Constraints on temporal velocity variations associated with an underground gas storage in the Gulf of Valencia using earthquake and seismic ambient noise data

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CASTOR UNDERGROUND GAS STORAGE

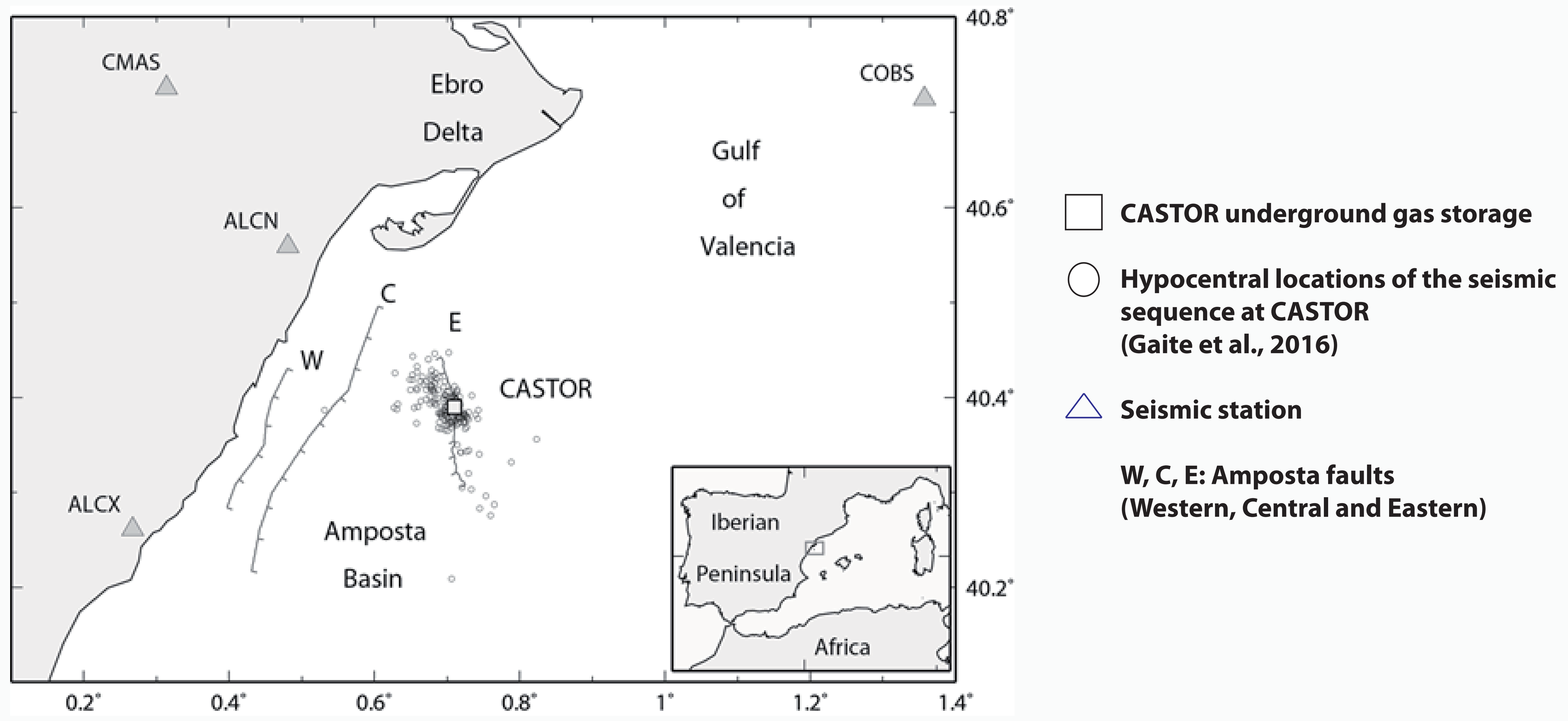
The CASTOR Underground Gas Storage project was designed to use the depleted Amposta oil field in the Gulf of Valencia as a submarine natural gas storage facility for the Spanish Mediterranean region.

It is located **22 km offshore** the eastern Spanish coast, in a region characterized by low strain and low-to-moderate seismicity. Two injection tests in June and August 2013 did not cause a seismic activity increase. Nevertheless, the continuous **injection of base gas** at a depth of ~1750 m that took place from September 2nd to 16th induced more than **550 shallow earthquakes** with mbLg **magnitudes ranging from 0.7 to 4.2** that were located close to the gas injection well.

Induced earthquakes linked to gas storage operations increase the seismic hazard and even may deteriorate the hydraulic integrity of the caprock. To understand the effects of fluid injection activities and help design fluid injection programs, quantitative measurements of the induced changes are needed.

Injection and movement of fluids in geologic formations cause **changes in seismic velocities** that can be associated to changes in fluid saturation, increase in pore pressure or opening or enlargement of cracks due to the injection process. Fluid injection can generate a failure on a fault through the reduction of the effective normal stresses caused by pore pressure increase in the reservoir. And changes in the local stress field can propagate and trigger a seismic event at faults located kilometers away from the injection area.

Monitoring seismic velocity changes provides a good means to study changes in medium properties over the course of the fluid injection process.



CODA WAVE INTERFEROMETRY (Earthquakes & Noise)

We use **Coda Wave Interferometry (CWI)** to detect temporal changes in the medium by comparing multiply scattered waves from repeating sources at different times. The relative perturbations of the background seismic velocity (Δv/v) can be estimated, to a first order approximation, from the relative travel time shift (Δτ/t) between the two waveforms:

$$\frac{\Delta v}{v} = -\frac{\Delta \tau}{t}$$

The coda time shifts (Δτ) are measured in this work using the **moving window cross-spectral (MWCS)** technique in the frequency domain and the **dynamic time warping technique (DTW)** in the time domain.

A continuous function of velocity changes with time γ(t) can be obtained by combining estimations of the relative velocity changes from all the repeating earthquake pairs.

Forward problem: $d_{ij} = \gamma(t_j) - (\gamma t_i)$ where d_{ij} is the measured relative velocity change between any pair ofearthquakes at times t_i and t_j.

System equation solver: Singular value decomposition (SVD).

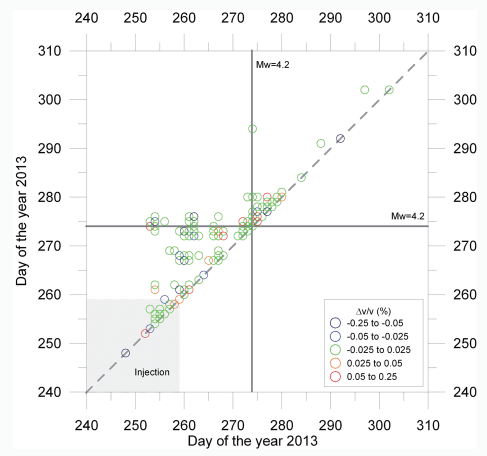
Assumption: Velocity changes with less than a day time separation are a measurement of resolution.

Repeating earthquakes

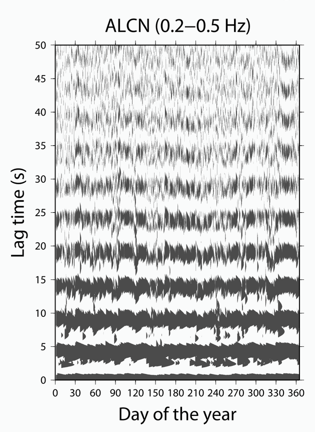
1. Earthquakes.
2. Remove mean and trend.
3. band-pass filter at 1-10 Hz.
4. Cut 20 s window including P & S arrivals.
5. Cross correlation functions.
6. Select doublets with Cross-Correlation Coeficient ≥ 0.85.

Ambient Seismic Noise

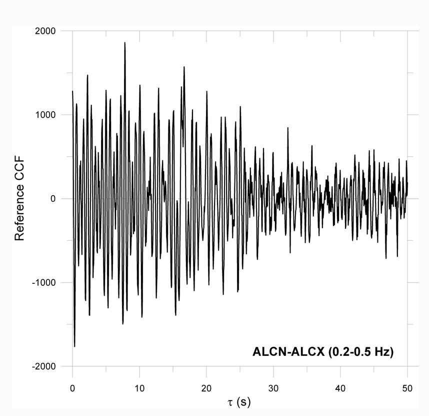
1. One year continuous records.
2. Remove mean and trend.
3. Band-pass filter at 0.2-0.5 Hz, 0.5-1 Hz and 1-10 Hz.
4. Whiten (only cross-correlations).
5. 1-bit normalization in time domain.
6. Auto and Cross correlation functions.
7. Average over 24 hours.



***Earthquake pairs** and relative velocity variations at station ALCN for the 0.2-0.5 Hz frequency band.*



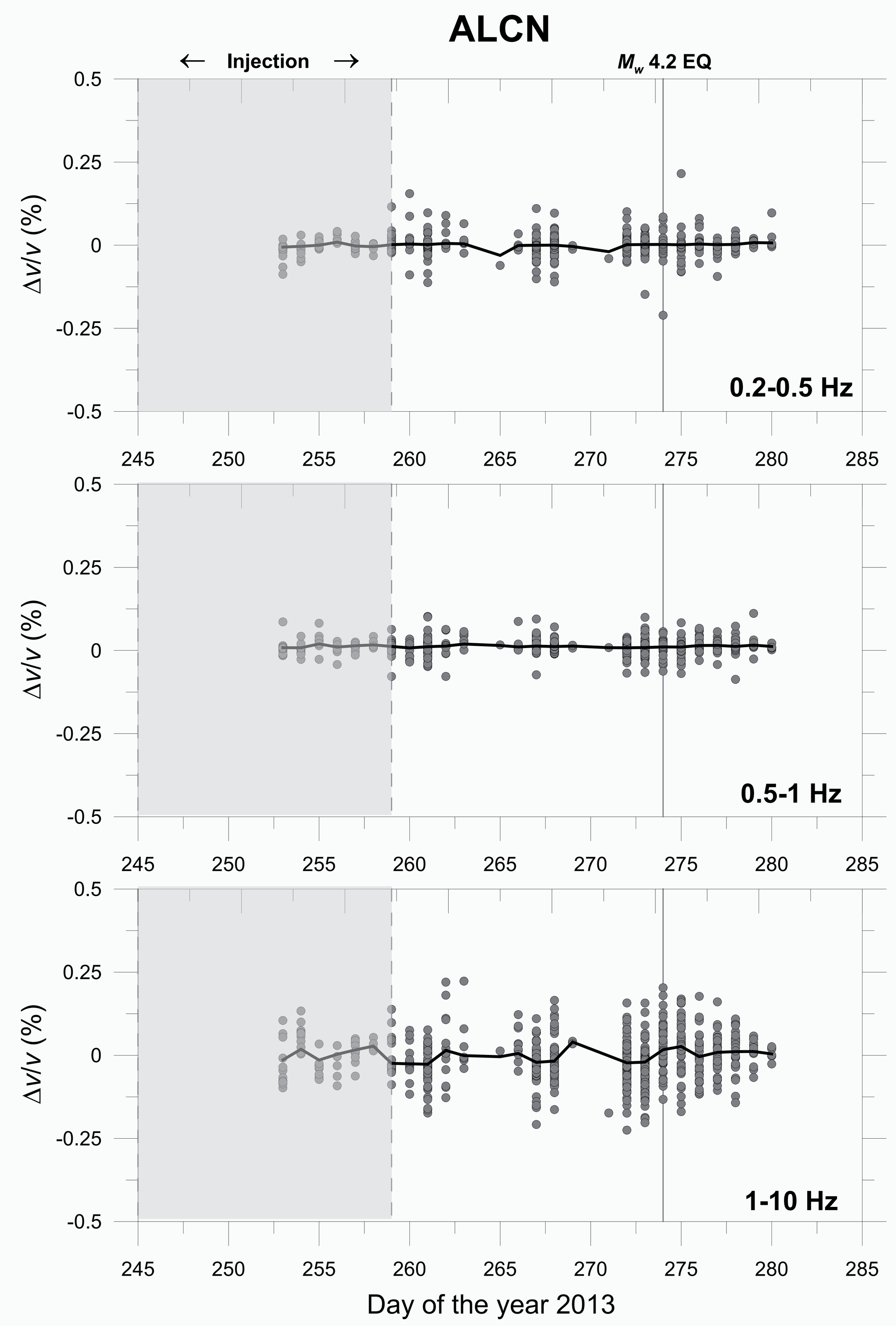
*Daily **autocorrelation function** at station ALCN for the year 2013 .*



*Reference **crosscorrelation function** for station pair ALCN-ALCX for the year 2013.*

VELOCITY VARIATIONS AROUND GAS INJECTION PERIOD

Repeating earthquakes

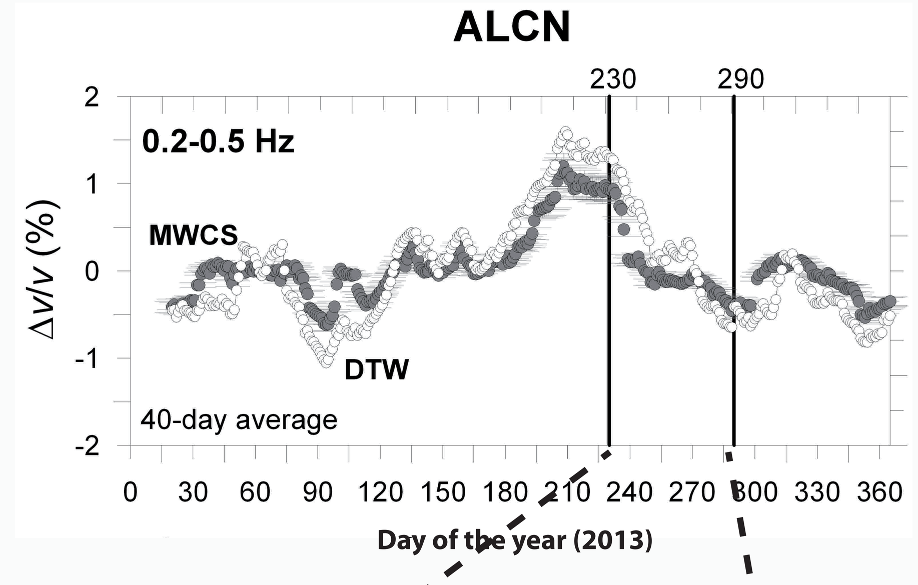


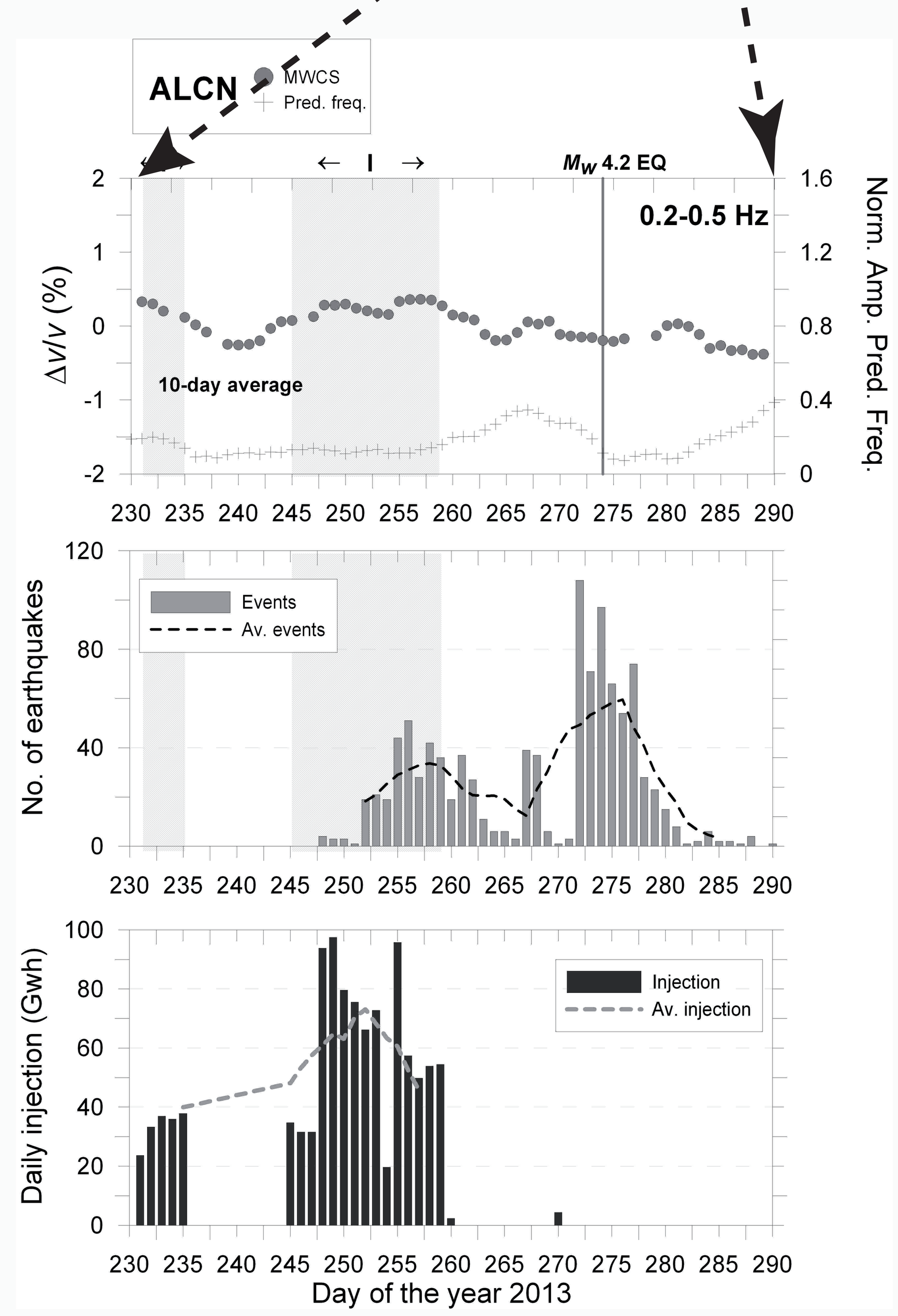
Relative velocity variations at station ALCN. Gray dots represent measurements for every single pair of events. Dots are plotted at the time of the first and the second earthquake for a single earthquake pair, being their vertical separation the observed relative velocity change. The average error bars for the relative velocity changes at station ALCN is 0.02% The black line is the inverted velocity change function.

Shaded areas mark the injection period

MWCS moving window cross-spectral
DTW dynamic time warping technique

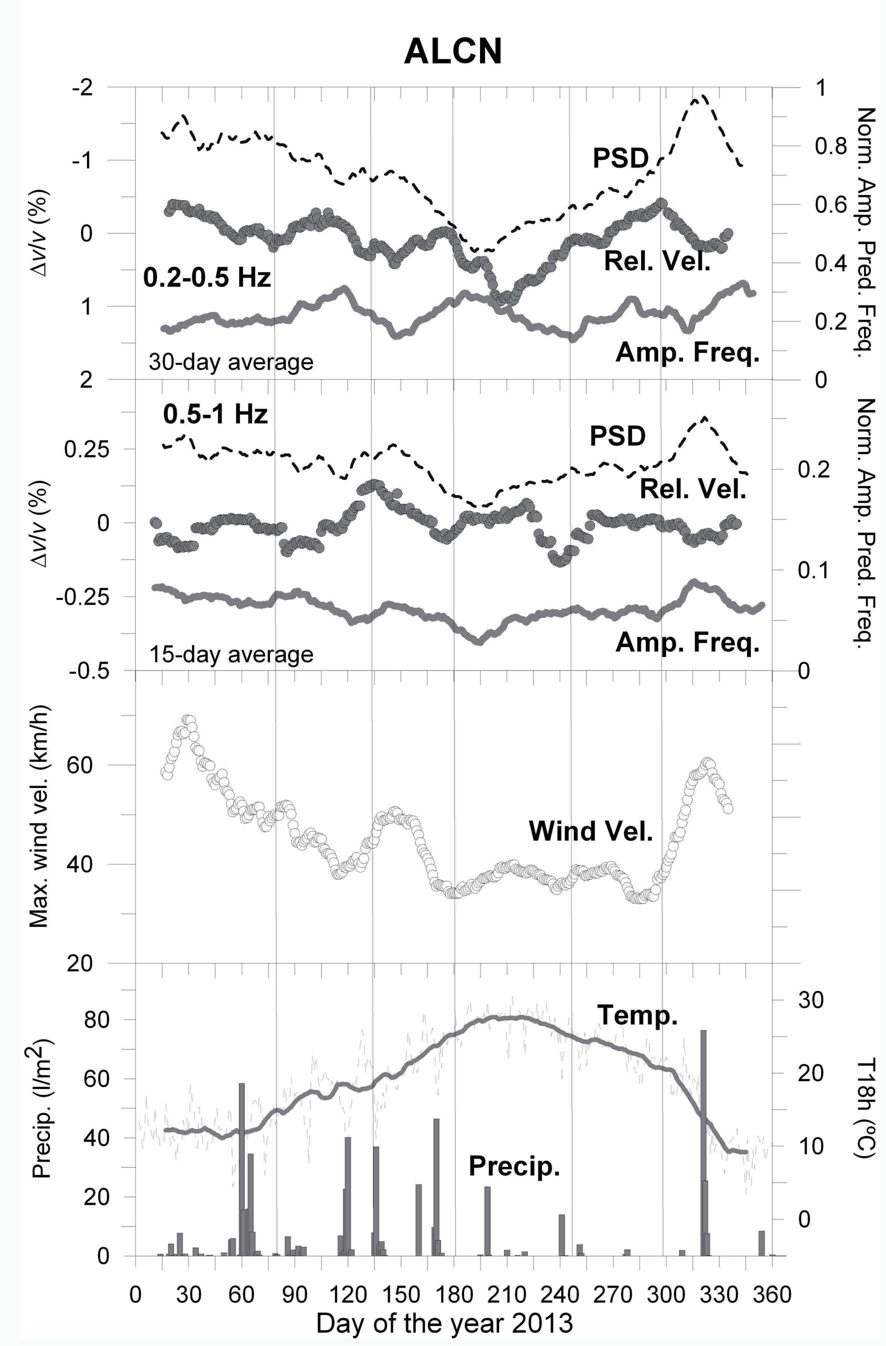
Ambient seismic noise





Velocity variations at station ALCN for the year 2013 using the MWCS for the time period September-October 2013. A comparison with the earthquake activity and fluid injection rate is performed.

ANNUAL VELOCITY VARIATIONS



Relative velocity variations at station ALCN for the year 2013. Long period variations are compared with meteorological observations of wind speed, temperature and rainfall. A comparison with the amplitude variation of the predominant frequency and the Power Spectral Density (PSD) is also plotted.

RELATIVE VELOCITY VARIATIONS WORLDWIDE AFTER EARTHQUAKE OCCURRENCE

Region	Date	M	Mainshock name	Source data	Velocity change (%)	Time delay (ms)	Reference
California	06/08/1979	5.7	Coyote Lake	Repeating earthquakes	-0.2%		Poupinet et al. (1984)
California	24/04/1984	6.2	Morgan Hill 1984	Repeating earthquakes	-3.5		Schaff and Beroza (2004)
California	18/10/1989	6.9	Loma Prieta 1989	Repeating earthquakes		+50	Rubinstein and Beroza (2004a)
					-3.5		Schaff and Beroza (2004)
California	18/07/1990	5.4	Chittenden 1990	Repeating earthquakes		+15	Rubinstein and Beroza (2004b)
California	28/06/1992	7.3	Landers 1992	Active seismic survey	+1.5%		Li et al. (1998)
California	16/10/1999	7.1	Hector Mine 1999	Active seismic survey	+1.4		Li et al. (2003)
California	22/12/2003	6.5	San Simeon 2003	Ambient seismic noise	-0.04		Brenguier et al. (2008)
California	28/09/2004	6.0	Parkfield 2004	Active survey and repeating earthquakes	-2.5		Li et al. (2006)
				Ambient seismic noise	-0.08		Brenguier et al. (2008)
					-0.15		Schaff (2012)
Chile	14/11/2007	7.7	Tocopilla 2007	Ambient seismic noise	-1.2		Richter et al. (2013)
China	12/05/2008	7.9	Wenchuan 2008	Ambient seismic noise	-0.4		Cheng et al. (2010)
					-0.08		Chen et al. (2010)
					-0.2		Froment et al. (2013)
					-2		Obermann et al. (2014)
					-0.2		Liu et al. (2014)
					-0.07		Stehly et al. (2015)
					-0.5		Gong et al. (2015)
China	24/03/2011	7.2	Myanmar 2011	Ambient seismic noise	-0.5/+0.5		Yang et al. (2015)
Greece	08/04/2001	4.3	Agios Ioanis 2001	Repeating earthquakes	-0.2		Cociani et al. (2010)
Indonesia	26/12/2004	9.1	Sumatra-Andaman 2004	Ambient seismic noise		+106	Xu and Song (2009)
	28/03/2005	8.6	Nias-Simeulue 2005			+144	
	12/09/2007	8.5	Sumatra 2007			+136	
Italy	06/04/2009	6.1	L'Aquila 2009	Ambient seismic noise	-0.3		Zaccarelli et al. (2011)
					-0.25		Soldati et al. (2015)
Japan	03/09/1998	6.1	Shizukuishi 1998	Active seismic survey	-1%		Nishimura et al. (2000)
				Active seismic survey and repeating events		+20	Nakamura et al. (2000)
Japan	06/10/2000	7.3	Western Tottori	Active seismic survey		+1	Ikuta et al. (2002)
				Local earthquakes	-30		Sawazaki et al. (2009)
Japan	26/09/2003	8.0	Tokachi-oki 2003	Repeating earthquakes	-0.3		Rubinstein et al. (2007)
Japan	23/10/2004	6.6	Mid-Niigata	Ambient seismic noise	-0.5		Wegler et al. (2009)
Japan	25/03/2007	6.6	Noto Hanto 2007	Ambient seismic noise		+50	Ohmi et al. (2008)
Japan	13/06/2008	6.9	Iwate-Miyagi Nairiku 2008	Strong motion data	-24		Yamada et al. (2010)
				Ambient seismic noise	-0.5		Takagi et al. (2012a)
					-3.6		Hobiger et al. (2012)
					-0.76		Hobiger et al. (2014)
Japan	11/03/2011	9.0	Tohoku-oki 2011	Local earthquakes	-10		Takagi et al. (2012)
				Ambient seismic noise	-1.5		Minato et al. (2012)
					-1.86		Hobiger et al. (2014)
				Local earthquakes	-10		Nakahara (2015)
				Repeating earthquakes	-0.2		Sawazaki et al. (2015)
Taiwan	22/10/1999	6.4	Chia-Yi 1999	Local earthquakes		+21	Chao and Peng (2009)
Taiwan	01/04/2006	6.1	Taitung 2006	Ambient seismic noise	-1%		Yu and Hung (2012)
Turkey	12/11/1999	7.1	Düzce 1999	Repeating earthquakes		+30	Peng and Ben-Zion (2006)
Turkey	23/10/2011	7.1	Van 2011	Ambient seismic noise	-0.76%		Acarel et al. (2014)
Vanuatu	09/04/2008	7.3	-	Repeating LP volcanic events	-2%		Battaglia et al. (2012)

CONCLUSIONS

Repeating earthquakes

Given the dots scatter that illustrates the uncertainty in the continuous solution, the positive and negative relative velocity changes observed at these seismic stations have no obvious association with the gas injection nor with the time of the major event.

Ambient seismic noise

Velocity variations do not show a clear correlation with the gas injection period nor with the occurrence of the major earthquake. Velocity variations at 0.2-0.5 Hz seem to correlate with the long term variations of the Power Spectral Amplitude.

General conclusion

We found no measurable velocity changes in the 0.2-10 Hz frequency range during the gas injection period nor associated with stress changes caused by an Mw 4.2 earthquake. Given the actual network configuration and the resolution of the technique, we conclude that any temporal changes in seismic velocities in the gas storage area should be smaller than 0.2%.