BLIND TEST FOR KINEMATIC SOURCE INVERSION – MODEL SETUP AND DETAILED DESCRIPTIONS

P.M. Mai, C. Francois-Holden and G. Festa

August 29, 2005

1 Introduction

Kinematic source inversion of near-fault data allow to retrieve important properties of earthquake ruptures, such as the distribution of the slip, the rupture timing, and, with limitations, the local slip-function. With that, kinematic source inversions have become a crucial input for dynamic modelling of the faulting process.

The challenge these kinematic source models have to face is the resolution of the model parameters (slip, rupture velocity etc.). In fact, depending on the inversion strategy and the *a priori* assumptions on the rupture and the Earth properties, the data processing and data selection, the final slip maps and distribution of rupture onset times are generally different, sometimes even incompatible with each other.

We therefore organize this **Blind Test for Kinematic Source Inversion**. The idea is that one research group generates near-source ground-motions for some scenario earthquake, and provides these synthetics to researchers who then conduct the source inversion. The correct solution of the earthquake rupture model is hence known only to one person/group, while interested participants can apply whatever inversion strategy to solve for the model parameters.

The goal of this endeavor is to be to able to compare different inversion methods in terms of resolution and efficiency, to assess their weaknesses and strength, and to understand their limits and advantages. This will also help us to better understand the general properties of such inversion techniques, and perhaps aid in the future development of improved methods. Another aspects of this blind test is to verify the signal analysis in the pre-processing phase (picking of first arrival times, filtering of waveforms, selection of components and stations etc.) which introduces a certain level of arbitrariness in the source-inversion procedure.

This blind test for kinematic source inversion will be initially carried out within the frame work of the EC-project SPICE (**S**eismic Wave **P**ropagation and **I**maging in **C**omplex Media: A **E**uropean Network), but the we glady invite participants who are not directly involved in the SPICE-project. We envision that this blind-test exercise will continue for at least 18-months, with increasing levels of sophistication and complexity in the to-be-inverted source model. Workshops along the way will be held to compare results, discuss progress and future steps, and to develop common strategies for the next generation of source-inversion codes (workshops may be attached to international meetings like EGU or AGU for simplicity of travel and schedules.

As discussed during an initial workshop in Naples (June 24-25, 2005), the general mechanics of the blind test are as follows:

- The test is based on a fault geometry and station distribution similar to the 2000 Tottori earthquake, with a denser coverage of stations in the fault vicinity.
- The dimensions of the rupture plane **are not known** *a priori*, but it is embedded within a rectangular fault area of dimensions L_{max} and W_{max}. The dimension of the earthquake rupture (i.e. source extent), however, is compatible with source-scaling relations.
- We assume that the CMT-solution is known, i.e. the strike ϕ, the rake angle λ and the dip δ of the fault are given. Likewise the final seismic moment M_o, the hypocenter location and the origin time are given.
- Earth's structure is assumed to be a simple, layered medium; the velocity-density model is given. Initially, no attenuation ($Q_S = Q_P = \infty$) is assumed.
- Any "inverter" is free to choose whatever method he/she desires to use to carry out the source inversion. There are no constraints on the fitness function to be used. We only require that the methodology is clearly documented.

In order to test the capabilities of current source-inversion approaches under different conditions, the blind-test exercise will consist of three stages with increasing complexity in the earthquake rupture model:

1. The slip is heterogeneous, while rupture velocity and rise-time are constant. All are unknown to the "inverters". The slip-velocity function used for computing the to-be-inverted ground-motions is simple. Synthetics are generated without any random noise on the signals.
2. Slip, rupture velocity and rise-time are heterogeneous; additionally a more complex (realistic) slip-velocity may be used. No noise on the synthetics signals.
3. Same as in (2), but now random noise is added to the synthetics.

As independent tests in a second step, "inverters" should perform so-called "spike tests" by perturbing a uniform model in a point or cell to analyze the sensitivity of the inversion procedure to such variations. The sensitivity analysis should also address the variation of the fitness function in the vicinity of the global minimum, i.e. what is variability of the model parameters for all 'successful' models close to the minimum of the misfit norm? Boot-strap test on the station selection is also highly recommended (i.e. how does the model change when using only a subset of stations? Is the model then able to accurately forward-predict the motions for those stations that have not been used in the inversion itself?).

Time frame: as mentioned above, the entire exercise is likely to continue for up to 18-months. Deadlines and further details will be defined at the SPICE meeting in Smolenice Castle (Sept 5 - 9, 2005). We anticipate that the first tests will be concluded by the end of 2005, and that results on the first tests (and perhaps second test) can be reported at the intermediate SPICE meeting (Spring 2006) and at international conferences in Spring 2006. We also plan to summarize and document the findings in publications.

2 Station coordinates

The origin of the reference frame is located at the epicenter with coordinates $LAT = 35.27N$, $LON = 133.35E$. Station coordinates are then given in a Cartesian system where X denotes the East-West direction, increasing eastward, and Y the North-South direction, increasing upwards (see figure on geometry).

Station name	North (km)	East (km)	Lat. North	Long. East
SMN015	9.72	-15.869	35.3613	133.1730
SMN003	-10.83	-22.94	35.1763	133.0955
TTR007	0.607	12.90	35.2794	133.4902
TTR008	16.53	-1.38	35.4227	133.3327
TTR009	-11.83	-3.09	35.1676	133.3139
TTR005	16.78	43.49	35.4258	133.8280
SMN004	1.20	-39.93	35.2850	132.9030
TTR006	25.61	26.25	35.5075	133.6330
OKY004	-35.57	14.58	34.9547	133.5044
OKY005	-29.28	35.52	35.0066	133.7344
OKY015	0.15	52.65	35.2761	133.9283
SMNH12	-12.73	-44.62	35.1603	132.8583
SMN001	28.75	-16.71	35.5341	133.1638
HRS021	-36.09	-20.86	34.9497	133.1197
OKYH08	-40.82	5.49	34.9071	133.4081
SMNH10	31.03	0	35.5547	133.3031
SMN002	21.45	-25.16	35.4683	133.0708
OKYH09	-10.79	30.17	35.1763	133.0955
HRS002	-42.50	-6.39	34.8919	133.2781

3 1D Velocity model

The "corner points" for the velocity model define the layer boundaries where it is assumed that between these points, the velocities/densities are interpolated linearly. Thus, we have no strong velocity discontinuities, but also no "thick" layer of constant velocity (which would cause troubles in ray methods since those layers would generate horizontally travelling rays).

h(km)	$v_p(km/s)$	$v_s(km/s)$	$d(g/cm^3)$	Q_p	Q_s
0	5.50	3.18	2.6	∞	∞
2	6.05	3.50	2.7	∞	∞
16	6.60	3.81	2.8	∞	∞
38	8.03	4.62	3.1	∞	∞

4 Fault Rupture Properties

The rupture model is a pure left-lateral strike-slip event (rake $\lambda = 0 = const.$) on a fault that strikes at $\phi = 150^o$ (see geometry figure). With the given Cartesian coordinate system, the epicenter is at [0,0], hypocentral depth is $Z_h = 12.5\,\text{km}$. The scalar seismic moment is $M_o = 1.43 \times 10^{19}\,\text{Nm}$, translating into moment magnitude $M_w = 6.7$. For computing the seismic moment I did consider depth-dependent shear-modulus μ.

In the **first part** of the blind test, the following properties apply for the rupture model:

- The fault dimensions are computed based on standard scaling relations for extended faults (*Mai & Beroza, 2000; Wells & Coppersmith, 1994*). The rupture length is **LESS** than what the fault-trace in the geometry figure implies!
- The fault is buried, and DOES NOT rupture the surface!
- The fault is buried, and DOES NOT rupture the surface!
- Rupture velocity v_{rup} is constant.
- Rise time T_r is constant as well.
- Synthetic seismogram are computed for a simple slip-velocity function of width T_r; each point is allowed to slip only once (i.e. a single-time-window calculation is done)
- The rupture model is created using a subfault size of $0.5 \times 0.5\,\text{km}$; inversion results should be given on the inversion-grid as well as interpolated onto a $1 \times 1\,\text{km}$ grid.

Strike	150
Dip	90
Rake	0
Hypocenter depth	12.5 km
Seismic Moment	$1.43 \times 10^{19} N\,m$

5 Synthetic Waveforms

Synthetic waveforms are computed for 19 well-distributed sites (see geometry figure) using discrete frequency-wavenumber integration without attenuation (COMPSYN code by *Spudich & Xu, 2002*). The frequency range of the calculations spans 0.01 - 3.0 Hz, and no post-filtering is applied. The COMPSYN-code calculates seismograms in a fault-plane coordinate system, generating motions in the fault-parallel (FP) and fault-normal (FN) direction (as well as vertical). The two-horizontal waveforms are then rotated by 30^o in clockwise direction to produce N-S and E-W oriented synthetics. Both sets of waveforms are provided for your use. The following convention applies for the synthetic waveforms:

- Positive North-South motion is directed towards the positive "Northing" direction (i.e. increasing Y direction)
- Positive East-West motion is directed towards the positive "Easting" direction (i.e. increasing X direction)
- Positive motion on the Z-component points upwards.

6 Your Tasks

- The rupture plane of length L, width W could be located anywhere along the fault trace which is 60 km long. By inverting the synthetics waveforms, find the location of the rupture plane, as well as its length L and with W. How close to the surface does the fault plane reach?
  NOTE In standard practice, aftershock locations would help to delineate the actual rupture plane. IF this problem turns out to be too difficult/ambigious, I can provide the actual rupture-plane definitions.
- Once the location and extent of the rupture plane has been defined, invert the synthetics waveforms with your choice of inverse method, fitness function, data processing and data selection. Find the optimal **constant** (in step 1) rupture velocity and rise time. Find the subfault-specific displacements.

6.1 Reporting Your Results

In order to submit your inversion results, use the following format:

$XPOS$	$ZPOS$	TON	$TRISE$	$SLIP-SS$	$SLIP-DS$
-14.75	3.00	10.98	1.00	0.25	0.0001
-14.25	3.00	10.81	1.00	0.40	0.0001
-13.75	3.00	10.64	1.00	0.68	0.0001
-13.25	3.00	10.48	1.00	1.30	0.0001
:	:	:	:	:	:
:	:	:	:	:	:
-14.75	15.00	3.85	1.00	3.15	0.0001
-14.25	15.00	3.78	1.00	2.40	0.0001
-13.75	15.00	3.64	1.00	2.67	0.0001

where $XPOS$ is the along-strike position of the center of each subfault, with respect to the origin of the coordinate system (i.e. the epicenter), and $ZPOS$ is the respective depth of each subfault with respect to the top of the rupture plane, with positive Z downwards. If you perform a multi-time-window inversion, report the slip values in each time-window by simply appending the needed column at the right.

$XPOS$: along-strike on-fault position of grid-point / center of thesubfault
$ZPOS$: down-dip on-fault position of grid-point / center of the subfault
TON: rupture onset time for each subfault, in sec
$TRISE$: rise time for each subfault, in sec
$SLIP-SS$: strike-slip displacement, in m
$SLIP-DS$: dip-slip displacement, in m (should be zeros here)

This slip model information should be preceeded with a header that describes the details of your inversion; the header should look like the following example:

```
    ------------- FINITE-SOURCE RUPTURE MODEL -----------------

Event :  BLIND TEST EXAMPLE BY CHRISTOPHER COLUMBUS
EventTAG: sblindCC.slp

Loc :  LAT = 34.590 LON = -116.270 DEP = 15.00
```

```
Size :  LEN = 54.00 km WID = 16.00 km Mw = 7.18 Mo = 6.70e+019
Mech :  STRK = 333 DIP = 80 RAKE = 175 Htop = 0.01 km
Rupt :  HypX = 17.50 km HypZ = 14.80 km avTr = 3.2 s avVr = 2.1 km/s

------------ inversion-related parameters ----------------

Invs :  Nx = 18 Nz = 6
Invs :  Dx = 3.00 km Dz = 2.66 km
Invs :  Fmin = 0.02 Hz Fmax = 1.0 Hz
Invs :  Ntw = 1 Nsg = 3 (time-windows, fault segments)
Invs :  LEN = 1.00 s SHF = 0.00 s (time-window length and time-shift)
SVF : triang (type of slip-velocity function used)
```

Most of these entries are self-explanatory; if you have questions, you can be find the details at `http://www.seismo.ethz.ch/srcmod/FileFormats.html` when you look for the *fsp format description.

- Inversion results should be given on the grid-spacing (subfault size) used in the inversion, BUT ALSO interpolated onto a 1x1 km grid. The latter is important that I can easily compare the various solutions.
- The above file format allows easy comparison if the inversion returns a single best result, however, it makes it less attractive if you return a family of solutions (for instance from non-linear methods) that all fit the data well. In fact, such solutions are beneficial since they allow us to assess the uncertainty of the slip inversion by looking at the marginal distributions of slip at each subfault. IF YOUR INVERSE APPROACH ALLOWS YOU TO RETRIEVE SUCH MULTIPLE- SOLUTIONS, PLEASE GENERATE ONE BEST-MODEL FROM YOUR SET OF POSSIBLE GOOD MODELS. Submit also the set of solutions, in the same format as given above, all clearly named and bundeled in a separate *zip, *tar or *gz file. The single-best-model solution should be given in an extra file!
- When submitting your inverse solution, provide also a brief summary of the method(s) you used ($\approx$ 10 lines), your fitness criteria or how the best-model(s) was (were) selected. Document each step of the inversion (data processing, finding the rupture plane etc) with a few sentences.
- For simplicity, DO NOT SEND YOUR PREDICTED GROUND MOTIONS in some file format, but simply send some explanatory figures of your waveform fits (as *eps or *jpg). Provide also a plot of your final slip model (with hypocenter location)

6.2 Some hints

- When you search for the optimal location of the rupture plane, note that the hypocenter is fixed, but your plane may extend from say $X' = -25$ km to $X' = +7$ km. Likewise, the fault is buried, and you have to find the burial depth, $Htop$. The coordinates of the on-fault rupture nucleation point, $HypX$ and $HypZ$ are then measured in that plane, starting from the top-left corner of your rupture model (viewing angle from the South-West!). Example: if you find a 30 km long fault that starts rupturing in its center along strike, is buried at 4 km depth, and has a fault width of 16 km, then $HypX = 15$ km, $HypZ = 8.5$ km (because absolute hypocentral depth is fixed to Z = 12.5 km.

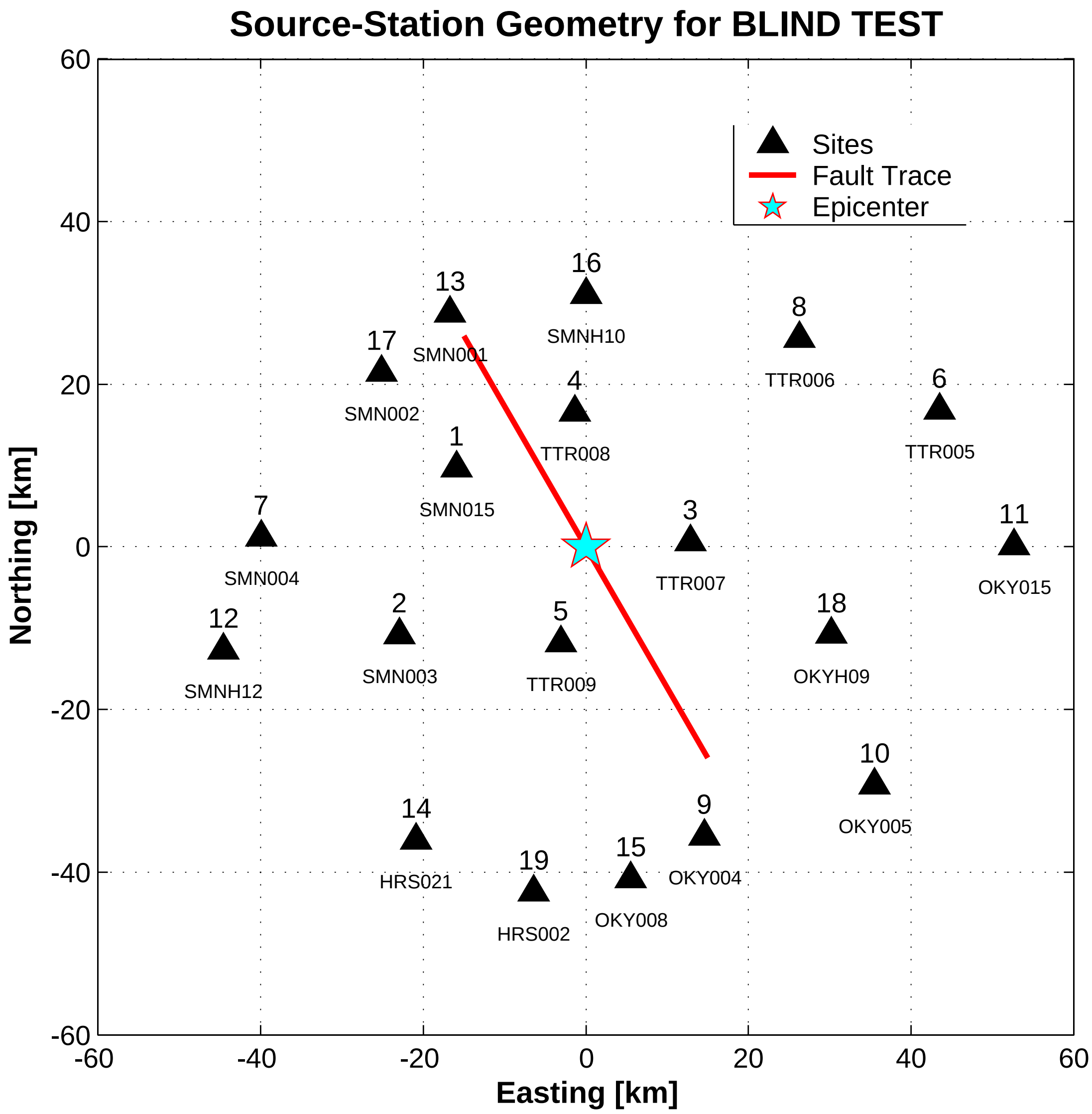

Figure 1: Geometrical setup for blind-test inversion.

- It is fairly easy for the noise-free seismograms in step 1 to find the "theoretical" arrival times of the first incoming P- and S-waves by using the given velocity model and the distance of each station to the known hypocenter. **Beware** that low-frequency near-field terms in the seismograms may blur the expected arrivals to some extent.

====================================

MOST IMPORTANTLY – HAVE FUN !!!

====================================

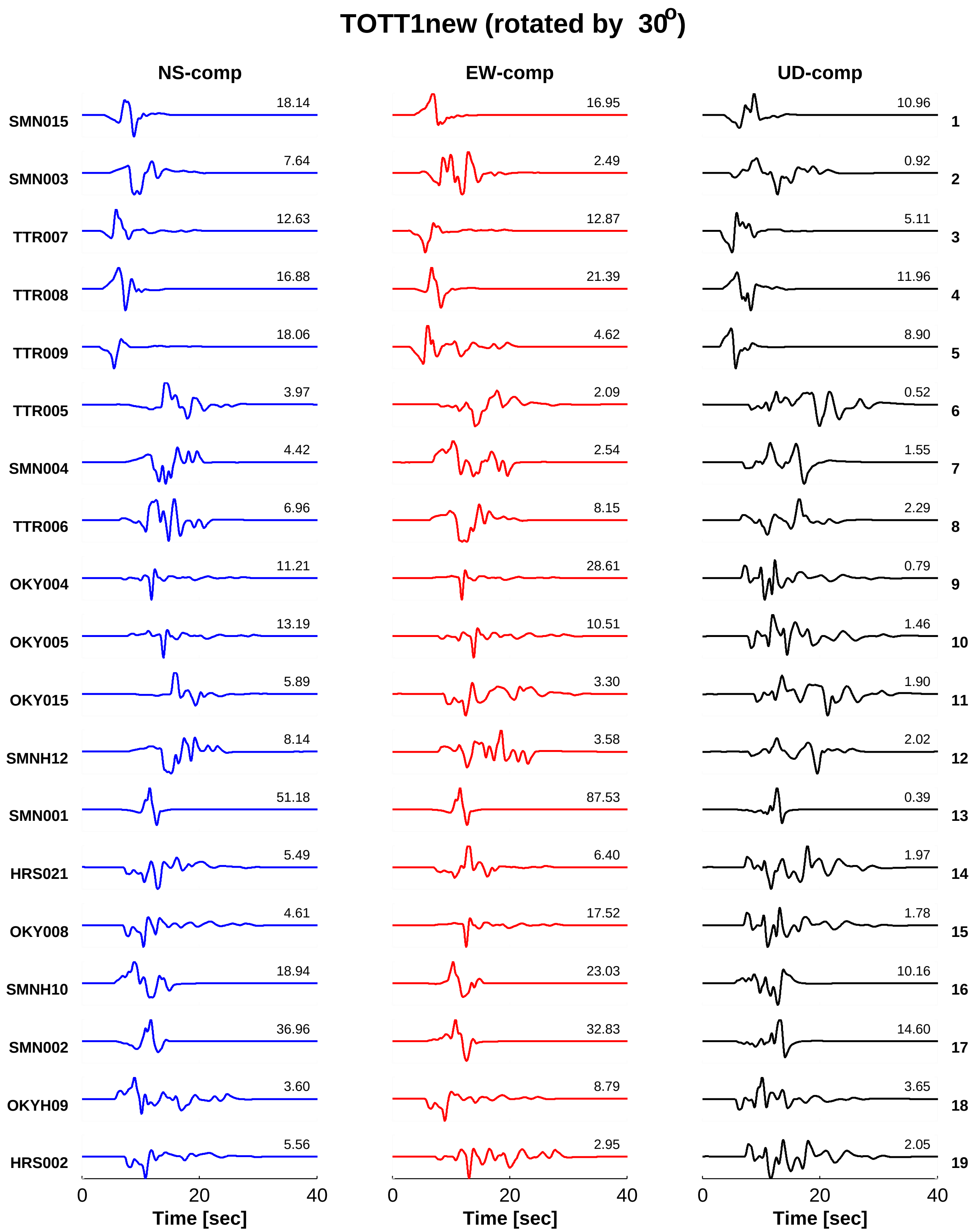

Figure 2: Synthetic velocity seismograms at all sites; small numbers at each trace denote the max. ground velocity for that trace, the numbers to the very right indicate the station index. The horizontal seismograms have been rotated by 30^o clockwise to change from a fault-normal/fault-parallel coordinate system the NS-EW reference frame of Figure 1.