The inverse problem of earthquake source mechanics with several applications

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Cargèse May 2007

The inverse problem of earthquake source mechanics :

Given a set of seismograms, find the details of the earthquake rupture process

$$u_k(\mathbf{x}_1, t_1) = \int_0^{t_1} dt \iint_\Sigma K_{ik}(\mathbf{x}_1, \mathbf{x}, t_1, t) \dot{a}_i(\mathbf{x}, t) dS$$

Seismogram = Green function kernel * slip rate

*** means space-time convolution**

The method of inversion is fully described in Das & Kostrov (JGR, 1990; PEPI, 1994) with all relevant equations fully written out

$$\mathbf{A}\,\underline{x} = \underline{b}$$

min ℓ_1 *norm of* $(\mathbf{A}\,\underline{x} - \underline{b}\,) = \underline{r}$

Constraints:

$\underline{x} \geq 0$

$x_i = 0$ for i's prevented from slipping by causality

Additional constraints such as preassigning seismic moment, looking for the smoothest solution that fits the data, etc. are easily incorporated into the method. It results in adding additional equations to the original system.

We shall use the method of Linear Programming to solve the problem.

(See Numerical Recipes by Press et al. 1989 for a simple version of the program and explanation of details of the method)

Synthetic tests:

Artificial data is constructed for some chosen rupture process and the data inverted using the *same* station distribution as would be used to invert the real data, giving us insight into the inversion – many tens of such tests are carried out.

Robustness tests

We test the preferred solution in the following way:

If we have a region of high (or low) slip,can we try to reduce (or increase) the slip in that region and still fit the data. This again leads to additional equations in our original system of equations. We even find the fault shape and area in this way.

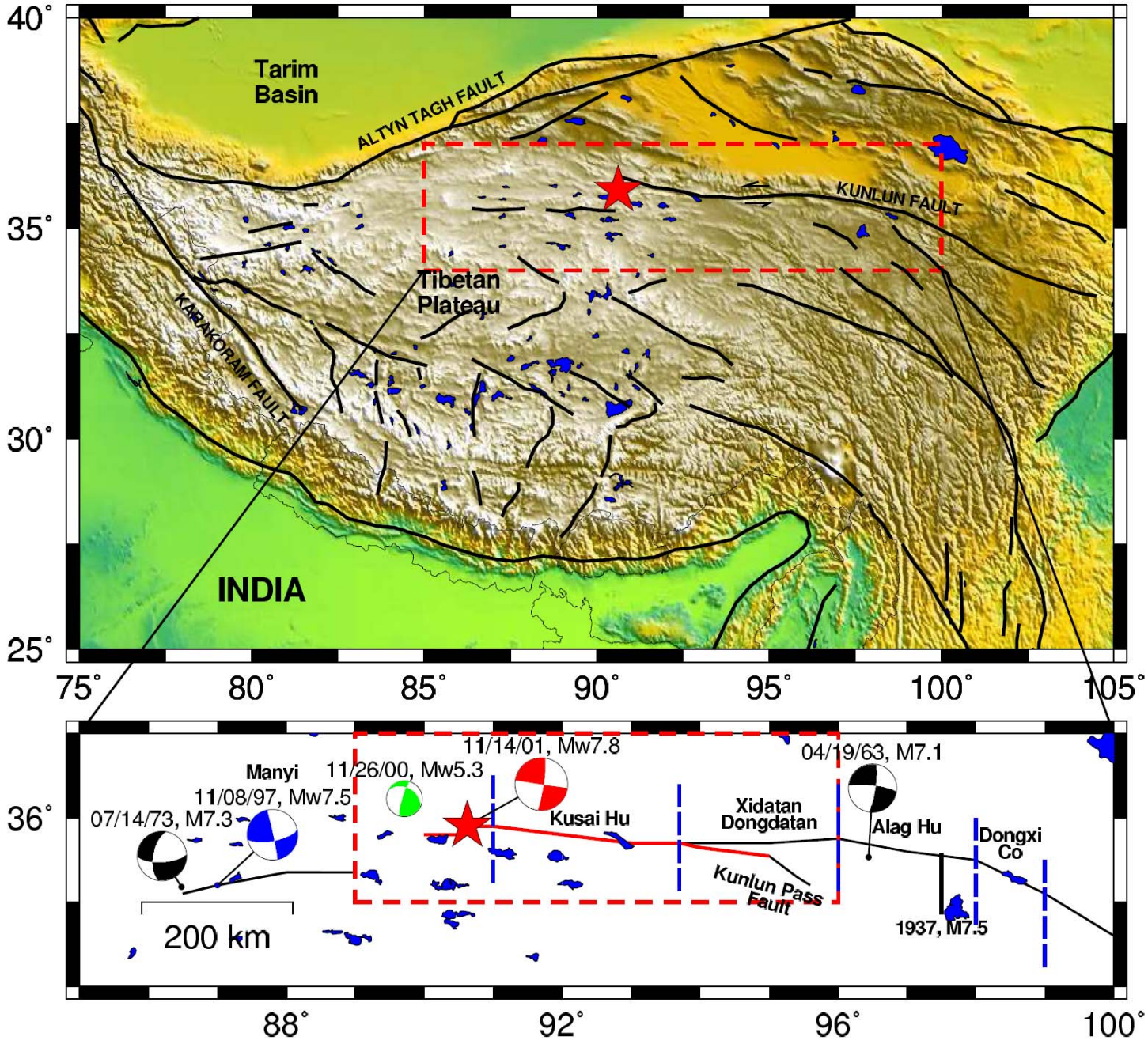
Robustness tests (contd)

If we have a very high rupture speed, we test if we can decrease it *and still fit the data*, and so on, testing all interesting aspects of the solution

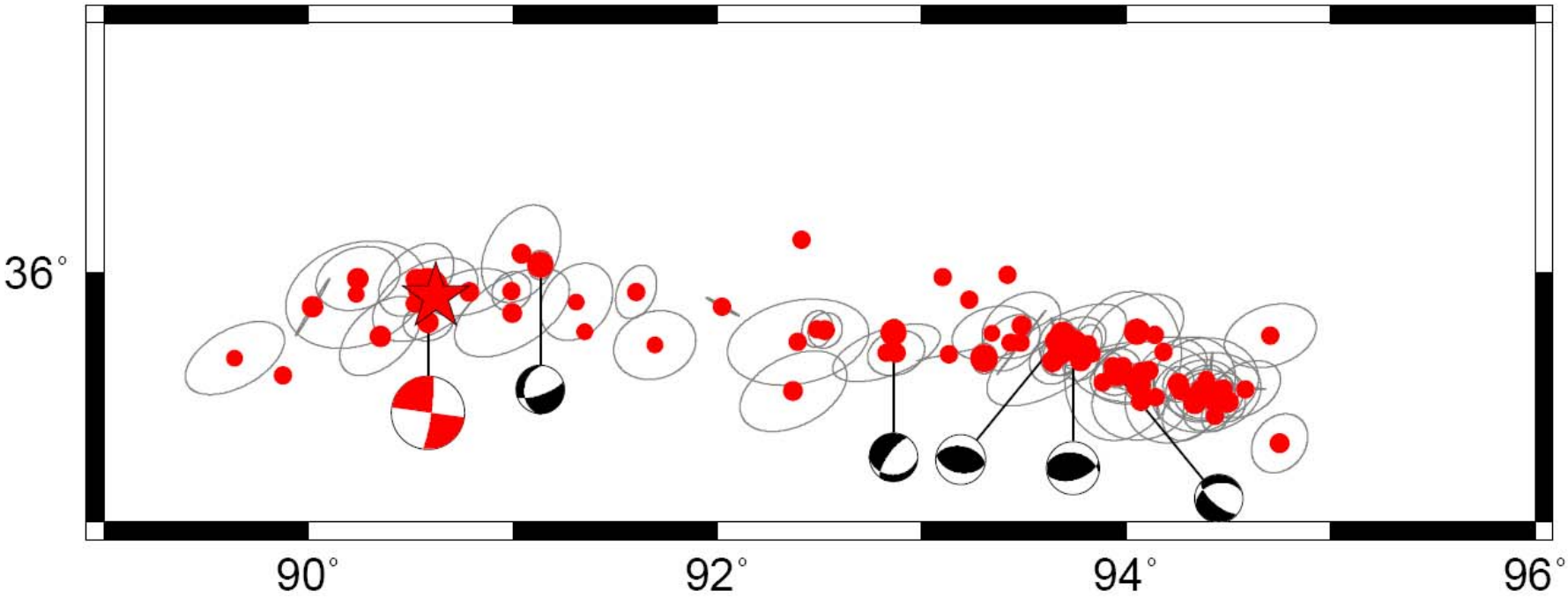
Unlike other methods of inversion, we allow the *entire* region behind the main rupture front to slip, if the data requires it. This is important to find if there is slip well behind the main rupture front. Theoretical models showed that such slip is possible.

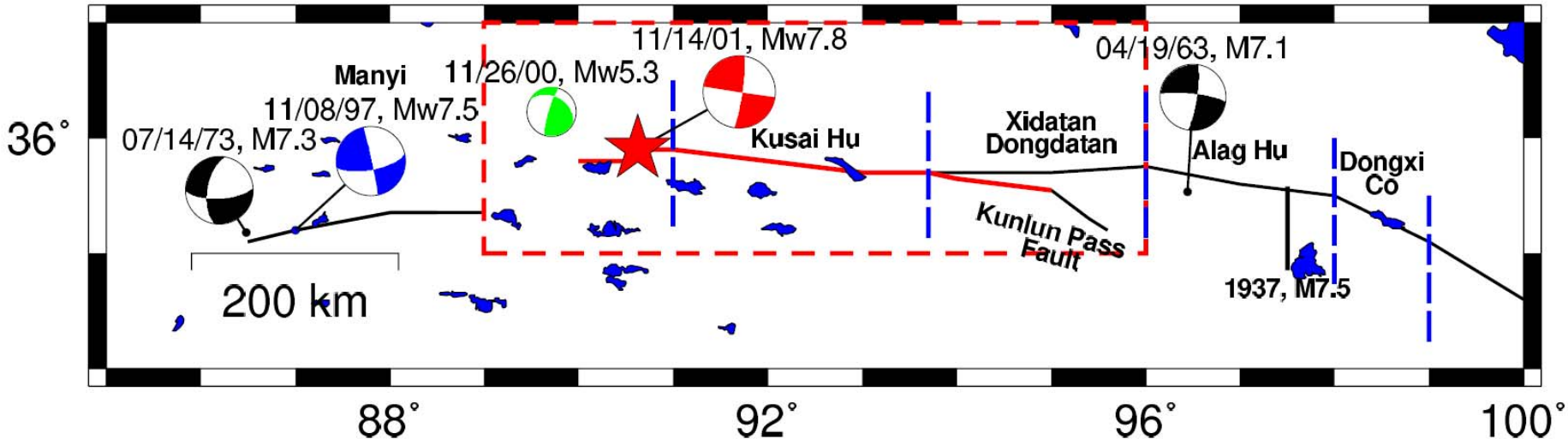
Also, unlike some other studies, we use only pure waves, e.g. when we invert *SH* waves, say, we terminate the seismogram when either *ScS* or *SS* arrive.

The Mw 7.8 2001 Kunlun, Tibet earthquake

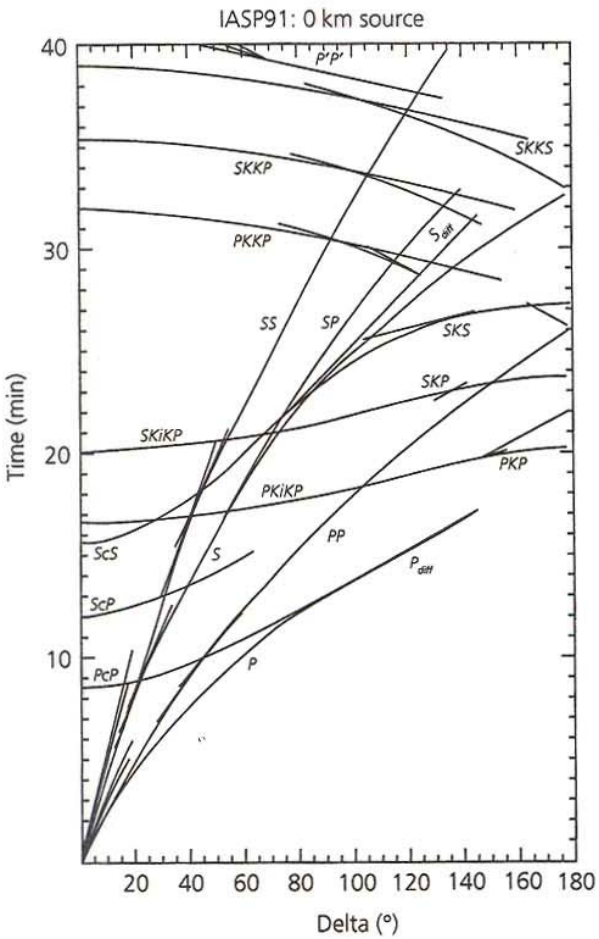

Tarim Basin
ALTYN TAGH FAULT
KUNLUN FAULT
Tibetan Plateau
KARAKORAM FAULT
INDIA
40˚
35˚
30˚
25˚
75˚
80˚
85˚
90˚
95˚
100˚
105˚
11/14/01, Mw7.8
11/26/00, Mw5.3
Manyi
11/08/97, Mw7.5
07/14/73, M7.3
Kusai Hu
Xidatan
Dongdatan
04/19/63, M7.1
Alag Hu
Dongxi Co
Kunlun Pass Fault
1937, M7.5
200 km
36˚
88˚
92˚
96˚
100˚

6-month

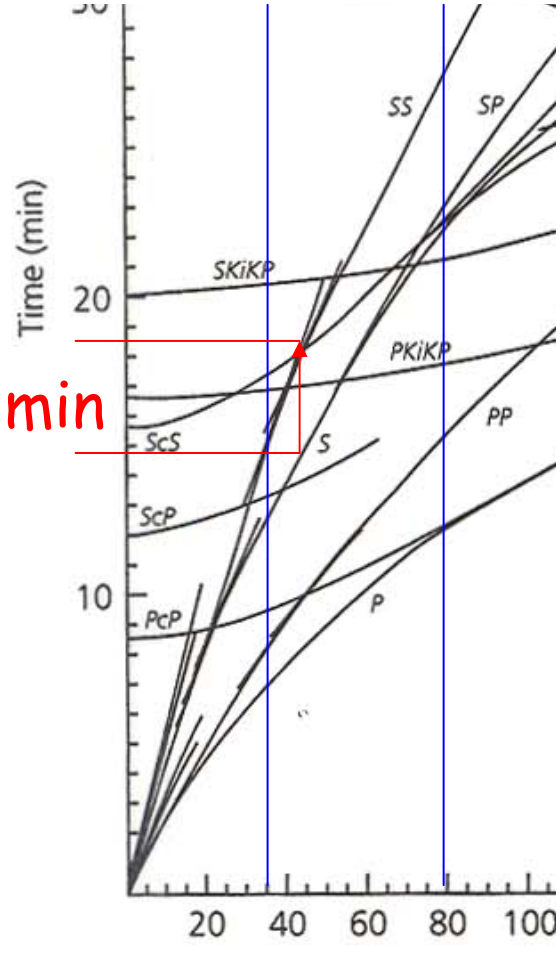



11/14/01, Mw7.8
11/26/00, Mw5.3
Manyi
11/08/97, Mw7.5
07/14/73, M7.3
Kusai Hu
04/19/63, M7.1
Xidatan
Dongdatan
Alag Hu
Dongxi
Co
Kunlun Pass
Fault
1937, M7.5
200 km
36˚
88˚
92˚
96˚
100˚

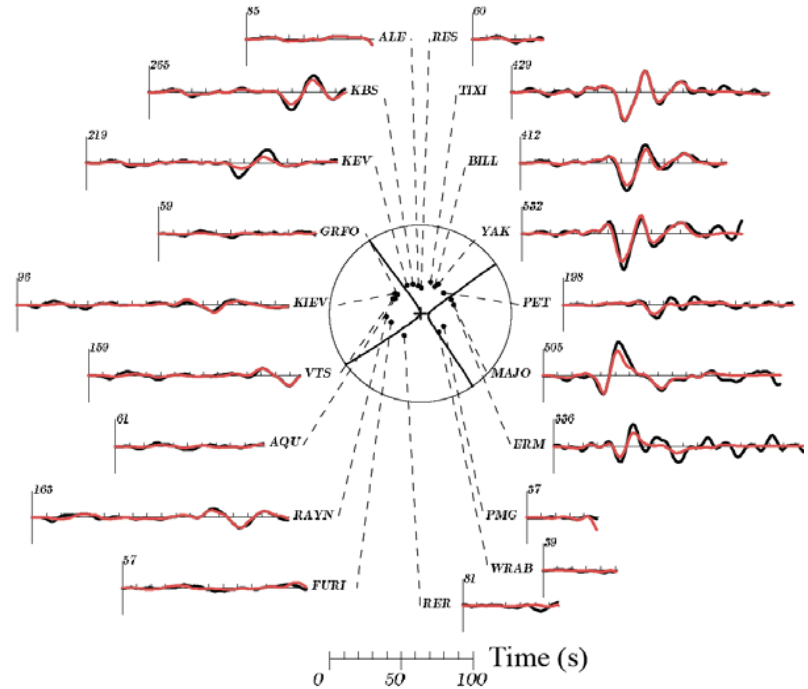
Source Duration Limitations

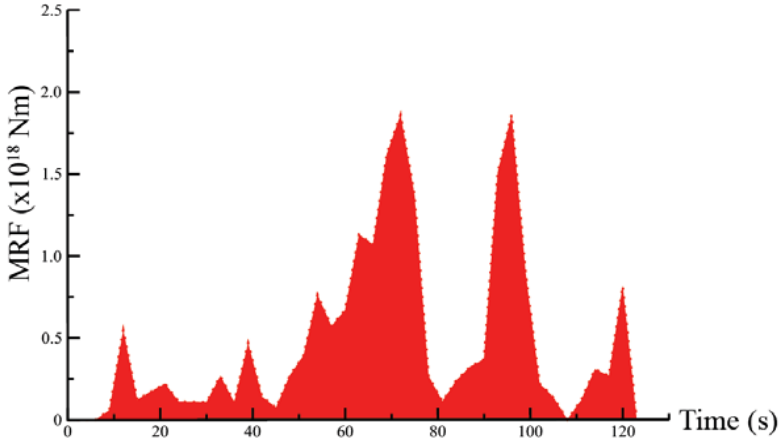


c. 3.5 min

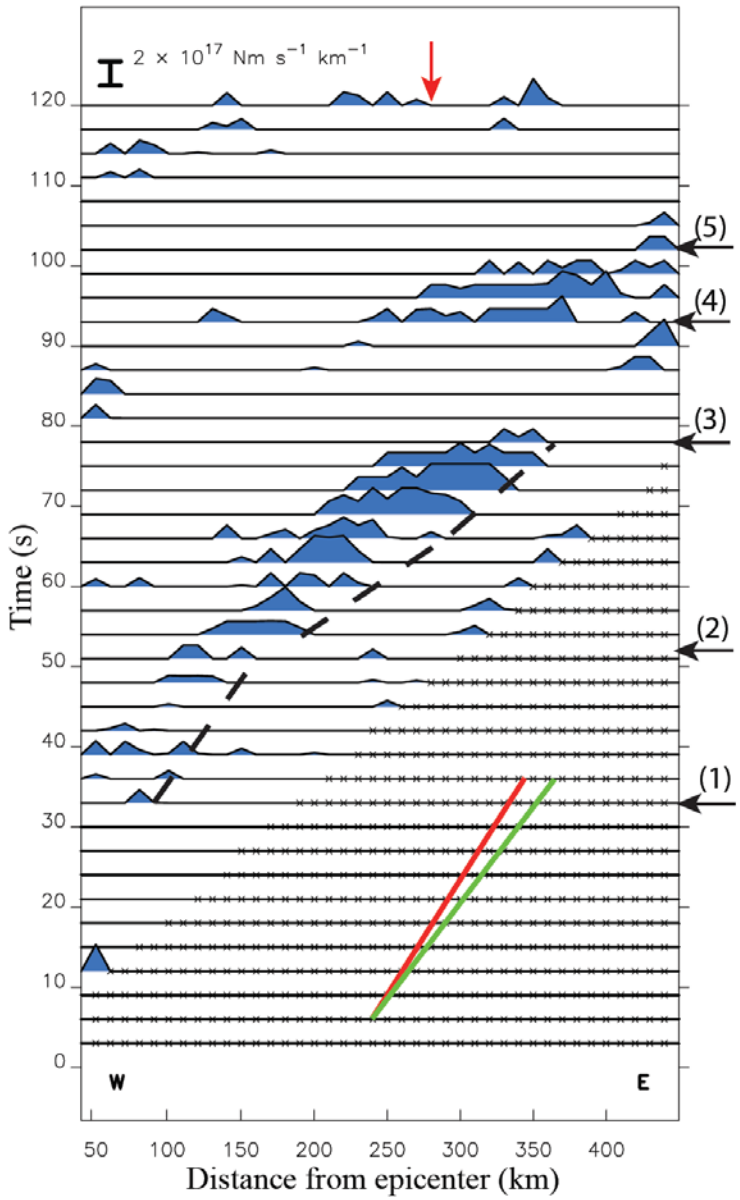


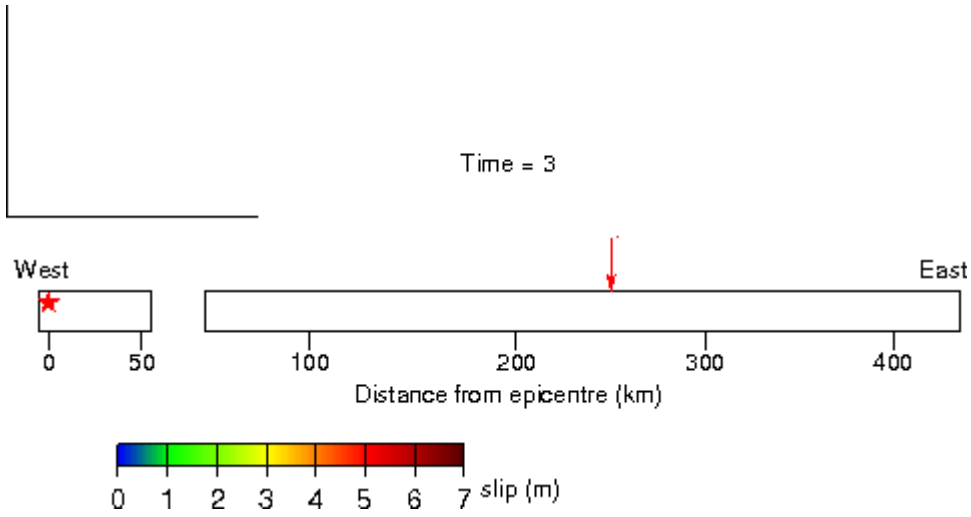
SH waves

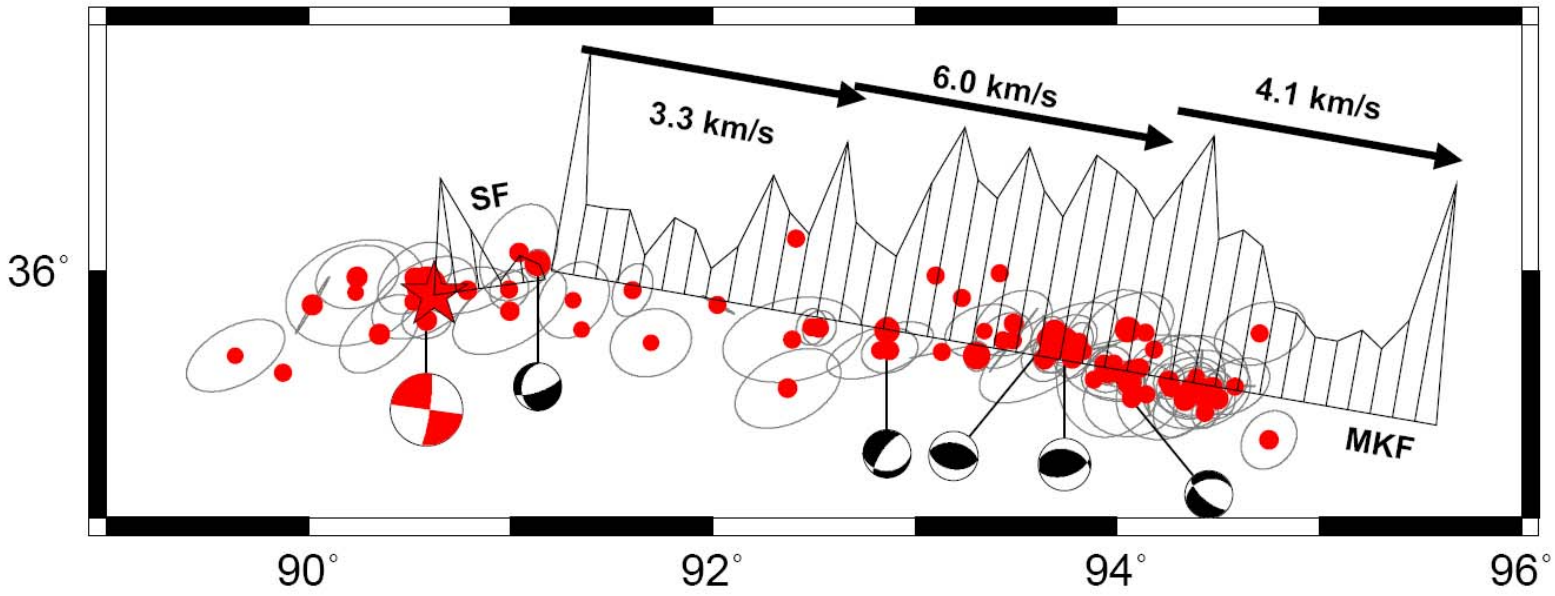

85
ALE
RES
60
255
KBS
TIXI
429
219
KEV
BILL
412
59
GRFO
YAK
552
95
KIEV
PET
198
159
VTS
MAJO
505
61
AQU
ERM
356
165
RAYN
PMG
57
57
FURI
WRAB
59
RER
81
Time (s)
0
50
100

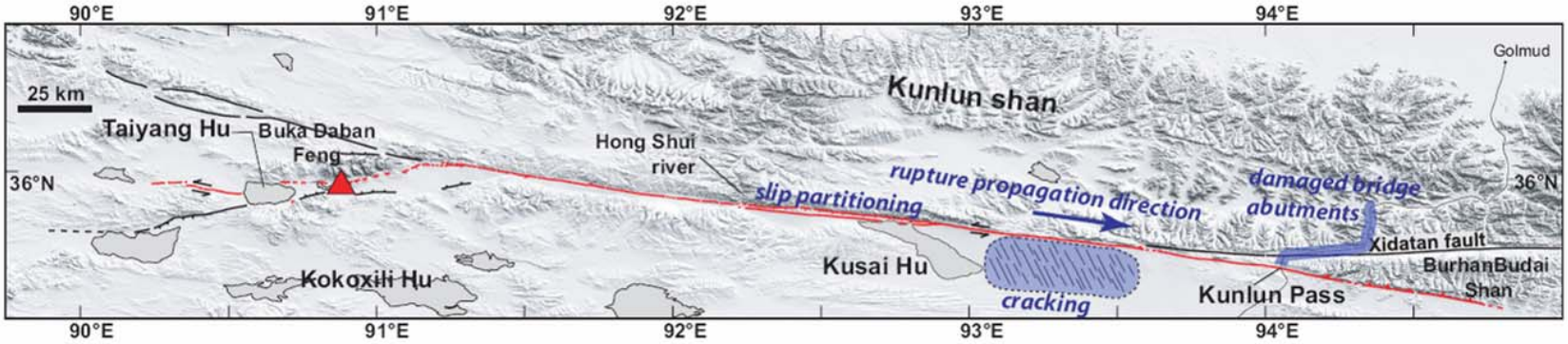

MRF (x10^{18} Nm)
2.5
2.0
1.5
1.0
0.5
0
0
20
40
60
80
100
120
Time (s)

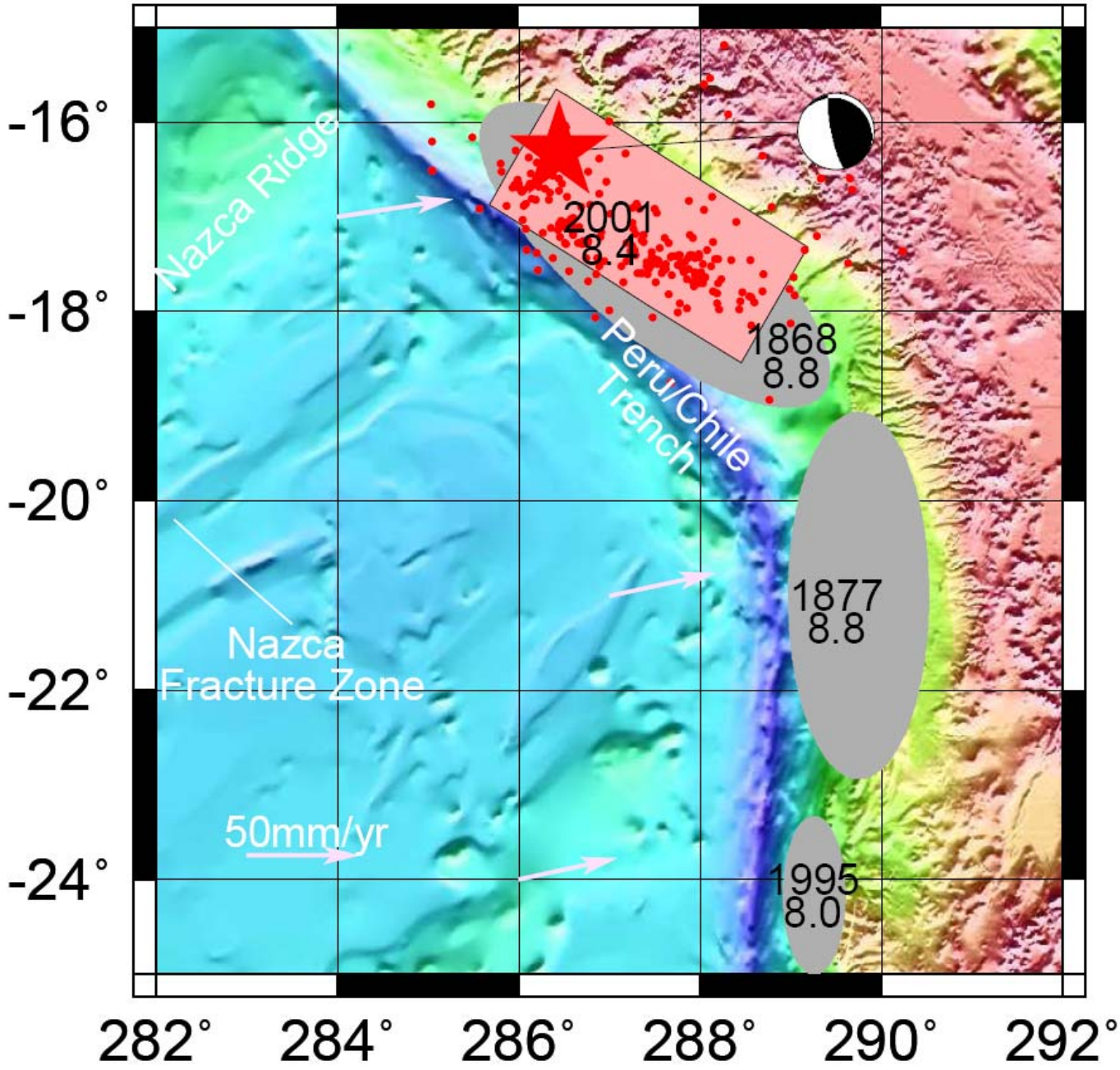
Preferred solution



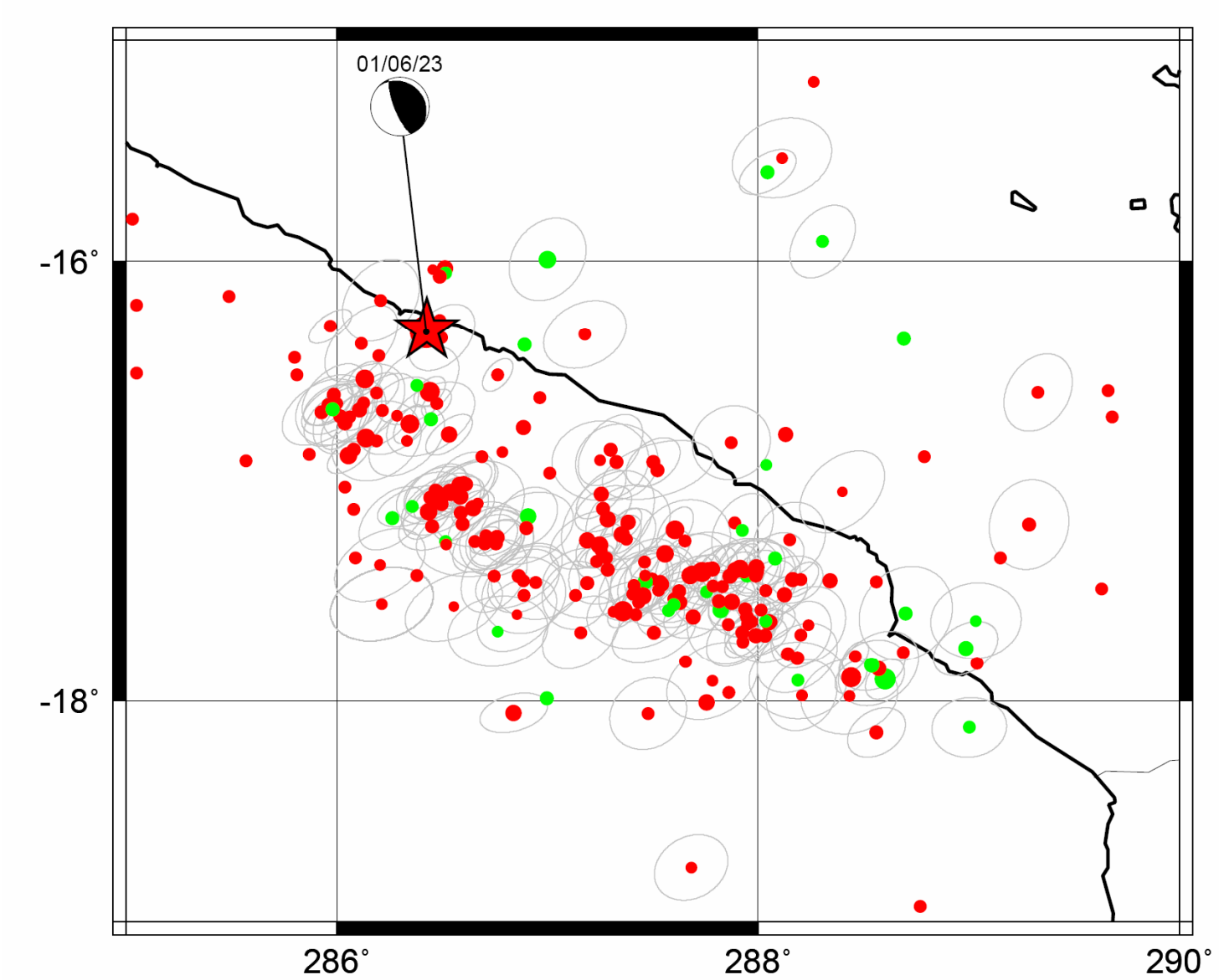

Time = 3
West
East
0
50
100
200
300
400
Distance from epicentre (km)
0 1 2 3 4 5 6 7 slip (m)


3.3 km/s
6.0 km/s
4.1 km/s
SF
MKF
36°
90°
92°
94°
96°

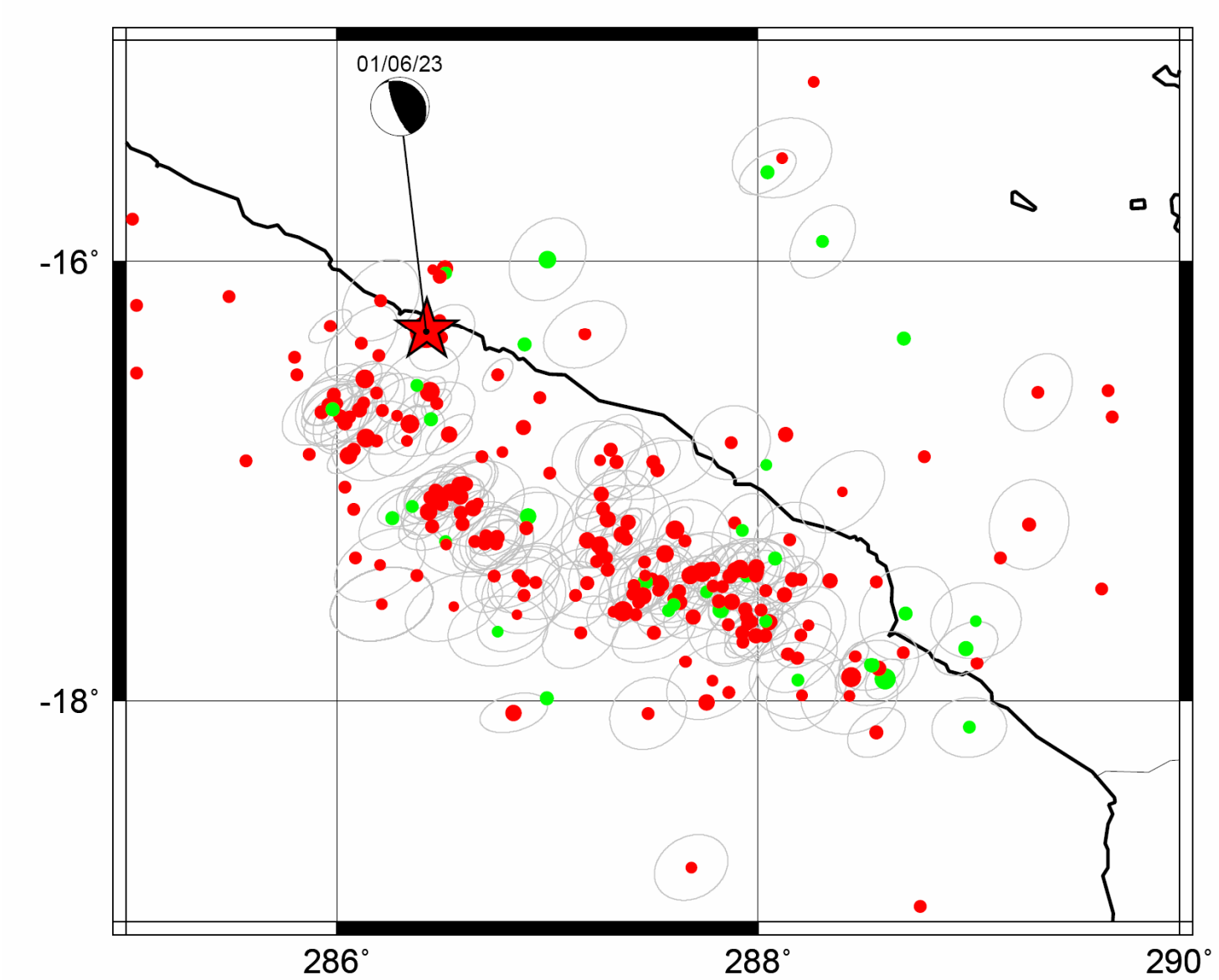

90°E
91°E
92°E
93°E
94°E
25 km
Taiyang Hu
Buka Daban Feng
Kunlun shan
Golmud
Hong Shui river
36°N
slip partitioning
rupture propagation direction
damaged bridge abutments
Xidatan fault
Kusai Hu
Kokoxili Hu
cracking
Kunlun Pass
BurhanBudai Shan


-16°
-18°
-20°
-22°
-24°
282°
284°
286°
288°
290°
292°
Nazca Ridge
2001
8.4
Peru/Chile
Trench
1868
8.8
1877
8.8
Nazca
Fracture Zone
50mm/yr
1995
8.0

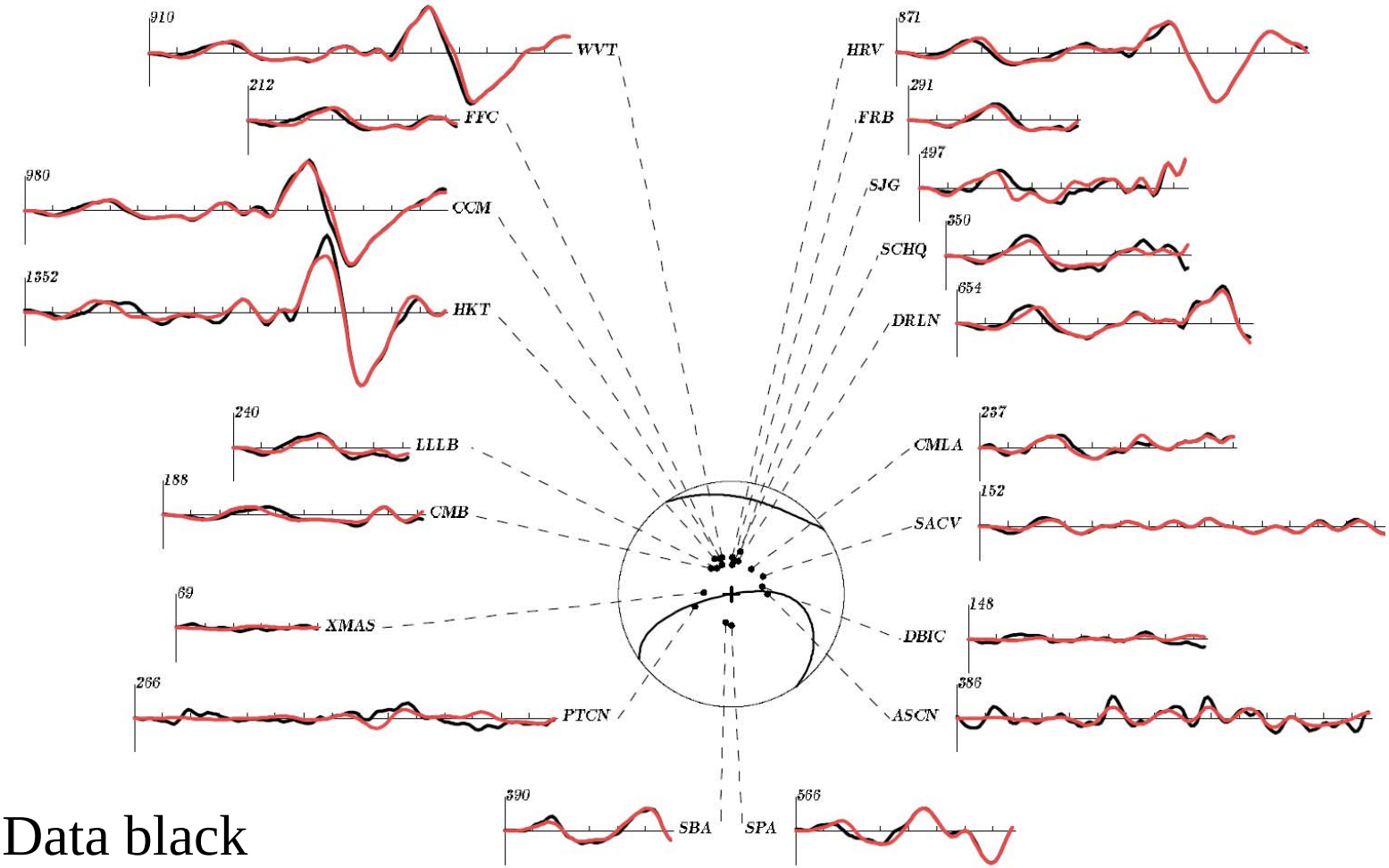
24 hour aftershocks



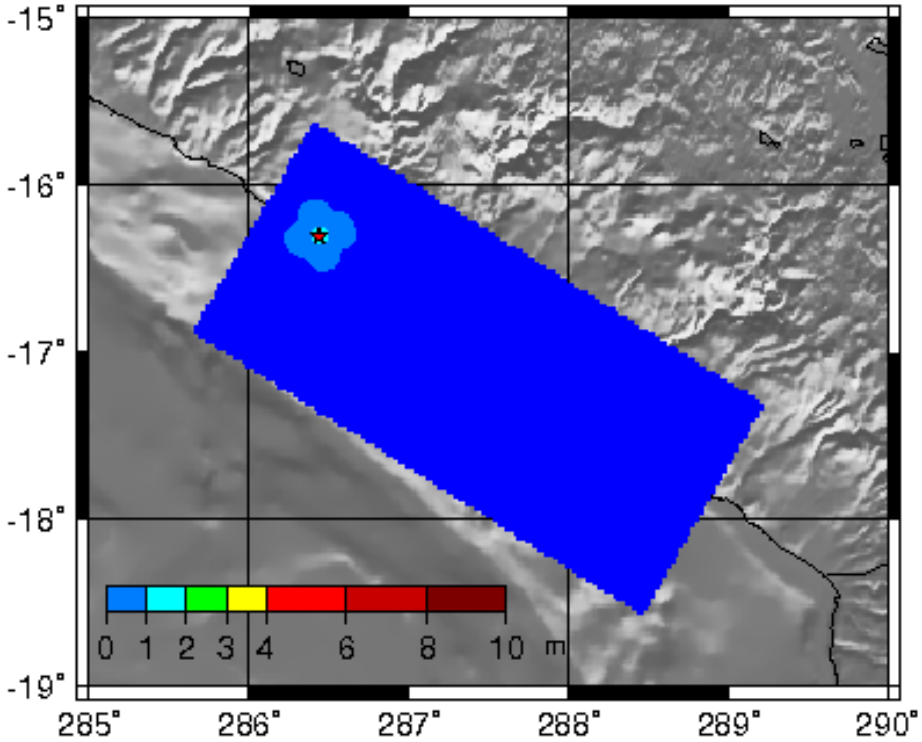
24 hour aftershocks



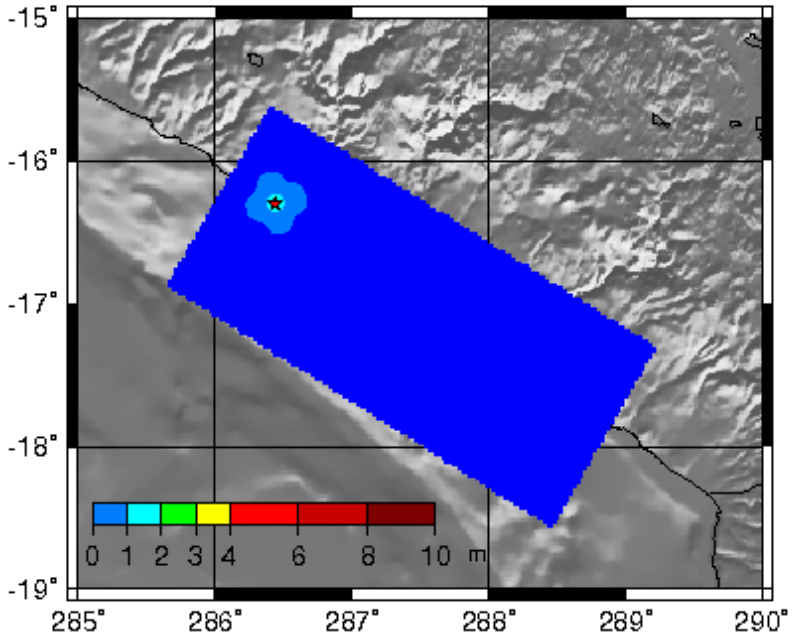
SH waves



Data black
Solution red

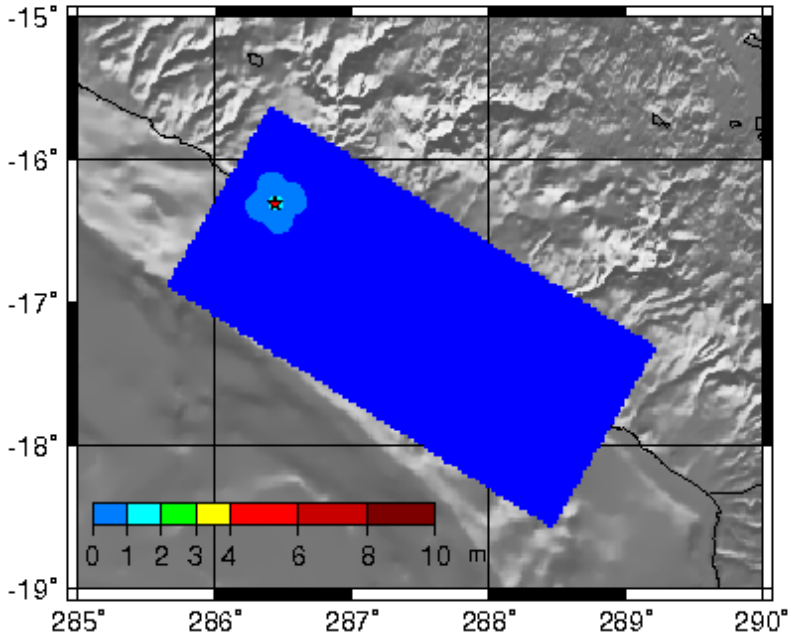

-15°
-16°
-17°
-18°
-19°
285°
286°
287°
288°
289°
290°
0 1 2 3 4 6 8 10 m

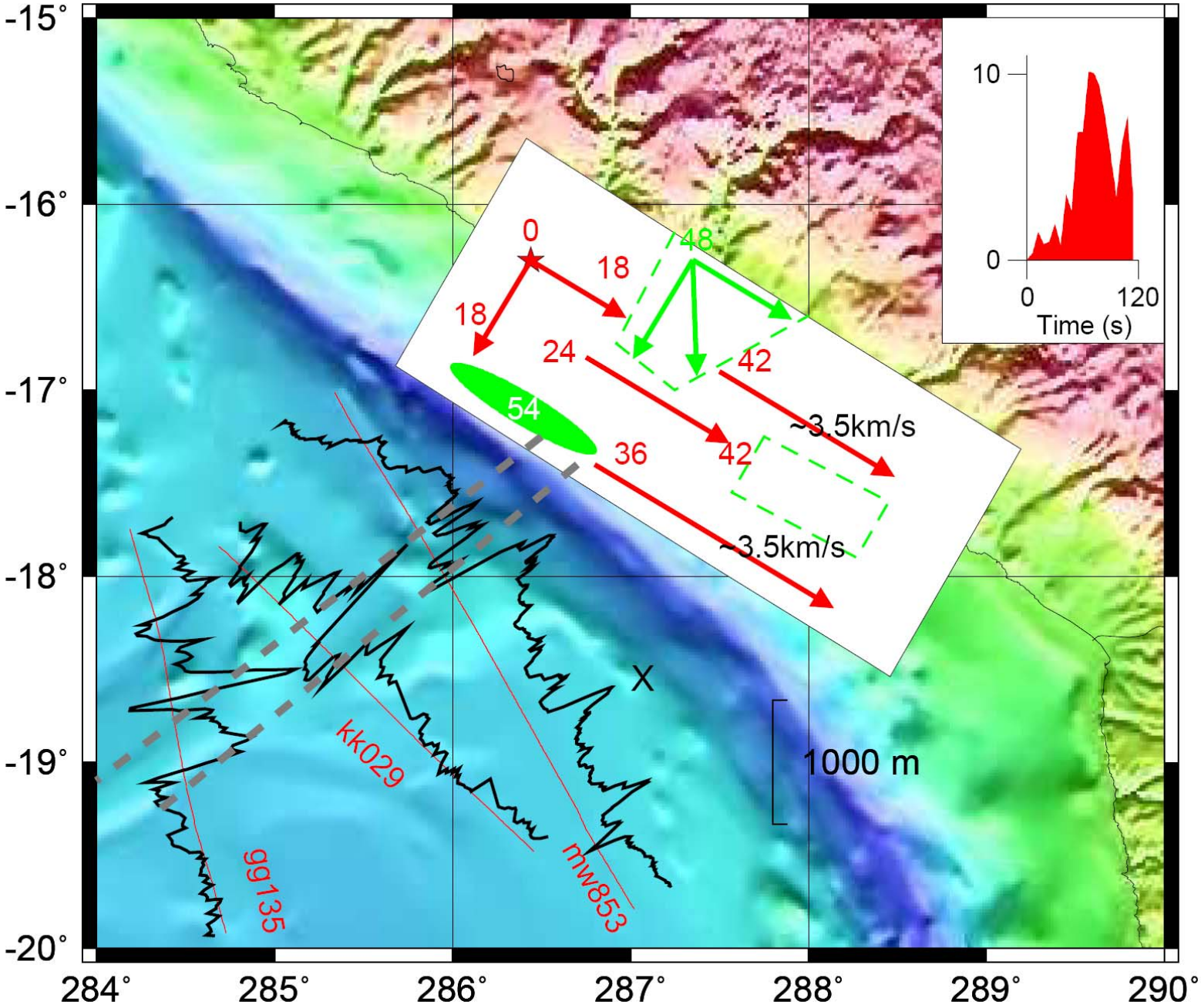
Solution in which we try to maximize slip on barrier during 0-60s

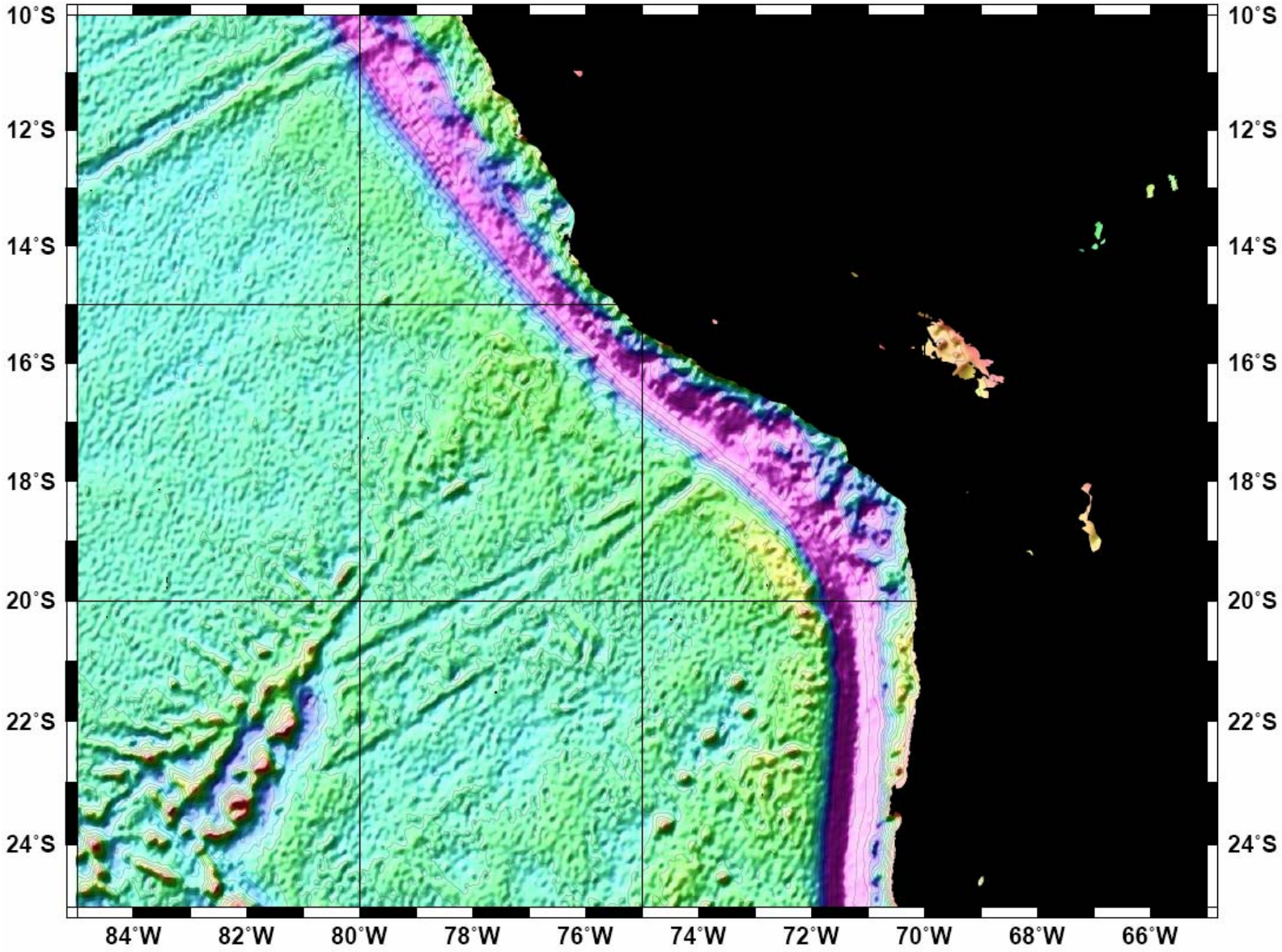


Preferred solution:

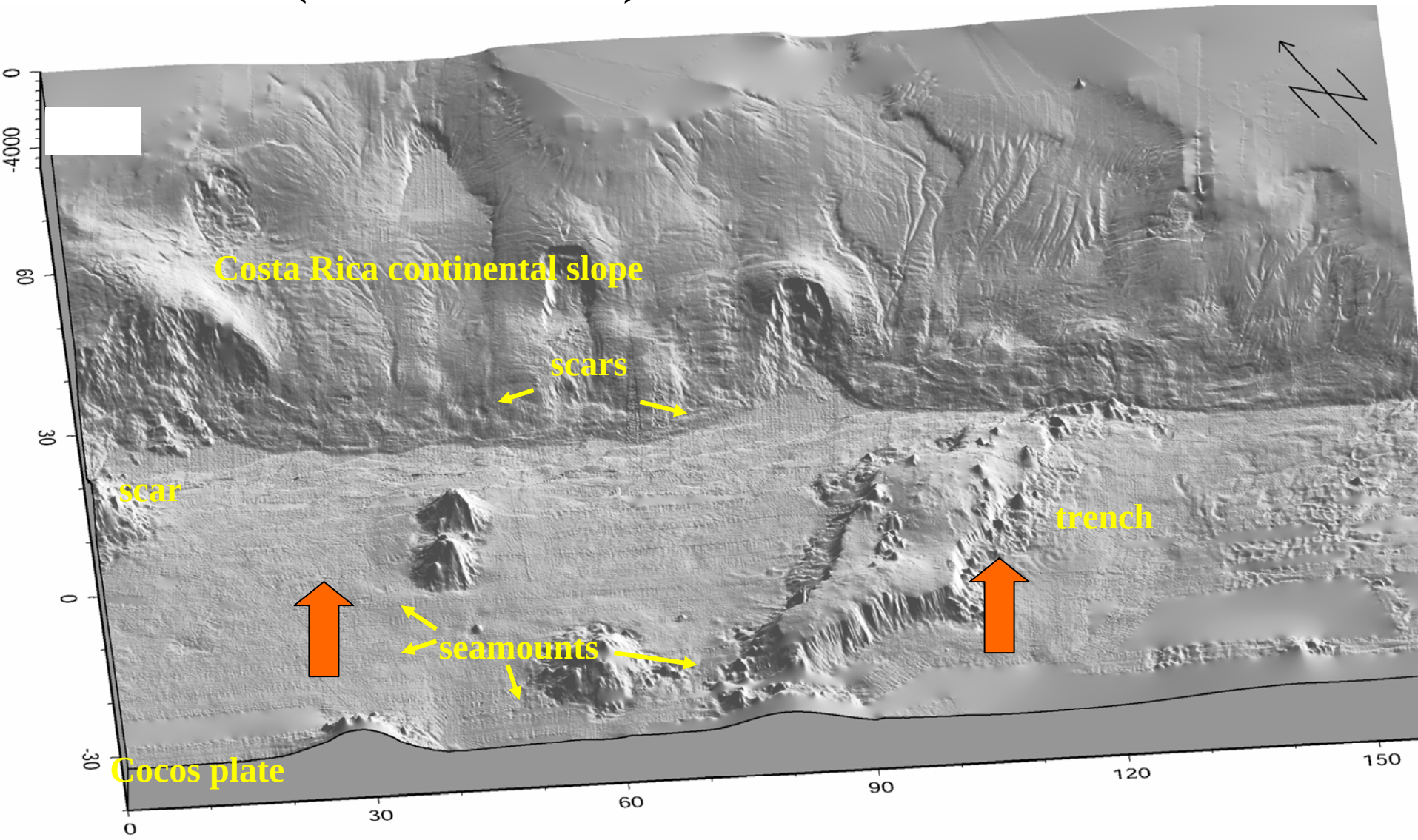
positivity, Mo=cmt value smoothed

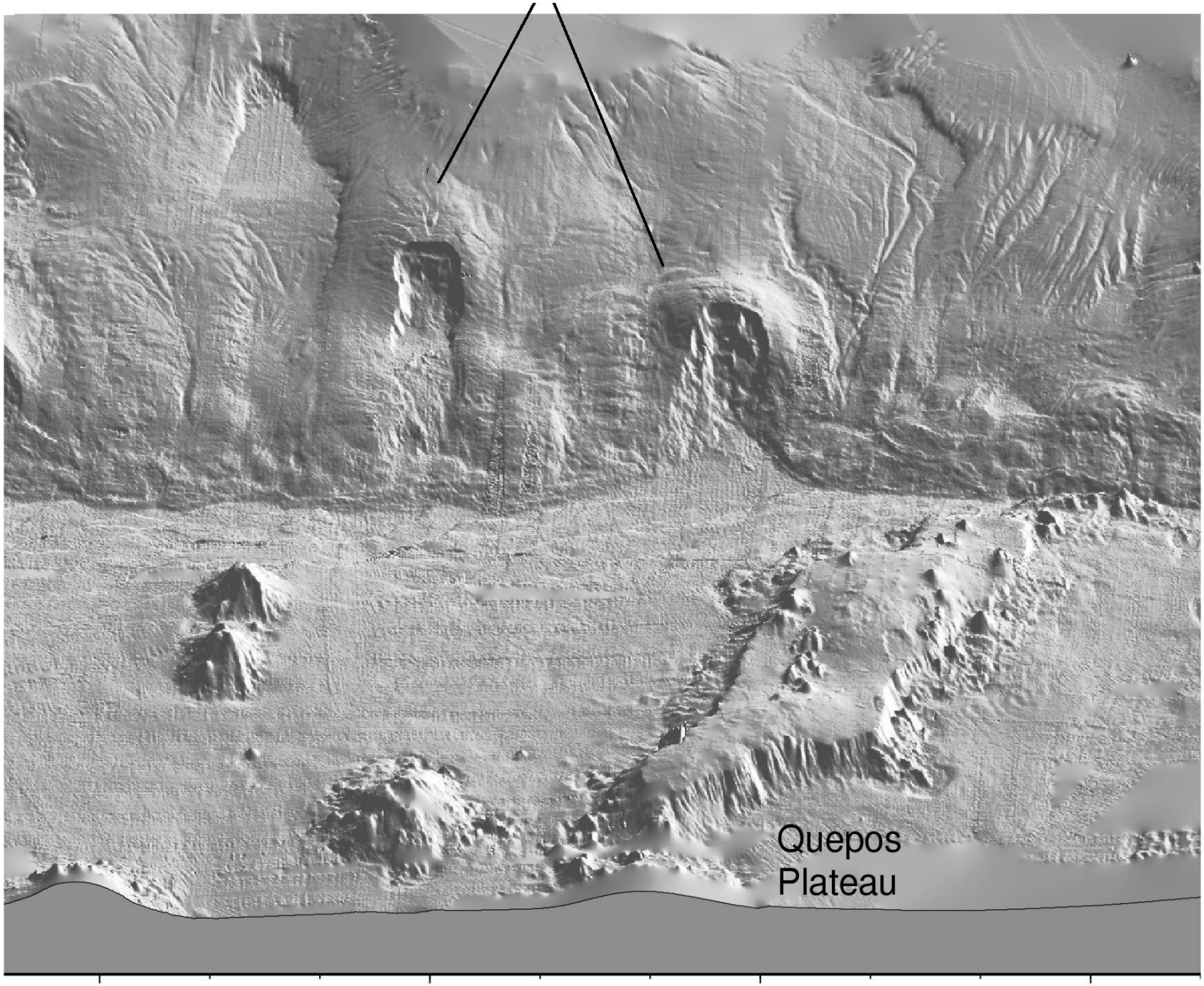


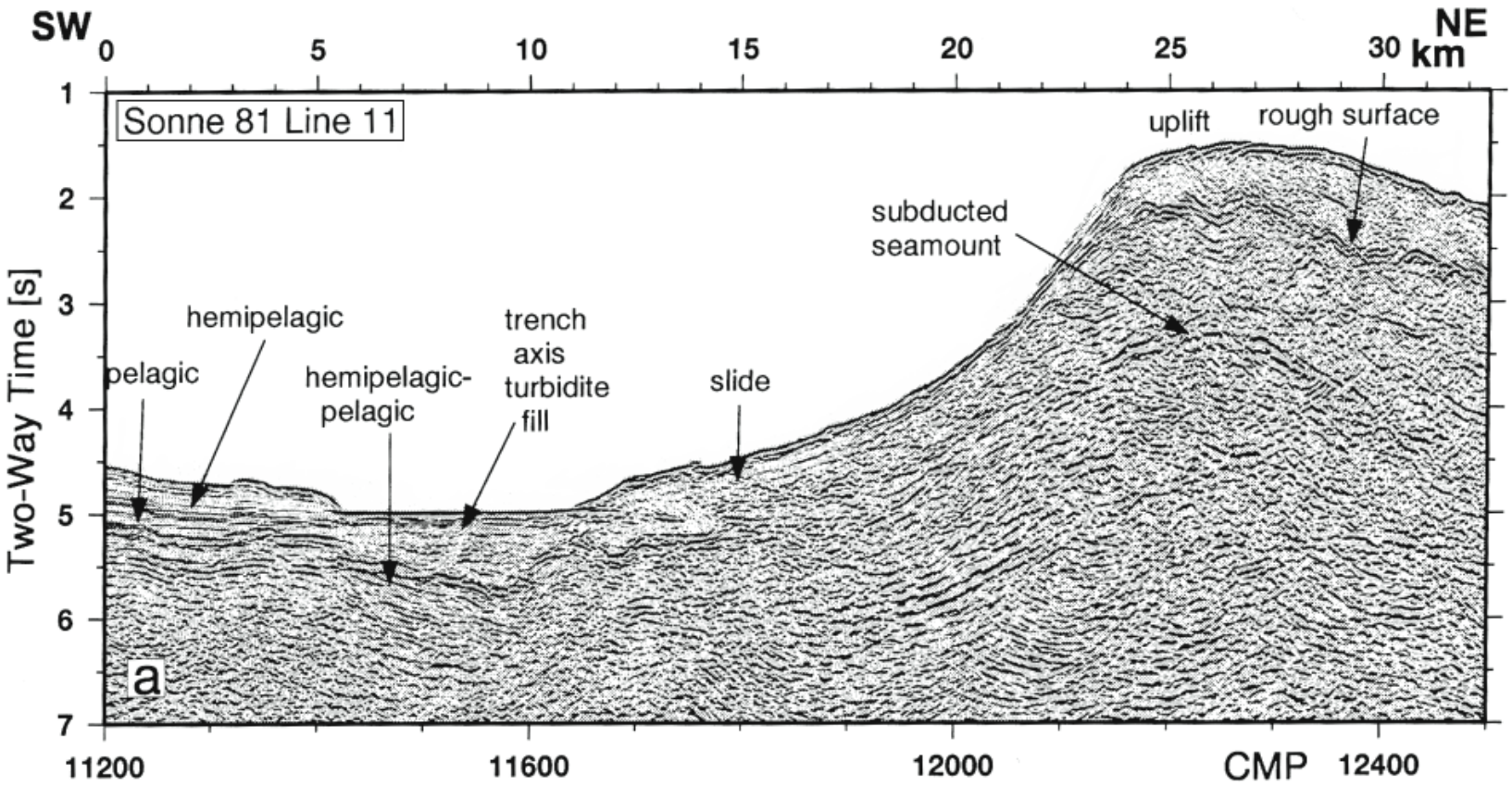

-15°
-16°
-17°
-18°
-19°
-20°
284°
285°
286°
287°
288°
289°
290°
0
18
18
48
24
42
54
36
42
~3.5km/s
~3.5km/s
10
0
0
120
Time (s)
X
1000 m
kk029
gg135
mw853


10°S
12°S
14°S
16°S
18°S
20°S
22°S
24°S
84°W
82°W
80°W
78°W
76°W
74°W
72°W
70°W
68°W
66°W

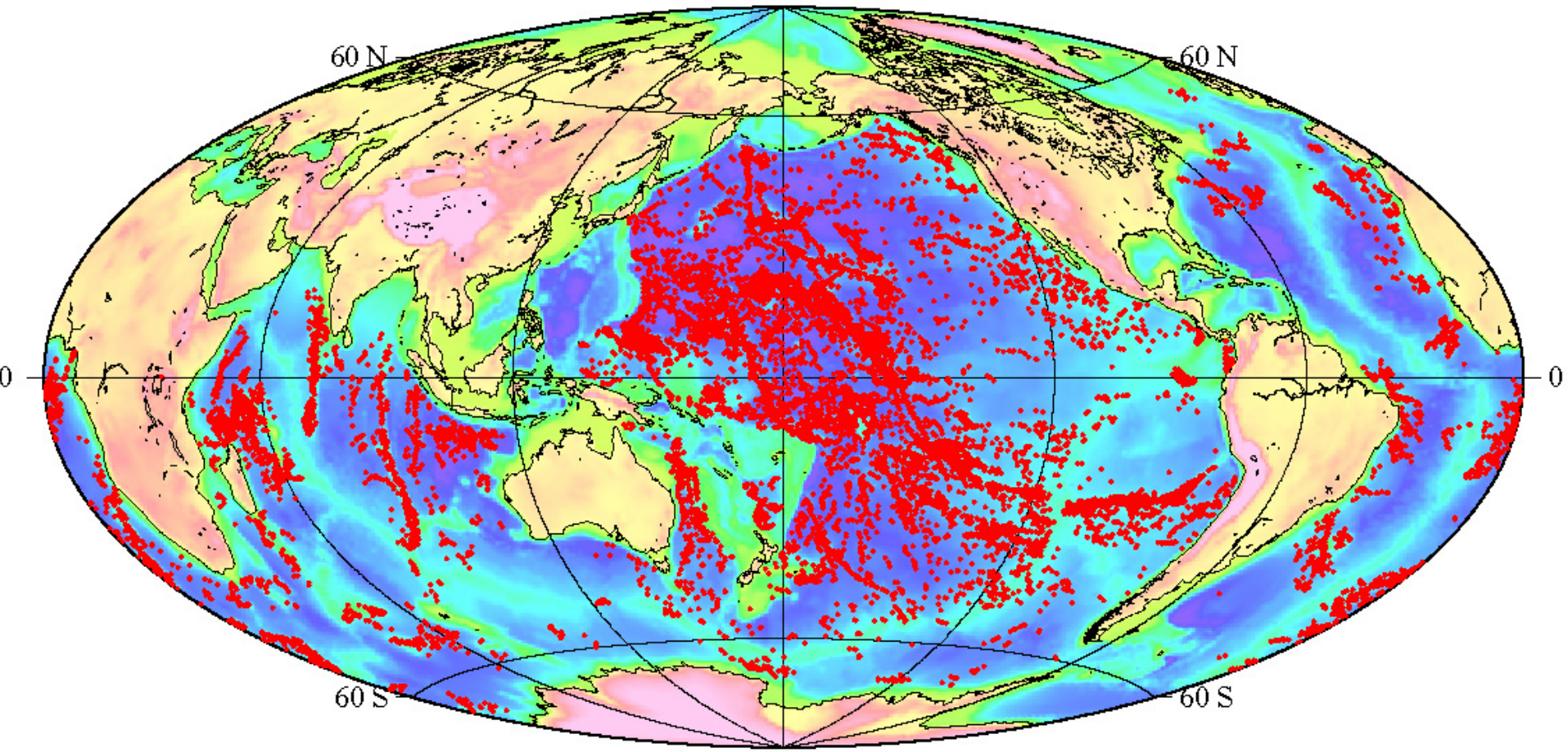
Seamount subduction along Costa Rica (*von Huene et al.*)



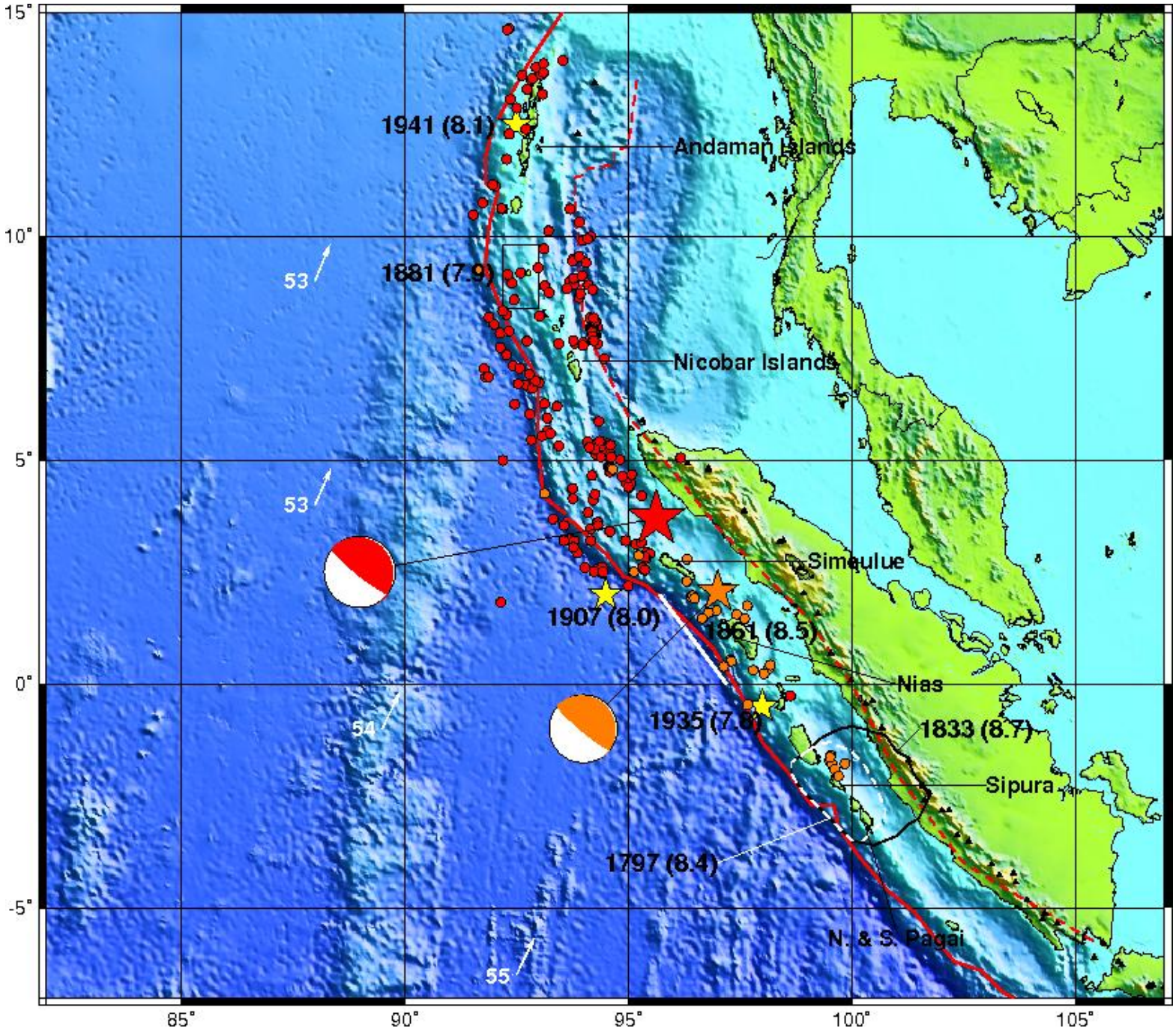

Quepos
Plateau

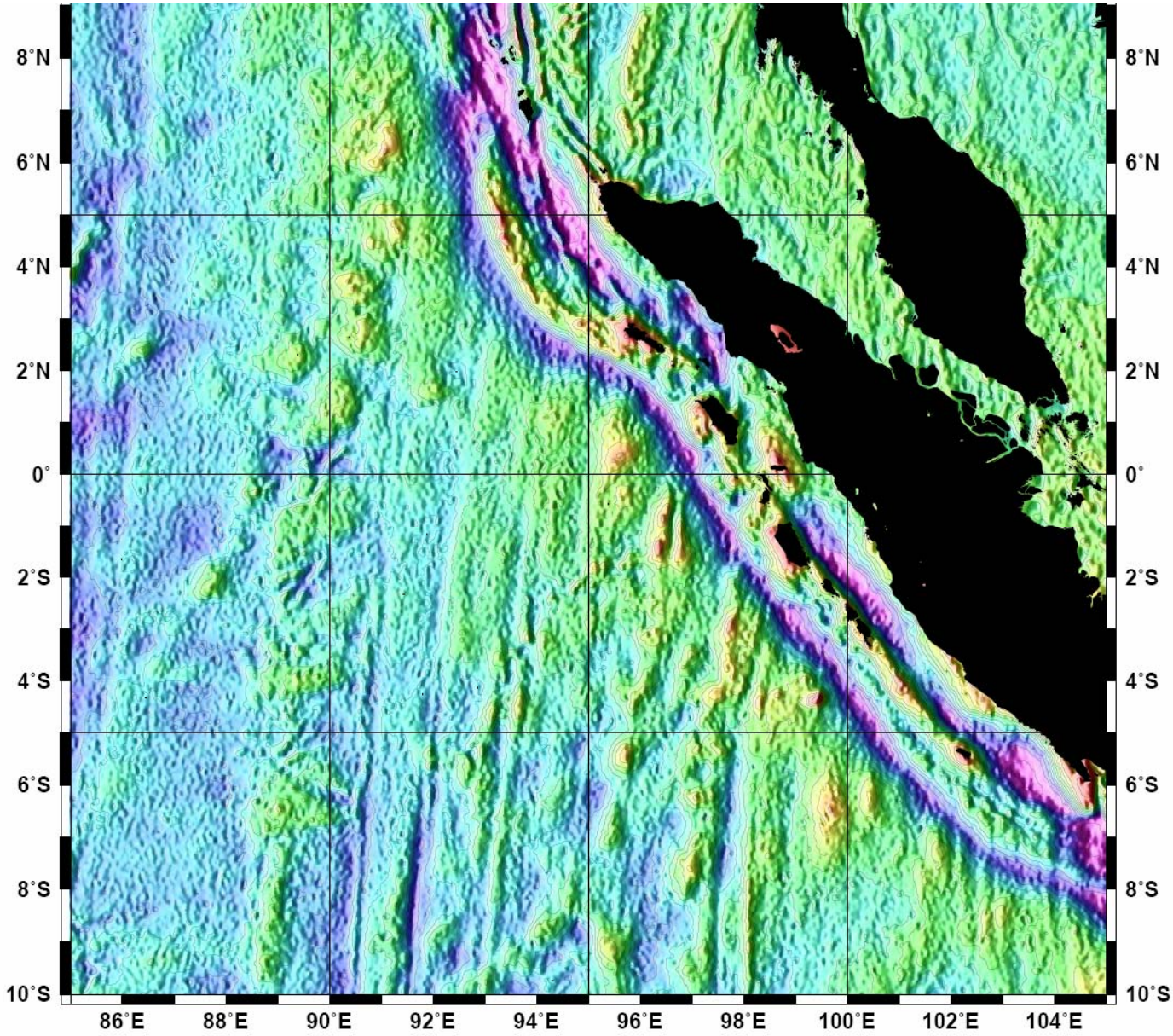

SW
NE
0
5
10
15
20
25
30
km
Sonne 81 Line 11
uplift
rough surface
subducted
seamount
hemipelagic
pelagic
hemipelagic-
pelagic
trench
axis
turbidite
fill
slide
Two-Way Time [s]
1
2
3
4
5
6
7
a
11200
11600
12000
CMP
12400

Seamounts (Height > 1500 m)

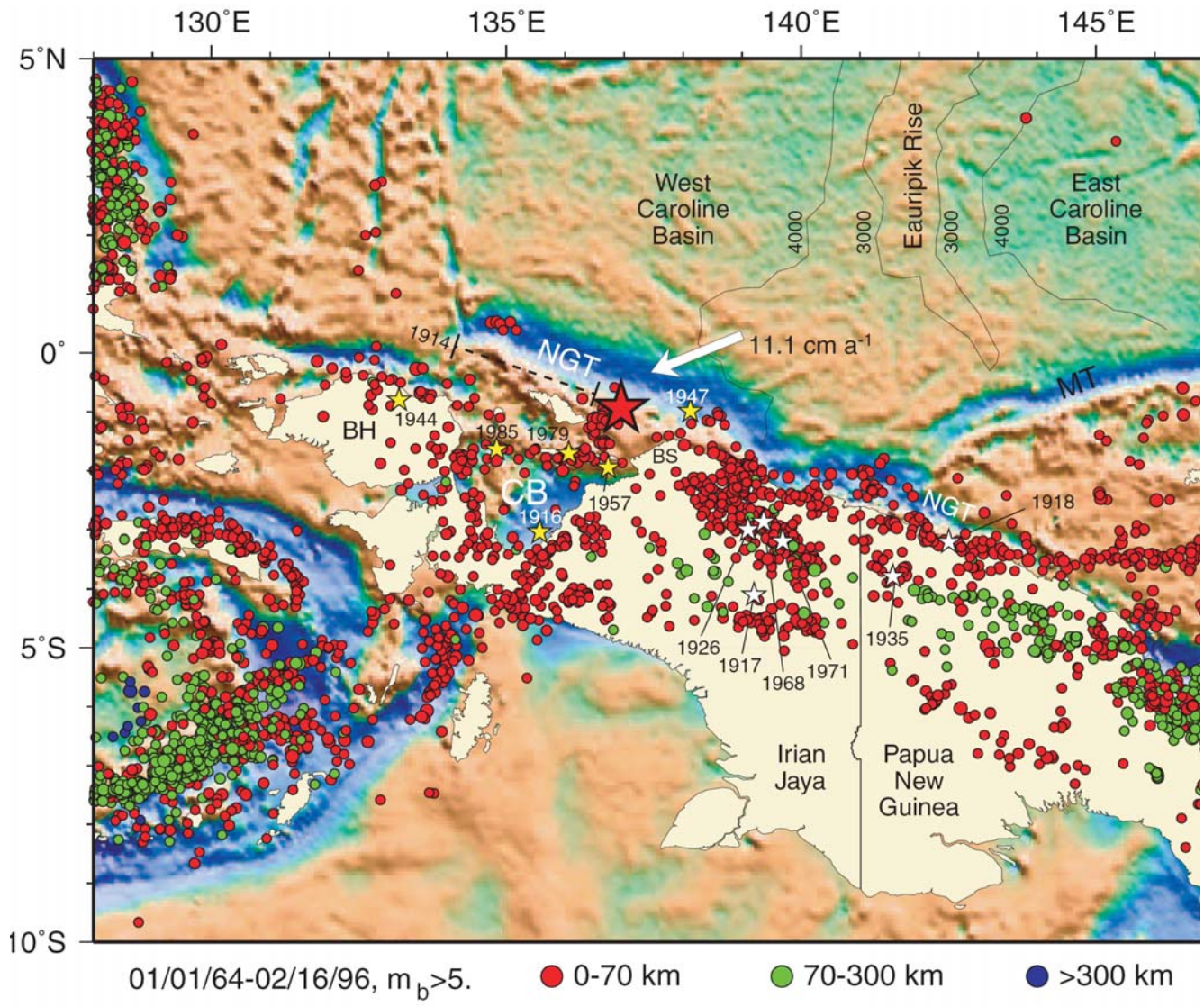


Source: Satellite altimetry (Wessel, 2001)

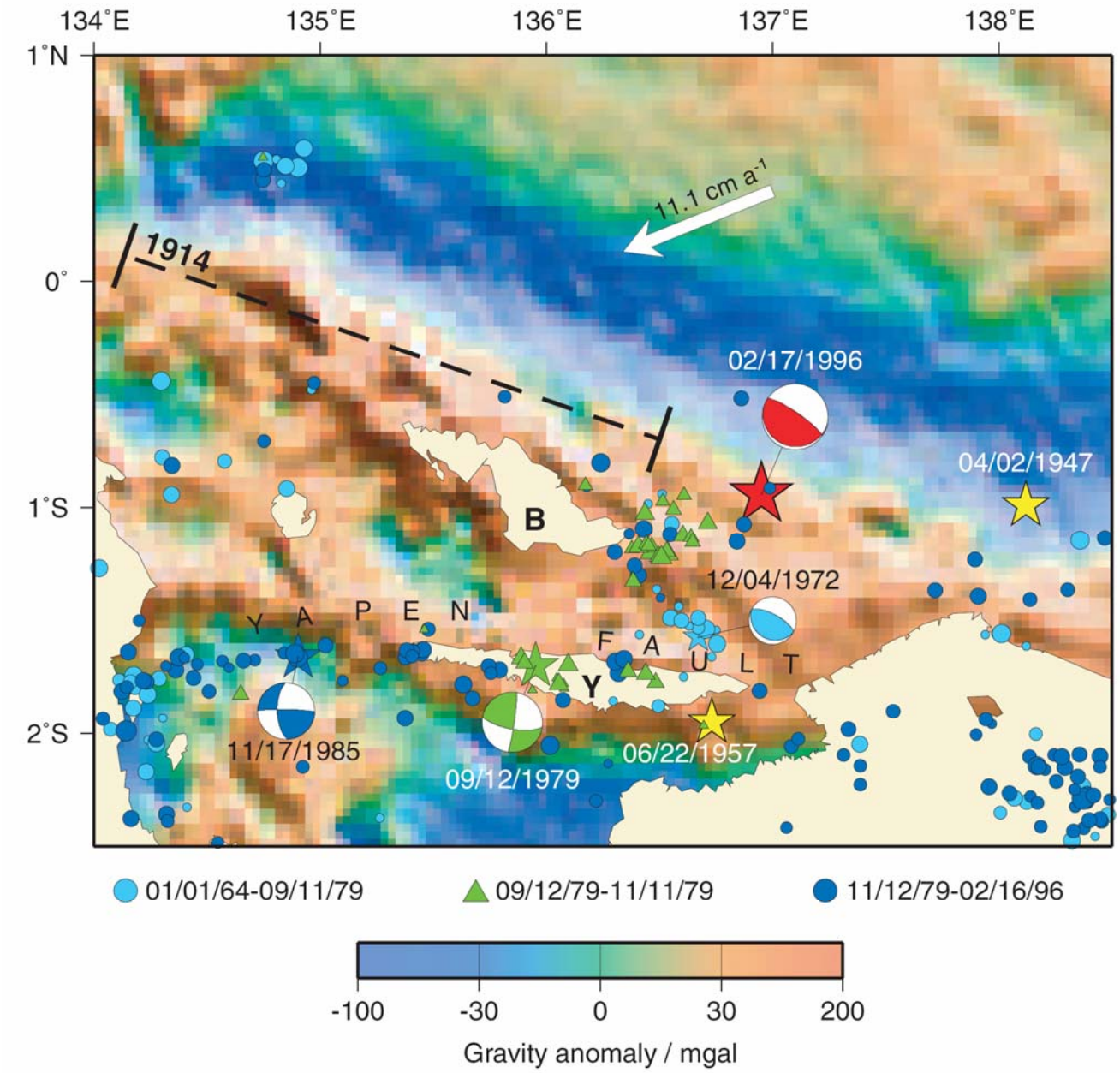

15°
10°
5°
0°
-5°
85°
90°
95°
100°
105°
1941 (8.1)
Andaman Islands
1881 (7.9)
Nicobar Islands
53
53
54
55
Simeulue
1907 (8.0)
1861 (8.5)
Nias
1935 (7.6)
1833 (8.7)
Sipura
1797 (8.4)
N. & S. Pagai


8°N
6°N
4°N
2°N
0°
2°S
4°S
6°S
8°S
10°S
86°E
88°E
90°E
92°E
94°E
96°E
98°E
100°E
102°E
104°E

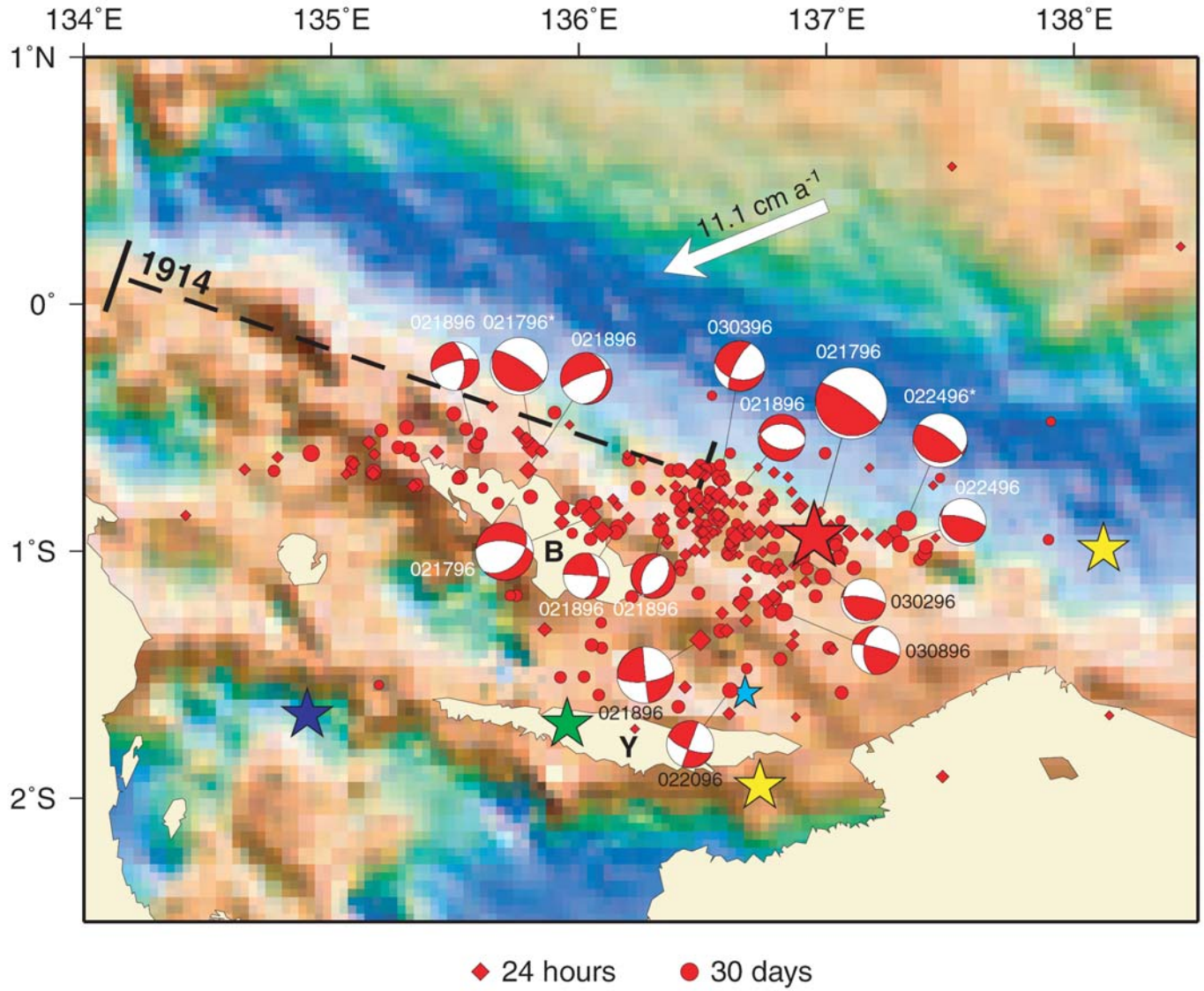
The Mw 8.2 1996 Biak, Indonesia earthquake

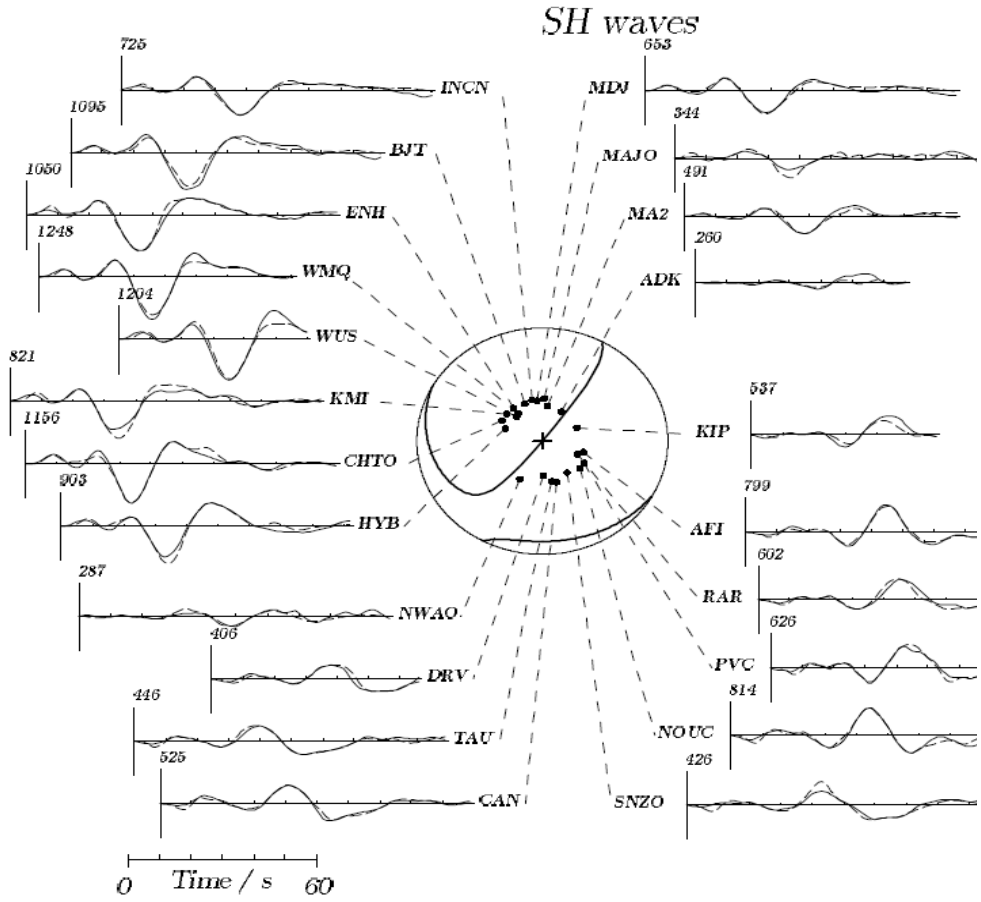


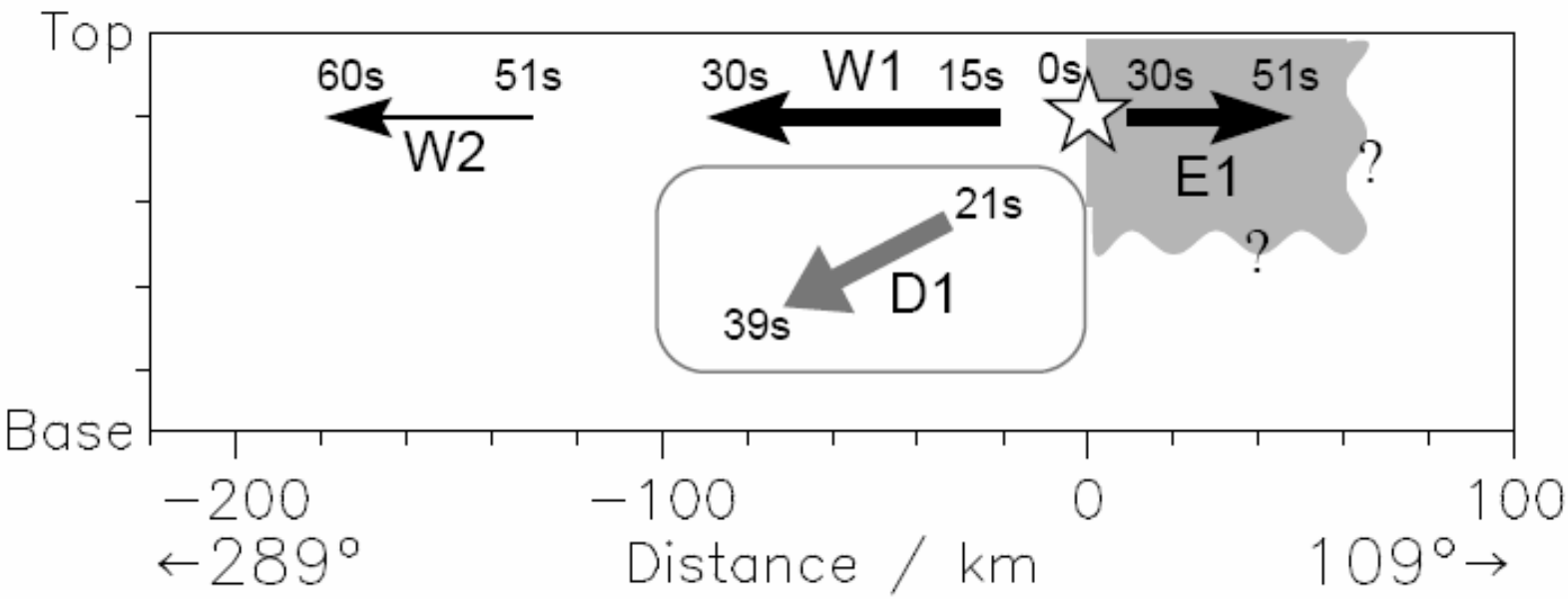
Reliably relocated seismicity prior to earthquake



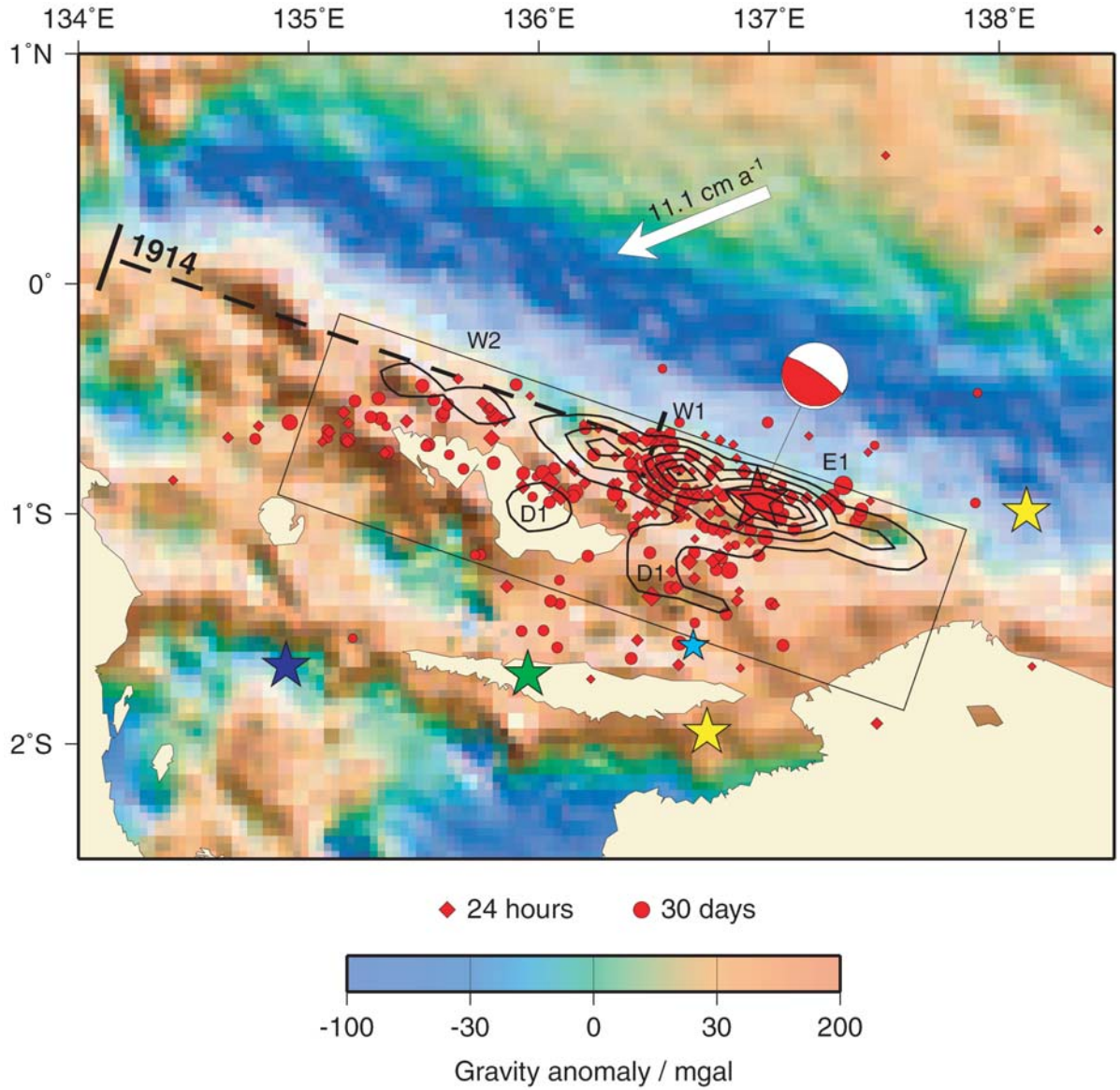
Reliably relocated 1-month aftershocks

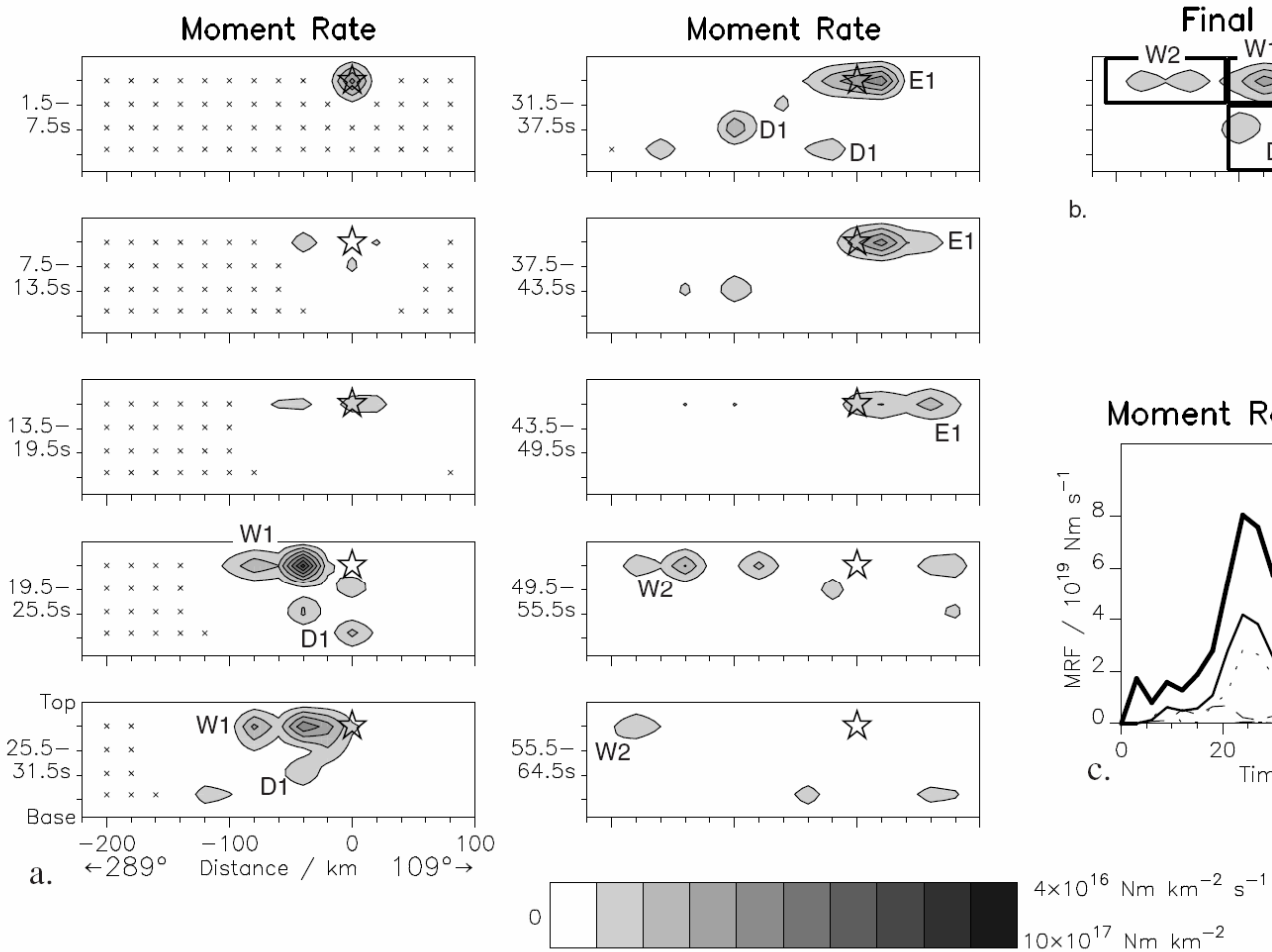


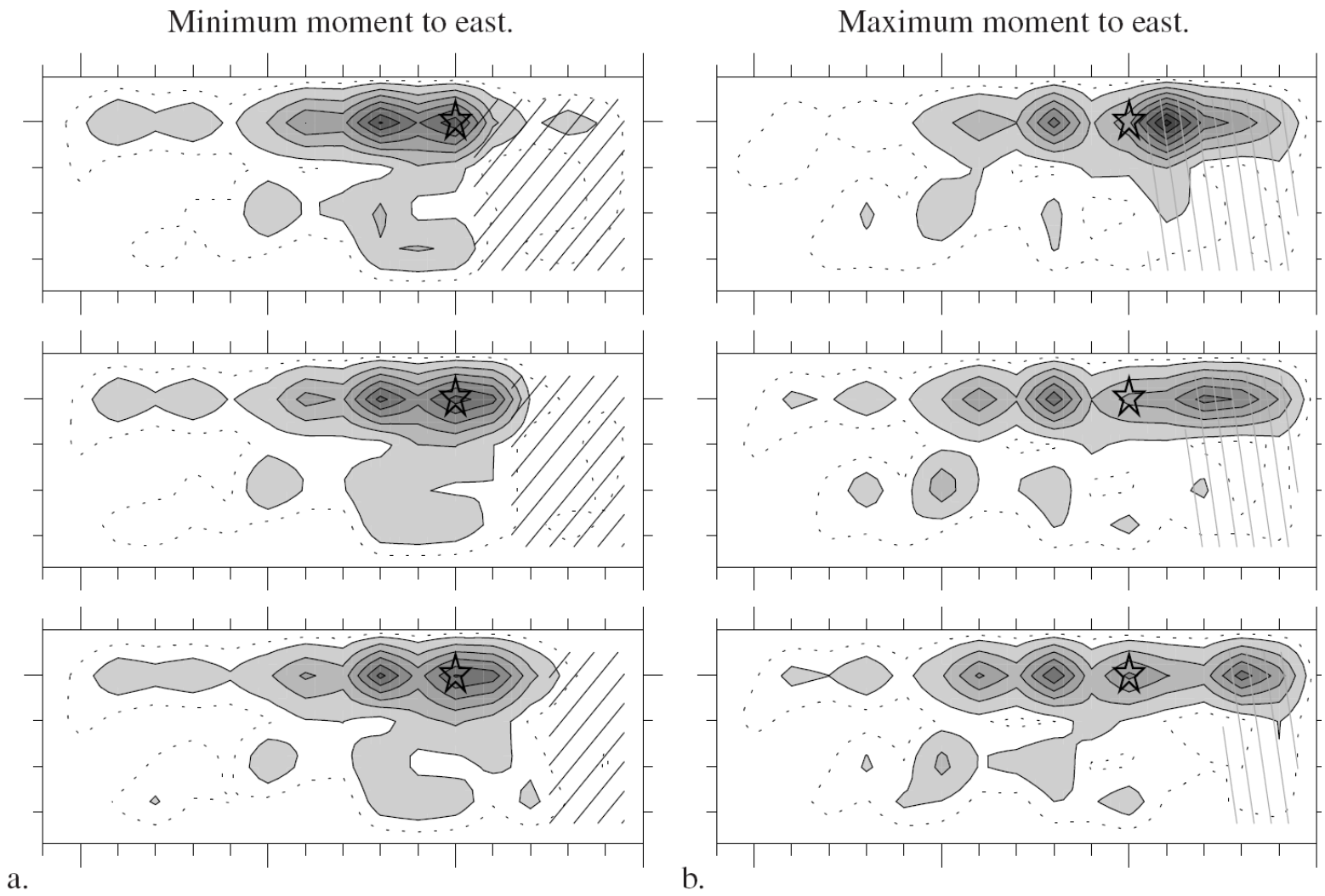

SH waves
725
INCN
1095
BJT
1050
ENH
1248
WMQ
1204
WUS
821
KMI
1156
CHTO
903
HYB
287
NWAO
406
DRV
446
TAU
525
CAN
653
MDJ
344
MAJO
491
MA2
260
ADK
537
KIP
799
AFI
602
RAR
626
PVC
814
NOUC
426
SNZO
0
Time / s
60

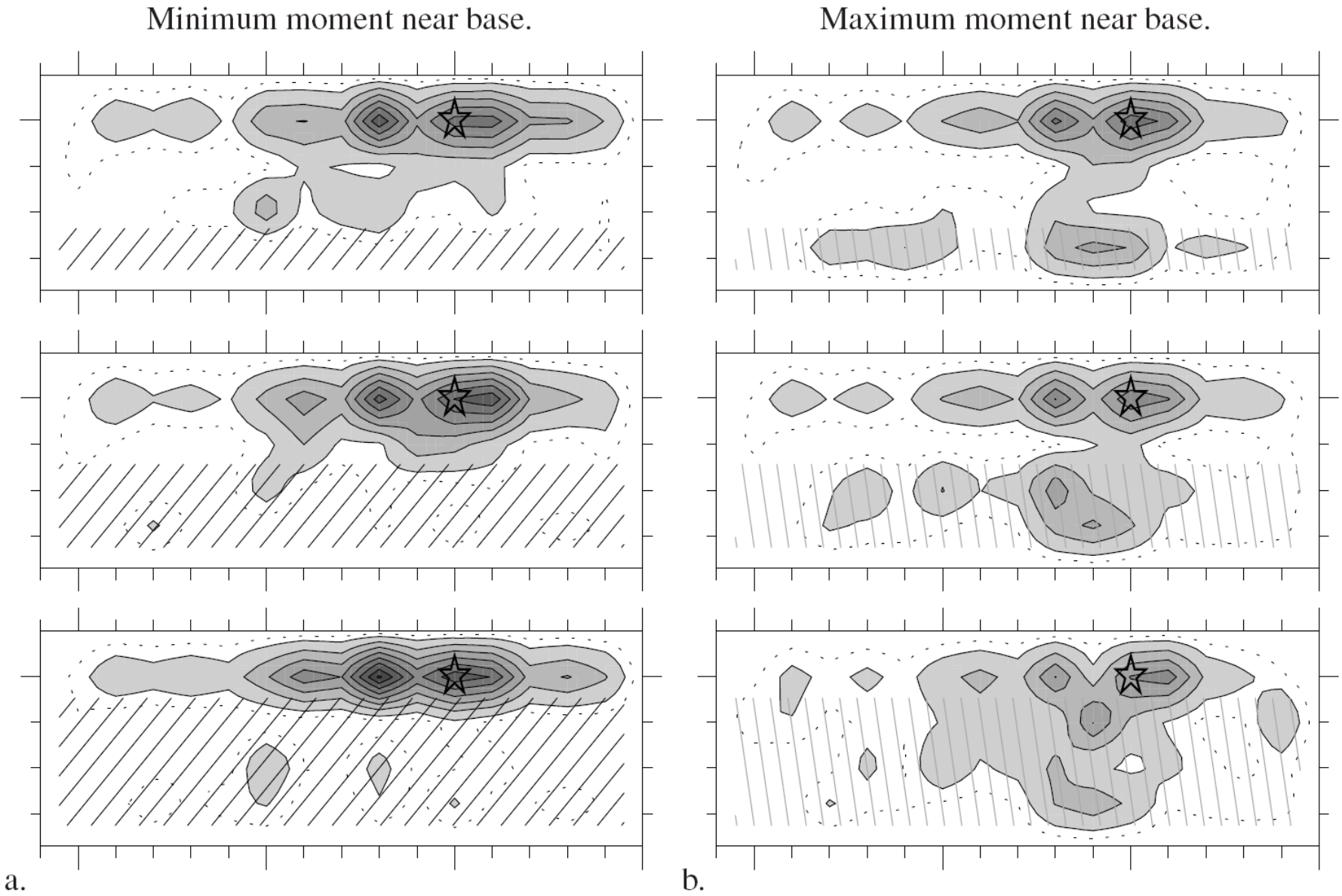

Top
Base
60s
51s
W2
30s
W1
15s
0s
30s
51s
E1
?
?
21s
D1
39s
−200
←289°
−100
0
100
109°→
Distance / km

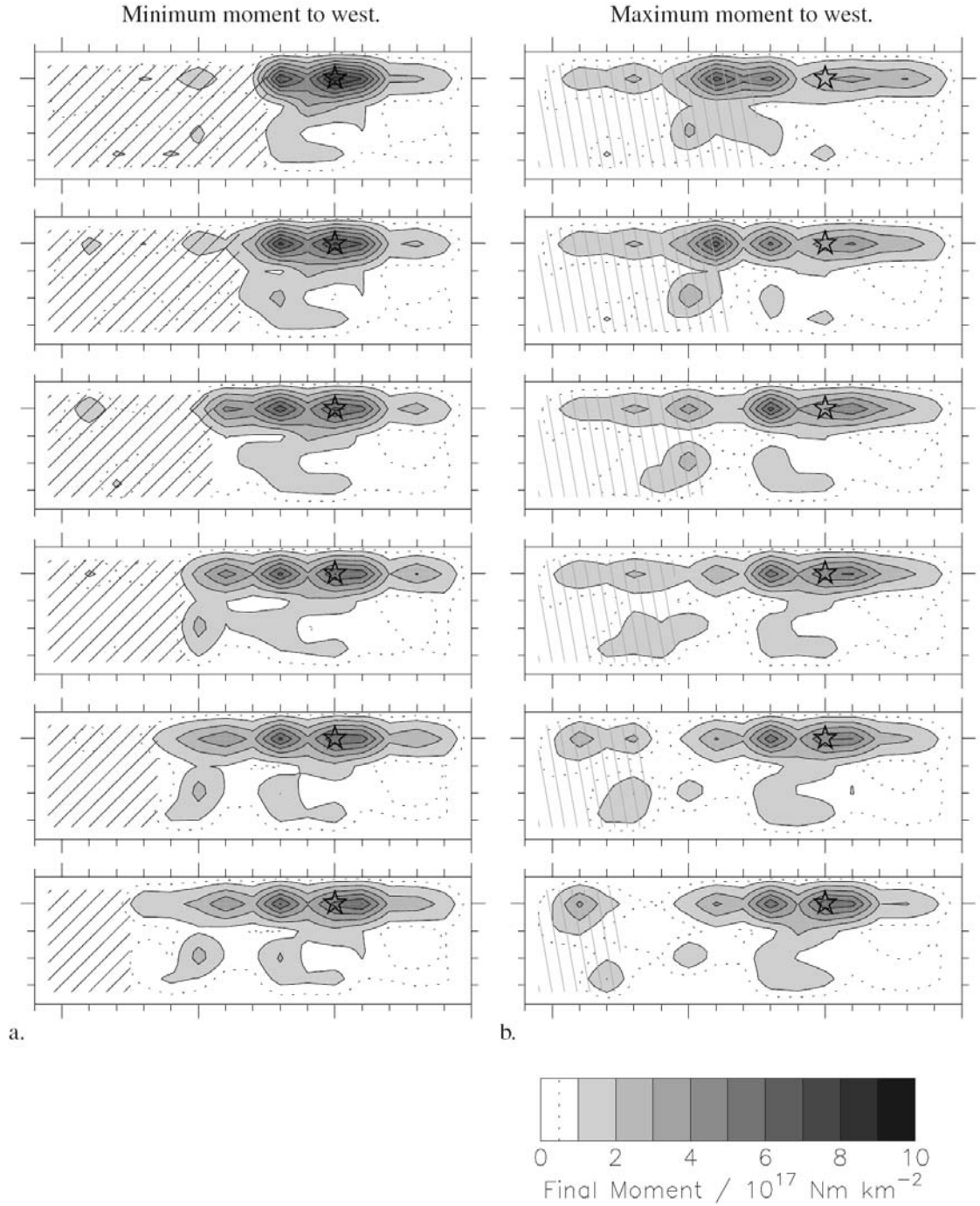
Final moment distribution (contours at 10^{20} N mkm^{-2})



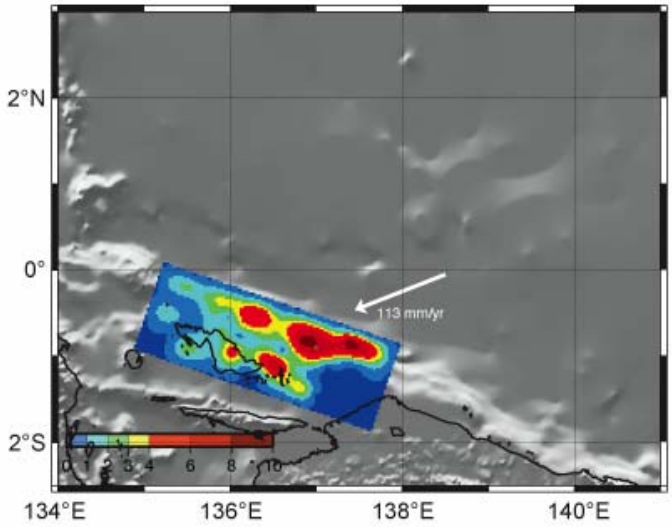

Moment Rate
1.5–
7.5s
7.5–
13.5s
13.5–
19.5s
19.5–
25.5s
25.5–
31.5s
Top
Base
W1
D1
−200
−100
0
100
←289°
Distance / km
109°→
a.
Moment Rate
31.5–
37.5s
37.5–
43.5s
43.5–
49.5s
49.5–
55.5s
55.5–
64.5s
E1
D1
E1
E1
W2
W2
Final Moment
W2
W1
E1
D1
b.
Moment Rate Function
Total
W1
E1
W2
D1
MRF / 10^19 Nm s^-1
0
2
4
6
8
0
20
40
60
Time / s
c.
0
4×10^16 Nm km^-2 s^-1
10×10^17 Nm km^-2

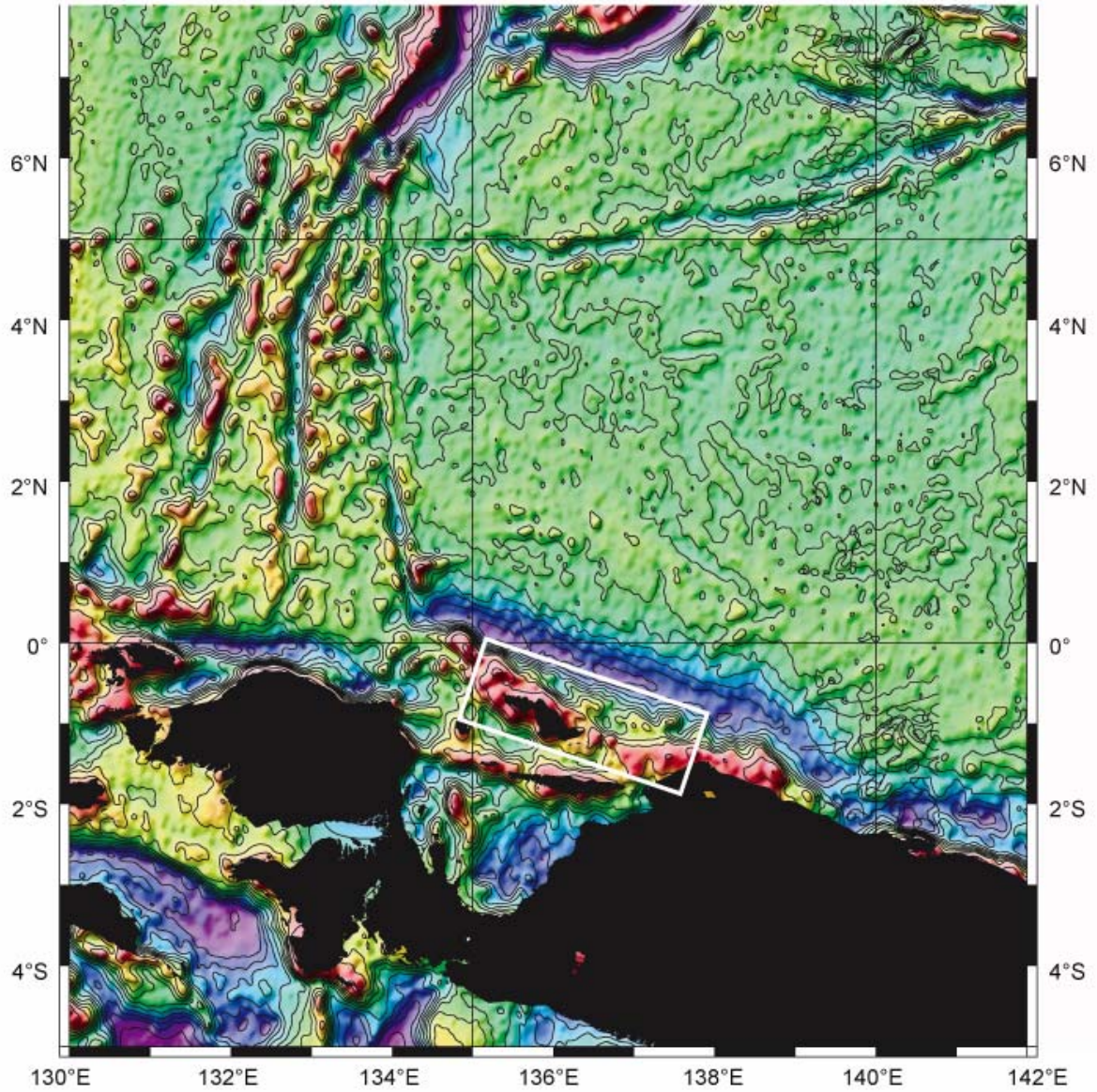

Minimum moment to east.
Maximum moment to east.
a.
b.


Minimum moment near base.
Maximum moment near base.
a.
b.


Minimum moment to west.
Maximum moment to west.
a.
b.
0
2
4
6
8
10
Final Moment / 10^{17} Nm km^{-2}

Mw 8.2 1996 Biak, Indonesia earthquake





Earthquake rupture stalled by a subducting fracture zone

D. P. Robinson, S. Das & A.B. Watts

Science, **32**, 1203 (May 2006)