Likelihood-based Optimization in Strong-motion Seismology

Sebastian von Specht

國立中央大學 地震災害鏈風險評估及管理研究中心
Earthquake-Disaster & Risk Evaluation and Management Center (E-DREaM)

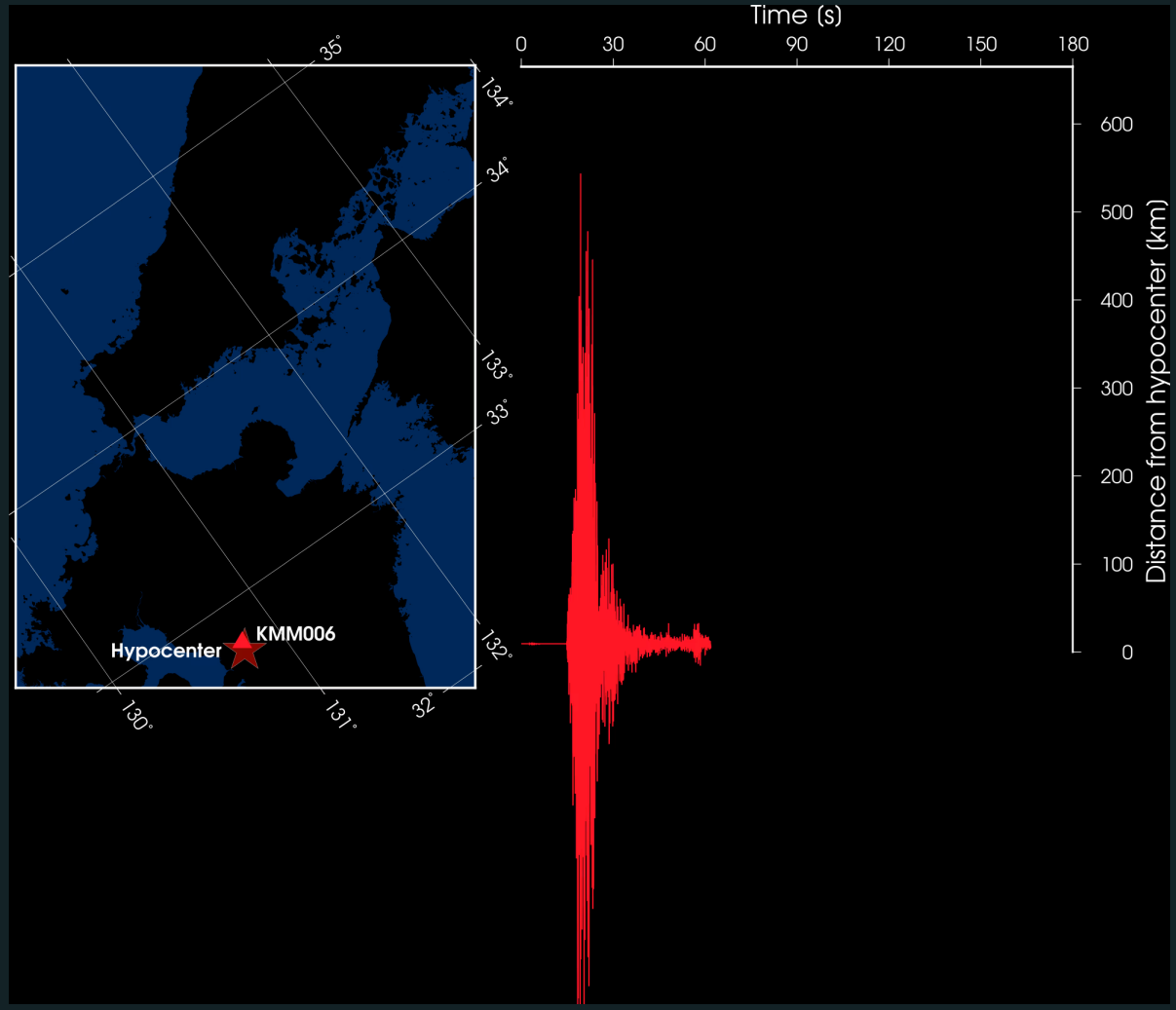
Strong Ground Shaking

Strong Ground Shaking

Hiroshi Fukuoka,
The Japan
Landslide Society

What is strong ground shaking?

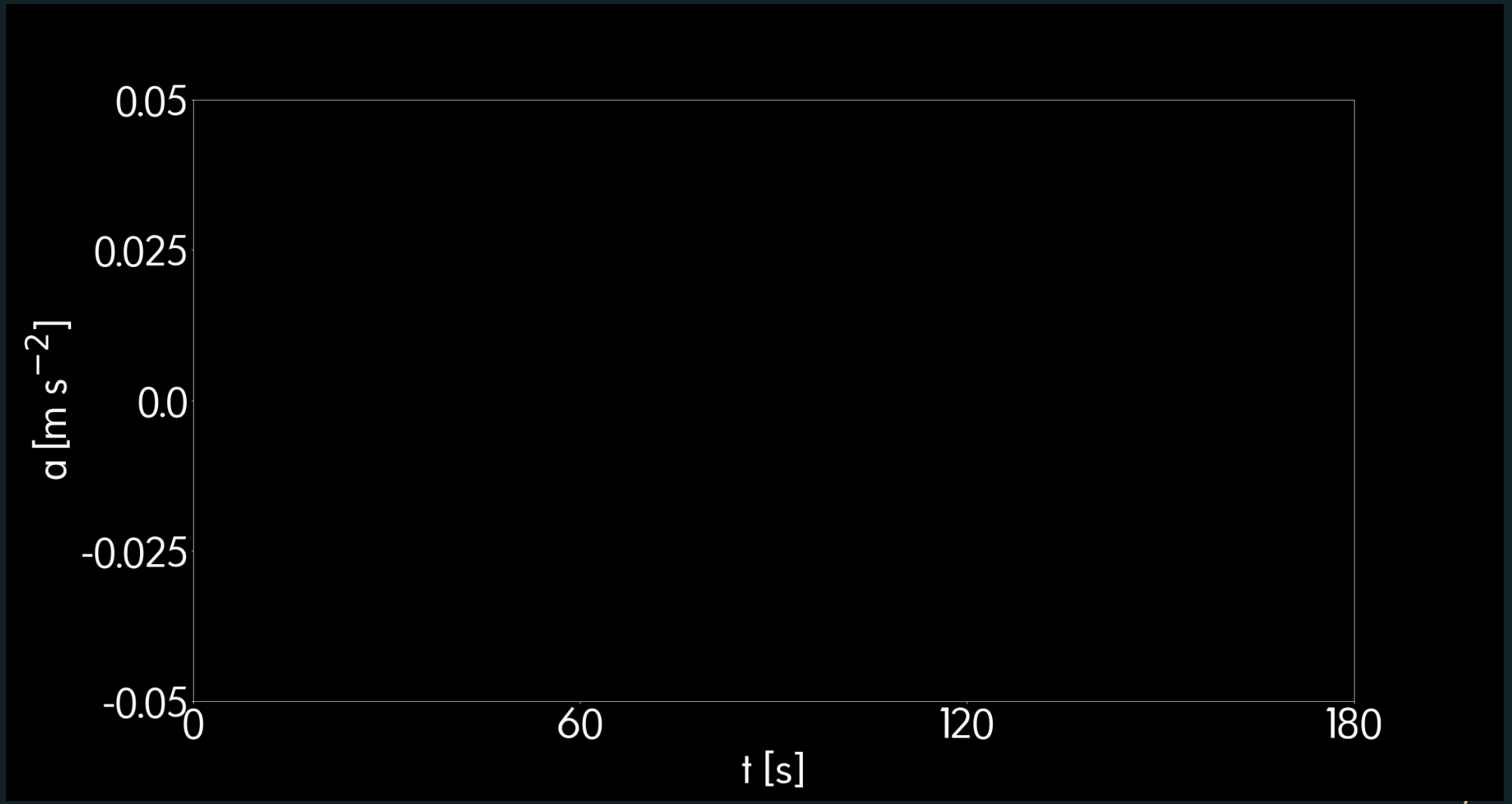
Shaking close to epicenter


Time (s)
0
30
60
90
120
150
180
Distance from hypocenter (km)
600
500
400
300
200
100
0
35°
134°
34°
133°
33°
132°
32°
130°
131°
Hypocenter
KMM006

What is strong ground shaking?

Shaking close to epicenter

with amplitudes capable to cause structural damage


0.05
0.025
0.0
-0.025
-0.05
a [m s^{-2}]
0
60
120
180
t [s]

What is strong ground shaking?

Shaking close to epicenter

with amplitudes capable to cause structural damage

→ This is of engineering concern!

Trigger for more disasters (e.g. landslides)

→ Multihazard

The Goal:

Modeling ground-shaking with
data-driven methods to reduce expert elicitation
and to tackle the increase of data with automation

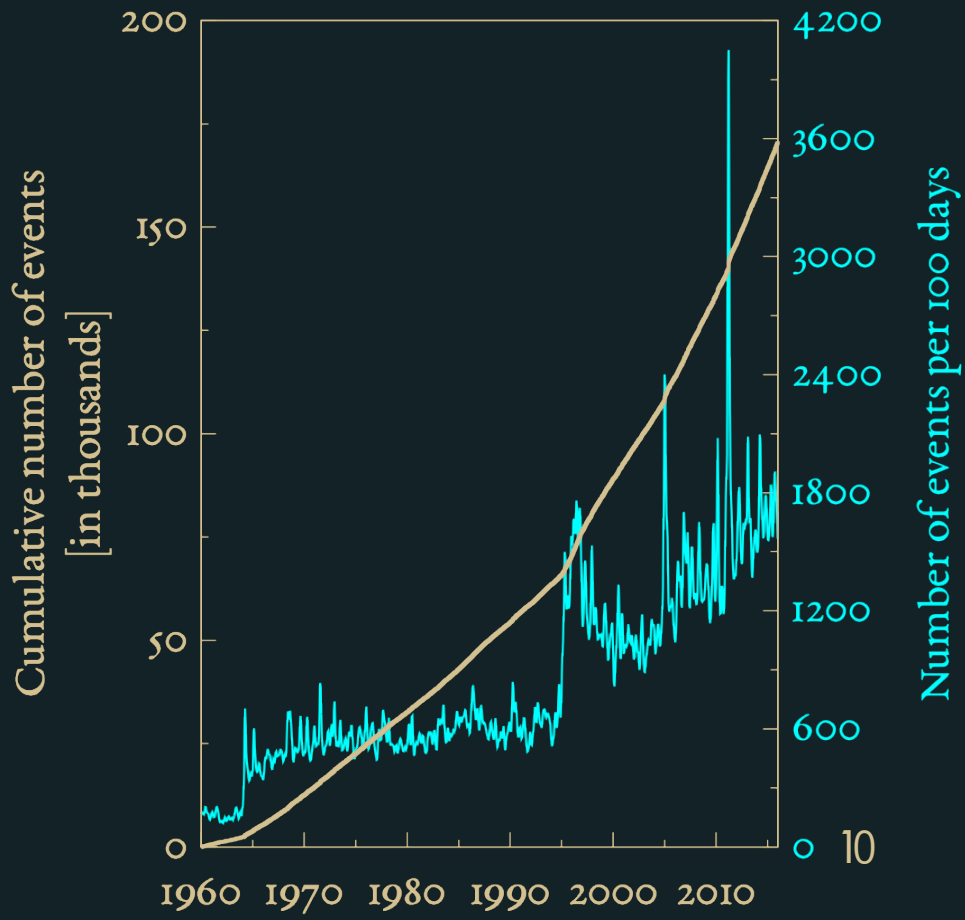
Motivation

Accumulation of data with time

increasing rate of data accumulation

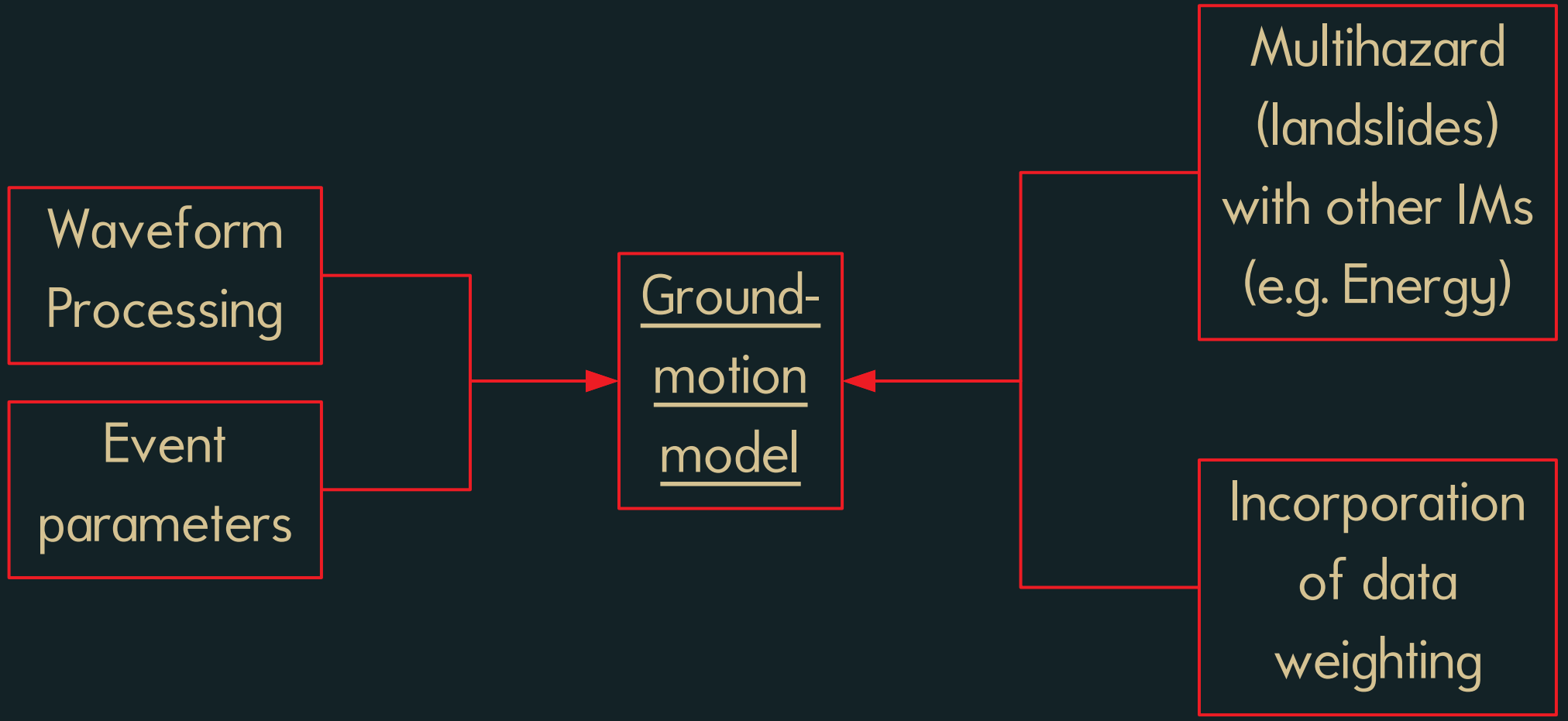
limit of manual processing

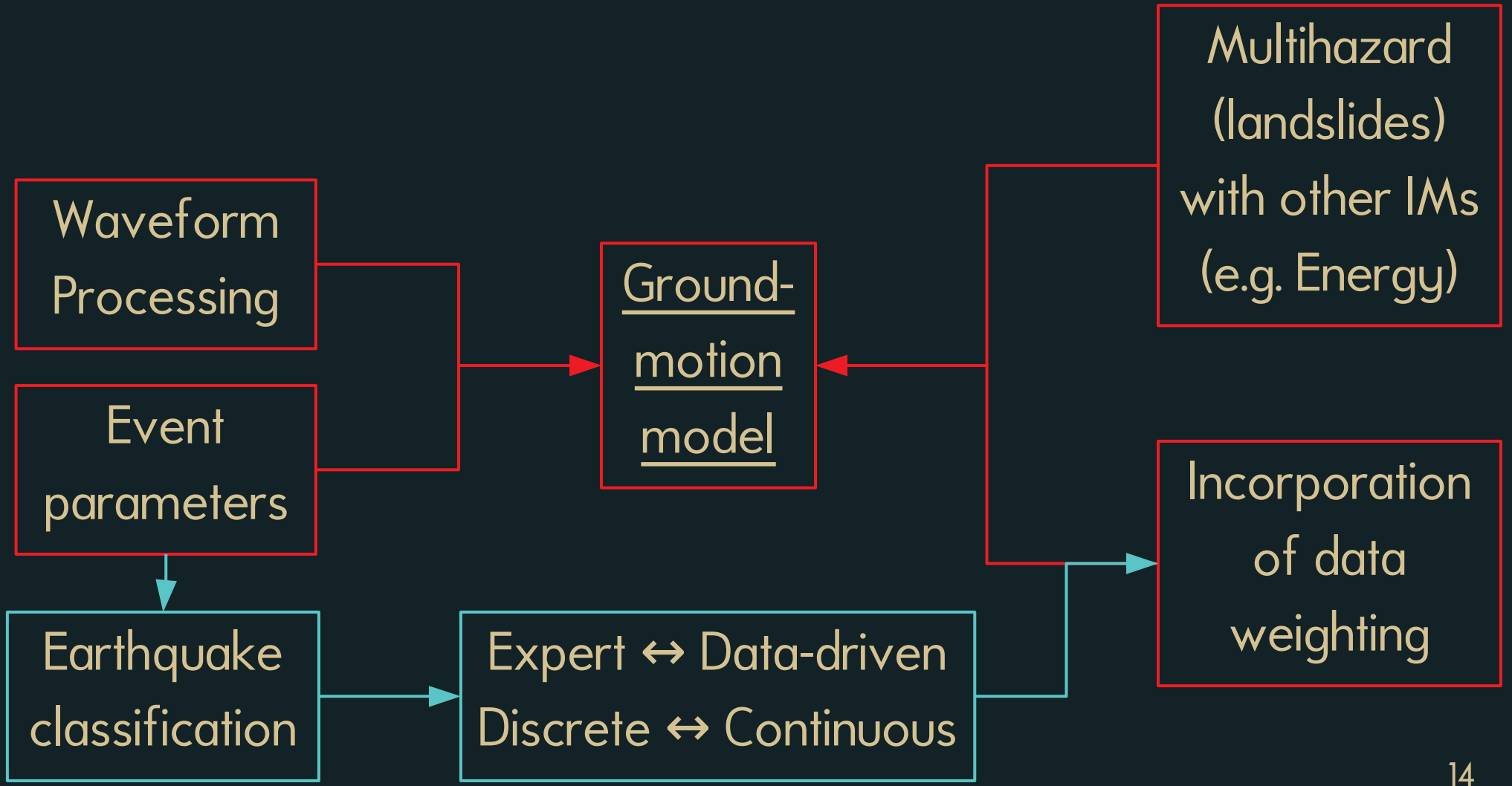
→ Automation

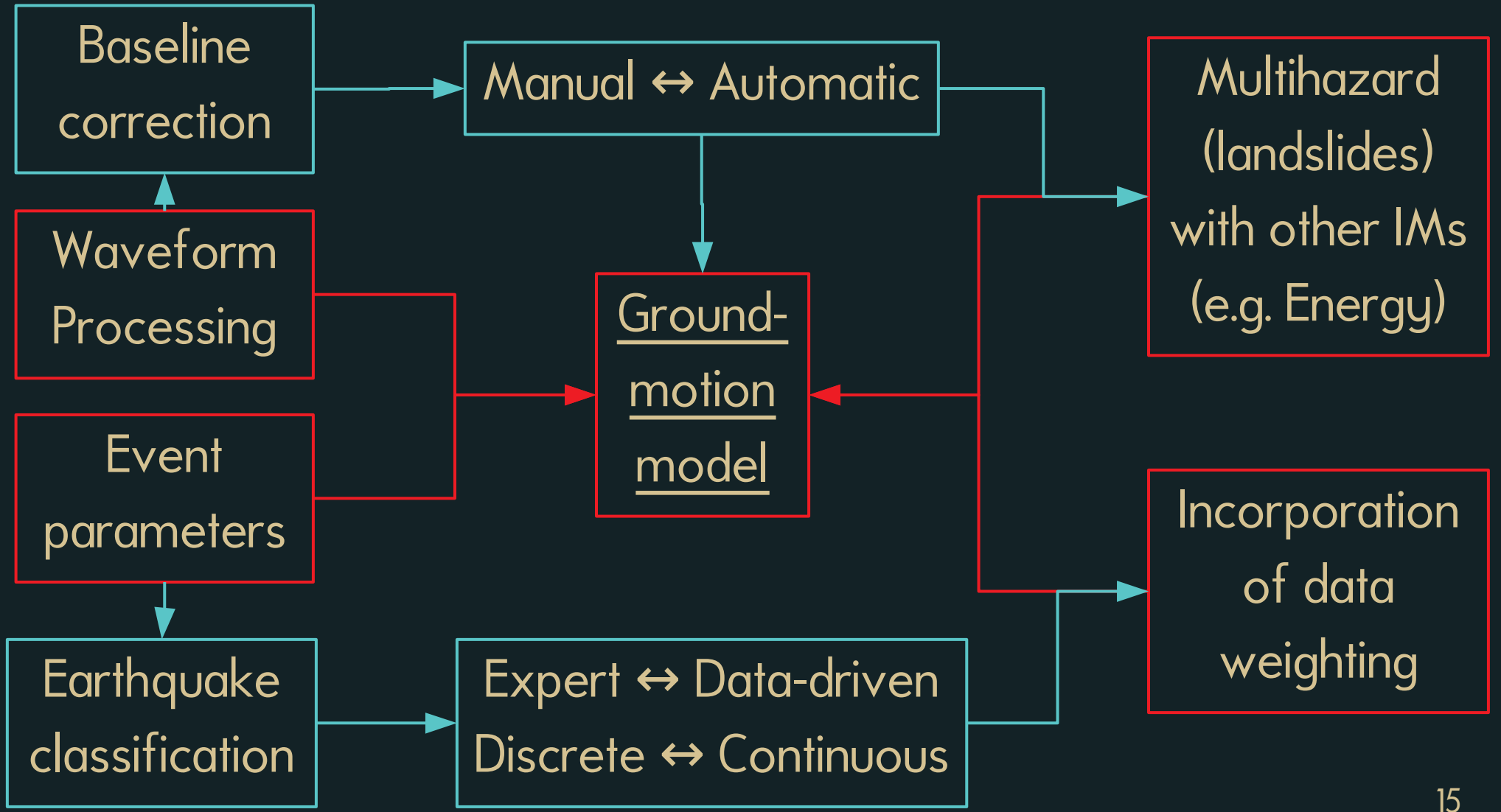


Ground-motion model


Waveform Processing
Event parameters
Ground-motion model


Waveform Processing
Event parameters
Ground-motion model
Multihazard (landslides) with other IMs (e.g. Energy)
Incorporation of data weighting


Waveform Processing
Event parameters
Earthquake classification
Ground-motion model
Expert ↔ Data-driven
Discrete ↔ Continuous
Multihazard (landslides) with other IMs (e.g. Energy)
Incorporation of data weighting


Baseline correction
Manual ↔ Automatic
Multihazard (landslides) with other IMs (e.g. Energy)
Waveform Processing
Ground-motion model
Event parameters
Incorporation of data weighting
Earthquake classification
Expert ↔ Data-driven
Discrete ↔ Continuous

I addressed these questions by a common method

The likelihood

Likelihood

Number of Observations

Observation

$$\ln \mathcal{L} = \sum_{i=1}^{N} \ln p(x_i|\theta)$$

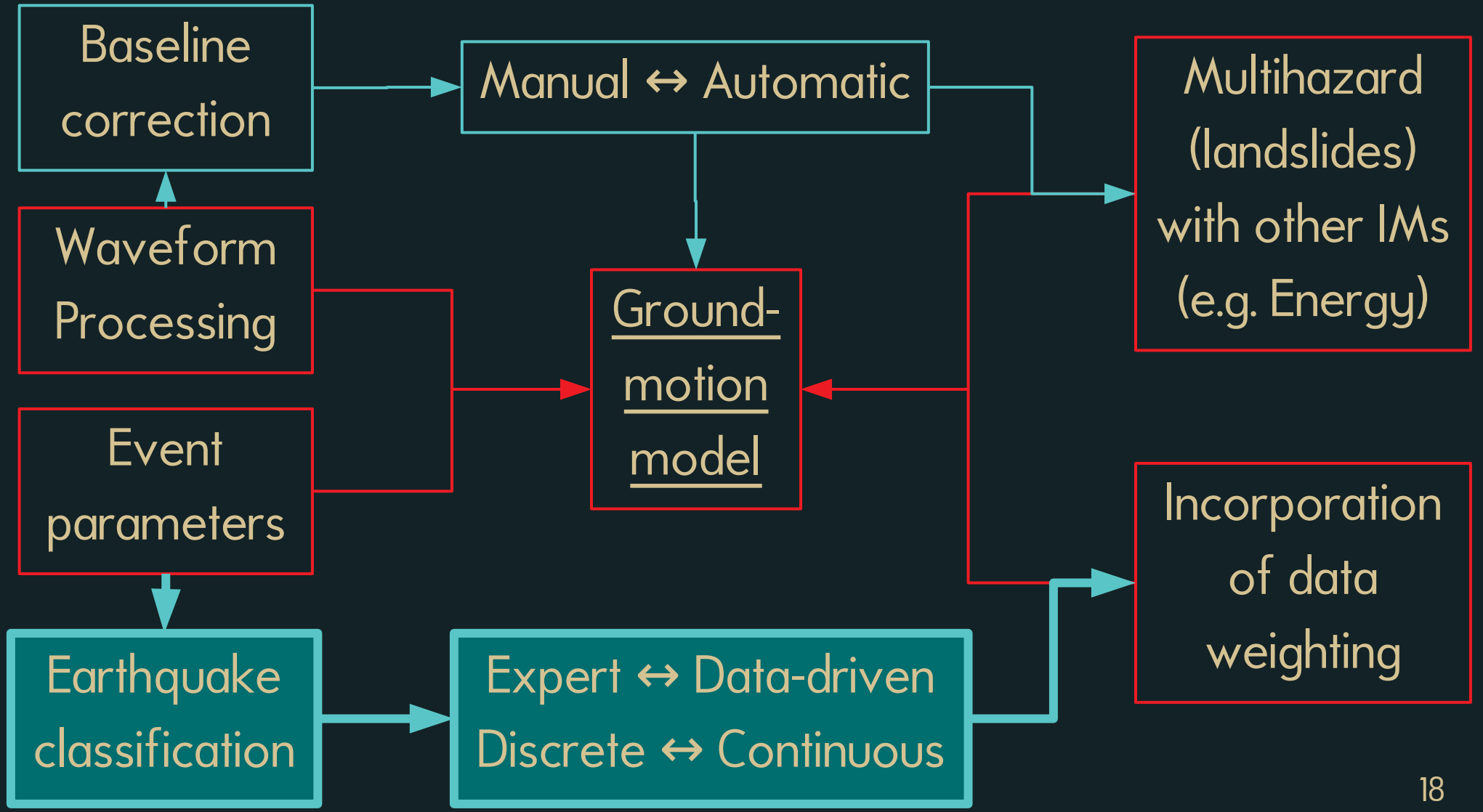
Parameter(s)

Statistical model: probability distribution

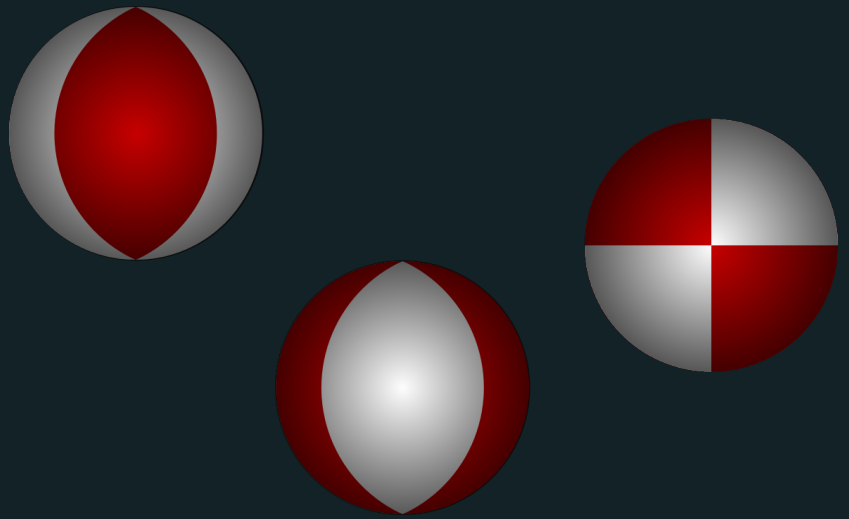
Objective:

Maximize the Likelihood

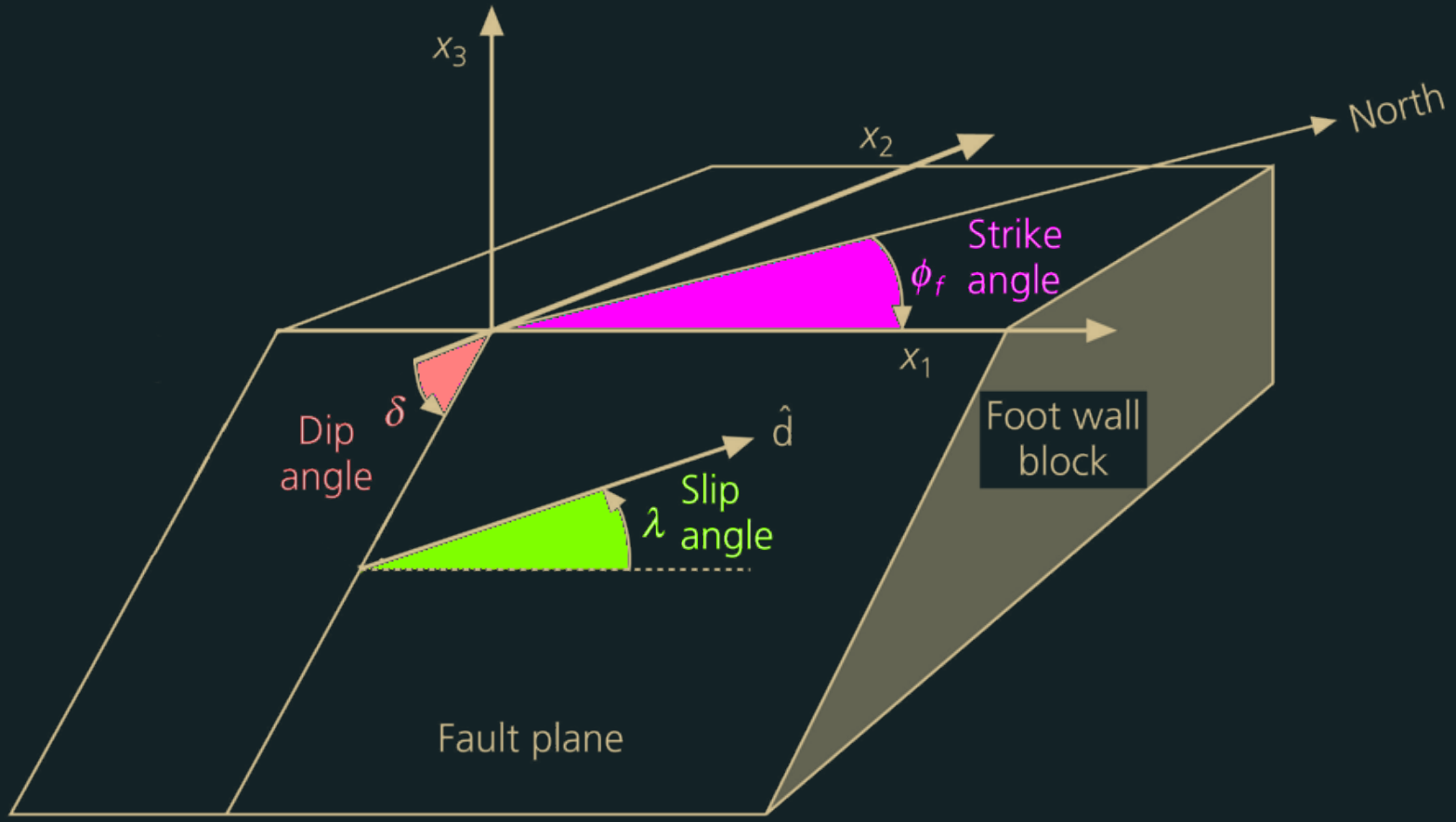
$$\frac{d \ln \mathcal{L}}{d\theta} = 0$$


Baseline correction
Manual ↔ Automatic
Multihazard (landslides) with other IMs (e.g. Energy)
Waveform Processing
Ground-motion model
Event parameters
Incorporation of data weighting
Earthquake classification
Expert ↔ Data-driven
Discrete ↔ Continuous

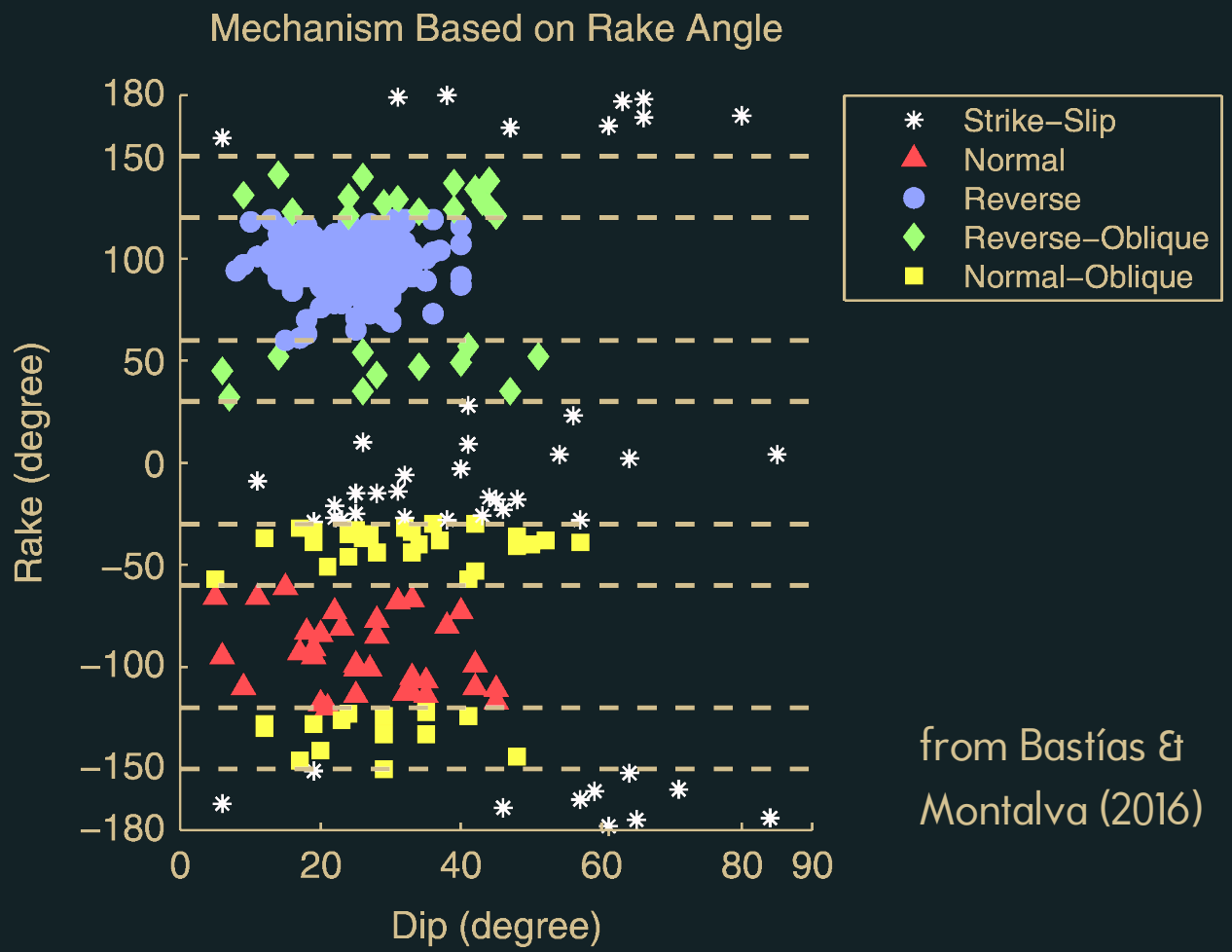
Angular Clusterization with Expectation-Maximization



Angular representation



The classical classification



from Bastías & Montalva (2016)

Expectation-Maximization

Mixture of probability distributions

Parameterization of models of latent variables

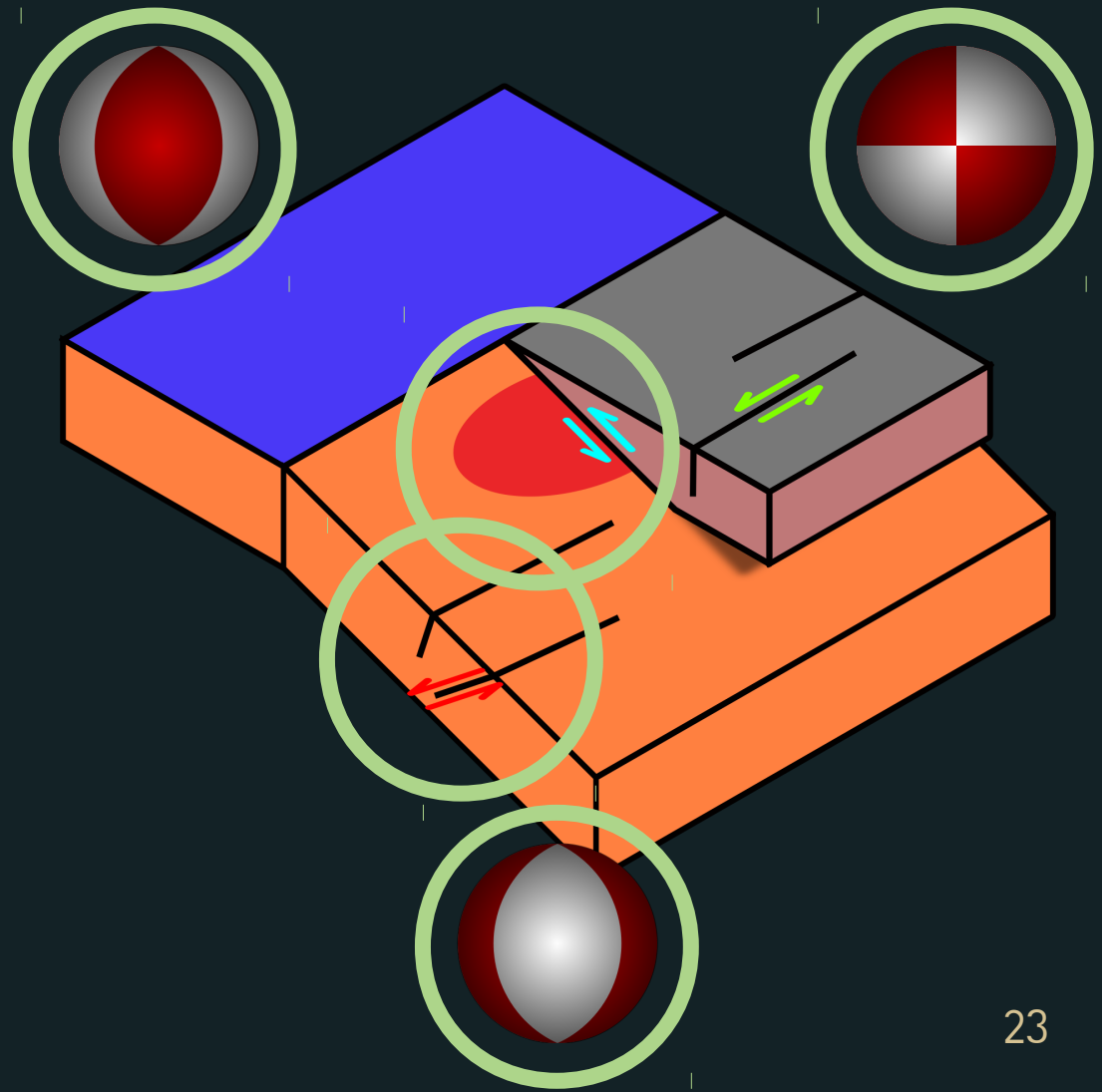
Latent Variables in ACE:

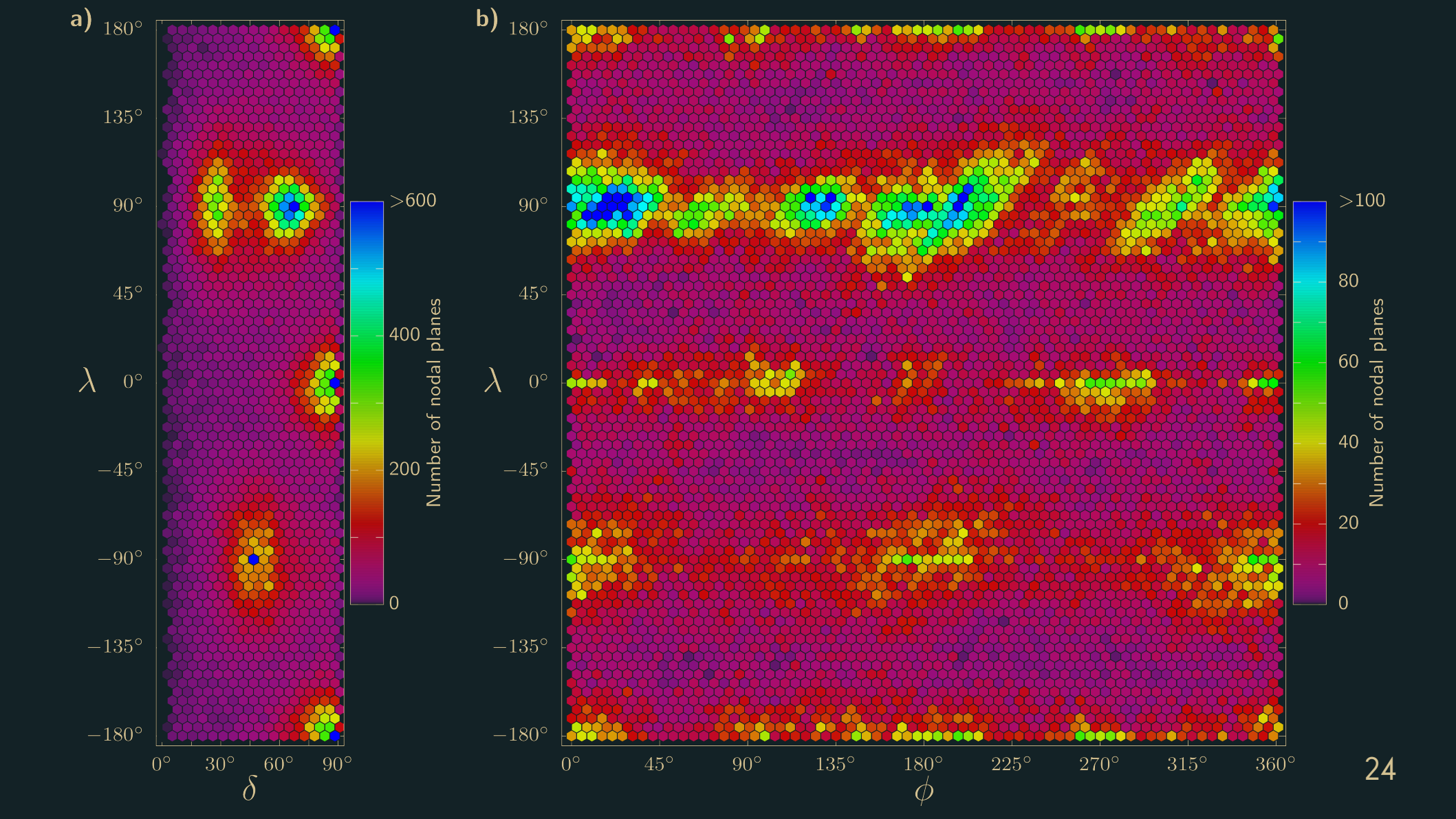
Style-of-Faulting

- Reverse
- Normal
- Strike-Slip

Tectonic setting

- Interface
- Intraslab




a)
b)
180°
135°
90°
45°
0°
−45°
−90°
−135°
−180°
λ
0°
30°
60°
90°
δ
>600
400
200
0
Number of nodal planes
45°
180°
225°
270°
315°
360°
ϕ
>100
80
60
40
20
0
Number of nodal planes

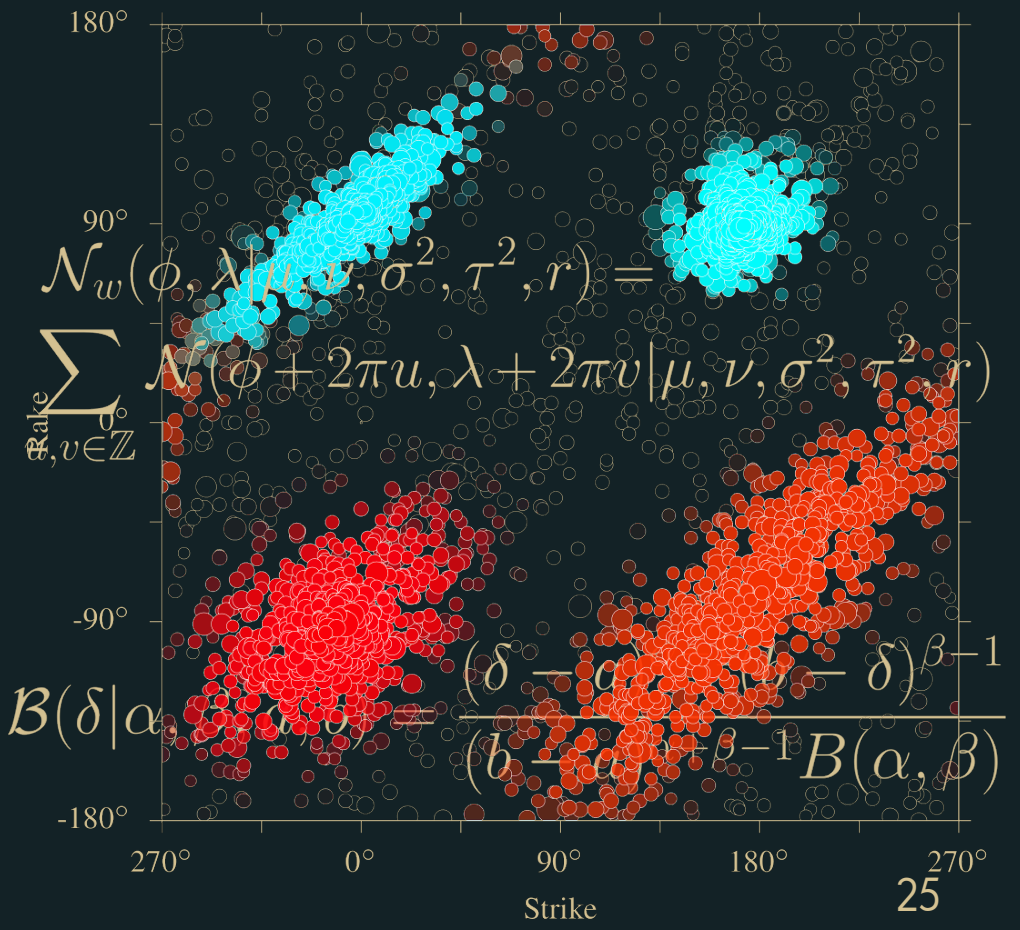
Objective

Identify clusters of same SoF / tectonic setting

Model: joint probability

Bivariate wrapped normal distribution

Beta distribution



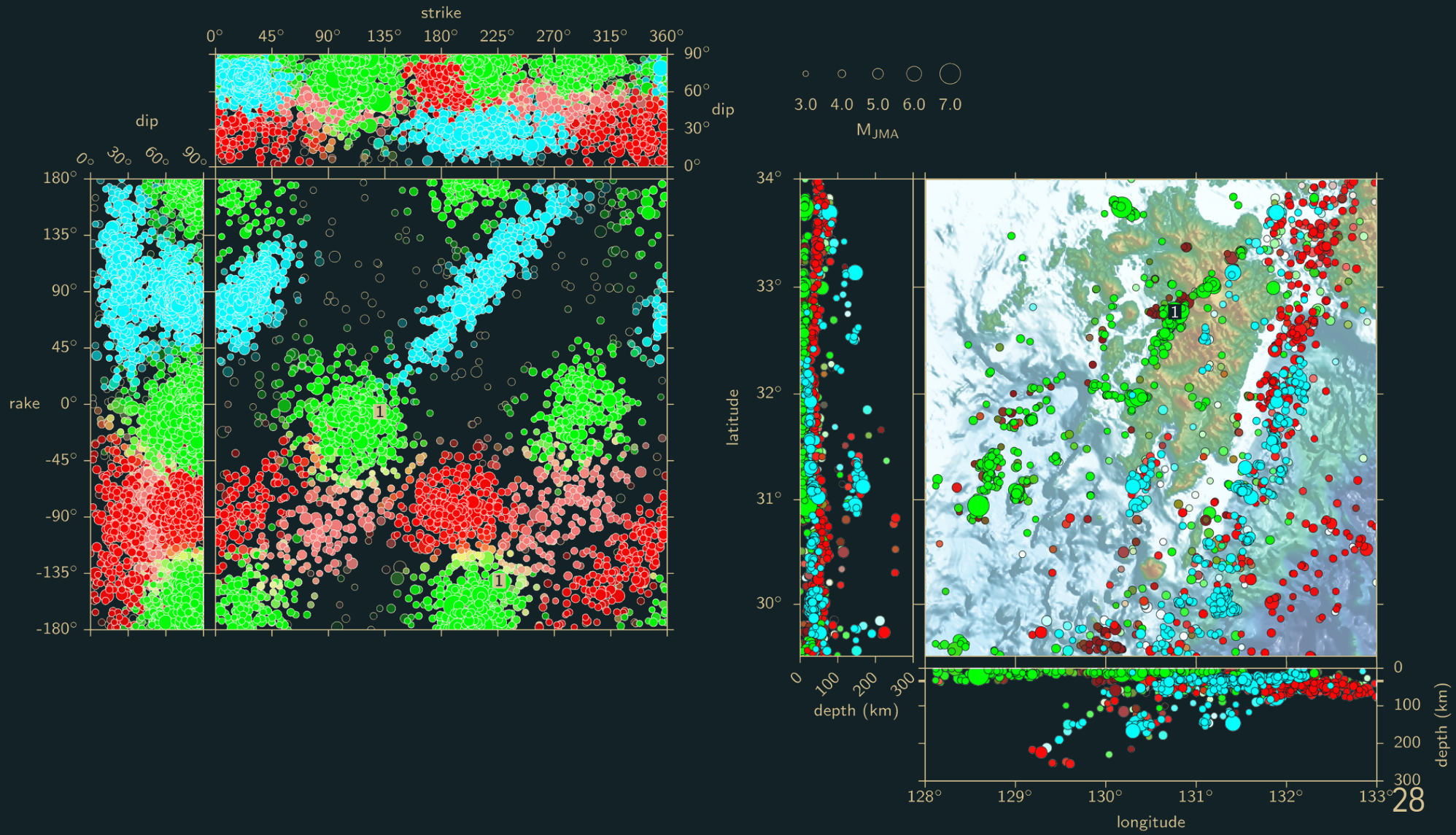
discrete

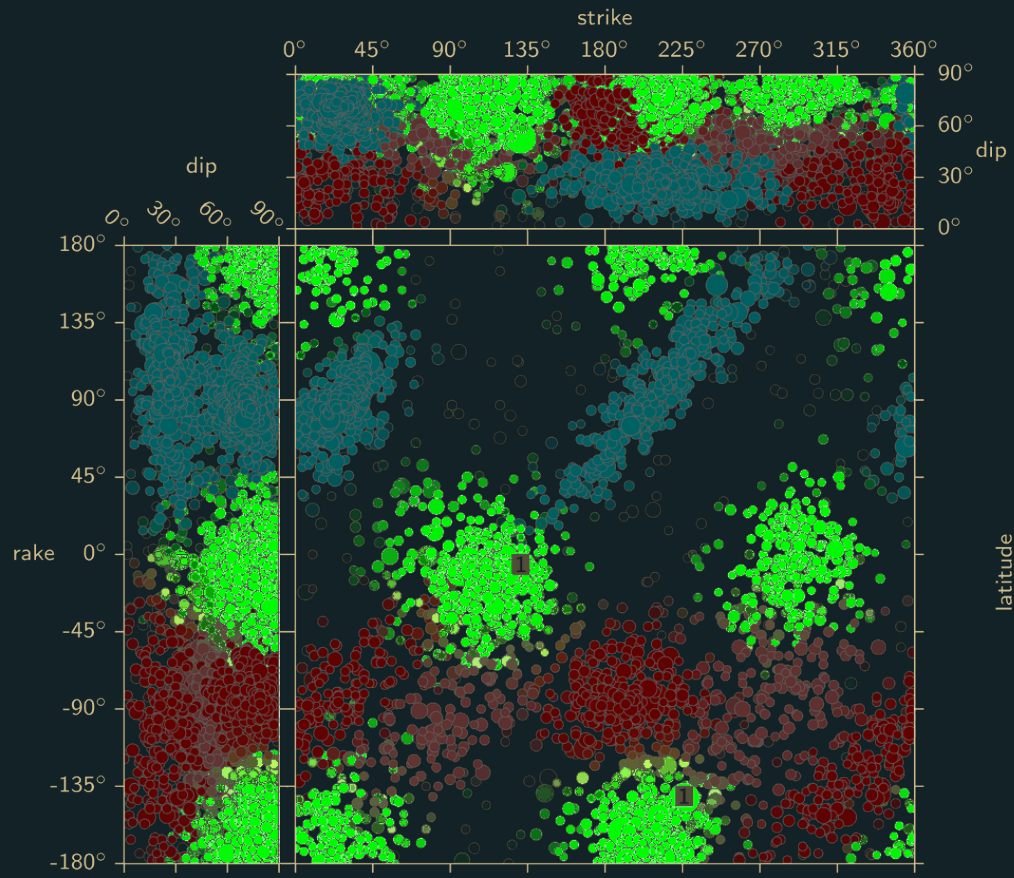
VS

continuous

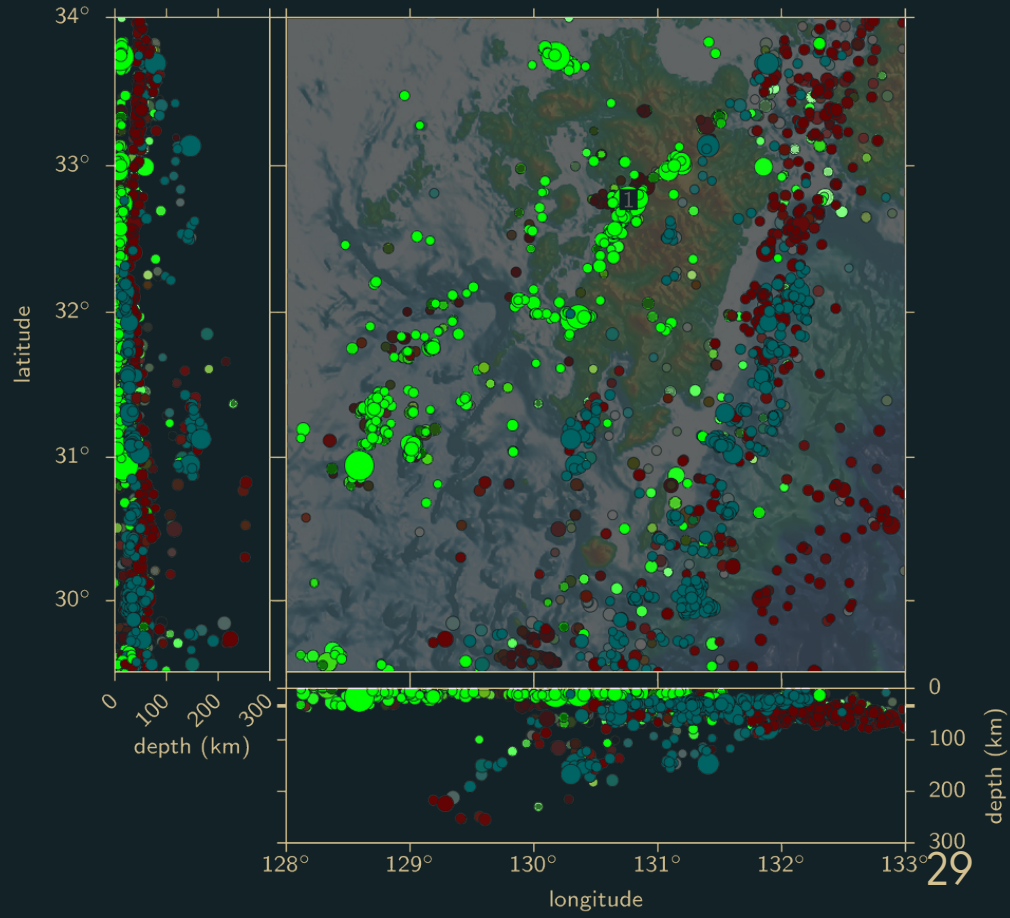
Example

九州（日本）
Kyushu (Japan)

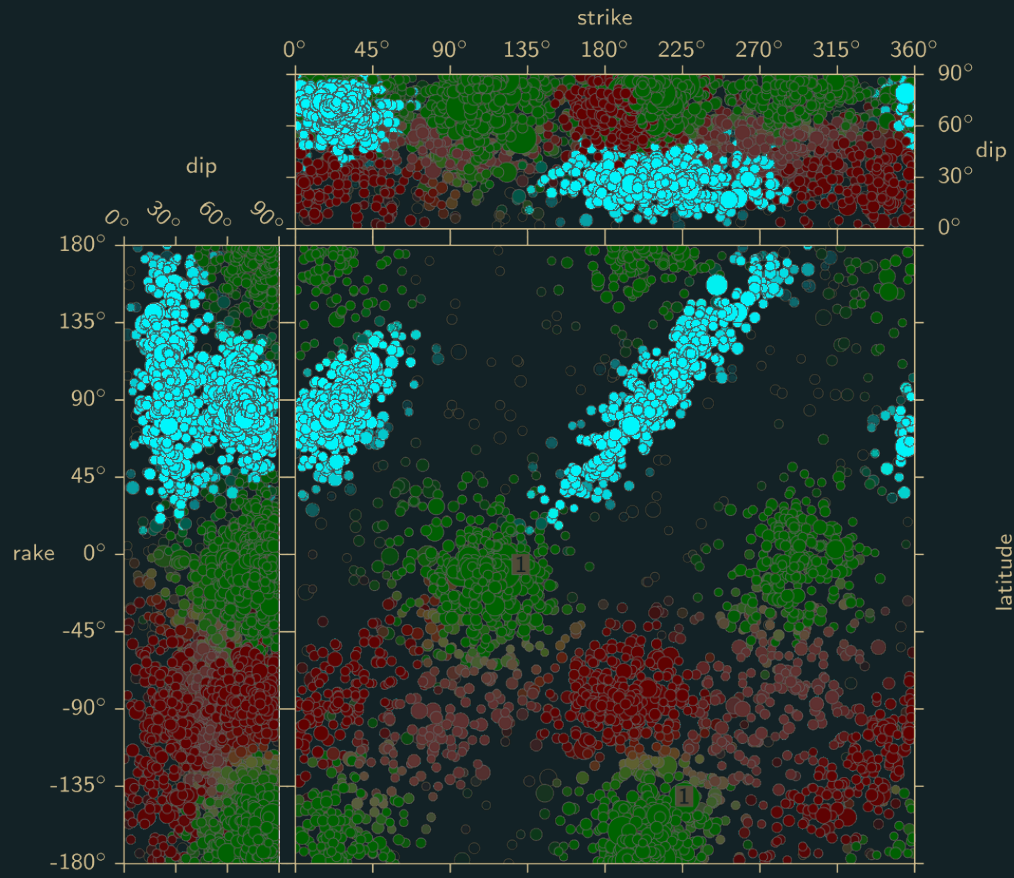

strike
0°
45°
90°
135°
180°
225°
270°
315°
360°
dip
0°
30°
60°
90°
rake
180°
135°
90°
45°
0°
-45°
-90°
-135°
-180°
1
1
3.0
4.0
5.0
6.0
7.0
M_{JMA}
latitude
34°
33°
32°
31°
30°
depth (km)
0
100
200
300
longitude
128°
129°
130°
131°
132°
133°
1
28

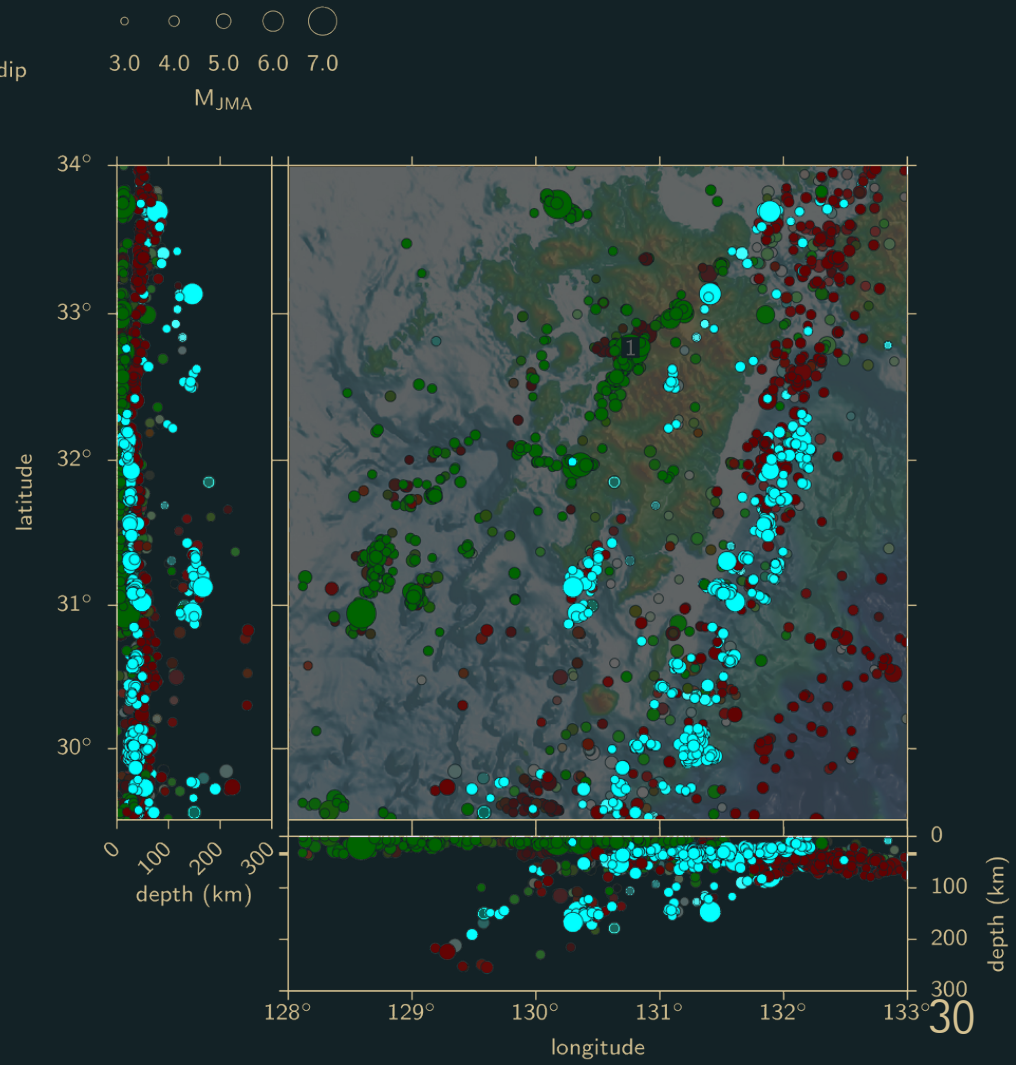

strike
0°
45°
90°
135°
180°
225°
270°
315°
360°
dip
90°
60°
30°
0°
dip
0°
30°
60°
90°
180°
135°
90°
45°
rake
0°
-45°
-90°
-135°
-180°


3.0
4.0
5.0
6.0
7.0
M_{JMA}

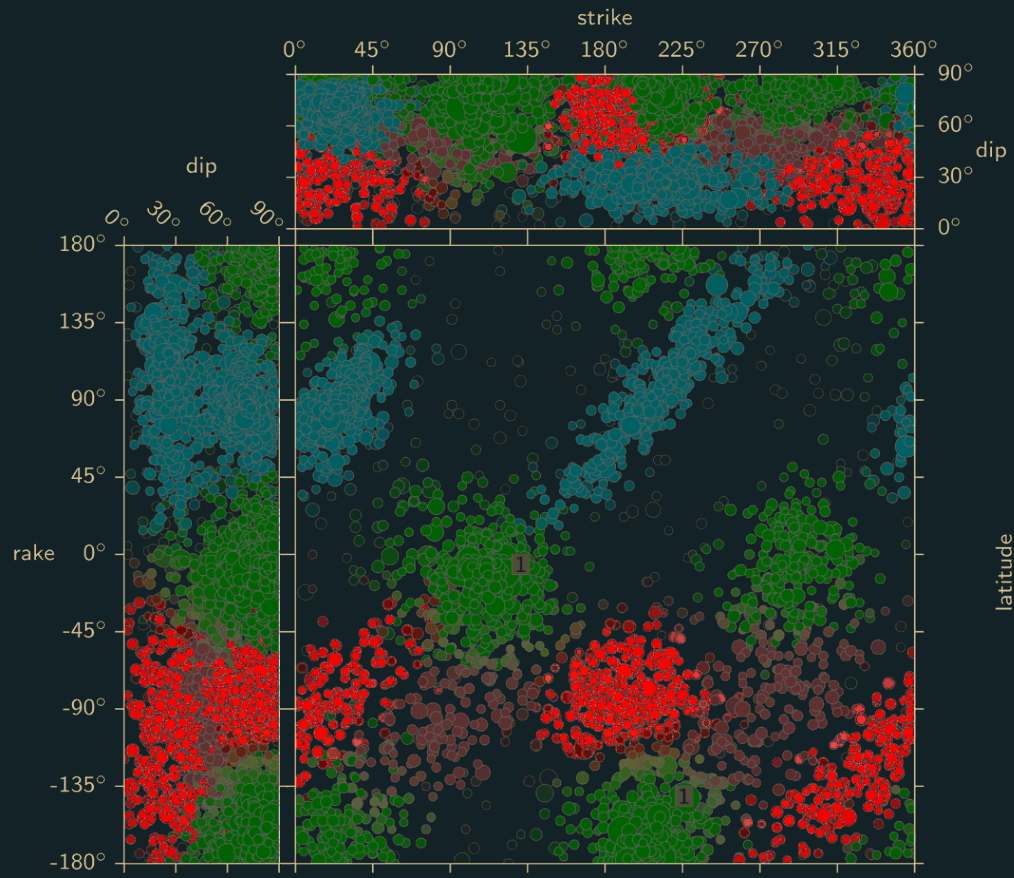

34°
33°
32°
31°
30°
latitude
0
100
200
300
depth (km)
128°
129°
130°
131°
132°
133°
longitude
0
100
200
300
depth (km)

Strike-Slip

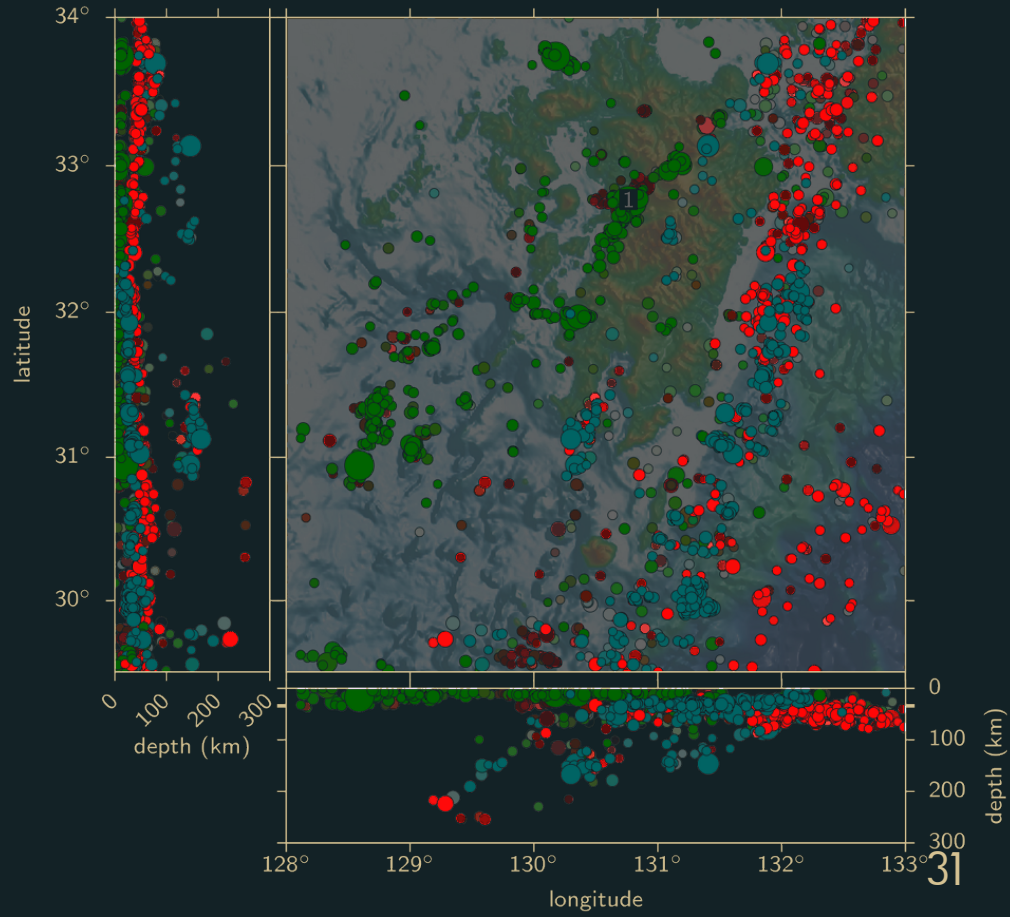

strike
0°
45°
90°
135°
180°
225°
270°
315°
360°
dip
0°
30°
60°
90°
rake
180°
135°
90°
45°
0°
-45°
-90°
-135°
-180°
1
1


3.0
4.0
5.0
6.0
7.0
M_{JMA}
latitude
34°
33°
32°
31°
30°
1
0
100
200
300
depth (km)
128°
129°
130°
131°
132°
133°
longitude
depth (km)

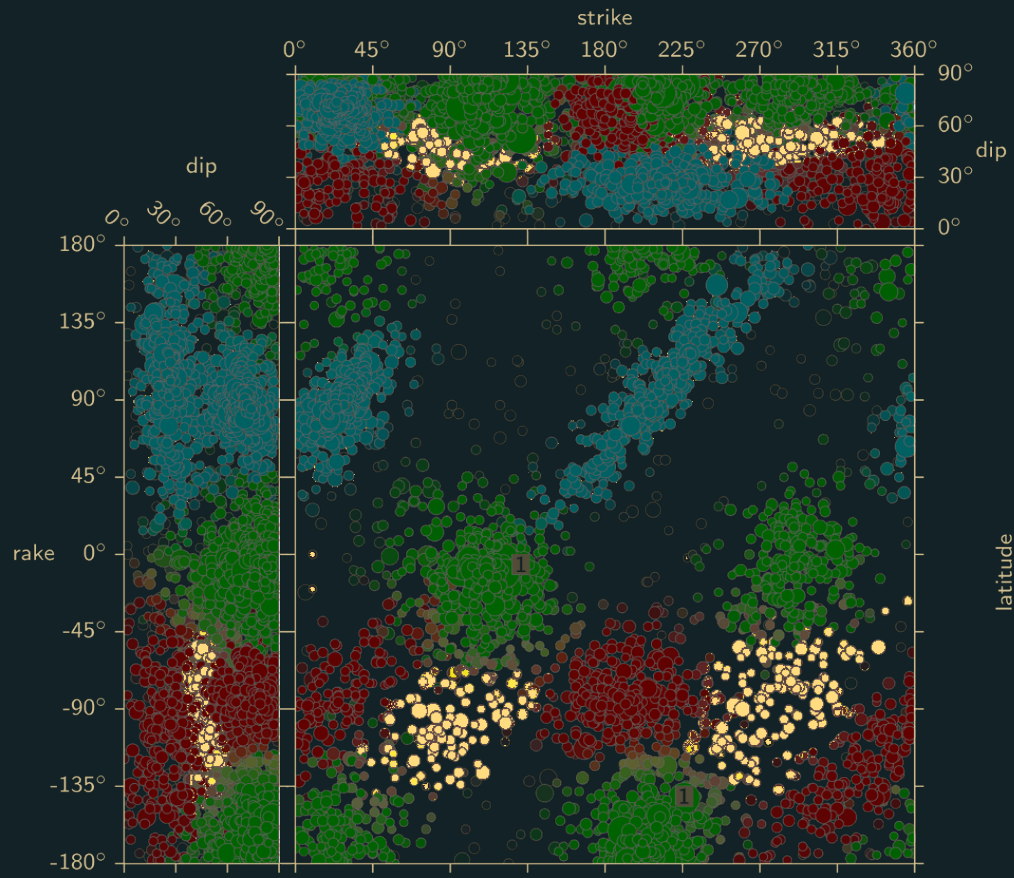
Interface

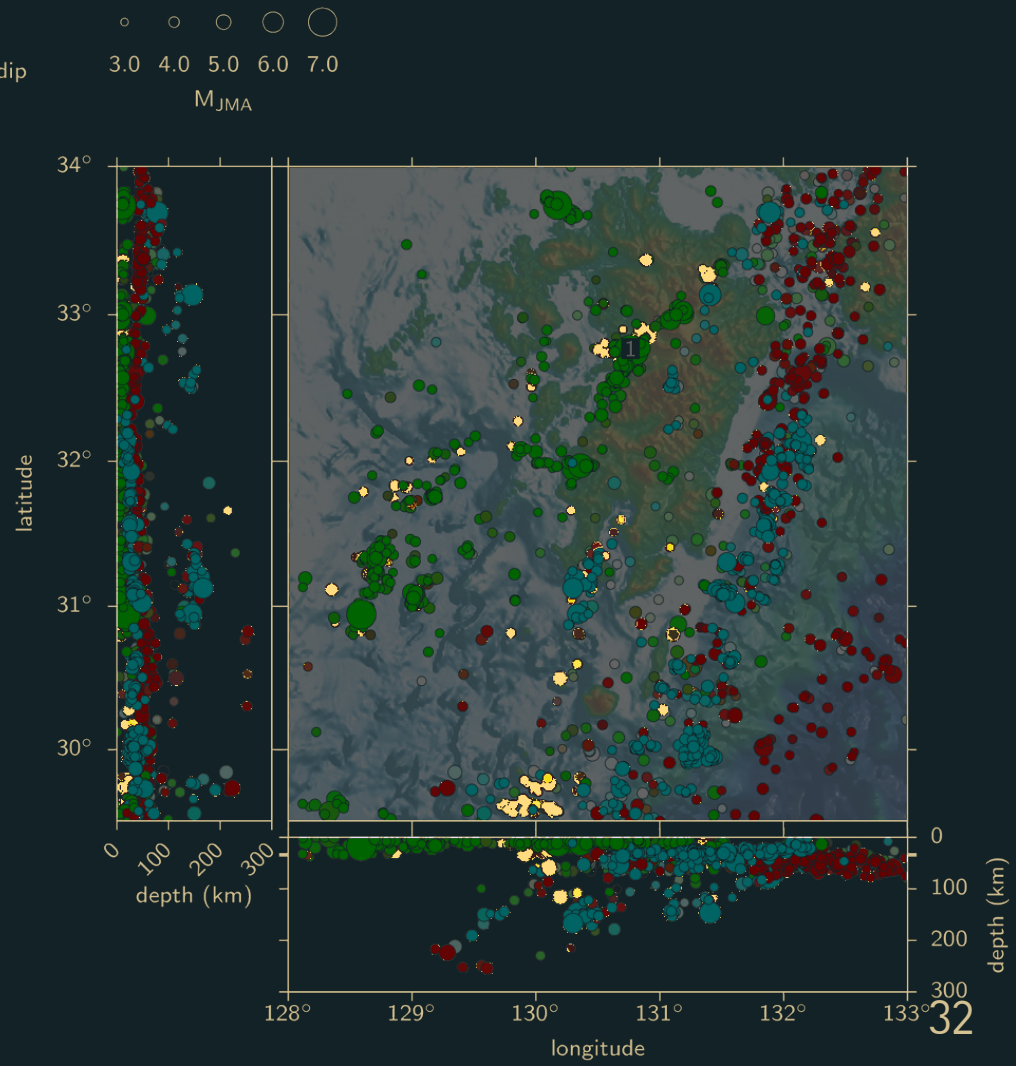

strike
0°
45°
90°
135°
180°
225°
270°
315°
360°
90°
60°
30°
0°
dip
dip
0°
30°
60°
90°
180°
135°
90°
45°
rake
0°
-45°
-90°
-135°
-180°
1
1


3.0
4.0
5.0
6.0
7.0
M_{JMA}

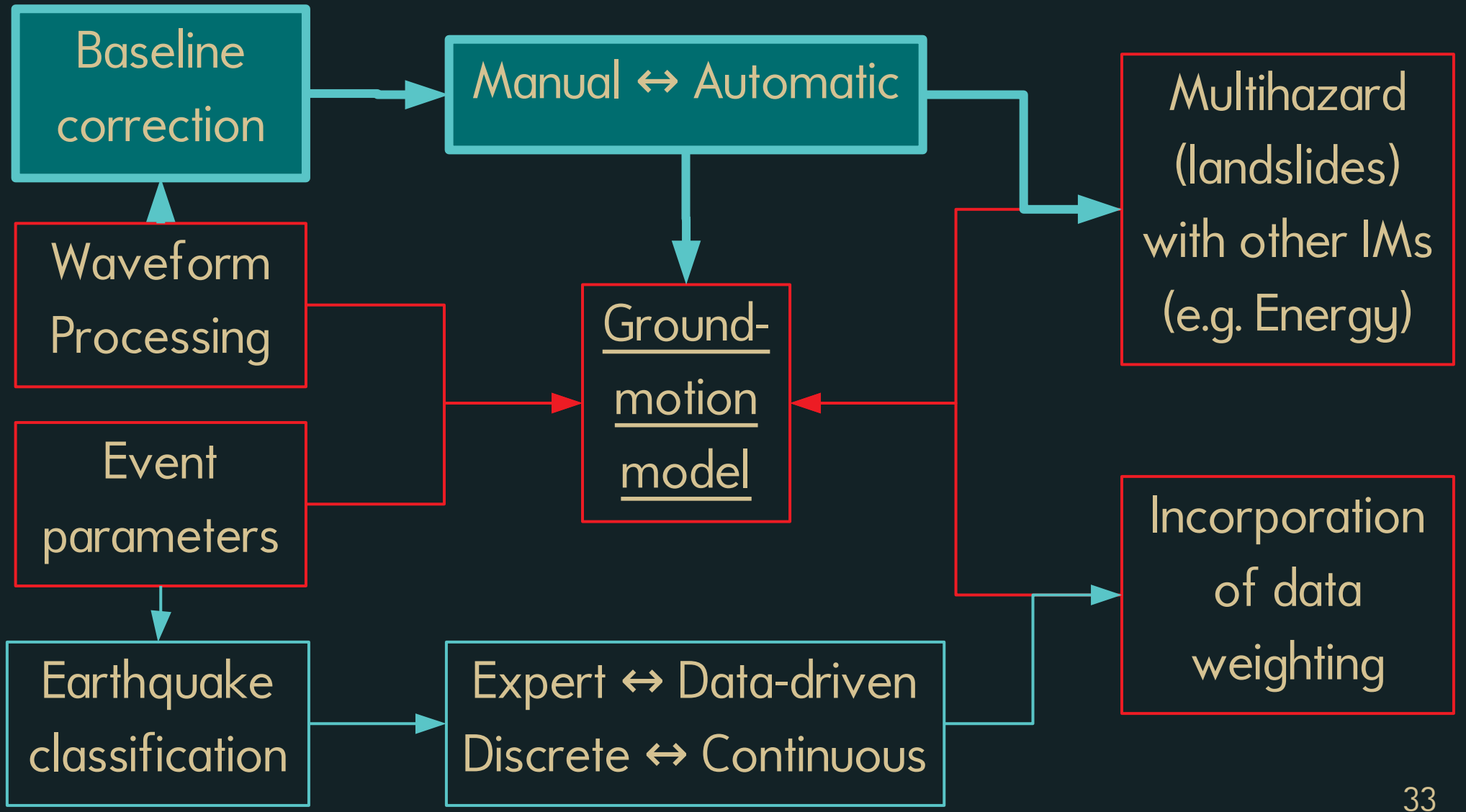

34°
33°
32°
31°
30°
latitude
0
100
200
300
depth (km)
1
128°
129°
130°
131°
132°
133°
longitude
0
100
200
300
depth (km)

Intraslab





Okinawa trough


Baseline correction
Manual ↔ Automatic
Multihazard (landslides) with other IMs (e.g. Energy)
Waveform Processing
Ground-motion model
Event parameters
Incorporation of data weighting
Earthquake classification
Expert ↔ Data-driven
Discrete ↔ Continuous

Integrated Combined Baseline Modification

Why correcting?

Spurious discontinuities in accelerograms

Causes:

tilt, station movement

instrument noise

Effects:

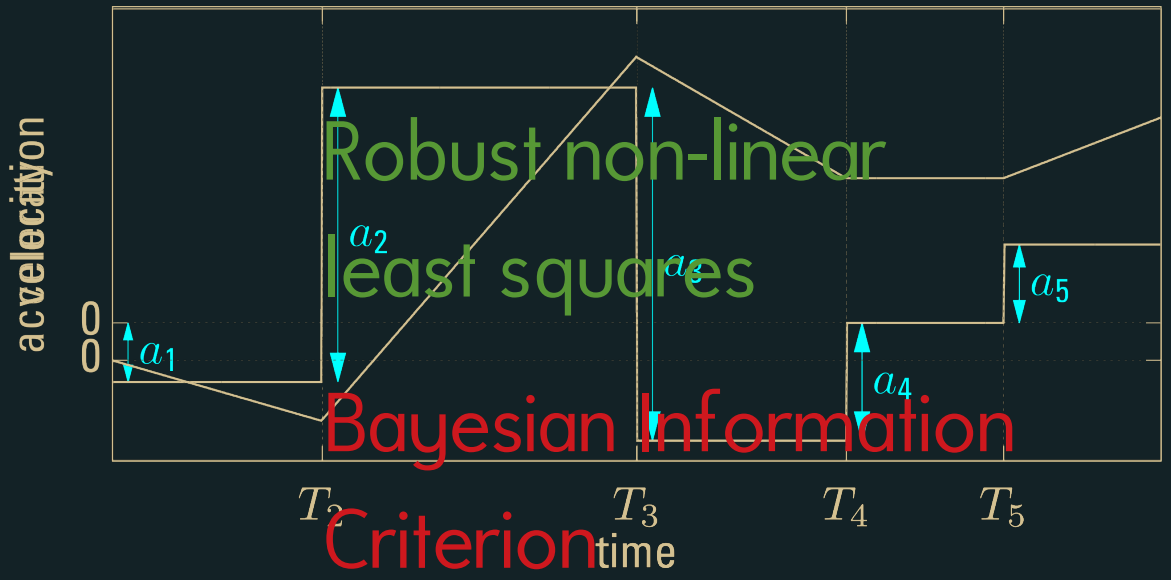
drift in velocity & displacement traces

bias in seismic energy, high period response spectra, PGV / PGD

Objective

Identify number, amplitudes and times of jumps

use integrated traces (velocity)

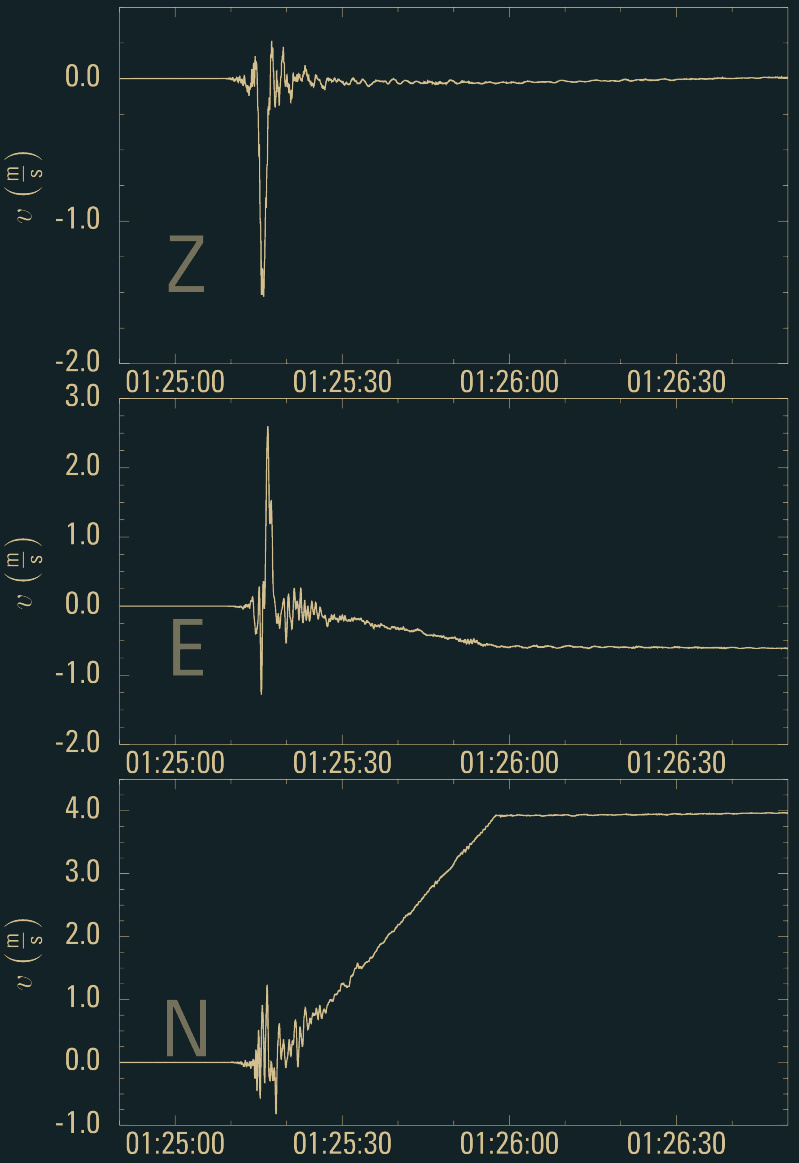


$$v(t) = a(t_0) + a_1 t + \sum_{j=2}^{M} a_j h(t - T_j)(t - T_j)$$

Conditions

Simultaneous jumps on up to all three instrument components

→ reduction of free parameters



Conditions

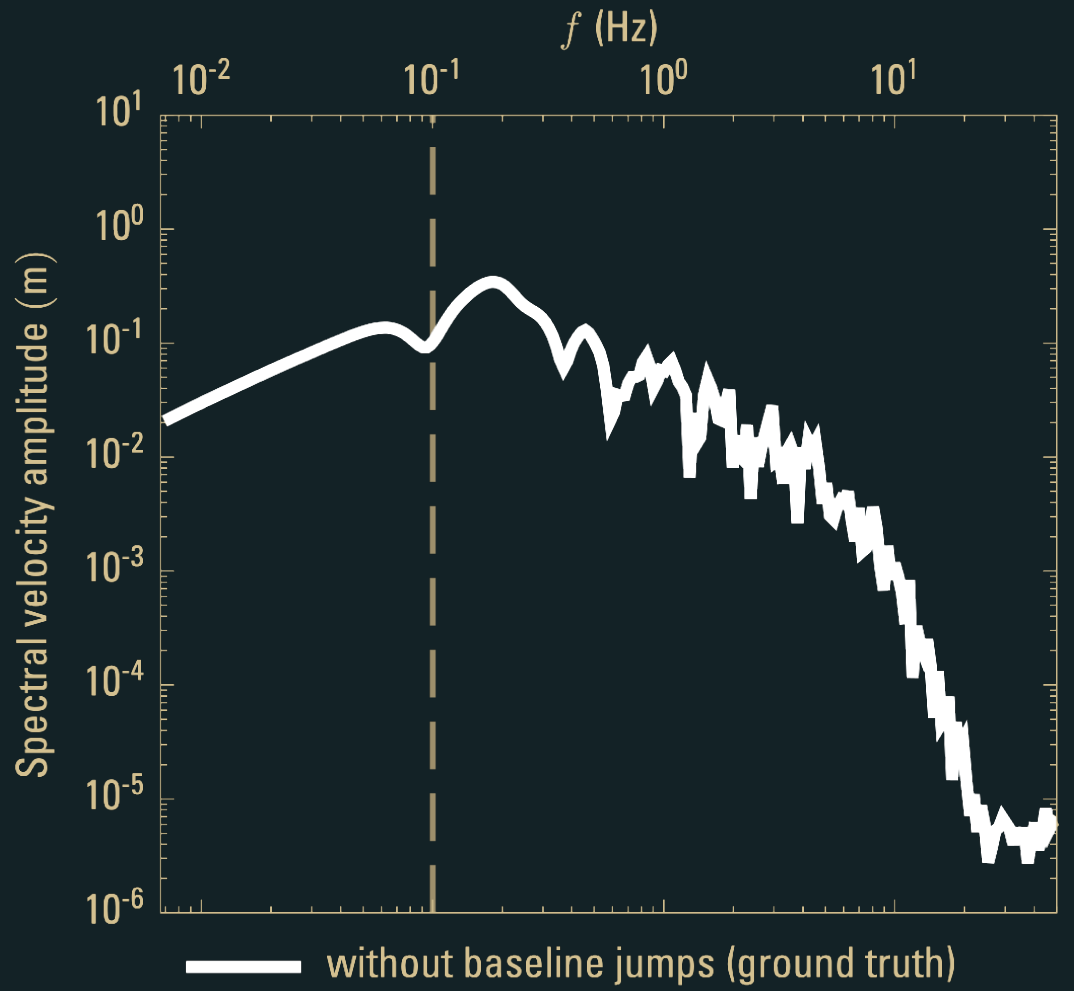
Avoid spectral contamination

jump segments related to corner frequency / signal duration

Conditions

Example:

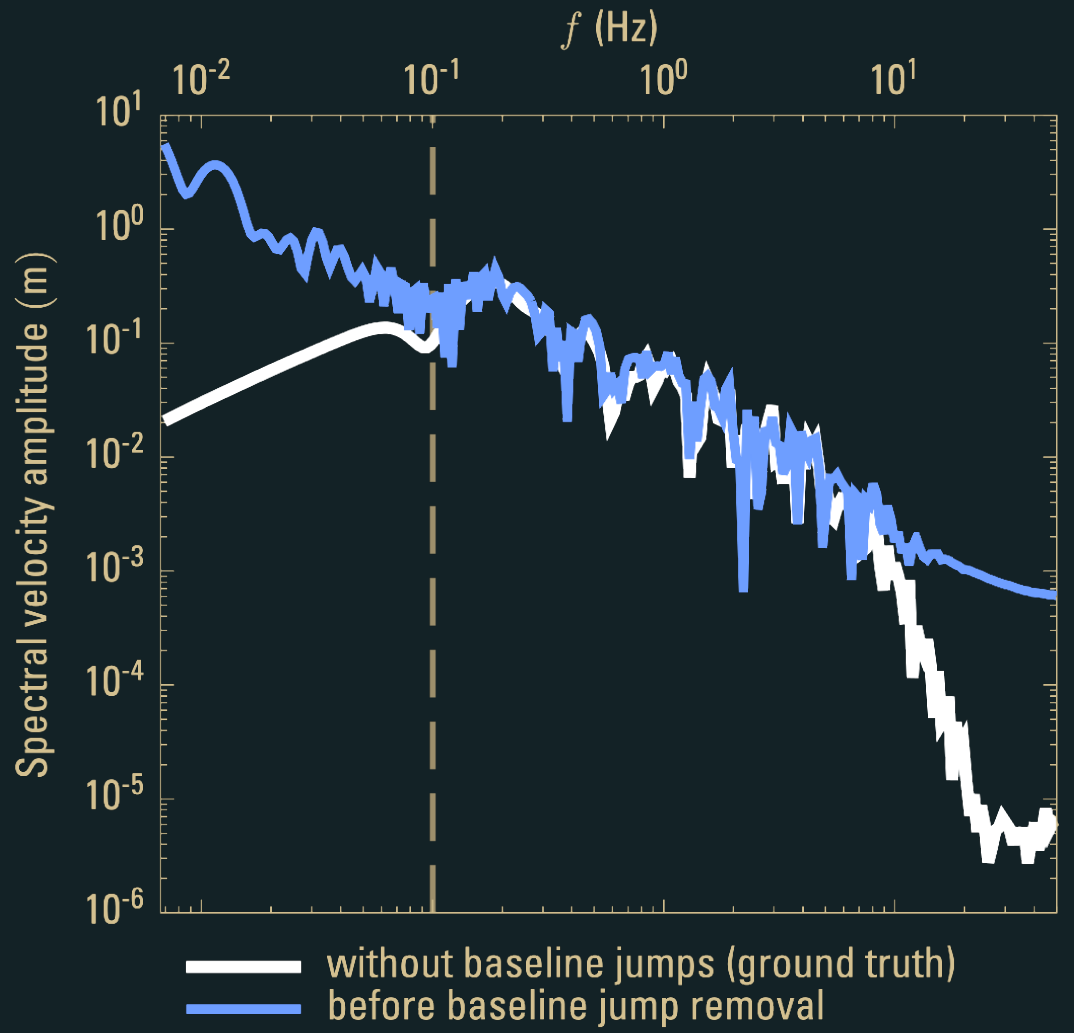
Synthetic spectrum (after Boore 2003)



Conditions

Example:

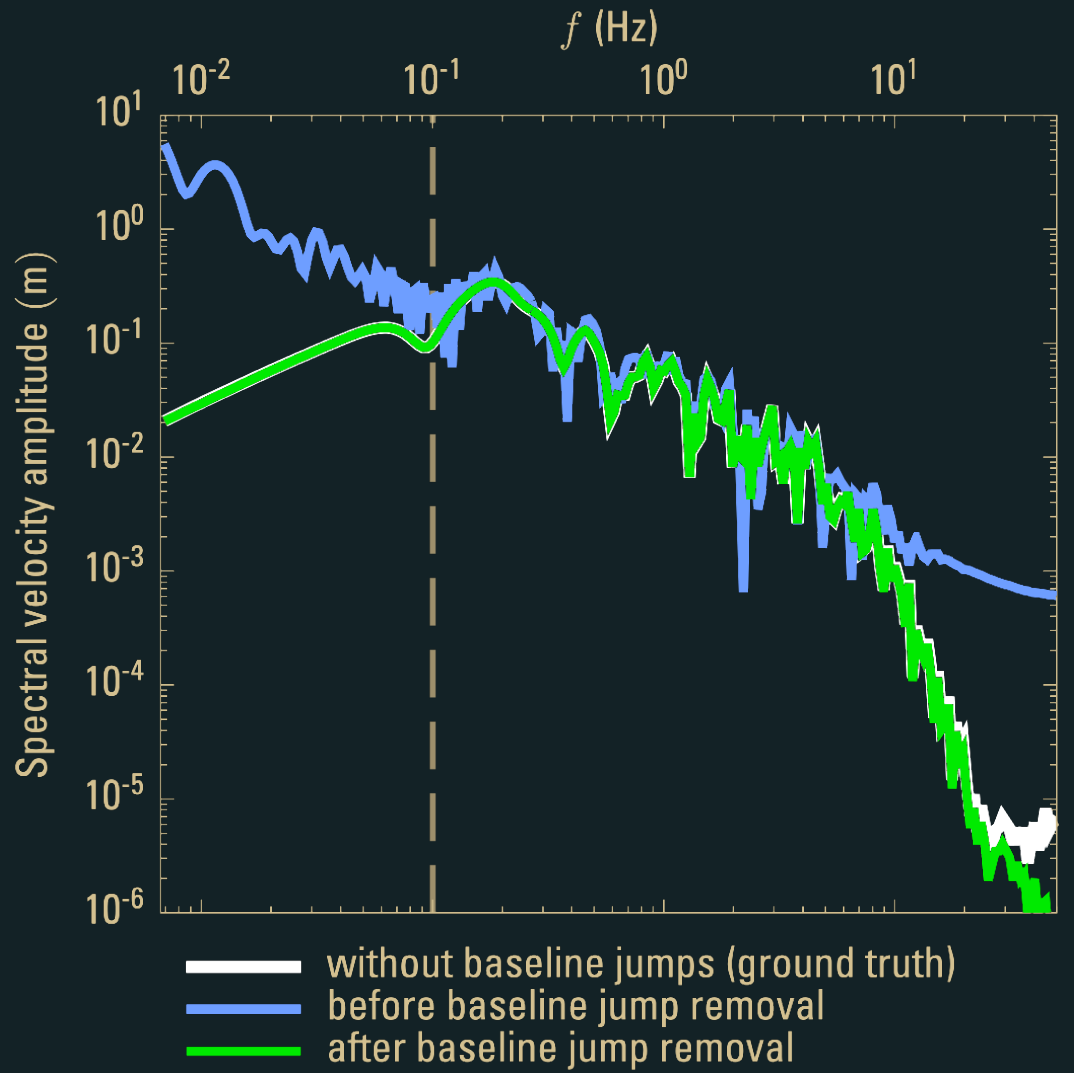
add baseline jumps
(on acceleration)



Conditions

Example:

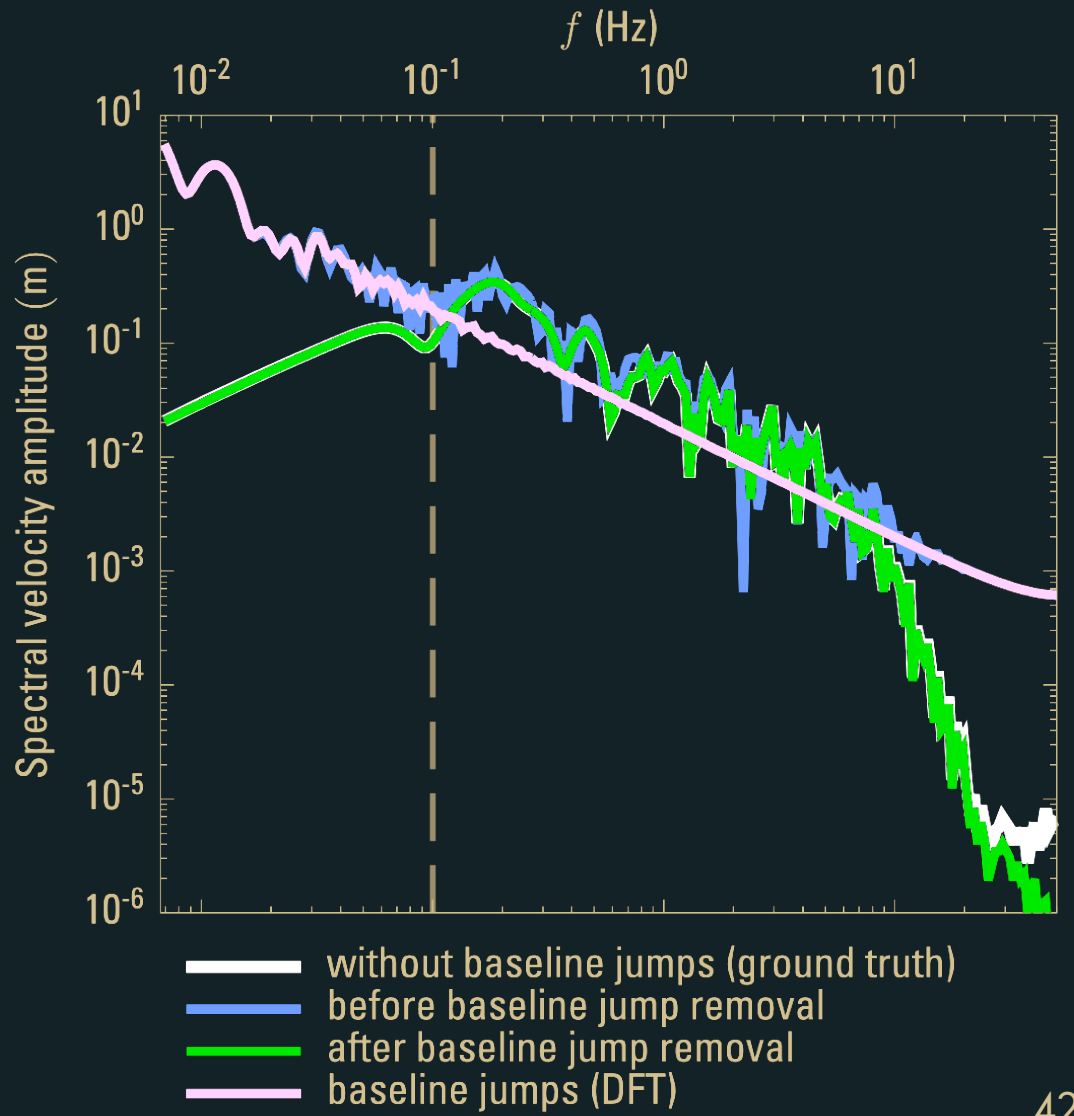
invert for baseline jumps and remove them



Conditions

Example:

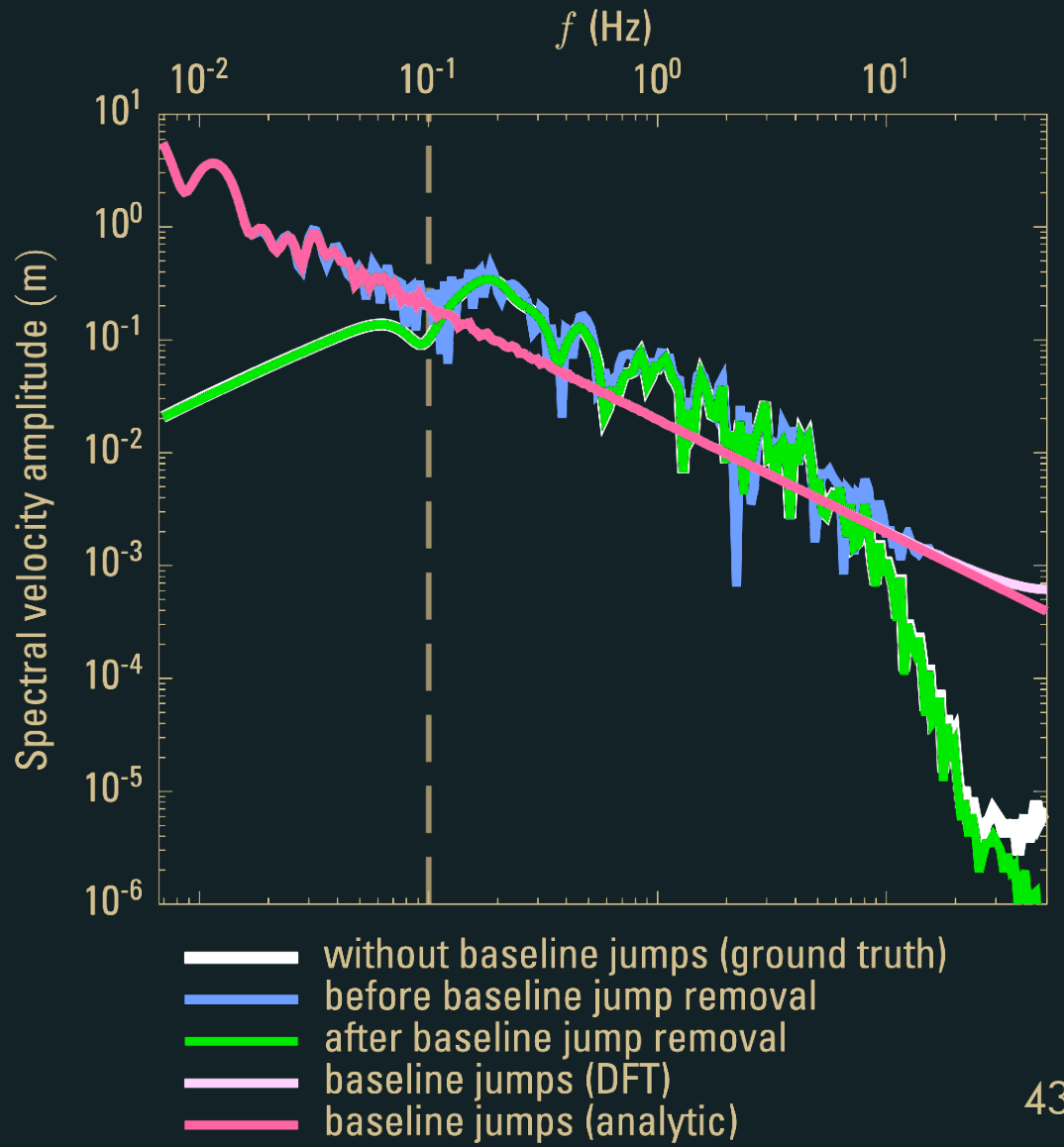
actual baseline jump spectrum versus ...



Conditions

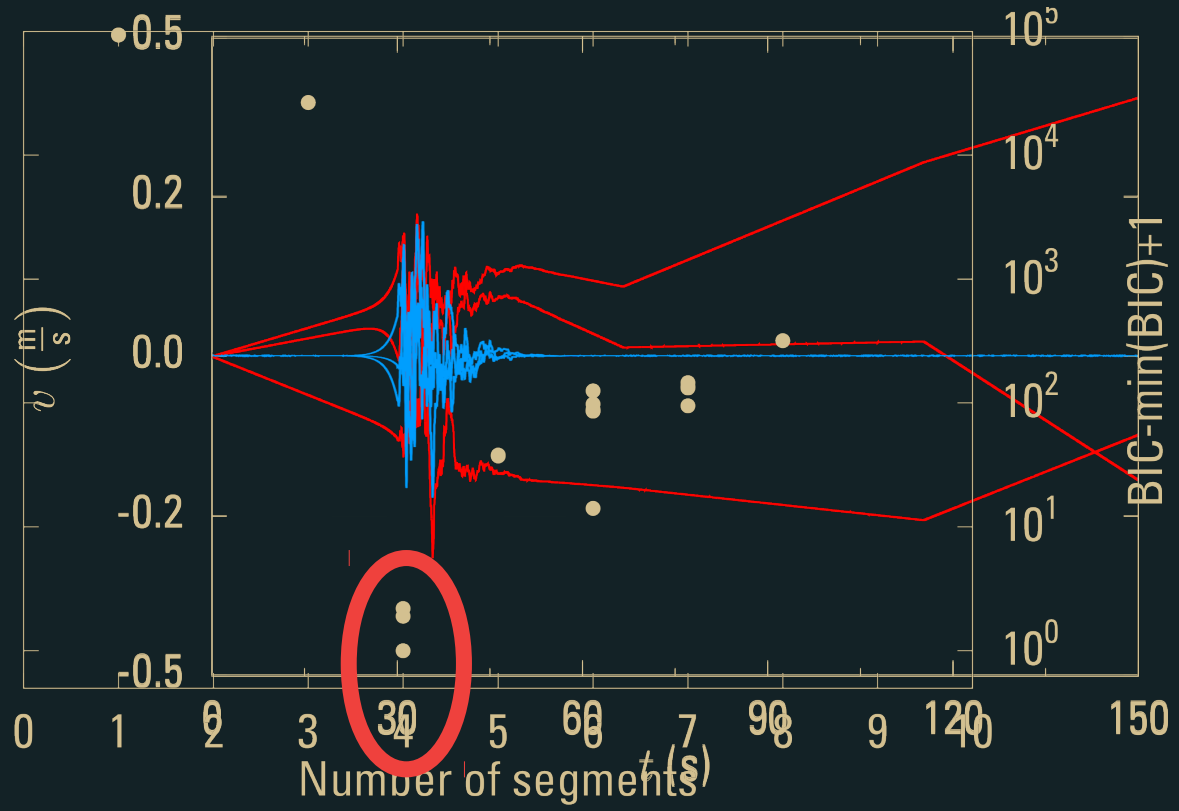
Example:

... analytic form (which has been actually removed)



Number of segments

parsimonious selection with Bayesian Information Criterion (BIC)



Example

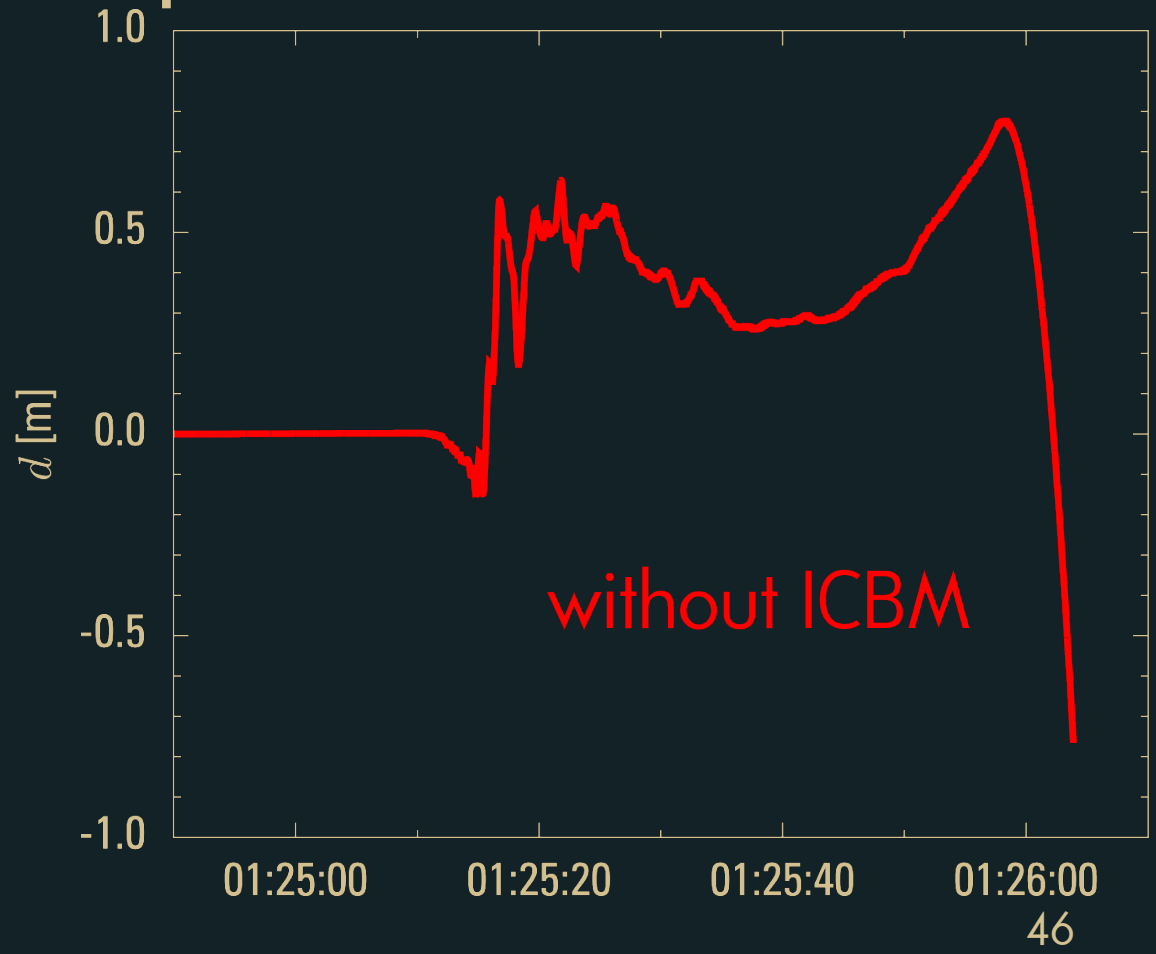
Estimation of static displacement

double integration of acceleration after Wang et al., 2012

Example

Estimation of static displacement

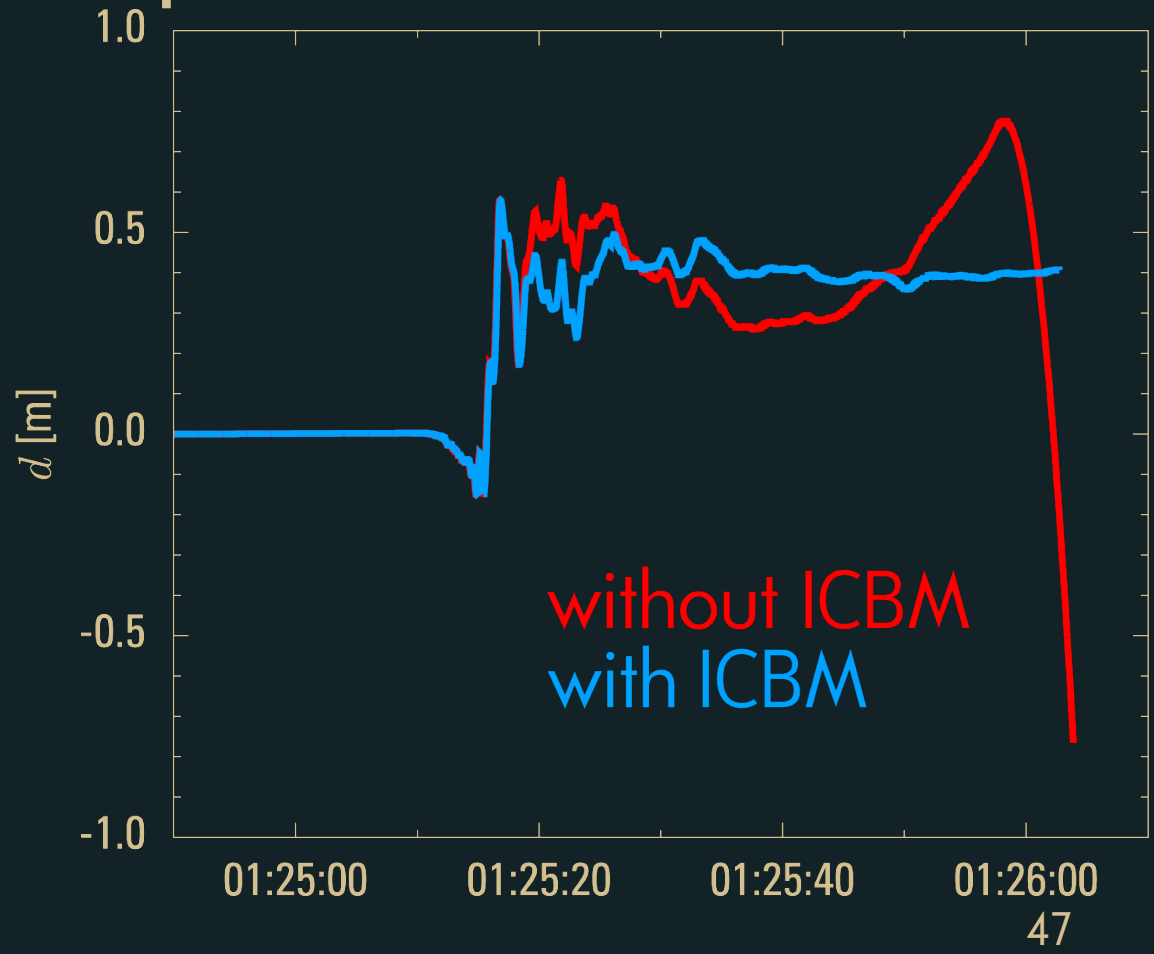
double integration of acceleration after Wang et al., 2012



Example

Estimation of static displacement

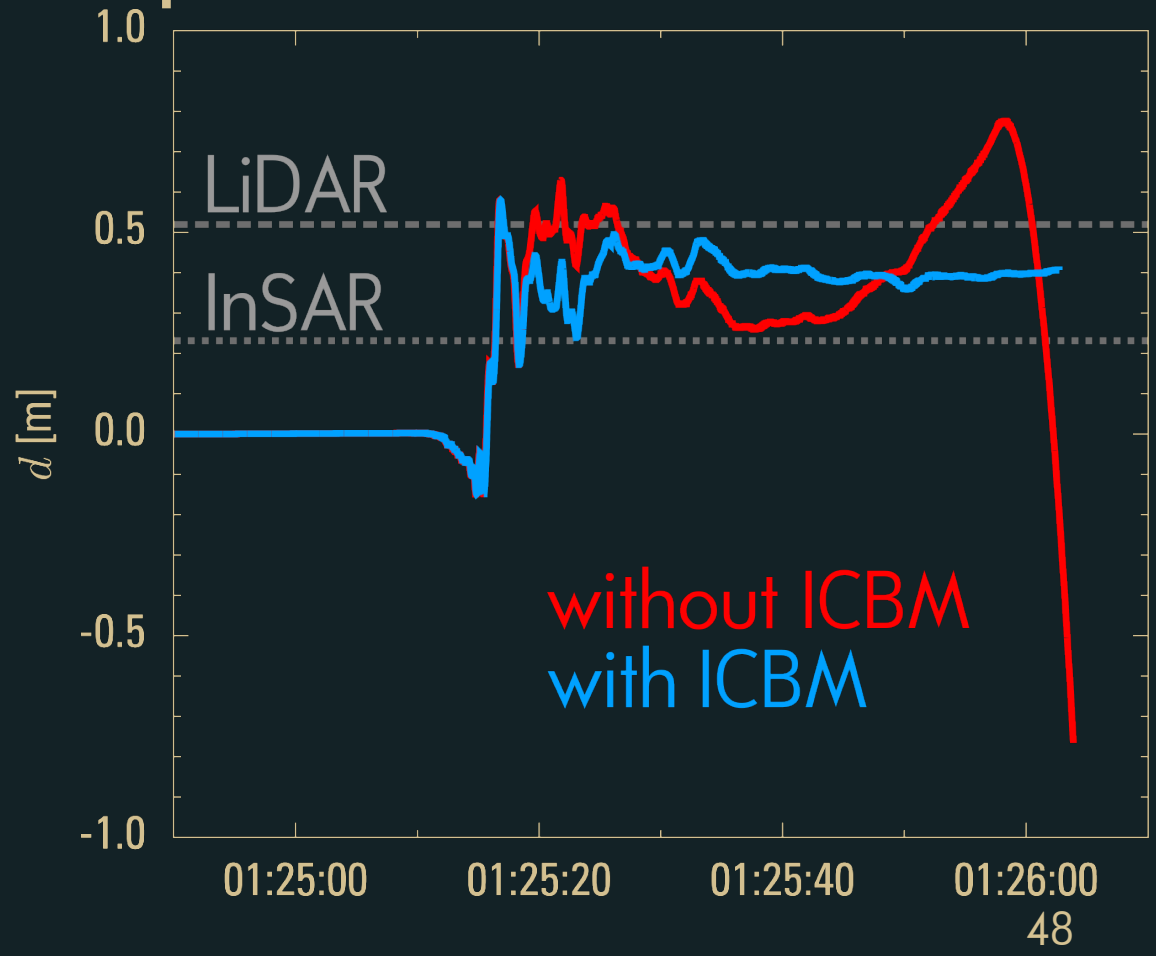
double integration of acceleration after Wang et al., 2012

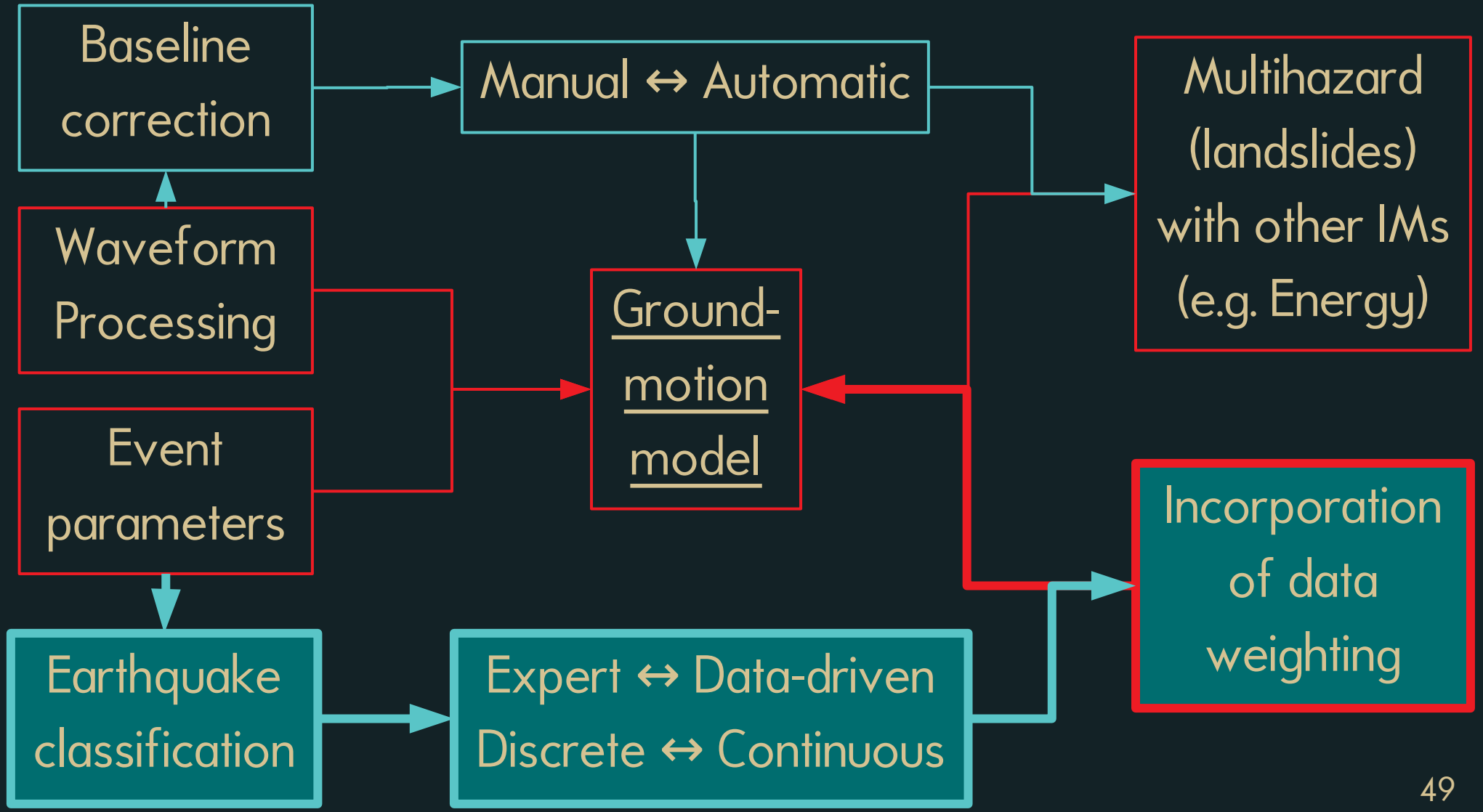


Example

Estimation of static displacement

double integration of acceleration after Wang et al., 2012




Baseline correction
Manual ↔ Automatic
Multihazard (landslides) with other IMs (e.g. Energy)
Waveform Processing
Ground-motion model
Event parameters
Incorporation of data weighting
Earthquake classification
Expert ↔ Data-driven
Discrete ↔ Continuous

Mixed effect regression

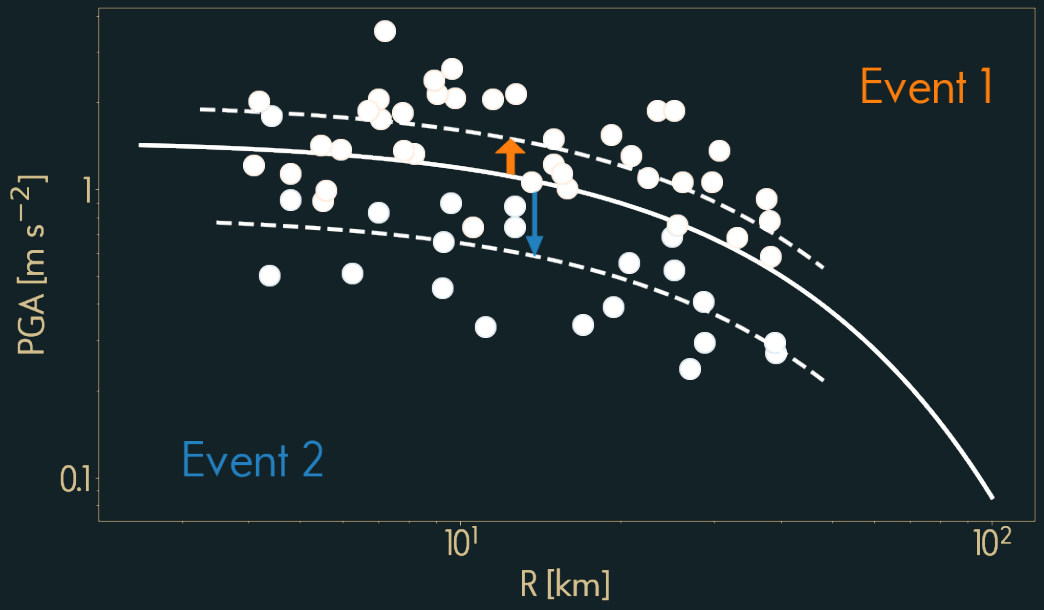
Widely used model

consists of two parts:

fixed effects model

random effects model

$$y = Ap + Bq + \epsilon$$



Mixed effect regression

Different approaches to handle random effects

some hybrid models inconsistent with theory

possibly biased results

harder to reproduce

How to incorporate data classification, e.g. SoF?

Discrete:

easy → leave out

Continuous:

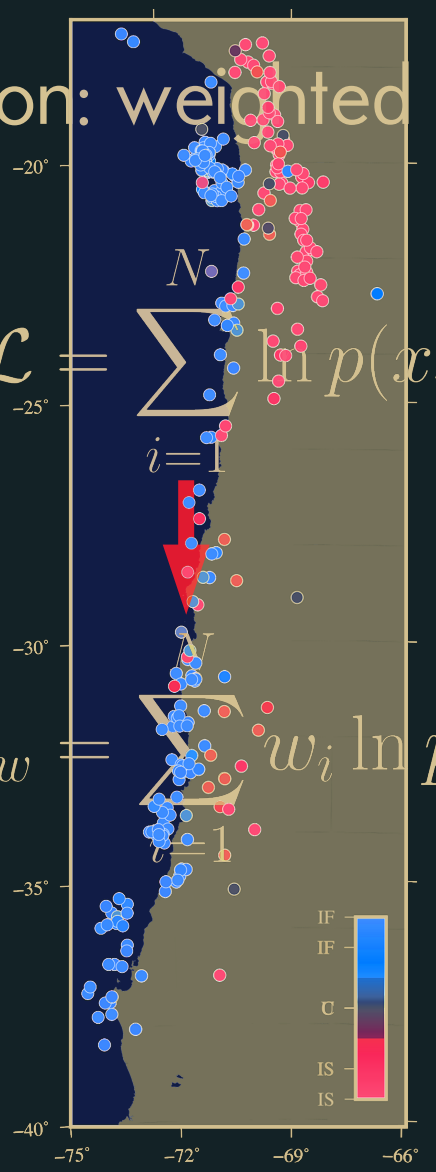
treat as measurement error?

→ bias in variance estimates

Solution: weighted likelihood

$$\ln \mathcal{L} = \sum_{i=1}^{N} \ln p(x_i|\theta)$$

$$\ln \mathcal{L}_w = \sum_{i=1}^{N} w_i \ln p(x_i|\theta)$$



One form to fit them all

Standardized approach:

implementation of any function type

→ meta-model

Example:

$$
\begin{aligned}
y = & a M_W + b r_{rup} - (c + d M_W) \ln r_{rup} \\
& + e \begin{cases} z & \text{if } z \leq 125 \text{ km} \\ 125 & \text{otherwise} \end{cases} \\
& + \begin{cases} w_i (q_i (M_W - 6.3)^2 + s_i) \\ w_s (q_s (M_W - 6.5)^2 + s_s + s_{sl} \ln r_{rup}) \end{cases} \\
& + x \ln v_{S30}
\end{aligned}
$$

from Händel et al. (2015)

One form to combine them

clear work frame for any

random effect structure

and

continuous data

classification

$$\hat{\mathbf{p}} = \left(\mathbf{A}^{\mathrm{T}}\mathbf{V}\mathbf{S}^{-1}\mathbf{V}\mathbf{A}\right)^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{V}\mathbf{S}^{-1}\mathbf{V}\mathbf{y}$$

One form to bring them all...

... and in the
covariance bind them

$$\mathbf{C} = \sigma^2\mathbf{I}$$

Within-event covariance

$$\mathbf{B} = \begin{pmatrix}\mathbf{B_1} & \mathbf{B_2} & \cdots & \mathbf{B_K}\end{pmatrix}$$

random effects matrix
(between events,
between sites, etc.)

$$\mathbf{S} = \mathbf{C} + \mathbf{BDB^T}$$

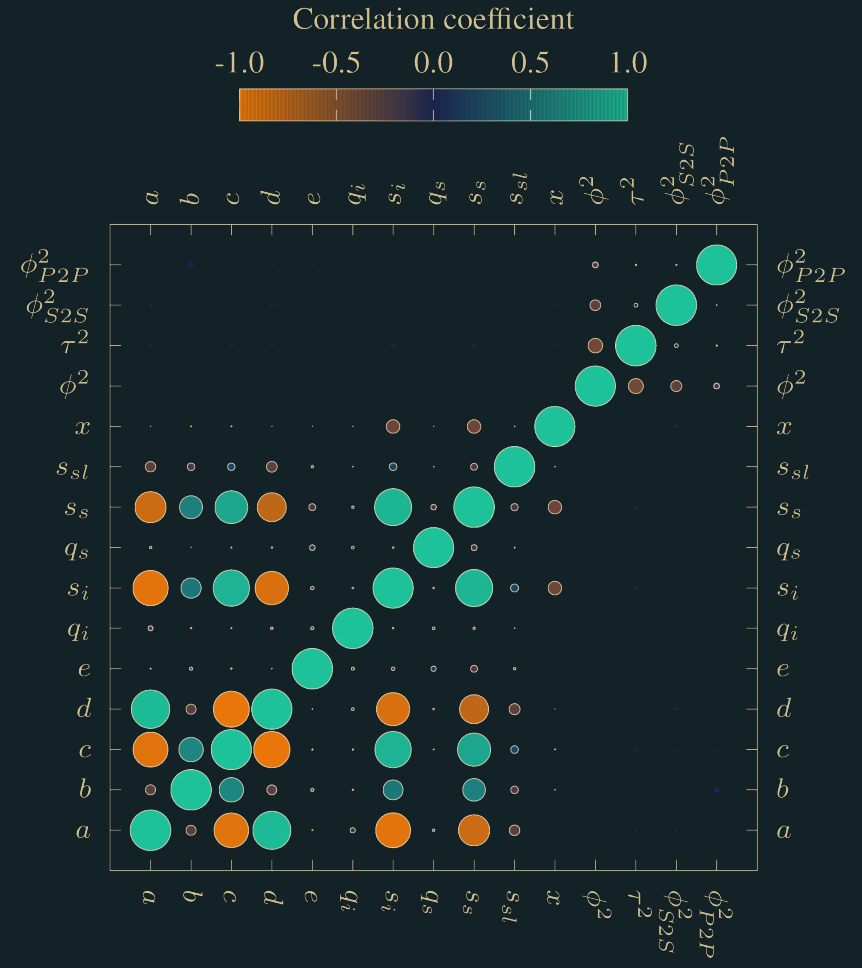
$$\mathbf{D} = \begin{pmatrix} \tau_1\mathbf{I} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \tau_2\mathbf{I} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \tau_K\mathbf{I} \end{pmatrix}$$

random effects covariance
factor matrix

Random effects splitting

variable residual splitting possible

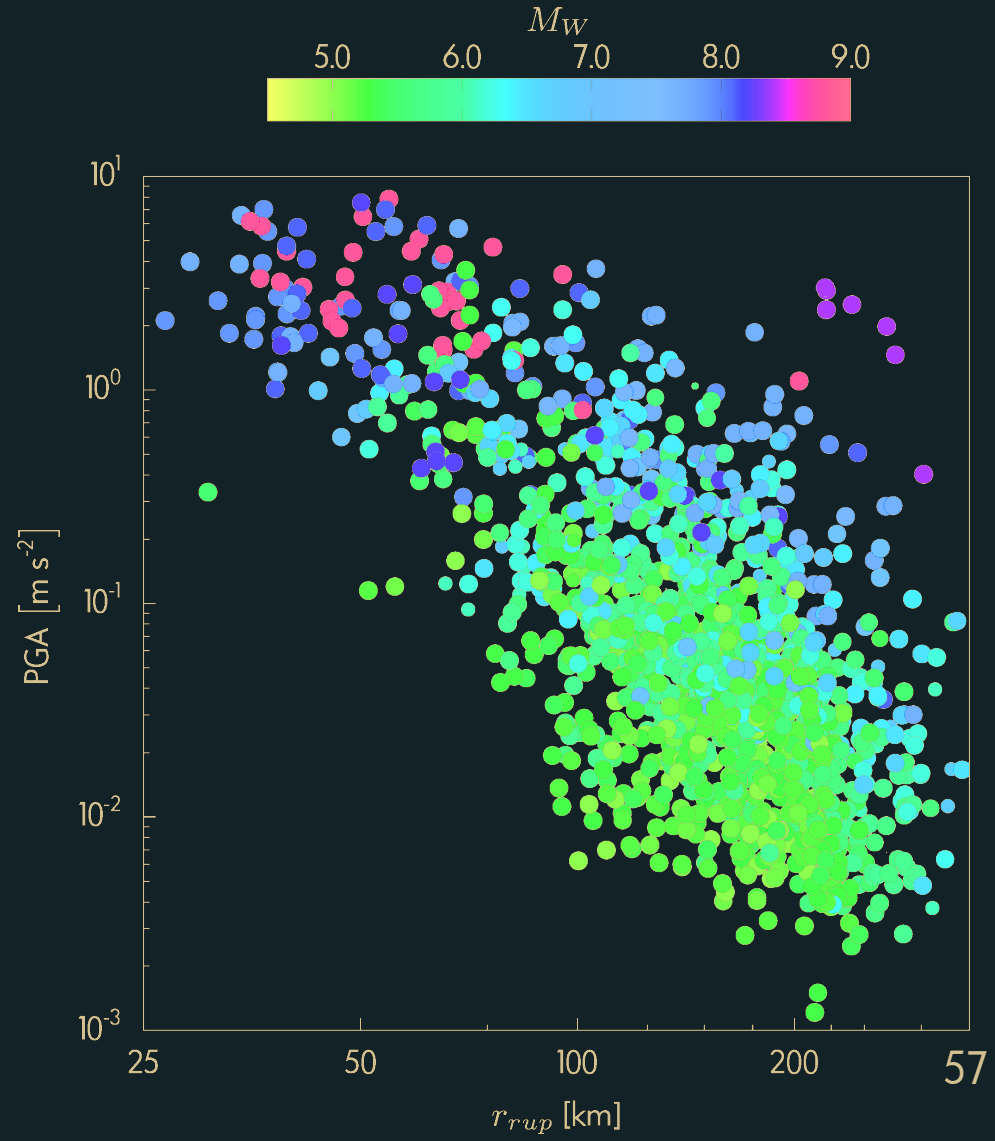
→ Fisher information shows: random effect variances independent from fixed effects parameters



Model for Chile

Strong-motion flatfile (Bastias & Montalva, 2016)

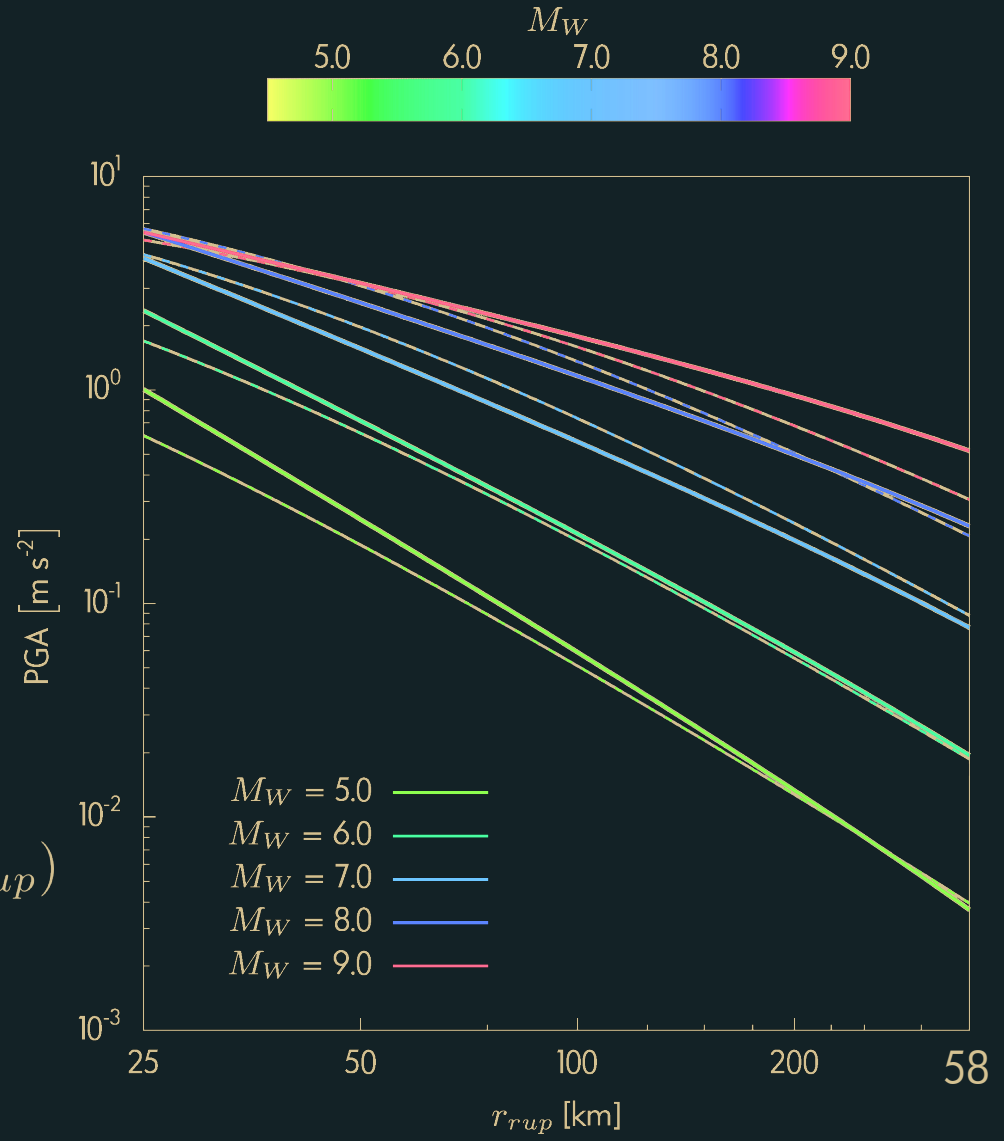
Focal mechanisms for ACE from Global CMT



Model for Chile

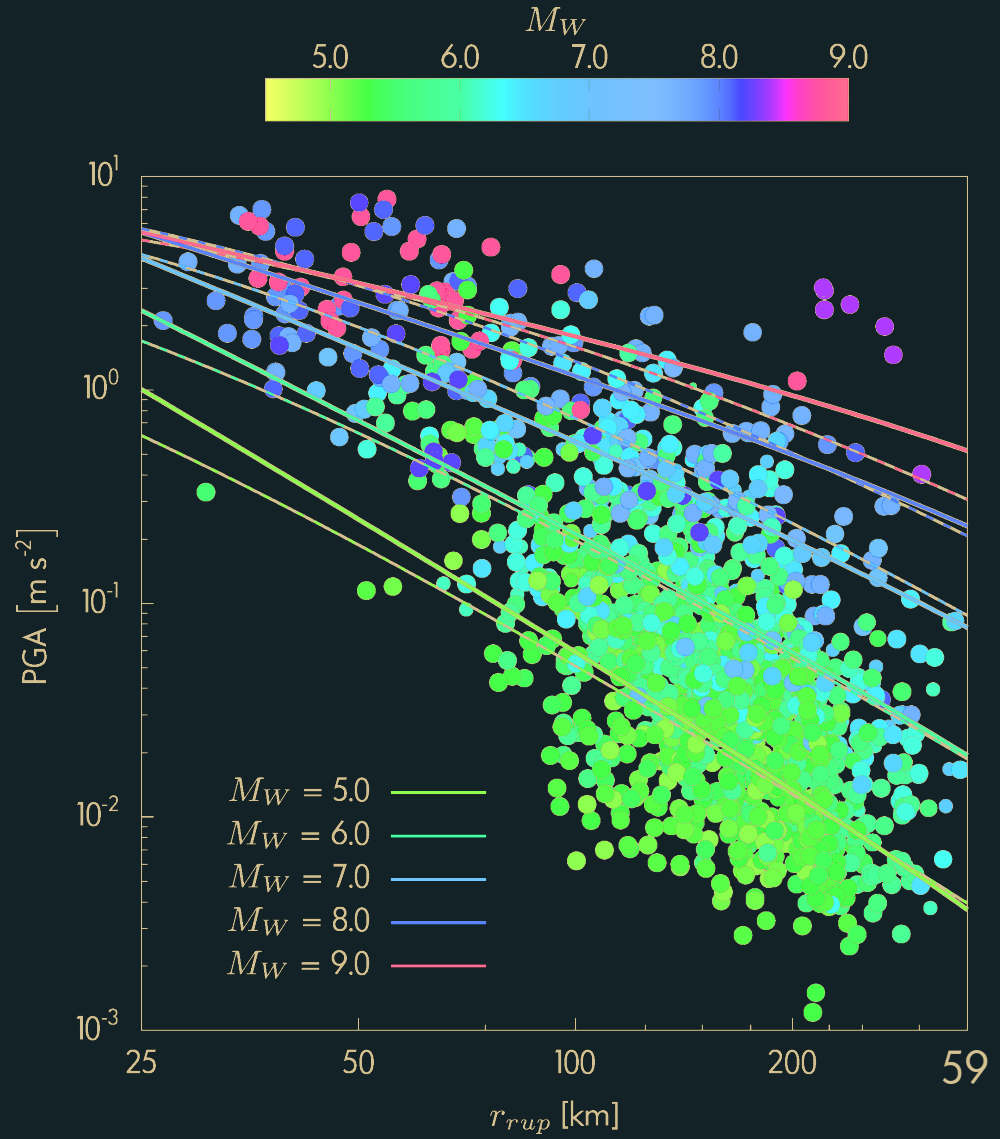
Functional form:

$$
\begin{aligned}
y =& aM_W + br_{rup} - (c + dM_W)\ln r_{rup} \\
&+ e \begin{cases} z & \text{if } z \leq 125\ \text{km} \\ 125 & \text{otherwise} \end{cases} \\
&+ \begin{cases} w_i(q_i(M_W - 6.3)^2 + s_i) \\ w_s(q_s(M_W - 6.5)^2 + s_s + s_{sl}\ln r_{rup}) \end{cases} \\
&+ x \ln v_{S30}
\end{aligned}
$$



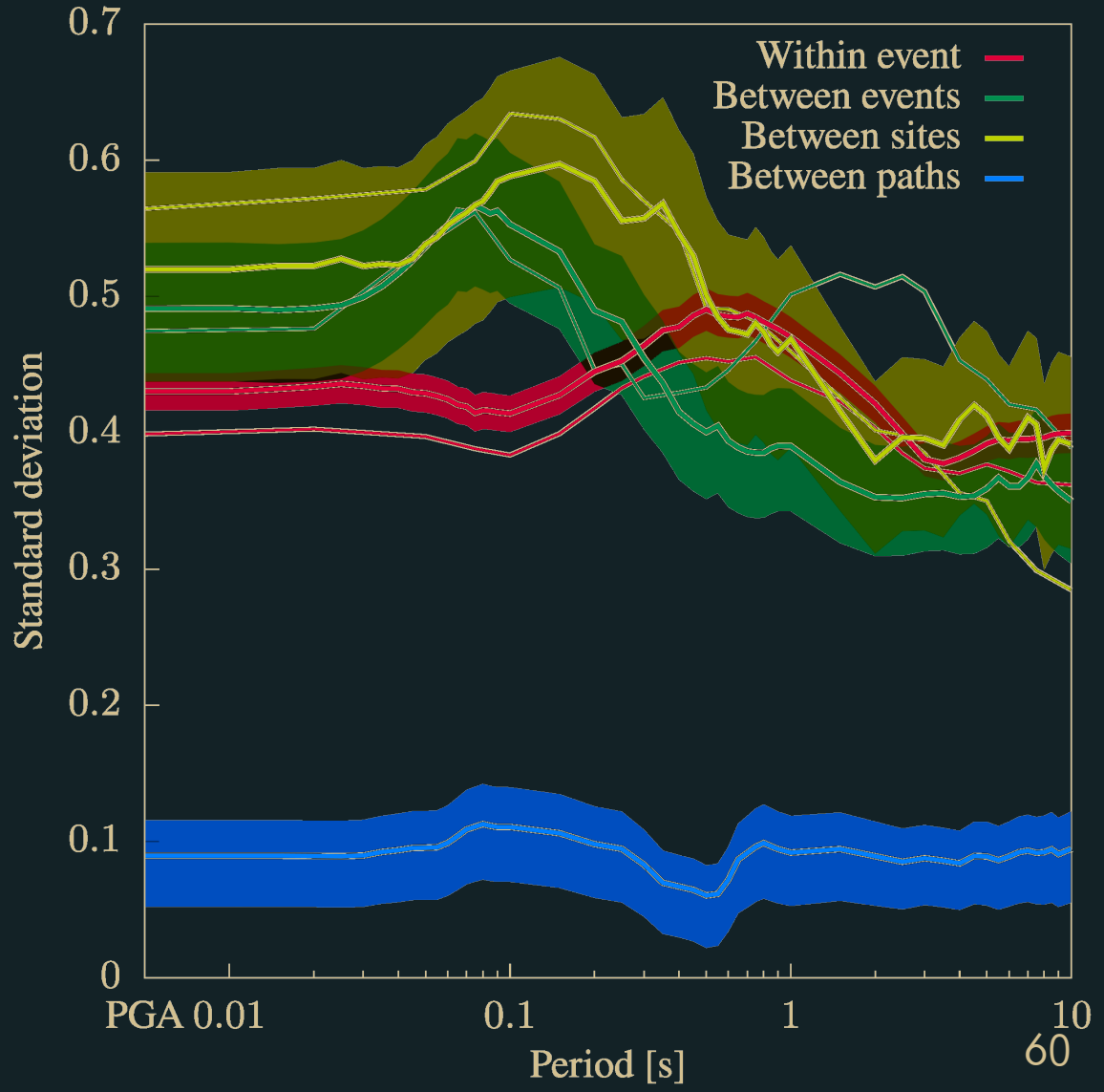
Model for Chile

Similar performance in fixed effects and ...



Model for Chile

... random effect variances



Conclusion & Outlook

- Event classification
  - apply globally
  - combination with seismicity models (e.g. Bayona et al., 2019)
  - use in stress tensor inversion (von Specht et al., 2018)
  - time dependent parameters

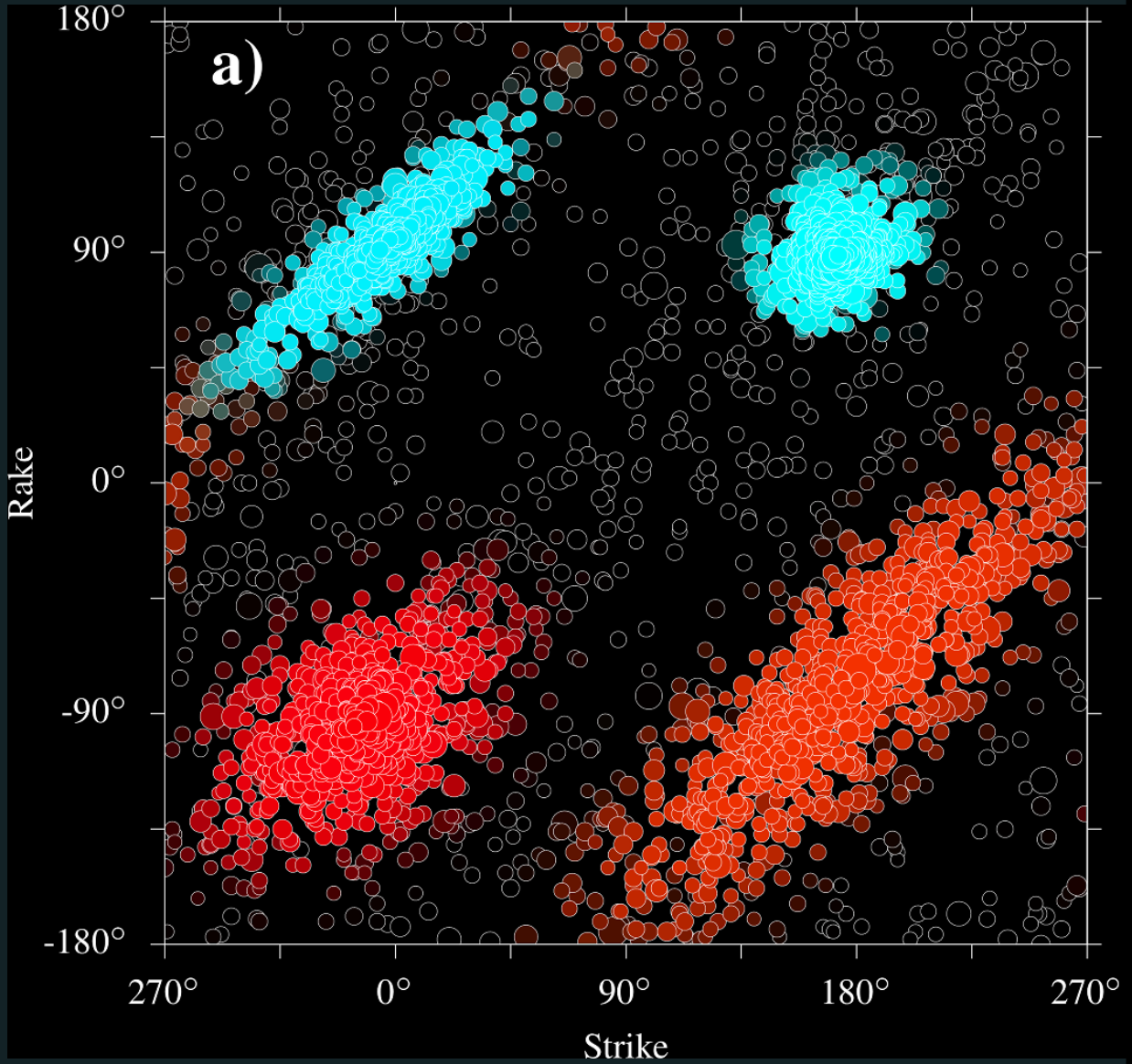
Conclusion & Outlook

- Baseline correction
  - implement in standard processing for strong motion flat files (e.g. NGAwest)
  - preprocessing step for radiated seismic energy estimation (e.g. von Specht et al., 2019)

Conclusion & Outlook

- Ground motion model
  - development of purely data-driven ground motion models (from database to final model)
  - random effect terms as function of magnitude, distance etc.
  - hazard cascade specific models (seismically triggered landslides)

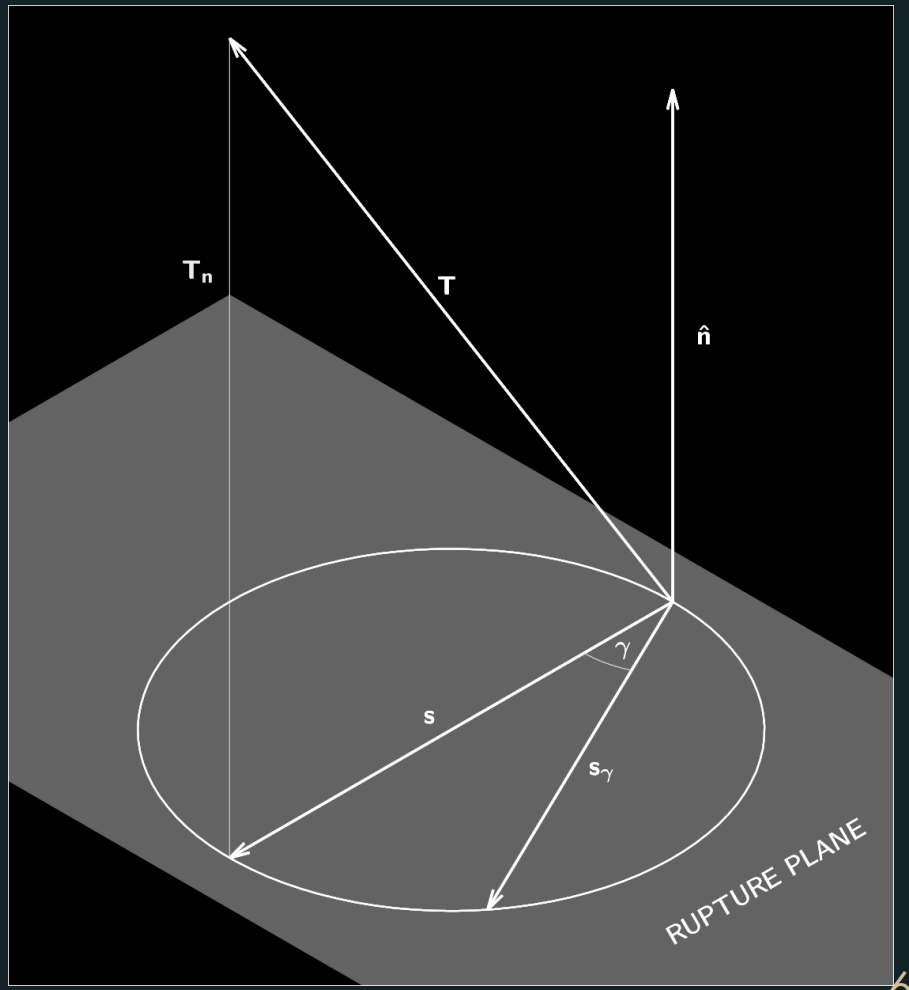

Thank you!
地震の桜

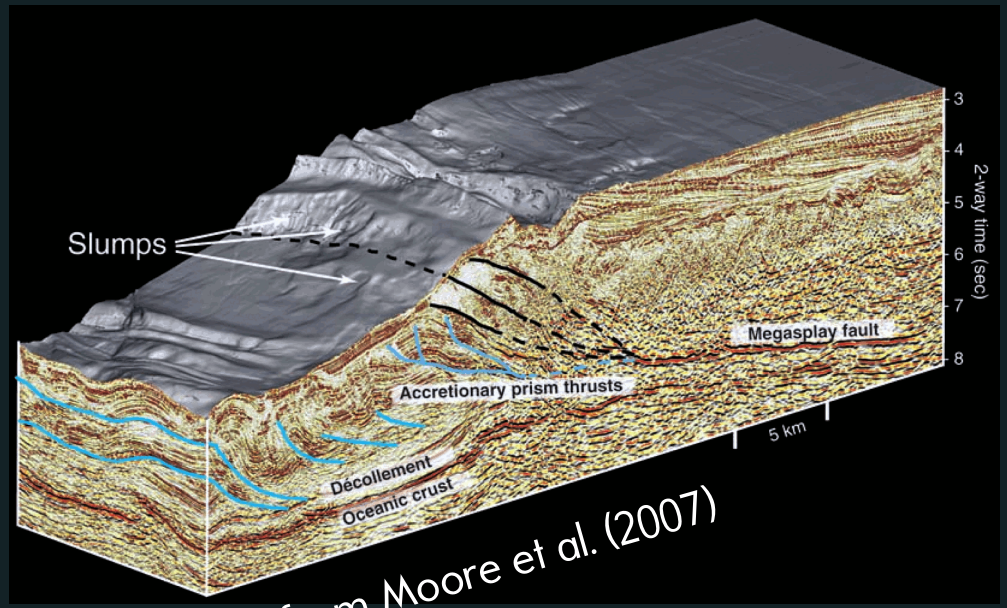

a)
180°
90°
0°
-90°
-180°
Rake
270°
0°
90°
180°
270°
Strike

All models are wrong – some are useful

Fault slip oriented in maximum resolved shear stress (Wallace-Bott hypothesis)

→ large deviation possible but less likely



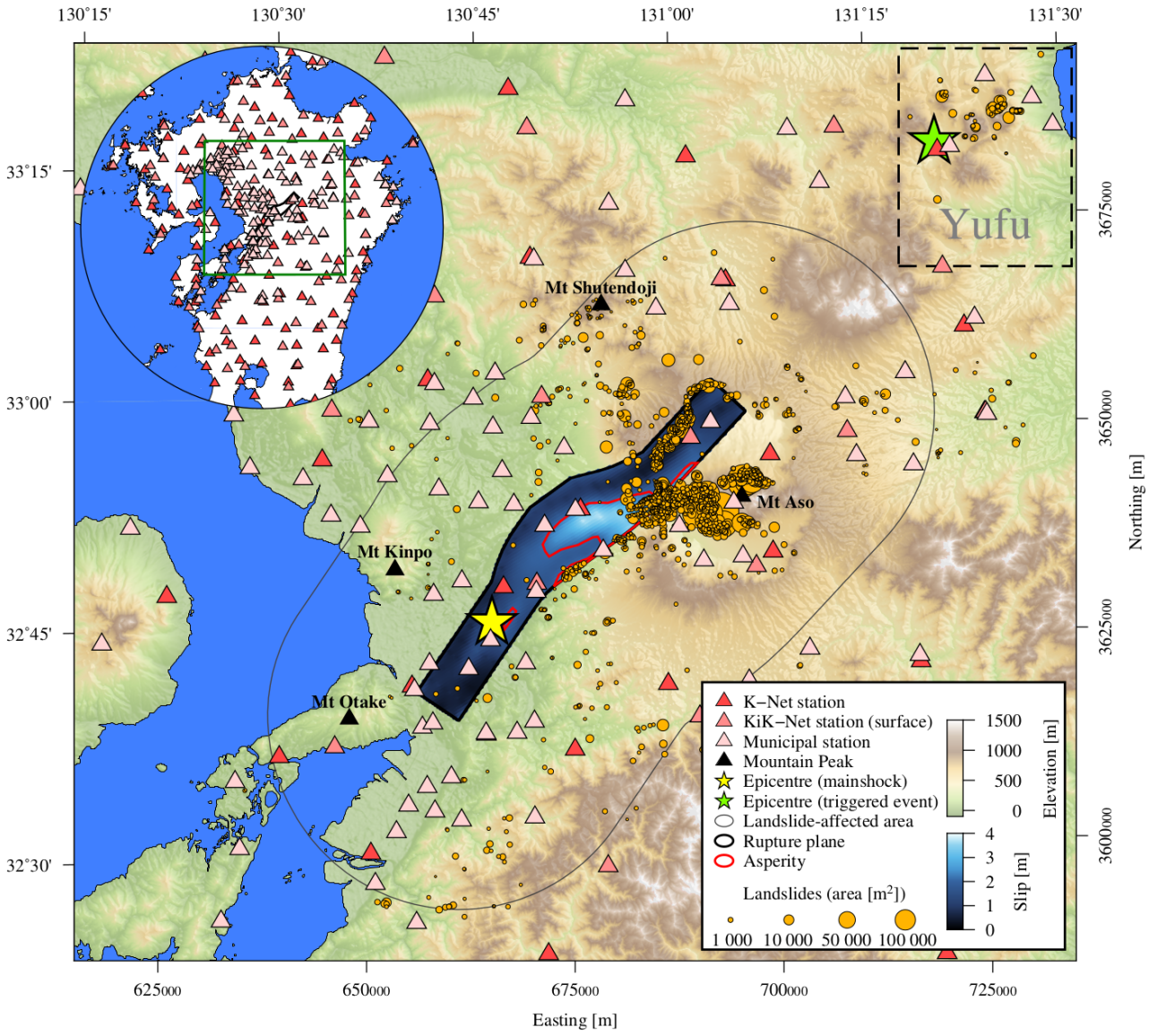


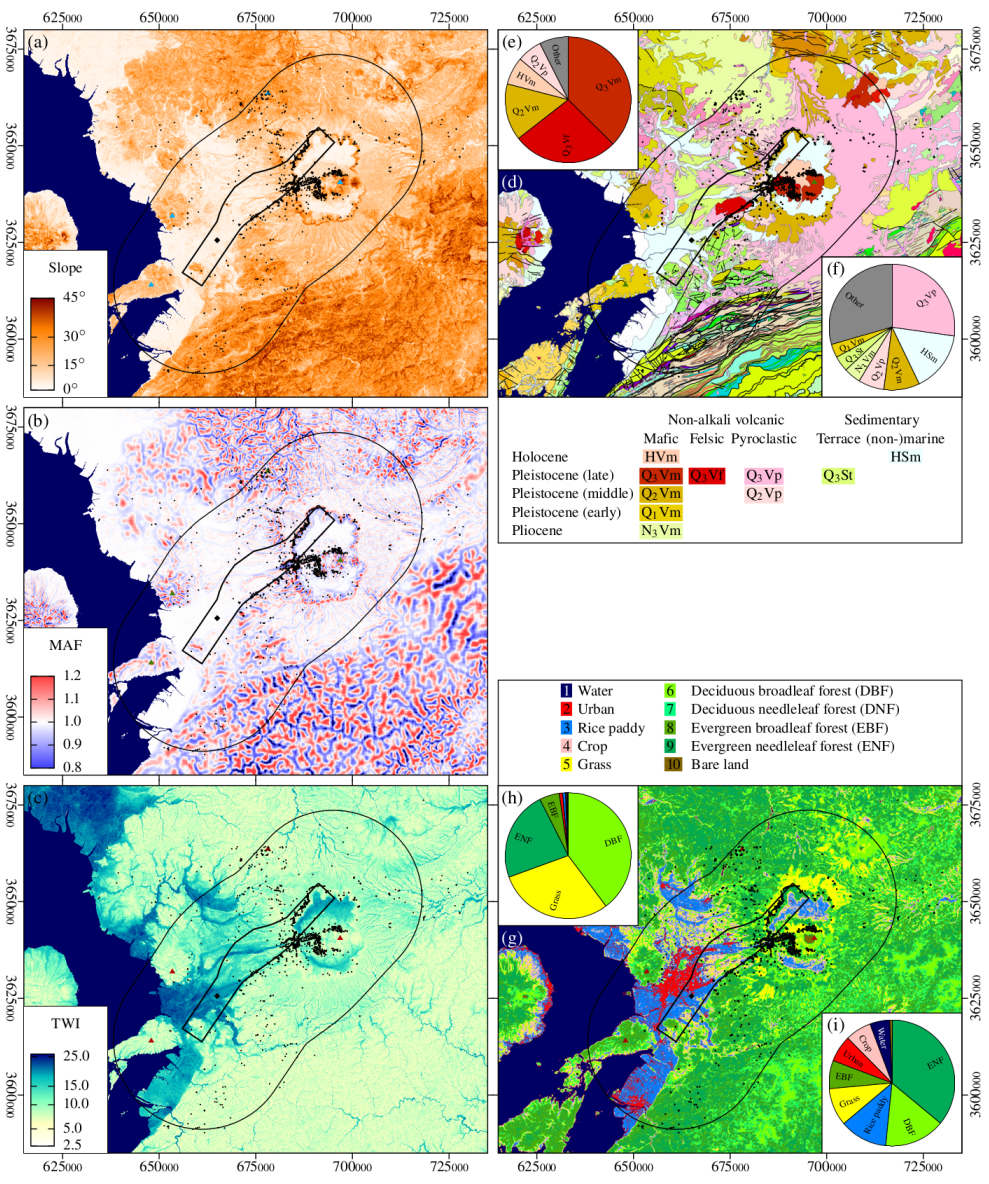
from Moore et al. (2007)

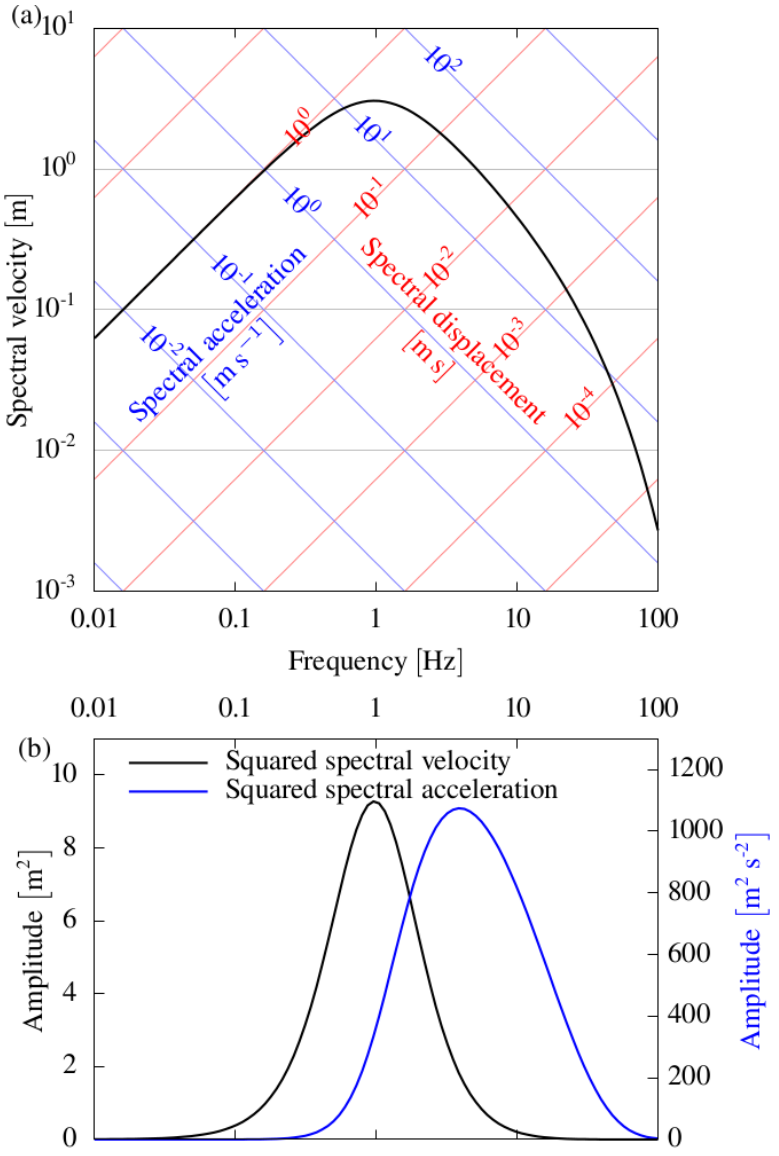
Thrust but not interface:

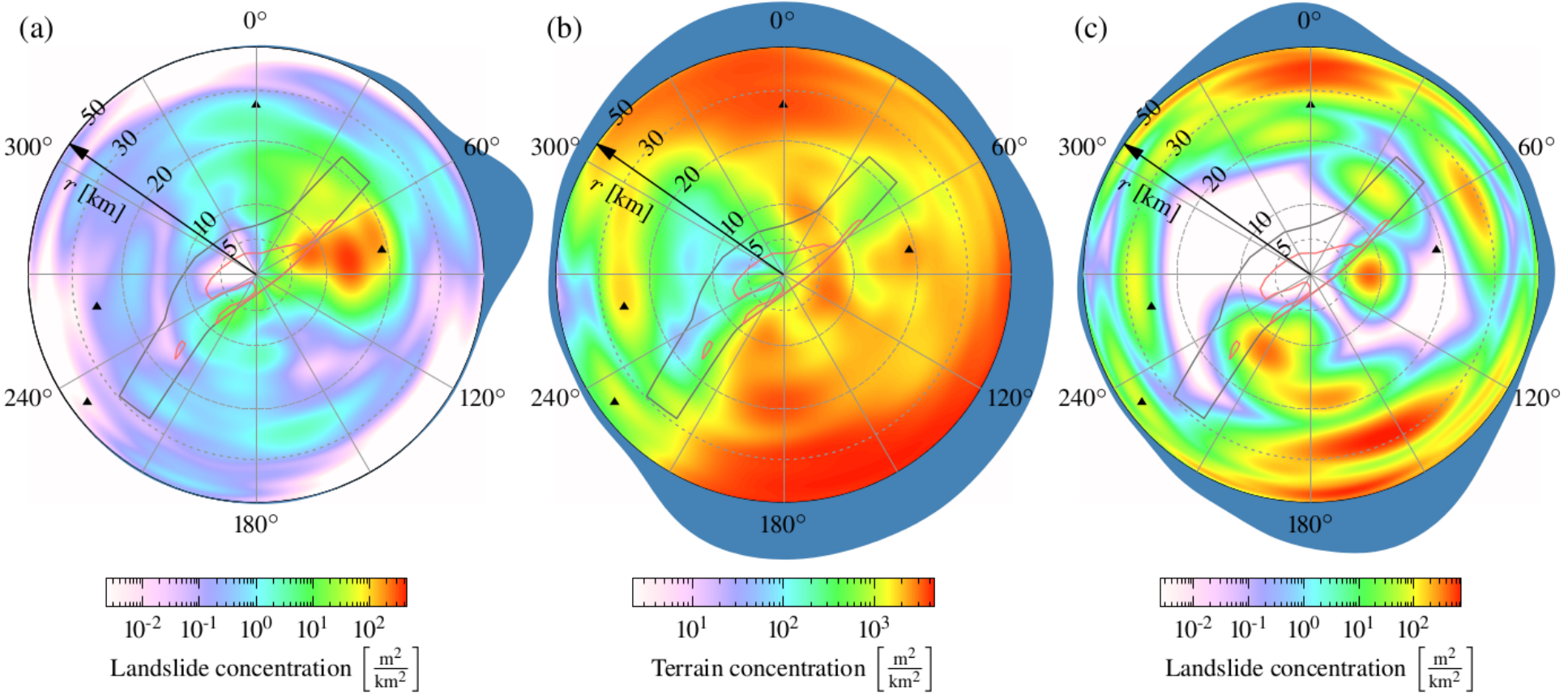
splay faults in accretionary prism dip steeper than subduction interface

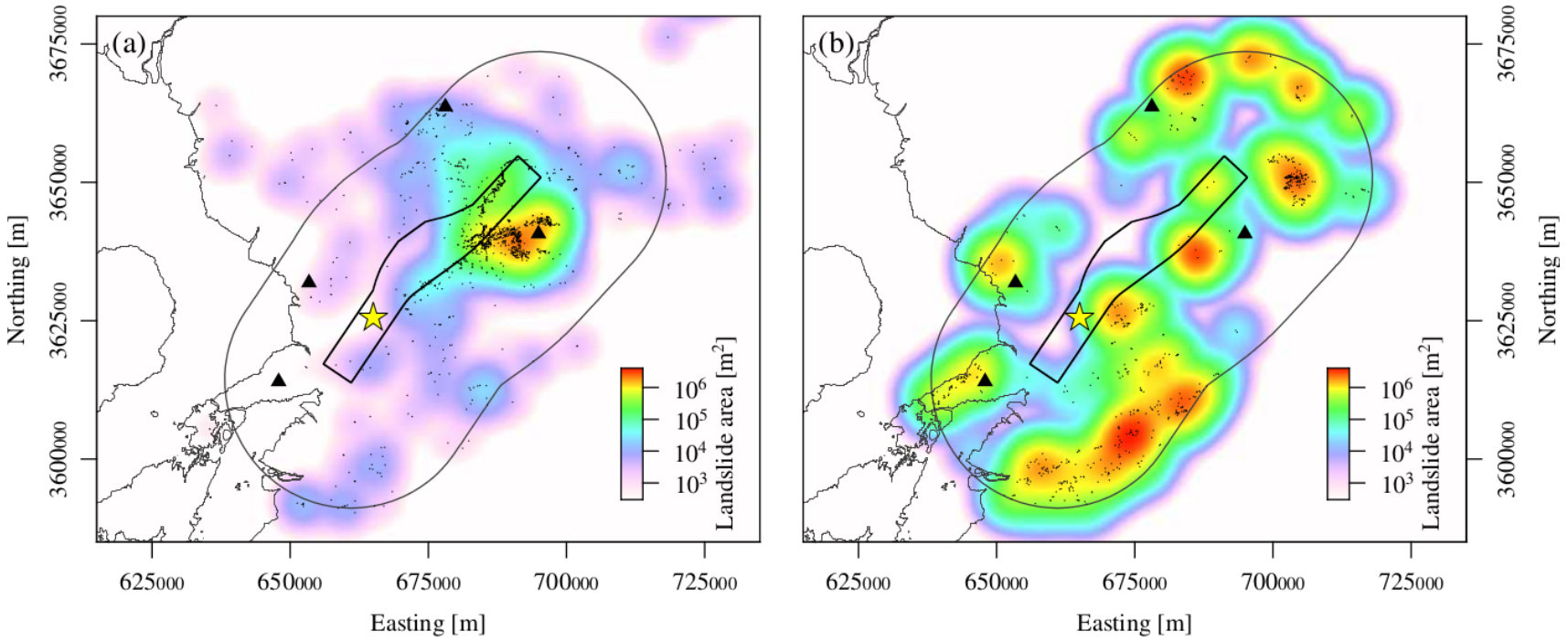
→ less seismicity

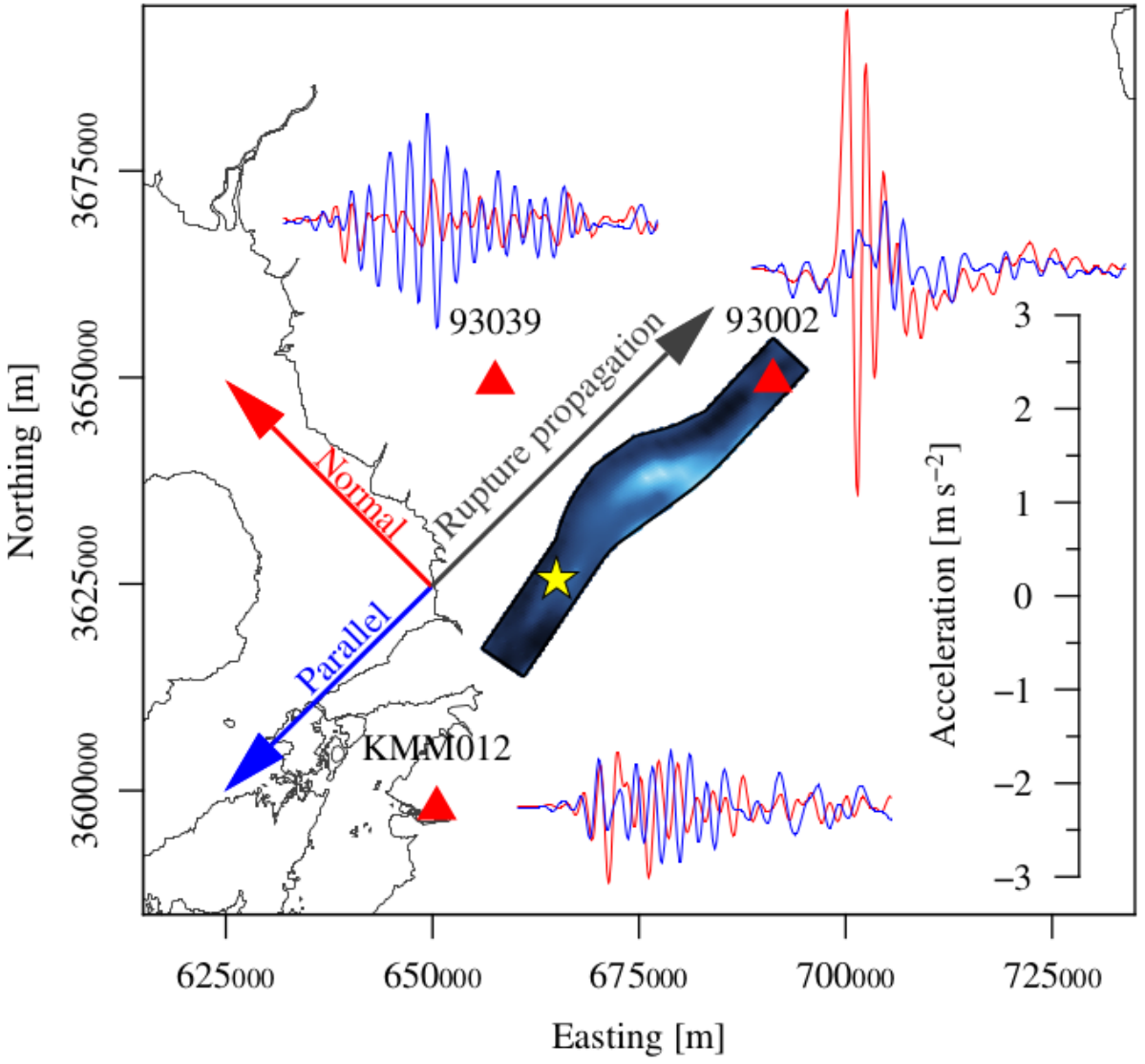

130°15'
130°30'
130°45'
131°00'
131°15'
131°30'
33°15'
33°00'
32°45'
32°30'
Yufu
Mt Shutendoji
Mt Aso
Mt Kinpo
Mt Otake
K−Net station
KiK−Net station (surface)
Municipal station
Mountain Peak
Epicentre (mainshock)
Epicentre (triggered event)
Landslide-affected area
Rupture plane
Asperity
Landslides (area [m²])
1 000
10 000
50 000
100 000
1500
1000
500
0
Elevation [m]
4
3
2
1
0
Slip [m]
625000
650000
675000
700000
725000
Easting [m]
3675000
3650000
3625000
3600000
Northing [m]

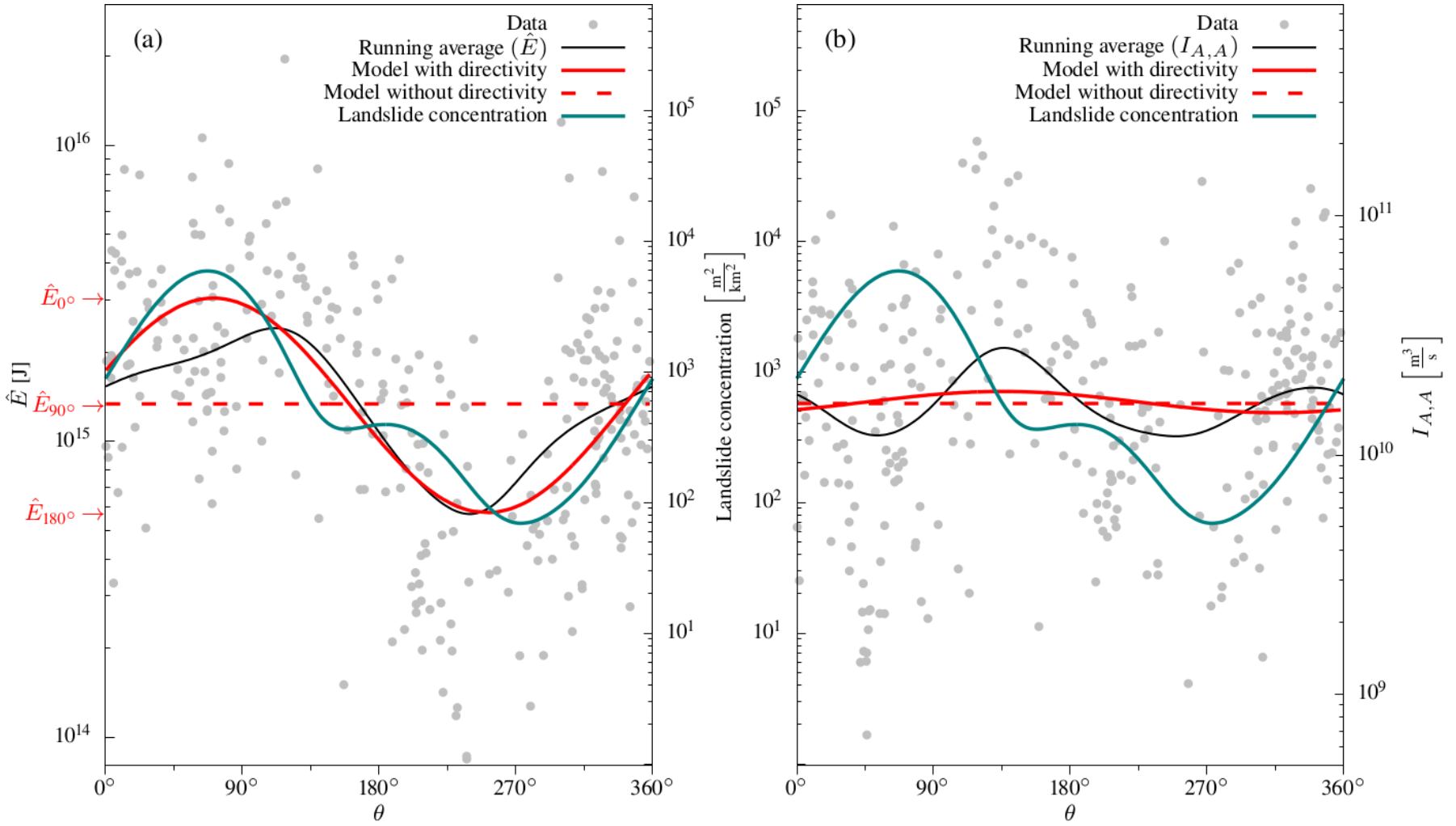

(a)
Slope
45°
30°
15°
0°
(b)
MAF
1.2
1.1
1.0
0.9
0.8
(c)
TWI
25.0
15.0
10.0
5.0
2.5
(d)
(e)
(f)
Non-alkali volcanic
Mafic
Felsic
Pyroclastic
Sedimentary
Terrace
(non-)marine
Holocene
HVm
HSm
Pleistocene (late)
Q3Vm
Q3Vf
Q3Vp
Q3St
Pleistocene (middle)
Q2Vm
Q2Vp
Pleistocene (early)
Q1Vm
Pliocene
N3Vm
1 Water
2 Urban
3 Rice paddy
4 Crop
5 Grass
6 Deciduous broadleaf forest (DBF)
7 Deciduous needleleaf forest (DNF)
8 Evergreen broadleaf forest (EBF)
9 Evergreen needleleaf forest (ENF)
10 Bare land
(g)
(h)
(i)
625000
650000
675000
700000
725000
3675000
3650000
3625000
3600000

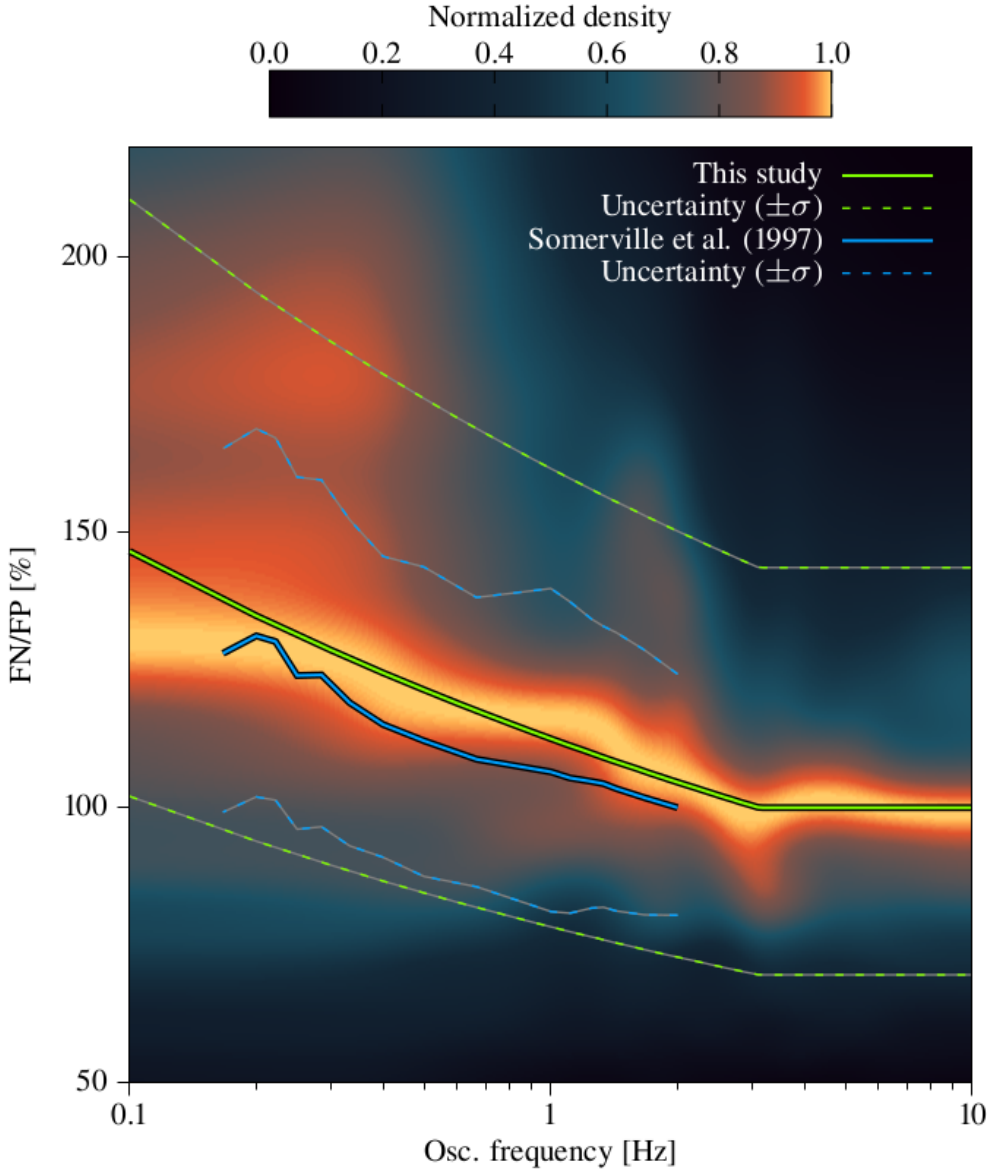

(a)
Spectral velocity [m]
Frequency [Hz]
Spectral acceleration [m s⁻¹]
Spectral displacement [m s]
(b)
Squared spectral velocity
Squared spectral acceleration
Amplitude [m²]
Amplitude [m² s⁻²]

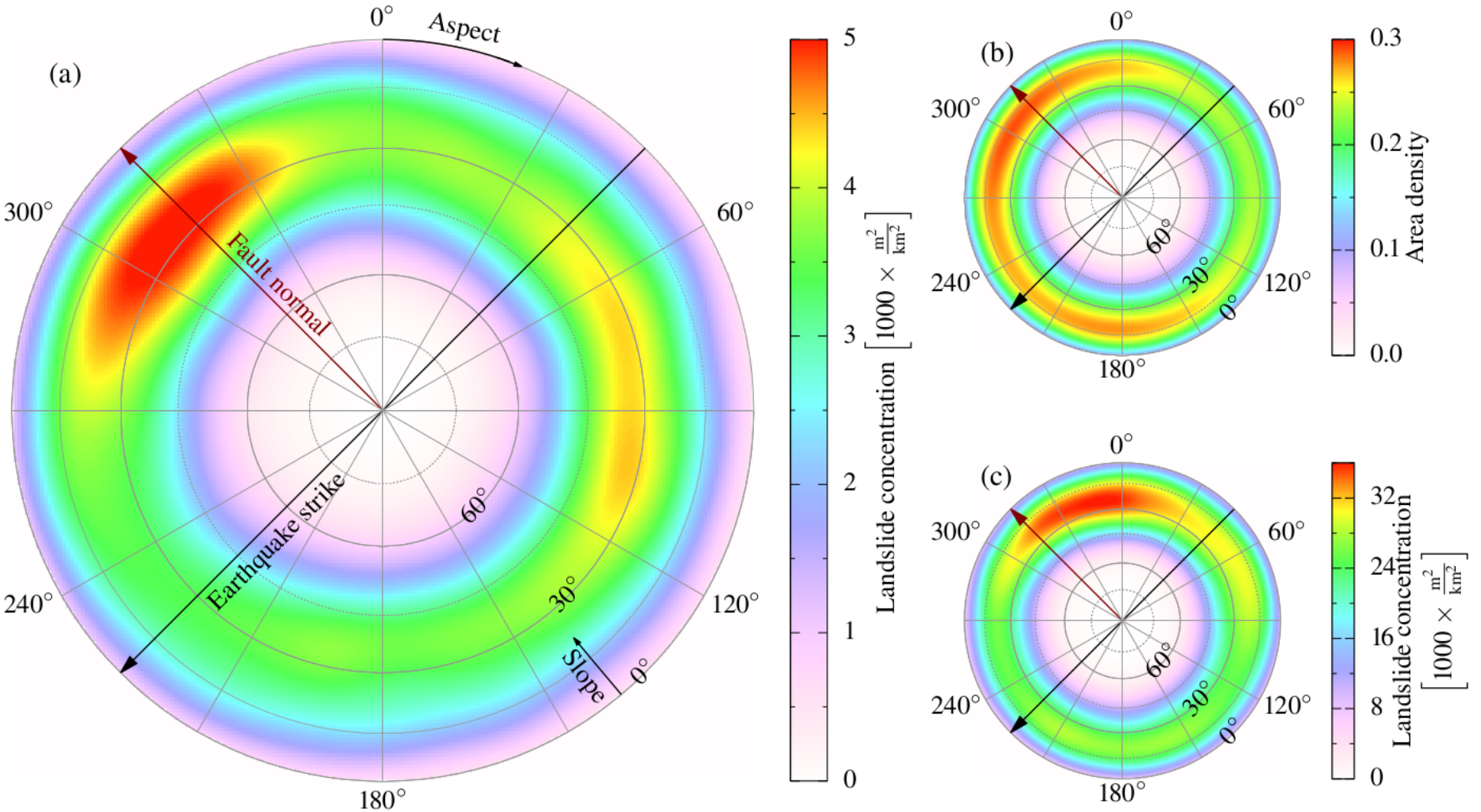

(a)
(b)
(c)
0°
60°
120°
180°
240°
300°
r [km]
50
30
20
10
5
0
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
Landslide concentration $\left[\frac{m^2}{km^2}\right]$
10^{1} 10^{2} 10^{3}
Terrain concentration $\left[\frac{m^2}{km^2}\right]$
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
Landslide concentration $\left[\frac{m^2}{km^2}\right]$

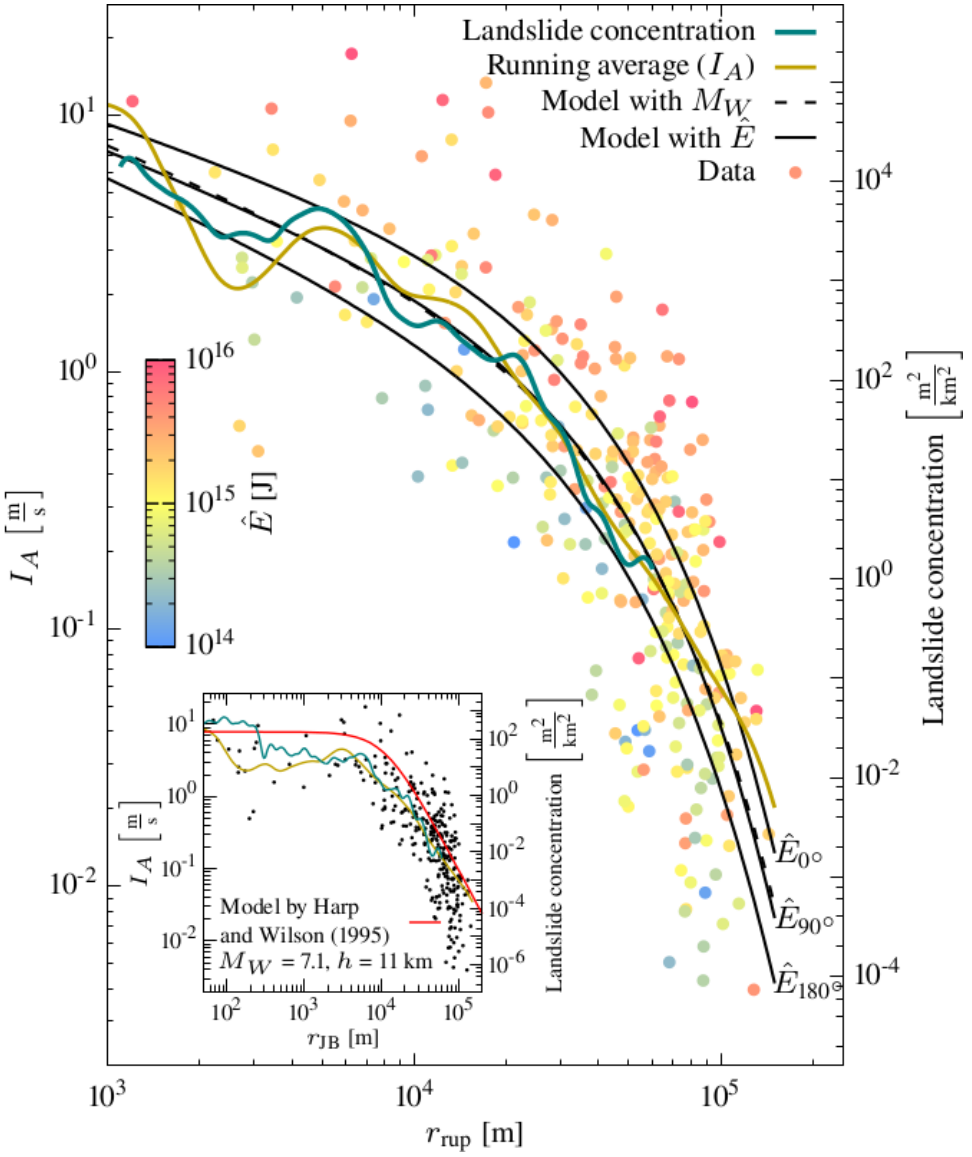

(a)
(b)
Northing [m]
3675000
3650000
3625000
3600000
625000
650000
675000
700000
725000
Easting [m]
Landslide area [m²]
10⁶
10⁵
10⁴
10³

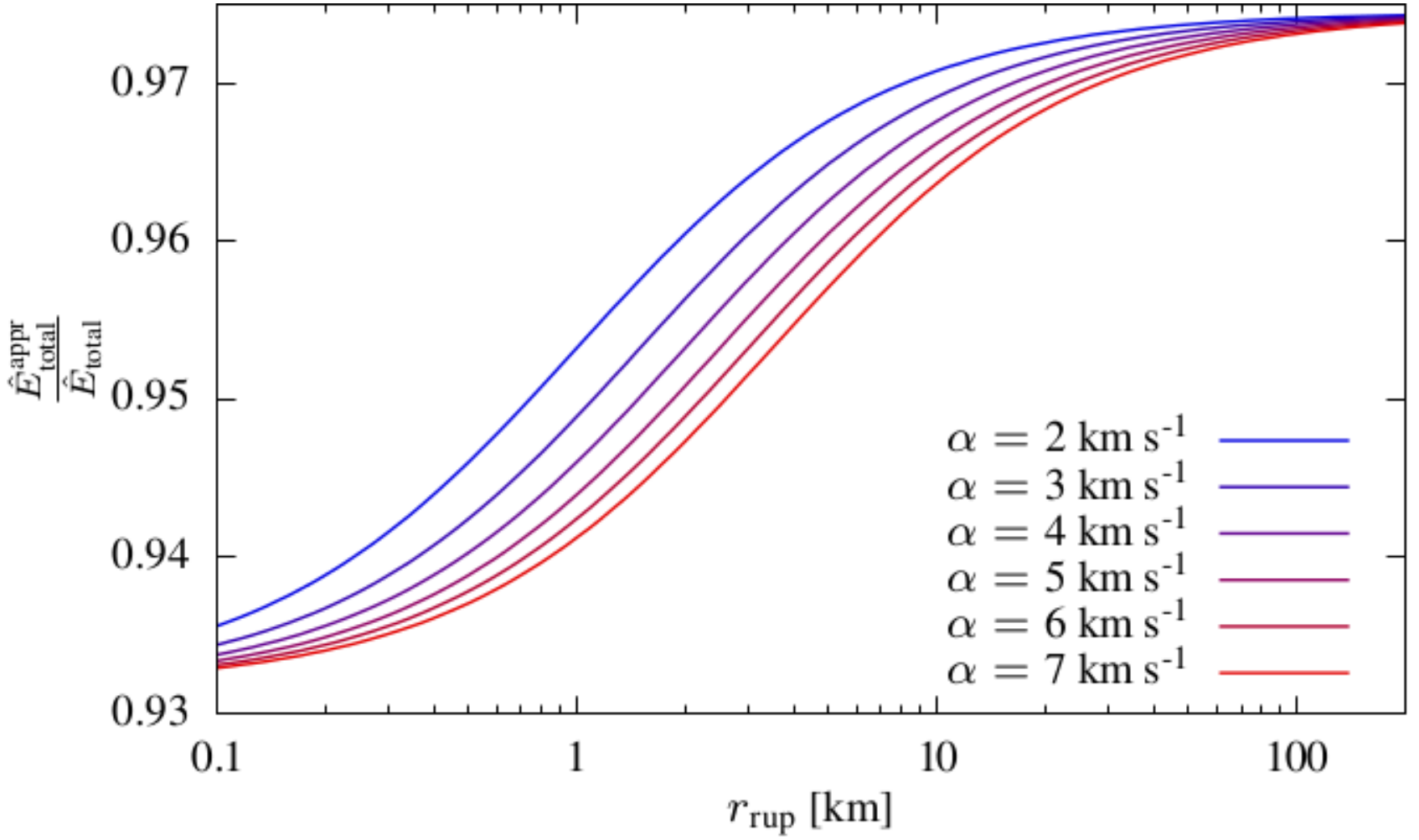

93039
93002
KMM012
Normal
Parallel
Rupture propagation
Northing [m]
Easting [m]
Acceleration [m s^{-2}]
3675000
3650000
3625000
3600000
625000
650000
675000
700000
725000
3
2
1
0
−1
−2
−3

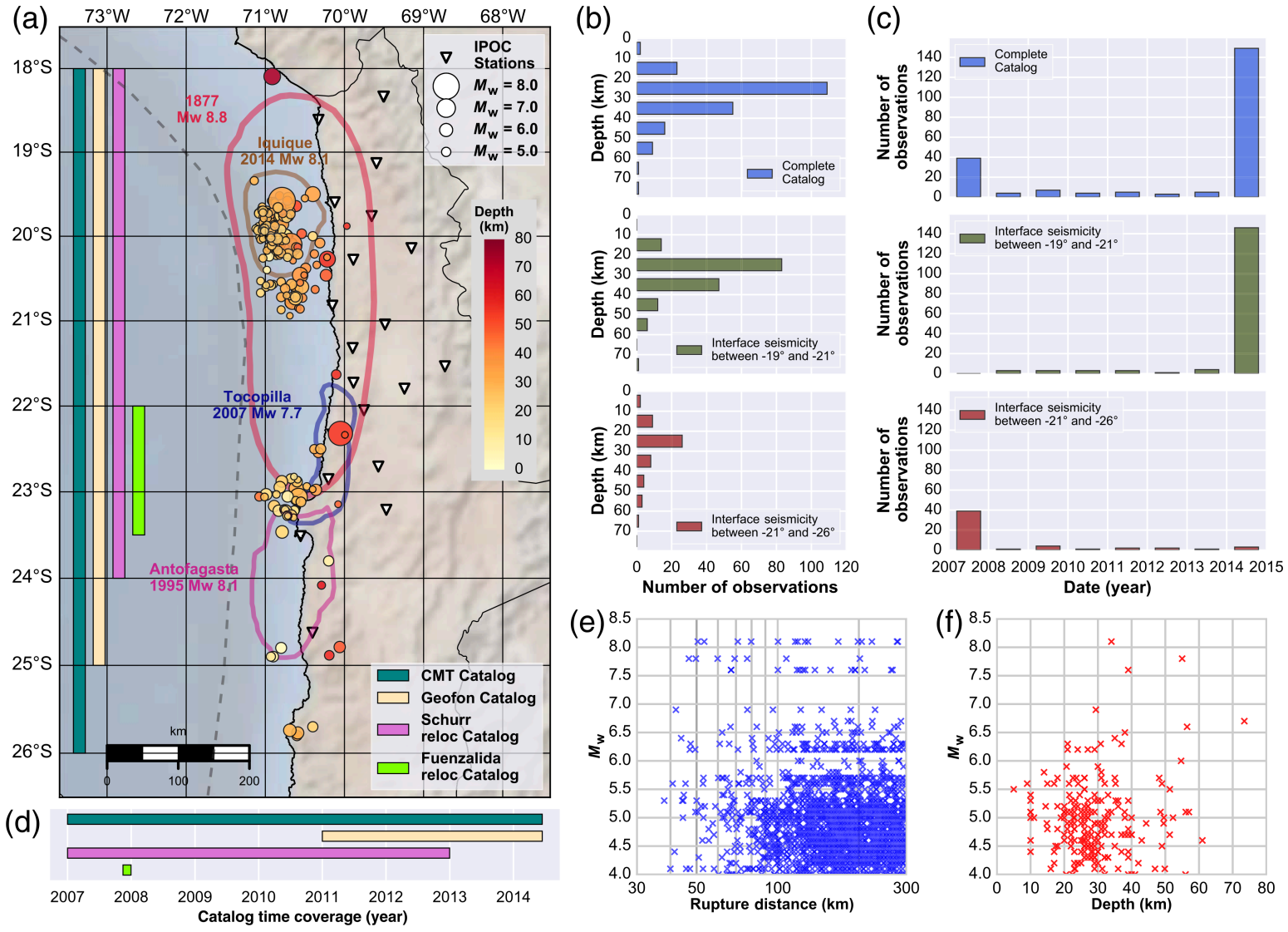

(a)
Data
Running average ($\hat{E}$)
Model with directivity
Model without directivity
Landslide concentration
$\hat{E}$ [J]
$\hat{E}_{0°}$
$\hat{E}_{90°}$
$\hat{E}_{180°}$
10^{16}
10^{15}
10^{14}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
Landslide concentration $\left[\frac{m^2}{km^2}\right]$
0°
90°
180°
270°
360°
θ
(b)
Data
Running average ($I_{A,A}$)
Model with directivity
Model without directivity
Landslide concentration
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{11}
10^{10}
10^{9}
$I_{A,A}$ $\left[\frac{m^3}{s}\right]$
0°
90°
180°
270°
360°
θ

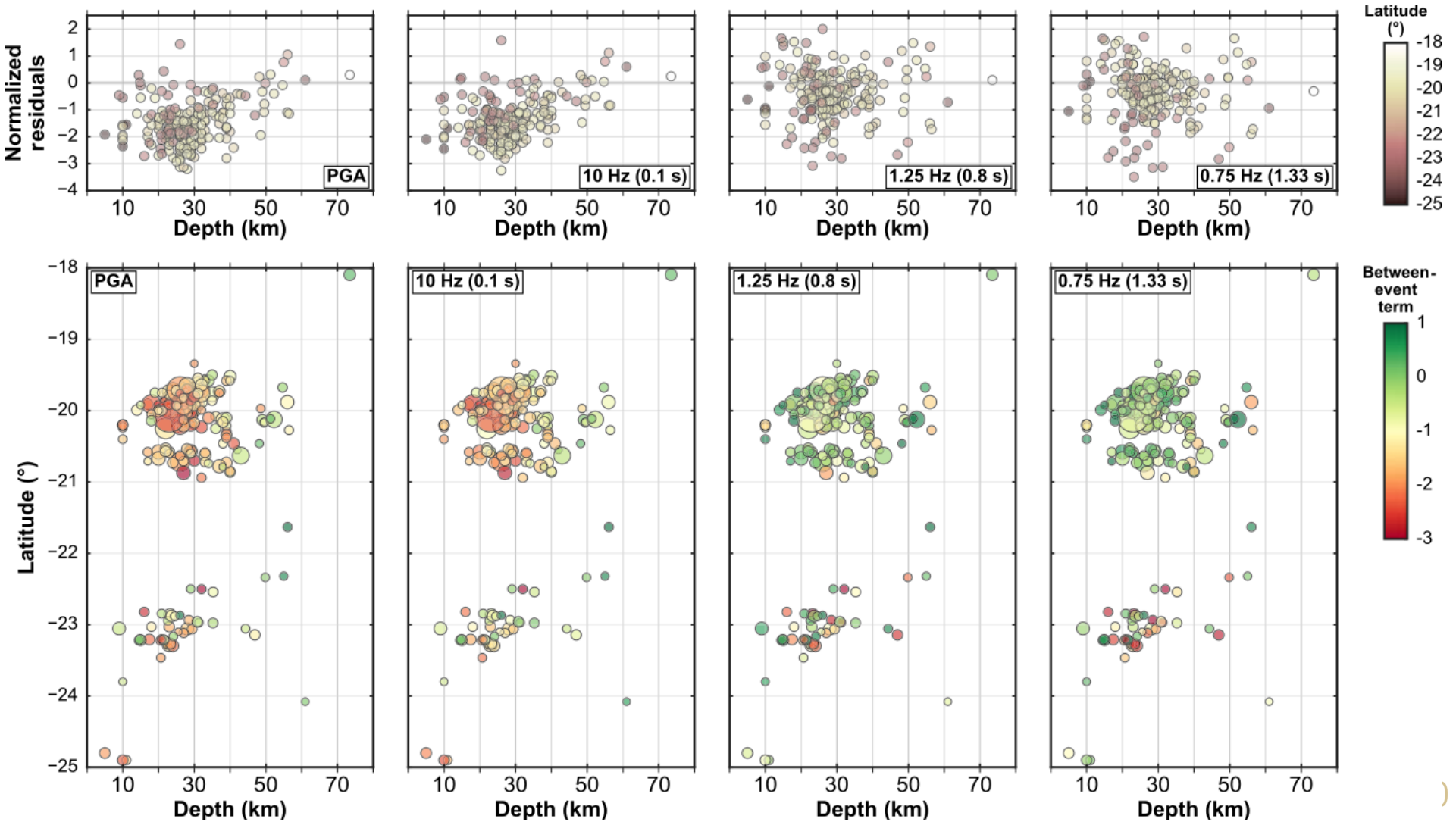

Normalized density
0.0
0.2
0.4
0.6
0.8
1.0
This study
Uncertainty (±σ)
Somerville et al. (1997)
Uncertainty (±σ)
200
150
100
50
FN/FP [%]
0.1
1
10
Osc. frequency [Hz]

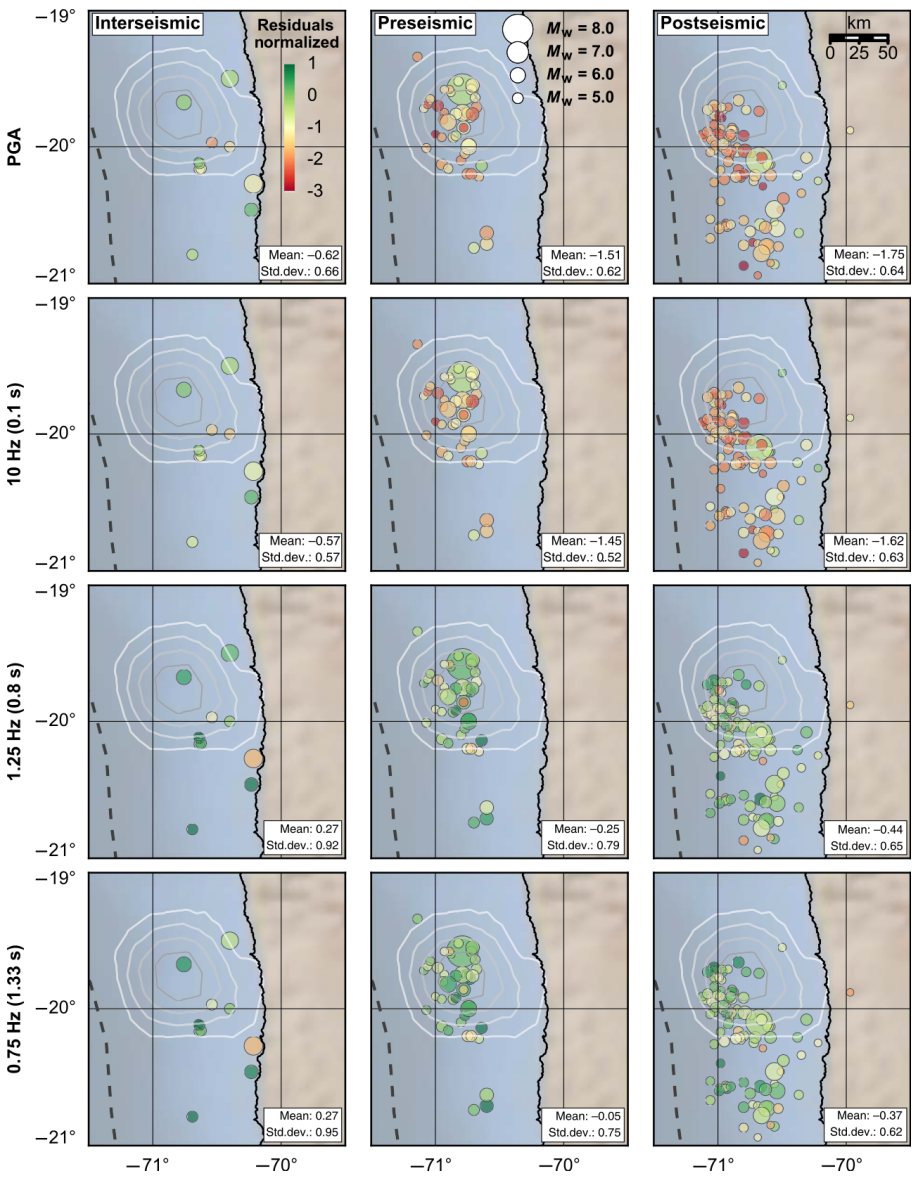

(a)
0°
Aspect
300°
60°
240°
120°
180°
Fault normal
Earthquake strike
Slope
60°
30°
0°
5
4
3
2
1
0
Landslide concentration $\left[1000 \times \frac{m^2}{km^2}\right]$
(b)
0°
300°
60°
240°
120°
180°
60°
30°
0°
0.3
0.2
0.1
0.0
Area density
(c)
0°
300°
60°
240°
120°
180°
60°
30°
0°
32
24
16
8
0
Landslide concentration $\left[1000 \times \frac{m^2}{km^2}\right]$

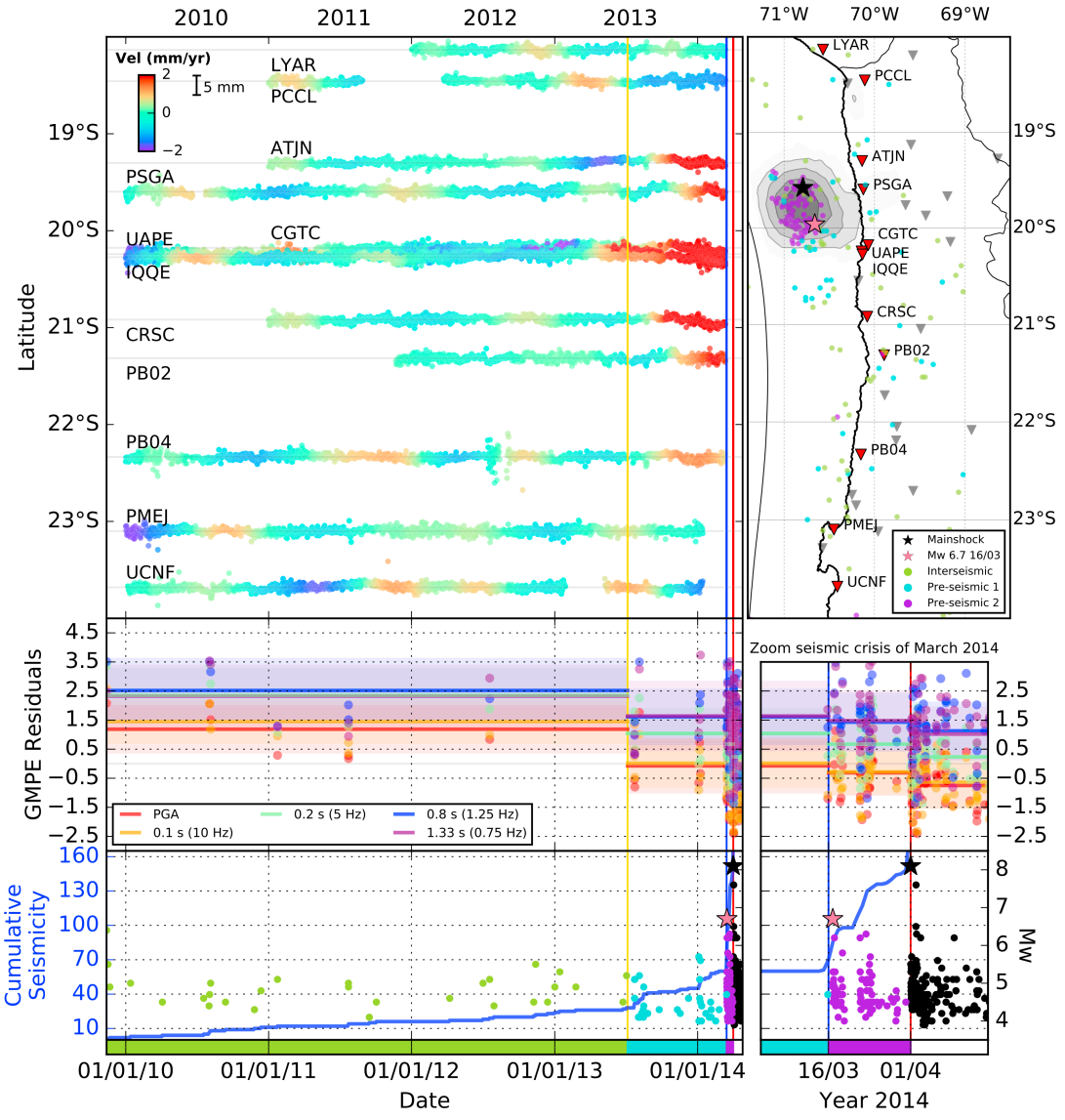

Landslide concentration
Running average (I_A)
Model with M_W
Model with $\hat{E}$
Data
I_A [m/s]
$\hat{E}$ [J]
Landslide concentration [m²/km²]
r_{rup} [m]
$\hat{E}_{0°}$
$\hat{E}_{90°}$
$\hat{E}_{180°}$
Model by Harp and Wilson (1995)
M_W = 7.1, h = 11 km
r_{JB} [m]

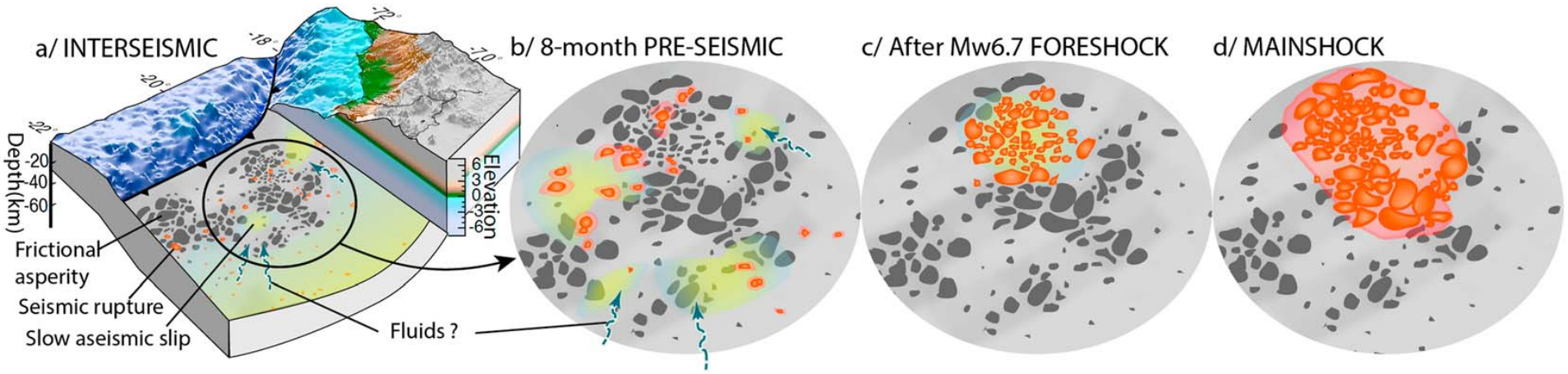

0.97
0.96
0.95
0.94
0.93
$\frac{\hat{E}_{\text{total}}^{\text{appr}}}{\hat{E}_{\text{total}}}$
0.1
1
10
100
r_{rup} [km]
$\alpha = 2$ km s^{-1}
$\alpha = 3$ km s^{-1}
$\alpha = 4$ km s^{-1}
$\alpha = 5$ km s^{-1}
$\alpha = 6$ km s^{-1}
$\alpha = 7$ km s^{-1}

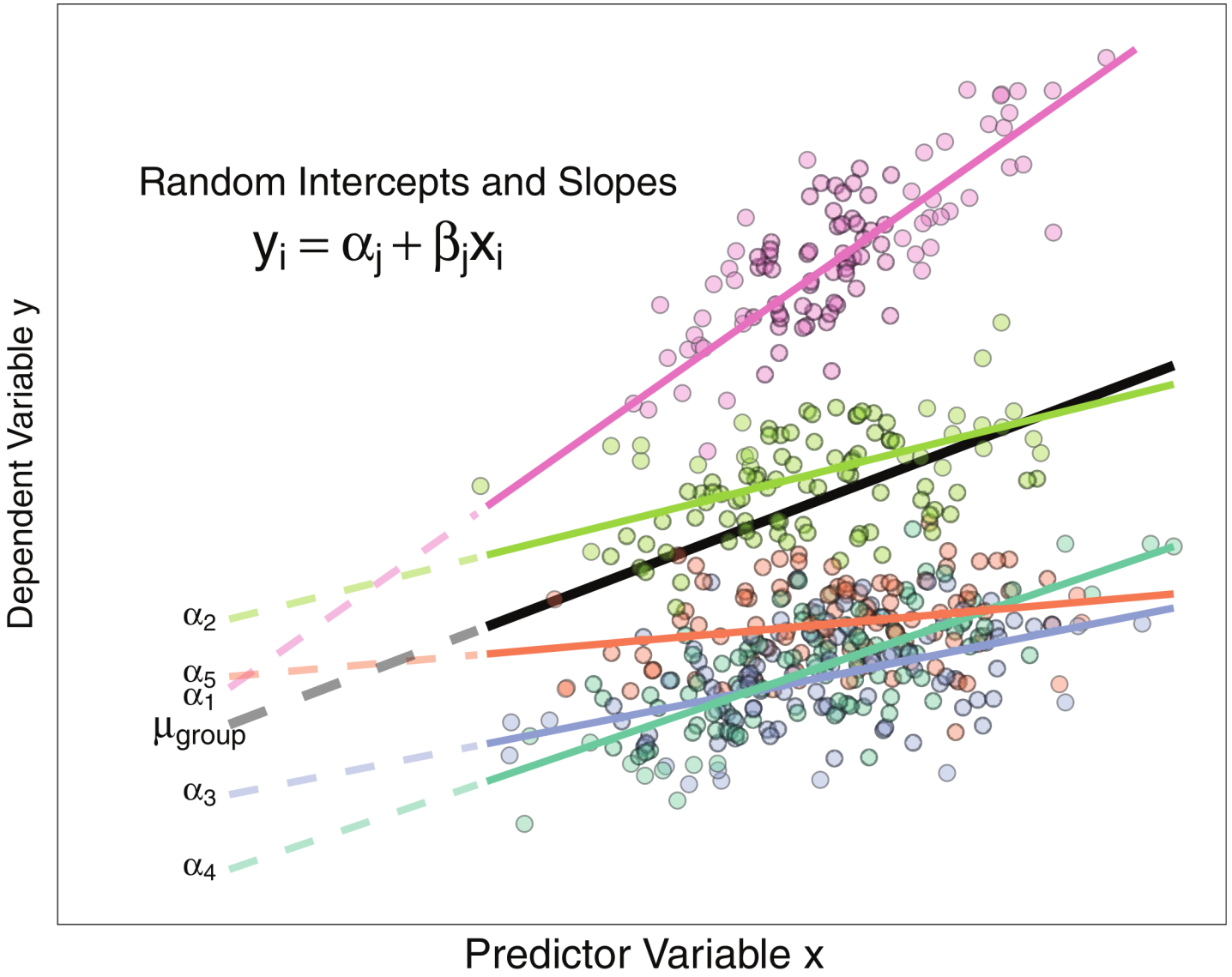

(a)
73°W
72°W
71°W
70°W
69°W
68°W
18°S
19°S
20°S
21°S
22°S
23°S
24°S
25°S
26°S
IPOC Stations
M_w = 8.0
M_w = 7.0
M_w = 6.0
M_w = 5.0
1877 Mw 8.8
Iquique 2014 Mw 8.1
Tocopilla 2007 Mw 7.7
Antofagasta 1995 Mw 8.1
Depth (km)
CMT Catalog
Geofon Catalog
Schurr reloc Catalog
Fuenzalida reloc Catalog
km
0
100
200
(b)
Depth (km)
Complete Catalog
Interface seismicity between -19° and -21°
Interface seismicity between -21° and -26°
Number of observations
(c)
Number of observations
Complete Catalog
Interface seismicity between -19° and -21°
Interface seismicity between -21° and -26°
2007 2008 2009 2010 2011 2012 2013 2014 2015
Date (year)
(d)
2007 2008 2009 2010 2011 2012 2013 2014
Catalog time coverage (year)
(e)
M_w
Rupture distance (km)
(f)
M_w
Depth (km)

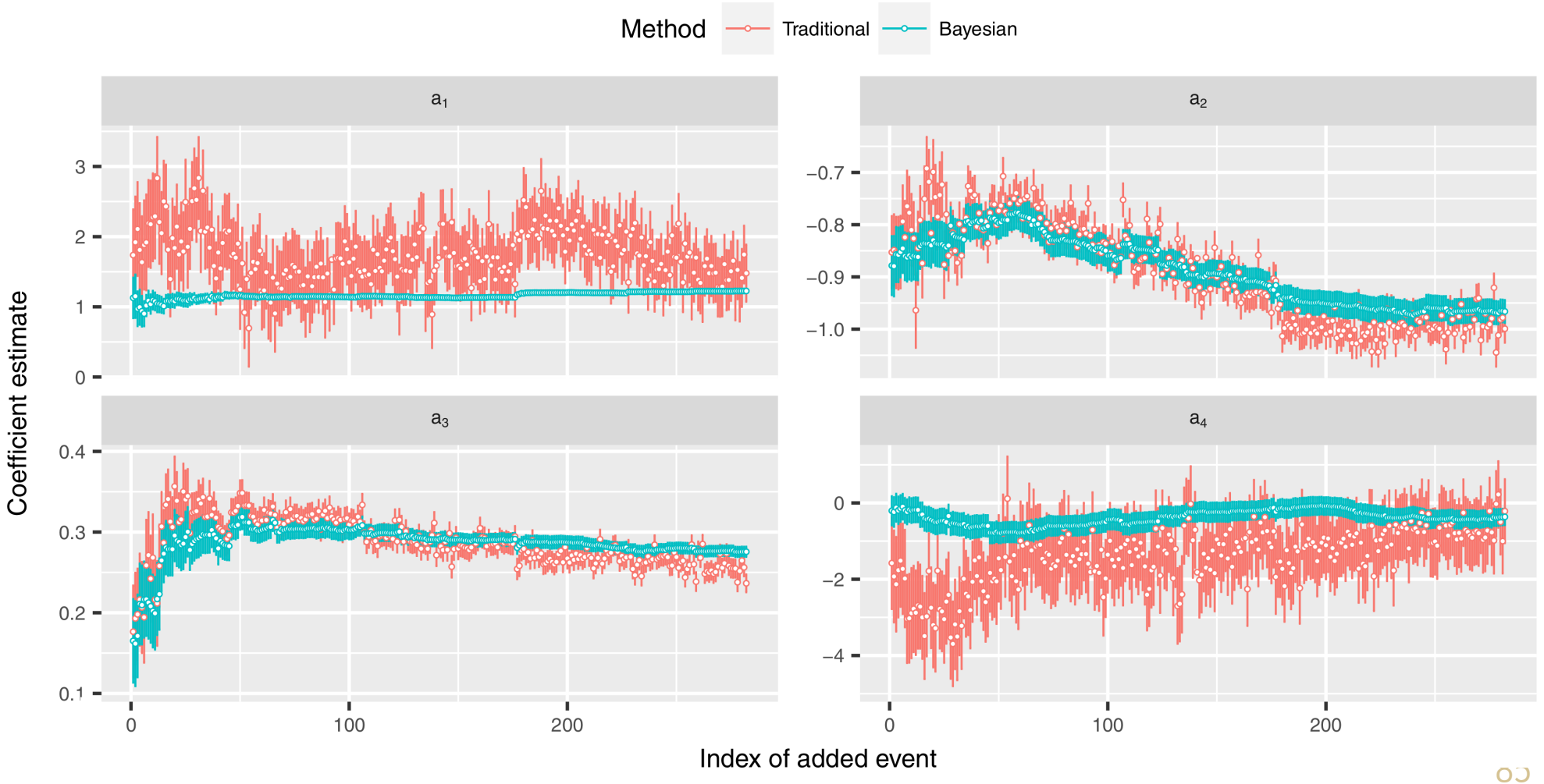

Normalized residuals
PGA
10 Hz (0.1 s)
1.25 Hz (0.8 s)
0.75 Hz (1.33 s)
Depth (km)
Latitude (°)
Between-event term
Latitude (°)

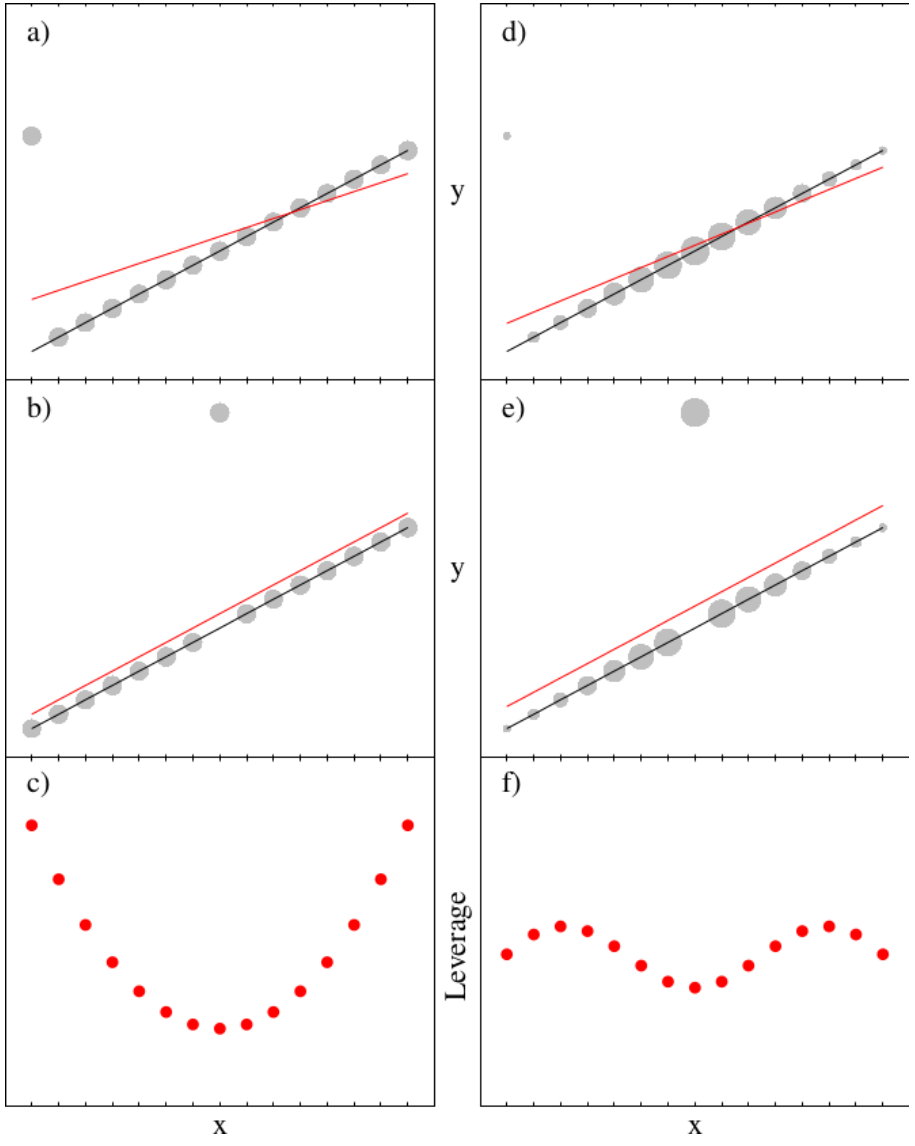

Interseismic
Residuals normalized
1
0
-1
-2
-3
Preseismic
M_w = 8.0
M_w = 7.0
M_w = 6.0
M_w = 5.0
Postseismic
km
0 25 50
PGA
10 Hz (0.1 s)
1.25 Hz (0.8 s)
0.75 Hz (1.33 s)
−19°
−20°
−21°
−71°
−70°
Mean: −0.62
Std.dev.: 0.66
Mean: −1.51
Std.dev.: 0.62
Mean: −1.75
Std.dev.: 0.64
Mean: −0.57
Std.dev.: 0.57
Mean: −1.45
Std.dev.: 0.52
Mean: −1.62
Std.dev.: 0.63
Mean: 0.27
Std.dev.: 0.92
Mean: −0.25
Std.dev.: 0.79
Mean: −0.44
Std.dev.: 0.65
Mean: 0.27
Std.dev.: 0.95
Mean: −0.05
Std.dev.: 0.75
Mean: −0.37
Std.dev.: 0.62

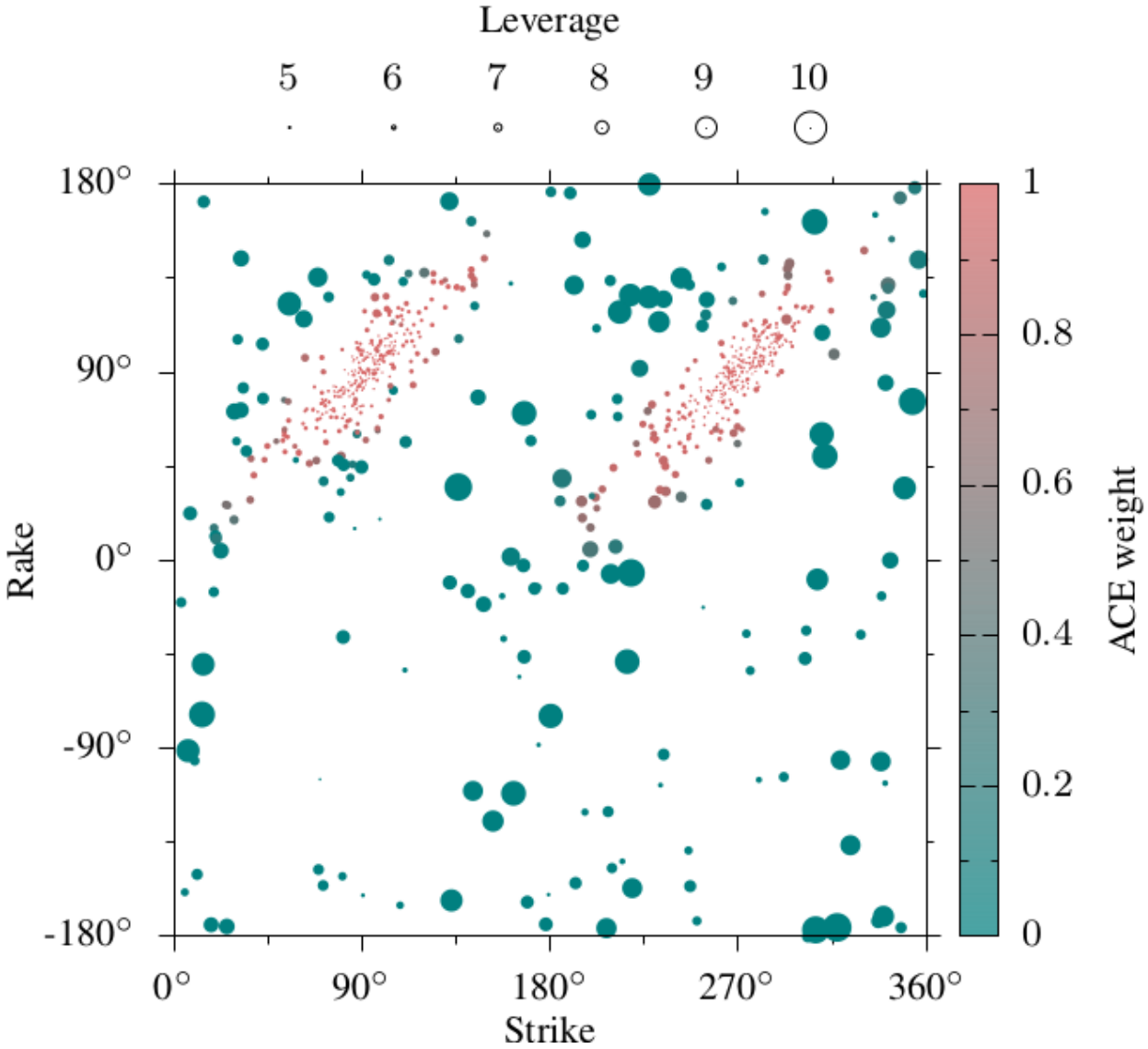

2010
2011
2012
2013
Vel (mm/yr)
2
0
−2
5 mm
LYAR
PCCL
ATJN
PSGA
CGTC
UAPE
IQQE
CRSC
PB02
PB04
PMEJ
UCNF
Latitude
19°S
20°S
21°S
22°S
23°S
71°W
70°W
69°W
Mainshock
Mw 6.7 16/03
Interseismic
Pre-seismic 1
Pre-seismic 2
GMPE Residuals
PGA
0.1 s (10 Hz)
0.2 s (5 Hz)
0.8 s (1.25 Hz)
1.33 s (0.75 Hz)
Cumulative Seismicity
Zoom seismic crisis of March 2014
Mw
01/01/10
01/01/11
01/01/12
01/01/13
01/01/14
Date
16/03
01/04
Year 2014

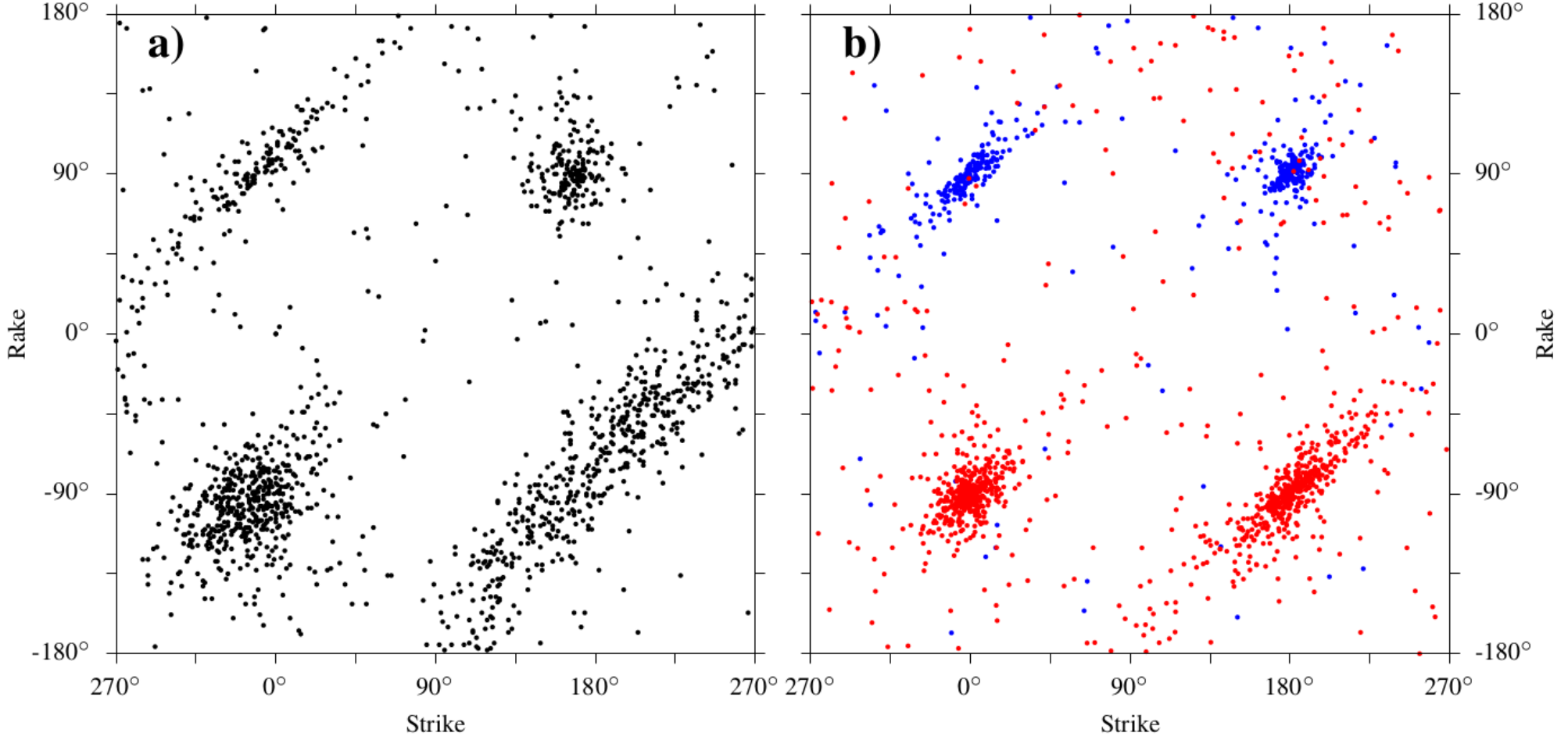

a/ INTERSEISMIC
b/ 8-month PRE-SEISMIC
c/ After Mw6.7 FORESHOCK
d/ MAINSHOCK
Depth(km)
-20
-40
-60
Elevation
6000
-6
Frictional asperity
Seismic rupture
Slow aseismic slip
Fluids ?

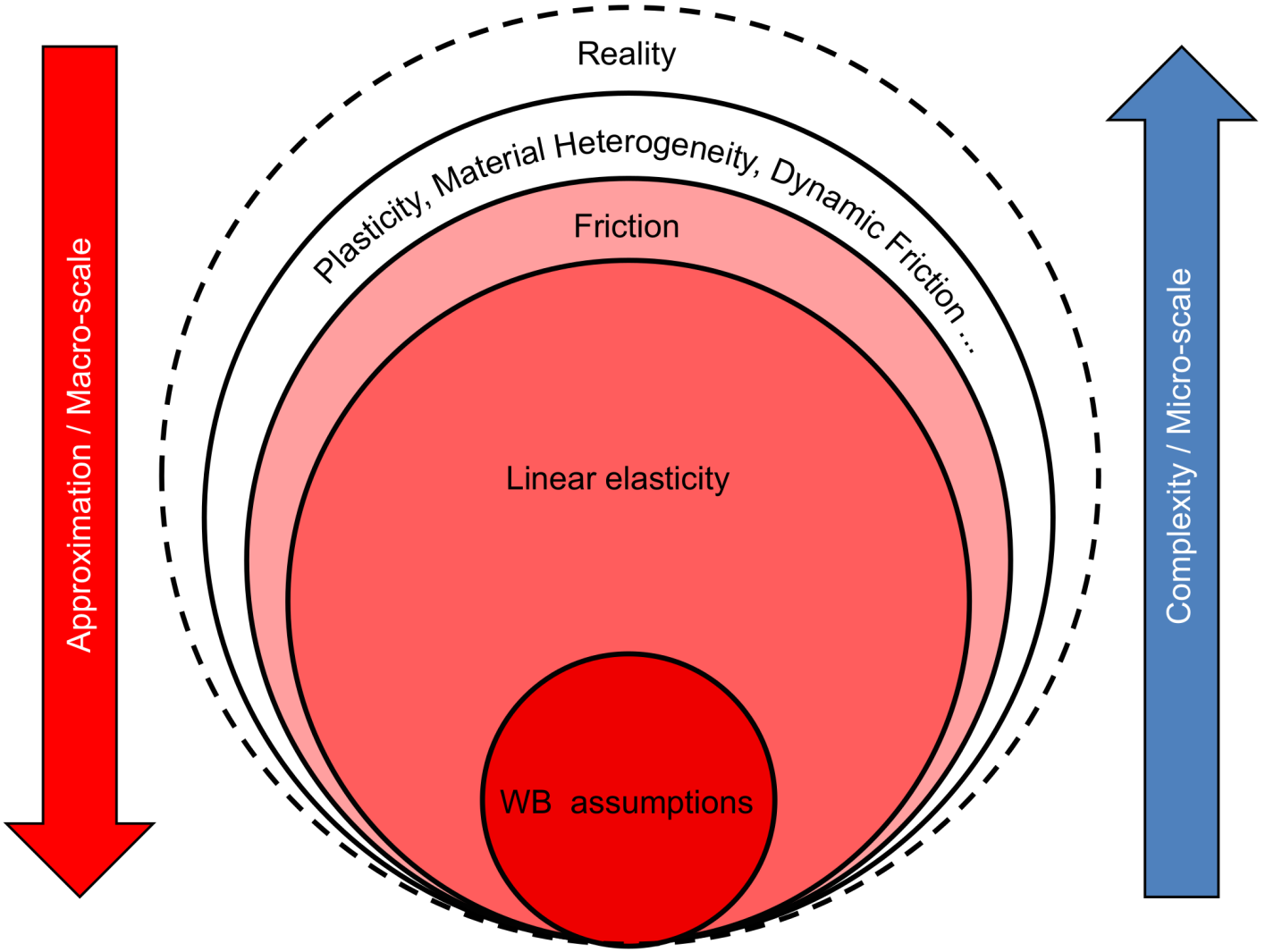

Random Intercepts and Slopes
$y_i = \alpha_j + \beta_j x_i$
Dependent Variable y
Predictor Variable x
α_2
α_5
α_1
μ_{group}
α_3
α_4

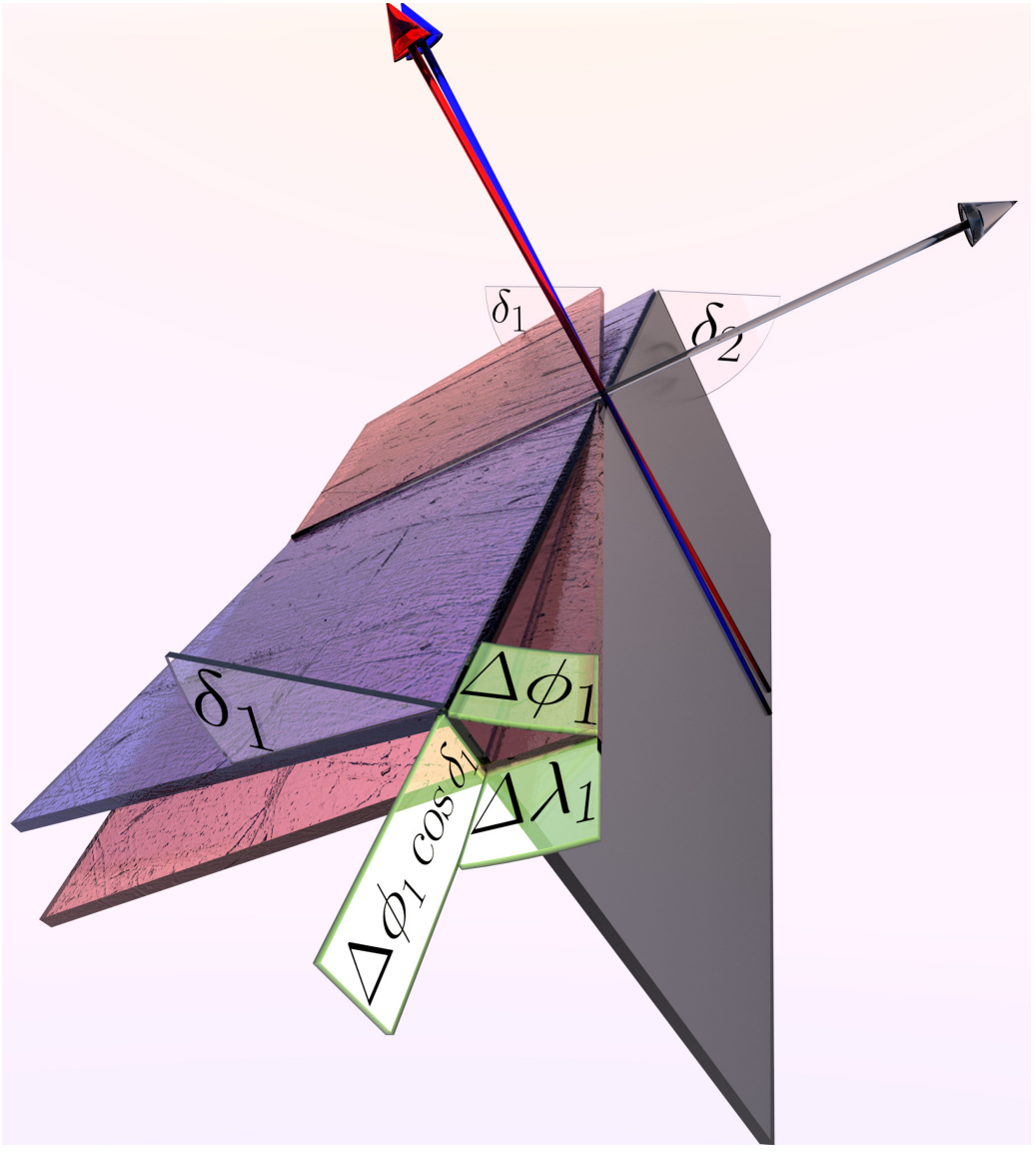

Method
Traditional
Bayesian
a_1
a_2
a_3
a_4
Coefficient estimate
Index of added event
3
2
1
0
−0.7
−0.8
−0.9
−1.0
0.4
0.3
0.2
0.1
0
−2
−4
0
100
200

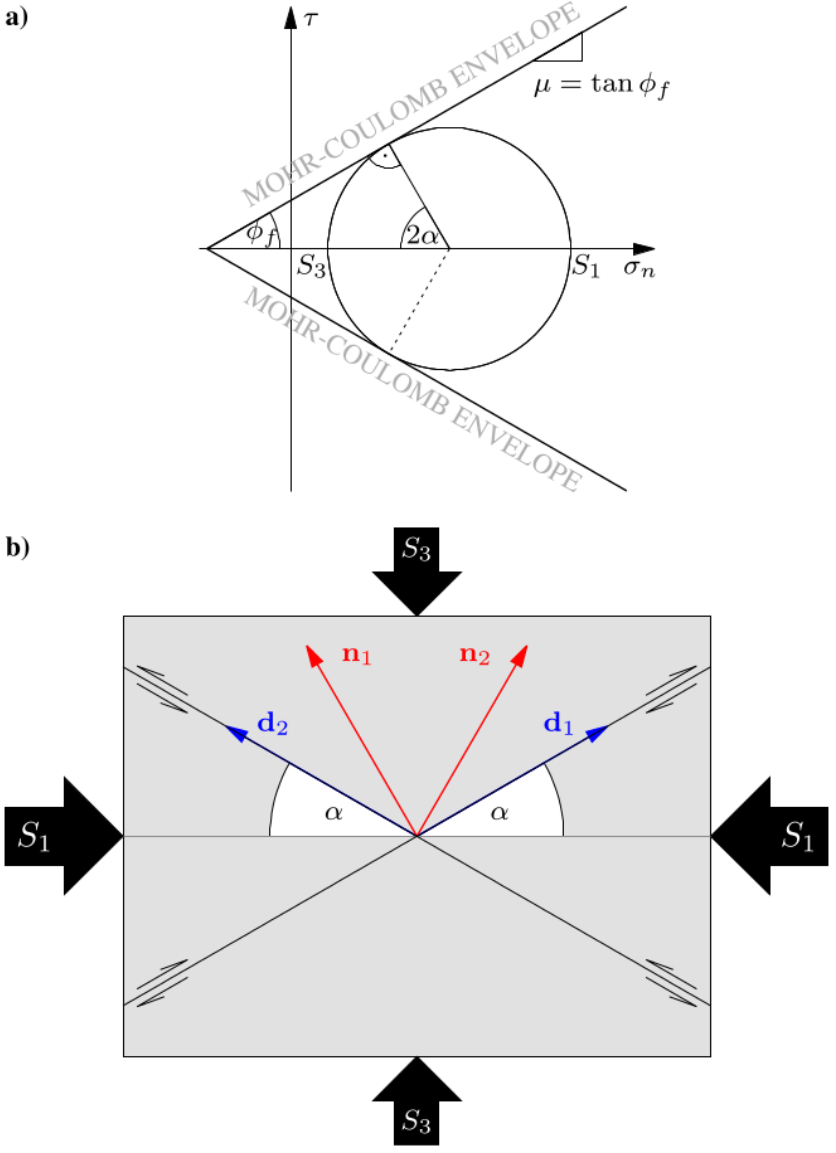

a)
b)
c)
d)
e)
f)
y
y
Leverage
x
x

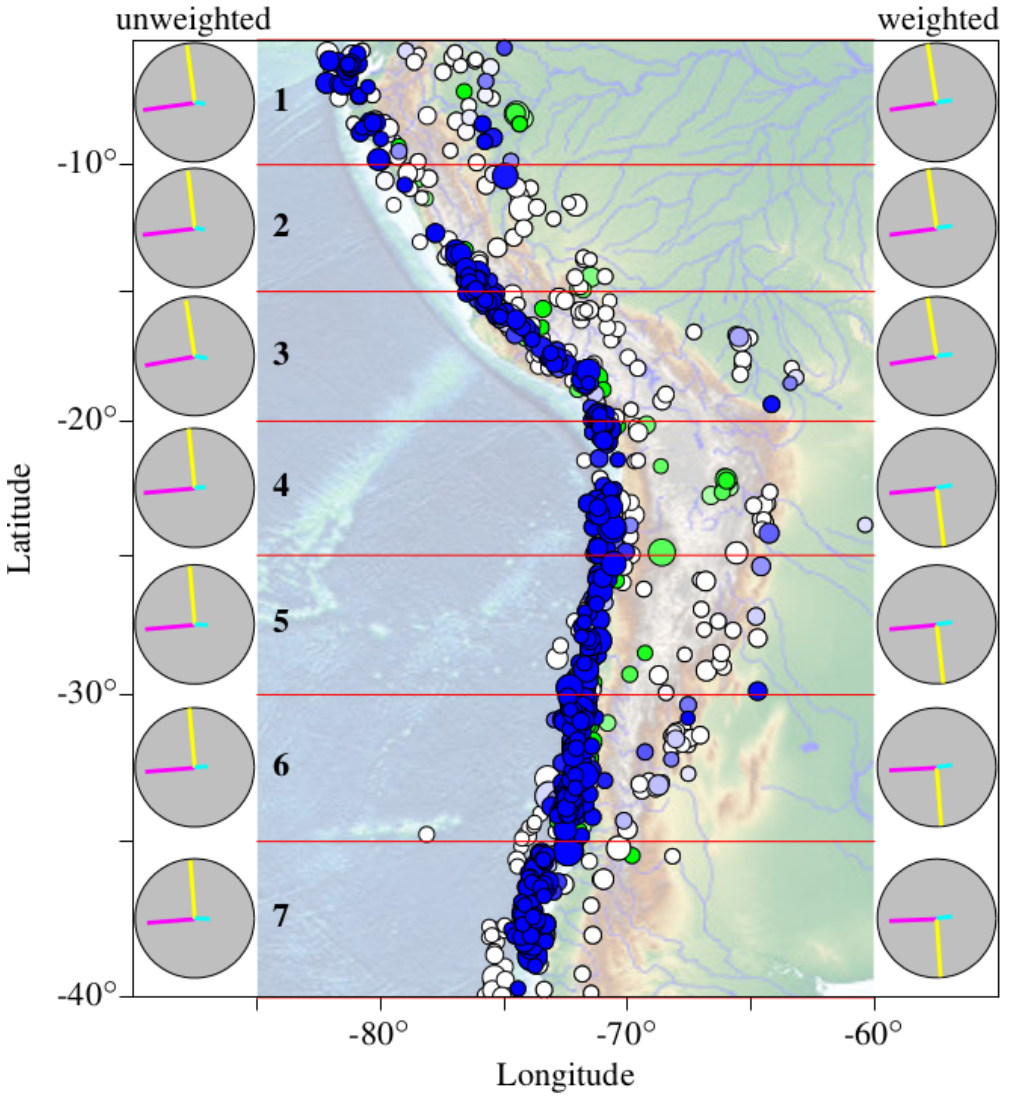

Leverage
5
6
7
8
9
10
180°
90°
0°
-90°
-180°
Rake
0°
90°
180°
270°
360°
Strike
1
0.8
0.6
0.4
0.2
0
ACE weight

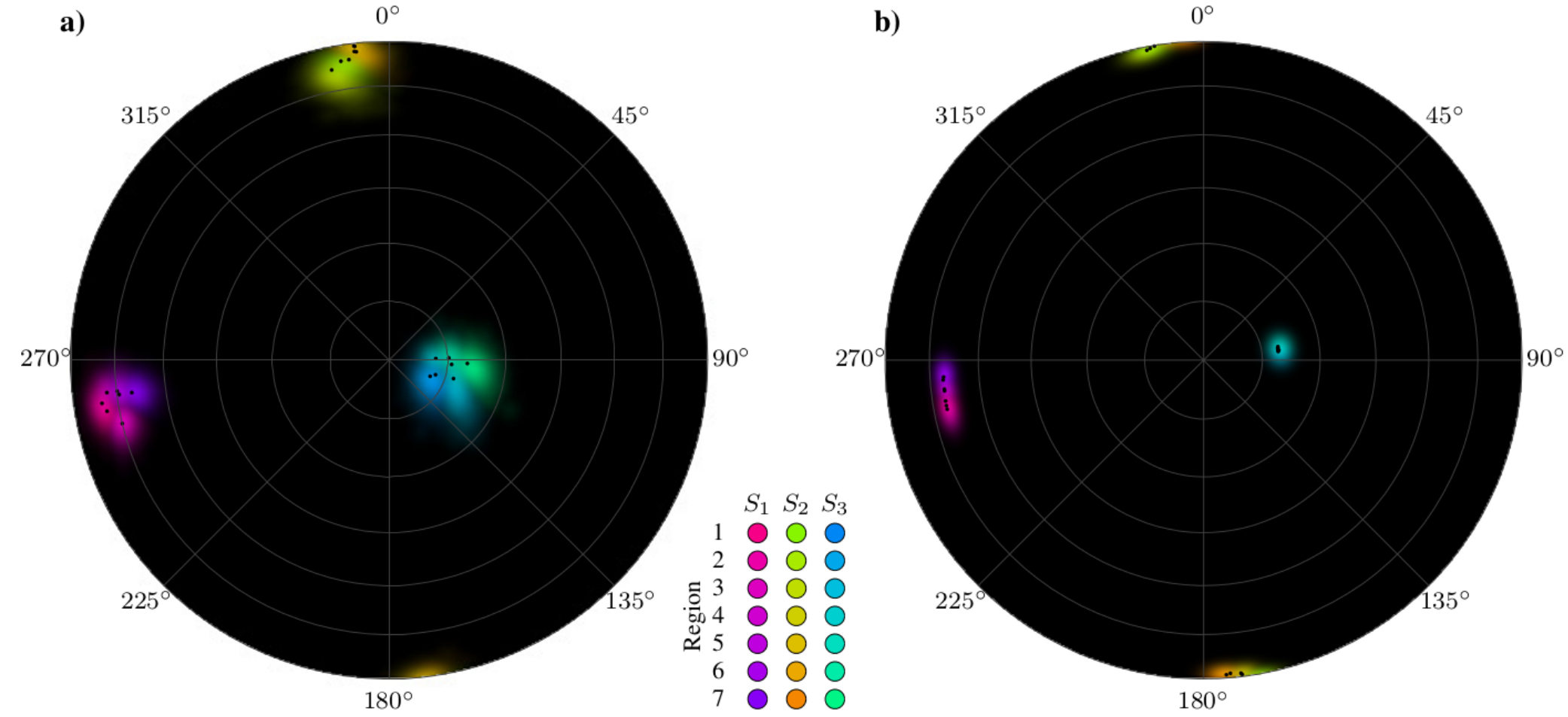

a)
b)
180°
90°
0°
-90°
-180°
Rake
270°
0°
90°
180°
270°
Strike

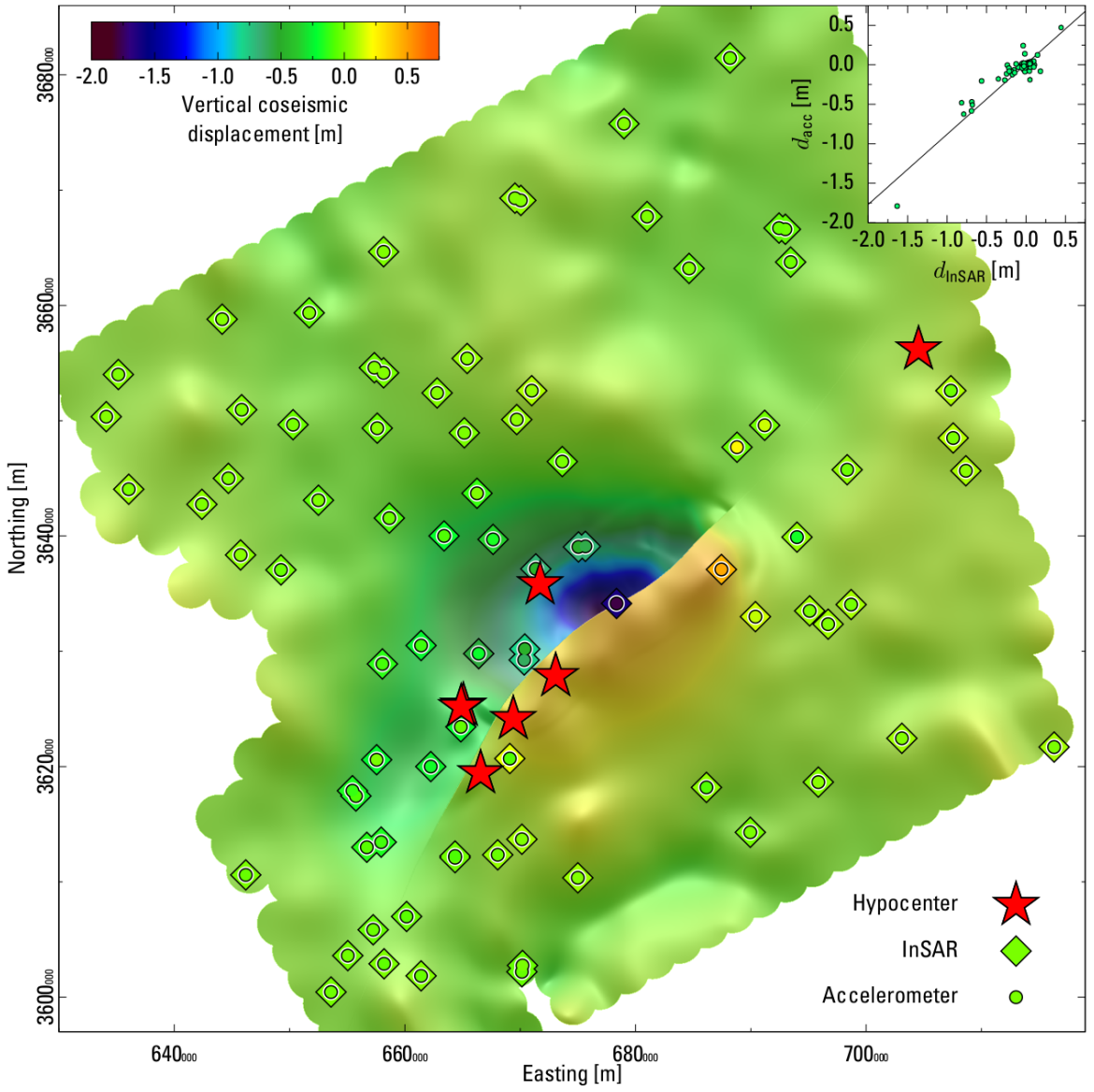

Reality
Plasticity, Material Heterogeneity, Dynamic Friction ...
Friction
Linear elasticity
WB assumptions
Approximation / Macro-scale
Complexity / Micro-scale


δ_1
δ_2
δ_1
$\Delta\phi_1$
$\Delta\phi_1 \cos\delta_1$
$\Delta\lambda_1$

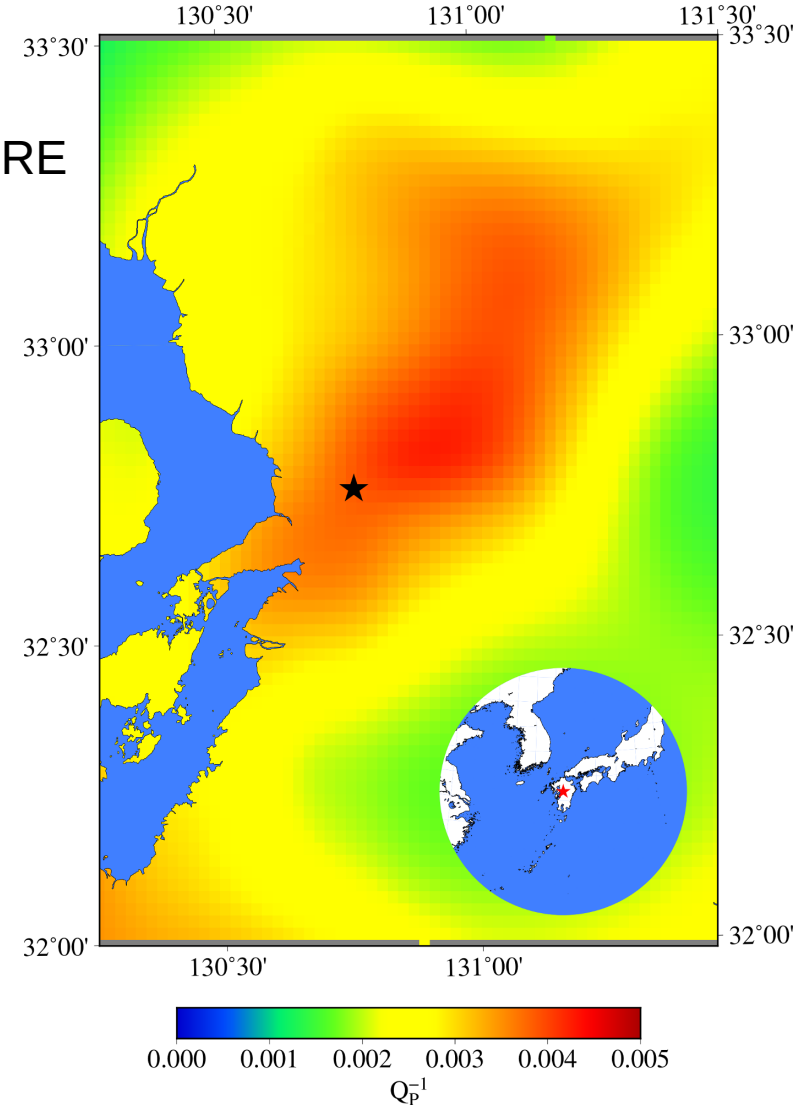

a)
τ
MOHR-COULOMB ENVELOPE
$\mu = \tan \phi_f$
ϕ_f
2α
S_3
S_1
σ_n
MOHR-COULOMB ENVELOPE
b)
S_3
$\mathbf{n}_1$
$\mathbf{n}_2$
$\mathbf{d}_2$
$\mathbf{d}_1$
α
α
S_1
S_1
S_3


unweighted
weighted
1
2
3
4
5
6
7
-10°
-20°
-30°
-40°
Latitude
-80°
-70°
-60°
Longitude


a)
b)
0°
45°
90°
135°
180°
225°
270°
315°
S_1 S_2 S_3
Region
1
2
3
4
5
6
7


-2.0 -1.5 -1.0 -0.5 0.0 0.5
Vertical coseismic displacement [m]
0.5 0.0 -0.5 -1.0 -1.5 -2.0
d_{acc} [m]
-2.0 -1.5 -1.0 -0.5 0.0 0.5
d_{InSAR} [m]
Hypocenter
InSAR
Accelerometer
Northing [m]
3680000
3660000
3640000
3620000
3600000
640000
660000
680000
700000
Easting [m]

BEFORE



AFTER