Seismic Moment Tensor Inversion Using 3D Velocity Model and Its Application to the 2013 Lushan Earthquake Sequence

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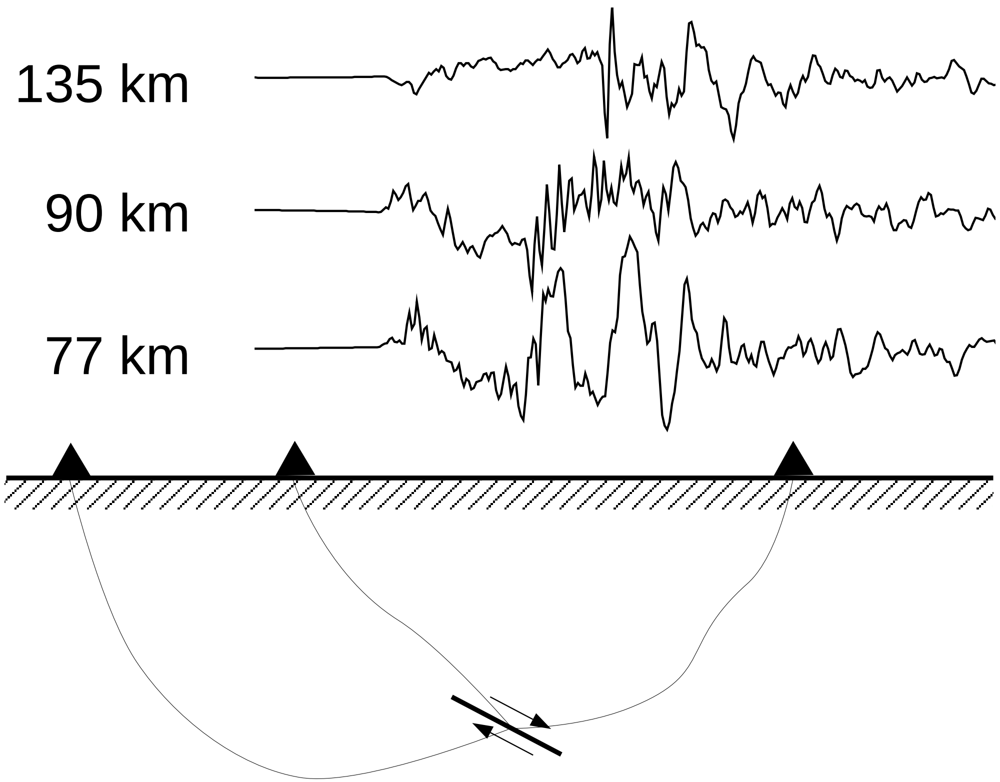
- Zhu and Zhou, Physics and Chemistry of the Earth, 2016.

Outline

1. Moment tensor inversion for a general seismic source.
2. Cut-and-Paste (CAP) moment inversion method.
3. Application to southern California earthquakes.
4. Application to the 2013 Ms 7.0 Lushan earthquake sequence.
5. Conclusions

Moment tensor and the Green's functions

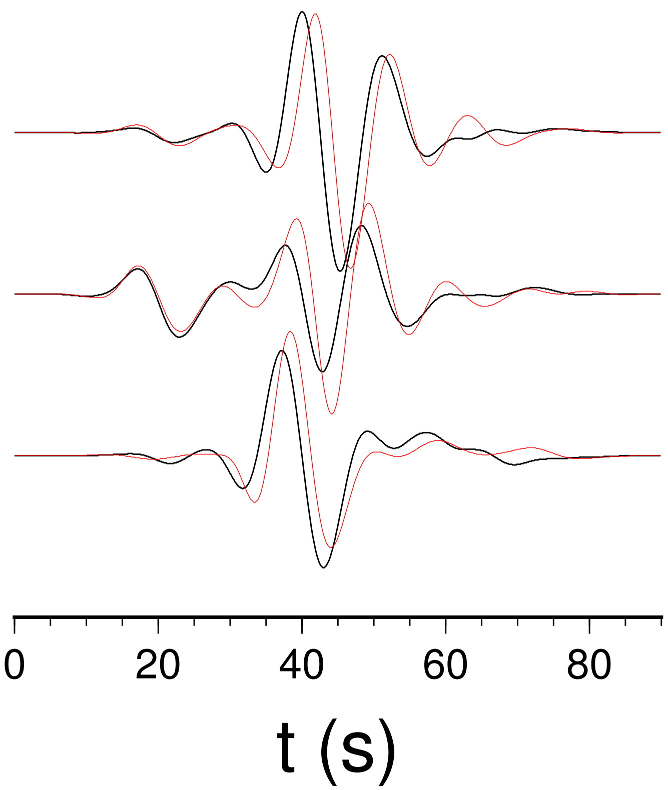


For a point seismic source of impulse source time function,

$$u(t) = M_{ij} G_{ij}(t), \qquad (1)$$

where $\mathbf{M}$ is the source moment tensor (symmetric, 6 independent components) and $G(t)$ is the Green's function.

Moment tensor inversion



Eq. (1) is a linear function of M_{ij} when the Green's functions are known. But imperfect velocity model and source location/origin time introduce a unknown time shift Δt,

$$u(t) = M_{ij} G_{ij}(t - \Delta t), \tag{2}$$

which makes the moment tensor inversion non-linear.

Parameterization of moment tensor

$$M_{ij} = M_0 D_{ij}, \quad (|\mathbf{D}| = \sqrt{2}) \tag{3}$$

$$D_{ij} = \zeta D_{ij}^{\mathrm{ISO}} + \sqrt{1-\zeta^2}\left(\sqrt{1-\chi^2} D_{ij}^{\mathrm{DC}} + \chi D_{ij}^{\mathrm{CLVD}}\right), \tag{4}$$

$$D_{ij}^{\mathrm{ISO}} = \sqrt{\frac{2}{3}}\delta_{ij}, \tag{5}$$

$$D_{ij}^{\mathrm{DC}} = n_i v_j + v_i n_j, \tag{6}$$

$$D_{ij}^{\mathrm{CLVD}} = \frac{1}{\sqrt{3}}(2b_i b_j - v_i v_j - n_i n_j), \tag{7}$$

where M_0 is the scalar moment, $\hat{\mathrm{n}}$ is the fault normal vector (determined by the strike ϕ and dip δ of the fault plane), $\hat{\mathrm{v}}$ is the slip direction vector (determined by the rake λ), and $|\zeta| \leq 1$ and $|\chi| \leq 1/2$ are non-dimensional parameters quantifying the strength of isotropic and CLVD components, respectively.

Generalized Cut-and-Paste (gCAP3D) method

gCAP3D uses a grid search to solve Eq. (2) for source parameters

$$\mathbf{m} = (\zeta, \chi, \phi, \delta, \lambda)^{\mathrm{T}}. \tag{8}$$

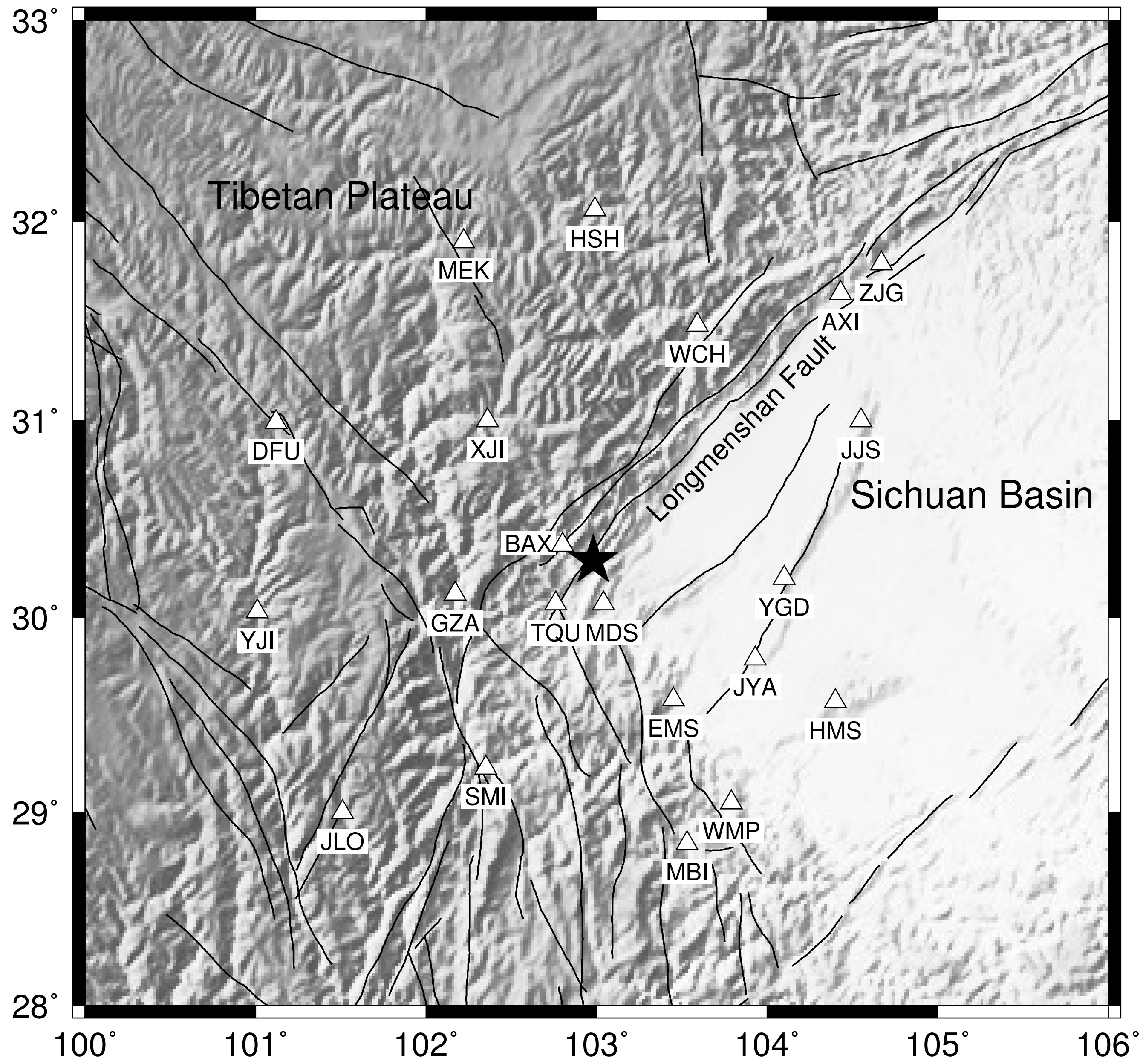
For each possible set of source parameters, it first finds Δt by cross-correlating $u(t)$ and $s(t) = D_{ij}G_{ij}(t)$ and estimates the scalar moment,

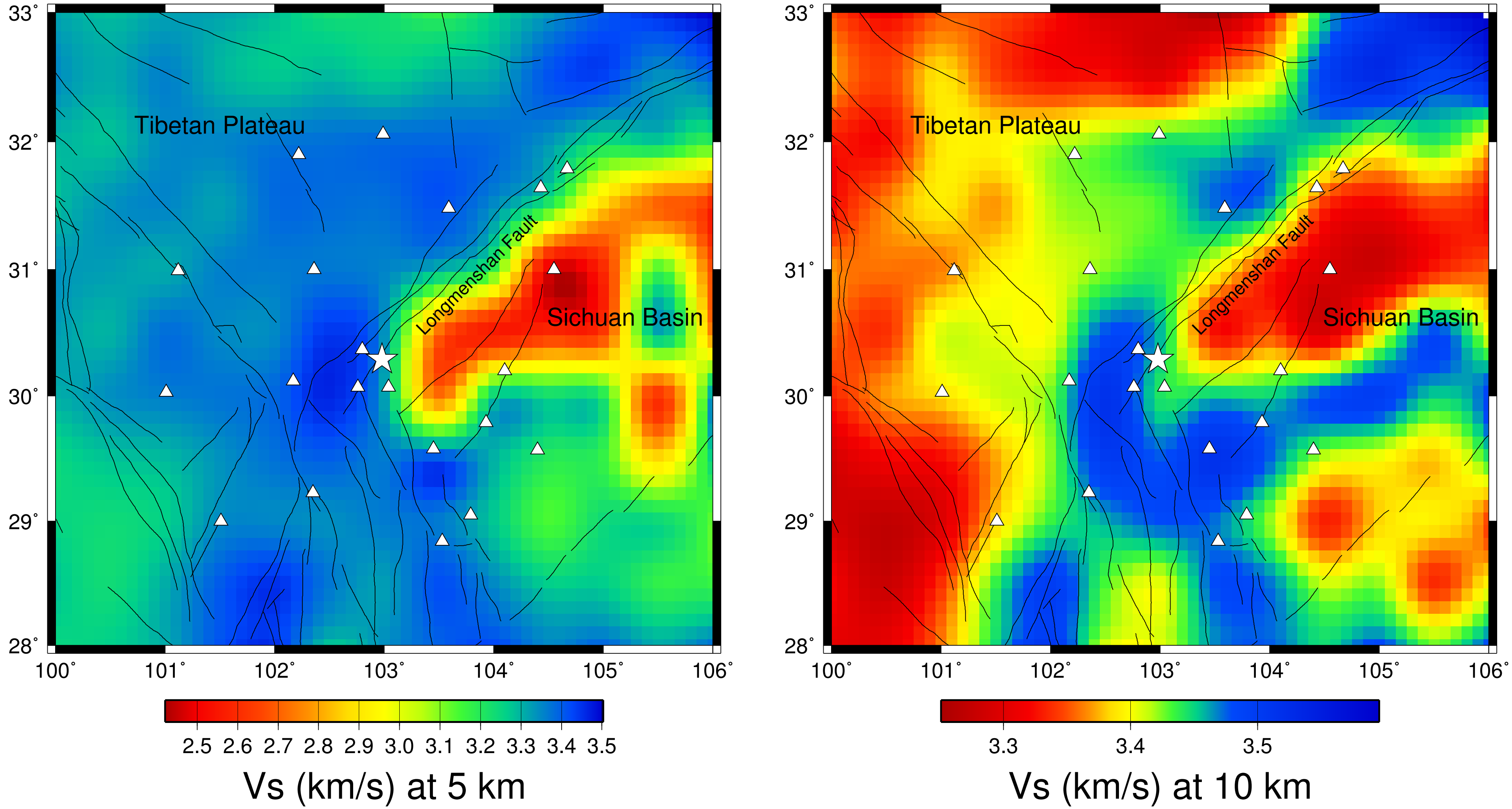
$$M_0 = \frac{\|u\|}{\|s\|}. \tag{9}$$

It then calculates the waveform misfit e using the L_2 norm of the difference between observed and predicted waveform,

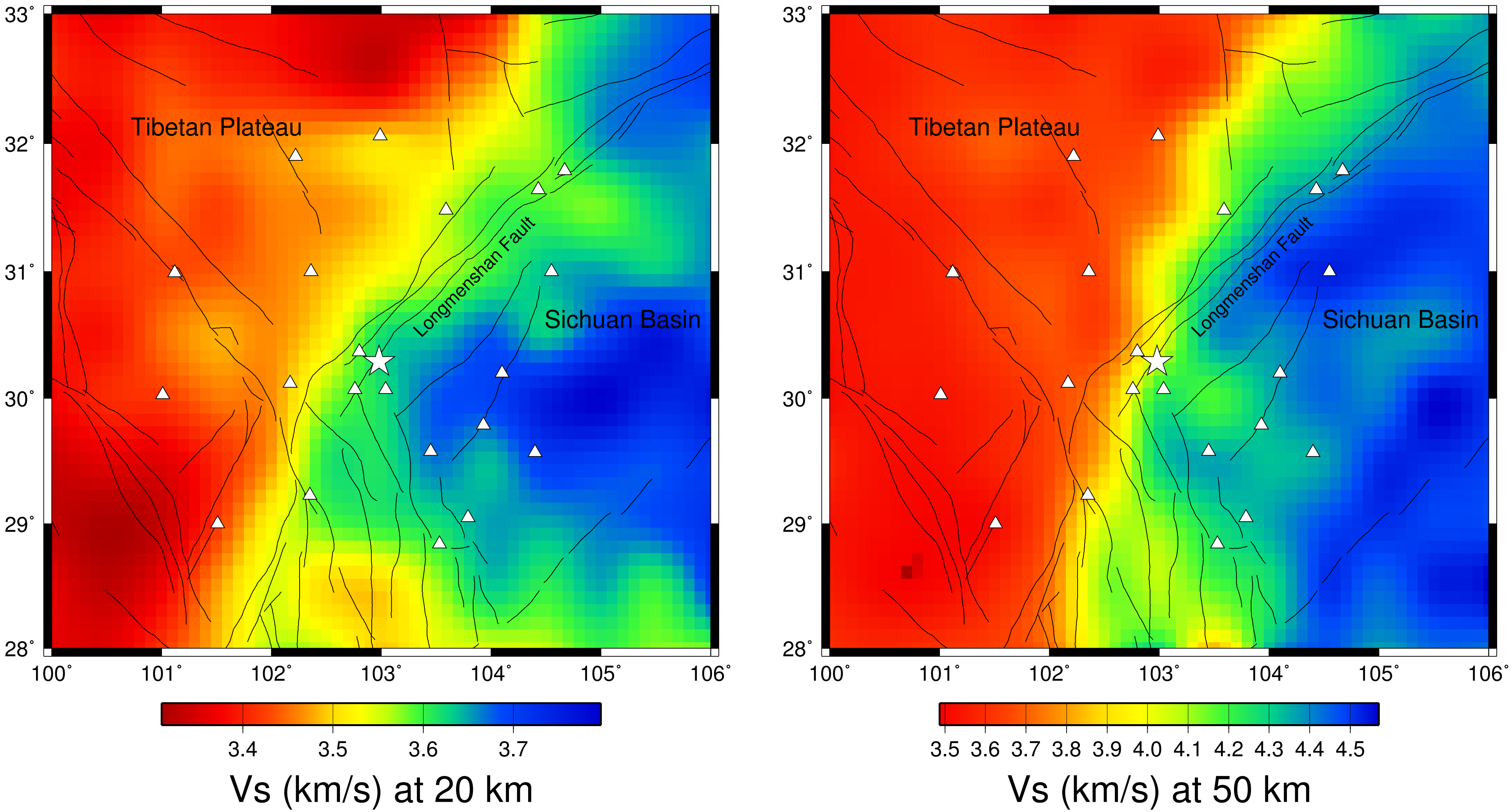
$$E = \sum_{i=1}^{N_s} \left(w^2 \left(\frac{r_i}{r_0}\right)^2 \left(e_i^{PnlZ} + e_i^{PnlR}\right) + \frac{r_i}{r_0} \left(e_i^{RaylZ} + e_i^{RaylR} + e_i^{Love}\right) \right), \tag{10}$$

$$e = \|u(t) - M_0 s(t - \Delta t)\|^2. \tag{11}$$


33°
32°
31°
30°
29°
28°
100°
101°
102°
103°
104°
105°
106°
Tibetan Plateau
Sichuan Basin
Longmenshan Fault
HSH
MEK
WCH
ZJG
AXI
DFU
XJI
JJS
BAX
GZA
TQU
MDS
YGD
YJI
JYA
EMS
HMS
SMI
JLO
WMP
MBI

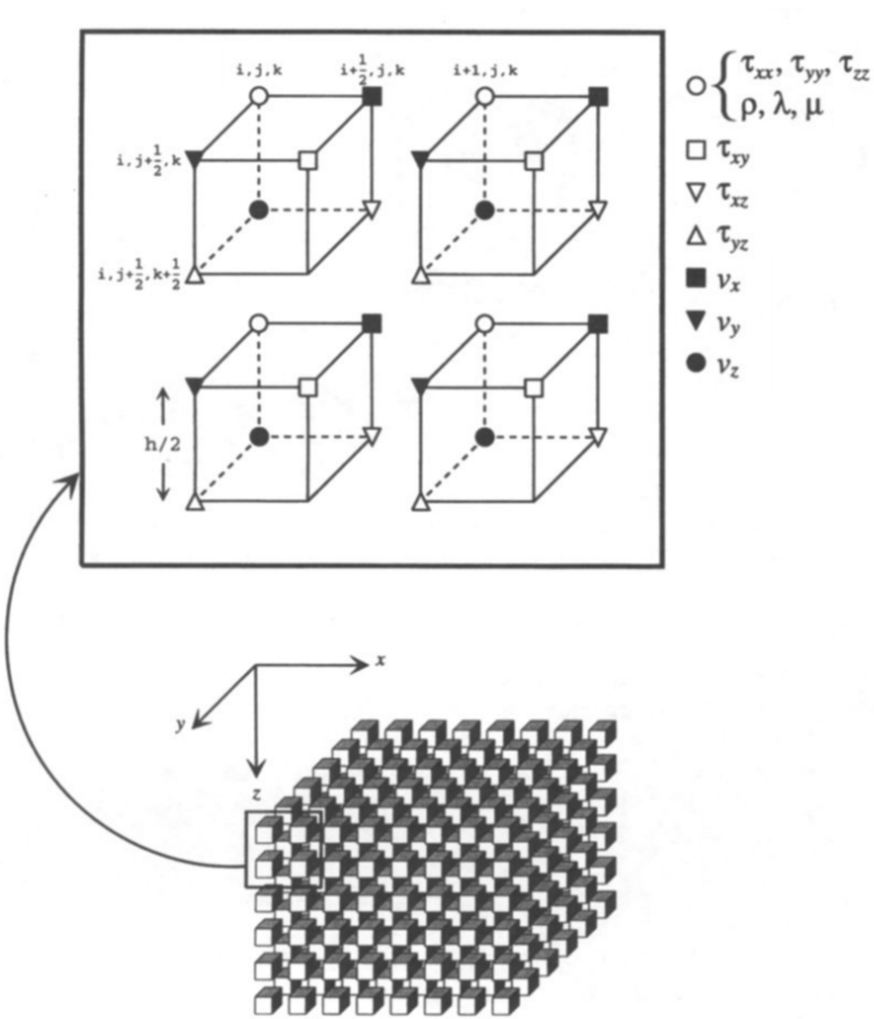


Zhen et al., 2013

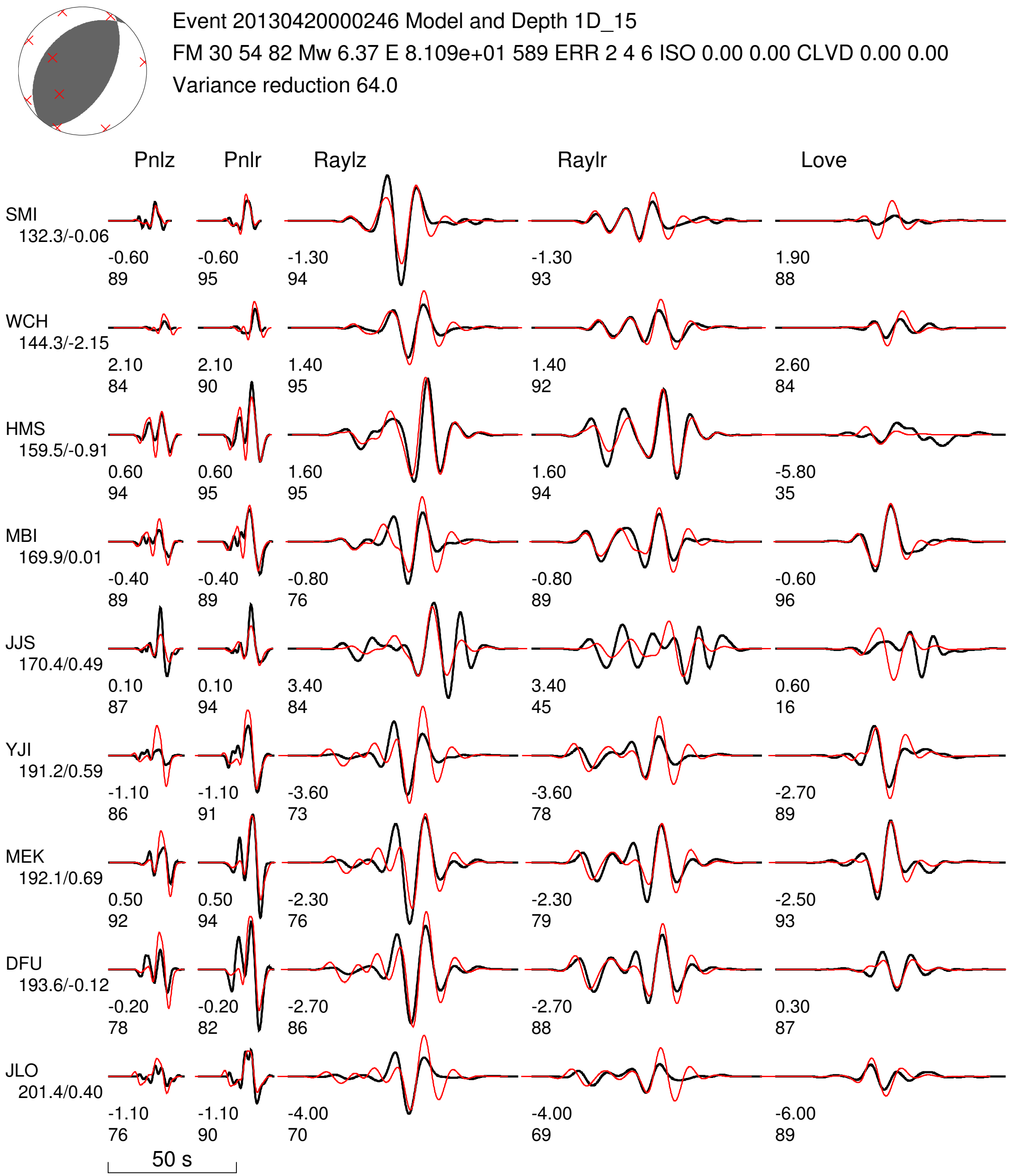


Zhen et al., 2013

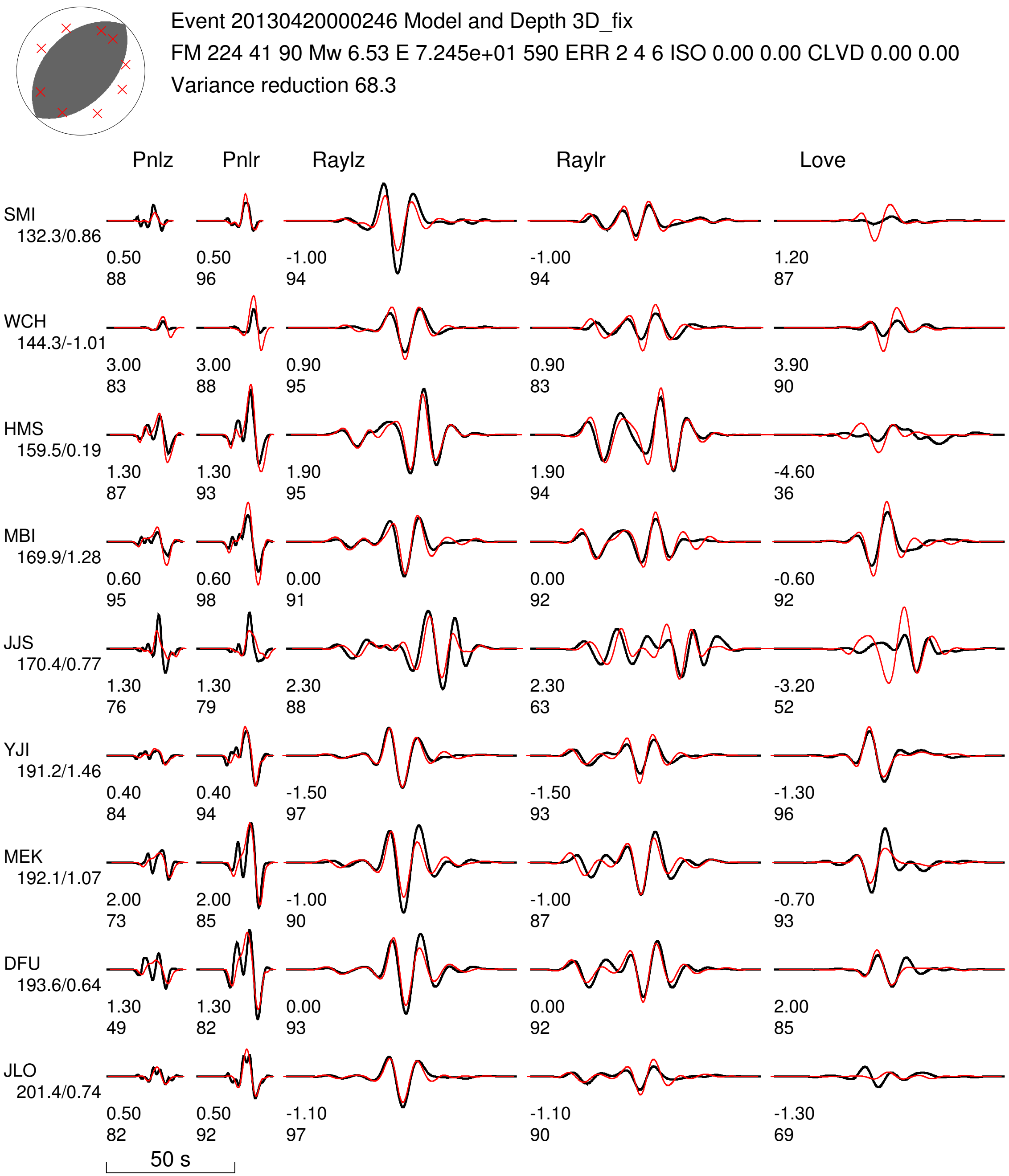
Unit Cell for Staggered-Grid Formulation

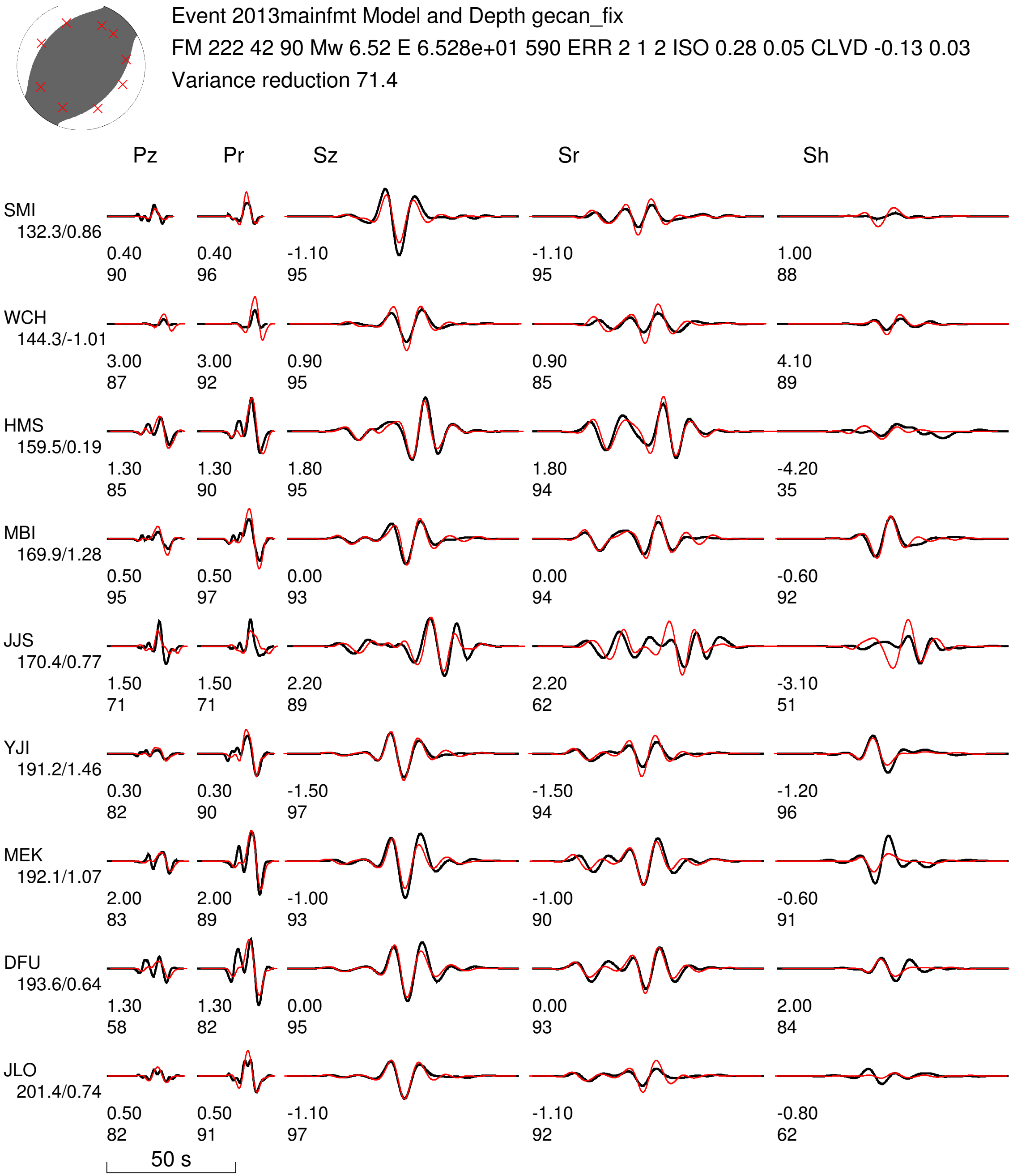


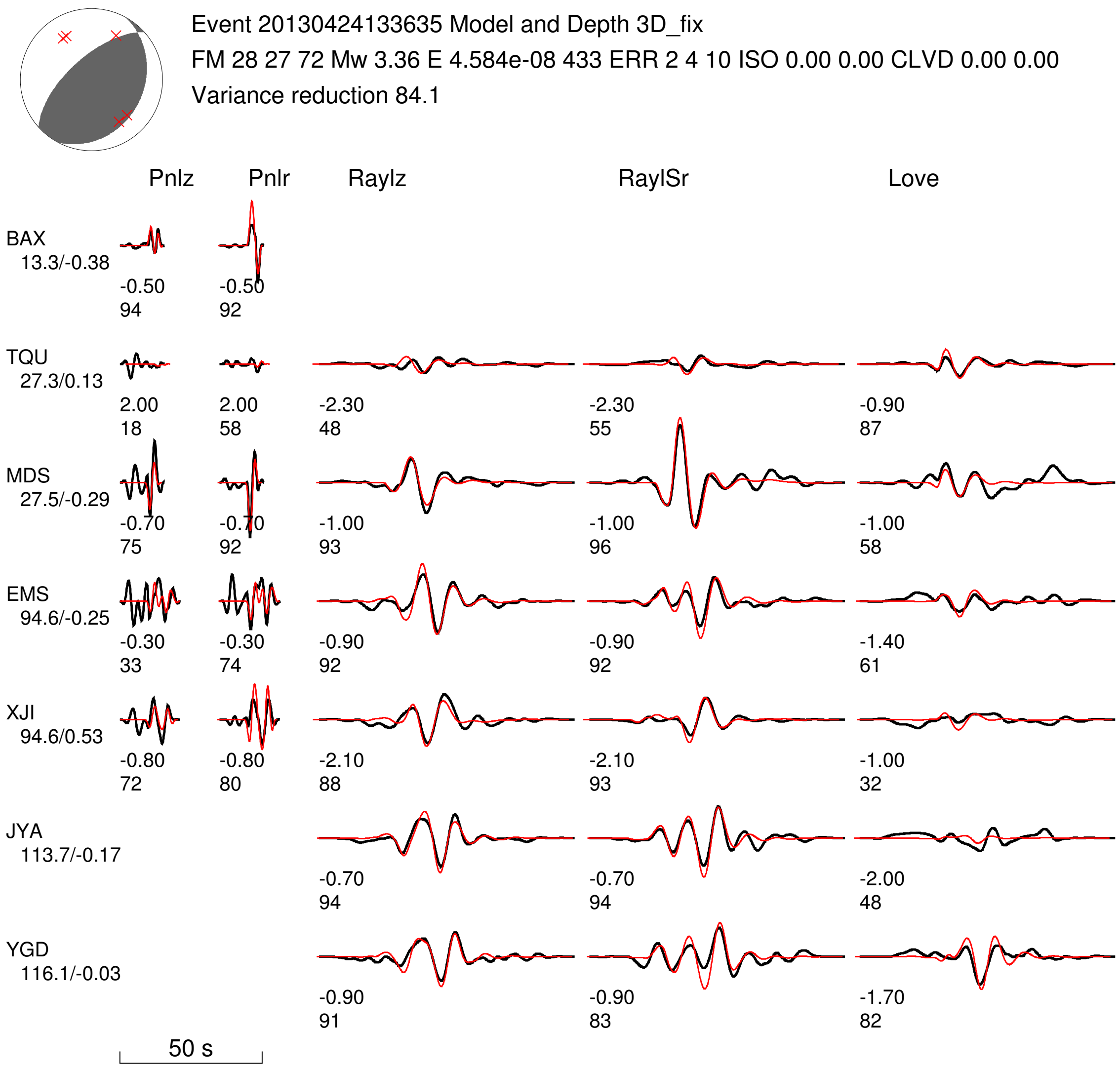
- EMOD3D code by R. Graves (1996).
- Staggered grid, 4th-order FD.
- 450×450×150 km.
- Grid spacing 1 km, f_{max}=0.4 Hz.
- Use the reciprocity principle to reduce the number of FD runs.
- Takes ∼4 Hrs. per station.

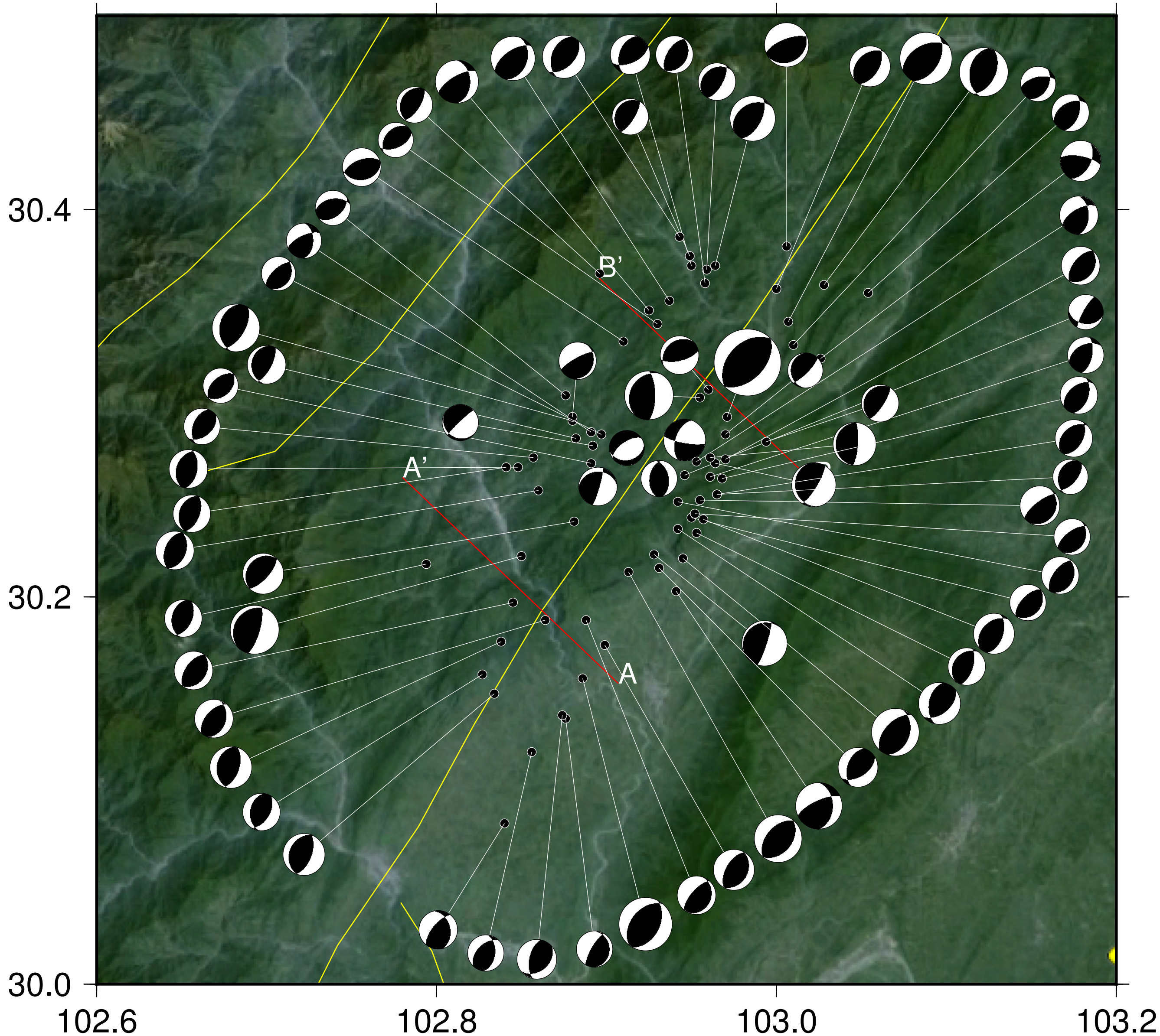


Event 20130420000246 Model and Depth 1D_15
FM 30 54 82 Mw 6.37 E 8.109e+01 589 ERR 2 4 6 ISO 0.00 0.00 CLVD 0.00 0.00
Variance reduction 64.0
Pnlz
Pnlr
Raylz
Raylr
Love
SMI
132.3/-0.06
-0.60
89
-0.60
95
-1.30
94
-1.30
93
1.90
88
WCH
144.3/-2.15
2.10
84
2.10
90
1.40
95
1.40
92
2.60
84
HMS
159.5/-0.91
0.60
94
0.60
95
1.60
95
1.60
94
-5.80
35
MBI
169.9/0.01
-0.40
89
-0.40
89
-0.80
76
-0.80
89
-0.60
96
JJS
170.4/0.49
0.10
87
0.10
94
3.40
84
3.40
45
0.60
16
YJI
191.2/0.59
-1.10
86
-1.10
91
-3.60
73
-3.60
78
-2.70
89
MEK
192.1/0.69
0.50
92
0.50
94
-2.30
76
-2.30
79
-2.50
93
DFU
193.6/-0.12
-0.20
78
-0.20
82
-2.70
86
-2.70
88
0.30
87
JLO
201.4/0.40
-1.10
76
-1.10
90
-4.00
70
-4.00
69
-6.00
89
50 s

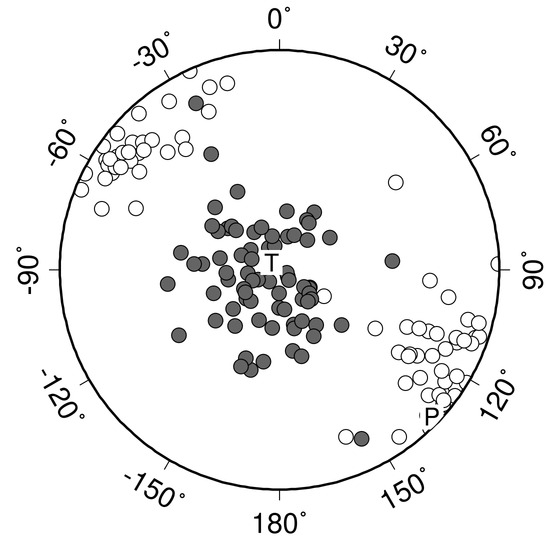

Event 20130420000246 Model and Depth 3D_fix
FM 224 41 90 Mw 6.53 E 7.245e+01 590 ERR 2 4 6 ISO 0.00 0.00 CLVD 0.00 0.00
Variance reduction 68.3
Pnlz
Pnlr
Raylz
Raylr
Love
SMI
132.3/0.86
0.50
88
0.50
96
-1.00
94
-1.00
94
1.20
87
WCH
144.3/-1.01
3.00
83
3.00
88
0.90
95
0.90
83
3.90
90
HMS
159.5/0.19
1.30
87
1.30
93
1.90
95
1.90
94
-4.60
36
MBI
169.9/1.28
0.60
95
0.60
98
0.00
91
0.00
92
-0.60
92
JJS
170.4/0.77
1.30
76
1.30
79
2.30
88
2.30
63
-3.20
52
YJI
191.2/1.46
0.40
84
0.40
94
-1.50
97
-1.50
93
-1.30
96
MEK
192.1/1.07
2.00
73
2.00
85
-1.00
90
-1.00
87
-0.70
93
DFU
193.6/0.64
1.30
49
1.30
82
0.00
93
0.00
92
2.00
85
JLO
201.4/0.74
0.50
82
0.50
92
-1.10
97
-1.10
90
-1.30
69
50 s


Event 2013mainfmt Model and Depth gecan_fix
FM 222 42 90 Mw 6.52 E 6.528e+01 590 ERR 2 1 2 ISO 0.28 0.05 CLVD -0.13 0.03
Variance reduction 71.4
Pz
Pr
Sz
Sr
Sh
SMI
132.3/0.86
0.40
90
0.40
96
-1.10
95
-1.10
95
1.00
88
WCH
144.3/-1.01
3.00
87
3.00
92
0.90
95
0.90
85
4.10
89
HMS
159.5/0.19
1.30
85
1.30
90
1.80
95
1.80
94
-4.20
35
MBI
169.9/1.28
0.50
95
0.50
97
0.00
93
0.00
94
-0.60
92
JJS
170.4/0.77
1.50
71
1.50
71
2.20
89
2.20
62
-3.10
51
YJI
191.2/1.46
0.30
82
0.30
90
-1.50
97
-1.50
94
-1.20
96
MEK
192.1/1.07
2.00
83
2.00
89
-1.00
93
-1.00
90
-0.60
91
DFU
193.6/0.64
1.30
58
1.30
82
0.00
95
0.00
93
2.00
84
JLO
201.4/0.74
0.50
82
0.50
91
-1.10
97
-1.10
92
-0.80
62
50 s

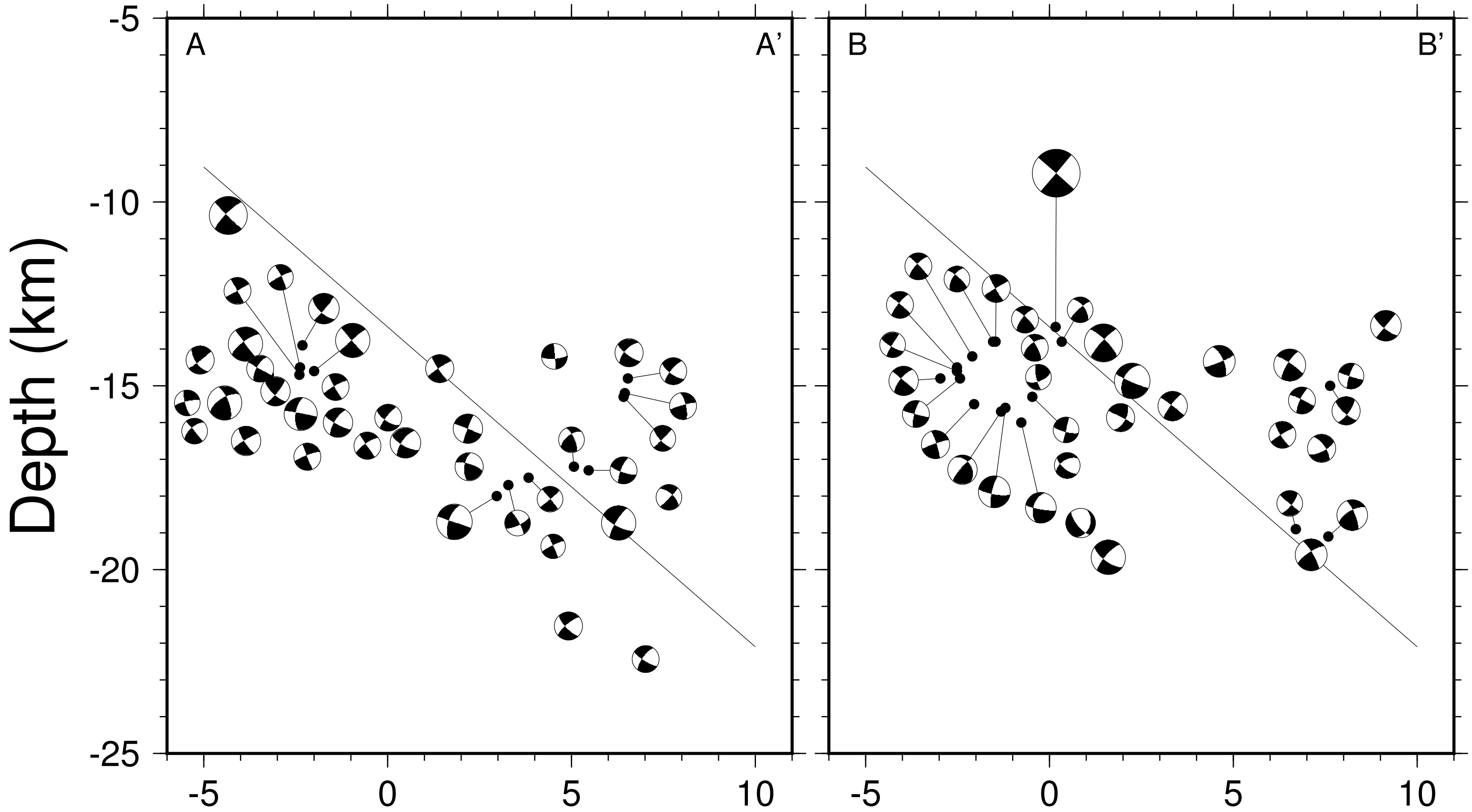

Event 20130424133635 Model and Depth 3D_fix
FM 28 27 72 Mw 3.36 E 4.584e-08 433 ERR 2 4 10 ISO 0.00 0.00 CLVD 0.00 0.00
Variance reduction 84.1
Pnlz
Pnlr
Raylz
RaylSr
Love
BAX
13.3/-0.38
-0.50
94
-0.50
92
TQU
27.3/0.13
2.00
18
2.00
58
-2.30
48
-2.30
55
-0.90
87
MDS
27.5/-0.29
-0.70
75
-0.70
92
-1.00
93
-1.00
96
-1.00
58
EMS
94.6/-0.25
-0.30
33
-0.30
74
-0.90
92
-0.90
92
-1.40
61
XJI
94.6/0.53
-0.80
72
-0.80
80
-2.10
88
-2.10
93
-1.00
32
JYA
113.7/-0.17
-0.70
94
-0.70
94
-2.00
48
YGD
116.1/-0.03
-0.90
91
-0.90
83
-1.70
82
50 s



30.4
30.2
30.0
102.6
102.8
103.0
103.2
B'
A'
A



0°
30°
60°
90°
120°
150°
180°
-150°
-120°
-90°
-60°
-30°
T
P



A
A'
B
B'
Depth (km)
-5
-10
-15
-20
-25
-5
0
5
10
-5
0
5
10

Conclusions

- We developed a method for determining moment tensors using 3D Greens functions.
- It uses grid search for the best source parameters that minimize waveform misfit.
- We applied the method to the 2013 Ms 7.0 Lushan earthquake sequence.
- We obtained 75 moment tensor solutions ranging from Mw 6.5 to 3.4.
- The mainshock is a reverse faulting on a plane dipping 40-47°. to the NW.