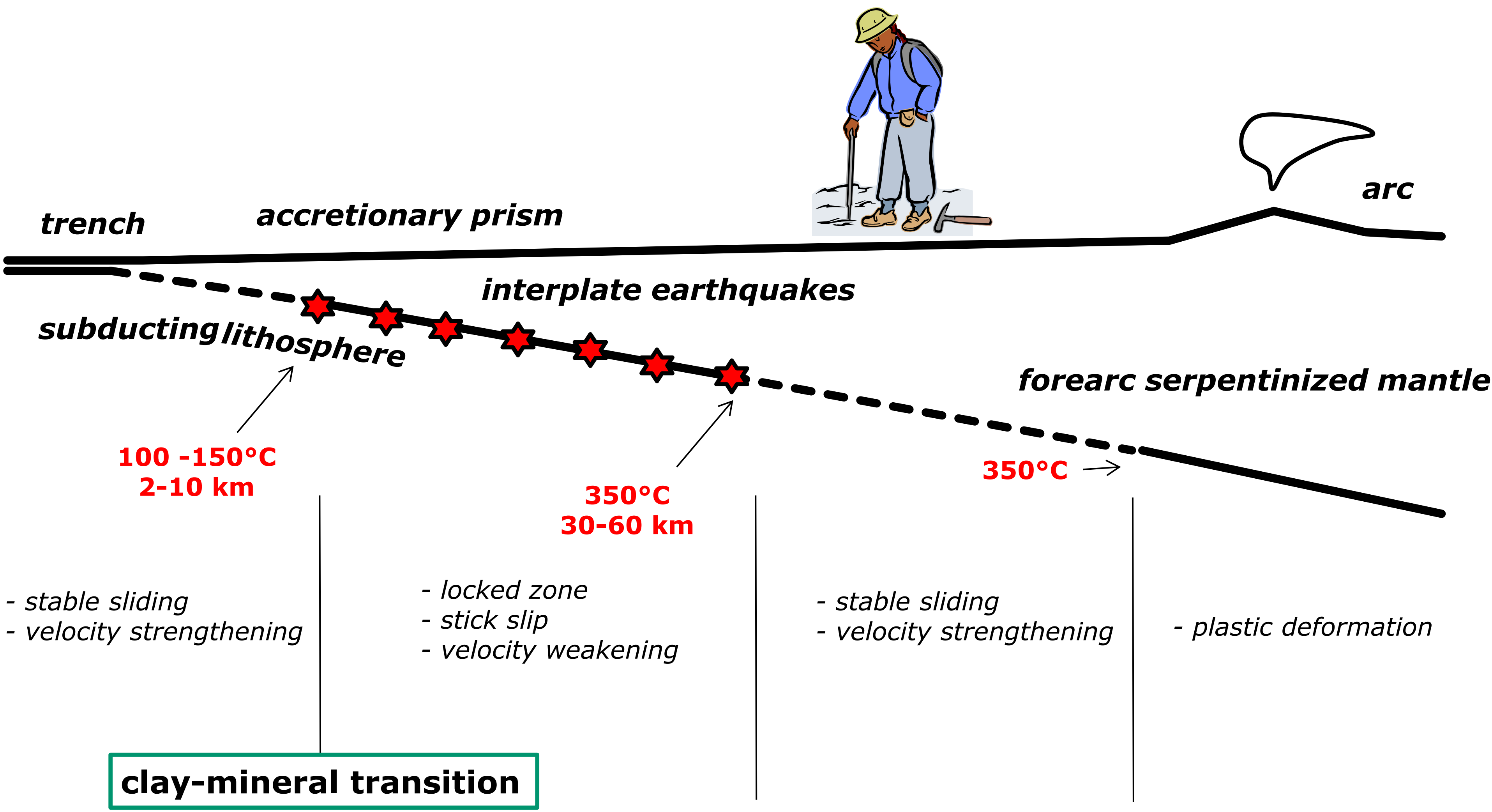
Only 6 (interplate) earthquakes over the last 106 years account for over half of the energy released during that time!!!





HOW
can be studied the subduction thrust fault?

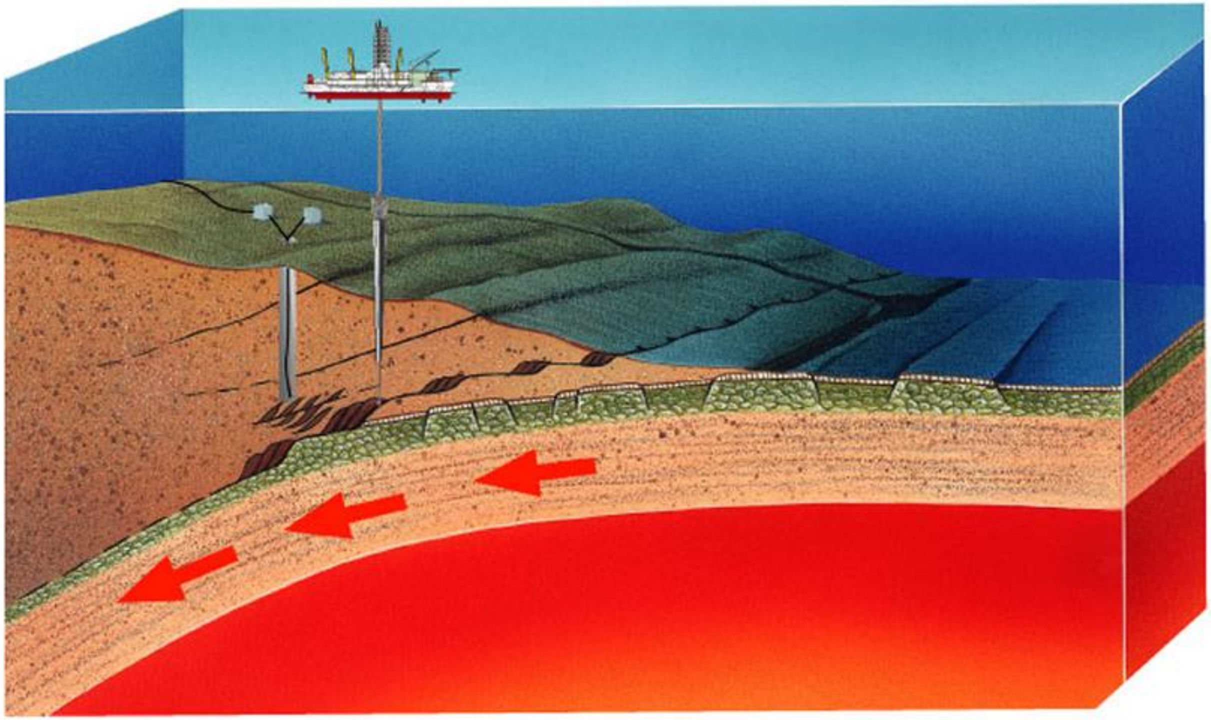




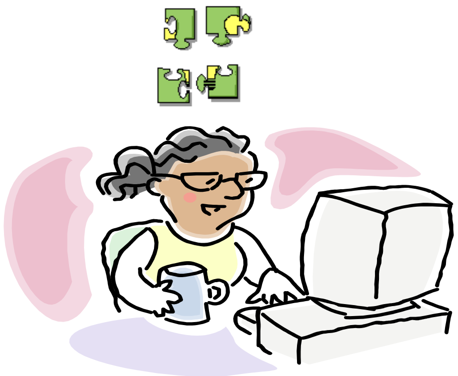
after Byrne et al., 1988; Scholz, 1998; Saffer & Marone, 2003

CHIKYU 地球 HAKKEN 発見

IODP
INTEGRATED OCEAN DRILLING PROGRAM



http://www.jamstec.go.jp/chikyu/eng/



exhumed faults

modeling

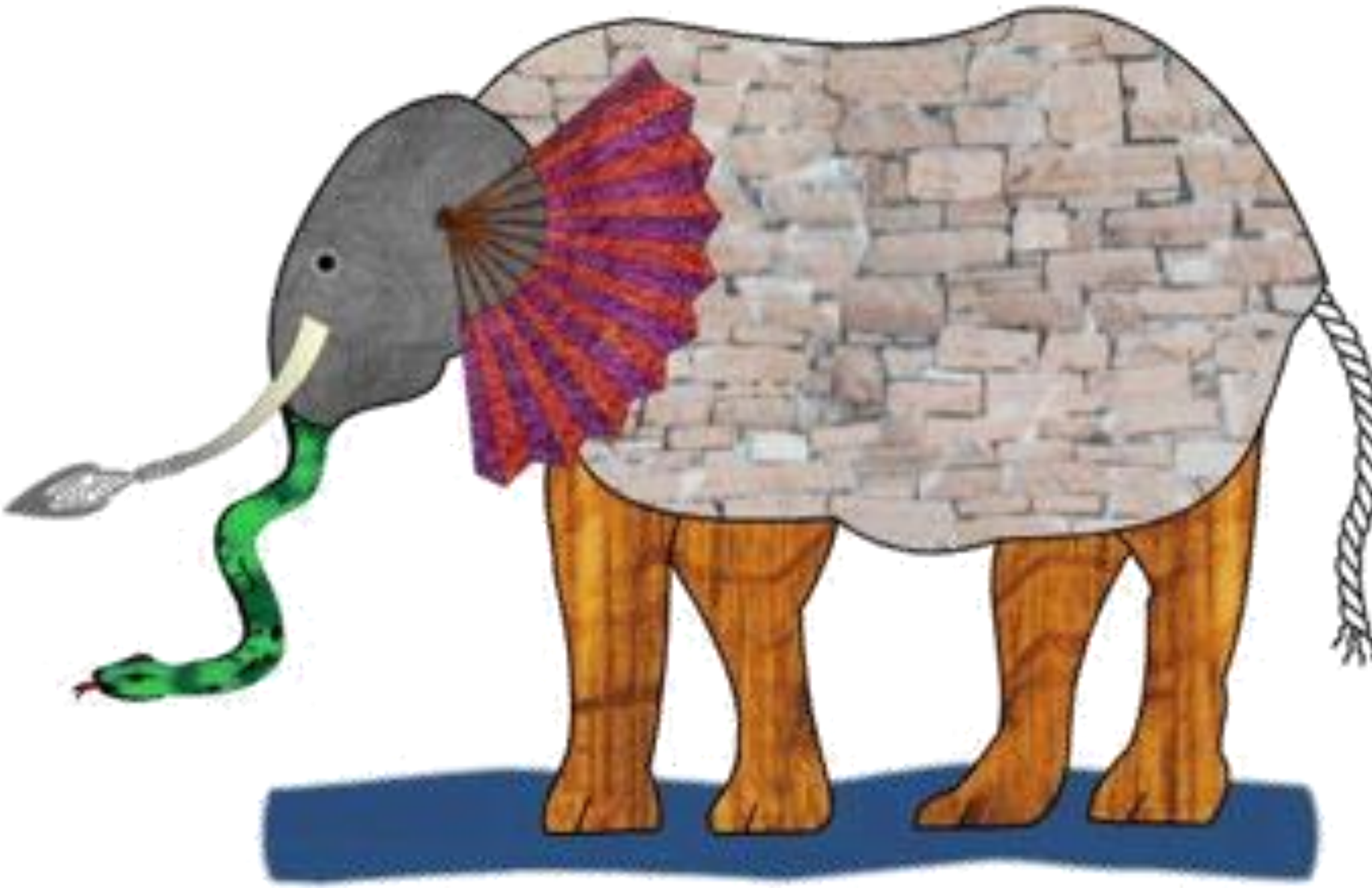
analysis of interplate events

stress indicators along the plate boundary

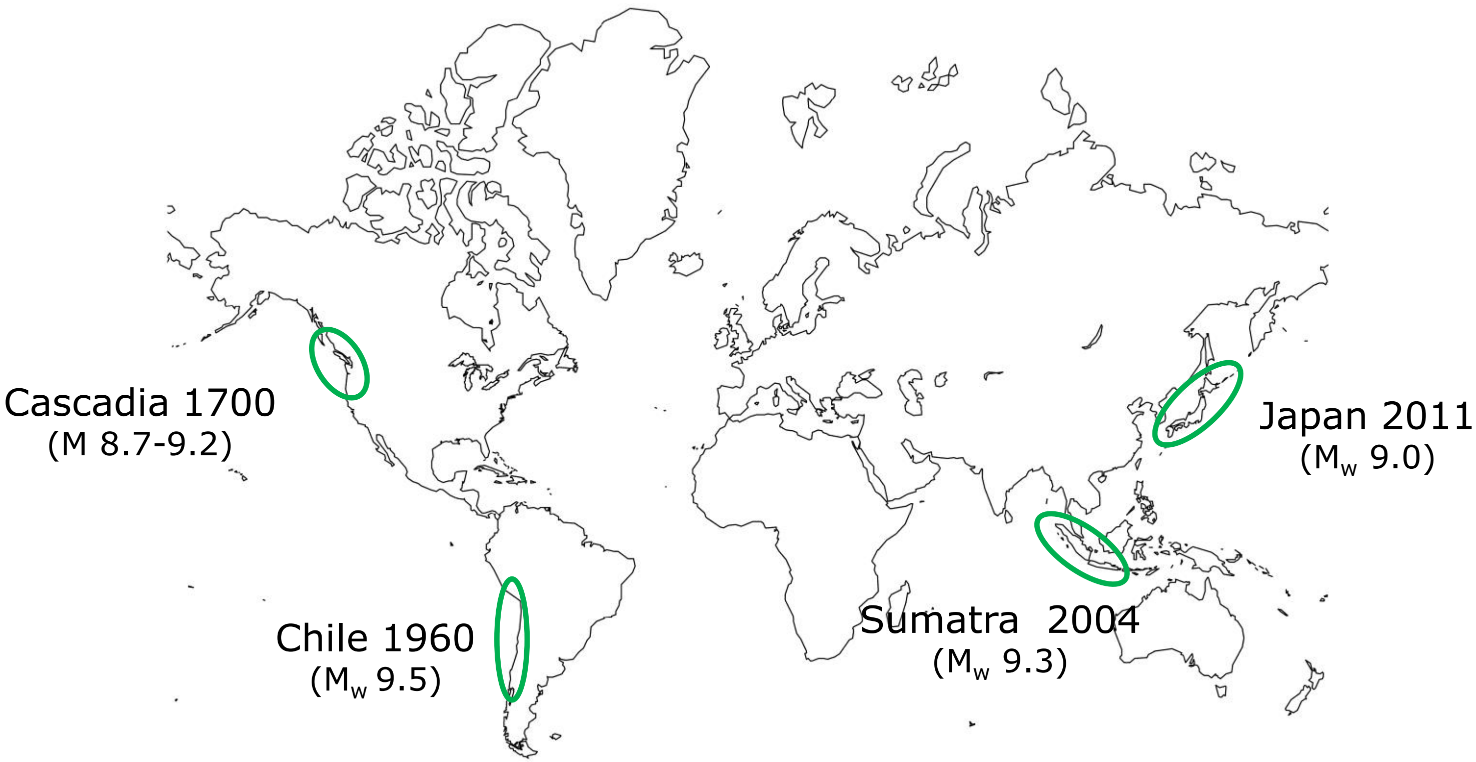
geodetic data

geophysical and geothermal data

seismic sections



- Earthquake cycle is a common process.
- Study of multiple subduction zones, that are presently at different phases of the earthquake cycle, help to understand the full cycle.

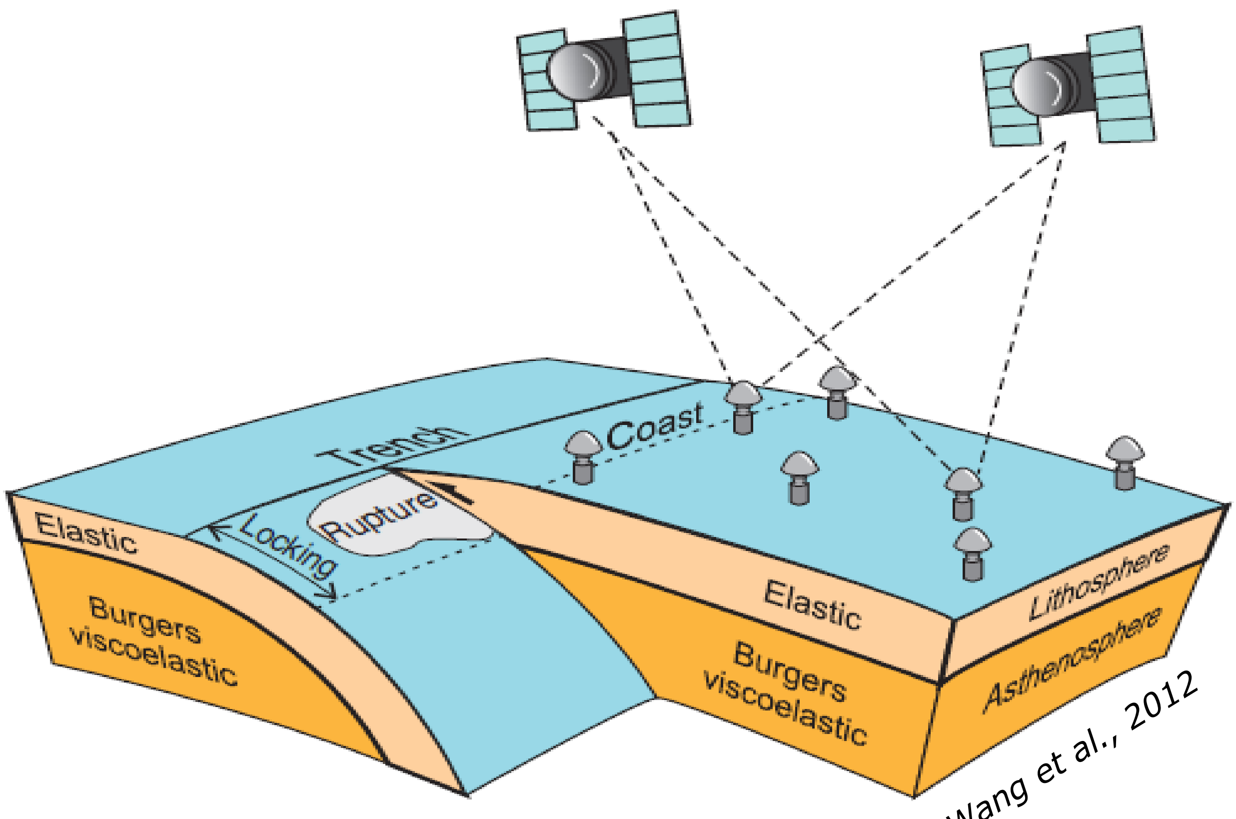


THE GEODETIC REVOLUTION

piecing together geodetic ‘snapshots’ from different subduction zones leads to a unifying picture of strain accumulation

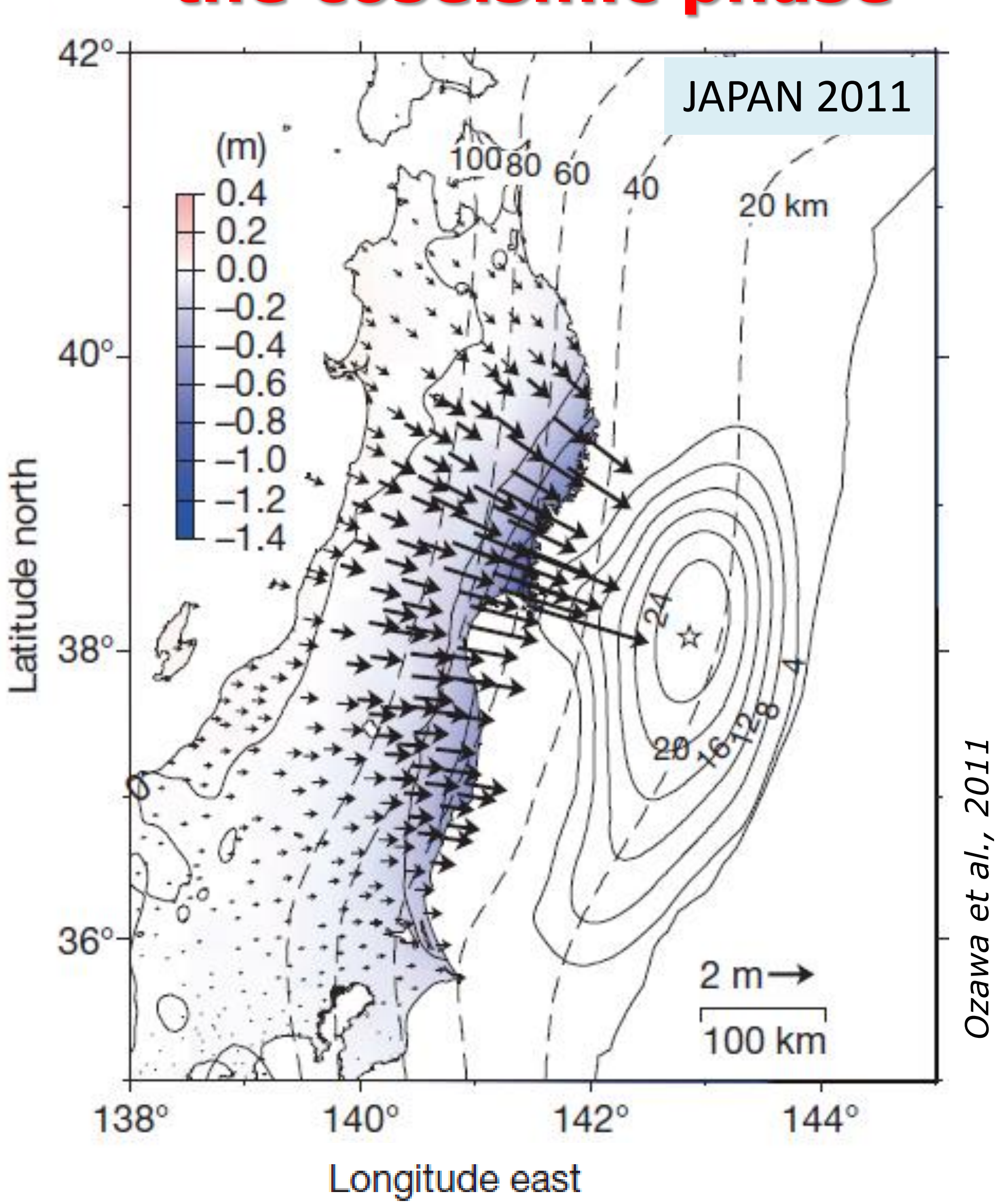
↓

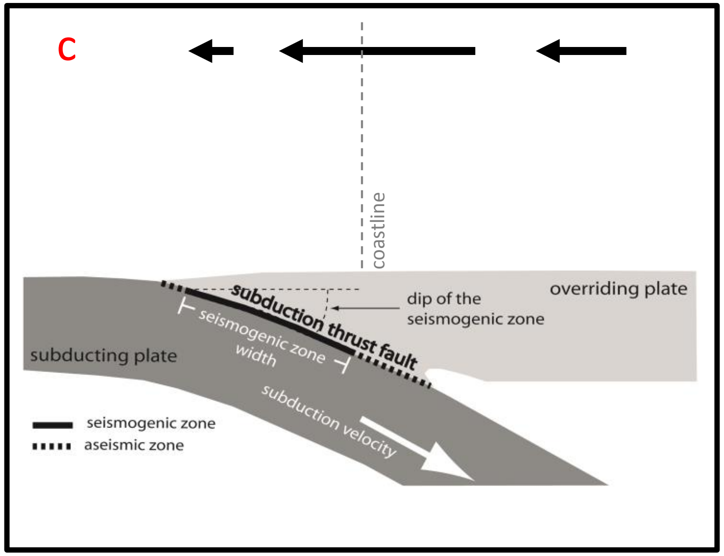
a new tool for evaluating seismic potential



Wang et al., 2012

few catastrophic seconds …
the coseismic phase





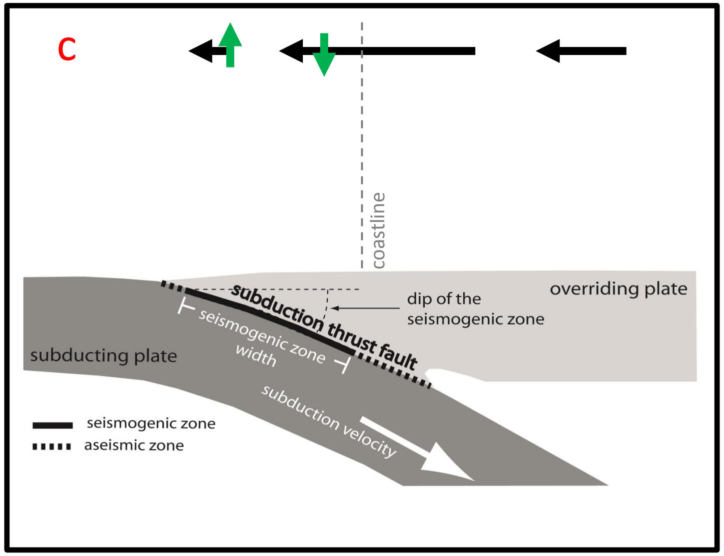
coseismic deformation
due to the
2011 Tohoku-Oki
earthquake
(one of the best
monitored event)

all sites move seaward

few catastrophic seconds … the coseismic phase

sudden uplift and subsidence

coseismic vertical displacement off the coast of Sumatra



few km from the trench

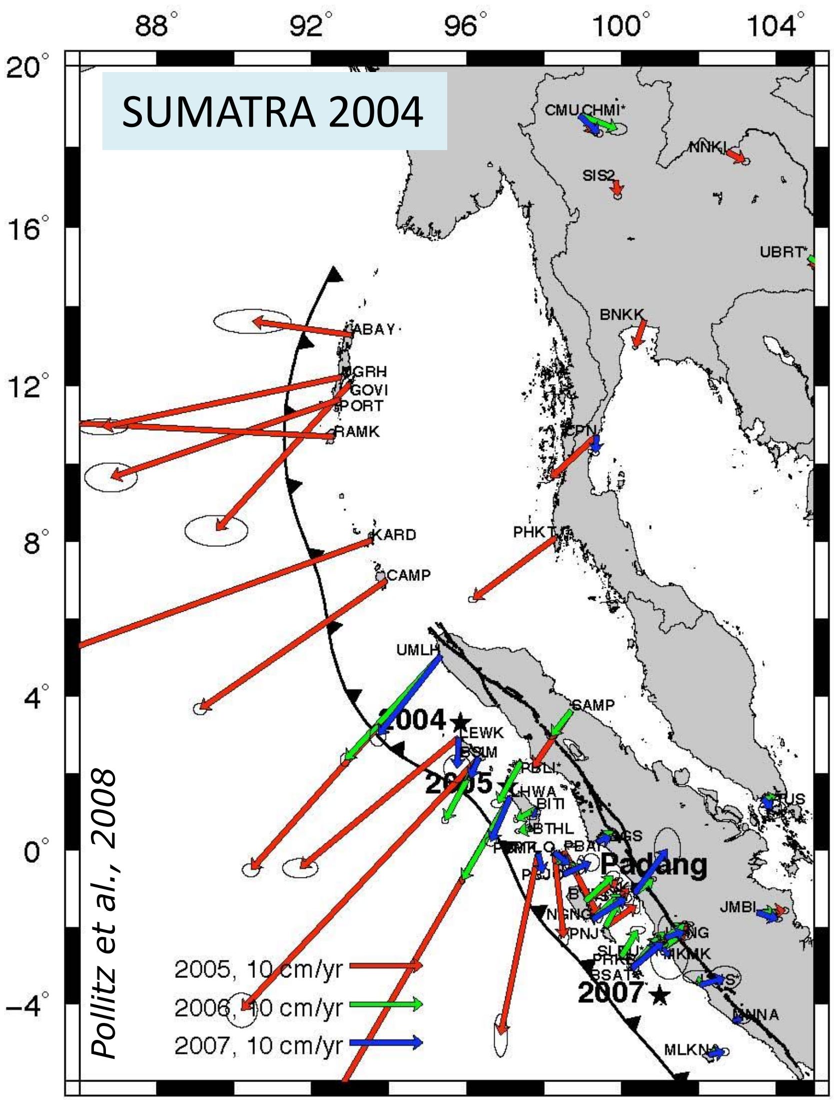
inland site

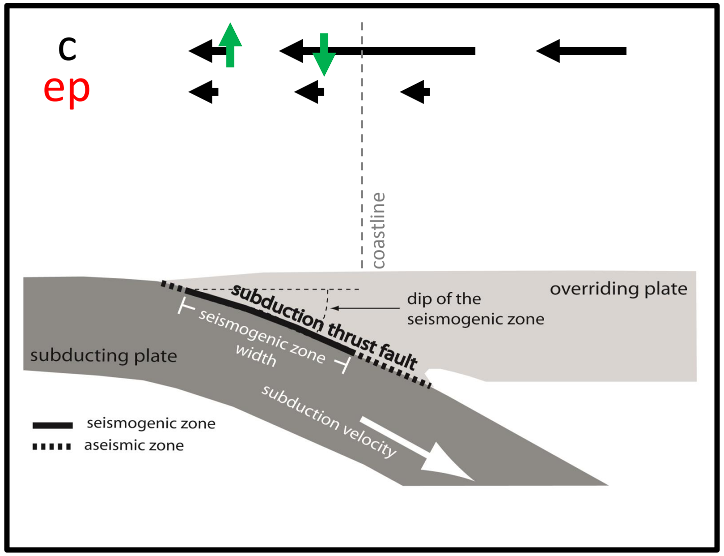
SUMATRA 2004

from CalTech Obs Sumatra

1-3 years later…

the early post-seismic phase



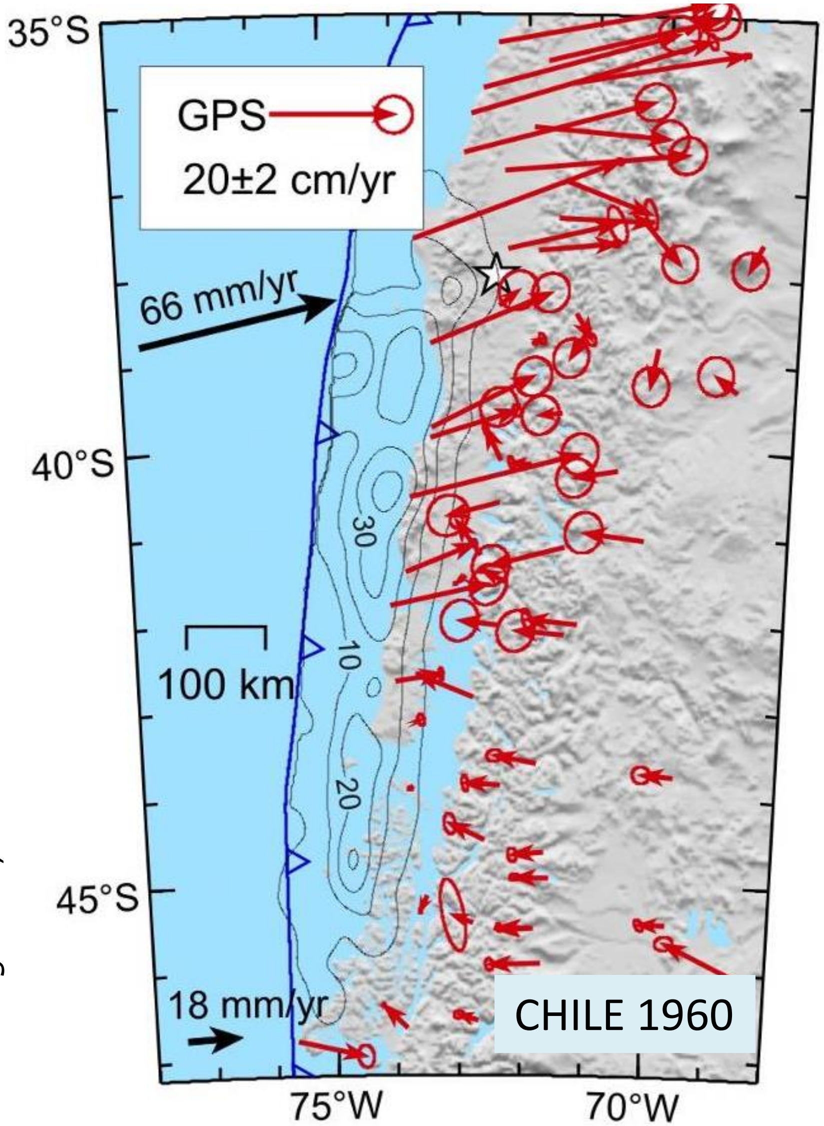


seaward motion is the result of afterslip and viscoelastic mantle relaxation

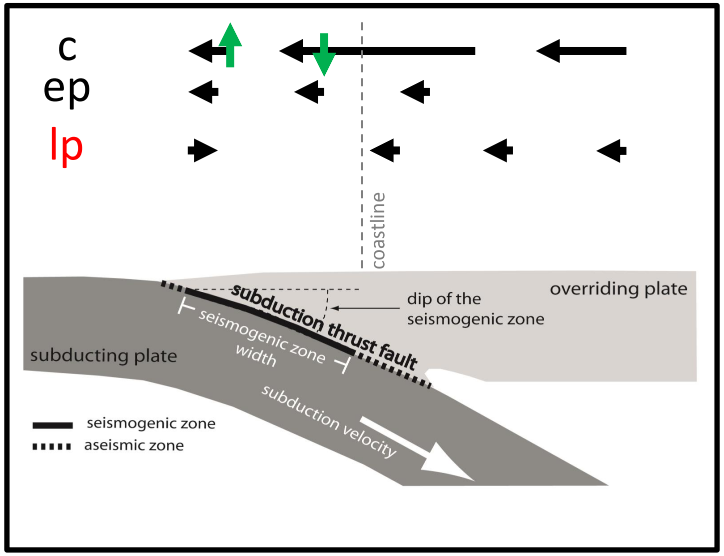
seaward motion decreasing with time!

50 years later…

the late post-seismic phase



Wang et al., 2012

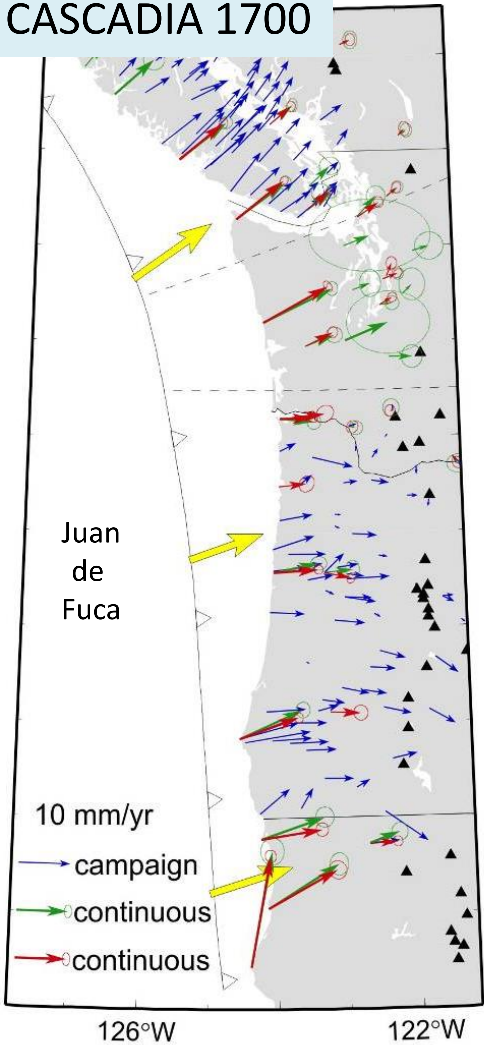


opposing motion of coastal and inland sites

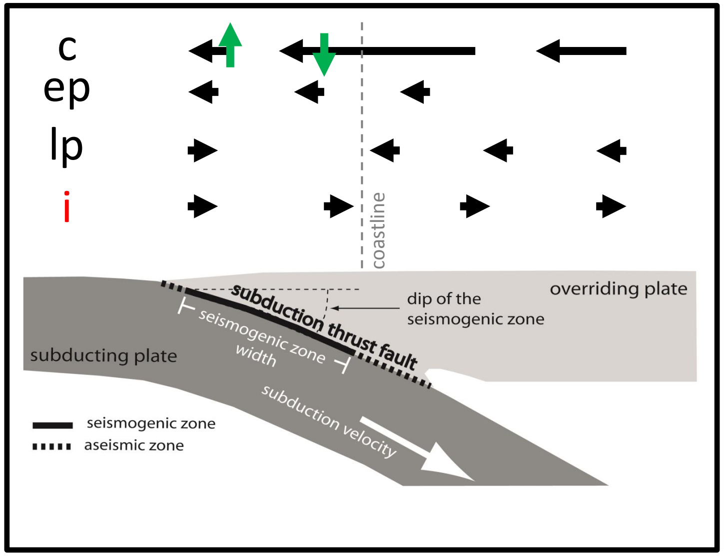
~300 (or more) years later...

interseismic phase

CASCADIA 1700

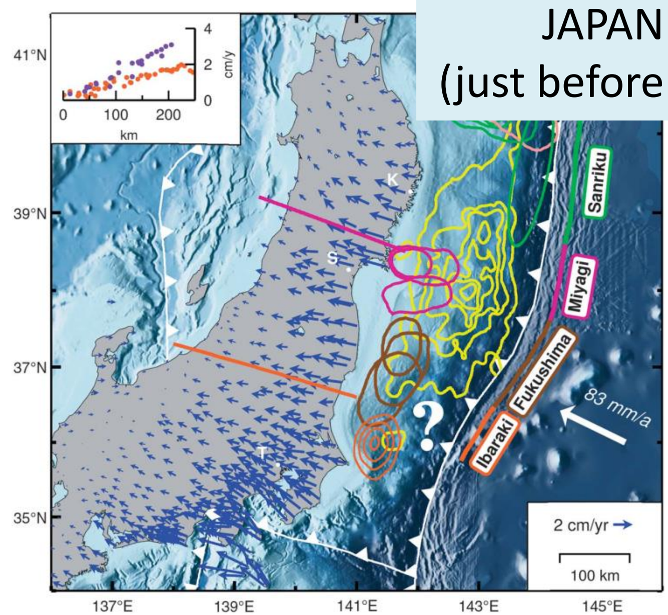


courtesy K. Wang

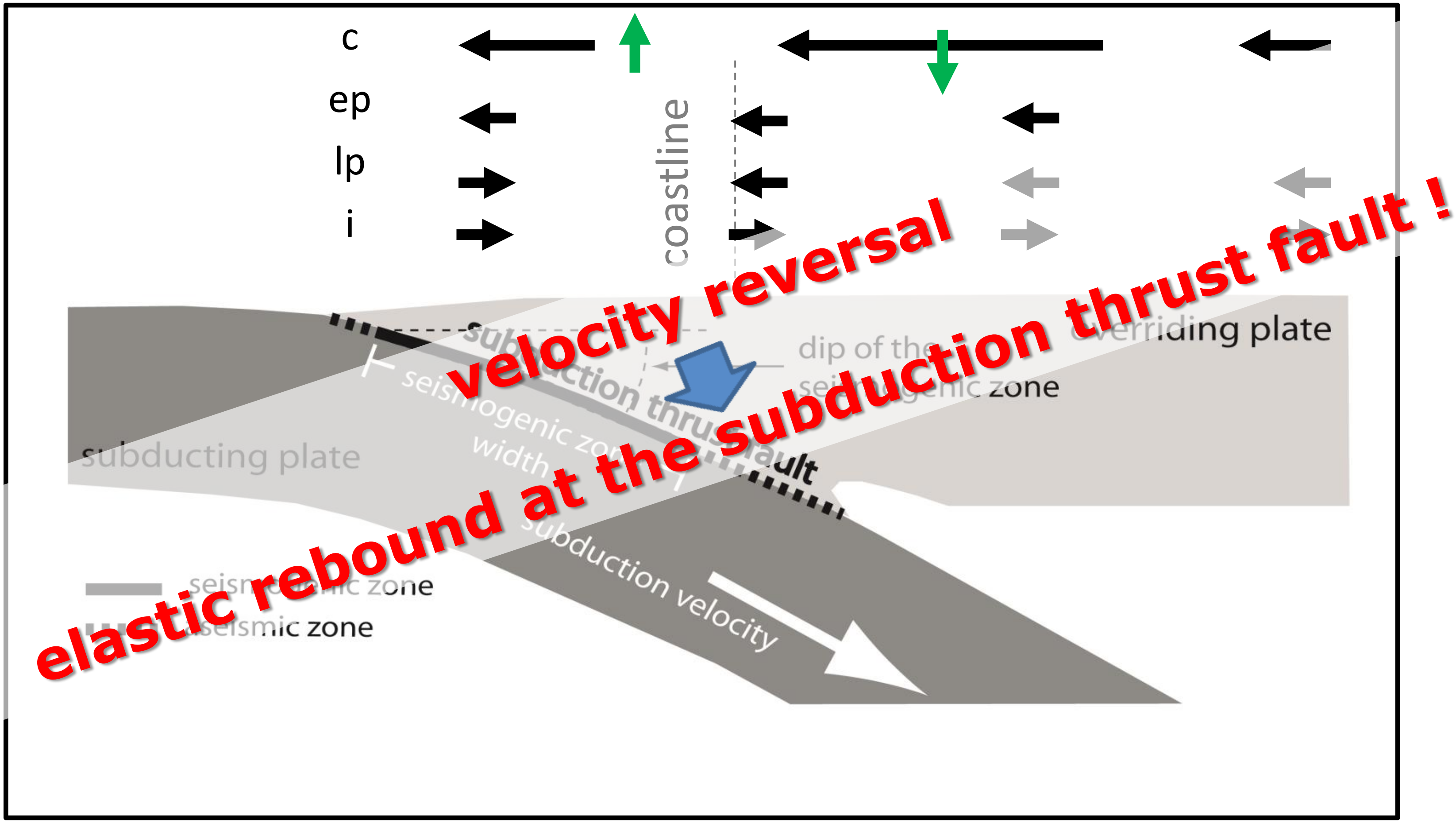


all sites move landward

JAPAN 2011
(just before the event)



Simons et al., 2011



c
ep
lp
i
coastline
velocity reversal
elastic rebound at the subduction thrust fault !
overriding plate
dip of the seismogenic zone
subduction thrust fault
seismogenic zone width
subducting plate
subduction velocity
seismogenic zone
aseismic zone

A SINGLE MECHANISM ...

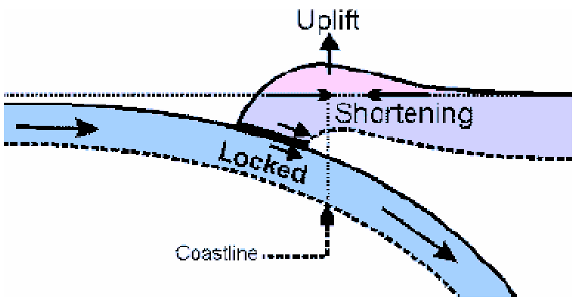
INTERSEISMIC PHASE

seismic cycle

COSEISMIC PHASE

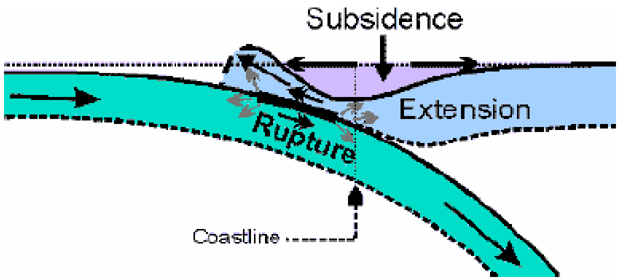
10-200 yrs

While plate convergence is occurring, the two plates are locked over some width of the subduction thrust fault, resulting in both uplift and horizontal shortening of the plate margin.



A few minutes

Once the accumulating stress exceeds the strenght of the fault, the locked zone fails abd a great earthquake occurrs. During the rupture, stored elastic strain is released, resulting in subsidence and horizontal extention in those regions where slow uplift and horizontal shortening had accumulated.
Underwater displacement can cause tsunami.
Once stress s releived, the cycle begins again.

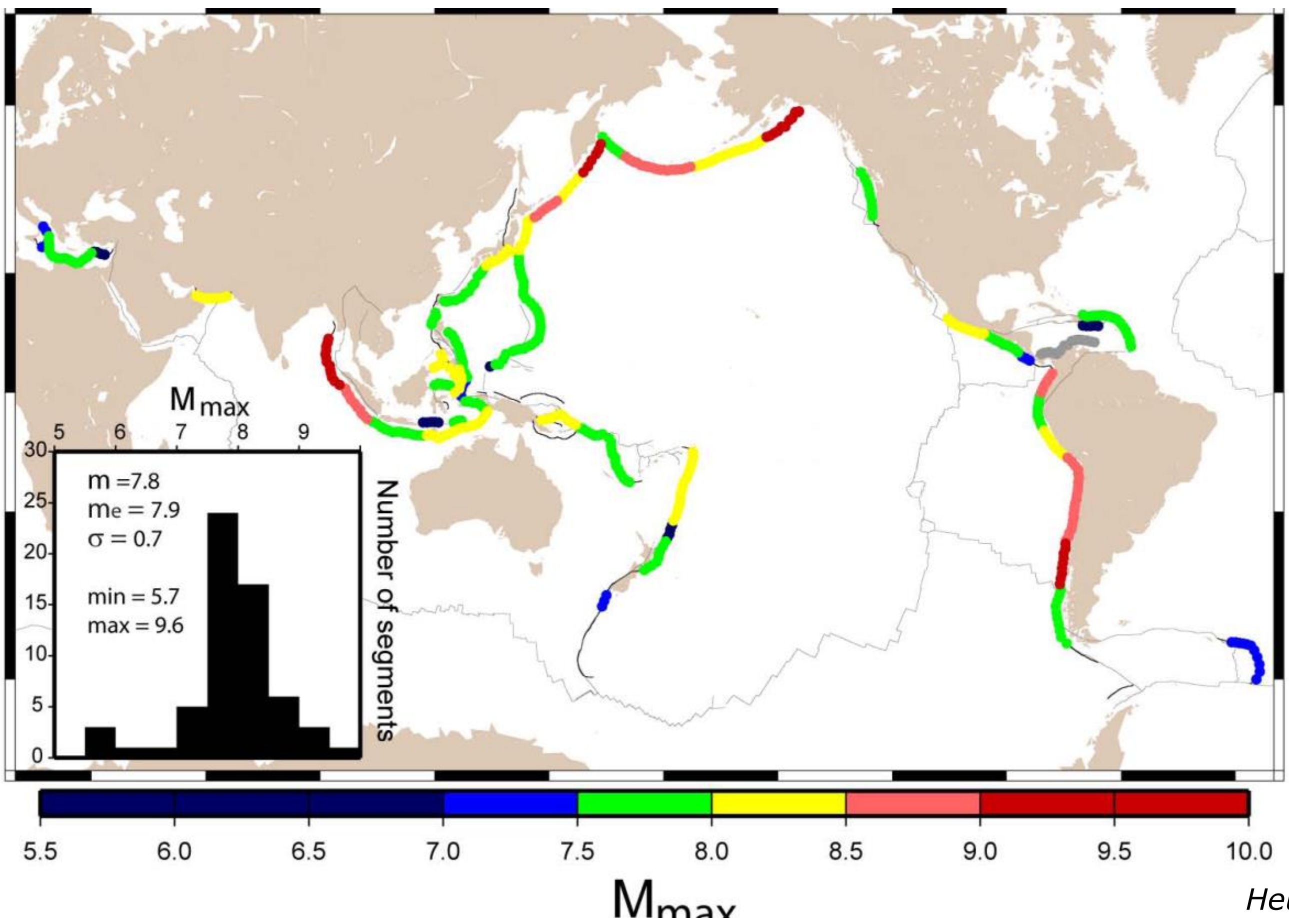


modified from Hyndman

A SINGLE MECHANISM …
… DIFFERENT BEHAVIOURS!

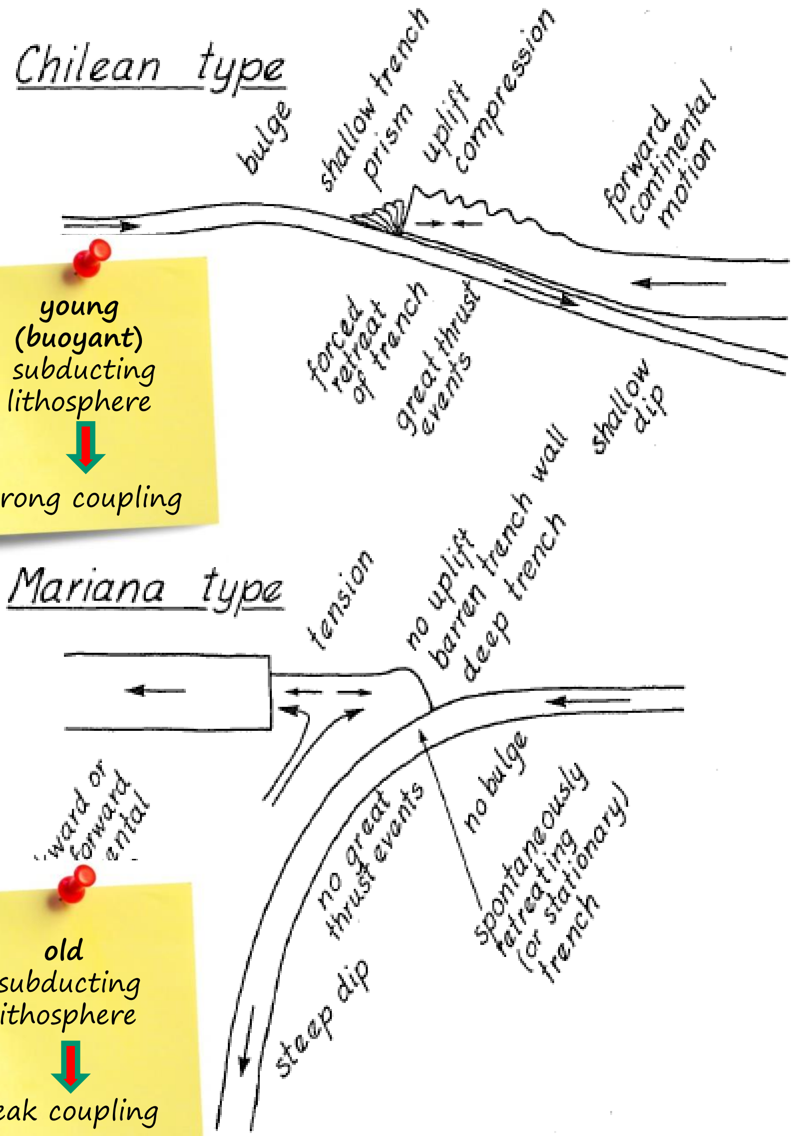
Some subduction zones produce great earthquakes with magnitude over M9 (Japan, Chile)

… other relatively smaller events (Marianas, Caribbean)



Heuret et al, 2011

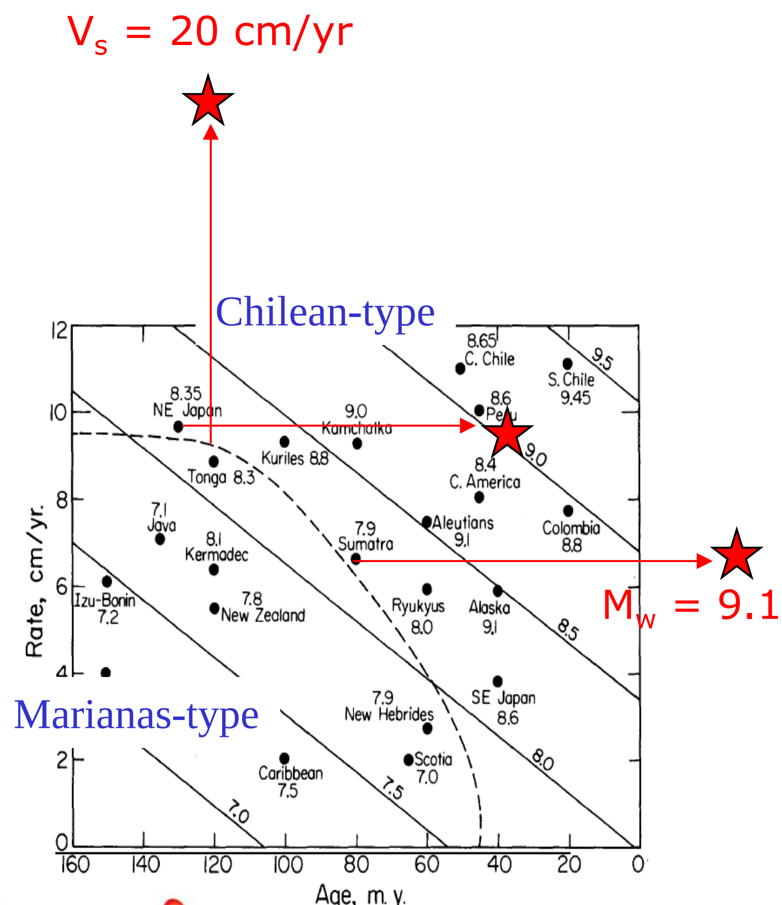
THE ANCESTRAL IDEA



young (buoyant) subducting lithosphere
↓
strong coupling

old subducting lithosphere
↓
weak coupling

Uyeda and Kanamori, 1979



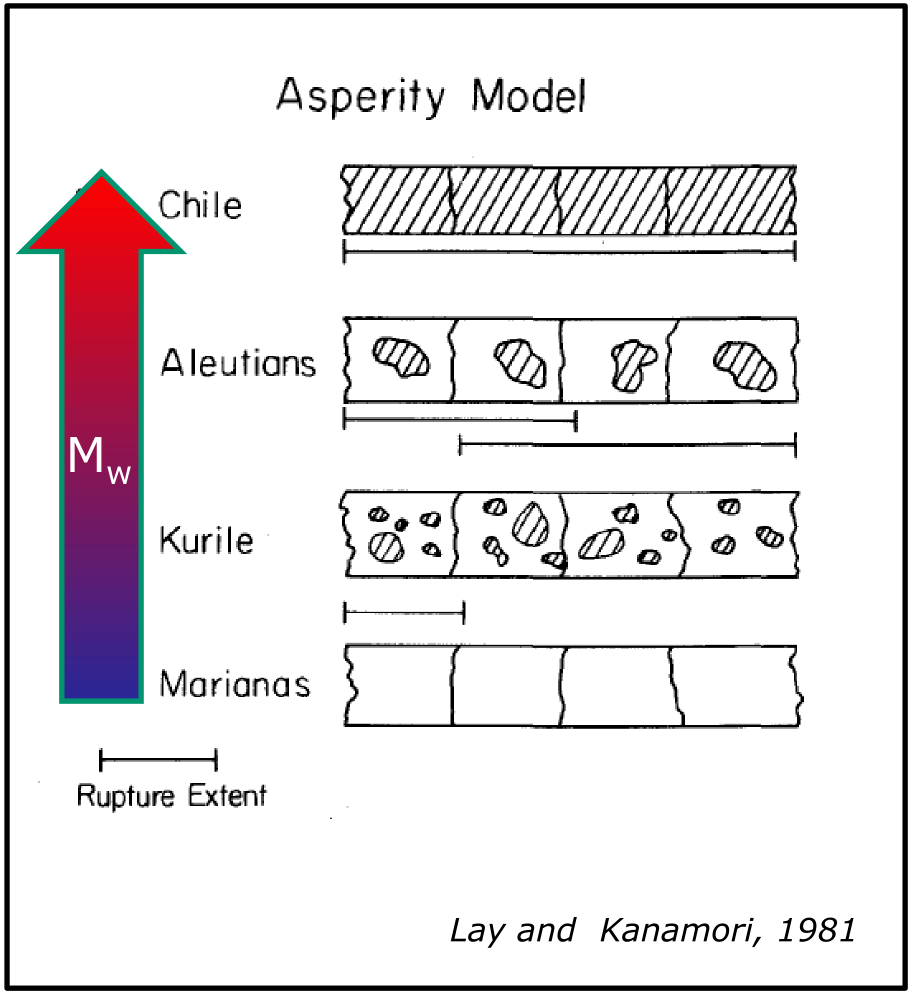
History of earthquakes is too short to draw conclusions about long-term distributions

Ruff and Kanamori, 1980

STILL TRYING TO FIND A GOVERNING PARAMETER

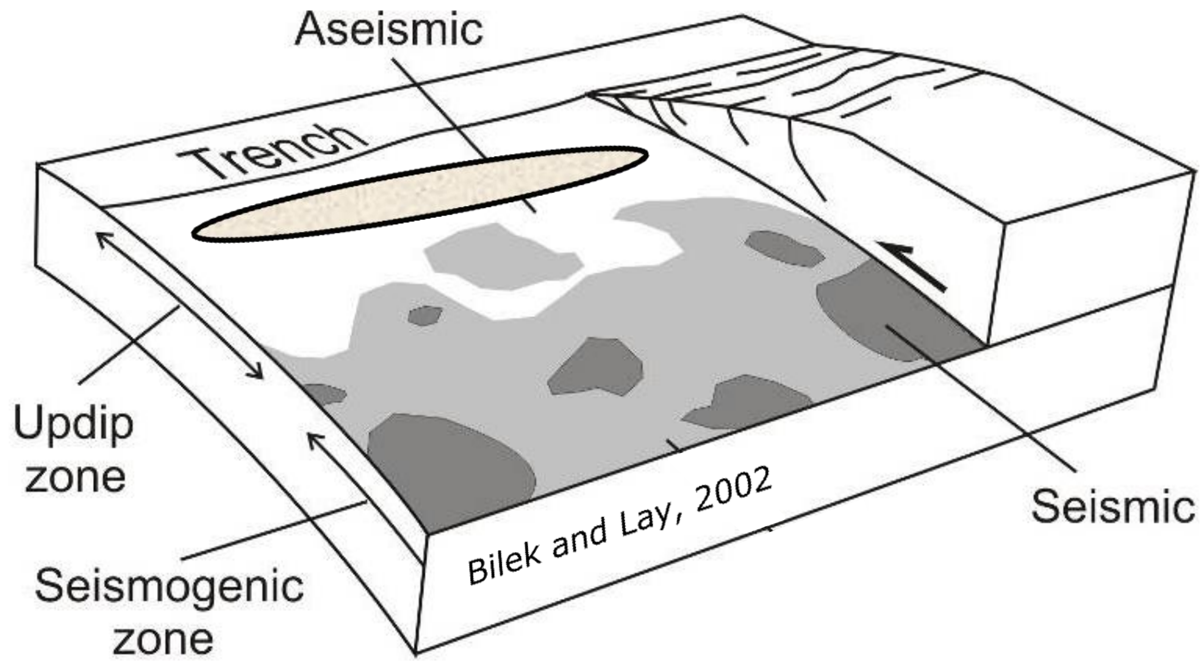
Which parameter is governing the subduction interplate seismicity?

FROM THE ASPERITY MODEL ...



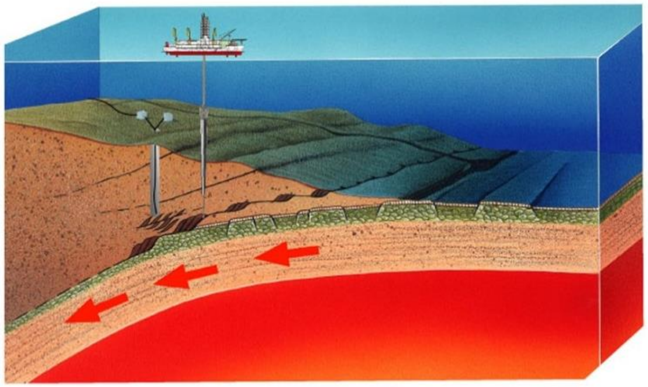
heterogeneity
of strength and frictional
properties
of the subduction
thrust fault

FROM THE ASPERITY MODEL TO THE MULTI-SEGMENTS EVENT CONCEPT



- slip seismically
- slip aseismically
- conditionally stable regions that slip aseismically (creep) unless adjacent slips drive them to slide seismically
- slow- rupturing regions that experience large slip at shallow depths generating tsunami earthquakes

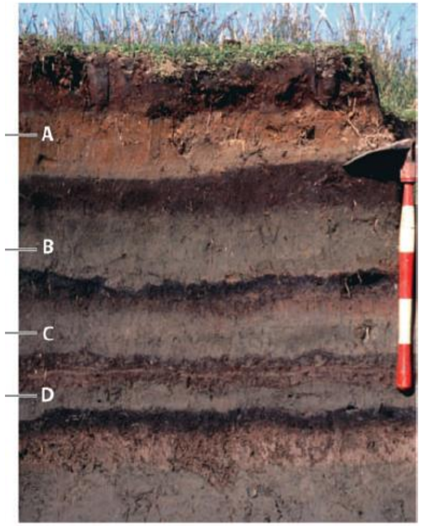
WHAT IS STILL MISSING?



Our knowledge is based exclusively on remote measurements.

From an observational point of view the subduction earthquake cycle is problematic because reliable records of earthquakes date back only a century in most places.

Other information (e.g., written accounts, geological observations) can be used to extend the observational record. However, these data may lack in resolution and completeness.



#1: IMPORTANT TO STUDY RECENT GREAT EARTHQUAKES

#2: IMPORTANCE OF MULTIDISCIPLINARY STUDIES AND MODELING

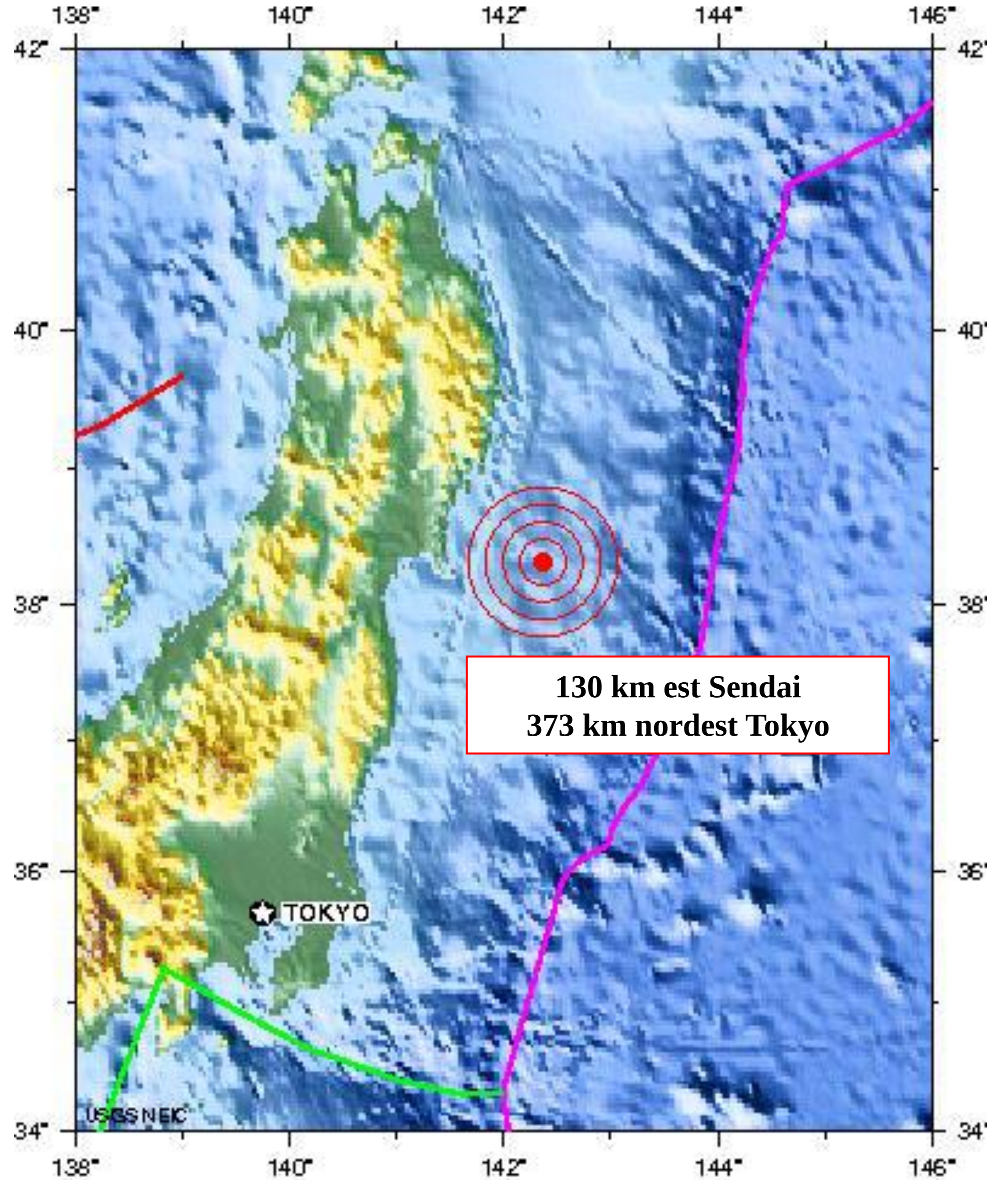
東北地方太平洋沖地震

Tōhoku Chihō Taiheiyō-oki Jishin

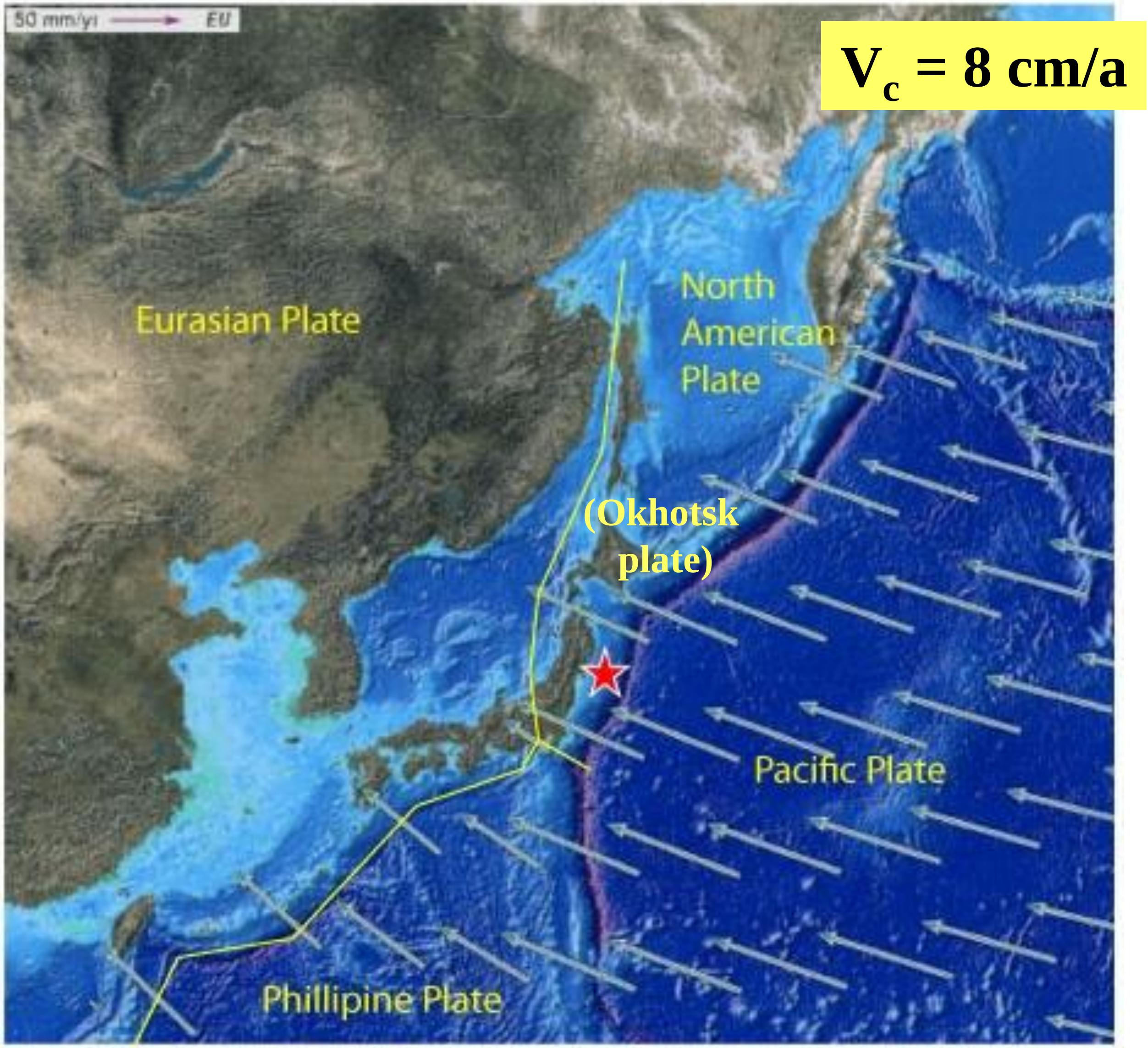
(*earthquake of the* Tohoku region in the Pacific Ocean - “Dai Jishin”)

WHERE

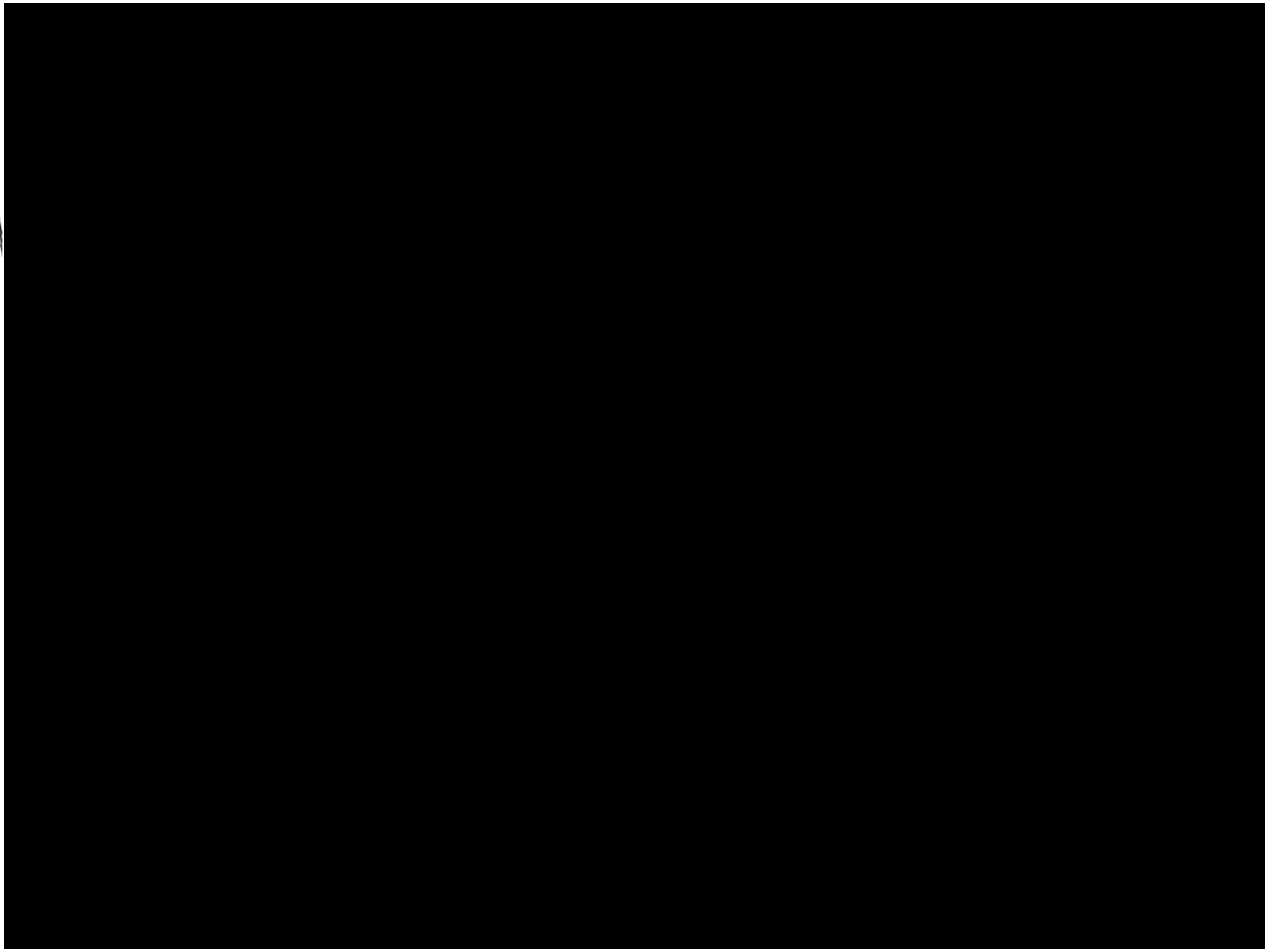
Images courtesy of the US Geological Survey



GEODYNAMICAL FRAMEWORK



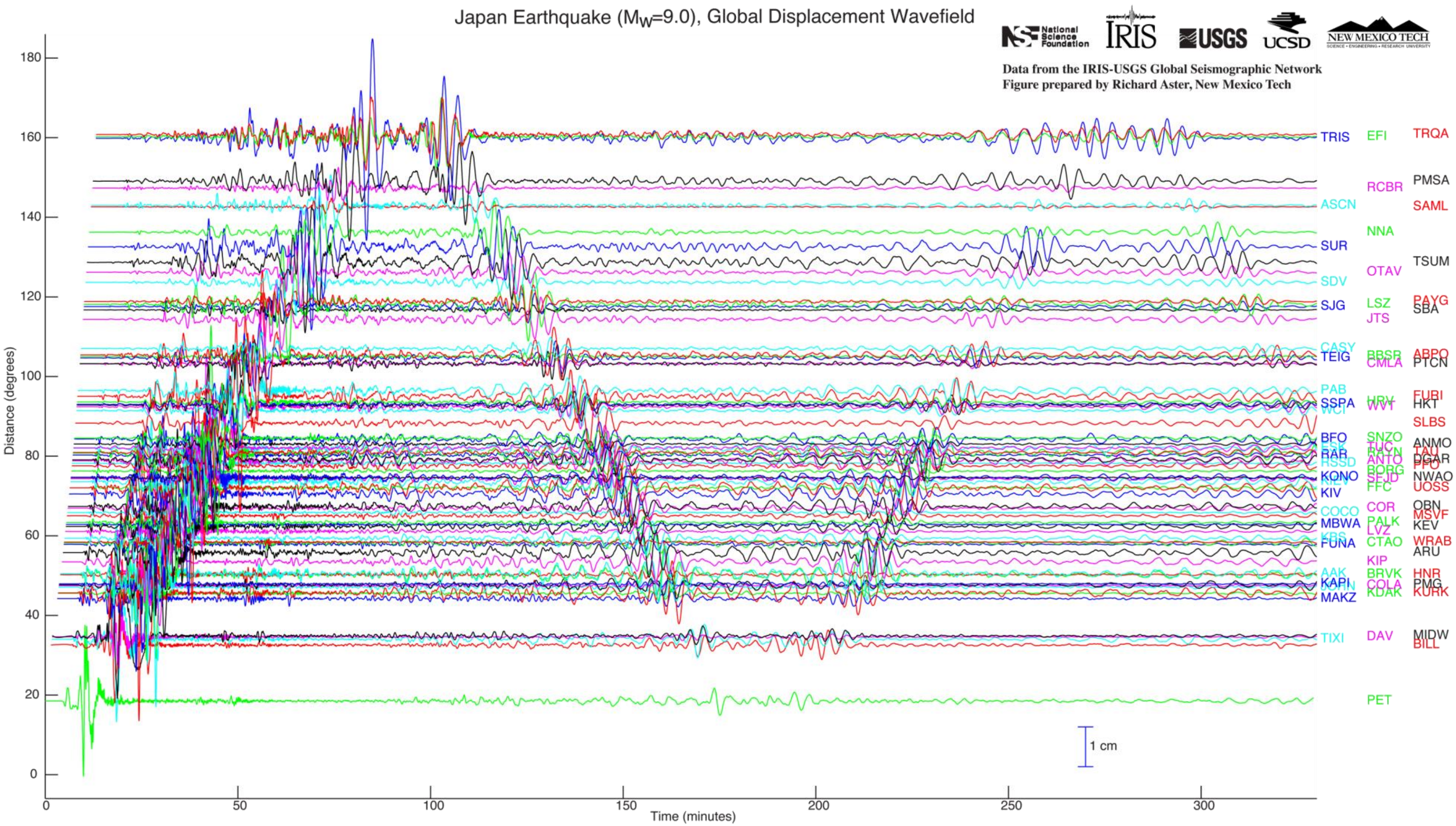
TOHOKU-OKI SEISMIC SEQUENCE



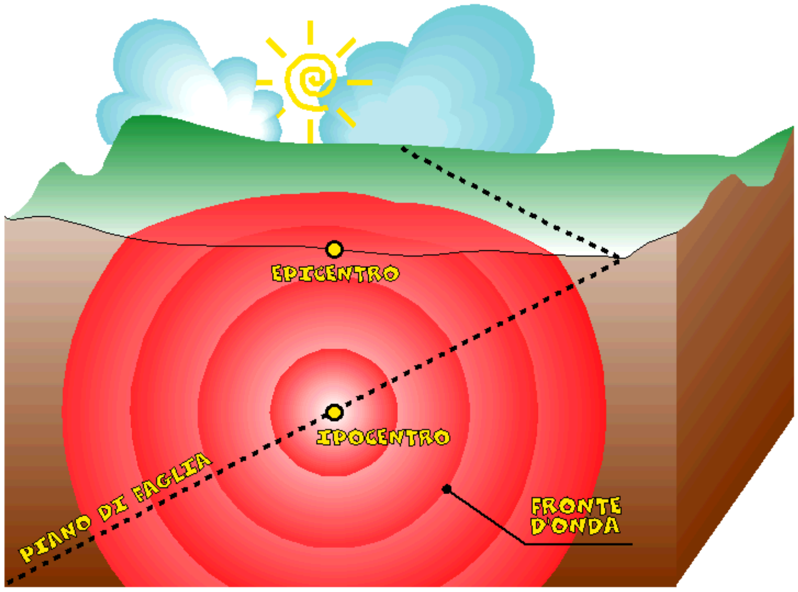
4 foreshocks …

(M_w 7.2 9.3.11, z=32 km)

SEISMIC WAVES…IN «WORLD TOUR» !



MAIN PARAMETERS



Coordinates:
38.322° N, 142.369 ° E

Depth: 24.4 km

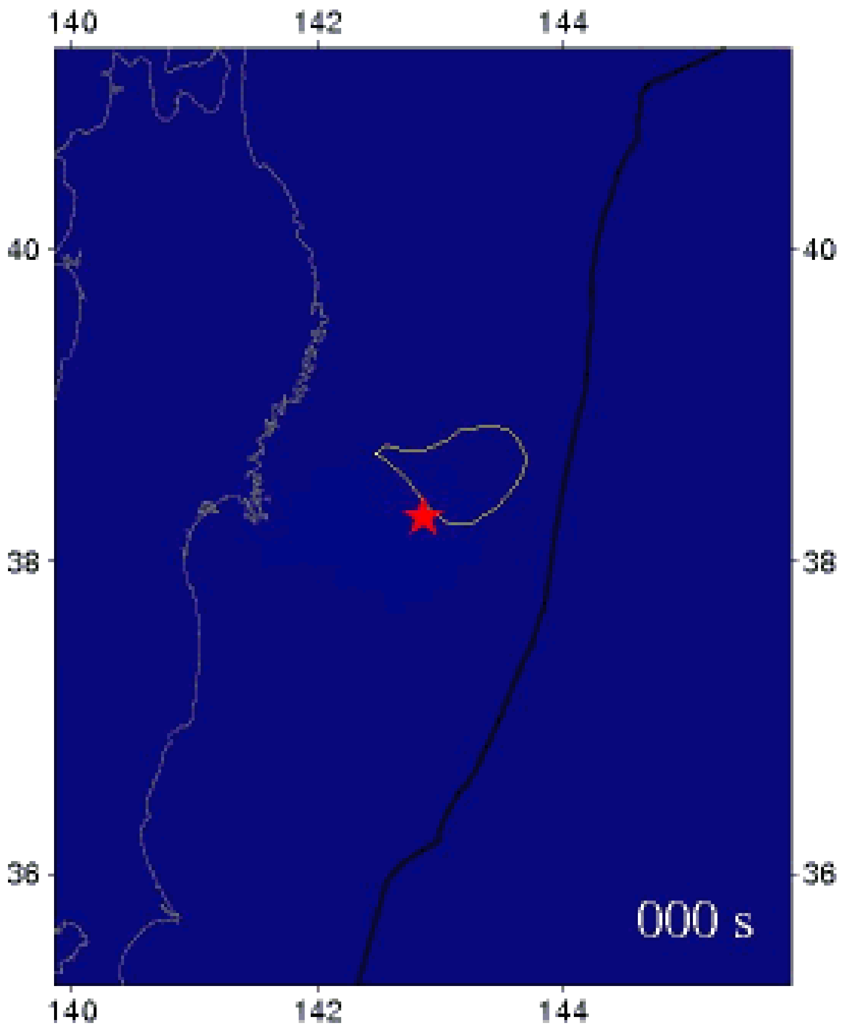
Region: offshore Honshu

Magnitude: M_w 9.0

Energy (USGS): 3.9 × 10^{22} joules

Stress drop: 15– 30 MPa

RUPTURE SPATIO/TEMPORAL EVOLUTION



squared amplitude of the back-projected stacks, i.e., proportional to released energy at high frequencies

cascading failure of the plate interface

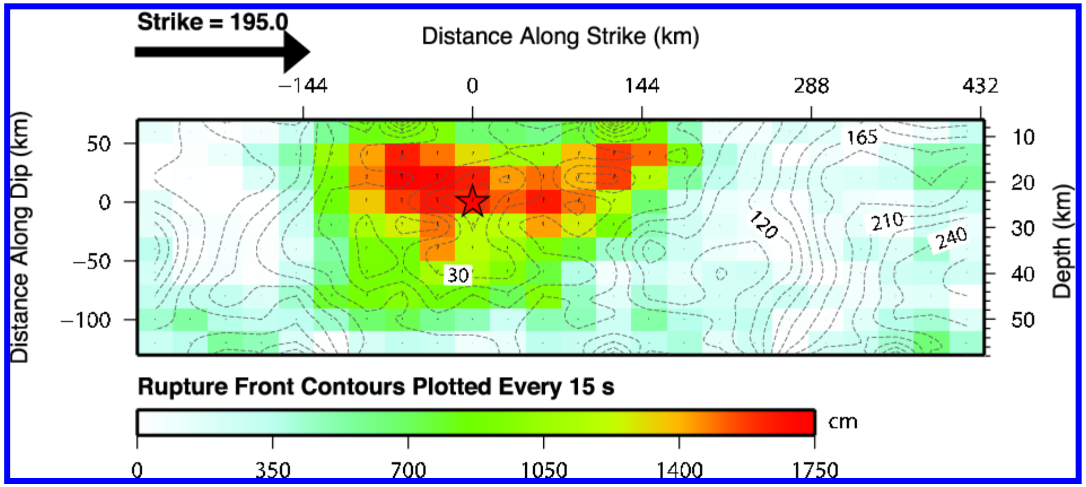
composite event with attributes of a tsunami earthquake for the shallow portion of the rupture and attributes of a typical megathrust earthquake in the deeper portion of it

Kiser and Ishii, 2012

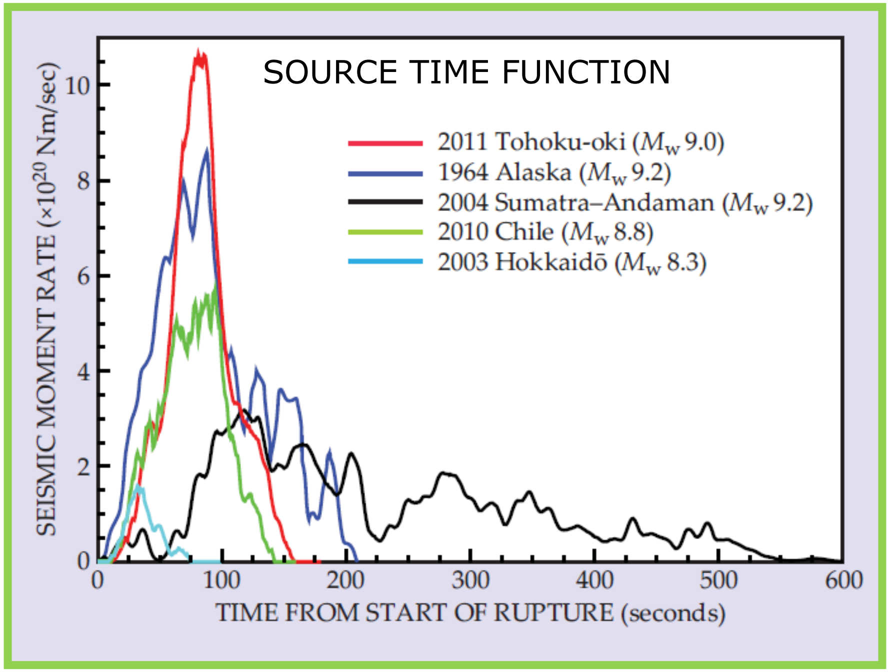
RUPTURE SPATIO/TEMPORAL EVOLUTION

500 km length and up to 50 km depth

Slip
40 m (average)
60-80 m close to the trench



Max rupture in the first 100 s but minor moviments recorded up to 175 s from the beginning.



$V_{rupture}$= 0.5-3.5 km/s

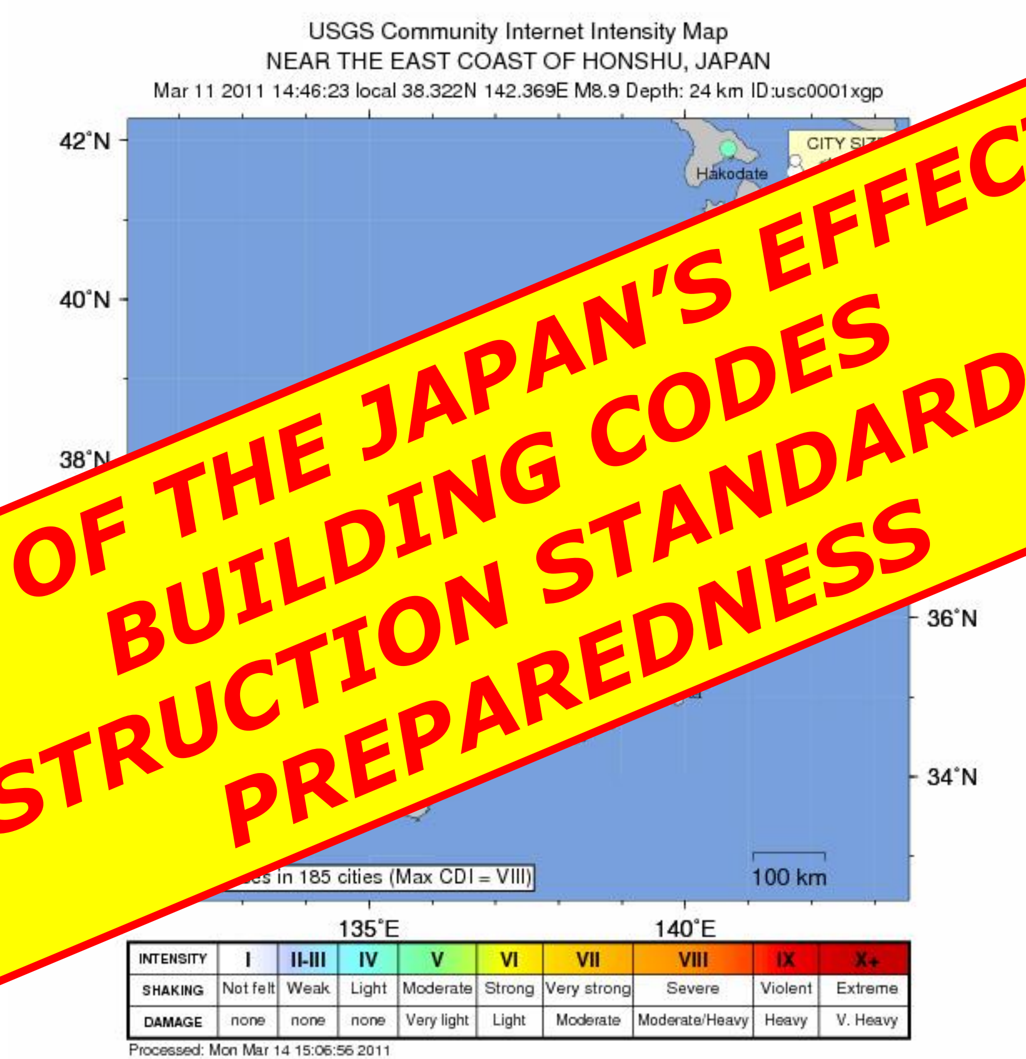
CASUALTIES

- 15.500 people killed (at least!) and 5344 missing
- 5314 injured
- 332.395 buildings, 2126 roads, 56 bridges and 26 railways destroyed

The total economic loss in Japan was estimated at **309 billion US dollars**.

USGS

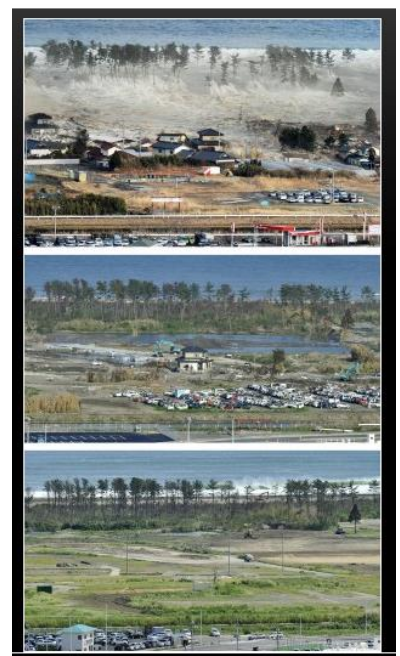
INTENSITY MAP



PROOF OF THE JAPAN'S EFFECTIVE BUILDING CODES CONSTRUCTION STANDARDS AND PREPAREDNESS

Energy **1000** larger than L'Aquila (2009)!

... AFTER 6 MONTHS!



MEGAEARTHQUAKES

\+

densely populated areas

=

HIGH HAZARD IS NOT ALWAYS HIGH RISK!

DISASTER RIS… …ability, exposure)

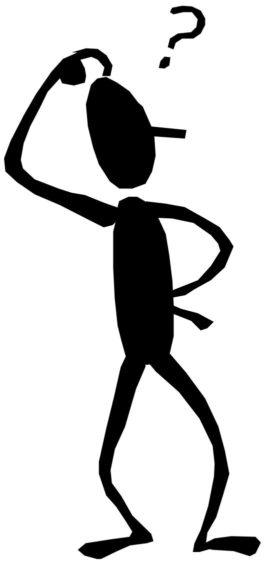
haz… …dicity of natural phenomena

vulnerability → *physical, social, economic and environmental factors increasing the susceptibility of a community to the impact of an hazard*

exposure → *economic loss (people and properties)*

Katsushika Hokusai

WAS A PREDICTABLE EVENT?



If “PREDICTION” means

WHERE [ipocenter],

HOW [magnitude and/or epicentral intensity] **and**

WHEN [date and time]

will be the next mega-earthquake then …


No!

But is prediction is intended as "see before" what *could* *happen* in a specific area…

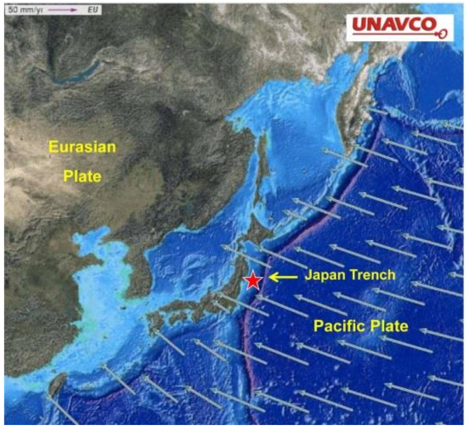
YES, we can: we have data suggesting

WHERE and HOW

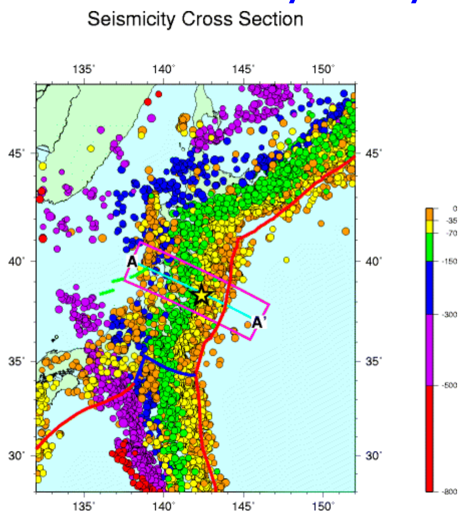
future earthquakes may occur.

JAPAN IDEAL COUNTRY FOR HAZARD MAPS

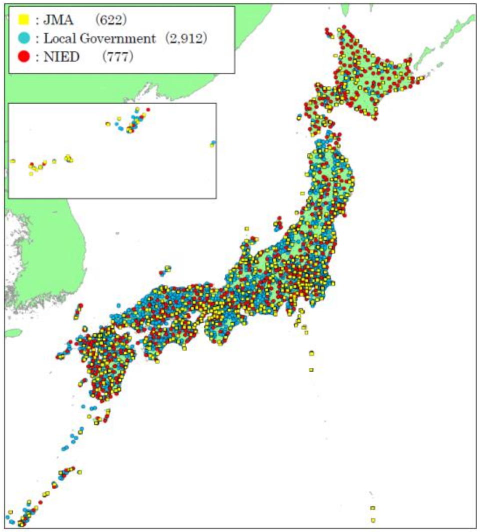
High convergence velocities
(8 cm/yr)



Area seismically very active



Excellent seismic network



Historical record

M_w in 30yr

Off Sanriku-oki North ~M8.0 up to10%

Off Sanriku-oki Central ~M7.7 80-90%

Off Miyagi~M7.5 <90%

Off Fukushima ~M7.4 7

Off Ibaraki ~M6.7 – M7.2 90%

Sanriku to Boso M8.2 (plate boundary) 20%

Sanriku to Boso M8.2 (Intraplate) 4-7%

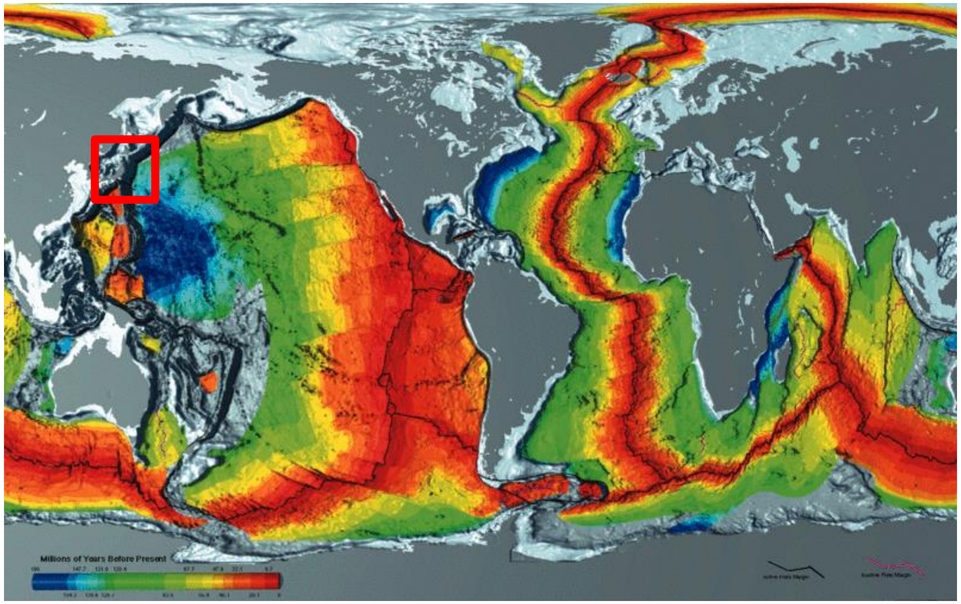
ASSUMPTION:

NO M_w > 8.2

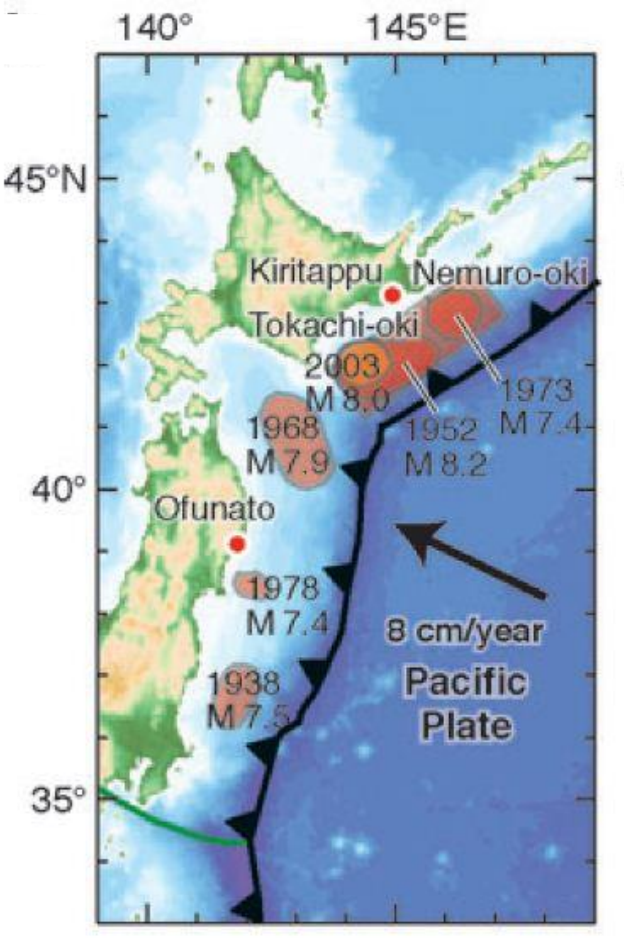
Earthquake Research Committee, 2009, 2010

WHY THE ASSUMPTION NO M_w > 8.0?

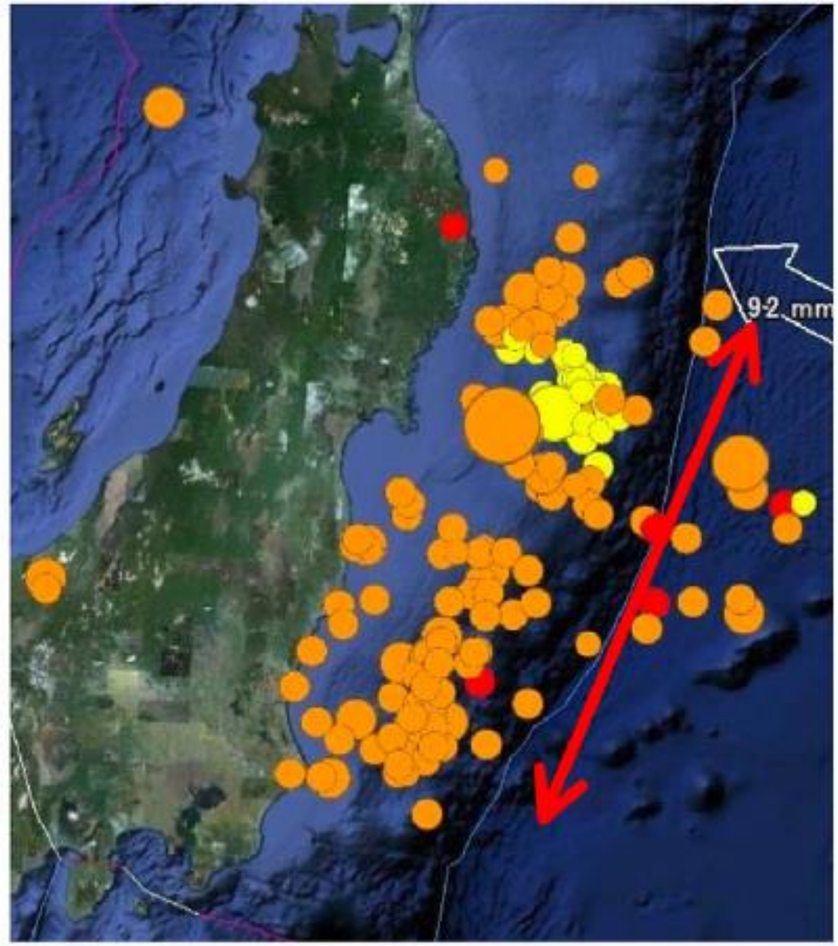
OLD subducting lithosphere



Any M>8.0
(short historical data)



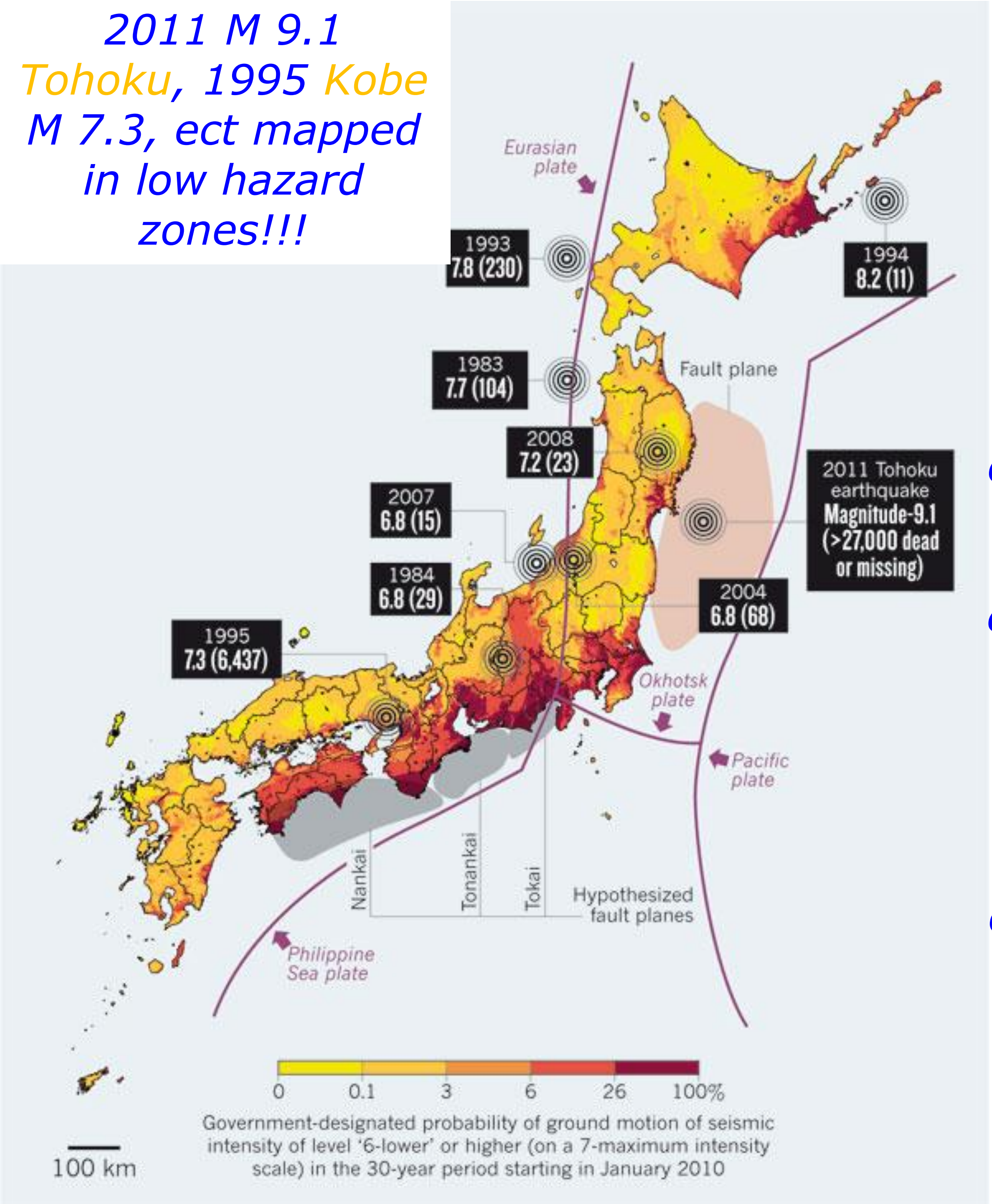
WHY THE ASSUMPTION NO M_w > 8.0?



Stein et al., 2012

The model assumed that different segments of the trench would not break simultaneously.
However, the March 2011 earthquake broke five segments.

2011 M 9.1 Tohoku, 1995 Kobe M 7.3, ect mapped in low hazard zones!!!



High hazard in Tokai, Tonankai and Nankai based on:

"Characteristic earthquake"
assumes that parts of a fault or fault segment will rupture in a predictable fashion, producing characteristic earthquakes with quasi-regular recurrence intervals

"seismic gaps"
where the fault has not ruptured recently relative to other parts of the fault and are thus most likely to rupture in the future

Geller, 2011

WHY DO HAZARD MAPS NOT (ALWAYS) WORK?

- wrong physics/assumptions

- wrong data *(missing, incomplete, or underestimated)*

- bad luck *(low frequency events)*

and combinations.

SENDAI: INTERPLATE FREQUENCY OF SIGNIFICANT EVENTS (in the «characteristic earthquake» view!)

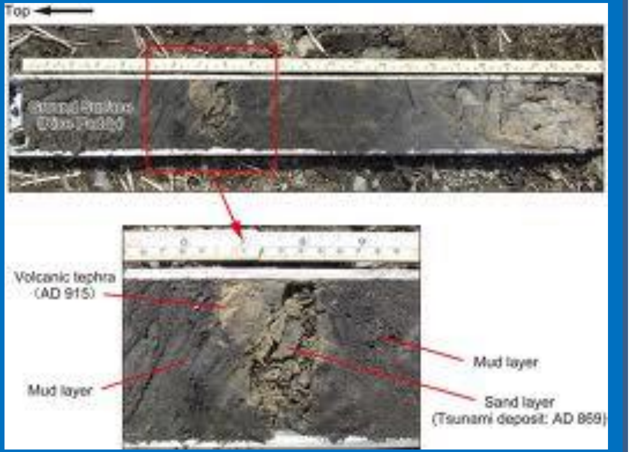
30-40 yrs

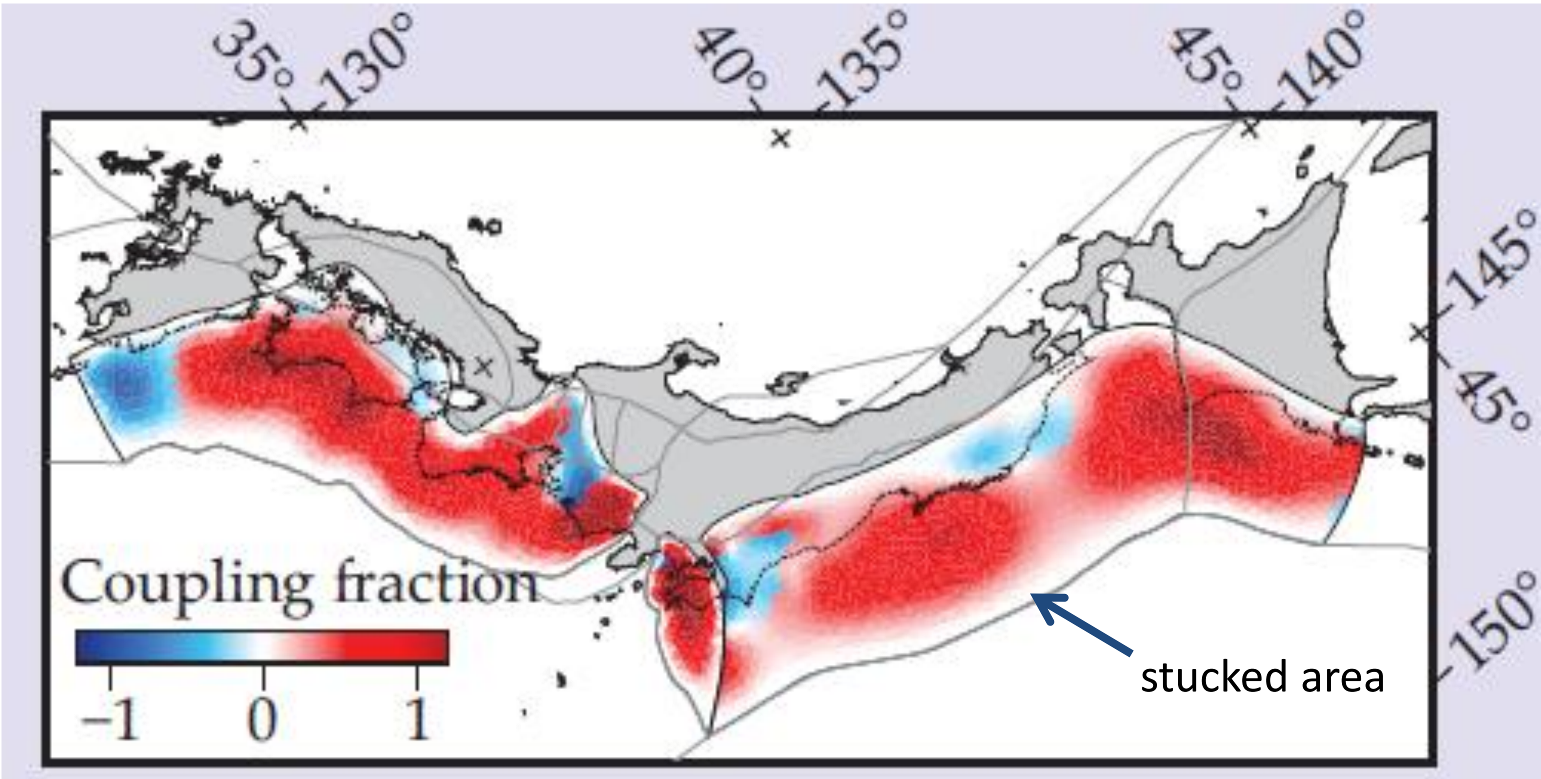
(1793, 1835, 1861, 1897, 1936, 1978, 2005?)

SENDAI: FREQUENCY OF TSUNAMI AND MEGA-EVENTS

3 sequences of tsunamigenic deposits in the Holocenic Sendai valley in the last 3000 yrs → recurrence time 800- 1100 yrs

Last event : 869 Jogan tsunami M=8.6 (Minoura et al., 2001, Nanayama et al., 2003)





GPS data recognized a much higher rate of strain accumulation on the plate interface than would be expected if a large fraction of the subduction occurred aseismically.

Including these data would have strengthened the case for considering the possibility of large earthquakes!!!

Loveless and Meade, 2010

#1: IMPORTANT TO STUDY RECENT GREAT EARTHQUAKES

#2: IMPORTANCE OF MULTIDISCIPLINARY STUDIES AND MODELING

- ☞ **The earthquake phenomenon (in a nut-shell)**
- ☞ **Geodynamic framework of global seismicity**
- ☞ **Mega-Earthquakes**
- ☞ **Subduction and Mega-Earthquakes @ Roma TRE**

(AMONG) GEOLOGIST'S DREAMS…

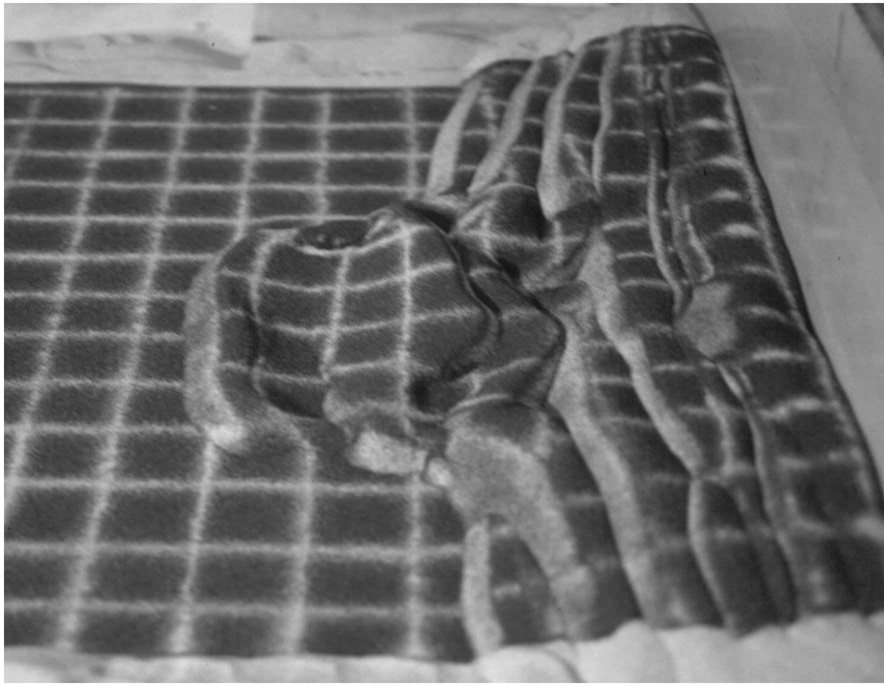
… travel to the Earth's center!

… travel back in time !

A MODEL IS AN ATTEMPT TO REPRODUCE A NATURAL PROCESS AT DIFFERENT SCALES:

SPATIAL + TEMPORAL

Nature
km, Myr



Model
cm, h

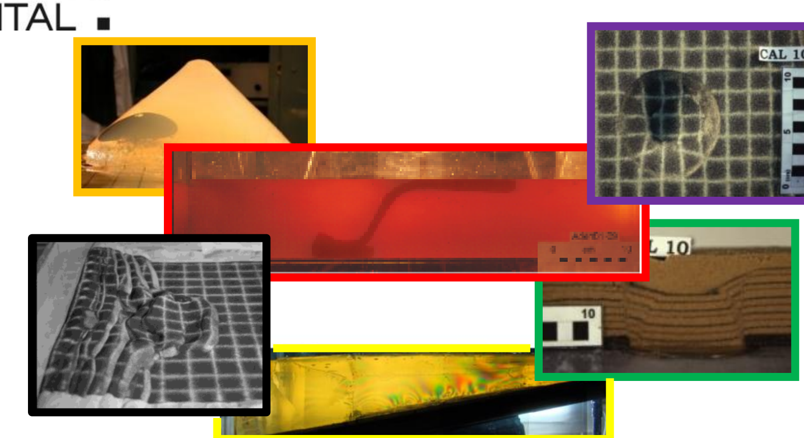
ROMA TRE UNIVERSITÀ DEGLI STUDI

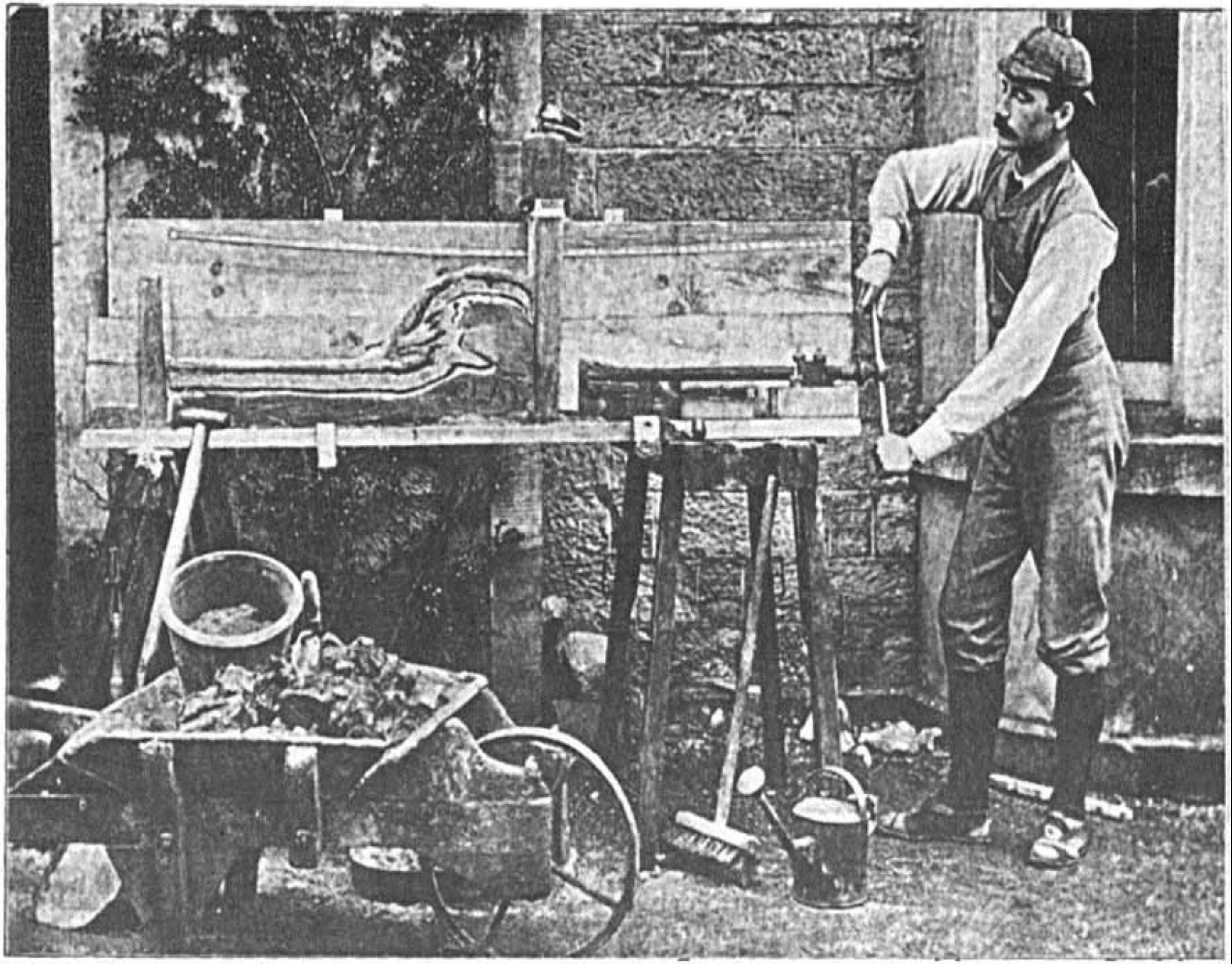
ET

LABORATORY

TECTONICS

EXPERIMENTAL





Experiments in Mountain Building

"RECIPE" TO BUILD UP A LABORATORY MODEL

1. identification of the problem to study
2. application of the similarity criteria
3. determining materials that satisfy the similarity criteria
4. running of models
5. ensure repeatability
6. interpretation of obtained results
7. definition of a theory

SIMILARITY CRITERIA

According to the **scaling model theory** model must be scaled for its

geometric, *kinematic*, *dynamic* and rheologic

conditions.

These similarities are fulfilled if the ratio of any

model - prototype pairs of

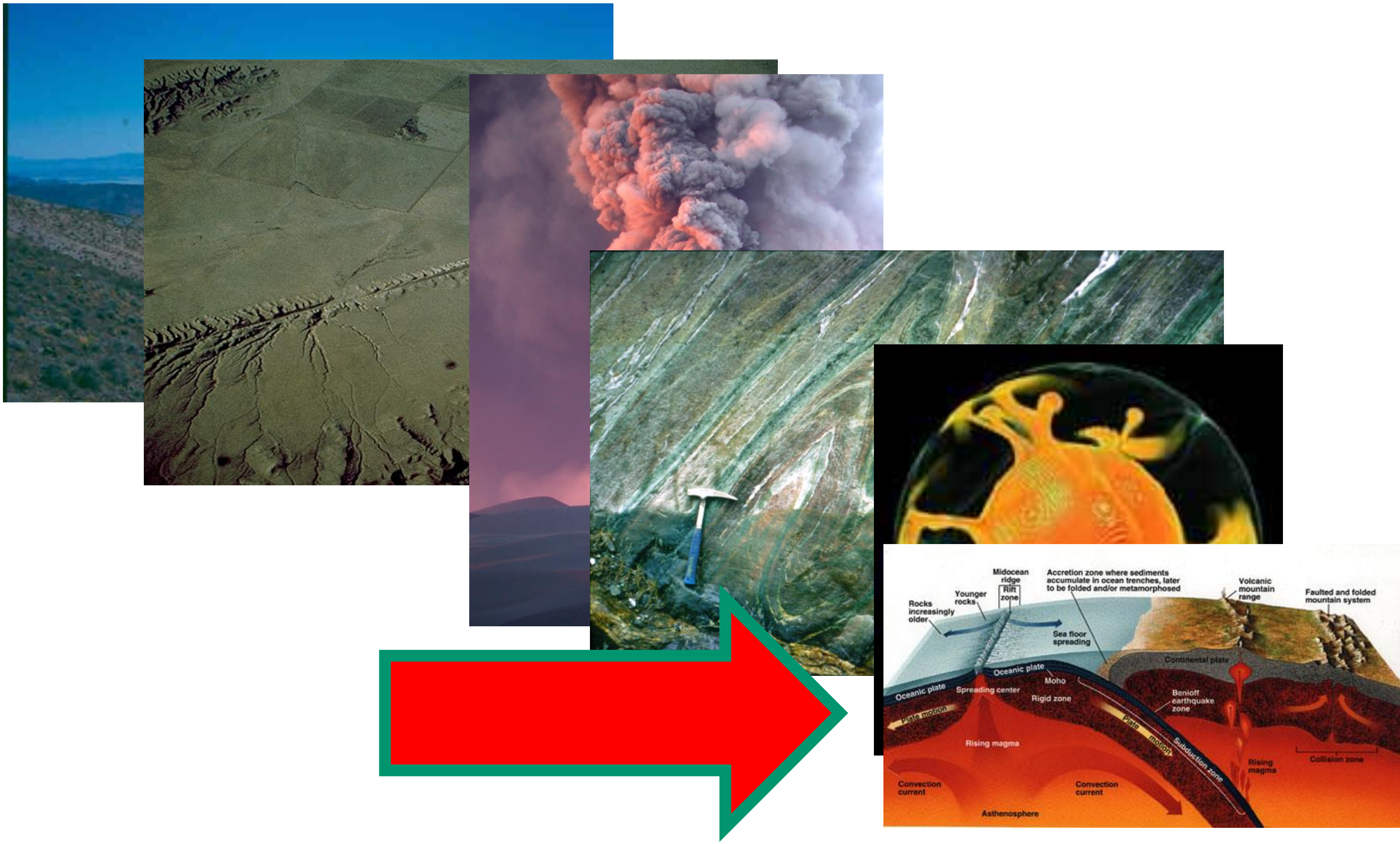
lengths and angles, *velocities*, forces and rheological parameters

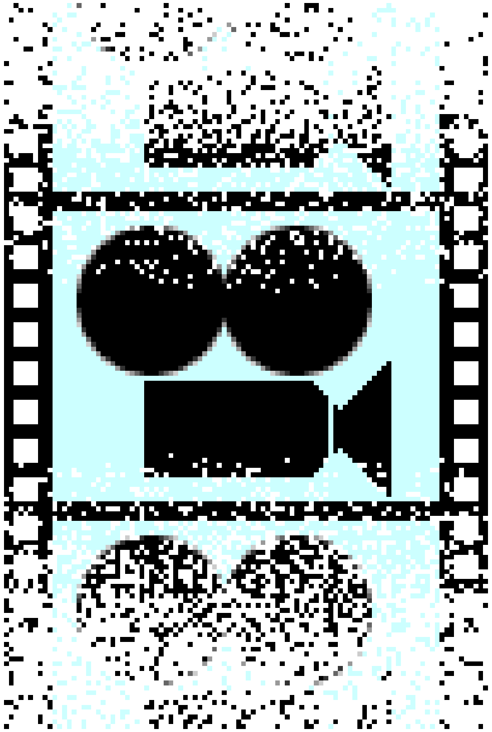
are **identical**, respectively

Hubbert, 1937, 1951; Horsfield, 1977; Schemenda, 1983; Richard, 1991; Davy and Cobbold; Cobbold and Jackson, 1992 …

ANALOGUE MATERIALS

ANALOGUE MATERIALS


Midocean ridge
Rift zone
Accretion zone where sediments accumulate in ocean trenches, later to be folded and/or metamorphosed
Volcanic mountain range
Faulted and folded mountain system
Younger rocks
Rocks increasingly older
Sea floor spreading
Continental plate
Oceanic plate
Moho
Oceanic plate
Spreading center
Rigid zone
Benioff earthquake zone
Plate motion
Plate motion
Subduction zone
Rising magma
Rising magma
Collision zone
Convection current
Convection current
Asthenosphere



EURYI
European Young Investigator
Awards

«CONVERGENT MARGINS AND SEISMOGENESIS»

global data on convergent margins and statistical analysis

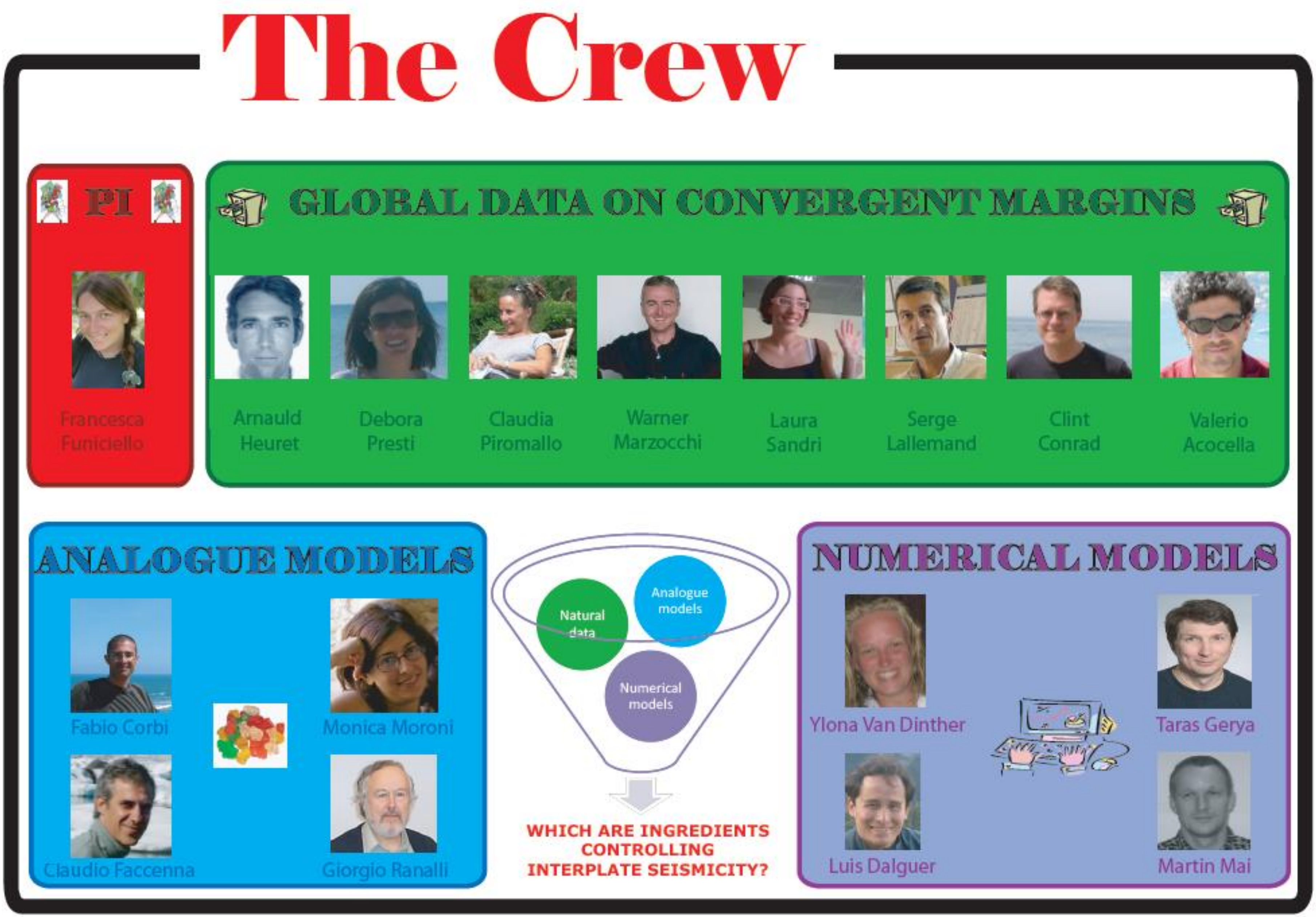
modelling

laboratory modelling

numerical modelling

TASK 1: characterize force parameters of worldwide convergent margins at both shallower and deeper levels (geometry, kinematics, dynamics)

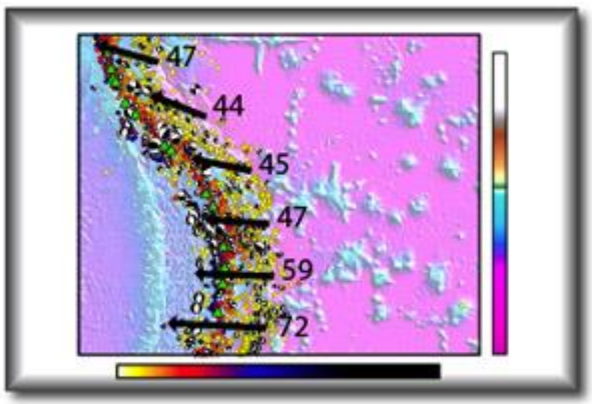
TASK 2: (try to) define critical condition for the occurrence of great earthquakes highlighting rupture length, depth, and recurrence intervals of the events produced by the subduction faults

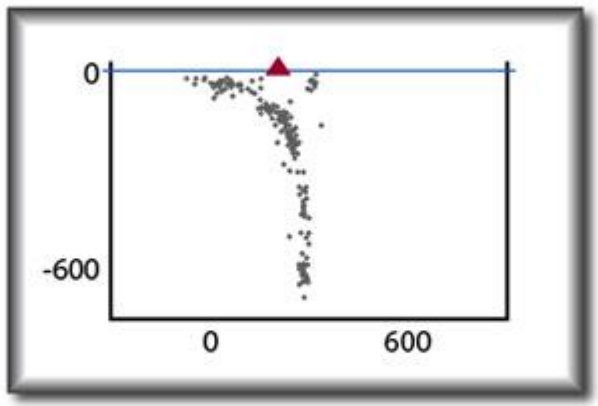


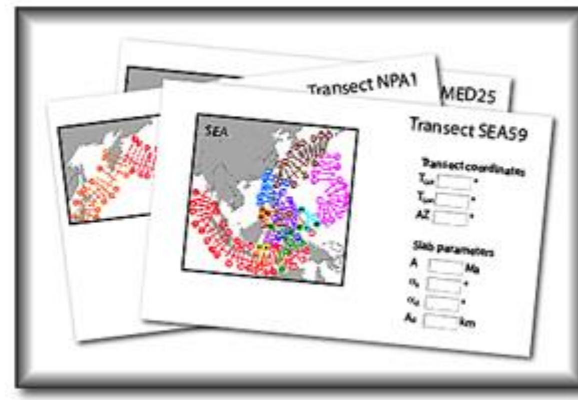
LET Laboratory of Experimental Tectonics · Géosciences Montpellier · ETH Eidgenössische Technische Hochschule Zürich, Swiss Federal Institute of Technology Zurich · Istituto Nazionale di Geofisica e Vulcanologia · Sapienza Università di Roma · KAUST King Abdullah University of Science and Technology · soest university of hawai'i · Carleton University

TOOLS

Global data on convergent margins







http://submap.gm.univ-montp2.fr/

Global data on convergent margins

uses of the database

a) statistical analysis on the entire set of parameters;

b) input parameters for laboratory and numerical modelling;

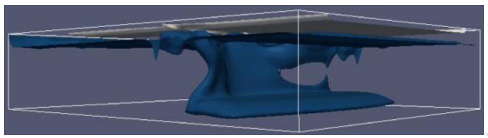
c) test the modelling predictions.

Modelling

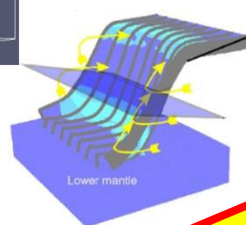
Numerical

Analog

Large-scale subduction models

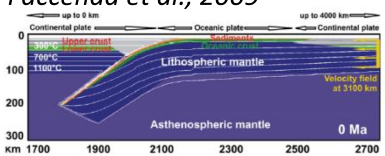


Magni et al., 2011



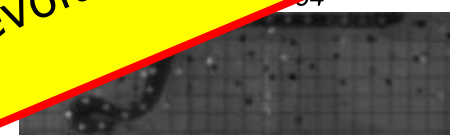
Morra et

Faccenda et al., 2009



3

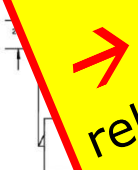
04



TIME TO FILL THIS GAP!!!

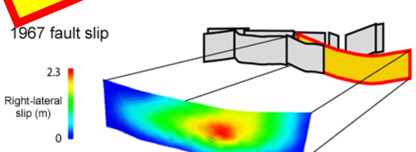
→ models with a) realistic rheology, able also to catch the viscoelastic relaxation response; b) realistic geometry without a-priori defined rupture plane and proper frictional laws; c) spontaneous evolution of faults/stresses.

els

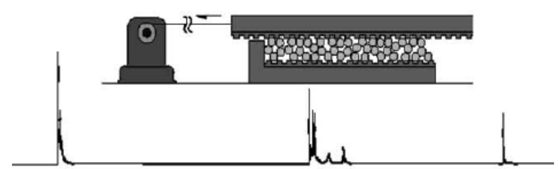


Lapus

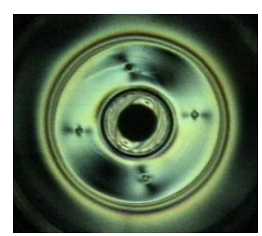
Mai, Finite-Source Rupture Model Database website



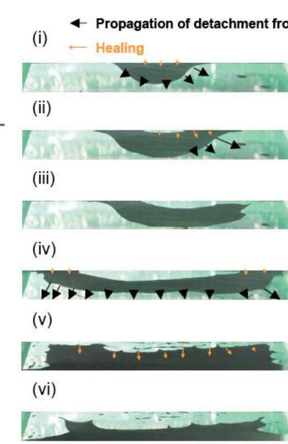
Muller, 2001



Bretz et al., 2006

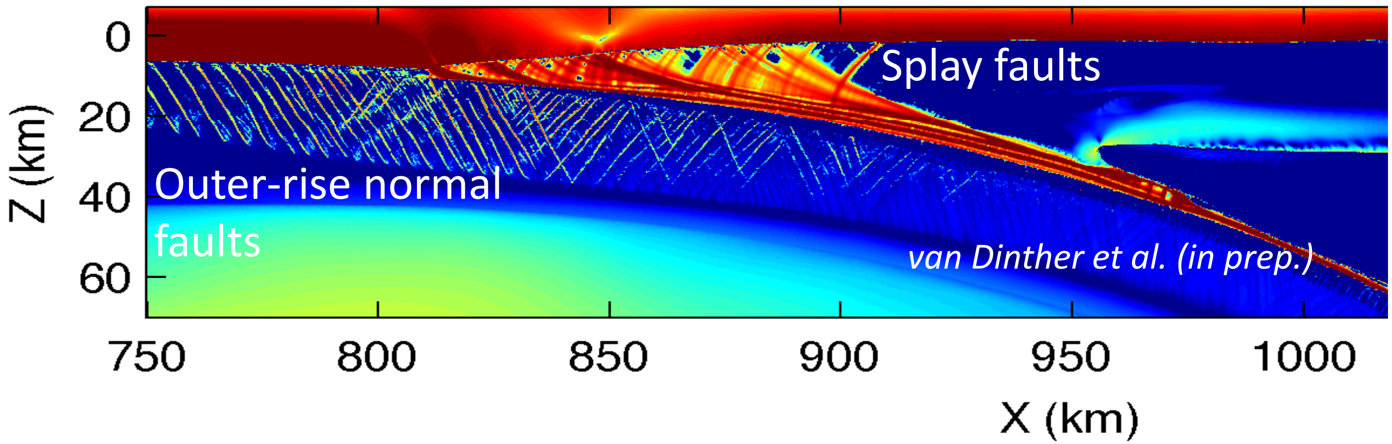


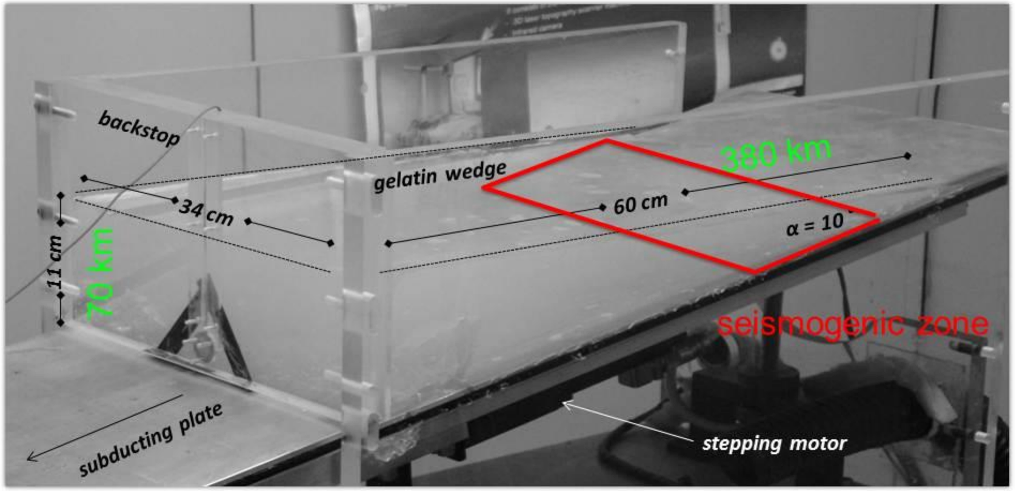
Rubio and Galeano, 1994



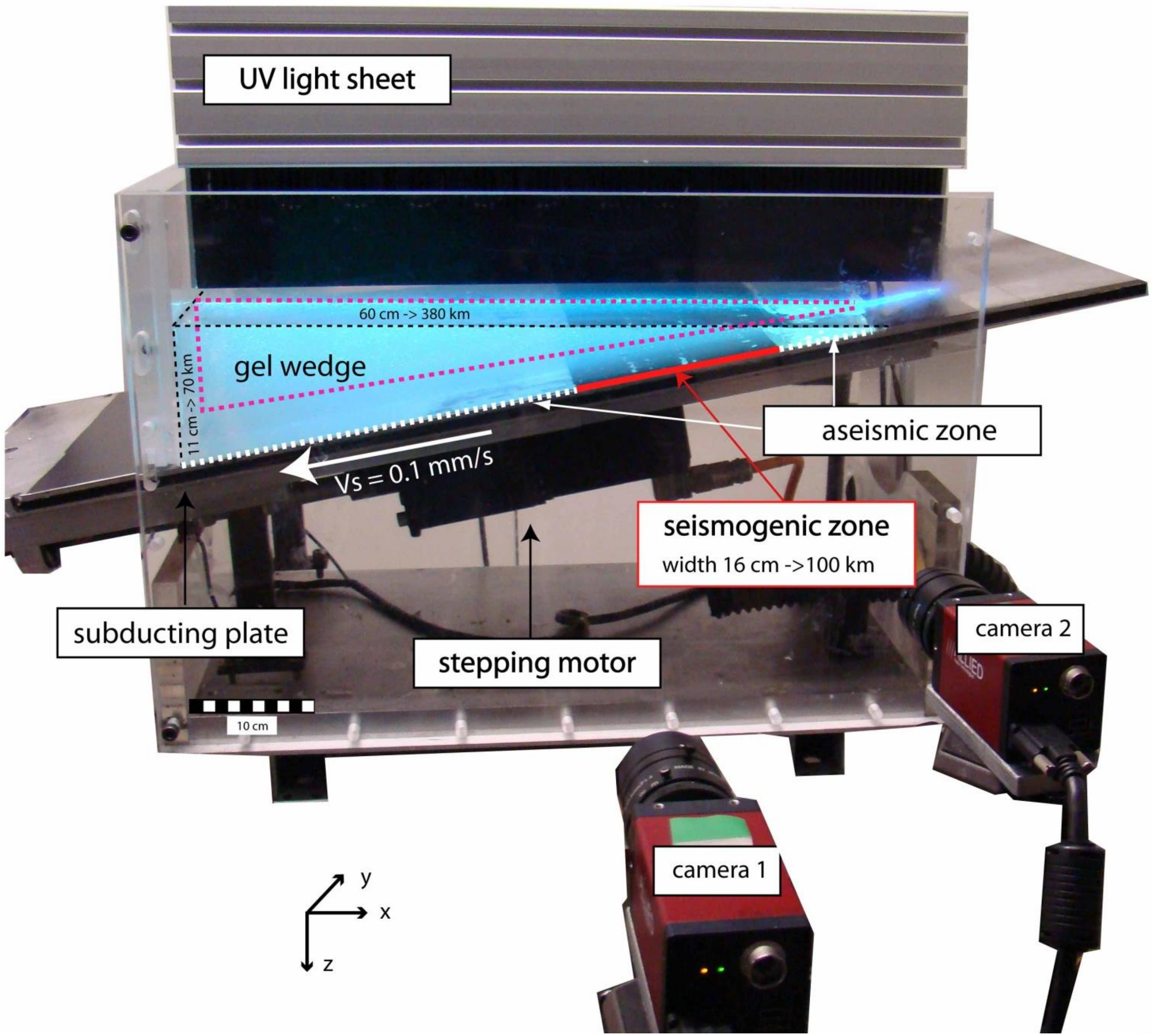
Yamaguchi et al., 2011

Modelling





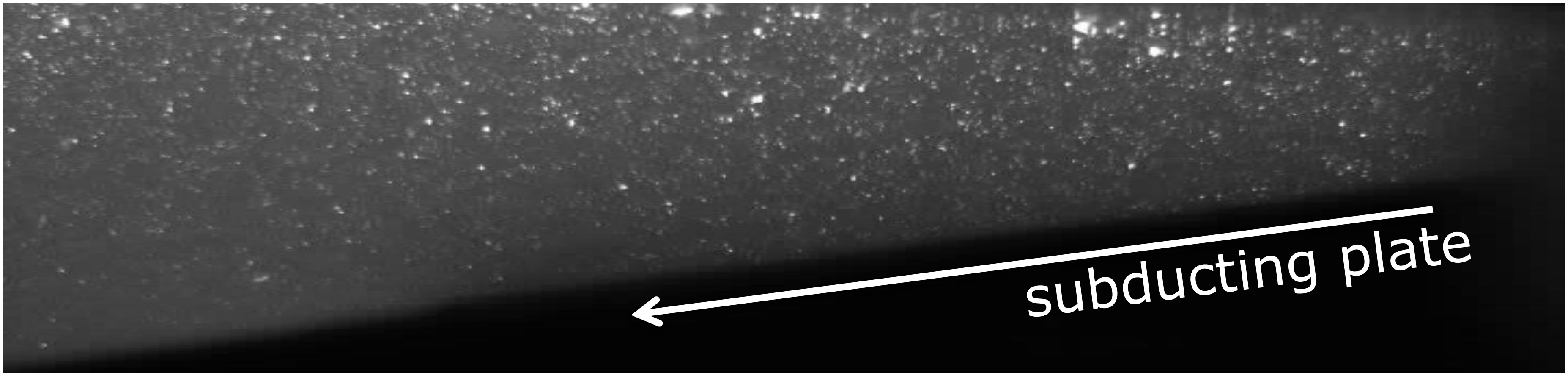
potentiality to investigate conditions governing rupture mode



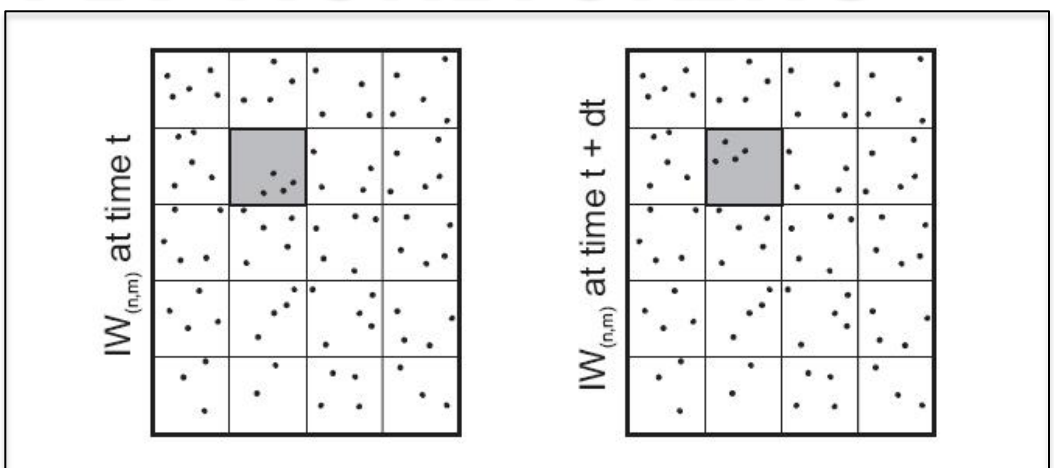
UV light sheet
60 cm -> 380 km
gel wedge
11 cm -> 70 km
Vs = 0.1 mm/s
aseismic zone
seismogenic zone
width 16 cm ->100 km
subducting plate
stepping motor
camera 2
camera 1
10 cm
y
x
z

MODEL BEHAVIOR

25x; camera 2

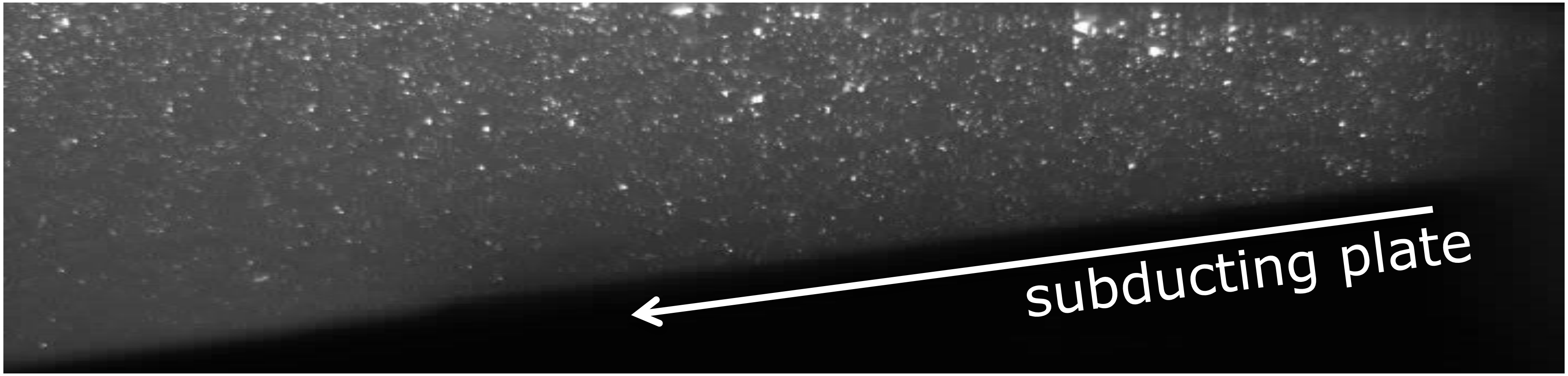


PIV MONITORING

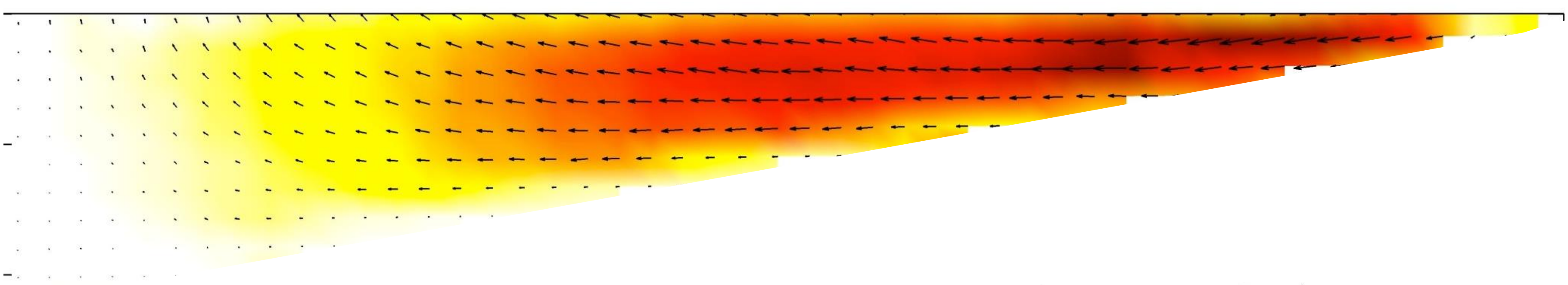


MODEL BEHAVIOR

25x; camera 2

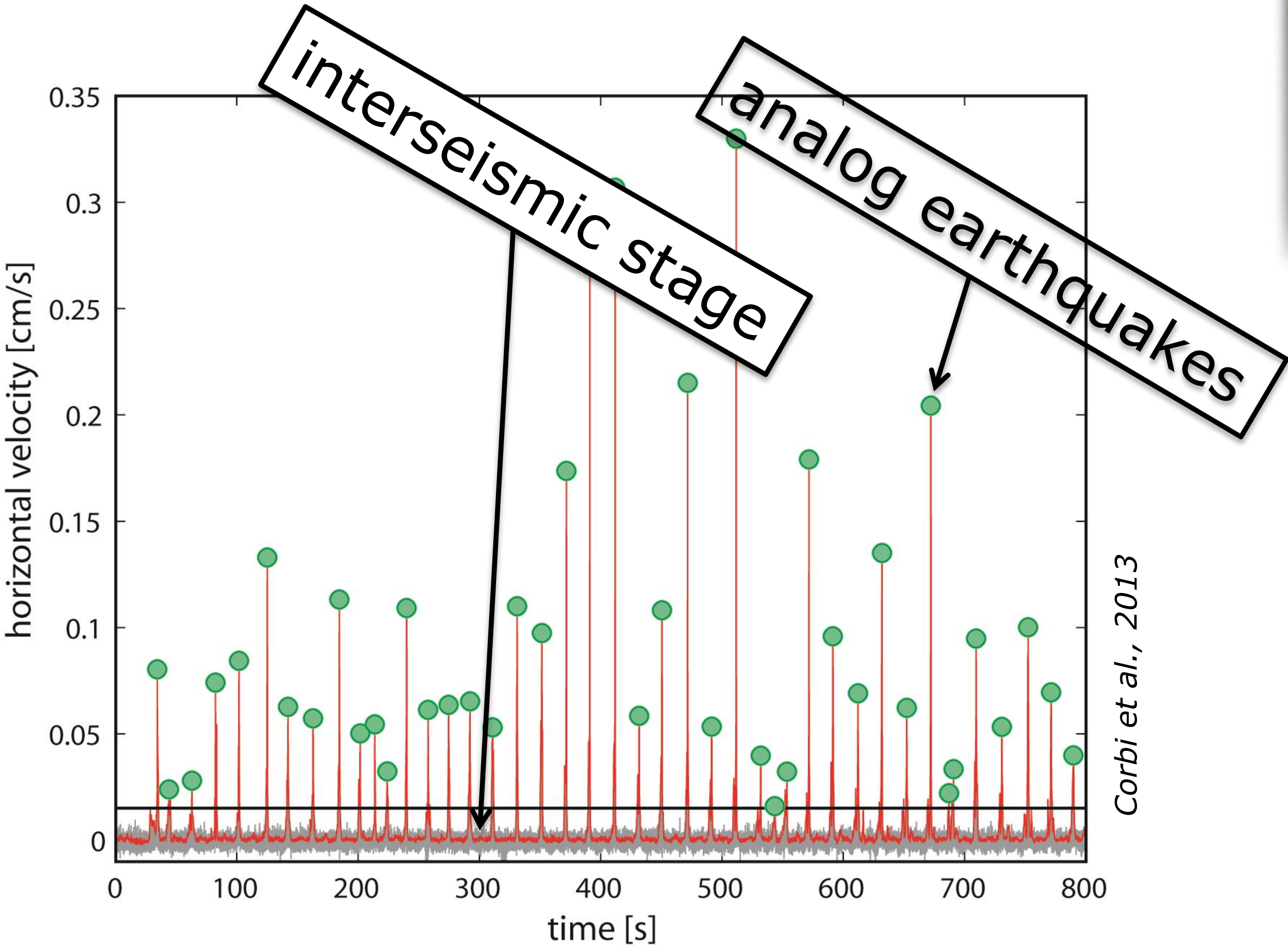


PIV OUTPUT

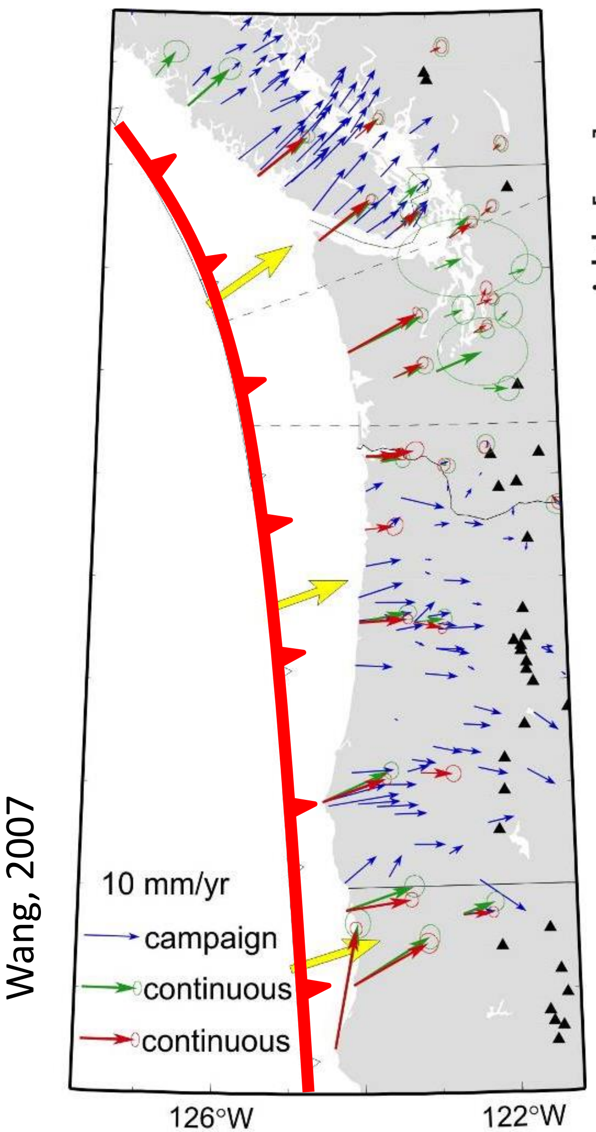


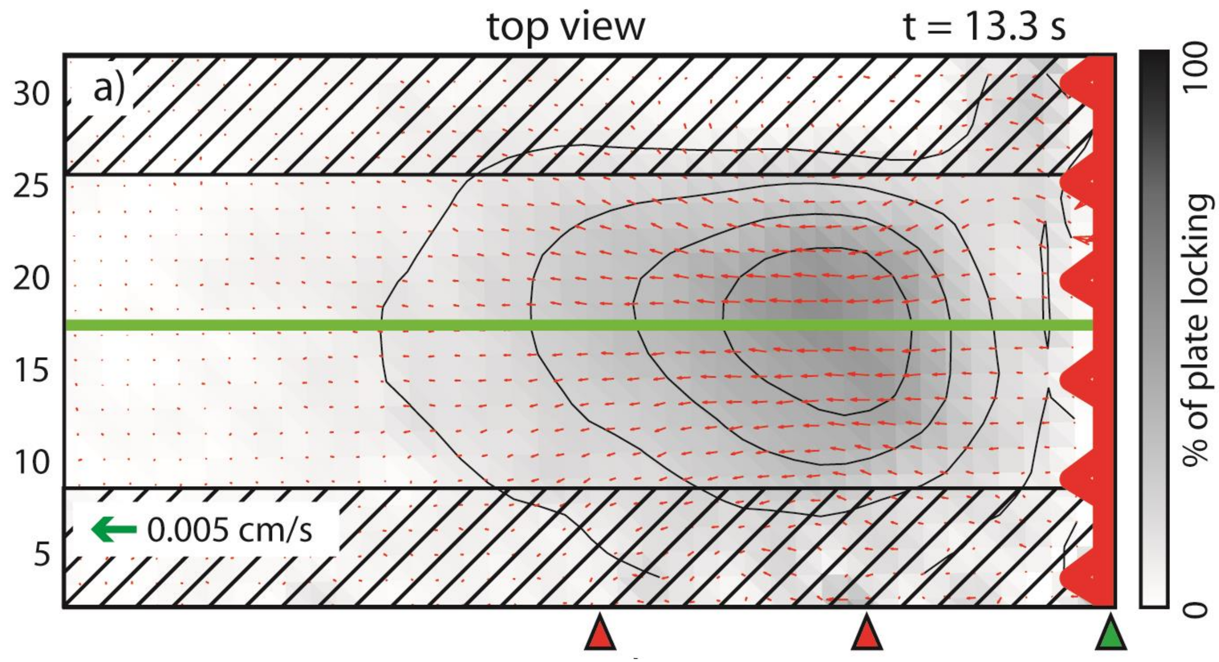
VELOCITY TIME SERIES

Alternate phases of quiescence with phases of high speed



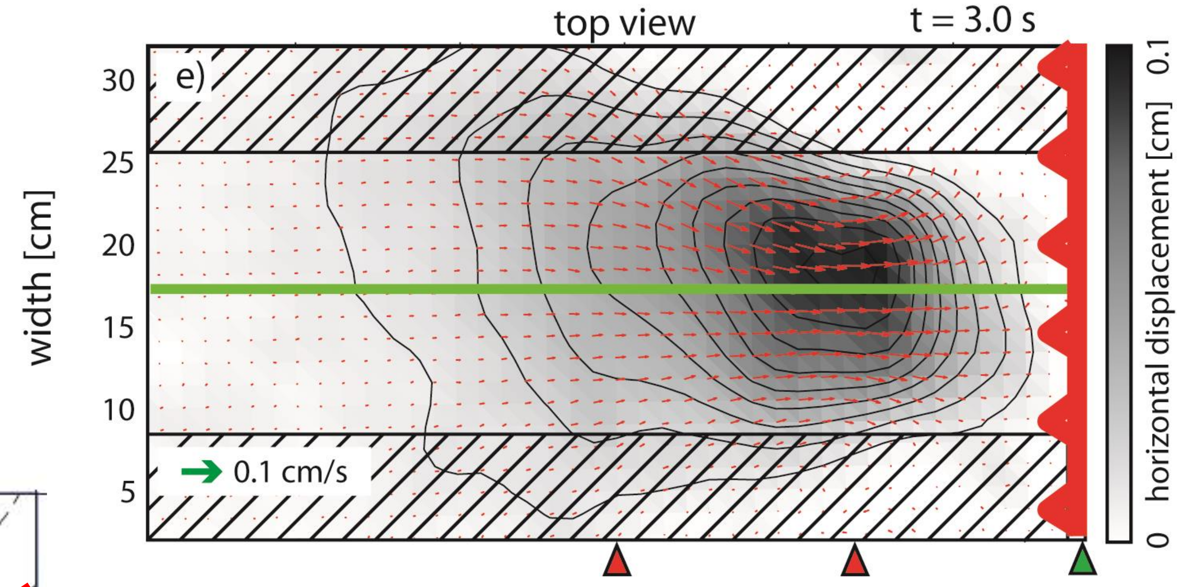
interseismic stage

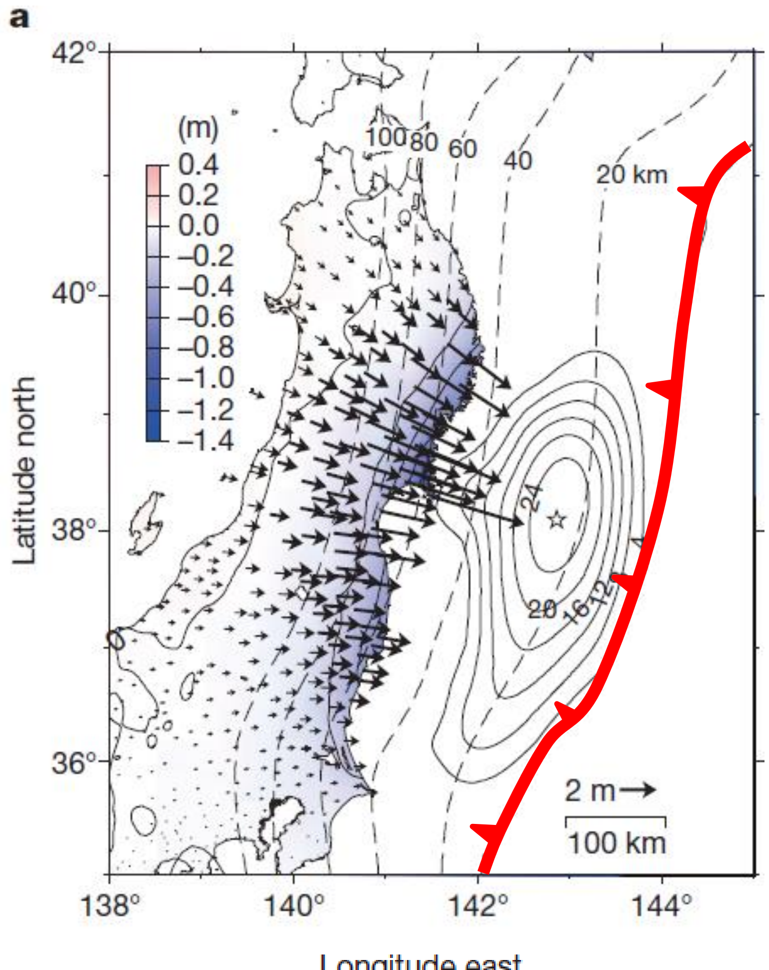




all sites move landward like Cascadia!!!

coseismic stage

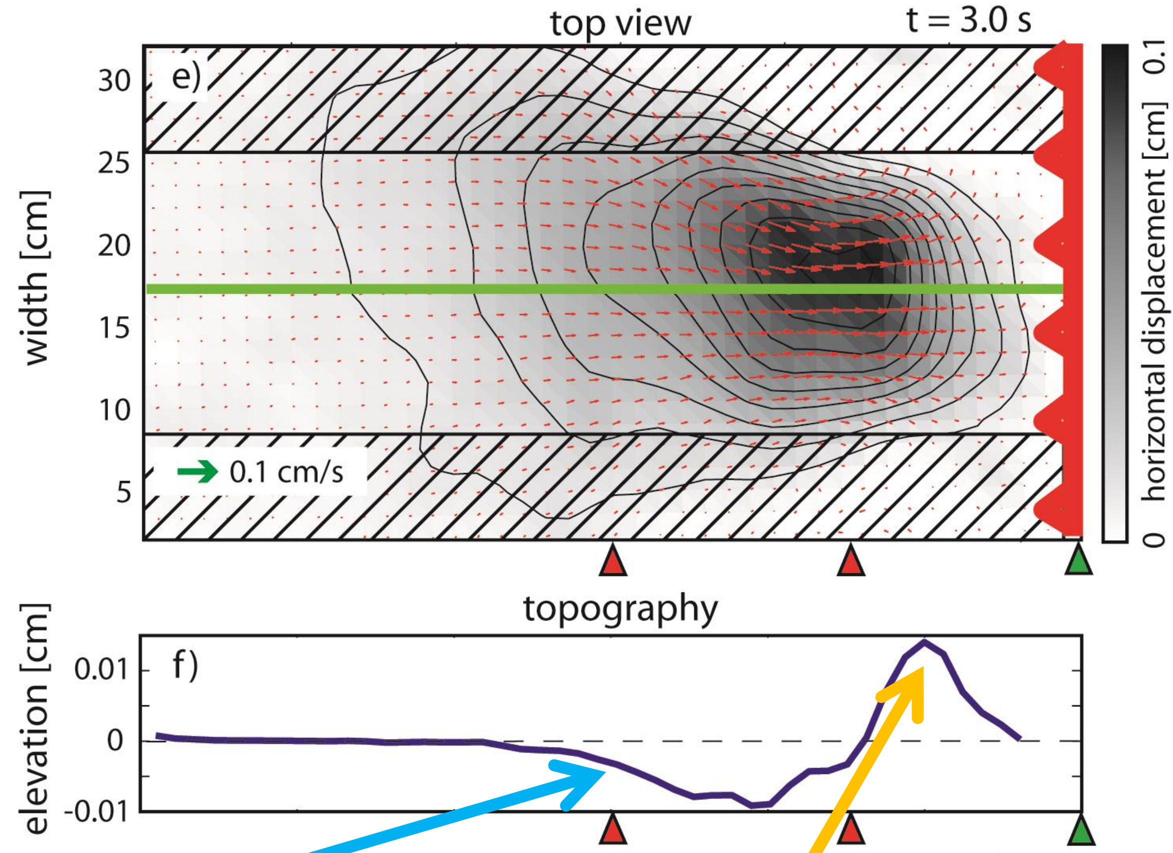




Ozawa et al., 2011

all sites move seaward like Tohoku!!!

coseismic stage

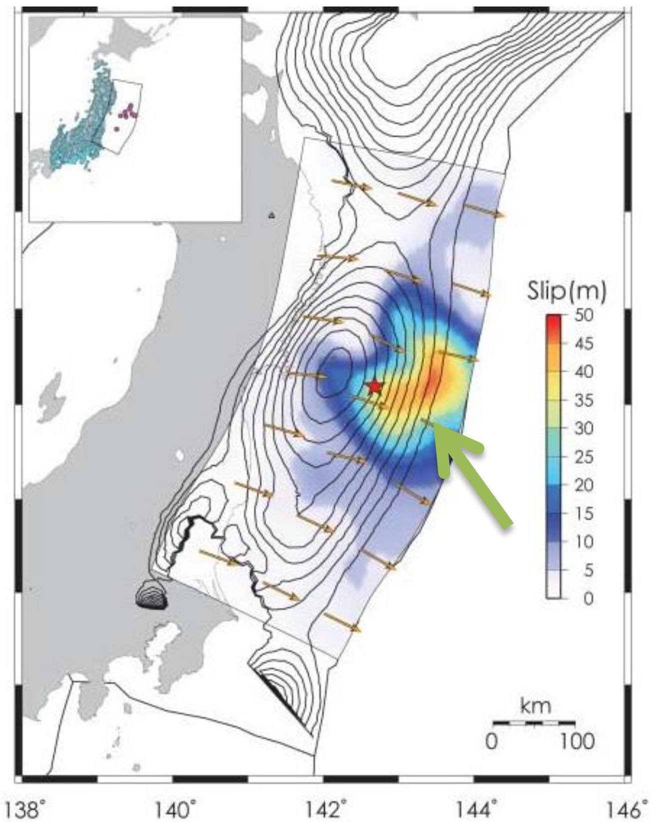


sudden uplift and subsidence like Sumatra!!!

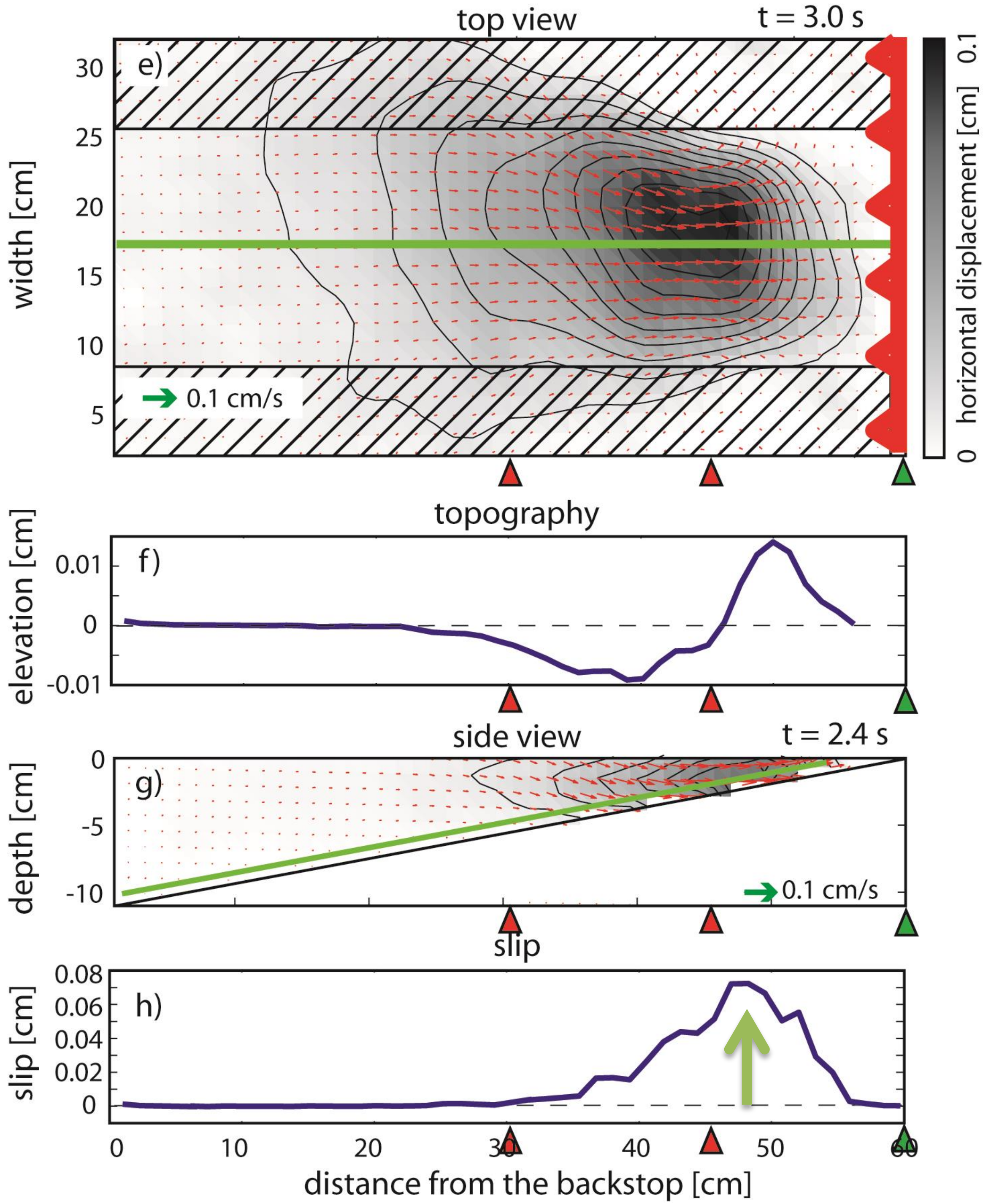
both pictures from TO - Caltech

coseismic stage

like Tohoku!



Romano et al., 2012




WORK IN PROGRESS
EURYI
European Young Investigator
Awards

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AND OUR LAB !!!

TAKE-HOME MESSAGES

Mega-earthquakes are (mainly) generated in convergent tectonic settings, along the subduction thrust faults.

Mega-earthquakes are unfrequent but not rare events.

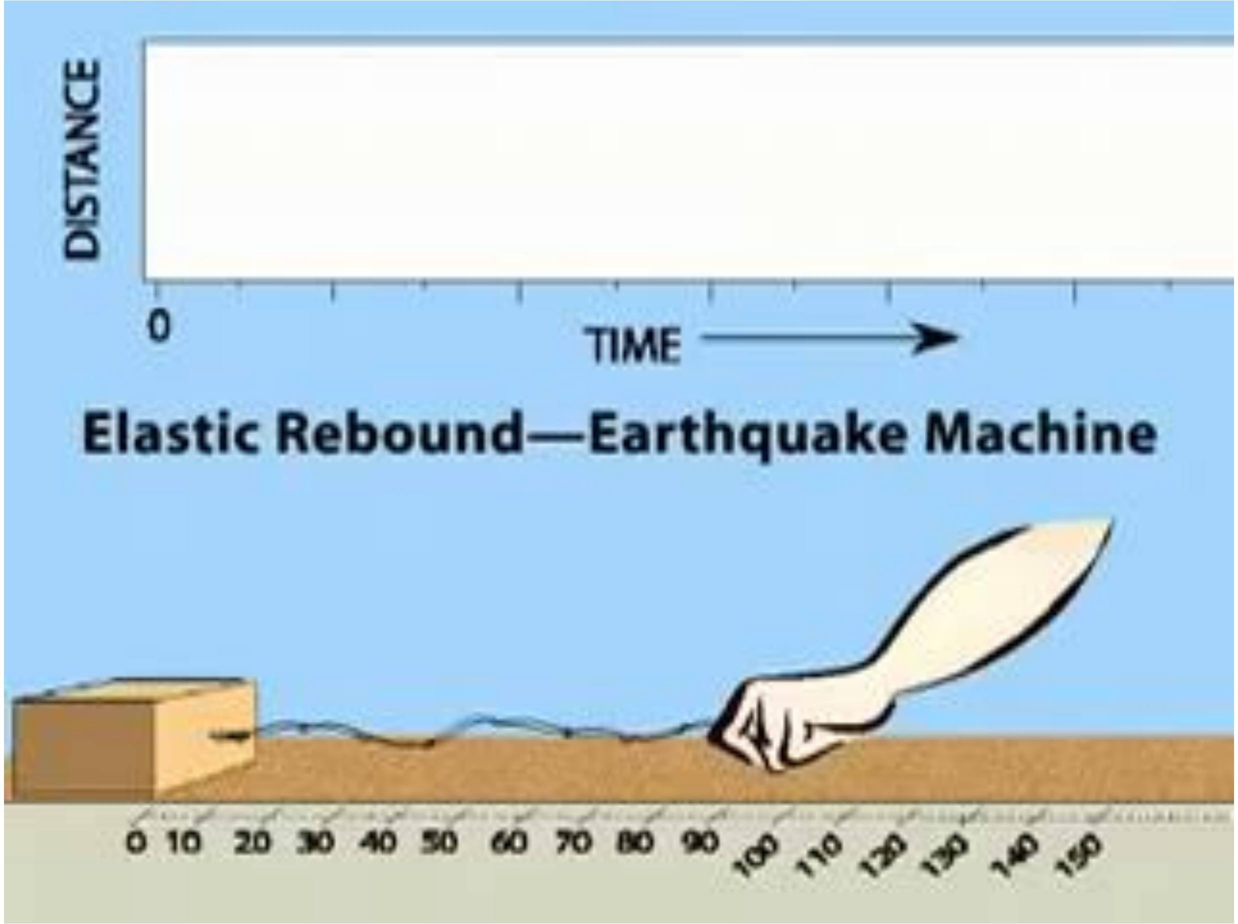
Mega-earthquakes are generated by a multi-segments rupture.

The historical seismic record is too limited to adequately asses the hazard from these devastating events. Studies of events in other regions can help to overcome this limitation.

Multidisciplinary studies, application of modern technologies (also offshore), earthquake and tsunami early warning and structural engineering together with public preparation and enhanced infrastructure are the key toward effectively reducing the impact of these potential devastating events.


THE
END

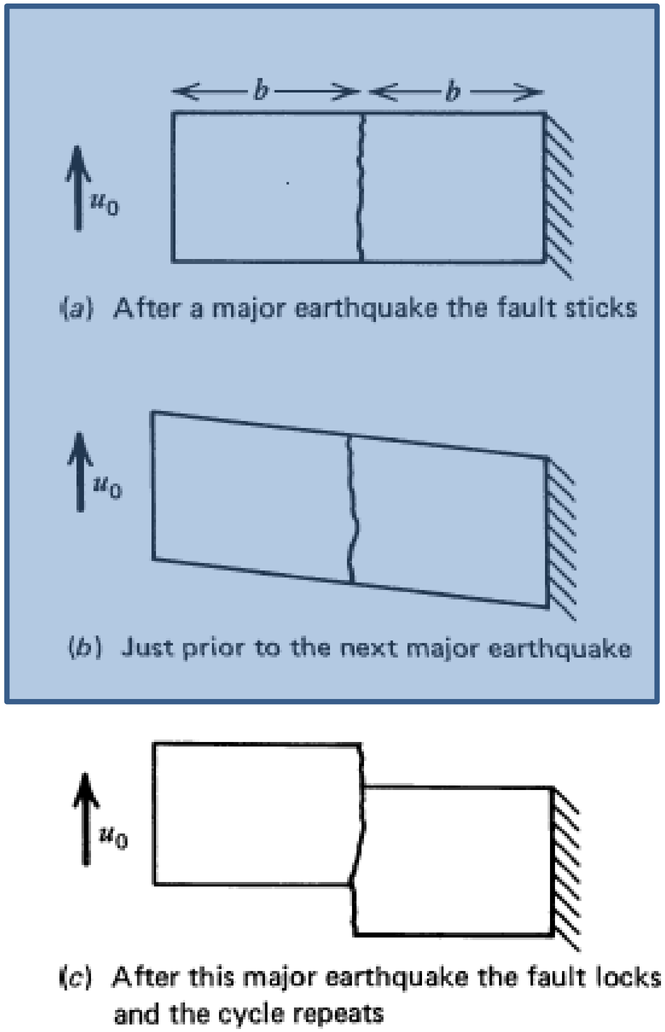
ELASTIC REBOUND & STICK- SLIP BEHAVIOR



http://www.iris.edu/

FRICTION ON FAULTS

quantitative elastic rebound



The stress across the fault is τ_{fd}, the frictional stress that is operative on the fault at the end of faulting. A uniform relative velocity u_0 is applied at a distance b from the fault, and the shear strain increases with time according to

$$\varepsilon(t) = u_0 t/(4b)$$

The shear stress on the fault as a function of time t since the last displacement on the fault is:

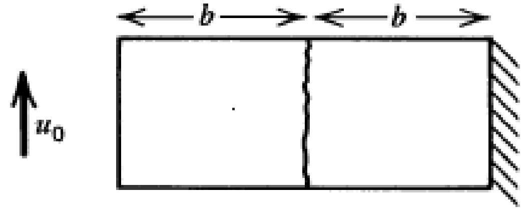
$$\tau = \tau_{fd} + (G u_0 t)/2b$$

The locked fault can transmit any shear stress less than the static frictional stress τ_{fs}. When this stress is reached, slip occurs. Therefore, the time $t = t*$ when the next displacement occurs on the fault is:

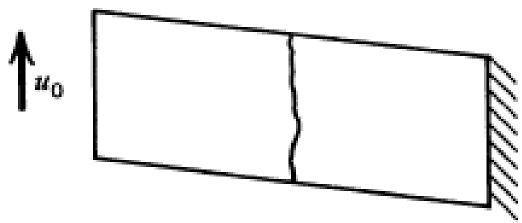
$$t* = (2b/G u_0)\,(\tau_{fs} - \tau_{fd})$$

FRICTION ON FAULTS

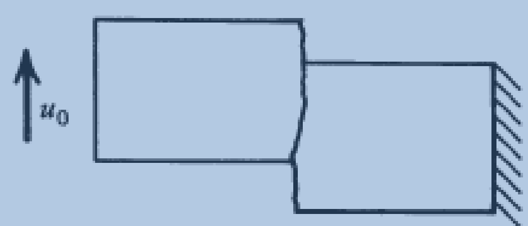
quantitative elastic rebound



(a) After a major earthquake the fault sticks



(b) Just prior to the next major earthquake



(c) After this major earthquake the fault locks and the cycle repeats

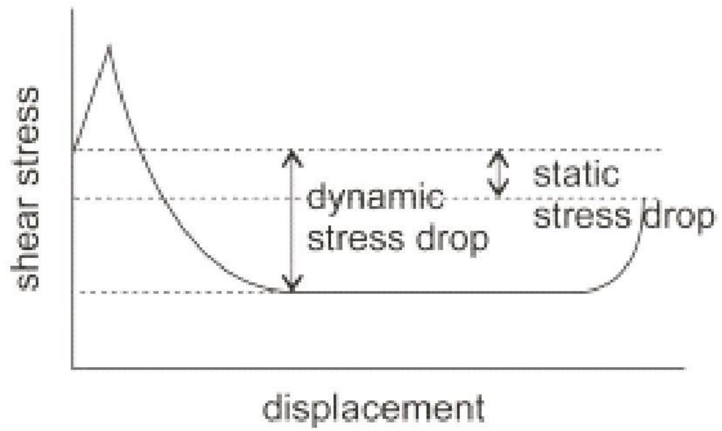
The slip on the fault generates an earthquake. The displacement on the fault during the earthquake occurs in a few seconds so that the edges of the plates can be assumed to be stationary during this time. The accumulated shear strain $\varepsilon = u_0 t^*/4b$ is recovered by the plates in a process known as ***elastic rebound***. The resulting displacement on the fault w is:

$$\Delta w = 2\varepsilon(2b) = 4b\left(\frac{u_0 t^*}{4b}\right) = \frac{2b}{G}(\tau_{fs} - \tau_{fd})$$

The quantity $\tau_{fs} - \tau_{fd}$ is the ***stress drop*** on the fault during the earthquake.
After the earthquake, the fault locks and the cycle repeats.

FRICTION ON FAULTS

stress drop



stress drops during large earthquakes
$\tau_{fs} - \tau_{fd}$ = 1-100 MPa

$$\Delta w = 2\varepsilon(2b) = 4b\left(\frac{u_0 t^*}{4b}\right) = \frac{2b}{G}(\tau_{fs} - \tau_{fd})$$

w= 5 m; $G_{crustal\ rocks}$=30 GPa; $\tau_{fs} - \tau_{fd}$ = 1-100 MPa

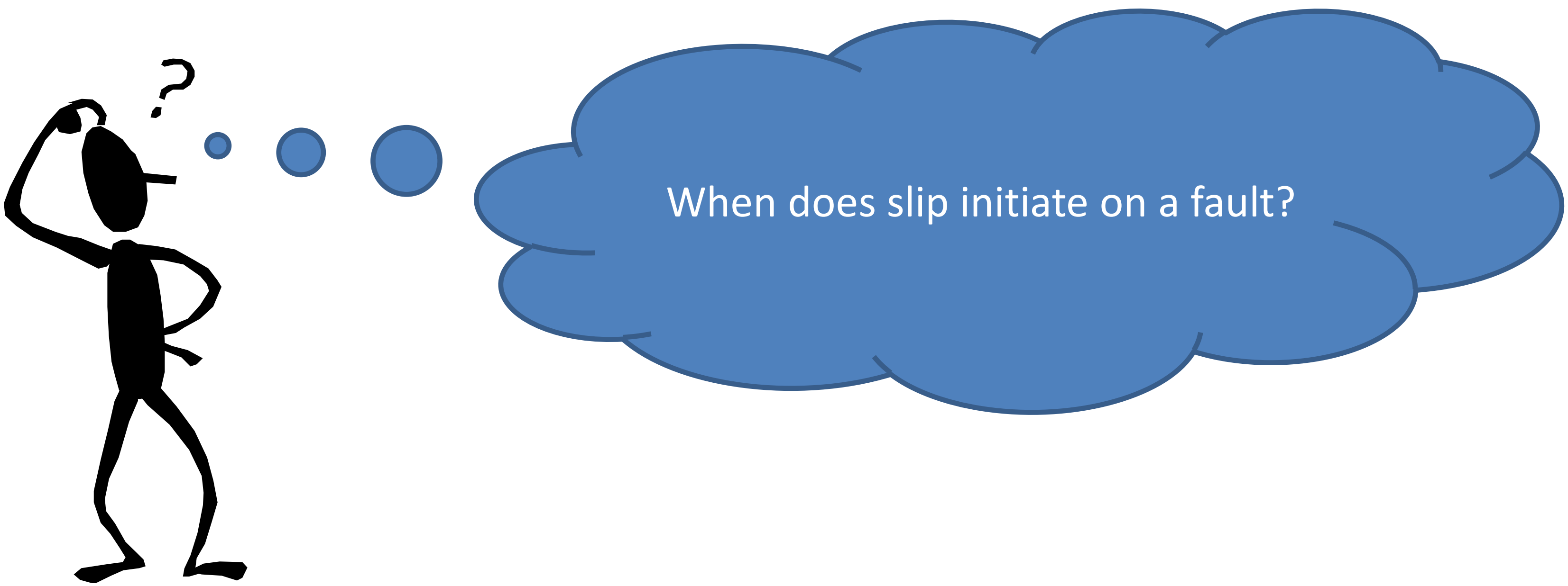
b = 75 m - 7.5 km

FRICTION ON FAULTS

The **static frictional stress, τ_{fs}**, is the stress on the fault when earthquake rupture initiates on the fault.

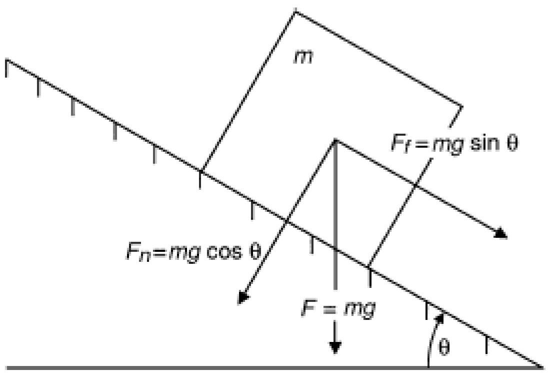
During rupture, slip is occurring on the fault and the shear stress on the fault is the **dynamic frictional stress, τ_{fd}**.

Stick–slip behavior occurs as long as the static frictional stress τ_{fs} is greater than the dynamic frictional stress τ_{fd}, **$\tau_{fs} > \tau_{fd}$**.



FRICTION ON FAULTS

Amonton's law



$$\sigma_n = \frac{mg \cos \theta}{A}$$

normal stress that the block exerts on the surface

$$\tau_f = \frac{mg \sin \theta}{A}$$

the frictional shear stress on the surface required to keep the block from slipping

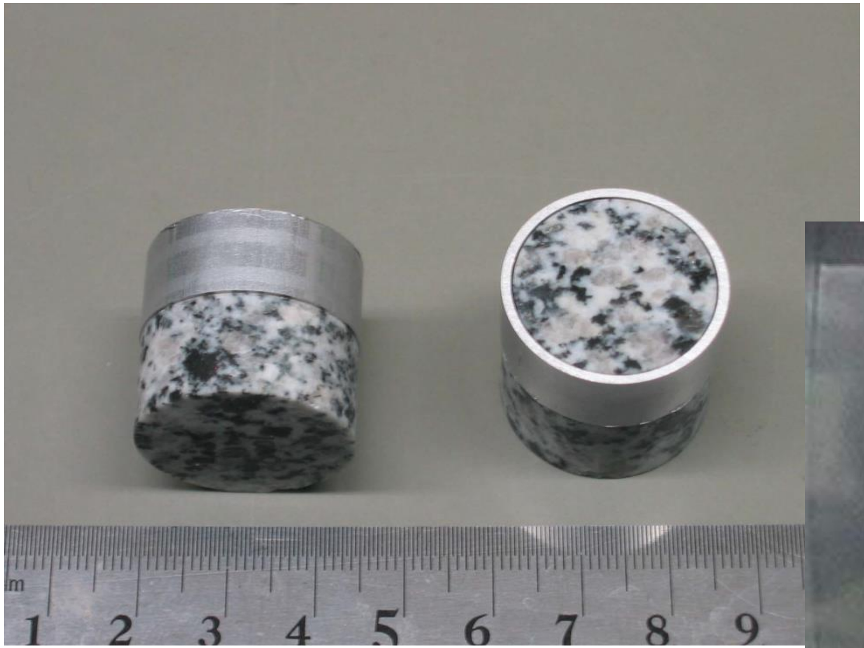
Slip will occur when $\tau_f = \tau_{fs}$, the static frictional stress. Under a wide variety of conditions it is found experimentally that:

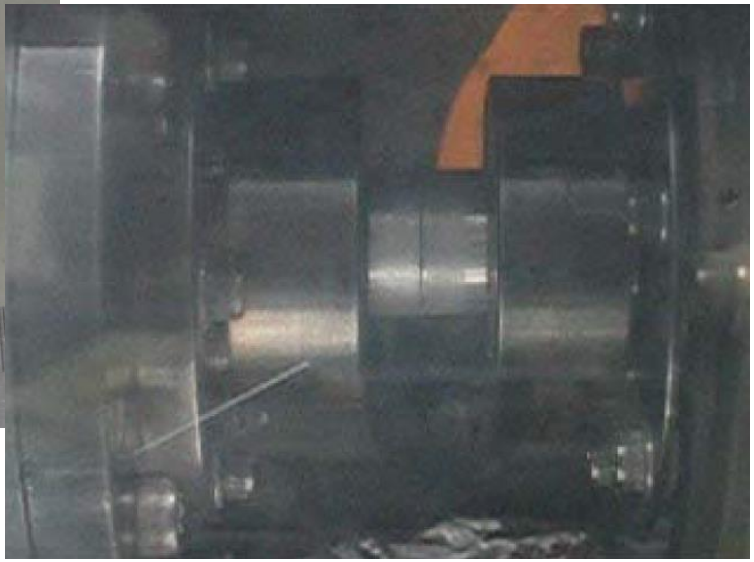
$$\tau_{fs} = f_s \sigma_n$$

where fs is the *coefficient of static friction*. This relation is known as *Amonton's law*. The coefficient of friction depends weakly on the types of material in contact but is independent of the normal stress.

FRICTION ON FAULTS

Amonton's law





Look at:
http://www.youtube.com/watch?v=YTfwJ3Elw5s

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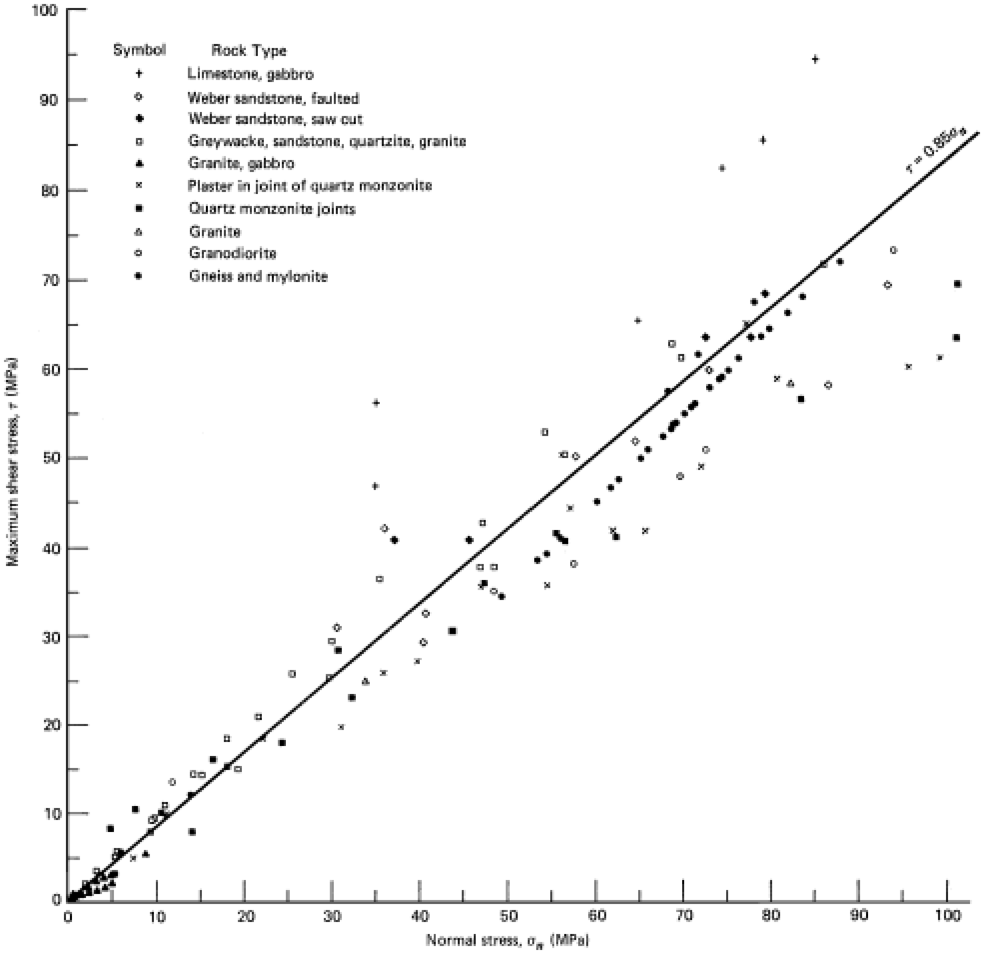
FRICTION ON FAULTS

Amonton's law



Maximum shear stress to initiate sliding as a function of normal stress for a variety of rock types. The linear fit defines a maximum coefficient of static friction max *f*s equal to 0.85. Data from Byerlee (1977)

FRICTION ON FAULTS

Amonton's law

$$\tau_{fs} = f_s \sigma_n$$

The pressure of water on a fault is referred to as the pore pressure pw.
The effective normal stress acting on a wet fault is the actual normal stress less the pore pressure. Therefore on a wet fault Amonton's law can be written

$$|\tau| = f_s(\sigma_n - p_w)$$

EARTHQUAKE ENERGY

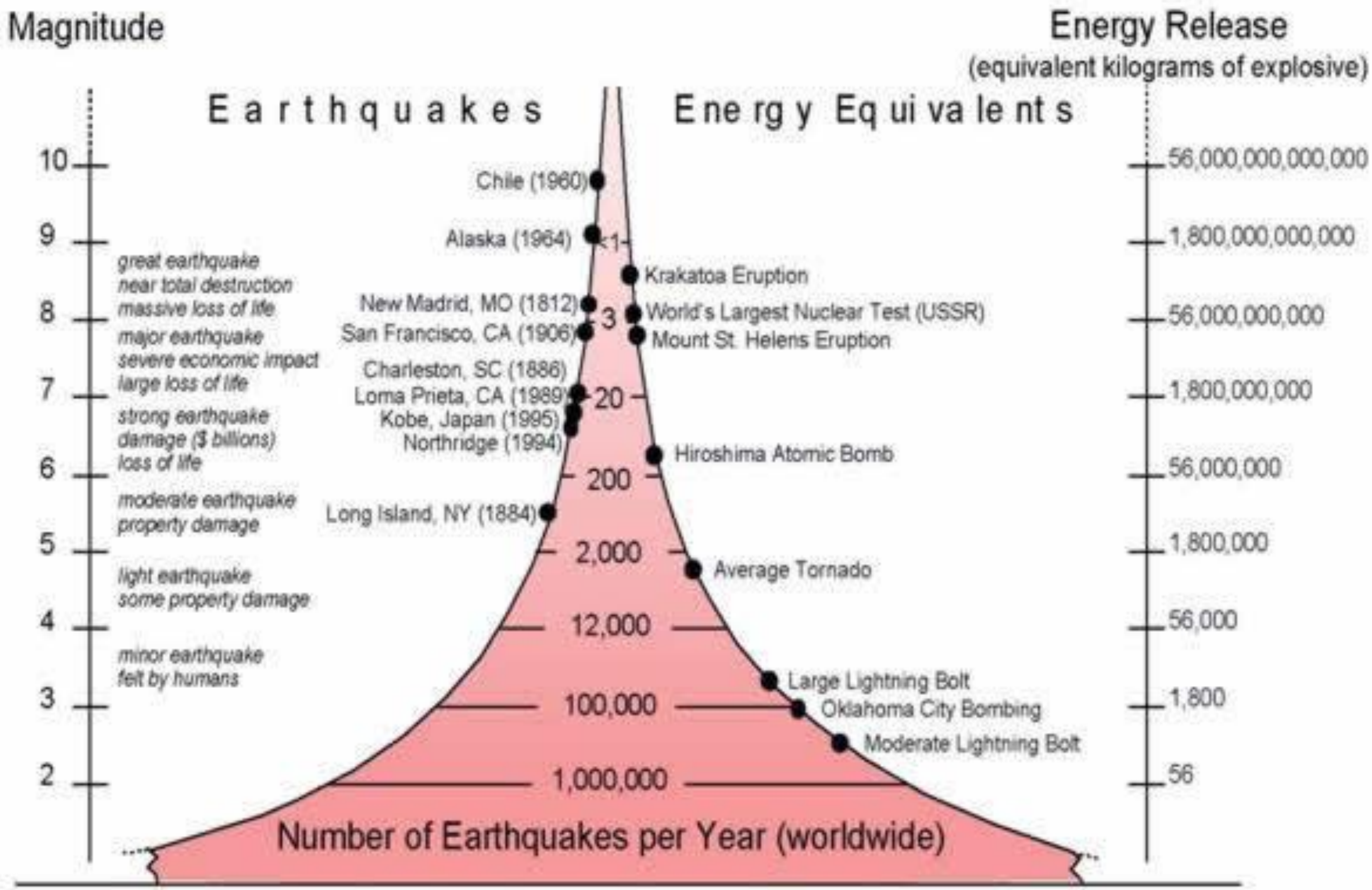
$$U_e = \overline{\sigma} A \delta$$

σ = mean stress during slip
A = rupture area
δ = average slip displacement

$$\Delta U_e = U_s + U_k + U_f$$

ΔU_e = change in elastic strain energy
U_s = surface energy (to create new crack surface area)
U_k = kinetic energy (seismic)
U_f = frictional energy (heat)
For U_s, see Chester et al., 2005, Nature 437, 133-136

EARTHQUAKE ENERGY

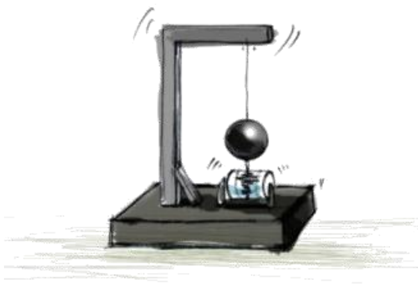


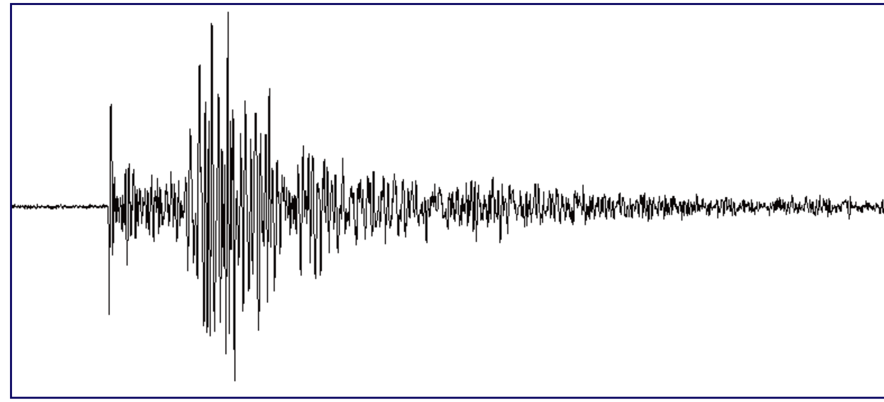
EARTHQUAKE ENERGY

Example: **1960 Chile earthquake**
– 21 m slip, 800 km x 200 km rupture
– Mw = 9.5
– ~1019 Joules (total global annual energy consumption ~3 x 1020 J)
– equivalent 2000 megaton nuclear explosion

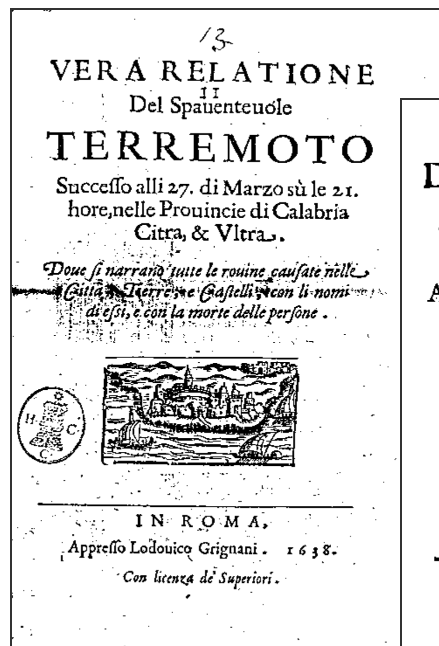
MEASURING EARTHQUAKES

Instrumental data





Historical data



13

VERA RELATIONE

Del Spauenteuole

TERREMOTO

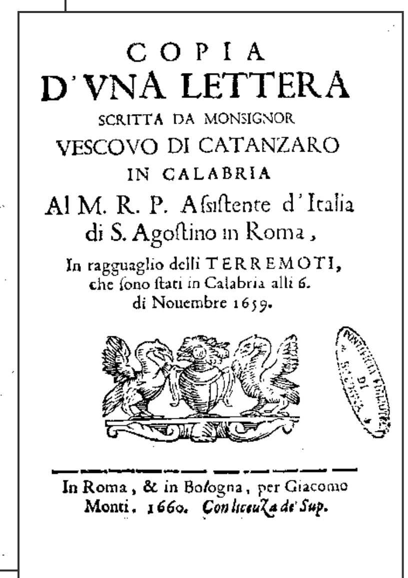
Successo alli 27. di Marzo sù le 21. hore, nelle Prouincie di Calabria Citra, & Vltra.

Doue si narrano tutte le rouine causate nelle Città, Terre, e Castelli, con li nomi di essi, e con la morte delle persone.

IN ROMA,

Appresso Lodouico Grignani. 1638.

Con licenza de' Superiori.



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D'VNA LETTERA

SCRITTA DA MONSIGNOR

VESCOVO DI CATANZARO

IN CALABRIA

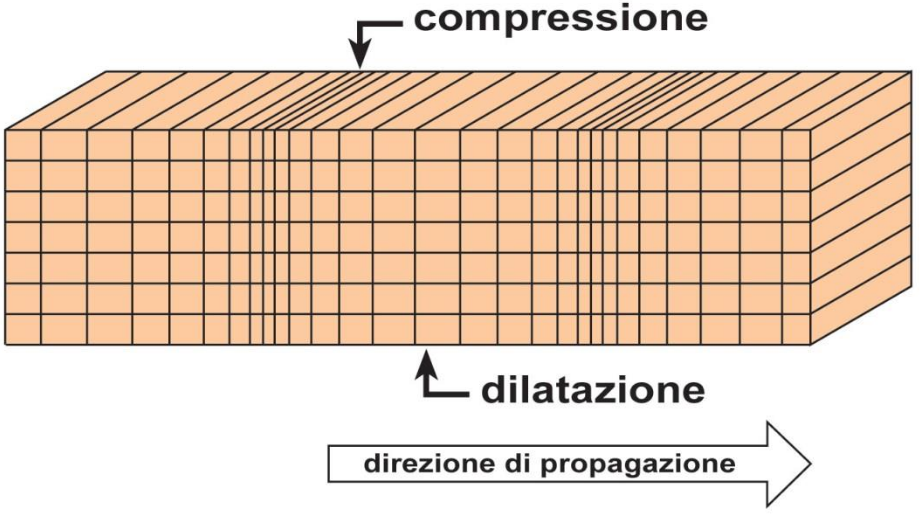
Al M. R. P. Assistente d'Italia di S. Agostino in Roma,

In ragguaglio delli TERREMOTI, che sono stati in Calabria alli 6. di Nouembre 1659.

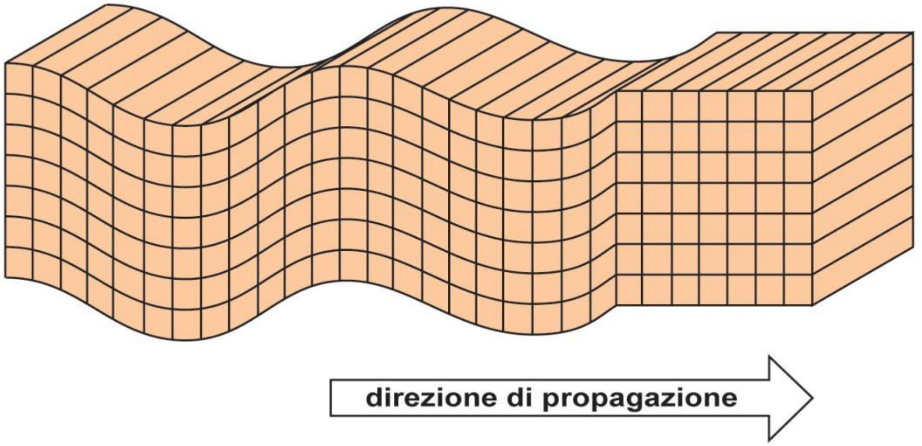
In Roma, & in Bologna, per Giacomo Monti. 1660. *Con licenza de' Sup.*

Instrumental data are based on properties of seismic waves

ONDA LONGITUDINALE

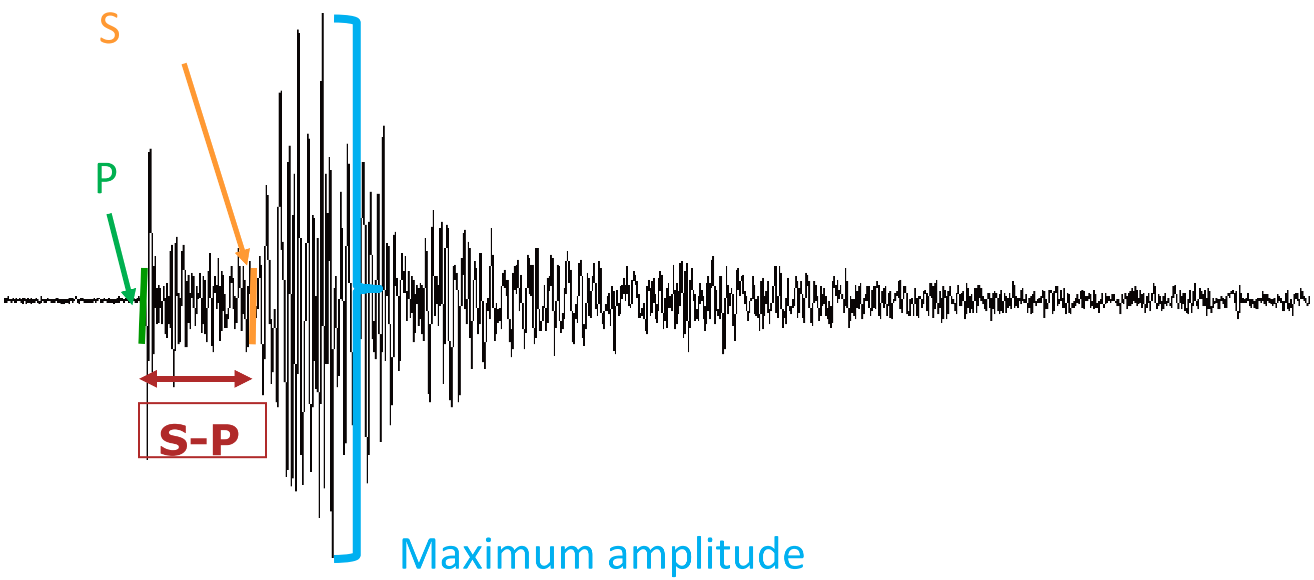


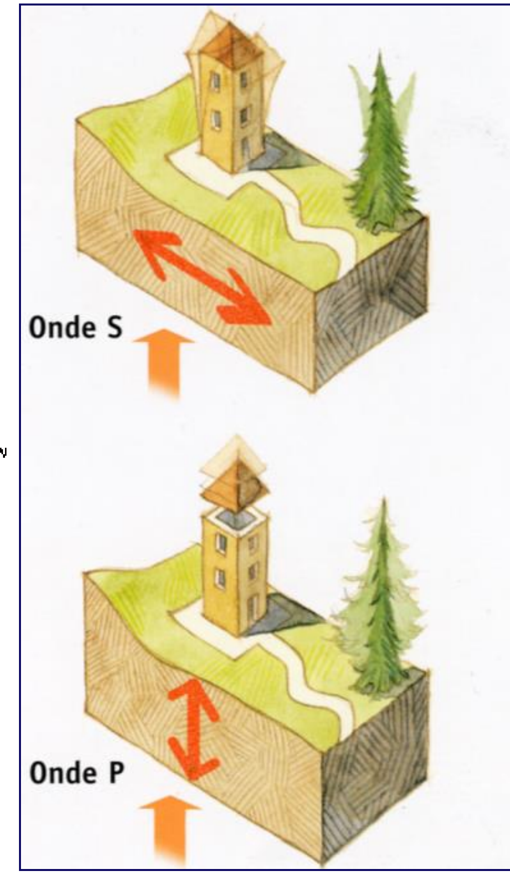
ONDA TRASVERSALE



From the seismogram to…

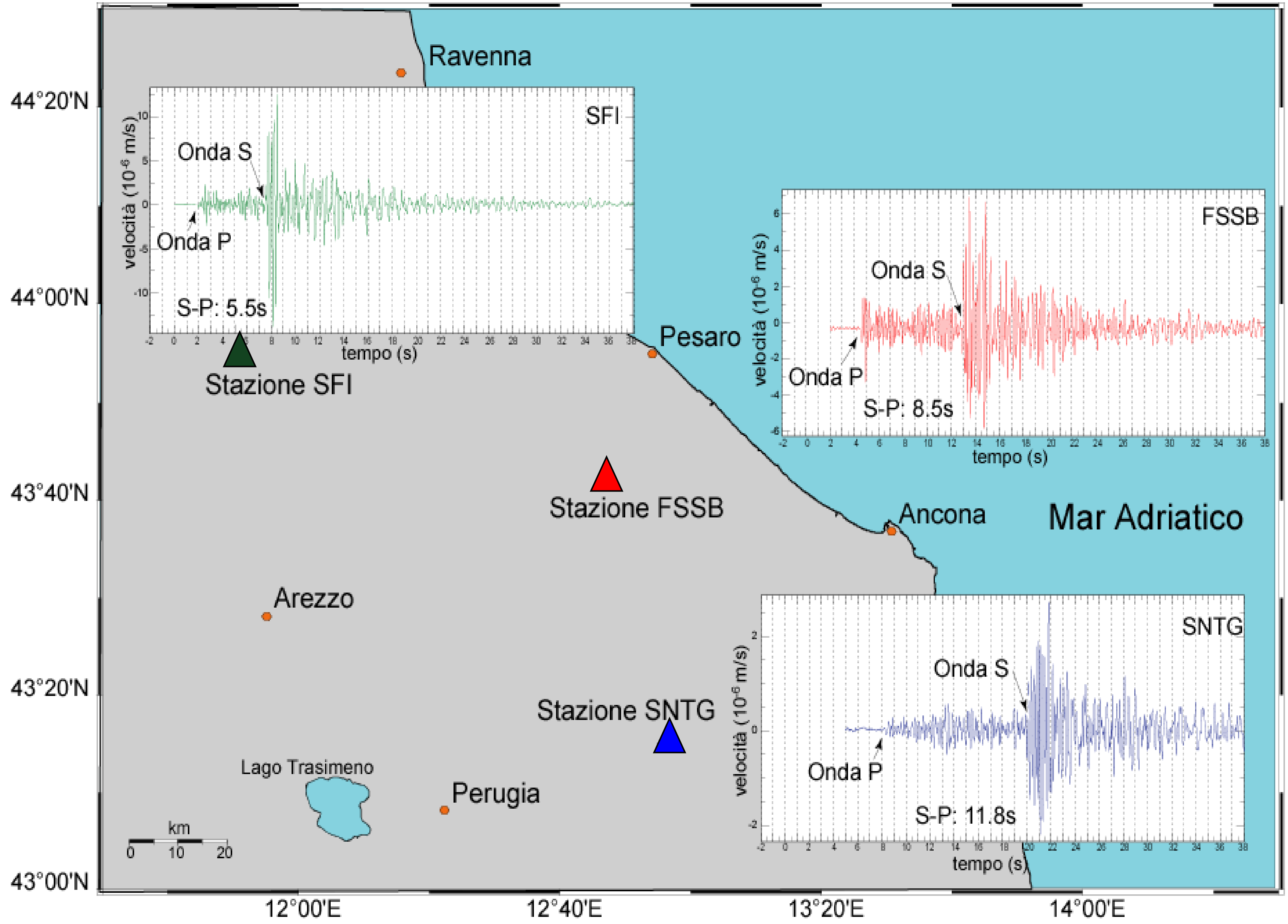
… **ipocenter** (difference in the S-P arrival times from several stations)





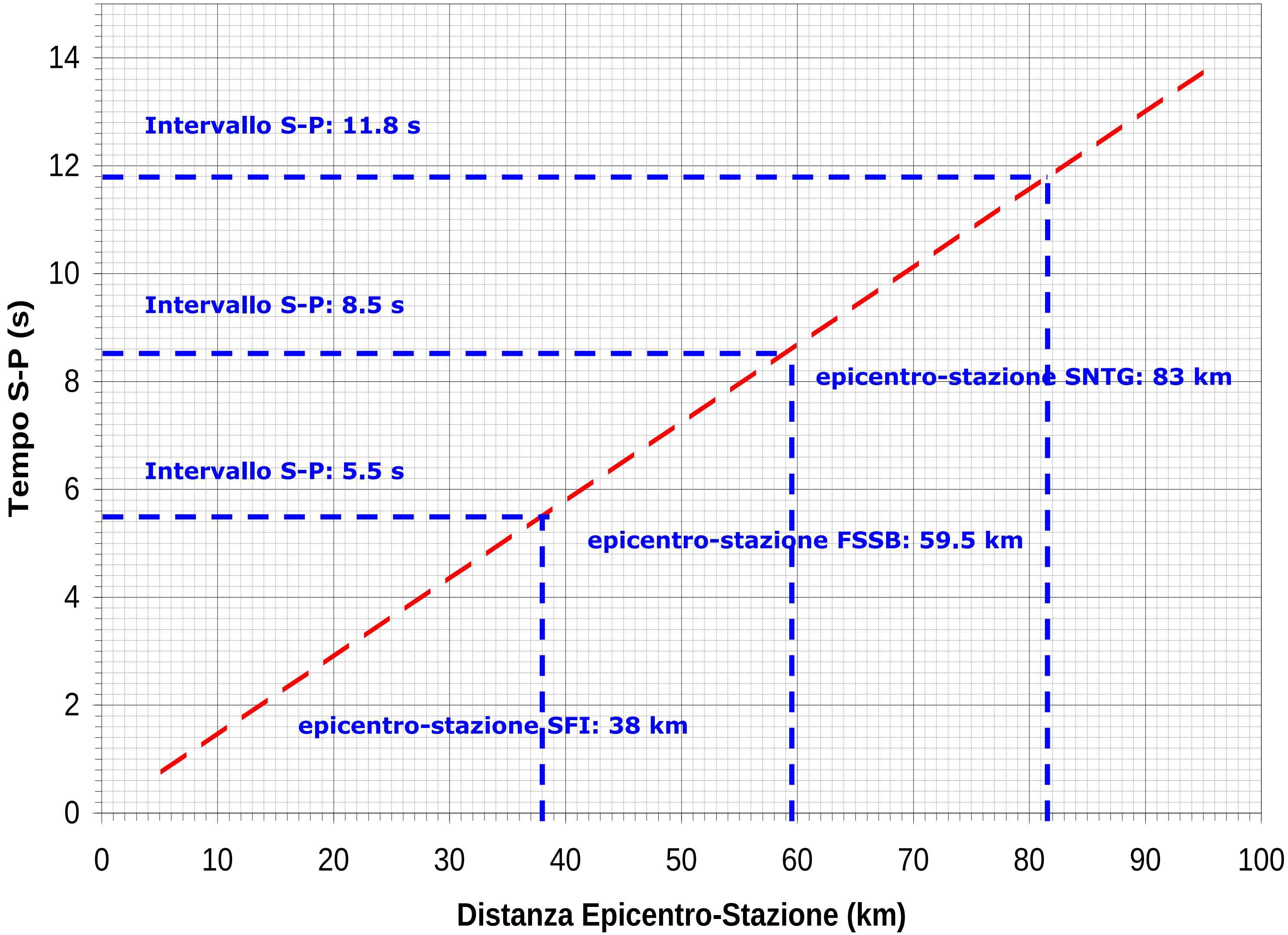
… earthquake's energy or Richter magnitude (maximum amplitude of the seismic signal).

Looking for the ipocenter

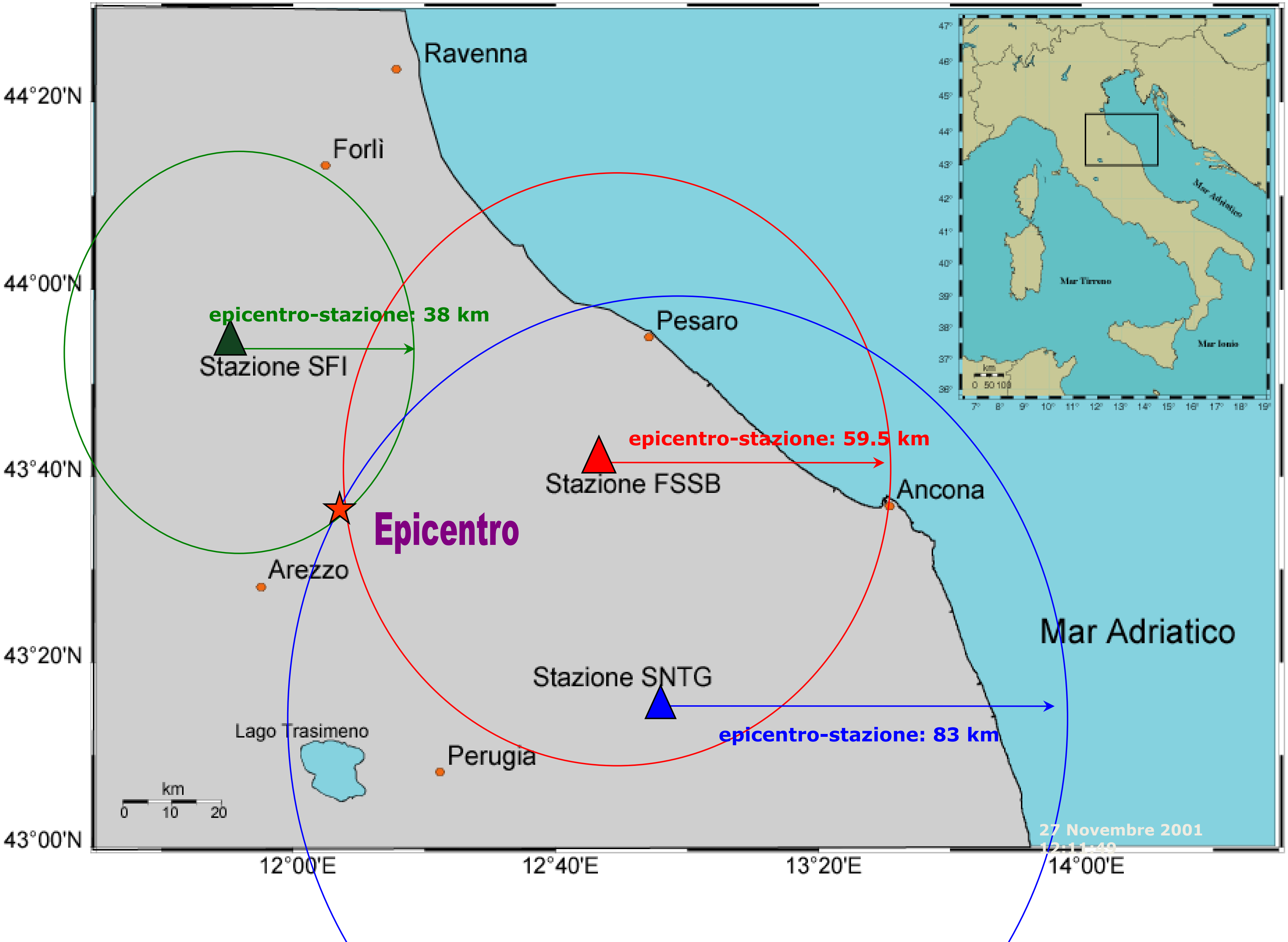


Looking for the ipocenter

Arrival times → distances

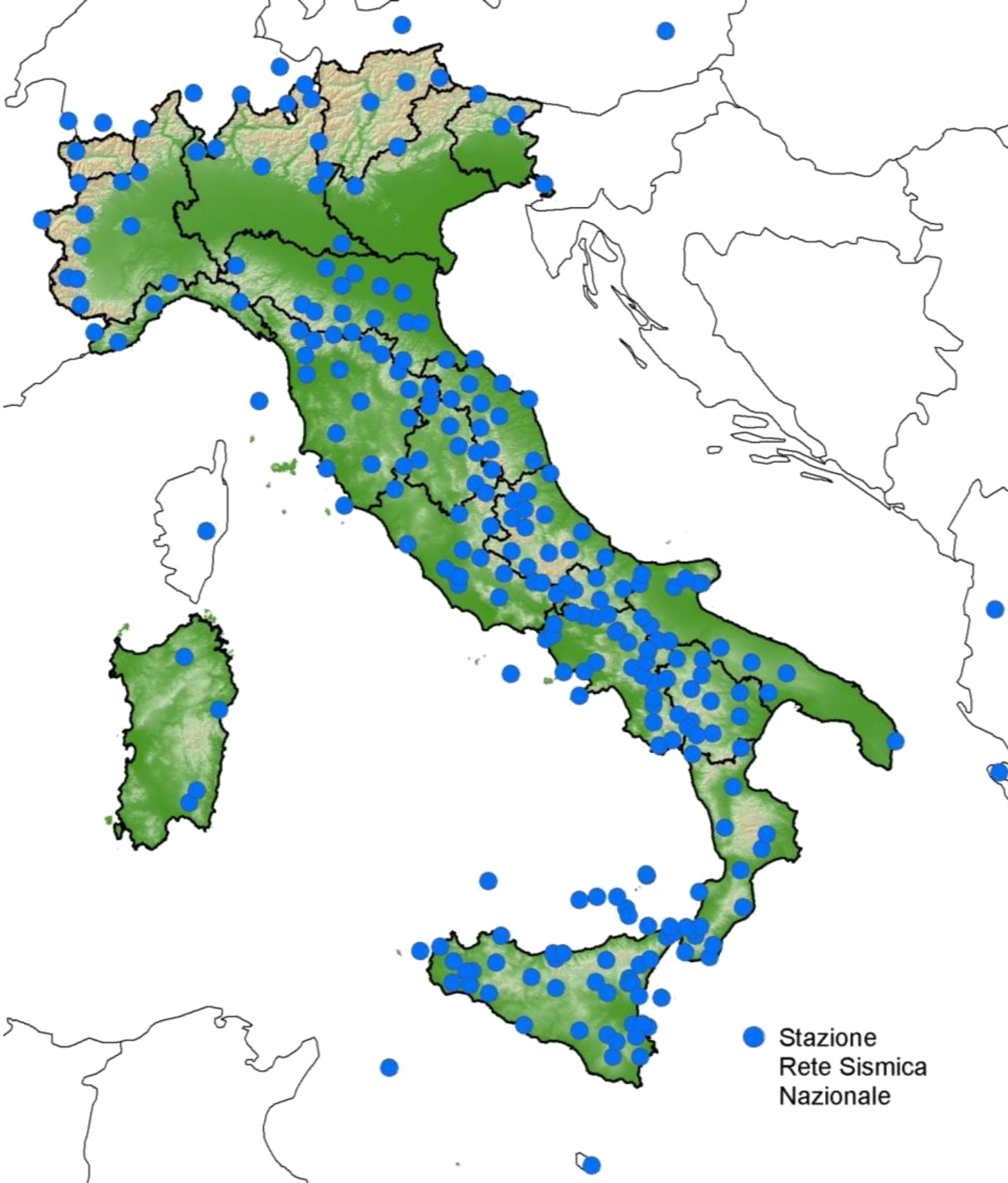


Looking for the ipocenter



National Seismic Network

about 250 stations for civil defence and research.



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INGV Seismic Survey – 24/7

1) to
2) Ipocenter coordinates
3) magnitude

2 min — Area (province), Magnitude

5 min → Coordinates, Magnitude

30 min — Final coordinates, and magnitude

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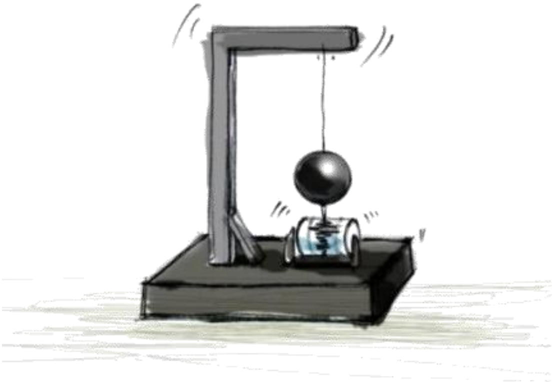
MAGNITUDE	INTENSITY
	
Earthquake's magnitude	**Earthquake's effect of persons and stuff.**
Physical measurement (→ sismometers)	**No need for instruments**
It is possible to determine it everywhere	**Difficult/impossible to determine if in Difficile determinarla in desert areas or sea**
Expressed as a real number (e.g. M=5.4)	**Expressed in degrees of a reference scale (e.g., MCS I-XII)**

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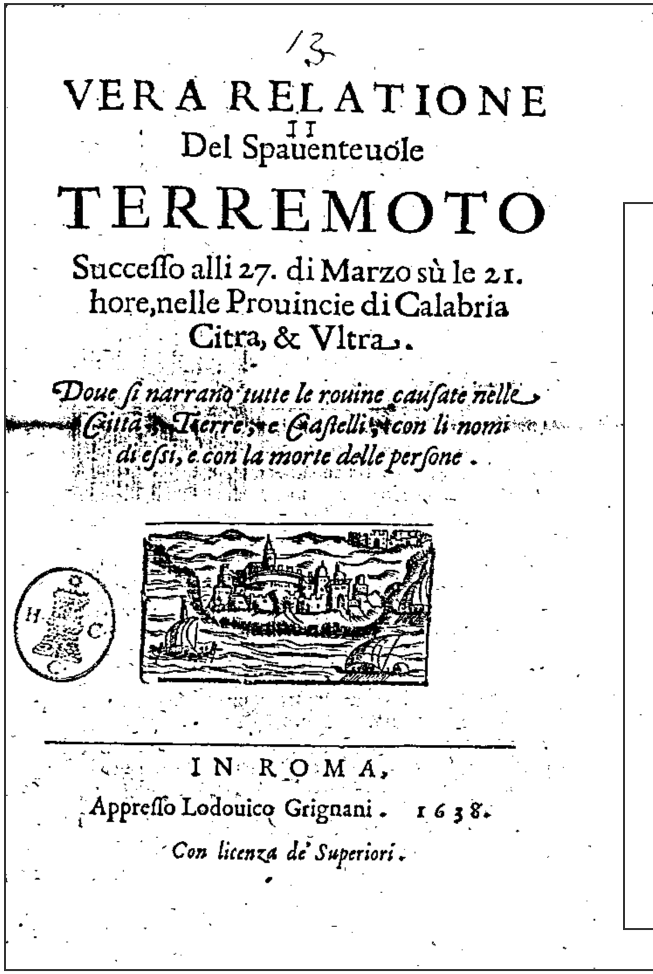
Historical data → (MCS) Intensity



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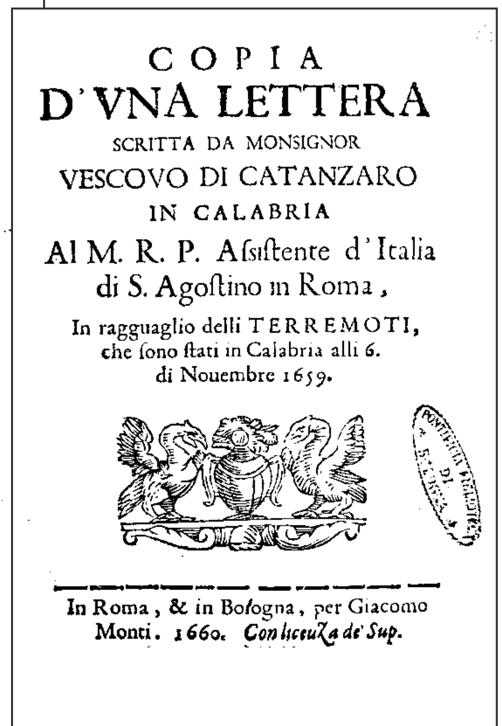

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MCS Intensity

I	Not felt.
II	Felt by a few people.
III	Hanging objects sway.
IV	Windows and doors rattle.
V	Sleepers waken.
VI	Windows and glassware broken.
VII	Difficult to stand.
VIII	Branches broken from trees.
IX	Cracks in ground – general panic.
X	Large landslides – most masonry structures destroyed.
XI	Nearly total destruction.

I. Effects on persons (please mark or choose the appropriate)

1a. Location during the quake:	unknown
1b. Which floor?	no remark
2. What did you do during the quake:	unknown
3a. How strong did you feel the quake?	not felt
3b. In which way was the quake felt?	no remark
3c. Who else has felt the quake?	I was alone
4. Reaction?	☐ none ☐ surprise ☐ awakening ☐ frightened ☐ problems with the balance ☐ running to the outside ☐ panic

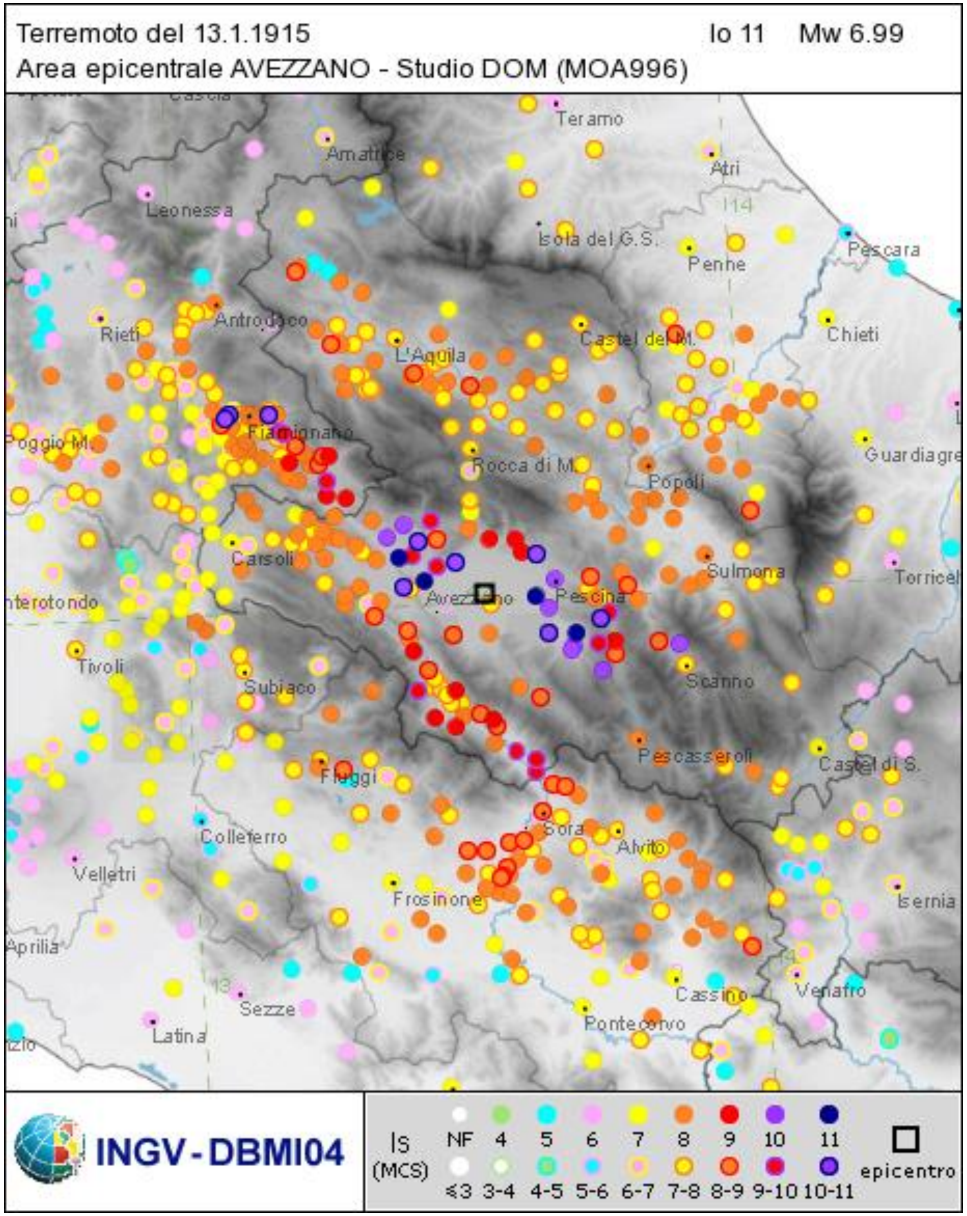
II. Effects on objects and surroundings

1. Hanging objects (Lamps, pictures, etc.):	no swinging
2. China, glass:	nothing remarked
3. Windows, doors:	nothing remarked
4. Windows:	☐ broken to pieces
5. Wood:	☐ creak, crack
6. Small, easy to move objects (single books, vases, etc.):	nothing remarked
7. Small objects of normal stability (e.g. books in shelfs):	nothing remarked
8. Light furniture:	nothing remarked
9. Furniture:	nothing remarked
10. Bigger objects (TV, computer, etc.):	☐ overturned
11. Fluids in well filled containers:	nothing remarked
12. Water in containers, tanks, pools:	nothing remarked
13. Tombstones:	☐ shifted, rotated, overturned
14. Visible waves in the soil:	nothing remarked

Part of SED-ETH questionnaire

MCS Intensity

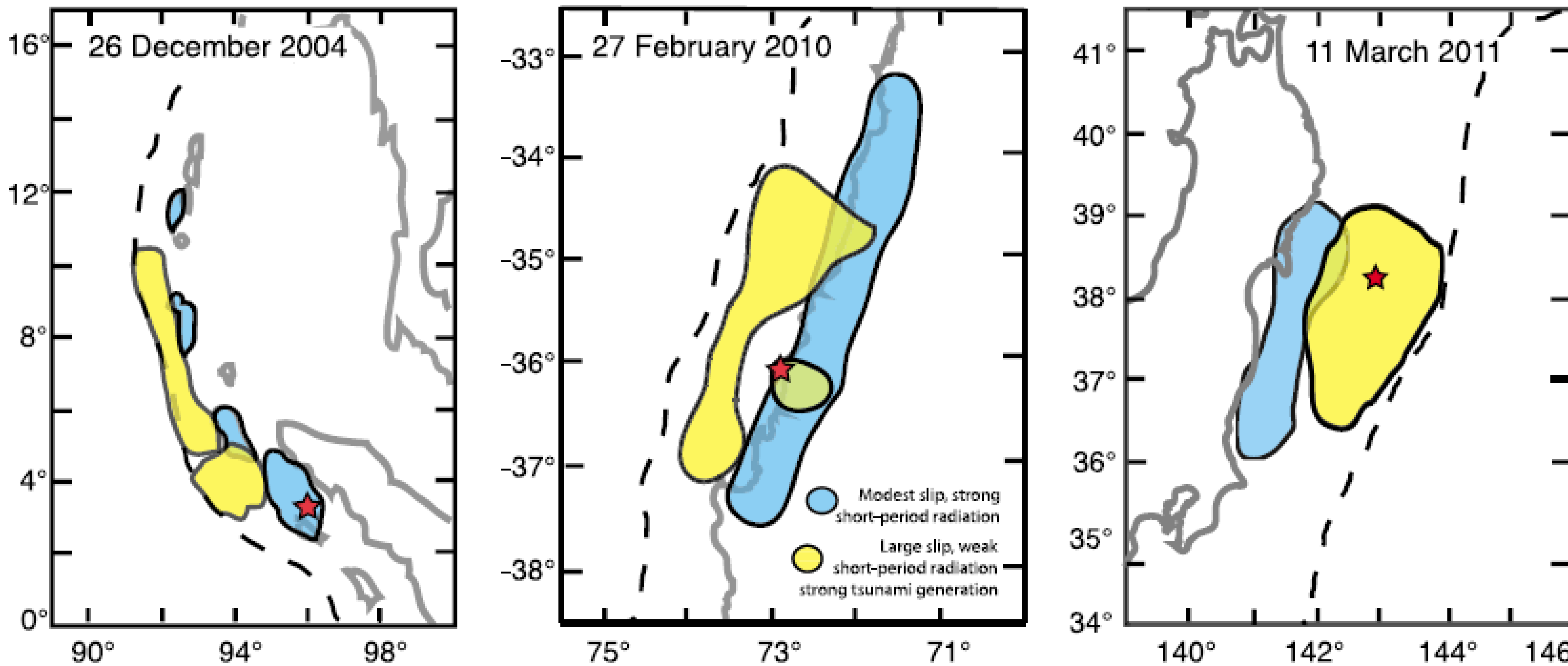
Fucino's earthquake, 13.12.1915



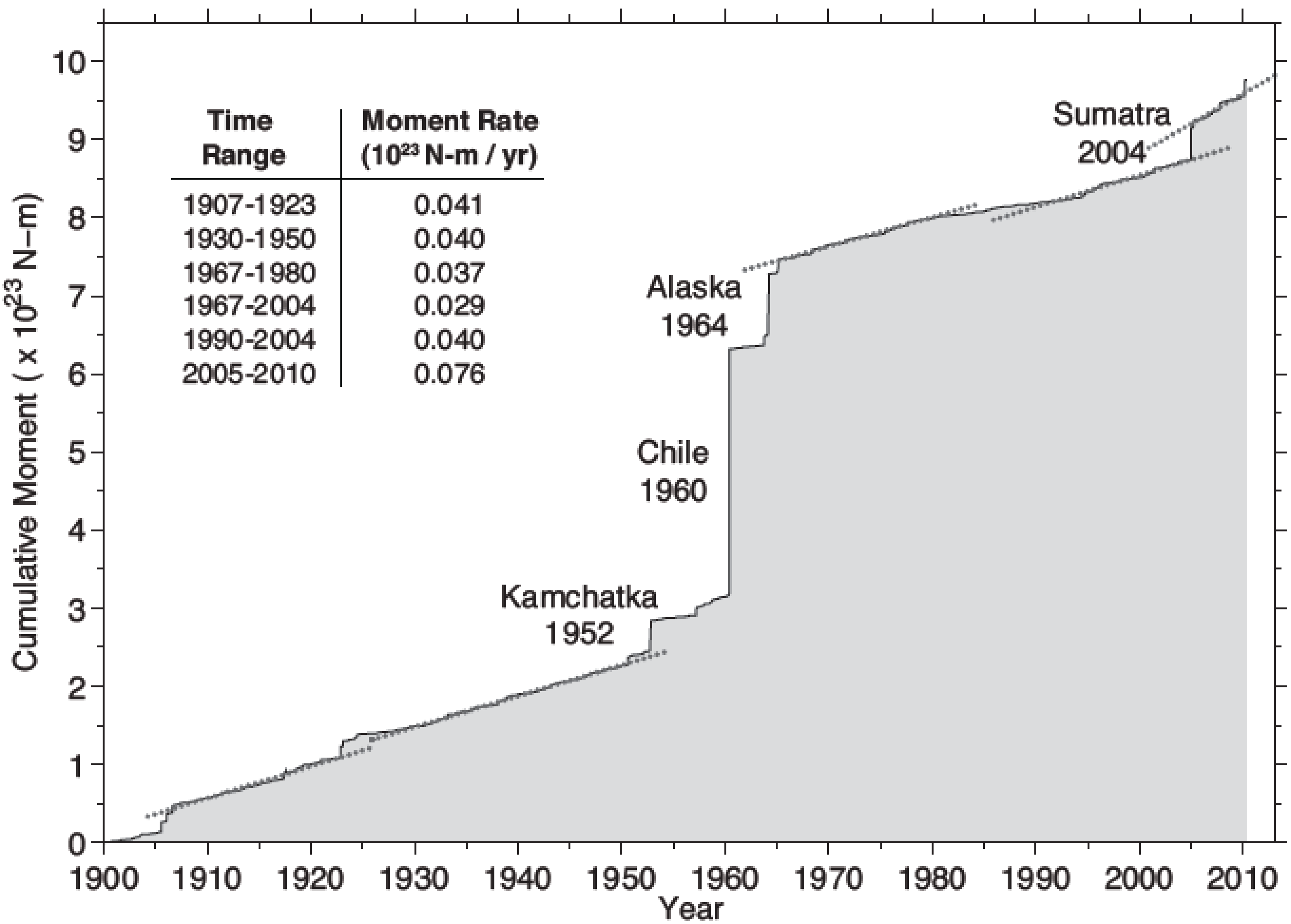
MAGNITUDE

Different way to measure magnitudes as a function of kind of waves and seismometers

Magnitude type	Applicable magnitude range	Distance range	Comments
Duration (Md)	<4	0-400 km	Based on the duration of shaking as measured by the time decay of the amplitude of the seismogram. Often used to compute magnitude from seismograms with "clipped" waveforms due to limited dynamic recording range of analog instrumentation, which makes it impossible to measure peak amplitudes.
Local (ML)	2-6	0-400 km	The original magnitude relationship defined by Richter and Gutenberg for local earthquakes in 1935. It is based on the maximum amplitude of a seismogram recorded on a Wood-Anderson torsion seismograph. Although these instruments are no longer widely in use, ML values are calculated using modern instrumentation with appropriate adjustments.
Surface wave (Ms)	5-8	20-180 degrees	A magnitude for distant earthquakes based on the amplitude of Rayleigh surface waves measured at a period near 20 sec.
Moment (Mw)	>3.5	all	Based on the moment of the earthquake, which is equal to the rigidity of the earth times the average amount of slip on the fault times the amount of fault area that slipped.
Energy (Me)	>3.5	all	Based on the amount of recorded seismic energy radiated by the earthquake.
Moment (Mi)	5-8	all	Based on the integral of the first few seconds of P wave on broadband instruments (Tsuboi method).
Body (Mb)	4-7	16-100 degrees (only deep earthquakes)	Based on the amplitude of P body-waves. This scale is most appropriate for deep-focus earthquakes.
Surface wave (MLg)	5-8	all	A magnitude for distant earthquakes based on the amplitude of the Lg surface waves.



26 December 2004
27 February 2010
11 March 2011
Modest slip, strong short-period radiation
Large slip, weak short-period radiation strong tsunami generation
16°
12°
8°
4°
0°
90°
94°
98°
-33°
-34°
-35°
-36°
-37°
-38°
75°
73°
71°
41°
40°
39°
38°
37°
36°
35°
34°
140°
142°
144°
146°



Ammon et al., 2010

MOMENT MAGNITUDE

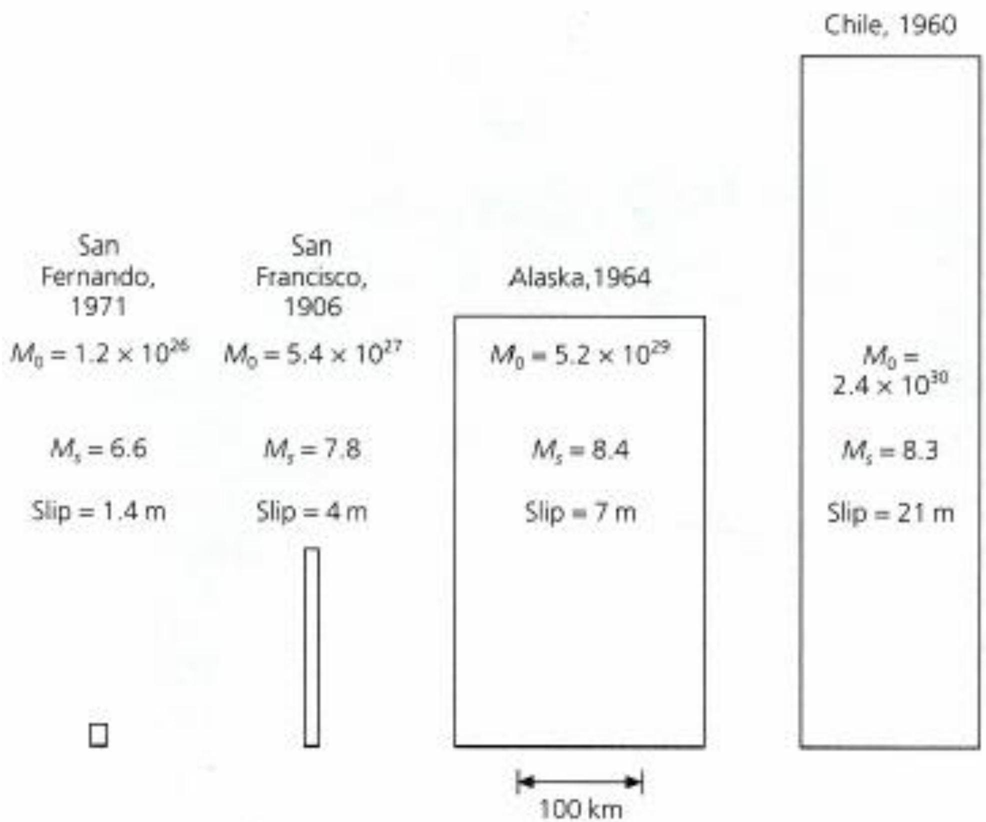
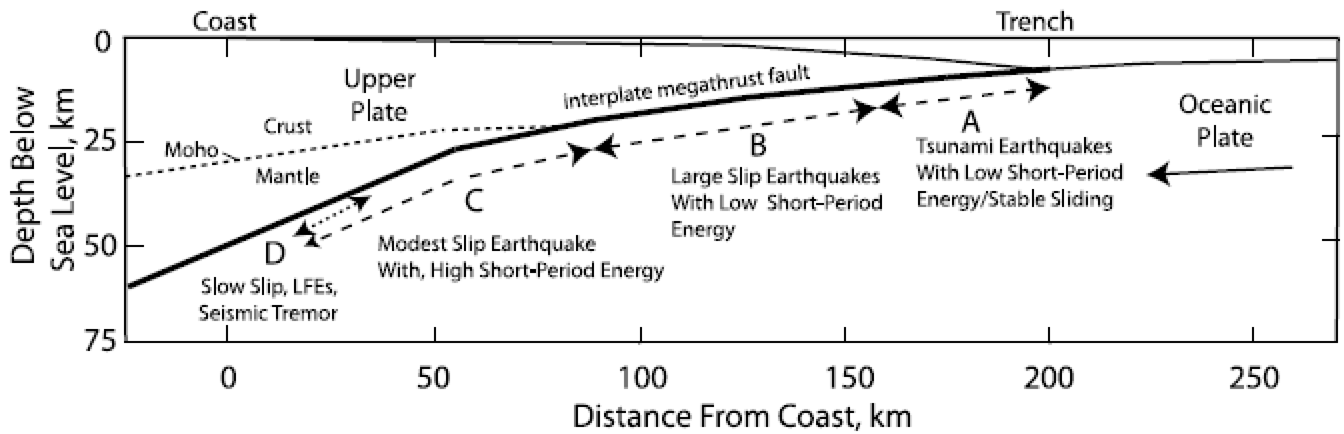


Fig. 4.6-3 Comparison of moment, magnitudes, fault area, and fault slip for four earthquakes listed in Table 4.6-1. M_s saturates for events with $M_w > 8$ and so is no longer a useful measure of earthquake size.

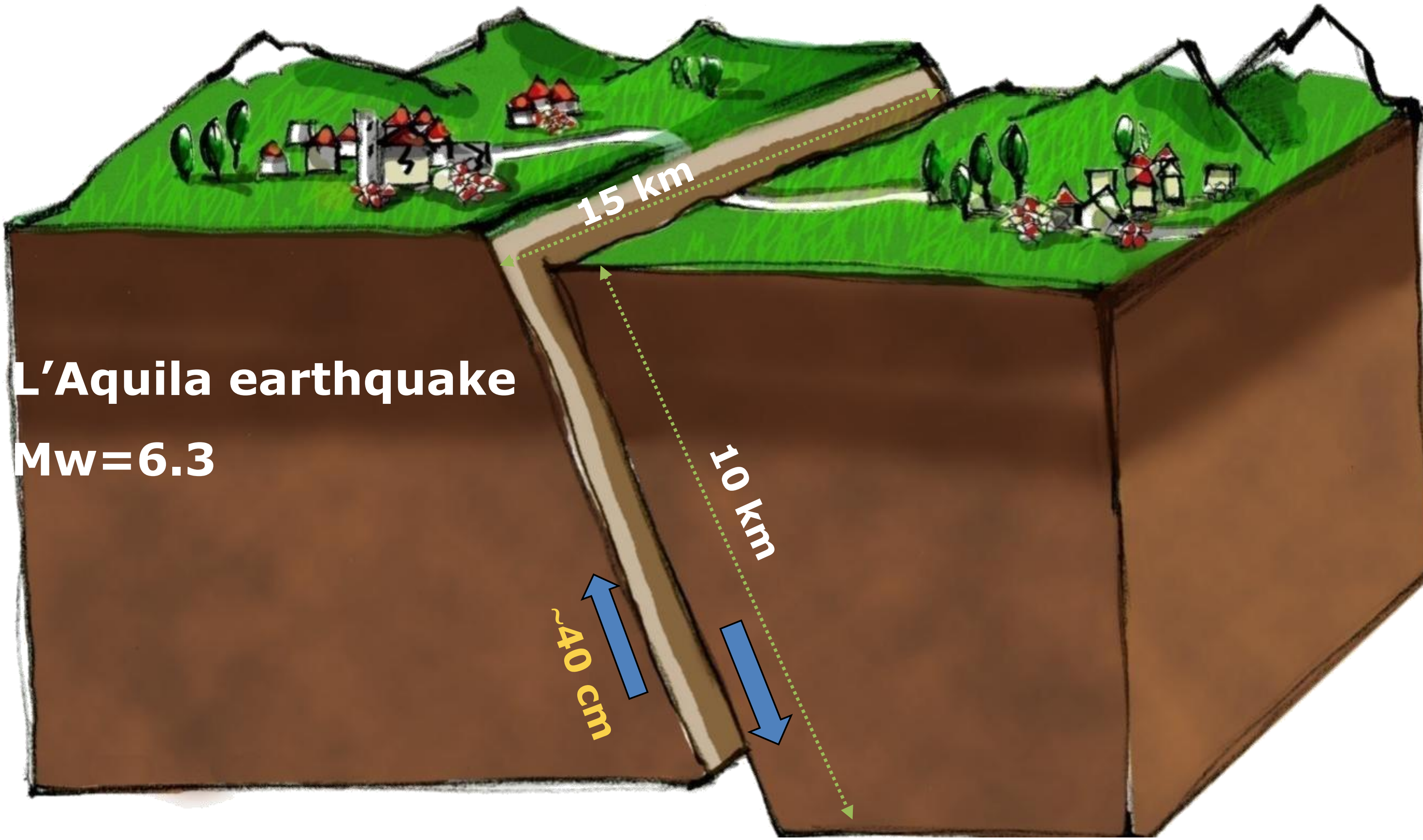


Coast
Trench
0
25
50
75
Depth Below
Sea Level, km
Upper
Plate
interplate megathrust fault
Crust
Moho
Mantle
Oceanic
Plate
A
Tsunami Earthquakes
With Low Short-Period
Energy/Stable Sliding
B
Large Slip Earthquakes
With Low Short-Period
Energy
C
Modest Slip Earthquake
With, High Short-Period Energy
D
Slow Slip, LFEs,
Seismic Tremor
0
50
100
150
200
250
Distance From Coast, km

MOMENT MAGNITUDE

used by seismologist to measure the size of earthquakese in terms of the energy released

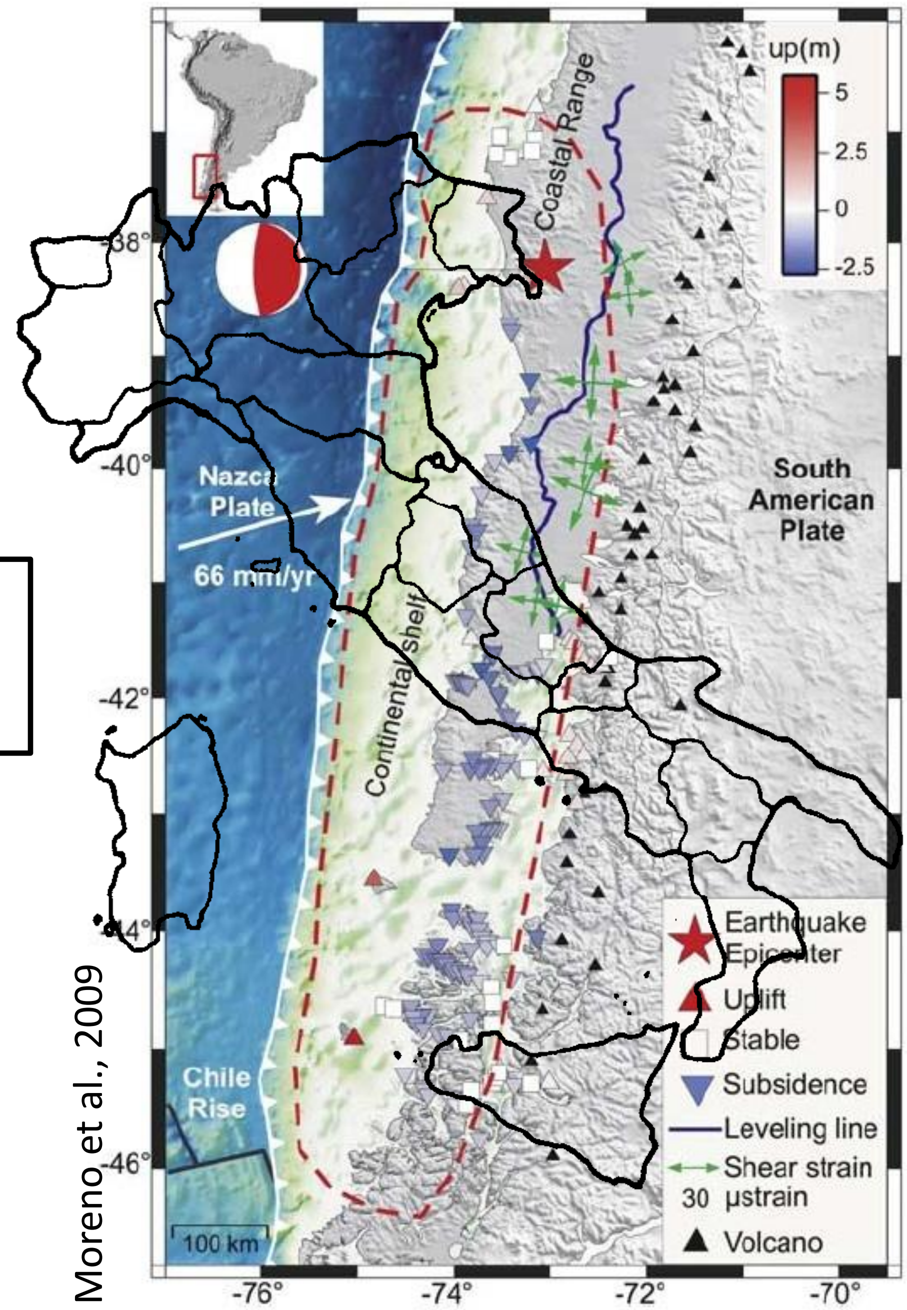
$M_w \propto M_o = \mu A u$ (μ rigidity, *A rupture area*, *u* slip)



why so large magnitudes?

the 1960 M9.5 Chile earthquake:
largest natural example of failure surface

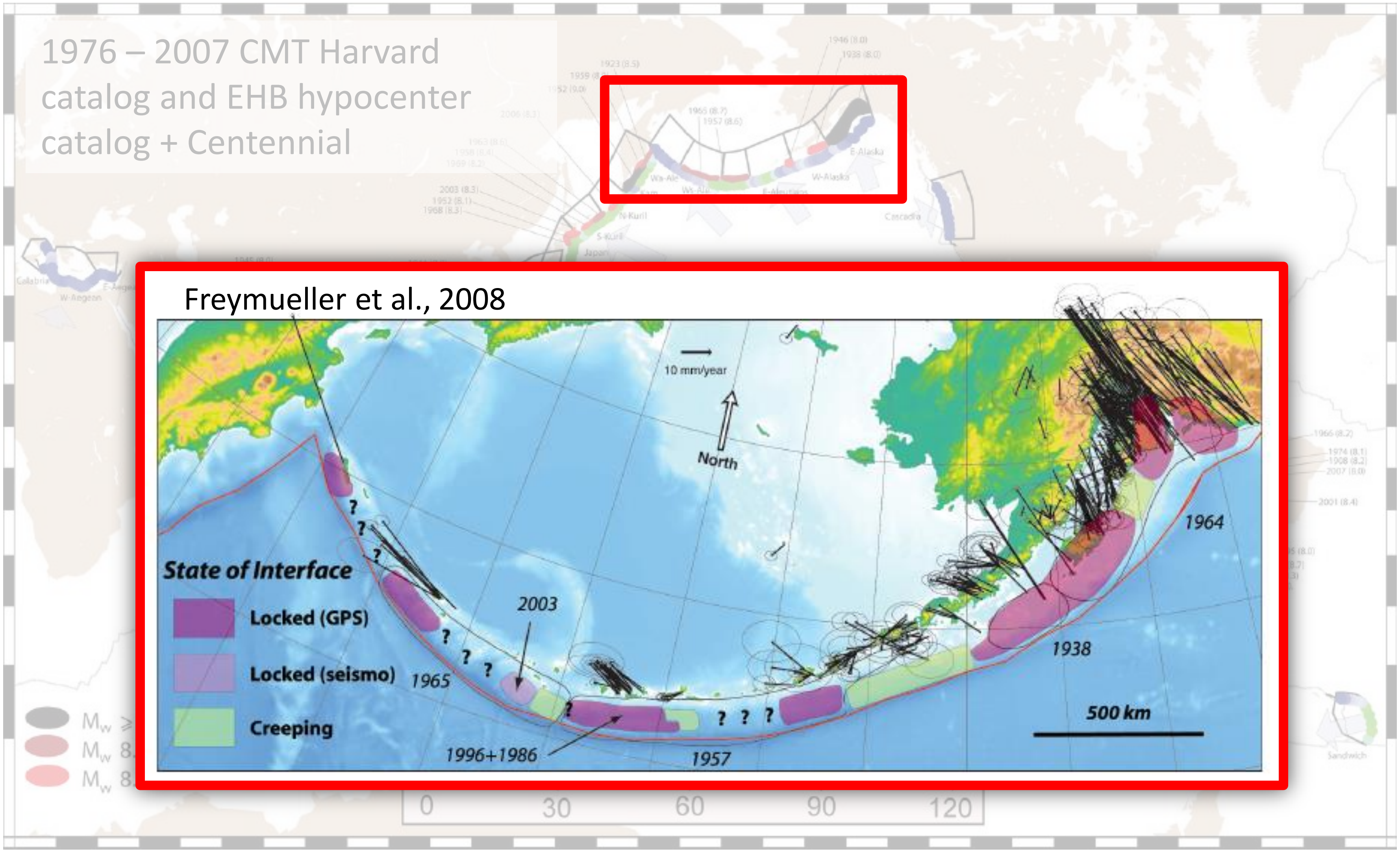
present evidence cannot rule out that any subduction zone may produce a magnitude 9 or larger earthquake (McCaffrey, 2008)!

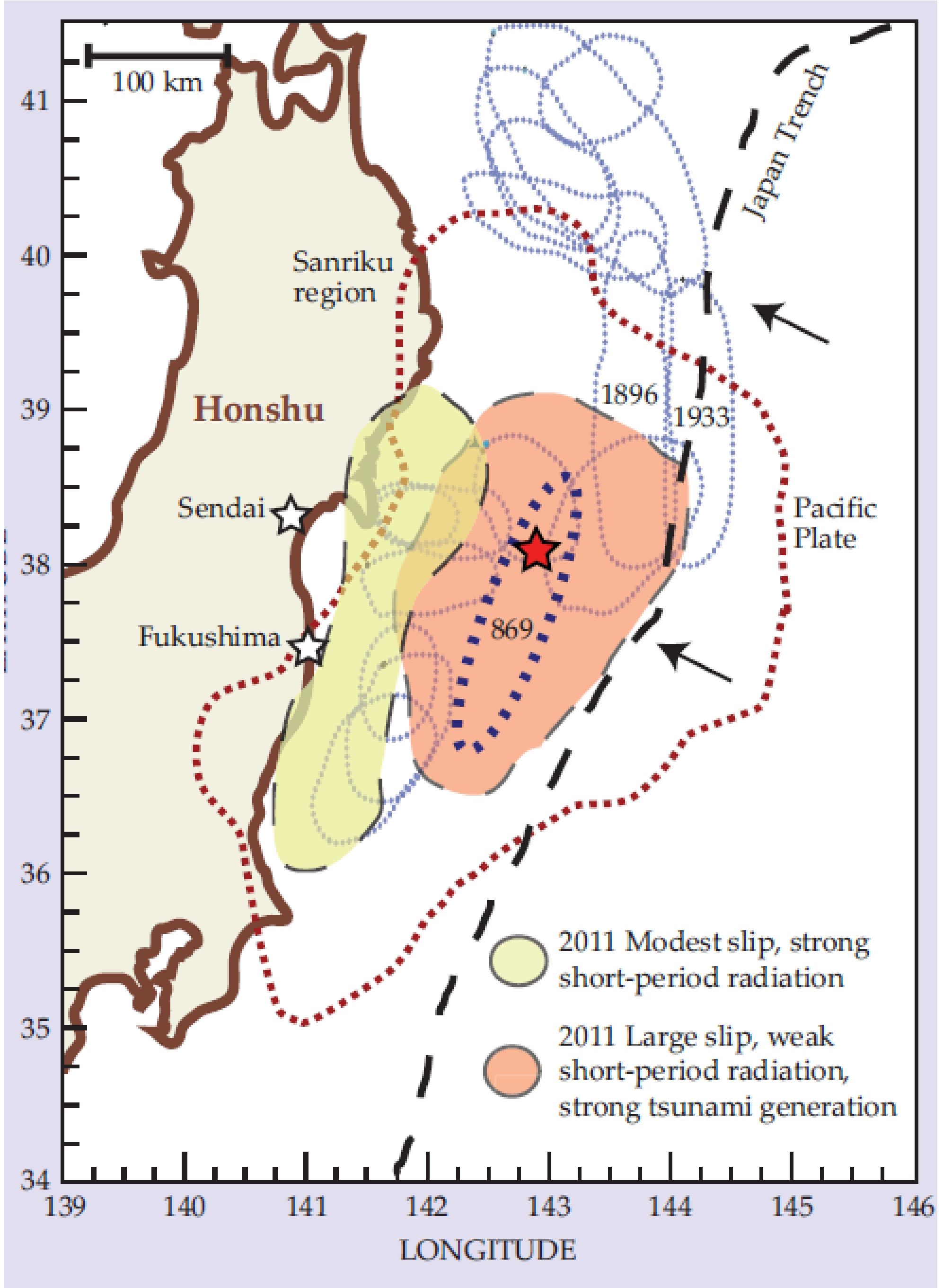


Moreno et al., 2009

a complex (variable in space) system

Heuret et al., 2011





100 km
Sanriku
region
Honshu
Sendai
Fukushima
Japan Trench
1896
1933
869
Pacific
Plate
2011 Modest slip, strong
short-period radiation
2011 Large slip, weak
short-period radiation,
strong tsunami generation
41
40
39
38
37
36
35
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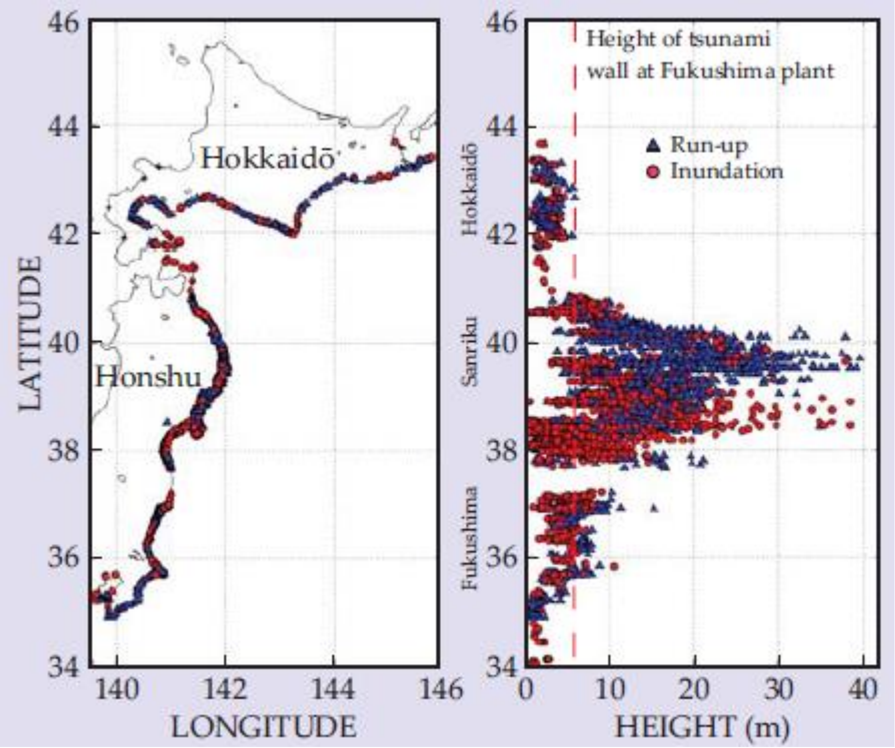
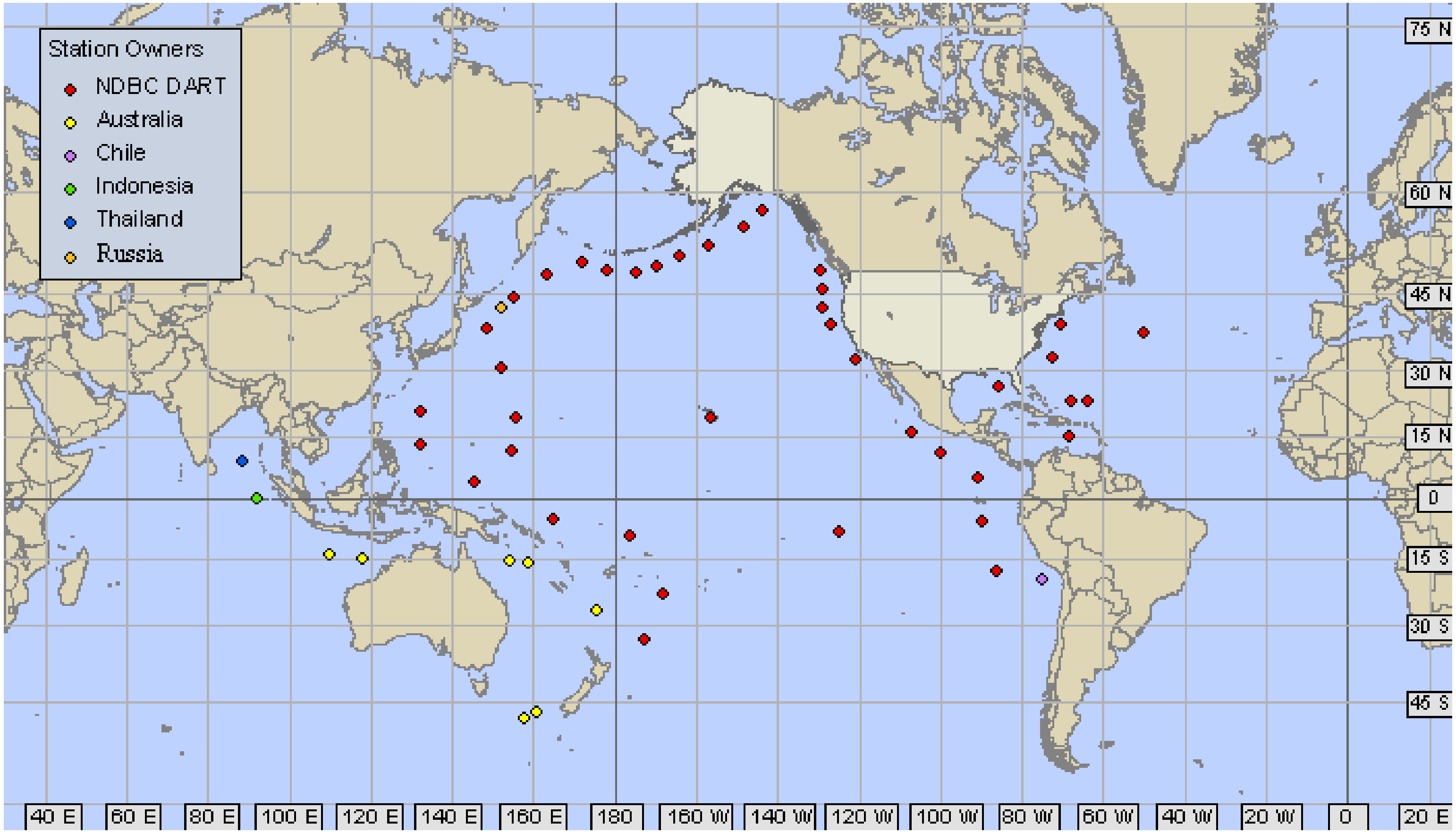
LONGITUDE



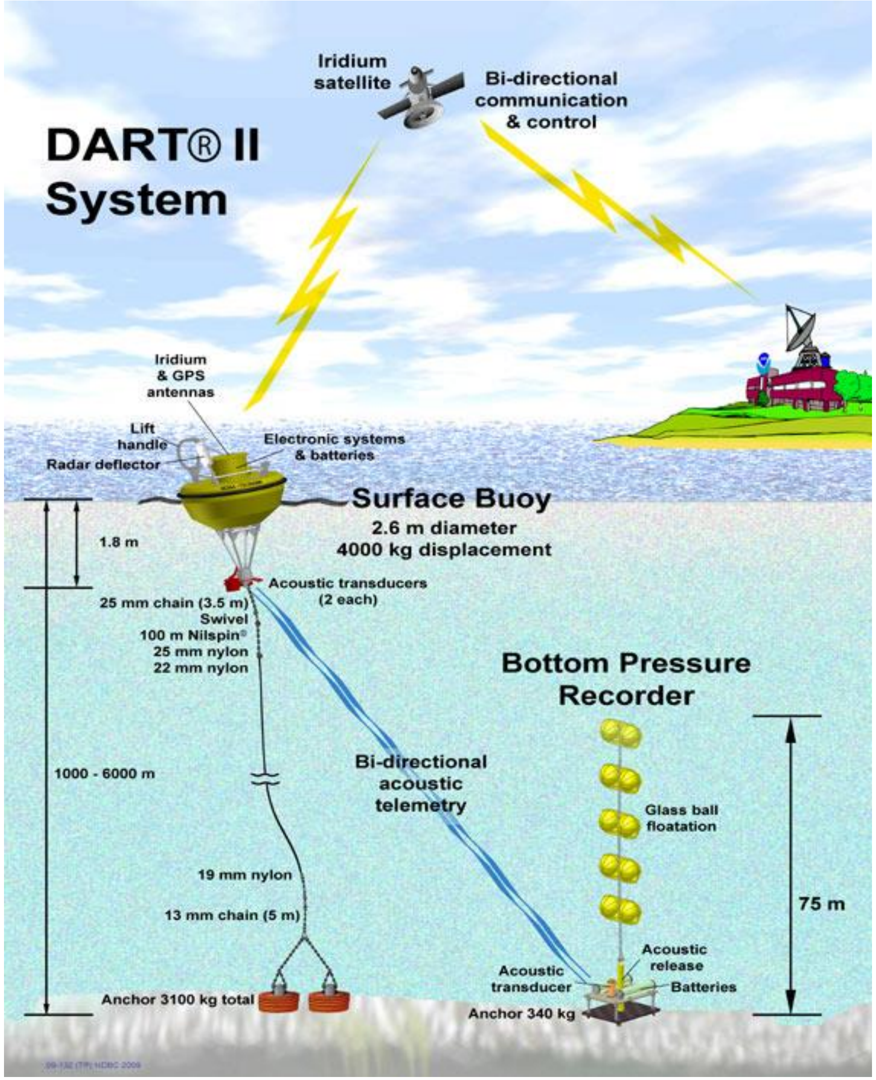
http://www.coastal.jp/tsunami2011/index.php

Pacific Tsunami Warning Center National Oceanic and Atmospheric Administration (NOAA)



NOAA', National Data Buoy Center (NDBC).

Pacific Tsunami Warning Center National Oceanic and Atmospheric Administration (NOAA)



The DART II® system consists of a seafloor bottom pressure recording (BPR) system capable of detecting tsunamis as small as 1 cm, and a moored surface buoy for real-time communications.

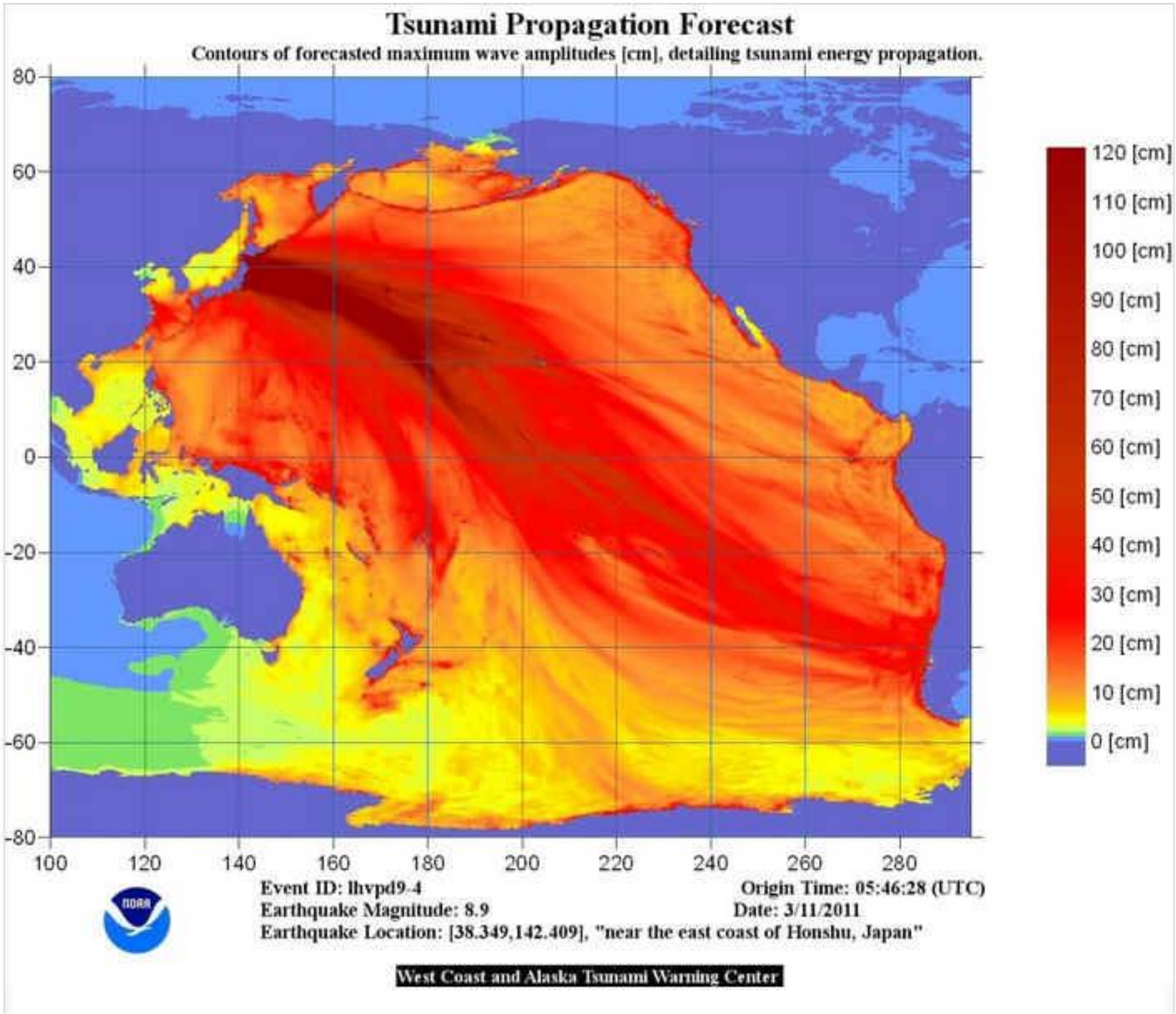
DART II has two-way communications between the BPR and the Tsunami Warning Center (TWC) using the Iridium commercial satellite communications system. The two-way communications allow the TWCs to set stations in event mode in anticipation of possible tsunamis or retrieve the high-resolution (15-s intervals) data in one-hour blocks for detailed analysis.

DART II systems transmit standard mode data, containing twenty-four estimated sea-level height observations at 15-minute intervals, once very six hours.

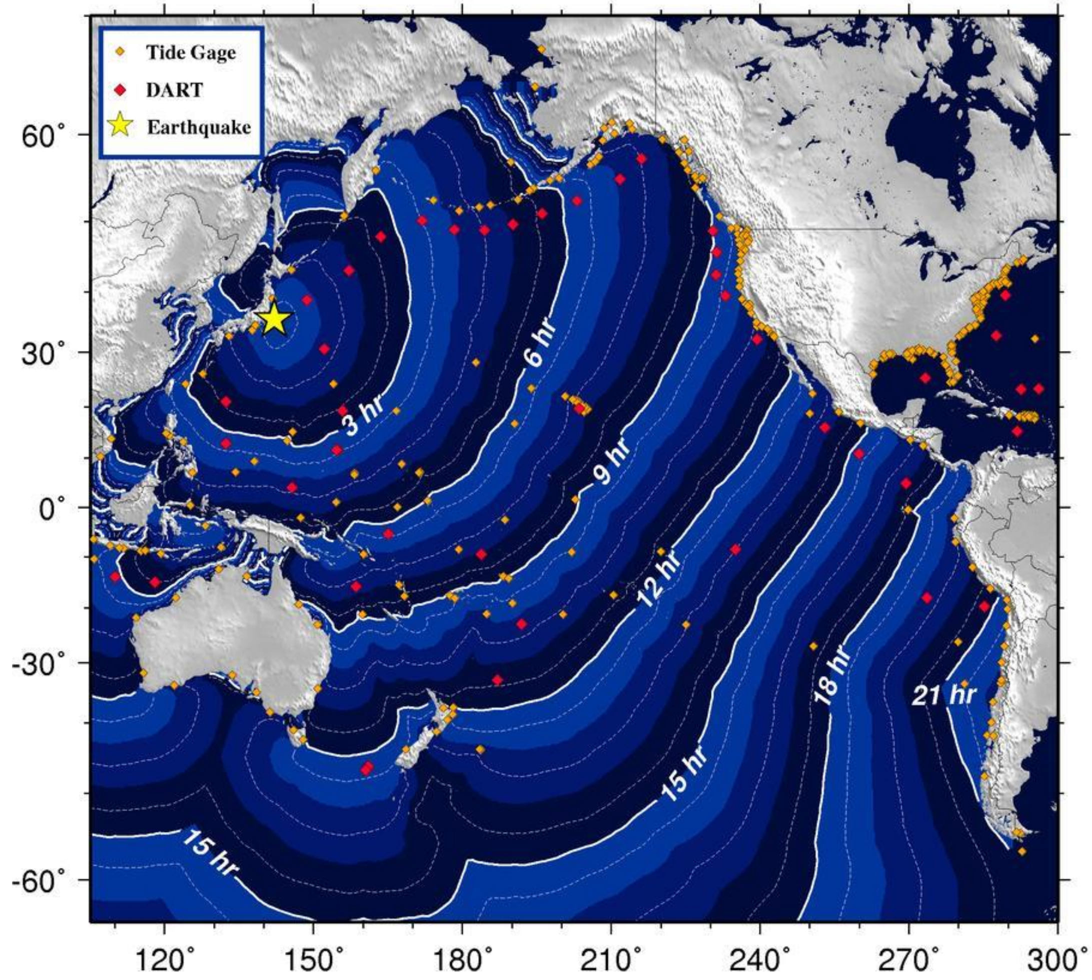
TSUNAMI MODELING

NOAA's West Coast and Alaskan Tsunami Warning Center


TSUNAMI
EVACUATION
ROUTE



NOAA's West Coast and Alaskan Tsunami Warning Center



NOAA's West Coast and Alaskan Tsunami Warning Center

BEFORE THE TSUNAMI…

… AFTER THE TSUNAMI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