Towards real-time double-difference earthquake location in Switzerland

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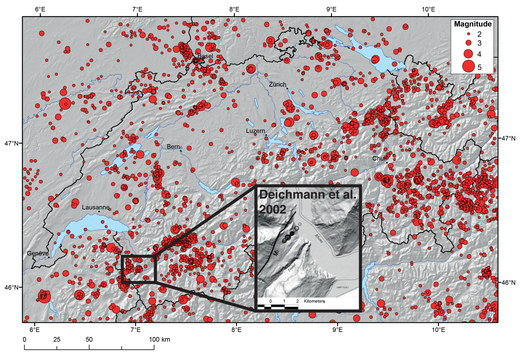
AbsNo: S101PS.07

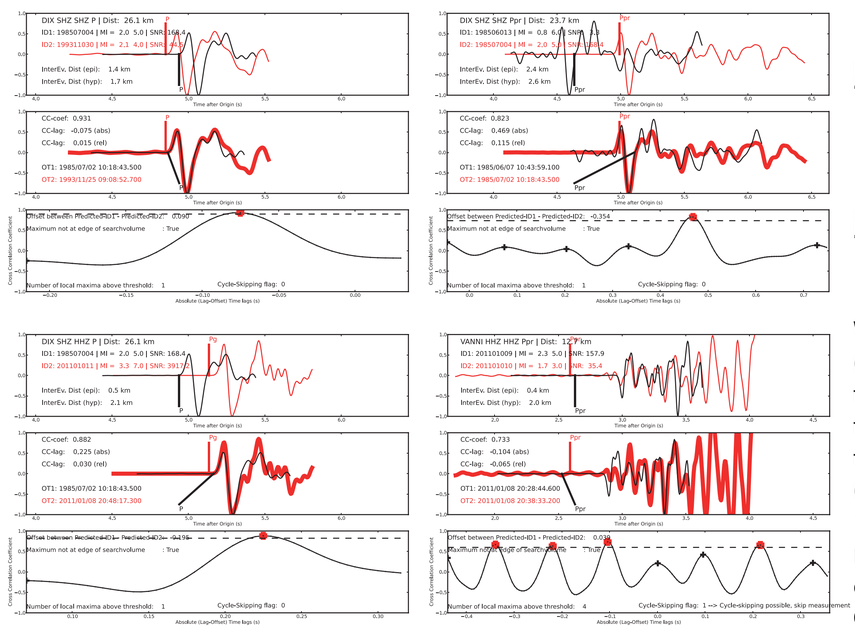
1. Introduction

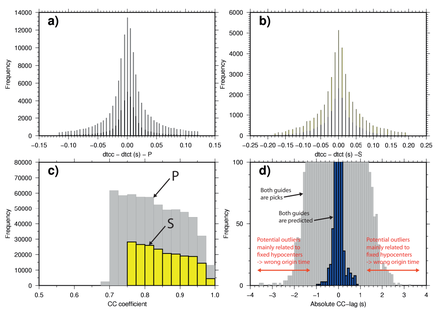


Detailed information on the spatio-temporal migration of seismic activity within earthquake sequences provides an important seismotectonic context for rapid hazard evaluation. For those applications, monitoring the migration of seismicity requires the precise location of hypocenters in real-time. The double-difference (DD) location method in combination with differential times measured from arrival-time picks and waveform cross-correlation (Waldhauser & Ellsworth 2000) provides high-resolution images of seismicity. The method was adopted for real-time application (Waldhauser 2009). The concept of this approach is an algorithm locating a new event with respect to a background catalog using the DD-formulation.

In the presented work, we applied waveform cross-correlation and double-difference relocation to the entire digital archive of the Swiss Seismological Service (SED) to derive a background catalog for real-time DD applications. We present the first results of the relocation approach and compare them with similar studies of isolated earthquake sequences and known quarry blasts in Switzerland.

2. Time-Domain Waveform Cross-Correlation





Waveform CC Parameters:

 # Events processed: 14,239
(SED archive 1984-2013)
 # Stations processed: 342

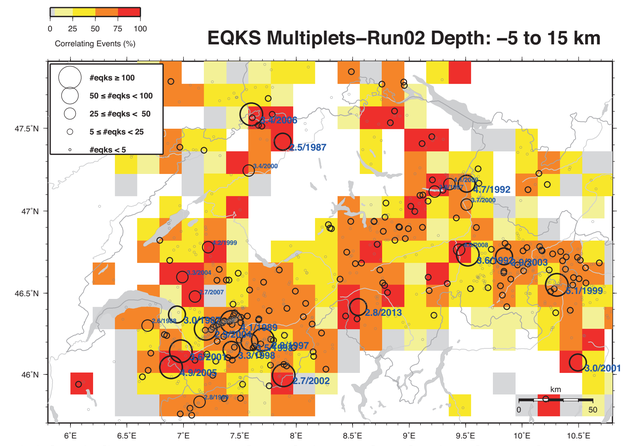
P: Window-Length: -0.5 to +0.5 s (Pick)
: -0.5 to +1.0 s (Pred)
Max. Lag : ±0.125 s (Pick)
: ±0.400 s (Pred)
(Re-)Sampling interval: 0.005 s

S: Window-Length: -0.5 to +0.75 s (Pick)
: -0.5 to +1.0 s (Pred)
Max. Lag : ±0.200 s (Pick)
: ±0.800 s (Pred)
(Re-)Sampling interval: 0.010 s

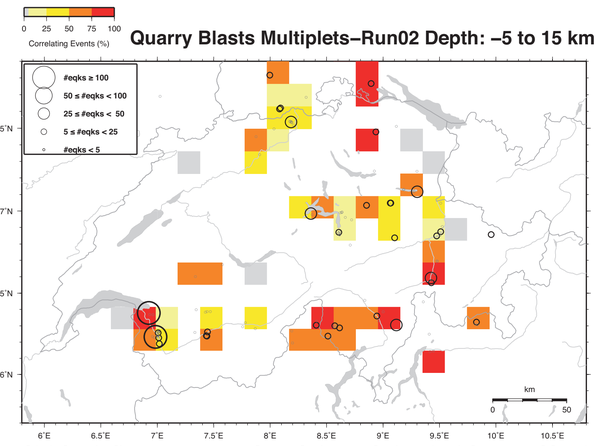
 # Accepted dt-CC P: 584,720
 # Accepted dt-CC S: 201,874

Waveform cross-correlation (CC) of neighboring events (separation ≤5 km) is used to improve the resolution of differential times. CC-windows are based on manual picks or predicted traveltimes from a 3D velocity model (”guides”). Lengths of time windows and maximum time lags depend on phase type (P or S) and available “guides”. Frequency band for all events is 1-30 Hz (4th order). Thresholds for CC-coefficients, signal-to-noise ratios, and the number of local maxima in the CC-function close to the global maximum are used as quality criteria for the CC-measurements to be used in the double-difference location.

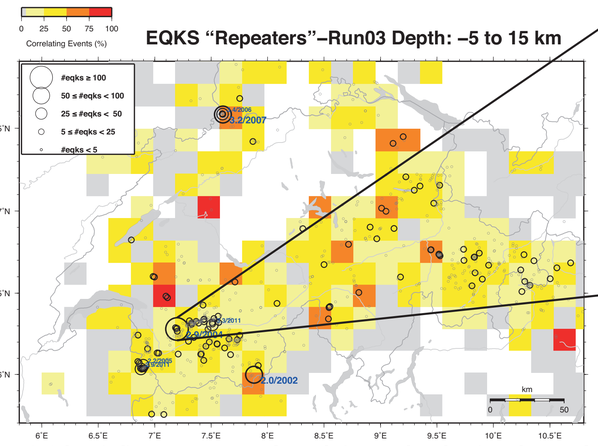
3.Waveform Similarities & Clusters from Waveform Cross-Correlation



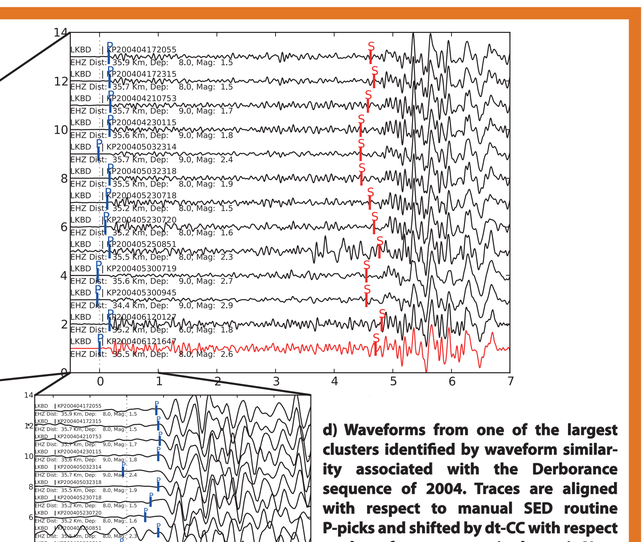
a) Colors indicate percentage of correlating earthquakes in volumes of 15x15x20 km. Correlating events are defined as pairs linked with ≥3 observations (CC-coefficient ≥ 0.8). Circles indicate centroid location of clusters of similar waveforms (groups of correlating events). Sizes of circles indicate number of events in group. Numbers next to circles indicate magnitude & year of largest event in group.



b) Colors indicate percentage of correlating explosions (mainly quarry blasts) in volumes of 15x15x20 km. Correlating events are defined as pairs linked with ≥3 observations (CC-coefficient ≥ 0.8). Circles indicate centroid location of clusters of similar waveforms (groups of correlating events). Sizes of circles indicate number of events in group.

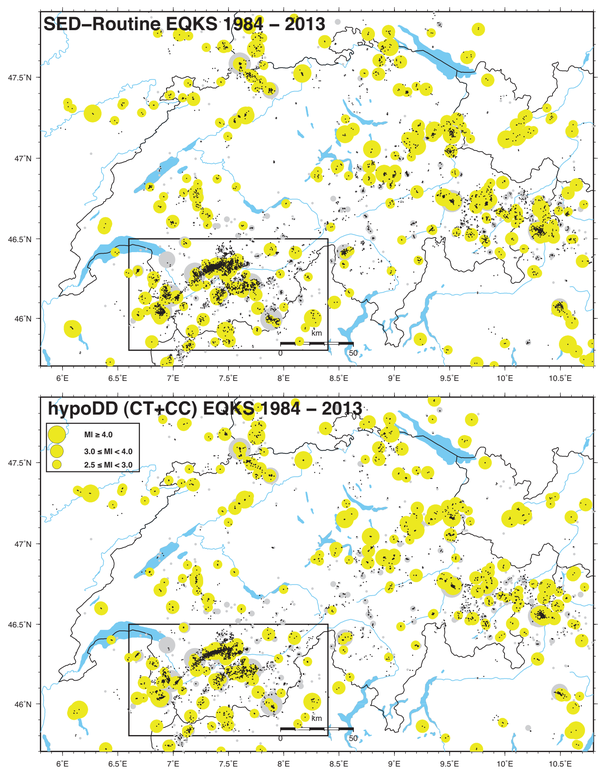


c) Colors indicate percentage of correlating earthquakes in volumes of 15x15x20 km similar to a). In order to identify repeating earthquakes (high similarity of the entire waveform), the window length in the CC was extended to 25 s and the maximum time lag was increased to 0.4 s for all “guides”.

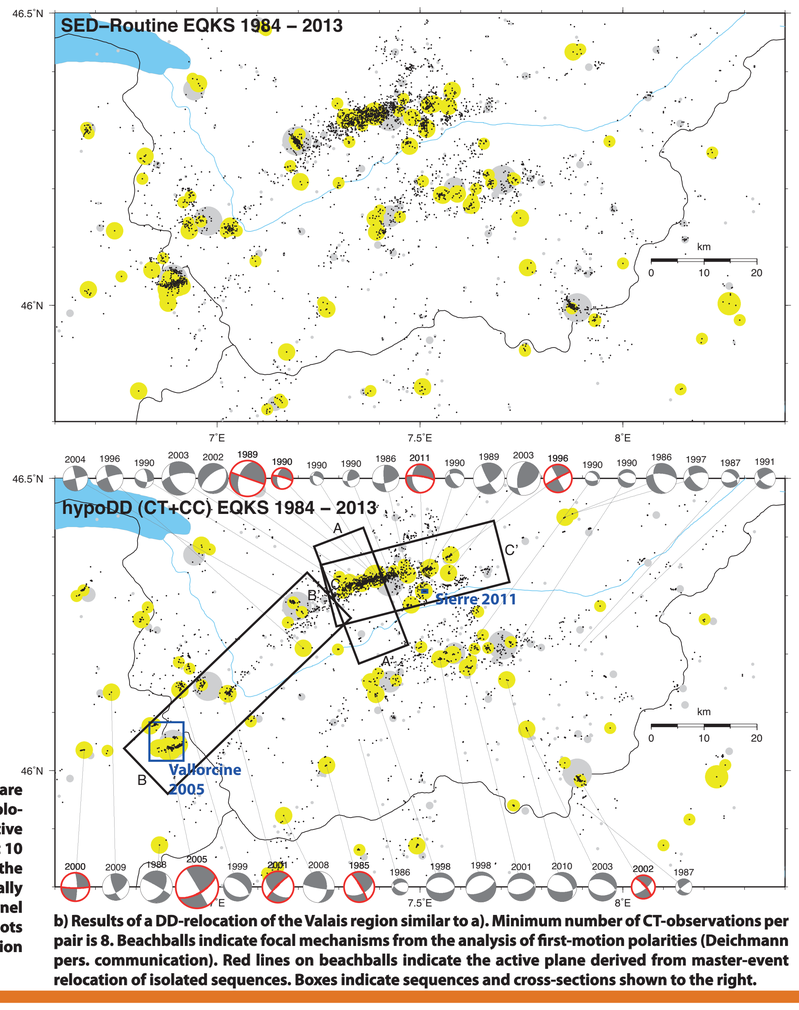


d) Waveforms from one of the largest clusters identified by waveform similarity associated with the Derborance sequence of 2004. Traces are aligned with respect to manual SED routine P-picks and shifted by dt-CC with respect to the reference event (red trace). Note the magnitude dependence of first arrival P-picks apparent in the bulletin data.

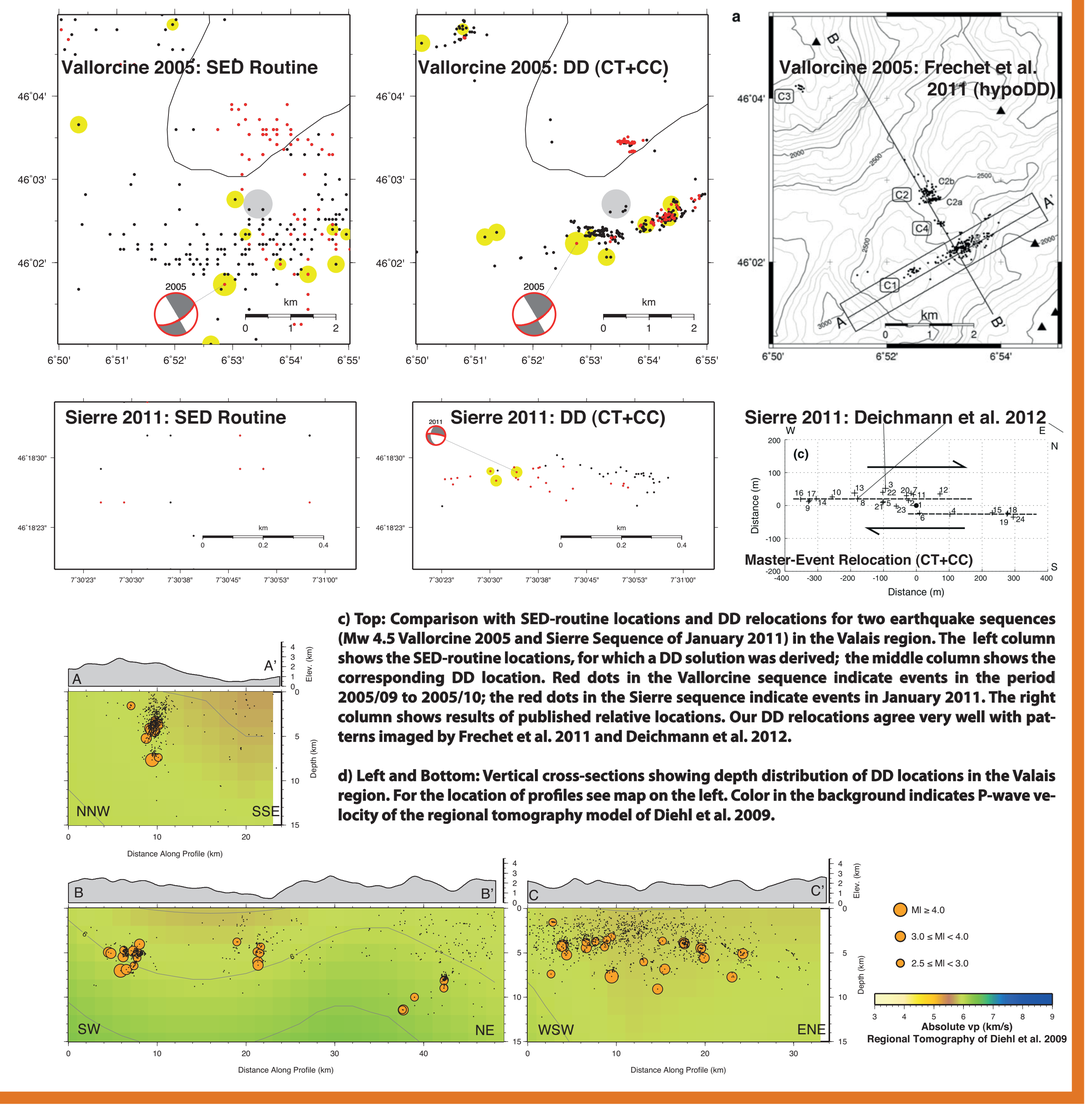
4.Double-Difference Relocation: Earthquakes



a) Preliminary results of the double-difference (DD) relocation using the hypoDD software (Waldhauser & Ellsworth 2000). Differentials times of event pairs (earthquakes and explosions) from SED bulletin picks and waveform cross-correlation have been inverted for relative locations of the entire SED-catalog. In this regional attempt, only events linked by at least 10 (CT-pick) observations per pair have been considered. The final RMS after 45 iterations is in the order of 30 ms (CT-data) and 5 ms (CC-data), respectively. The top panel shows the (manually revised) SED-routine locations, for which a DD-location has been derived. The lower panel shows the corresponding DD-locations. Yellow dots indicate magnitudes MI≥2.5, gray dots indicate centroid of multiplets (clusters of similar waveforms). The box indicates the location of a more detailed analysis in the Valais region (SW Switzerland) shown to the right.



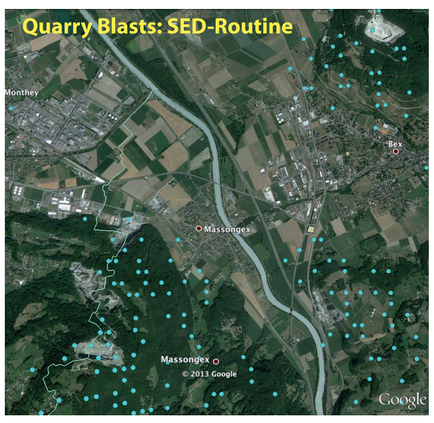
b) Results of a DD-relocation of the Valais region similar to a). Minimum number of CT-observations per pair is 8. Beachballs indicate focal mechanisms from the analysis of first-motion polarities (Deichmann pers. communication). Red lines on beachballs indicate the active plane derived from master-event relocation of isolated sequences. Boxes indicate sequences and cross-sections shown to the right.

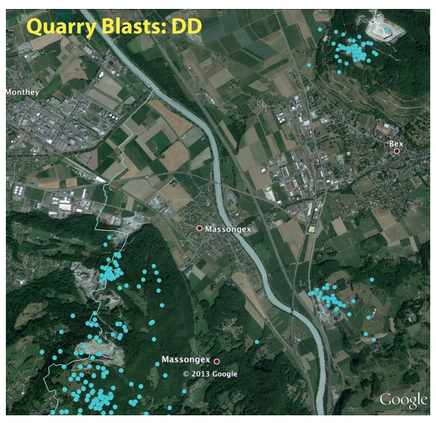


c) Top: Comparison with SED-routine locations and DD relocations for two earthquake sequences (Mw 4.5 Vallorcine 2005 and Sierre Sequence of January 2011) in the Valais region. The left column shows the SED-routine locations, for which a DD solution was derived; the middle column shows the corresponding DD location. Red dots in the Vallorcine sequence indicate events in the period 2005/09 to 2005/10; the red dots in the Sierre sequence indicate events in January 2011. The right column shows results of published relative locations. Our DD relocations agree very well with patterns imaged by Frechet et al. 2011 and Deichmann et al. 2012.

d) Left and Bottom: Vertical cross-sections showing depth distribution of DD locations in the Valais region. For the location of profiles see map on the left. Color in the background indicates P-wave velocity of the regional tomography model of Diehl et al. 2009.

5.Double-Difference Relocation: Explosions

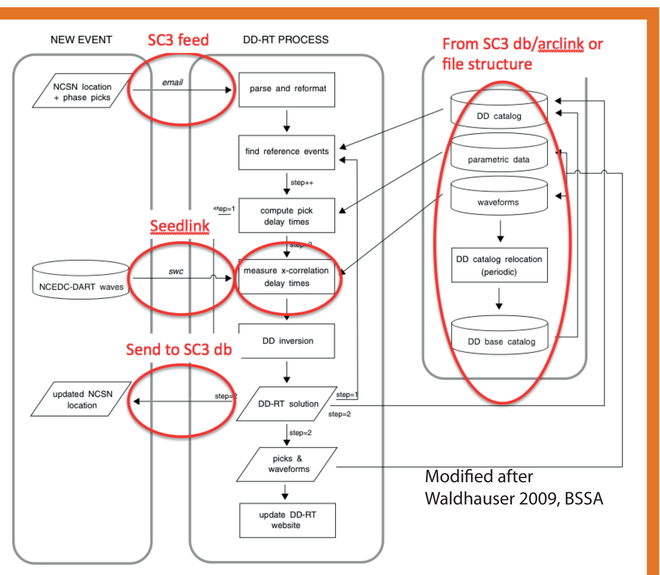




Maps on the left show examples for locations of quarry blasts (blue dots) close to the city of Monthey in the Valais. The map on the left shows the SED-routine locations, for which a DD location was derived. The Map on the right shows the corresponding DD relocations. The DD locations improve the resolution significantly and clearly resolve the different quarries in the area, with an absolute shift of a few hundred meters.

6.Towards Real-Time Implementation in the SC3 Environment

The chart on the right shows the real-time DD procedure operational in the Northern California Seismic Network (Waldhauser 2009). In red we show our strategy to implement a similar real-time DD approach in the SeisComp3 framework of the Swiss National Network operated by the Swiss Seismological Service.



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Frechet, J., et al., 2011, The Mw 4.5 Vallorcine (French Alps) earthquake of 8 September 2005 and its complex aftershock sequence, J Seismol, DOI 10.1007/s10950-010-9205-8.
Waldhauser, F. and Ellsworth, W.l., 2000, A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, California, Bull. Seismol. Soc. Am., 90(6), 1353–1368.
Waldhauser, F., 2009, Near-real-time double-difference event location using long-term seismic archives, with application to Northern California, Bull. Seismol. Soc. Am., 99(5), 2736–2748.