An automatic modular procedure to generate high-resolution earthquake catalogues: application to the Alto Tiberina Near Fault Observatory (TABOO), Italy.

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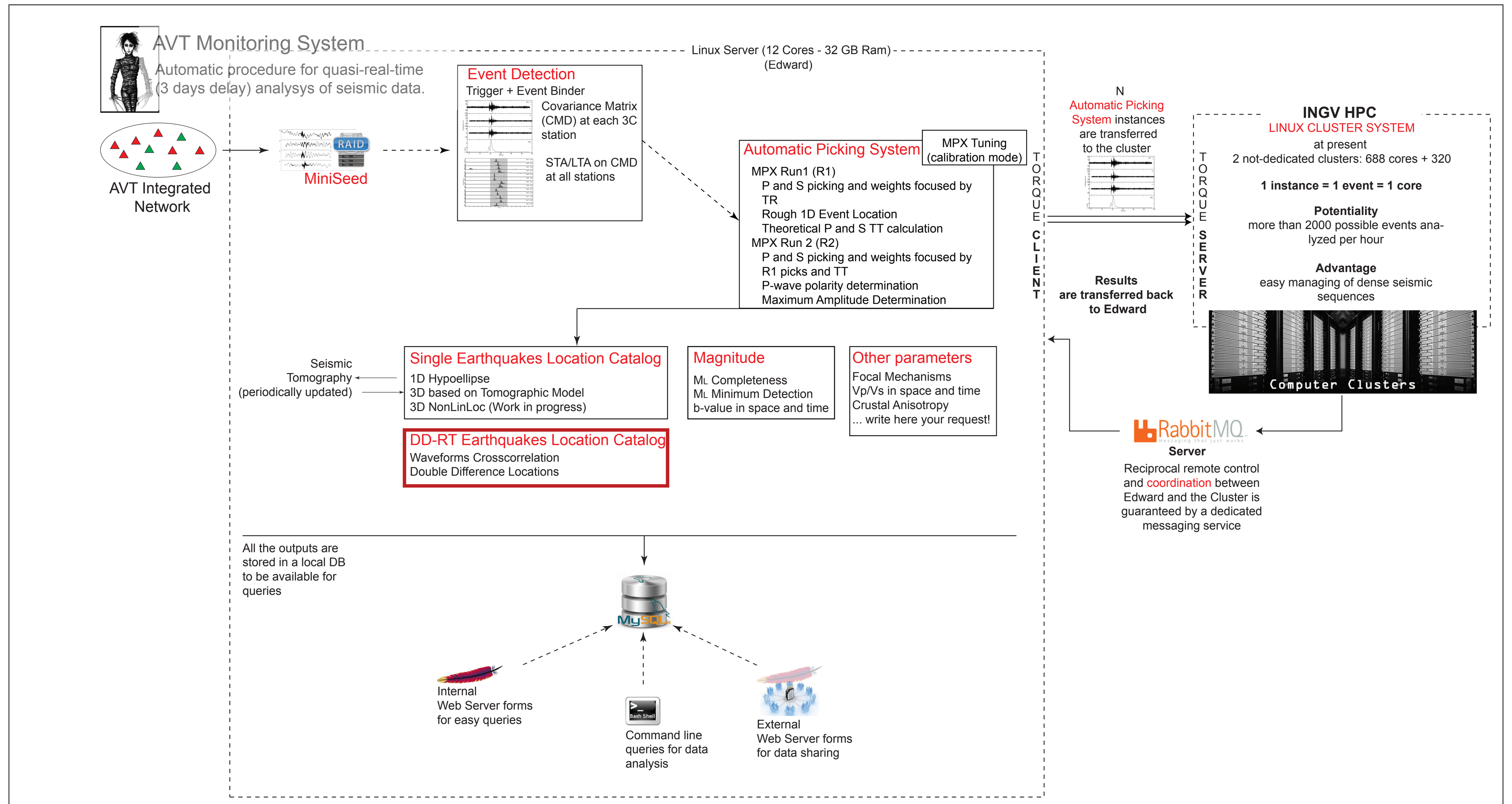
Abstract

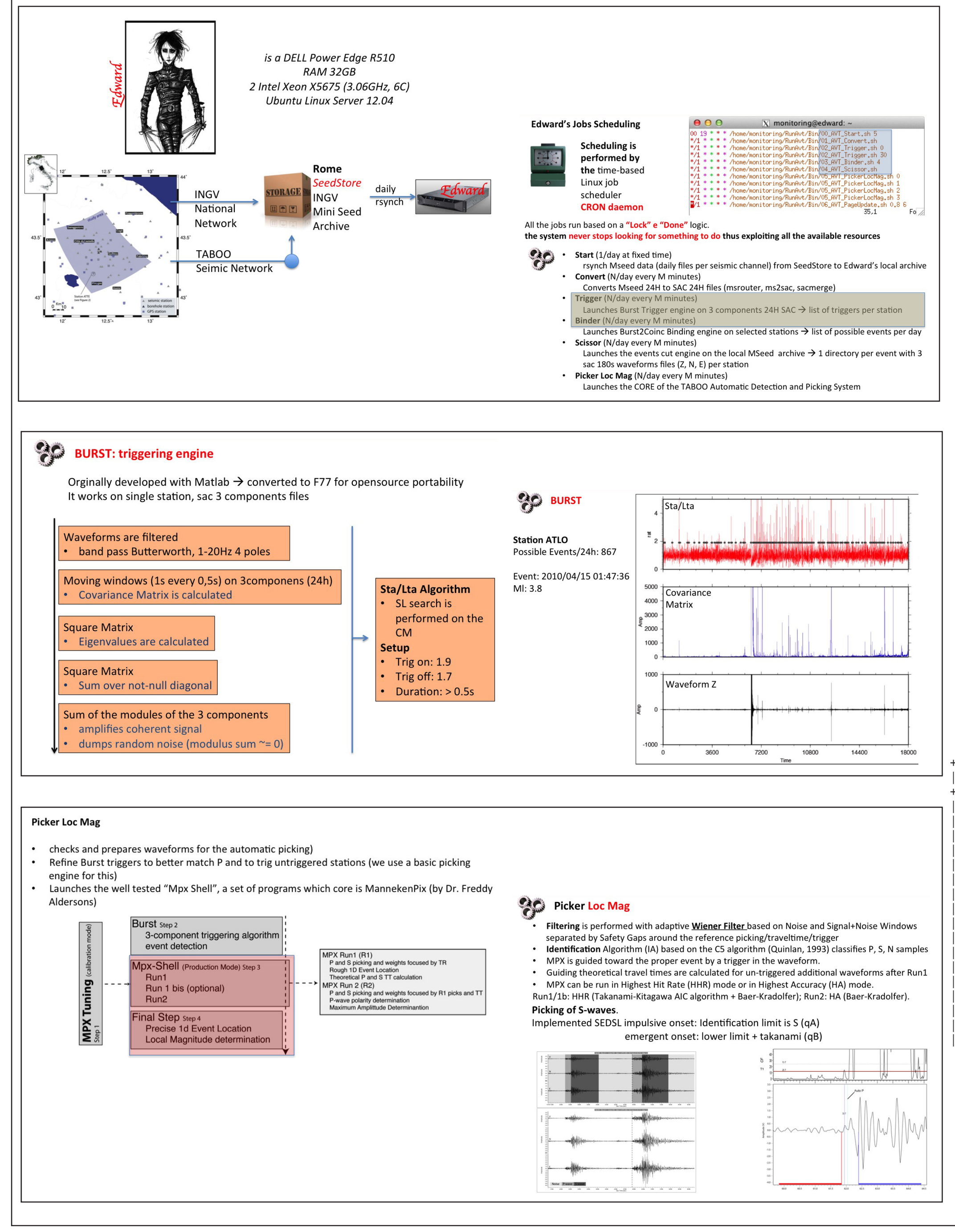
The Alto Tiberina Near Fault Observatory (TABOO) in the upper Tiber Valley (northern Appennines) is a INGV research infrastructure devoted to the study of preparatory processes and deformation characteristics of the Alto Tiberina Fault (ATF), a 60 km long, low-angle normal fault active since the Quaternary.
The TABOO seismic network, covering an area of 120 × 120 km, consists of 60 permanent surface and 250 m deep borehole stations equipped with 3-components, 0.5s to 120s velocimeters, and strong motion sensors. Continuous seismic recordings are transmitted in realtime to the INGV, where we set up an automatic procedure that produces high-resolution earthquakes catalogues (location, magnitudes, 1st motion polarities) in near-real-time. A sensitive event detection engine running on the continuous data stream is followed by advanced phase identification, arrival-time picking, and quality assessment algorithms (MPX). Pick weights are determined from a statistical analysis of a set of predictors designed to correctly apply an a-priori chosen weighting scheme. The MPX results are used to routinely update earthquakes catalogues based on a variety of (1D and 3D) velocity models and location techniques.
We are also applying the DD-RT procedure which uses cross-correlation and double-difference methods in real-time to relocate events with high precision relative to a high-resolution background catalog. P- and S-onset and location information are used to automatically compute focal mechanisms, VP/VS variations in space and time, and periodically update 3D VP and VP/VS tomographic models.
We present results from four years of operation, during which this monitoring system analyzed over 1.2 million detections and recovered ~60,000 earthquakes at a detection threshold of ML 0.5. The high-resolution information is being used to study changes in seismicity patterns and fault and rock properties along the ATF in space and time, and to elaborate ground shaking scenarios adopting diverse slip distributions and rupture directivity models.

TABOO Monitoring System WorkFlow

A



Data Products



The Level 1 data products of the TABOO seismic workflow is a set of observations related to the P and S arrival times, stored in a MySQL database.

P-onsets, S-onsets, related weights, and P-wave polarities are the basic data used in the following steps of data analysis, accessed via command line or web interface data queries.

Between April 2010 and August 2014 the TABOO monitoring system located ~800k events ~60,000 of which have at least 6 P and 6 S automatic observations with hypoinverse weight <= 2, 1D location Rms <= 0.5s, vertical and horizontal errors <= 1km, and azimuthal gap <= 240°.

These events are tagged as well constrained real earthquakes, which produced 756,183 P phases (125,887 W<=2) and 1236242 S phases (1038103 W<=2).
About 57,000 of these events also have well constrained 3D locations.

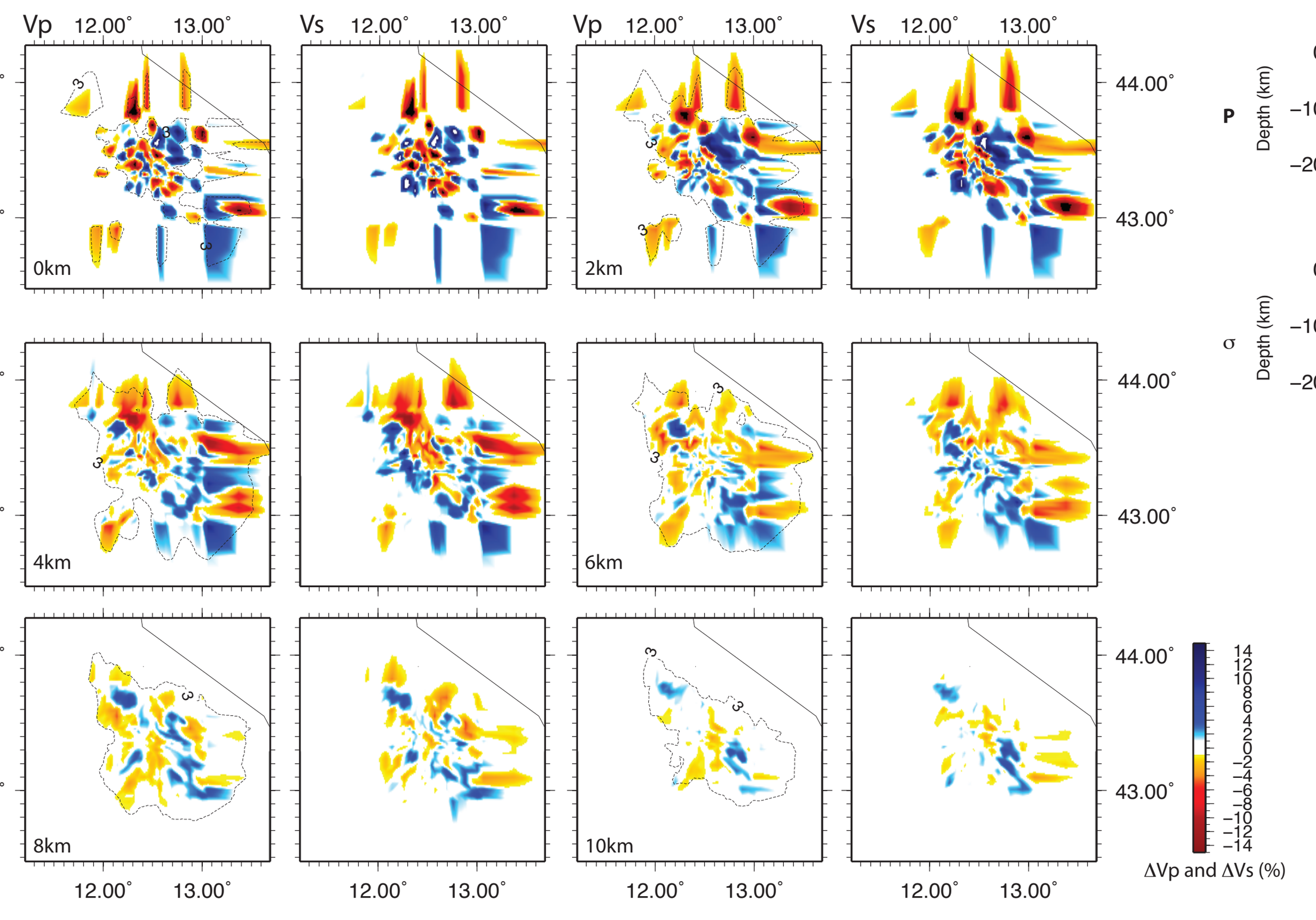
eqkID	eqkID	cuttime	stacode	loco	type	pol	wei	pick	wavename
1270117226	1270117226	20100401102026	AT04	00	P	U	1	2010-04-01 10:21:20.090	20100401102026.at04 z n
1270117226	1270117226	20100401102026	AT04	00	S		2	2010-04-01 10:21:22.260	20100401102026.at04 z n
1270117226	1270117226	20100401102026	AT09	00	P	U	1	2010-04-01 10:21:18.740	20100401102026.at09 z n
1270117226	1270117226	20100401102026	ATBU	00	S		2	2010-04-01 10:21:22.920	20100401102026.atbu z n
1270117226	1270117226	20100401102026	ATCC	00	S		2	2010-04-01 10:21:25.230	20100401102026.atcc z n
1270117226	1270117226	20100401102026	ATFO	00	P	D	1	2010-04-01 10:21:18.590	20100401102026.atfo z n
1270117226	1270117226	20100401102026	ATFO	00	S		1	2010-04-01 10:21:19.600	20100401102026.atfo z n
1270117226	1270117226	20100401102026	ATLO	00	P	U	1	2010-04-01 10:21:19.830	20100401102026.atlo z n
1270117226	1270117226	20100401102026	ATLO	00	S		0	2010-04-01 10:21:21.740	20100401102026.atlo z n
1270117226	1270117226	20100401102026	ATMI	00	S		1	2010-04-01 10:21:24.750	20100401102026.atmi z n
1270117226	1270117226	20100401102026	ATPI	00	S		1	2010-04-01 10:21:23.120	20100401102026.atpi z n
1270117226	1270117226	20100401102026	ATVO	00	P	D	1	2010-04-01 10:21:19.680	20100401102026.atvo z n
1270117226	1270117226	20100401102026	ATVO	00	S		0	2010-04-01 10:21:21.640	20100401102026.atvo z n
1270117226	1270117226	20100401102026	BADI	00	S		2	2010-04-01 10:21:27.560	20100401102026.badi z n
1270117226	1270117226	20100401102026	CAFI	00	S		1	2010-04-01 10:21:30.520	20100401102026.cafi z n
1270117226	1270117226	20100401102026	CDCA	00	P	D	2	2010-04-01 10:21:21.150	20100401102026.cdca z n
1270117226	1270117226	20100401102026	CPGN	00	S		1	2010-04-01 10:21:33.150	20100401102026.cpgn z n

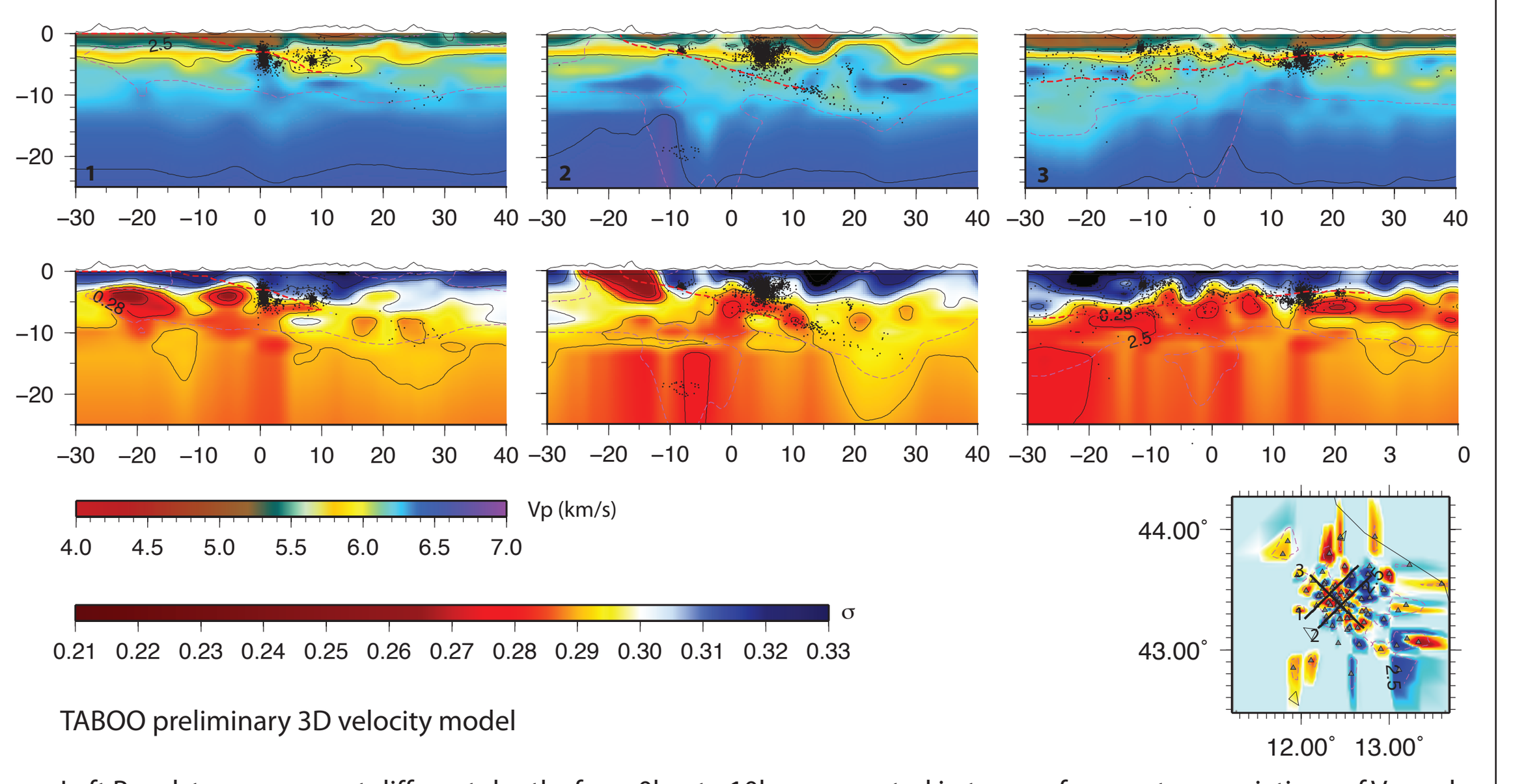
Example of a query to the MySQL database to extract P- and S-waves arrival times, P-wave polarities, observations weight, earthquake unique ID, station names, and related waveform name, for specific events selected based on quality parameters.

Automatic Earthquakes Locations in the TABOO Observatory

B

Every new possible event identified by the event detector (see panel A) is submitted to the picking engine and subsequently to the 1D location code (Hypoellipse). The 1D location, when available, and/or the related P- and S-waves arrival times, become the input of subsequent procedures. The first of which is the 3D location.
To define a 3D refererence seismic waves velocity model, a tomographic inversion of P- and S-waves arrival times is performed, and periodically updated with new data, with the SimulPS code. About 13,000 earthquakes with very well constrained 1D locations (P obs = 237,779, S obs =171,255) have been used to build the gridded velocity model within which all the new incoming earthquakes are located in 3D.





TABOO preliminary 3D velocity model

Left Panel: tomograms, at different depths from 0km to 10km, presented in terms of percentage variations of Vp and Vs. The light grey dashed line encloses the well resolved area.
Right Panel: vertical sections cut through the 3D velocity model along specific strikes across the Alto Tiberina Fault (red dashed line). Vp/Vs ratio is expressed in terms of the linearly related Poisson Ratio (σ).
The circles reported in the vertical sections are the 3D locations of the ~13,000 earthquakes used to produce the model, plotted within +/- 5km from the plane of the section.

DD-RT Location Basics

Waldhauser, F., 2009, BSSA 99(5)
doi: 10.1785/0120080294

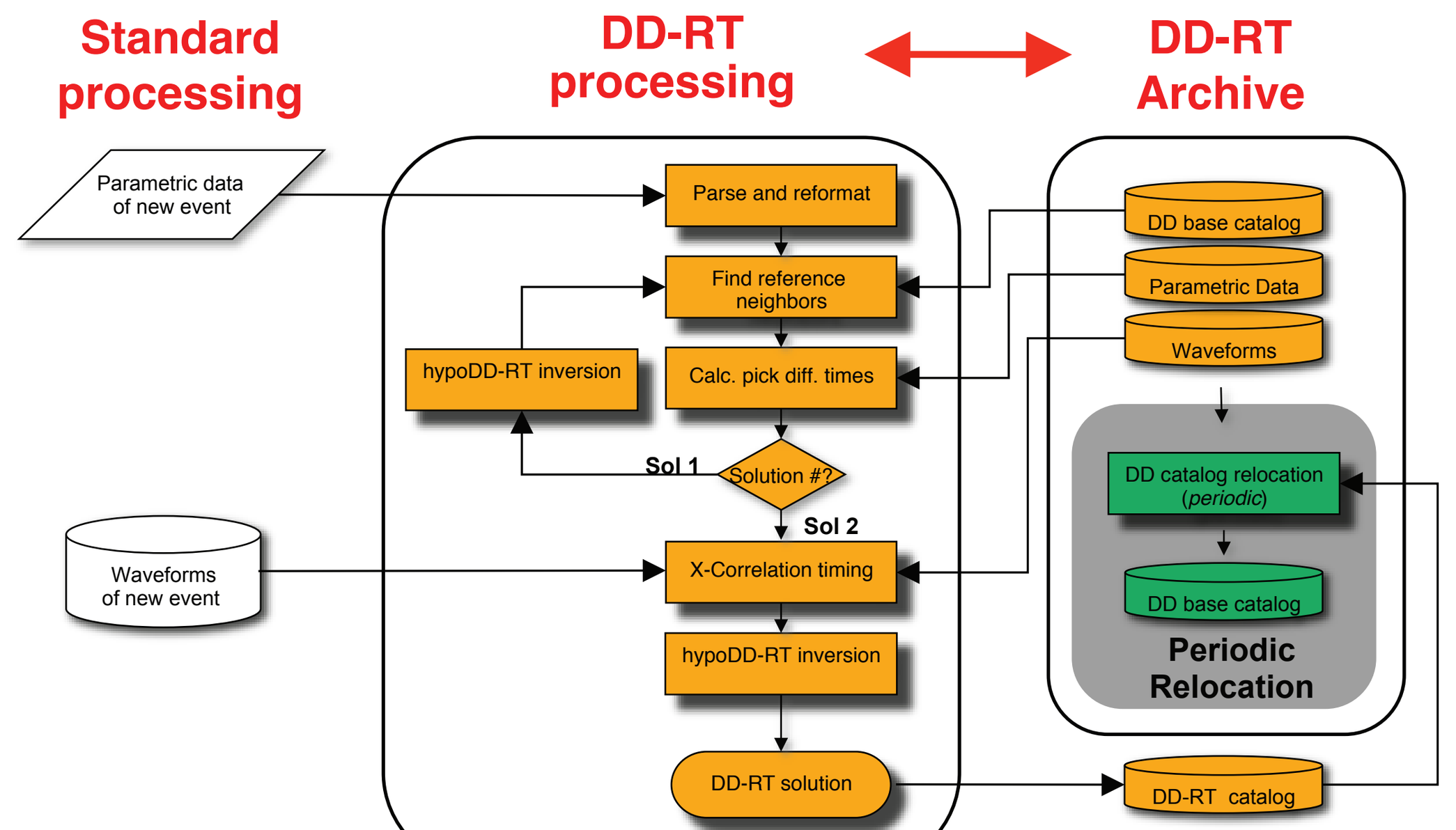


Figure 1

DD base catalog (HypoDD):

$$\frac{\partial t_k^i}{\partial m}\Delta m^i - \frac{\partial t_k^j}{\partial m}\Delta m^j = dr_k^{ij}$$

DD-RT catalog (HypoDD-RT):

$$\frac{\partial t_k^{i=1}}{\partial m}\Delta m^i - \frac{\partial t_k^{j=1,ref}}{\partial m}\Delta m^j = dr_k^{ij}$$

$$W\begin{bmatrix}G\\ \lambda I\end{bmatrix}\begin{bmatrix}m^{i=1}\\ m^{j=1,ref}\end{bmatrix} = W\begin{bmatrix}dr\\ 0\end{bmatrix}$$

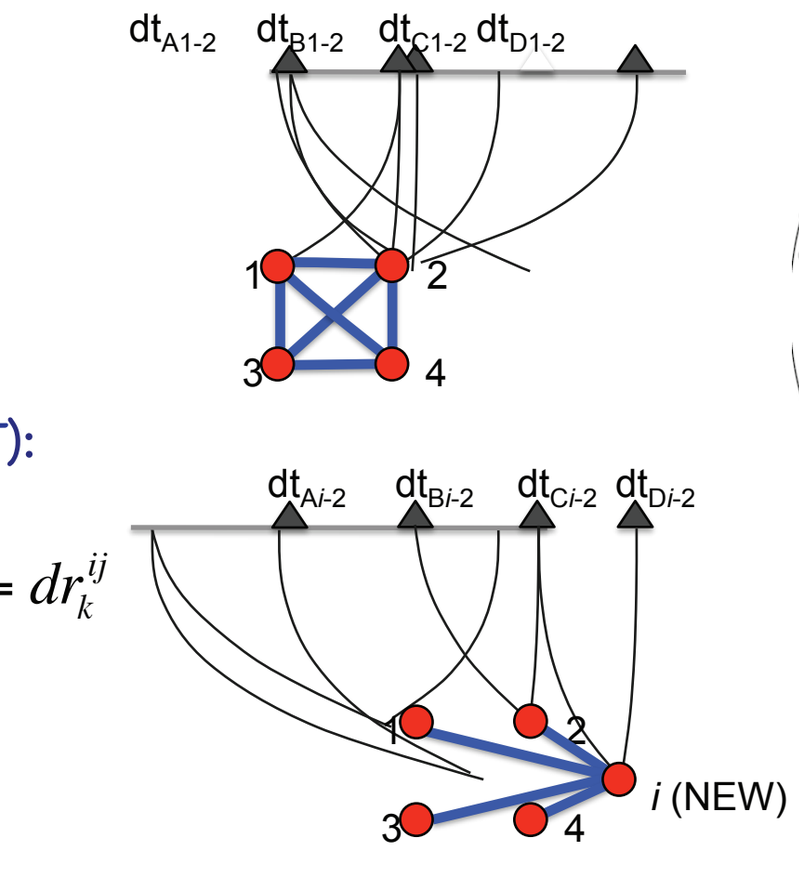


Figure 2

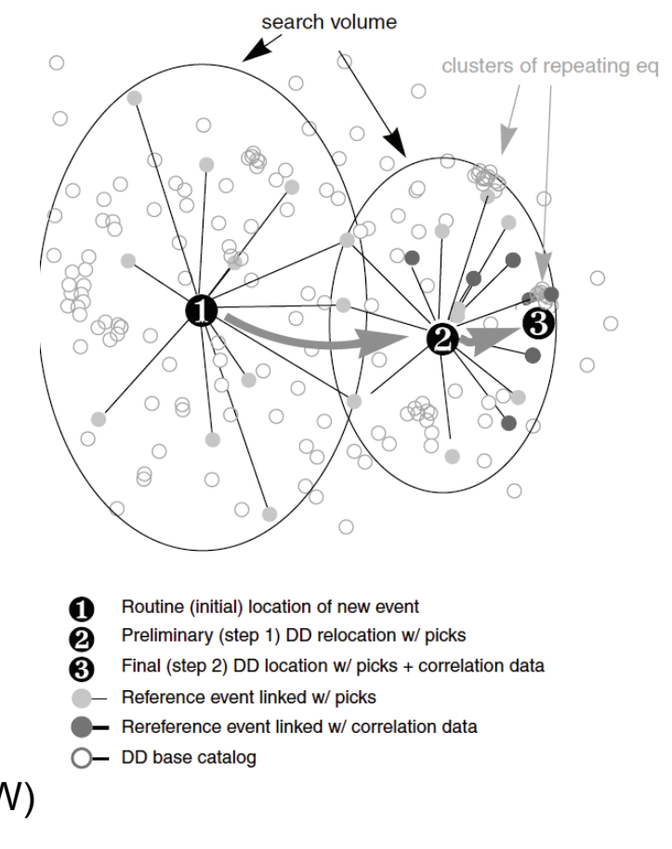


Figure 3

DD-RT is a real-time procedure that uses cross-correlation and double-difference methods to rapidly relocate new seismic events with high precision relative to past events with accurately known locations. Waveforms of new events are automatically cross correlated with those archived for nearby past events to measure accurate differential phase arrival times. These data, together with delay times computed from arrival time picks, are subsequently inverted for the vector connecting the new event to its neighboring events using the double-difference algorithm.
This real time procedure, already working at USGS and Lamont-Doherty Earth Observatory (Waldhauser, 2009), has now been implemented in the TABOO - Alto Tiberina Near Fault Observatory.
The procedure workflow is based on the following steps (Figure 1):
1. Find reference events in the DD base catalog that are near the new event's routine location (1 in Figure 3); 2. Compute a preliminary DD location for the new event (2 in Figure 3) by using pick delay times between new event and reference events; 3. Find reference events in the DD base catalog that are near the new event's preliminary (pick-based) DD location; 4. Compute delay times between new event and reference events from phase picks and by cross-correlating pairs of seismograms recorded at common stations; 5. Invert pick and cross-correlation delay times for final DD solution (3 in Figure 3).

DD-RT TABOO Base Catalog

The DD base catalog has a key relevance in the DD-RT procedure since all subsequent incoming new earthquakes will be located relative to the neighboring earthquakes included in it. Thus important characteristics of the reference catalog are quality and stability of the absolute starting locations.

For this reason we built the TABOO DD base catalog based on a further very strict quality selection applied to the ~42,000 earthquakes happened from 2010/04 to 2014/03 for which a well constrained 3D location is available.
The selection produced ~28,000 DD located earthquakes and 352,721 P- and 247,143 S-waves related arrival times.

Results

C

We located ~300 earthquakes, happened after the DD base catalog time lapse, with the DD-RT procedure and then analyzed the differences in latitude, longitude, depth, and origin time with respect to the corresponding 1D and 3D locations.
Moreover, we compared the DD-RT results to the standard DD locations by including the 300 test events into the starting dataset and then re-buiding an extended reference base catalog.
Both the statistical analysis (Figure 1) and the seismicity distribution (Figure 2) demonstrate the great improvement of the DD-RT approach with respect to the 1D, mainly, and the 3D location procedures and the small differences between the DD-RT and the base catalog DD locations.

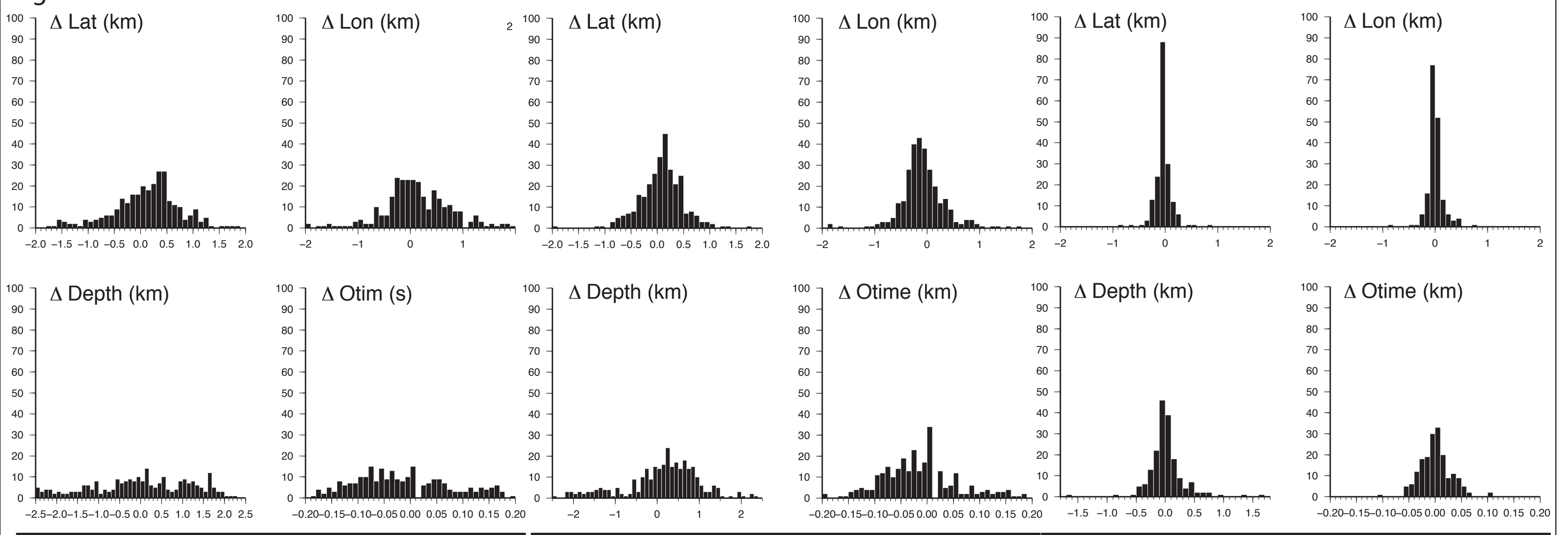


Figure 1

Histograms show the differences in latitude, longitude, depth, and origin time between DD-RT locations and 1D (left), 3D (middle), and standard DD locations (right). The greatest differences are found with respect to the 1D locations where the standard deviation is close to the formal 1D horizontal errors. Depth and origin time show the greatest standard deviation being the less stable parameter in the 1D location. Differences are smaller with respect to the 3D location, but depth is still the parameter getting the gretest improvement from the DD-RT approach. Finally, differences between DD-RT and DD locations are generally compatible with the very small formal errors of the latter.

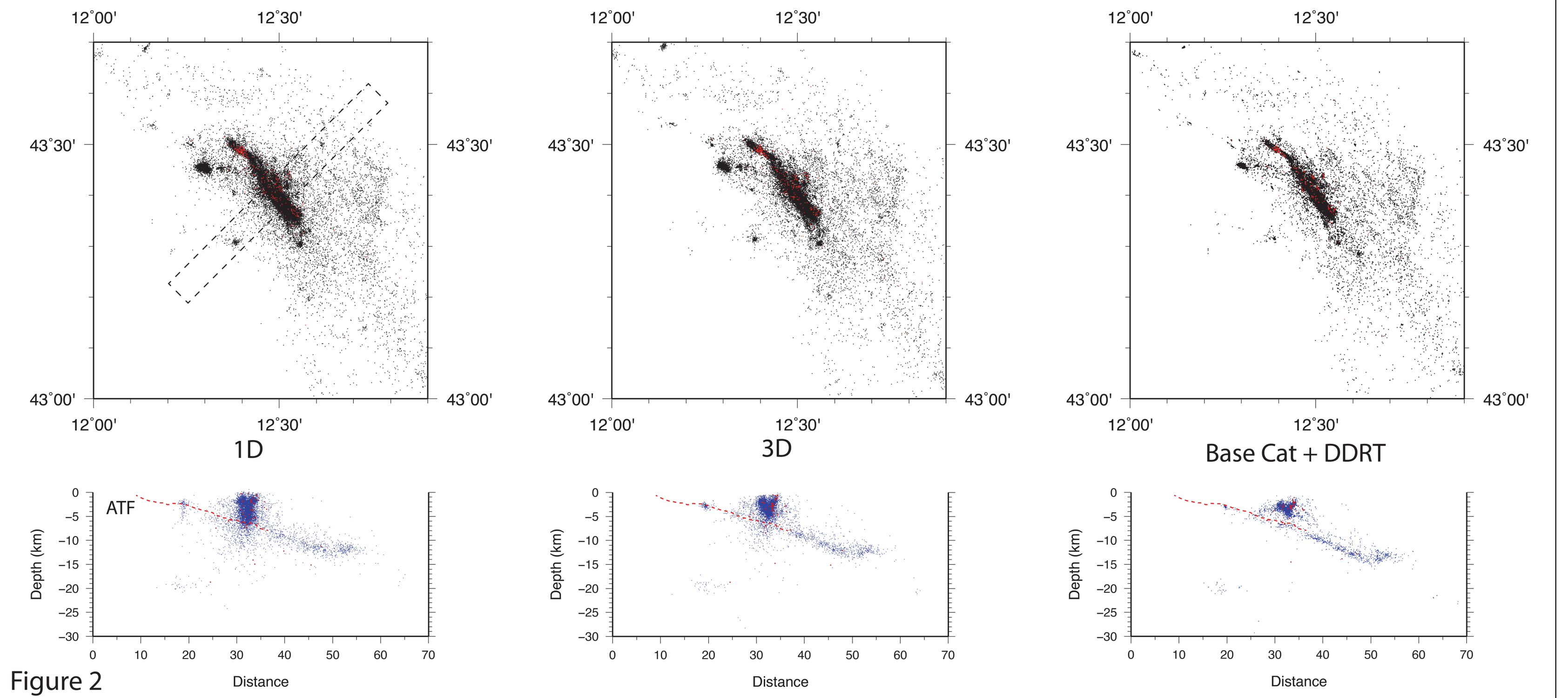


Figure 2

Map view (top) and vertical section view (bottom) of the seismicity distribution of the ~28,000 base catalog earthquakes (black and blue dots) and of the ~300 additional test earthquakes (red dots) in 1D (left), 3D (middle), and DD-RT (right). ATF is the trace in vertical section of the Alto Tiberina Fault from the controlled source seismology investigations.
Images show the progressive improvement of the fault imaging, induced by the use of the 3D relocation as the base for the DD-RT procedure. Both the DD base catalog and the additional DD-RT locations show an impressive fit with the a-priori known information about the ATF and the related structures.

Work in Progress

In the framework of the TABOO Near Fault Observatory we built, by using a completely automatic modular procedure, high-resolution 3D and DD earthquakes catalogues.
The encouraging results obtained by combining different location methods (1D, 3D, hypoDD, DD-RT) to the same dataset pushes us to extend such approach to further enhance the quality of the final locations, being the base to precisely analyze the variation of seismological parameters, e.g. Vp/Vs, in space and time.
The first of our next steps will be to introduce the NonLinLoc code (by A. Lomax), aside the 1D hypoellipse location procedure. We believe that this approach will (1) increase the reliability of the 1D locations by better managing the possible outliers always introduced by a completely automatic procedure, thus (2) strongly increasing the quality of the 3D and DD-RT locations and, subsequently, of the imaged Alto Tiberina Fault system anatomy.