SUBDUCTION AND GREAT EARTHQUAKES: INSIGHTS FROM NATURAL DATA AND ANALOGUE MODELLING

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OUTLINES

- ☞ **Scientific problem**
- ☞ **Tools**: - database on current subduction zones
  - analogue models
- ☞ **Selection of results**
- ☞ **Future directions**

☞ **Scientific problem**

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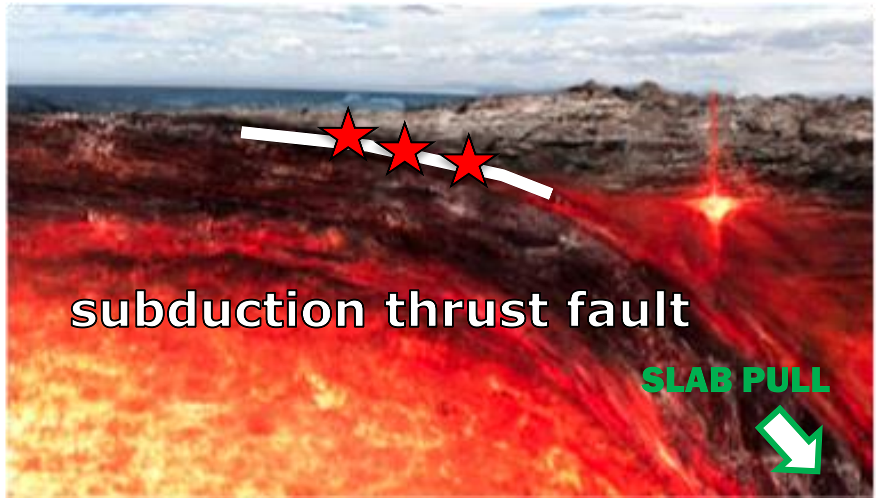
SUBDUCTION

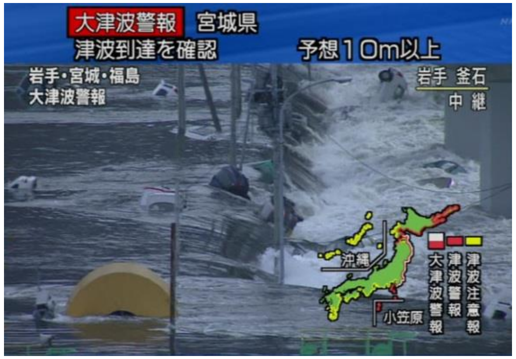


SUBDUCTION INTERPLATE SEISMICITY

Sumatra eq, M_w 9.1
Dec 26th 2004

Chile eq, M_w 8.8
Feb. 27th 2010

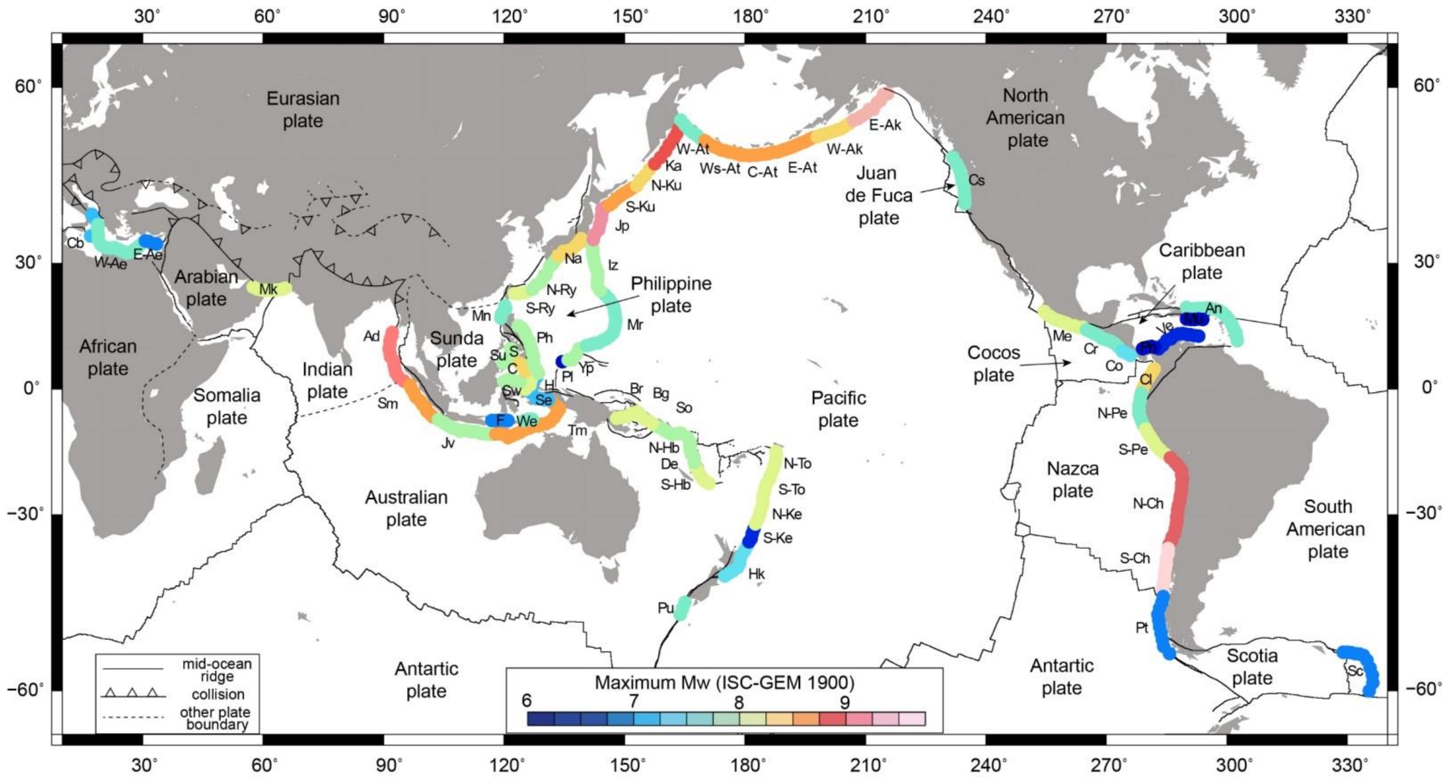
Sendai eq, M_w 9.0
Mar. 11st 2011



A SINGLE MECHANISM…
DIFFERENT OBSERVABLES!

some subduction zones produce great earthquakes with magnitude >9 (Japan, Chile) …

… other minor seismic activity with moderate sized events (Marianas, Caribbean)



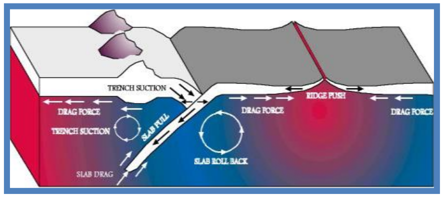
- ***short instrumental seismic record***

- ***lack of direct observables***

- ***information (e.g., written accounts and geologic observations) may lack in resolution and completeness***

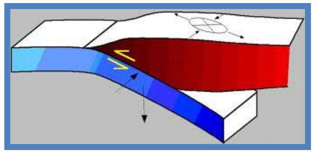
WHICH ARE INGREDIENTS CONTROLLING INTERPLATE SEISMICITY?

unravelling the behaviour of global convergent margins

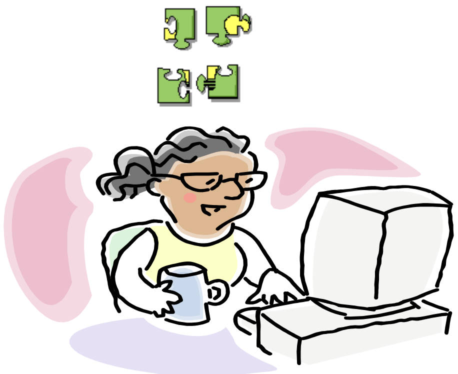


long term-large scale

(try to) define behaviour of the subduction thrust fault, analyzing if and how the parameter space of the long-term subduction process influences the interplate activity (→ rupture length, depth, magnitude, recurrence intervals)



short term-small scale



geological data

modeling

seismic data

plate motion recostructions

geodetic data

geothermal

and other geophysical data

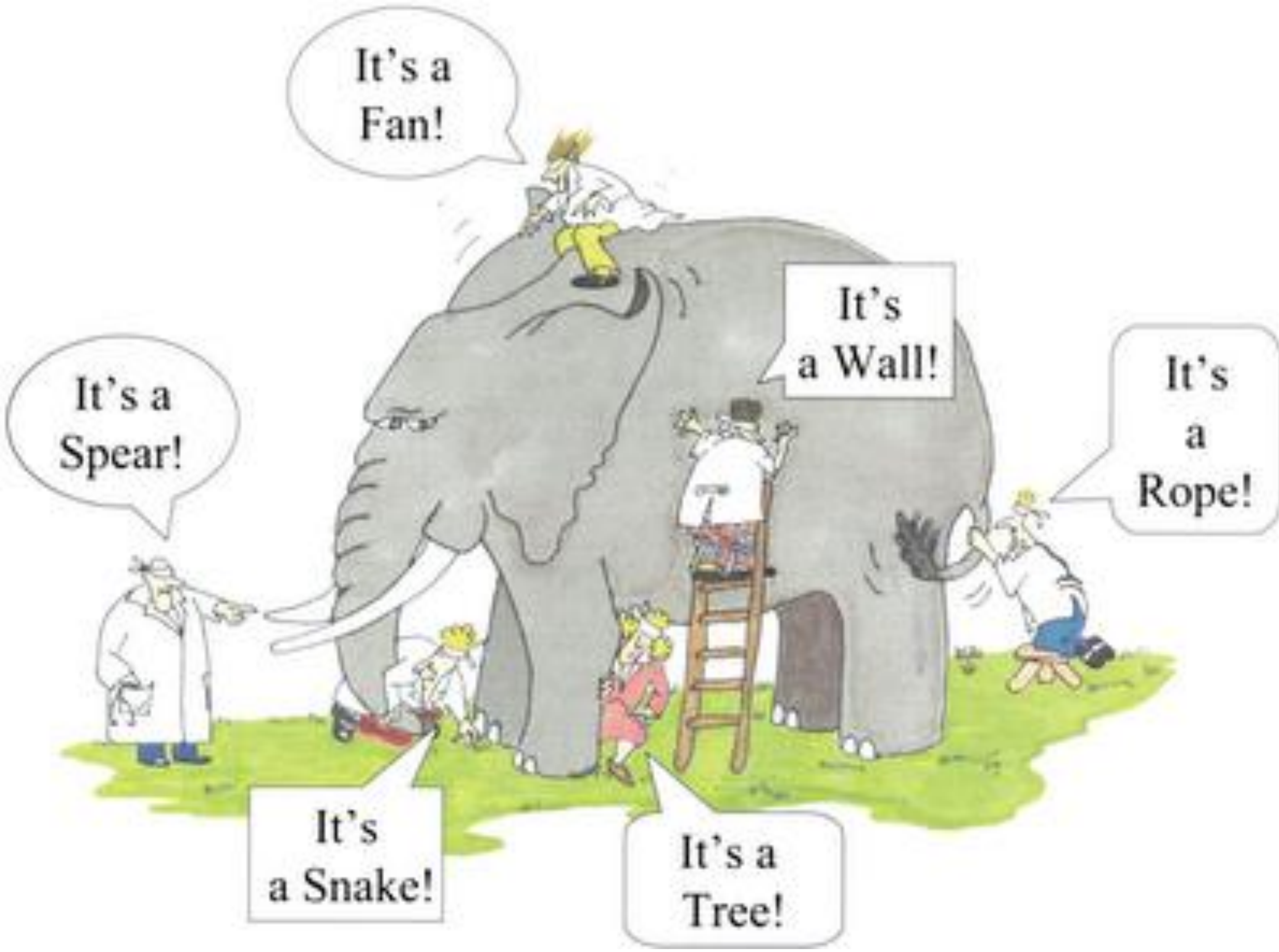
seismic sections

geochemical

data

petrology

...


It's a Fan!
It's a Wall!
It's a Spear!
It's a Rope!
It's a Snake!
It's a Tree!

MULTIDISCIPLINARY AND MULTISCALE APPROACH

collection of global data on convergent margins and statistical analysis

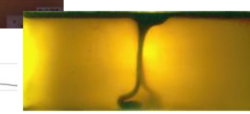
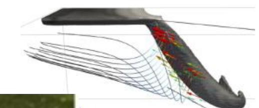
modelling

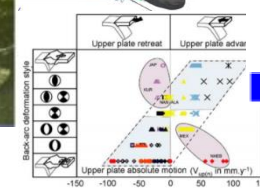
laboratory modelling

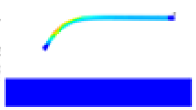
numerical modelling

WHICH ARE INGREDIENTS CONTROLLING INTERPLATE SEISMICITY?

unravelling the behaviour of global convergent margins





geometry vs. kinematics vs. dynamics of subduction

(try to) define behaviour of the subduction thrust fault, analyzing if and how the parameter space of the long-term subduction process influences the interplate activity (→ rupture length, depth, magnitude, recurrence intervals)

↓

subduction thrust fault

☞ **Scientific problem**

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☞ **Future directions**

GLOBAL DATA ON CONVERGENT MARGINS

Physics of the Earth and Planetary Interiors, 23 (1980) 240–252
Elsevier Scientific Publishing Company, Amsterdam – Printed in The Netherlands

SEISMICITY AND THE SUBDUCTION PROCESS *

LARRY RUFF and HIROO KANAMORI
Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125 (U.S.A.)

(Received February 6, 1980; accepted for publication March 25, 1980)

REVIEWS OF GEOPHYSICS, VOL. 24, NO. 2, PAGES 217–284, MAY 1986

Relations Among Subduction Parameters

RICHARD D. JARRARD
Lamont-Doherty Geological Observatory, Palisades, New York

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 98, NO. B8, PAGES 14,133–14,159, AUGUST 10, 1993

Nature of Seismic Coupling Along Simple Plate Boundaries of the Subduction Type

JAVIER F. PACHECO,[1] LYNN R. SYKES, AND CHRISTOPHER H. SCHOLZ
Lamont-Doherty Earth Observatory and Department of Geological Sciences of Columbia University Palisades, New York

Geochemistry Geophysics Geosystems G3
Published by AGU and the Geochemical Society
Article
Volume 12, Number 1
19 January 2011
Q01004, doi:10.1029/2010GC003230
ISSN: 1525-2027

Physical characteristics of subduction interface type seismogenic zones revisited

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Physics of the Earth and Planetary Interiors
journal homepage: www.elsevier.com/locate/pepi
ELSEVIER

Global correlations between maximum magnitudes of subduction zone interface thrust earthquakes and physical parameters of subduction zones ☆

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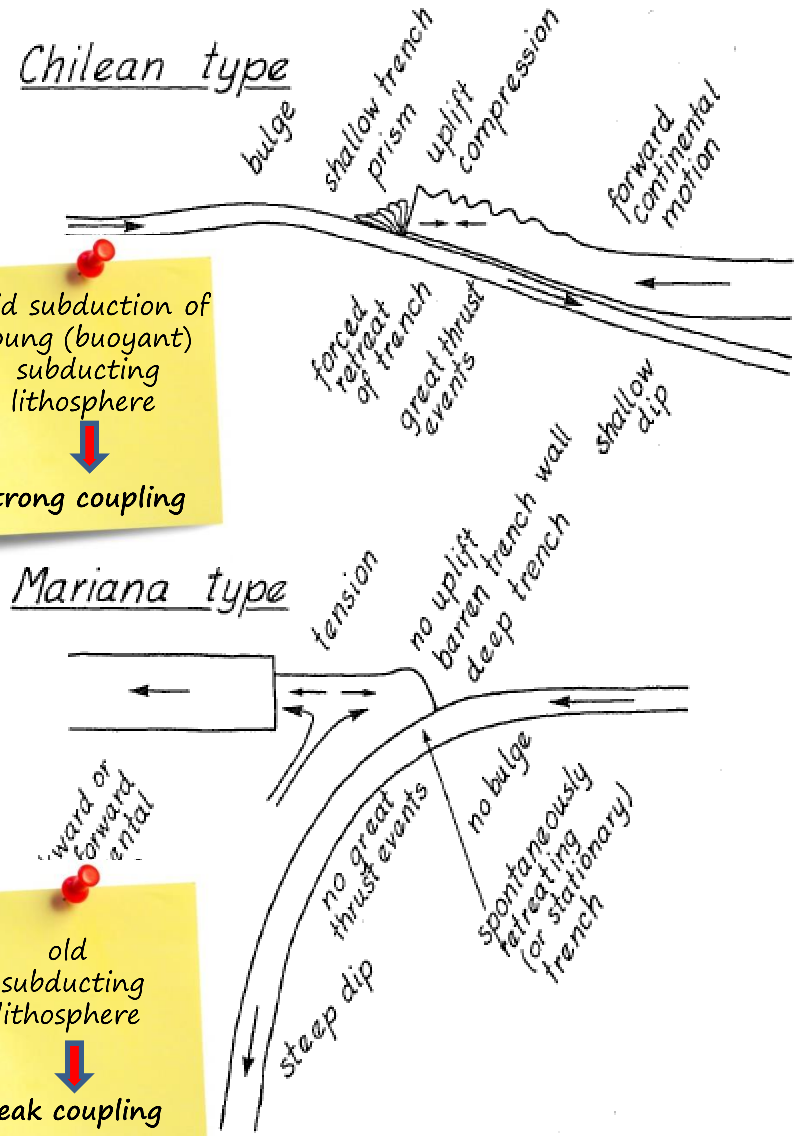
GLOBAL DATA ON CONVERGENT MARGINS

THE ANCESTRAL IDEA



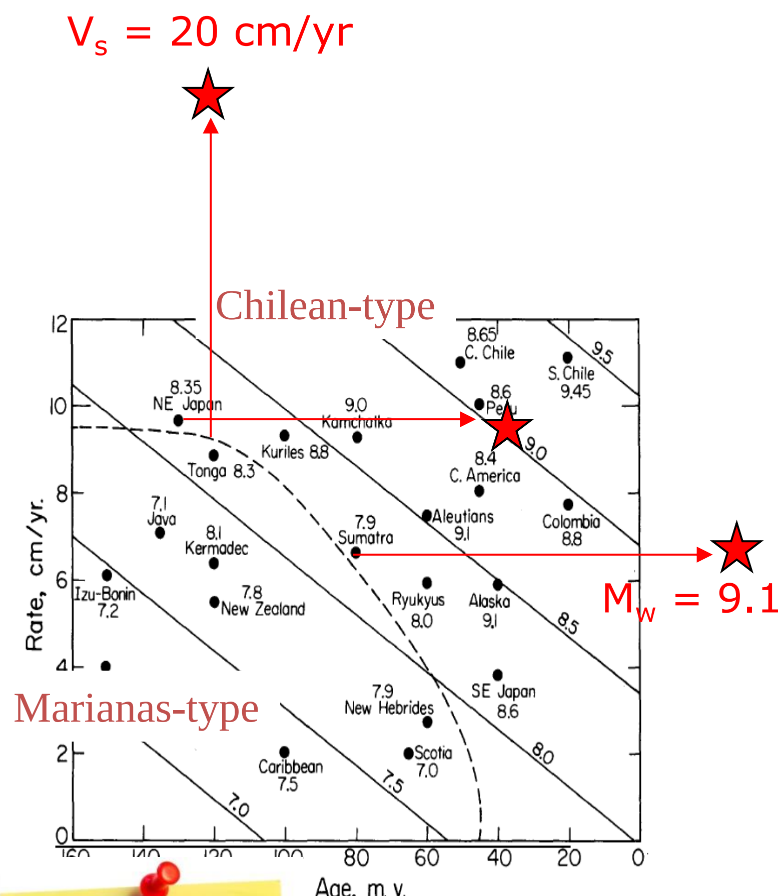
rapid subduction of young (buoyant) subducting lithosphere

strong coupling

old subducting lithosphere

weak coupling

Uyeda and Kanamori, 1979



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

Ruff and Kanamori, 1980

GLOBAL DATA ON CONVERGENT MARGINS

New reviewed and updated database improved both in accuracy and homogeneity of data sources

parameters

kinematic

- absolute motion (convergence and subduction velocities)
- relative motion (trench and plate velocities) in different RF

geometric

- along-strike length of the trench
- trench-arc distance
- arc curvature
- radius of bending of the slab
- dip of the slab
- geometry and structure of the overriding plate
- geometry and structure of the subducting plate

physical…

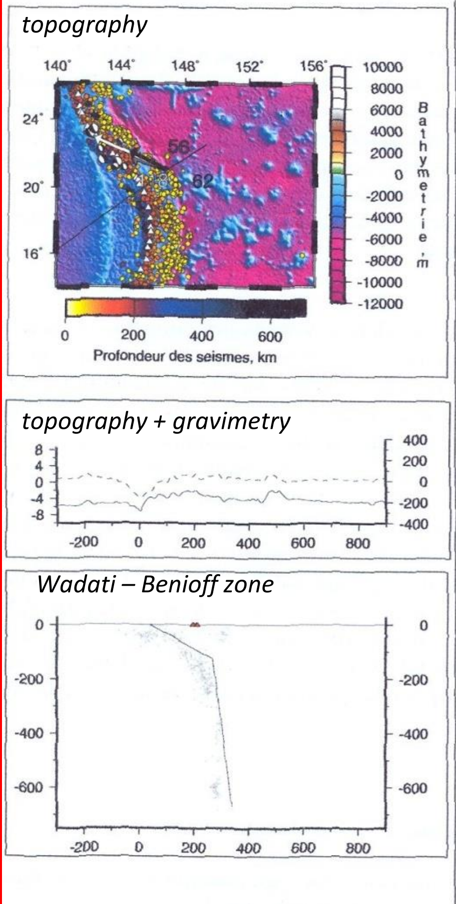
- subducting plate age
- upper plate strain class
- upper plate nature
- slab thermal parameter

\+

… & new items!

- sediments at trench
- magmatic output (eruptive rates) of active arcs
- accretion/erosive margin

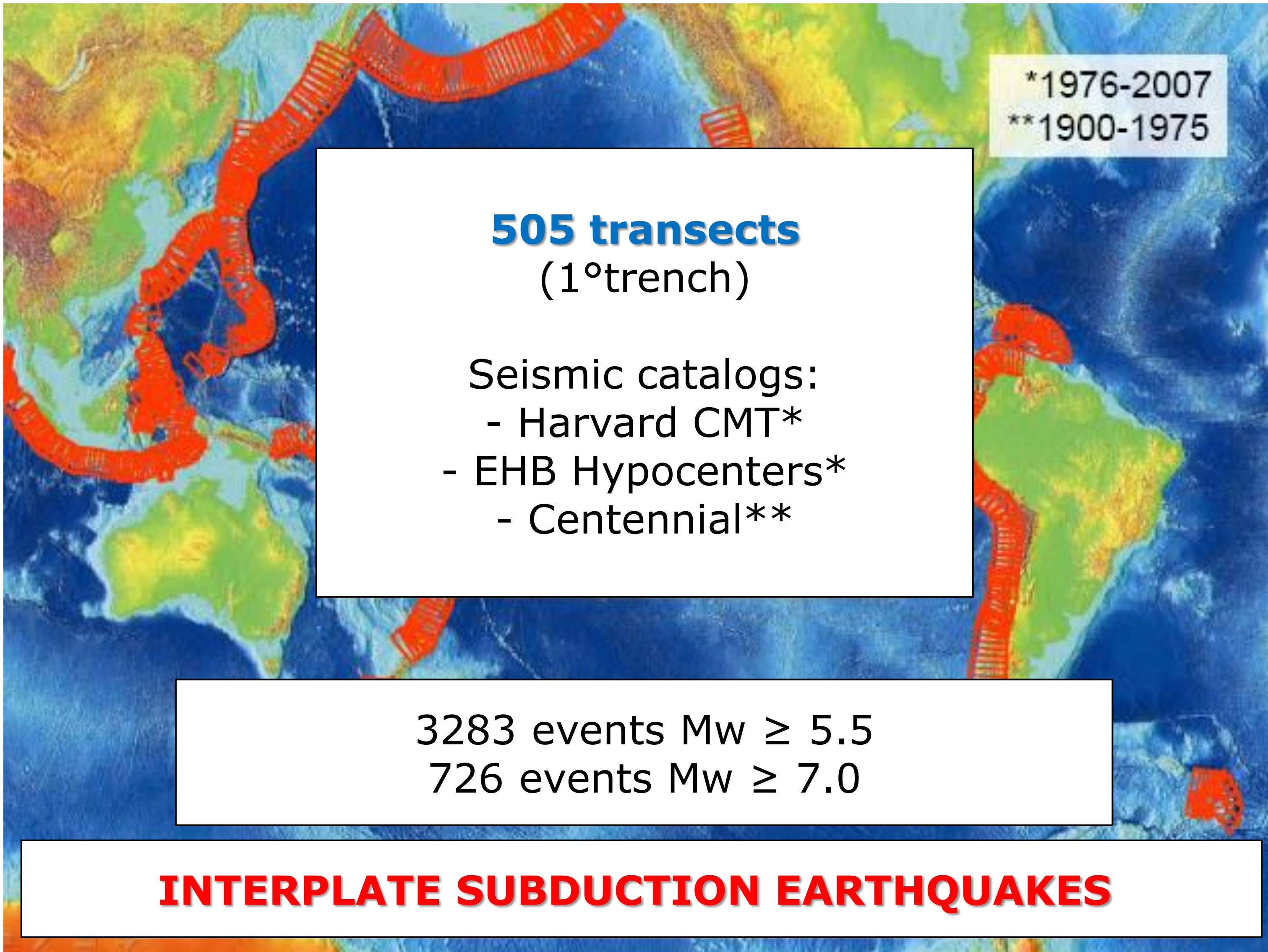
MARIANNE (21°N)



Latitude de la fosse (deg):	21.0
Longitude de la fosse (deg):	146.9
Profondeur de la fosse (km):	7.1
Larg. du seg. de fosse (km):	222.4
Dist. fosse-arc moyenne (km):	204.4
dist. fosse-arc min (km):	196.0
dist. fosse-arc max (km):	213.1
Profondeur ss arc (km):	89.1
profondeur min ss arc (km):	84.8
profondeur max ss arc (km):	94.0
Plongement > -125km (deg):	28.5
Plongement < -125km (deg):	82.7
XMAX:	485.0
ZMAX:	-1.7
XMIN gravi:	2.0
ZMIN gravi:	-157.1
XMAX gravi:	208.0
ZMAX gravi:	71.8
XMAX gravi-XMAX:	-277.0
Age moyen a la fosse (Ma):	146.6
Prof. max des seismes (km):	684.8
Magnit. max des seismes:	6.4
Vc (mm/a)	43.0
azimut (deg):	298.0
obliquite (deg):	63.0
vcn (mm/an):	20.0
vcp (mm/an):	38.0
vz(0-125) (mm/an):	15.7
vz(125-670) (mm/an):	32.6
Vsup (mm/a):	75.0
azimut (deg):	292.0
obliquite (deg):	57.0
sens:	-1
vsup(n) (mm/an):	41.0
Vsub (mm/a):	118.0
azimut (deg):	294.0
obliquite (deg):	59.0
vsub(n) (mm/an):	60.8

Heuret and Lallemand, 2005

GLOBAL DATA ON CONVERGENT MARGINS



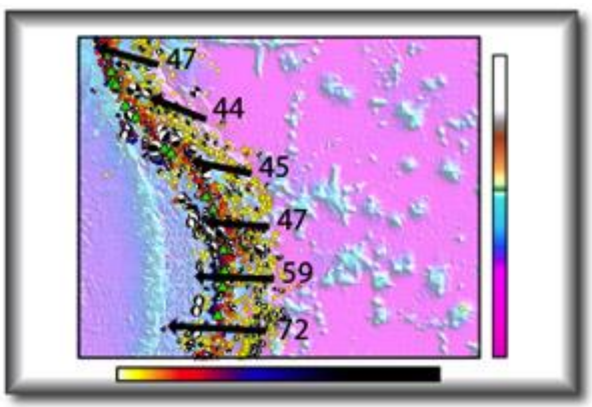
505 transects
(1°trench)

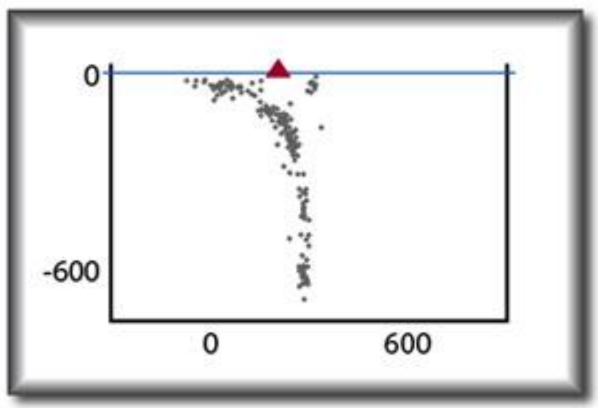
Seismic catalogs:
- Harvard CMT*
- EHB Hypocenters*
- Centennial**

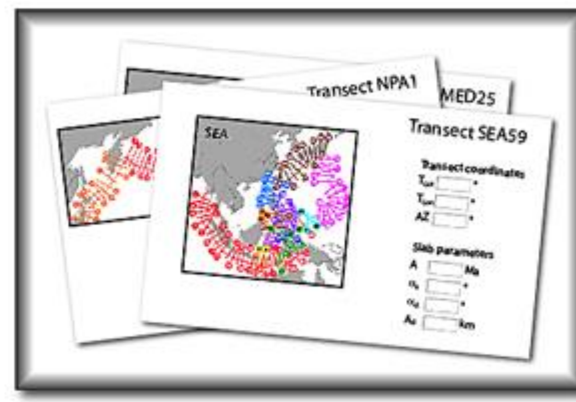
3283 events Mw ≥ 5.5
726 events Mw ≥ 7.0

INTERPLATE SUBDUCTION EARTHQUAKES

GLOBAL DATA ON CONVERGENT MARGINS





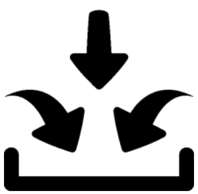


http://submap.gm.univ-montp2.fr/

GLOBAL DATA ON CONVERGENT MARGINS

uses of the database

a) statistical analysis on the entire set of parameters;



b) input parameters for laboratory/numerical modelling;

c) test the modelling predictions.

☞ **Scientific problem**

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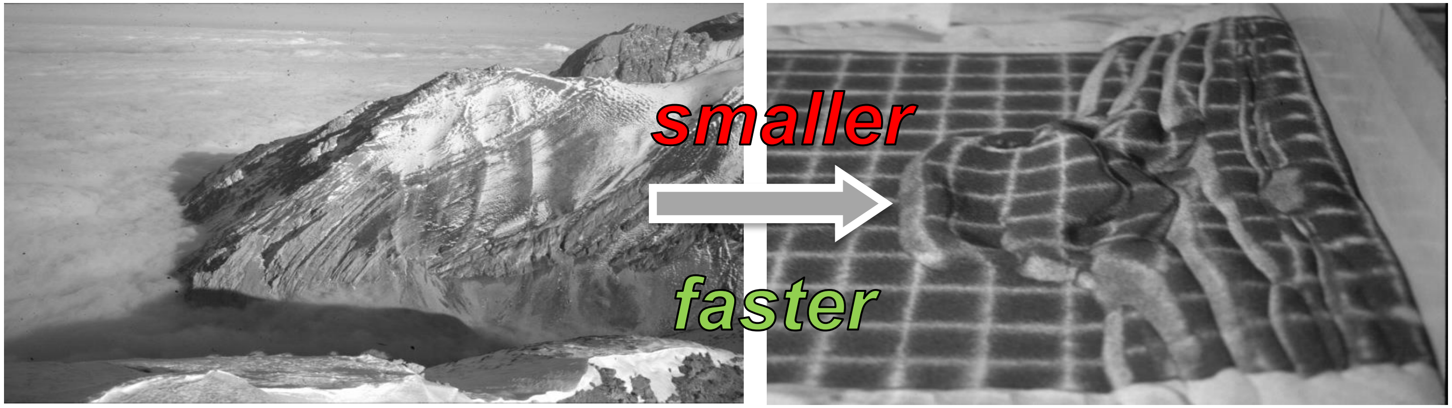
ANALOGUE MODELS

A model is an attempt to reproduce a natural process at different scales:

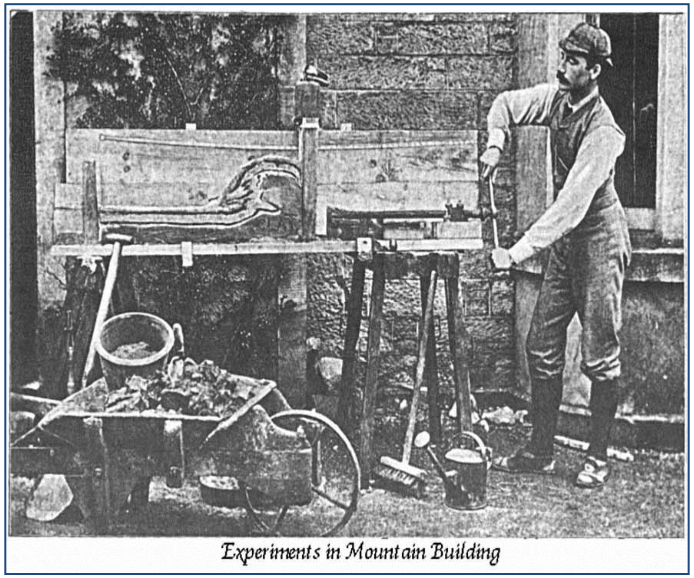
spatial & temporal



Nature
(km, Myrs)

Model
(cm, hours)

ANALOGUE MODELS

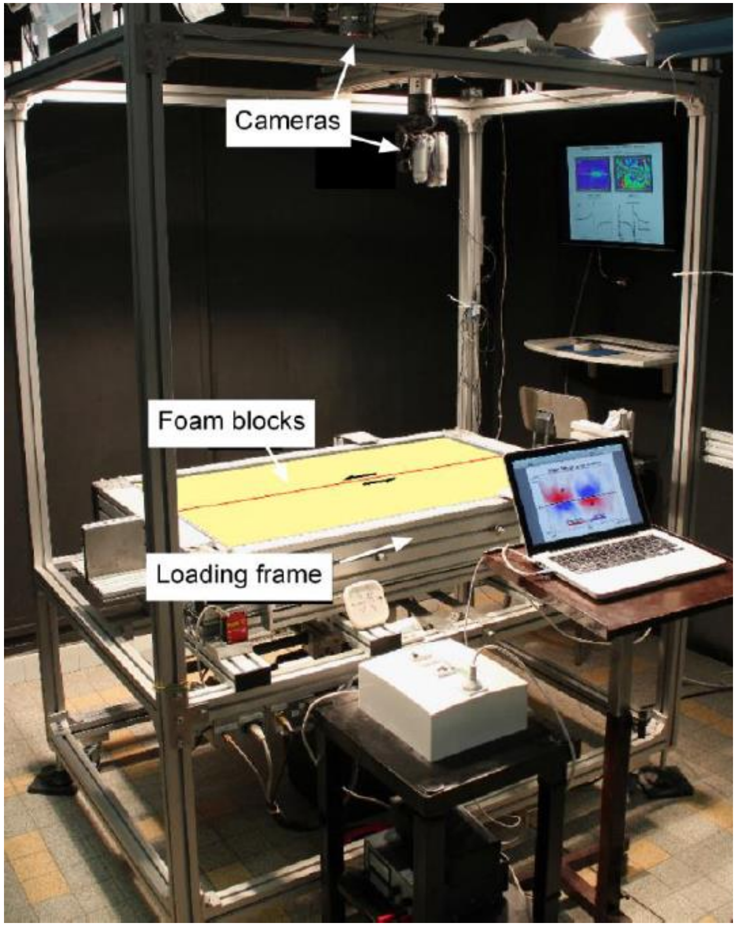


Cadell, 1888

high resolution monitoring techniques

increasingly complex models

new rock analogue materials

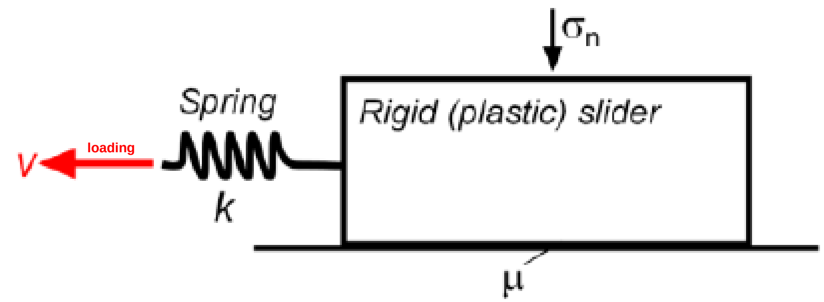


Univ. Montpellier lab

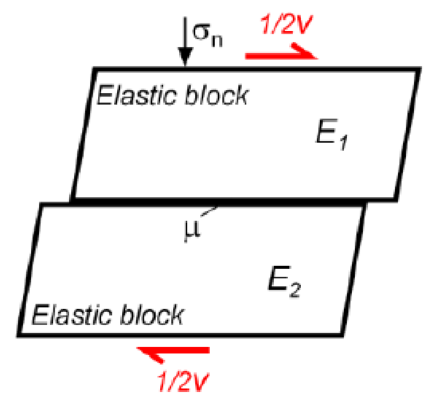
ANALOGUE MODELS

increasing complexity

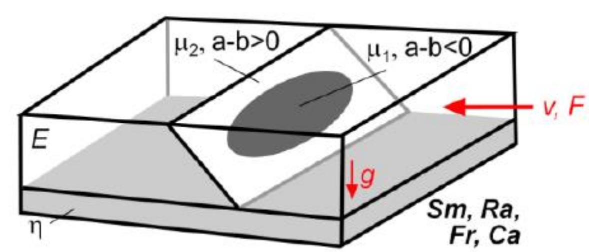
Spring slider models: elastic and frictional elements are physically discrete components of the setup *(only conceptually applied to nature).*



Fault block models: two elastic blocks, with similar or different elastic properties, are in frictional contacts *(qualitatively extrapolated to nature).*



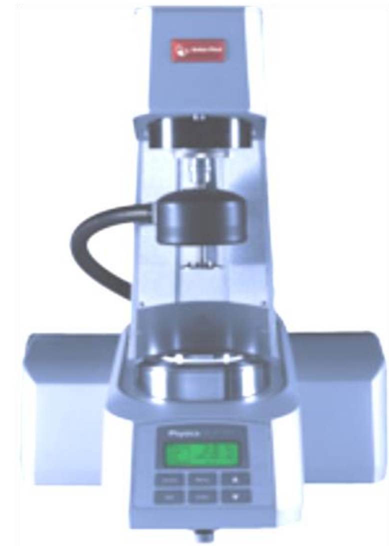
Scaled models: tectonic settings are realistically simulated at small scale and with boundary conditions mimicking the natural prototype *(quantitatively upscaled to nature).*

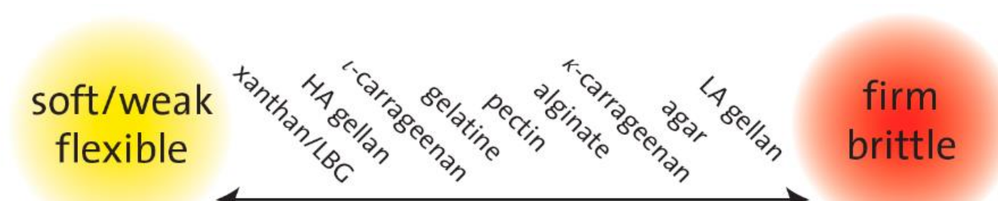


Rosenau et al, 2016

DESIGNING A NEW APPARATUS

ANALOGUE MODELS



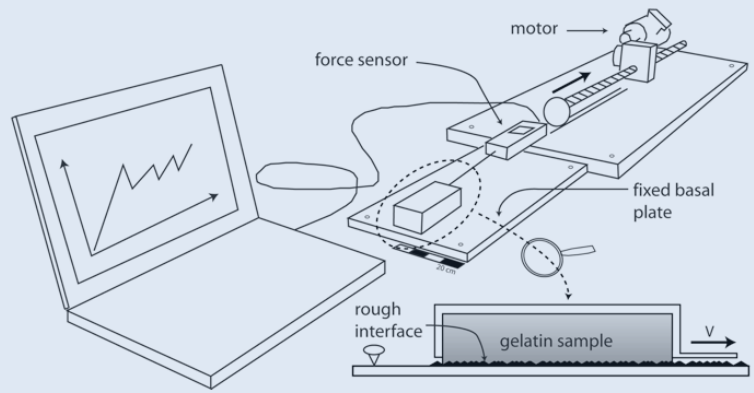


Di Giuseppe et al., 2009

ANALOGUE MODELS

new analog material

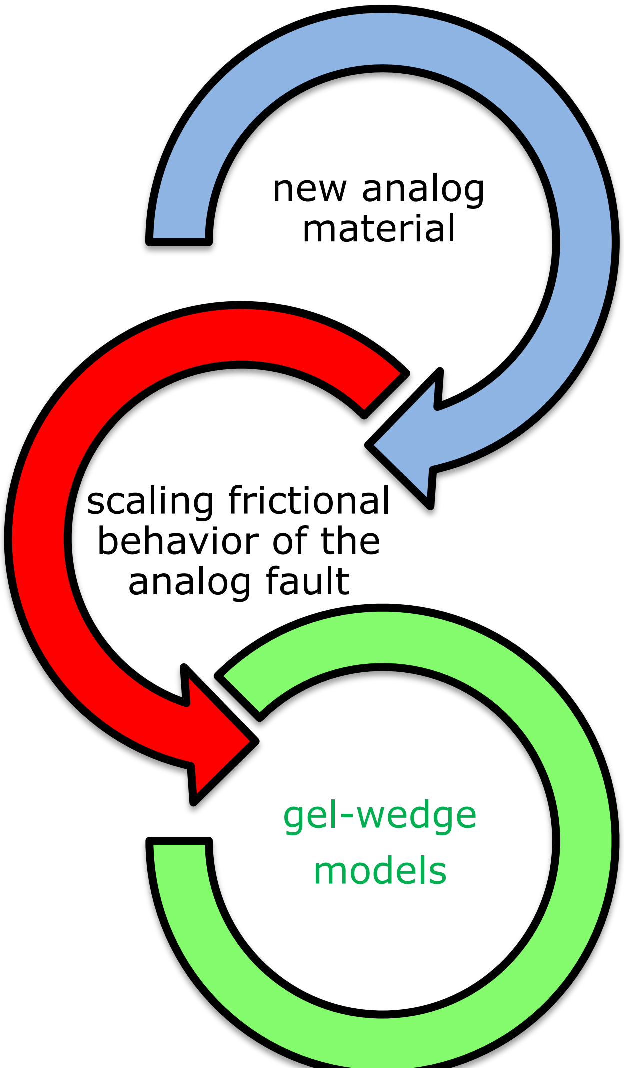
scaling frictional behavior of the analog fault



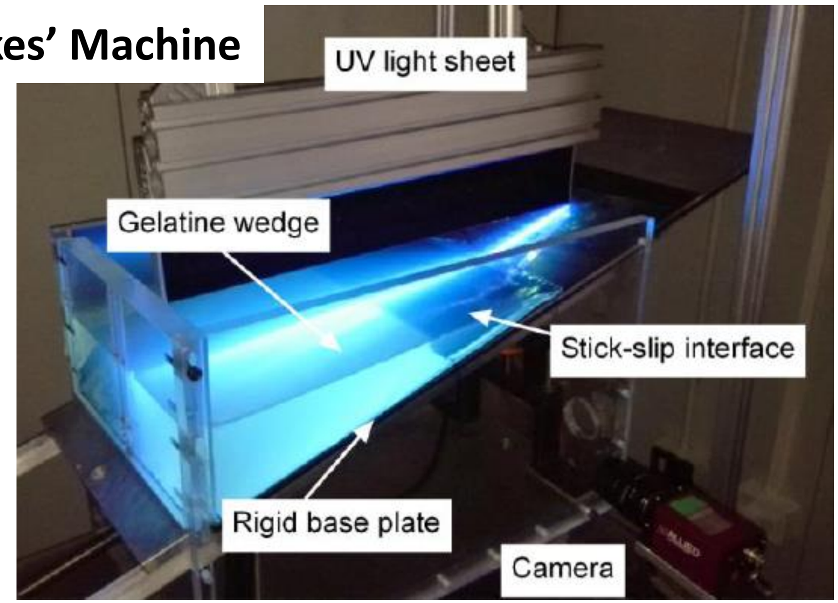
explore the role of loading rate, normal pressure and interface roughness on friction dynamics

Corbi et al., 2011

ANALOGUE MODELS



Gelquakes' Machine

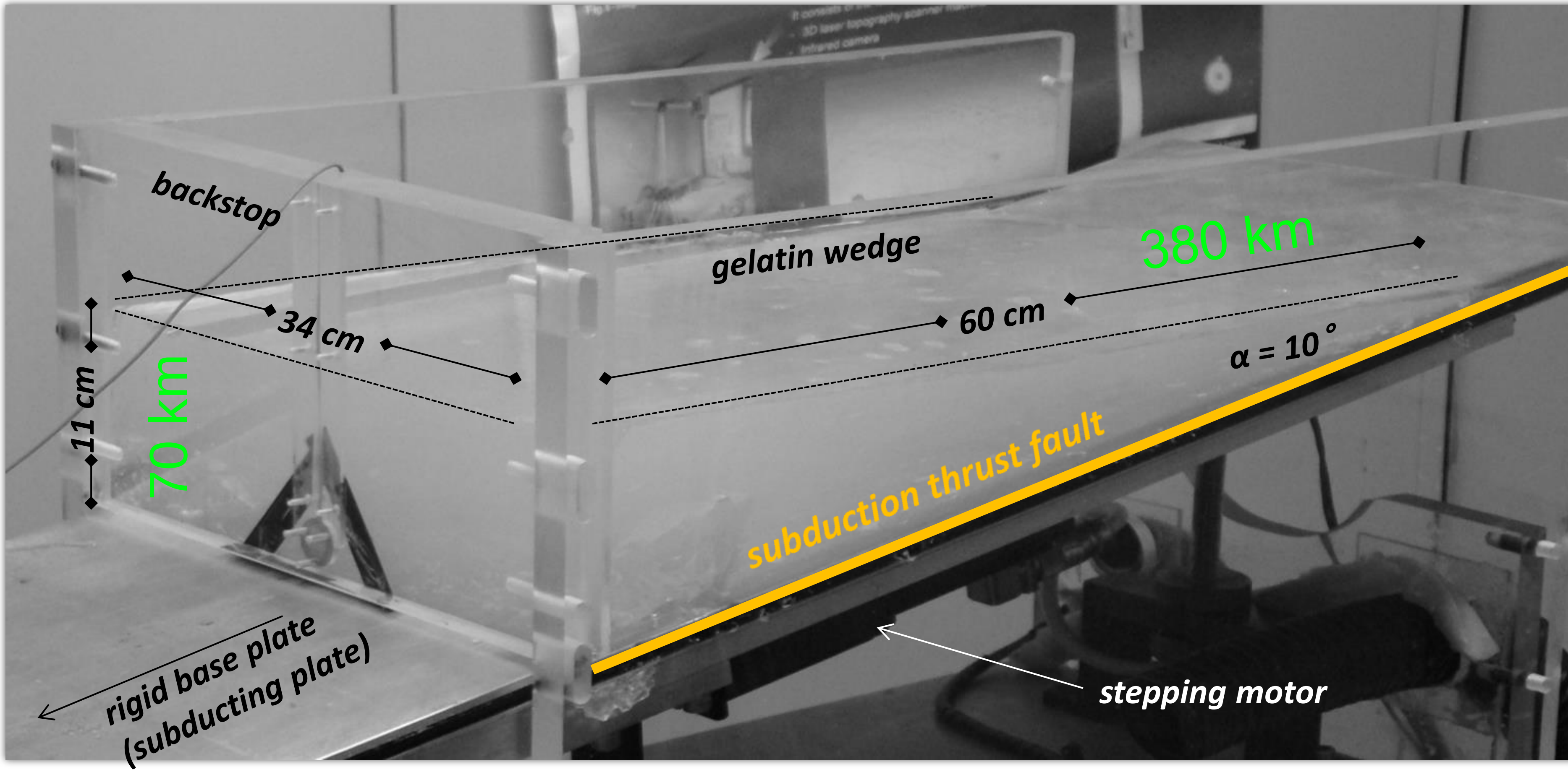


new analogue setting to model subduction zone seismic cycle featuring:

- realistic tectonic loading;
- rate-dependent frictions at plate interface;
- viscoelastic stress relaxation of the lithosphere.

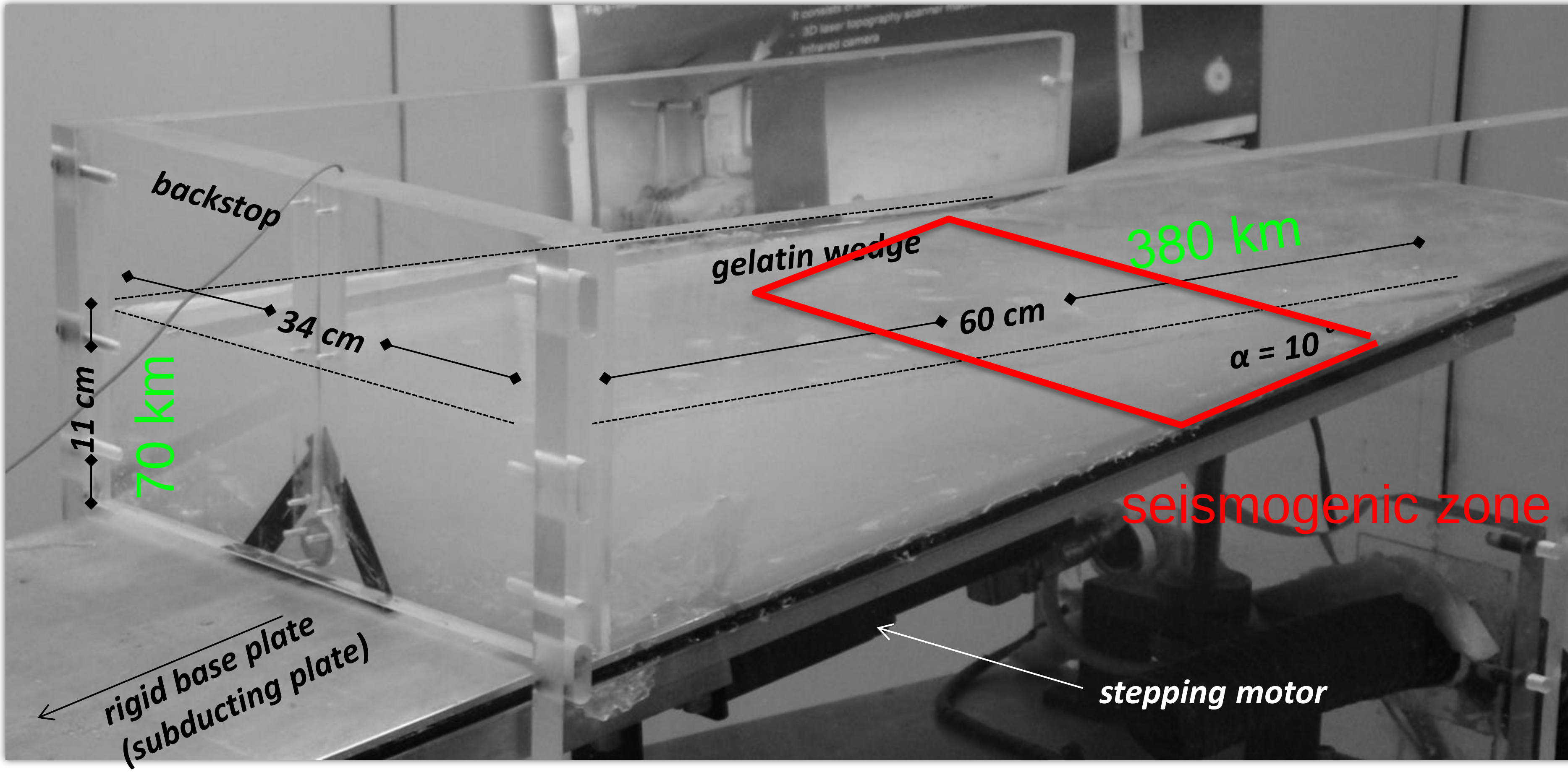
ANALOGUE MODELS

the setup



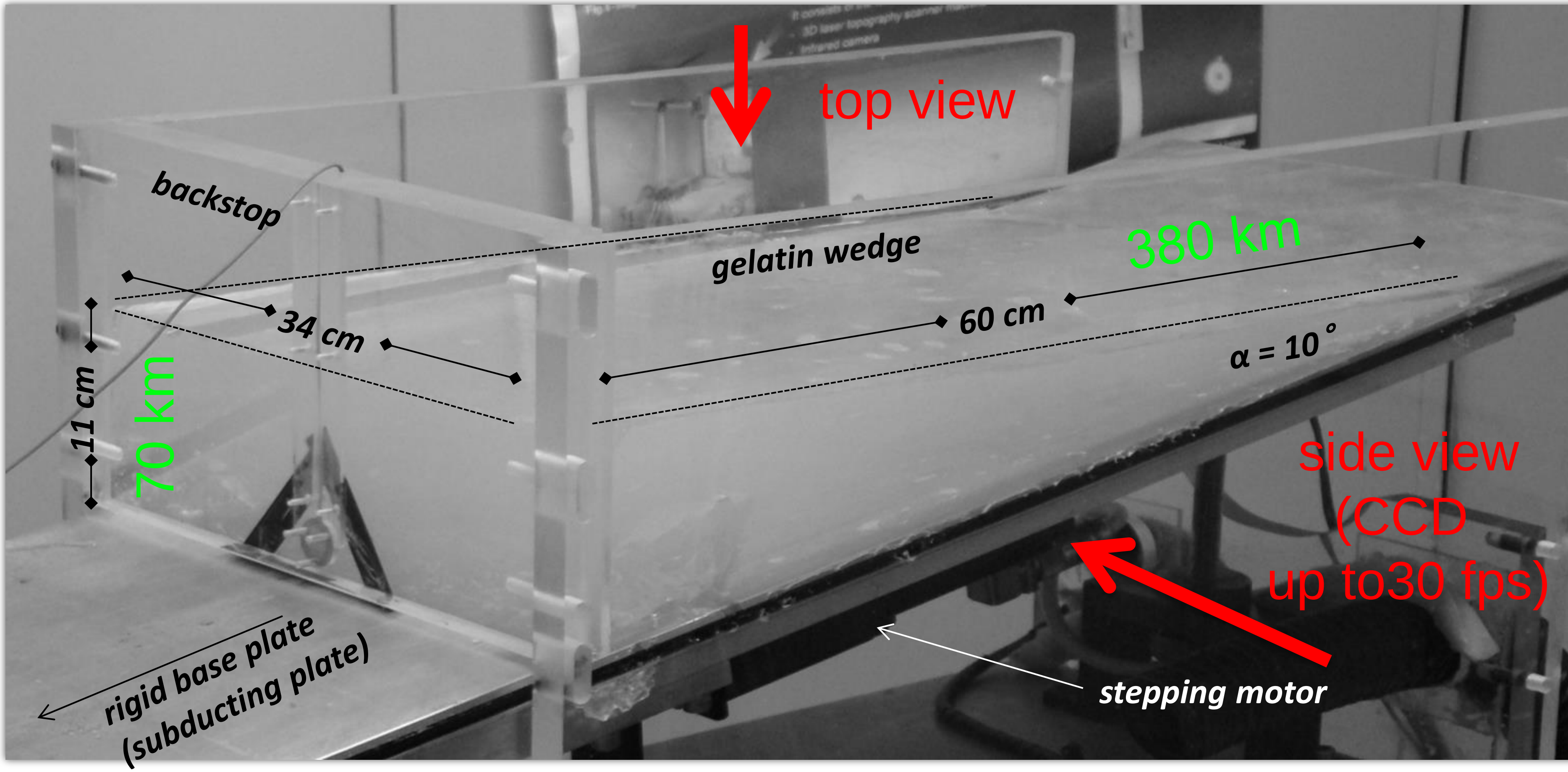
ANALOGUE MODELS

the setup



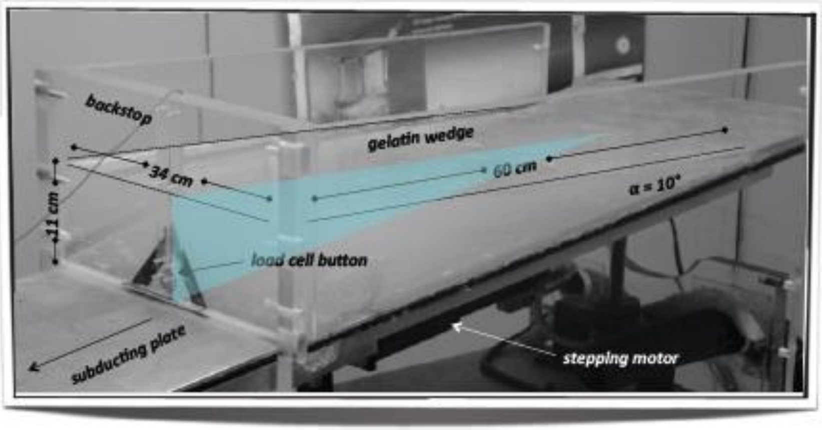
ANALOGUE MODELS

the setup



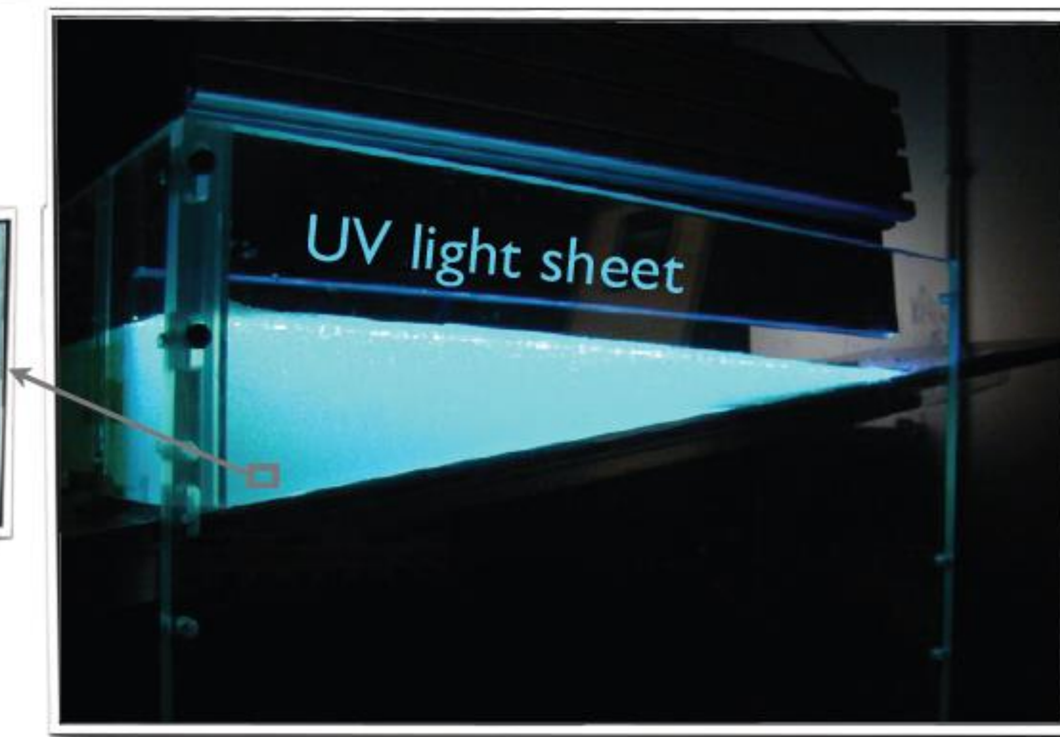
ANALOGUE MODELS

the setup



side view

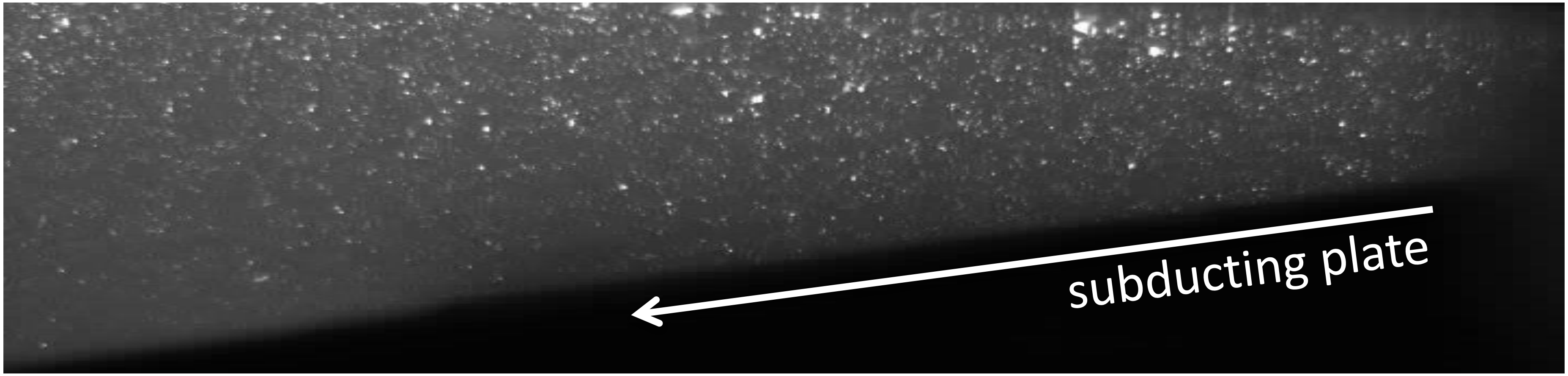
50 micron passive tracers



ANALOGUE MODELS

model behaviour

25x; lateral view

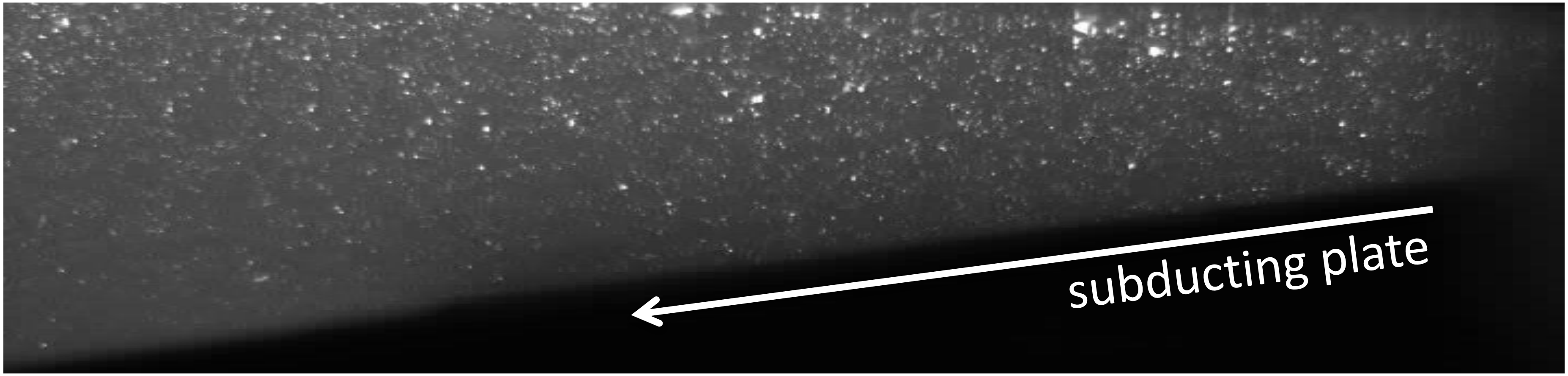


spontaneously nucleating
frictional instabilities
(i.e., analog earthquakes)
as result of
stress buildup
and plate interface
strength

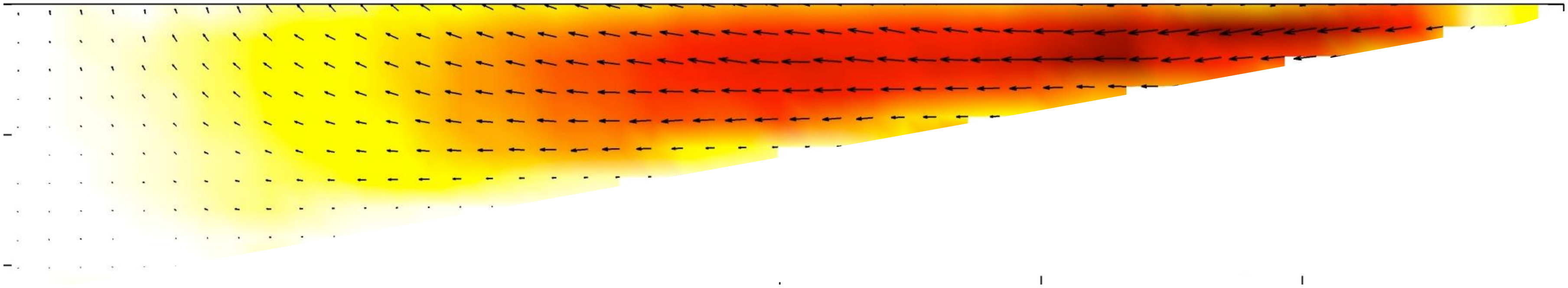
ANALOGUE MODELS

model behaviour

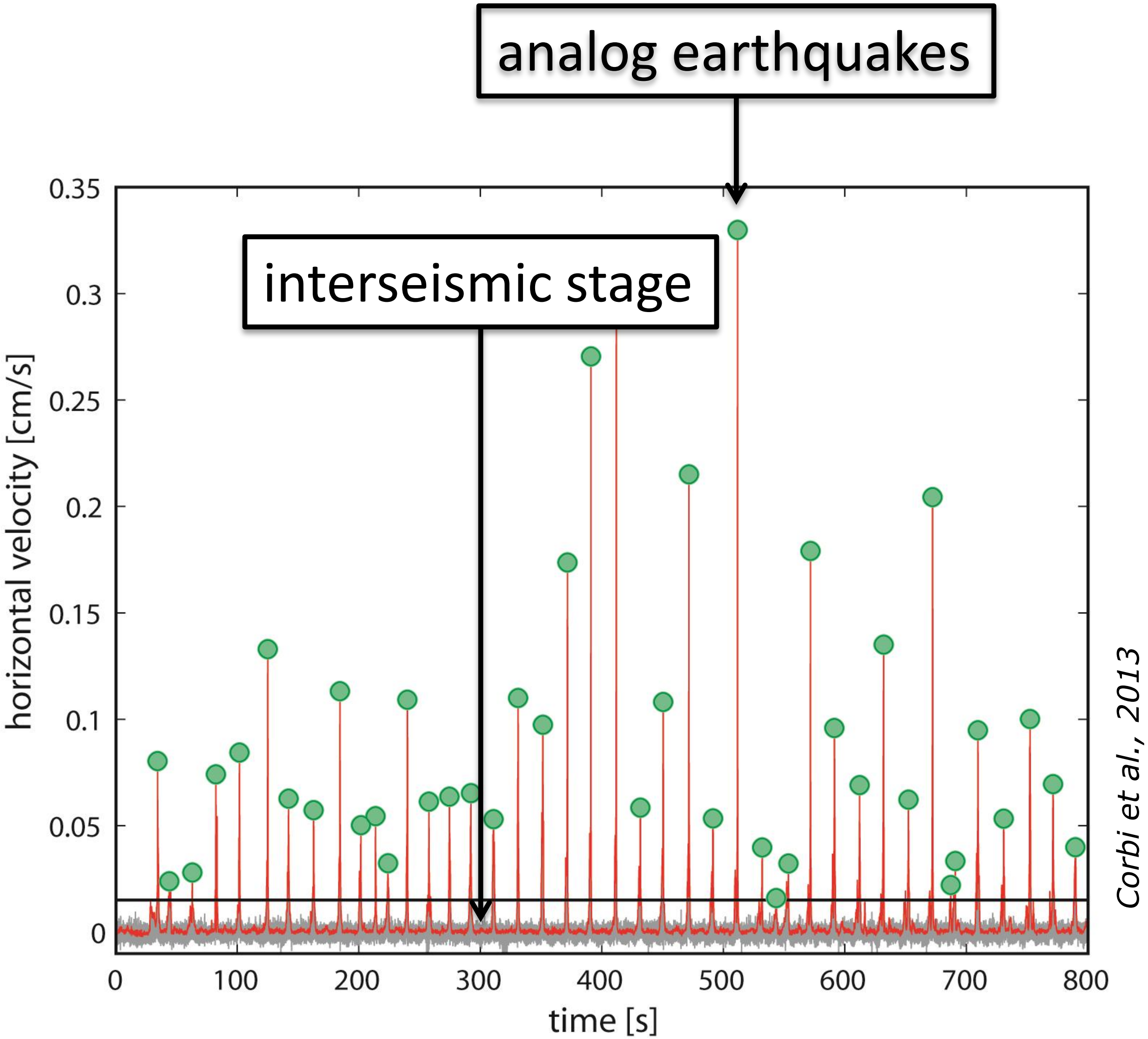
25x; lateral view



Particle Image Velocimetry output



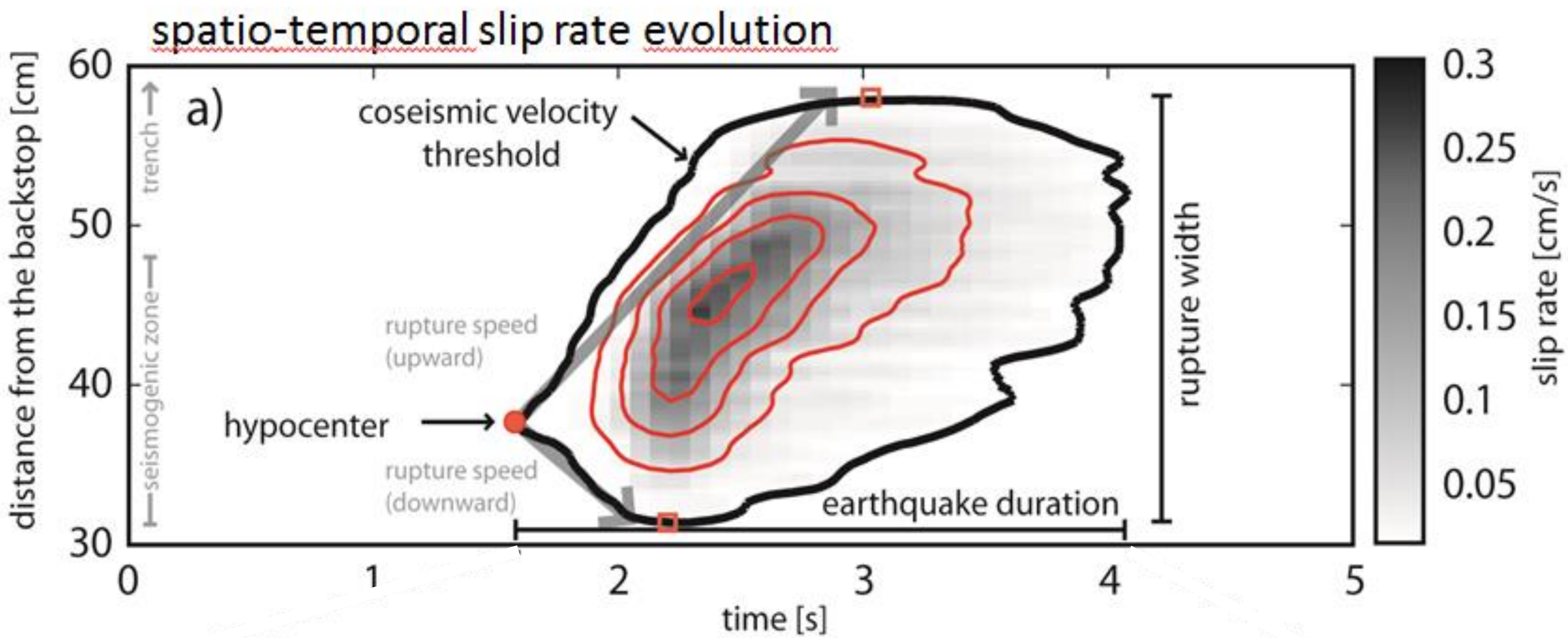
VELOCITY TIME SERIES



hundreds of scaled analog microquakes and associated seismic cycles

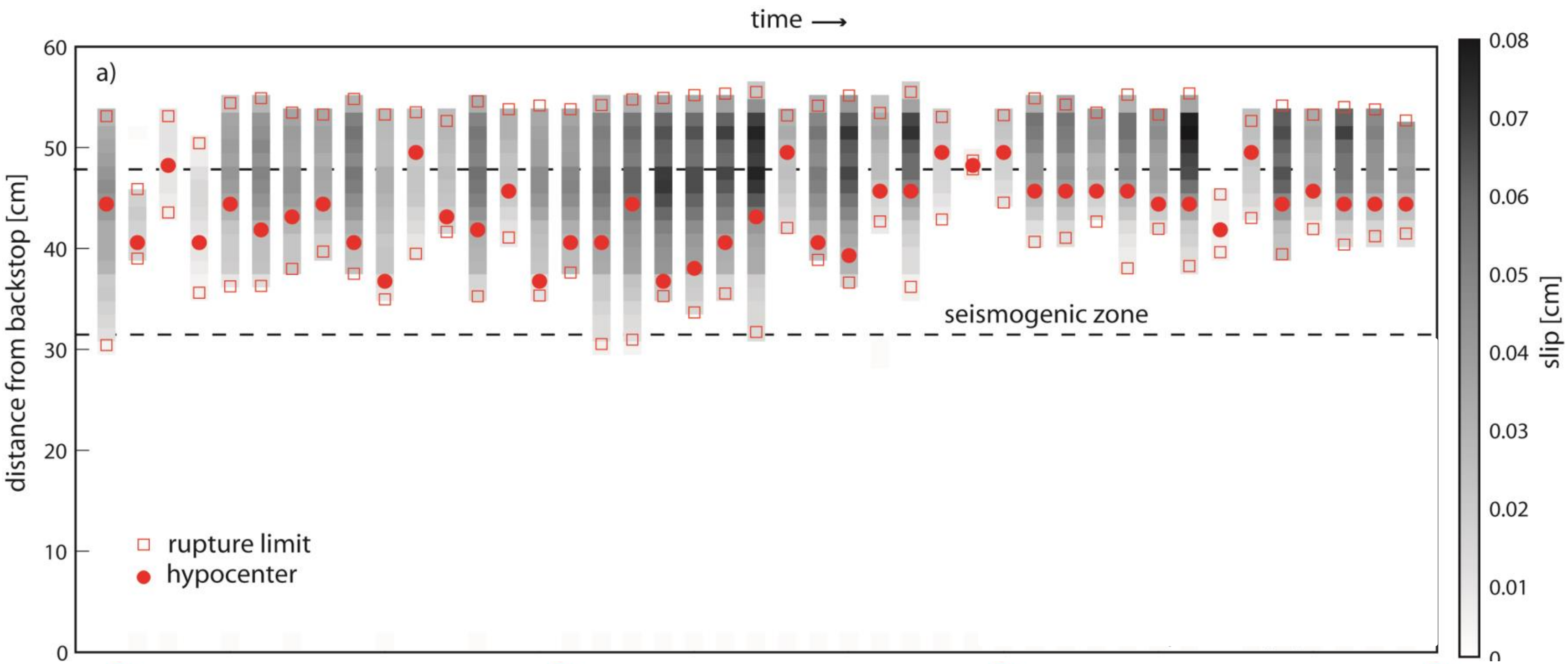
alternate phases of quiescence with phases of high speed

RUPTURE BEHAVIOR



Corbi et al., 2013

SLIP DISTRIBUTION ON THE SUBDUCTION MEGATHRUST



we capture events of various size

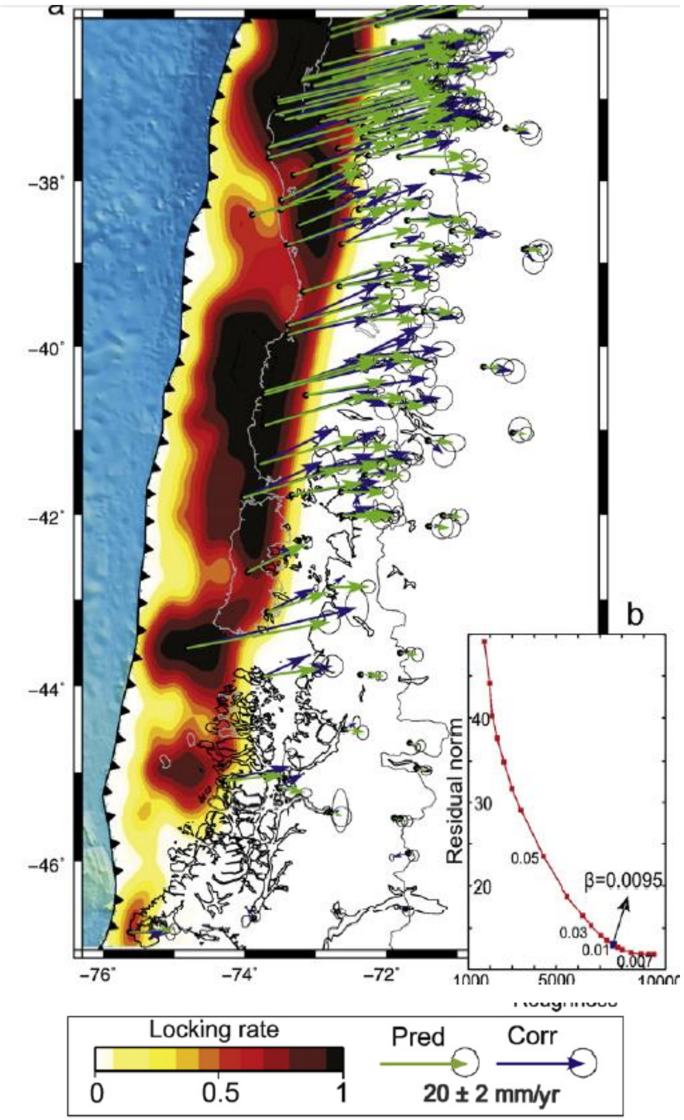
the majority of earthquakes nucleate in the vel weakening zone and propagate in the vel strength

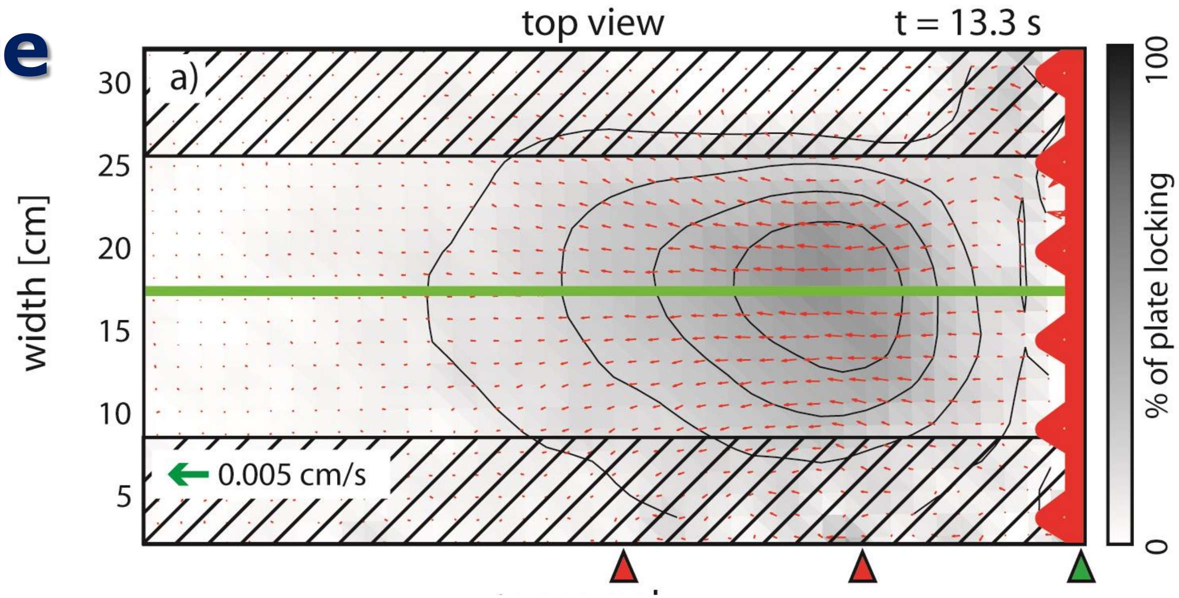
nucleate in the deeper part of the rupture and propagate preferentially seaward

there is a clear proportionality between slip and rupture width as in nature

interseismic stage

Moreno et al., 2011

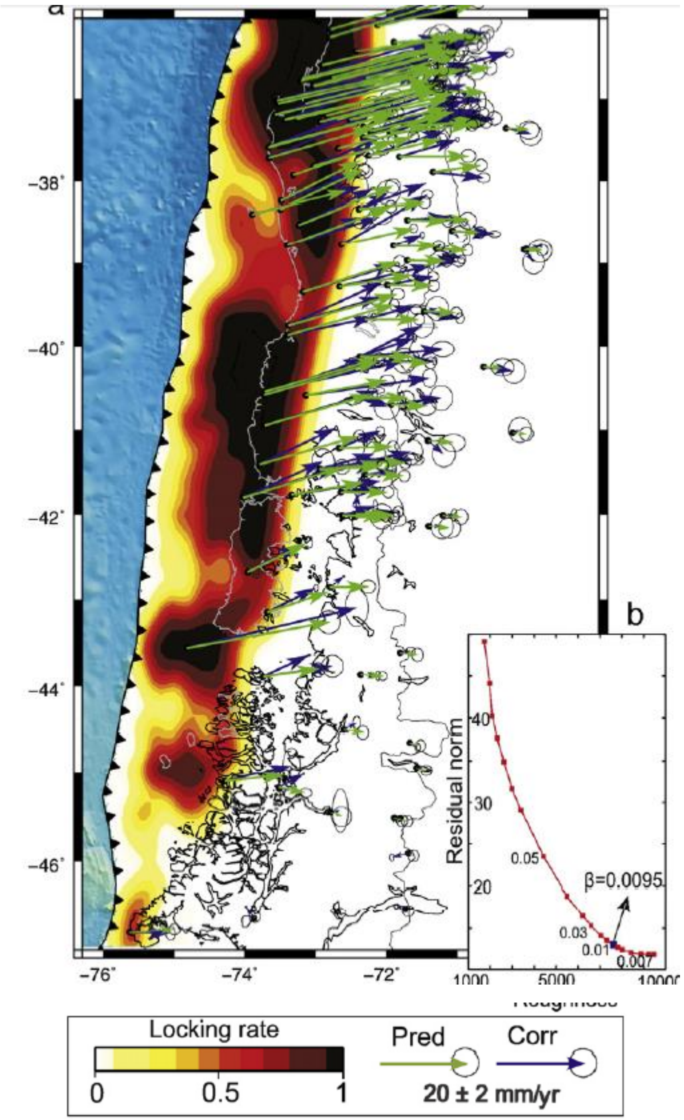


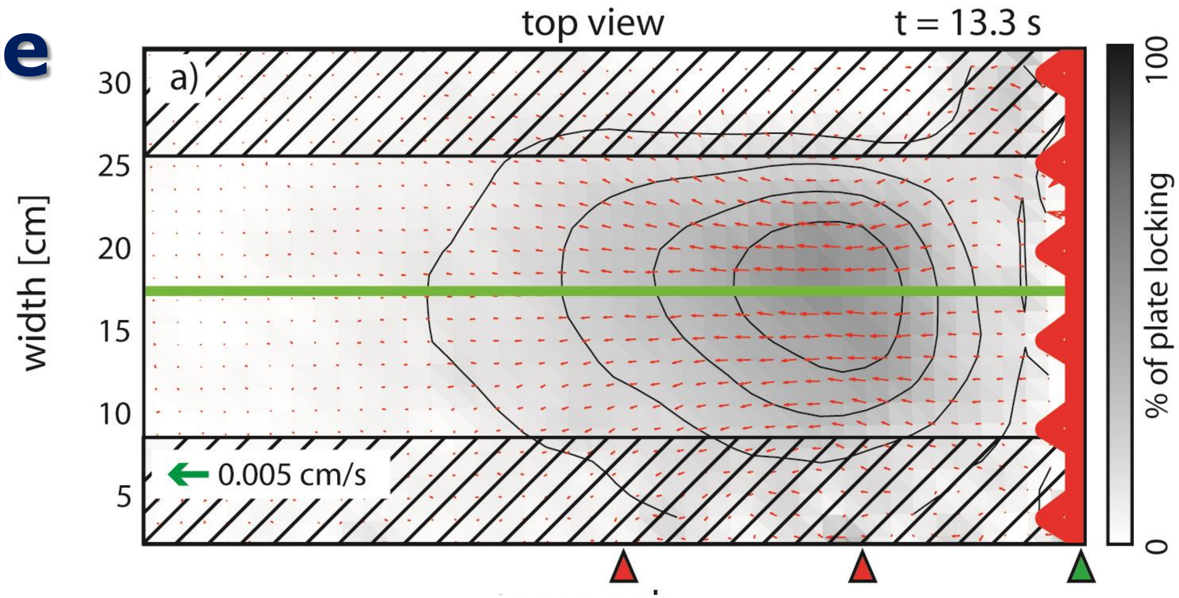


like Chile!

interseismic stage

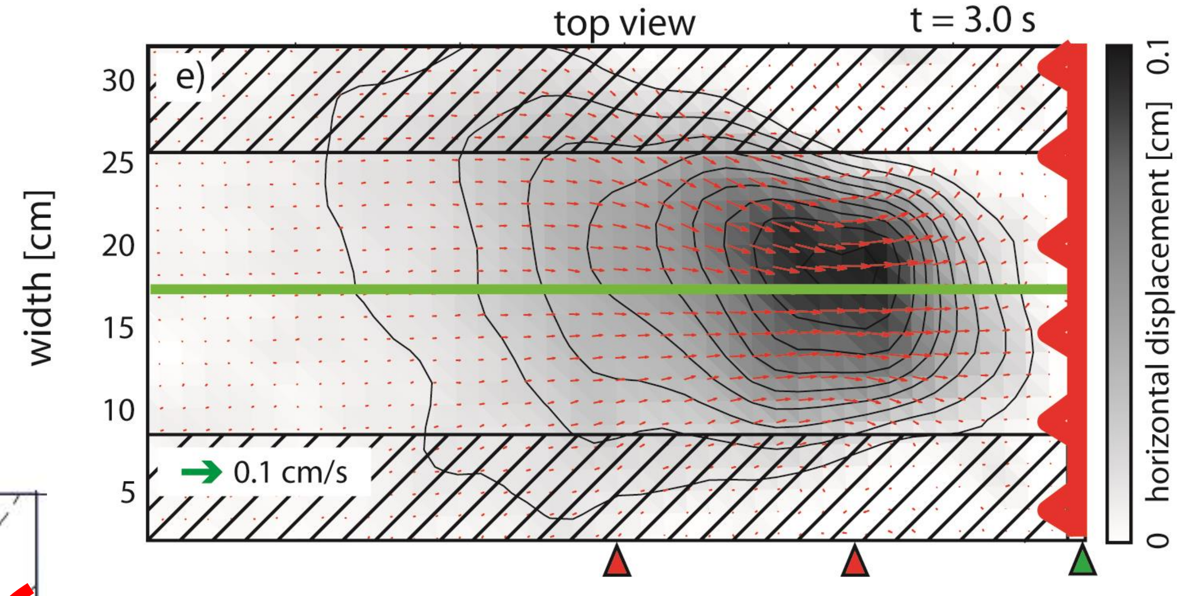
Moreno et al., 2011

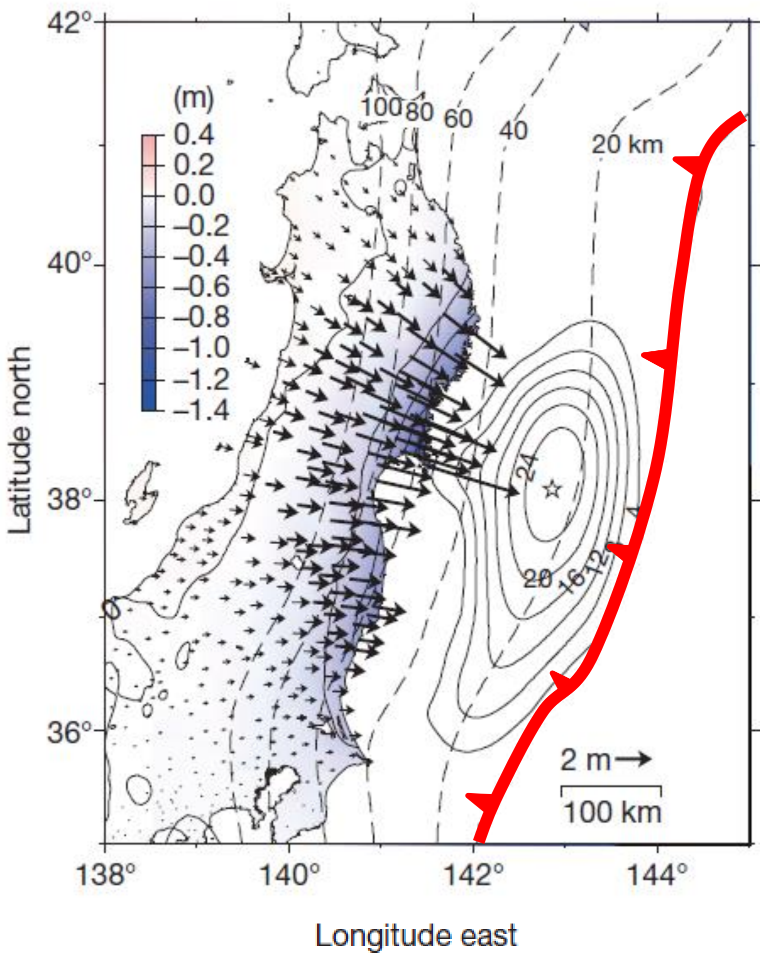




like Chile!

coseismic stage

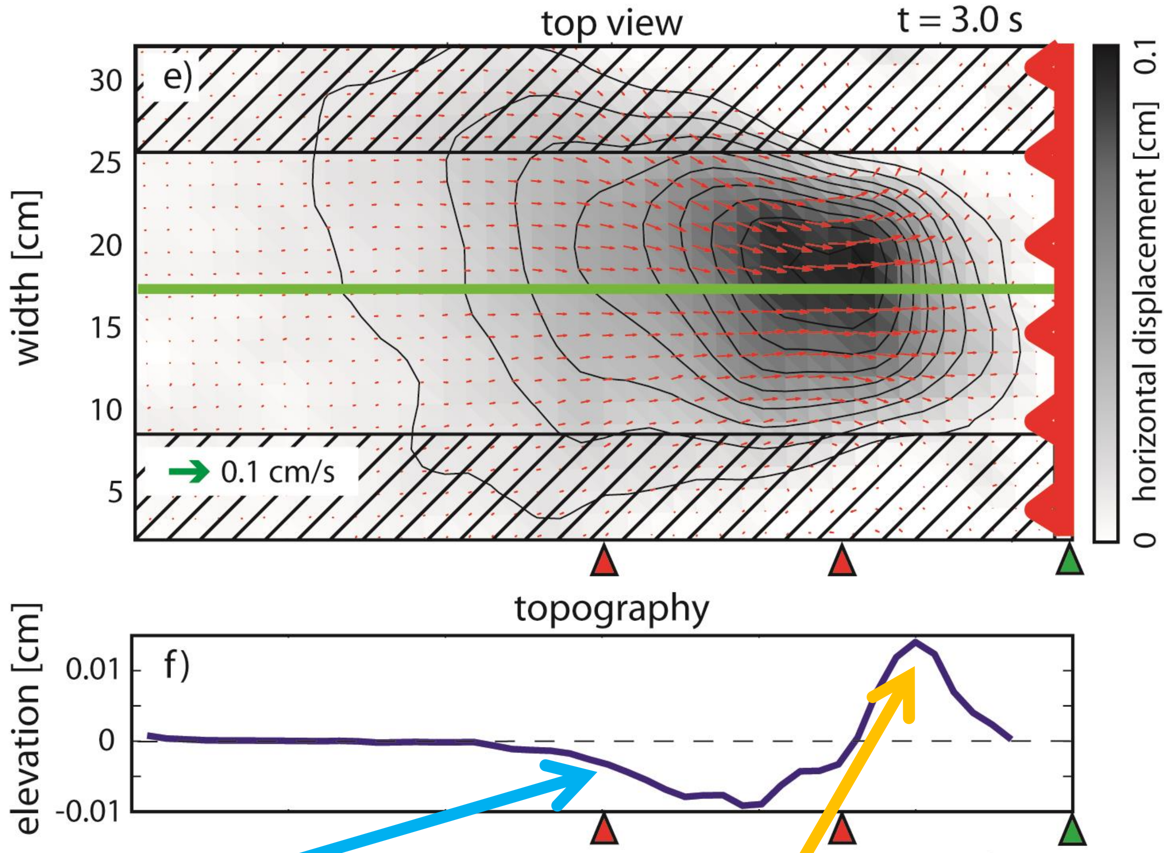




Ozawa et al., 2011

like Tohoku!

coseismic stage

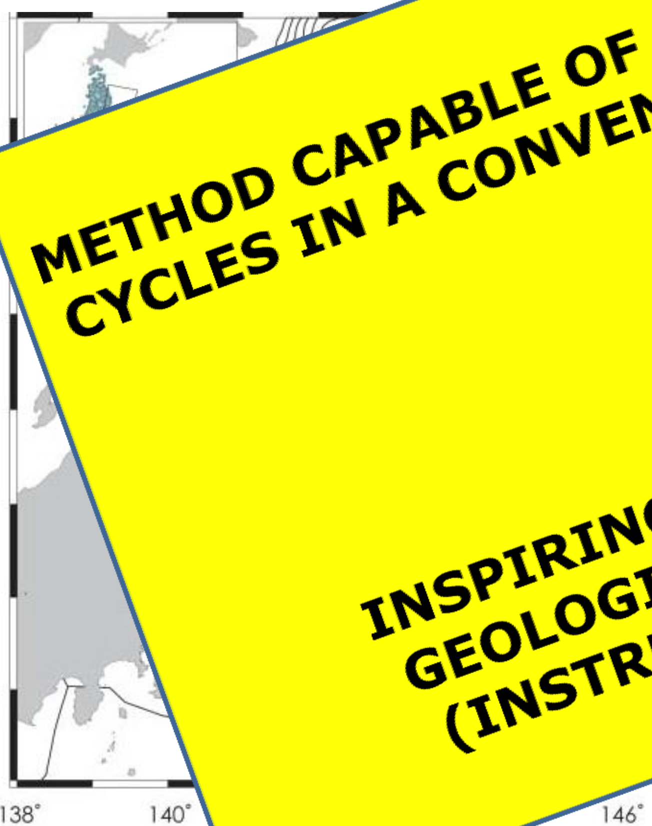


like Sumatra!

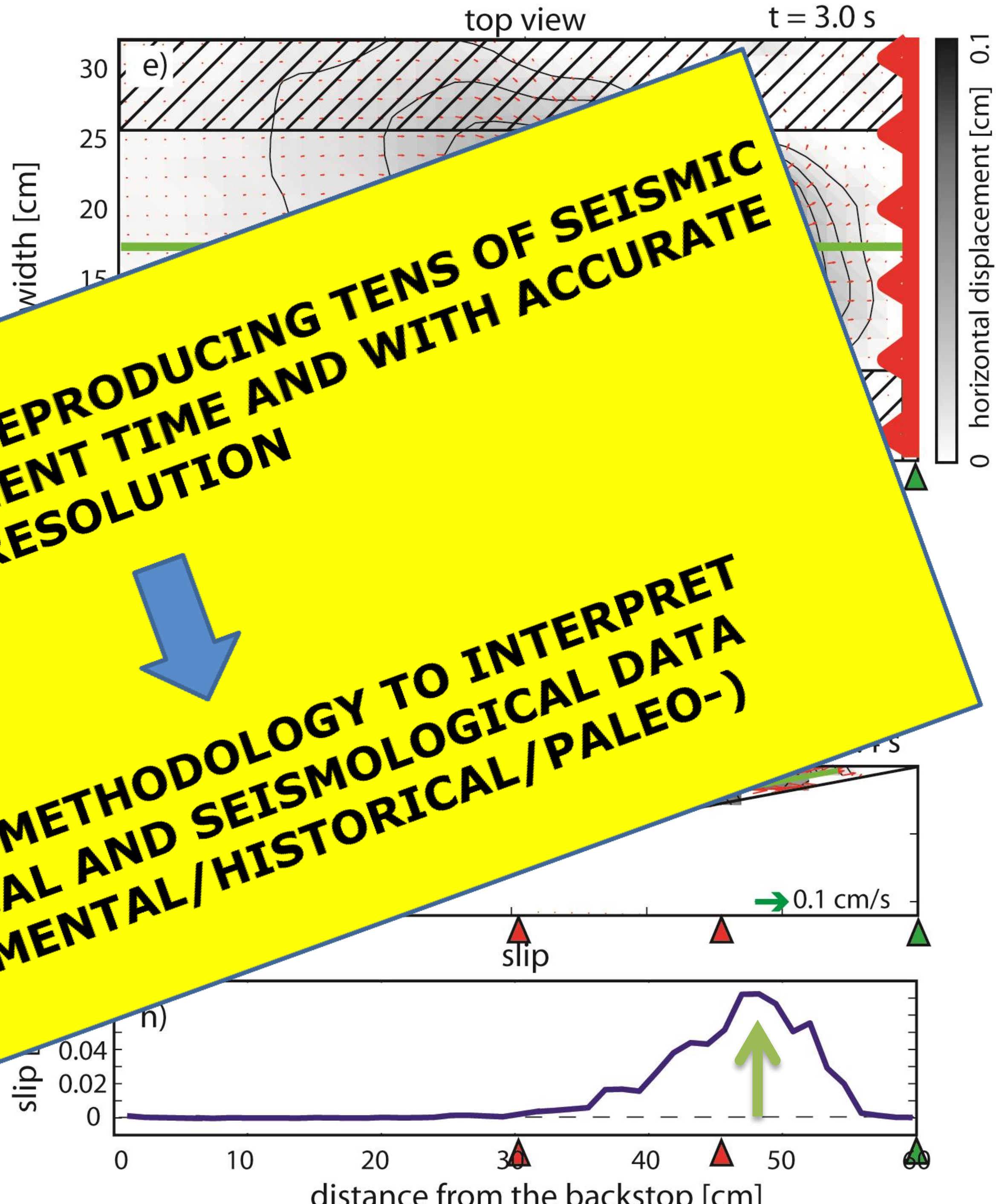
coseismic vertical displacement

coseismic stage

like Tohoku!



…no et al., 2012

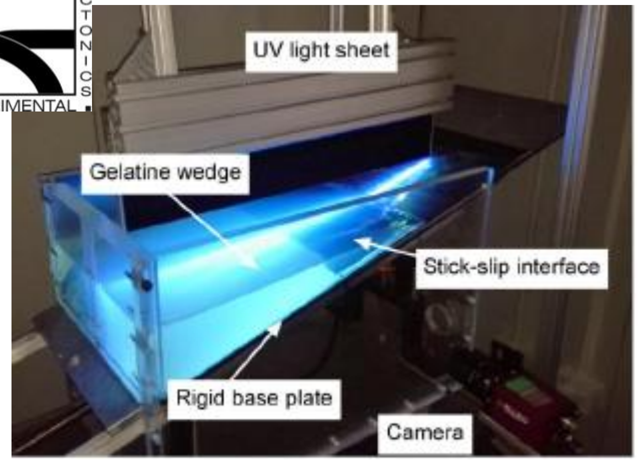


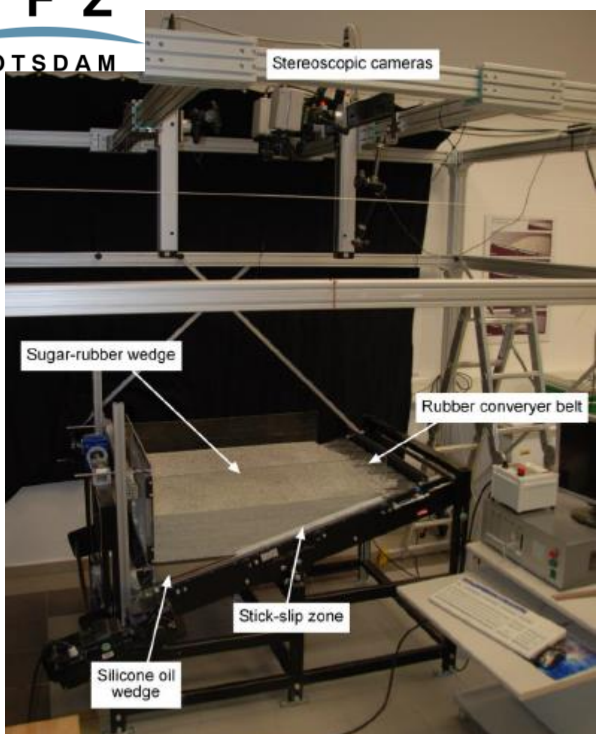
METHOD CAPABLE OF REPRODUCING TENS OF SEISMIC CYCLES IN A CONVENIENT TIME AND WITH ACCURATE RESOLUTION

⬇

INSPIRING METHODOLOGY TO INTERPRET GEOLOGICAL AND SEISMOLOGICAL DATA (INSTRUMENTAL/HISTORICAL/PALEO-)

NOT ONLY LET...

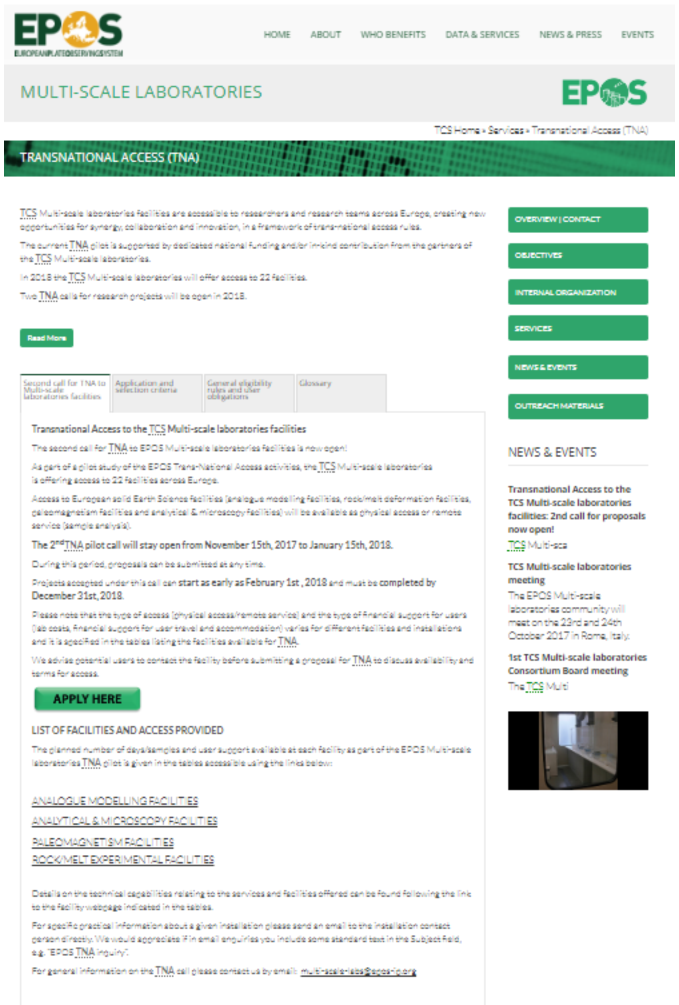

UV light sheet
Gelatine wedge
Stick-slip interface
Rigid base plate
Camera


Stereoscopic cameras
Sugar-rubber wedge
Rubber converyer belt
Stick-slip zone
Silicone oil wedge


Force sensors
Silicone reservoir
Foam wedge
Foam slab

TNA: COME AND USE OUR LABS!

https://www.epos-ip.org/tcs/multi-scale-laboratories


HOME ABOUT WHO BENEFITS DATA & SERVICES NEWS & PRESS EVENTS

MULTI-SCALE LABORATORIES

TCS Home » Services » Transnational Access (TNA)

TRANSNATIONAL ACCESS (TNA)

TCS Multi-scale laboratories facilities are accessible to researchers and research teams across Europe, creating new opportunities for synergy, collaboration and innovation, in a framework of trans-national access rules.

The current TNA pilot is supported by dedicated national funding and/or in-kind contribution from the partners of the TCS Multi-scale laboratories.

In 2018 the TCS Multi-scale laboratories will offer access to 22 facilities.

Two TNA calls for research projects will be open in 2018.

Read More

Second call for TNA to Multi-scale laboratories facilities | Application and selection criteria | General eligibility rules and user obligations | Glossary

Transnational Access to the TCS Multi-scale laboratories facilities

The second call for TNA to EPOS Multi-scale laboratories facilities is now open!

As part of a pilot study of the EPOS Trans-National Access activities, the TCS Multi-scale laboratories is offering access to 22 facilities across Europe.

Access to European solid Earth Science facilities (analogue modelling facilities, rock/melt deformation facilities, paleomagnetism facilities and analytical & microscopy facilities) will be available as physical access or remote service (sample analysis).

The 2nd TNA pilot call will stay open from November 15th, 2017 to January 15th, 2018.

During this period, proposals can be submitted at any time.

Projects accepted under this call can **start as early as February 1st , 2018** and must be **completed by December 31st, 2018.**

Please note that the type of access (physical access/remote service) and the type of financial support for users (lab costs, financial support for user travel and accommodation) varies for different facilities and installations and it is specified in the tables listing the facilities available for TNA.

We advise potential users to contact the facility before submitting a proposal for TNA to discuss availability and terms for access.

APPLY HERE

LIST OF FACILITIES AND ACCESS PROVIDED

The planned number of days/samples and user support available at each facility as part of the EPOS Multi-scale laboratories TNA pilot is given in the tables accessible using the links below:

ANALOGUE MODELLING FACILITIES
ANALYTICAL & MICROSCOPY FACILITIES
PALEOMAGNETISM FACILITIES
ROCK/MELT EXPERIMENTAL FACILITIES

Details on the technical capabilities relating to the services and facilities offered can be found following the link to the facility webpage indicated in the tables.

For specific practical information about a given installation please send an email to the installation contact person directly. We would appreciate if in email enquiries you include some standard text in the Subject field, e.g. "EPOS TNA inquiry".

For general information on the TNA call please contact us by email: multi-scale-labs@epos-ip.org

OVERVIEW | CONTACT
OBJECTIVES
INTERNAL ORGANIZATION
SERVICES
NEWS & EVENTS
OUTREACH MATERIALS

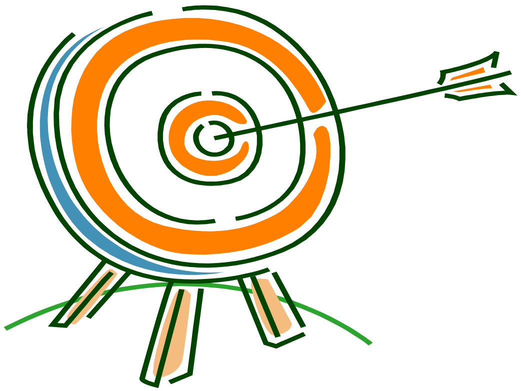
NEWS & EVENTS

Transnational Access to the TCS Multi-scale laboratories facilities: 2nd call for proposals now open!
TCS Multi-sca

TCS Multi-scale laboratories meeting
The EPOS Multi-scale laboratories community will meet on the 23rd and 24th October 2017 in Rome, Italy.

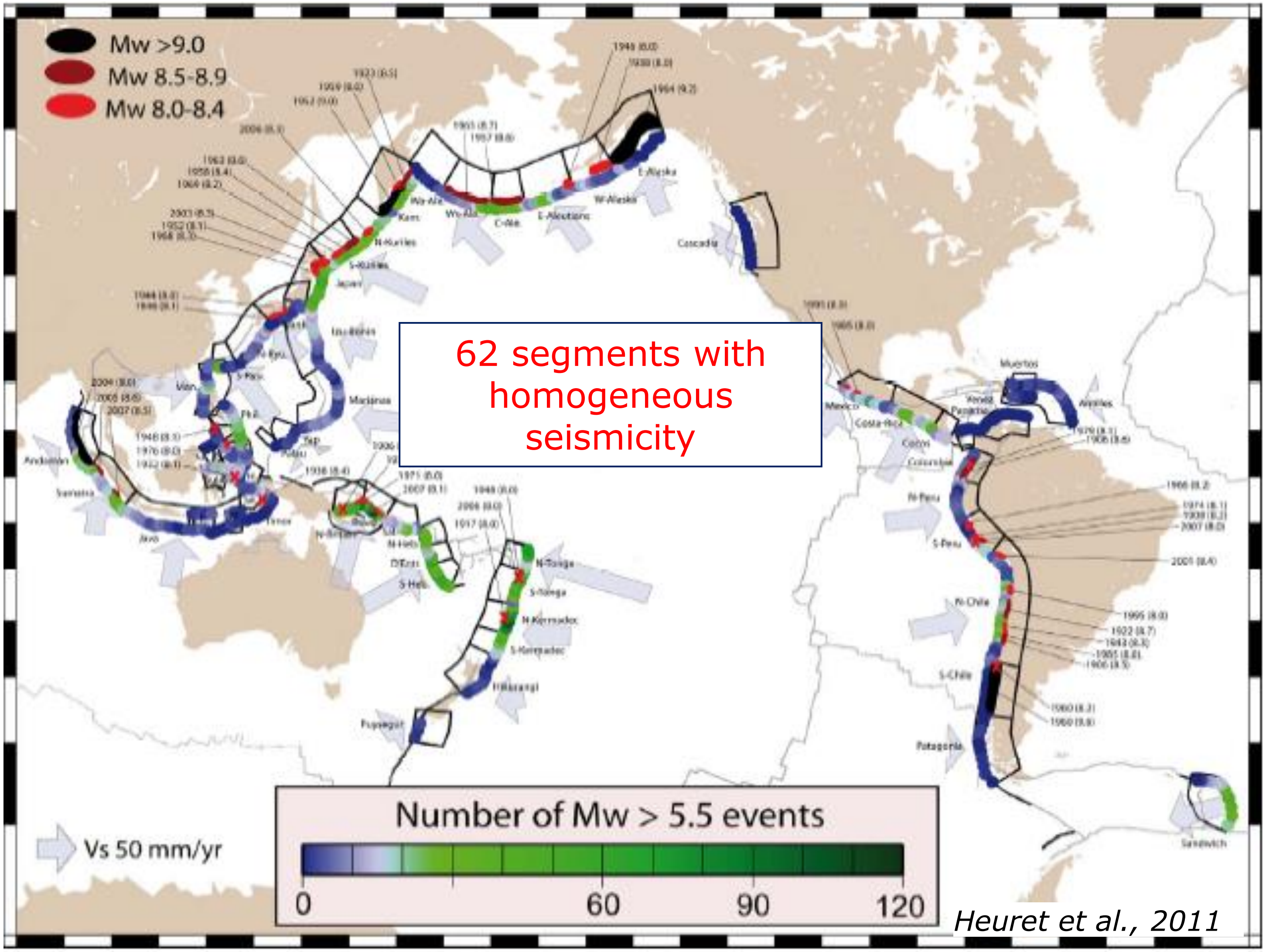
1st TCS Multi-scale laboratories Consortium Board meeting
The TCS Multi

- ☞ **Scientific problem**
- ☞ **Tools**: - database on current subduction zones
  - analogue models
- ☞ **Selection of results**
- ☞ **Future directions**



GOAL #1

DEFINING THE SEISMOGENIC ZONE GEOMETRY

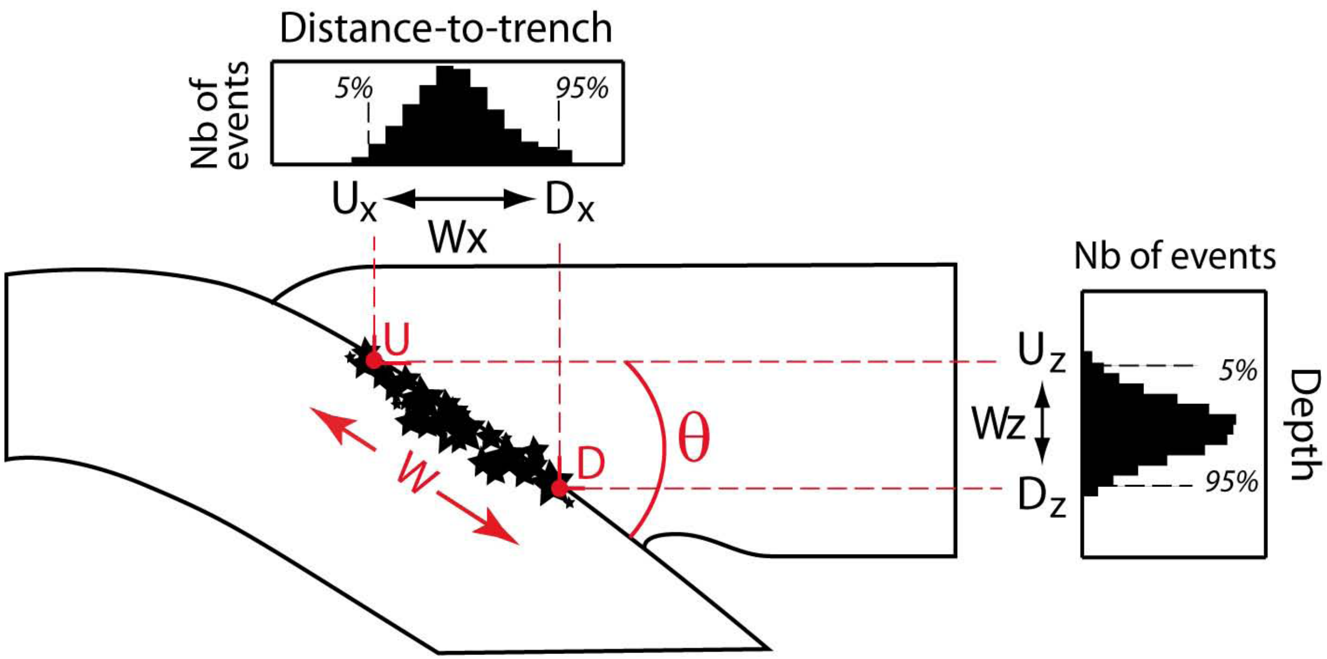


62 segments with homogeneous seismicity

Heuret et al., 2011

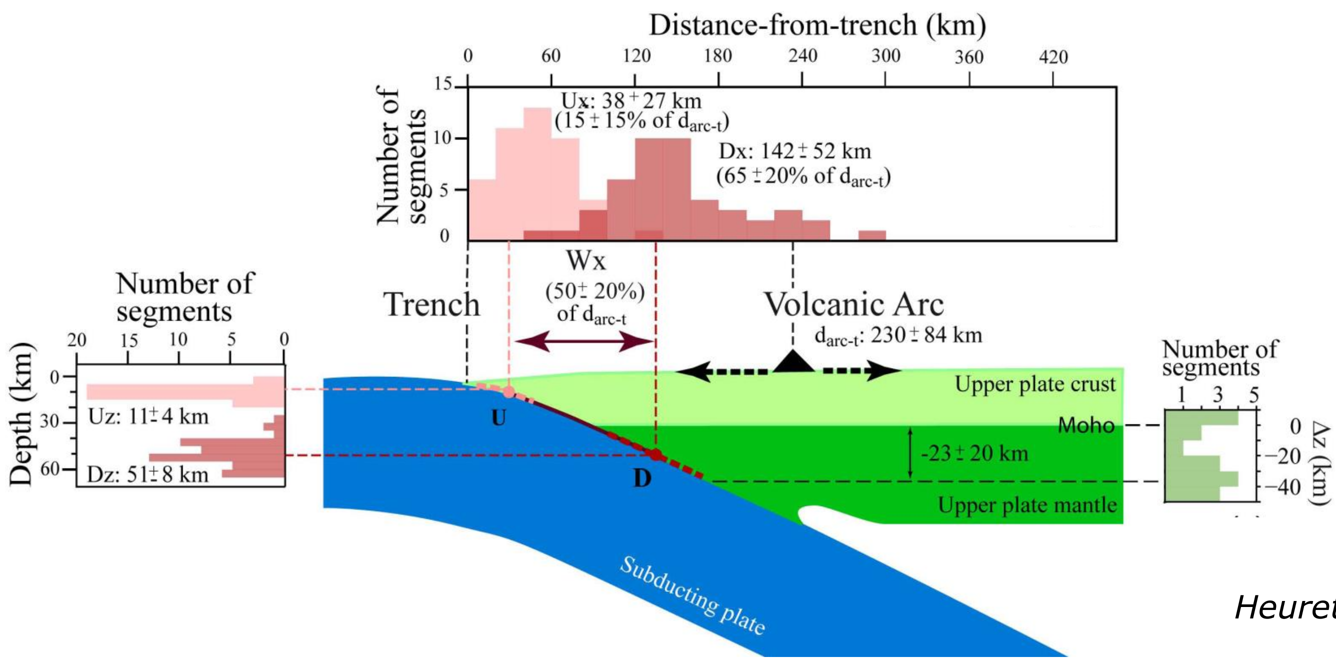
HOW TO DESCRIBE THE SEISMOGENIC ZONE?

- Coseismic rupture area
- Interseismic locked area
- Thermally defined seismogenic zone (100-150°C to 350-450°C)
- Moderately sized earthquakes



Heuret et al., 2011

DEFINING THE SEISMOGENIC ZONE… AS MODERATELY SIZED EARTHQUAKES NUCLEATION AREA



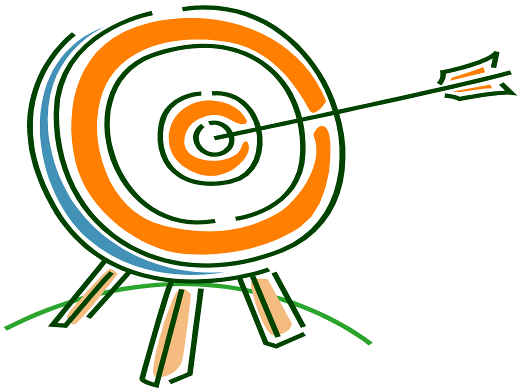
Heuret et al., 2011

$\theta_{mean} = 23° \pm 8°$
W= 60-180 km
$U_z = 11 \pm 4$ km; $D_z = 51 \pm 8$ km
$U_x = 38 \pm 27$ km; $D_x = 142 \pm 52$ km

70% of the SZs extend > 10 km below the forearc Moho (defined by Wada and Wang, 2009)

↓

extent of serpentinization of the mantle wedge (enhancing the formation of stable sliding minerals) may differ locally (e.g., *Seno, 2005*)



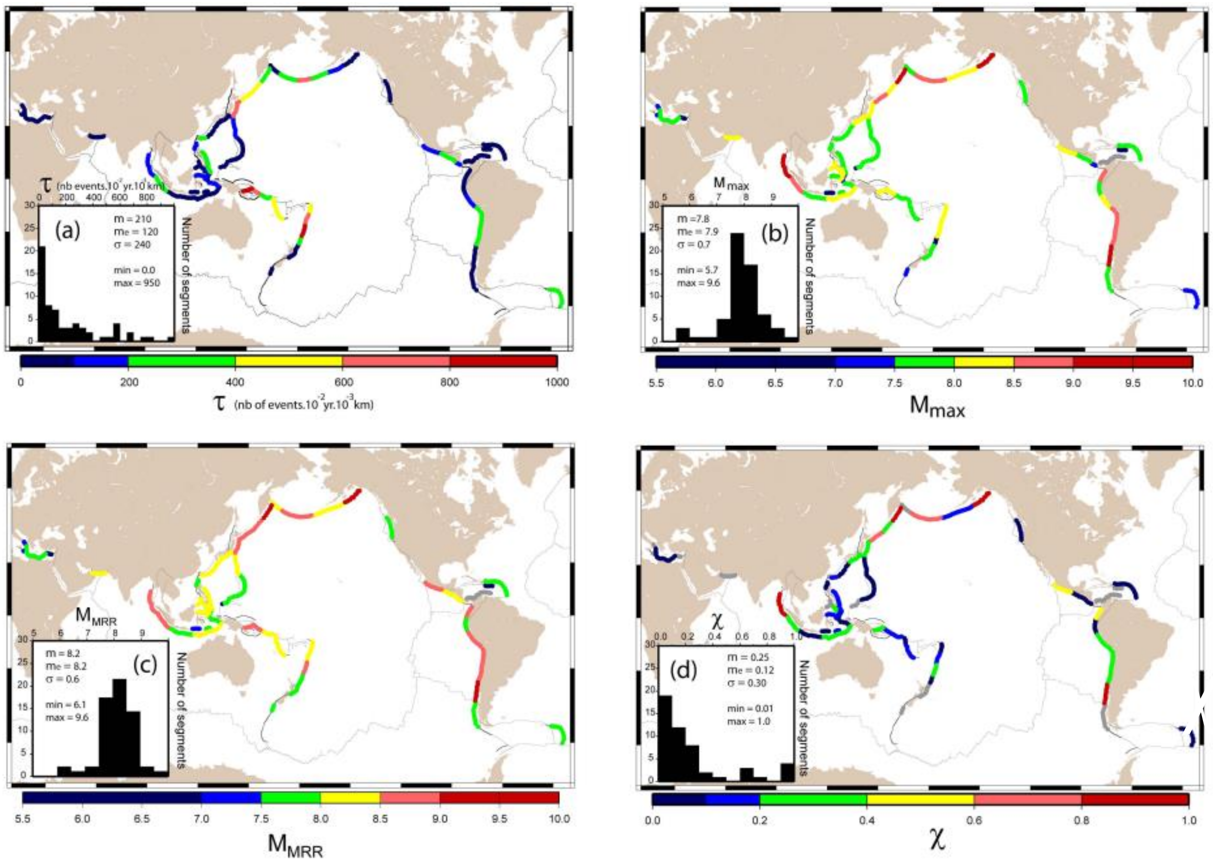
GOAL #2

DEFINING THE SEISMOGENIC ZONE ACTIVITY

seismic activity parameters

τ	**Seismic moment rate** (n° of Mw>5.5 events by year by 1000 km of trench)
MMR	**Moment released rate**
M_{MMR}	**Equivalent representative magnitude** sensu Ruff and Kanamori, 1980
χ	**Seismic coupling** (seismic rate/subduction rate)
M_{max}	**Highest earthquake magnitude observed along the section**

τ



M_{max}

mean value 7.8 ± 0.7

M_{MMR}

mean value 8.2 ± 0.6

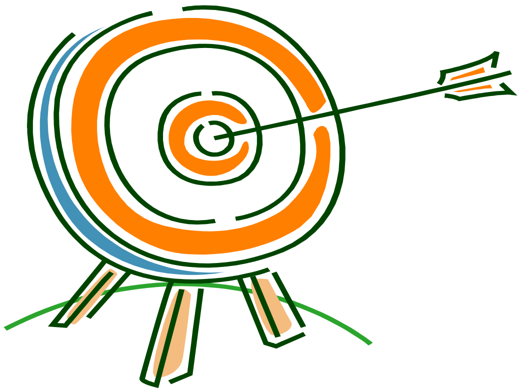
χ

mean value 0.25 ± 0.30

↓

slip mostly aseismic or strain accumulating

Heuret et al., 2011



GOAL #3

SUBDUTION THRUST FAULT PARAMETERS

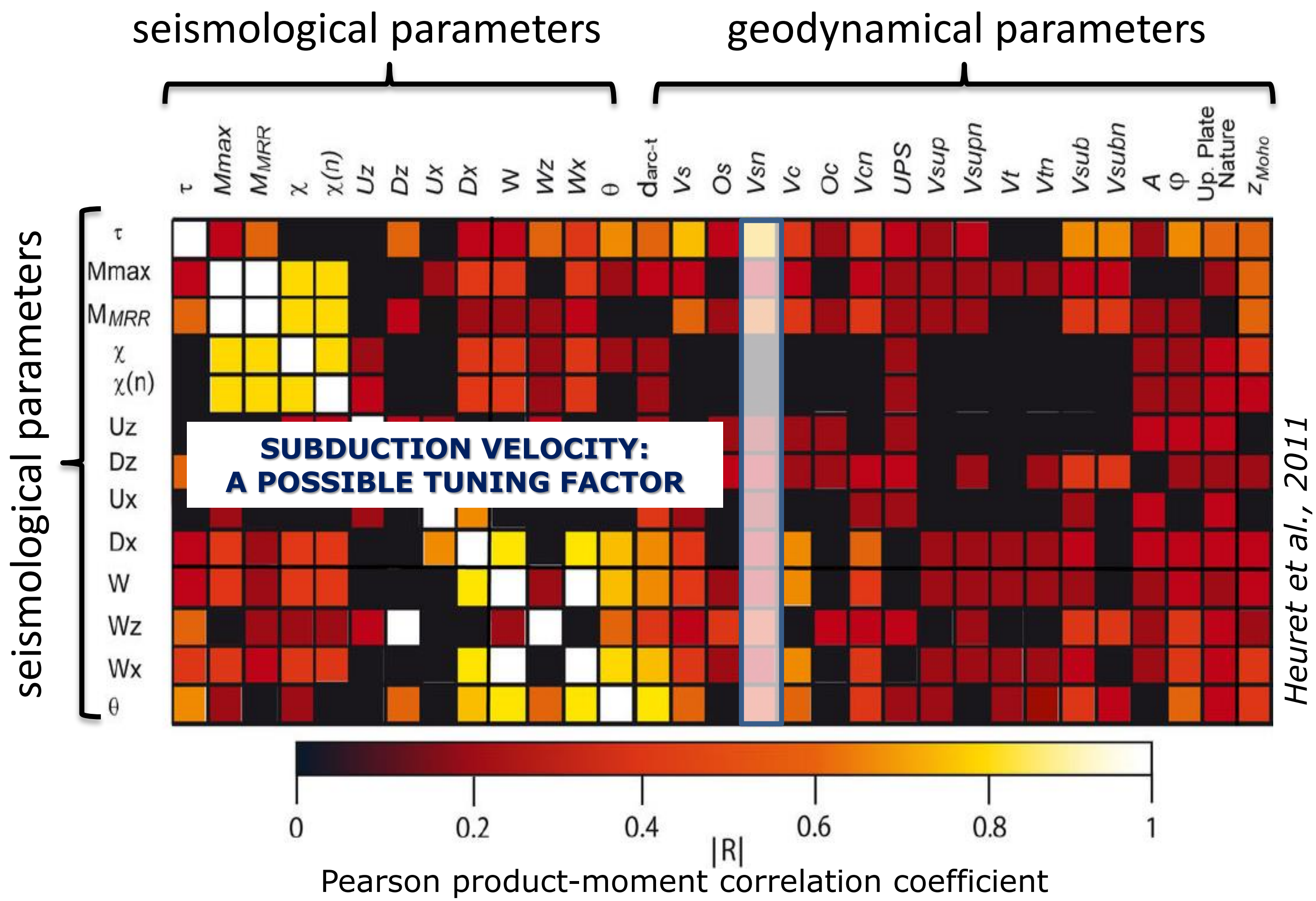
vs.

SUBDUTION PARAMETERS

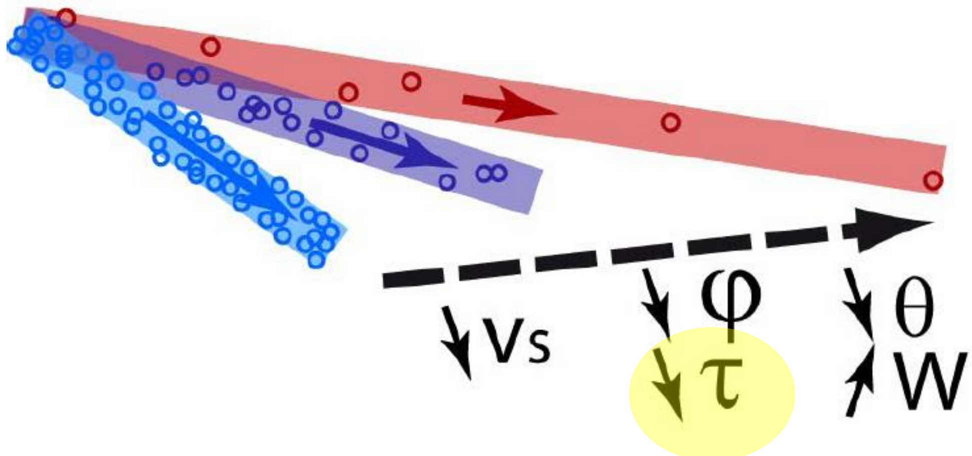
Heuret et al., 2011

Mirror of the intricate subduction related physical processes.
A single parameter is
never
able to robustly explain the whole diversity observed at subduction interfaces!!!

Multiparametric analysis



SUBDUCTION VELOCITY: A POSSIBLE TUNING FACTOR

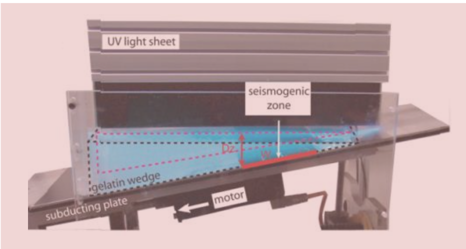


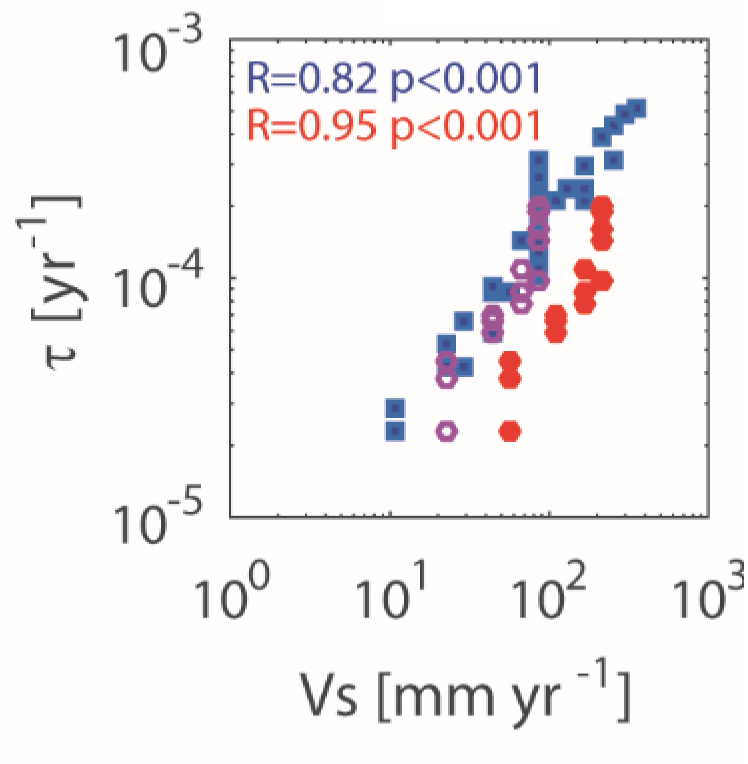
fast (and cold) subduction zones
produce a large number of
moderate earthquakes over a narrow, deep and steeply dipping
seismogenic interface

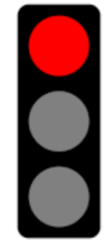
↓

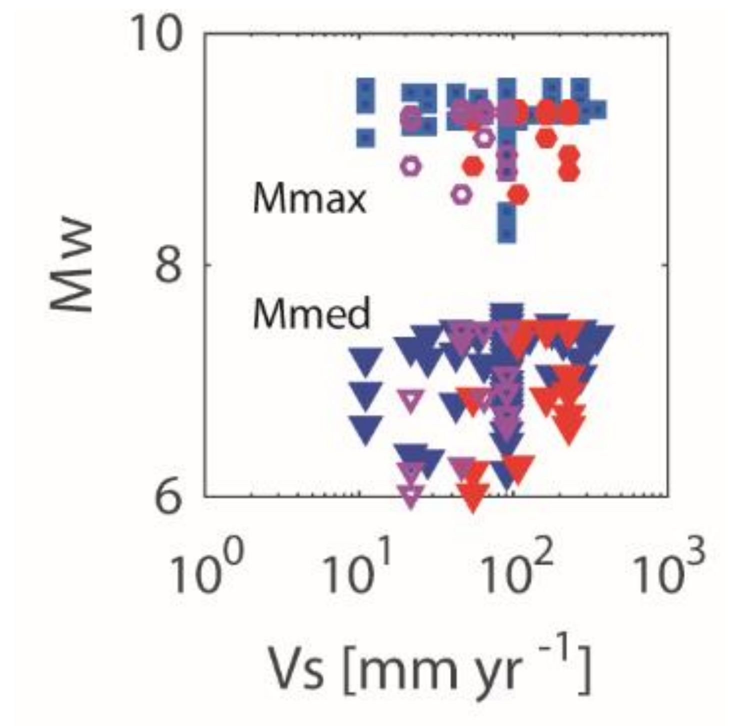
stress accumulation (i.e. shear velocity) +T-related process

SUBDUCTION VELOCITY TUNES STICK-SLIP DYNAMICS

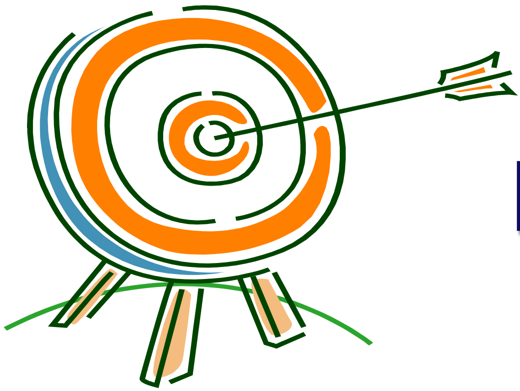






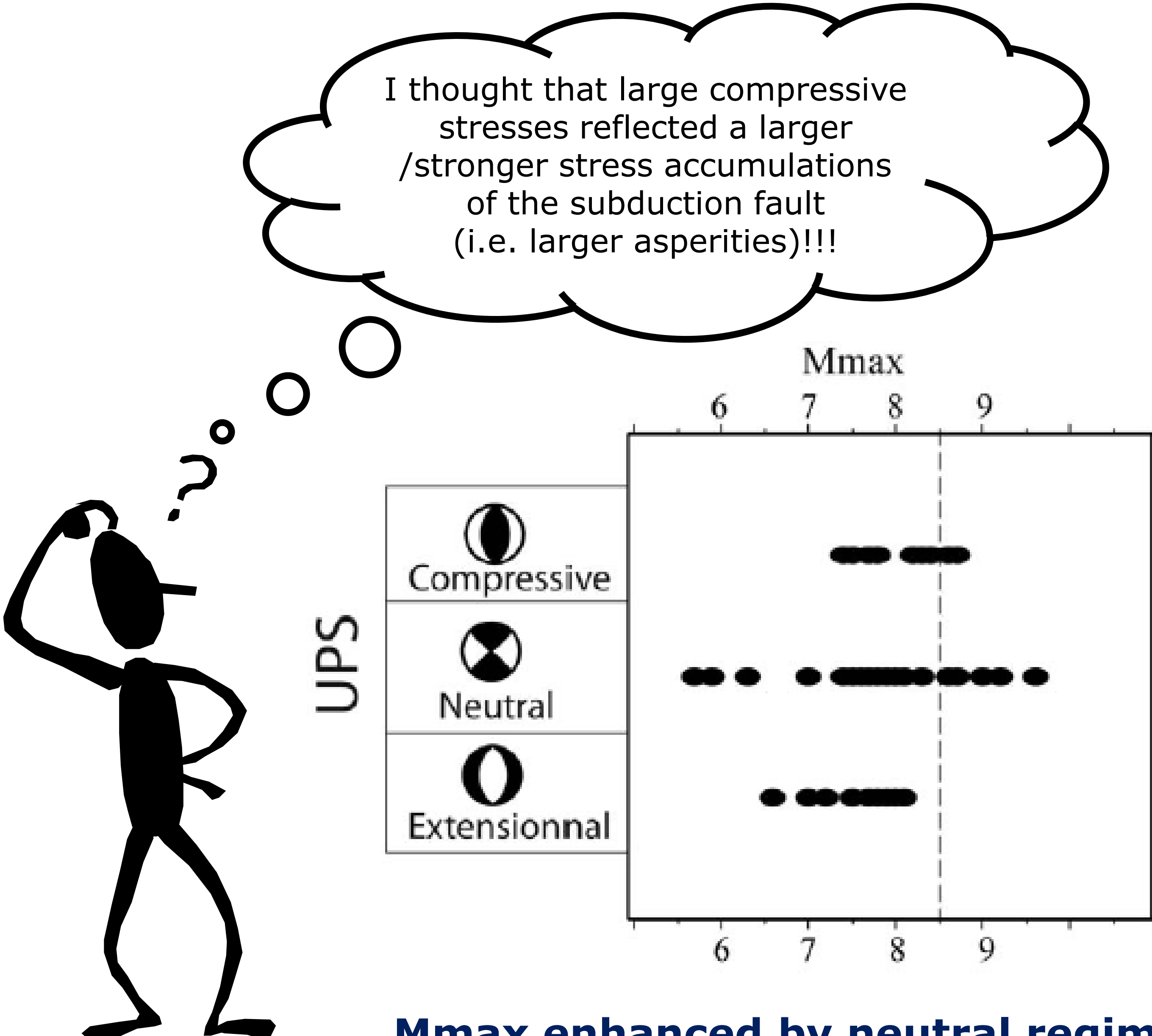


Corbi et al., 2017



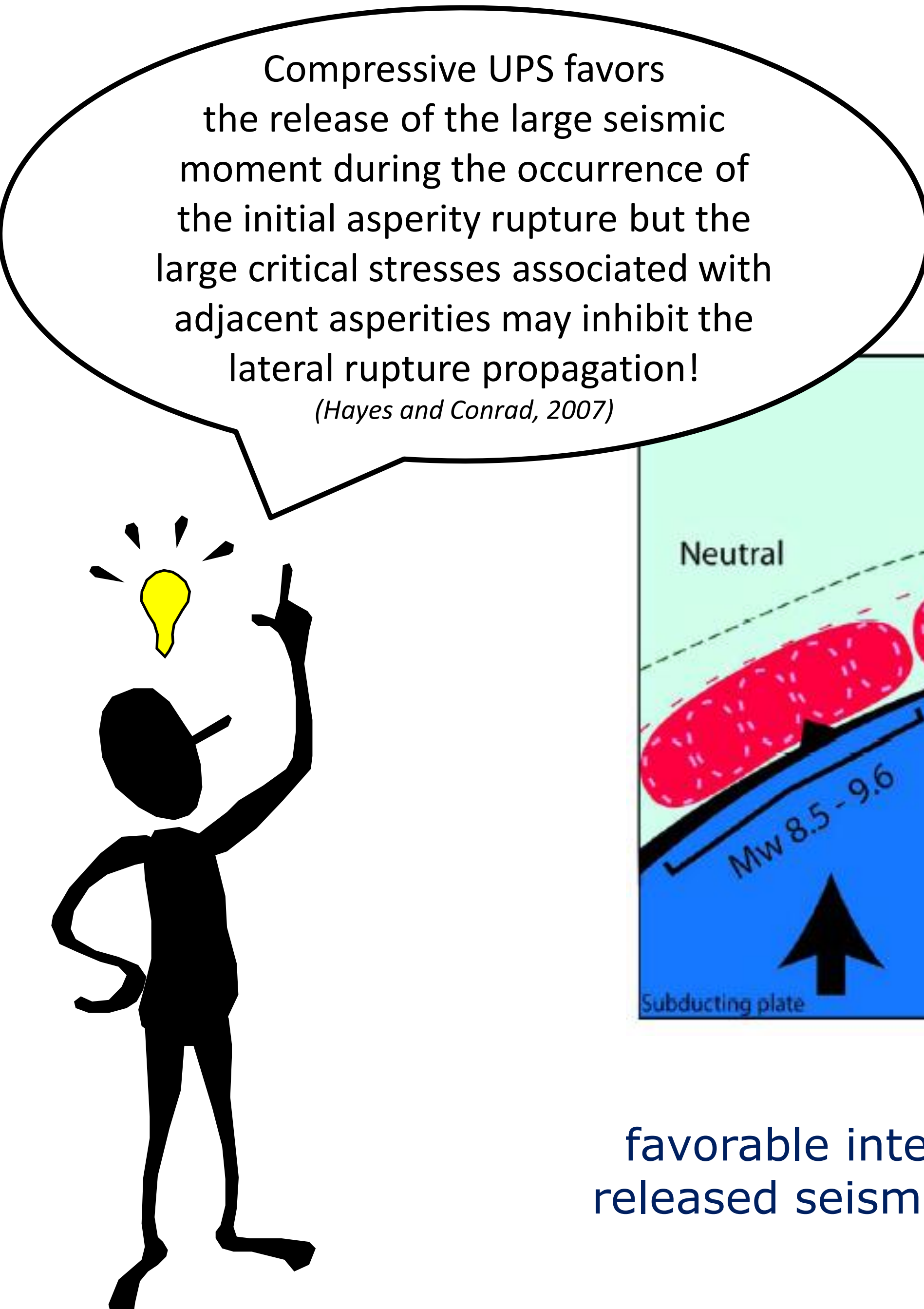
GOAL #4

CONDITIONS FOR MEGA-EARTHQUAKES GENESIS

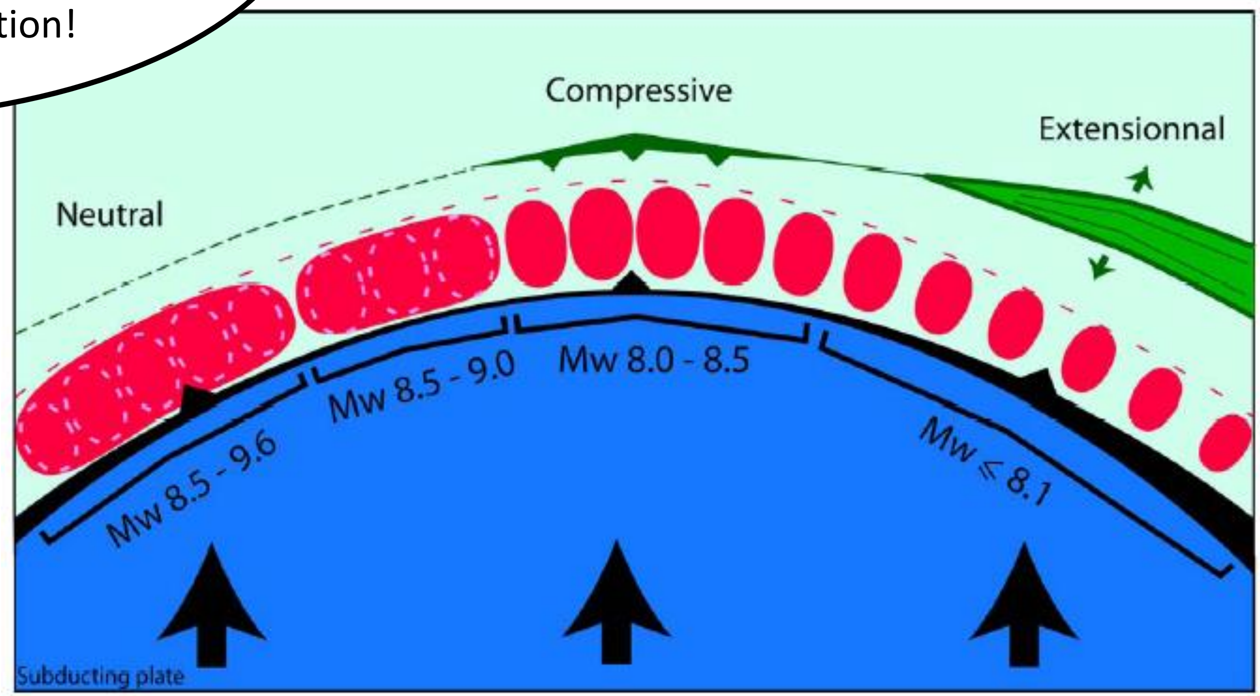


Mmax enhanced by neutral regimes

Heuret et al., 2011



"UPS REGIME MODEL"



NEUTRAL REGIME
favorable interplay between a significantly large initial released seismic moment and a low critical stress for the lateral rupture propagation

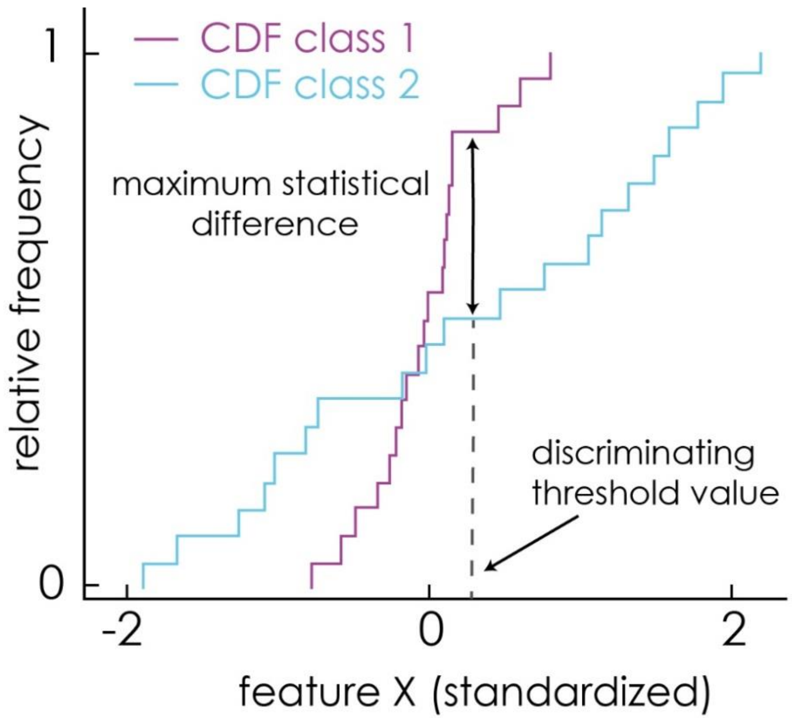
Heuret et al., 2011

MULTIVARIATE STATISTICS

PATTERN RECOGNITION ANALYSIS

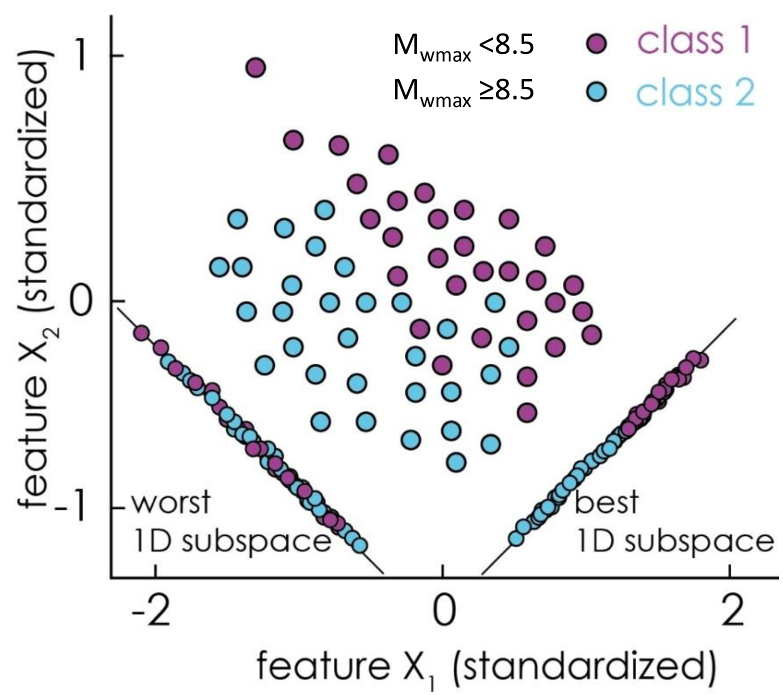
MULTIVARIATE STATISTICS

Binary Decision Tree



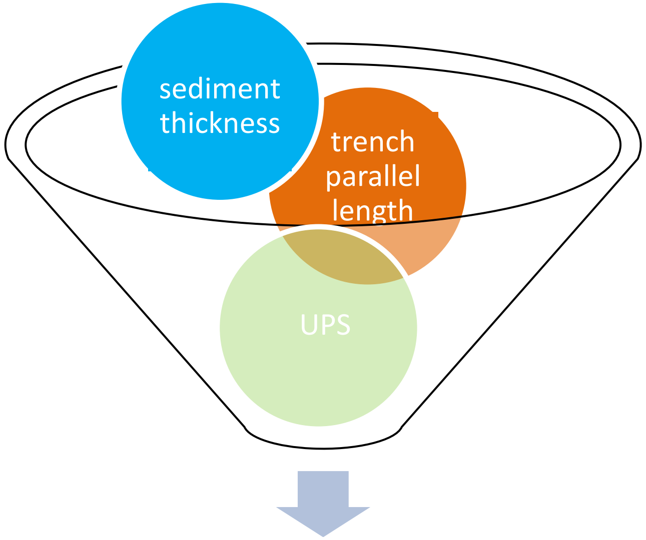
Empirical distribution function of each feature for both classes finding the one showing the max stat difference → main order feature.
Then the algorithm looks for the higher order features until no further branching is possible.

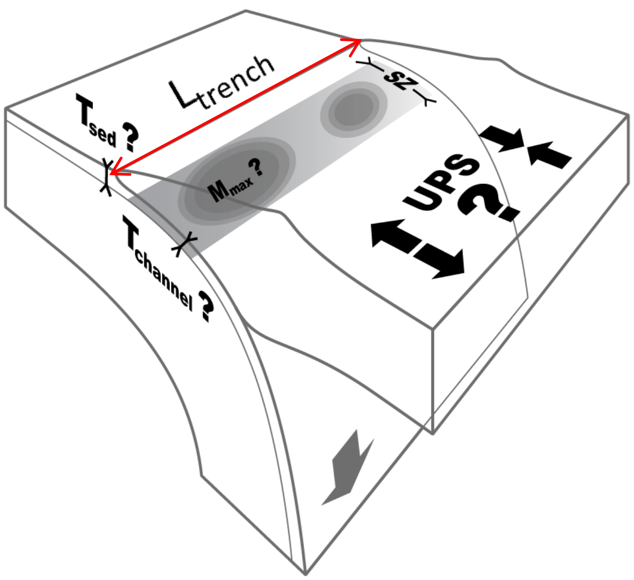
Fisher Discriminant analysis



Projection of the data along the direction that maximize dispersion between the classes to the dispersion within the classes. This direction is a linear combination of parameters having influence on the Mmax

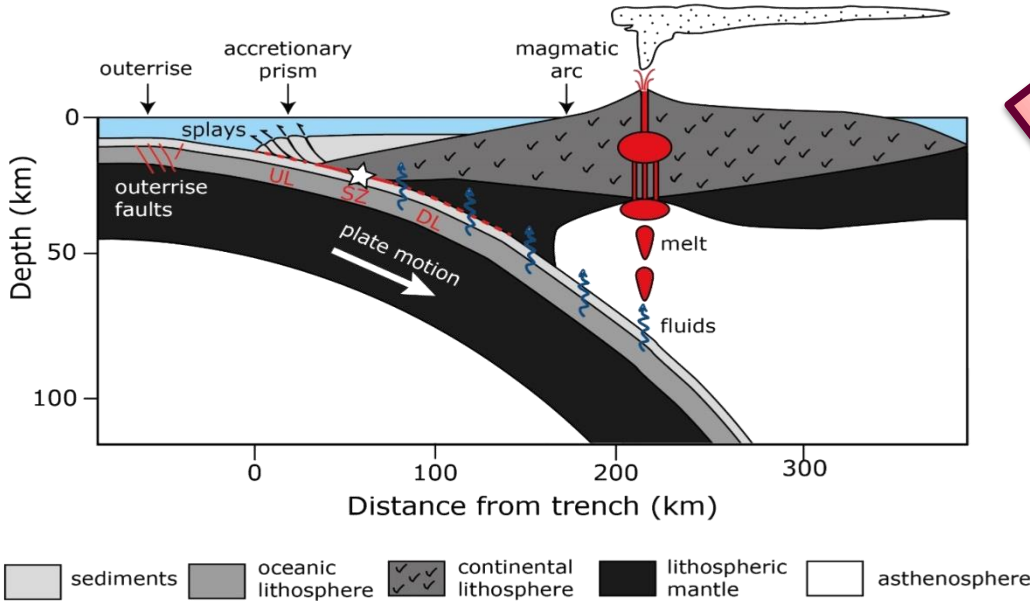
INGREDIENTS ABLE TO TUNE THE ABILITY OF RUPTURE TO PROPAGATE LATERALLY





combined control on MEQs generation?

ROLE OF SEDIMENTS



sediments smoothen the seafloor

sediments are (frictionally) weak

PAGEOPH, Vol. 129, Nos. 1/2 (1989) 0033–4553/89/020263–20$1.50 + 0.20/0

Do Trench Sediments Affect Great Earthquake Occurrence in Subduction Zones?

LARRY J. RUFF[1]

...he proposed chain of cause-and-effect mechanisms that connects trench ...arthquake size: excess trench sediments → subduction of a coherent ...r → smooth seismic strength distribution → large earthquake ...ough this chain of mechanisms is presently untested, future ...xamine these speculations.

(2013) 1–16

Review Article

Invited review paper: T... of subduction zone structural complexity and geometry ... segmentation and seismicity

H. Kopp *
GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhof...

... a et al., 1997). Hence the ... erosional debris) (Bilek and Lay, ... ust earthquakes is later- key physical matter in generating ... erplate surface. This al coupling 'smoothness' of the ...

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, B05409, doi:10.1029/2008JB006089, 2009

Frictional and hydrologic properties of clay-rich fault gouge

Matt J. Ikari,[1] Demian M. Saffer,[1] and Chris Marone[1]

Received 9 September 2008; revised 11 February 2009; accepted 10 March 2009; published 19 May 2009.

shale, and powdered chlorite schist. Friction measurements indicate th... are consistently weak, with steady state coeffici...

Tectonophysics 610 (2014) 1–24

Review Article

Invited review paper: Fault creep caused by subdu... seafloor relief

Kelin Wang [a,*], Susan L. Bilek [b]
[a] Pacific Geoscience Centre, Geological Survey of Canada, Natural Resources Canada, 9860 West Saanich Road, Sidney, British Columbia...
[b] Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, NM 87801...

Although not fully explored in this review, there seems to be a gen... al tendency that very large subduction earthquakes occur in areas of smooth subducting seafloor but are absent or rare in areas of very rugged subducting seafloor. For both earthquake physics and hazard

...OURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, B07401, doi:10.1029/2005JB003916, 2006

Shear stresses on megathrusts: Implications for mountain building behind subduction zones

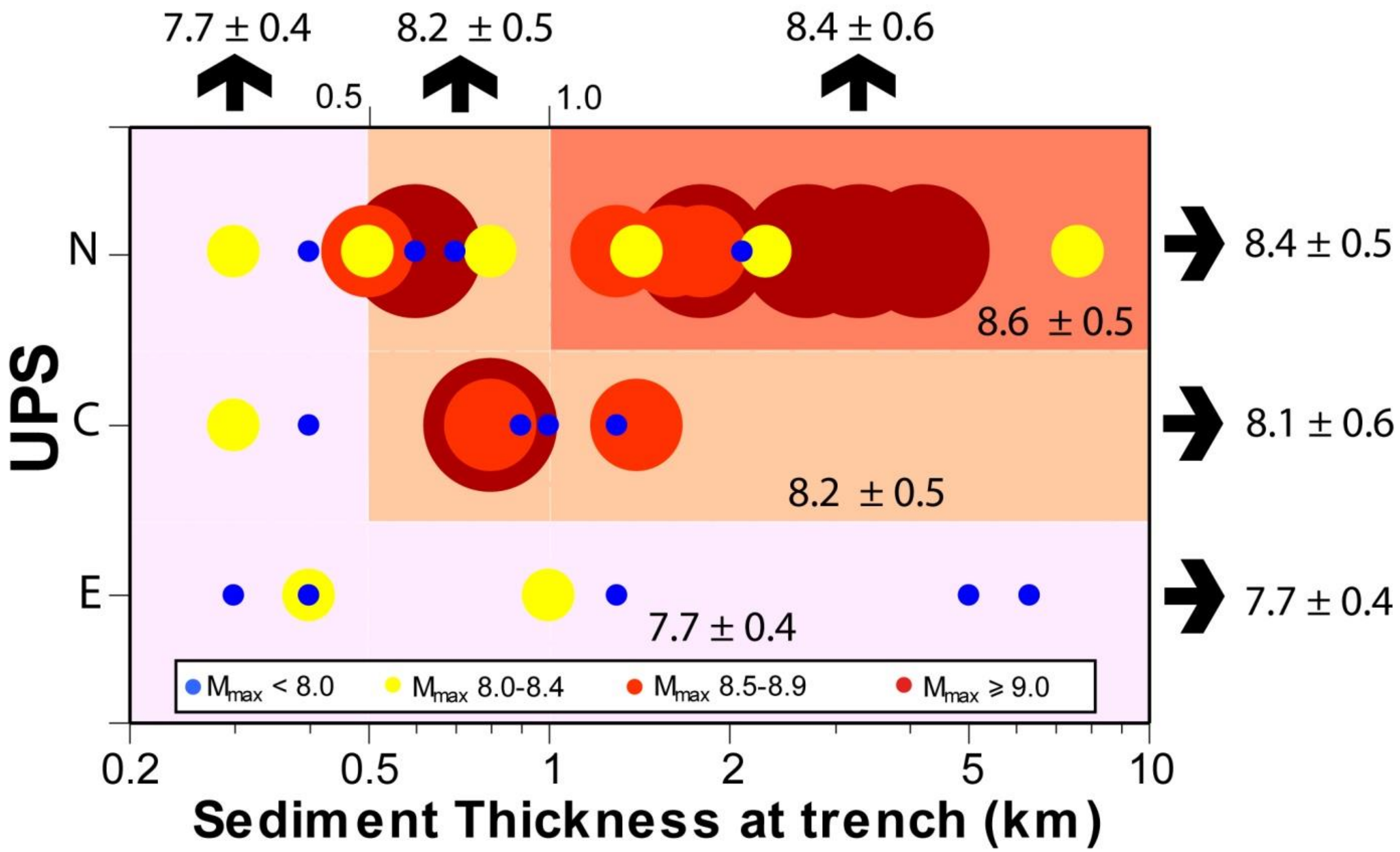
Simon Lamb[1]

Received 30 June 2005; revised 19 January 2006; accepted 28 February 2006; published 4 July 2006.

stresses, particularly in the crust, may be kept low by some sort of lubricant such as abundant water-rich trench fill, which lowers the frictional sliding coefficient or effective viscosity and/or raises pore fluid pressure. The unusual high stress subduction

SEDIMENTS AND UPS vs. Mmax

proxy for the normal stresses applied to the subduction interface

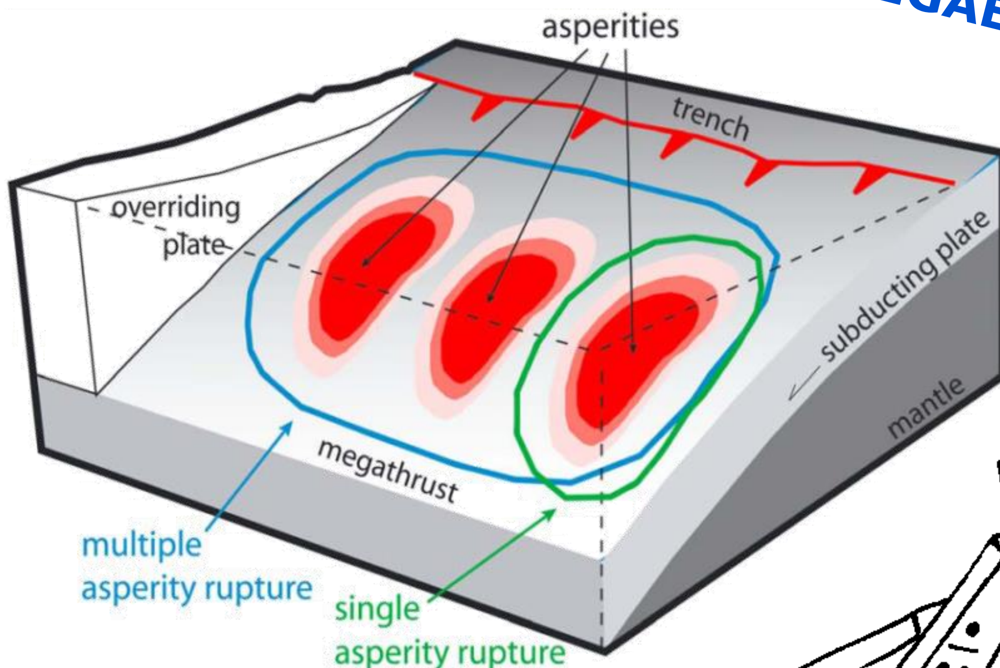


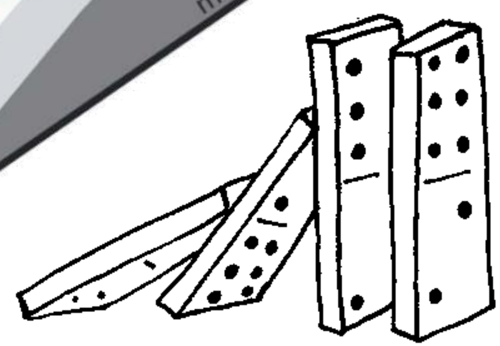
proxy for sediment input into the subduction channel

Heuret et al., 2012

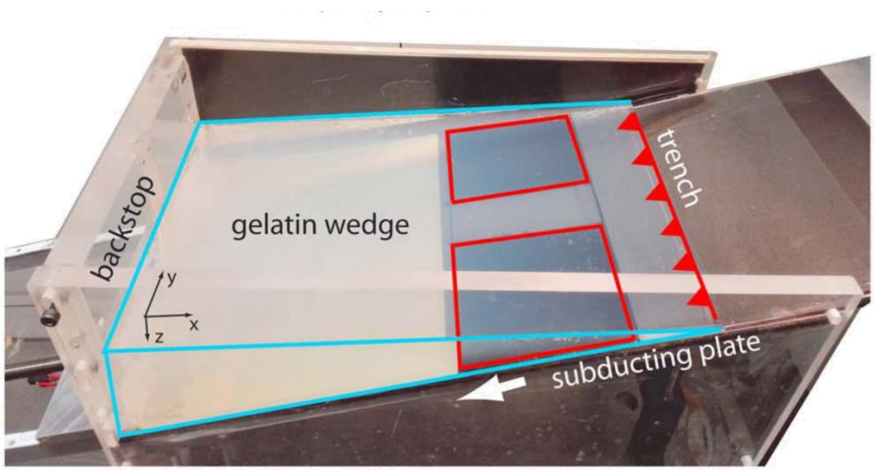
MEGAEARTHQUAKE RUPTURE

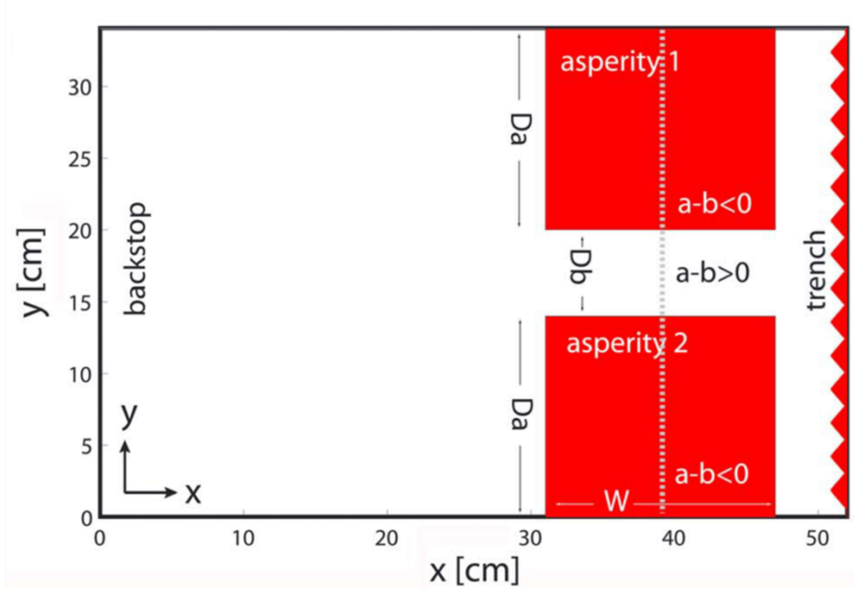
MECHANISM COMMON TO (ALMOST) ALL SUBDUCTION MEGAEARTHQUAKES





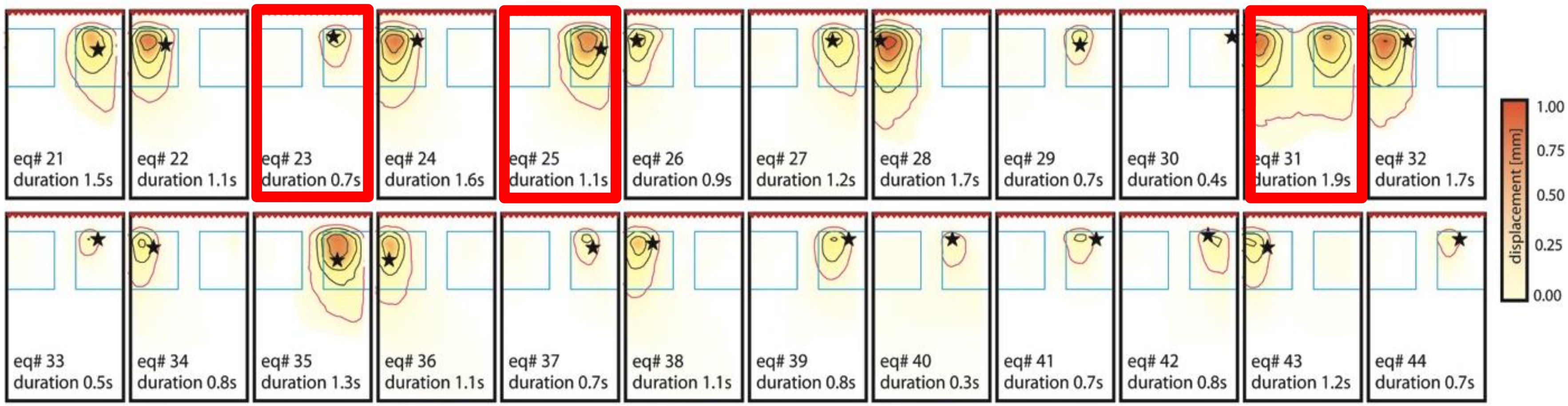
WHAT IS ENHANCING LATERAL RUPTURE PROPAGATION?





Corbi et al., 2017

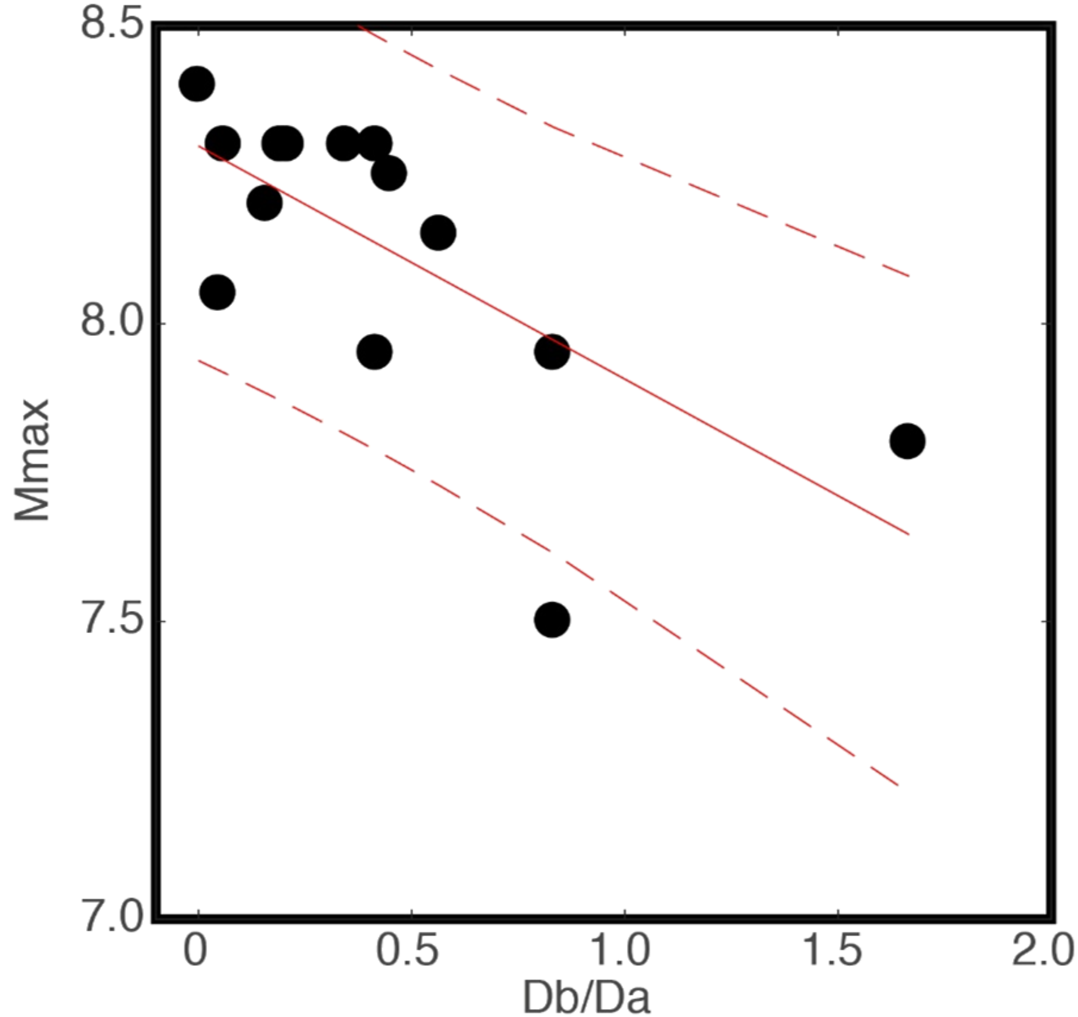
WHAT IS ENHANCING LATERAL RUPTURE PROPAGATION?



Mapping coupling is not sufficient to anticipate the rupture dynamics: need to reconstruct the segment history (and the frictional parameters).

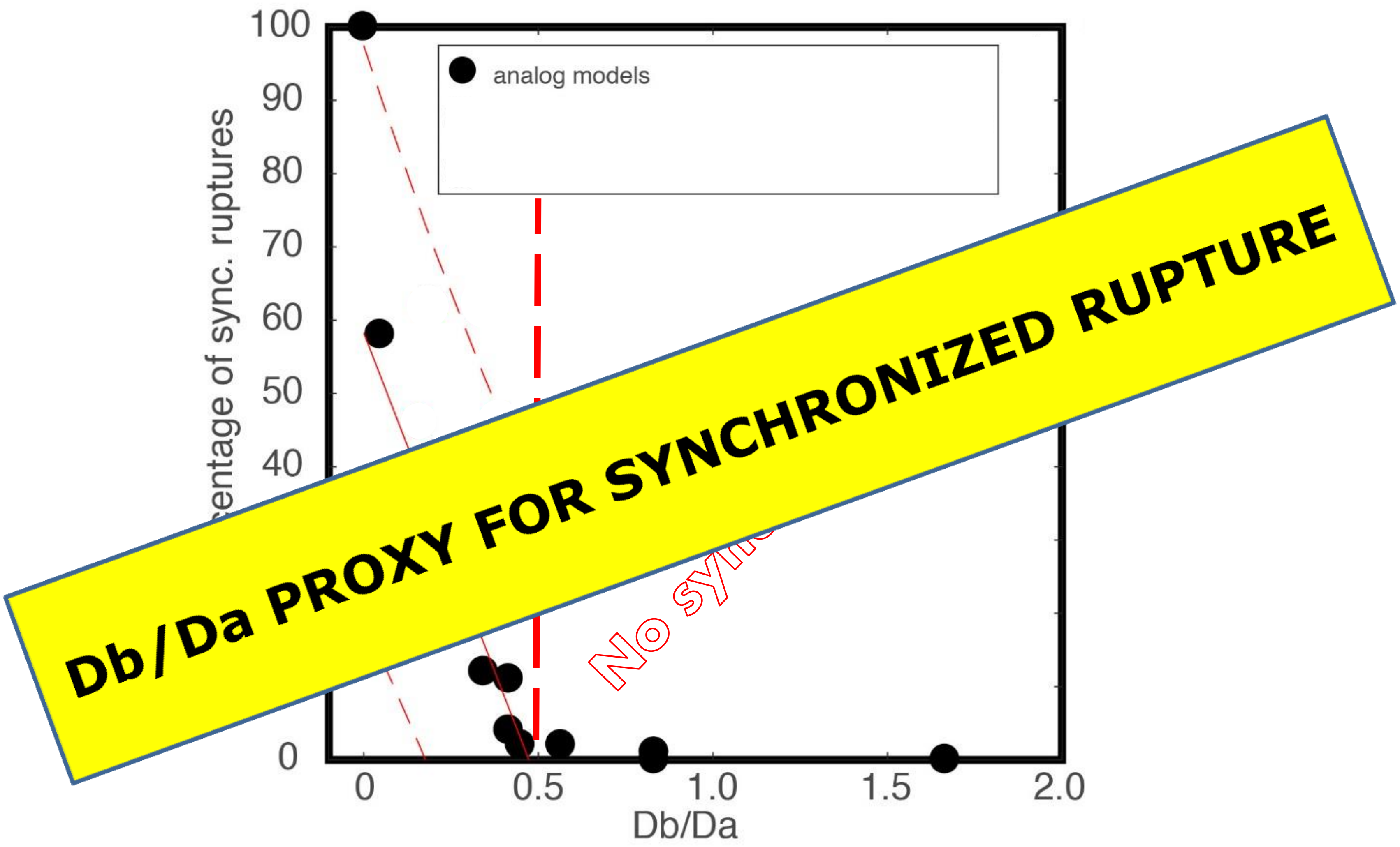
Corbi et al., 2017

WHAT IS ENHANCING LATERAL RUPTURE PROPAGATION?

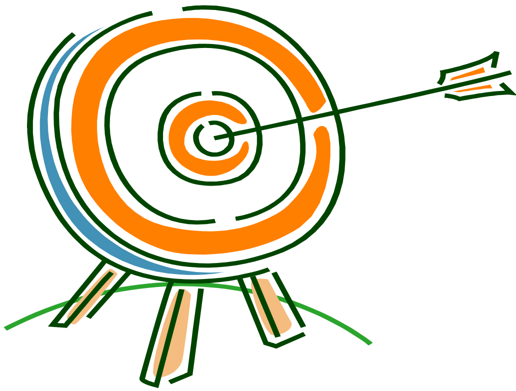


Corbi et al., 2017

WHAT IS ENHANCING LATERAL RUPTURE PROPAGATION?



- ☞ **Scientific problem**
- ☞ **Tools**: - database on current subduction zones
  - analogue models
- ☞ **Selection of results**
- ☞ **Future directions**



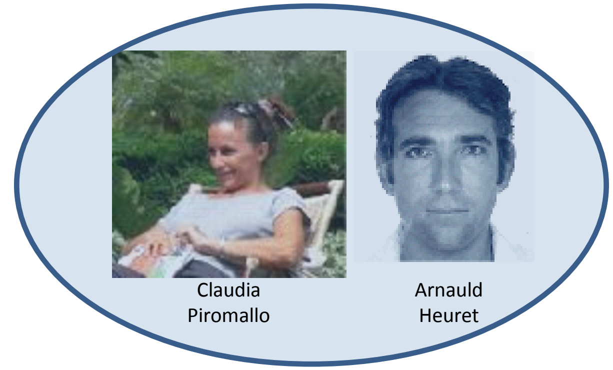
GOAL #5
(…a dream?)

WHERE INTERPLATE MEGA-EARTHQUAKES ARE MORE LIKELY TO OCCUR


UPDATE

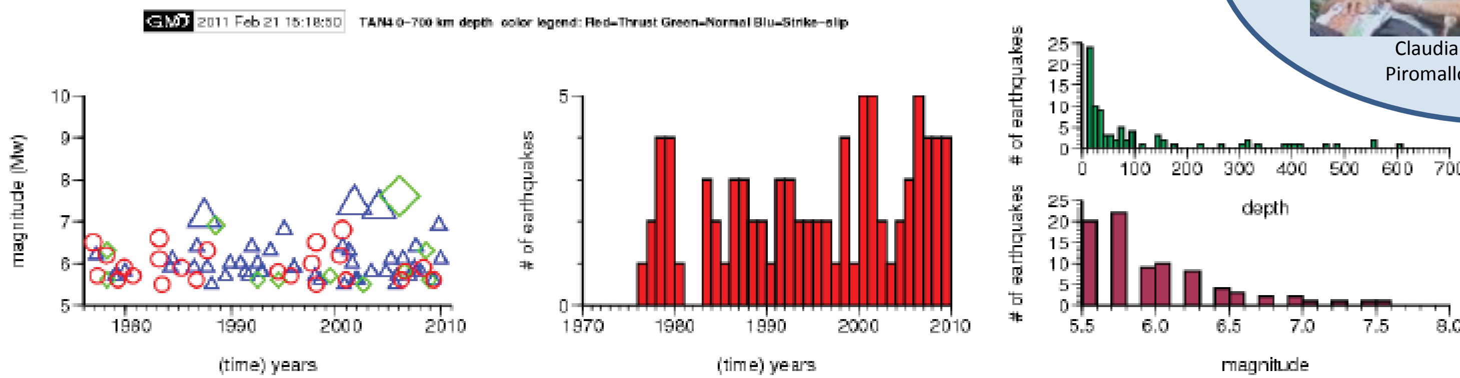

improve

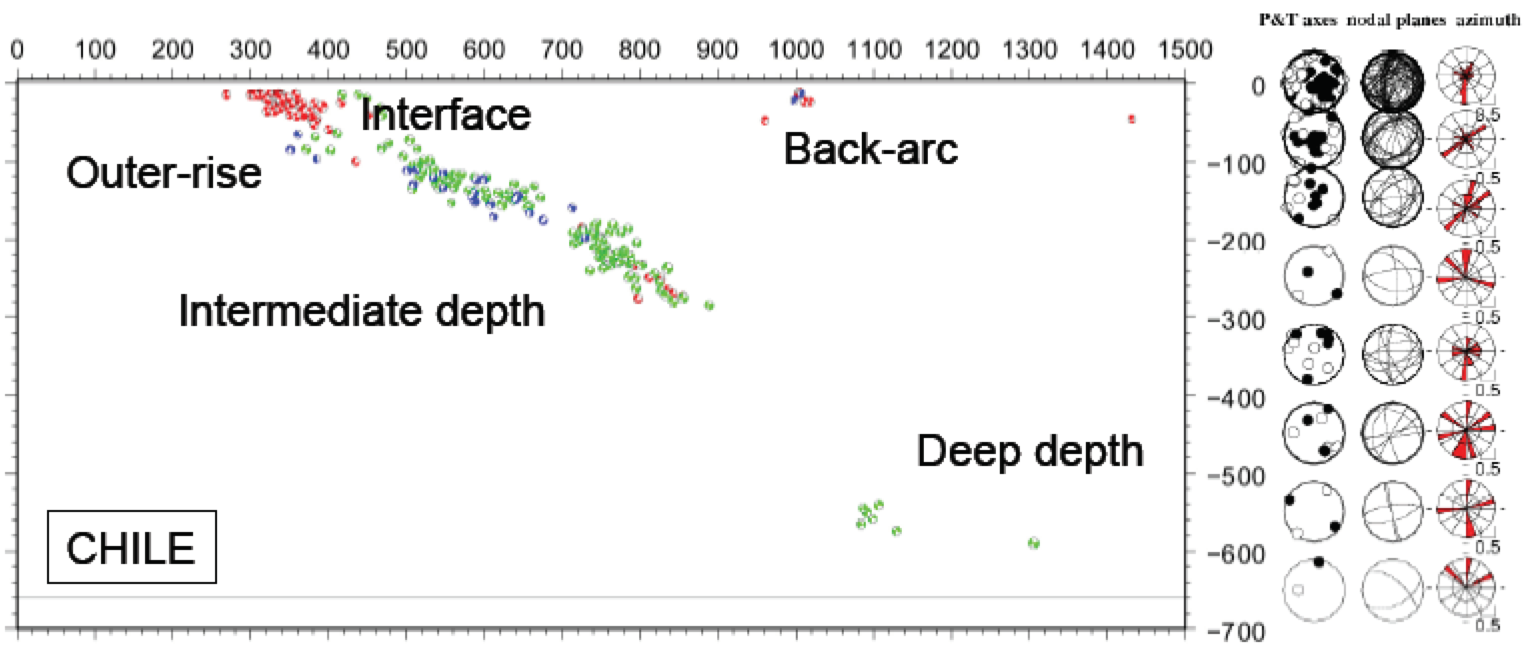
NEW GLOBAL DATA ON CONVERGENT MARGINS



Claudia Piromallo

Arnauld Heuret

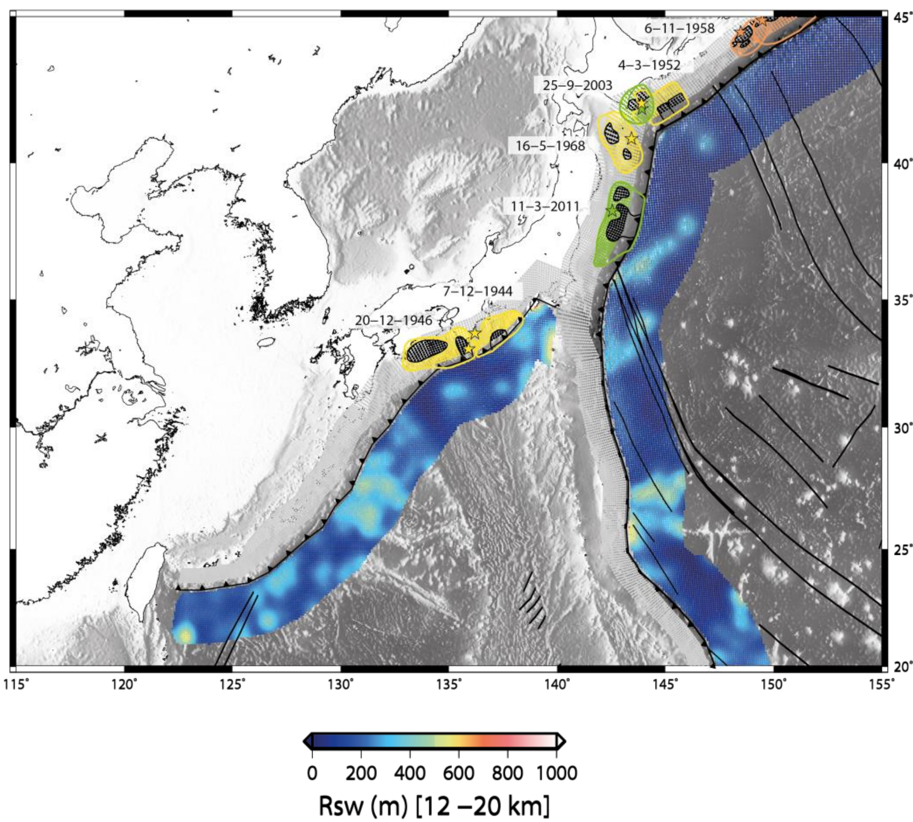


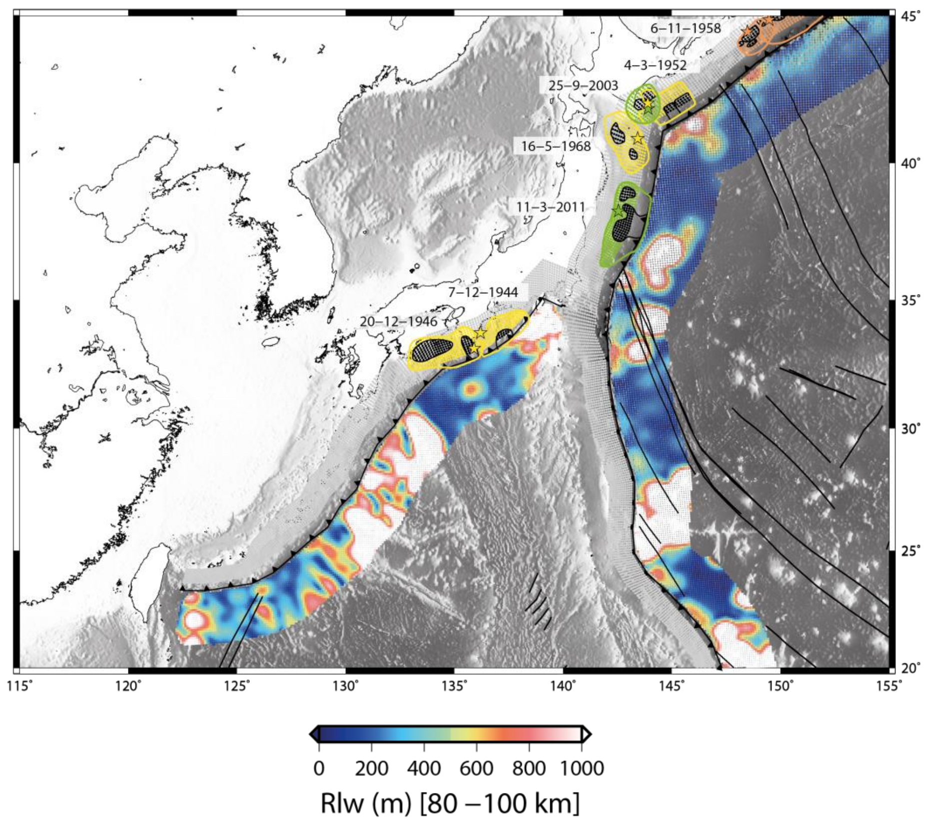


NEW GLOBAL DATA ON CONVERGENT MARGINS

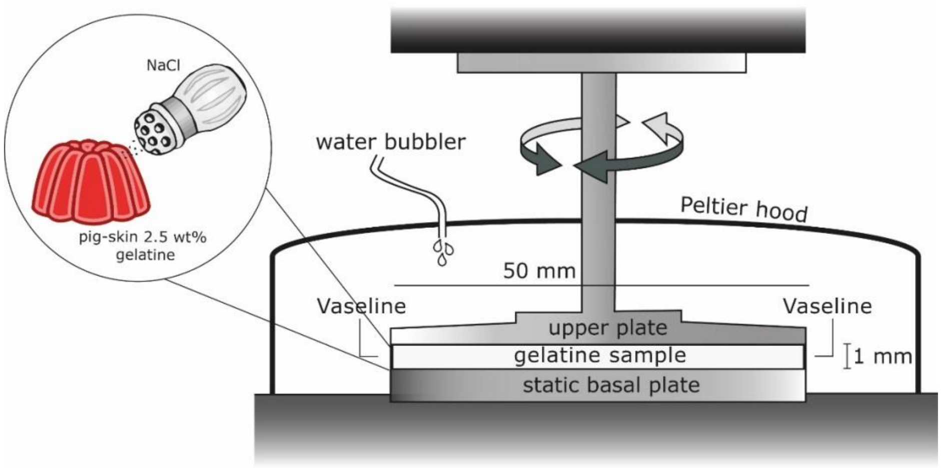
Serge
Lallemand

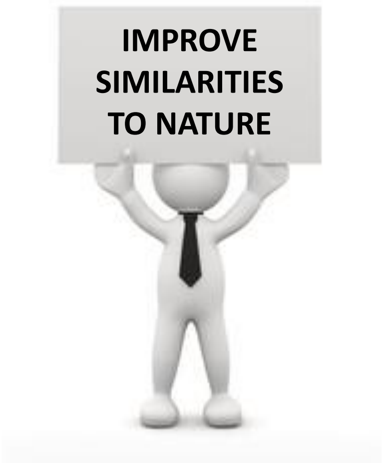
Elenora
Van Rjsingen

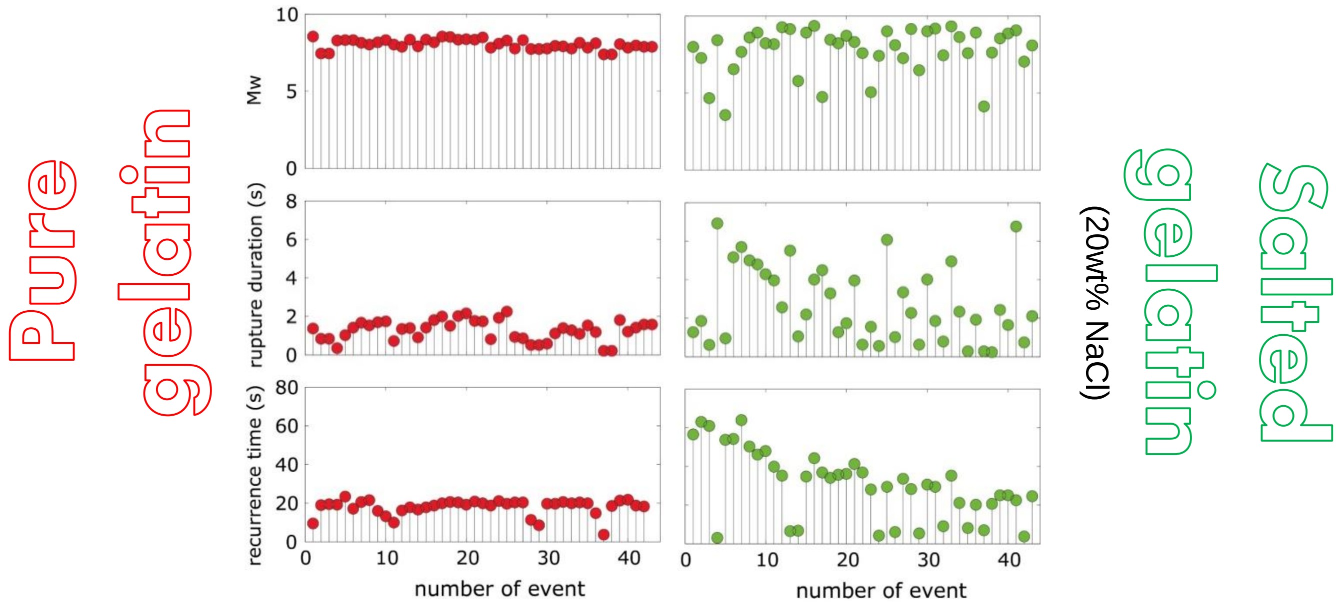




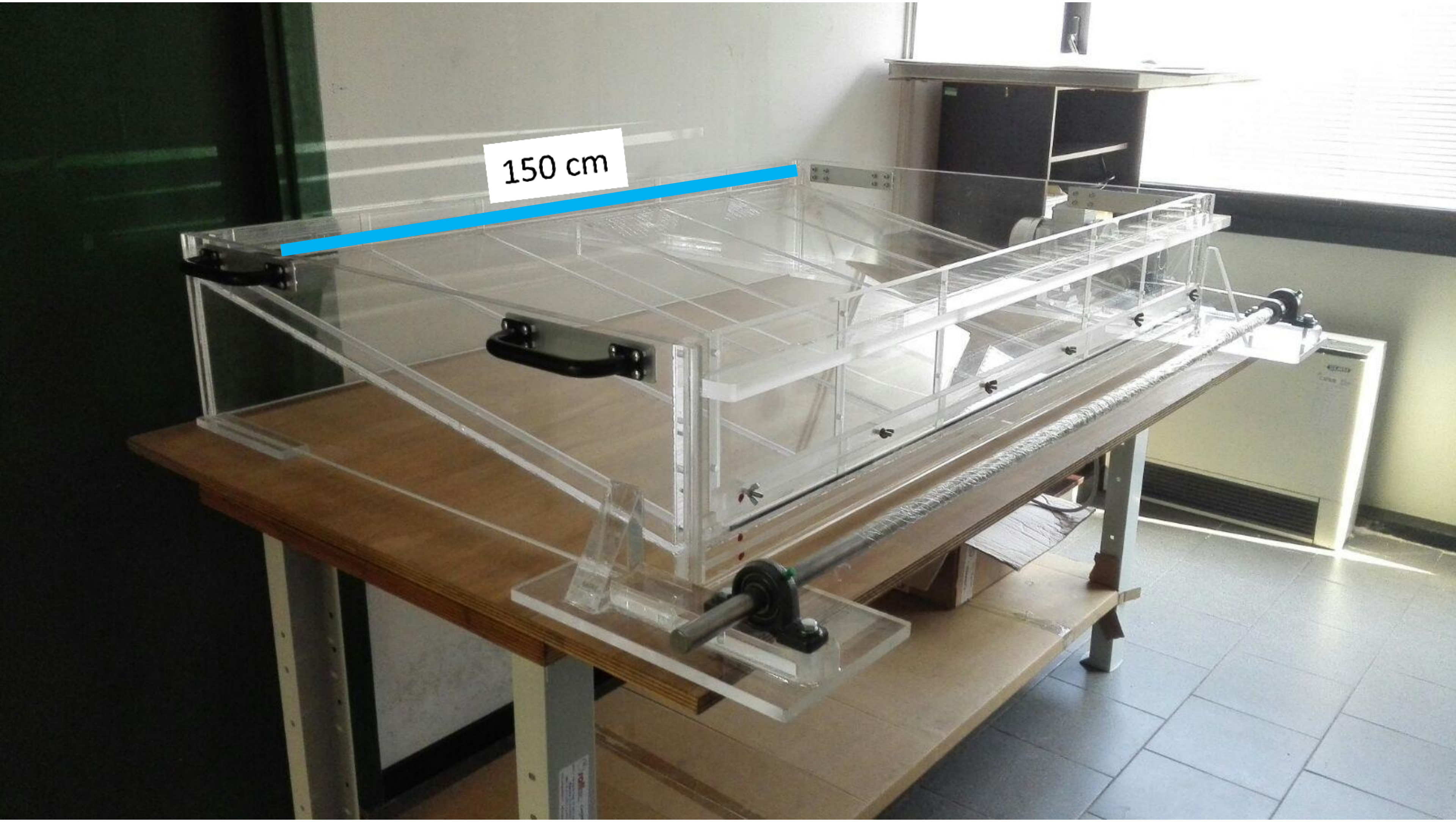
FINDING FOR NEW ANALOGUE MATERIALS



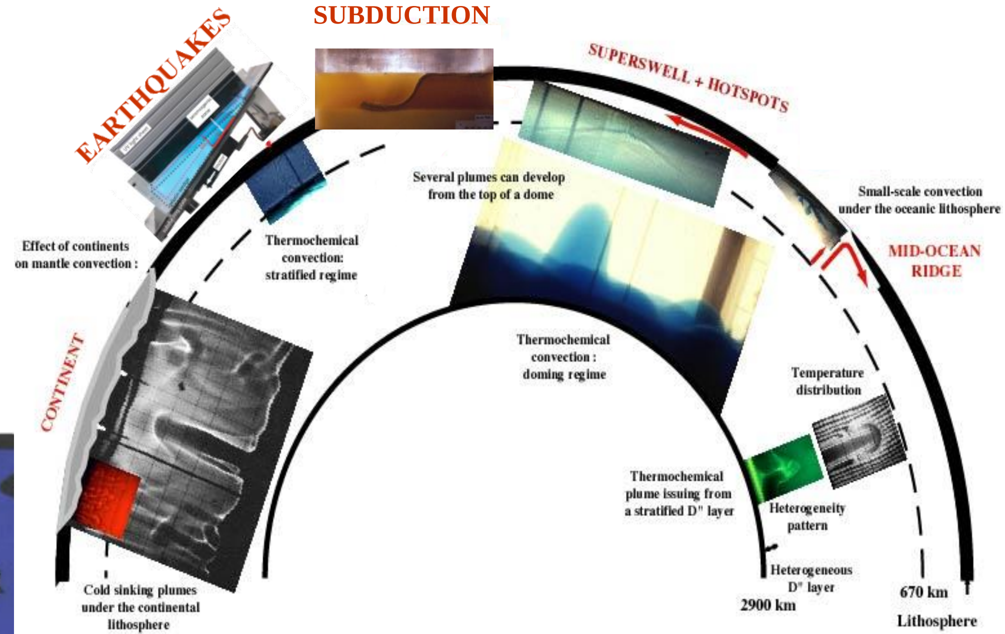




MOVE TO A LARGER APPARATUS…




WORK IN
PROGRESS



modified from Davaille, 2003

3-D

dynamically self-consistent

slab-mantle fully coupled

short- and long-scales

The End