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Seismicity and Geodynamics in the Vanuatu Subduction Zone

In collaboration with :
- Wayne C. Crawford, IPGP
- Valérie Ballu, LIENSs
- Marc Régnier, Géoazur, IRD
- Bernard Pelletier, IRD
- Esline Garaebiti, Geohazards

Strasbourg, Janvier 2016

Outline

1. Introduction
   - General context of the Vanuatu subduction zone
   - Main questions asked
   - Description of the GPS & Seismological networks

2. Seismological analysis
   - Automatic picking procedures
   - 1D Velocity model
   - Earthquake location and error estimates
   - Relocation of earthquakes and focal mechanisms
   - 3D determination of seismogenic interfaces

3. Interpretation
   - Seismological study
   - 2D mechanical model

4. Conclusions & Perspectives

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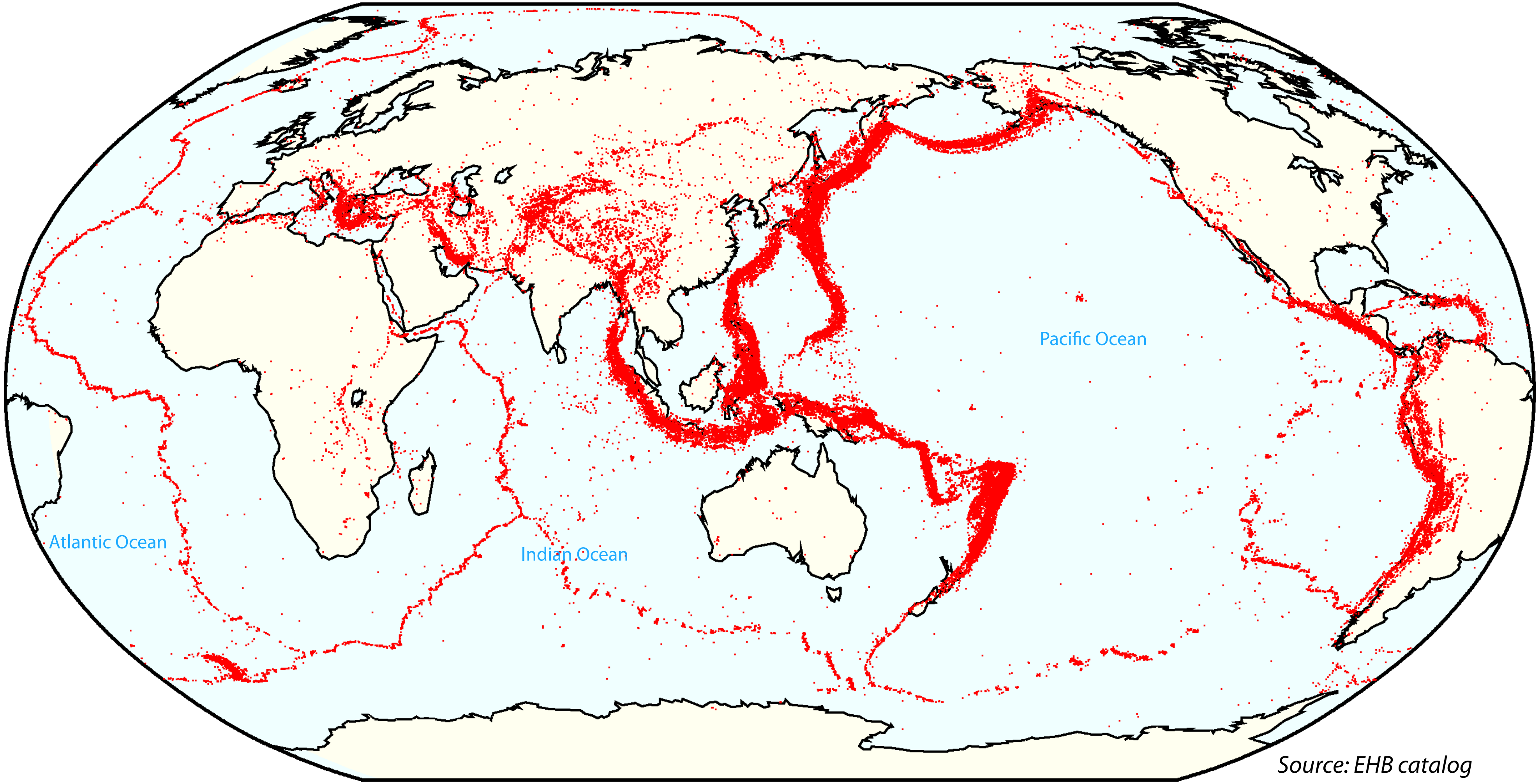
General context

Worldwide seismicity since 1960 (Mw > 5.5)



Source: EHB catalog

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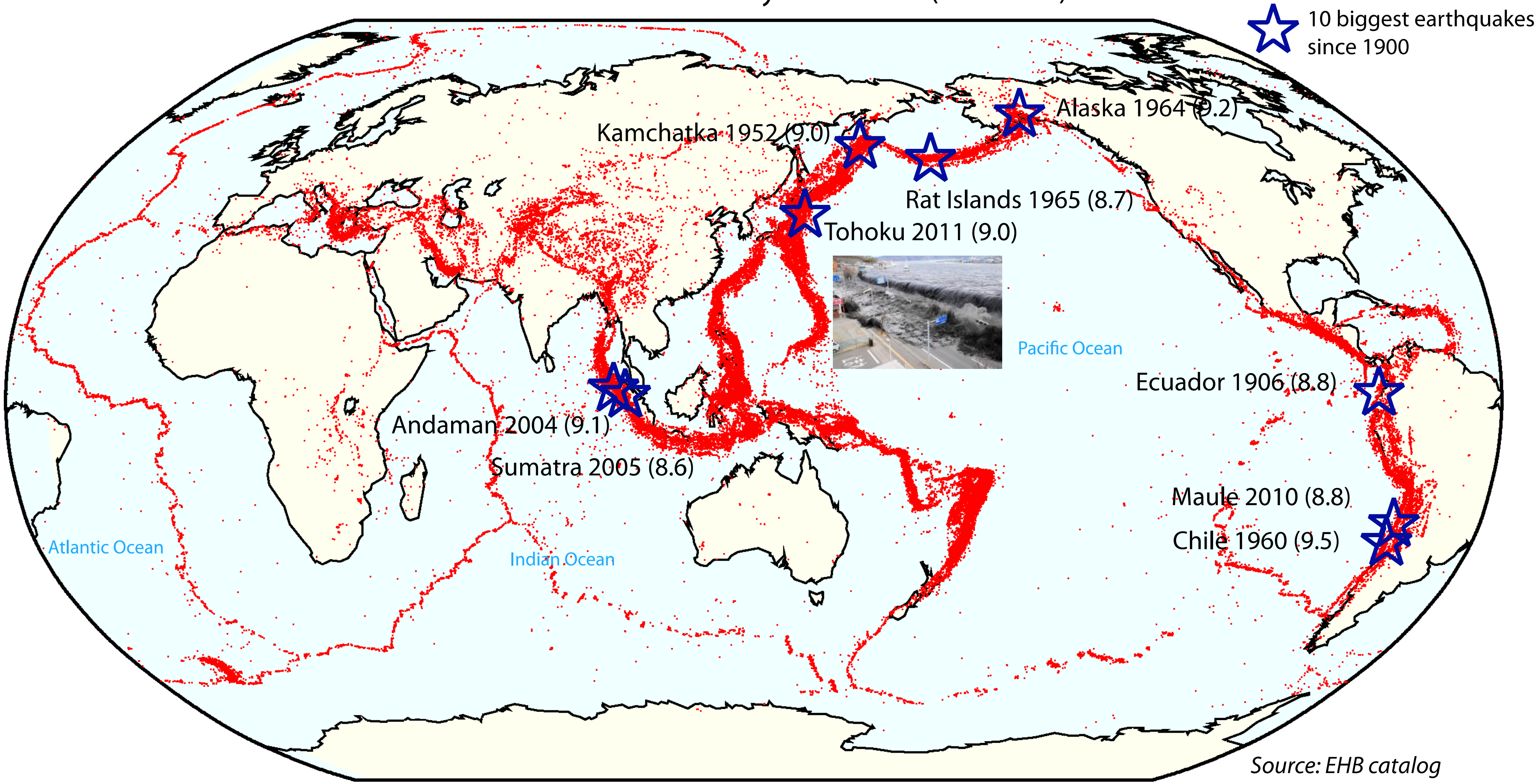

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90% of the world's seismic energy is released by subduction zone earthquakes

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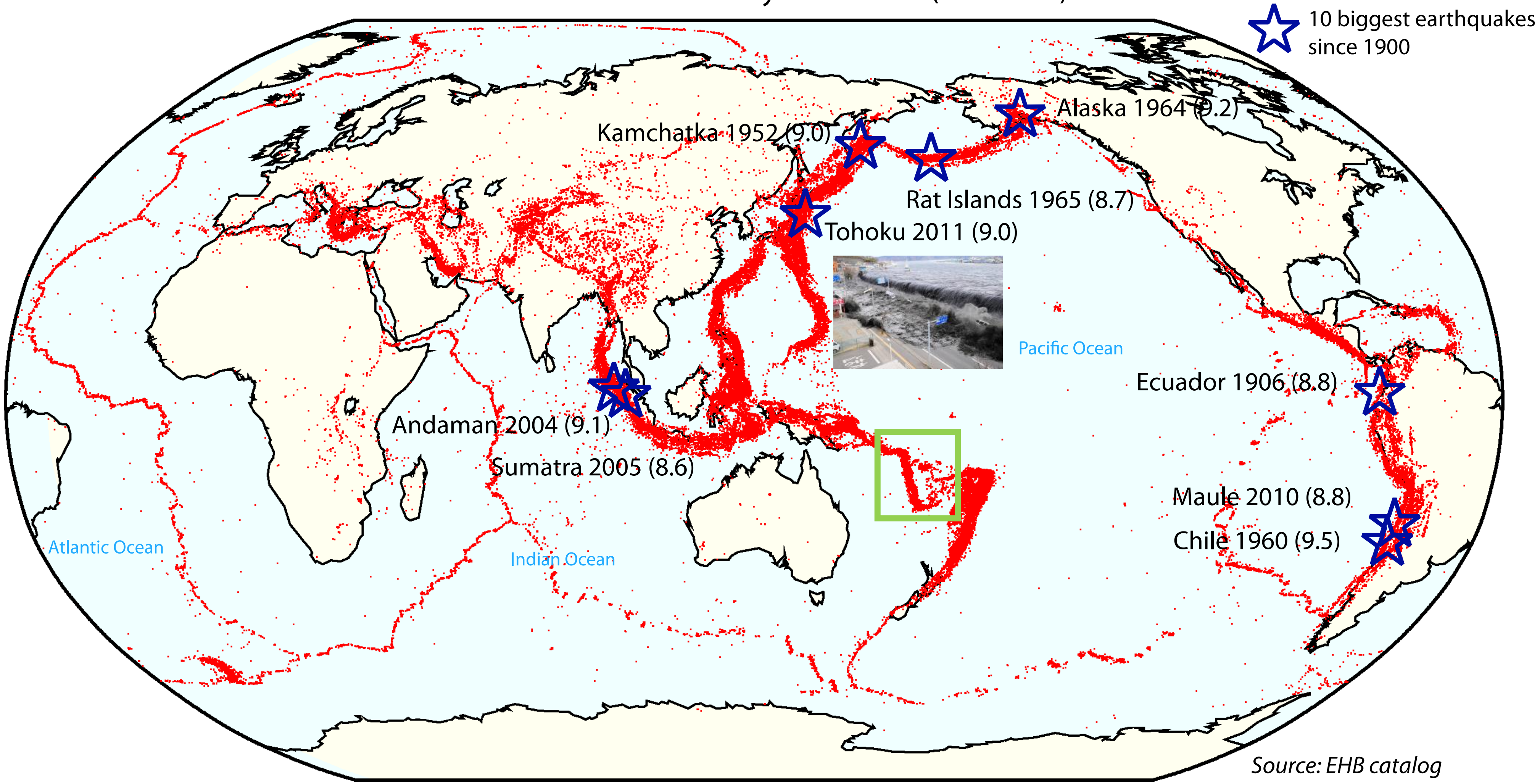

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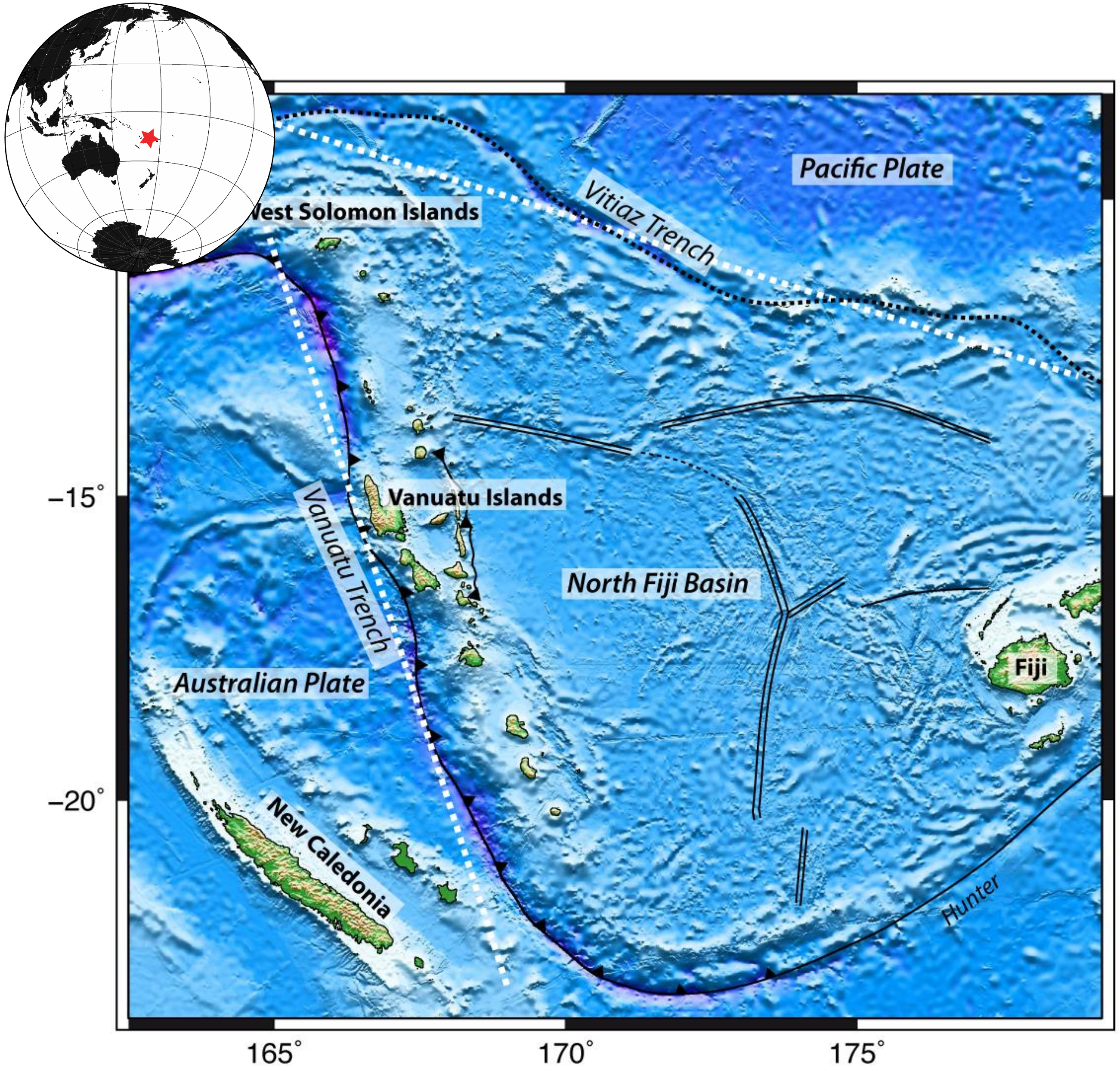
The Vanuatu subduction zone



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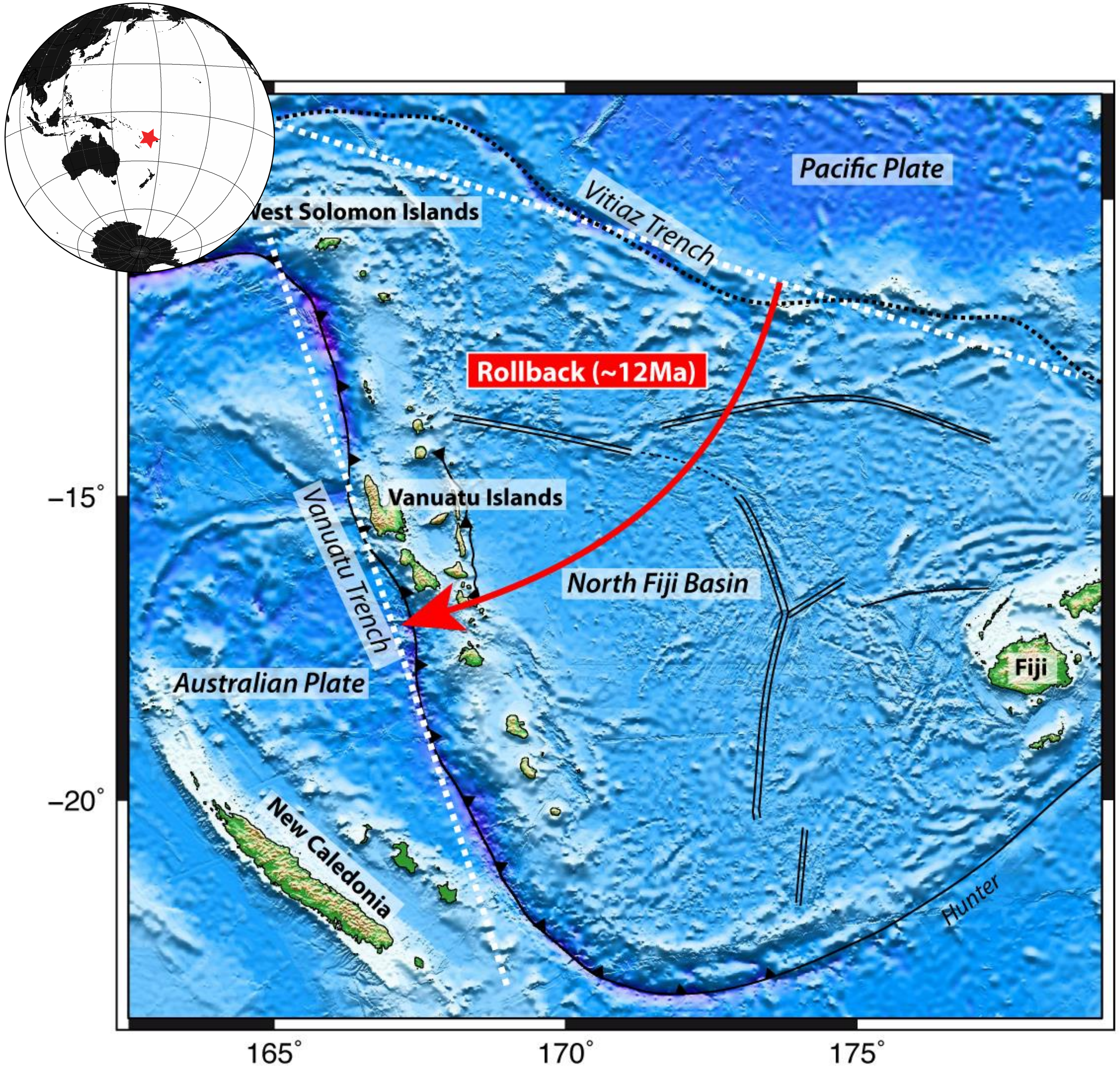
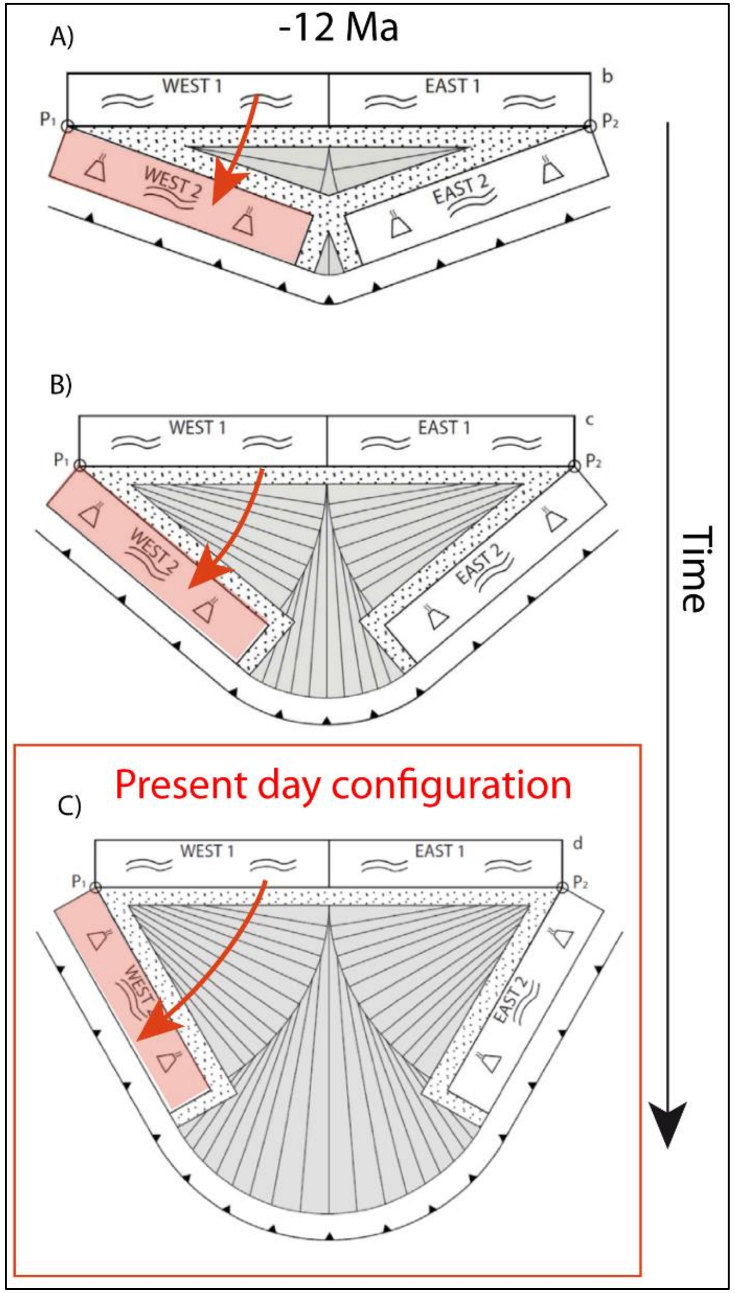
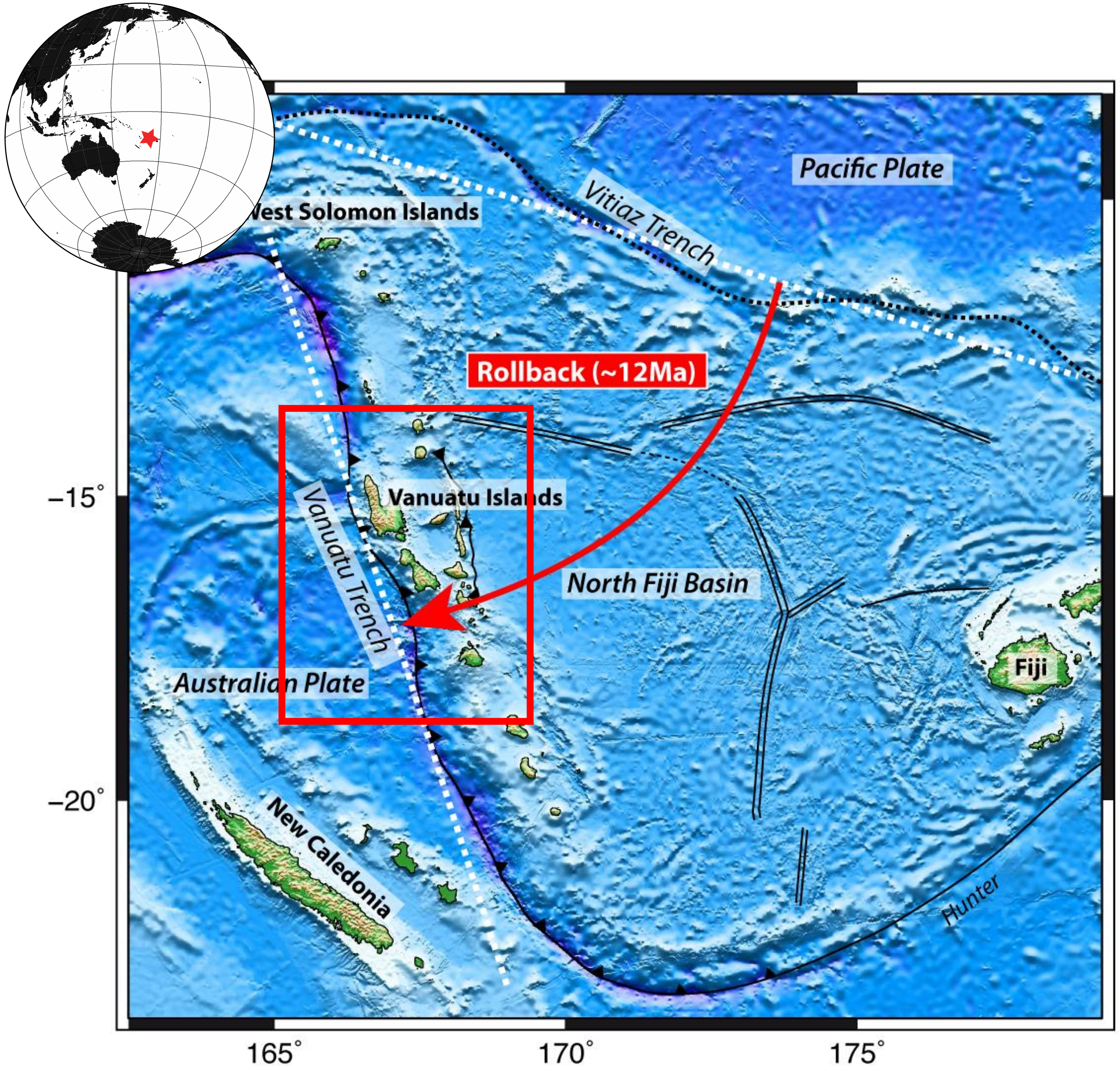
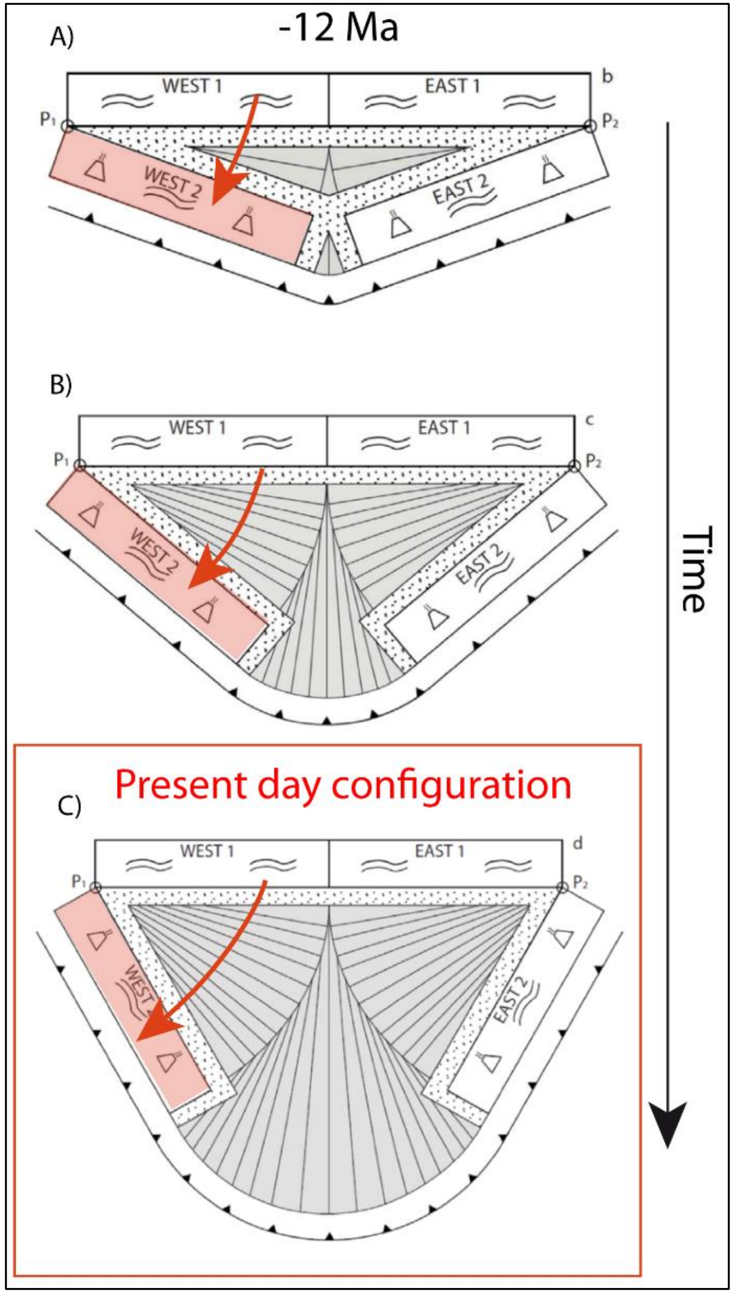




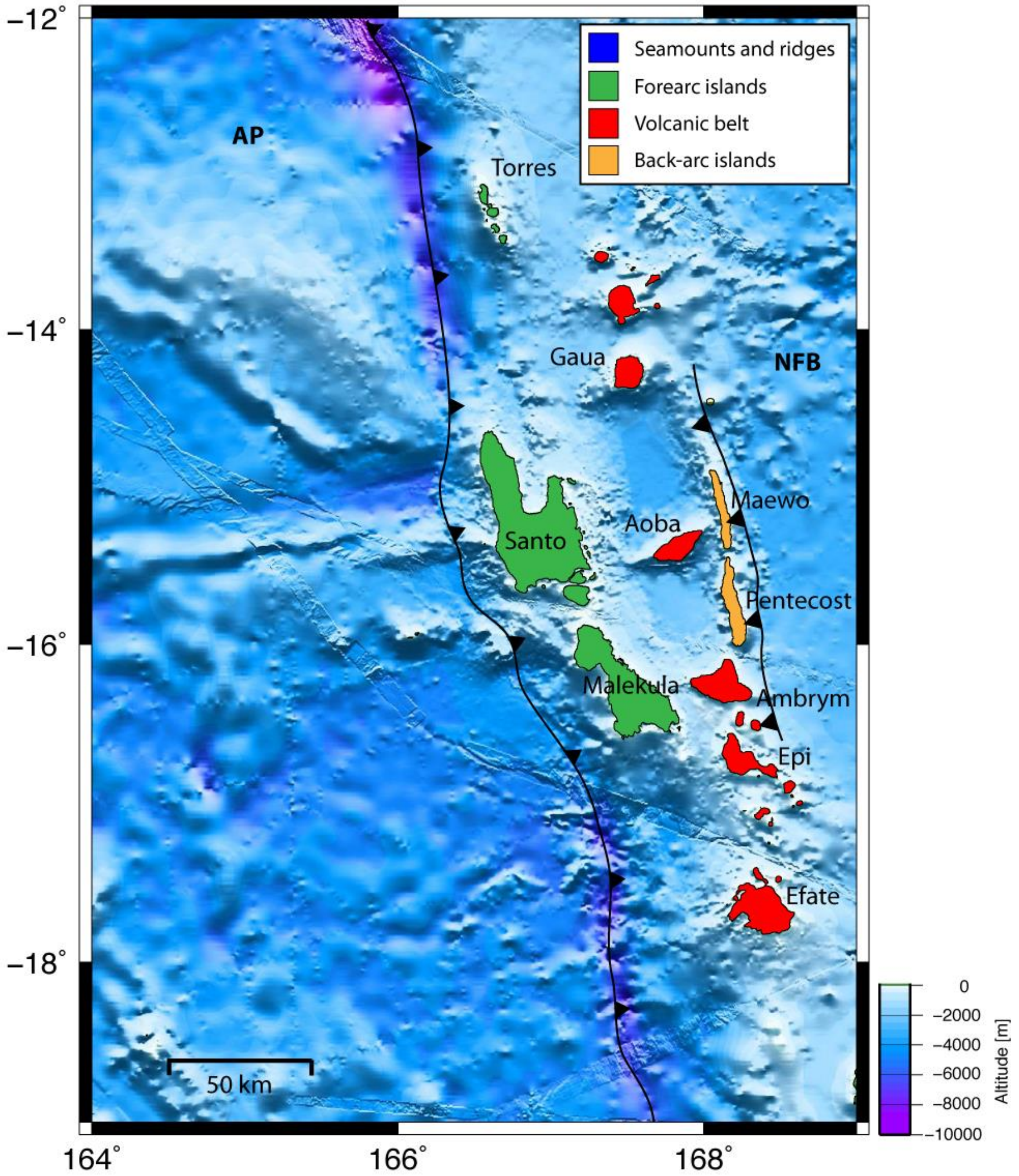
Martin 2013; Schellart et al., 2006; Pelletier et al., 1993; Auzende et al.,1995

The Vanuatu subduction zone





Structure of the central part of the arc



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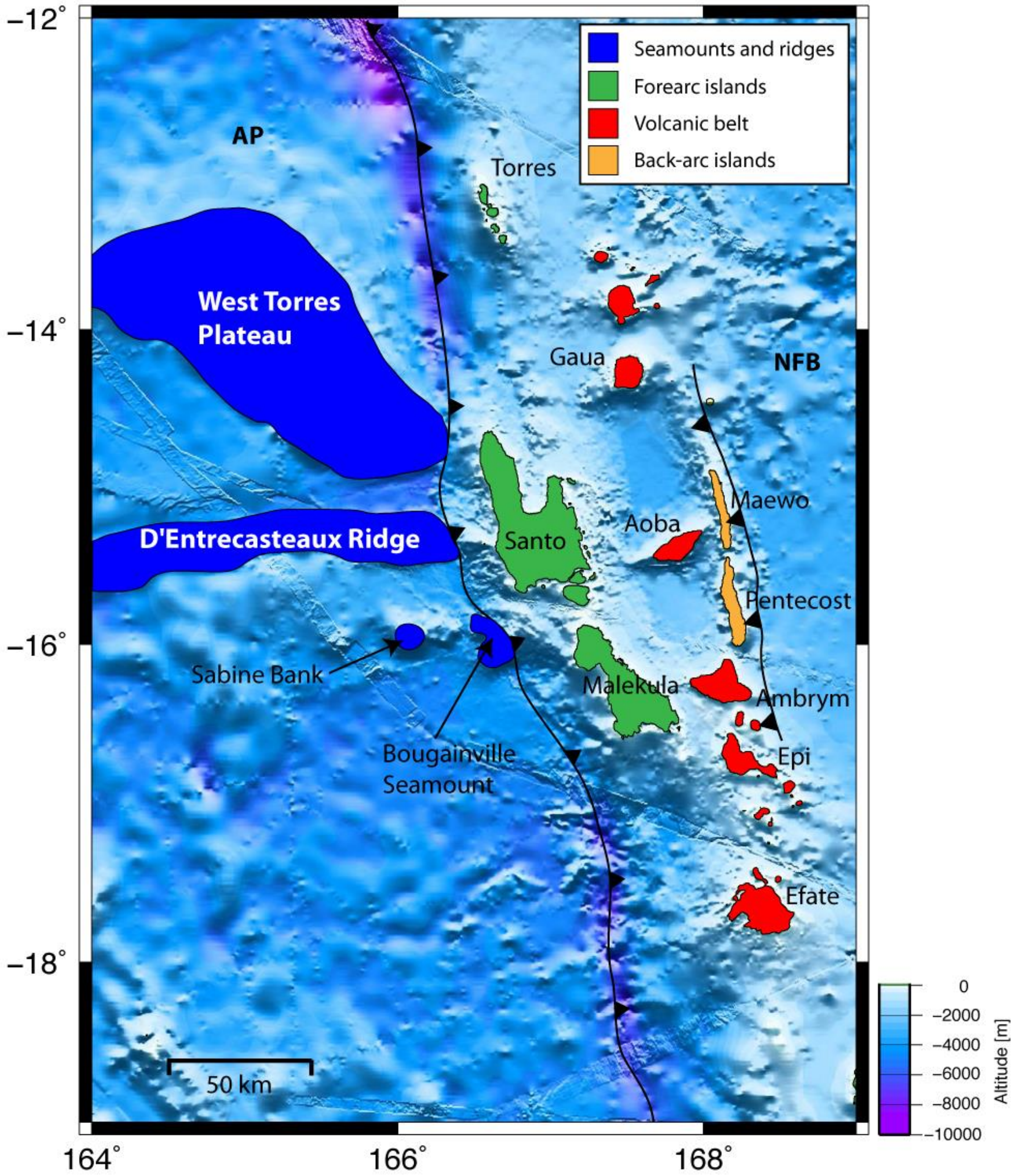
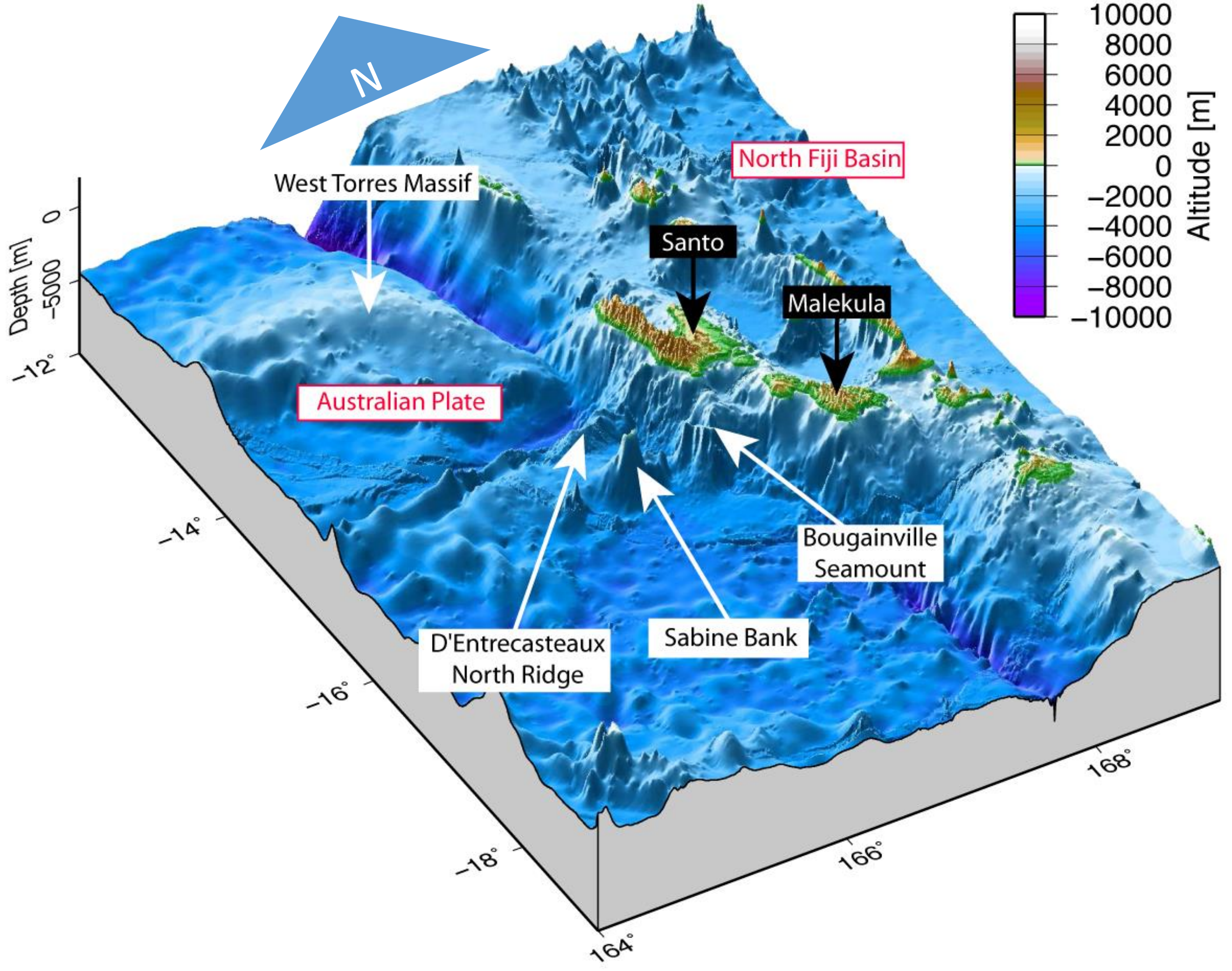


The famous subduction cannibalization !



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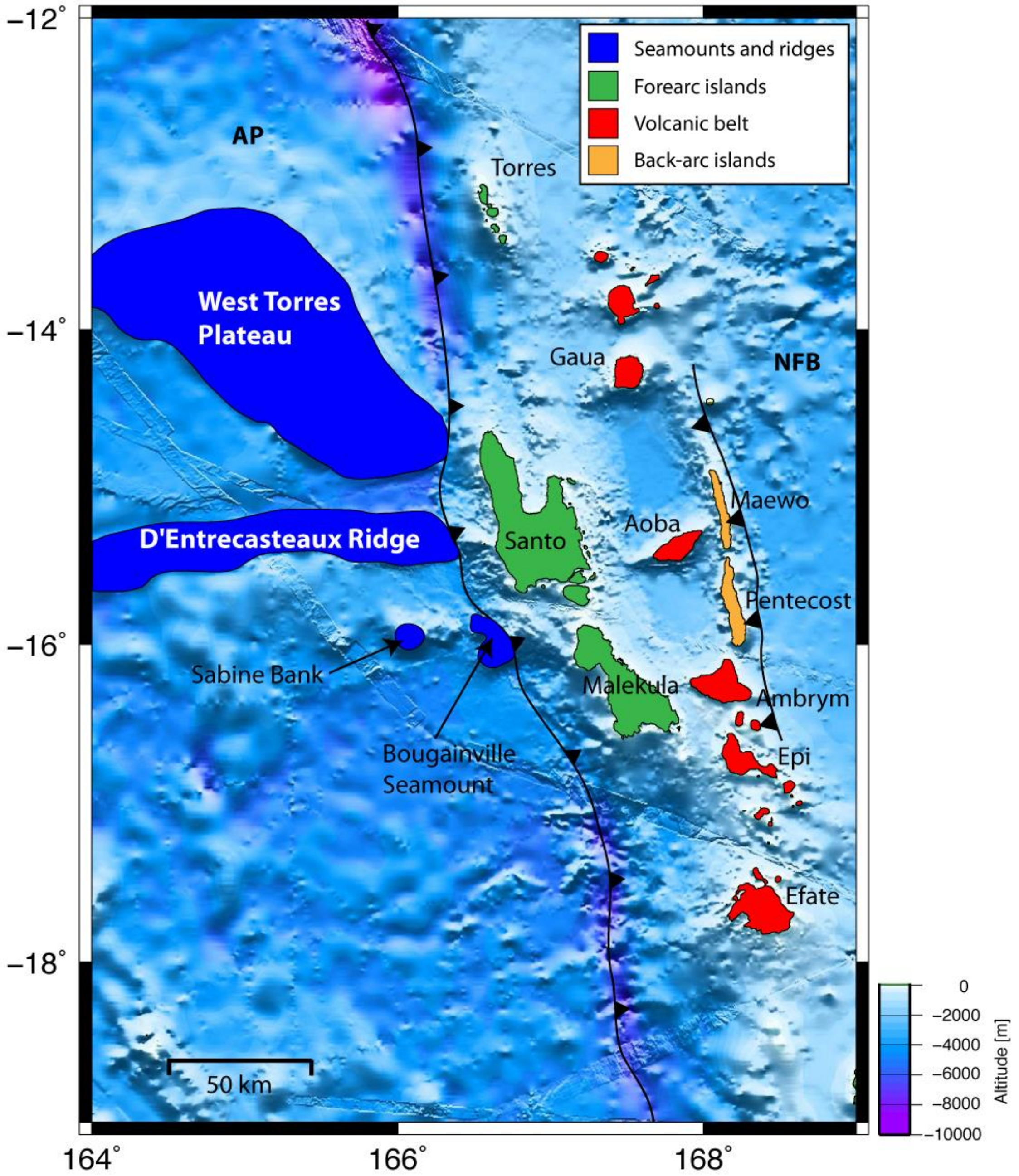
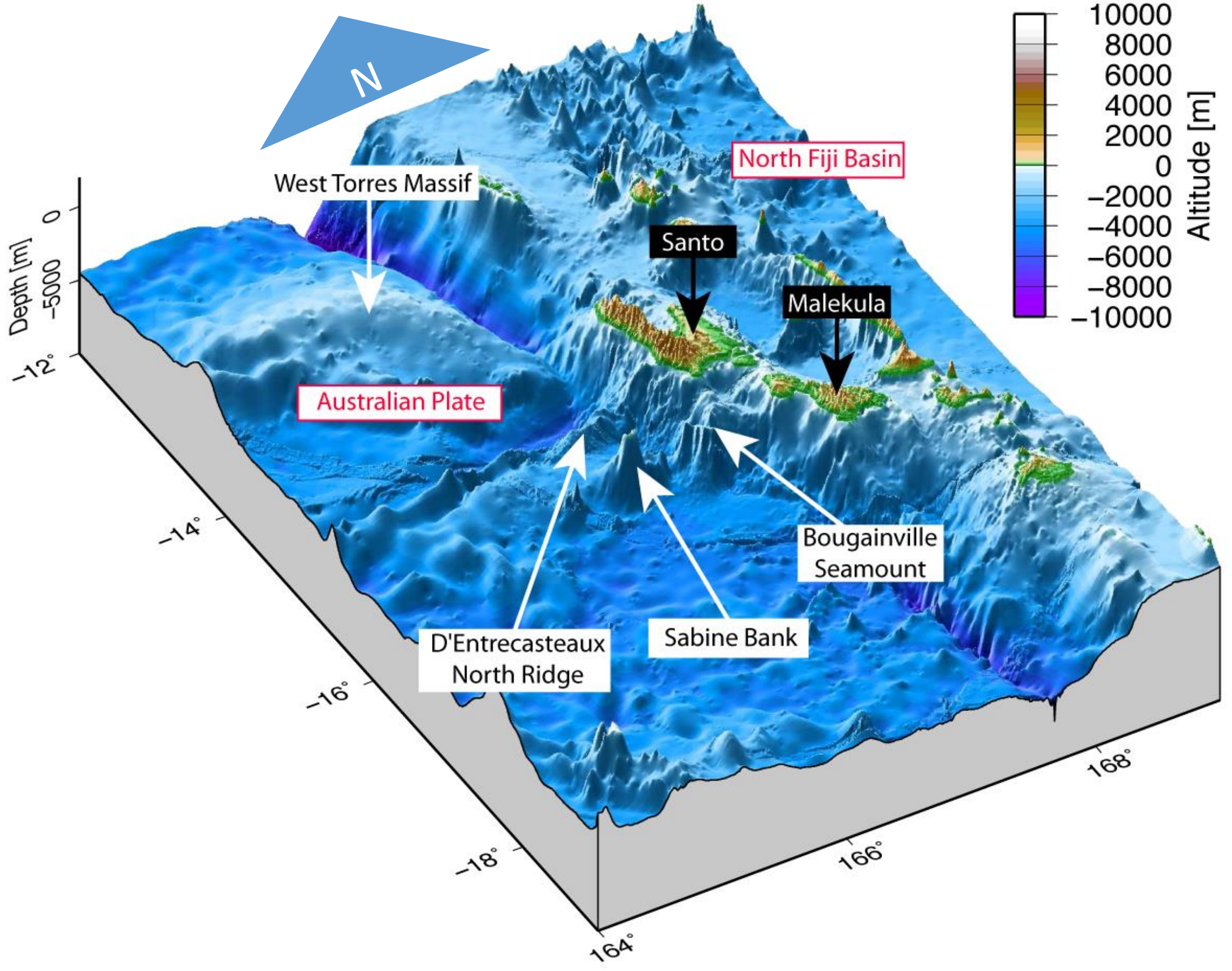
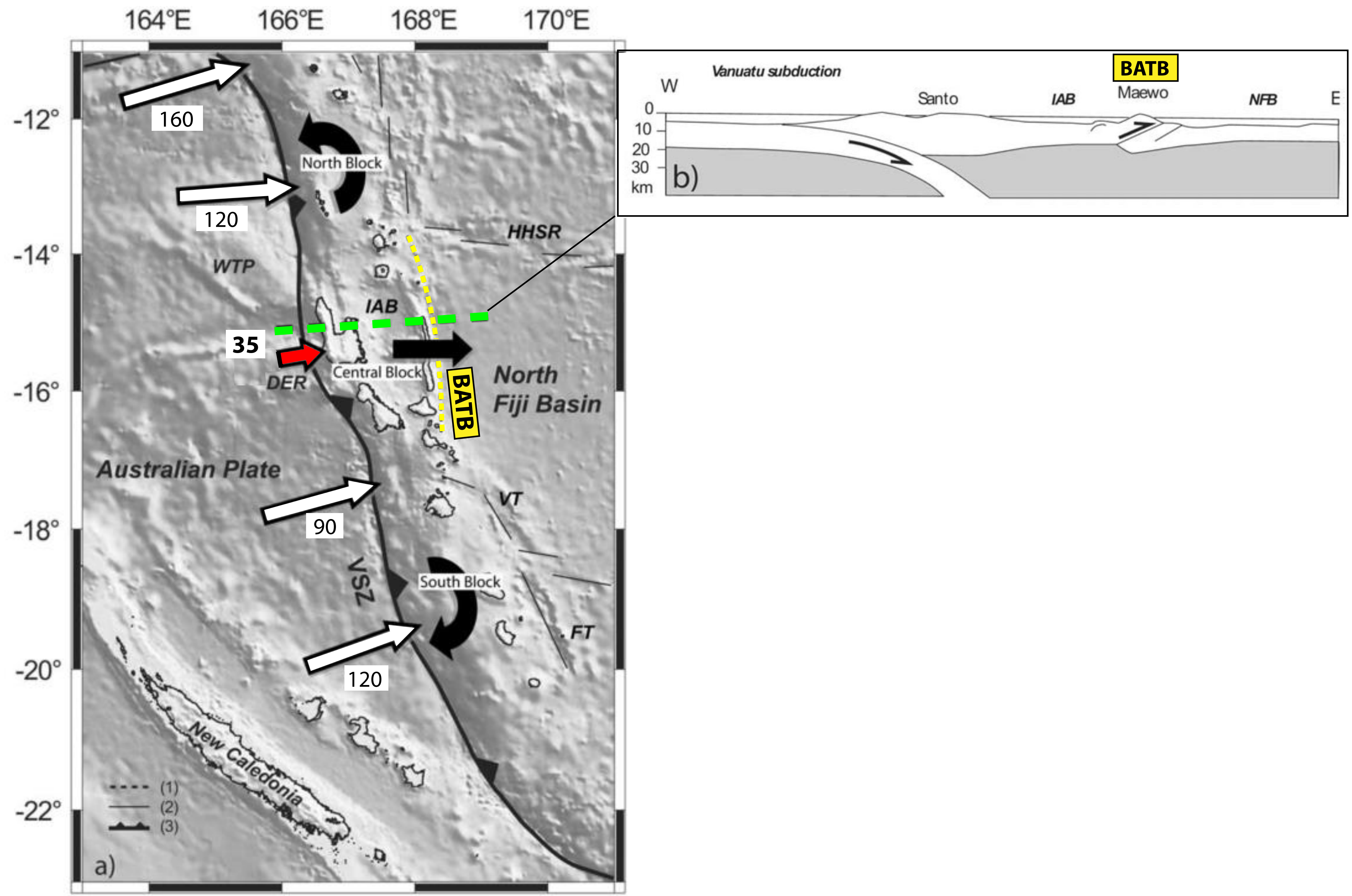


What is the influence of the subducted bathymetric highs on geodynamics and seismicity ?



About the long-term geodynamics



Calmant et al., 2003;
Bergeot et al., 2009

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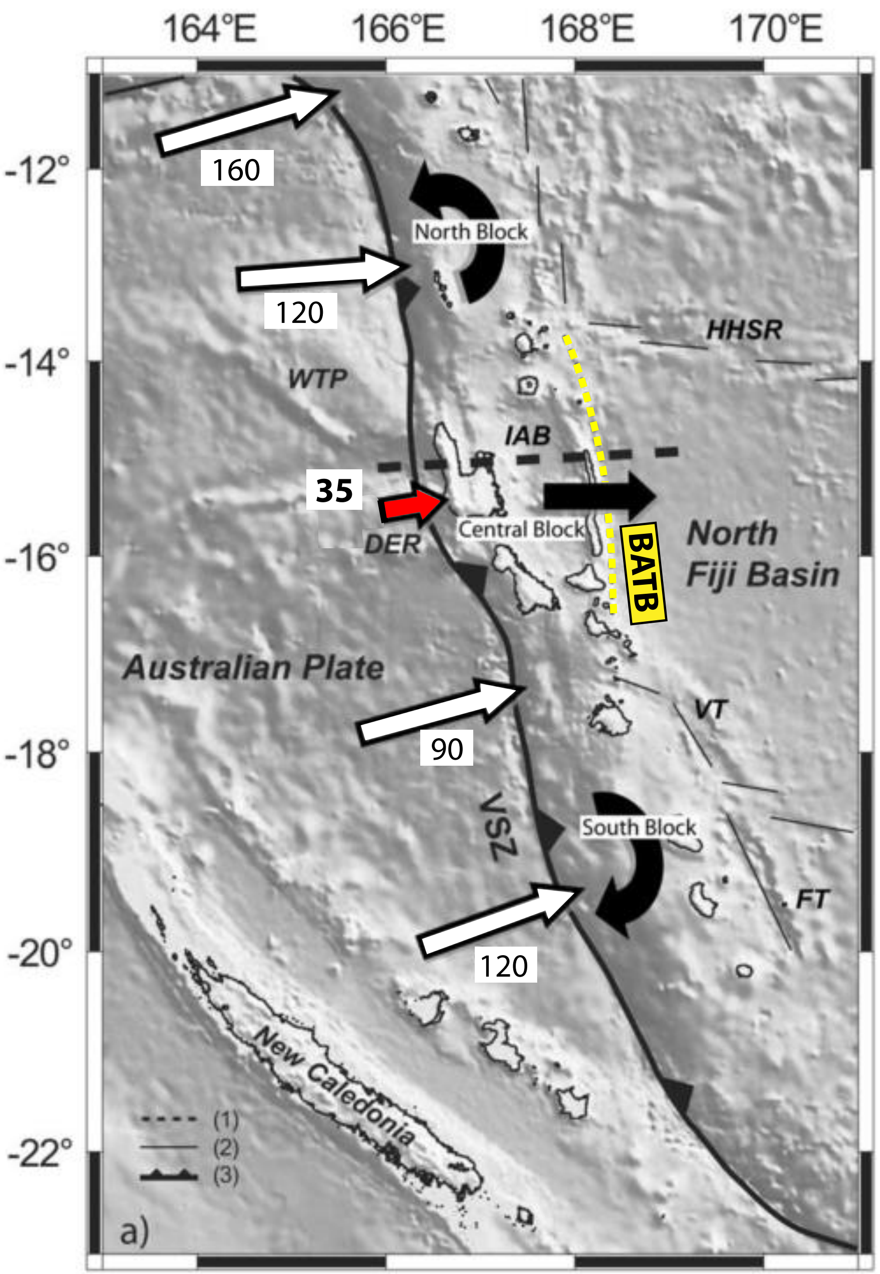
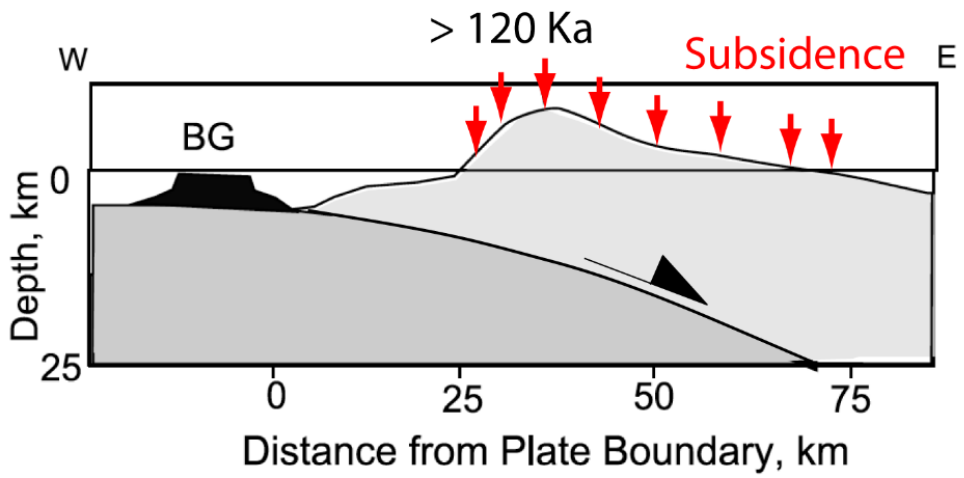
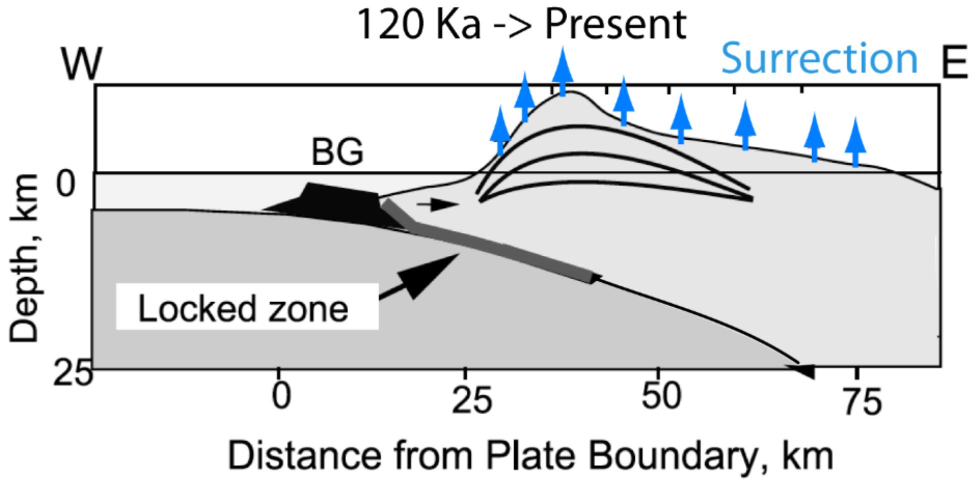
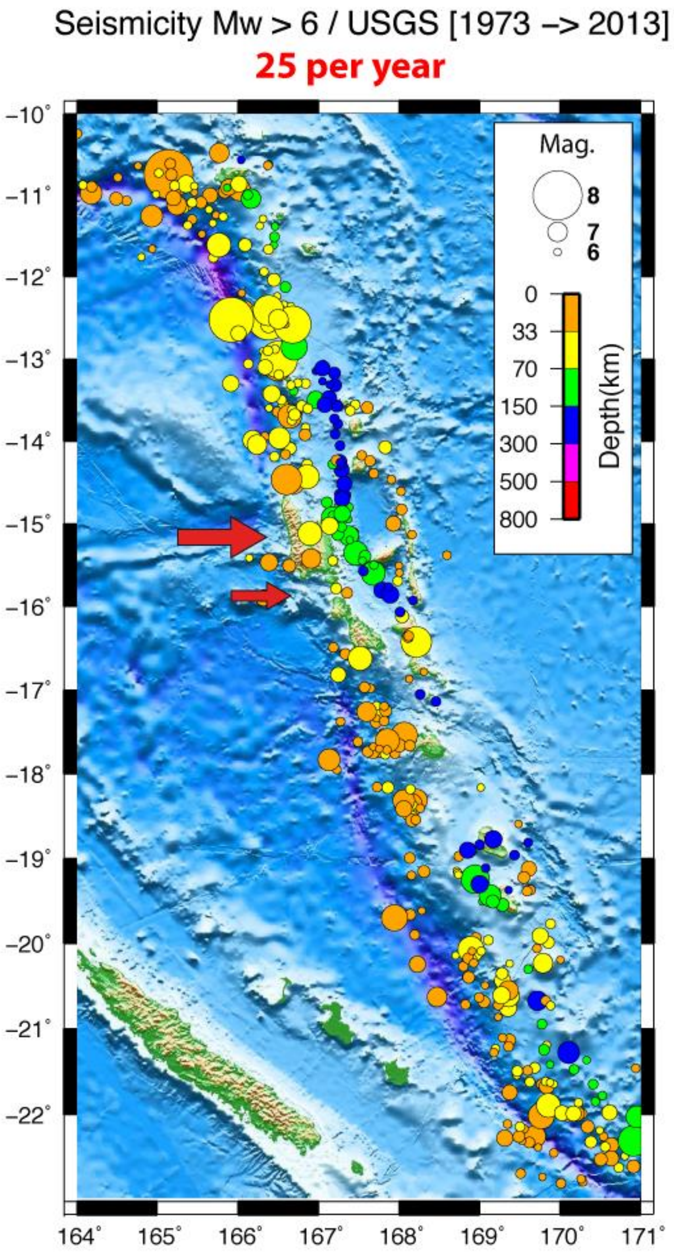


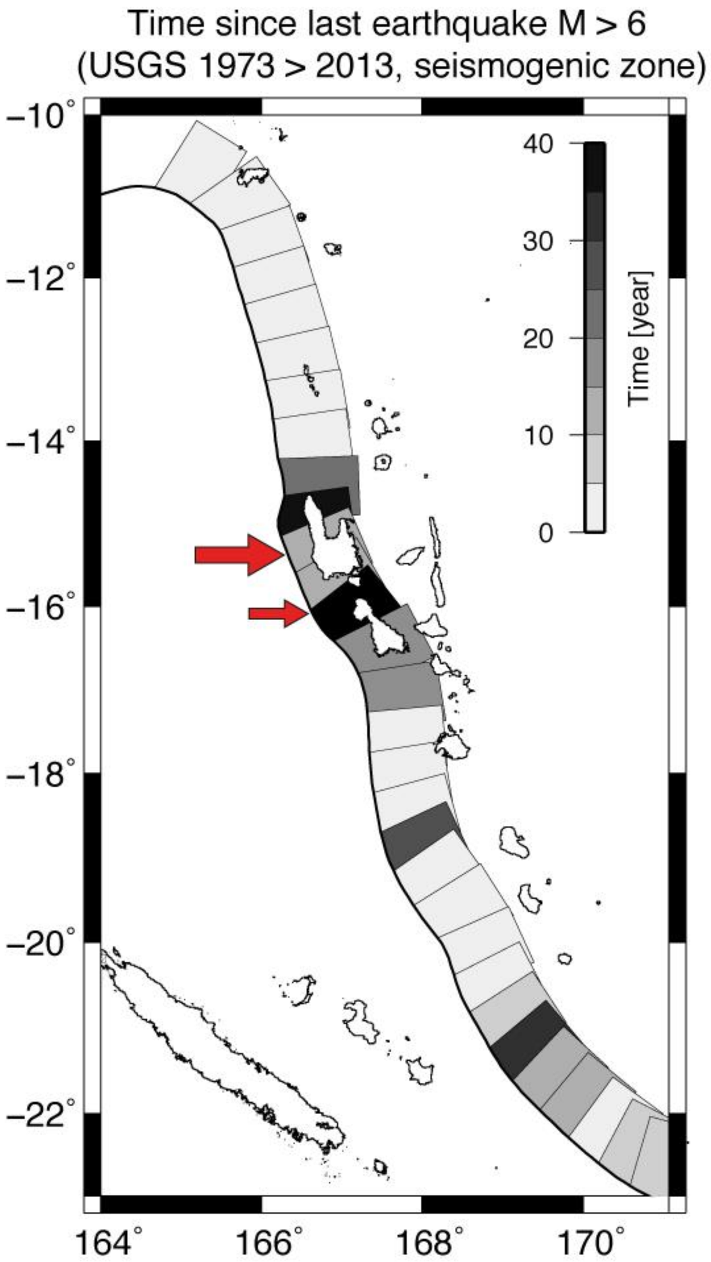




Taylor et al., 2005

About the Seismicity





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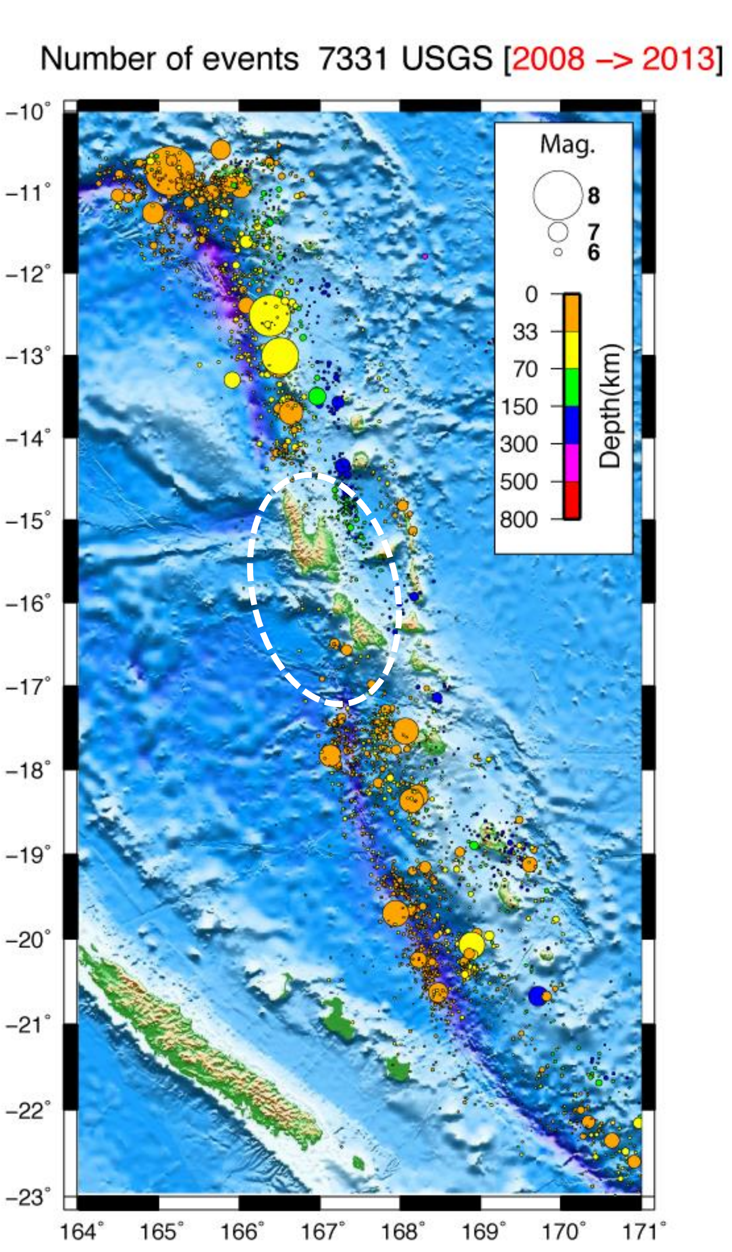

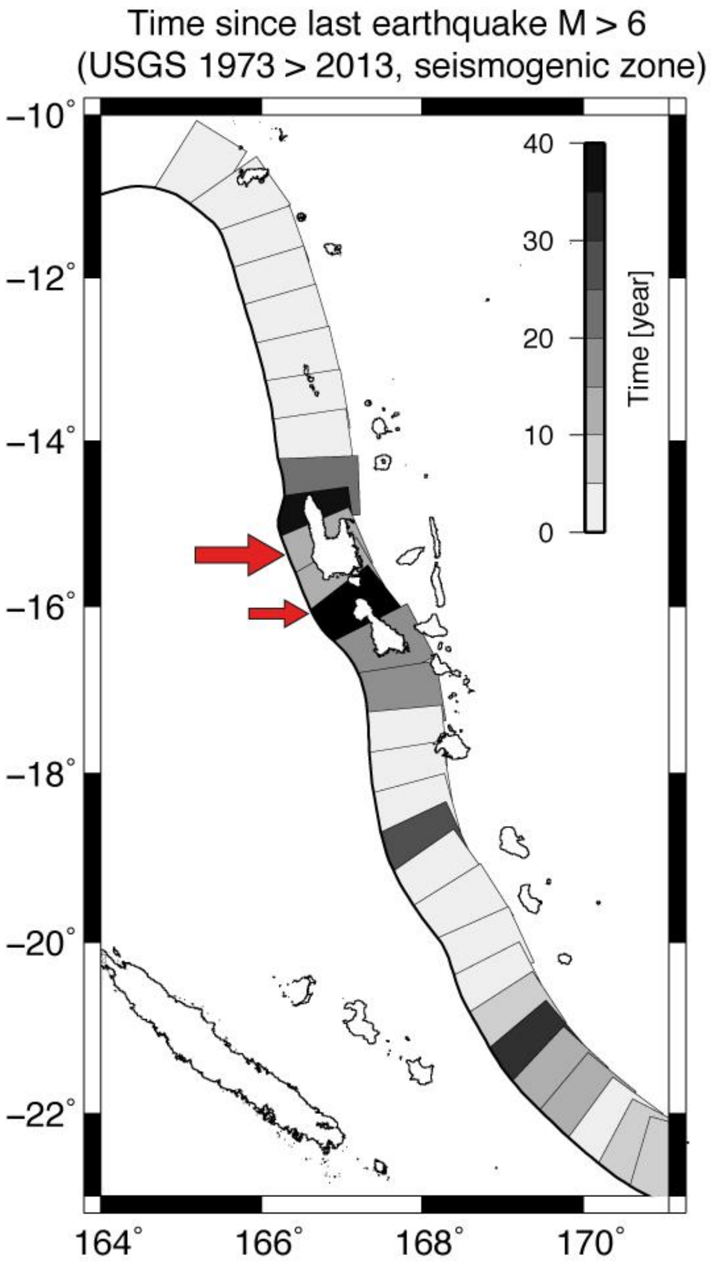

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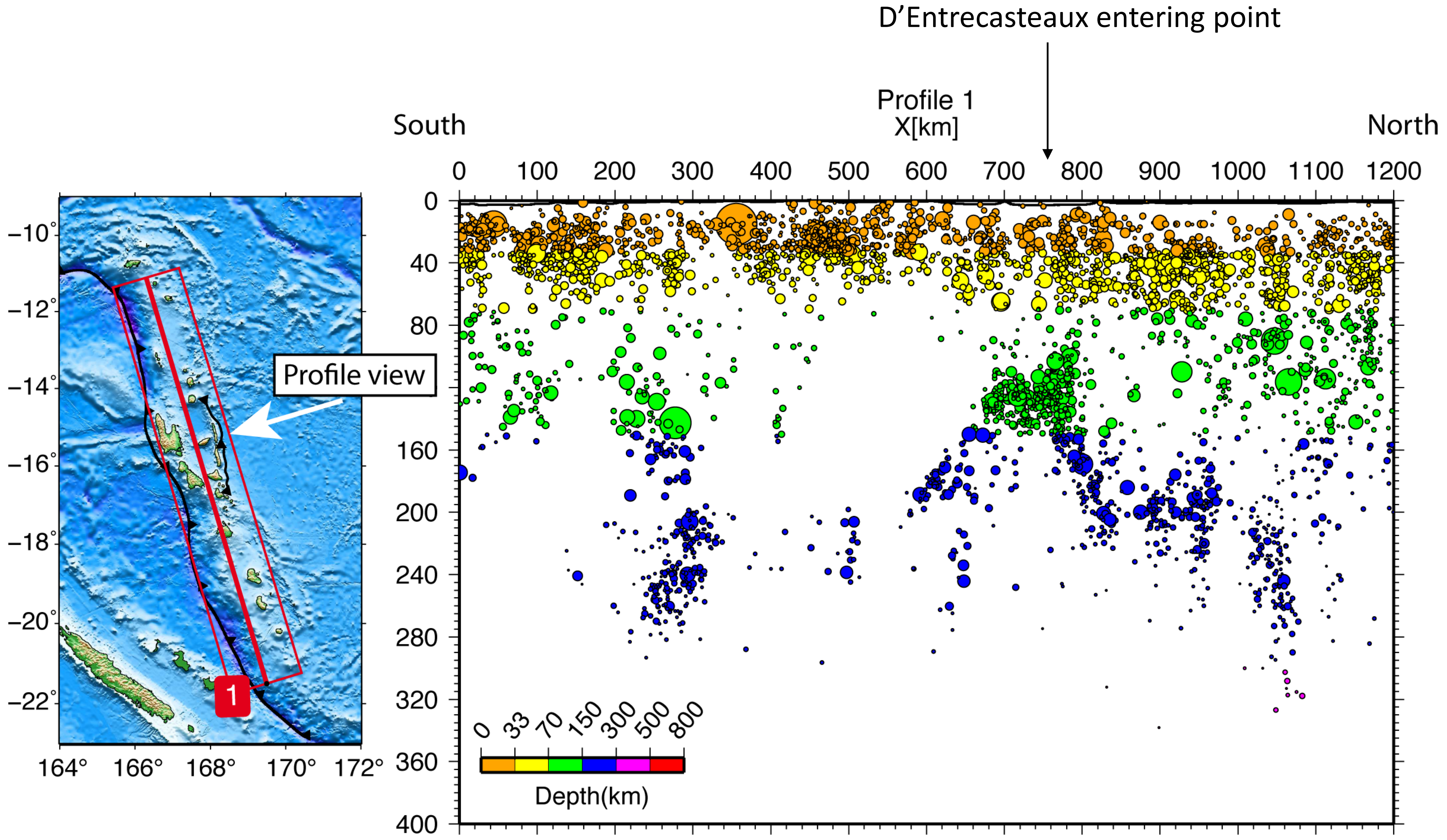

Main questions

Main questions concerning the Vanuatu subduction zone…

1. What is the earthquake distribution with depth under the central part of the arc ?

2. What is the geometry of the subduction interface ?

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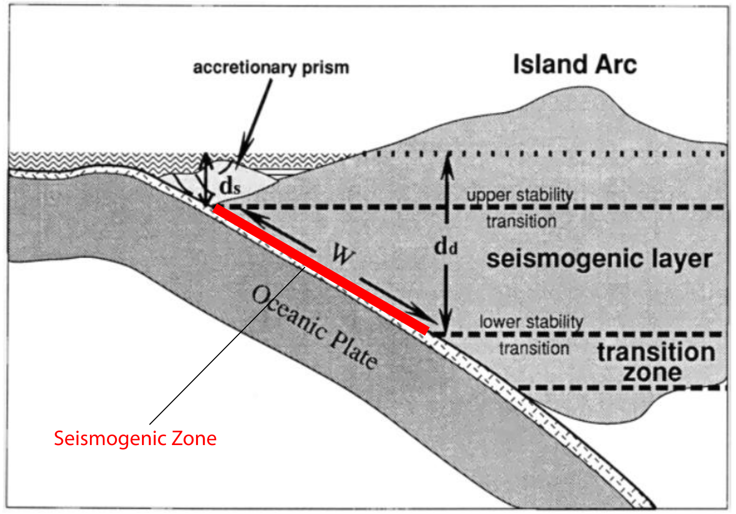

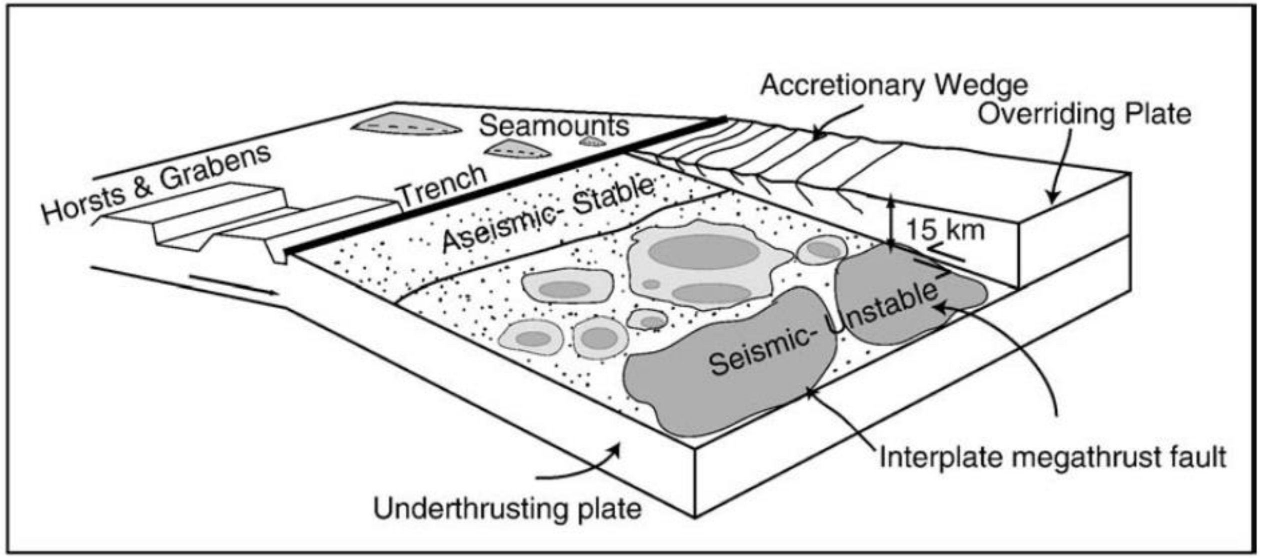

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Intermediate depth earthquake distribution

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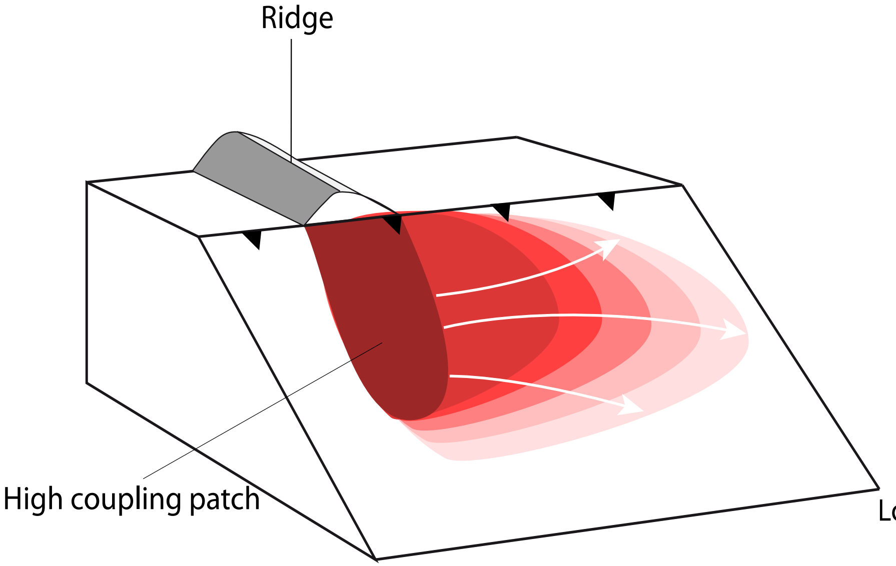
Intermediate depth earthquake distribution

Coupling

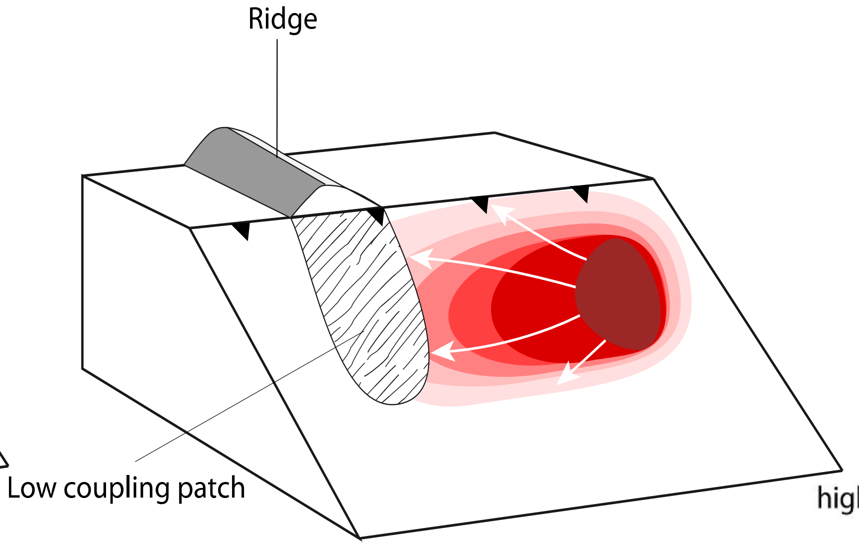
3 main coupling models

A) Ridge as a strong asperity



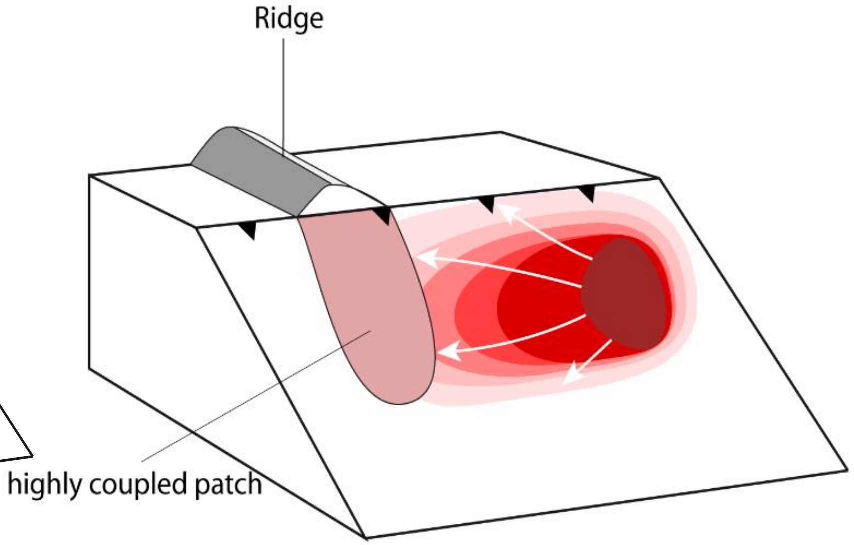
Cloos, 1992; Scholz & Small, 1997

B) Aseismic ridge barrier



Wang & Bilek 2011; Singh et al., 2011

C) Strong asperity barrier



Collot et al.,2004; Graindorge et al., 2004

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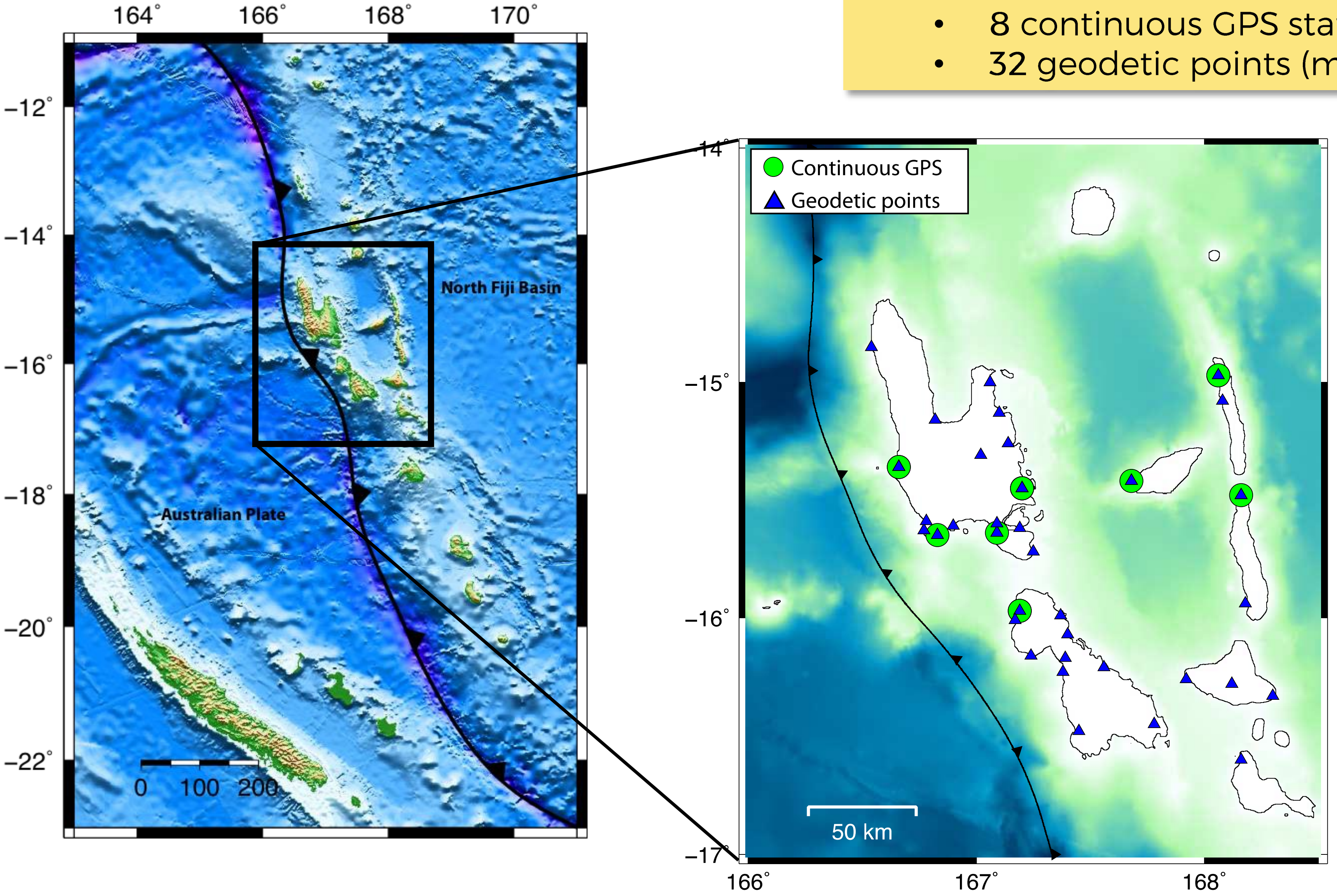
GPS Data

Seismic Data

GPS data

GPS network :

- 8 continuous GPS stations (ARC-VANUATU)
- 32 geodetic points (measured since 1996)

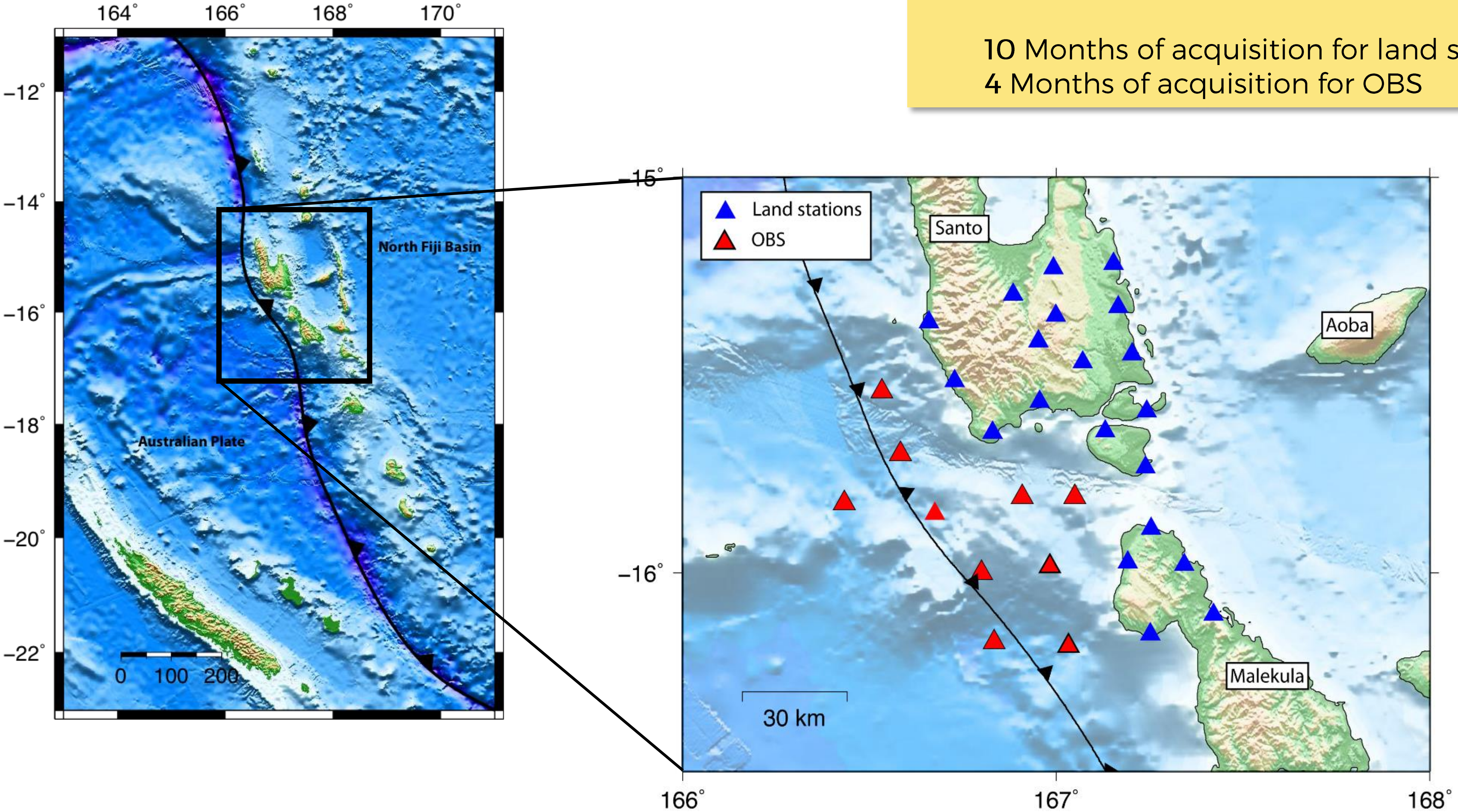


Seismic data

ARC-VANUATU seismic network (2008):

- 20 Broadband land stations
- 10 Ocean Bottom Seismometers

10 Months of acquisition for land stations
4 Months of acquisition for OBS



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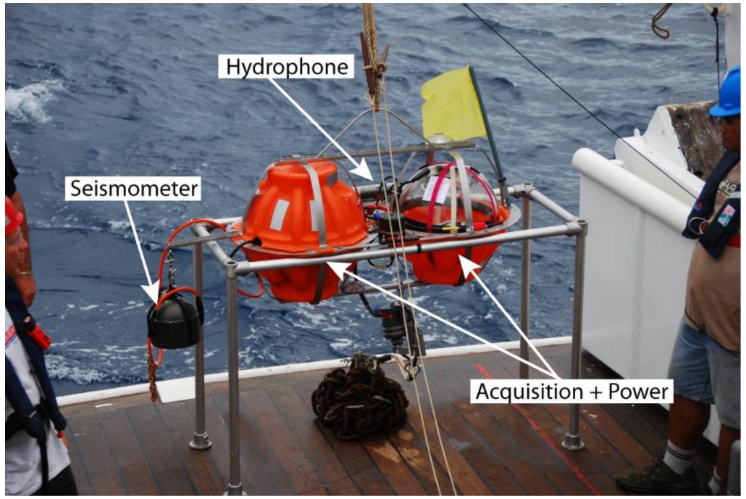
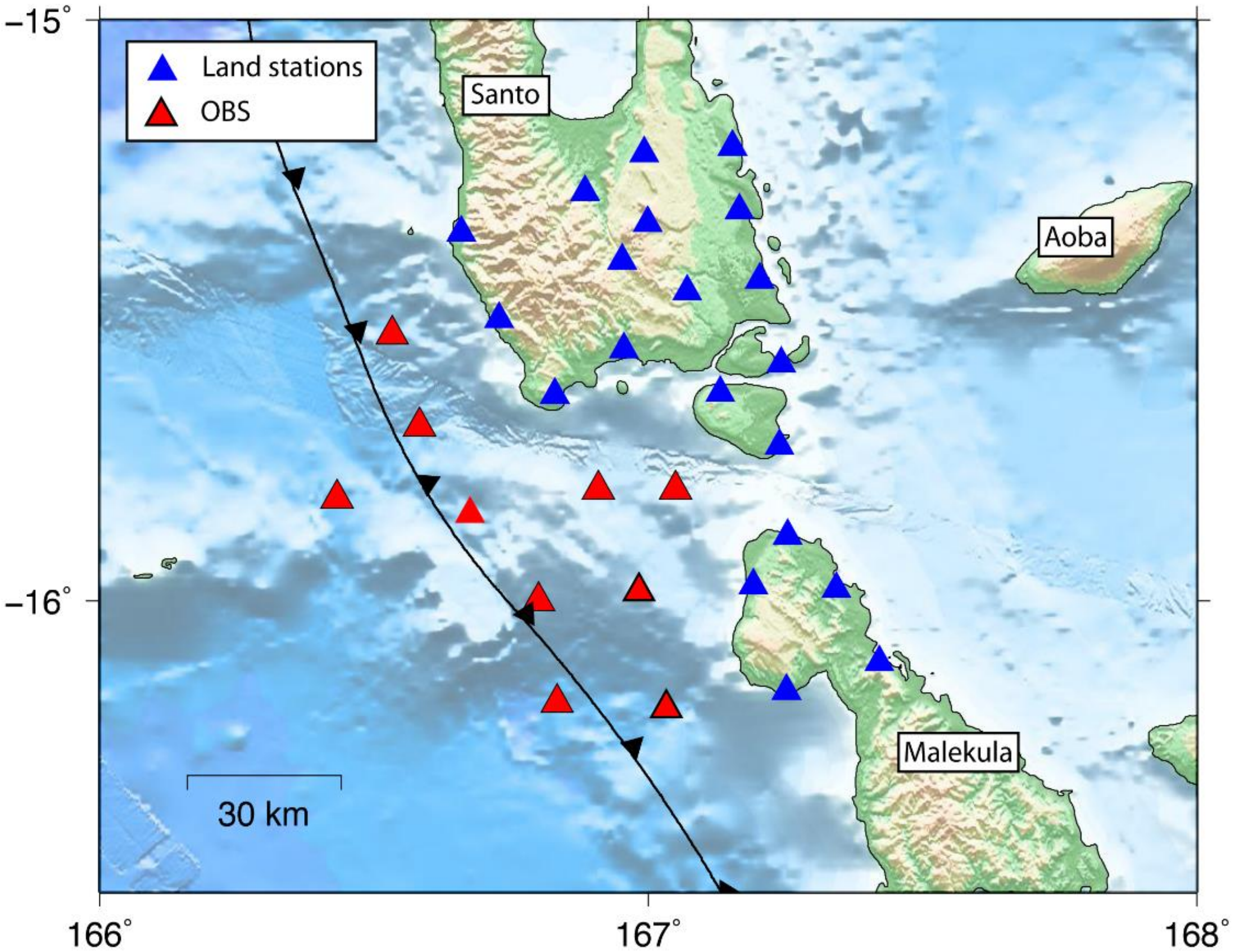


~ 40.000 events detected during the monitoring



About the seismic catalog

Recipe on how to get a reliable seismic catalog:

1. Perform picking of the onsets

2. Update the velocity model

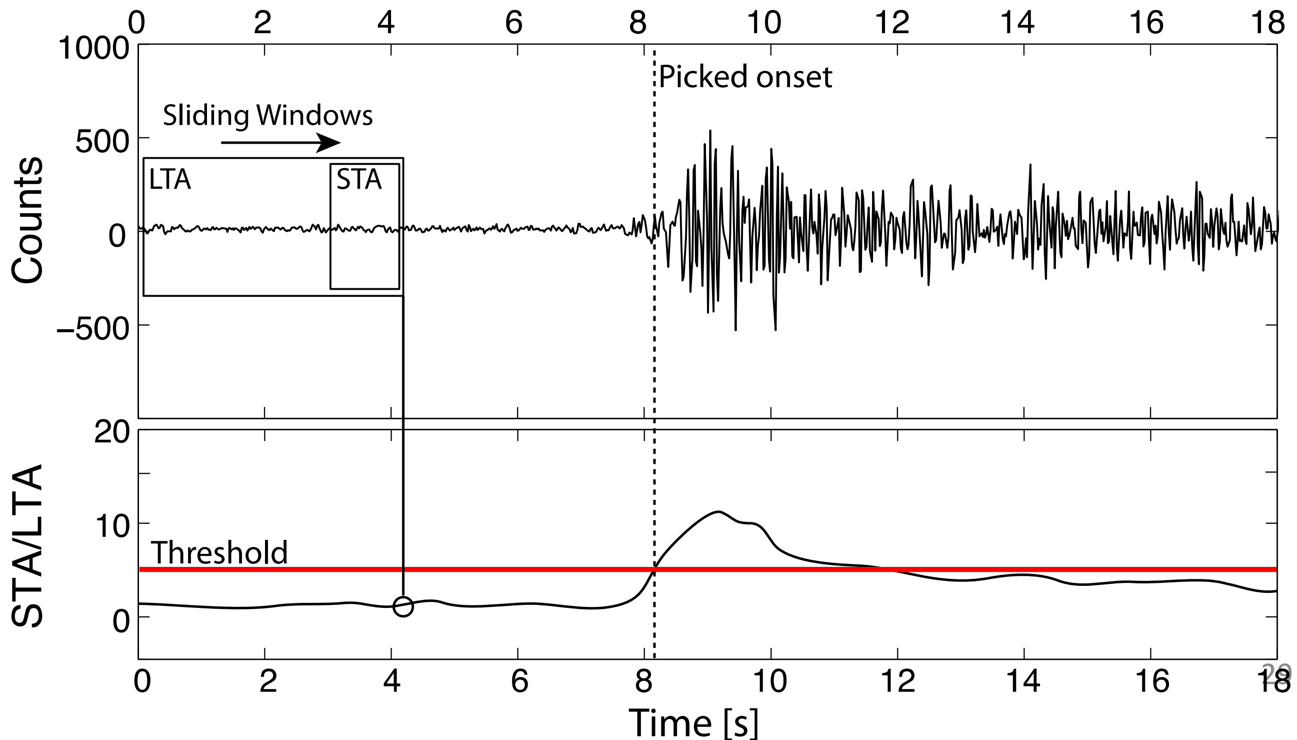
3. Perform relocation

4. Compute focal mechanisms

Perform picking of the onsets

What about already existing tools…?

Existing Methods	⊕	⊖
STA/LTA	- Stable - Fast computing	- **Important residuals** (Manual/Automatic time comparison) - frequency dependant
Waveform cross-correlation classification	- Precise time shifting between traces belonging to same family event	- Accurate absolute picking of master still needed - **Events with no family are not computed**

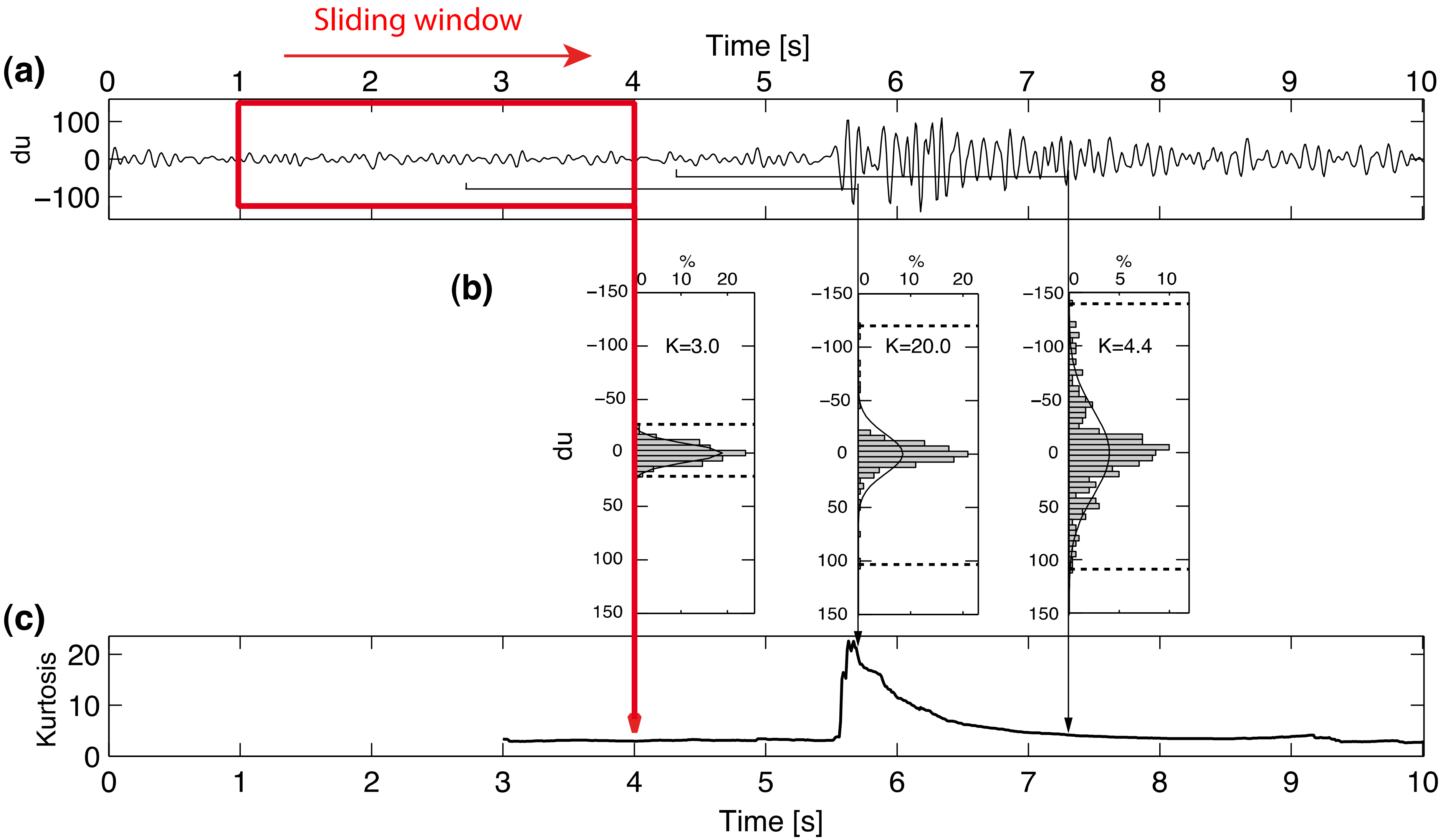


STA/LTA principle
Allen, 1982

Perform picking of the onsets

Introduced by Saragiotis et al., (2002) for automatic picking of seismic onset

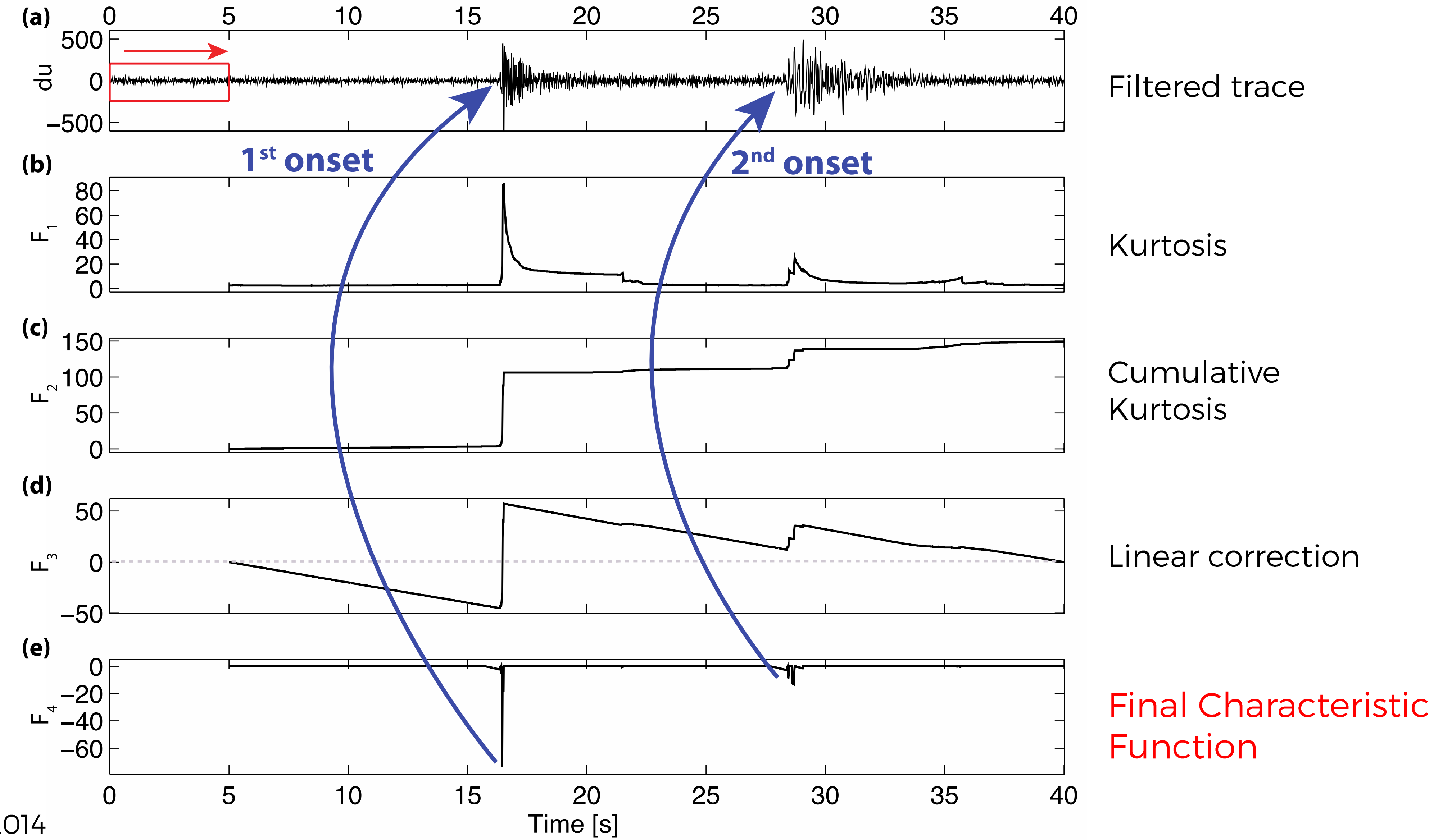
$$K \equiv \frac{E[(X-\mu)^4]}{\{E[(X-\mu)^2]\}^2} = \frac{m_4}{\sigma^4}$$



Baillard et al., 2014

Perform picking of the onsets

Obtaining the final characteristic function – **4 steps process**



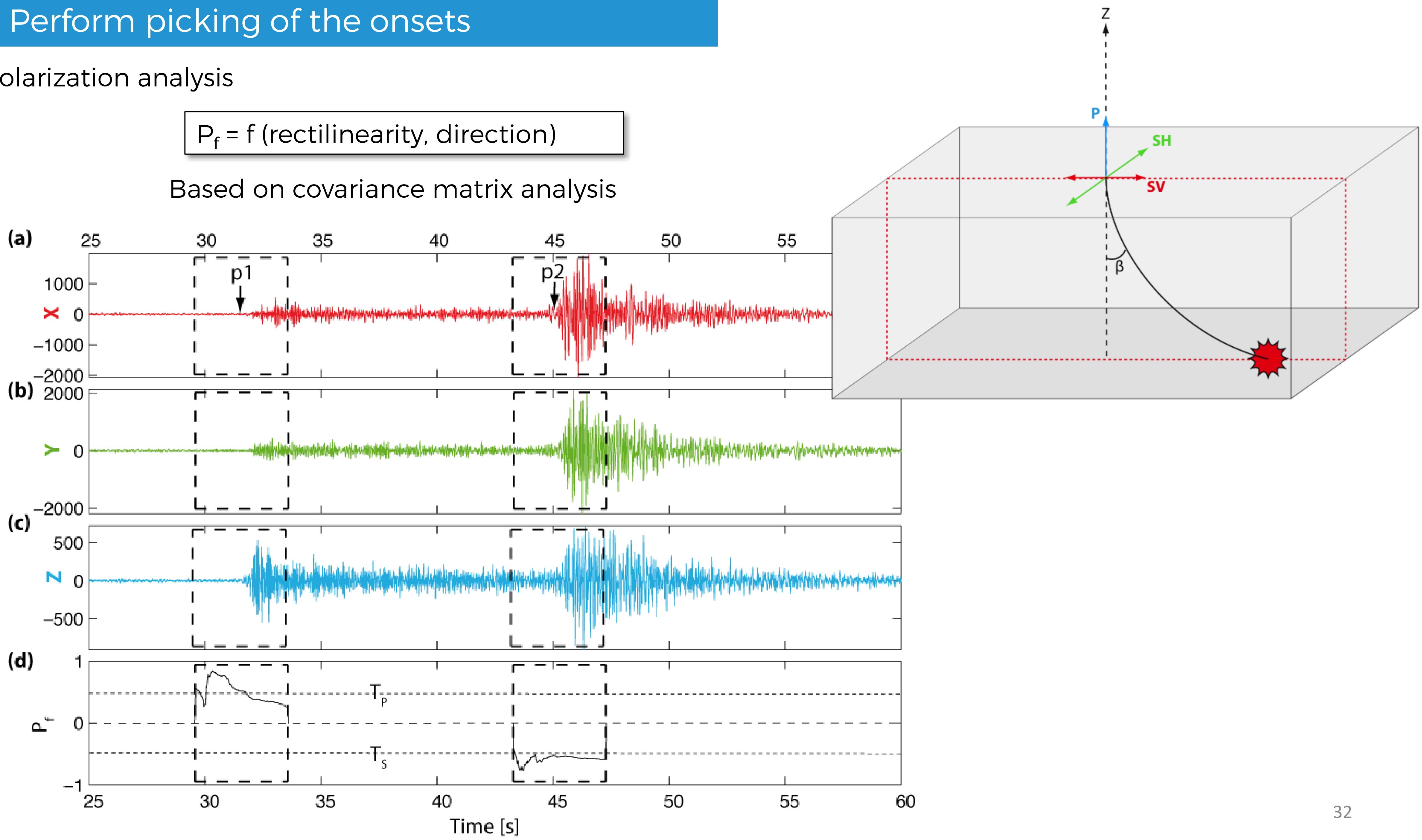
Baillard et al., 2014

Perform picking of the onsets

Polarization analysis

P_f = f (rectilinearity, direction)

Based on covariance matrix analysis



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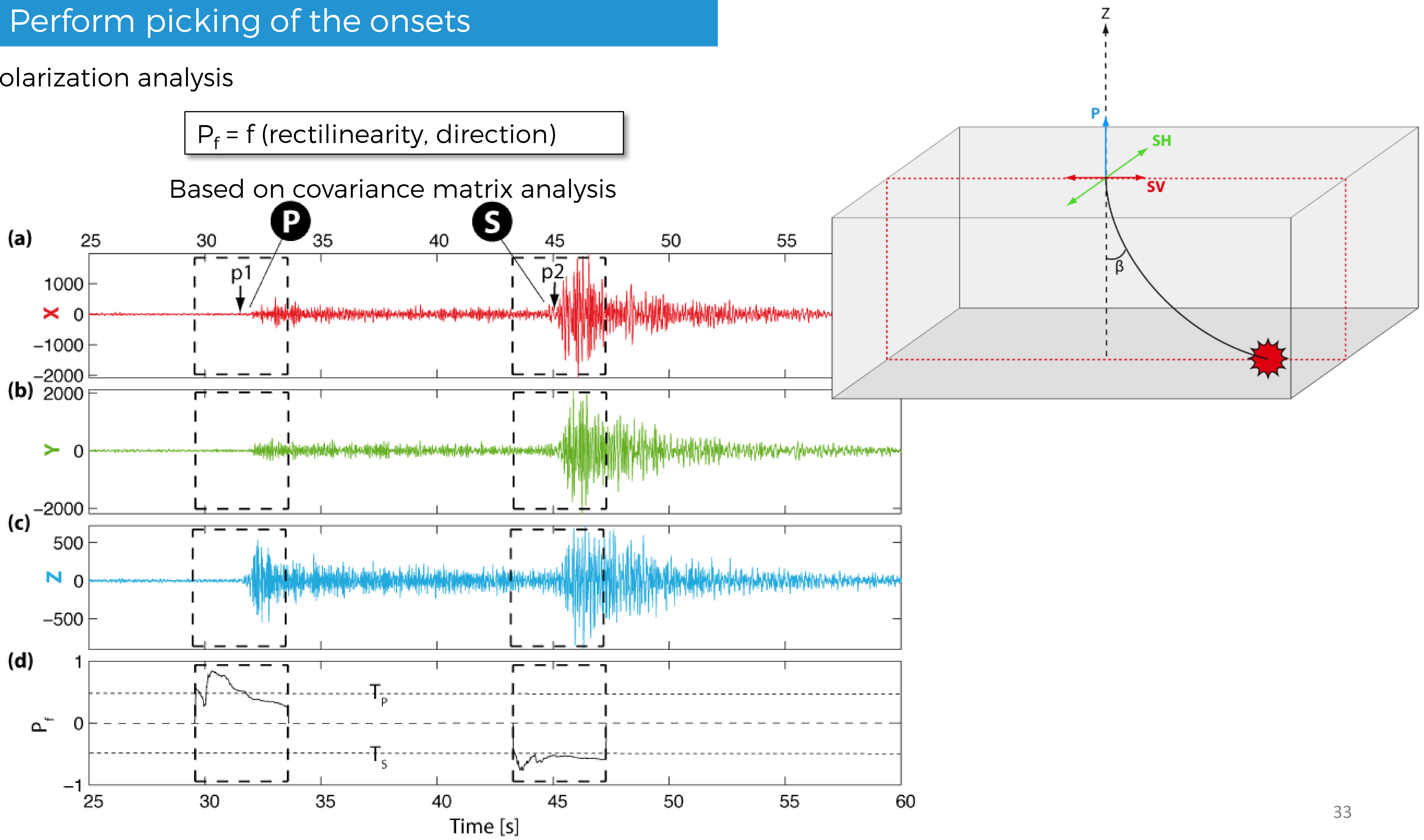

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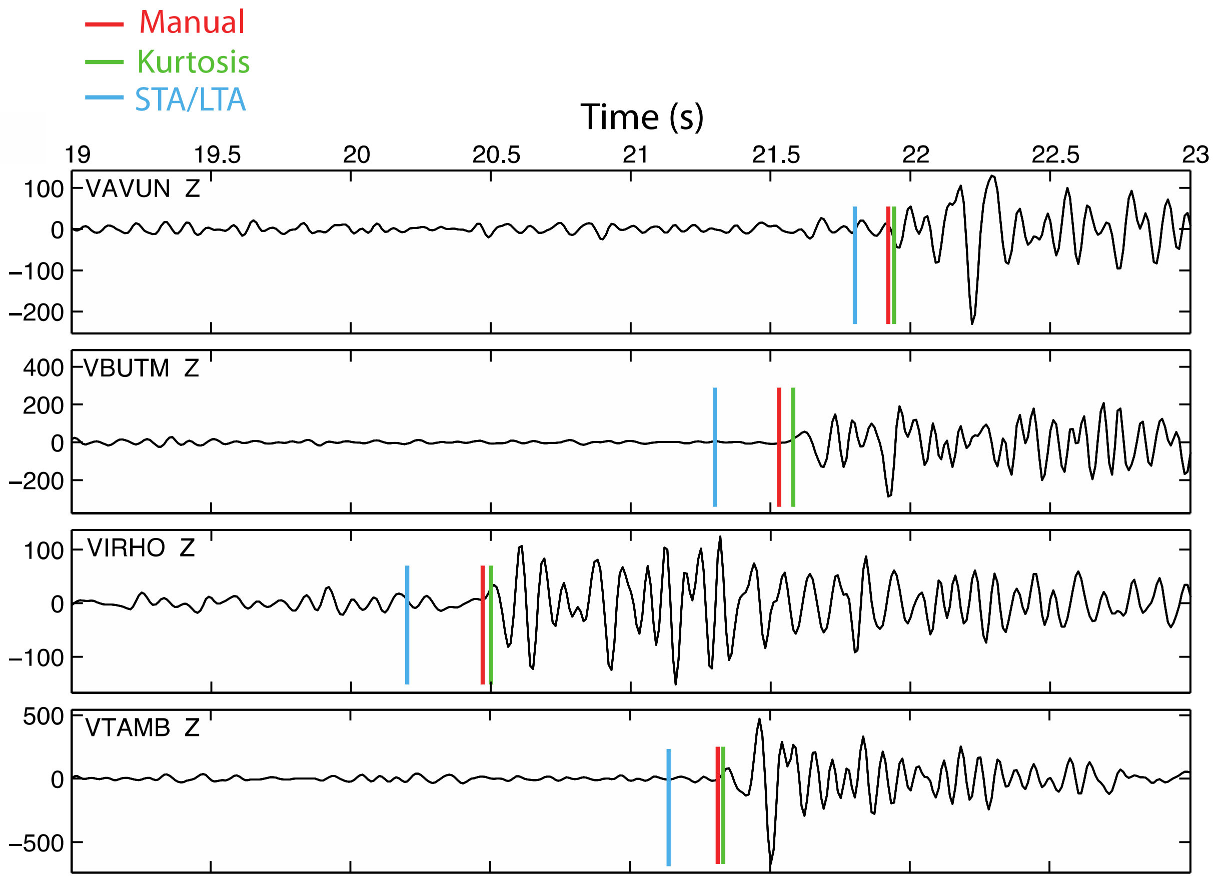
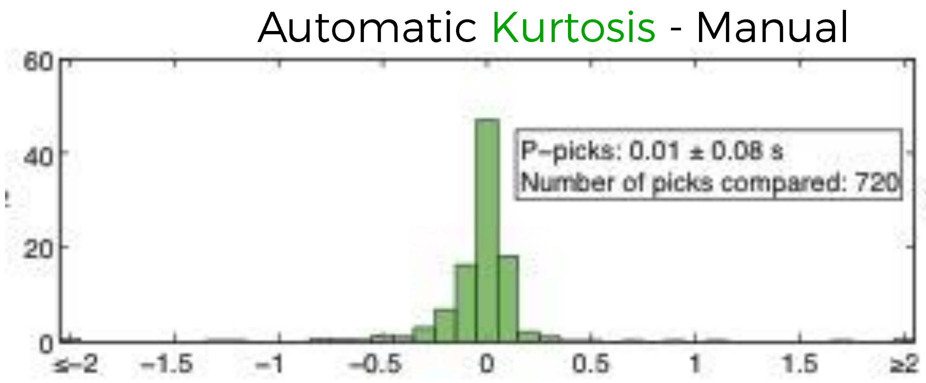
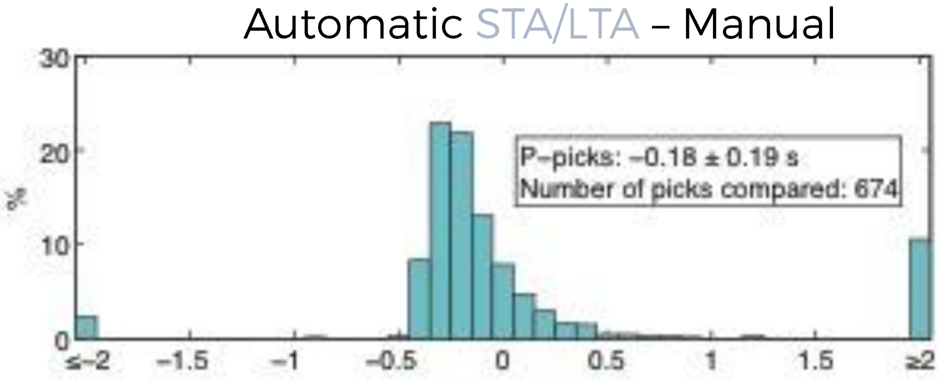


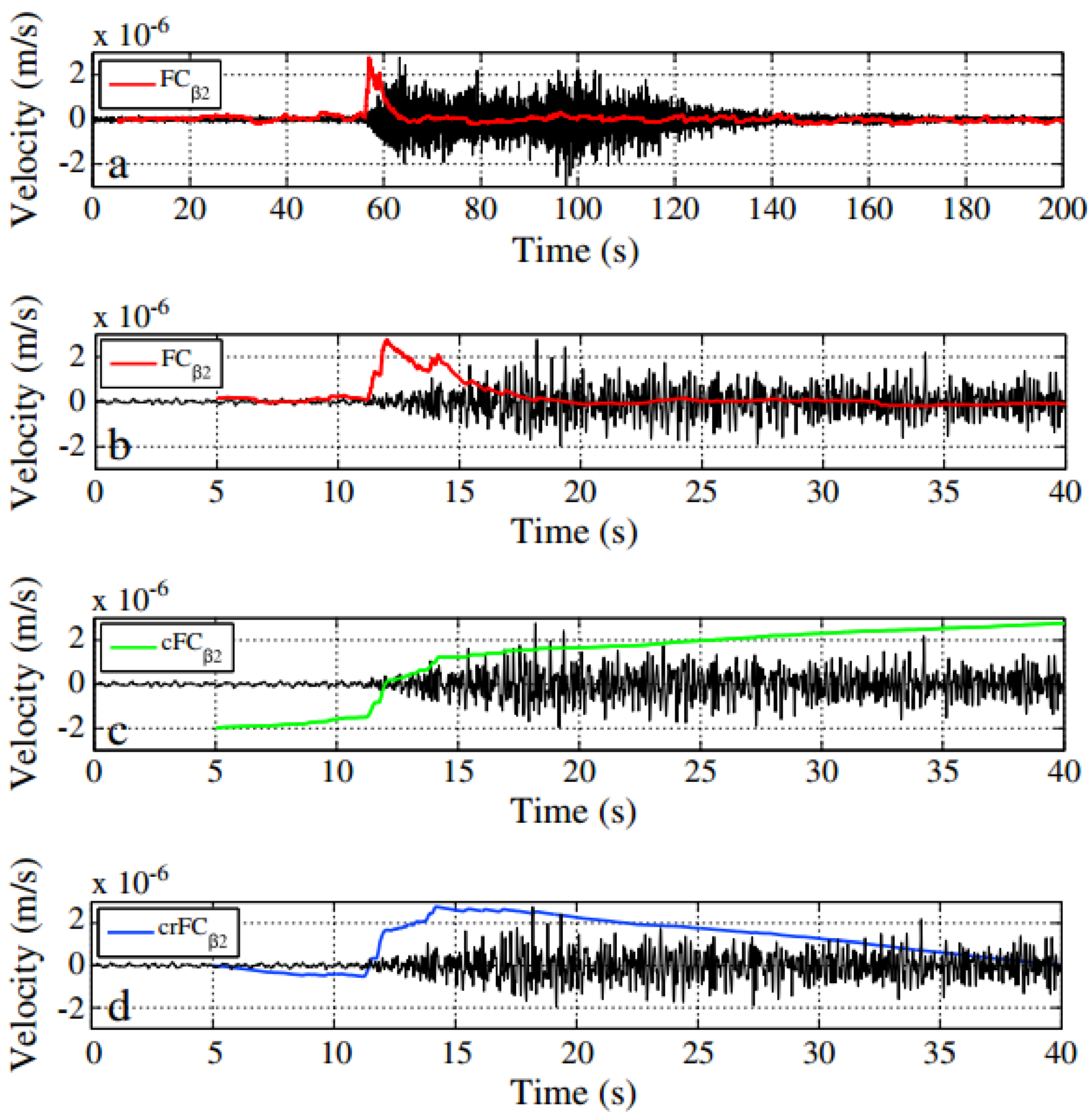
- Fast
- Easy to use
- Applicable to different types of waveforms and networks (Baillard et al.,2014; Hibert et al.,2014, Levy et al, 2015)





Perform picking of the onsets

Example on rockfall events (Piton de la Fournaise)

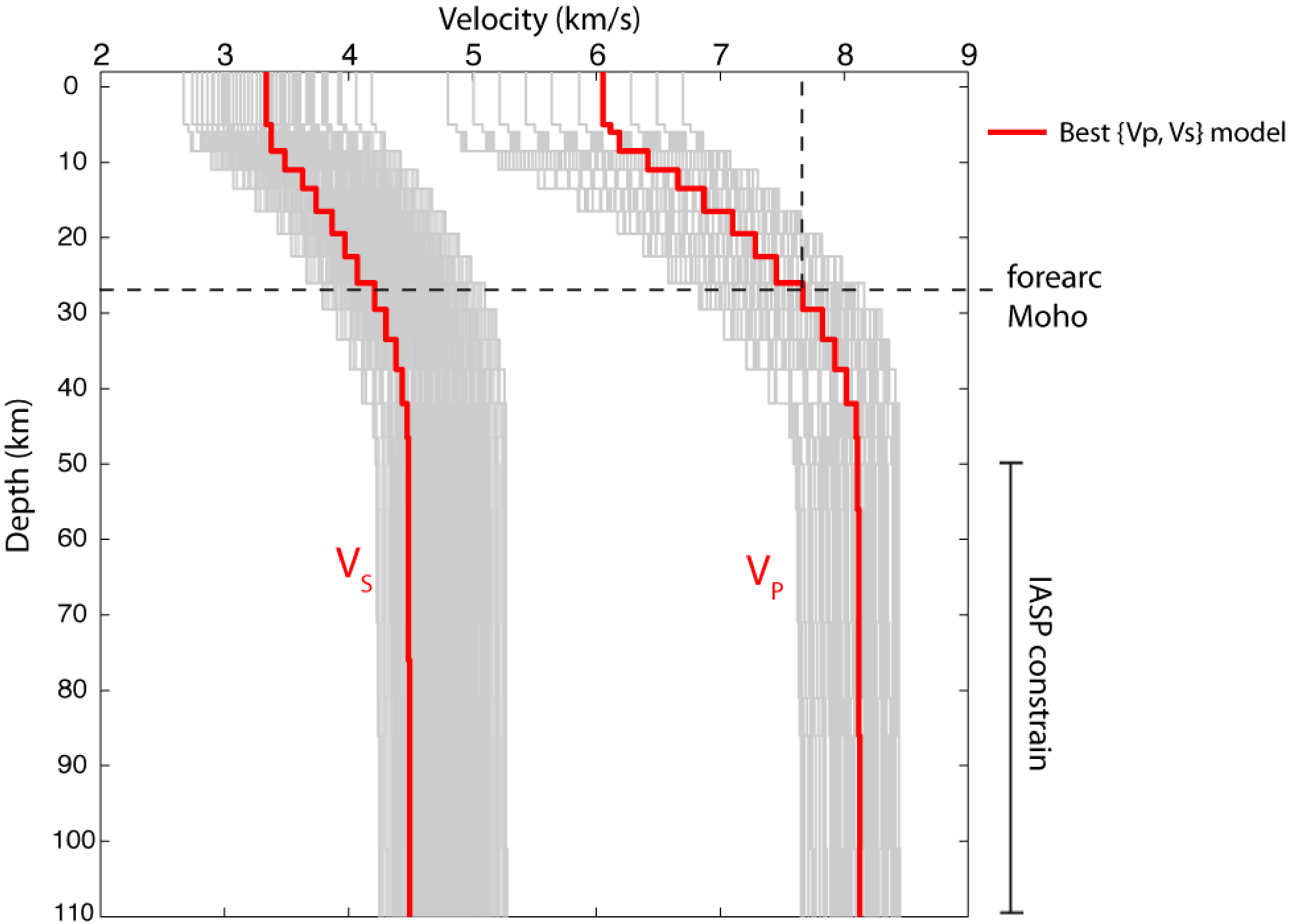


Hibert et al, 2014

Update the velocity model

Goal: Reduce location errors

- Monte-Carlo approach
- 400 models tested
- Vp/Vs = 1.8

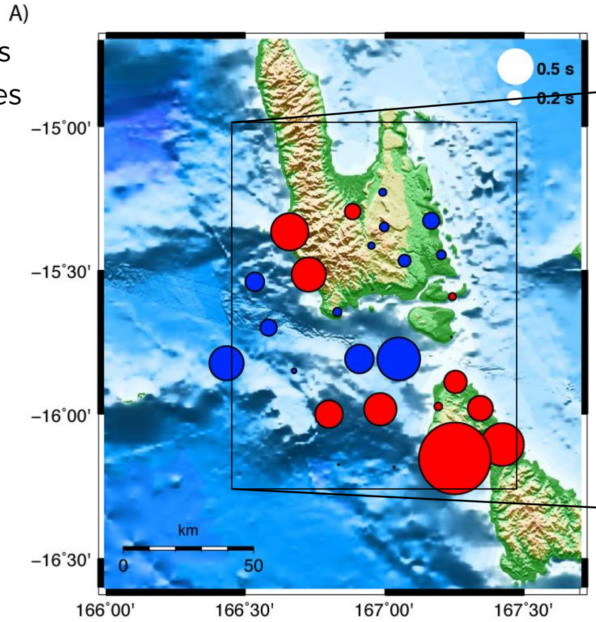


Update the velocity model

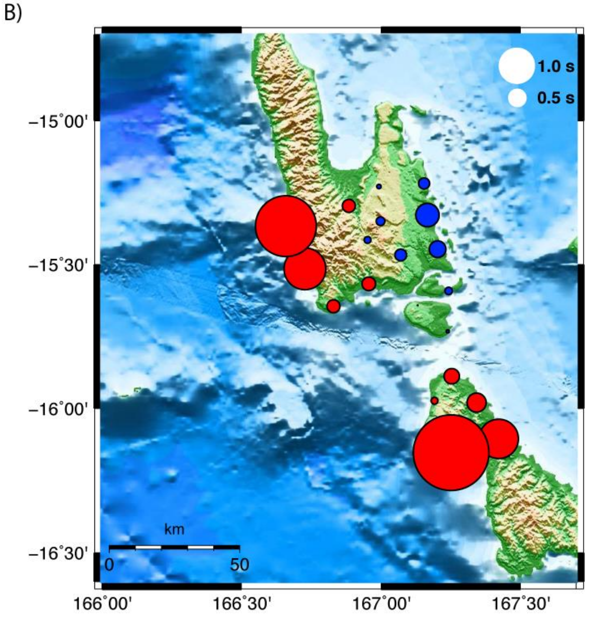
Station corrections

Low velocities
High velocities

P corrections

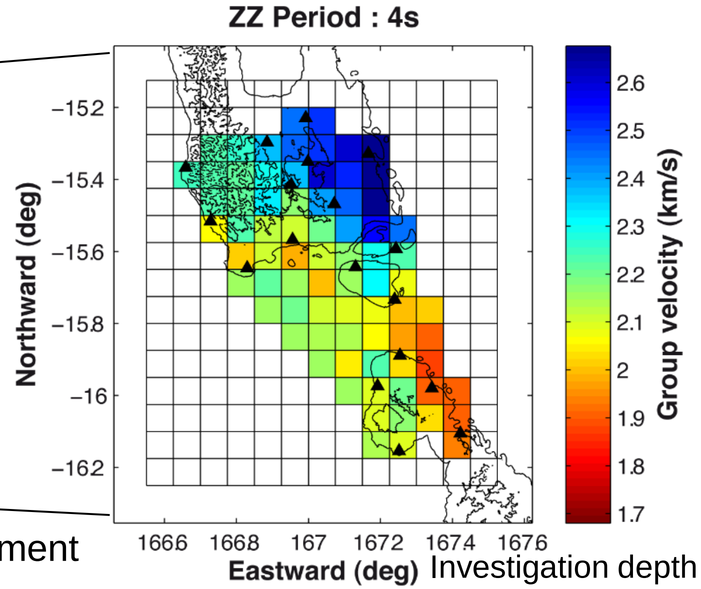


S corrections

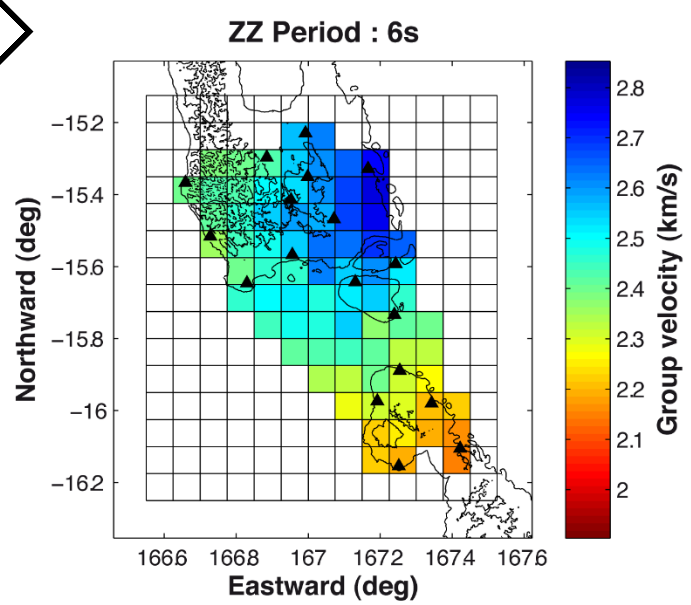


Good agreement

Ambient noise tomography



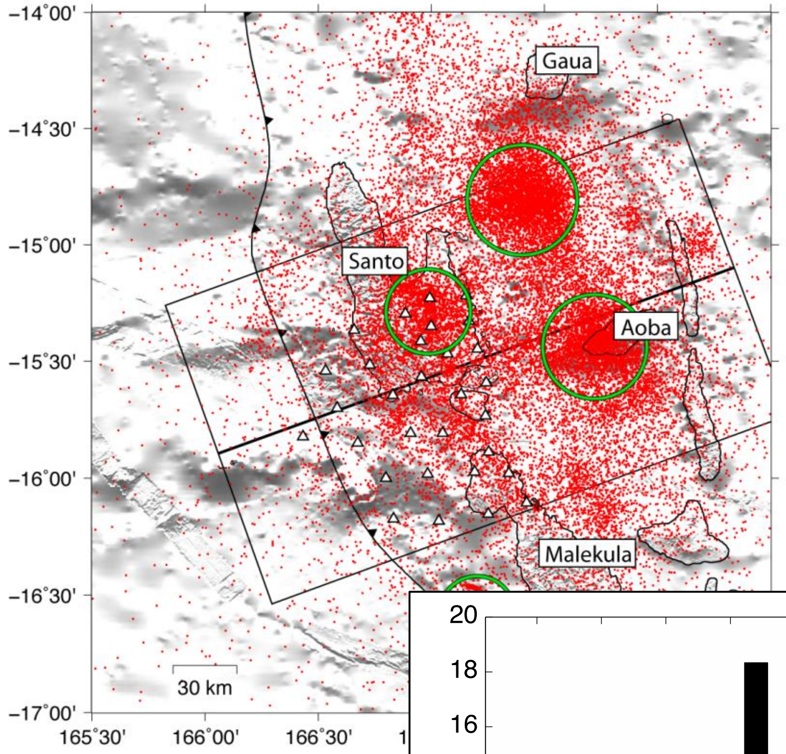
Investigation depth ~ 3 km

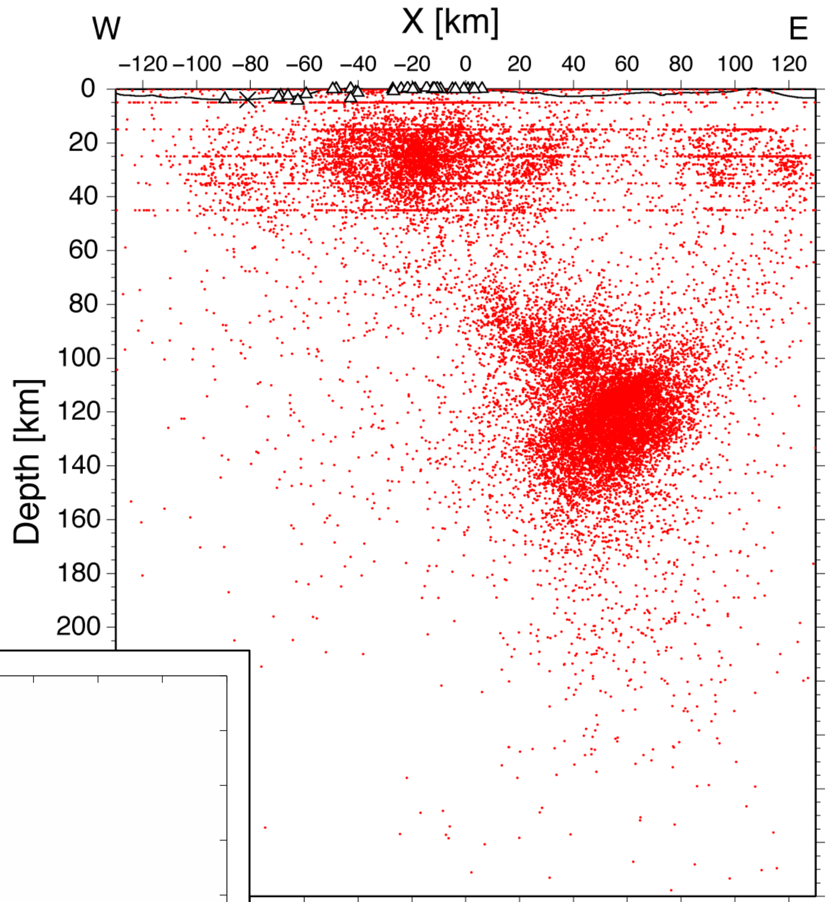


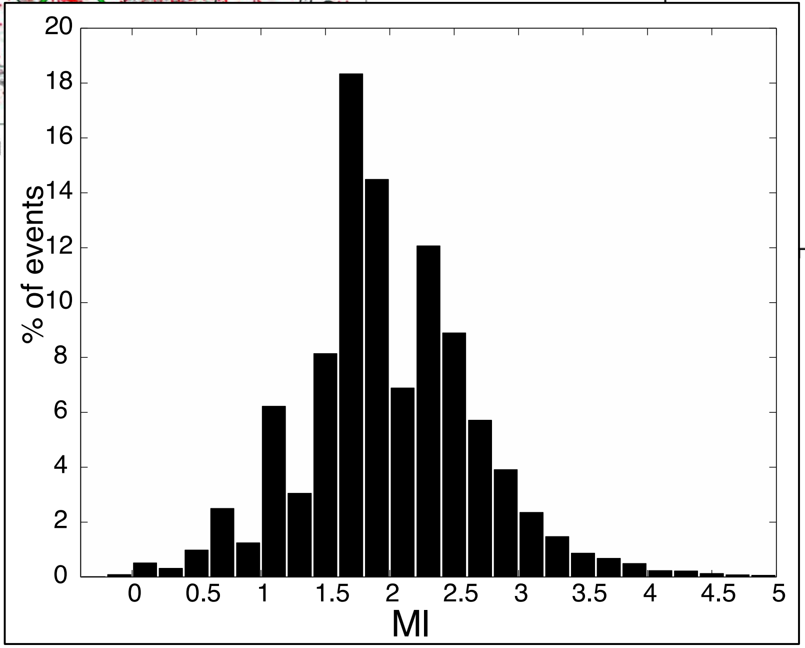
(in collaboration with A. Mordret)

About the seismic catalog

Preliminary catalog ~ 28000 events



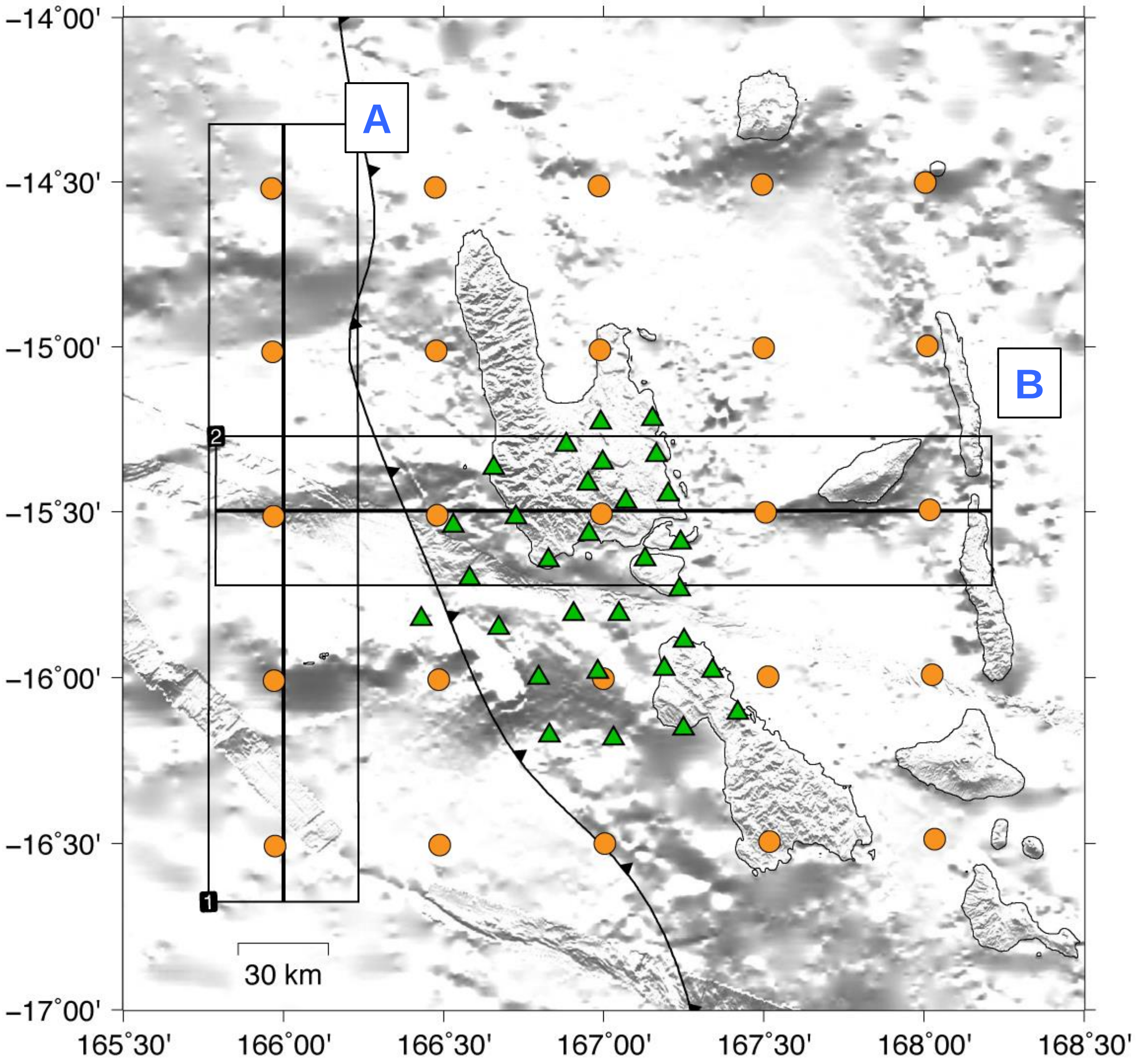


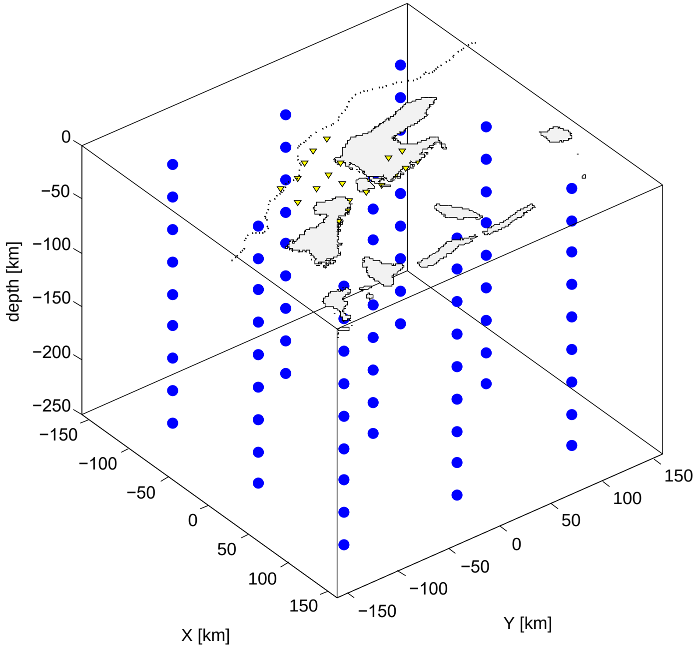


Distribution of event magnitudes

Error estimates

The “Bootstrap” method





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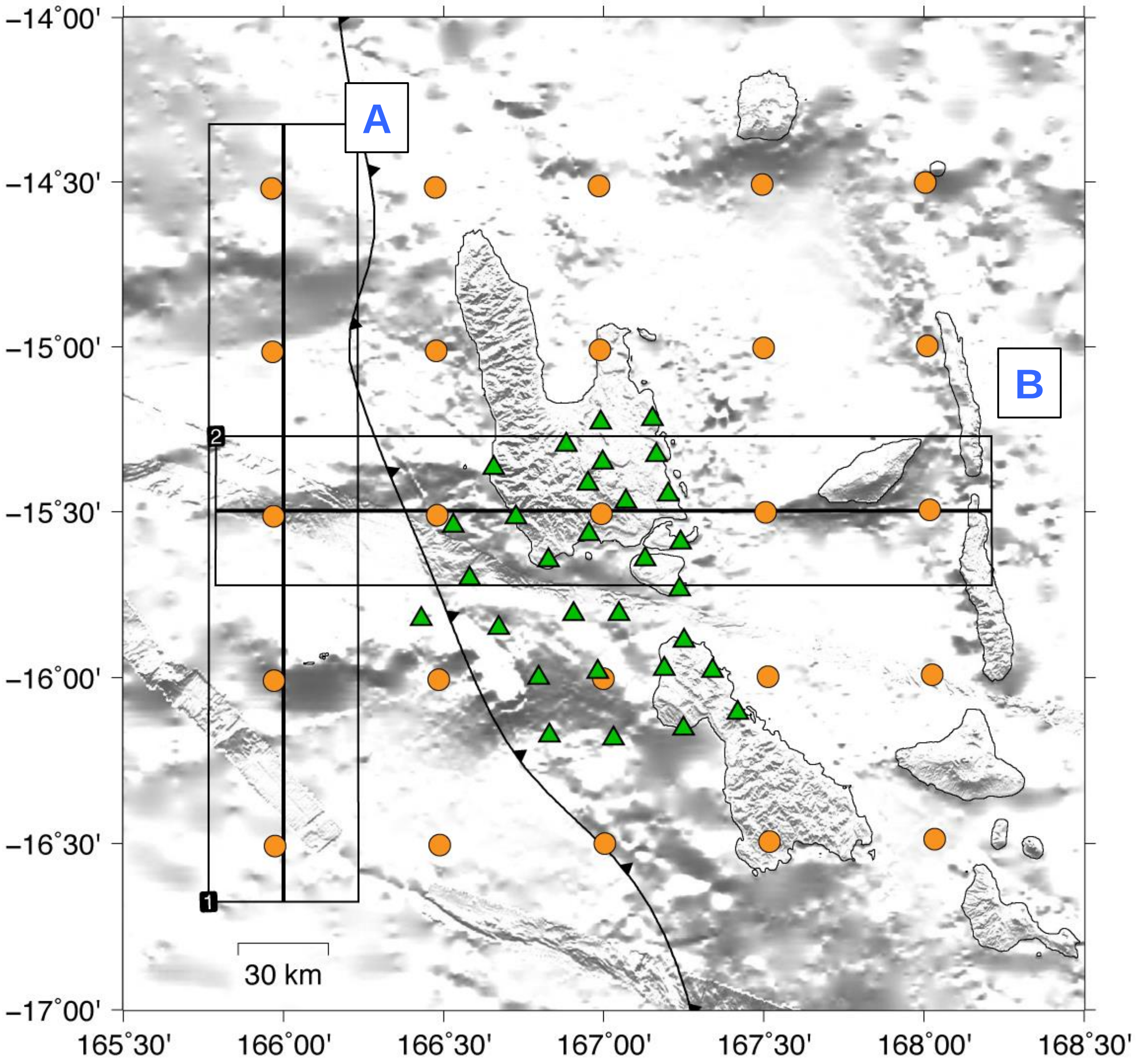
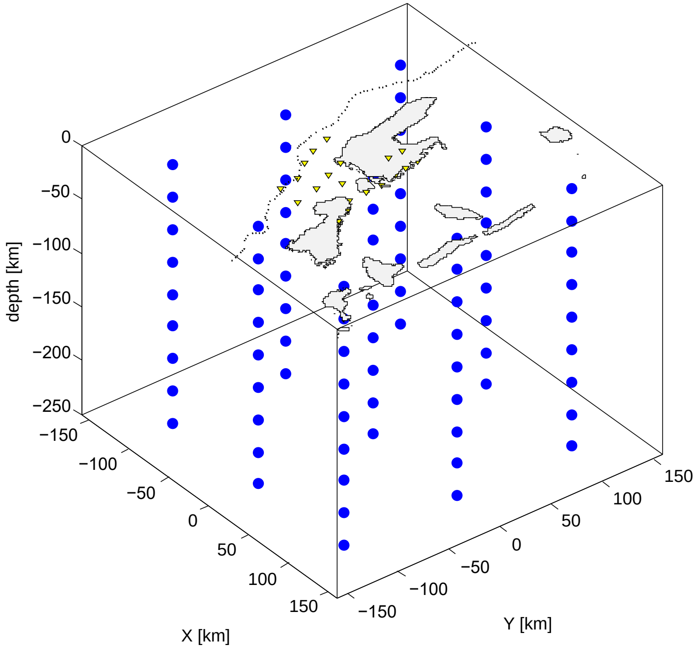
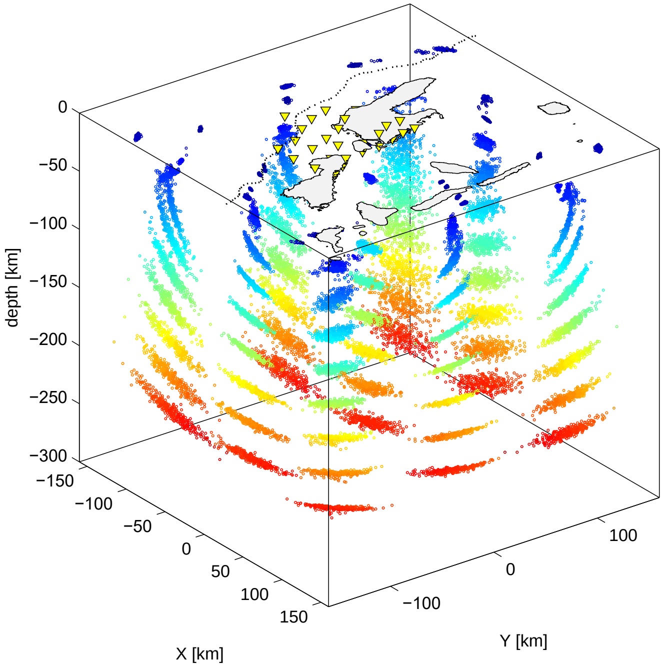




×300

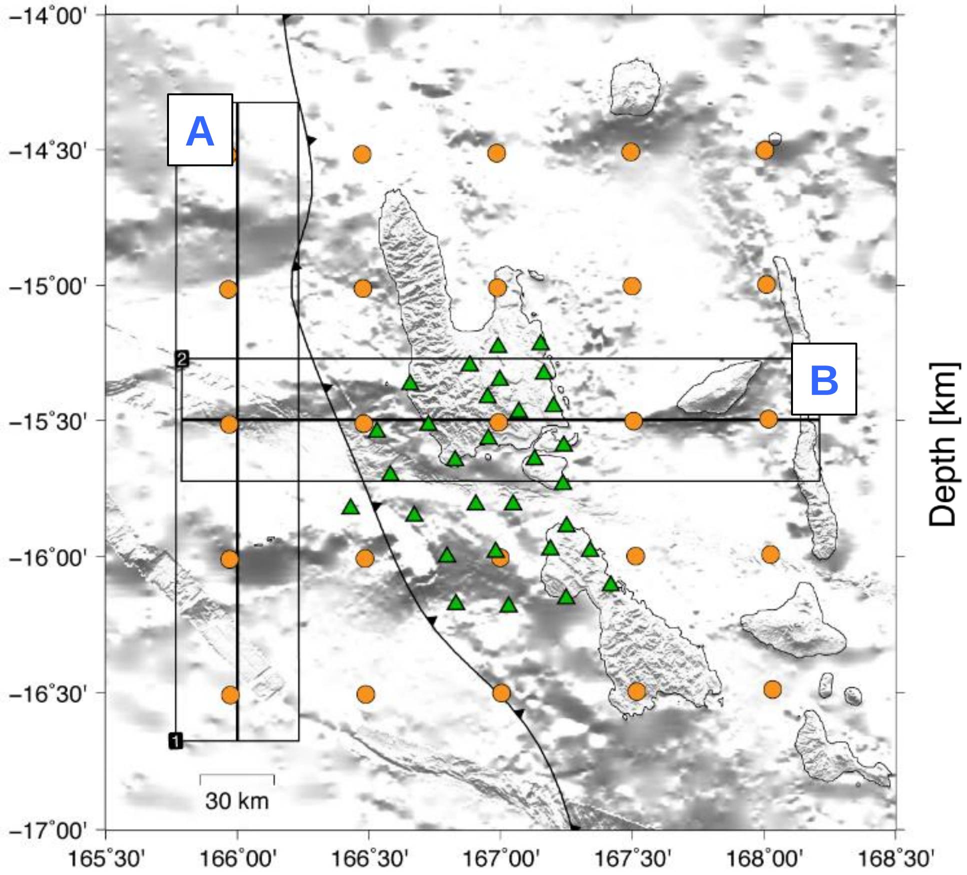


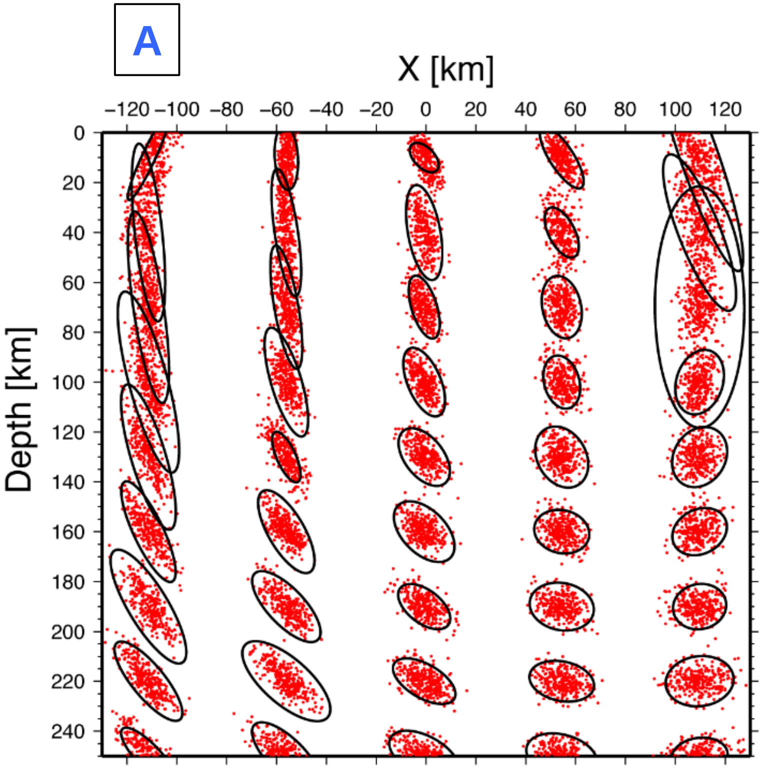
Error estimates

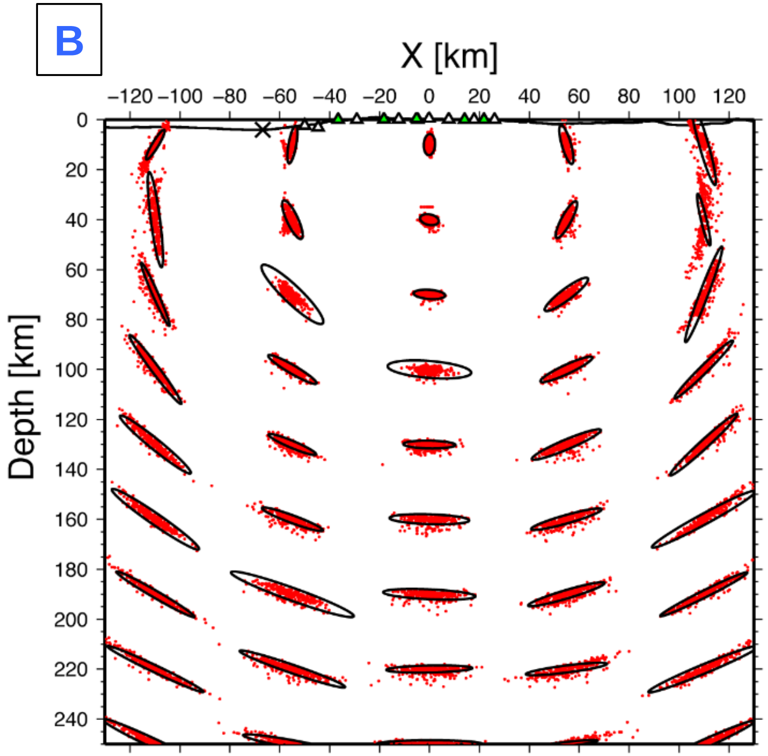
Standard deviations applied:
0.1s for P-picks
0.2s for S-picks

Result of the bootstrap

Picked on 10 land stations







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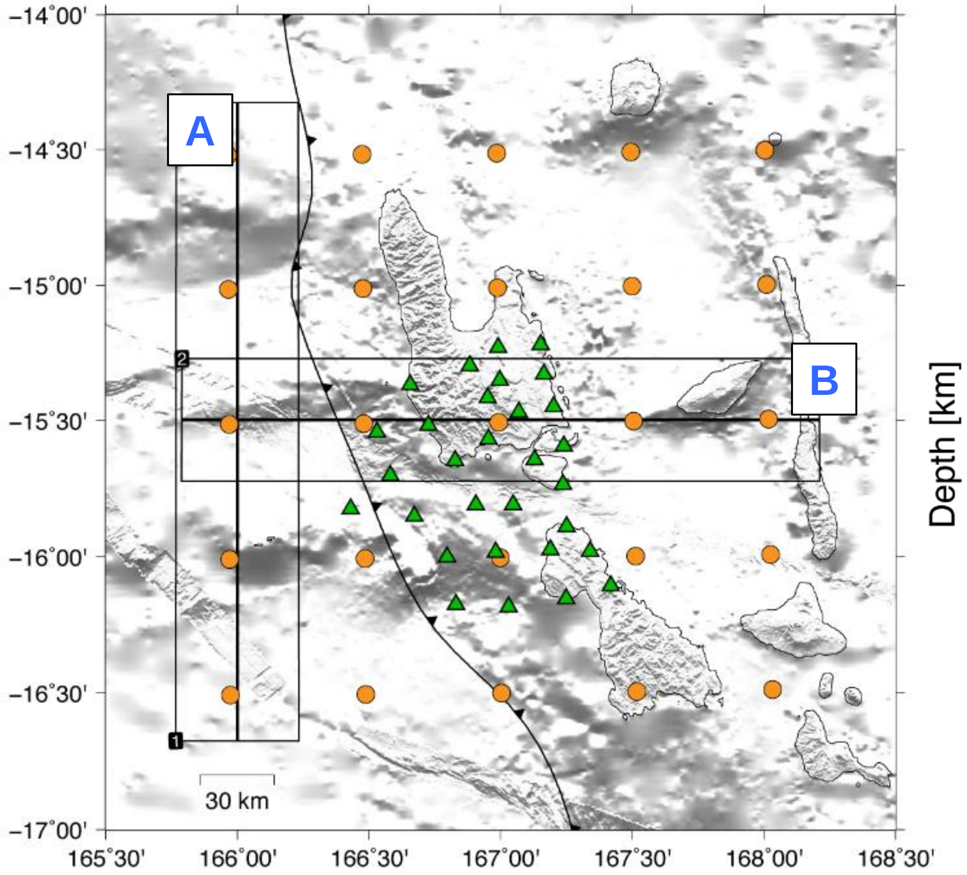
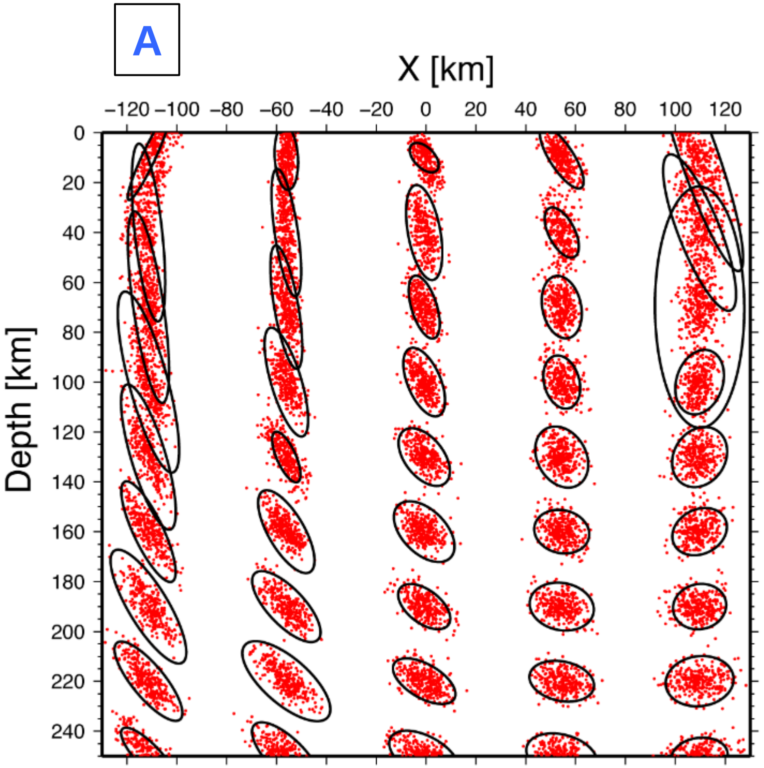
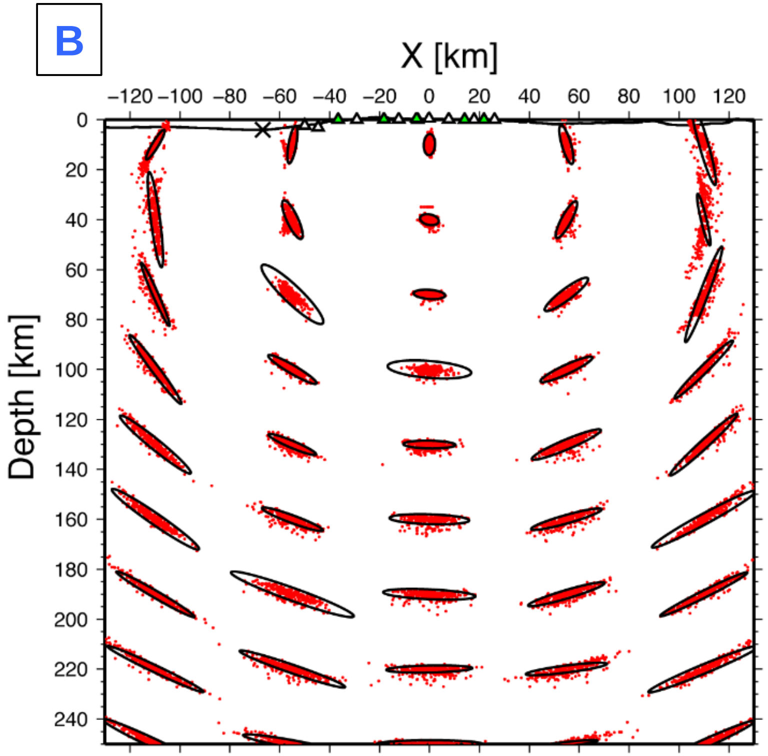
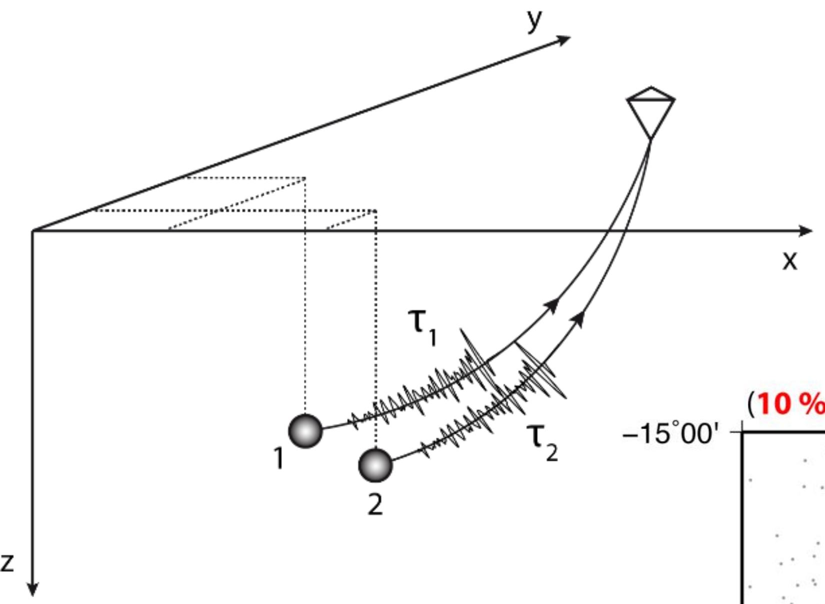






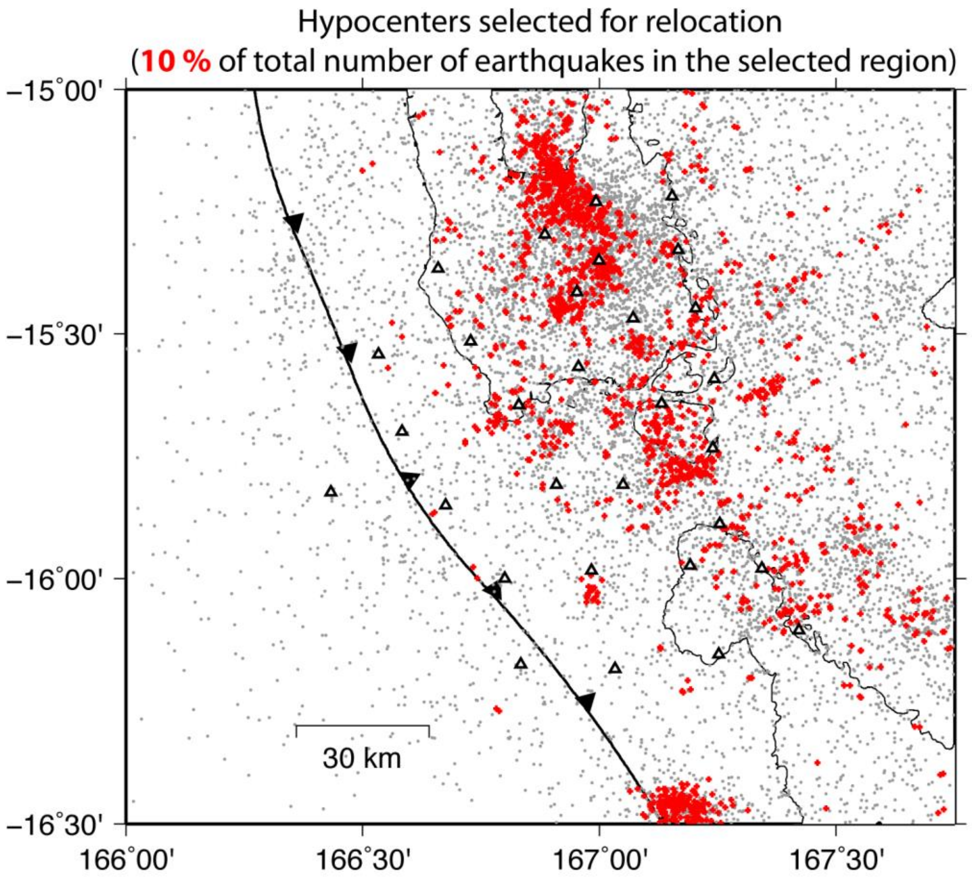
How to reduce these uncertainties ?

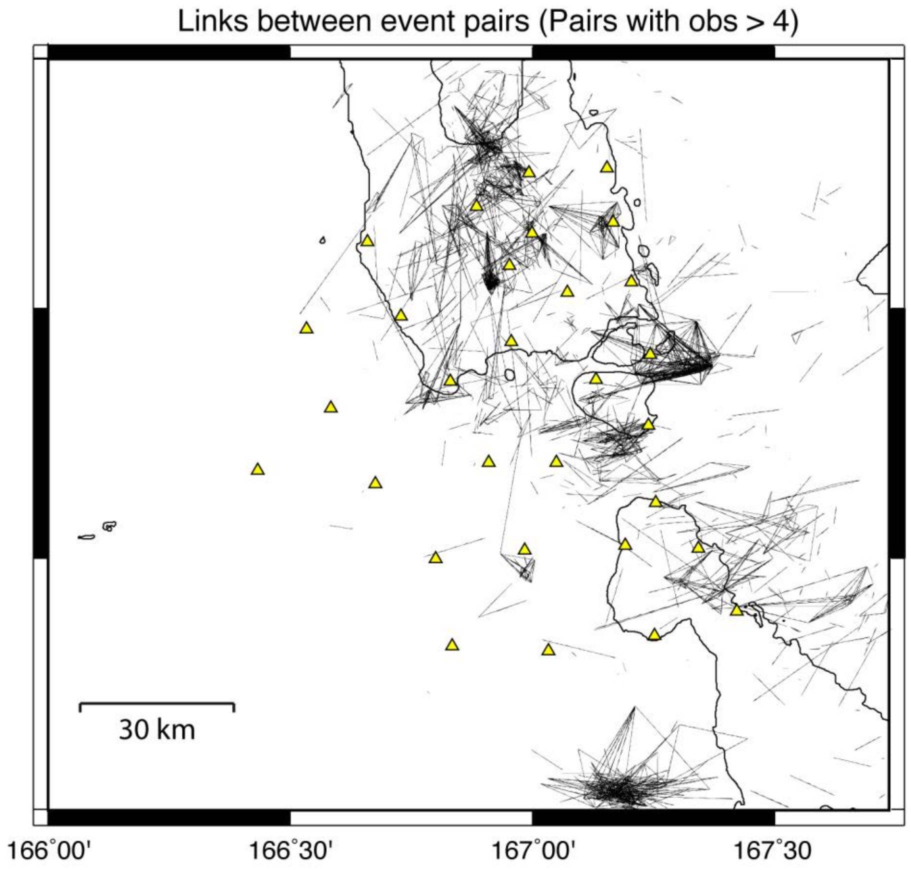
Perform relocation



Relative relocation method

Method: HypoDD
Waldhauser, 2000

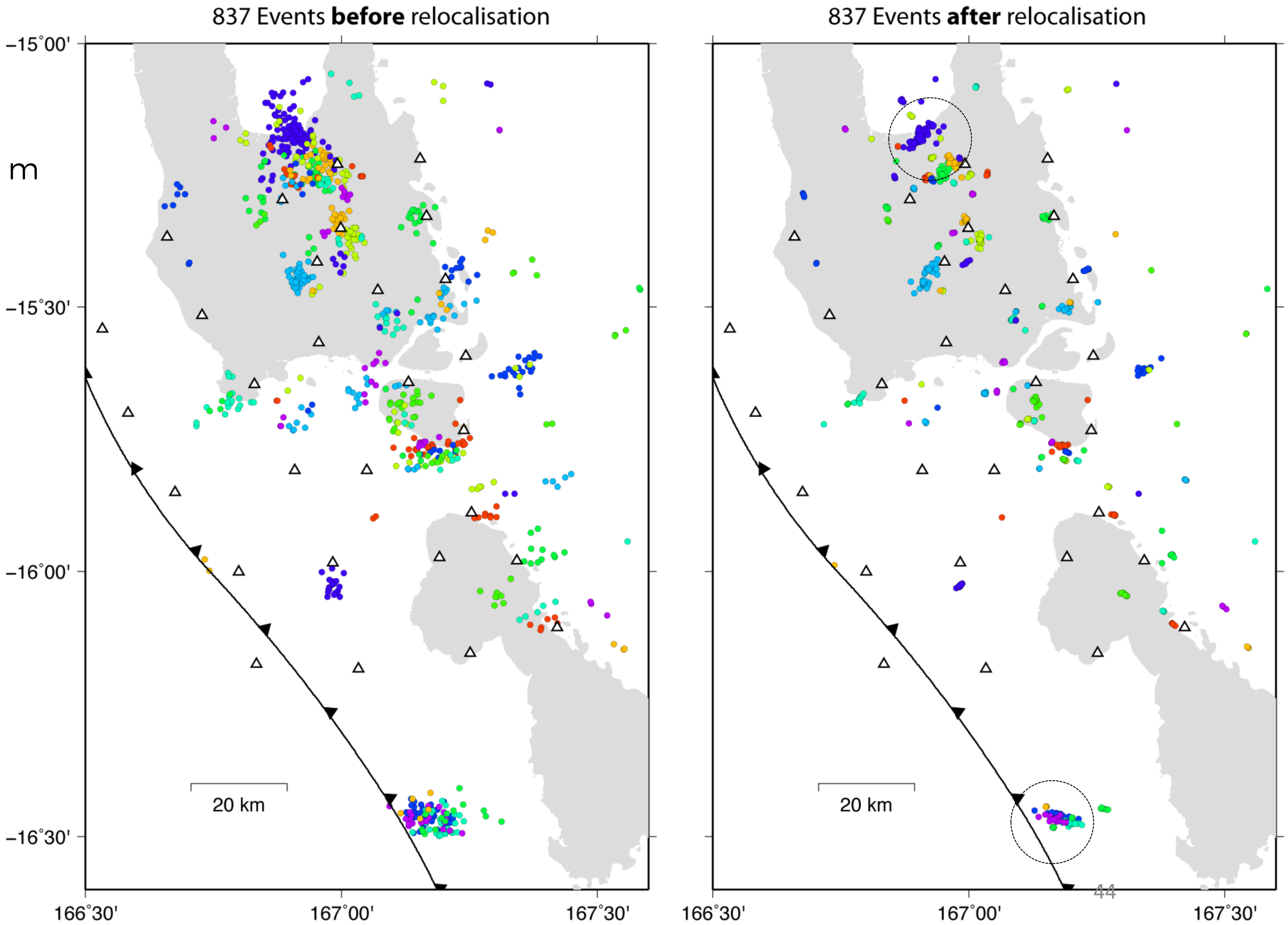




Perform relocation

Relative error of about ~100 m

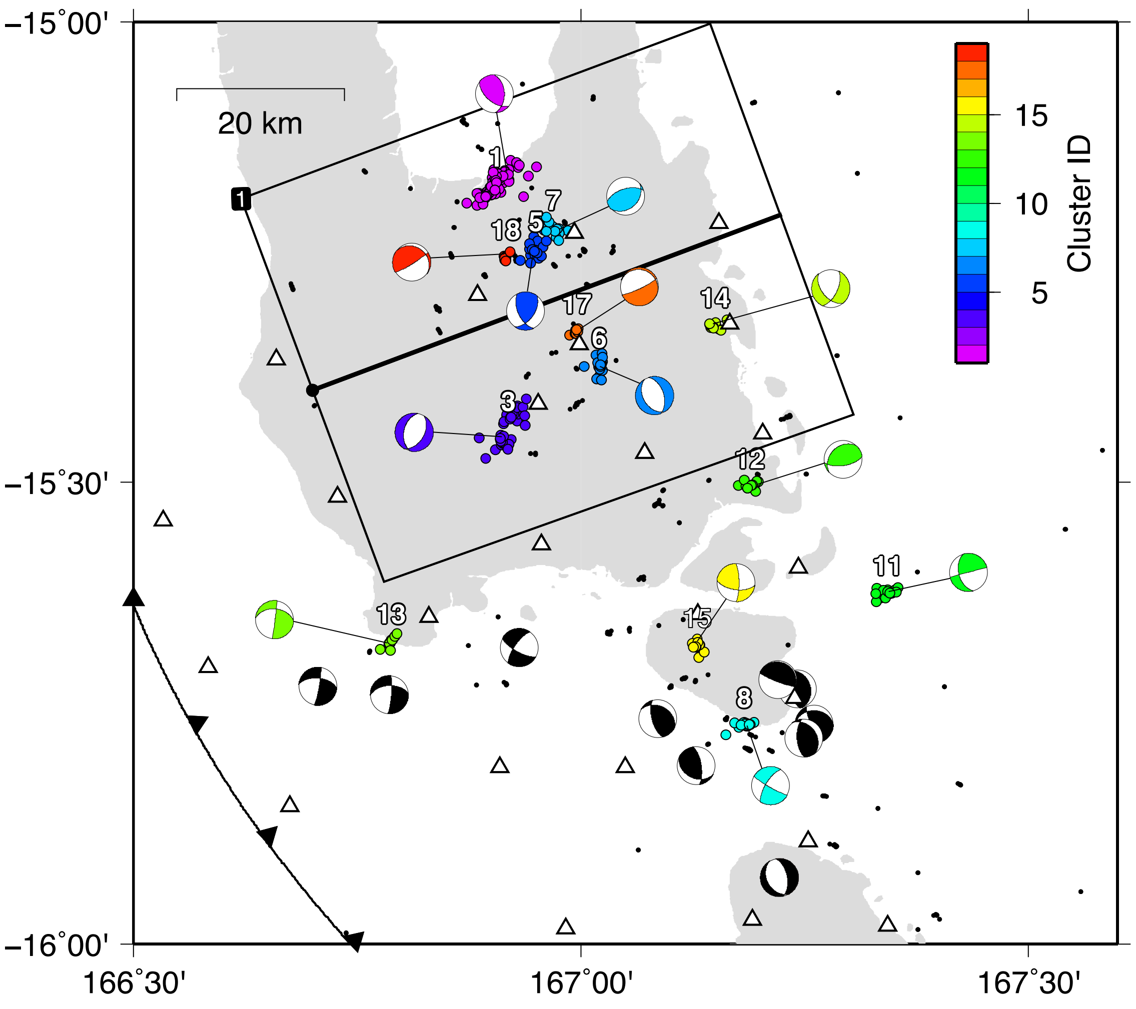
Baillard et al., 2015

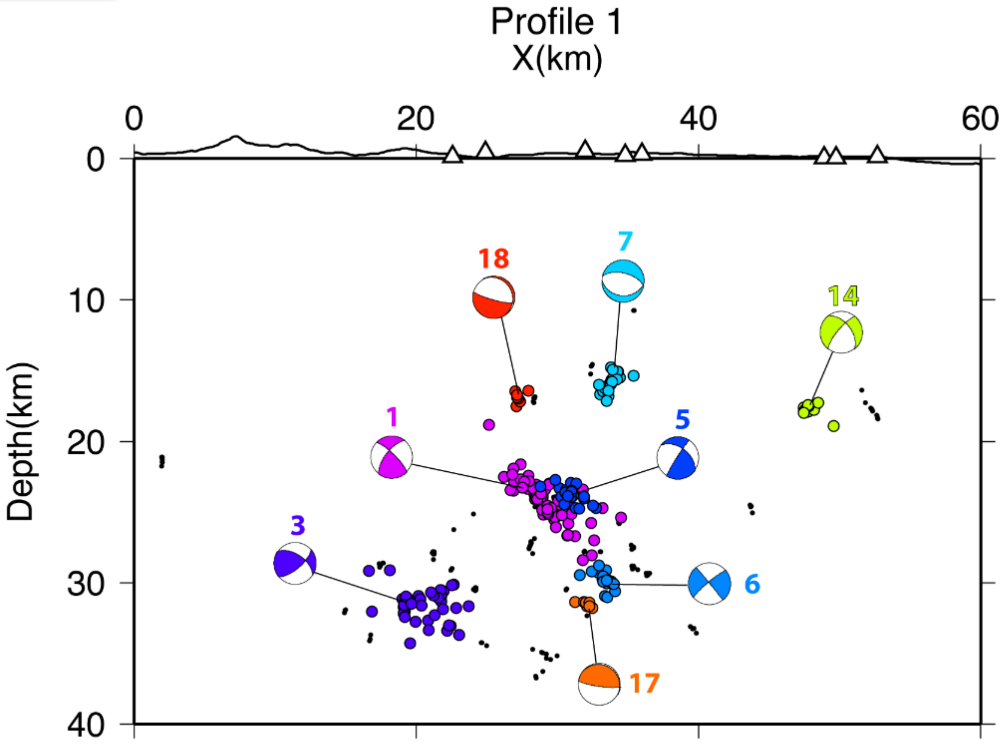


Compute focal mechanisms

Focal mechanism computation on relocated clusters
2104 *P*-polarities 13 clusters

Method: HASH
Hardebeck & Shearer, 2002





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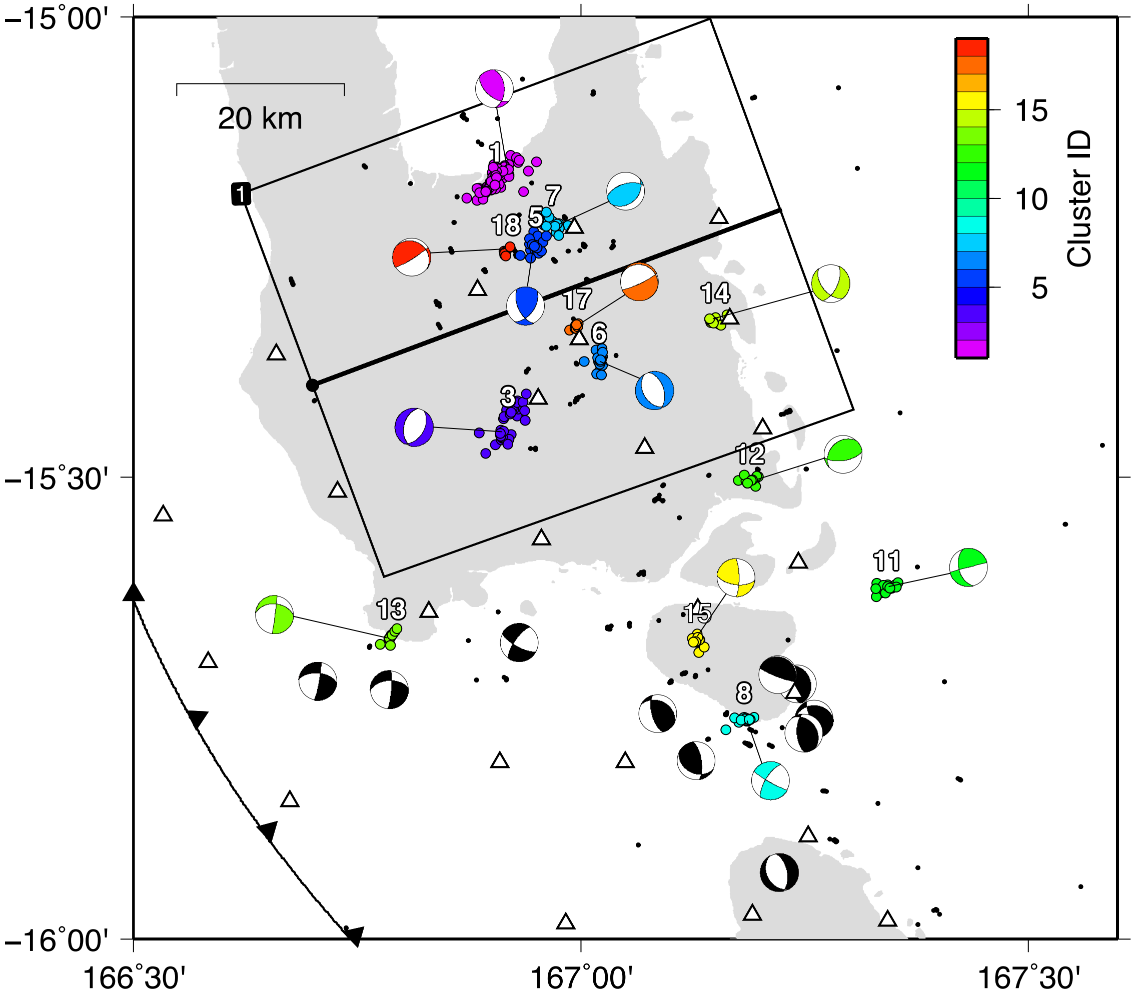
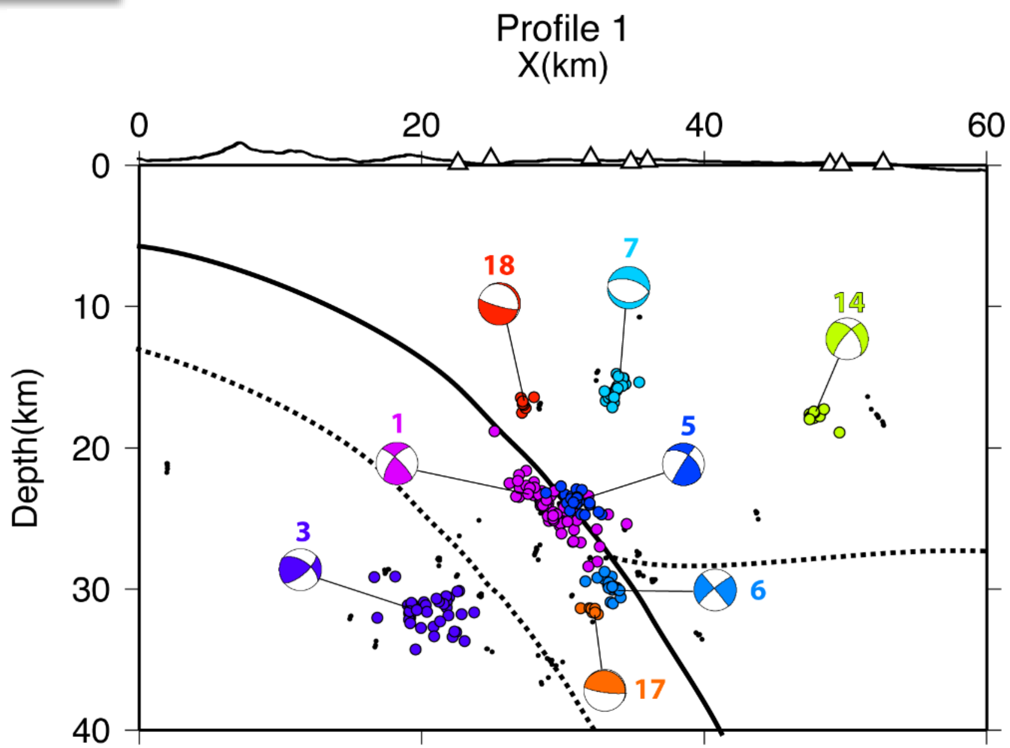


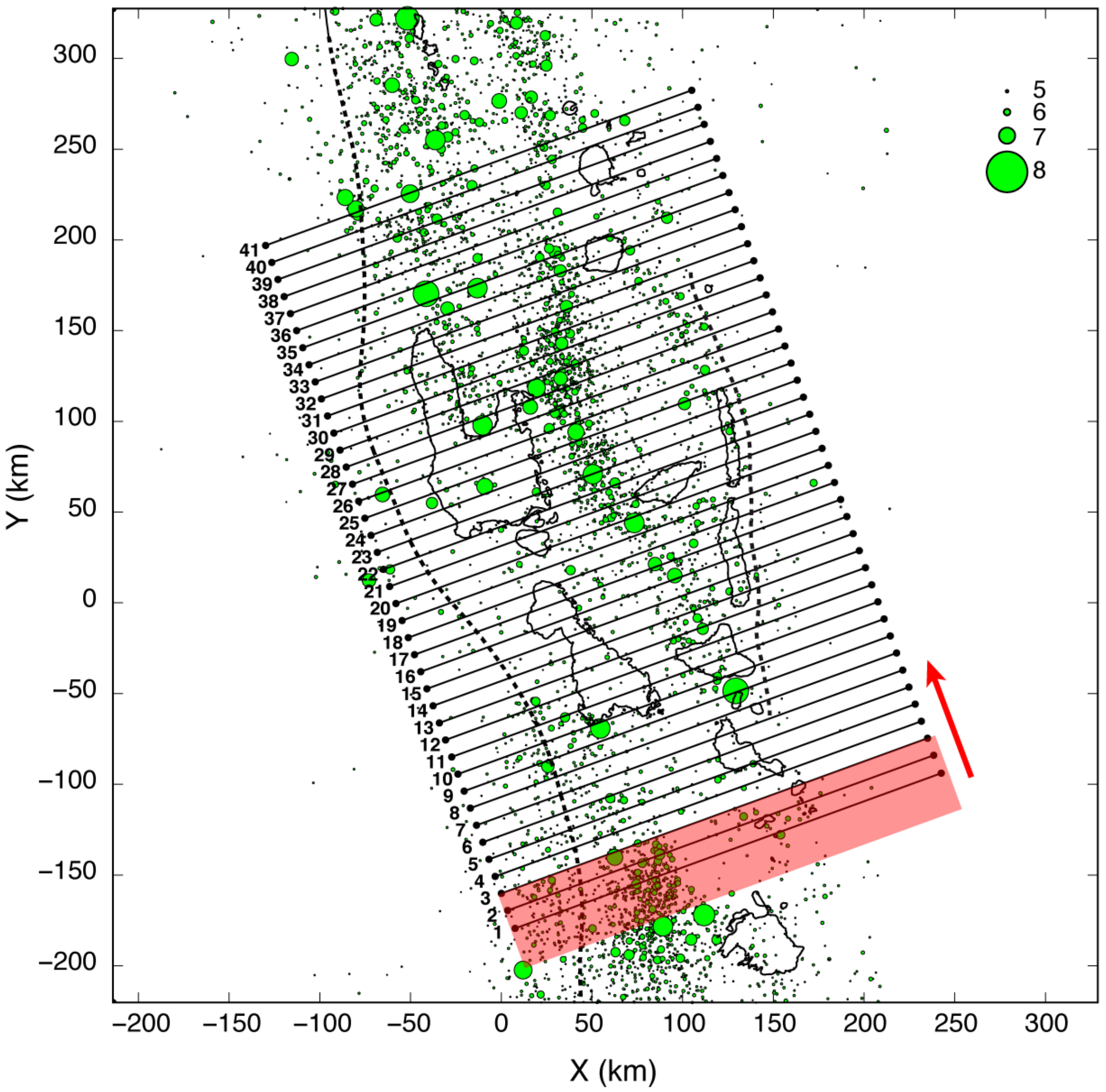


Subduction Interface interpretation

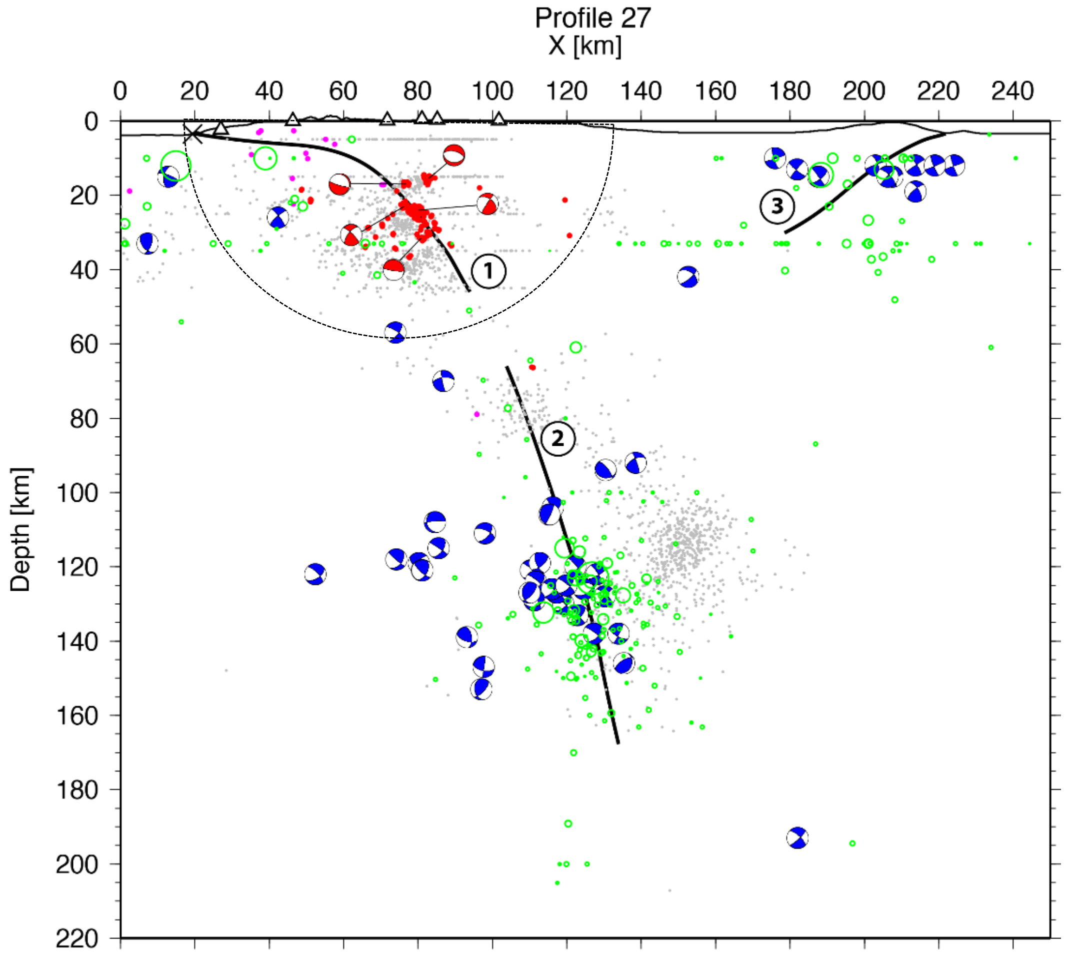
Normal fault mechanism (sideview)

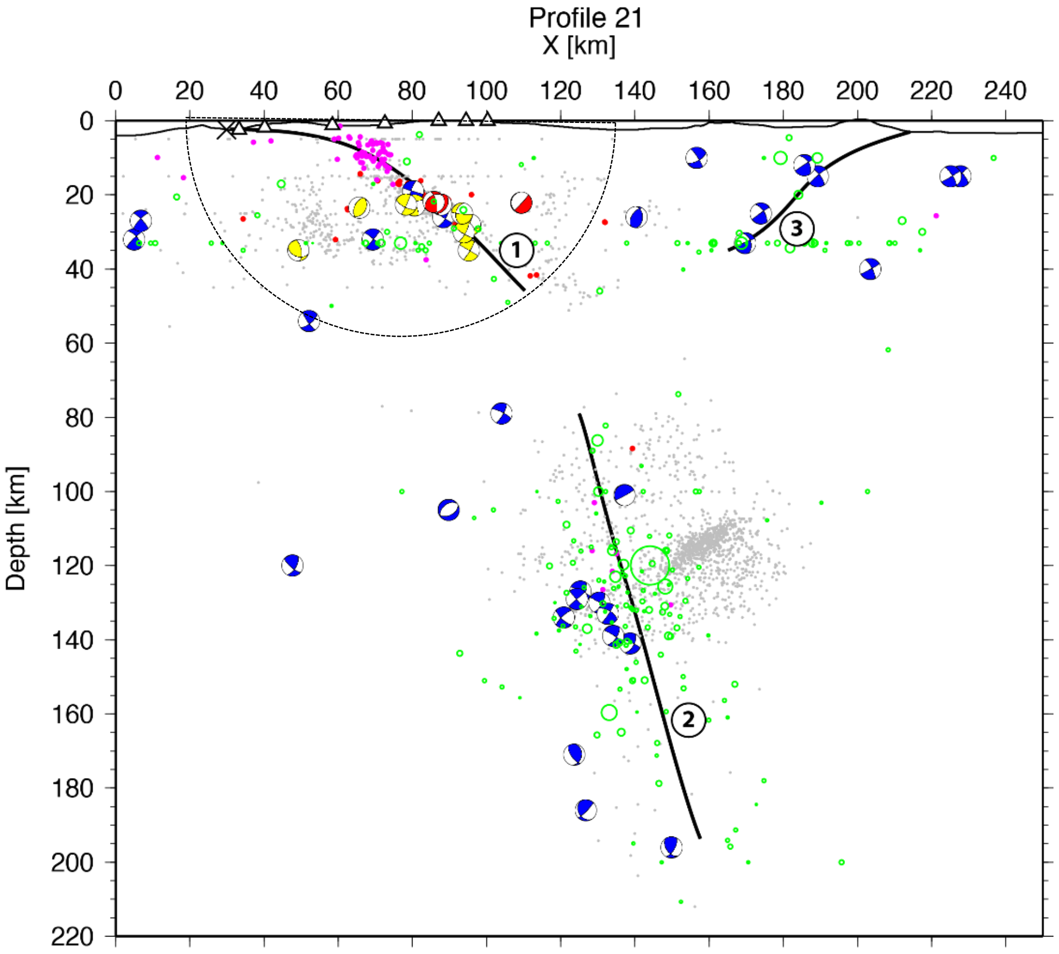
Thrust fault mechanism (sideview)

Manually picking the seismogenic planes under Santo and Maewo on **41** profiles (N70°)



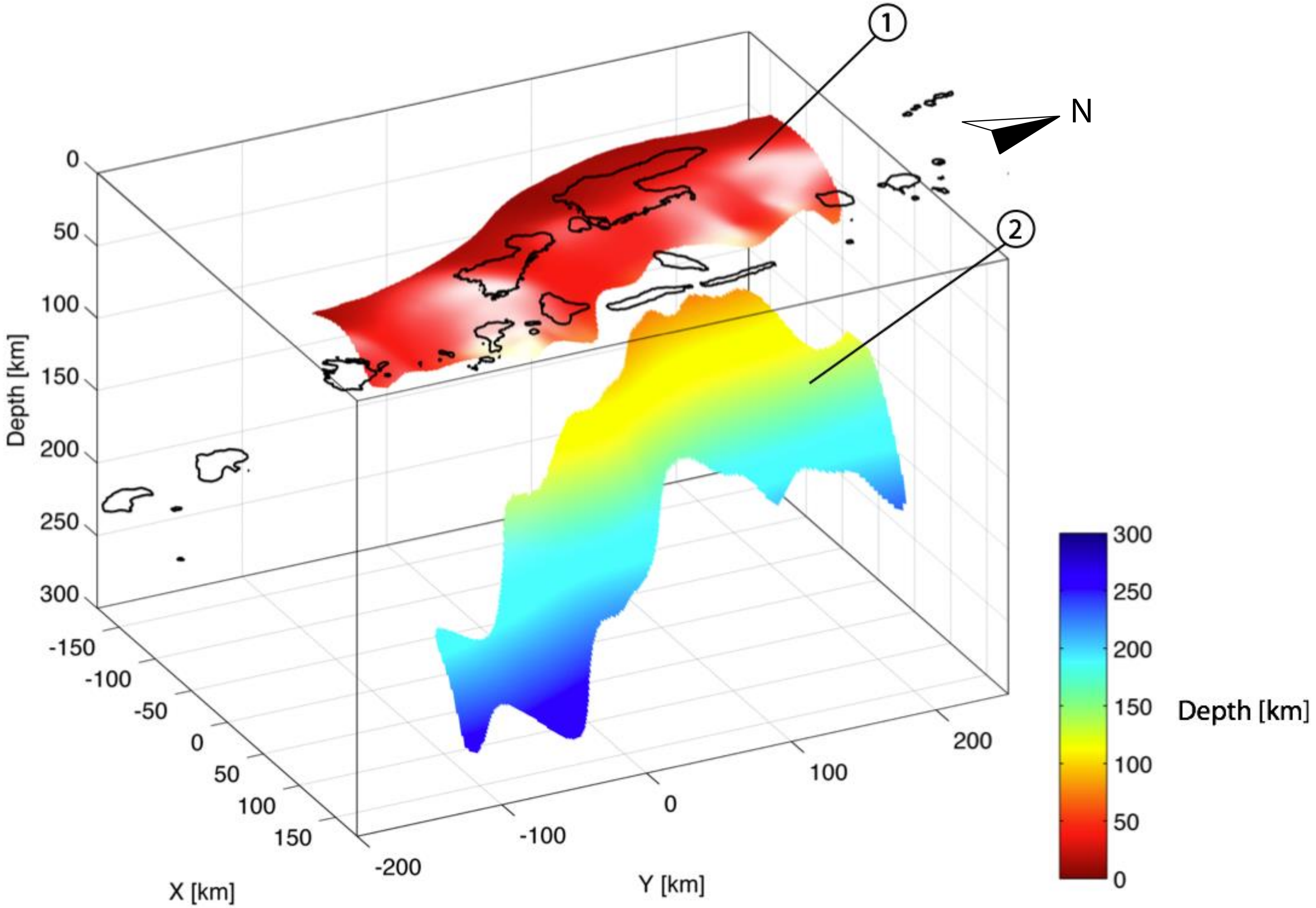
Getting the interface geometry

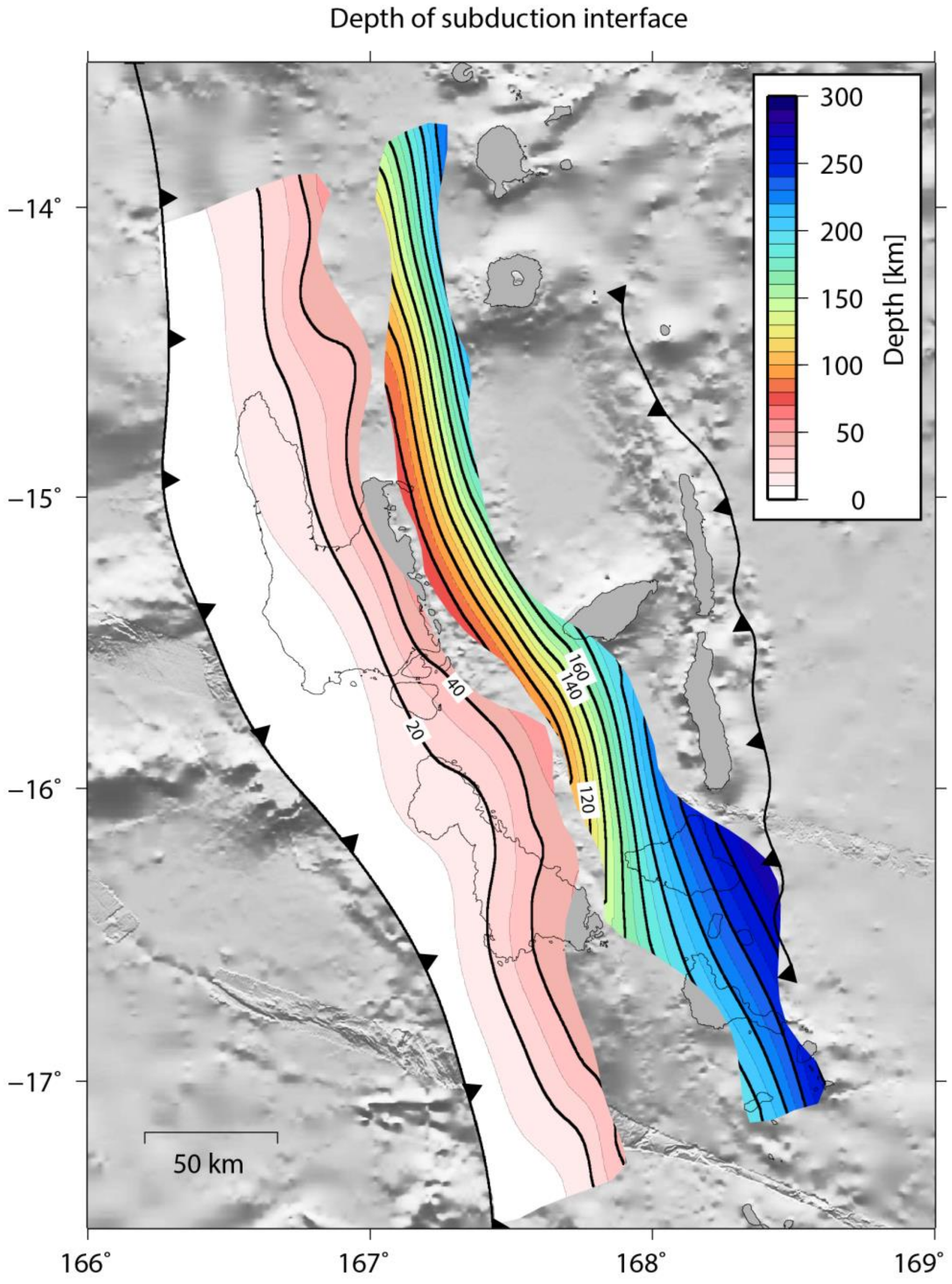




- Local catalog (2008-2009)
- Relocated hypocenters
- Santo 2000 Mw=6.9 sequence (Personal communication M. Régnier)
- NEIC catalog
- Local composite focal mechanism
- Local simple focal mechanism
- Global CMT catalog

Getting the interface geometry





Baillard et al., 2015

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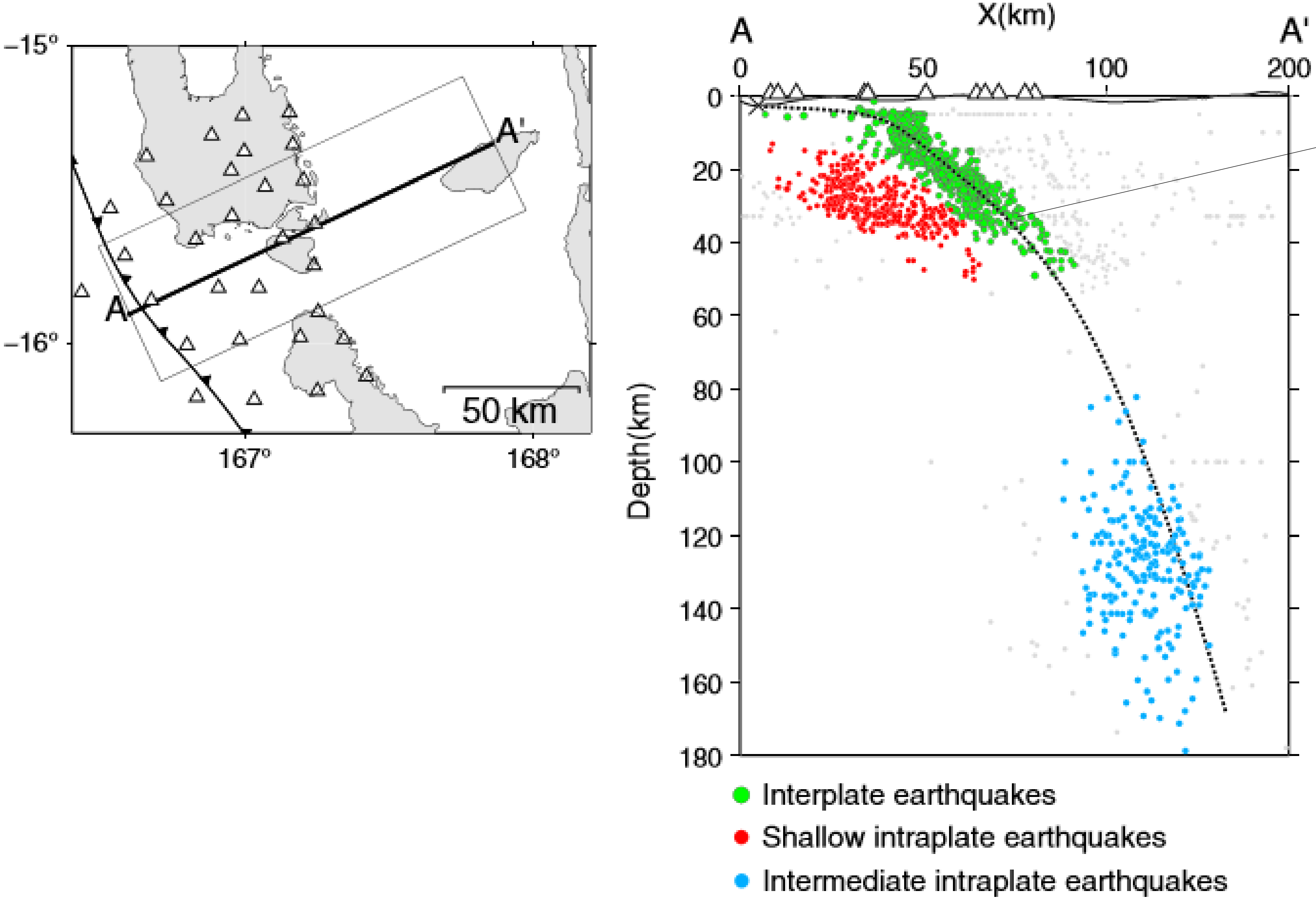
   - 2D mechanical model

4. Conclusions & Perspectives

Interpretation of geometry and seismicity



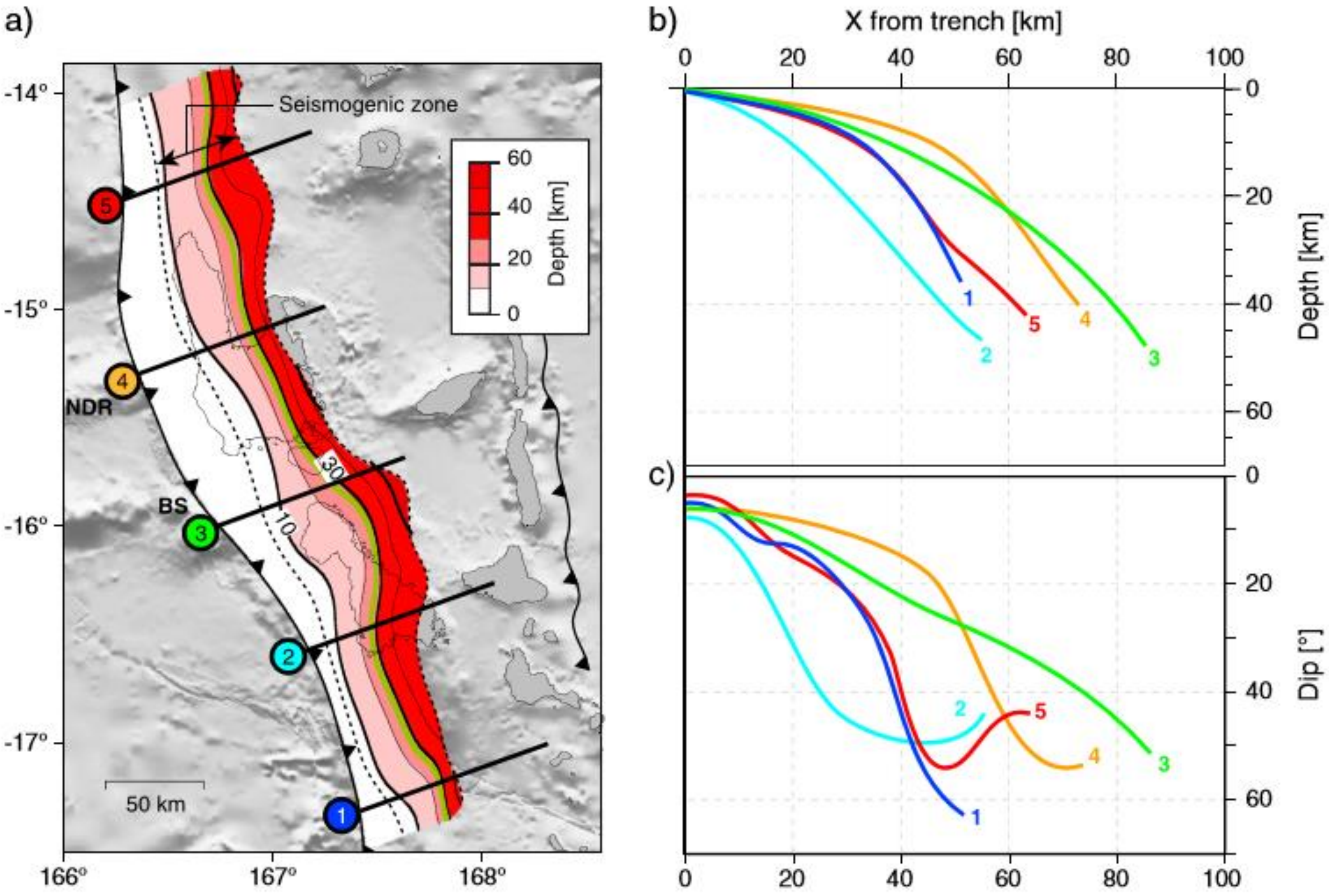
1. Interface geometry

2. Shallow seismogenic zone

3. Shallow intraplate earthquakes

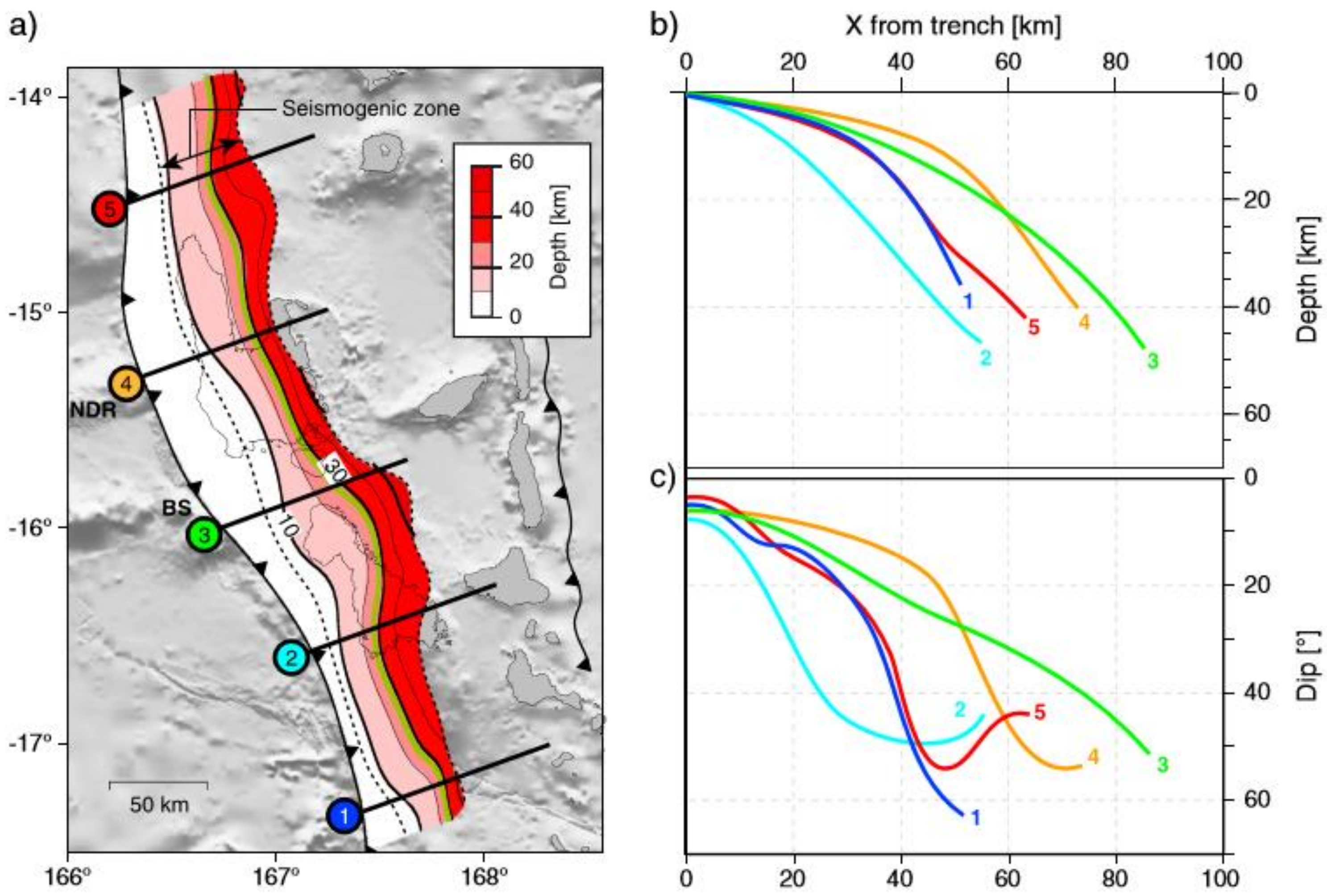
4. Deep intraplate earthquakes

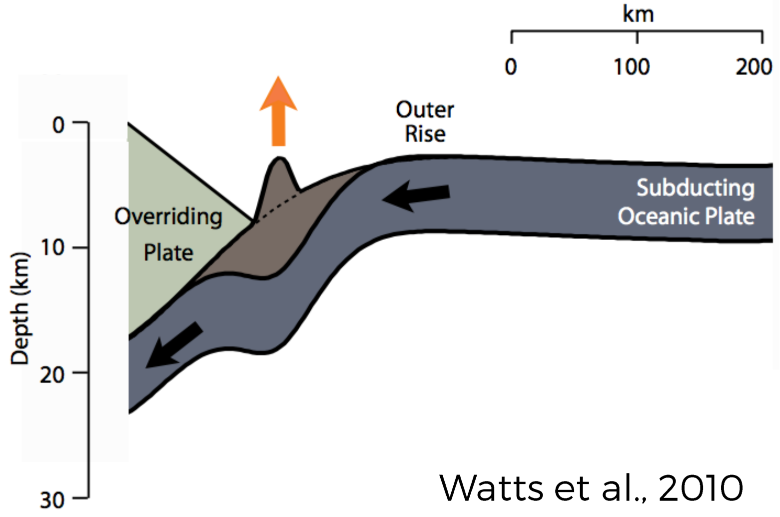
Geometry of the interface



Geometry of the interface

Bump induced by the **buoyancy effect of the d'Entrecasteaux ridge**





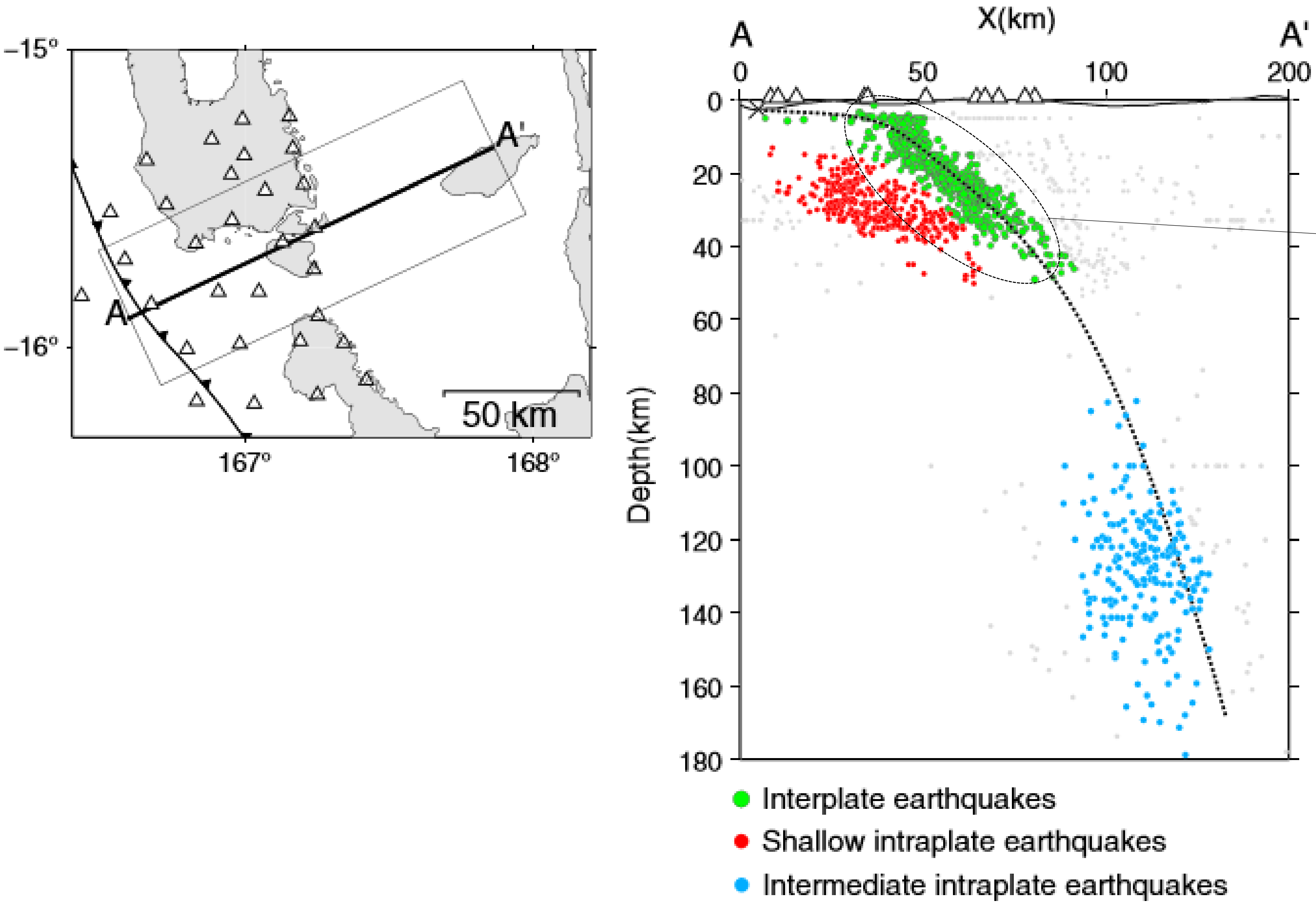
Watts et al., 2010

This buoyancy effect could explain 20% to 60% of the uplift observed on the forearc islands

Gardner et al., 1992; Litchfield et al., 2007

Baillard et al., 2015

Shallow seismogenic zone



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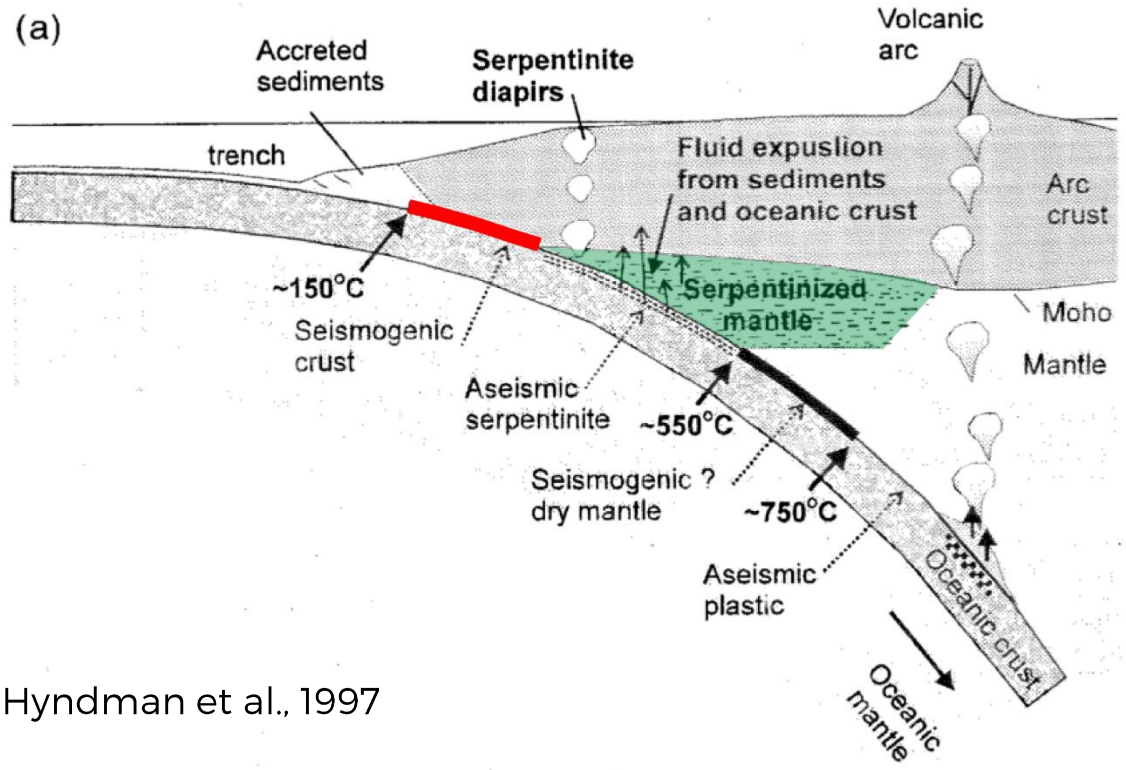
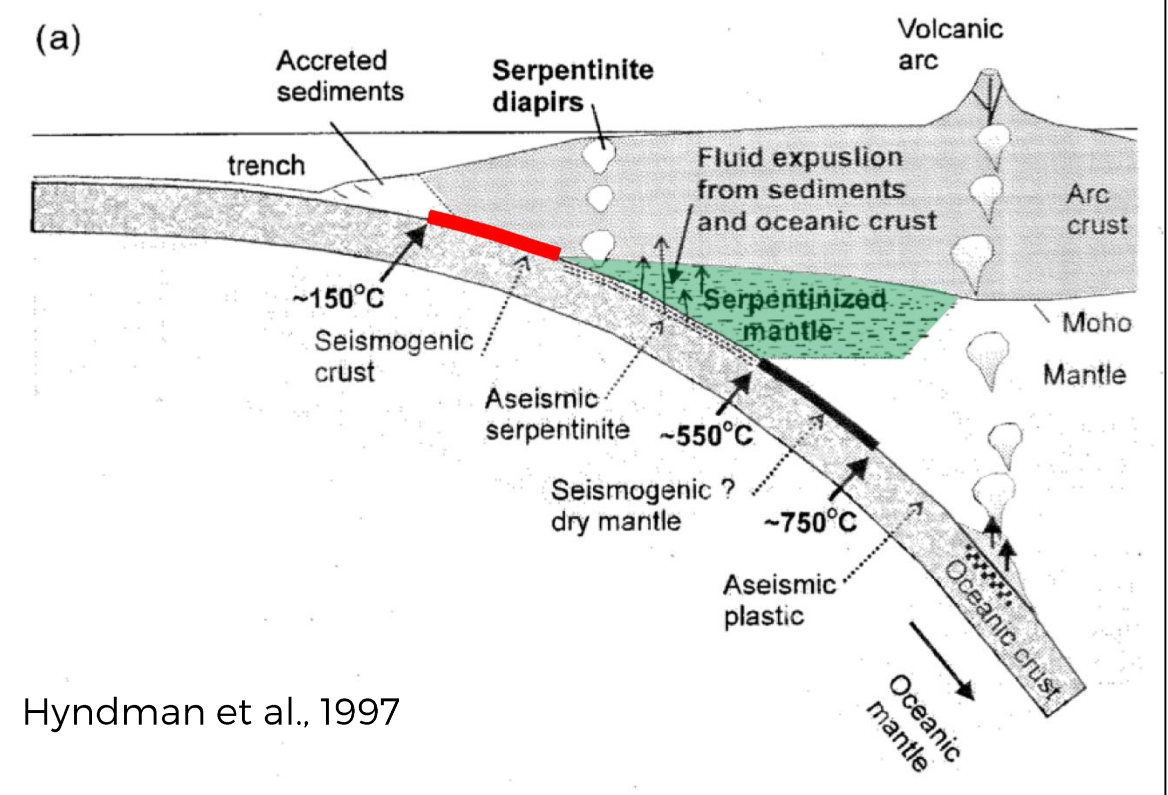
Previous model



Hyndman et al., 1997

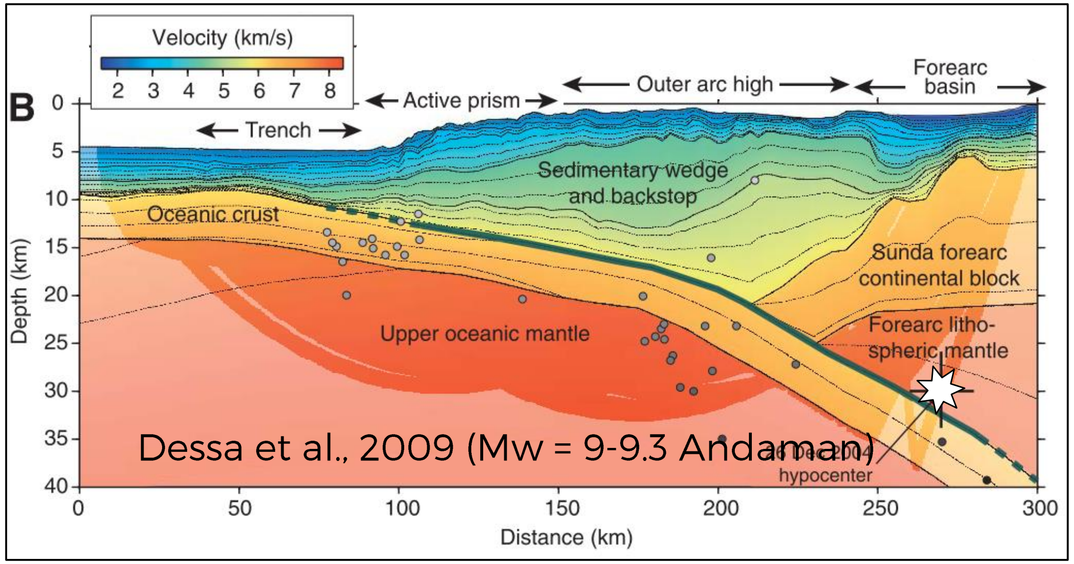
Shallow seismogenic zone

Previous model



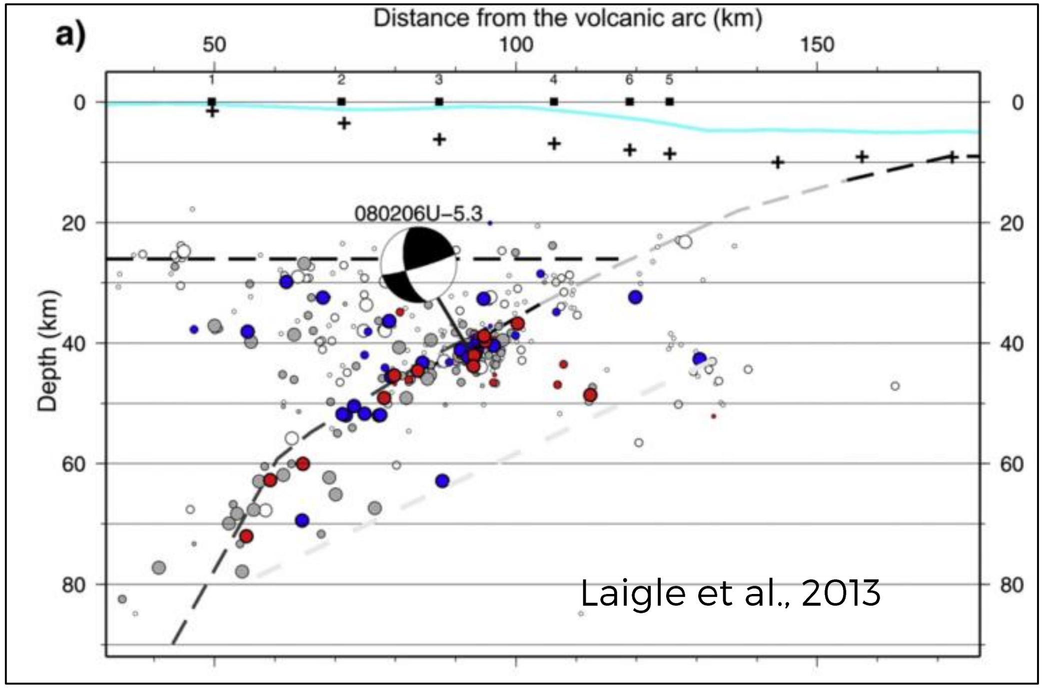
Hyndman et al., 1997

Andaman



Dessa et al., 2009 (Mw = 9-9.3 Andaman)

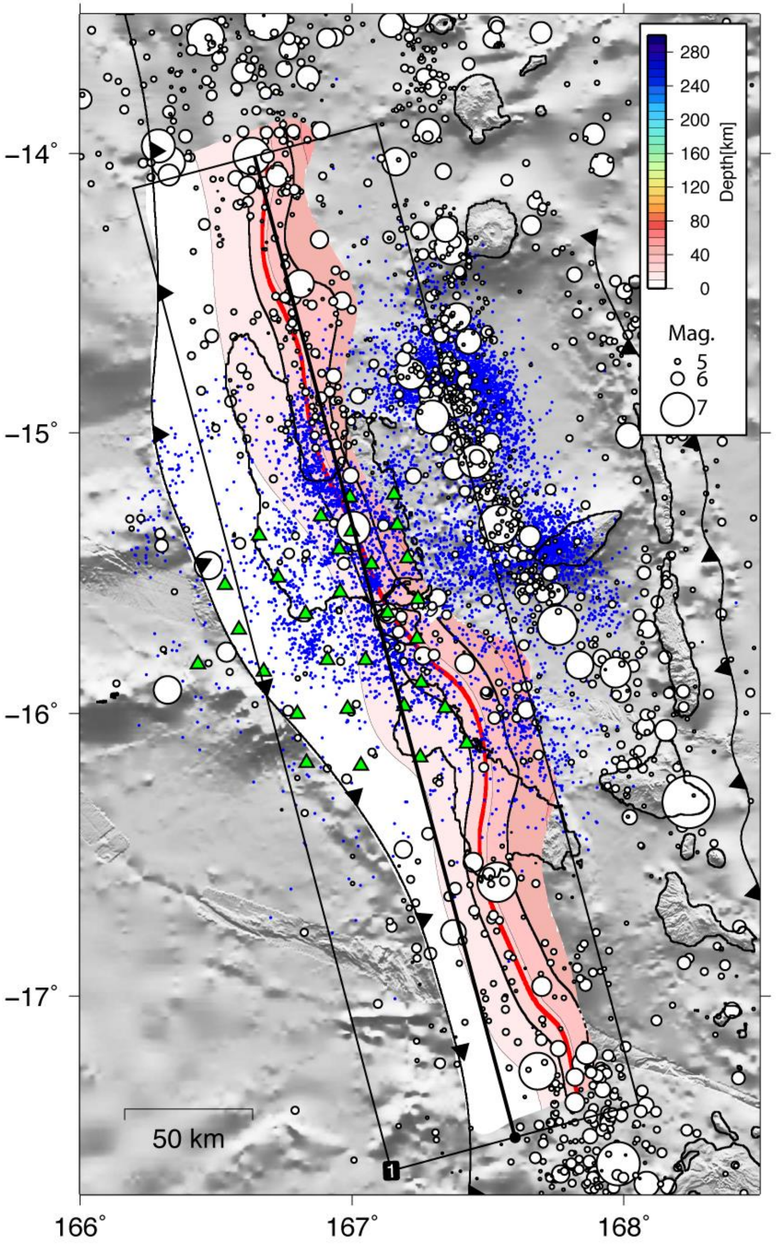
Martinique



Laigle et al., 2013

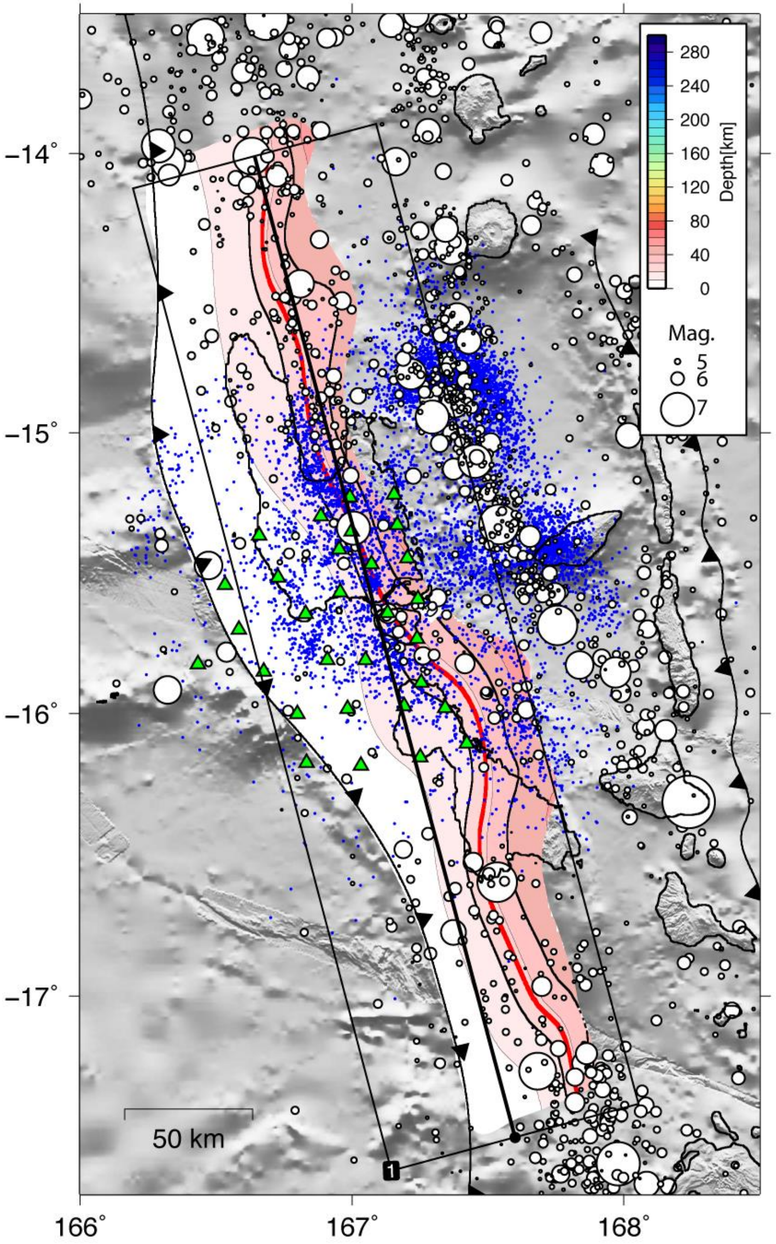
Shallow seismogenic zone

Seismicity in the central Vanuatu region

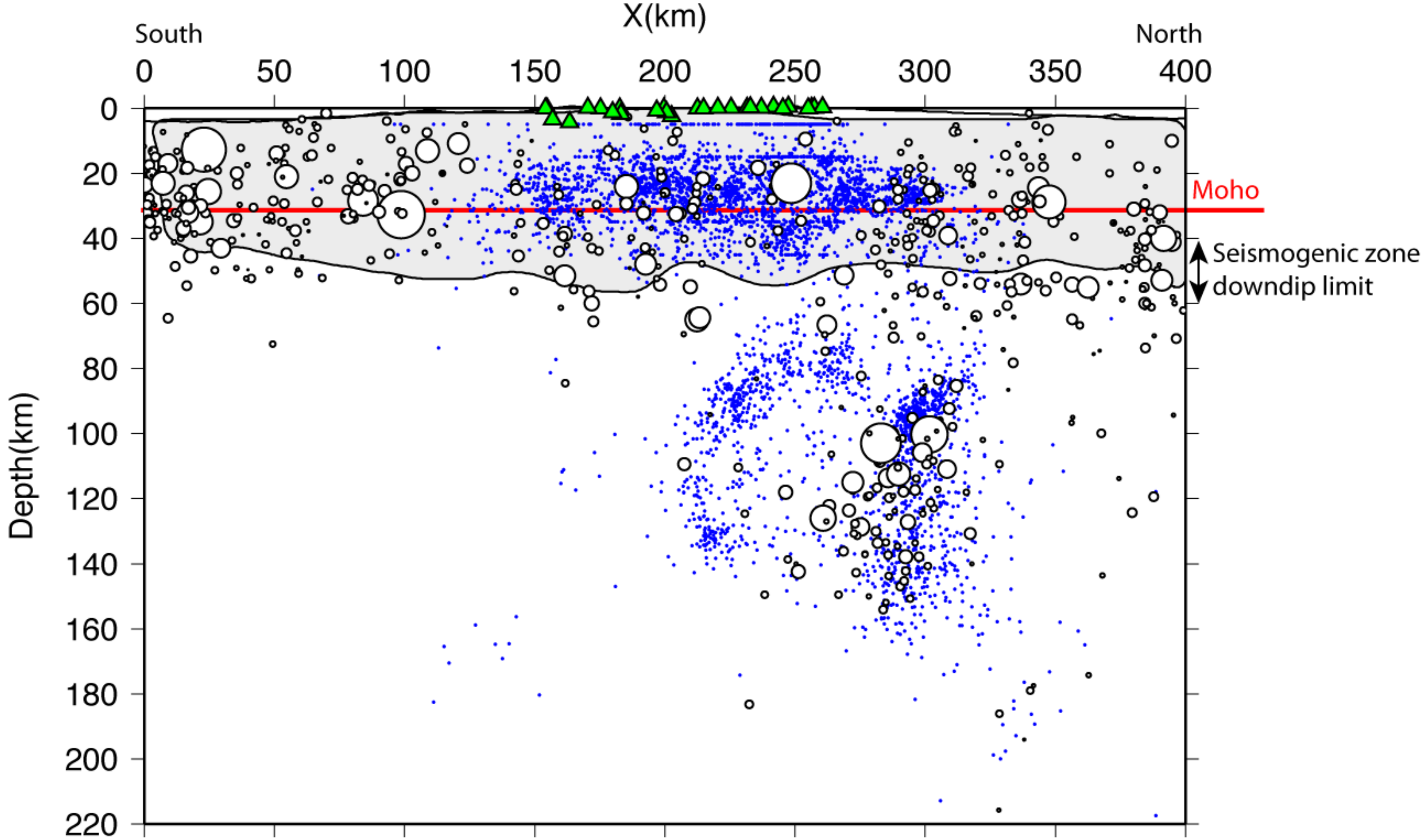


Shallow seismogenic zone

Seismicity in the central Vanuatu region



Profile 1



The seismogenic downdip limit is 20 km under the forearc moho

- Seismicity at the crust/mantle contact
- Stick-slip behavior of the contact

Why ?

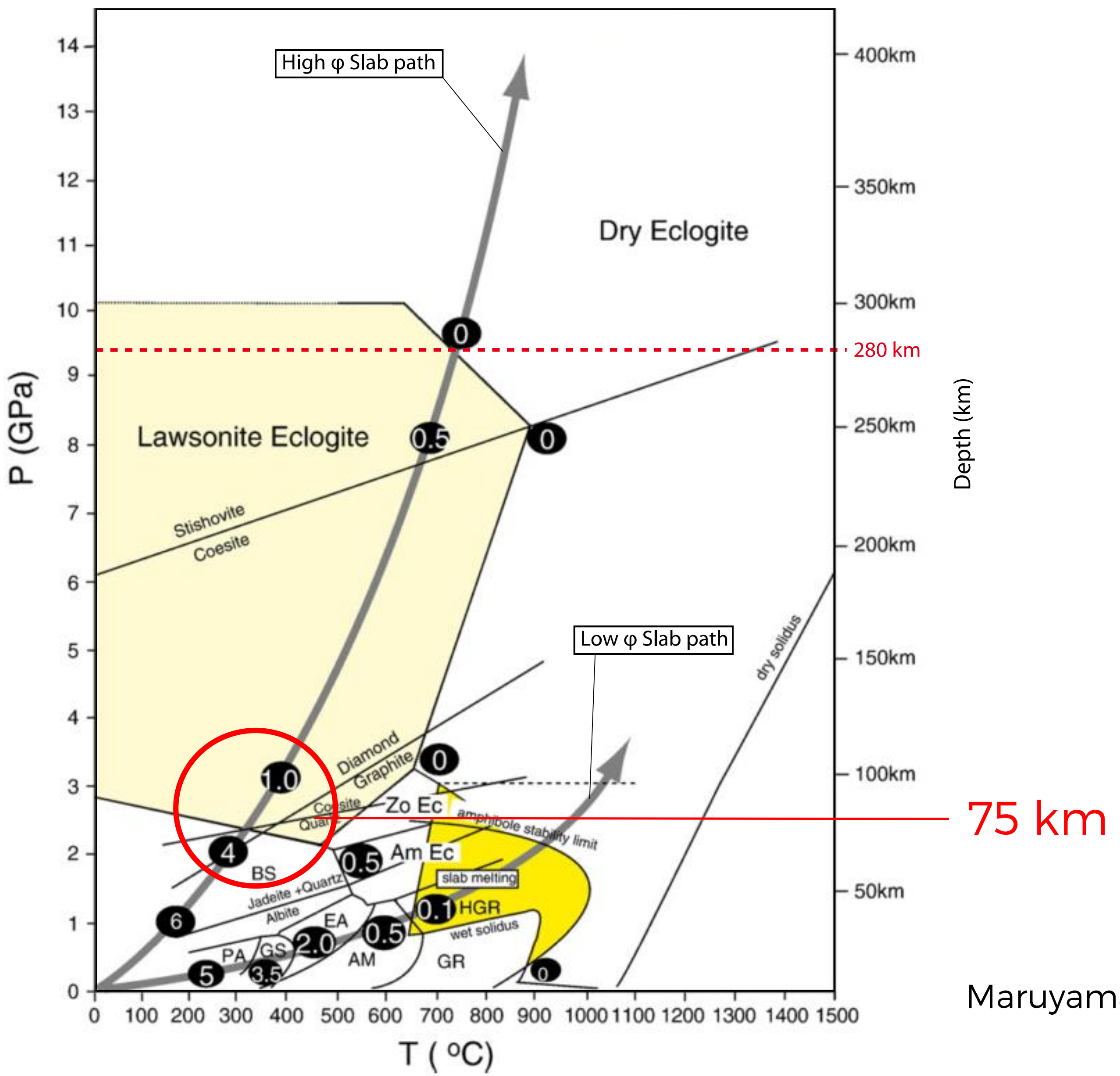
Shallow seismogenic zone

Thermal parameter: $\phi = A.V.\sin\delta$

~ 3500 for australian plate in Vanuatu
(Mean ~1000 for other subduction zones)

Shallow seismogenic zone

P-T diagram indicating facies of crustal rocks



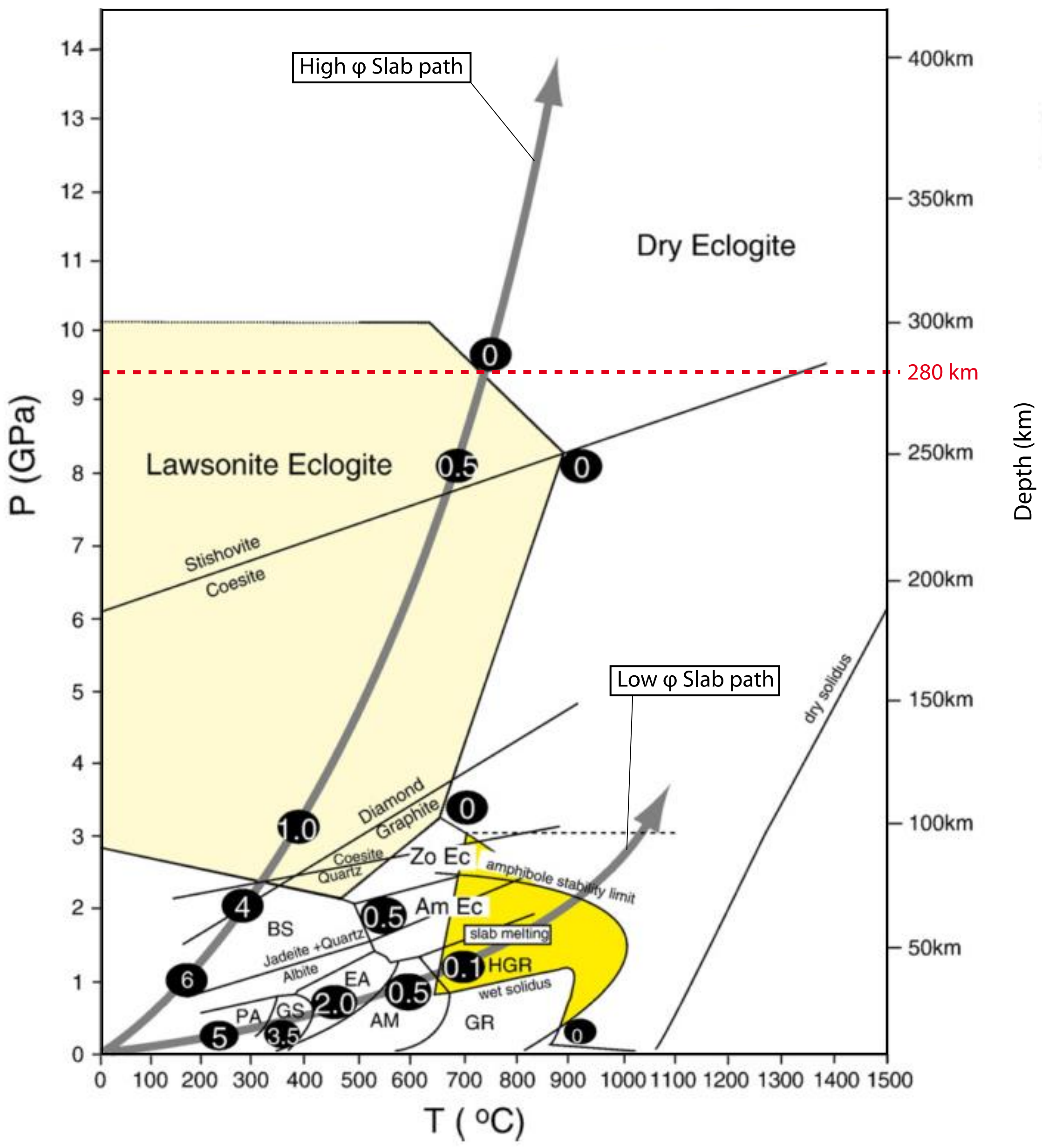
Thermal parameter: $\phi = A.V.\sin\delta$

~ 3500 for australian plate in Vanuatu
(Mean ~1000 for other subduction zones)

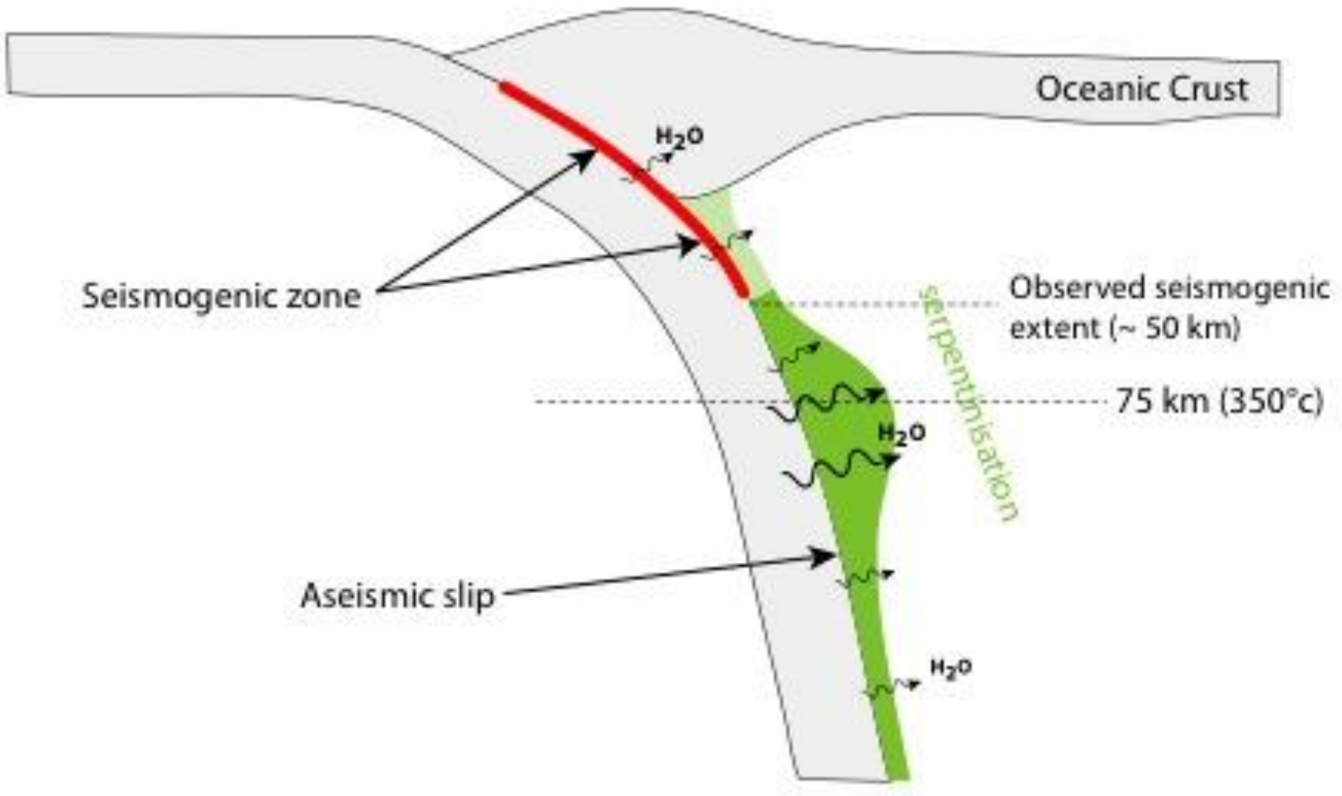
Maruyama & Okamoto., 2007

Shallow seismogenic zone

P-T diagram indicating facies of crustal rocks

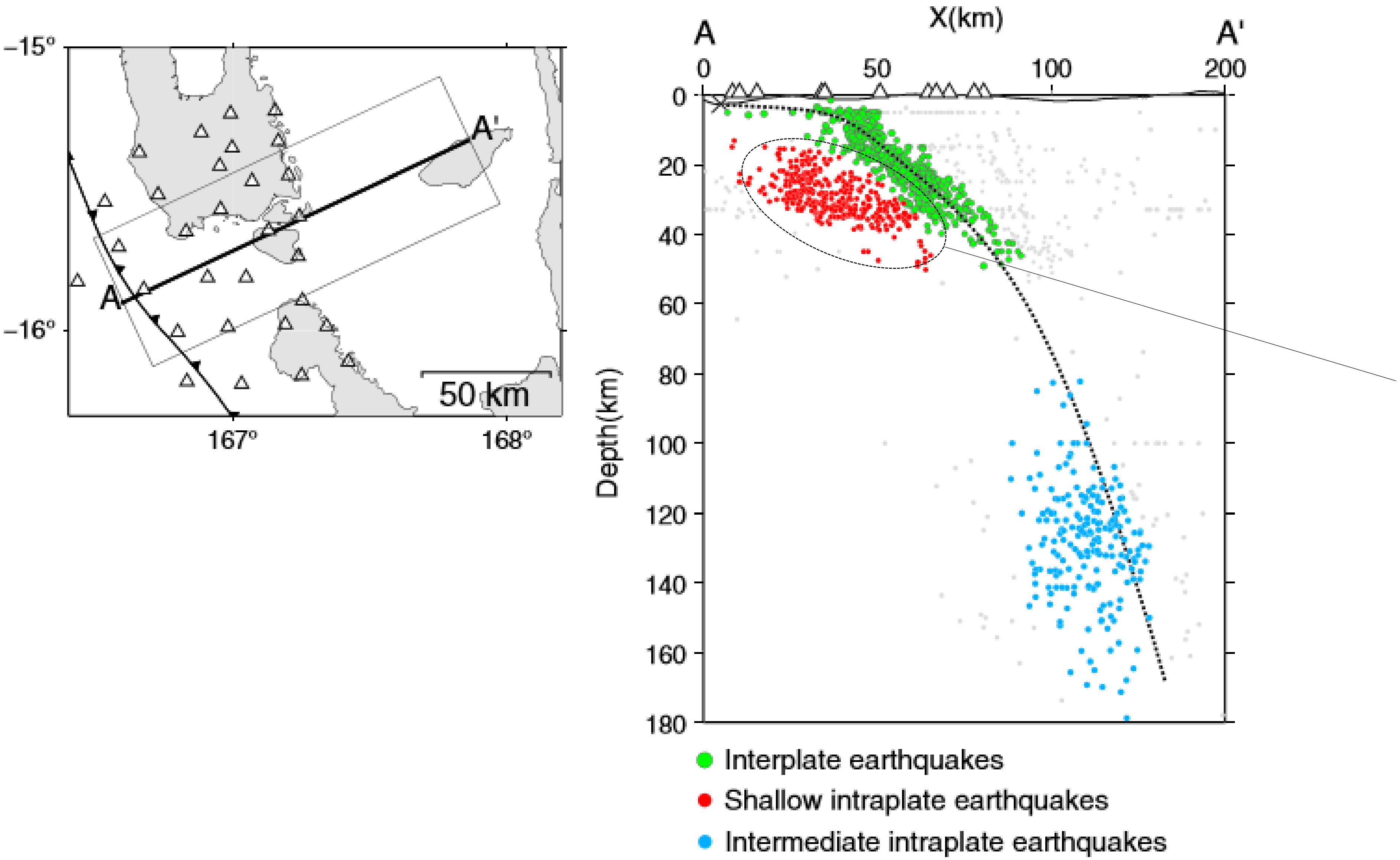


Proposed conceptual model



stick-slip behavior of the crust/mantle contact possible

Shallow intraplate earthquakes



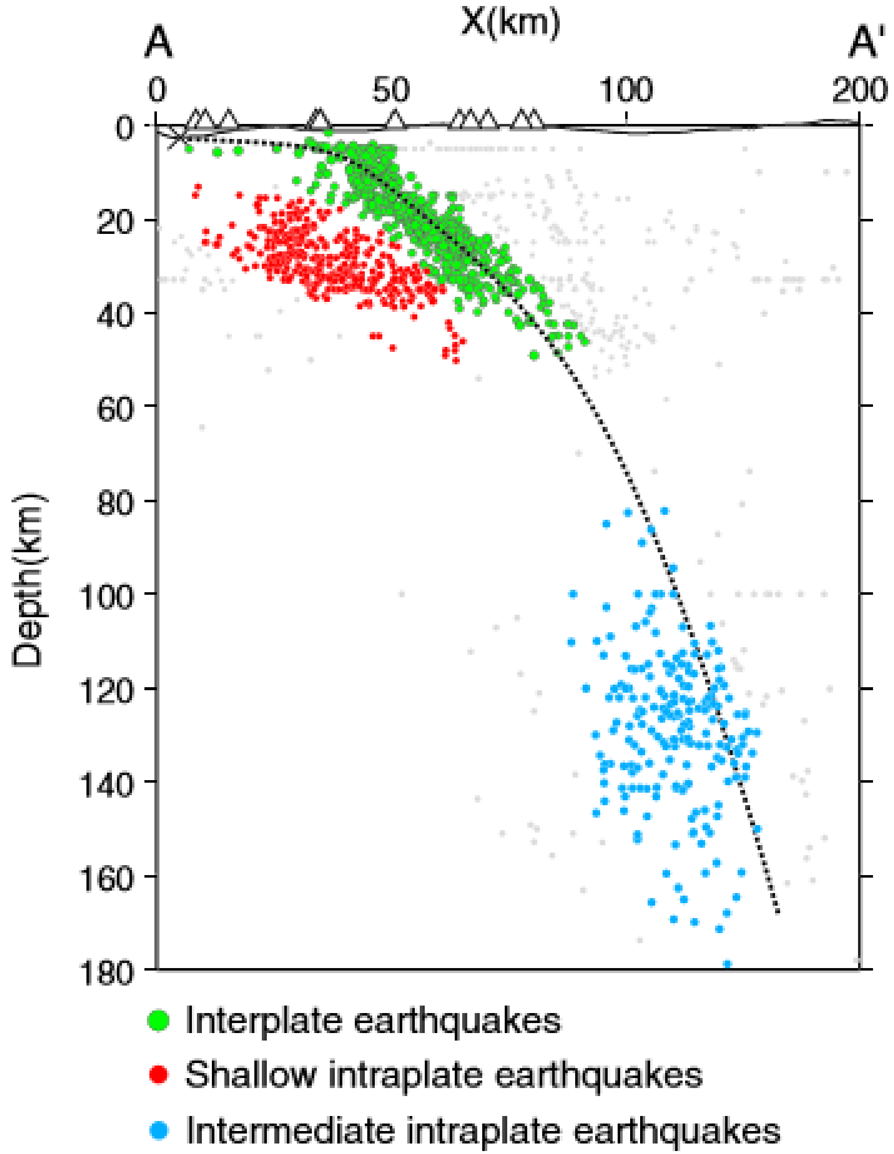
1. Interface geometry

2. Shallow seismogenic zone

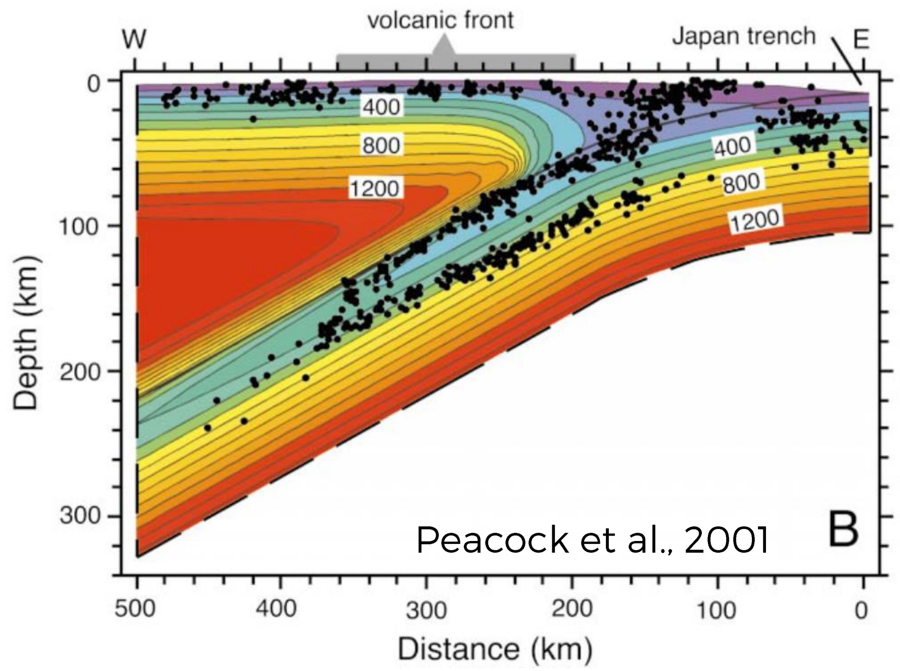
3. Shallow intraplate earthquakes

4. Deep intraplate earthquakes

Shallow intraplate earthquakes



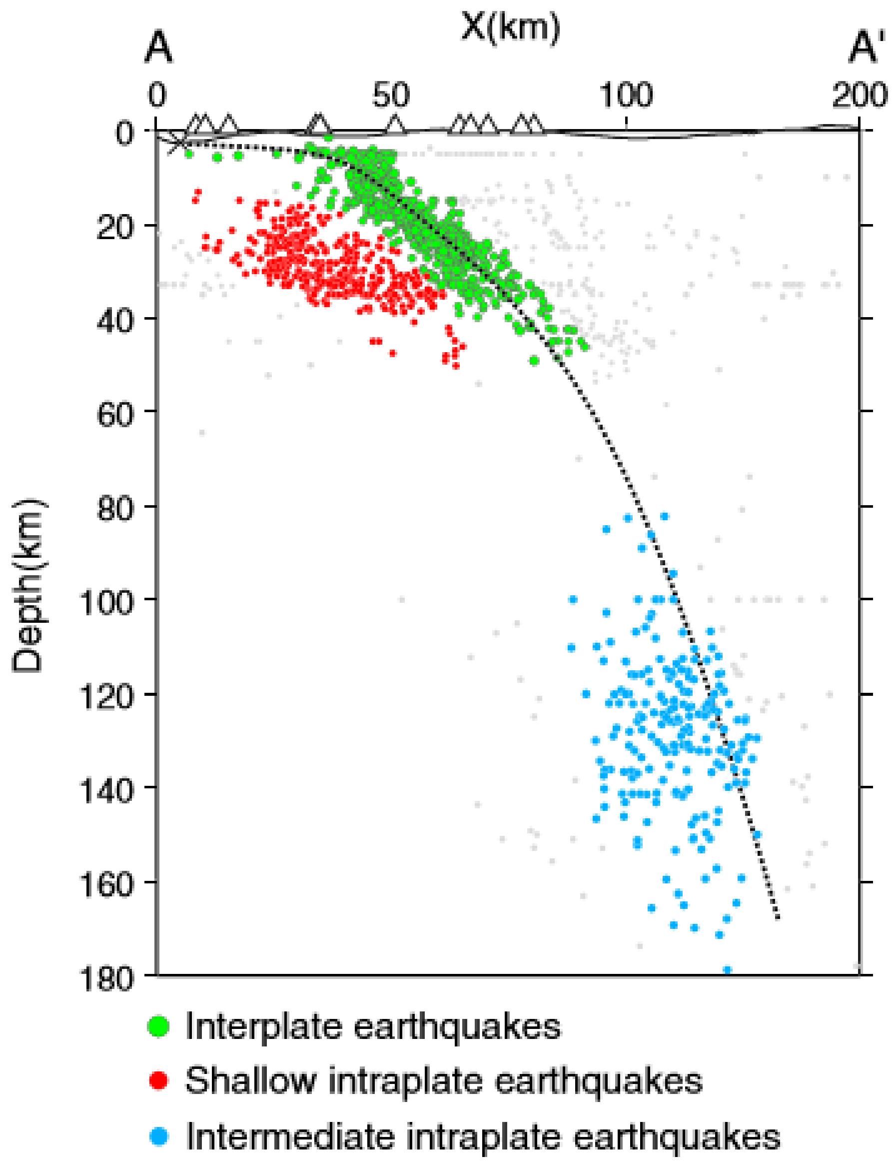
Double seismic zone observed in Japan

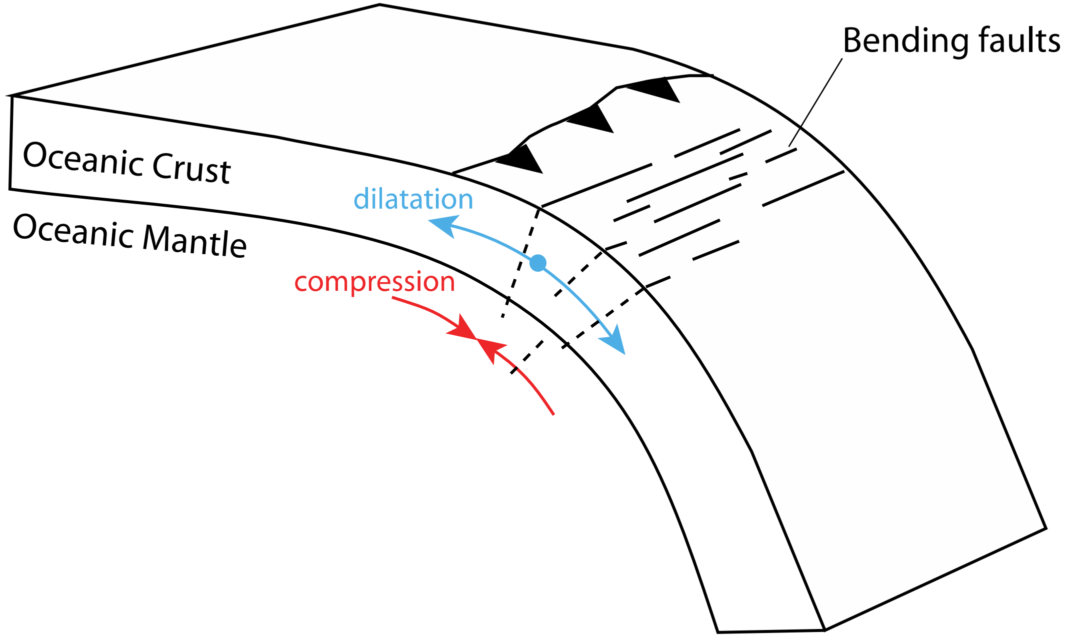


Deserpentinization and dehydration embrittlement is a possible cause of seismicity in the lower layer of the double seismic zone.
(Bradley et al., 2003; Rüpke et al., 2004)

In the Vanuatu case the double seismic zone is at depth lower than 45 km. Temperature is probably lower than 450°C preventing deserpentinization in the upper mantle of the subducting slab

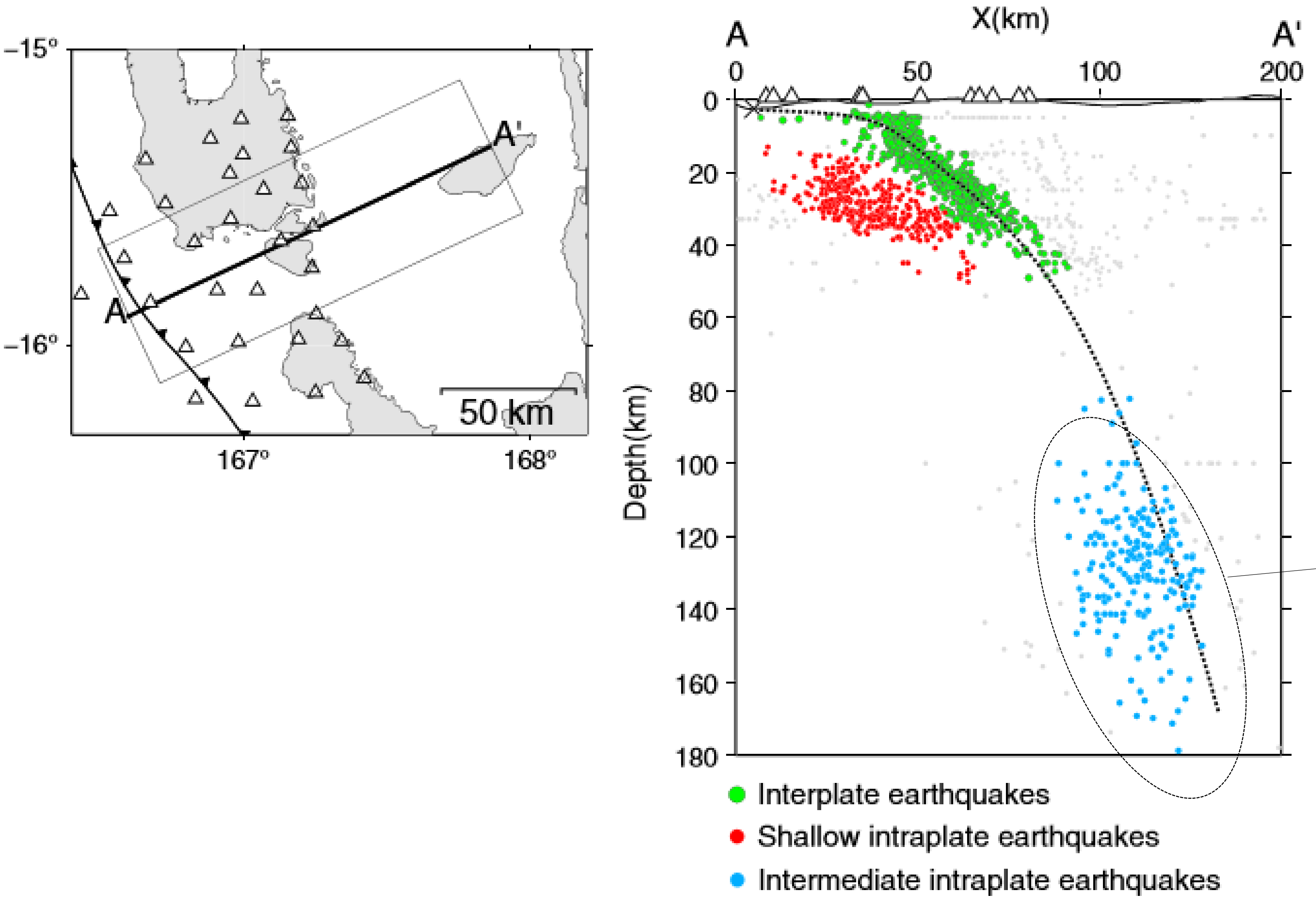
Shallow intraplate earthquakes





From Miyoshi & Obara, 2011

Deep intraplate earthquakes



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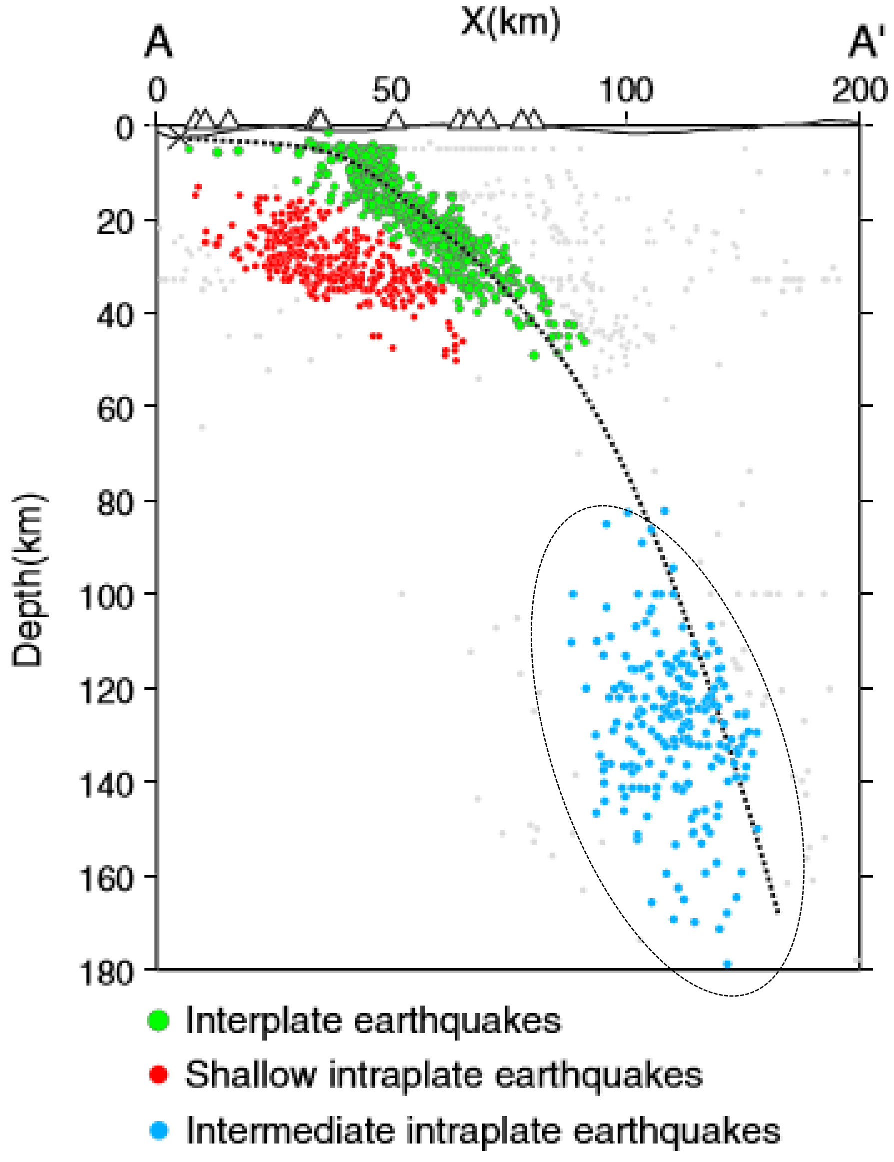
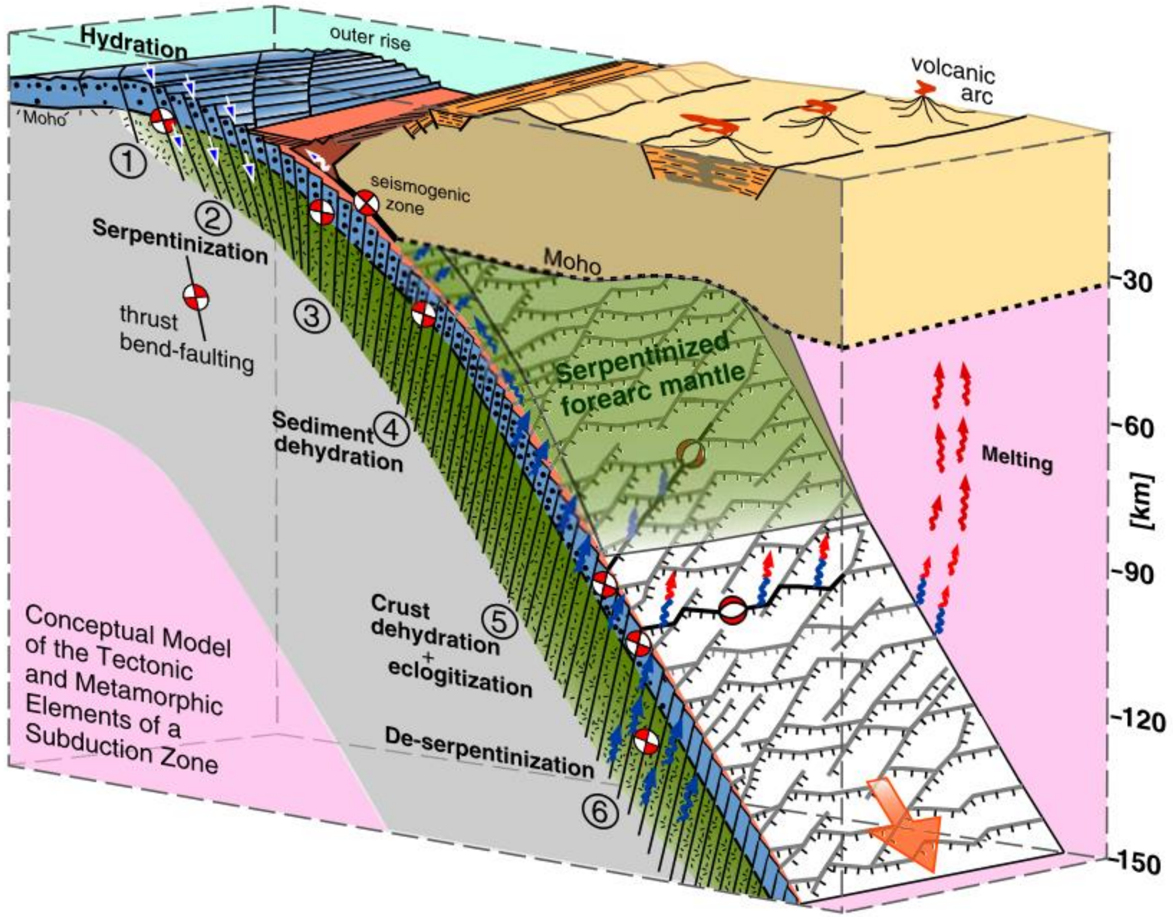
Deep intraplate earthquakes

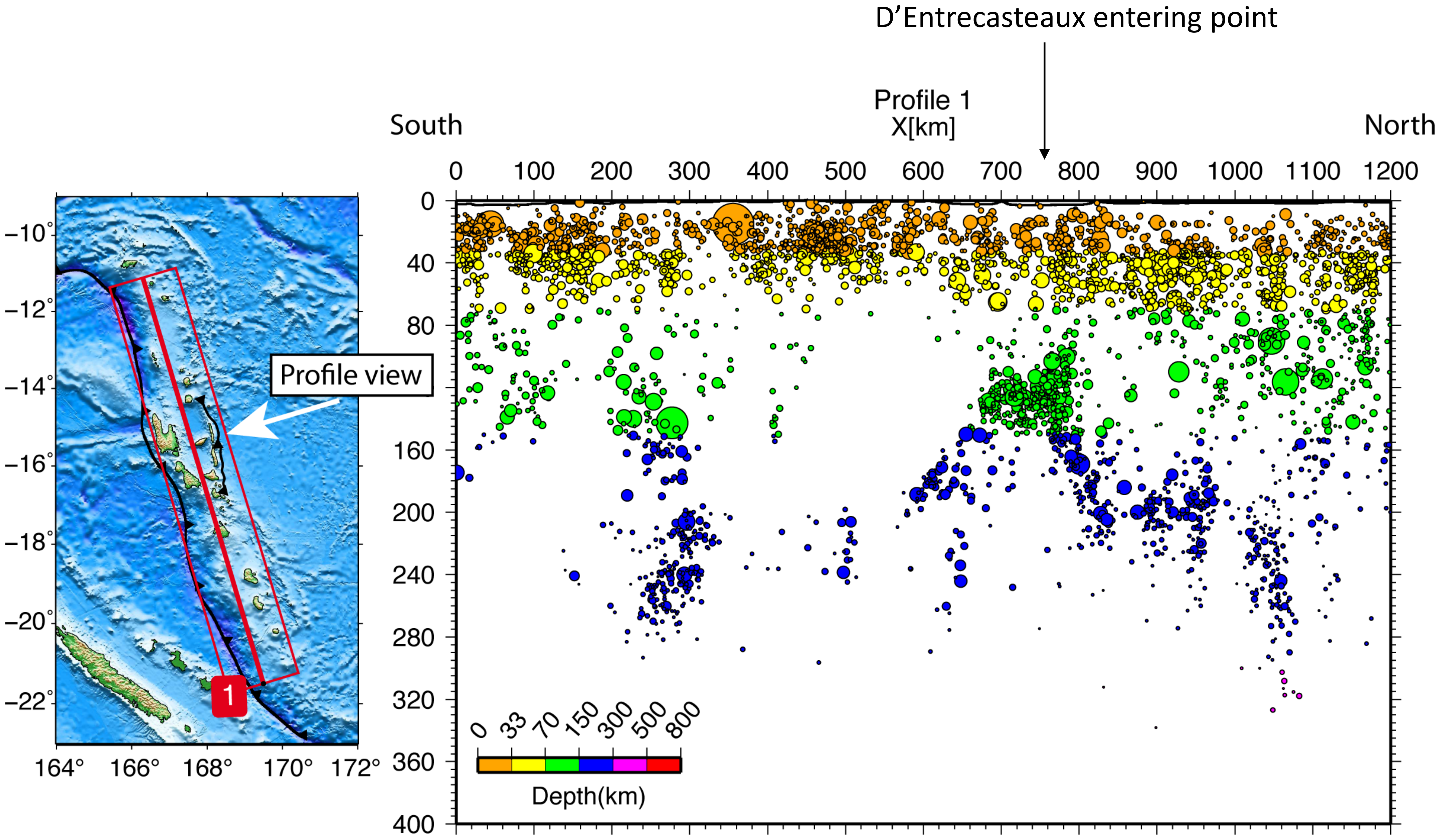
Ranero et al., 2005





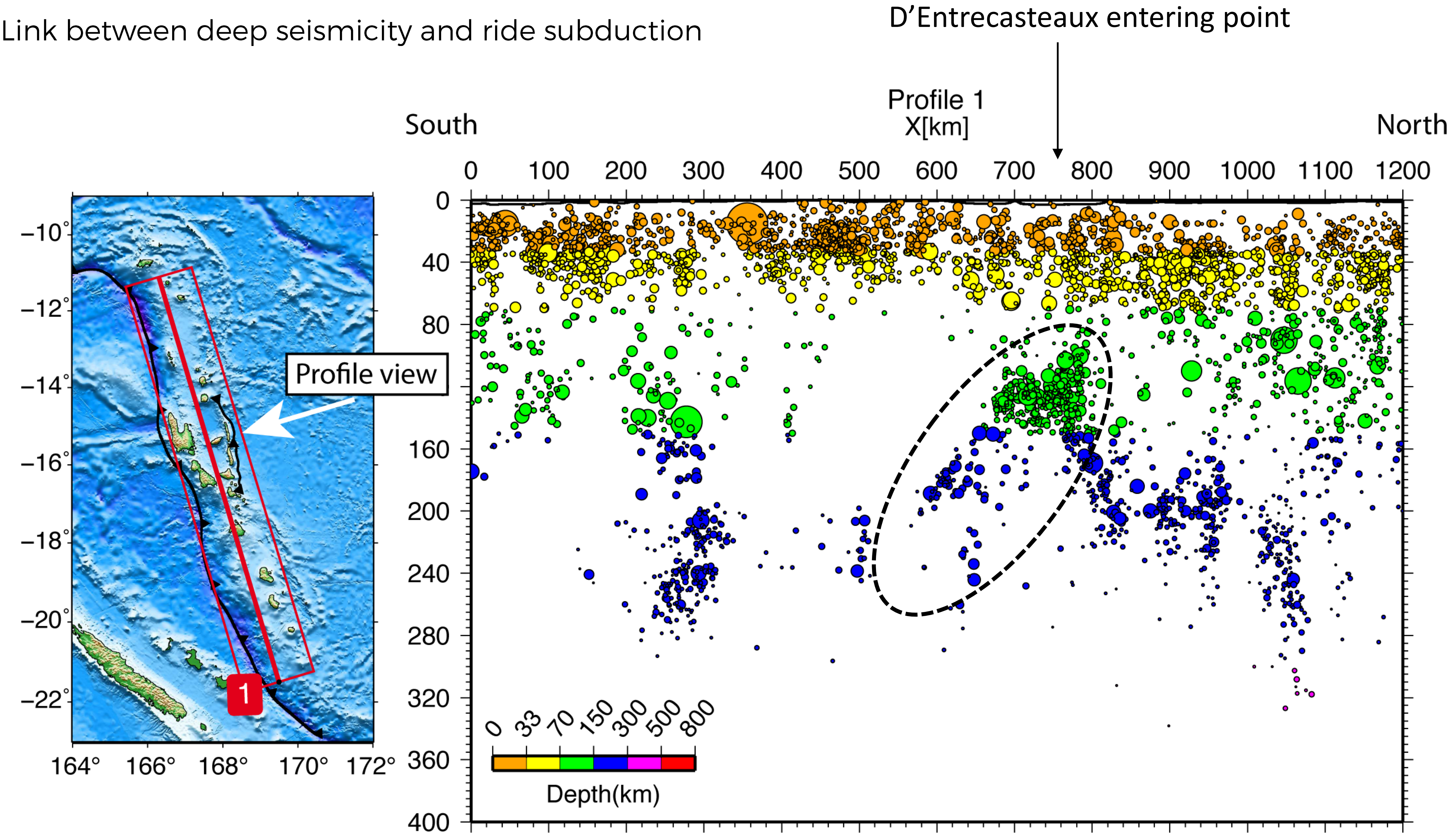
Deep intraslab activity due to:
crust dehydration
+
deserpentinization

Deep intraplate earthquakes



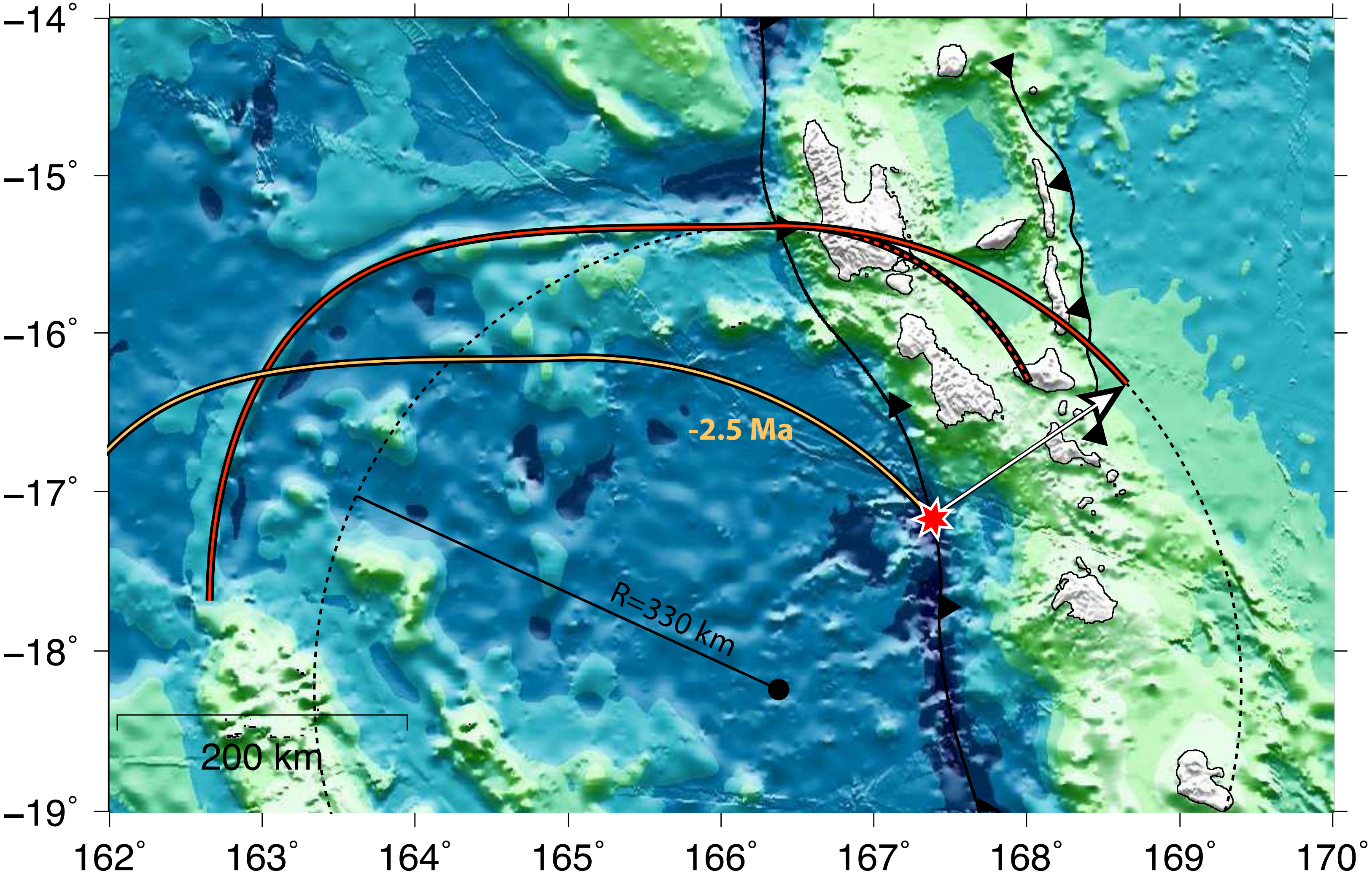
Deep intraplate earthquakes

Link between deep seismicity and ride subduction

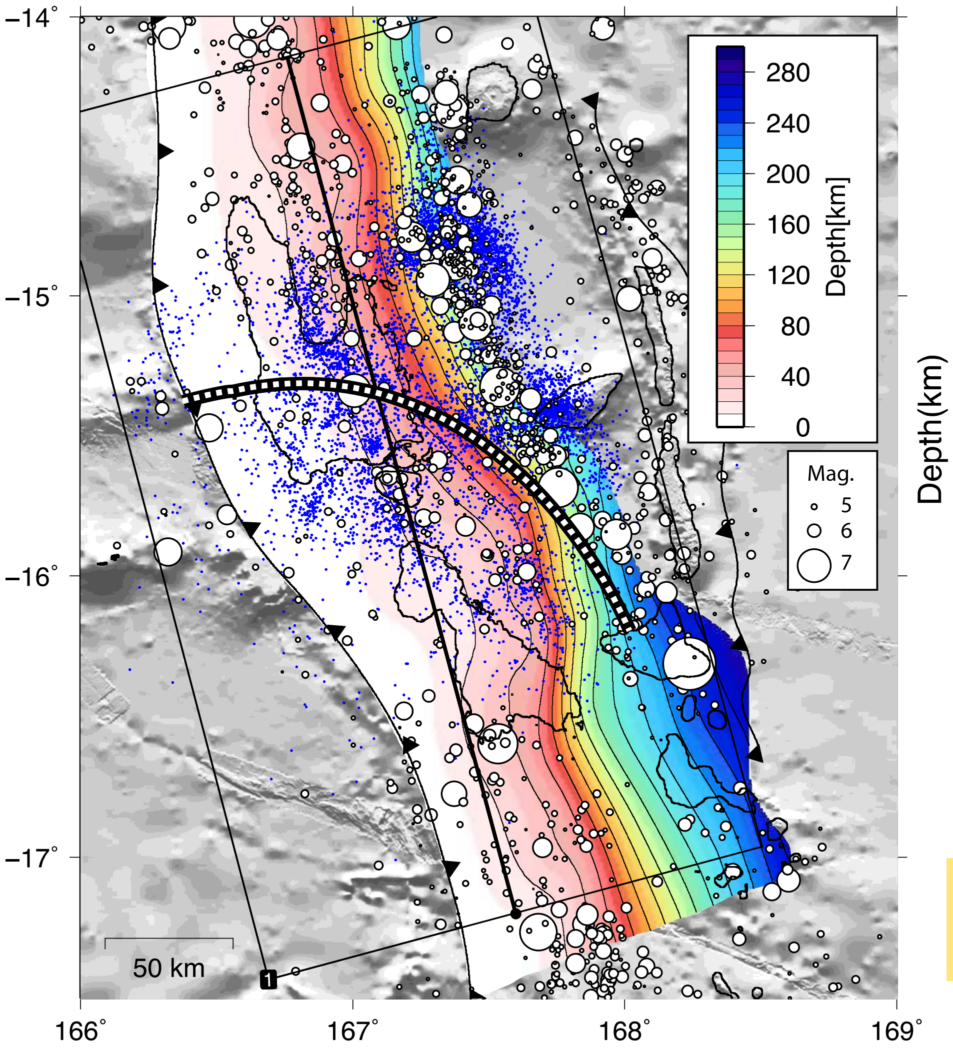


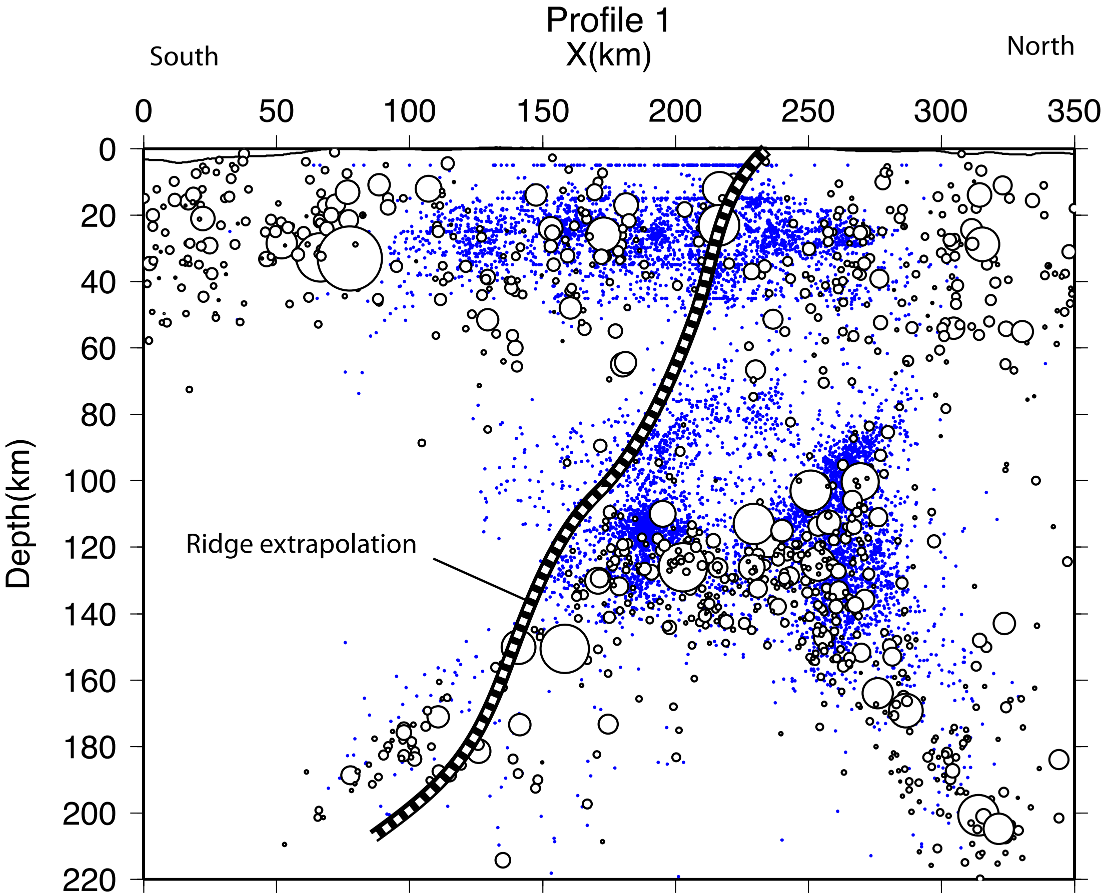
Deep intraplate earthquakes

Kinematic reconstruction of D'Entrecasteaux ridge position and projection on subduction interface



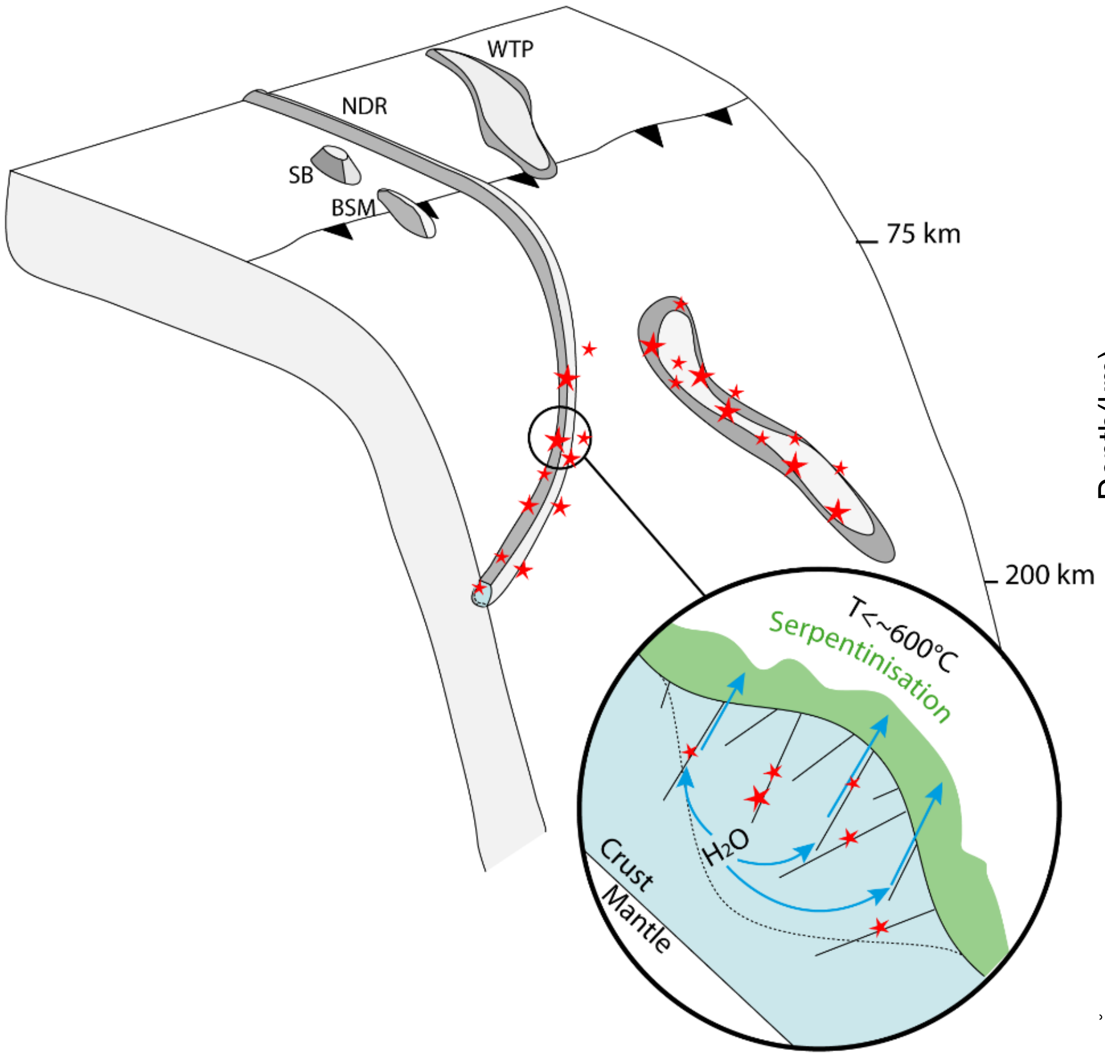
Deep intraplate earthquakes

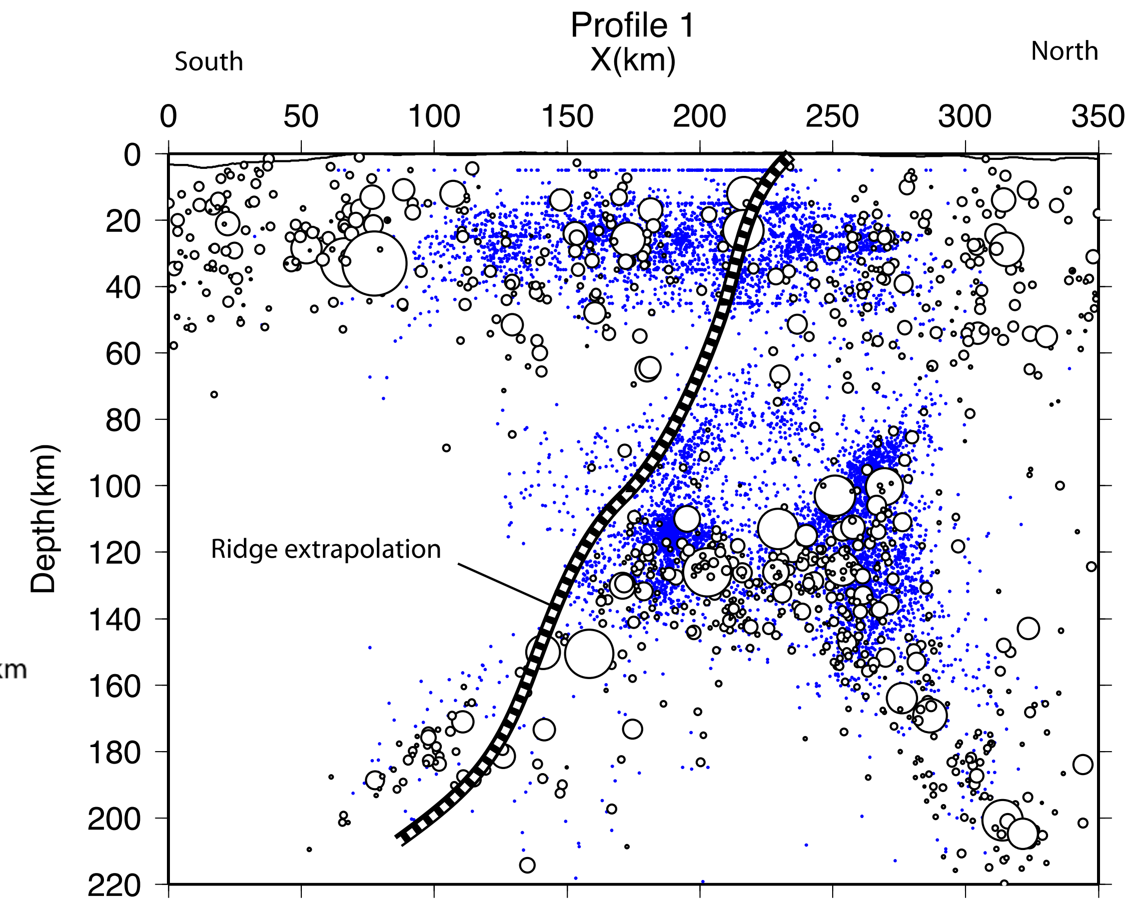




- Lineation of earthquakes correlates with ridge extension

Deep intraplate earthquakes





- Lineation of earthquakes correlates with ridge extension
- Hydrous content of the ridge promotes dehydration embrittlement and earthquakes generation

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Concept of locking

Conceptual model for strain accumulation and release

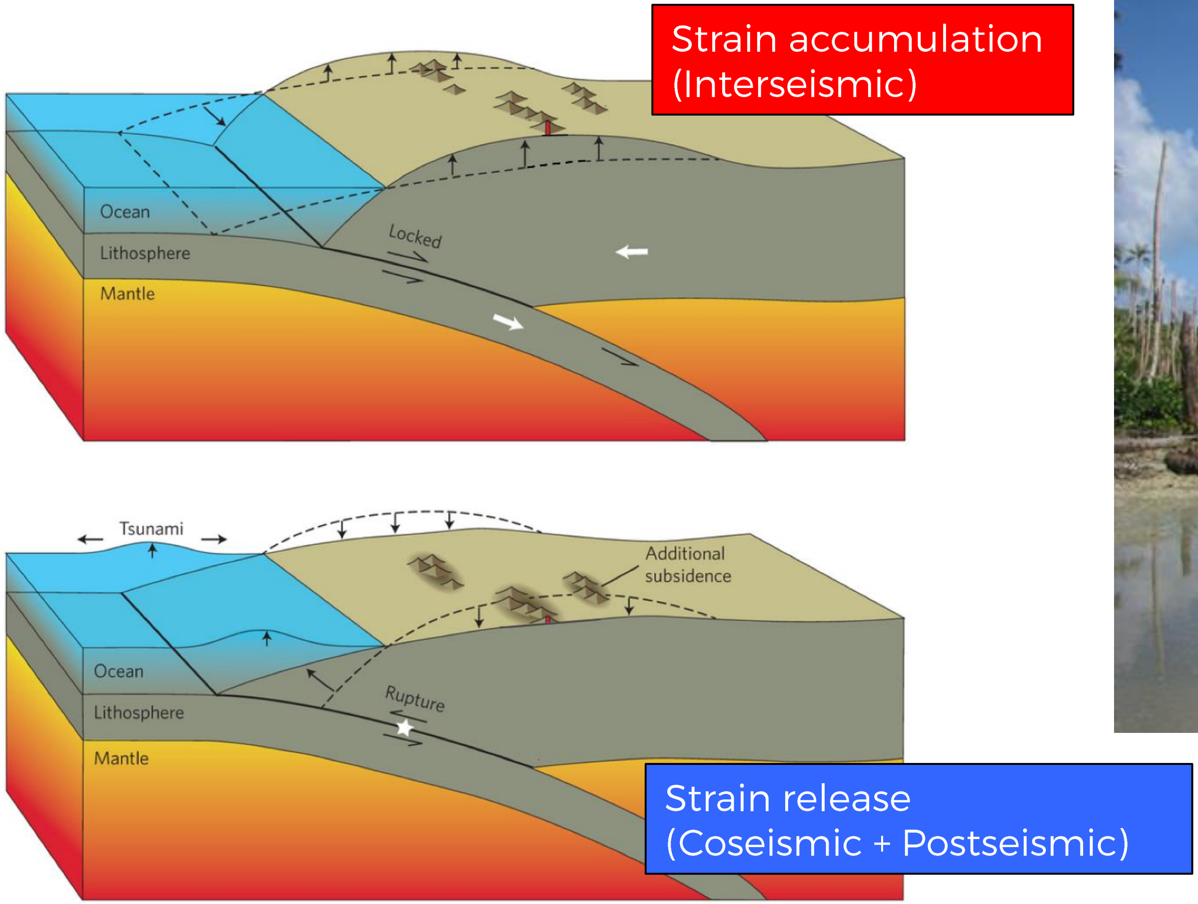


Illustration from *Jonsson, 2013*

Coconut plantation underwater
(Torres islands, IRD source)

Concept of locking

Conceptual model for strain accumulation and release

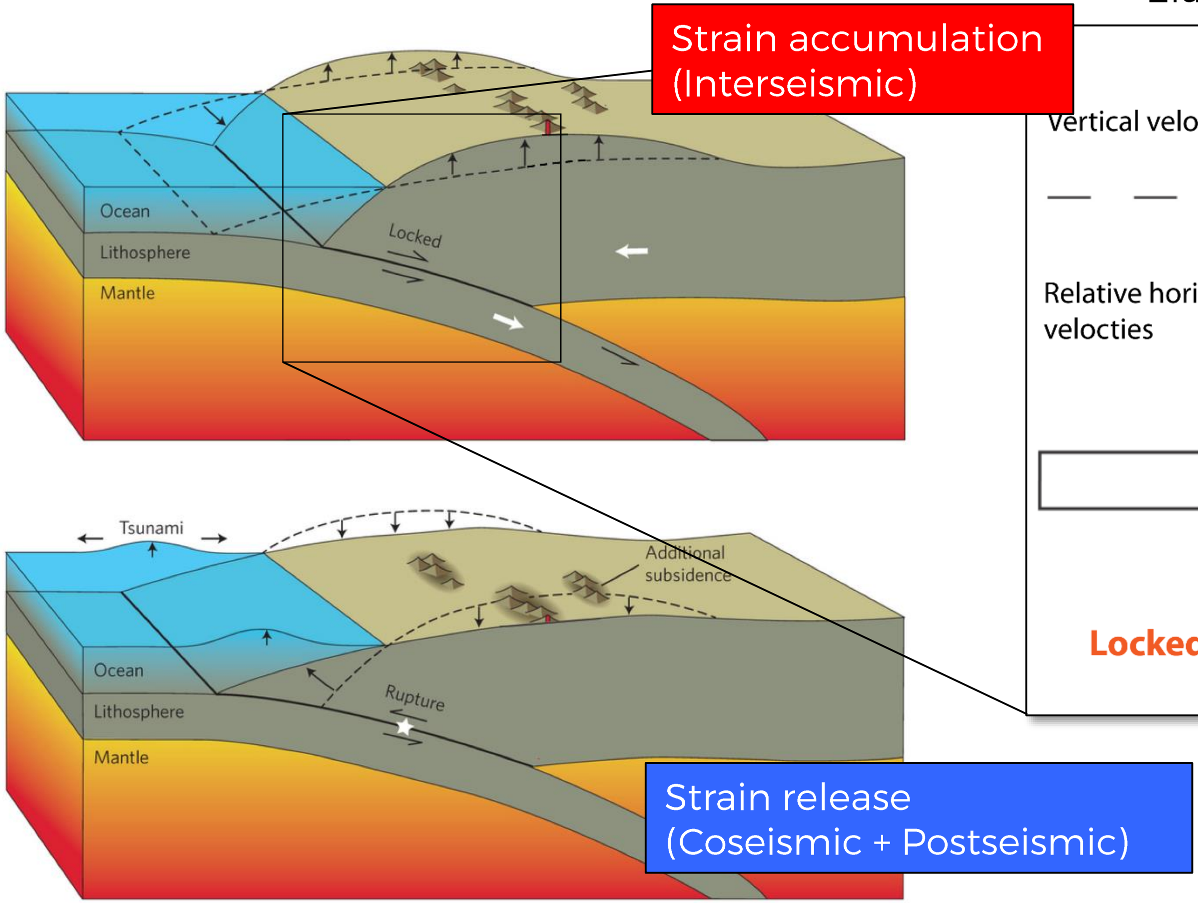
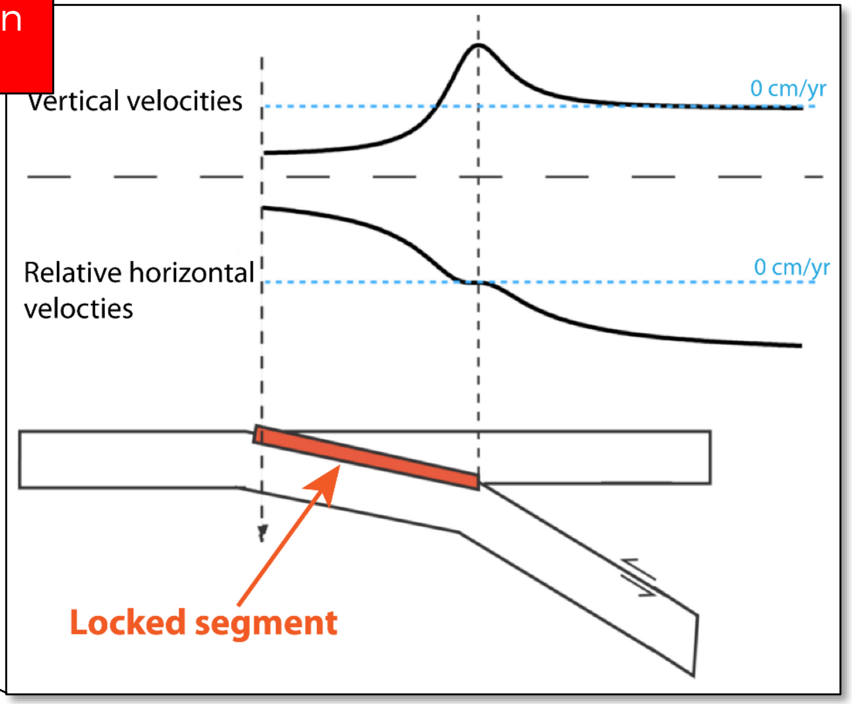


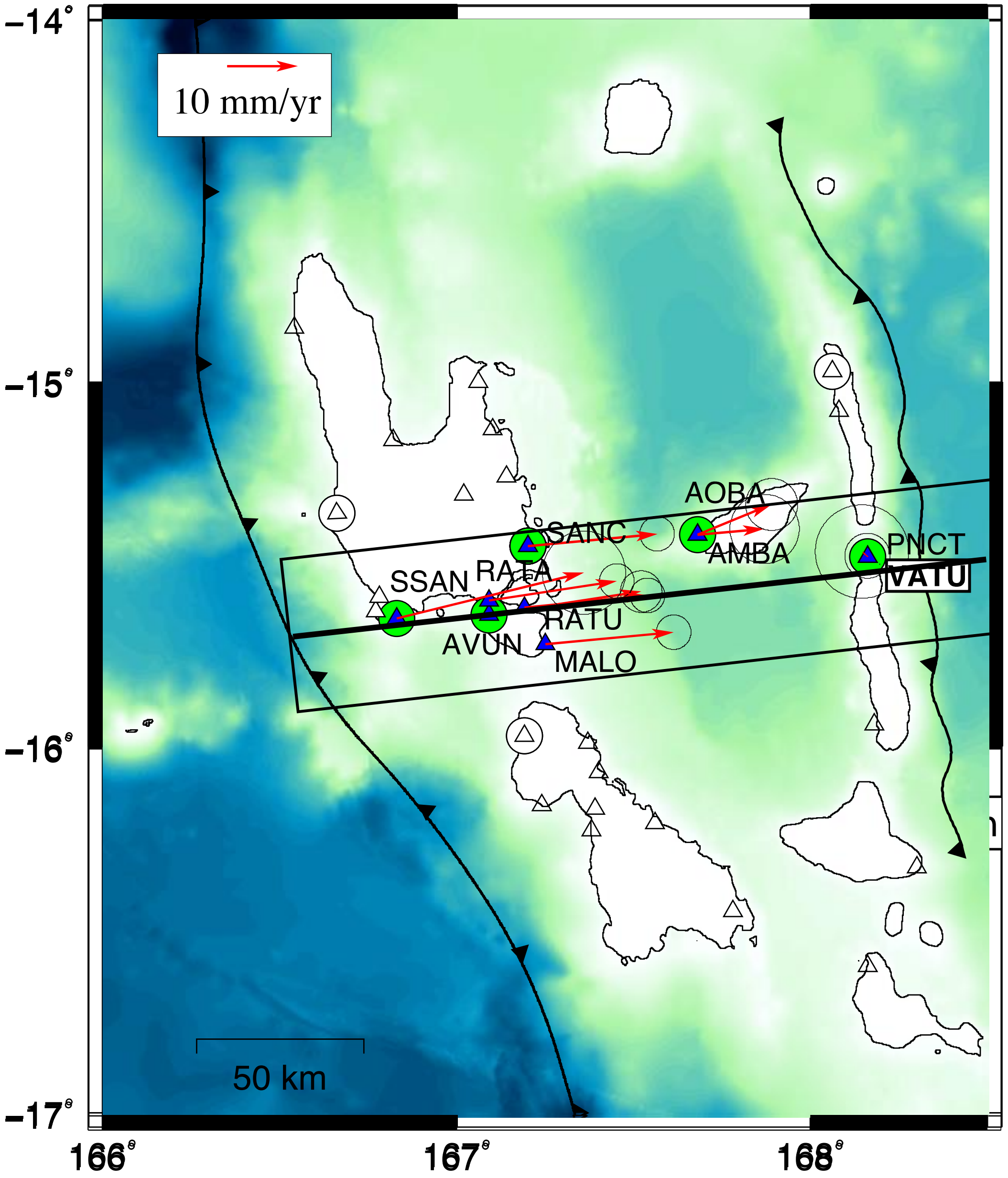
Illustration from *Jonsson, 2013*

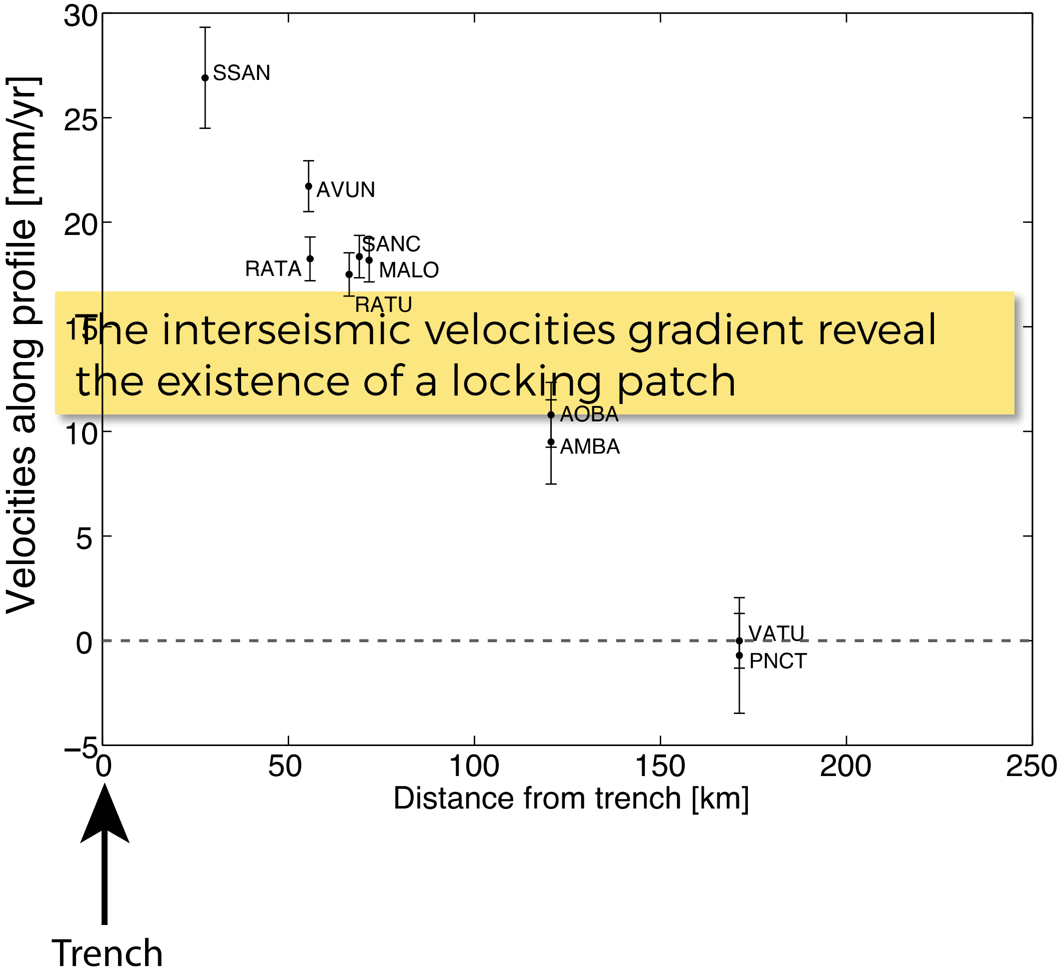
Elastic model after Savage, 1983



GPS horizontal velocities

GPS horizontal interseismic velocities into Maewo – Pentecost rigid bloc reference

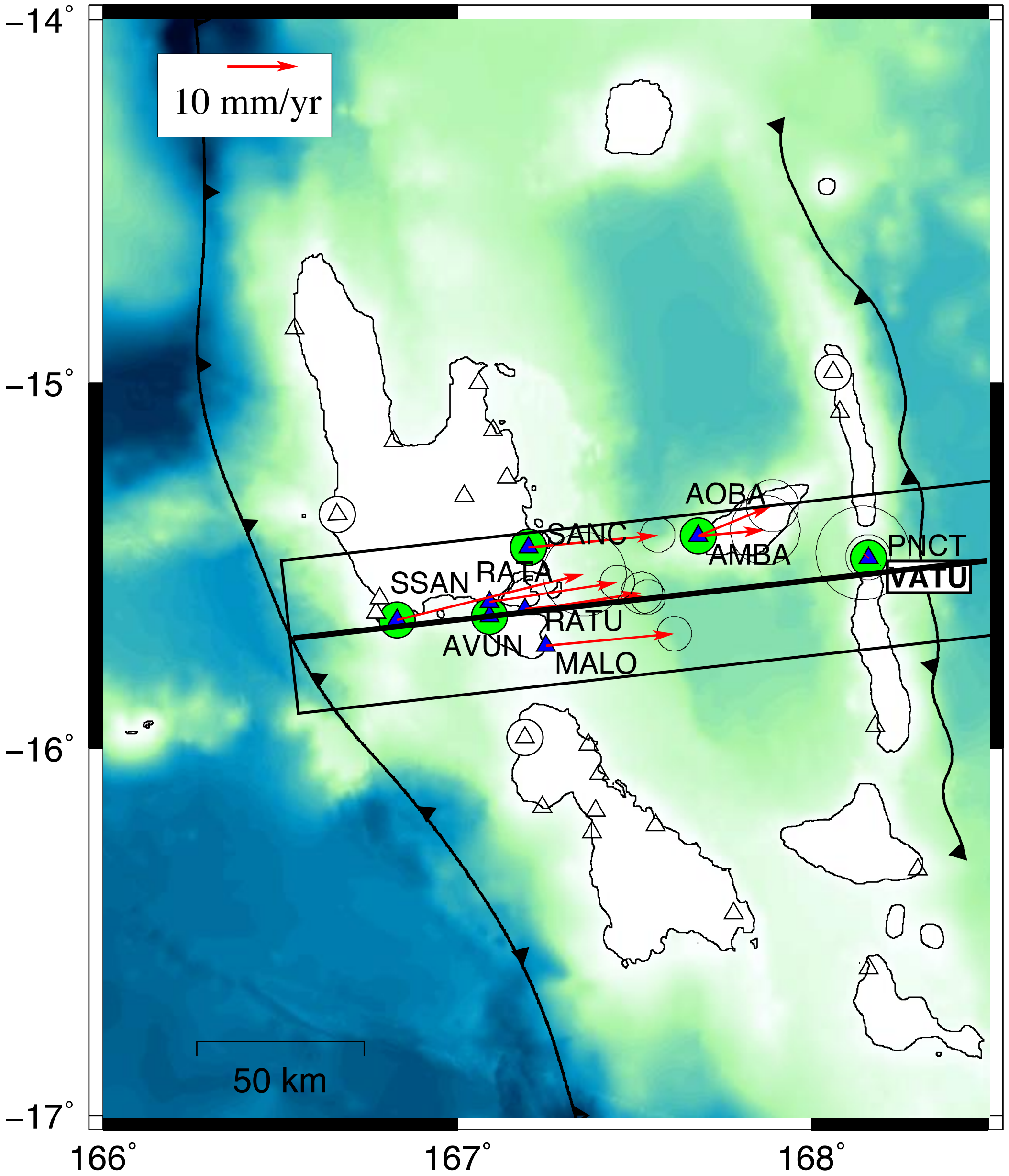


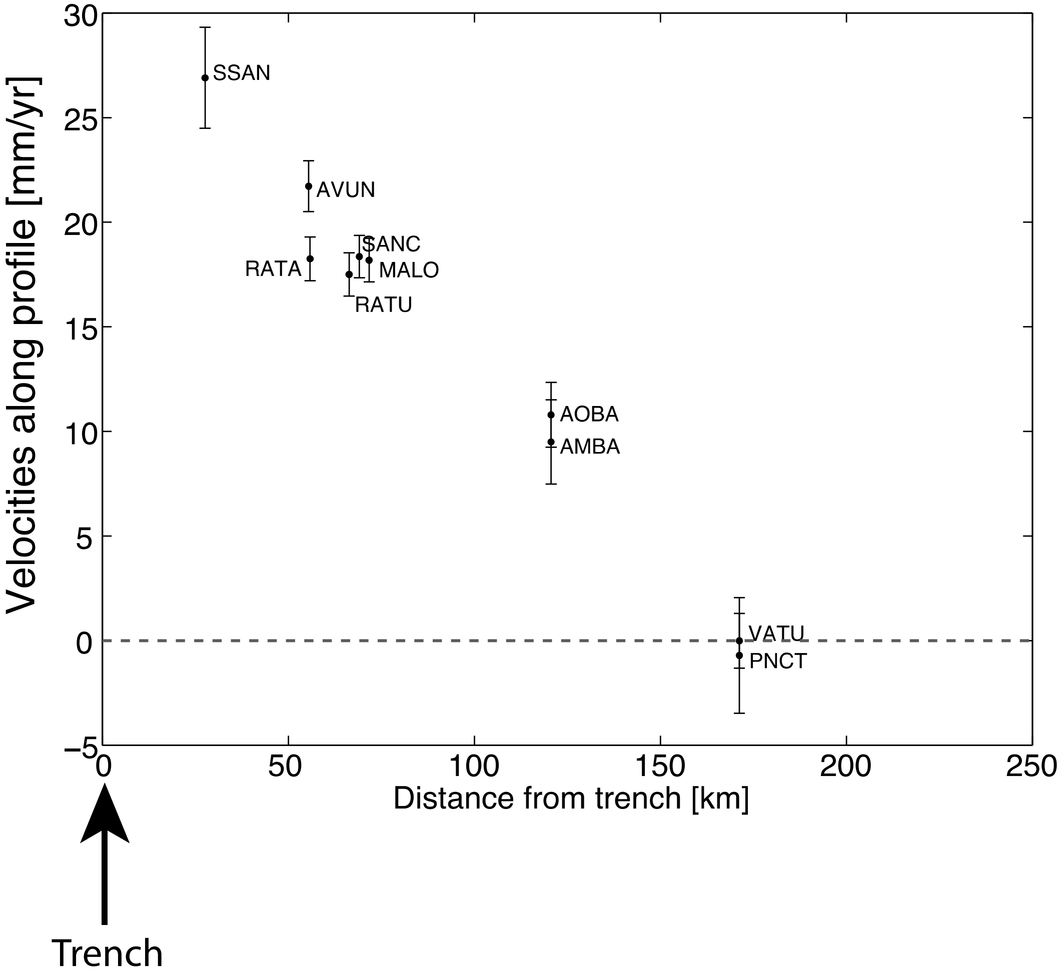


The interseismic velocities gradient reveal the existence of a locking patch

GPS horizontal velocities

Velocities selected for 2D mechanical model

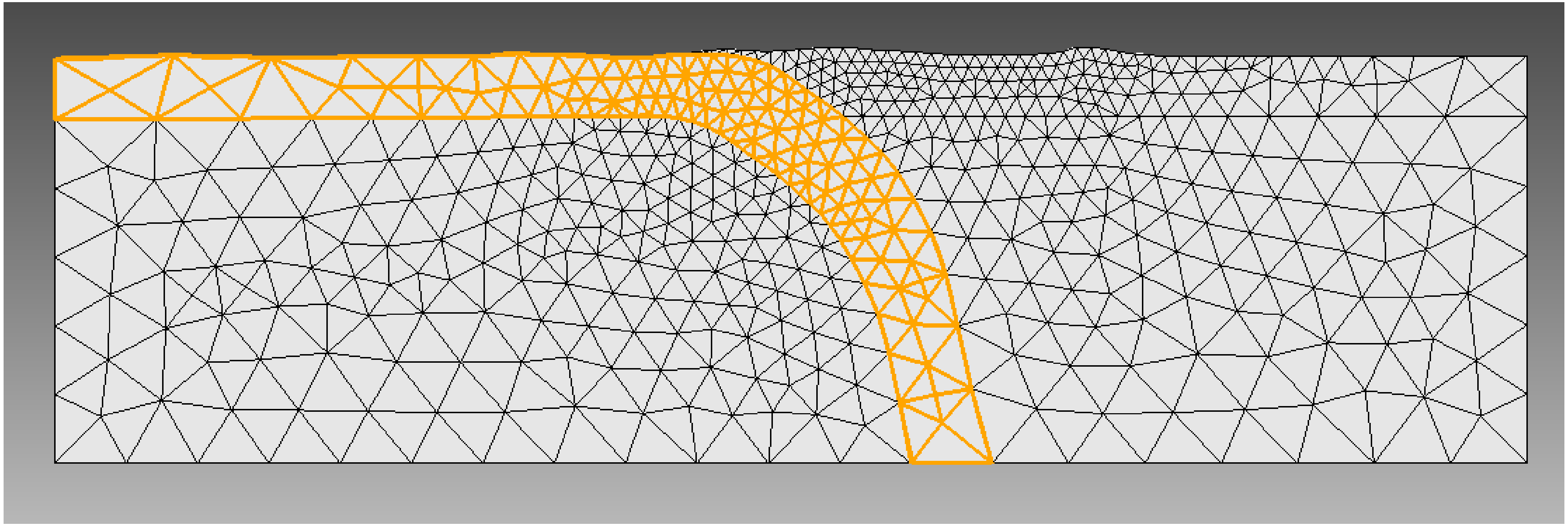




2D mechanical model

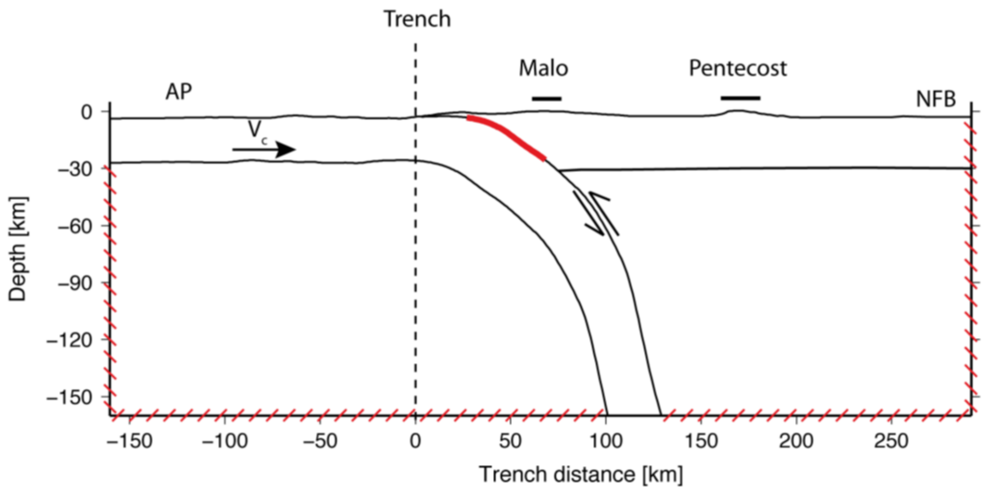
- Integrates interpreted slab geometry
- Visco-elastic asthenosphere supporting an elastic lithosphere

Method: PYLITH
Aagaard et al.,2013

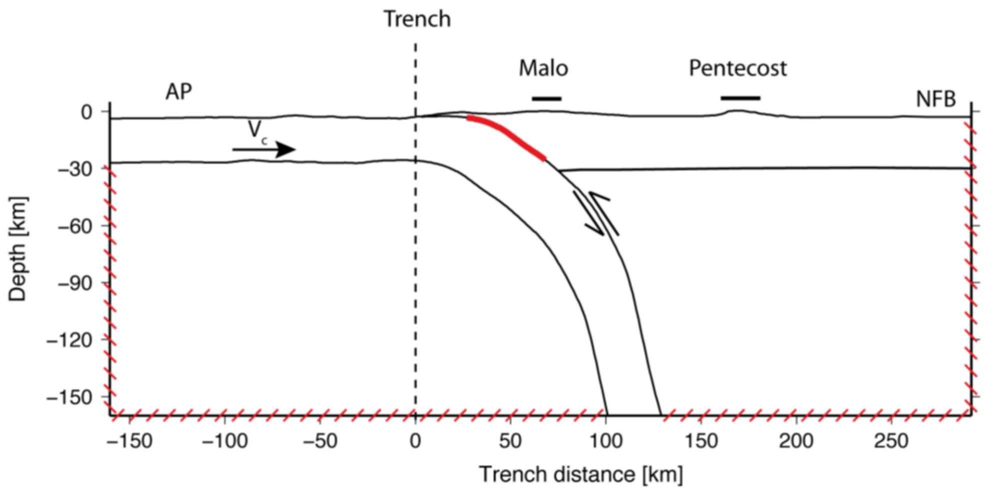


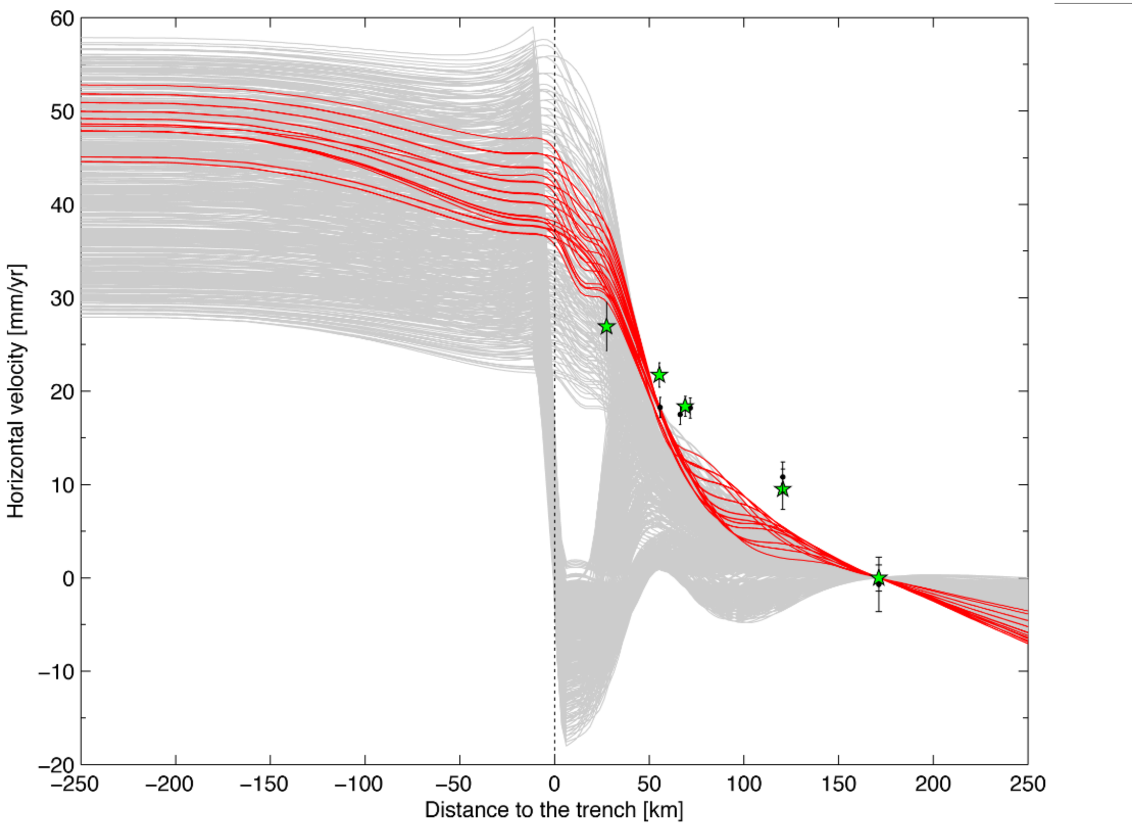
Mesh generated by software CUBIT

Fitting the data



Fitting the data





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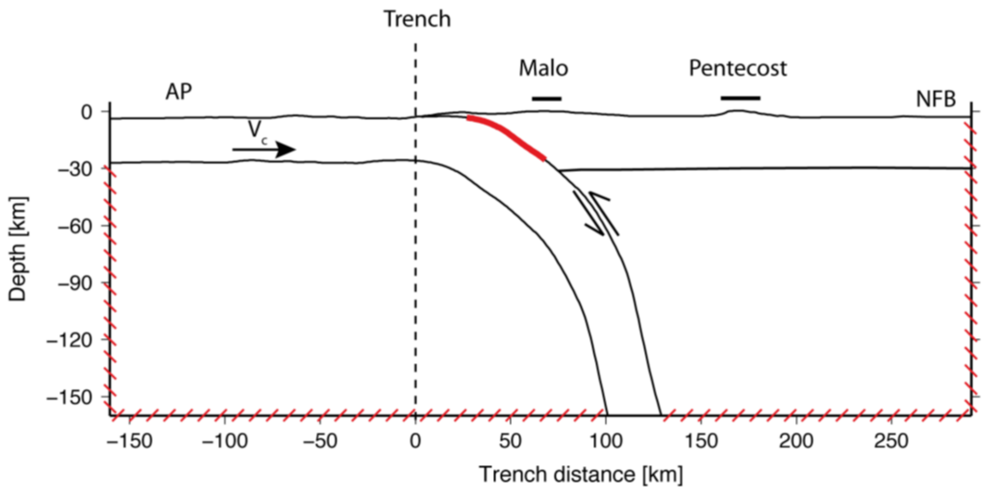

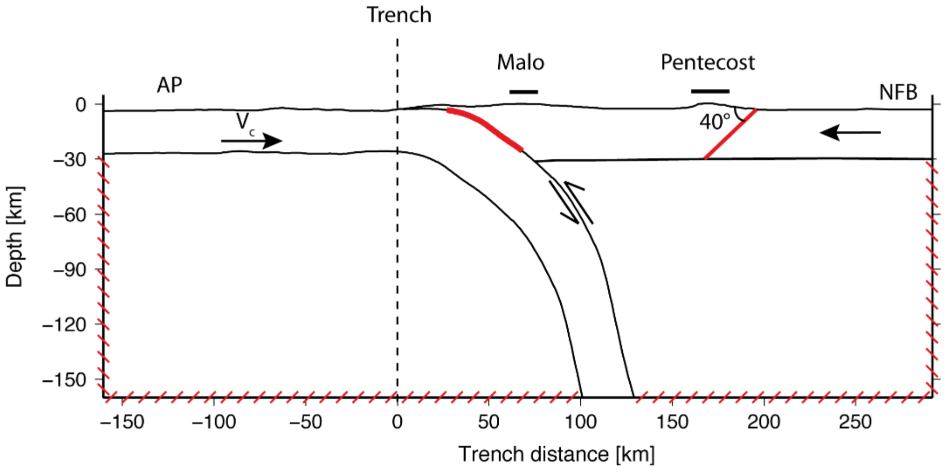

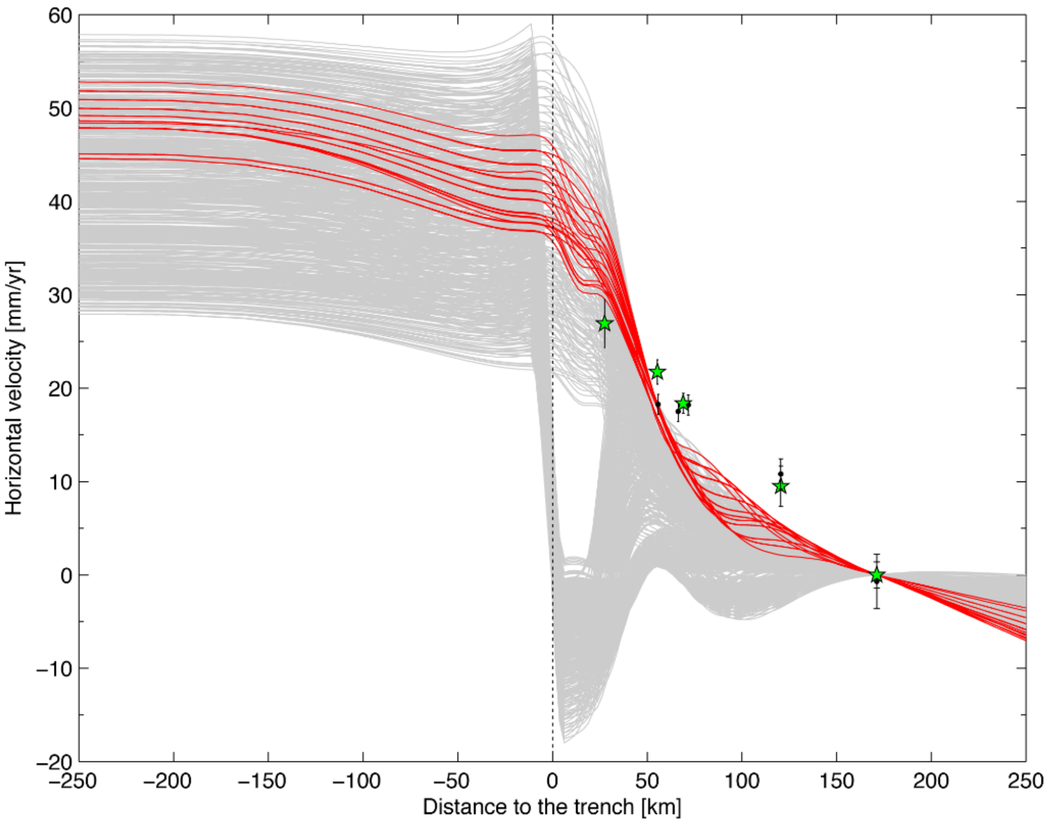

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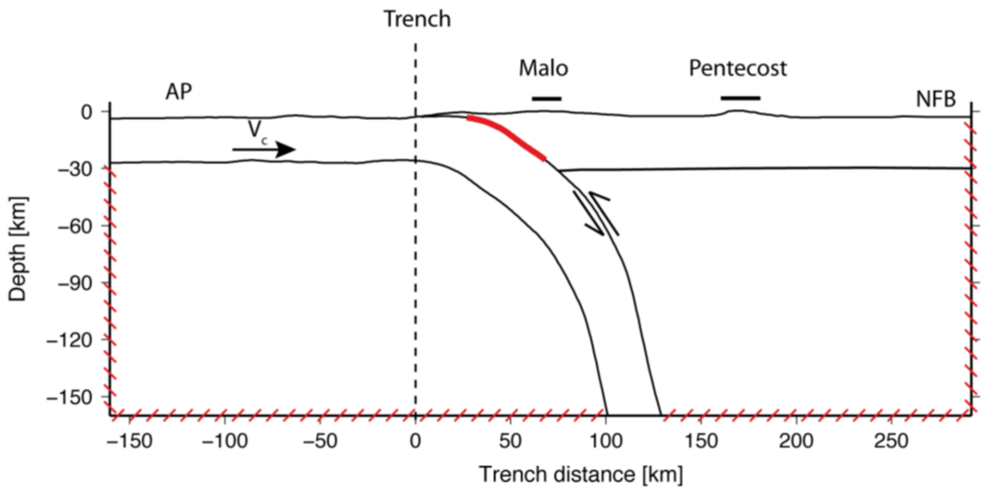
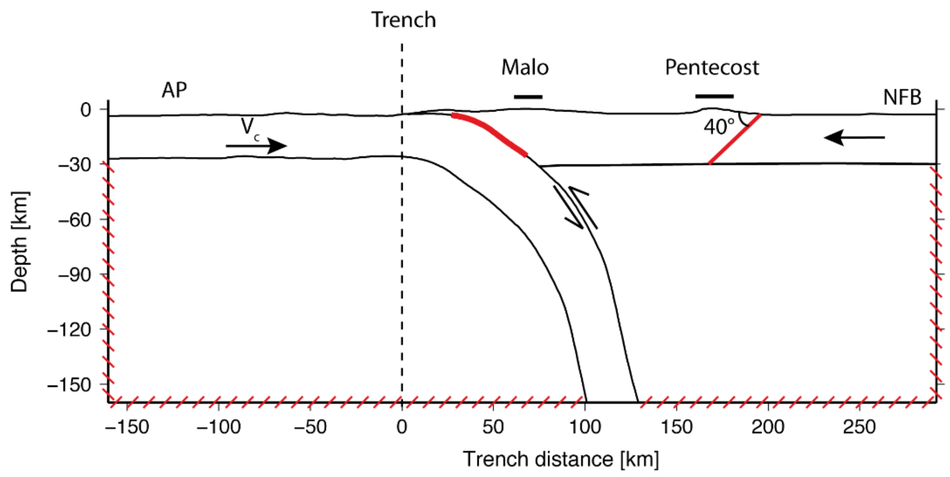
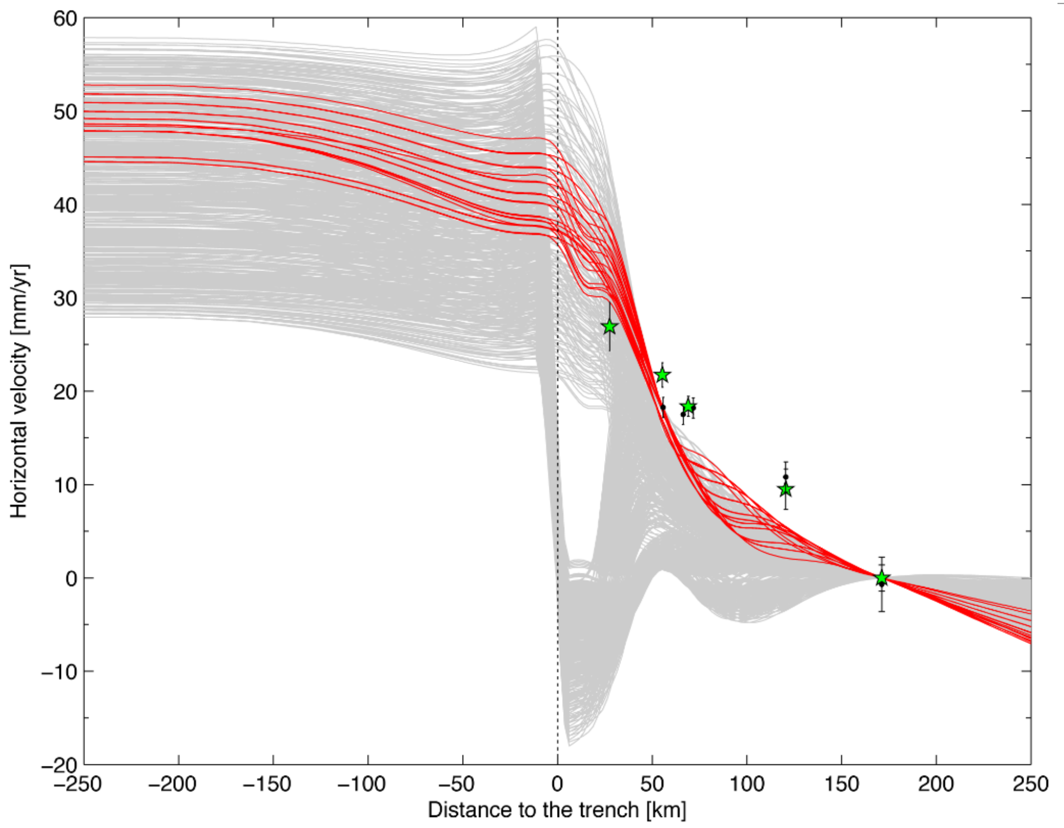
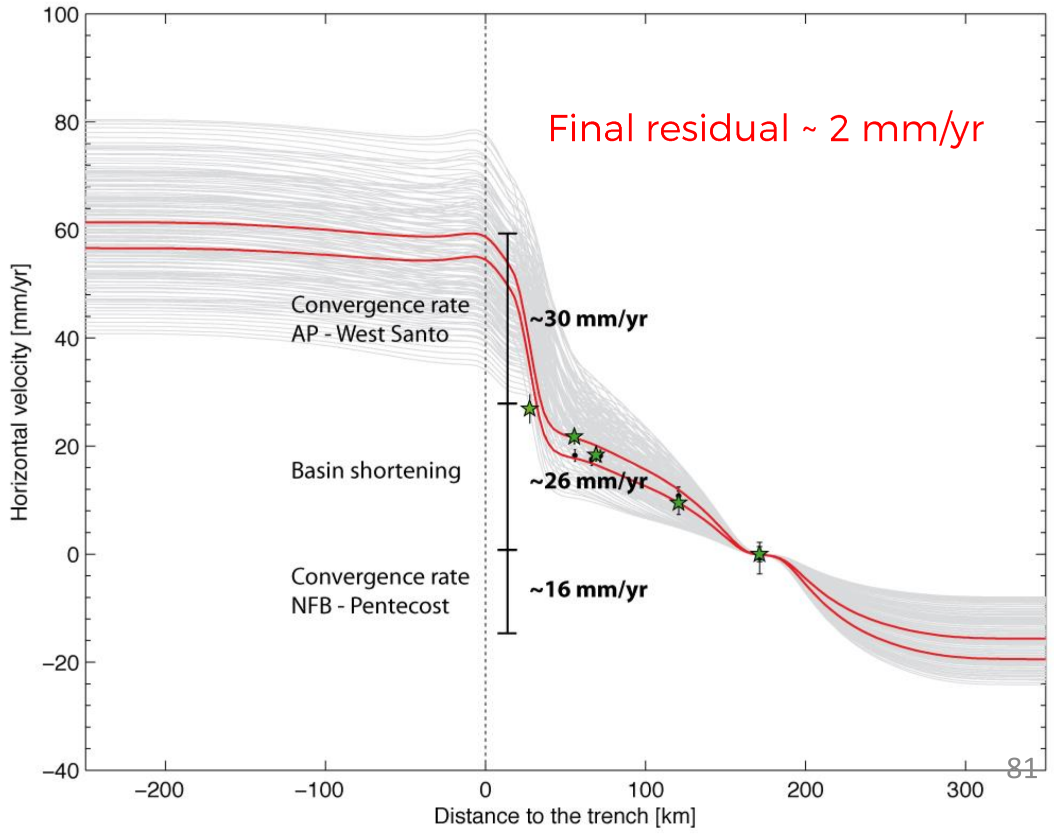
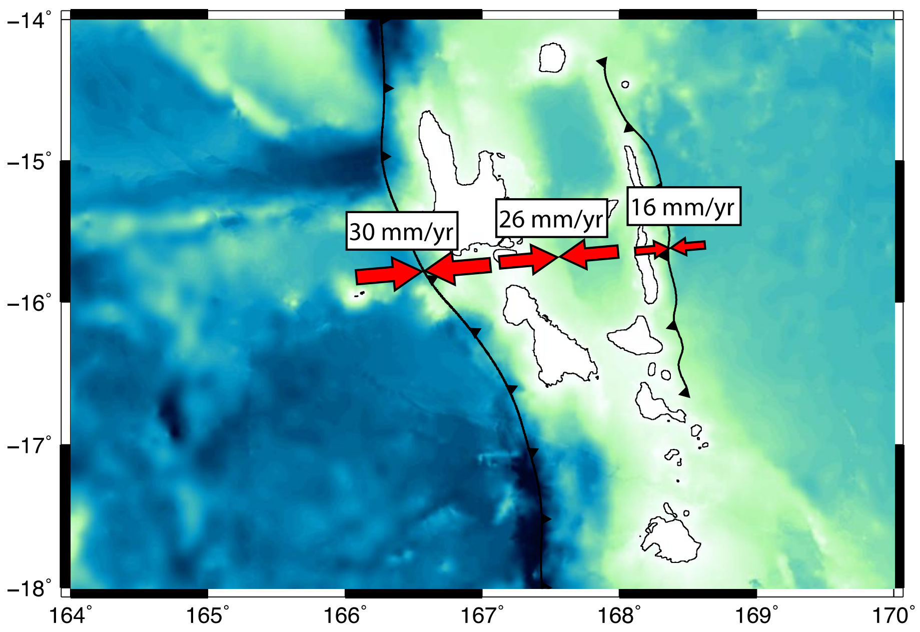




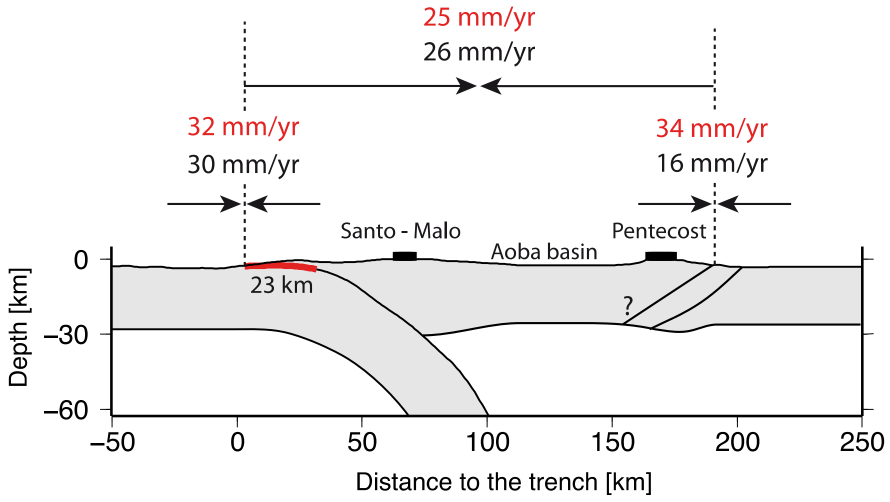




Results

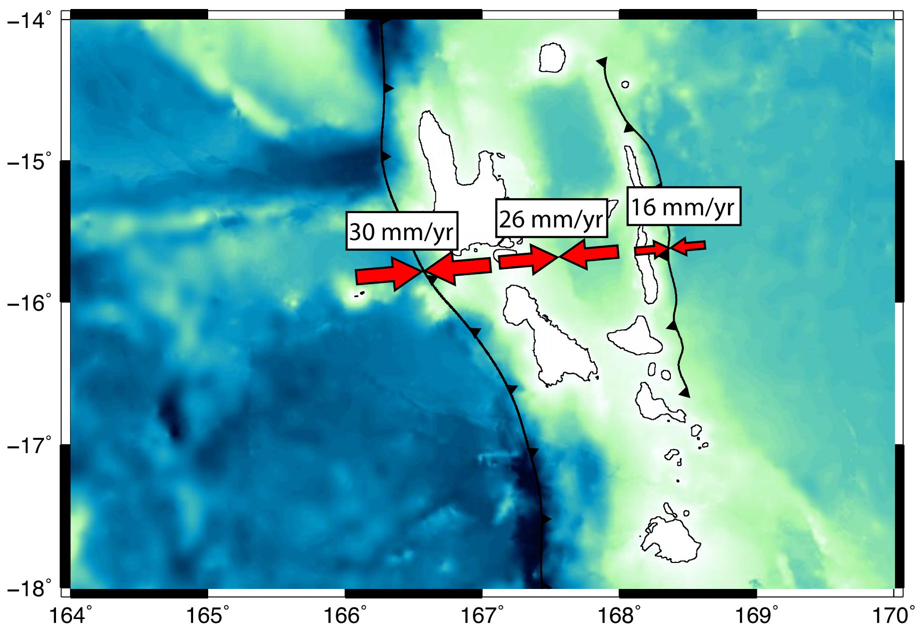


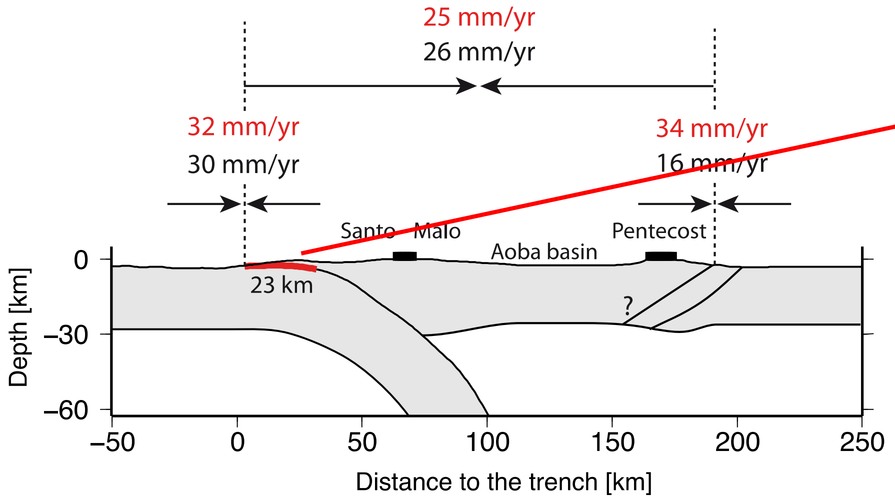
−14˚
−15˚
−16˚
−17˚
−18˚
164˚
165˚
166˚
167˚
168˚
169˚
170˚
30 mm/yr
26 mm/yr
16 mm/yr



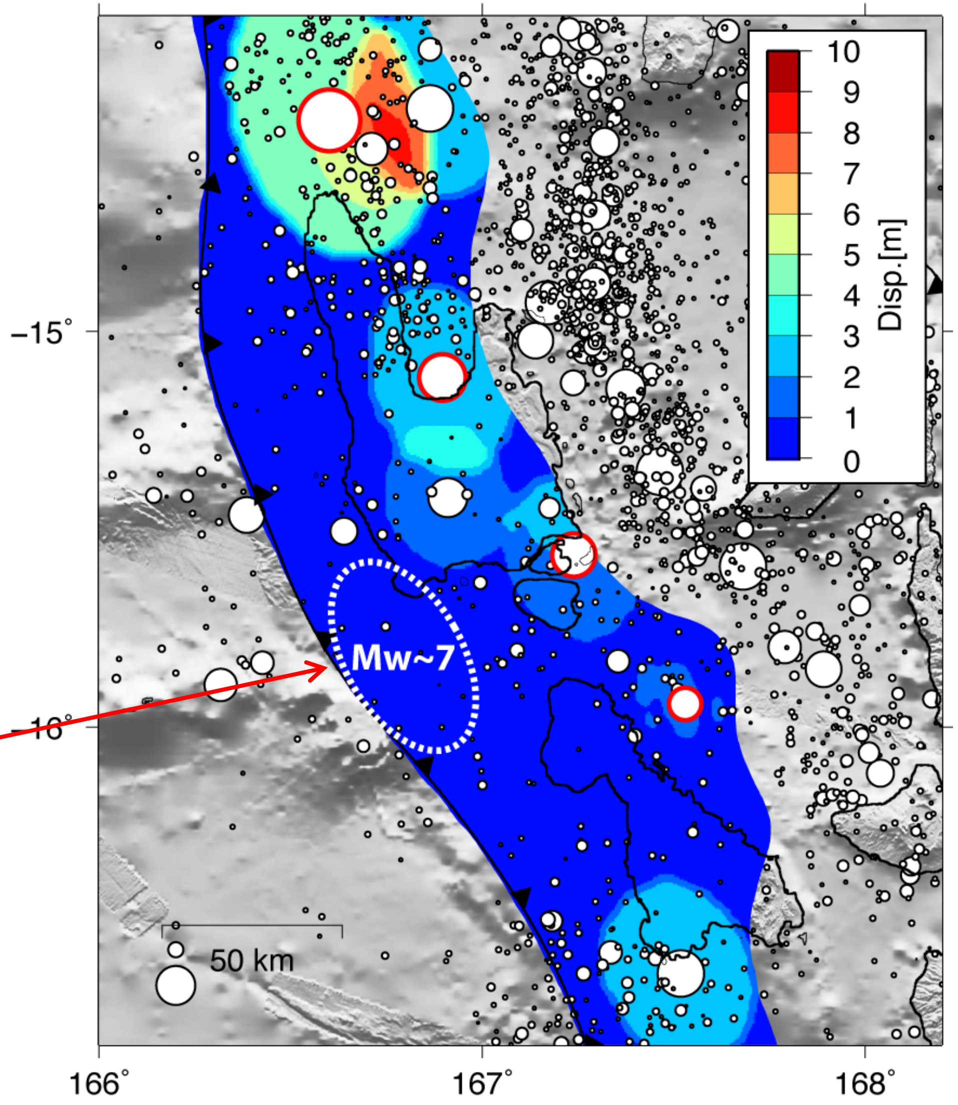
25 mm/yr
26 mm/yr
32 mm/yr
30 mm/yr
34 mm/yr
16 mm/yr
Santo - Malo
Aoba basin
Pentecost
23 km
?
0
−30
−60
Depth [km]
−50
0
50
100
150
200
250
Distance to the trench [km]

Results

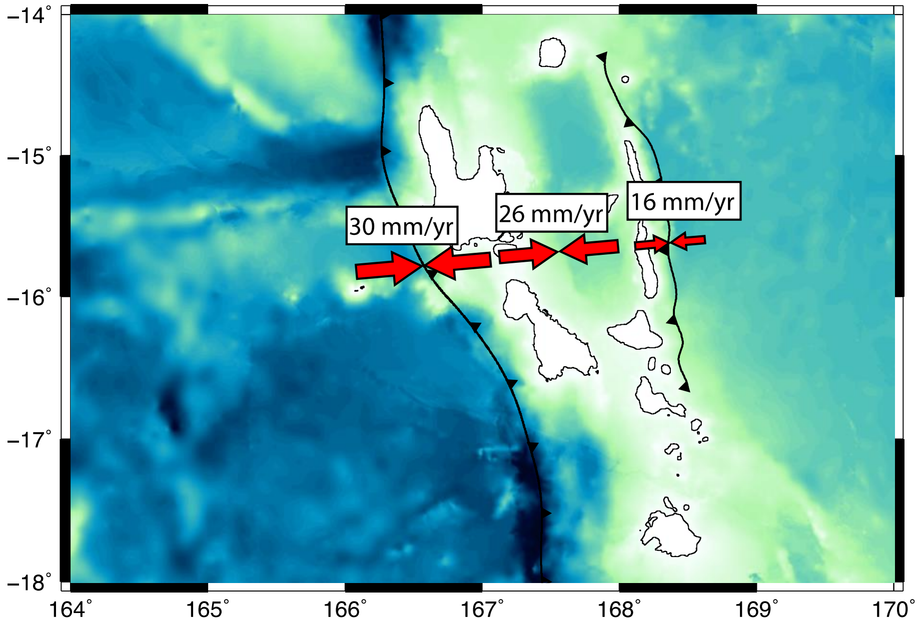


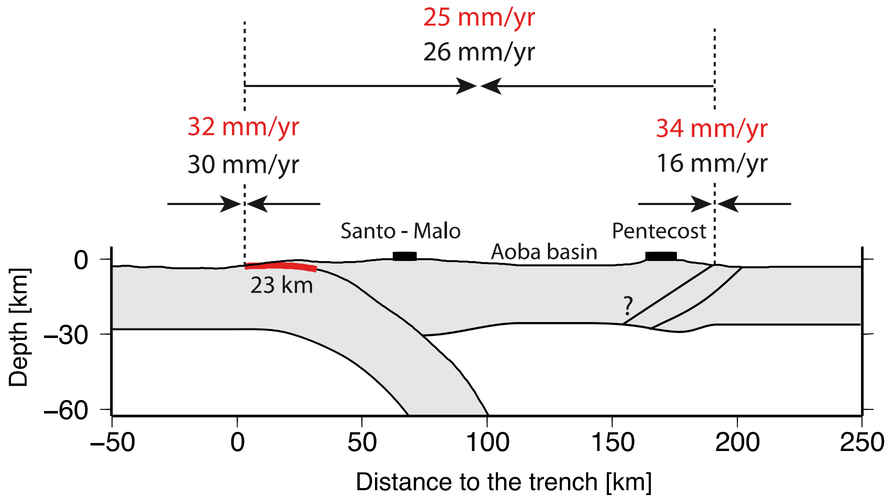


Rupture patches since 1971

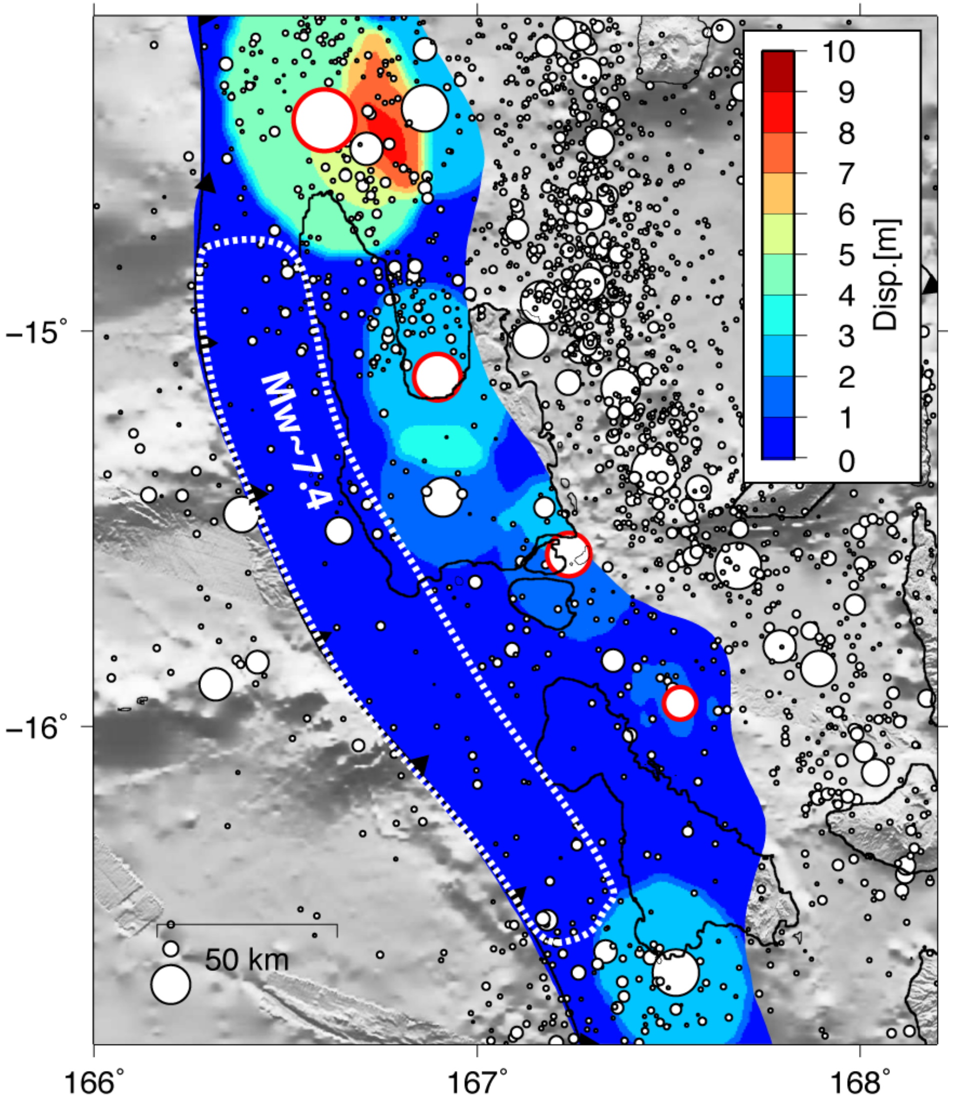


Results





Rupture patches since 1971



Outline

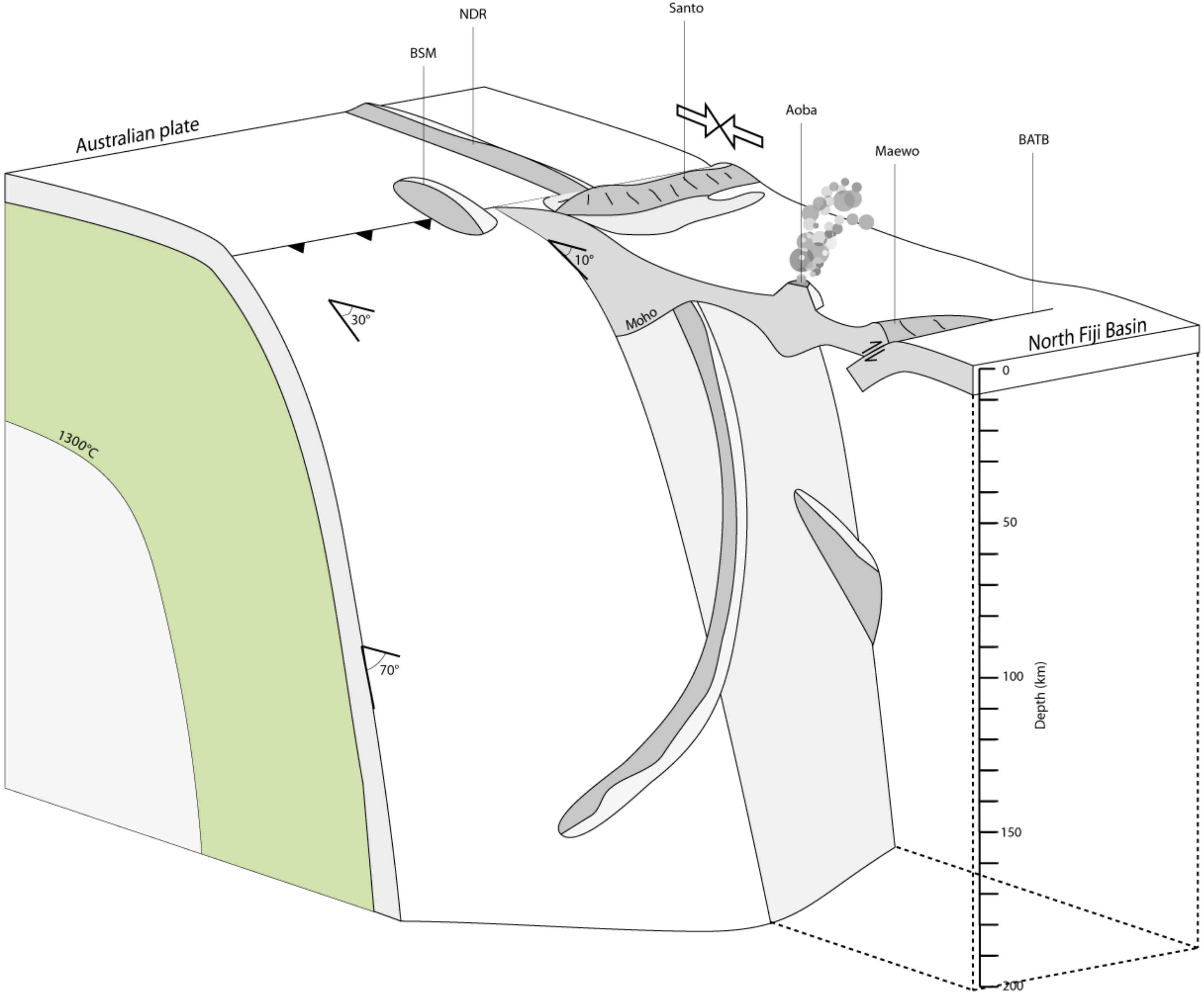
1. Introduction
    - General context of the Vanuatu subduction zone
    - Main questions asked
    - Description of the GPS & Seismological networks

2. Seismological analysis
    - Automatic picking procedure
    - 1D Velocity model
    - Earthquake location and error estimates
    - Relocation of earthquakes and focal mechanisms
    - 3D determination of seismogenic interfaces

3. Interpretation
    - Seismological study
    - 2D mechanical model

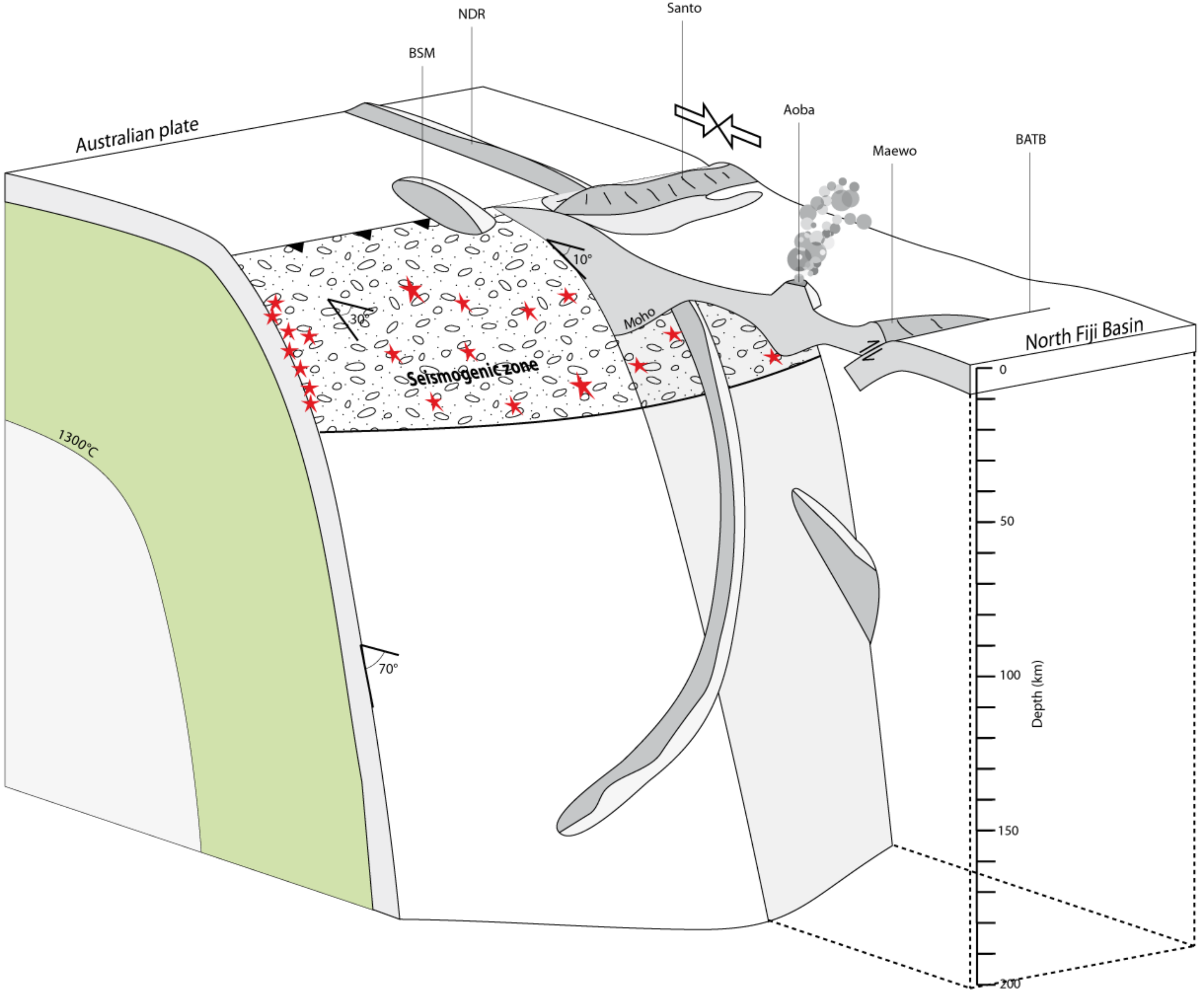
4. Conclusions & Perspectives

Conclusion



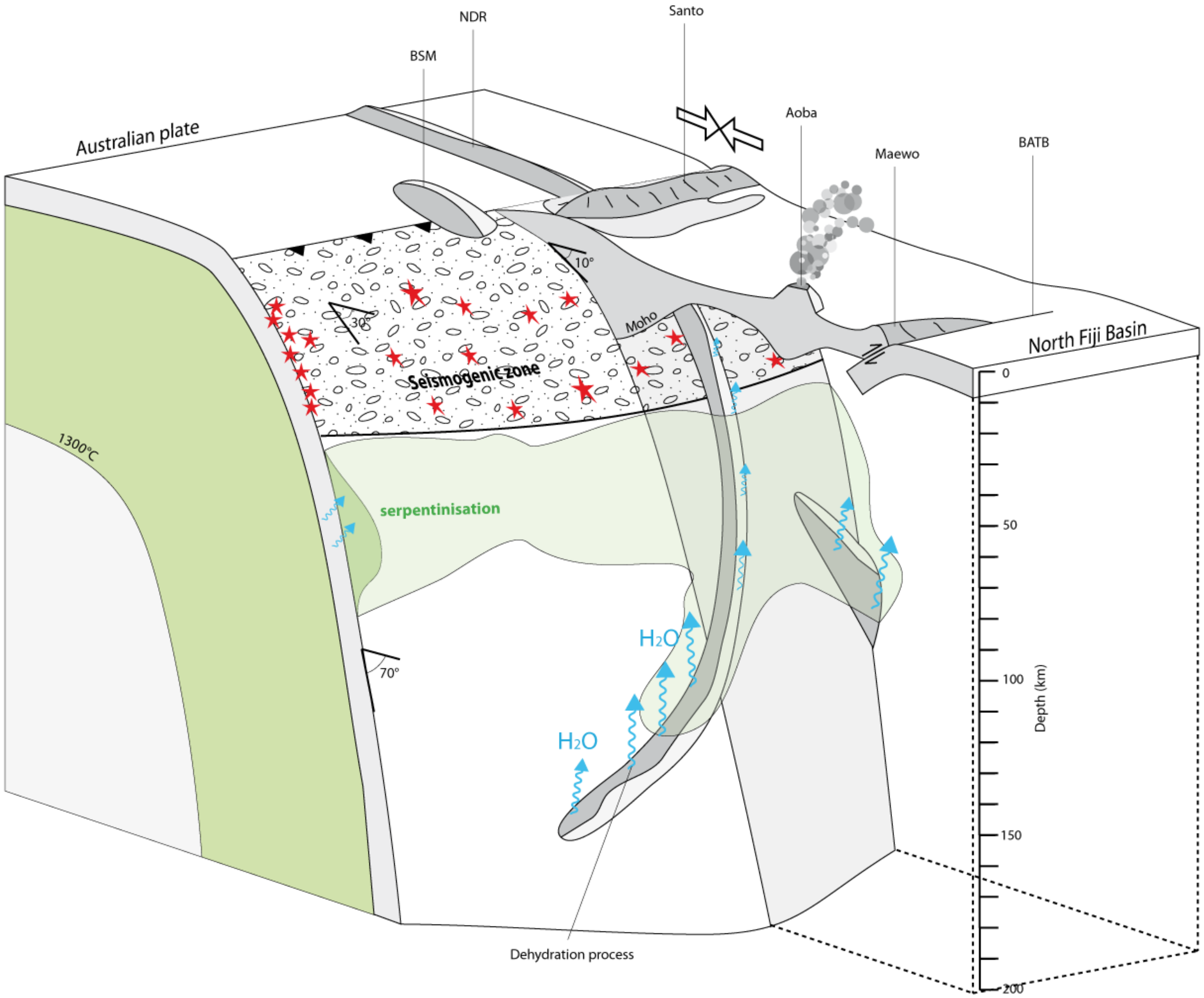
NDR
Santo
BSM
Australian plate
Aoba
Maewo
BATB
10°
30°
Moho
North Fiji Basin
0
1300°C
50
70°
100
Depth (km)
150
200

Conclusion



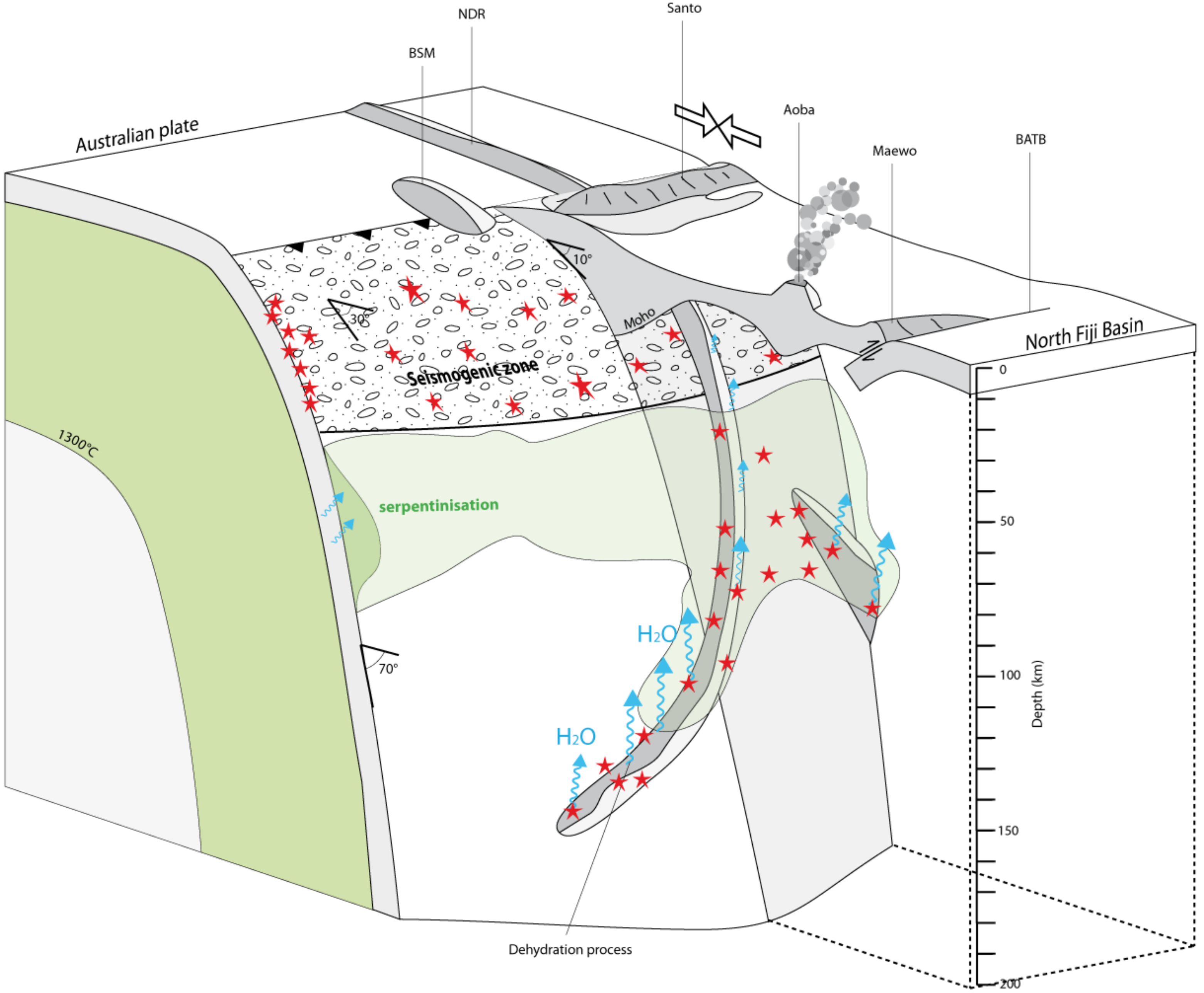
NDR
Santo
BSM
Aoba
Maewo
BATB
Australian plate
10°
30°
Seismogenic zone
Moho
North Fiji Basin
1300°C
70°
0
50
100
150
200
Depth (km)

Conclusion



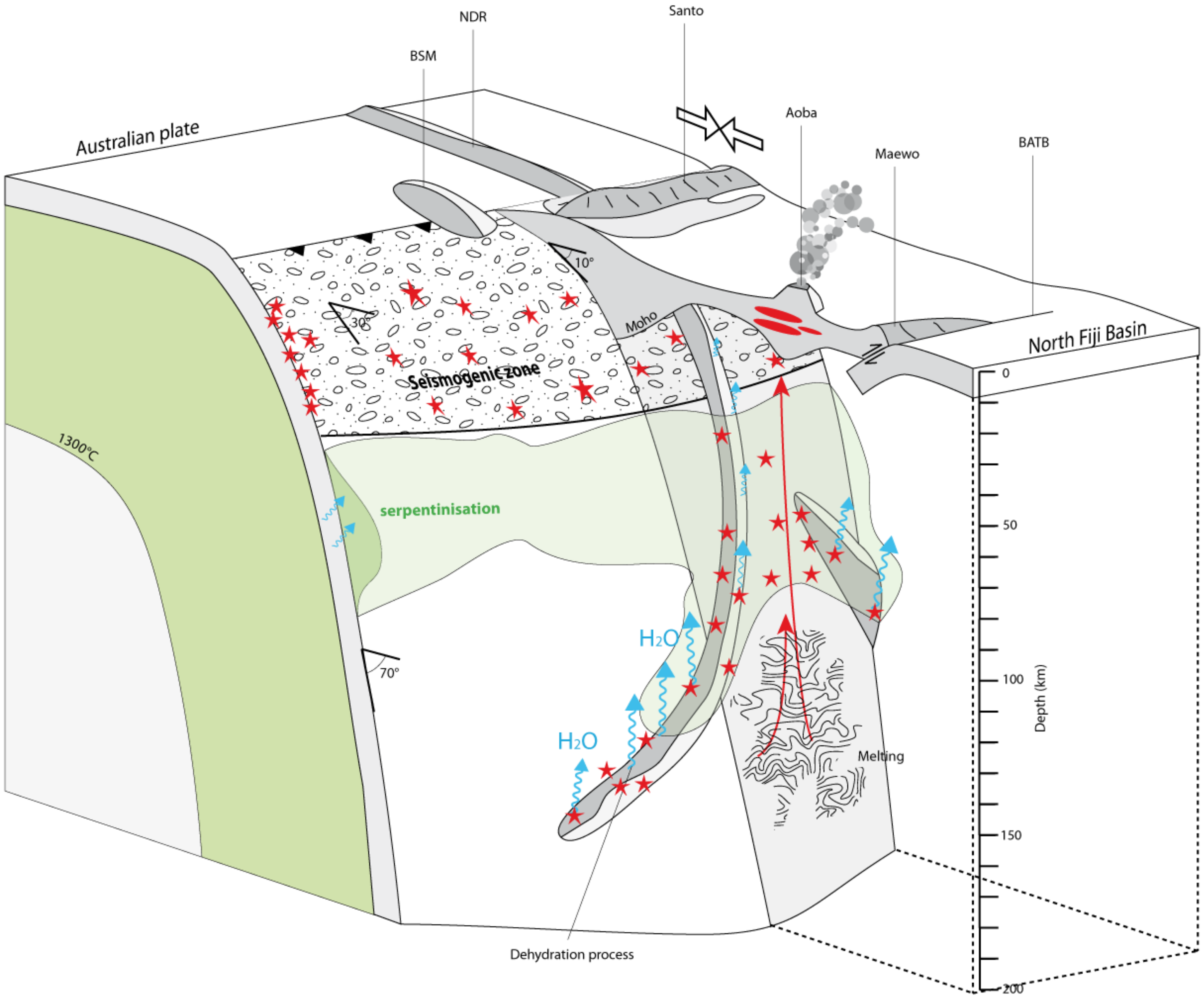
NDR
Santo
BSM
Aoba
Maewo
BATB
Australian plate
North Fiji Basin
10°
30°
Moho
Seismogenic zone
1300°C
serpentinisation
0
50
100
150
200
Depth (km)
70°
H2O
H2O
Dehydration process

Conclusion



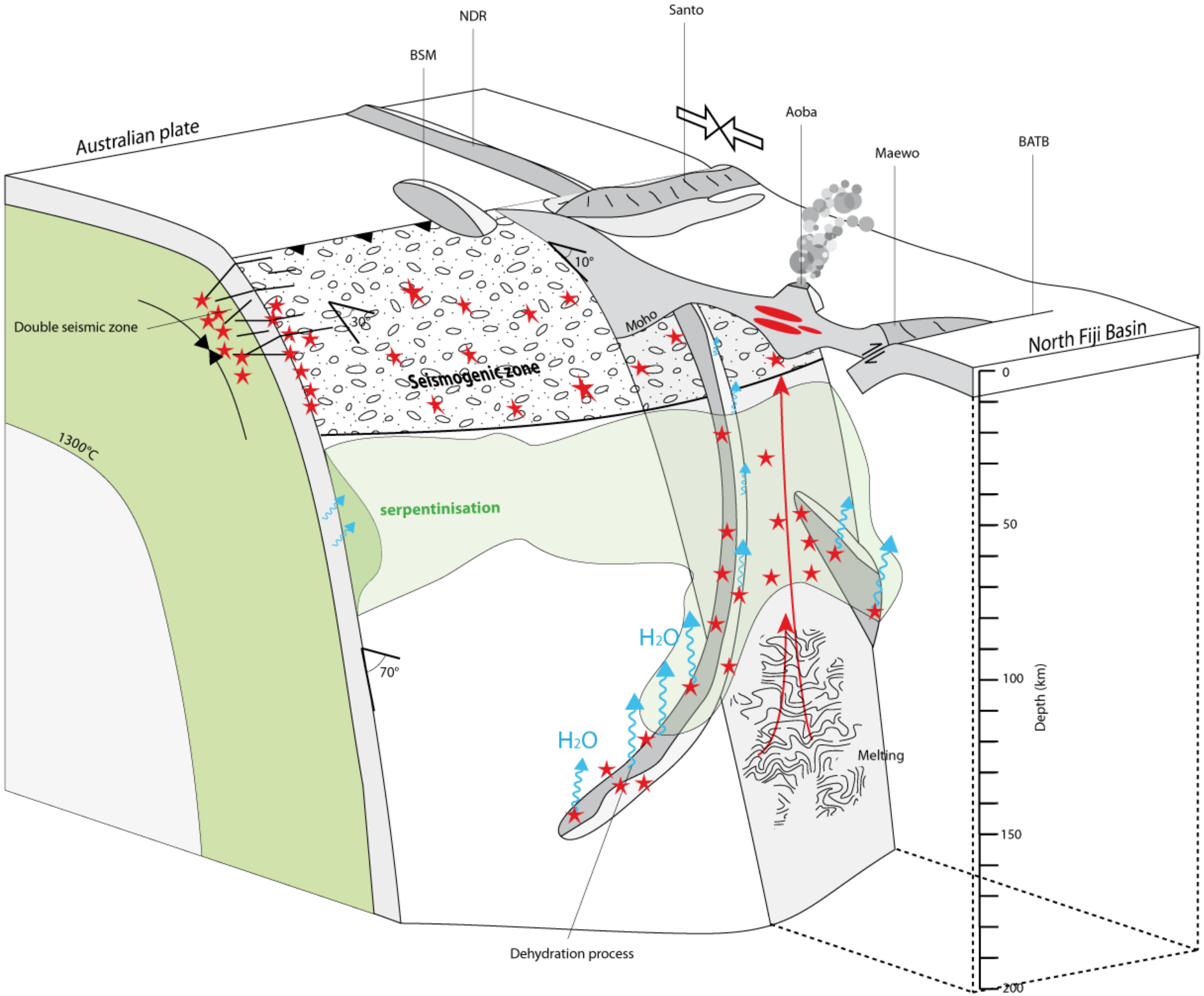
NDR
Santo
BSM
Aoba
Maewo
BATB
Australian plate
North Fiji Basin
10°
30°
Moho
Seismogenic zone
1300°C
serpentinisation
H2O
H2O
70°
0
50
100
150
200
Depth (km)
Dehydration process

Conclusion



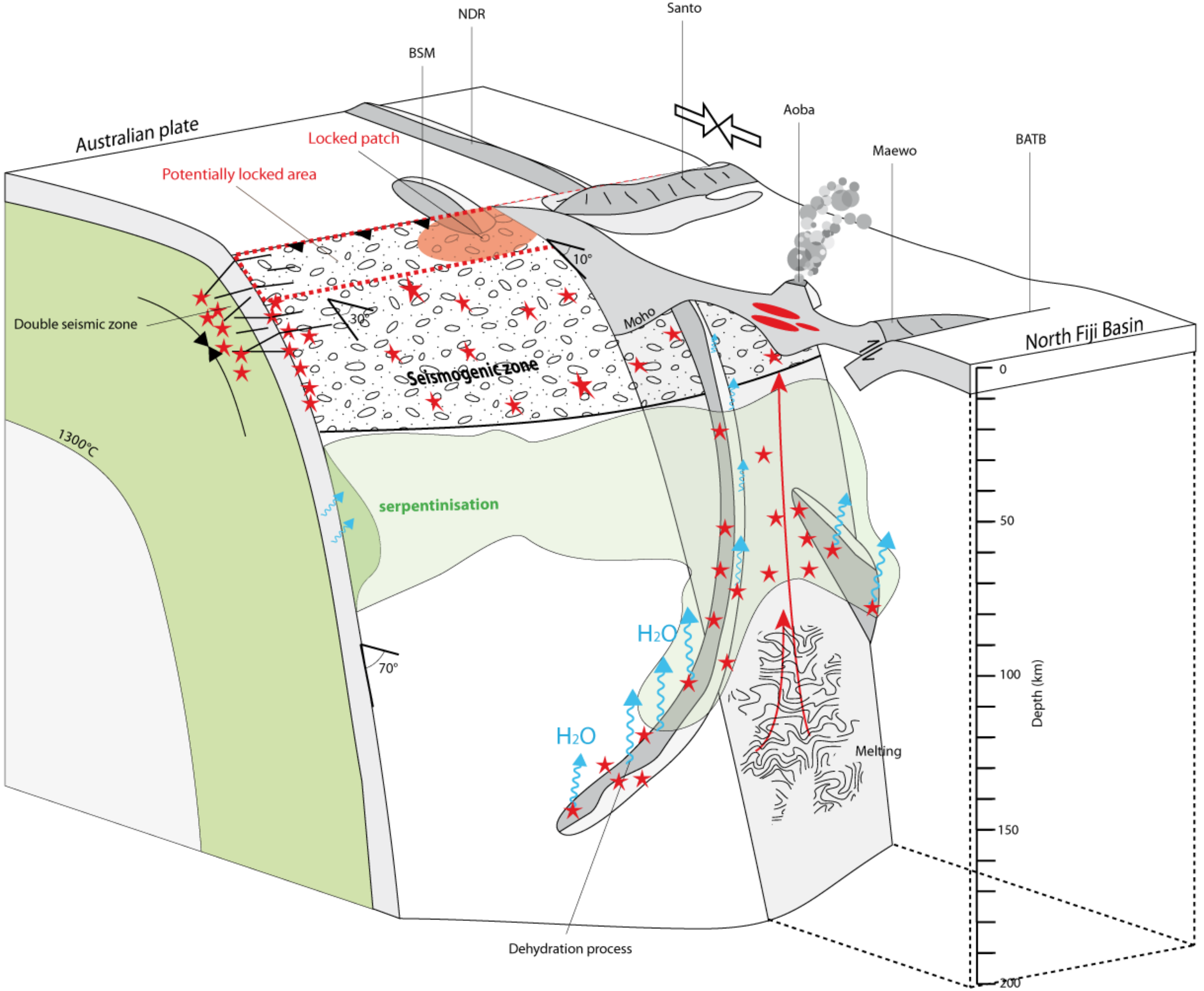
NDR
Santo
BSM
Aoba
Maewo
BATB
Australian plate
North Fiji Basin
10°
30°
Moho
Seismogenic zone
1300°C
serpentinisation
H2O
H2O
70°
Melting
Dehydration process
0
50
100
150
200
Depth (km)

Conclusion



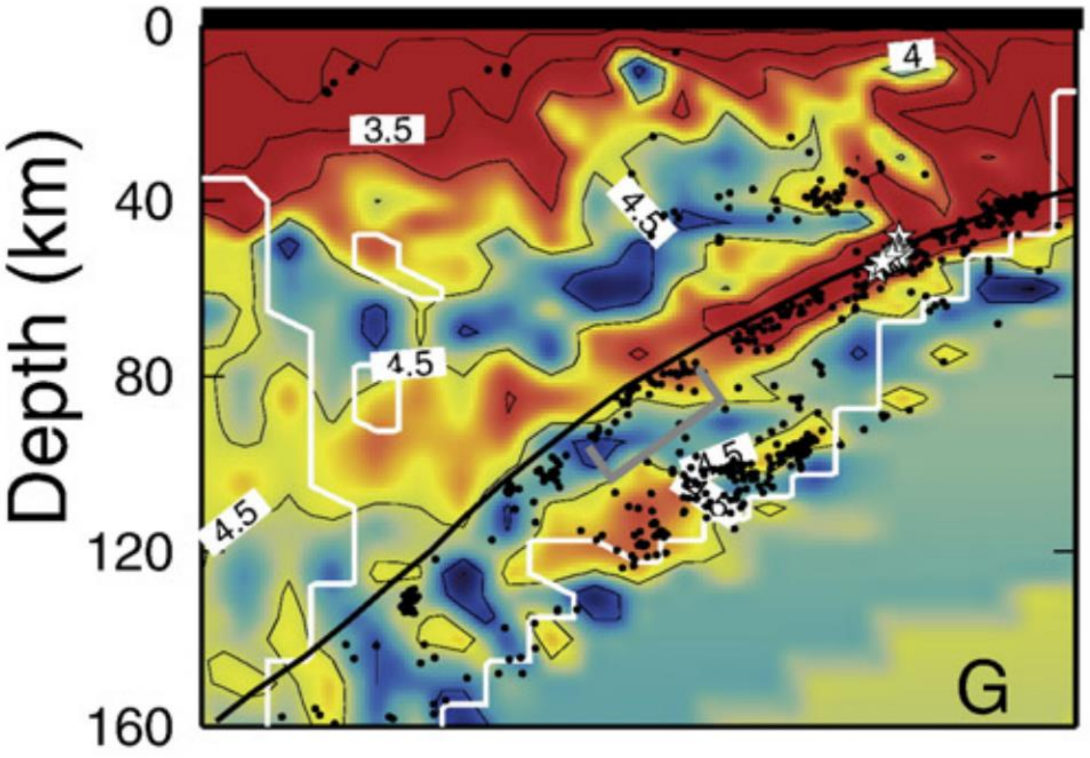
NDR
Santo
BSM
Aoba
Maewo
BATB
Australian plate
North Fiji Basin
10°
30°
70°
Double seismic zone
Moho
Seismogenic zone
1300°C
serpentinisation
H2O
H2O
Melting
Dehydration process
0
50
100
150
200
Depth (km)

Conclusion



NDR
Santo
BSM
Aoba
Maewo
BATB
Australian plate
Locked patch
Potentially locked area
10°
30°
Double seismic zone
Moho
North Fiji Basin
Seismogenic zone
1300°C
serpentinisation
0
50
100
150
200
Depth (km)
H2O
H2O
70°
Melting
Dehydration process

- P-S 2D/3D tomography using 2008-2009 catalog
  - Existence of **Low Velocity Layer** that can indicate presence of hydrous minerals in subducting upper crust



Perspectives

- P-S 2D/3D tomography using 2008-2009 catalog
  - Existence of **Low Velocity Layer** that can indicate presence of hydrous minerals in subducting upper crust

Perspectives

- P-S 2D/3D tomography using 2008-2009 catalog
  - Existence of Low Velocity Layer that can indicate presence of hydrous minerals in subducting upper crust

- Perform 3D mechanical modelling and use of vertical interseismic GPS velocities to know extension of the locked patch

- Improve the Automatic Picker

- P-S 2D/3D tomography using 2008-2009 catalog
    - Existence of Low Velocity Layer that can indicate presence of hydrous minerals in subducting upper crust
- Perform 3D mechanical modelling and use of vertical interseismic GPS velocities to know extension of the locked patch
- Improve the Automatic Picker

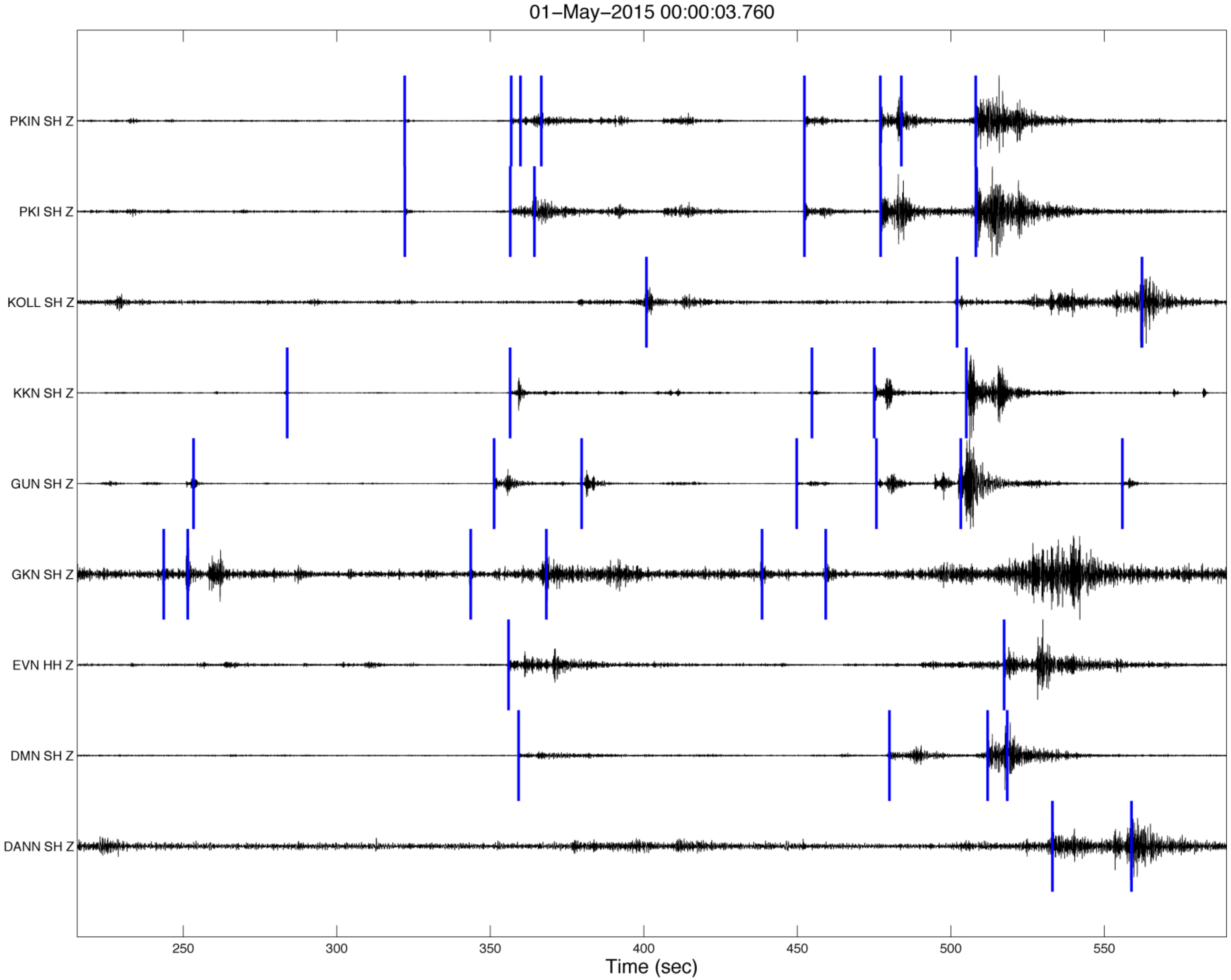
Thank you for your attention !



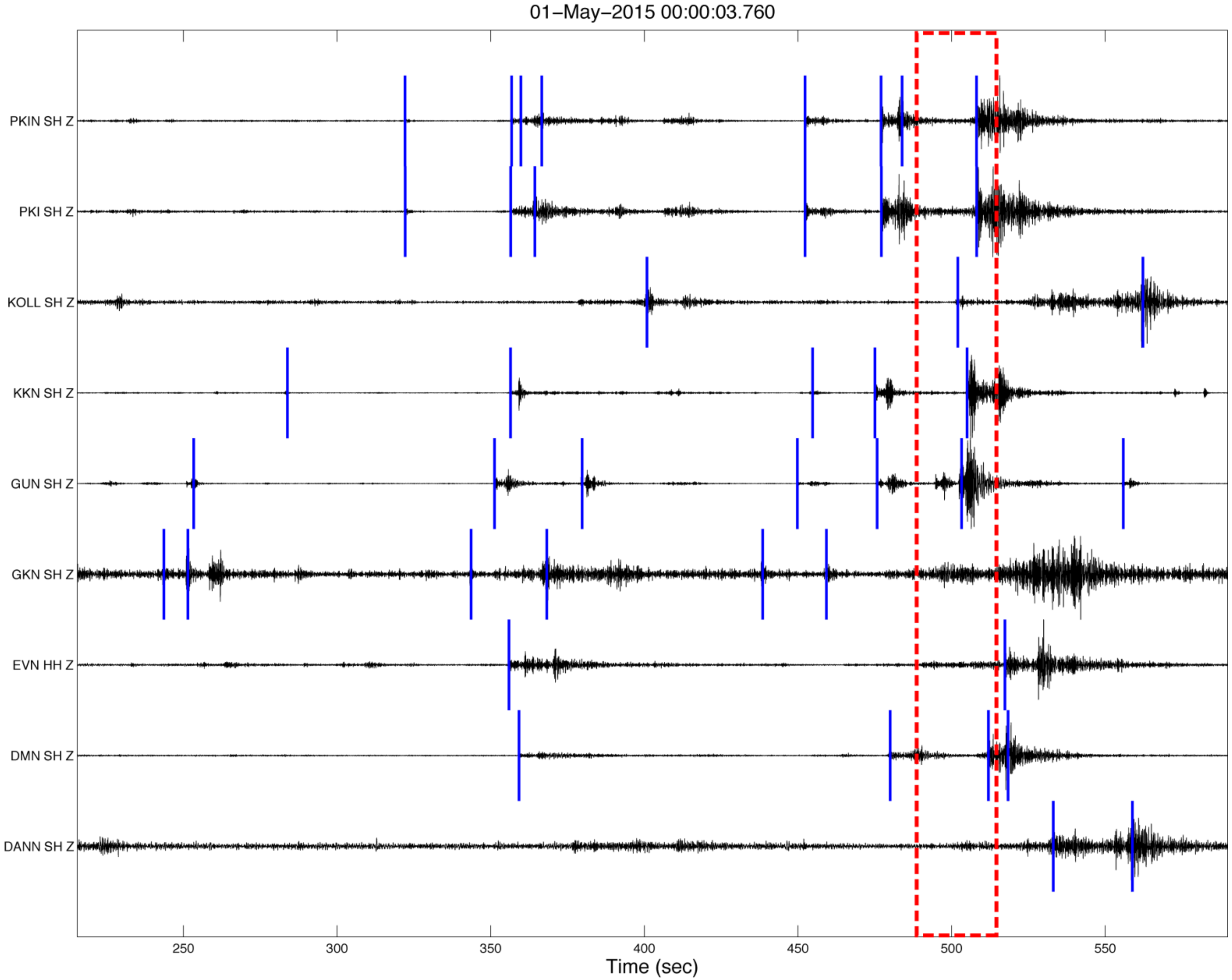



Additional slides

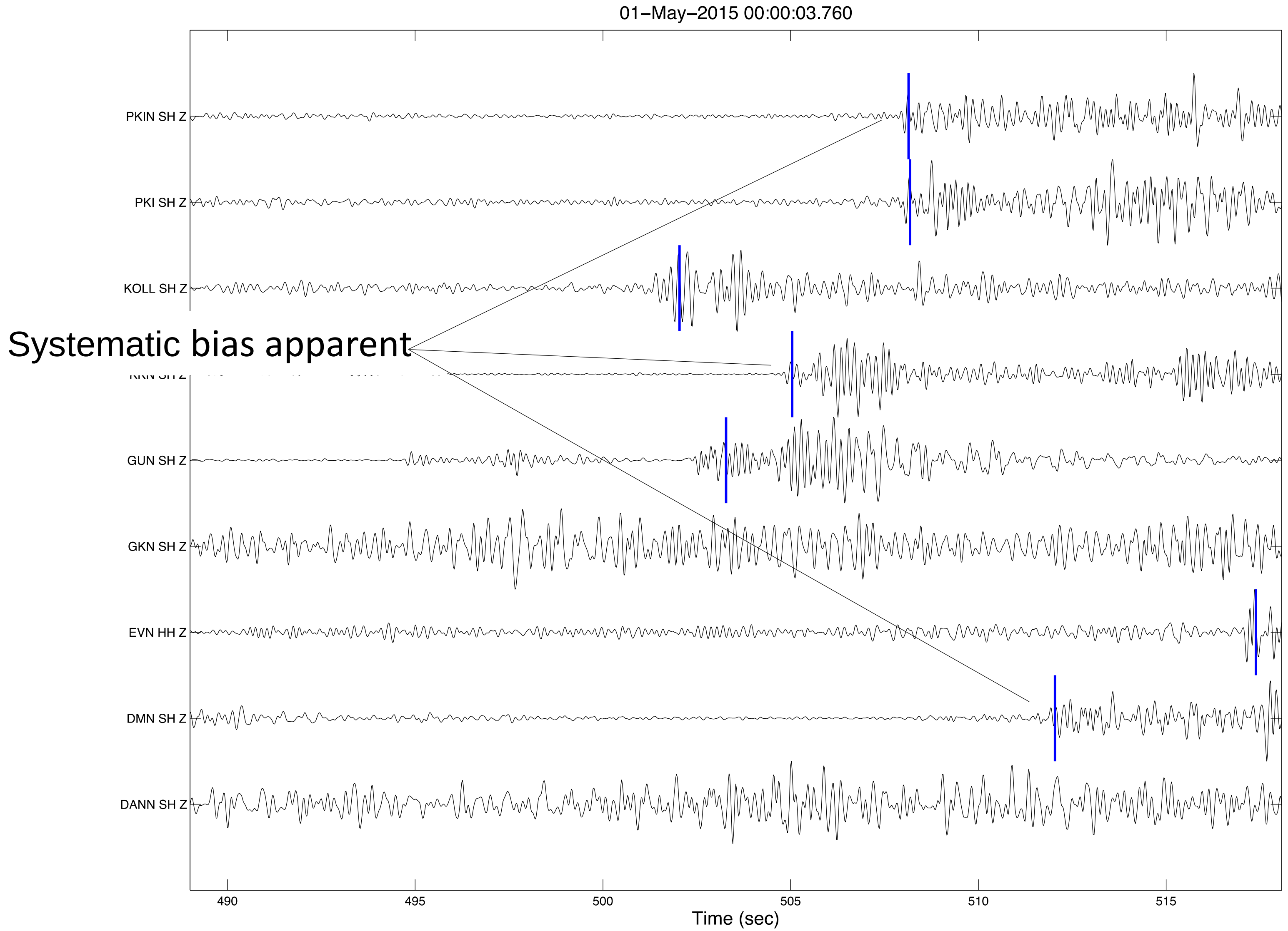
1) STA/LTA Picking



1) STA/LTA Picking

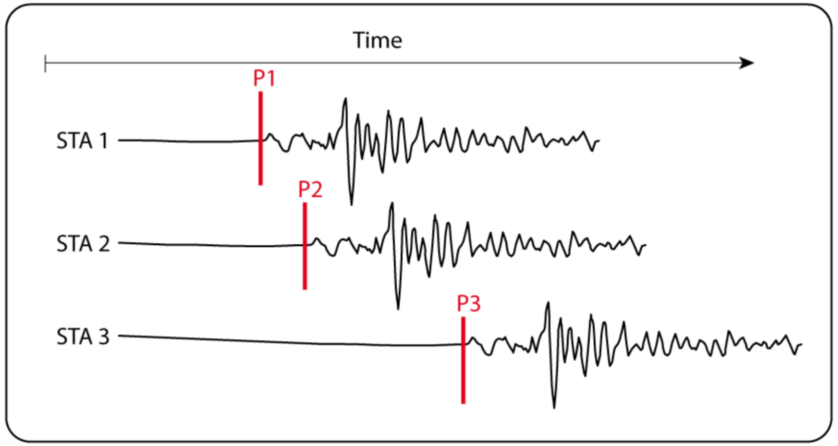


1) STA/LTA Picking

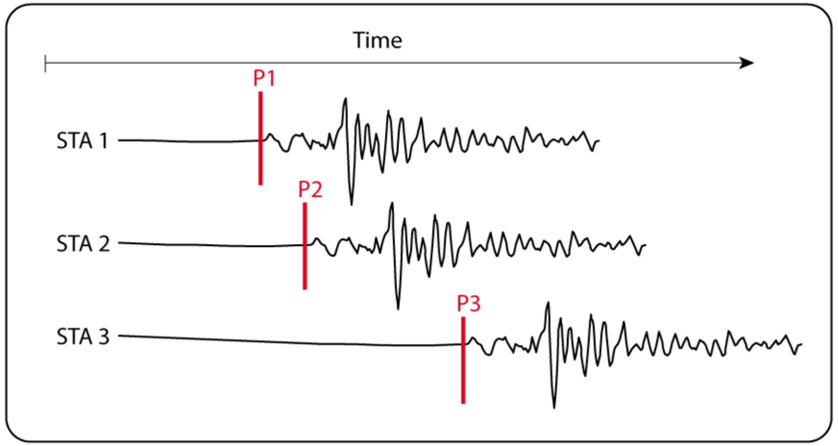


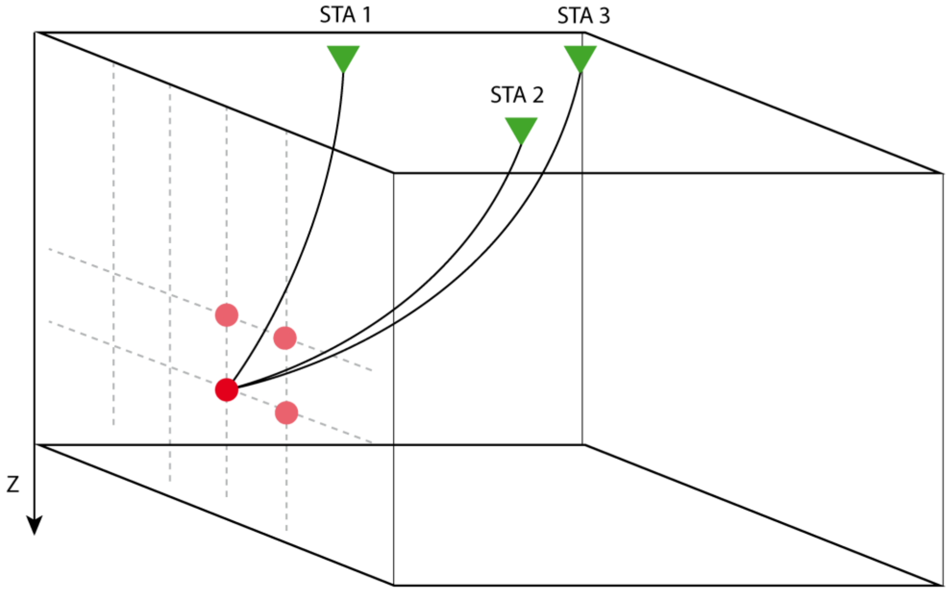
2) Phase Association

Perform coarse phase picking

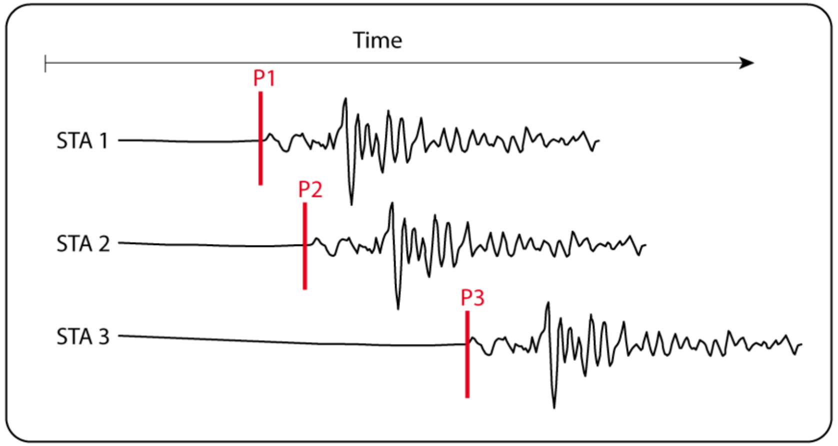


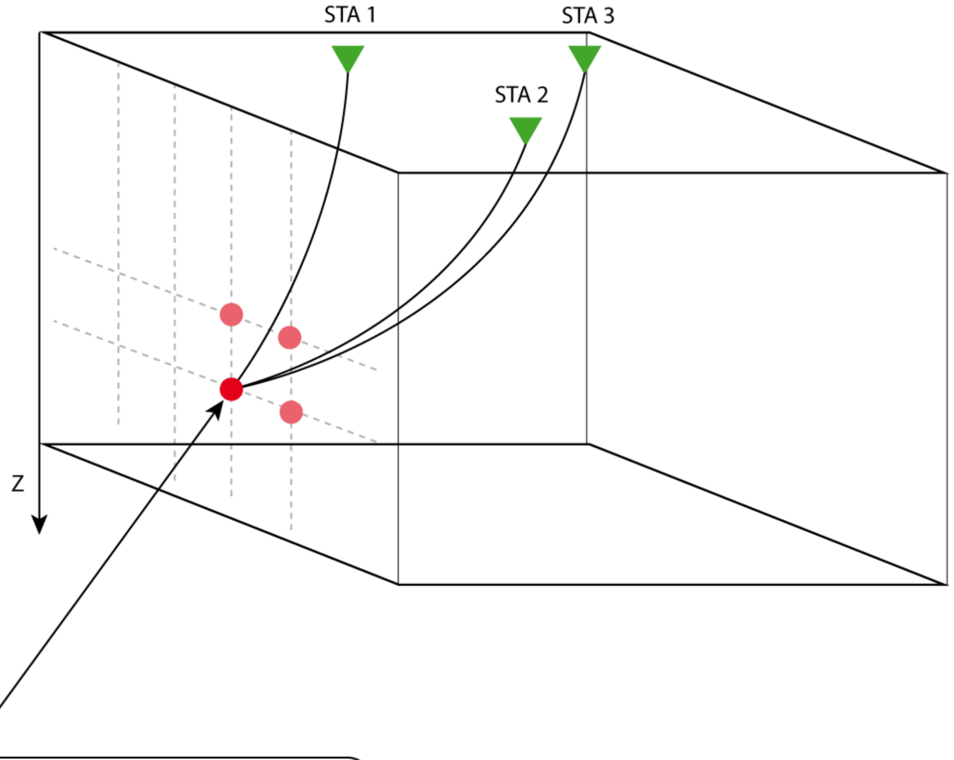
Compute theoretical arrival times
from stations to each bin of the grid



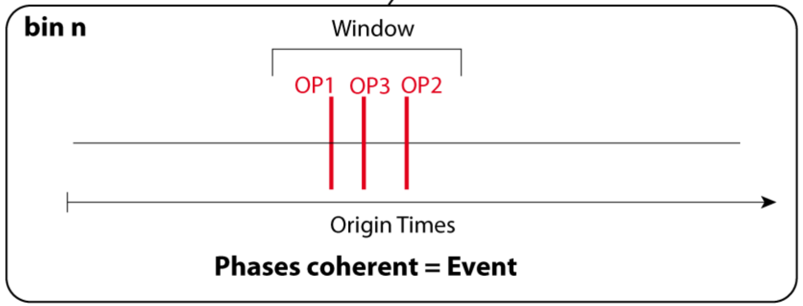


2) Phase Association

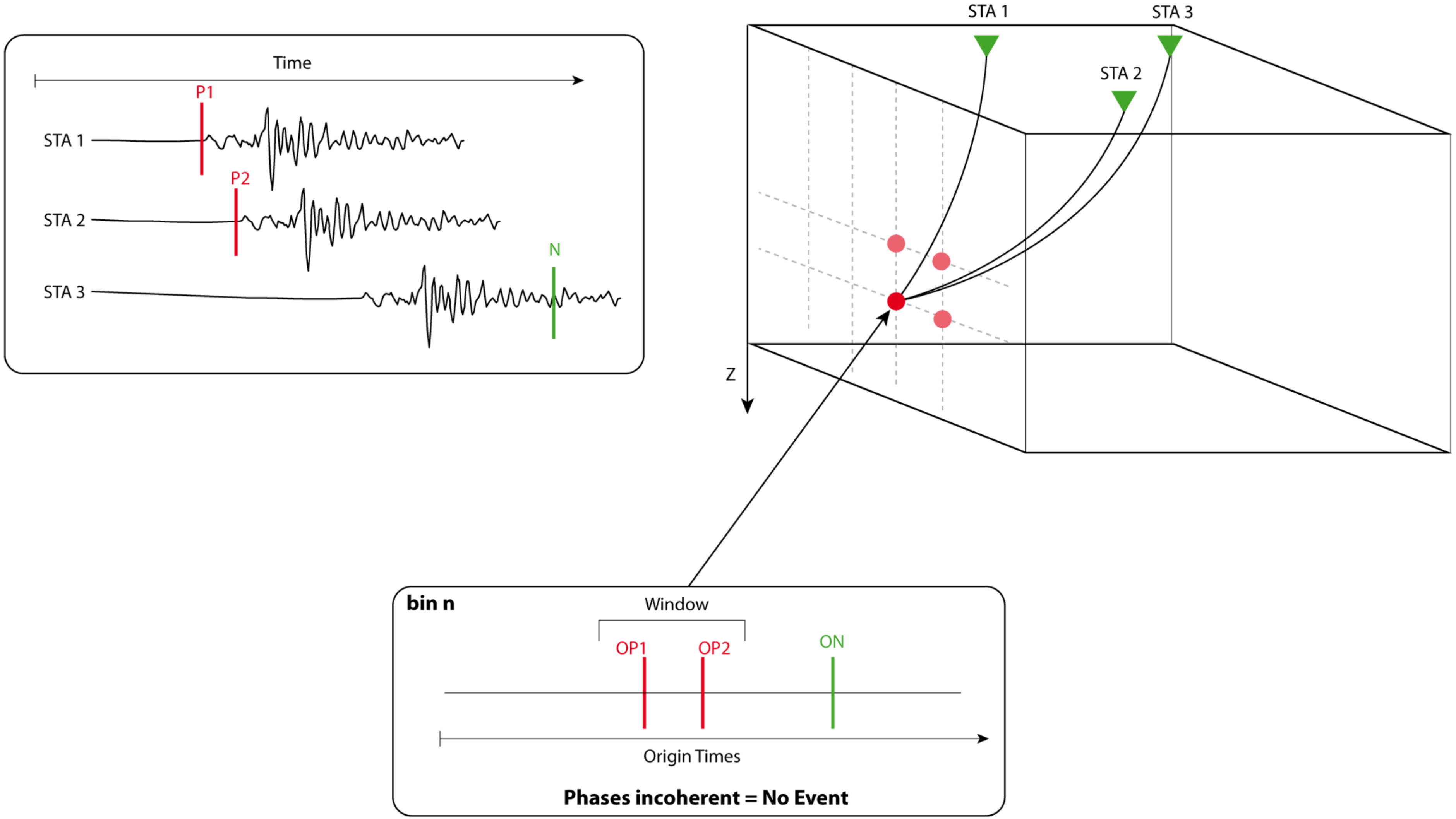




Get the bin that shows coherent origin times

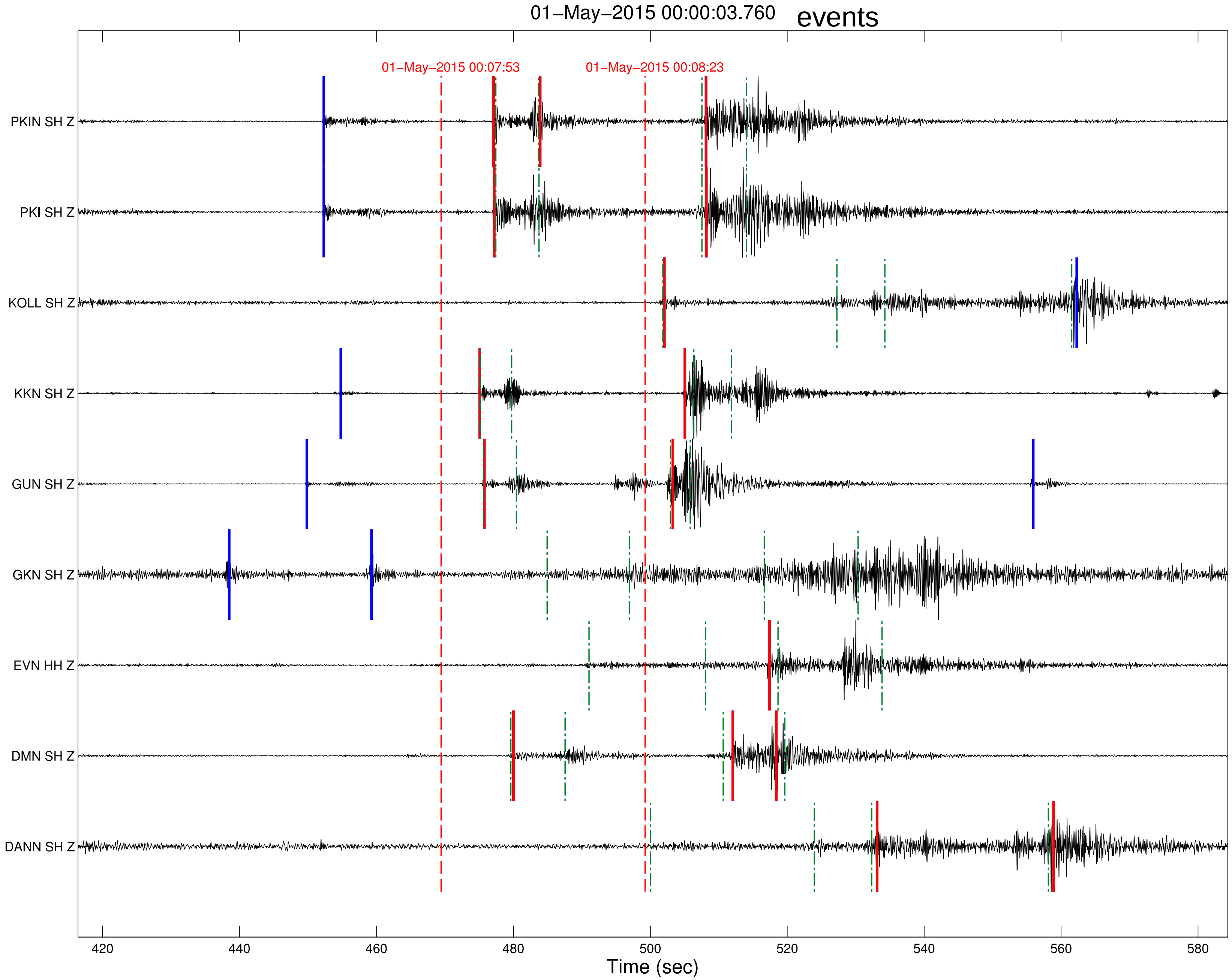


2) Phase Association



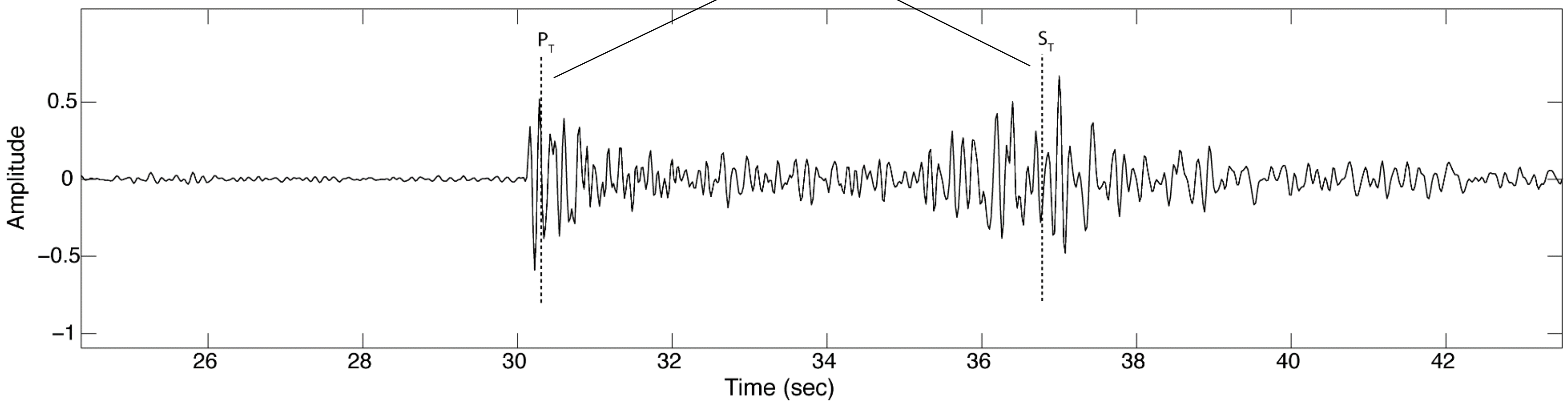
2) Phase Association

Output of phase association
> **Origin times** and **initial locations** of events

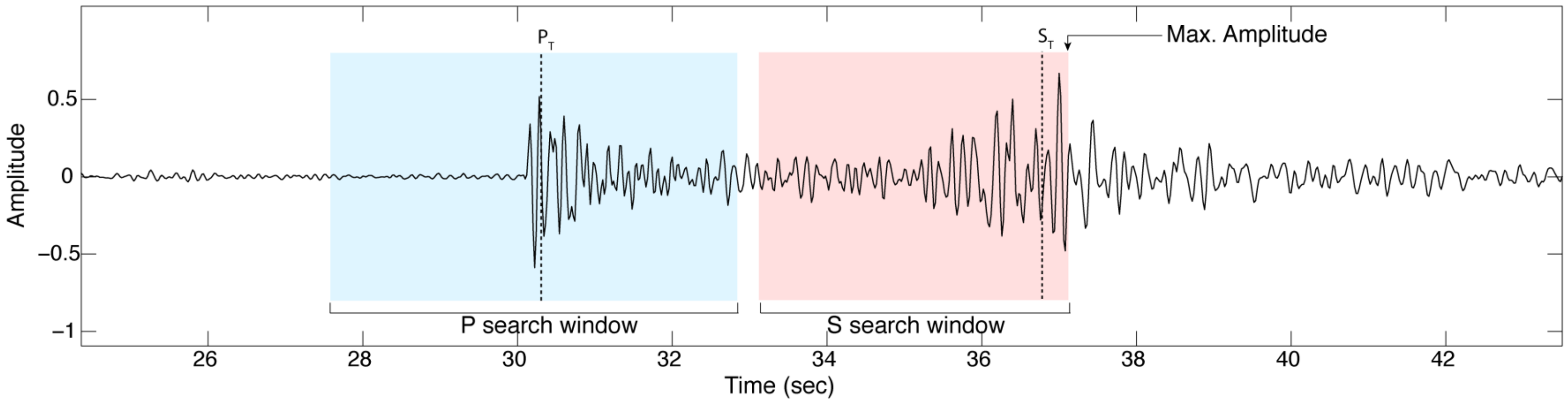


3) Picking refinement

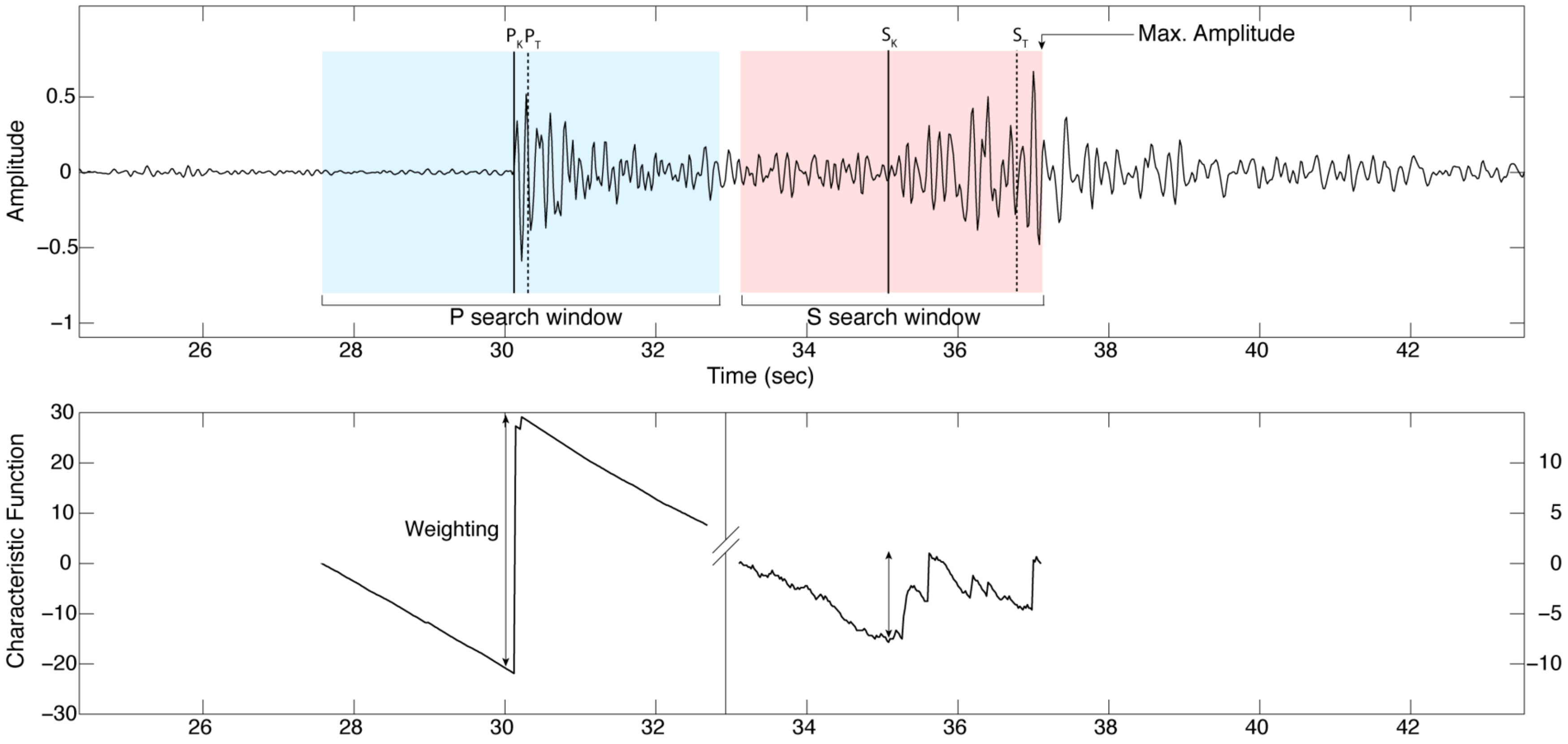
Theoretical arrival times delivered by the phase association process



3) Picking refinement



3) Picking refinement



About the mantle upwelling under NFB

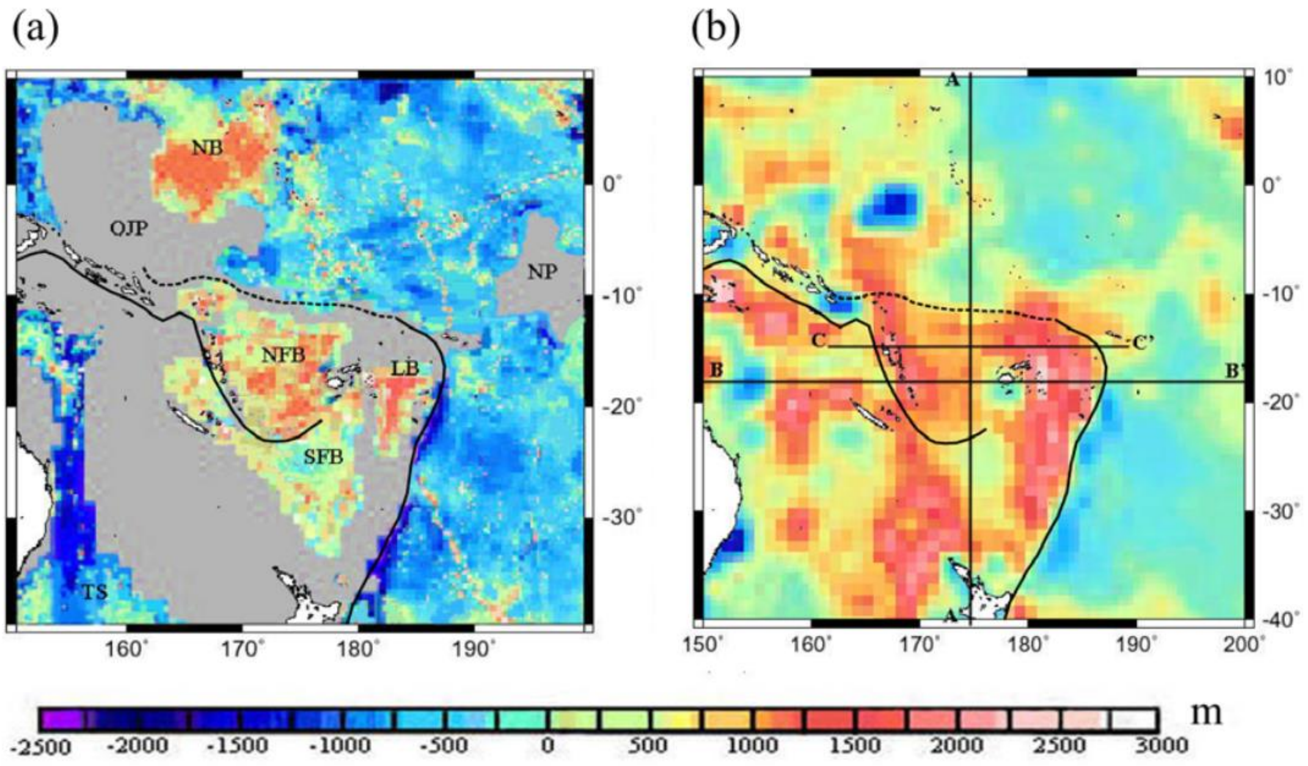


Figure 2. (a) Anomalous topography corrected from GDH1 plate cooling and subsidence model. (b) Residual topographies corrected from CRUST 2.0 data. The AA′, BB′, and CC′ are locations of cross sections shown in Figures 3 and 4.

Zhang et al., 2006

About the mantle upwelling under NFB

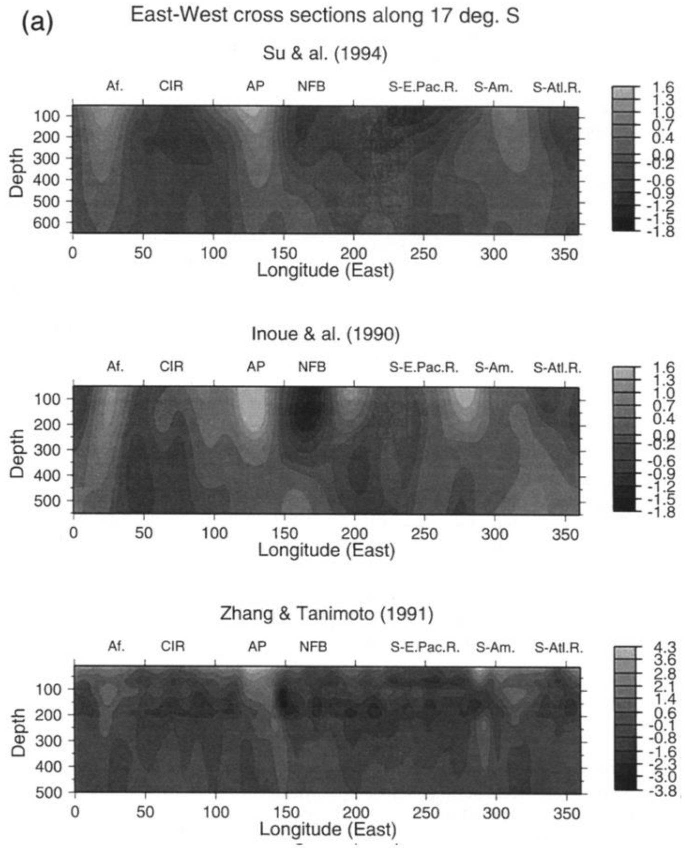
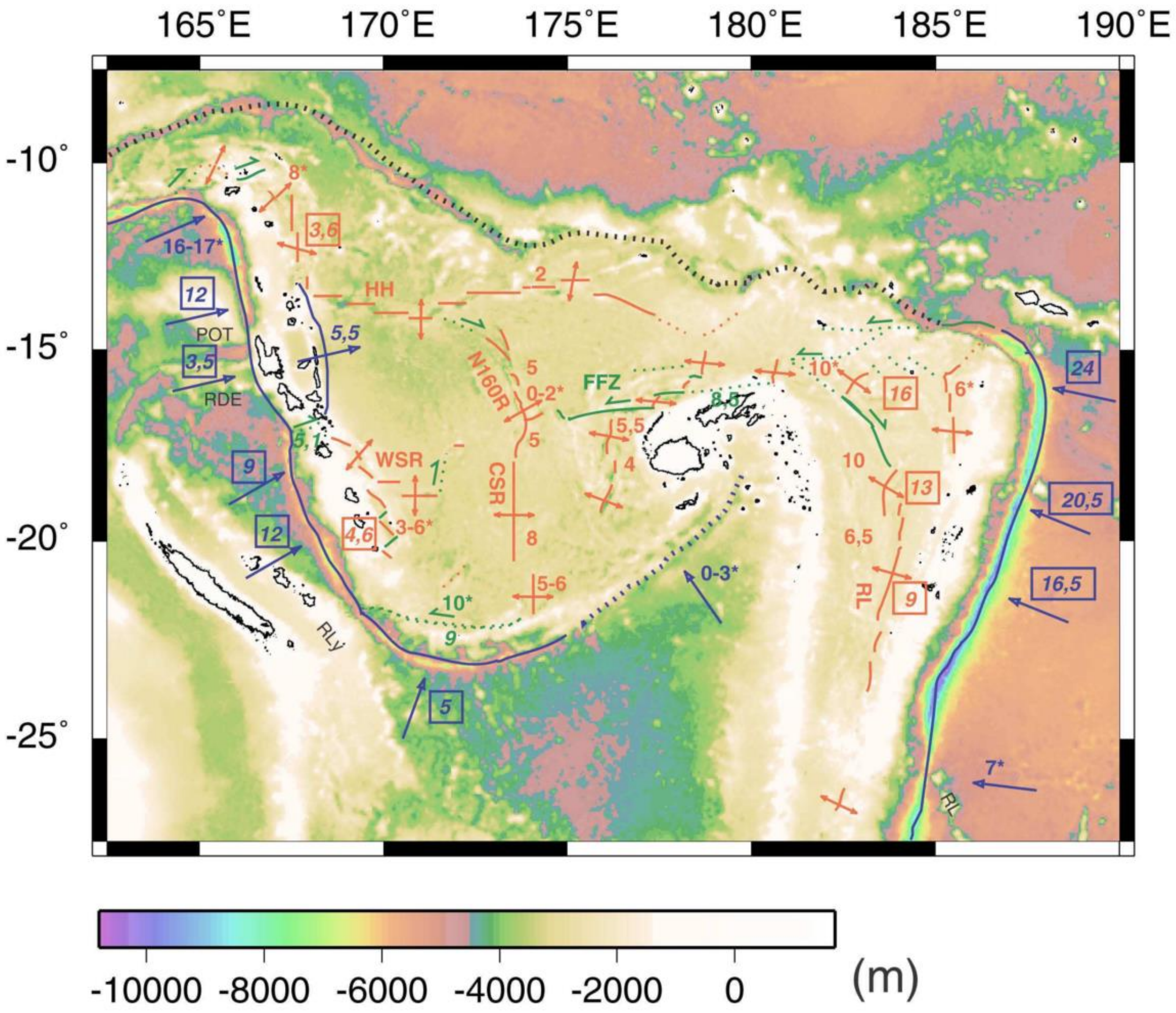


Fig. 3. (a) East–West cross sections along 17°S. The uppermost cross-section displays the velocity anomalies (in percentage of the average velocity for each cross-section, scale on the right) for model SH-12 [36], expanded up to angular order 12, obtained from SS-S differential travel times and surface waves. Below is the Inoue et al. [39] model for P waves, obtained from P-wave arrival times given by the International Seismic Center. The lowermost cross-section is the model of Zhang and Tanimoto [37] expanded up to angular order 36, obtained from surface waves inversion. *Af* = Africa; *CIR* = Central Indian Ridge; *AP* = Australian Plate; *NFB* = North Fiji Basin; *S-E.Pac.R.* = South-East Pacific Ridge; *S-Am.* = South America Plate; *S-Atl.R.* = South Atlantic Ridge.

Lagabrielle et al., 1997

- This upwelling has been shown by velocity anomalies, high heat flow, geoid anomalies
- Upwelling could explain low viscosity and mantle flux associated to steep interface.

About the mantle upwelling under NFB



Pelletier et al., 1998

About sediments going into subduction in the Vanuatu region

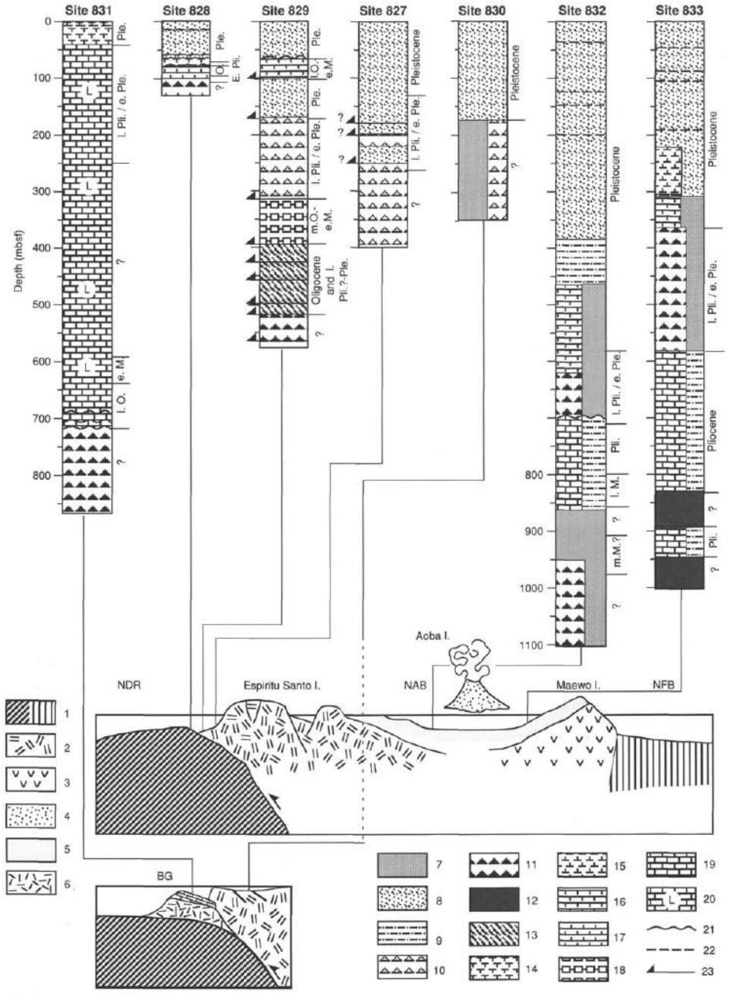
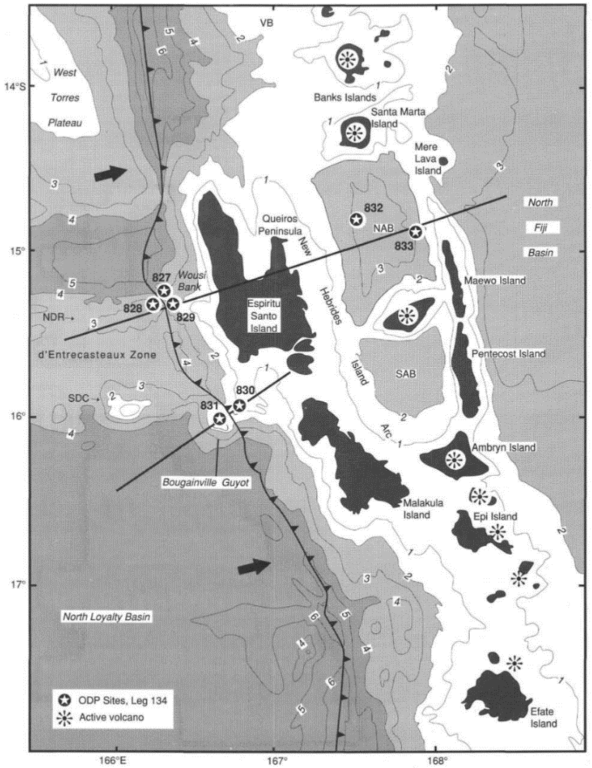


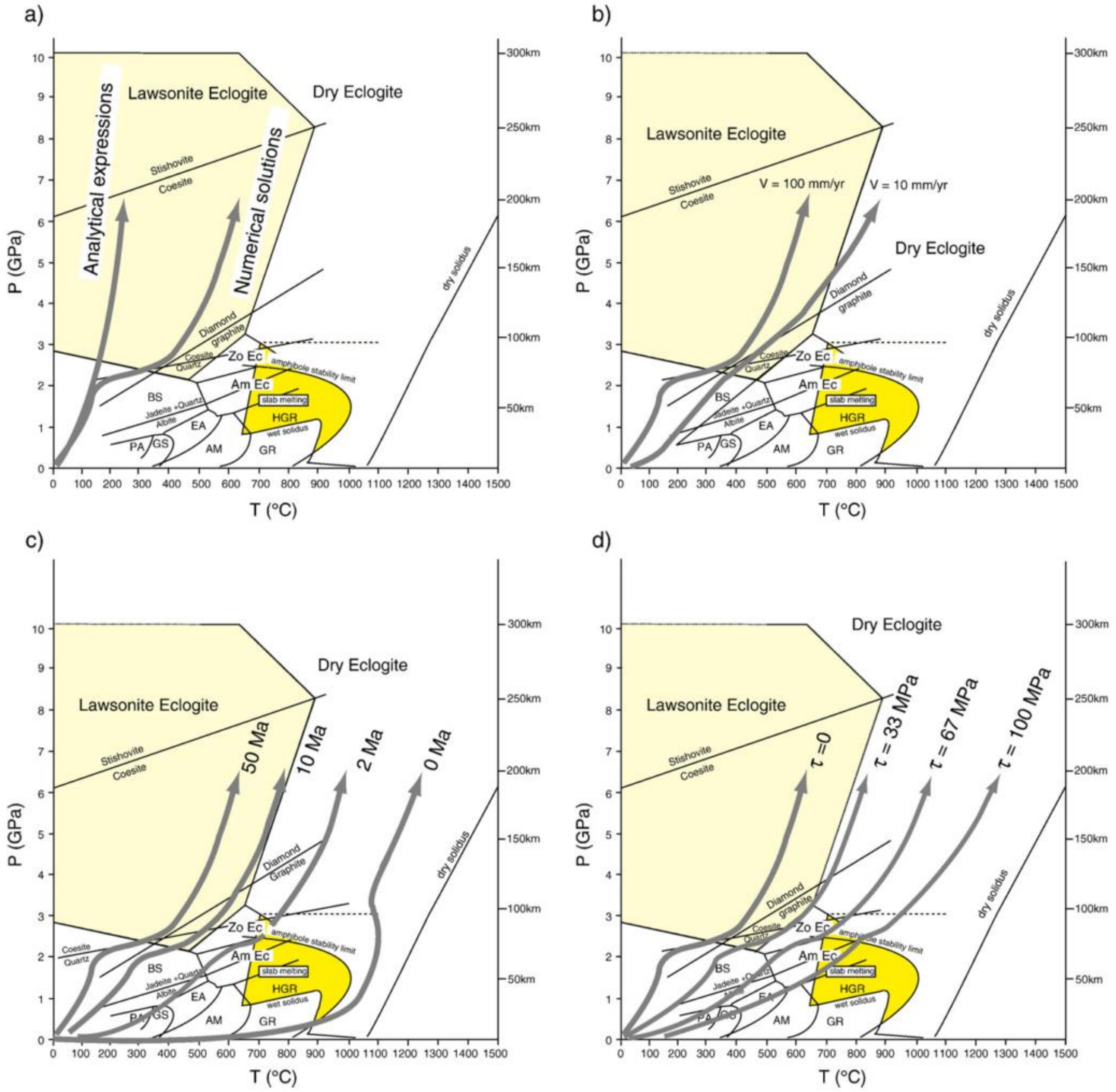
Figure 3. Geologic columns and cross sections, Leg 134. Location of cross sections is indicated in Figure 2. 1 = oceanic crust; 2 = Western Belt volcanic rocks; 3 = Eastern Belt volcanic rocks; 4 = Central Chain volcanic rocks; 5 = basin fill; 6 = guyot volcanic rocks; 7 = volcanic sand/sandstone; 8 = volcanic silt/siltstone; 9 = volcanic sandstone/siltstone/claystone; 10 = sed-lithic breccia; 11 = volcanic breccia; 12 = basalt chalk; 13 = multiple slivers of siltstone and chalk; 14 = foraminiferal ooze; 15 = nannofossil ooze; 16 = foraminiferal chalk; 17 = nannofossil chalk; 18 = calcareous chalk; 19 = pelagic limestone; 20 = lagoonal limestone; 21 = unconformity; 22 = ash; 23 = thrust fault. NDR = North d'Entrecasteaux Ridge; BG = Bougainville Guyot; NAB = North Aoba Basin; NFB = North Fiji Basin.

- Thin layer of sediment. ~50 m on NDR. Bougainville seamount exhibit thicker lagonal limestone that cannot be extended to other part of seafloor
- Small amount of sediments could explain coupling near the surface



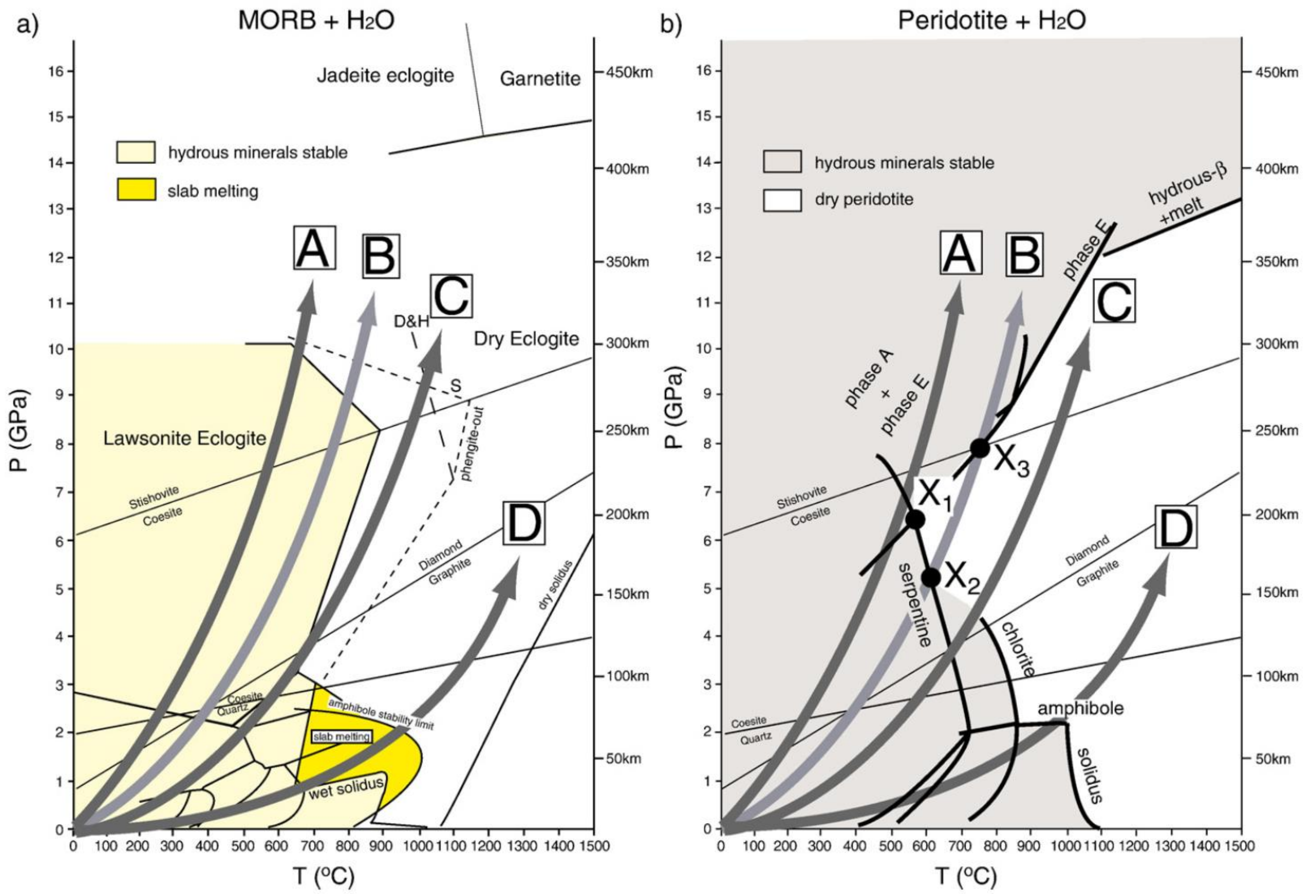
Collot et al., 1992.
LEG 134

About P-T stability domain of minerals



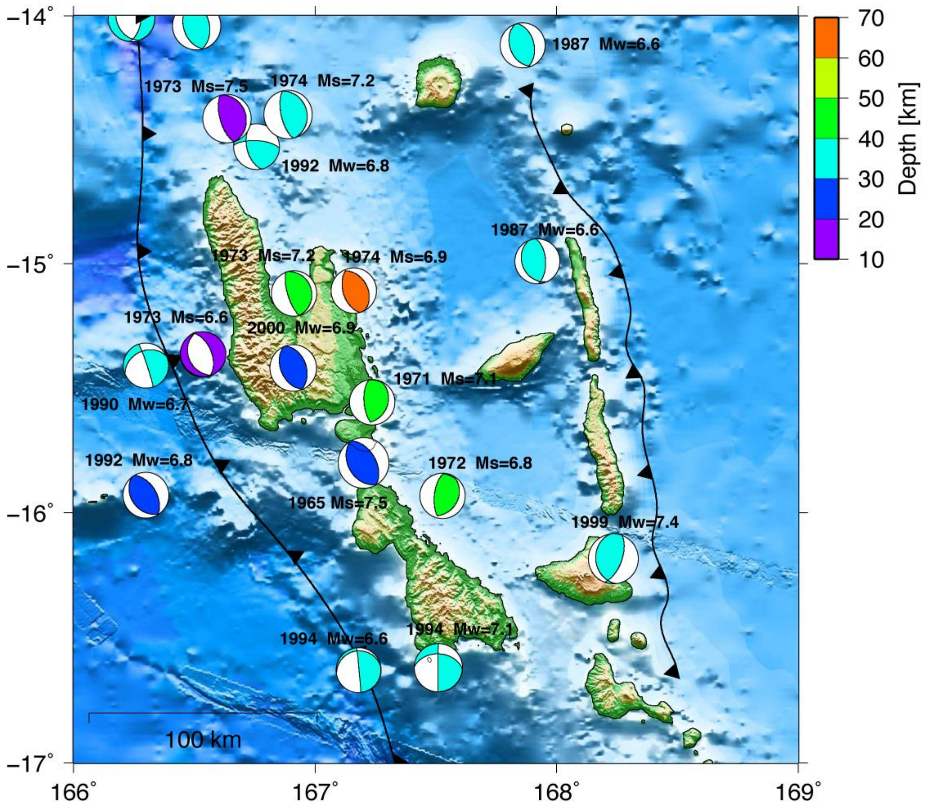
Maruyama & Okamoto., 2007

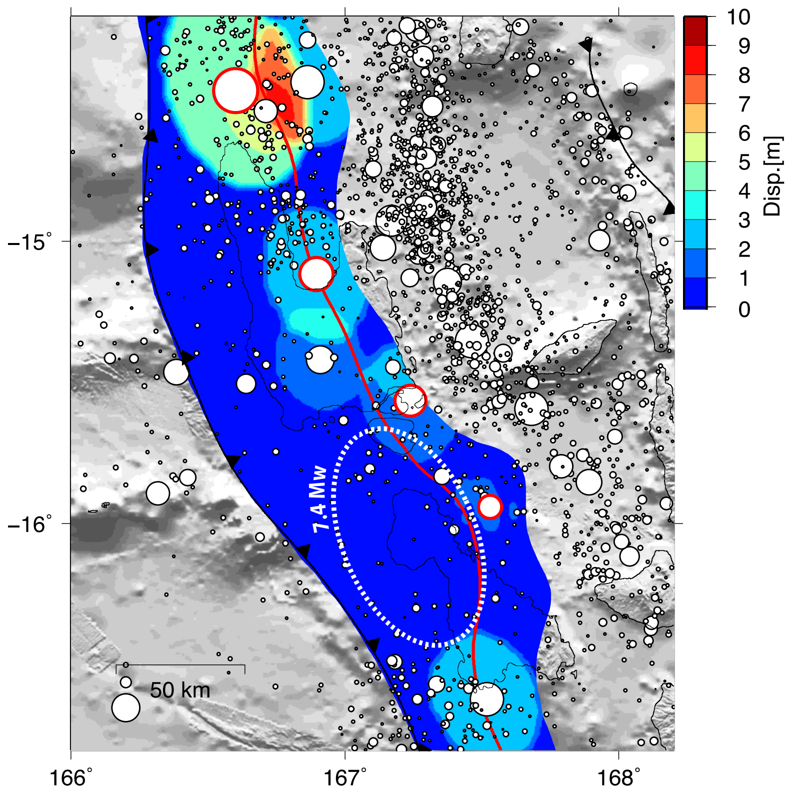
About P-T stability domain of minerals



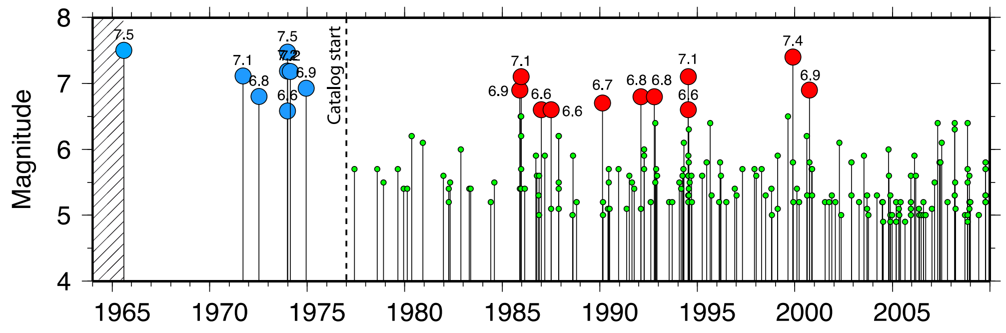
Serpentinisation could be maintain to 150 km in the case of high thermal parameter slab path (< 650°C)

About historical seismicity

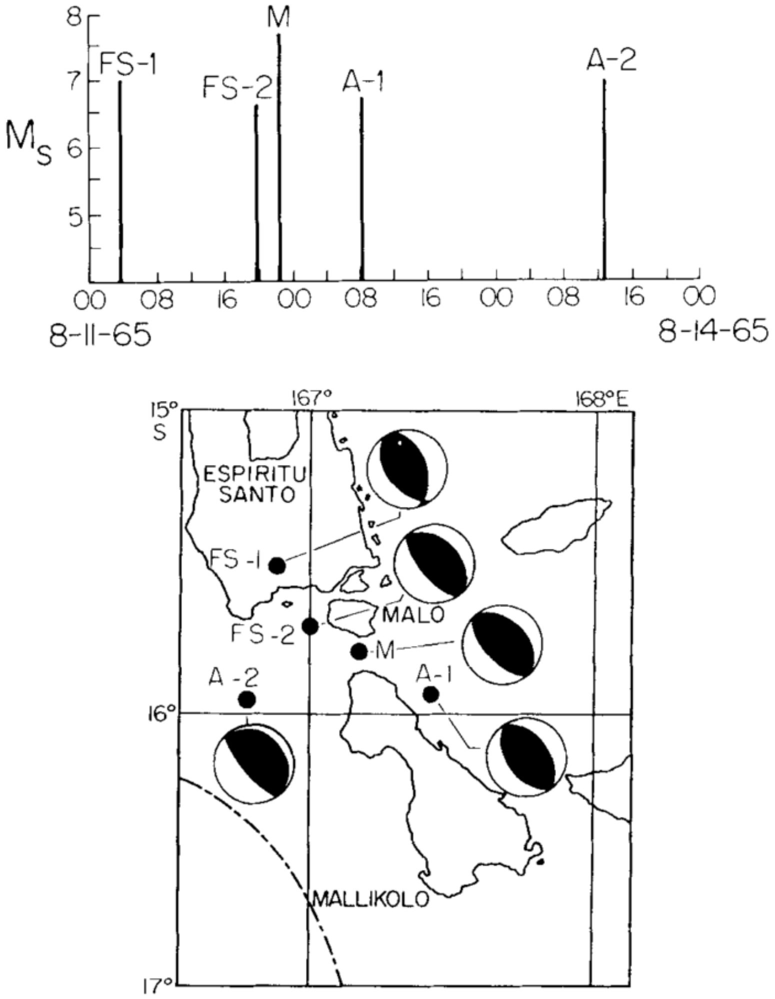




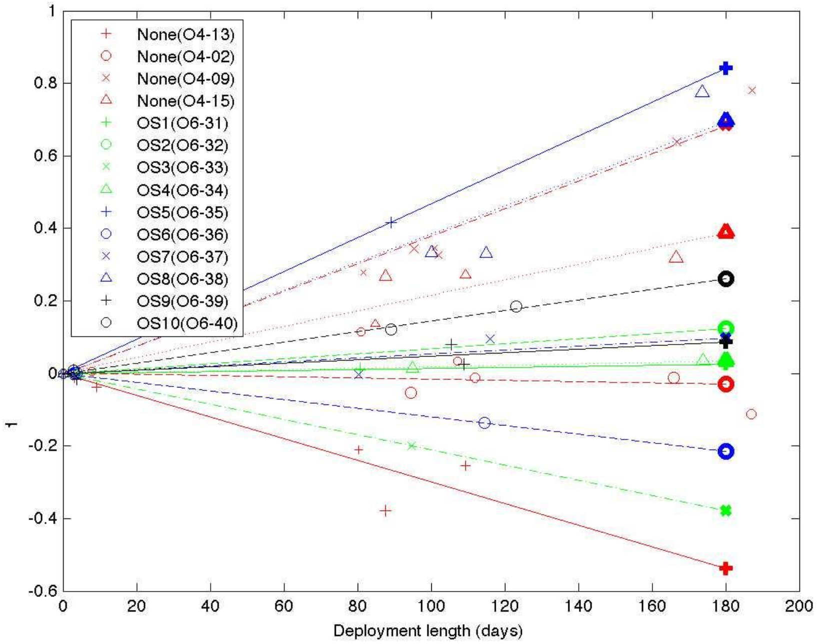
Earthquakes 166/169°N - 17°/14°S



About 1965 Mw 7.5 earthquake

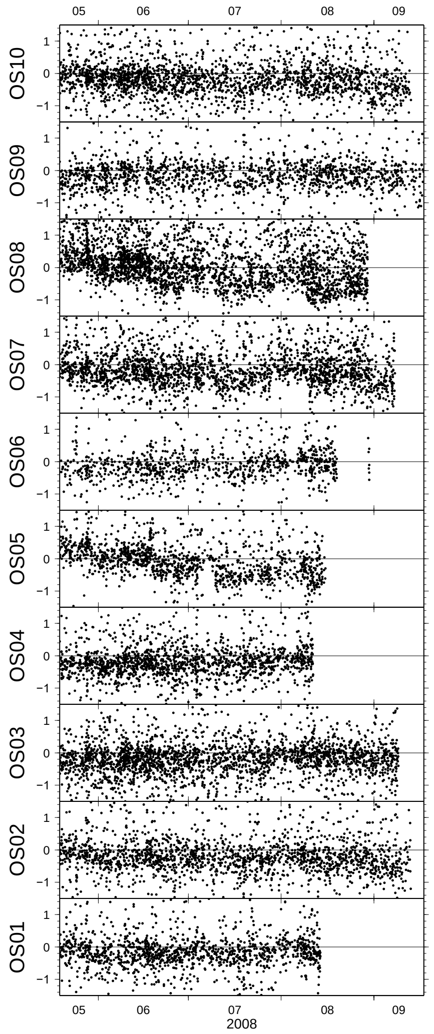


About OBS data

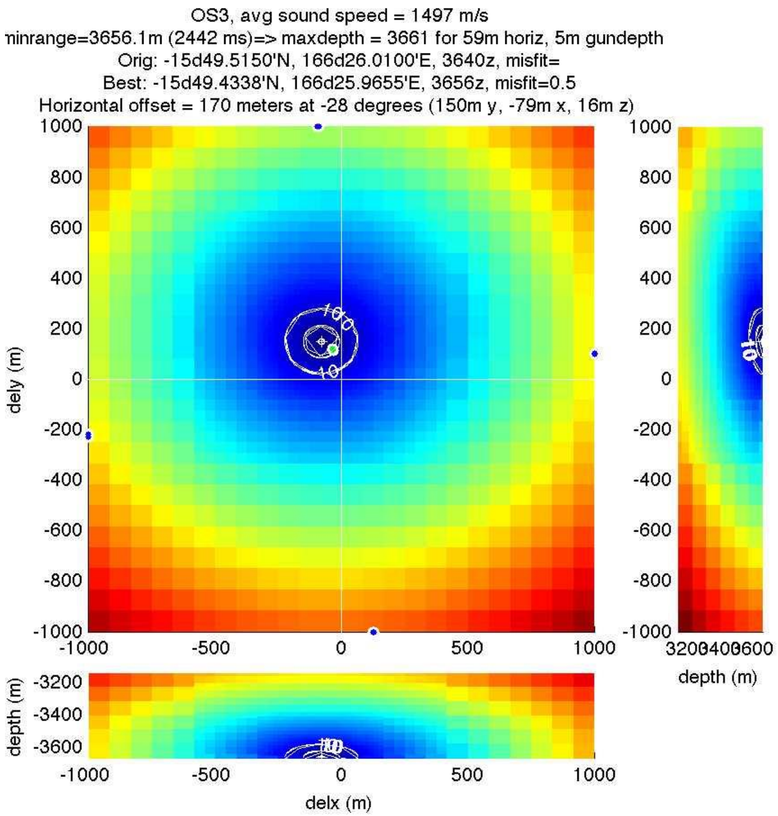


Site	Last Data	Z	X	Y	P	End Sync?
OS1	15 Aug	Bad	OK	OK	OK	Non
OS2	15 Sept	OK	OK	OK	OK	Non
OS3	10 Sept	FLAT	FLAT	FLAT	OK	Non
OS4	12 Aug	Chopped	Chopped	Chopped	OK	Yes
OS5	16 Aug	Chopped	Chopped	Chopped	OK	Non
OS6	31 Aug	FLAT	Chopped	Chopped	Weak	Non
OS7	8 Sept	Chopped	Chopped	Chopped	OK	Non
OS8	30 Aug	Chopped	Chopped	Chopped	OK	Yes
OS9	18 Sept	Chopped	Chopped	Chopped	OK	Non
OS10	13 Sept	OK	OK	OK	OK	Non

FINAL Network EQ time residuals



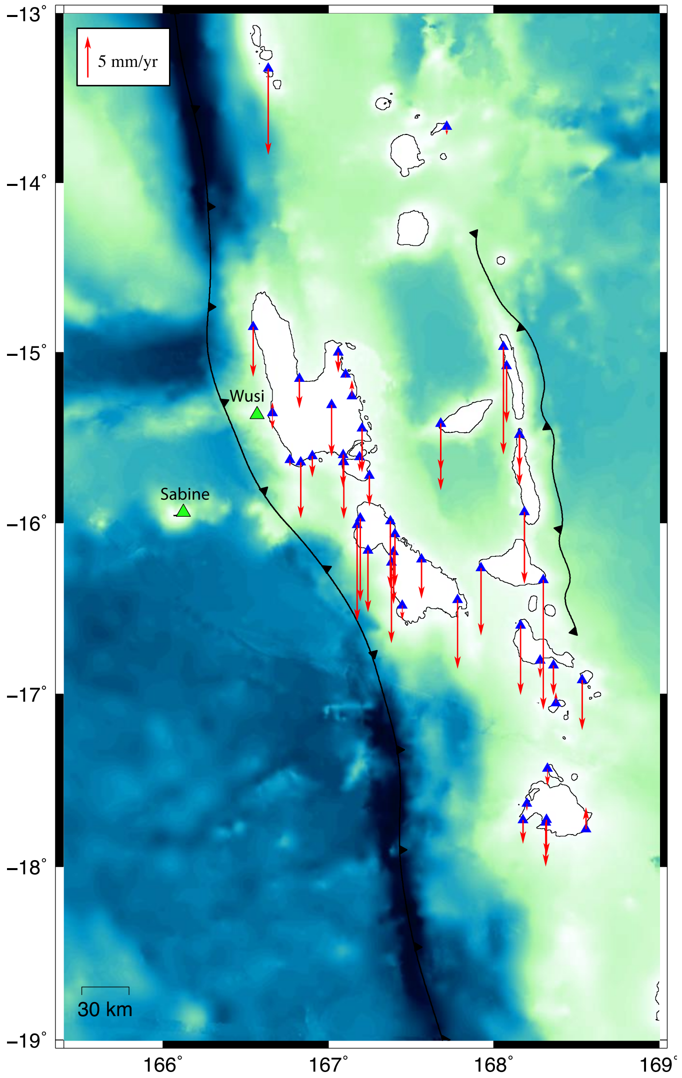
About OBS data

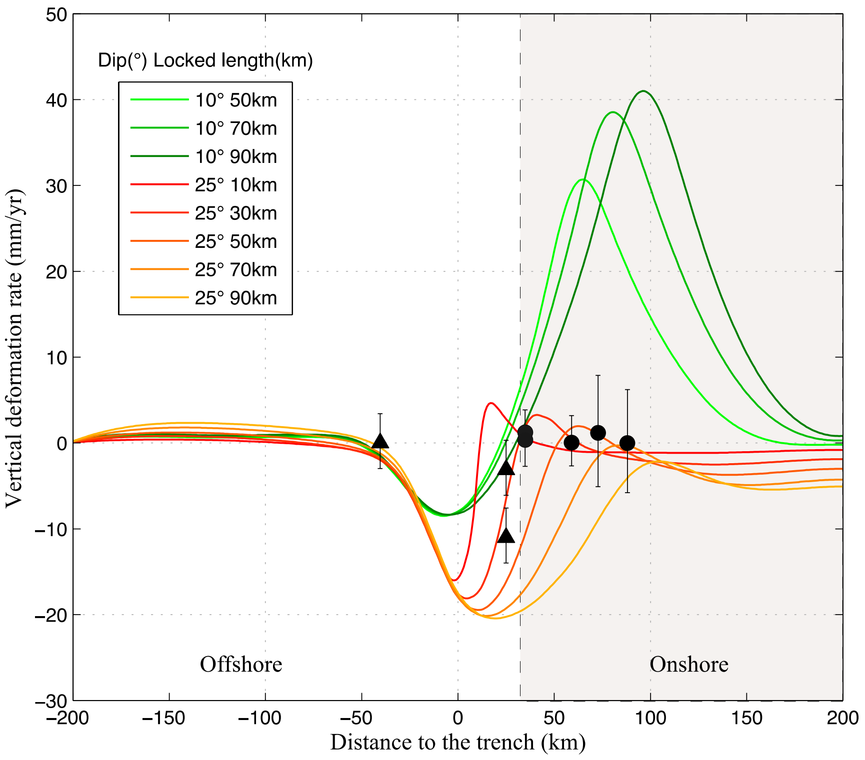


Dérive de 170 m

Our 2D model parameter:
$E=1.6 \times 10^{11}$ $N.m^{-2}$ (litho)
$\eta=10^{19}$ Pa.s (astheno)

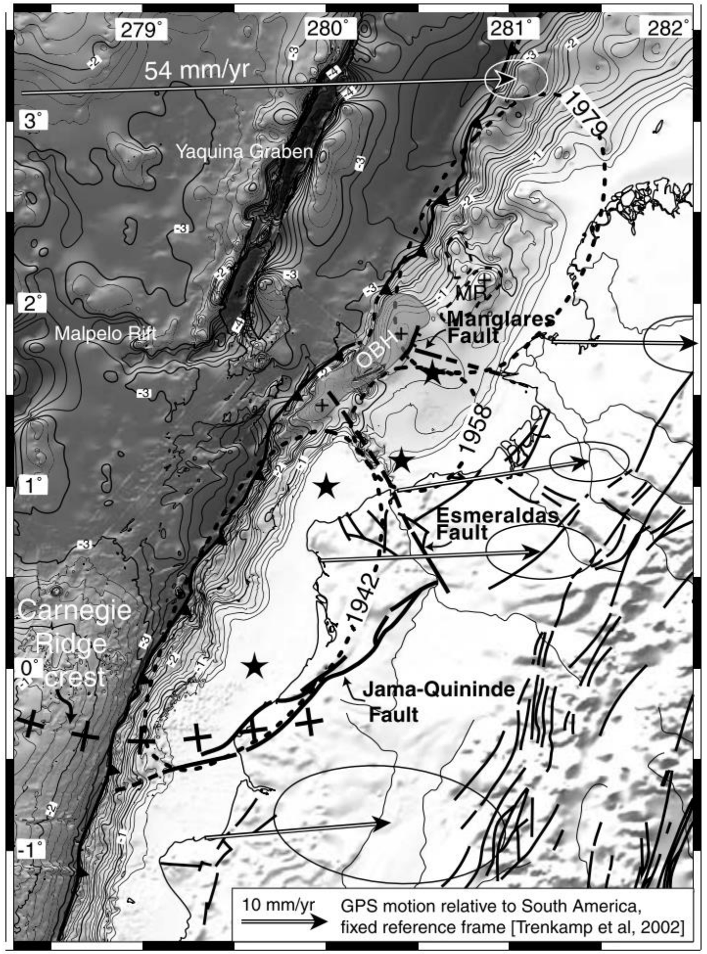
About the mechanical model

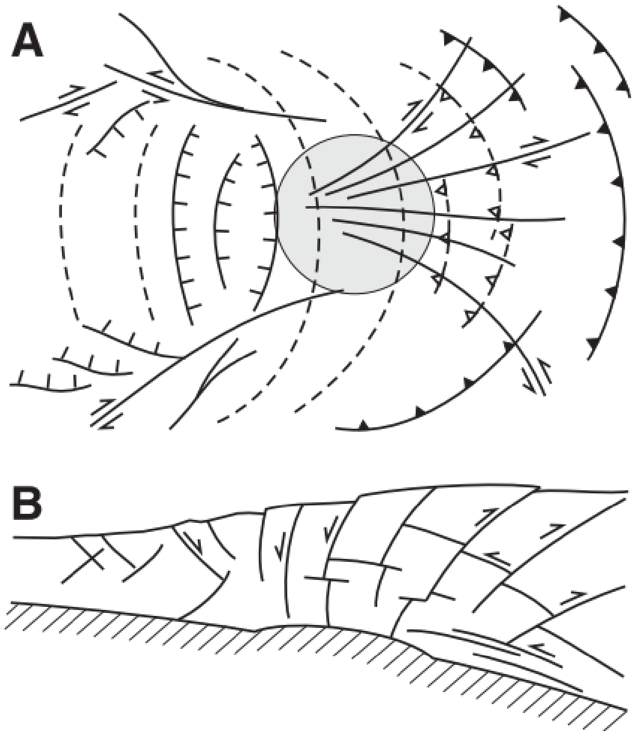




Our 2D model parameter:
E=1.6×10^{11} N.m^{-2} (litho)
η=10^{19} Pa.s (astheno)

About rupture barrer





Influence of the inner forearc structure.
Faults distribution

Collot et al., 2004

- **New automatic picking tool based on Kurtosis**
  - Accurate onset picking with P-S characterization
  - Fast
  - Adaptable to a wide range of local network geometries

- **New P-S velocity model**

- **Accurate earthquake catalog of ~10,000 events under the network**

- **3D geometry for the subduction interface and the Maewo-Pentecôte back-arc thrust belt**

- **Conceptual model for the Vanuatu subduction zone**