

# Estimation of full moment tensors, including uncertainties, for earthquakes, volcanic events, and nuclear explosions

Celso Alvizuri<sup>1,2</sup>, Vipul Silwal<sup>1</sup>, Lion Krischer<sup>3</sup>, Carl Tape<sup>1</sup>

<sup>1</sup>University of Alaska Fairbanks, USA; <sup>2</sup>University of Lausanne, Switzerland; <sup>3</sup>University of Munich, Germany. Email: cralvizuri@alaska.edu

## Abstract

A seismic moment tensor is a  $3 \times 3$  symmetric matrix that provides a compact representation of seismic events within Earth's crust. We develop an algorithm to estimate moment tensors and their uncertainties from observed seismic data. For a given event, the algorithm performs a grid search over the six-dimensional space of moment tensors by generating synthetic waveforms at each grid point and then evaluating a misfit function between the observed and synthetic waveforms. The moment tensor  $M$  for the event is then the moment tensor with minimum misfit. To describe the uncertainty associated with  $M$ , we first convert the misfit function to a probability function. The uncertainty, or rather the confidence, is then given by the 'confidence curve'  $P(V)$ , where  $P(V)$  is the probability that the true moment tensor for the event lies within the neighborhood of  $M$  that has fractional volume  $V$ . The area under the confidence curve provides a single, abbreviated 'confidence parameter' for  $M$ . We apply the method to data from events in different regions and tectonic settings: small ( $M_w < 2.5$ ) events at Uturuncu volcano in Bolivia, moderate ( $M_w > 4$ ) earthquakes in the southern Alaska subduction zone, and natural and man-made events at the Nevada Test Site. Moment tensor uncertainties allow us to better discriminate among moment tensor source types and to assign physical processes to the events.

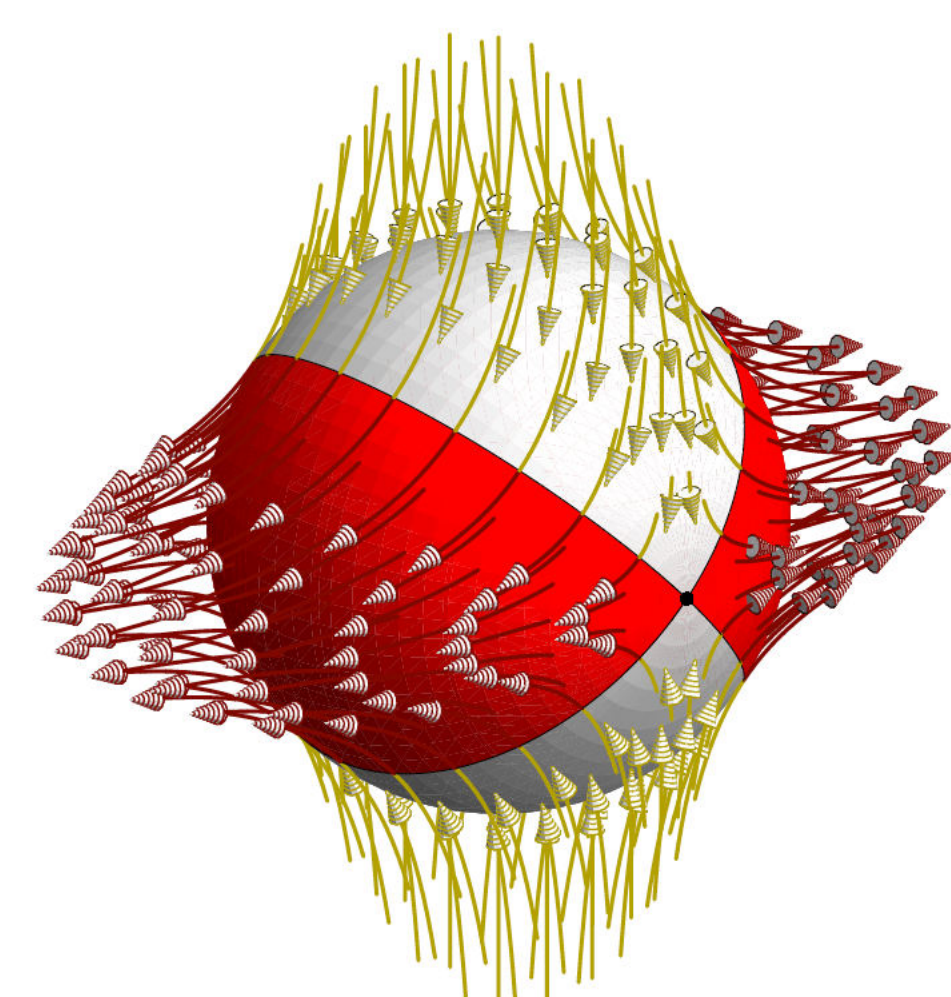
## Method

### The seismic moment tensor

$$\mathbf{M} = \mathbf{U} [\mathbf{\Lambda}] \mathbf{U}^{-1}$$

$$[\mathbf{\Lambda}] = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}$$

- $3 \times 3$  symmetric matrix
- $\mathbf{M}$ : moment tensor
- $\mathbf{U}$ : Orientation matrix
- $\mathbf{\Lambda}$ : moment tensor eigenvalues
- $\lambda_1 > \lambda_2 > \lambda_3$



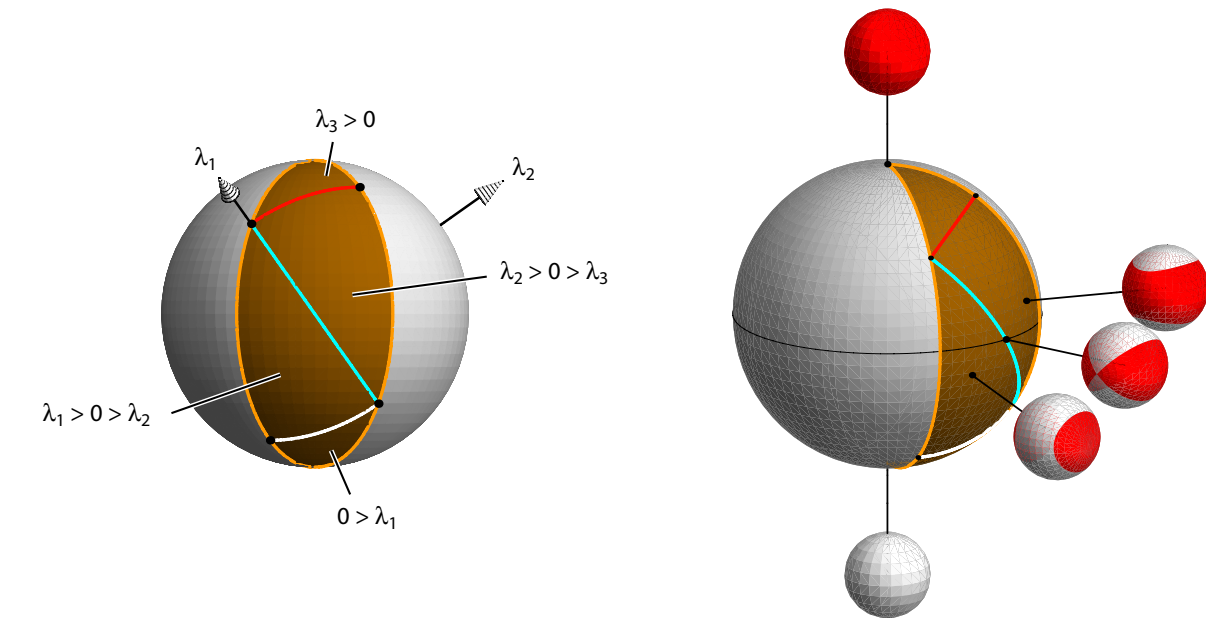
- Red: compression (motions out)
- White: dilatation (motions in)

## Moment tensor parameterization

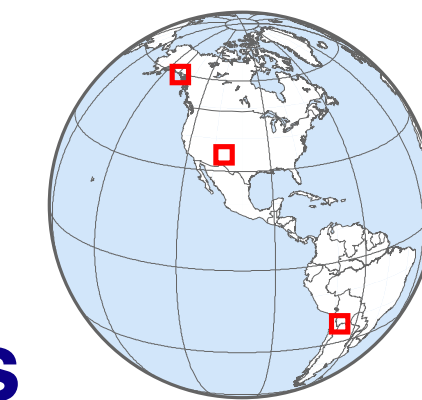
$$\mathbf{M}(\gamma, \delta, \kappa, \theta, \sigma) = [\mathbf{\Lambda}(\gamma, \delta)] \hat{\mathbf{U}}(\kappa, \theta, \sigma)$$

- Eigenvalues organized on a section of a lune
- Two parameters describe location on the lune:  $\gamma, \delta$
- Three parameters describe the orientation:  $\kappa, \theta, \sigma$
- Magnitude search  $|\mathbf{\Lambda}| \propto Mw$

## Four regimes for moment tensors



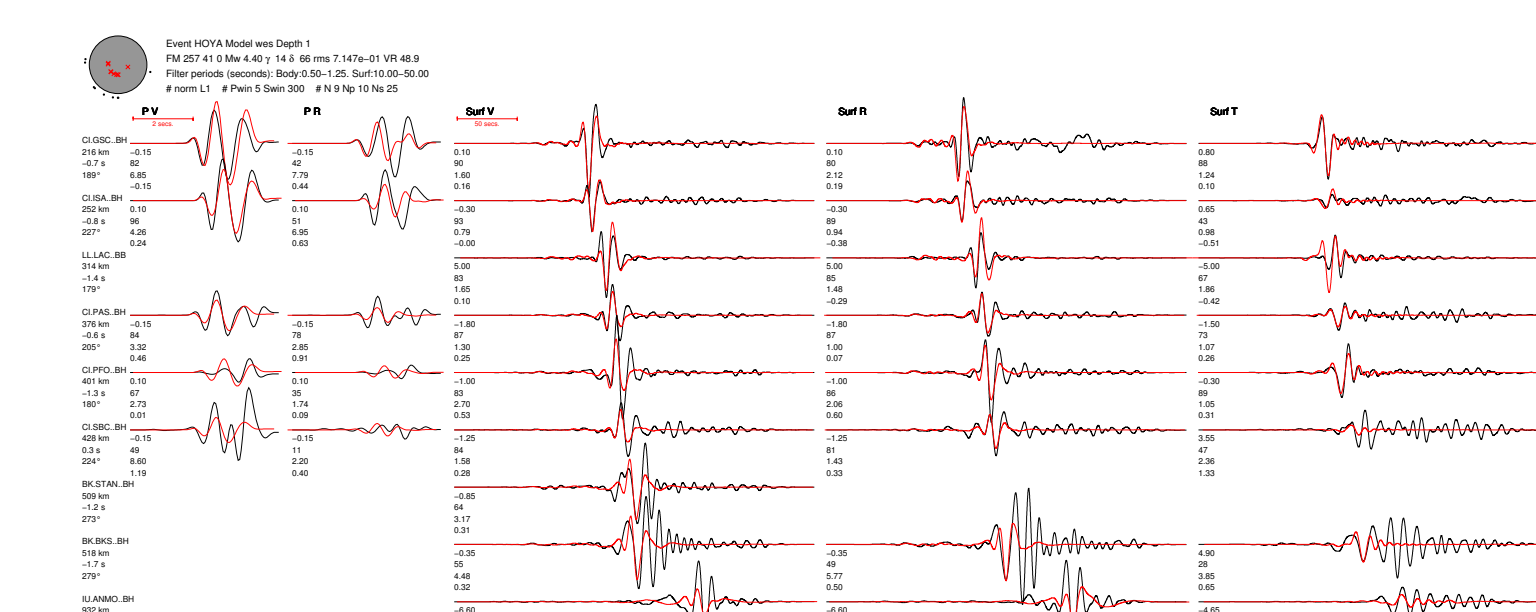
All motions out  $\lambda_3 > 0$     All motions in  $\lambda_1 < 0$   
 White caps  $\lambda_1 > 0 > \lambda_3$     Red caps  $\lambda_1 > 0 > \lambda_2$



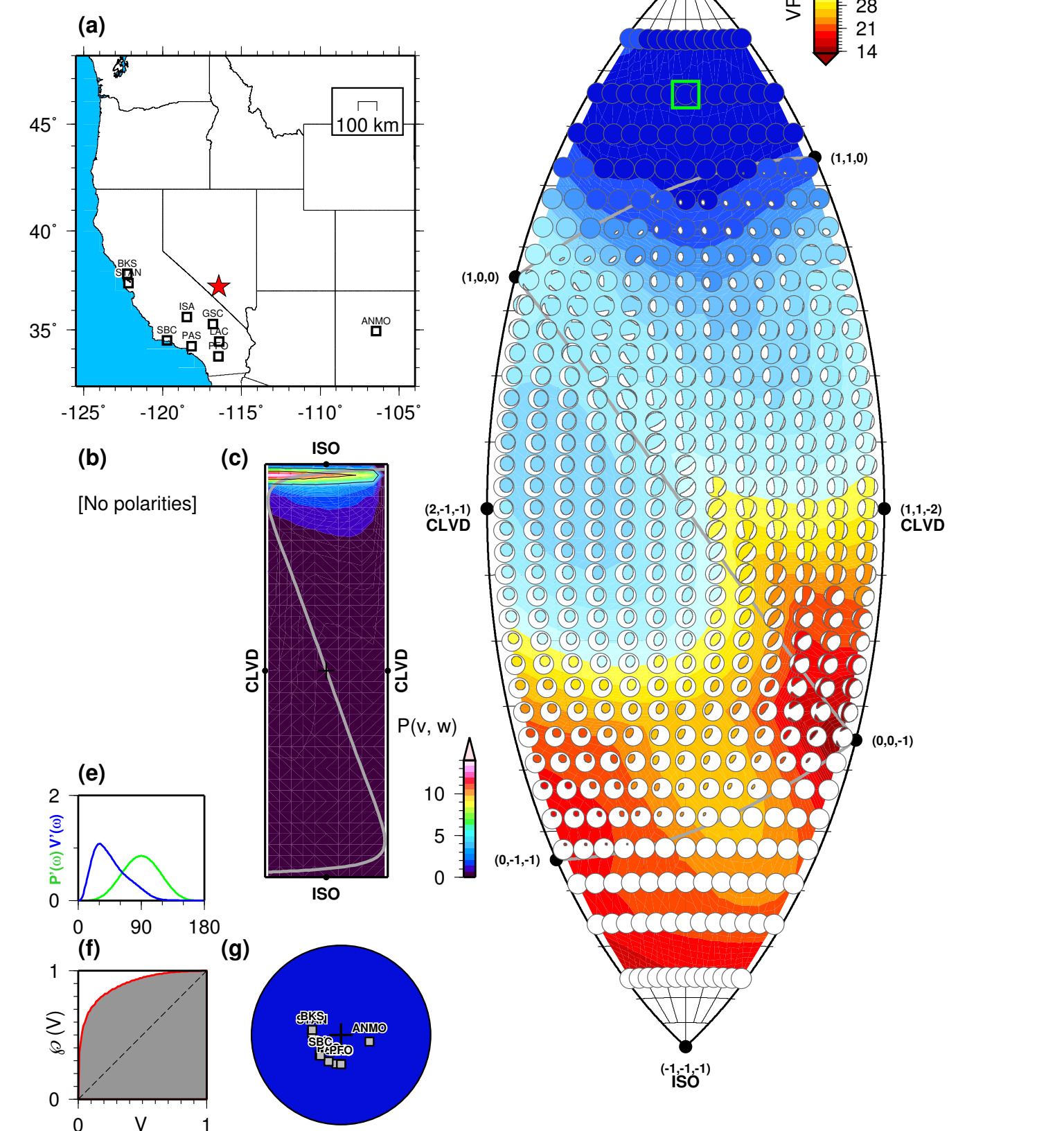
## Applications

- Nevada Test Site (Western U.S.)
- Alaska
- Uturuncu volcano, Bolivia

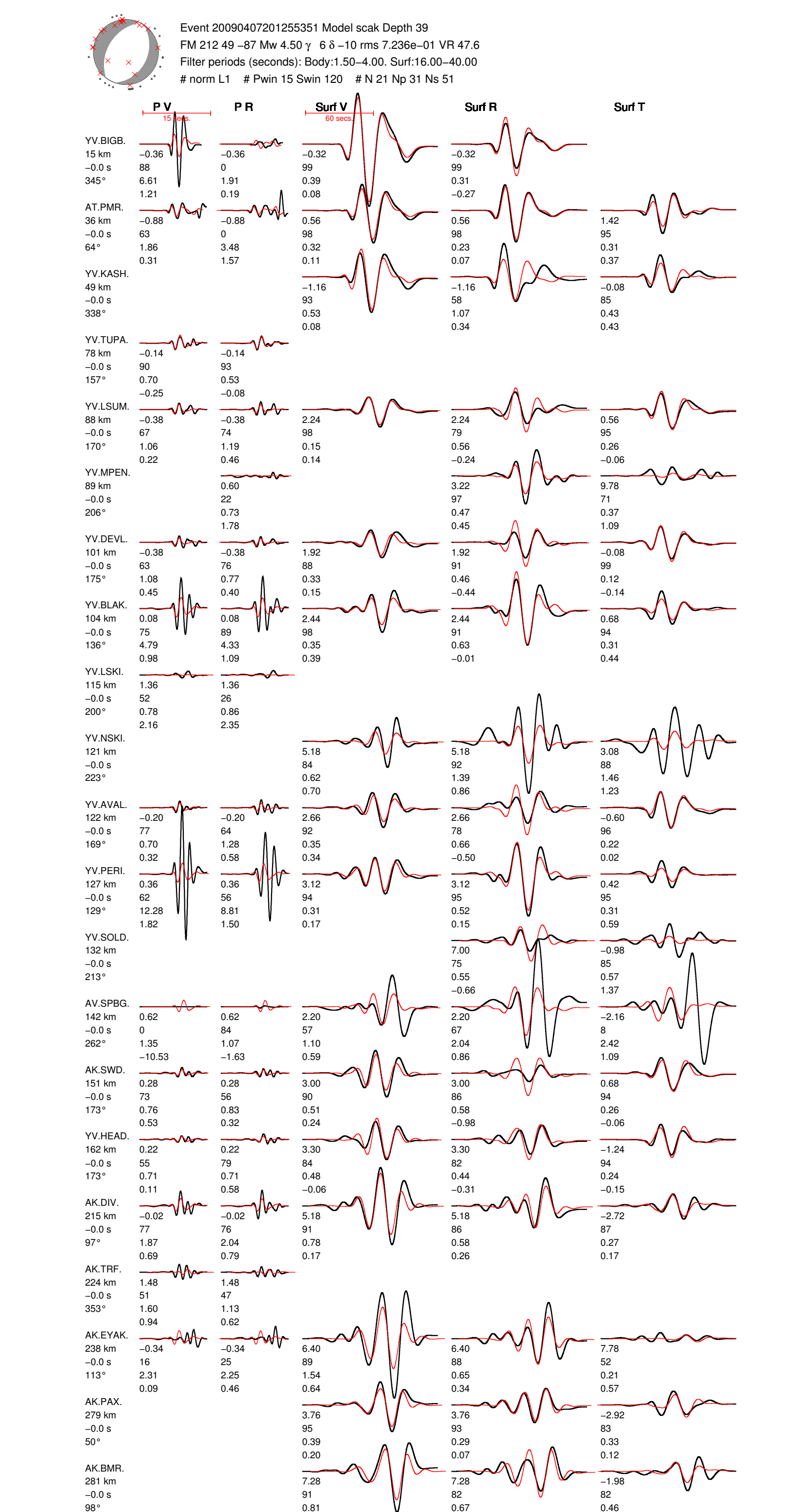
## Nuclear explosions at the Nevada Test Site, USA



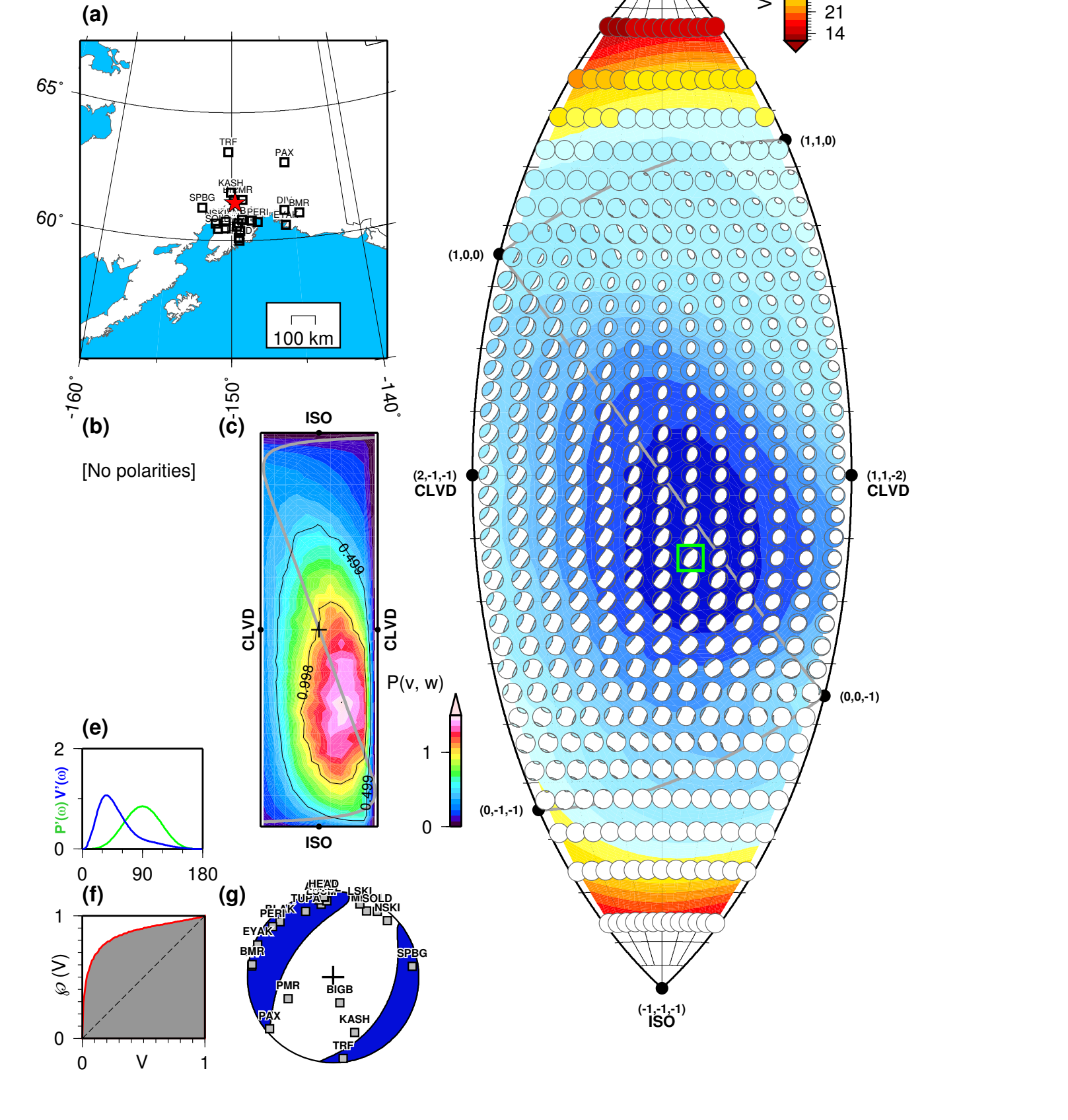
Event HOYA, M 4.40  
 Lon -116.4280, Lat 37.2280  
 Dep 0.0 km (inversion 1 km)  
 Best source type  $\gamma 0^\circ, \delta 66^\circ$



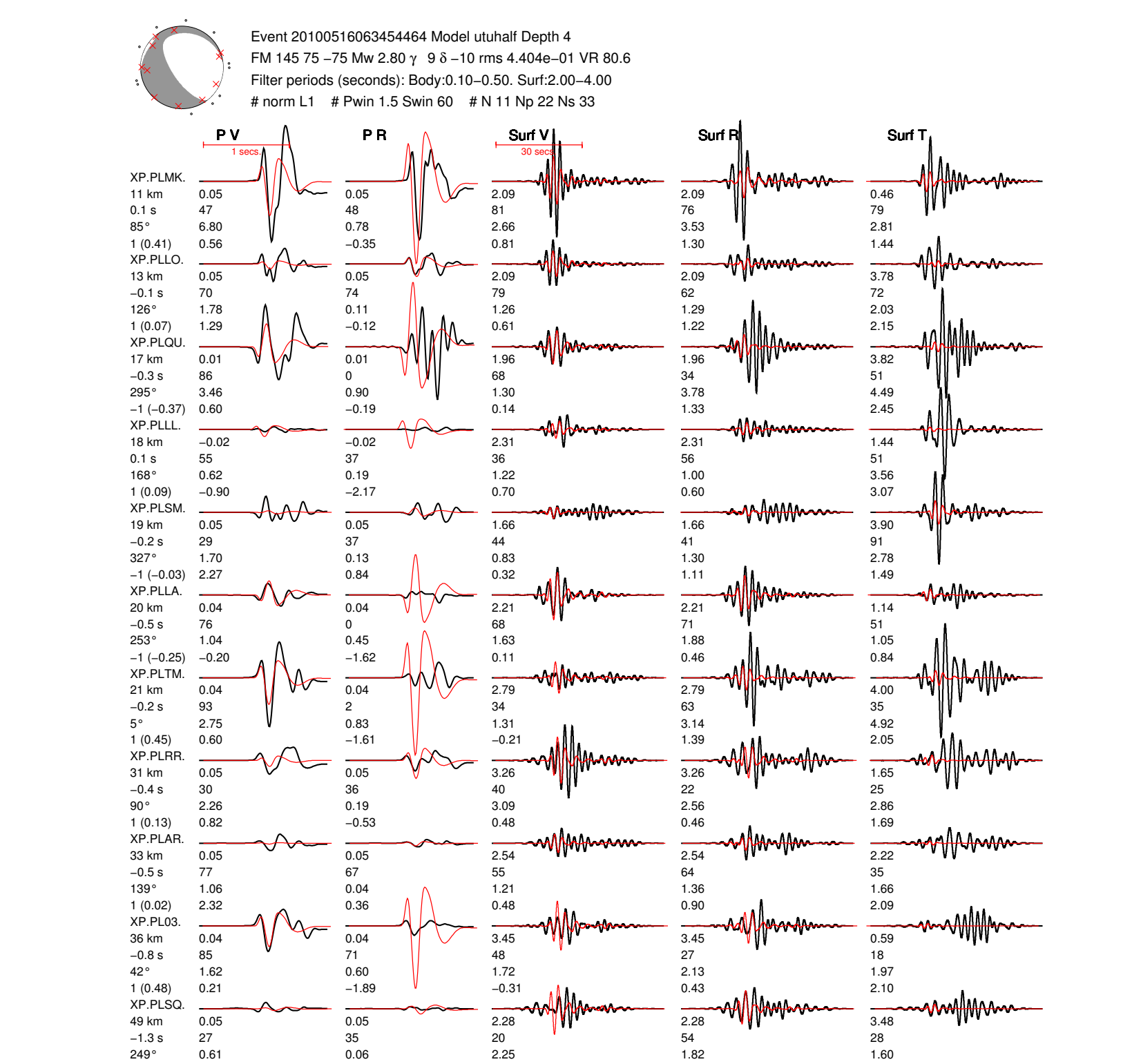
## Earthquakes in south-central Alaska, USA



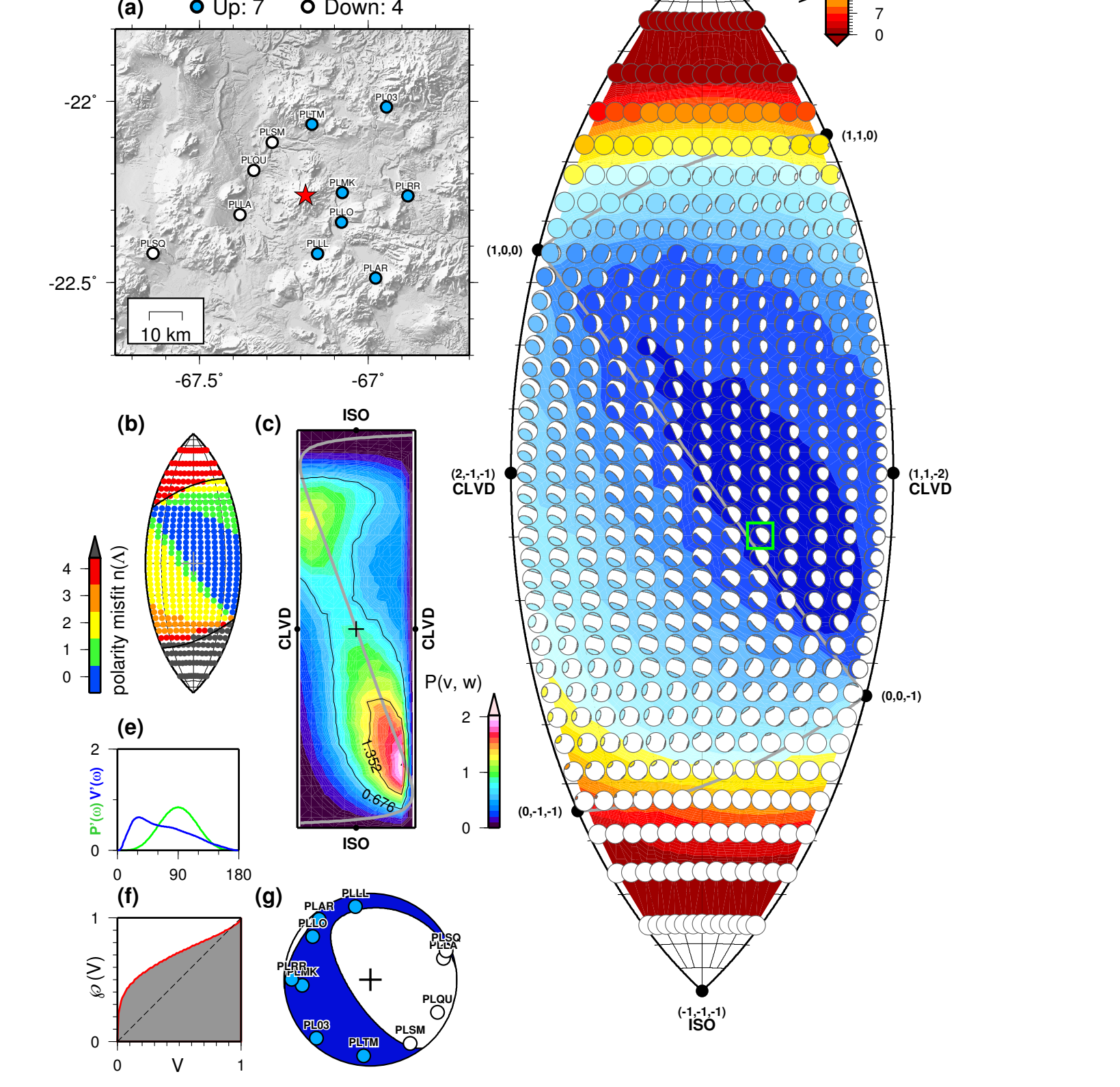
Event 20090407201255351, M 4.50  
 Lon -149.7428, Lat 61.4542  
 Dep 39.0 km (inversion 39 km)  
 Best source type  $\gamma 5^\circ, \delta -13^\circ$



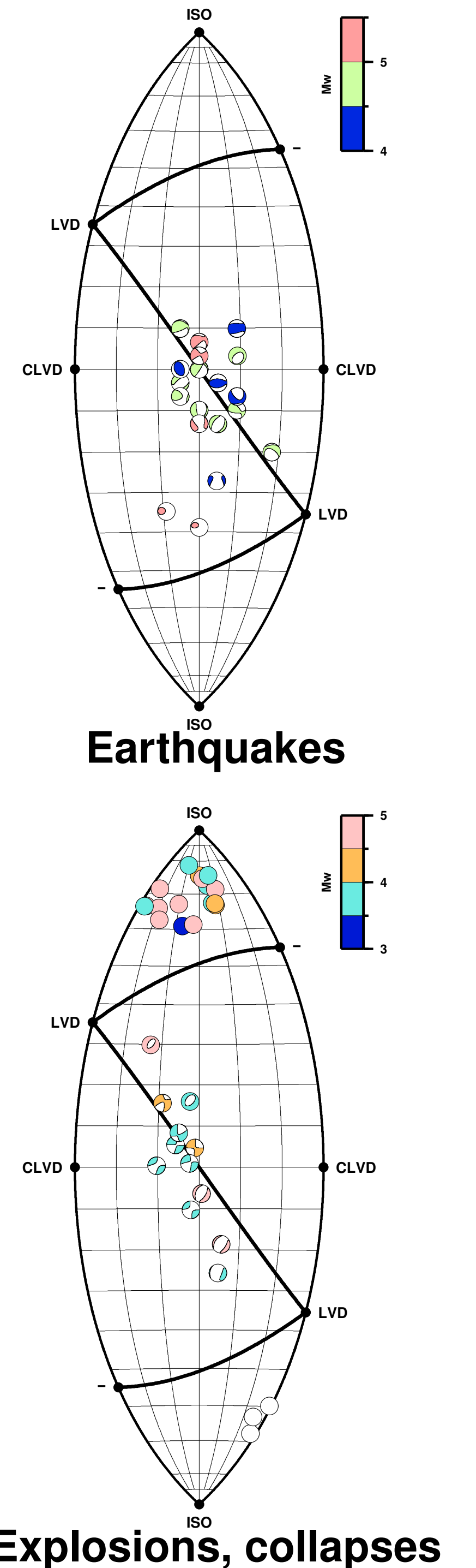
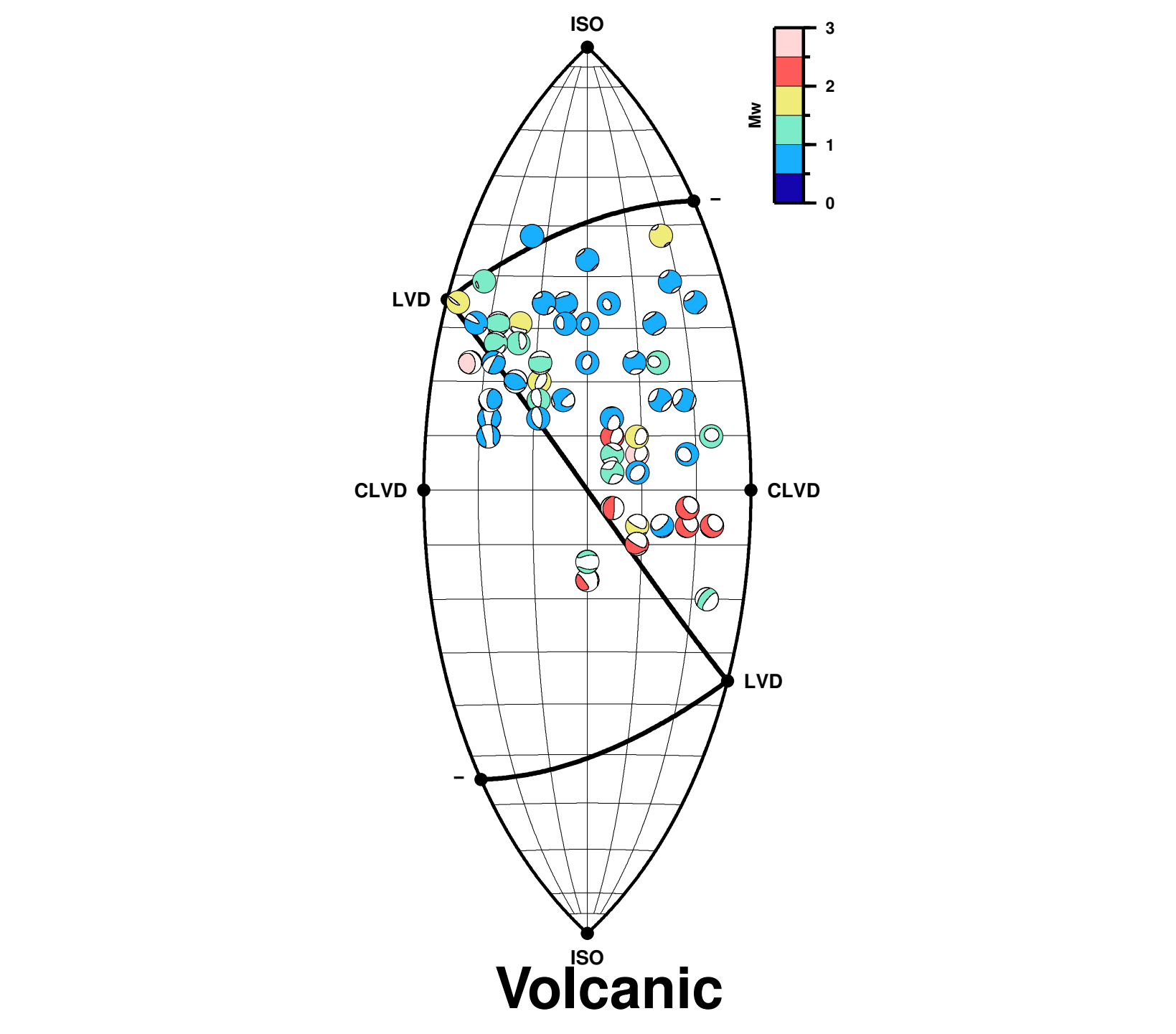
## Volcanic events at Uturuncu volcano, Bolivia



Event 20100516063454464, M 2.80  
 Lon -67.1856, Lat -22.2800  
 Dep -0.6 km (inversion 4 km)  
 Best source type  $\gamma 9^\circ, \delta -10^\circ$



## Moment tensor catalogs



## Summary

### Methodological development

- Efficient full moment tensor estimation
- Uncertainties for full moment tensors
- Confidence parameter
- Probability for source types

### Applications

- Nuclear explosions (Alvizuri et al., 2017)
- Earthquakes (Alvizuri et al., 2017)
- Volcanic events (Alvizuri and Tape, 2016)

### Future work

- Analyze non-DC mechanisms in deep events
- Model physical mechanisms for non-DC events
- Estimate moment tensors for 3D structure

### References

Alvizuri, C., and C. Tape (2016), Full moment tensors for small events ( $M_w < 3$ ) at Uturuncu volcano, Bolivia, *Geophys. J. Int.*, 206, 1761–1783, doi:10.1093/gji/ggw247.

Alvizuri, C., V. Silwal, L. Krischer, and C. Tape (2017), Estimation of full moment tensors, including uncertainties, for earthquakes, volcanic events, and nuclear explosions, *Geophysics* (in prep.).

Ford, S. R., D. S. Dreger, and W. R. Walter (2009), Identifying isotropic events using a regional moment tensor inversion, *J. Geophys. Res.*, 114, B01306, doi:10.1029/2008JB005743.

Tape, W., and C. Tape (2012), A geometric setting for moment tensors, *Geophys. J. Int.*, 190, 476–498, doi:10.1111/j.1365-246X.2012.05191.x.

Tape, W., and C. Tape (2015), A uniform parameterization of moment tensors, *Geophys. J. Int.*, 202, 2074–2081, doi:10.1093/gji/ggv262.

Tape, W., and C. Tape (2016), A confidence parameter for seismic moment tensors, *Geophys. J. Int.*, 205, 936–953, doi:10.1093/gji/ggv057.