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Seismic Monitoring of an Underground Natural Gas Storage Facility: The Collalto Seismic Network

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Online Material: Seismic-hazard map, figures of event location and waveforms, phase reading distribution, and background seismic noise; and tables of event parameters, 1D regional model, and earthquake catalog.

INTRODUCTION

The Collalto Seismic Network (Rete Sismica di Collalto, or RSC) is the infrastructure used to monitor the natural and induced seismicity of the natural gas storage concession known as Collalto Stoccaggio, which is located in northeastern Italy. This network was realized and is currently managed by the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), a public research institute, on behalf of Edison Stoccaggio S.p.A., the storage concession holder.

The storage exploits a depleted natural gas reservoir that was converted into a seasonal reservoir in the 1990s. The reservoir is a geologic trap, with porous and permeable rock layers, a few meters thick, sealed by impermeable formations. The production levels are located at 1500–1600 m depth (Picotti, 2007) and extend approximately over a 10 km × 4 km wide area (Fig. 1). The gas storage activity affects four municipalities, all of which are located in the province of Treviso: Susegana, Nervesa della Battaglia, S. Pietro di Feletto, and Conegliano.

The storage is run on annual cycles, that is, the gas is injected into the reservoir during the warm season and extracted during the cold season, under the directives of the Ministry of Economic Development (Ministero dello Sviluppo Economico, or MISE) and the Authority for Electricity and Gas (Autorità per l'Energia Elettrica ed il Gas) and according to the nation's needs.

The Collalto storage facility has been in operation since 1994. According to the license, storage pressure should not exceed 160 bars, which was the original pressure of the reservoir. The development of the storage facility was carried out gradually. Accordingly, during the first 15 years of gas storage, the operating pressure was limited to about 70% of the original pressure due to some limitations of the surface installations (compression station). To authorize the upgrading of the surface equipment to allow for the injection of up to 100% of original pressure, Edison Stoccaggio S.p.A. and the municipality of Susegana signed an agreement in 2008. This agreement stipulated that a microseismic monitoring system had to be developed and that this service had to be undertaken by an independent, public institute to ensure safe storage operations for the local community.

The need for this type of monitoring was later recognized by the Ministry for the Environment during the procedure to obtain authorization of Environmental Impact Assessment (Valutazione d'Impatto Ambientale, or VIA). Thus, the Collalto plant was the first case of a storage facility developed in Italy with a seismic monitoring infrastructure according to ministerial regulations.

Seismic monitoring has since become mandatory for new storage concessions, according to regulations defined by the VIA of the Ministry of the Environment. Detailed information (in Italian only) about existing and planned underground gas storage concessions, as well as regulations and technical data, can be found at the MISE website (http://unmig.sviluppoeconomico.gov.it; last accessed September 2014).

With the exception of two experimental test sites, the Collalto storage facility is the first in Italy that was allowed to operate with maximum gas storage pressure corresponding to 100% of the original confining pressure. The OGS was asked by the storage concession holder, Edison Stoccaggio S.p.A., to design the seismic monitoring network according to ministerial regulations specified in the VIA document. As a public research institute, the OGS set itself the task of guaranteeing the best monitoring service and research activity, as well as providing full and transparent information, public data, and unbiased opinions. At present, the RSC is the only network in Italy devoted to monitoring the seismicity potentially induced by underground gas storage activity that is managed by a public authority.

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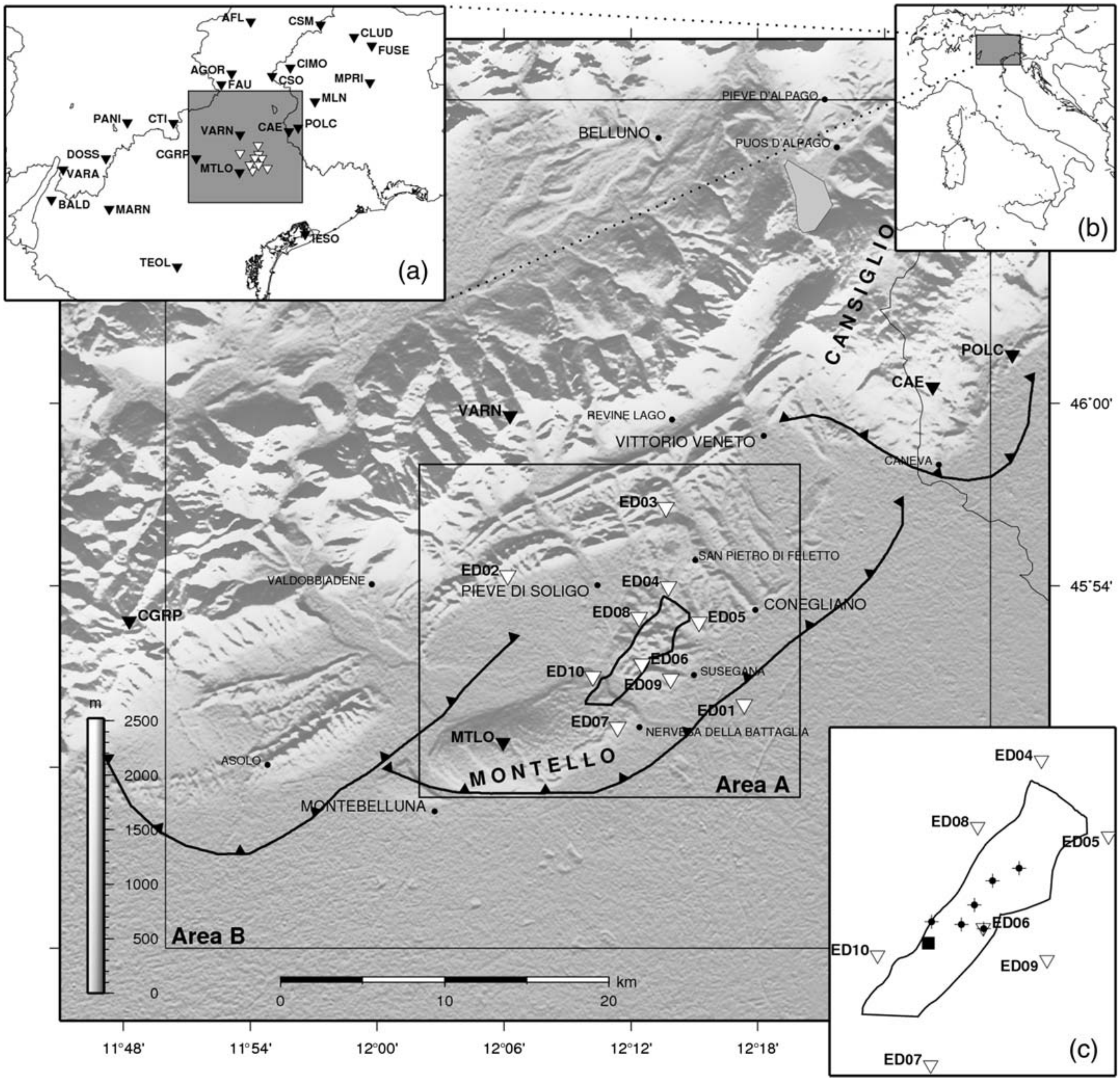


▲ **Figure 1.** Location of the study area, including the Collalto Seismic Network (RSC). Seismometric stations are indicated by triangles; the 10 RSC stations by white triangles (labels start with ED; all are located within area A); and the stations of the Northeastern Italy Integrated Seismic Network (NEI) by black triangles, respectively. All the stations indicated are managed by the OGS. The two rectangles bordered by thin lines indicate the two target areas, A and B. The irregular area bordered by a thick black line within area A corresponds to the surface projection of the gas storage reservoir. The fault lines indicate the active faults known for the study area according to Poli *et al.* (2008). Insets (a) and (b) show the location of the study area at regional and national scale, respectively. Inset (c) focuses on the area of the gas storage reservoir to show the location of the gas injection/extraction wells (black circles) and the storage plant (black square).

The Collalto gas storage facility is located in a hilly stripe at the front of the southeastern Alps, at the northern margin of the Venetian Plain (Venice is about 50 km away). The region is characterized by medium-high seismic hazard (Working Group MPS, 2004; Ⓔ see also electronic supplement available to this article); the four municipalities affected by the gas storage activity have been included in seismic zone 2 (zone 1 being the most dangerous one) since 1982.

A review of the seismological and seismotectonic data available for the whole Veneto region is given in Sugan and Peruzza (2011). The gas storage facility is located in the so-called Pedemontana Sud (PS) district, characterized by thrusts and folds trending east-northeast–west-southwest, verging mainly south-southeast, and buried under alluvial deposits (Poli *et al.*, 2008; Fig. 1). The deformation in the PS district goes back to compressive phases of the Messinian–Pliocene age (Castellarin *et al.*, 1998), and it still features tectonic activity, with a deformation rate of 2–3 mm/yr (Serpelloni *et al.*, 2005). The greatest historical seismic event was an earthquake on 25 February 1695, with Mercalli–Cancani–Sieberg intensity (I_{MCS}) IX–X (M_w 6.5, according to the 2011 Catalogo Parametrico dei Terremoti Italiani; Rovida *et al.*, 2011), in the area of Asolo, about 20–25 km west of Collalto. Two other major events occurred, respectively, on 29 June 1873 (I_{MCS} = IX–X, M_w 6.3) and 18 October 1936 (I_{MCS} = IX, M_w 6.1), at about 35 km northeast of Collalto, in the adjacent Alpago–Cansiglio (A) district. The instrumental seismicity recorded by the OGS since 1977 (http://rts.crs.inogs.it; last accessed September 2014) is moderate in the PS district, the biggest event having M_D 4.0, and few events exceeding magnitude 3. It is worth mentioning that this area could have been affected by a deficit in detection capability due to the less dense station distribution in the Veneto, compared to the adjacent Friuli and Trentino regions (Priolo *et al.*, 2005; Garbin and Priolo, 2013).

Both of the recent studies that have suggested the presence of several seismogenic structures capable of generating M_w 6+ earthquakes (Galadini *et al.*, 2005; DISS Working Group, 2010) and microseismic analyses based on a dense temporary network (Anselmi *et al.*, 2011; OMBRA Project Group, 2011) have not yet sketched out convincing images of the hypothetical silent sources in the Venetian piedmont area. The RSC network data will contribute to fill this gap of knowledge, as far as an adequate number of events will be recorded.

THE COLLALTO SEISMIC NETWORK

The RSC was designed keeping in mind a twofold aim of monitoring both the microseismicity potentially induced by the storage activity on the natural underground reservoir and studying the natural seismicity in the surrounding area. The network instrumentation combines characteristics of high dynamics and high sensitivity to ensure high-quality registration of medium–strong earthquakes, as well as microseismic events, with enough resolution power at the reservoir depth. The goal is to reach completeness magnitude M_c in the 0–1 range in a restricted area surrounding the reservoir, preserving the capability of recording nonsaturated signals for natural medium–strong events ($M_w \geq 5$) that might occur throughout the study area. The RSC consists of 10 seismometric stations and 1 permanent Global Navigation Satellite System (GNSS) site (Fig. 1). Table 1 summarizes the main features of the sites. Station sites are named by the code ED followed by two numbers, and the network is registered with the code EV at the Federation of Digital Broadband Seismograph Networks of the Incorporated Research Institutions for Seismology (IRIS) consortium. The official starting date of the RSC is 1 January 2012. The GNSS permanent site is registered as SUSE at Scripps Orbit and Permanent Array Center (http://sopac.ucsd.edu; last accessed September 2014).

The network geometry is dense in the area above the reservoir, where the station spacing is about 2–4 km, and gradually rarifies to merge harmoniously in the regional seismic networks operated by the OGS (Priolo *et al.*, 2005; Bragato *et al.*, 2011). The RSC is equipped with a number of stations that preserve the monitoring capability in case of temporary malfunctioning of some instruments or communications.

All sites are on private property. Stations are equipped with telecommunication systems and Global Positioning System (GPS) antennas for precise time synchronization. Power is provided by photovoltaic plants in most cases and main power otherwise.

The seismological instrumentation was manufactured by Güralp Systems Ltd. and consists of the following items:

- ten digital acquisition units (24-bit, 3- or 6-channels, model CMG-DM24S3/6-EAM), equipped with Linux operating system, Ethernet, GPS antenna for time synchronization, and 16 GB internal USB Flash drive memory storage;
- one three-component broadband seismometer (model CMG-3T) with flat response to velocity from 0.00833 Hz (T = 120 s) to 100 Hz (BB120 code in Table 1);
- nine three-component borehole seismometers (model CMG-SP1) with flat response from 0.1 Hz (T = 10 s) to 100 Hz (BB10 code); and
- five three-component accelerometers (model CMG-5TC) with full scale set at $\pm 2g$ (ACC code).

The sampling frequency is set at 200 Hz for all acquisition units; this value is adequate for recording microseismicity with the adopted network geometry.

To achieve the best possible signal-to-noise ratio, all the seismological sensors are installed in boreholes with variable depth, depending on the local soil and instrument type. The well depth varies approximately from 13 to 33 m, with the exception of site ED01, which is located on the plain at a depth of 155 m, and site ED06, which hosts the broadband sensor at about 5 m depth.

Site ED06 has some peculiar features compared to the other sites and deserves a more detailed description. This site is located within the Edison Stoccaggio Cluster 6 field and hosts both the seismological and GNSS stations. The site was prepared by excavating to a depth of about 5–6 m, where a stiff formation of over-consolidated clays (argillites) was found; it constitutes a good bedrock for both the seismological instruments and the GNSS pillar. The seismic site consists of an underground medium-density polyethylene housing, with 1.2 m diameter and 4.7 m height. The housing is divided vertically into two sections, providing good thermal insulation of the deepest section, which hosts the sensors. The seismological sensors (i.e., the broadband seismometer and the accelerome-

Table 1
Summary of the RSC Stations

Sensor Location							Sensor Type			
Code	**Latitude**	**Longitude**	**Elevation (m.a.s.l.)***	**Depth (m)**	**Location Name**	**Site Condition**	**BB120[†]**	**BB10[†]**	**ACC[†]**	**GNSS[†]**
ED01	45.834582	12.289224	54	−155	Susegana S. Lucia	Alluvial plain. Uneven interlayering of clay, sand, gravel, and conglomerate. *P* velocity estimated by a VSP survey increases from 800 to 2500 m/s between 0 and 40 m, and from 2500 to 3000 m/s between 40 and 155 m		X		
ED02	45.905697	12.103050	205	−33	Farra di Soligo	Piedmont hill. 0–16 m weathering and red clay, 16–33 m light blue clay		X		
ED03	45.942908	12.227786	235	−31.9	Corbanese	Piedmont hill. 0–11 m weathering and red clay, 11–20 m sandy clay, 20–32 m light blue clay		X		
ED04	45.899373	12.229493	182	−26.9	S. Maria di Feletto	Collalto hills. 0–20 m weathering and red clay, 20–26 m light blue clay, 26–28 m conglomerate		X		
ED05	45.880123	12.253799	110	−14.5	S. Michele di Feletto	Collalto hills. 0–10 m weathering and red clay, 10–14.5 m conglomerate		X	X	
ED06	45.857011	12.208484	174	−5	Collalto Campo 6	Collalto hills. 0–2 m filling soil, 2–6 m well-consolidated yellow clay. V_P of clay 1400 m/s, estimated by a refraction survey	X		X	X
ED07	45.822174	12.189355	167	−14.5	Nervesa della Battaglia	Montello hills. 0–11 m weathering and red clay, 11–12.5 m gravel, 12.5–15 m conglomerate		X	X	
ED08	45.882510	12.206460	193	−14.3	Collalto Cucco	Collalto hills. 0–7 m debris, 7–14.5 m weakly consolidated conglomerate. Water table at 12.5 m		X	X	
ED09	45.848796	12.231489	105	−14.6	Susegana Castello	Collalto hills. 0–8 m weathering and sandy clay, 8–15 m consolidated conglomerate		X		
ED10	45.850026	12.170177	144	−13.6	S. Croce del Montello	Montello hills. 0–14 m weathering and uneven interlayering of clay and conglomerate		X		

*m.a.s.l., meters above sea level.
[†]BB120, broadband seismometer; BB10, extended band seismometer; ACC, accelerometer; and GNSS, geodetic sensor.

ter) lie on a thick concrete basement, which is solidly secured to the rock at a depth of about 5 m.

At the same site, close to the seismological station, the SUSE geodetic station is installed. The station base consists of a concrete pillar (1 m × 1 m thick and 5 m high), which is completely buried and solidly anchored to the rock, and terminates in a slender, free pillar (1.5 m high) with the GNSS antenna on top. The geodetic instrumentation consists of a Topcon CR-G3 GNSS choke ring antenna. The GNSS receiver is set for continuous acquisition with a 1 s sampling interval. This feature, together with the fact the GNSS receiver is co-located with the seismic receiver, will allow direct integration of the two types of data in the future, both in the long- and in the short-period band, in case of major earthquakes. The SUSE station is included in the Friuli Regional Deformation Network (FReDNet) system (Battaglia *et al.*, 2003).

At all the other stations, the seismometric sensors are located within a 12 cm wide borehole, whereas the other instruments (e.g., digital acquisition units, GPS, radio modem, etc.) are located at the surface. For the four three-component high-dynamic stations (ED05, ED06, ED07, and ED08), the accelerometric sensors are located at the surface within the top-borehole cockpit.

Concerning data communication, RSC stations are equipped with routers with GPRS/EDGE or UMTS interface, which provide Internet connection with the OGS acquisition centers located in Udine and Trieste.

The acquisition/processing system consists of:

- two Apple Mac Mini servers equipped with Intel Core 2 processors, which serve as acquisition and real-time processing systems, respectively;
- an Apple Mac Pro server equipped with two Intel Xeon Quadcore processors, used for both real-time and off-line data-processing; and
- a network storage system with about 20 TB of disk space, for permanent data storage.

Once raw data are acquired from the stations, they are converted into MiniSEED format to be stored and processed. Data are permanently archived with daily rate into two separate storage systems: a network unit currently used by the processing system and, primarily, the OGS Archive System of Instrumental Seismology (OASIS) (Priolo *et al.*, 2012; E. Priolo *et al.*, unpublished manuscript, 2015). The latter provides full information about the seismological sites as well as free access to continuous waveform data through its web portal (http://oasis.crs.inogs.it/; last accessed September 2014).

Similarly, for the SUSE GNSS station, RINEX files can be freely downloaded through the FReDNet website (http://www.crs.inogs.it/frednet; last accessed September 2014).

The stations in the acquisition system are set to record continuous data in both the proprietary format (Güralp compress format) and MiniSEED format. The real-time link and data archiving is performed through SeedLink protocol, which manages communications between stations and the acquisition server. The core of the acquisition system is a generic ring buffer and SeedLink server, called ringserver, which puts incoming data into a circular memory (ring buffer), recovers and fixes possibly missing pieces of data, and checks all server-client dialogs. Once raw data within the ring buffer are flagged as valid, they are archived in the permanent mass storages in MiniSEED format.

Data processing is performed in both real-time and off-line modes, respectively.

Real-time processing is based on Earthworm and SWARM softwares. Earthworm (www.earthwormcentral.org; last accessed September 2014) is an open-source software system developed for processing data acquired from seismological regional and local networks; in the RSC system, the event detection and notification functions are activated. The Seismic Wave Analysis and Realtime Monitor (SWARM, www.avo.alaska.edu/Software/swarm; last accessed September 2014), on the other hand, is used for displaying the acquired signals on dedicated monitors in real time and performing some basic analysis on the fly.

The main tasks of off-line processing are data archiving/distribution, signal quality control, seismic event detection and location, and monitoring surface movements via estimation of GNSS time series and velocities.

As previously said, the first task is managed by OASIS (Priolo *et al.*, 2012; E. Priolo *et al.*, unpublished manuscript, 2015). It consists of a database that contains full information about the seismic network sites, an archive of continuous waveforms and waveforms of selected earthquakes, and an interface website to access all the data. The RSC data are loaded daily into OASIS in the early morning (CET time zone) to ensure that possible delayed packets have been recovered. As a consequence, all waveform data from the previous day to the current one (Italian time) are readily available.

Signal quality control is performed by different tools. At present, the following functions are implemented for all the stations: (1) power spectral density plots (McNamara and Buland, 2004) for different time periods by PQLX (http://ds.iris.edu/ds/nodes/dmc/software/downloads/pqlx/; last accessed September 2014); (2) battery status plots; (3) a web page with the modem/router status; and (4) statistics on the communication system.

Much of the off-line processing, and in particular event detection, is performed by the BRTT Antelope system (http://www.brtt.com/; last accessed September 2014), which is the same system used by the Northeastern Italy Integrated Seismic Network (NEI), managed by the OGS (Priolo *et al.*, 2005; Bragato *et al.*, 2011). This part will be more broadly described in the following section.

Finally, as far as GNSS processing is concerned, time series and velocities are calculated using the GAMIT/GLOBK 10.40 package developed at Massachusetts Institute of Technology.

DETECTION AND CHARACTERIZATION OF SEISMIC EVENTS

Two areas have been defined as target areas for detecting seismic events. The large area (area B), which is used as a regional frame, is approximately 50 km wide; the small area (area A), which surrounds the reservoir, is 20 km wide (Fig. 1).

At present, the processing and specific analysis activities carried out for the RSC do not require continuous surveillance by operators or an on-call service, because events to approximately the perception threshold ($M_L \sim 2.8$) are detected by the regional seismic alert system managed by the OGS for the civil defense of the Veneto region.

The RSC detection and location system becomes operational after signal acquisition and data storage. The procedures for detecting microseismicity differ greatly from the ones used by the alert system for civil defense, whose aim is detecting and recognizing the relevant events in the shortest time; it must be fast but also robust and reliable in order to avoid false events, requirements which exist at the expense of low sensitivity. To make the best use of the seismic network and detect as many seismic events as possible in the target areas, the RSC system is not fully automatic and requires a manual off-line intervention. The processing and analysis functions are therefore tuned to detect weak events and solve different problems. An example is the ability to interpret signals and associate phases that are recorded by a small number of stations (minimum three), although accounting for some errors.

The off-line processing procedure is similar to the one already developed and used for seismic monitoring of the Trentino province and described in Garbin and Priolo (2013). Three steps are needed:

1. dataset preparation, by integrating the RSC data with those of some of the NEI network stations;
2. semiautomatic recognition of seismic events, based on automatic event detection and manual removal of false events by visual inspection;
3. manual repicking and relocation.

To improve the location capability within areas A and B, the detection area includes the Veneto, Trentino, and Friuli–Venezia Giulia regions, adding a group of about 20 stations of the NEI network to the 10 RSC stations. The most distant stations are used for recognizing the farthest events and as an aid to the subsequent seismologist's analysis. For local and regional events, Antelope calculates a provisional local magnitude M_L. To ensure compatibility between the M_L estimations made by the RSC and the NEI regional network, the same attenuation relationship is used, namely the one proposed by Bragato and Tento (2005).

The next step is the detection and removal of false events, which at this time is done with rapid manual checks by trained personnel. It must be noted that the high sensitivity setup of the detection system causes a large number of triggers that can lead to several false associations. Other false events derive from natural phenomena (i.e., thunderstorms, which are very frequent in that area) or artificial causes (the RSC network is located in a rather densely populated and industrial area).

After the detection and removal of false events, all waveforms for the events identified within area B are extracted and saved in Seismic Analysis Code format. Ⓔ Some examples of the waveforms recorded by the RSC for three events are shown in the electronic supplement.

Once the dataset of extracted waveforms for all identified events has been created, the procedure continues with the manual reading of arrival times for all seismograms and with location. The phase picking is done by Seisgram2K (Lomax, 2008).

We perform what we call a zero-level data processing for determining earthquake locations, with the goal of having locations that are coherent with those performed by the NEI network; in this way, data of new local events can be directly merged and compared with the seismicity data previously available for this study area. More sophisticated processing will be performed in the future, inasmuch as a richer seismological dataset and more reliable constraints on the geologic/geophysical model will be available; they will be the topics of a forthcoming article. Therefore, Hypo71 (Lee and Lahr, 1975) locates the events using the same regional velocity model adopted for the NEI network (Priolo *et al.*, 2005; Ⓔ see the electronic supplement).

The consistency of manual pickings and the presence of possible errors are verified by analyzing the modified Wadati diagram (Lay and Wallace, 1995). The diagram also reveals the average V_P/V_S ratio in the volume sampled by the ray paths.

The last step is that of magnitude calculation and calibration. The latter consists of compensating the systematic station residuals in order to reduce the difference between the average station magnitude and the estimated magnitude, through an iterative minimization process.

SEISMICITY DETECTED AND NETWORK PERFORMANCE

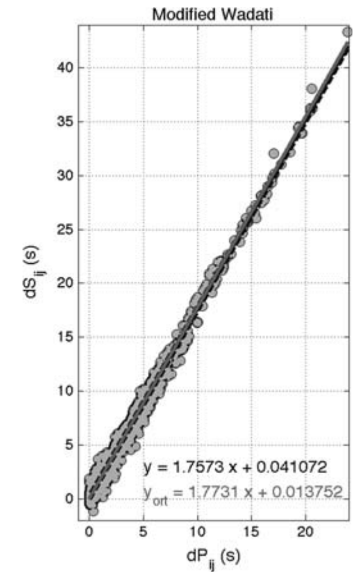
In this section, we describe the seismicity recognized in the first two years of activity of the network, from 1 January 2012 to 31 December 2013. This period includes a complete cycle of injection of the gas into and extraction from the reservoir. It should be noted that by "recognized" we mean events located by at least three stations and five phases and for which the local magnitude has been correctly estimated.

Figure 2 shows the modified Wadati diagram. The V_P/V_S ratio is nearly equal to 1.77 (assuming that the orthogonal regression provides the best fit), which is a value notably consistent with that assumed for the regional velocity model. The average uncertainty of the arrival-time readings is about 0.03 s (Ⓔ see the electronic supplement for more details). The largest uncertainties are on the order of 1 s and correspond to events for which the signal is embedded in the noise.

Figures 3 and 4 show the map and depth distribution of all recognized events, respectively, according to the list in Ⓔ Table S3 of the electronic supplement. The complete list of events recognized within the target areas is regularly updated at the RSC website (http://rete-collalto.crs.inogs.it/en/tags/dati-e-grafici; last accessed September 2014).

The following events were recognized for the period 1 January 2012 to 31 December 2013:

- within area A, 82 events with local magnitude $-0.6 \le M_L \le 1.2$;



▲ **Figure 2.** Modified Wadati diagram obtained from the 2012–2013 RSC dataset presented in this study. The x and y axes represent the arrival-time difference between pairs of stations for the P and S wave, respectively. The straight lines represent the result of the linear orthogonal (dark gray) and nonorthogonal (black) regressions, respectively. The regression equations and coefficients are also explicitly indicated. The slope of each line allows estimation of the V_P/V_S ratio of the crustal structure at local level.

- within area B (outside area A), 134 events with local magnitude $-0.4 \le M_L \le 2.3$; and
- within the whole area represented in Figure 3, 272 events with local magnitude $-0.6 \le M_L \le 2.3$.

Remarkably, all recognized events have magnitudes below a commonly accepted perception threshold (M_L 2.8) and below the level of completeness magnitude ($M_L > 2.0$) of the Italian National Seismic Network of Istituto Nazionale di Geofisica e Vulcanologia for the study region (Schorlemmer *et al.*, 2010). The only two events with $M_L > 2$ are located in the Col Visentin and Cansiglio highland areas, at about 16 km north and 20 km northeast, respectively.

Few epicenters fall near the surface projection of the reservoir. However, in most cases the depth of these events is between 7 and 10 km, whereas only a few of them are shallower (5 km). No clusters can be recognized within area A, whereas some clusters can be seen in area B; for instance, those located south of Montebelluna, in the Alpago area, and close to Vittorio Veneto, respectively (localities are shown in Fig. 1). In particular, the cluster closest to the reservoir, at a distance of about 6–7 km (i.e., north of the reservoir at the edge of area A) is not linked spatially to the gas storage activity by the presence of any other intervening event. It consists of very weak events, for which no additional analysis was carried out. Considering the distance from the reservoir, the matter has no practical interest for this study.

Figure 4a shows that most events recorded in area A occur at a depth between 5 and 13 km. Moreover, no event occurs at a distance of less than 3 km from the external boundaries of the reservoir (Fig. 4b). We checked that this condition persists even if different and slower velocity models are considered. The issue of refining the local model is certainly of the highest interest for this kind of study, but it cannot be properly addressed with the limited earthquake sample we have at our disposal at this time.

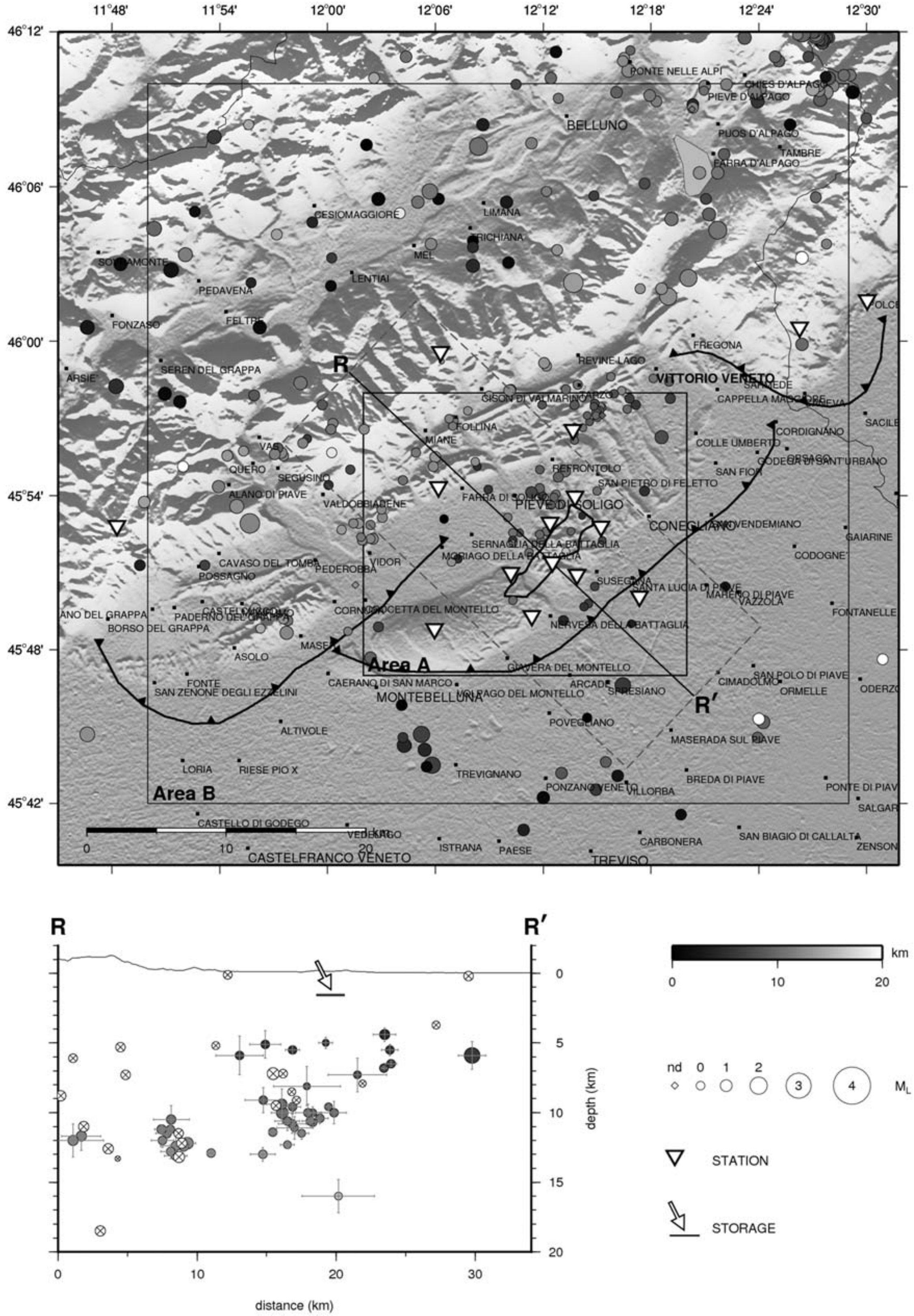
The vertical section of Figure 3 shows the location uncertainty of events detected in area A, horizontal and vertical errors (errh and errv, respectively) are included in Ⓔ Table S3). The average location errors are a few hundred meters, but for about 10 events the uncertainty is larger than 4 km. The estimated depth is unreliable (errv > 5 km) for a small number of events (white cross-hatched symbols), which are usually very shallow and correspond to quarry explosions. It should be noted that the network resolution power depends on the azimuthal coverage for the horizontal direction and the presence of a station above the event for the depth. For three to four very weak events, which are detected by a few stations, those conditions often fail.

Figure 5 compares the seismicity recognized in area A with the gas storage activity at Collalto, through curves representing the gas flow and gas pressure, respectively, measured at the mouth of the well. These data were provided to us by Edison Stoccaggio S.p.A. We emphasize that this is the first time that such kind of data have been published, at least for gas storage activities carried out in Italy. We point out the following phases of gas storage activity:

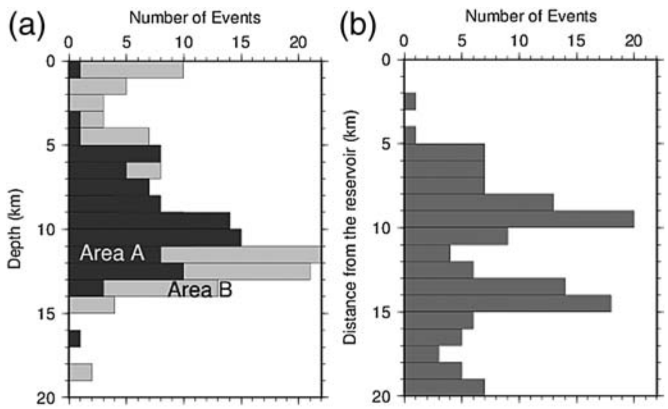
- gas supply (i.e., extraction) during the 2011–2012 winter period, until March 2012;
- gas injection from mid-April to mid-October 2012;
- gas supply from November 2012 to March 2013;
- gas injection from April 2013 to mid-October 2013; and
- gas supply from November 2013 to the end of 2013, when the observation period of this study ends.

Each phase is preceded and followed by a cessation period of 15–20 days, during which the storage manager carries out several control operations. The period of April 2012–April 2013 represents the first full cycle of gas storage carried out with dynamic pressure increased to about 140–150 bars, which allows the bottom static pressure of the reservoir to reach a value close to 90% of the maximum authorized pressure (original pressure).

The highest hourly average flow values during the extraction phases increase between the winter of 2011–2012 (when values range between 130 and 150 kSm^3/h) and the winters of 2012–2013 and 2013–2014 (when average values range between 160 and 190 kSm^3/h, respectively). The highest dynamic pressure, measured at the surface installations, exceeds 140 bars, but always remains below 150 bars, in the injection periods corresponding to late summer/early autumn. At the beginning of November, when injection is switched to extraction, the pressure suddenly decreases from approximately 130



▲ **Figure 3.** Seismic events (circles) located by the RSC in the period 1 January 2012 to 31 December 2013. The gray color scale and symbol size represent the event depth and local magnitude (M_L), respectively. White inverted triangles represent stations. Fault lines are as in Figure 1. The vertical cross section R–R' of the 14 km wide strip bordered by the thin dashed line in the map is shown in the bottom left panel. The horizontal and vertical bars represent the location errors. White circles with an internal cross represent events for which the horizontal or the vertical errors are larger than 3 and 5 km, respectively. In the vertical section, the storage facility is indicated by the black solid segment below the arrow.



▲ **Figure 4.** (a) Distribution of the depth and (b) the distance from the reservoir for the events located by the RSC in the period 1 January 2012 to 31 December 2013.

bars to approximately 70–80 bars. Toward the end of the supply phase, the gas pressure reaches about 30 bars.

The seismicity recognized by the monitoring system in area A is very weak: the cumulative number of events estimated on a 15 day basis is always of few units, and the event local magnitude is very low, usually $M_L < 1$. Only one event of $M_L \sim 2$ is recognized, located farther than 5 km from the reservoir (Figure 3). The small cluster of seismicity previously mentioned occurred at the end of 2012 and the beginning of 2013: it consists of 19 weak events ($M_L \leq 0.48$) located a few kilometers southwest of Vittorio Veneto.

Taking uncertainty into account, all events belonging to area A occur at a distance greater than 3 km from the reservoir. No clear correlation is appreciable between the seismicity and the activity developed within the reservoir.

Concerning the effectiveness of the RSC monitoring system, we cite the strong seismic sequence of Emilia on 20 May 2012, which produced thousands of events in subsequent months. These earthquakes represent a source of "noise" that reduces the capability of detecting the weak signals of small local earthquakes. However, the list of area B events does not feature clear evidence of a reduction in detection sensitivity.

We have also adopted the Gutenberg–Richter relationship to estimate the seismicity rate and the network performance (using ZMAP; Woessner and Wiemer, 2005). The results obtained for the whole dataset of the period 1 January 2012 to 31 December 2013 (Ⓔ see also Table S3) are shown in Figure 6 and Table 2. The completeness magnitude (M_c) and b-value are equal to $M_c = 0.86$ and $b = 1$ for area B, and $M_c = 0.19$ and $b = 1.2$ for area A, respectively. Compared to the existing neighboring networks, the OGS regional network NEI is the most dense network operating in northeastern Italy; it detects earthquakes with a completeness magnitude of about 1.5 (Gentili *et al.*, 2011). Moreover, the RSC improves the threshold completeness by about 0.6 and 1.3 magnitude units in areas B and A, respectively. Previous values have been obtained by the entire magnitude range (EMR) method, which is considered the most reliable and effective one (Woessner and Wiemer, 2005). We emphasize the still limited statistical significance of the estimates presented in this study, and we believe we cannot provide further comments at this stage.

Conversely, we believe that the excellent level of completeness magnitude attained is not only due to the quality of the instruments and electronic devices, but also to the site selection and, in particular, to the care with which the sensors are deployed. Ⓔ As evidence, we present a preliminary analysis of the noise level for some stations in the electronic supplement, while we postpone a more accurate analysis to a future paper.

INFORMATION, DATA DISSEMINATION, AND PUBLIC PRESENTATIONS

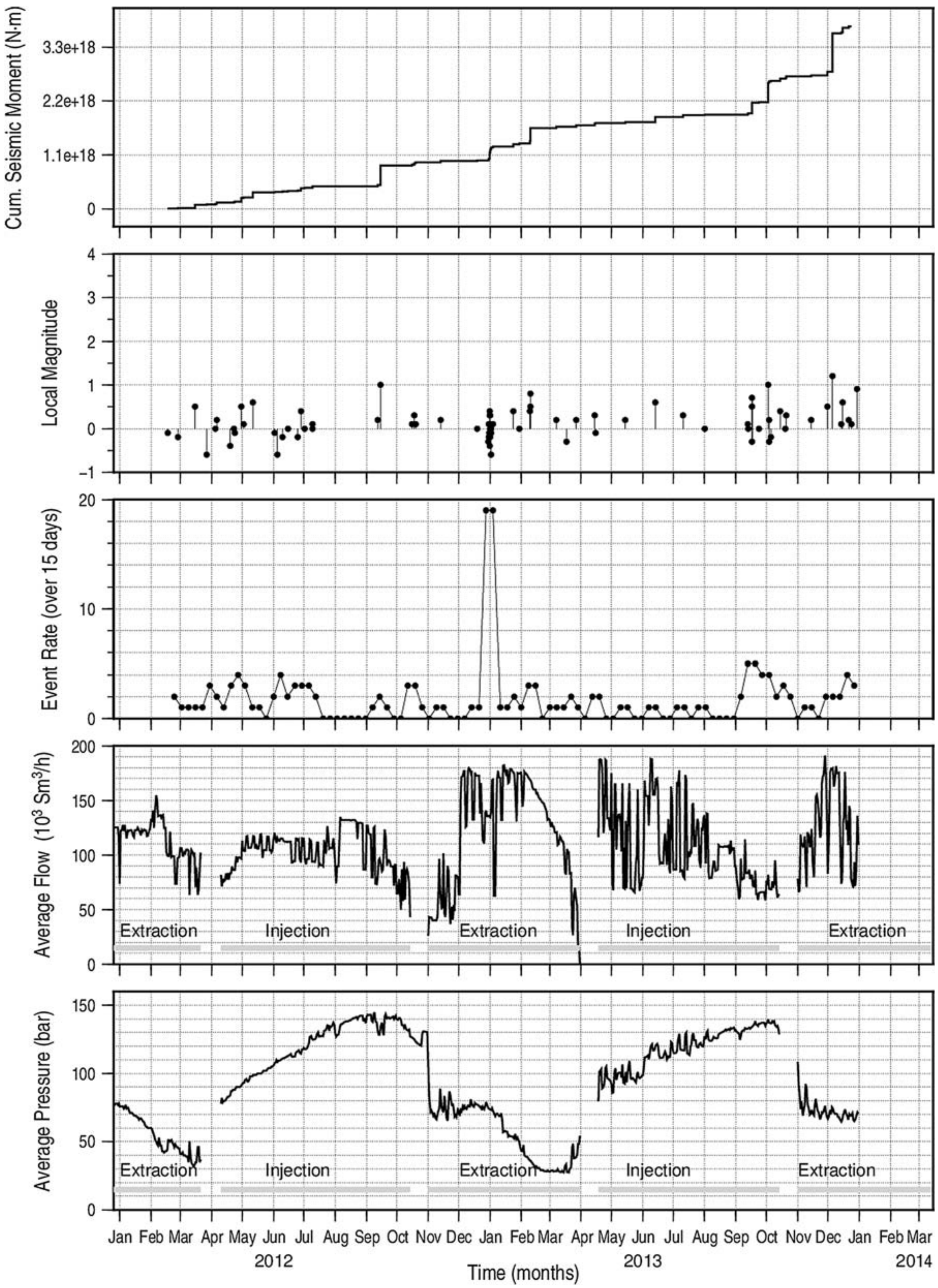
A key role of the RSC project is that of disseminating information and data. This is mainly done through the RSC website www.rete-collalto.crs.inogs.it (last accessed on September 2014). A brochure (in Italian) was also prepared and distributed to explain in a clear and simple way the scientific framework and the goals of the network's activities. This brochure can be downloaded from the Scientific Material and Documentation section of the RSC website http://rete-collalto.crs.inogs.it/en/tags/materiale-scientifico-e-documentazione (last accessed September 2014).

The RSC website (Figure 7a) also has a complete description of the network and aims at providing any related information in detail. Seismicity data are published on the website monthly, after the seismologist's revision. According to regulations, the scientific reports are sent to the company and controlling authorities, as well as released on the website, at the end of each injection/extraction cycle, that is, roughly every six months. However, we are also preparing a fast track for publication of detected events, with preliminary location parameters.

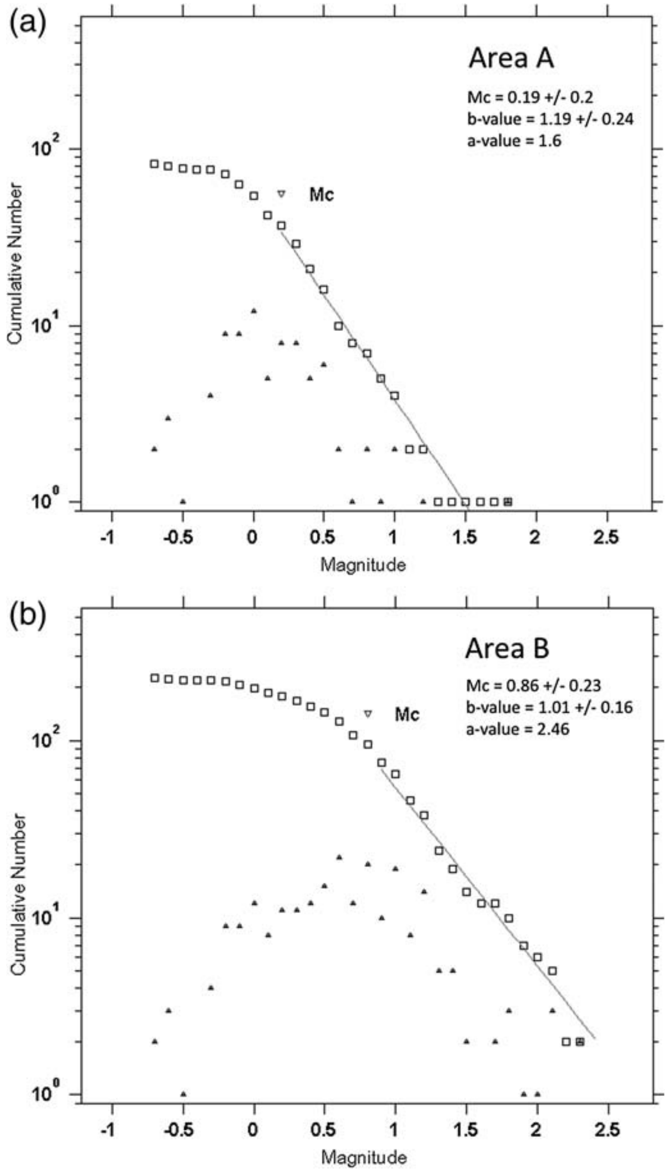
Original recorded data can be freely accessed through the RSC website as well. Continuous waveform data can be downloaded through the Data and Graphs section, which has a direct link to OASIS (http://oasis.crs.inogs.it/; last accessed September 2014), with a specific selection of the RSC stations (Fig. 7b).

The RSC project has been presented not only to the scientific community and authorities, but also to the population of the towns of Susegana and Collalto and to other areas hosting similar facilities. This is another distinct and particularly important aspect (in our opinion), as during public meetings part of the population has expressed strong disappointment about the overall management of the gas storage facility and underground exploitation at the national level. (See, for instance, the videos of the presentation by the RSC to local populations on 29 October 2012 [in Italian], posted on the RSC website under Scientific Material and Documentation.)

People are extremely worried, because they realize that the Italian territory (especially the Po Plain) is massively occupied by concessions for oil and gas exploitation, although they are of a conventional type (e.g., no shale gas) and limited in size. They feel that regulations are not completely clear and do not provide adequate protection of the environment and the population. Especially after the 2012 earthquakes in Emilia, they are



▲ **Figure 5.** Comparison between the seismicity recognized in area A in the period 1 January 2012 to 31 December 2013 and the gas storage activity carried out by Edison Stoccaggio S.p.A. The *x* axis represents the time with the same scale for all panels. The three upper panels represent seismicity, in terms of (from top to bottom) the cumulative seismic moment, the local magnitude M_L, and the seismic rate calculated in a 15-day window, respectively. The two bottom panels represent the gas storage activity, through the average flow (units in thousands of standard cubic meters per hour) and pressure, respectively. Pressure is measured at the well mouth. Thick gray lines indicate the periods of gas extraction from or injection into the reservoir. Gas storage data are provided by Edison Stoccaggio S.p.A.



▲ **Figure 6.** Magnitude–frequency distribution and completeness magnitude for earthquakes located in (a) area A and (b) area B during the period 1 January 2012 to 31 December 2013. Calculations are made by software ZMAP using the EMR method (Woessner and Wiemer, 2005). Magnitude is local, discretized in 0.1 wide bins. Triangles and squares represent the incremental and cumulative number of earthquakes, respectively. The straight line represents the estimated Gutenberg–Richter relationship. Estimated coefficients are explicitly written and given as annual values.

afraid that oil and gas exploration and geothermal exploitation activities might have induced or triggered earthquakes along existing faults; in general, they do not trust public managers, private companies, or even scientific institutions.

We have experienced two conflicting circumstances: (1) very reasonable points of view and requests that can be readily answered and (2) false beliefs and considerable confusion, for which an intense work of scientific outreach is needed. Both situations should be faced with transparency, following well-established rules and roles for the different actors (public administrations, energy companies, scientific institutions, and so on).

CONCLUSIONS

In this article, we have described the seismic network realized by the OGS for monitoring the natural and induced seismicity in the area of the natural gas storage facility of Collalto, managed by Edison Stoccaggio S.p.A. The monitoring infrastructure was designed and realized to provide the high-quality data needed to locate events accurately, estimate their magnitude, and characterize the seismic sources. We hope that, in addition to the strict fulfillment of ministerial specifications, the data acquired will allow more advanced studies, such as those relating the release of seismic energy to the pressure distribution inside the reservoir.

In the basic analyses of seismicity provided by the first two years of monitoring, no events have been detected at a distance lower than 3 km from the reservoir. The RSC system is able to detect and record a broad range of events, from strong earthquakes to microevents of a magnitude as low as 0.0. This kind of data has never been published before, at least for the gas storage activity carried out in Italy. Based on these "start-up" data, no correlation can be identified between the local seismicity and the gas storage activity.

The criteria used for defining an earthquake as induced consider, among other concepts, the spatial and temporal correlation between the events and the source of activity (Davis and Frohlich, 1993). According to the recent report entitled "Induced Seismicity Potential in Energy Technologies" (National Research Council, 2013), induced seismicity is due to an increase of the pore pressure above the levels existing *ex ante* to the fluid injection. As Astiz *et al.* (2014) wrote, "Injection-related earthquakes typically follow a pattern, wherein the points of initiation (hypocenters) of earthquakes in the sequence are both temporally and spatially correlated with the magnitude of the pressure increases on the causative faults. Most earthquakes that are allegedly induced by fluid injection occur within a few km of an injection well, where the injection pressures are greatest.". For oil and gas production activity, Eisner (2013) suggests that induced seismicity should occur within 2–5 km from the injection well. The earthquakes recorded by the RSC in 2012–2013 verified none of these conditions. In addition, the distinctive nature of the exploitation activity should be kept in mind: the Collalto storage facility uses a depleted gas reservoir enclosed by highly impermeable and rigid formations made of sandstone that kept it sealed for about 6 Ma (Picotti, 2007). The gas storage activity involves injecting into and extracting from the reservoir, a clearly established quantity of gas during a one-year cycle, with rigorous control of the gas flow. This is very different from activities such as enhanced geothermal systems, unconventional oil and gas production, or fluid injection and withdrawal, all of which require either high pressure or huge cumulative quantities.

Thus, in the still-open debate on what is the maximum distance for induced seismicity, considering the typology and

Table 2
Parameters of the Gutenberg–Richter Relationship (*a* and *b*) and Completeness Magnitude (M_c) Estimated for the Period 1 January 2012 to 31 December 2013

Area	*a**	*b*	M_c (EMR)	M_c (MAXC)
B	2.46	1.01±0.16	0.86±0.23	0.68
A	1.6	1.19±0.24	0.19±0.2	−0.02

For the completeness magnitude, we provide estimations obtained by entire magnitude range (EMR) and maximum curvature (MAXC) methods (Woessner and Wiemer, 2005).
**a* is normalized to 1 year.

size of the Collalto reservoir, and on the basis of the data recorded in the past two years, we believe that the value of 3 km might represent a reasonable maximum-distance range for induced seismicity.

This article presents what we would call the zero level of the research that has been developing with the RSC. We are currently working on two directions of classic investigations: (1) we strive to assess the network quality more rigorously

(a)

▲ **Figure 7.** Dissemination media for RSC activity. (a) Home page of the RSC website and (b) OGS Archive System of Instrumental Seismology web page showing the stations of the RSC network. (*Continued*)

(b)

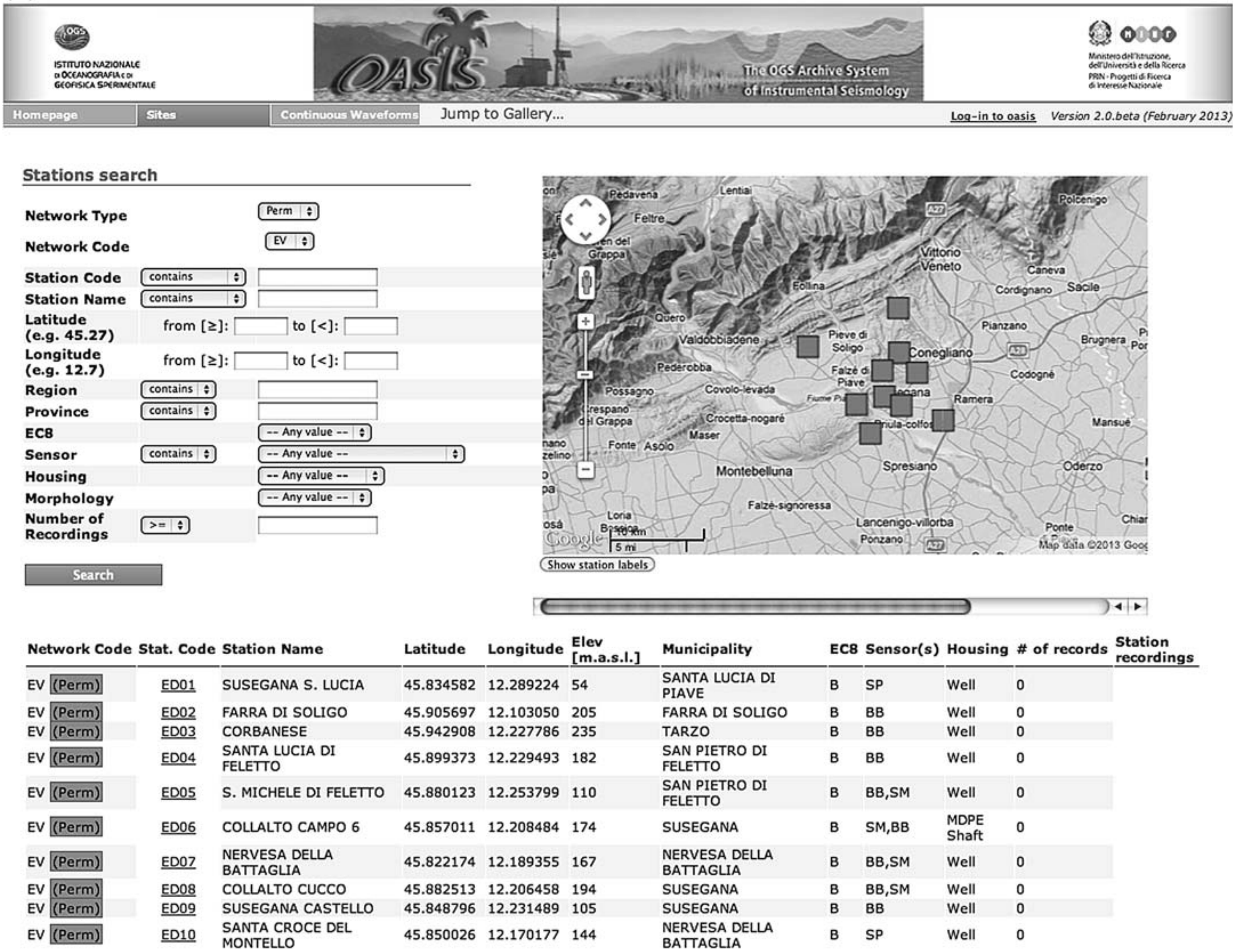


Figure 7. Continued.

through an analysis of background noise level versus detection performance and by the careful orientation of borehole sensors by means of teleseisms and (2) we aim to improve the overall seismicity image through a better definition of the structural model, the use of different location algorithms, and the estimation of focal mechanisms and magnitude calibration. All these analyses are feasible once a basic dataset, such as the dataset described in this article, has been established.

Finally, we would like to add some brief comments about the role of the OGS in this activity. The RSC was founded and is managed by the OGS on behalf of Edison Stoccaggio S.p.A., which is the concession holder. The OGS is a national research institute, and it carries out this activity within its own institutional role and according to two basic principles: (1) to provide high-quality service to the customer, with an added value in terms of scientific and research support and (2) to provide the community with monitoring of the highest quality, unbiased scientific evaluations, data dissemination, and the overall advancement of scientific knowledge. We believe that both these principles are extremely important.

DATA AND RESOURCES

Information and data on the Collalto Seismic Network (RSC) can be found at http://rete-collalto.crs.inogs.it (last accessed September 2014). In particular, the Data and Graphs section provides links to event data in the form of a list and a keyhole markup language (KML) Google Earth file, as well as an overall view on map and along a vertical section.

The full dataset of continuous waveforms of the RSC is freely available at OGS Archive System of Instrumental Seismology (OASIS), which is the database that archives the instrumental seismological data of the OGS. Its website (http://oasis.crs.inogs.it/; last accessed September 2014) provides access to all data, such as information on sites and continuous waveform data, as well as waveform data and ground-motion parameters for major events.

The GNSS station SUSE is also included in the Friuli Regional Deformation Network (FReDNet), which is the OGS high-precision GNSS network devoted to monitoring the deformation of the Friuli area in northeastern Italy. All data are accessible to the public and can be downloaded through its website (http://www.crs.inogs.it/frednet; last accessed September 2014).

Seismic events detected by the NEI network are reported on the OGS Real Time Seismology website at rts.crs.inogs.it (last accessed September 2014).

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The Collalto Seismic Network (RSC) was founded and is managed by the National Institute of Oceanography and Experimental Geophysics (OGS) on behalf of Edison Stoccaggio S.p.A. under requirements of the Italian Ministry for the Environment and Land and Sea Protection and in agreement with the Veneto Region. The RSC also uses data of the Northeastern Italy Integrated Seismic Network (NEI), managed by the OGS on behalf of the Veneto Region, the Autonomous Region of Friuli Venezia Giulia, and the Autonomous Province of Trento.

We would like to thank Edison Stoccaggio S.p.A., especially Gaetano Annunziata, Director of Operations, and Andrea Volpe, for the full collaboration provided during the various stages of activity. We would also like to thank the colleagues of the OGS Seismological Section: Marco Mucciarelli, for his continuous encouragement and support regarding this activity; and Michele Bertoni, Elvio Del Negro, Paolo Di Bartolomeo, Giorgio Durì, and Cristian Ponton for their invaluable support in technical and administrative matters. We also thank the *SRL* Editor Zhigang Peng and the two anonymous referees for their precious suggestions, as well as Elizabeth Holtam, who revised the article for the English.

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Seismic Monitoring of an Underground Natural Gas Storage Facility: The Collalto Seismic Network

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The Collalto Seismic Network (Rete Sismica di Collalto, or RSC) is the infrastructure used to monitor the natural and induced seismicity of the natural gas storage concession known as Collalto Stoccaggio, which is located in northeastern Italy. This network was realized and is currently managed by the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), a public research institute, on behalf of Edison Stoccaggio S.p.A., the storage concession holder.

In our article, we describe the seismic network and the results obtained in the first two years of monitoring, from 1 January 2012 to 31 December 2013.

This electronic supplement provides some additional material about the following topics: the seismic hazard of the study area; some examples of waveforms recorded by the RSC; the 1D velocity model for localizing events using the basic procedure; an analysis of the *P*- and *S*-phase reading uncertainty; a preliminary analysis of the noise level; and the catalog of events recognized in the period 1 January 2012–31 December 2013.

Seismic Hazard of the Area

According to the actual national seismic-hazard map (Working Group MPS, 2004), the area that hosts the Collalto gas storage facility is characterized by medium-high seismic hazard, with conventional values (i.e., horizontal peak ground acceleration on rock site, at 90% probability of nonexceedance in 50 years) of 0.225–0.25 g (**Fig. S1**). The four municipalities affected by the gas storage activity have been included in seismic zone 2 (zone 1 being the most dangerous one) since 1982.

Examples of Waveforms Recorded by the RSC

In this section, we show three examples of the waveforms recorded by the RSC stations. The first two examples refer to the two local events labeled as 107 and 243, which can be classified as weak and very weak, respectively. The parameters of these events are reported in **Table S1**, while their location is shown in **Figure S2**. The waveforms of the two events are displayed in **Figures S3** and **S4**, respectively.

The third example refers to a teleseismic event, the M_W 7.2 earthquake that occurred near the Coast of Guerrero, Mexico, on 19 April 2014 at origin time 14:27:36 UTC (see also http://www.iris.edu/spud/momenttensor/6703379; last accessed September 2014), at a distance of about 10,400 km from the RSC. **Figures S5** and **S6**, show the three-component seismograms recorded by stations ED06 and ED09, which are equipped with a very broadband sensor with proper period T = 120 s and a compact borehole sensor with proper period extended to T = 10 s, respectively. Thus, the two figures are useful to illustrate both the similar performance of the two sensors (**Fig. S5**) and the excellent performance of the compact sensor, even for the very long periods of a teleseismic event (**Fig.**

S6).

1D Velocity Model

The 1D velocity model adopted by the RSC for the so-called zero-level data processing is the same as the regional velocity model adopted by the Northeastern Italy Integrated Seismic Network (NEI), managed by the OGS (Priolo *et al.*, 2005; Bragato *et al.*, 2011). This model is listed in **Table S2**.

P- and *S*-phase Reading Uncertainty

Figure S7 shows the distribution of the picking uncertainty values for the 2012–2013 dataset for the *P* and *S* waves, respectively. The mean/median values for the *P*- and *S*-phase reading uncertainty are about 0.03/0.03 and 0.08/0.07 s, respectively. Note also that the 68% percentile of the uncertainty, which corresponds to the mean plus one standard deviation, has values of 0.15 s and 0.19 s for the *P* and *S* phases, respectively.

Preliminary Analysis of the Noise Level

We present here a preliminary analysis of the noise level for some of the RSC stations. **Figure S8** shows the probability density diagrams computed by PQLX software (http://ds.iris.edu/ds/nodes/dmc/software/downloads/pqlx/; last accessed September 2014) for three stations: ED06, ED07, and ED01 (see also Table 1 and the map in Fig. 1 in the main text). Station ED06 (Collalto Campo 6) is equipped with a broadband seismometer (Güralp CMG-3T, T = 120 s), which is located at a depth of about 5 m within one of the Edison Stoccaggio fields. ED07 (Nervesa della Battaglia) and ED01 (Susegana S. Lucia) are both equipped with an extended-band compact borehole seismometer (Güralp CMG-SP1, T = 10 s); sensors are located at depths of 14.5 m and 155 m, respectively. Unlike all the other stations, ED01 is located within the weakly consolidated alluvial sediments of the Venetian Plain; the well has been set deep in order to overcome this problem.

All the stations show a very good quality level in the period band $T \geq 2$ s, which is very close to the new low-noise model (NLNM) (**Fig. S8**). In particular, for the broadband station ED06, the high-quality band extends to the natural period of the sensor (i.e., 120 s). For the other two stations, the signal quality decays progressively at periods longer than the sensor's natural frequency (10 s); however, it still remains below the new high-noise model (NHNM) curve in a large band. In periods from about 0.1 to 2 s, the low noise level stays in the −130 dB and −140 dB range for all the displayed stations. Two facts are notable for this band: (1) a considerable presence of noise can be recognized (see several different higher density curves), and (2) the 150 m deep well of station ED01 is really effective in reducing the noise to a level comparable to the one featured by the other stations, which are located at a shallow depth on highly consolidated soil or rock.

The same analysis performed on the whole observation period reveals a larger signal dispersion due to several factors, such as local anthropogenic noise, seasonal/weather effects, and temporary malfunctioning of instruments and sensors. A more careful case-by-case analysis is needed in order to interpret data correctly.

Catalog of Events Recorded in the Period 1 January 2012–31 December 2013

Table S3 contains the catalog of the events recorded during the period 1 January 2012–31 December 2013.

Figures

Figure S1. Seismic hazard map of northeastern Italy (Working Group MPS, 2004). The yellow rectangle indicates the location of the Collalto gas storage license. Large and small labels indicate names of the administrative regions or autonomous provinces and major cities, respectively. For the Veneto region, the municipal administrative borders are shown. Thick-bordered areas in the Veneto show the municipalities entered into seismic zoning in the late 1930s (black color) and early 1980s (red color), respectively.

Figure S2. Locations of the local events 107 and 243, respectively, as reported in the full event list contained in Table S3.

Figure S3. Waveforms (*Z* component) recorded by the RSC station for the local event 107 with magnitude M_L 1.0. Waveforms have been band-pass filtered in the 5–12 Hz frequency band.

Figure S4. Same as Figure S3, but for local event 243 with magnitude M_L −0.3.

Figure S5. Three-component waveforms recorded by stations ED06 and ED09 for the teleseismic event M_w 7.2, which occurred off the Coast of Guerrero, Mexico, on 19 April 2014 at 14:27:36 UTC.

Figure S6. Same as Figure S5 except for the time window 2250–4500 s (total length of 1250 s), corresponding to the arrival of the first surface waves.

Figure S7. (a) *P*- and (b) *S*-phase reading distribution. The bar plots indicate the distribution of the values, and the red curves show the cumulative distribution. The insets show the values of the median, mean, and mean plus/minus the first standard deviation. The latter ones are estimated by assuming that data obey a semi-log distribution.

Figure S8. Example of background seismic noise levels estimated by PQLX software for three stations of the RSC network (ED06, ED07, and ED01). Each panel represents one month of data (vertical component) corresponding to the 1 June 2013–30 June 2013 period. The two solid curves represent the new low- and new high-noise models (NLNM and NHNM), respectively (Peterson, 1993).

Tables

Table S1. Parameters of the two local events shown in **Figure S2** (waveforms in **Figs. S3** and **S4**). Parameters are as follows: id, sequential identification number; area, area label; date, event date (yyyy/mm/dd); time, event origin time (hh:mm:ss.ss UTC); lat, event latitude (°); lon, event longitude (°); depth, event depth; Ml, event local magnitude (M_L); Q, localization quality; GAP, gap of localization; No, number of observations (i.e., phases) used for localizing; Ns, number of stations used for localizing; errh, horizontal error; errv, vertical error; rms, root mean residual; and Location, epicenter municipality.

Table S2. One-dimensional regional model adopted by the RSC for localizing events.

Table S3 [Plain Text; 32 KB]. Catalog of the events recorded during the period 1 January 2012–31 December 2013. Column heads are as listed for **Table S1**.

References

Bragato, P. L., P. Di Bartolomeo, D. Pesaresi, M. P. Plasencia Linares, and A. Saraò (2011). Acquiring, archiving, analyzing and exchanging seismic data in real time at the Seismological Research Center of the OGS in Italy, *Annals of Geophysics* **54**, no. 1, 67–75, doi: 10.4401/ag-4958

Peterson, J. (1993). Observation and modeling of seismic background noise, *U.S. Geol. Surv. Tech. Rept. 93-322*, 1–95.

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Working Group MPS (2004). Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM 3274 del 30 marzo 2003, *Rapporto conclusivo per il Dipartimento di Protezione Civile*, Istituto Nazionale di Geofisica e Vulcanologia (INGV), Milano–Roma, aprile 2004, 65 pp.+5 appendici (in Italian), http://zonesismiche .mi.ingv.it/documenti/rapporto_conclusivo.pdf (last accessed September 2014).

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Table S1.Parameters of the two local events shown in Figure S2 (Waveforms in Figures S3 and S4)

# ID	Area	Date	Time	Lat	Lon	Depth	Ml	*Q*	GAP	No	Ns	errh	errv	rms	Location
107	A	2012/09/15	00:40:17.89	45.916	12.220	10.0	1.0	B	125	26	15	0.8	0.8	0.22	Conegliano (Veneto)
243	A	2013/09/17	03:49:57.60	45.864	12.221	16.0	-0.3	C	100	11	8	2.6	1.2	0.15	Conegliano (Veneto)

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Table S2. One-Dimensional Regional Model Adopted by the RSC for Localizing Events

V_P (km/s)	V_P/V_S	Layer Thickness (km)
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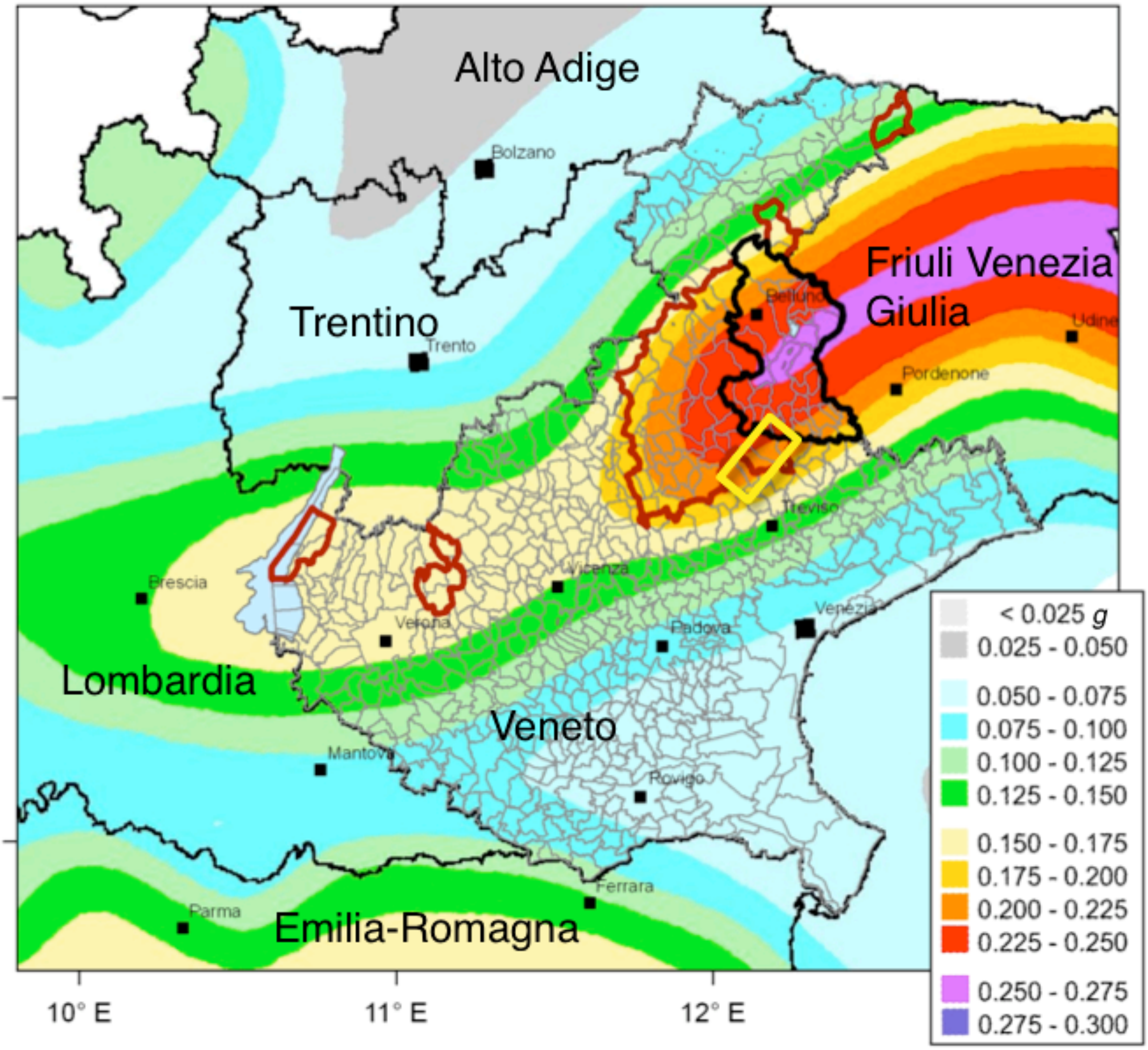
6.80	1.78	17.5
8.00	1.78	half-space

[Back]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Trento
Friuli Venezia Giulia
Belluno
Udine
Pordenone
Treviso
Vicenza
Brescia
Verona
Padova
Venezia
Lombardia
Veneto
Mantova
Rovigo
Ferrara
Parma
Emilia-Romagna
46° N
45° N
10° E
11° E
12° E
< 0.025 g
0.025 - 0.050
0.050 - 0.075
0.075 - 0.100
0.100 - 0.125
0.125 - 0.150
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0.175 - 0.200
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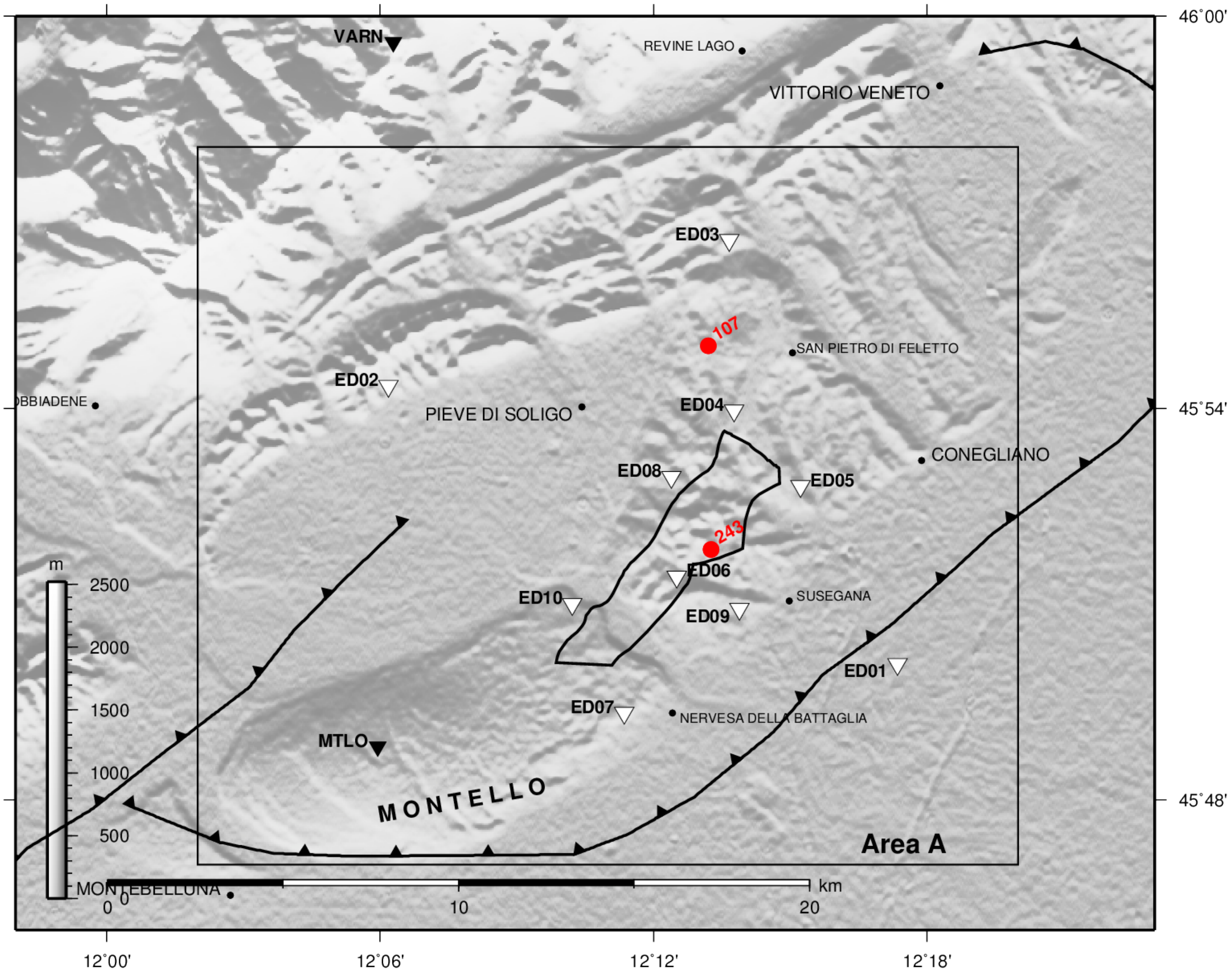
0.250 - 0.275
0.275 - 0.300



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45˚54'
45˚48'
12˚00'
12˚06'
12˚12'
12˚18'
VARN
REVINE LAGO
VITTORIO VENETO
ED03
107
SAN PIETRO DI FELETTO
ED02
PIEVE DI SOLIGO
ED04
CONEGLIANO
ED08
ED05
243
ED06
ED10
SUSEGANA
ED09
ED01
ED07
NERVESA DELLA BATTAGLIA
MTLO
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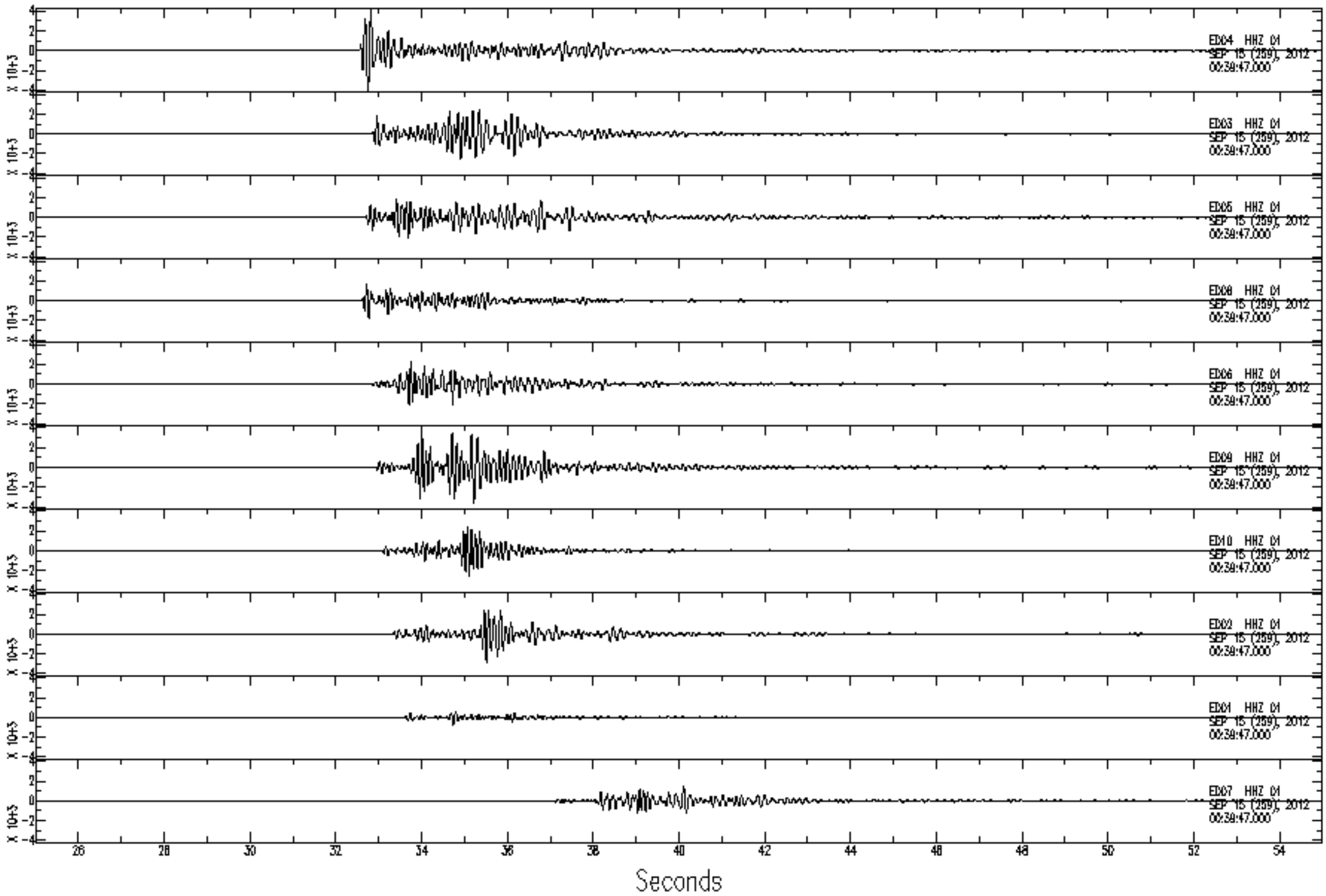
1500
1000
500
0
0
10
20
km



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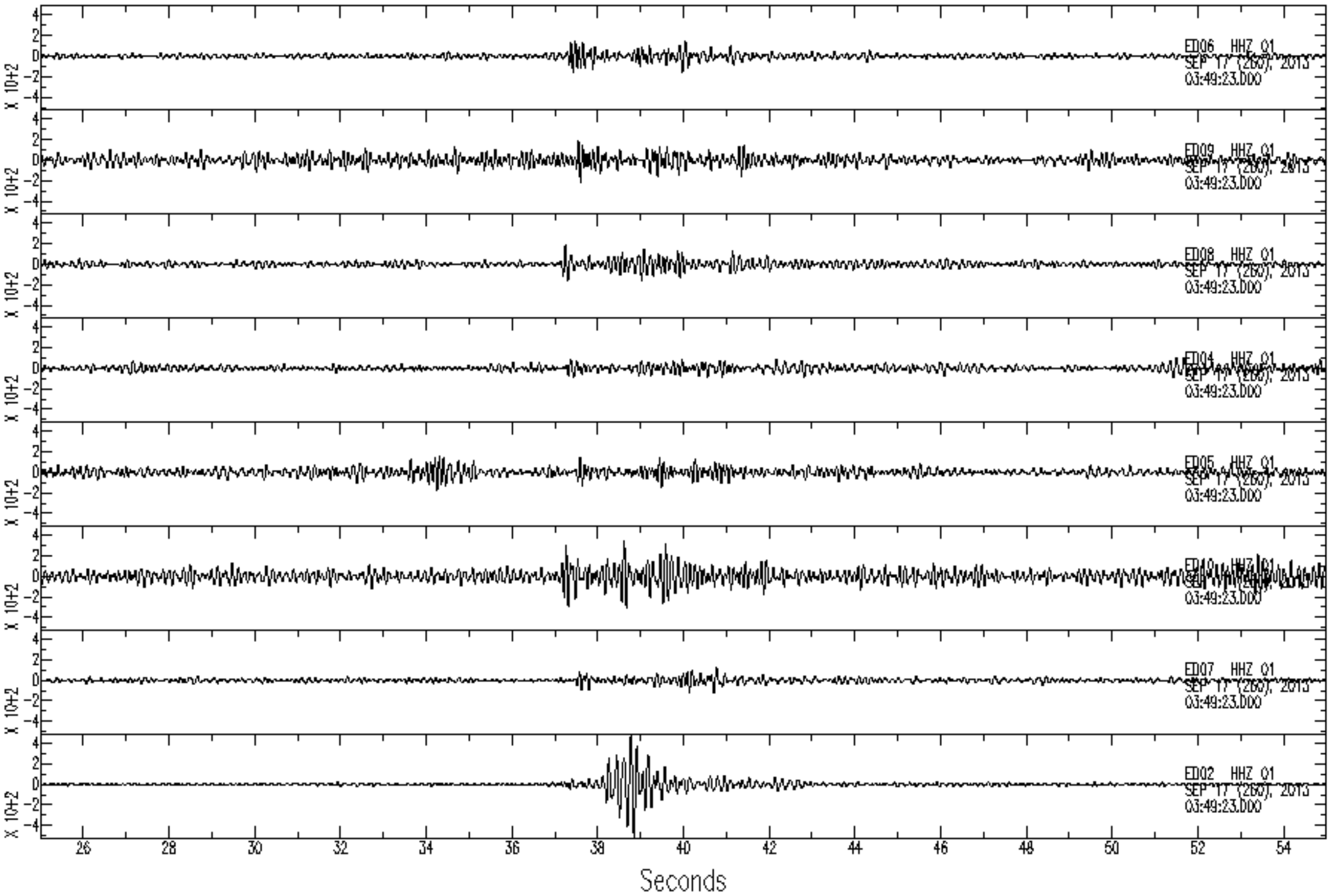
X 10+3
Seconds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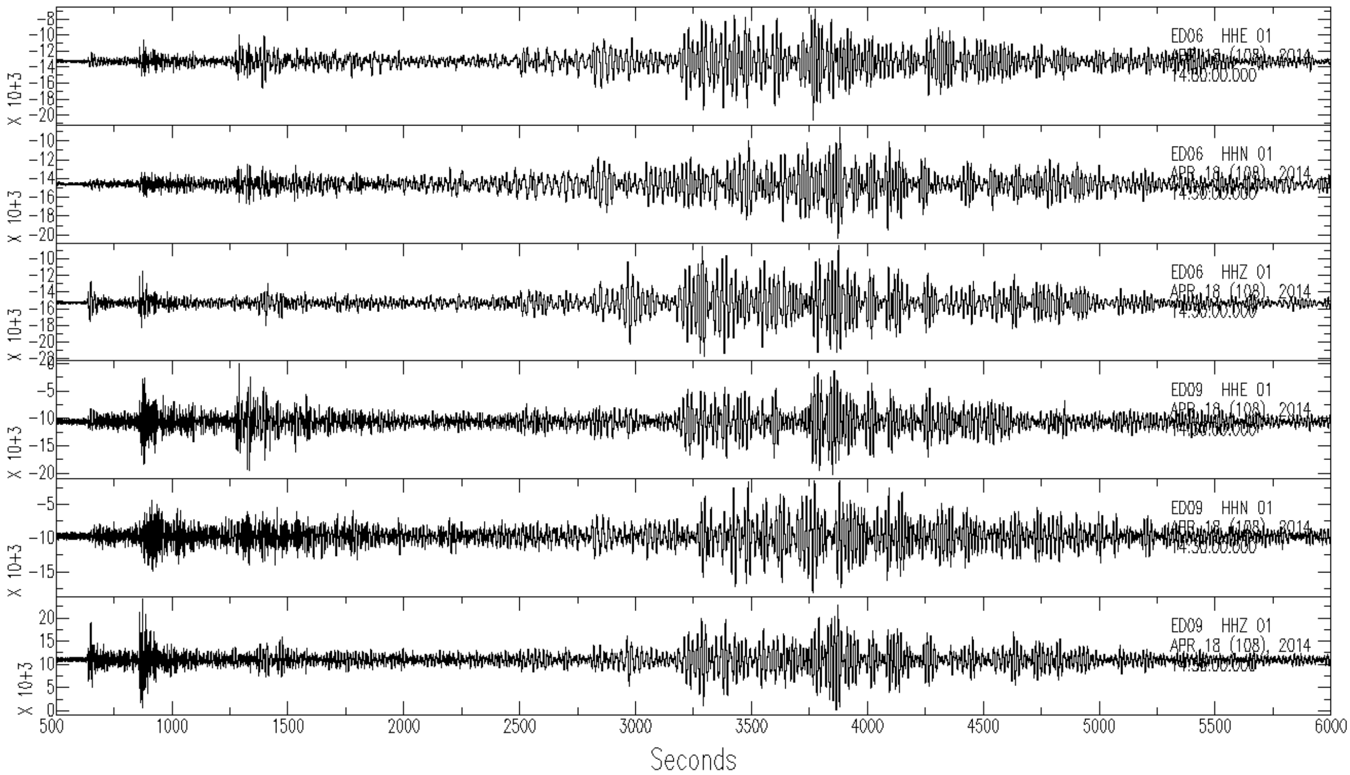
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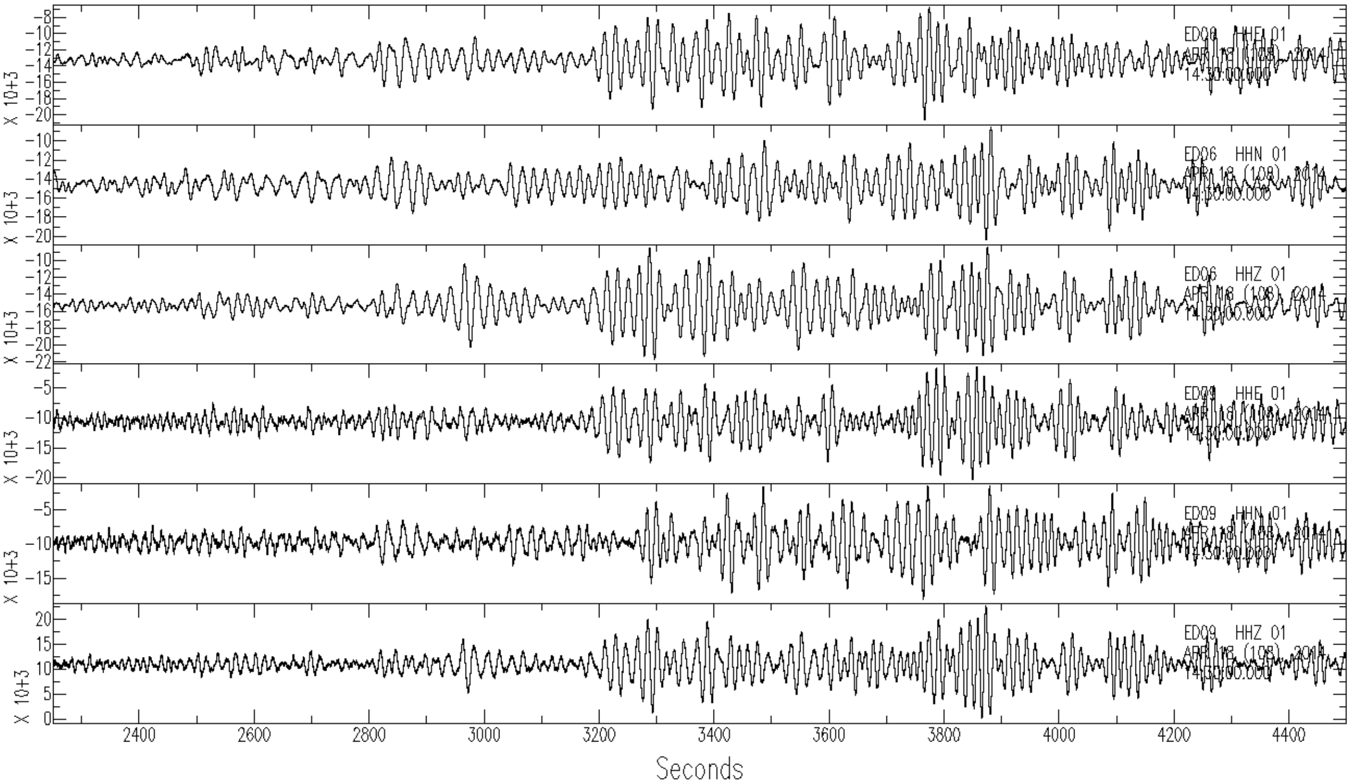
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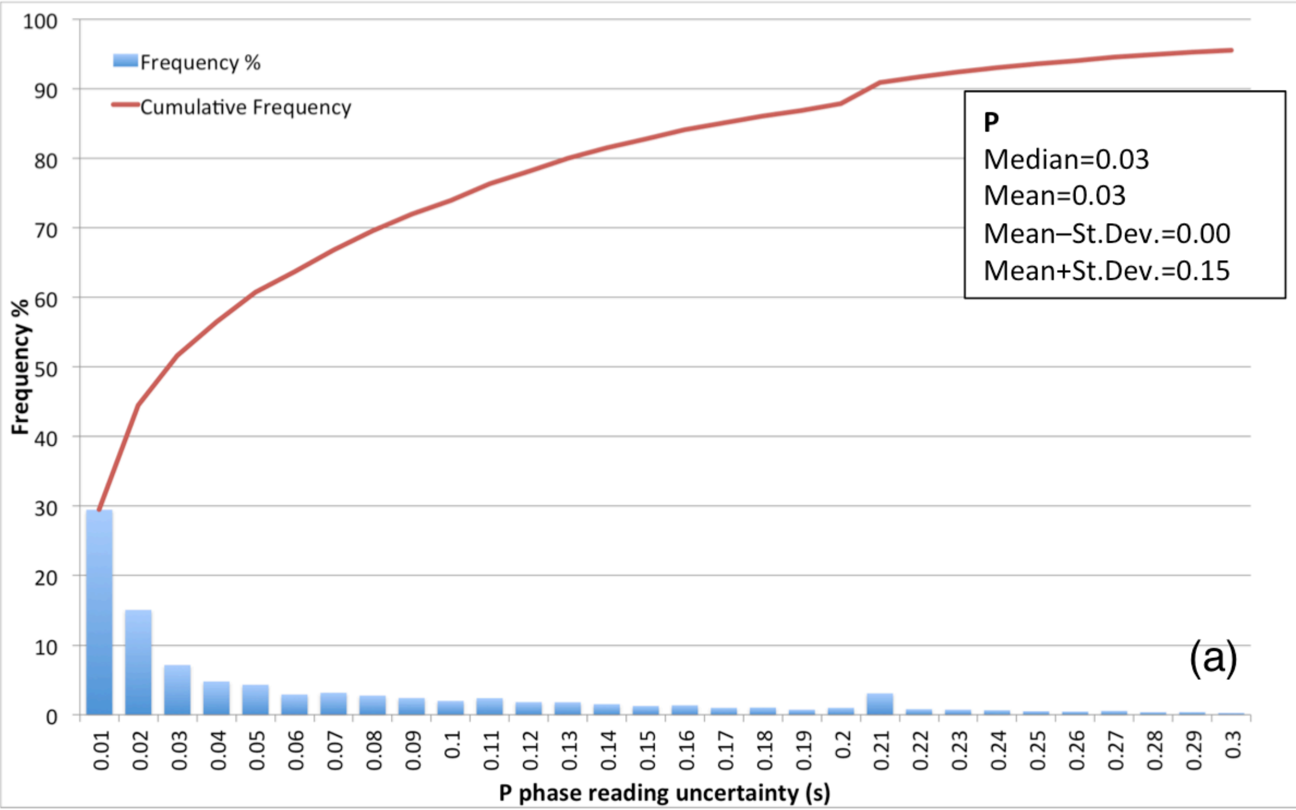
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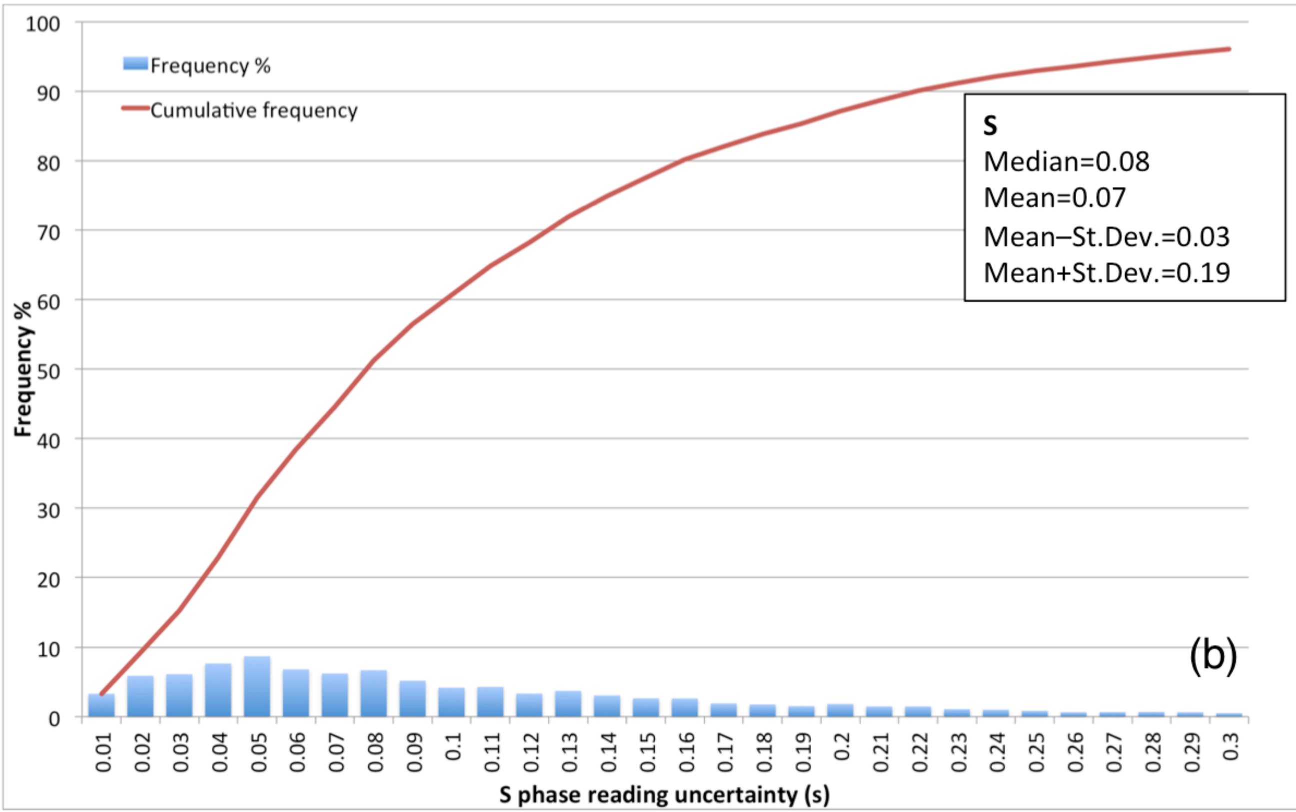
P phase reading uncertainty (s)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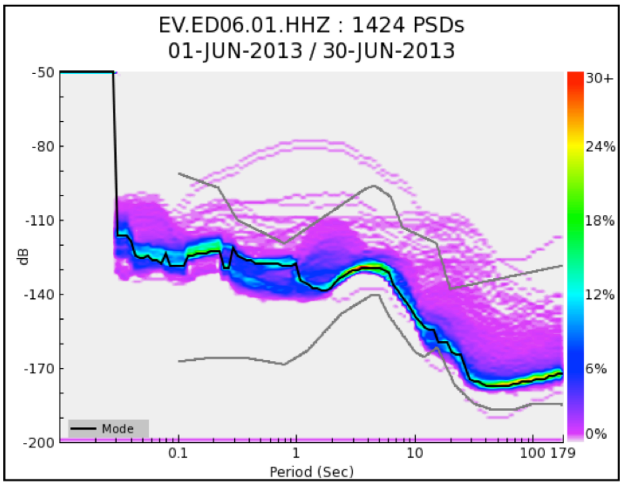
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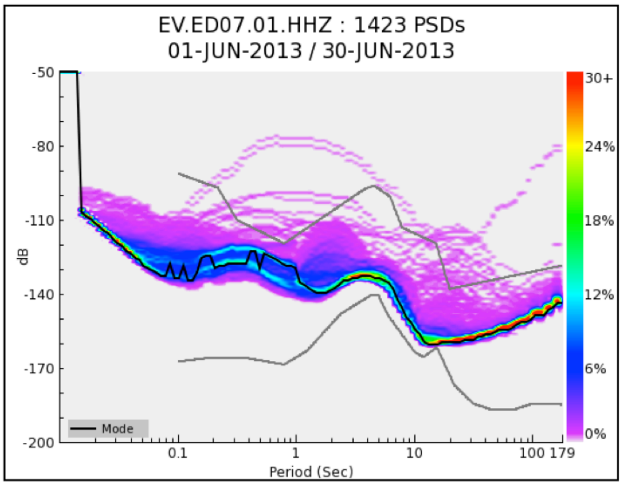
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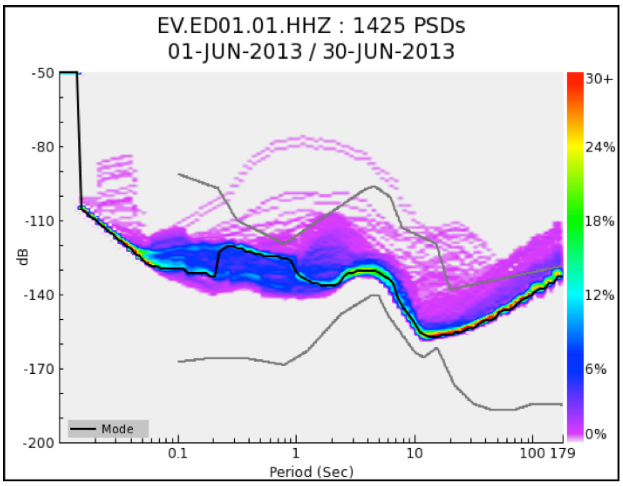
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18%
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