Source characteristics of modern and historical in-slab Cascadia earthquakes applicable to strong ground motion prediction

Annual Project Summary

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Gene A. Ichinose, Hong Kie Thio, and Paul G. Somerville

URS Group, Inc., 566 El Dorado St, 2nd Floor, Pasadena, CA 91101-2560

626.449.7650 (phone), 626.449.3536 (fax), *gene_ichinose@urscorp.com*

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Investigations undertaken

The objective of this project is to develop a detailed description of source characteristics for Benioff-zone (in-slab) earthquakes in the Cascadia subduction zone. The first part of this study produces a moment tensor catalog for in-slab earthquakes (see Table 1). Another part produces finite-fault rupture models for the 13 April 1949 Olympia, 29 April 1965 Seattle (Figure 3), and 28 February 2001 Nisqually (Figure 4) earthquakes. We are in the progress of simulating the Seattle and Nisqually earthquakes to generate shake maps of Peak Ground Acceleration and Pseudo Spectral Acceleration using the broadband method [*Pitarka et al*, 2000]. We are also generating source scaling relationships for in-slab earthquakes and will compare them to our database of global and regional source parameters.

Results

We have inverted the long-period regional displacements for the moment tensor of recent in-slab events (Table 1). The moment tensors and locations are shown in Figure 1 and the waveform fits are shown in Figure 2. We use the records from the 2001 Satsop earthquake recorded at Longmire (LON) to calibrate the local Green's functions. The new model is much slower in the upper-crust relative to the *Langston and Blum* [1977] PS-9 velocity model. PS-9, estimated from point-source teleseismic waveform modeling of the 1965 Seattle earthquake, best represents the source region at teleseismic distances. The regional data are instrument corrected to displacement and then filtered to within 20 to 200 seconds. The source depth and origin time are determined iteratively using a grid search scheme. The depth for the Nisqually event is 56 *km* but has an uncertainty of about 55 to 65 *km*. The two Satsop earthquakes had normal faulting focal mechanisms, similar to the Nisqually earthquake, but occurred updip at 41 and 45 *km*. We validated the moment tensor solutions by computing the predicted fit for ground motions up to frequencies of 1 *Hz* at local stations less than about 150 *km* from the source. These normal faulting earthquakes apparently resulted from localized tensile stresses within the subducting Juan de Fuca slab. The tensile stresses may be related to a bend in the slab where the largest earthquakes in the Puget Sound have occurred in historical time.

TABLE 1. Moment Tensor Inversion Results

Date Yr/Mo/Da	Origin Time UT	Nodal Plane 1 Strike/Dip/Rake	Nodal Plane 2 Strike/Dip/Rake	$M_o^{(1)}$ (dyne*cm)	Depth (km)	M_w	$DC^{(2)}$	Location
1999/07/03	01:43:54	194°/36°/-54°	332°/62°/-113°	1.22×10^{25}	41	5.99	93%	Satsop
2001/02/28	18:54:32	177°/22°/-89°	356°/68°/-90°	3.60×10^{26}	56	6.97	88%	Nisqually
2001/06/10	13:19:10	131°/33°/-113°	338°/60°/-76°	4.15×10^{23}	45	5.02	93%	Satsop

(1) seismic moment estimated using an upper mantle rather than crustal rigidity; (2)DC-percent double couple

We use the teleseismic seismograms in the inversion for the rupture history of the 1965 Seattle earthquake. *Langston and Blum* [1977] originally derived a point source model of the earthquake using 38 teleseismic recordings. The 104 WWSSN paper records from the 1965 earthquake were reproduced from the Caltech film chip library and then digitized. The instrument responses are convolved onto the Green's functions before the inversion. We use the PS-9 model to compute the Green's functions. We assume the steeply dipping fault plane from the focal mechanism estimated by *Langston and Blum* [1977] (strike=344, dip=70, rake=-75, $M_o=1.4\pm0.6\times10^{26}$; Z=63 *km*) using a 30 by 20 *km* fault plane with an 2 by

2 *km* grid spacing. We inverted 32 teleseismic P and 13 SH-waves (Figure 3) for the slip and variable rake using the multiple time window method [*Hartzell and Heaton*, 1983]. The rupture process is parameterized as 6 time windows spaced at 1 second intervals and a rupture velocity of 3.2 *km/sec*. The maximum dislocation rise time is 3 seconds and the source time function at each grid point is a triangle with 1 second rise and 1 second fall. We selected a maximum rise time of 3 seconds from the inspection of spectra from Nisqually strong motion records, which suggested a rise time between 1 and 3 seconds. The rise time should range from 0.6 seconds according to *Heaton* [1990] to 0.9 seconds according to *Somerville et al.* [1999]. The seismic moment is 9.43×10^{26} *dyne*cm* (M_w 6.6) and is similar to *Langston and Blum* [1977] although their total slip duration was only 3 seconds.

We have performed a slip inversion of 12 local strong ground motion, 30 teleseismic P-waves, 7 teleseismic SH-waves, and horizontal geodetic displacements from 8 GPS stations for the rupture history of the 2001 Nisqually earthquake (Figure 4). We assume the steeply dipping fault plane from the geometry determined in the moment tensor inversion (Table 1) to generate a 30 by 24 *km* fault using an 3 by 3 *km* grid spacing. There is an ambiguity of the rupture plane from the two nodal planes and the geodetic data alone does not appear to resolve the fault plane. We use the PS-9 model to compute the teleseismic Green's functions and the calibrated model from Longmire for the local Green's functions. Rupture is assumed to initiate at the hypocenter at 56 *km* depth, estimated by Univ. Washington local short-period network. The maximum rupture velocity is set to 3.2 *km/sec* and we use 6 time windows at 1 second intervals. We assume a maximum dislocation rise time of 3 seconds because the inspection of spectra from Nisqually strong motion records suggested a rise time between 1 and 3 seconds. An inversion using a rise time of 1 second did not change the rupture history. The seismic moment is 1.59×10^{26} *dyne*cm* (M_w 6.73). The greatest amount of slip (3.35 *m*) is located at the hypocenter with most of the rupture down dip and elongated in the north-south direction (Figure 4).

Non-Technical Summary

This study contributed towards improving future seismic hazard analyses in the urban Seattle and Puget Sound region. A moment tensor catalog will be valuable for future revisions of the national probabilistic seismic hazard maps, as those maps use moment magnitude as the basis for ground motion estimation. Another part of this study provided the rupture-history helpful in generating site-specific time-histories for engineering studies. The source parameters of these earthquakes will be valuable to future USGS efforts in producing other products to quantify shaking amplification useful for engineers and city planners. For example, theses source-models provide calibration for near-real-time shake-maps. The instrumental and intensity shake-maps are essential for the emergency response community in quickly assessing critical sites and lifelines for potential damage.

Reports Published

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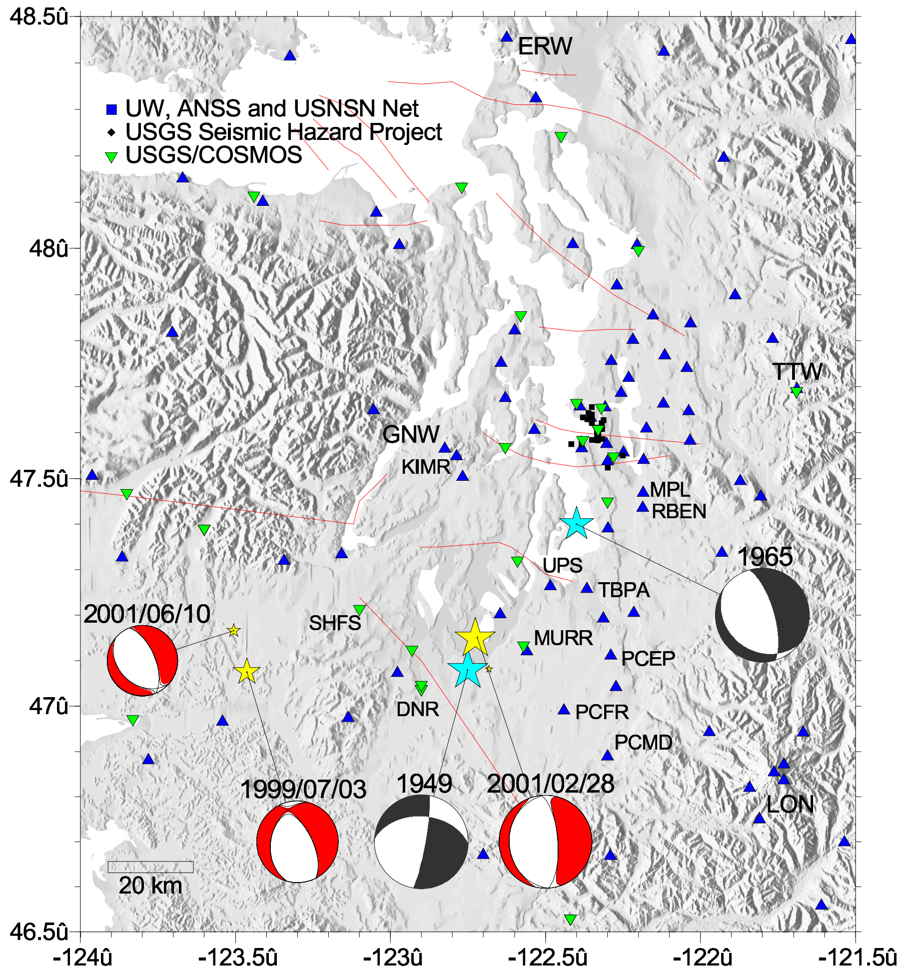
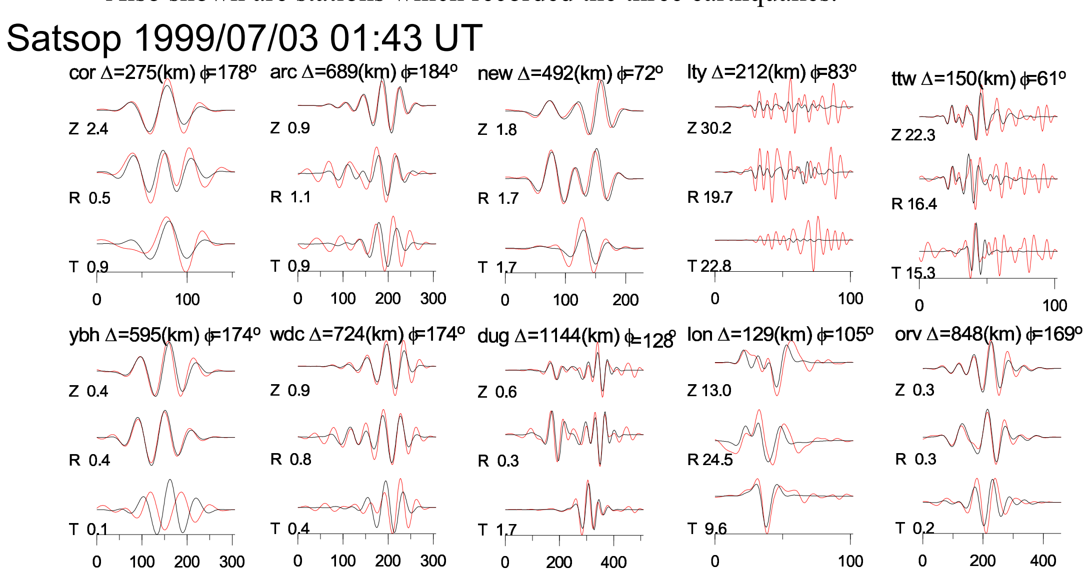


Figure 1. Location map of 1999 Satsop, 2001 Nisqually, and 2001 Satsop earthquakes. The focal mechanism of these earthquakes were determined using moment tensor inversion of locally and regionally recorded long period displacements and a grid search was performed for origin time and centroid depth. Also shown are stations which recorded the three earthquakes.



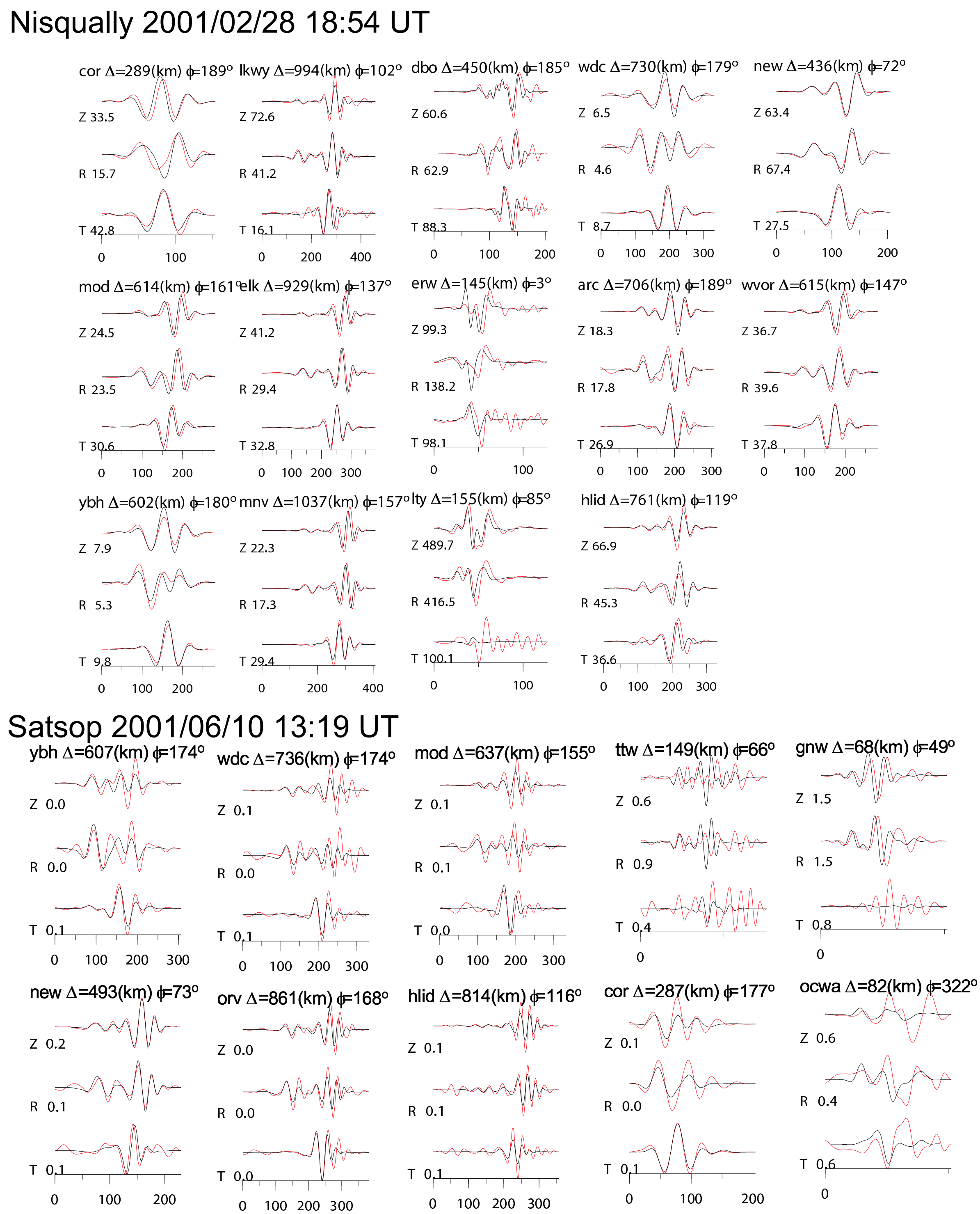


Figure 2. Synthetic (black) and observed (red) long-period (T = 200 to 2 seconds) displacements (amplitudes in μm) from local and regional broadband stations. The waveform fits resulted from regional moment tensor inversion (solutions in Figure 1 and Table 1.) for the 1999 Satsop (Mw 5.9), 2001 Nisqually (Mw 6.9) and 2001 Satsop (Mw 4.9) earthquakes. Local sites were not used in the moment tensor inversion and only shown as predictions. We used the LON P-and S-velocity model to compute the Green's functions.

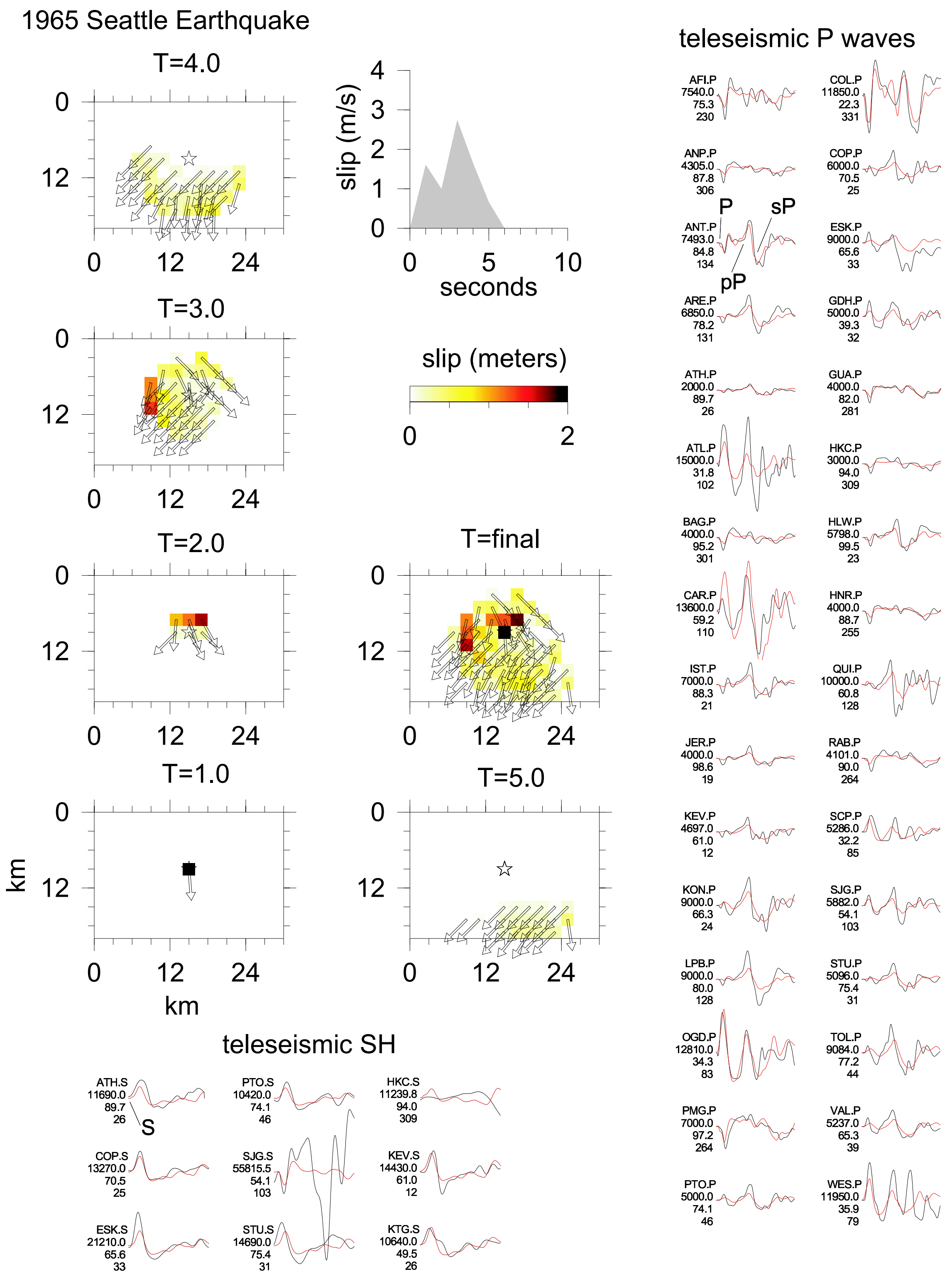
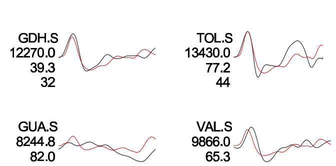



Figure 3. Rupture history, observed (black), and synthetic (red) teleseismic P- and SH- waveforms for the 1965/04/29 Seattle (Mw 6.7) earthquake. We inverted the P- and SH waves for the rupture history using the multuple time window method.

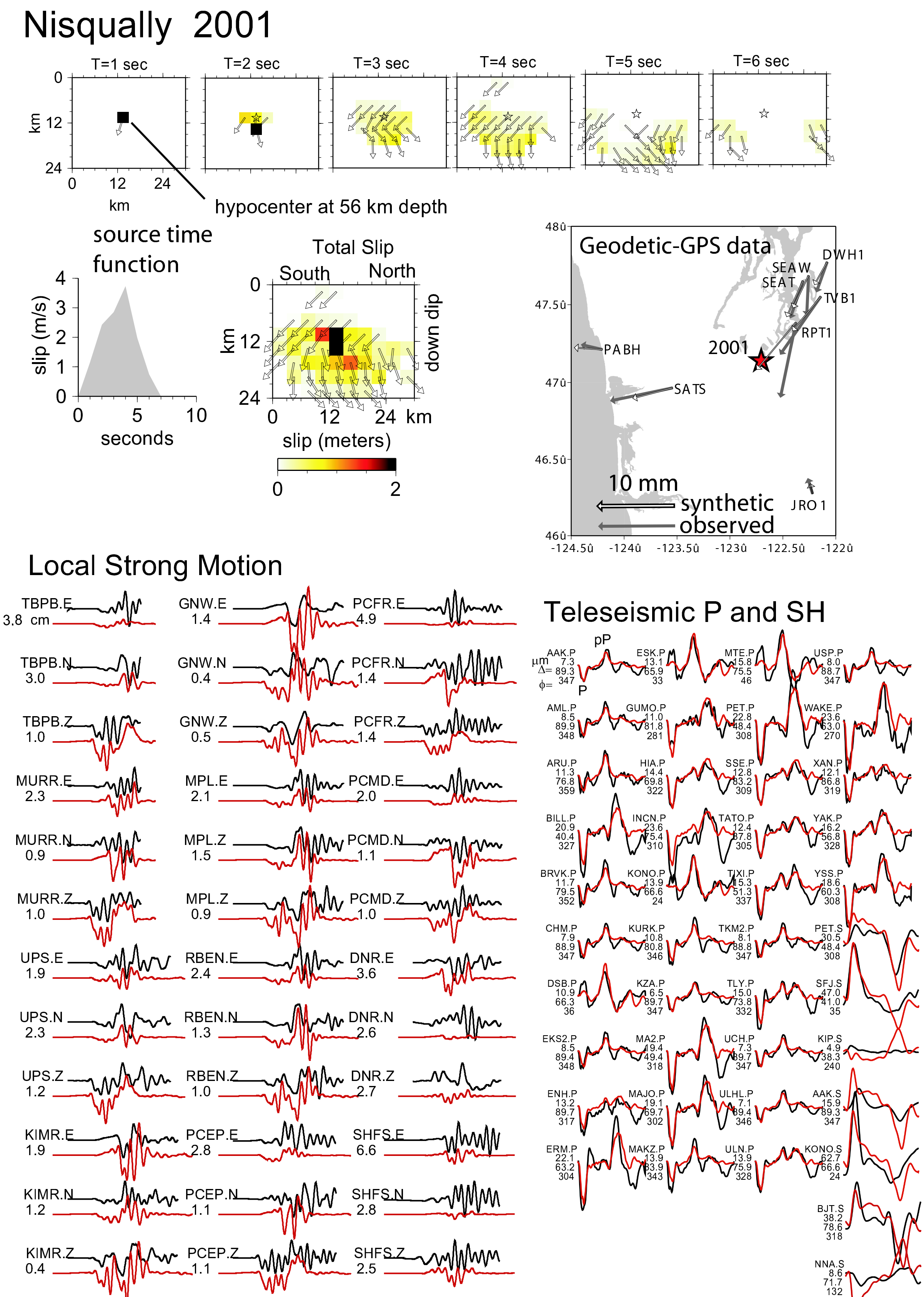


Figure 4. Rupture history of the 2001 Nisqually earthquake. Local strong ground motion amplitudes in cm and teleseismic amplitudes in micrometers.