Chemical Geology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Chemical Geology

journal homepage: www.elsevier.com/locate/chemgeo

Geochemical monitoring of the 2012 Po Valley seismic sequence: A review and update

G. Martinelli [a,*], A. Dadomo [b], F. Italiano [c], R. Petrini [d], F.F. Slejko [e]

[a] ARPAE Environmental Protection Agency, Emilia Romagna Region, 42100 Reggio Emilia, Italy
[b] Geoinvest Srl, Piacenza, Italy
[c] INGV Istituto Nazionale Geofisica Vulcanologia, Palermo, Italy
[d] University of Pisa, Dept. Earth Sciences, Pisa, Italy
[e] University of Trieste, Dept. Mathematics and Geosciences, Trieste, Italy

ARTICLE INFO

Article history:
Received 15 July 2016
Received in revised form 24 November 2016
Accepted 2 December 2016
Available online xxxx

Keywords:
Earthquake precursor
Earthquake effect
Geofluid monitoring
Geochemical monitoring Emilia earthquake
Po Valley

ABSTRACT

A seismic swarm characterized by a Ml = 5.9 mainshock occurred in the Po Valley, northern Italy, in 2012. The area has been studied for active compressional tectonics since the beginning of the twentieth century. A variety of geophysical and geochemical parameters have been utilized with the purpose of identifying possible precursory signals. This paper considers groundwater level data and geochemical data both in groundwaters and in gases. All considered parameters have led to the conclusion that possible long and medium precursory trends have been identified in geofluids. No short-term precursors have been clearly identified. Hydrogeological and geochemical monitoring could be more effectively utilized in a different geological context, and seismic hazard reduction procedures could benefit from geofluid monitoring.

1. Introduction

On May 20, 2012 a Ml = 5.9 mainshock rocked the northern part of the Modena province and was followed by six aftershocks characterized by Ml ≥ 5. In roughly the same epicentral area historical seismicity catalogues indicate that at least 26 4 < Ml < 5.5 occurred in the period 1200–1975 (Rovida et al., 2011), while a broader look at the entire southern Po Valley reveals that both the Apenninic belt and the buried geological structures close to the Po river were affected by significant seismic events in the period 1976–2012, before the Emilia seismic swarm (Fig. 1). During historical times liquefaction phenomena and variations in well water physico-chemical features were observed as a consequence of local seismicity (e.g. Boschi et al., 1995). A long term monitoring of water level data, water chemical composition and dissolved or free gas composition have been carried out. Further fluid related data collected in the studied area have been considered with the purpose of describing physico-chemical variations induced on terrestrial fluids by the 2012 seismic sequence.

2. Tectonic setting

The collision between the European continental margin and the Adria microplate generated a NE-verging fold and thrust belt corresponding to Northern Apennines and to buried replicas of the Apenninic chain during the Neogene and Quaternary. Buried geological structures are constituted by Triassic evaporites, Mesozoic carbonates, Oligocenic-Miocenic clastic successions and by Plio-Pleistocenic sands and clays (e.g. Chiarabba et al., 2014). Quaternary sediments fill synclines among buried anticlines. Quaternary sediments are characterized by 0–2 km thickness (Molinari et al., 2015 and references therein). The three most important buried folded arcs are the Monferrato in the western side of the Po Valley, the Emilia arc and the Ferrara-Romagna arcs. During the late-Oligocene and Plio-Pleistocene compressive tectonic pulses generated fold overthrusts involving the carbonate Mesozoic structures (Carminati et al., 2010; Vannoli et al., 2014; Carannante et al., 2015) (Fig. 2). Buried folded arcs host hydrocarbons and brackish water in the depth interval 800–3500 m (Buttinelli et al., 2011 and references therein) in Mesozoic carbonatic rocks and in Oligocenic-Miocenic sandstones. Brackish groundwaters also soak Pliocenic clays and sands which constitute more recent sediments of the buried anticlines. Biogenic methane is chiefly hosted in Quaternary and Pliocenic sediments (Elliot et al., 1993). Thermogenic methane is hosted in Mesozoic geological formations located in the north-western side of the Po

* Corresponding author.
E-mail address: giovanni.martinelli15@gmail.com (G. Martinelli).

http://dx.doi.org/10.1016/j.chemgeo.2016.12.013
0009-2541/© 2016 Elsevier B.V. All rights reserved.

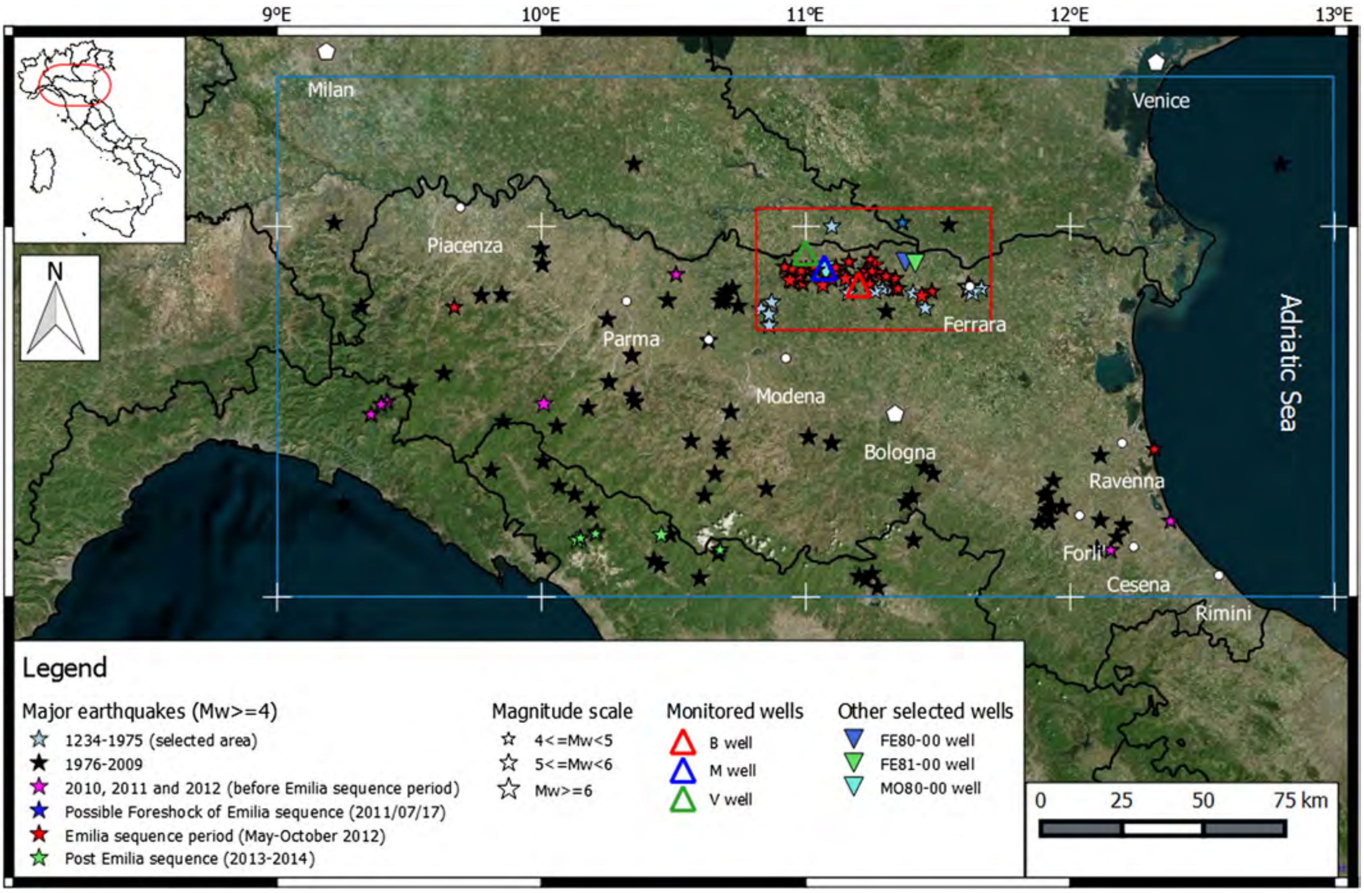


Fig. 1. Relevant seismic events occurred in the Po Valley in the period 1234–2014. Stars indicate different periods of seismic occurrence with magnitude scale. Relevant wells utilized for geochemical (B, M, V) and water level (FE80–00, FE81–00 and MO70–00) monitoring are also indicated.

Valley and in the western sector of the Northern Apennines (Mattavelli et al., 1983) (Fig. 3).

3. Materials and methods

3.1. Sampled gases

Dissolved gas samples and free gases were collected. The water samples were stored in 240 ml Pyrex bottles sealed in the field using silicon/teflon septa and purpose-built pliers (Italiano et al., 2009). The laboratory procedures for both free and dissolved gas were identical. The gas was extracted after equilibrium was reached at constant temperature with a high-purity argon gas phase injected into the sample bottle (Italiano et al., 2014). The composition of the dissolved gas phase was calculated using the solubility coefficients of each gas species, the volume of the extracted gas and the volume of the extracted water (Italiano et al., 2009, 2014). Chemical analyses were carried out by gas chromatography (Perkin Elmer Clarus 500 equipped with a double TCD-FID detector) using argon as the carrier gas. Typical uncertainties were within $\pm 5\%$.

Helium isotope analyses were done on extracted gas fractions following Hilton (1996). Isotopic analyses of the purified helium fraction were performed using a static vacuum mass spectrometer (GVI 5400 TFT) that allows the simultaneous detection of ^3He and ^4He ion beams, thereby keeping the $^3He/^4He$ measurement errors low. Typical uncertainties of samples with low ^3He content are $\pm 2\%$.

The isotopic composition of the total dissolved carbon (TDC), $\delta^{13}C$-TDC, of the water samples was measured on 2 ml of water sample introduced in containers where high purity helium was injected to remove atmospheric CO_2. The water samples were acidified with phosphorus pentoxide in an autosampler to ensure the complete release of CO_2 from acidified waters. CO_2 was then directly admitted to a continuous flow mass spectrometer (AP2003). The extracted CO_2 amounts represent the total content of dissolved carbon. The results are reported in δ units relative to the VPDB (Vienna Pee Dee Belemnite) international standard. The standard deviation of the $^{13}C/^{12}C$ ratios was ± 0.2.

3.2. Sampled waters

Temperature, pH and electrical conductivity were measured directly in the field; HCO_3 was measured by titration with 0.1 N HCl. Samples were stored in clean polyethylene bottles rinsed with the same water that was sampled. Major cations and trace elements were measured on samples filtered at 45 μm and stabilized by ultrapure HNO_3 for cation analysis. Major constituents were determined by a Dionex DX 120 ion chromatograph, and trace elements by a Jobin Yvon ICP-OES Ultima Due. 2-σ errors are within 2 and 5%, respectively. The Sr isotopic compositions on solute species were obtained on the filtered samples, after Sr collection, using standard chromatographic methods and loading samples on single tungsten filaments, using Ta-chloride as an emitter. Isotopic analyses were carried out by a VG 54 mass-spectrometer. The measured $^{87}Sr/^{86}Sr$ ratios were fractionation-corrected to $^{87}Sr/^{86}Sr = 0.1194$; data acquisition and reduction followed the procedure described by Ludwig (1994). The experimental uncertainties on Sr isotopic ratio represent in-run statistics at 95% confidence level.

3.3. Water level

Water level data were recorded by manual techniques (OTT® KL010 freatimeter) and by automatic STS® multiparametric probes able to

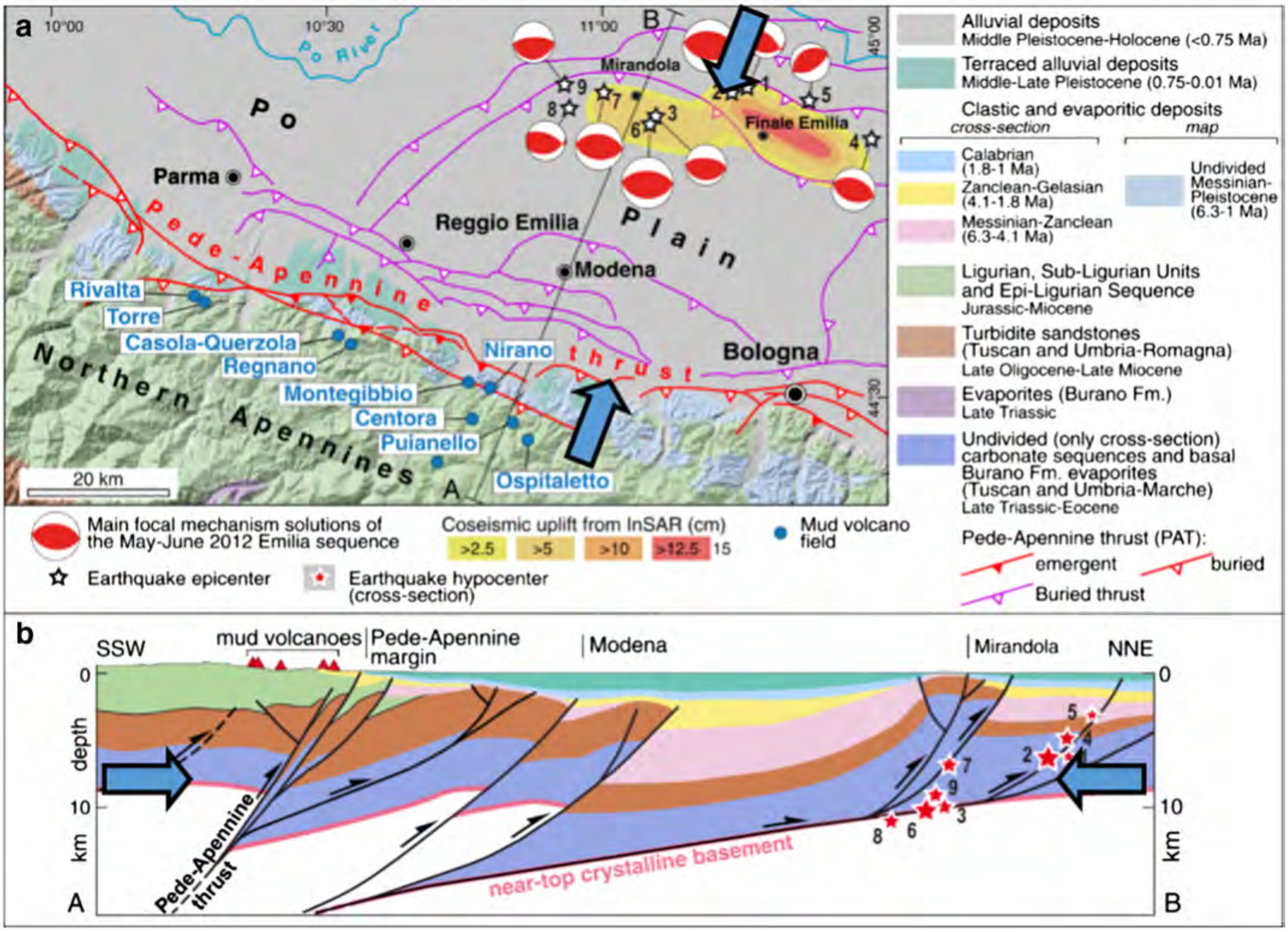


Fig. 2. a) Geological setting of the external Northern Apennines (northern Italy) and of the adjacent southern Po Valley. Number close to focal mechanism solutions indicate chronology of the seismic sequence. In the upper-right the area uplifted by seismic sequence is also indicated. b) Geological cross section through the Northern Apennines and Po Plain. Hypocenters of seismic events characterized by 4 < M < 6 are reported (after Bonini et al., 2016 and references therein, modified). Big blue arrows indicate main directions of tectonic compression according to Montone et al. (2004) and Cenni et al. (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

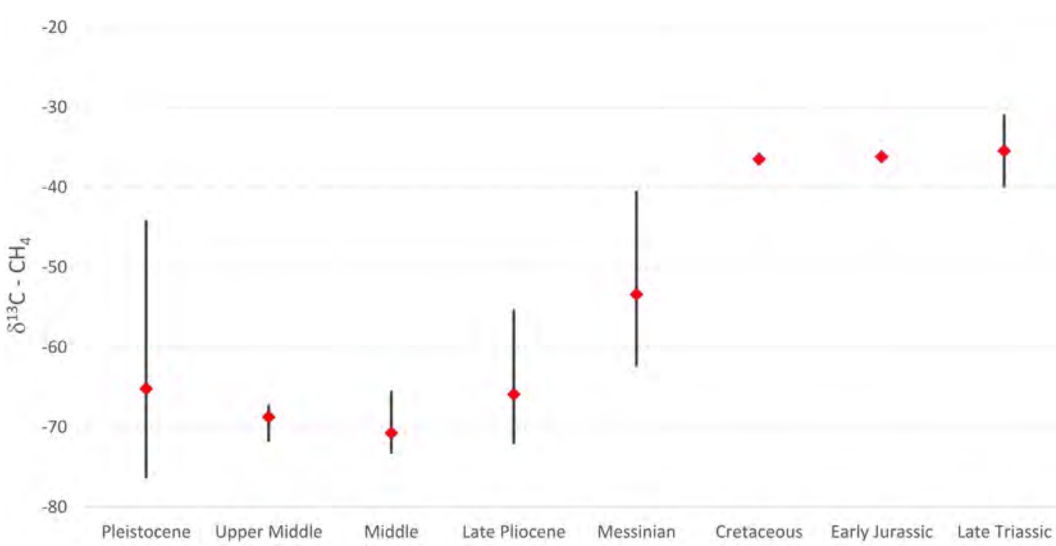


Fig. 3. $\delta^{13}C$ of CH_4 sampled during drillings for hydrocarbon researches. Youngest (left side) and oldest (right side) geological formations hosting gases considered by Mattavelli et al. (1983) are indicated.

Please cite this article as: Martinelli, G., et al., Geochemical monitoring of the 2012 Po Valley seismic sequence: A review and update, Chem. Geol. (2016), http://dx.doi.org/10.1016/j.chemgeo.2016.12.013

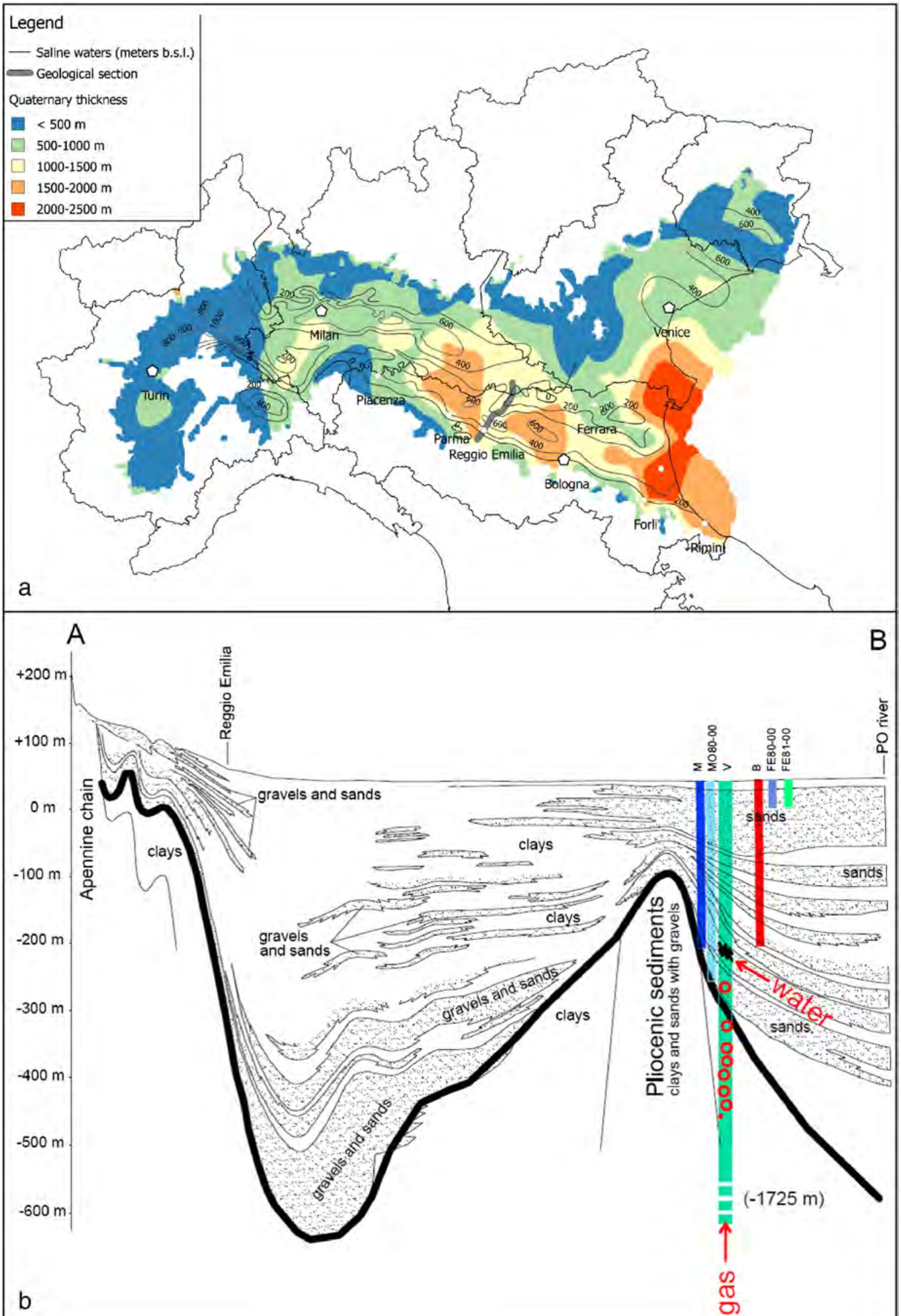


Fig. 4. a) Top of salt waters (m.b.s.l.) in the Po Valley and thickness of Quaternary sediments (Molinari et al., 2015); b) Geological cross section (A–B) of Apennine-Po river. Wells utilized for geochemical monitoring (B, V and M) and for automatic water level monitoring (MO80-00, FE80-00 and FE81-00) close to a buried anticline are also evidenced (after Martinelli et al., 2014 and references therein, modified).

measure at hourly rate water level (precision ≤0.1%FS) and temperature (precision ± 1 °C, resolution 0.1 °C).

4. Hydrogeological setting

The area included among the Alpine and Apenninic chains corresponds to the Po Valley in the central part and to the Adige and Brenta river on the north-eastern side. The whole plain area is a sedimentary basin filled by continental Pleistocenic and Holocenic sediments (Ori, 1993). These deposits of fluvial origin constitute an alternation of layers of gravels, sands and clays. Coarse and highly permeable sediments are located at the foot of Apenninic and Alpine belts while fine poorly permeable sediments are located along the Po river and close to the Adriatic coast (Giuliano, 1995; Sacchi et al., 2013; Saccon et al., 2013). Buried tectonic structures of Pliocenic and pre-Pliocenic age run parallel to the Apenninic belt. Sediments which constitute buried tectonic structures are often unconsolidated and are still in the dewatering phase. Thus brackish waters expelled by Pliocenic sediments follow the main topographic lineaments of the buried anticlines (Fig. 4) and constitute the base of the Quaternary groundwater system (Martinelli et al., 2014 and references therein).

Buried anticlines are separated by synclines in which the multilayered aquifer can reach about 2000 m. Aquifer depth is strongly reduced up to 50–100 m over the top of buried anticlines. Coarse grained aquifers located at the foot of Alpine and Apenninic chains are fed by meteoric waters (Lasagna et al., 2016) and are characterized by hydraulic gradients up to 10‰ and relatively high circulation velocities (2–4 m per day). Fine grained aquifers located along the Po river and close to the Adriatic sea are separated by clayey aquitards and are characterized by low hydraulic gradients (1–2‰ and by relatively low circulation velocities (0–0.1 m/day). Their mean residence time may reach 20–40 kyr (Pilla et al., 2006; Mayer et al., 2013; Martinelli et al., 2014). Convergence motions between Apenninic and Alpine chains were estimated to be in the range 3–5 mm/year (Cenni et al., 2015 and references therein). In the central and eastern part of the Po Valley aquifers are subjected to a tectonic pressure due to the shortening of the crust between Alps and Apennines, thus water in wells may reach or exceed the ground level due to slow deformations affecting aquifers. These hydrogeological features were also observed in other sedimentary basins characterized by similar sedimentological and tectonic characteristics (e.g. Toth and Almasi, 2001). Sacco (1912, 1924, 1933) listed wells drilled in the period 1910–1932 in the Po Valley and reported piezometric levels representative of the pre-industrial natural conditions. In particular wells characterized by a relatively high hydraulic head were identified in alluvial fan areas close to mountain chains. These wells caught aquifers fed by fast-circulating groundwaters due to recharge of recent precipitations. Other wells characterized by a high hydraulic head were localized in the central-eastern side of the Po Valley. Groundwaters in these wells hosted in fine-grained confined aquifers are characterized by extremely low circulation velocities. These aquifers are not linked to present-day recharge phenomena (Pilla et al., 2006; Martinelli et al., 2014) and, due to confinement conditions are, in principle, subject to groundwater pressure changes due to tectonic shortening phenomena affecting the geological formations of the Po Valley. Present day groundwater withdrawal induces a significant decrease in the volume of water in an aquifer that is easily detectable by land subsidence and by groundwater quality degradation due to the increase of chloride concentration from Plio-Pleistocenic clays and sands. Environmental Protection Agencies have monitored several hundred modern wells characterized by the depths >100 m taking groundwaters from confined or semiconfined aquifers. A number of wells characterized by high hydraulic head values, by recharge processes not directly linked to present-day meteorological events (Martinelli et al., 2014) and not located in highly exploited aquifers, were selected to study the long-term behaviour of hydraulic heads and possible relations of water level changes with tectonic events occurring in 2012 (Fig. 5).

5. Environmental effects of the 2012 seismic sequence

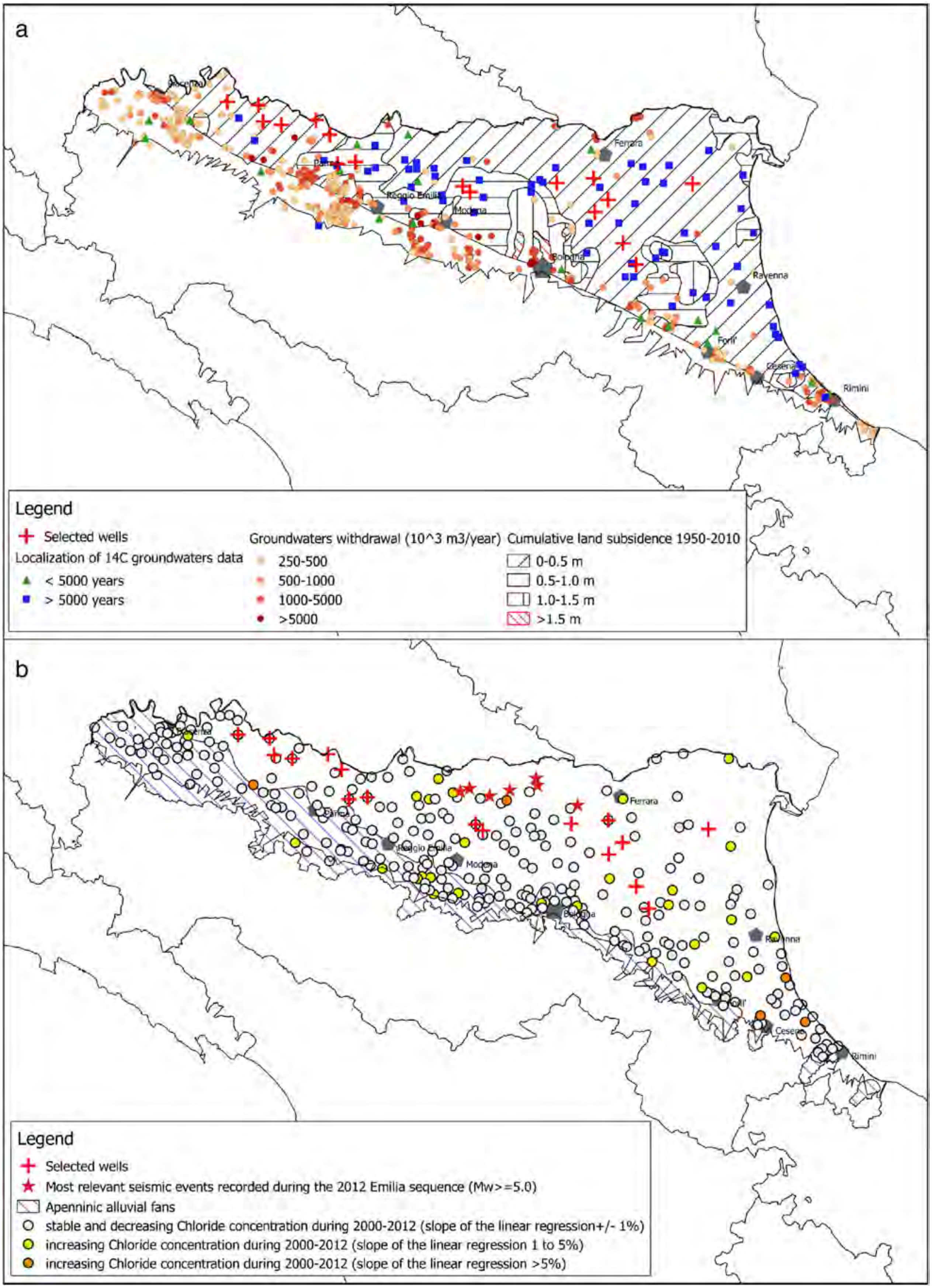
The most impressive environmental effects of the 2012 Emilia seismic sequence were represented by liquefaction phenomenon. This phenomenon is originated by shaking in the alluvial plains. Overpressured interstitial groundwaters gush upward and form sand sheets and sand volcanoes. Bertolini and Fioroni (2012), the Emergeo Working Group (2013), Fontana et al. (2015) and other authors carefully surveyed over one thousand liquefaction phenomena occurring in the epicentral area. Expelled sands belonging to phreatic or semiconfined shallow aquifers were found. No evidence of deep originating fluid was detected. Fractures due to intense ground shaking were also surveyed by the Emergeo Working Group (2013) and by Bertacchini et al. (2014), who found that almost all observed events affected only the shallower meters of Quaternary sediments. Most of observed phenomena were also similar to those previously reported in historical records (e.g. Boschi et al., 1995). Marcaccio and Martinelli (2012) and Nespoli et al. (2015) described some sharp increases in water levels of continuously monitored wells. Mattavelli et al. (1983), Orange et al. (2005), Martinelli et al. (2012), and Sciarra et al. (2013) listed various pre-existing hydrocarbon emissions in the Po Valley and observed that Quaternary and Pliocenic layers are still producing significant amounts of biogenic methane generated by frequent peat layers and by organic materials occurring in the interval 0–4000 m depth. In particular methane emissions in the plain area are biogenic methane generated by shallow peat layers while thermogenic methane emissions are located in the western belt of Northern Apennines. Thermogenic deep originated methane is also found in deep Miocenic, Paleogenic, Cretaceous, Jurassic and Triassic geological formations found during deep (1–5 km) hydrocarbon drillings, while no evidence of deep originated thermogenic methane was found in the epicentral area. No significant changes in local biogenic methane flow rate was observed before the seismic sequence, while ground shaking induced limited biogenic methane emissions at times linked to liquefaction. In particular, these short-lived events were observed by Bertolini and Fioroni (2012) by aerial survey. A mud volcano located 60 km south of the epicentral area (Fig. 2) increased the mud flow rate after the 2012, May 20, $M = 5.9$ mainshock (Bonini et al., 2016) as similarly recorded in historical times in previous mud volcanic eruptions after significant seismic events in various geologic contexts (Mellors et al., 2007). Bianchi et al. (2014 and references therein) listed several pre-existing sinkholes close to the epicentral area and tentatively attributed their existence to seismic activity occurred during historical times (e.g. Caputo et al., 2016). Sciarra et al. (2012, 2013) observed that the usual background level of biogenic methane sampled in soil gases and in sinkholes close to the epicentral area was not contaminated by any possible deep-seated gas component. Significant water level variations induced by the 2012 seismic sequence recorded by Marcaccio and Martinelli (2012) induced geochemical variations both in groundwaters and in gases dissolved in groundwaters (Italiano et al., 2012a,b). Italiano et al. (2012a,b) described in a preliminary way geochemical changes observed in groundwaters and in the dissolved gases of local deep wells but only a long-term monitoring strategy will allow a better understanding of the geochemical impact of the 2012 seismic sequence.

6. Long-term geofluid monitoring

6.1. Automatic water level monitoring in selected wells

The Environmental Protection Agency of the Emilia Romagna region (ARPAE), where the 2012 seismic sequence occurred, in 2010–2012 set up a network of about 40 wells equipped with sensors for water level and temperature measurements. Only wells located close to the epicentral area recorded significant signals. In particular, graphs obtained in wells FE80-00, FE81-00 (3 km north of the mainshock) and MO80-00 (5 km West of mainshock) are shown in Fig. 6. The fluid pressure is proportional to stress and volumetric strain (Rice and Cleary, 1976). Hence,

Please cite this article as: Martinelli, G., et al., Geochemical monitoring of the 2012 Po Valley seismic sequence: A review and update, Chem. Geol. (2016), http://dx.doi.org/10.1016/j.chemgeo.2016.12.013


a
Ferrara
Reggio Emilia
Ravenna
Rimini
Legend
Selected wells
Localization of 14C groundwaters data
< 5000 years
> 5000 years
Groundwaters withdrawal (10^3 m3/year)
250-500
500-1000
1000-5000
>5000
Cumulative land subsidence 1950-2010
0-0.5 m
0.5-1.0 m
1.0-1.5 m
>1.5 m
b
Ferrara
Modena
Rimini
Legend
Selected wells
Most relevant seismic events recorded during the 2012 Emilia sequence (Mw>=5.0)
Apenninic alluvial fans
stable and decreasing Chloride concentration during 2000-2012 (slope of the linear regression+/- 1%)
increasing Chloride concentration during 2000-2012 (slope of the linear regression 1 to 5%)
increasing Chloride concentration during 2000-2012 (slope of the linear regression >5%)

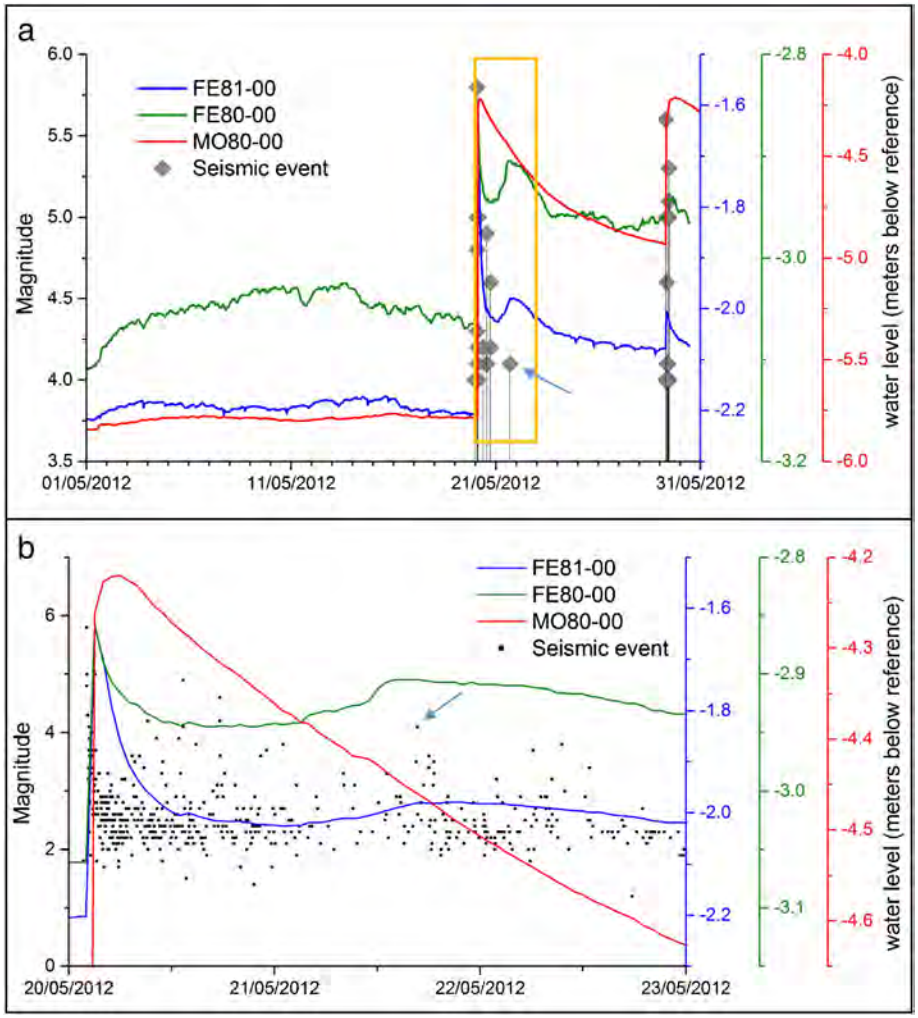


Fig. 6. a) Hourly water level data recorded in FE80-00, FE81-00 and MO80-00 wells during May 2012. Seismic events characterized by 4 < Ml < 6 are also indicated. The water level record of the period May 20–May 23 is evidenced by a box showing the short term anomaly in water level recorded on May in which a seismic event characterized by M = 4.1 was preceded by a short-term water level fluctuation. Seismic events characterized by M > 4 are indicated by arrows. b) The period May 20–May 23 is highlighted. Black dots indicate seismic events. The short-term fluctuation recorded on May 21 preceded a M = 4.1 seismic event indicated by a blue arrow and a period of increased frequency of low magnitude seismic events before the second mainshock occurred on May 2, 2012. The seismic event characterized by M = 4.1 is indicated by a blue arrow. See also further details in Fig. S.1 in Supplementary material. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

groundwaters can, in principle, be utilized as natural strainmeters water being incompressible and monitorable by large-scale networks. The stress tensor σ_{kk}, the volumetric strain ε_{kk} and the fluid pressure p under undrained conditions can be described as:

$$p = -B\sigma_{kk}/3$$

$$p = -2GB(1+\nu_u)\varepsilon_{kk}/3(1+\nu_u)$$

where:

- G is the shear modulus
- B is the Skempton coefficient
- ν_u is the Poisson's ratio under undrained conditions.

No significant variation was observed in water levels before the seismic sequence and no eventual short-term hydrogeological precursor related to most significant seismic events was observed. A short-lived increase in water level data was observed some hours before an increase in seismic events frequency (Fig. 6 and Fig. S.1 in Supplementary material) probably due to ongoing crustal deformation processes. Nespoli et al. (2015) calculated that significant pressure variations following the seismic sequence affected an area of about 30 km radius from the mainshock and induced compaction phenomena in deep aquifers (100–300 m) hosted in Quaternary sediments allowing any geochemical changes to be observed.

6.2. Geochemical monitoring of water geochemistry in selected wells

Three wells located within a radius of 30 km from the mainshock were chosen for post-seismic geochemical monitoring. The Mirandola (M) and the Bellentani (B) well (B, M and V in Fig. 1) reach a depth of about 200 m. Both are characterized by spontaneous groundwater and

Fig. 5. a) Age of groundwaters is indicated together with data concerning amounts of extracted groundwater. Land subsidence phenomena that occurred in the period 1950–2010 as a result of groundwater overexploitation are also indicated; b) wells unaffected (grey colour) and affected (yellow and orange colour) by chloride increase in the period 2000–2012 belonging to the regional Environmental Protection Agency monitoring network are indicated. Selected wells (red cross) were not affected by chloride variation during time and not located in land subsiding areas. Relevant seismic events of the Emilia 2012 swarm are reported (red star) while alluvial fans areas are also indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

gas gushing. In particular the water flow rate of the Mirandola well is of 0.1 L/s while flow rate of bubbling gases is 0.05 L/s. The water flow rate of the Bellentani well is 0.5 L/s while flow rate of bubbling gases is 0.05 L/s. The Vallalta well (V) was previously described by Gorgoni and Tosatti (2004). This is an old and abandoned 1742 m deep hydrocarbon well. Cement was put inside the well about 40 years ago to prevent hydrocarbon outflow but the shaft of the well was fissured some time ago. At present, the well allows gas seepage (1 L/s) and water outflows (2 L/s). Gas is mostly methane recharged from Miocenic geological formations while groundwaters are mostly caught by Quaternary aquifers by fissures in the well located at about 250 m in depth (Fig. 4). Small amounts of brackish waters are pushed to the surface by bubbling gases. Water and gas flow rates were about double that of the present day during the most intense phase of the seismic swarm in the month of May 2012. A significant lowering of the flow rate was observed during the month of June 2012 while normal values were reached in July 2012. Chemical and isotopic data obtained by the analysis of groundwaters sampled during the 2012 seismic swarm are listed in Table S.1 in the Supplementary material.

The geochemical and isotopic characters of groundwaters occurring in the southern part of the Po Valley were previously described by Martinelli et al. (2014, and references therein) on the basis of a wider data set including >200 wells. Piper's diagram (Fig. 7) evidences the main geochemical characteristics of groundwaters sampled during the seismic swarm (see also Table S.1 in Supplementary material). In particular, both the M well and V well groundwaters fall in the Na-Cl type waters on the Piper's diagram. The B well has Ca-HCO_3 type groundwaters mixed with a Na-Cl component. Groundwater monitoring was started by 29/05/2012 (9 days after the mainshock). The M well catches groundwaters from aquifers located at the boundary of the Quaternary-Pliocene. The B and the V wells have groundwaters belonging to Quaternary aquifers. $\delta^{18}O$ data indicate that the M well waters are mixed waters of meteoric ($\delta^{18}O = -11$) and marine-originating waters ($\delta^{18}O = 0$) (Fig. 8). The B and V samples are characterized by $\delta^{18}O$

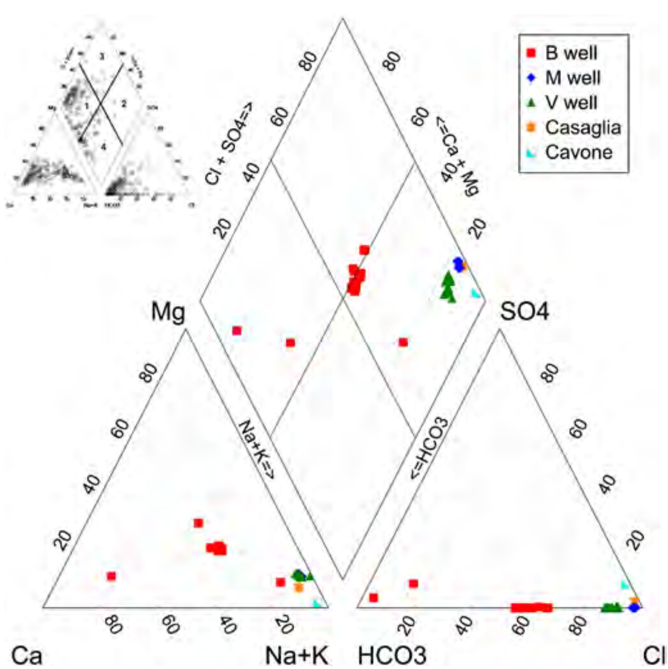


Fig. 7. Piper diagram of B, V and M sampled groundwaters. The close Casaglia (Carella, 1995) and Cavone (Martinelli, 1979) data belonging to connate waters sampled in 2–3 km depth hydrocarbon wells are also indicated. The small Piper diagram on the left describe the chemical composition of all groundwaters sampled in the southern Po Valley described by Martinelli et al. (2014). Fig. S.2 in Supplementary material show geographic distribution of geochemical families and top of saline waters according to Martinelli et al. (2014 and references therein).

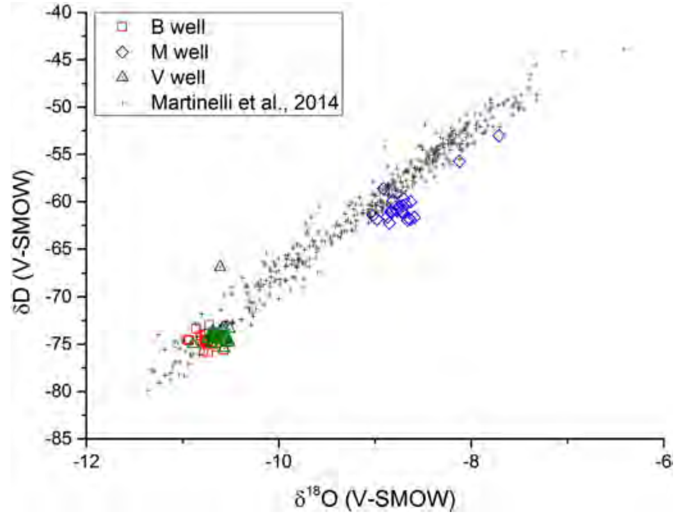


Fig. 8. The southern Po Valley stable isotopes meteoric water line obtained by Martinelli et al. (2014) in groundwaters is shown together with B well, V well and M well stable isotope data.

and δD values typical of aquifers originated by the Po river around 10 kyr ago (Martinelli et al., 2014).

Sr isotopic ratios were measured in waters gushing from the considered three wells. Petrini et al. (2014) reported the present-day $^{87/86}Sr$ value of waters sampled in Adriatic Sea. Conti et al. (2000) reported $^{87/86}Sr$ values collected in Pliocenic mud volcanic groundwaters emitted by local mud volcanoes. All obtained values do not fit with present day Adriatic waters while a contribution of Pliocenic Strontium probably due to local tectonic pumping phenomena is recognizable (Fig. 9).

Chloride concentration slightly decreased during the first week of sampling and reached relatively stable values in the three wells (Fig. 10). HCO_3 increased slightly during the first week of sampling and decreased for about a year. After the decreasing period, HCO_3 reached a sort of flat value indicating the reaching of more stable geochemical equilibria. Chapelle and Knobel (1985) and Herczeg et al. (1991), among others, found that bacterial activity in slow-circulating

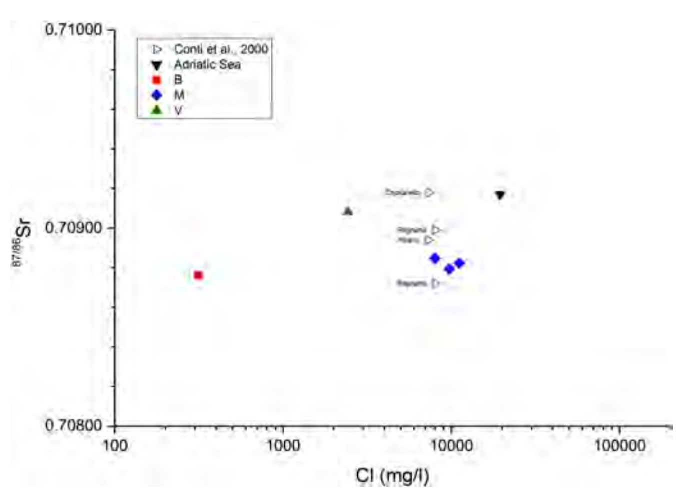


Fig. 9. $^{87/86}Sr$ data are shown together with Cl concentration data. Ospitaletto, Regnano and Nirano data are kept by Conti et al. (2000) and are referred to mud volcanoes shown in Fig. 2. Data obtained by groundwaters sampled in B, V and M wells are shown and compared to a $^{87/86}Sr$ data obtained by Petrini et al. (2014) in water samples of the close Adriatic Sea.

Please cite this article as: Martinelli, G., et al., Geochemical monitoring of the 2012 Po Valley seismic sequence: A review and update, Chem. Geol. (2016), http://dx.doi.org/10.1016/j.chemgeo.2016.12.013

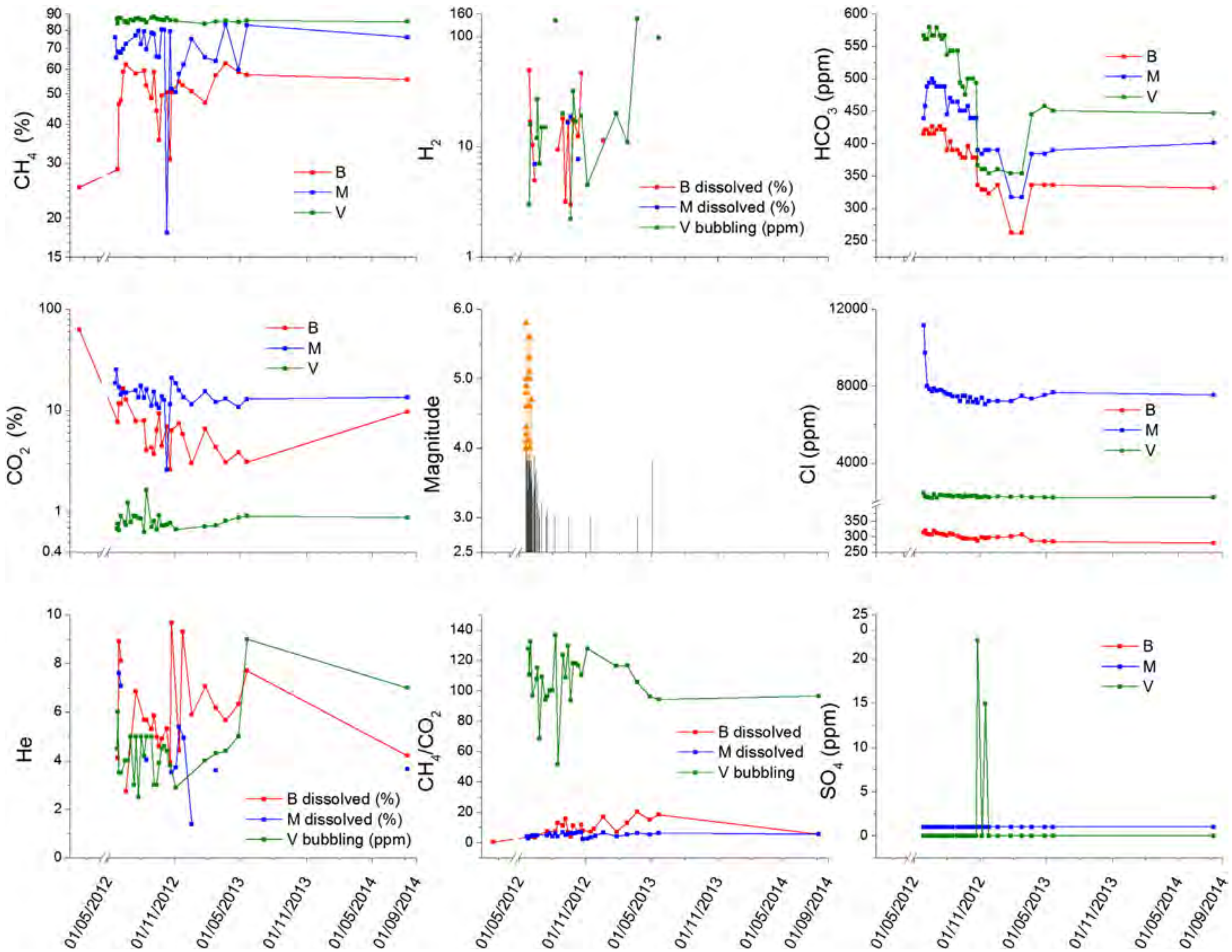


Fig. 10. Geochemical trends of anions and cations in groundwaters in the period 2012–2014. Analytical data about bubbling gases sampled in M and B wells are reported as well as free gases composition analyzed in the V well. Seismic events characterized by Ml > 3 are also reported. In 2007, the first sample in the B well (red colour) was collected. On May 25, 2012, monitoring of activity in the B, M and V wells was started. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

groundwaters hosted in organic material rich aquifers may produce CO_2 and CH_4. A significant increase in CH_4 was observed in the B well in respect to a pre-seismic sample. After the strong increase in the CH_4 concentration, CO_2 values also fluctuated for about a year. Strong fluctuations in CH_4 and in CO_2 values are probably due to sediment compaction due to ground shaking and to the passage of seismic waves as also observed in different geological environments (Gresse et al., 2016 and references therein). These fluctuations may also have been accompanied by Eh-pH changes due to the presence of H_2S and NH_4 in deep aquifers (Martinelli et al., 1998) able to influence, in principle, cation and anion equilibria in groundwaters. Furthermore, a lowering of the HCO_3 concentration was observed in all three wells for a period of about a year in concomitance with strong fluctuations in H_2 (Fig. 10).

Bennett et al. (2000) reported that bicarbonate consumption by methanogenesis may be due to following reaction:

$$2HCO_3^- + 4H_2 + Ca^{2+} = CaCO_3 + CH_4 + 3H_2O.$$

After this period, the HCO_3 concentration increased and reached a sort of stable plafond value.

6.3. Geochemical monitoring of gas geochemistry in selected wells

Gases are usually bubbling in the three selected wells. In particular, the relatively high gas flow rate found in the Vallalta well (1 L/s) allowed for the sampling of free gases, while the lower gas flow rate values found in the Bellentani and in Mirandola wells allowed for the sampling of dissolved gases. Obtained values are shown in Fig. 11.

Further chemical values obtained in close gas emissions have been included in Fig. 12. Chemical and isotopic data of gases utilized in Fig. 11 are shown in Table 1 and in Table 2.

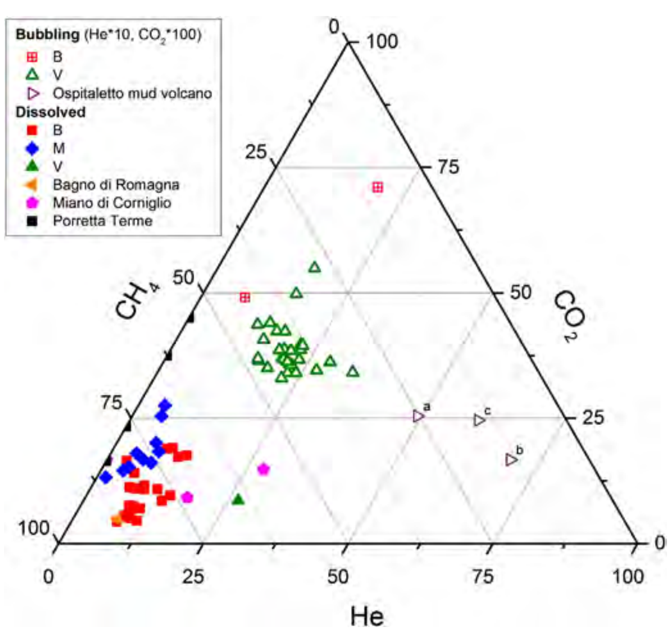


Fig. 11. Dissolved gases of B, V and M wells are reported as well as bubbling gases collected in the B and V wells. Bubbling gas analysis of the Ospitaletto mud volcano (Fig. 2) and dissolved gas analysis of Bagno di Romagna, Miano di Corniglio (Italiano et al., 2012a, 2012b) and Porretta Terme (Ciancabilla et al., 2007) are also reported. The Ospitaletto mud volcano analysis represented by the empty triangle "a" is kept by Minissale et al. (2000). The Ospitaletto mud volcano analysis represented by the empty triangle "b" is kept by Tassi et al. (2012) while the Ospitaletto mud volcano analysis represented by the empty triangle "c" refer to present work.

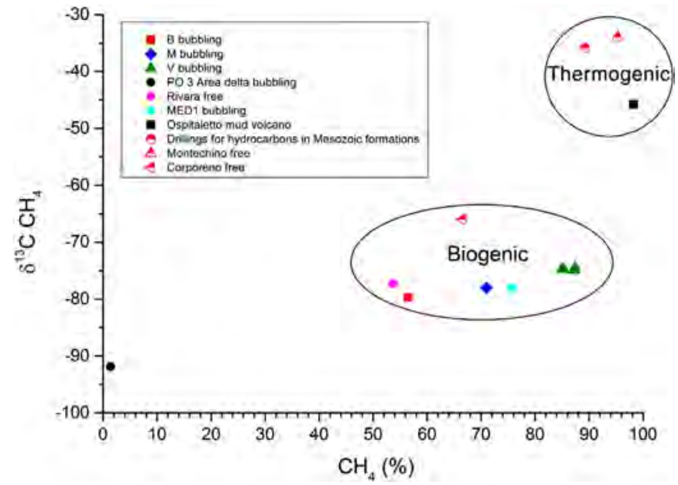


Fig. 12. CH_4 (%) and $\delta^{13}C$ data in B, M and V wells are reported. Thermogenic values (T) are in the upper right hand part of the graph while biogenic values are in the lower part of the graph. Analytical data of other gas samples are also reported. In particular the sample "PO 3 Area delta bubbling" was published by Orange et al. (2005), the sample "Rivara free gas" was published by Sciarra et al. (2013), the sample "MED1 bubbling gas" was published by Capaccioni et al. (2015), "Montechino free gas" and "Corporeno free gas" samples were published by Etiope et al. (2007) while the "Ospitaletto mud volcano bubbling gas" was sampled on May 29, 2012. The sample "Drillings for hydrocarbons in Mesozoic formations" corresponds to average values found in deep drillings by Mattavelli et al. (1983). B and T in capital letters identify biogenic and thermogenic gas families respectively. The sample PO 3 was collected by Orange et al. (2005) at a depth of 2 m in the area of the delta of Po river and represents the first stage of organic matter degradation producing methane (see also Fig. 3 in Supplementary material).

All considered gas samples are methane-dominating. $\delta^{13}C$ values indicate a biogenic origin from organic materials hosted in Quaternary and Pliocenic geological formations. Helium isotopes indicate a crustal origin of sampled gases and no mantle contributions are recognizable. Mattavelli et al. (1983), Sciarra et al. (2013) and Capaccioni et al. (2015) confirm that marine organic material hosted in underlying Pliocenic formations and frequent peat layers hosted in Quaternary geological formations are responsible for degassing in the whole Po Valley. Obtained gas composition time series are shown in Fig. 10.

A pre-seismic sample collected in the Bellentani well shows a lower CH_4 concentration as compared with other samples collected during the seismic swarm period. The lower CH_4 concentration could, in principle, be attributed to the relatively long period before sampling characterized by the lack of significant local seismic events lasting about two decades. In the meantime ground shaking induced strong fluctuations in CH_4 and in CO_2 values also due to possible gas detachment from solid sediments induced by the passage of seismic waves (Gresse et al., 2016 and references therein). Some helium values slightly higher than the average atmospheric value were detected in all three wells during different periods. The observed effect could be due to the expulsion of relatively older gas pockets hosted in Pliocene geological formations. Pliocenic methane dominated gases, although isotopically similar to Quaternary methane gases, could be slightly enriched in total helium due to their higher age. Gorgoni et al. (1982) measured radon in groundwaters in 80 wells of the Po Valley, while Martinelli and Vaccari (2007) measured radon in 330 wells of the southern Po Valley. Radon concentrations found in the area affected by the 2012 seismic sequence were in the range 3–6 Bq/L. Spot radon measurements were carried out by different research groups in soils and in wells of the area affected by the 2012 seismic swarm but observed values were in the range of previously reported data (Sciarra et al., 2012, 2013; Martinelli et al., 2015) probably due to a very low and short possible increase in carrier gas (CH_4) flow rate.

Please cite this article as: Martinelli, G., et al., Geochemical monitoring of the 2012 Po Valley seismic sequence: A review and update, Chem. Geol. (2016), http://dx.doi.org/10.1016/j.chemgeo.2016.12.013

Table 1
Analytical data of sampled free gases utilized to draw Figs. 10 and 11.

Site	Date	He (ppm)	H_2 (ppm)	O_2 (%)	N_2 (%)	CO (ppm)	CH_4 (%)	CO_2 (%)	δ^{13} (CO_2)	δ^{13} (CH_4)	R/Ra	He/Ne
B well	07/06/2012	1.0		2.1E + 00	38.3	21.0	56.5	0.64		−79.7		
	03/07/2012			1.7E + 01	71.8	9.0	5.8	0.08				
	27/09/2012	9.0	54	4.8E−01	52.4	0.4	42.8	3.26				
M well	07/06/2012						71.0			−78		
Ospitaletto	26/06/2012	37.0		3.9E−01	1.7	2.5	93.8	1.51				
V well	27/05/2012	4.5		1.0E−02	11.2	0.0	86.8	0.68	−9.16		0.14891	1.94106
	29/05/2012	6.0	3	6.9E−02	11.1	1.0	84.1	0.76	−7.38		0.16661	2.53463
	01/06/2012	3.5	16	7.4E−02	11.4	1.3	87.4	0.66		−74.4	0.21723	2.75166
	07/06/2012	3.5		1.0E−02	11.1	0.4	87.3	0.90		−74.9	0.23623	2.69397
	18/06/2012	4.0	12	7.2E−03	11.2	0.1	84.9	0.79		−74.7		
	20/06/2012	4.0	27	2.7E−02	11.3	1.8	85.3	0.74		−74.8		
	26/06/2012	4.0	7	2.4E−03	10.8	0.6	84.1	1.23				
	03/07/2012	5.0	15	1.9E−02	11.1	0.3	86.4	0.79				
	13/07/2012	3.0	15	1.7E−02	10.9	0.7	85.7	0.91				
	18/07/2012	5.0		7.6E−03	10.9	1.2	86.8	0.90				
	25/07/2012	2.5		2.9E−02	10.4	2.5	87.3	0.87				
	01/08/2012	5.0		8.3E−02	11.5	3.8	86.4	0.86				
	09/08/2012	4.2	140	3.0E−02	11.0	1.9	86.0	0.63				
	16/08/2012	5.0		3.2E−03	11.0	0.5	84.6	1.64				
	30/08/2012	5.0	20	8.6E−03	11.1	0.7	87.6	0.71				
	06/09/2012	3.0		1.3E−01	11.8	1.1	88.1	0.81				
	13/09/2012	3.0		7.7E−02	11.2	0.8	86.8	0.67				
	20/09/2012	3.9	2.2	7.6E−03	11.0	2.2	86.3	0.92				
	27/09/2012	4.5	32	3.6E−02	11.0	0.5	86.2	0.73				
	04/10/2012	4.6	17	3.0E−02	11.1	1.1	86.1	0.73				
	11/10/2012	4.4		4.7E−02	11.3	1.3	87.5	0.75				
	20/10/2012	3.8	19	1.0E−02	11.0	1.7	86.1	0.78				
	05/11/2012	2.9	4.5	3.5E−03	11.2	0.7	85.7	0.67				
	24/01/2013	4.0	20	9.0E−02	10.8	0.3	83.8	0.72				
	24/02/2013	4.3	11	1.5E−01	11.1	4.1	85.1	0.73				
	23/03/2013	4.4	145		11.1	0.5	85.6	0.81				
	27/04/2013	5.0		2.9E−01	11.9	0.2	84.8	0.88				
	21/05/2013	9.0	97		11.0	0.3	85.8	0.91				
	06/08/2014	7.0		9.0E−02	11.1	0.7	85.0	0.88				

6.4. Long- term water level manual monitoring in selected wells

Po Valley hosts thousands of wells drilled since Roman times. Most of them catch groundwaters of phreatic aquifers. These aquifers are directly connected with the atmosphere and are unsuited to tectonic oriented searches. At the beginning of the twentieth century deep wells were drilled as well with the help of modern technologies. In particular, all Quaternary aquifers overlying the top of salt waters (Fig. 4) in the depth interval 100–300 m became the subject of searches for groundwaters useful for agricultural, industrial and civil purposes (Giuliano, 1995; Martinelli et al., 2014). Due to the high cost of drilling only a few hundred wells were drilled in the period 1900–1940. In the period 1940–1980 many wells were drilled. Consequently, environmental policies became oriented to limiting the number of wells due to land subsidence as a result of overexploitation and an increase in chloride ion due to brackish groundwater diffusion from the top of saline waters under the effects of depressurization of the overexploited areas from the Quaternary aquifers. Groundwater levels recorded by Sacco (1912, 1924, 1933) are deemed unaffected by modern overexploitation phenomena due to poor industrialization of previous ages and have been utilized to draw a piezometric map (Fig. 13).

Red arrows indicate water level data significantly below the topographic surface. Green arrows indicate water level data grazing the topographic surface, while blue arrows indicate water level data above the topographic surface. Blue arrows located in the eastern part of the Po Valley indicate gushing wells surrounded by wells characterized by significantly lower water levels, which drew the attention of Sacco (1912, 1924, 1933). The blue arrow area identifies a well known highly pressurized aquifer system poorly connected hydrologically with the surrounding aquifers (Idroser, 1977; Giuliano, 1995; Martinelli et al., 2014). The identified pressurized confined aquifers host groundwaters characterized by extremely low circulation velocity with scarce or no evidence of recent recharge processes. Furthermore, these aquifers are characterized by extremely high hydraulic head values. These aquifers are not significantly fed by surrounding aquifers which are characterized by lower hydraulic head values (Martinelli et al., 2014). These peculiar confinement characteristics are due to a clay distribution which seals fine grained aquifers at depth. Aquitard characteristics of clays also extend to peripheric lateral sectors of aquifers (see also Fig. 4) and allow eastern Po Valley aquifers to act, in principle, as a big natural strainmeter (Bodvarsson, 1970; Rice and Cleary, 1976) due to fact that water is not compressible. Similar conditions were described by Toth and Almasi (2001) in the Hungarian Great Plain. In recent decades, the Environmental Agencies of the Po Valley have set up networks of wells with the purpose of monitoring environmental and hydrological aquifer conditions. In particular, long-term water level data measured by manual techniques are available in the Southern part of the Po Valley in Emilia Romagna region. Water wells located in the same area identified by Sacco in the period 1912–1933 have also been considered. Maps in Fig. 5 show the identification of wells drilled in aquifers relatively unaffected by overexploitation, land subsidence and chloride increases due to excessive withdrawal.

Water level data of the two areas described in Fig. 14 were examined. Water level data in the period 1976–2000 were collected manually every three months, while additional sets of data were collected every six months in the following years. Two families of water level patterns over time were identified. The longest time series scarcely affected by possible missing data were recorded in seven selected wells and shown in Fig. 14. Time series are shown in Fig. 15. In particular, in the Western area (blue colour wells in the graph of Fig. 15) a general lowering in the water level was observed in the period 1976–1990. The period

Table 2
Analytical data of sampled dissolved gases utilized to draw Figs. 10 and 11.

Site	Date	He (cm^3 STP/L)	H_2 (cm^3 STP/L)	O_2 (cm^3 STP/L)	N_2 (cm^3 STP/L)	CO (cm^3 STP/L)	CH_4 (cm^3 STP/L)	CO_2 (cm^3 STP/L)
B well	20/04/2007			3.26E−05	4.00E−04	2.70E−05	9.61E−04	2.41E−03
	29/05/2012	7.60E−04	9.11E−03	2.91E−06	1.90E−03		5.28E−03	1.43E−03
	01/06/2012	1.21E−03	2.28E−03	2.99E−06	2.18E−03	0.00E + 00	6.28E−03	1.60E−03
	07/06/2012	1.15E−03	1.46E−03	9.13E−06	2.61E−03	5.64E−04	6.71E−03	1.64E−03
	13/06/2012		2.95E−04	3.16E−06	1.16E−03	1.60E−05	3.51E−03	9.79E−04
	20/06/2012	2.02E−04		3.87E−06	1.59E−03	6.62E−05	4.54E−03	9.40E−04
	18/07/2012	2.13E−03		2.67E−05	8.46E−03		1.81E−02	2.45E−03
	09/08/2012	1.44E−03		3.72E−05	6.88E−03		1.50E−02	2.02E−03
	16/08/2012	5.49E−03	9.12E−03	5.69E−05	2.65E−02	2.32E−04	5.14E−02	3.91E−03
	30/08/2012	3.66E−03	1.24E−02	2.25E−05	1.61E−02	6.05E−04	3.34E−02	2.98E−03
	06/09/2012	2.73E−03	1.47E−03	3.11E−05	1.31E−02	5.07E−05	2.74E−02	1.72E−03
	13/09/2012	2.49E−03	8.53E−03	3.75E−05	1.36E−02	1.40E−04	2.21E−02	3.21E−03
	20/09/2012	1.72E−03	1.12E−03	3.81E−05	1.77E−02	7.78E−05	1.33E−02	3.48E−03
	27/09/2012	3.01E−03	1.08E−02	3.94E−05	1.45E−02		3.03E−02	2.74E−03
	11/10/2012	2.38E−03	5.59E−03	2.65E−05	1.09E−02	8.92E−05	2.27E−02	3.12E−03
	20/10/2012	4.47E−03	5.30E−02	4.30E−05	1.77E−02	2.75E−04	3.49E−02	2.96E−03
	24/10/2012	9.30E−03		4.43E−05	3.19E−02		4.86E−02	6.14E−03
	14/11/2012	2.31E−03		3.04E−05	1.74E−02	6.26E−05	2.85E−02	3.88E−03
	24/11/2012	6.21E−03		5.83E−05	2.10E−02		3.55E−02	3.89E−03
	19/12/2012	1.38E−02	2.67E−02	1.88E−04	6.68E−02	9.01E−04	1.19E−01	7.05E−03
	25/01/2013	6.87E−03	–	9.08E−05	3.85E−02		4.55E−02	6.38E−03
	23/02/2013	7.68E−03	–	1.00E−04	3.94E−02	6.75E−04	7.11E−02	5.40E−03
	23/03/2013	5.98E−03	–	4.13E−05	3.02E−02		6.62E−02	3.26E−03
	27/04/2013	6.64E−03	–	5.18E−05	3.25E−02	1.46E−04	6.15E−02	4.06E−03
	21/05/2013	7.05E−03		3.95E−05	2.90E−02		5.26E−02	2.84E−03
	06/08/2014	7.75E−04		1.02E−05	5.51E−03	1.10E−04	1.02E−02	1.80E−03
M well	22/05/2012			1.47E−06	3.08E−04	1.33E−04	6.00E−03	1.49E−03
	25/05/2012			4.99E−05	2.33E−04	1.80E−04	3.20E−03	1.24E−03
	01/06/2012	6.51E−04		2.91E−06	6.10E−04	0.00E + 00	5.85E−03	1.46E−03
	07/06/2012	6.04E−04		5.45E−06	8.60E−04	6.18E−05	5.77E−03	1.22E−03
	13/06/2012		2.46E−04	1.48E−06	2.95E−04		2.48E−03	5.41E−04
	20/06/2012			1.95E−06	2.47E−04	3.82E−04	3.57E−03	7.39E−04
	17/07/2012			2.03E−06	2.96E−04		3.09E−03	6.39E−04
	25/07/2012			2.84E−06	3.42E−04		3.93E−03	6.67E−04
	01/08/2012			3.12E−06	4.75E−04	9.18E−06	3.32E−03	8.11E−04
	09/08/2012			2.36E−06	3.38E−04		3.63E−03	6.11E−04
	16/08/2012	1.87E−04		5.57E−06	4.72E−04	9.18E−06	3.22E−03	7.48E−04
	30/08/2012			2.61E−06	4.62E−04	8.58E−06	3.61E−03	5.14E−04
	06/09/2012			6.47E−06	2.48E−04	1.13E−05	2.88E−03	5.70E−04
	13/09/2012		7.40E−04	1.24E−05	2.76E−04		2.96E−03	5.15E−04
	20/09/2012		1.05E−03	8.00E−06	2.94E−04	6.39E−06	3.68E−03	5.95E−04
	27/09/2012			3.10E−06	2.13E−04		2.97E−03	5.06E−04
	04/10/2012			4.58E−06	2.36E−04	2.59E−05	2.91E−03	4.57E−04
	11/10/2012		1.66E−03	3.64E−06	2.51E−04	2.15E−04	3.85E−03	5.60E−04
	20/10/2012			5.09E−06	5.06E−04	3.97E−05	4.73E−03	6.87E−04
	24/10/2012	1.29E−04		3.19E−06	8.66E−04	0.00E + 00	1.91E−03	7.75E−04
	05/11/2012	2.13E−04		3.91E−06	1.56E−03	0.00E + 00	2.91E−03	1.06E−03
	14/11/2012	2.61E−04		2.76E−06	1.00E−03	0.00E + 00	2.79E−03	7.65E−04
	27/11/2012	3.00E−04		2.36E−06	1.17E−03	1.92E−05	3.76E−03	8.21E−04
	19/12/2012	7.89E−05		3.82E−06	6.84E−04	9.59E−06	4.25E−03	6.56E−04
	25/01/2013			4.60E−06	7.70E−04	0.00E + 00	2.62E−03	6.18E−04
	23/02/2013	3.62E−04		8.07E−06	2.06E−03	0.00E + 00	6.39E−03	1.22E−03
	23/03/2013	–	–	2.54E−06	2.03E−04	–	5.48E−03	8.55E−04
	27/04/2013	–	–	2.83E−06	3.02E−04	–	3.24E−03	5.89E−04
	21/05/2013	–	–	4.77E−06	2.47E−04	–	5.01E−03	7.82E−04
	06/08/2014	1.37E−04		5.20E−06	2.57E−04	0.00E + 00	2.85E−03	5.09E−04
V well	29/05/2012	3.35E−03	1.52E−03	6.32E−06	8.42E−04		8.12E−03	1.08E−03

1991–2015 was characterized by an increase in the water level up to the present time. In the Eastern area (red colour wells in the graph of Fig. 15) a lowering of the water level was observed in the period 1976–1982, while in following years a constant increase in water levels up to the present time was observed. Long-term records allow us to observe that the seismic swarm of 2012 was preceded by a long period of water level rises. A slight reduction in the water level was observed in the years following the 2012 seismic swarm. Apparently, the seismic swarm that occurred in 2012 was not clearly preceded by short-term water level fluctuations; nonetheless, the observed long-term water level increase is probably due to the tectonic compression indicated by the arrows in Fig. 2a and in Fig. 2b. The general compressive nature of the considered area was also recognized by focal mechanisms of earthquakes recorded by Frepoli and Amato (1997). Cenni et al. (2012) estimated that Po Valley shortening due to compressive processes corresponds to about 2–4 mm/year. As a result the buried anticlines were uplifted. Present uplifting velocity was estimated about 1 mm/year by Burrato et al. (2003) on the basis of geological and seismological deductions. Cenni et al. (2013) and Pezzo et al. (2013) detected an uplift of the buried anticlines and of the Northern Apennines of about 1 mm/year by analysis of GPS recordings confirming the findings previously obtained by Burrato et al. (2003).

The analysis of groundwater level data (original data in Table S.3 in Supplementary material) reveal that, once anthropic noise was

Please cite this article as: Martinelli, G., et al., Geochemical monitoring of the 2012 Po Valley seismic sequence: A review and update, Chem. Geol. (2016), http://dx.doi.org/10.1016/j.chemgeo.2016.12.013

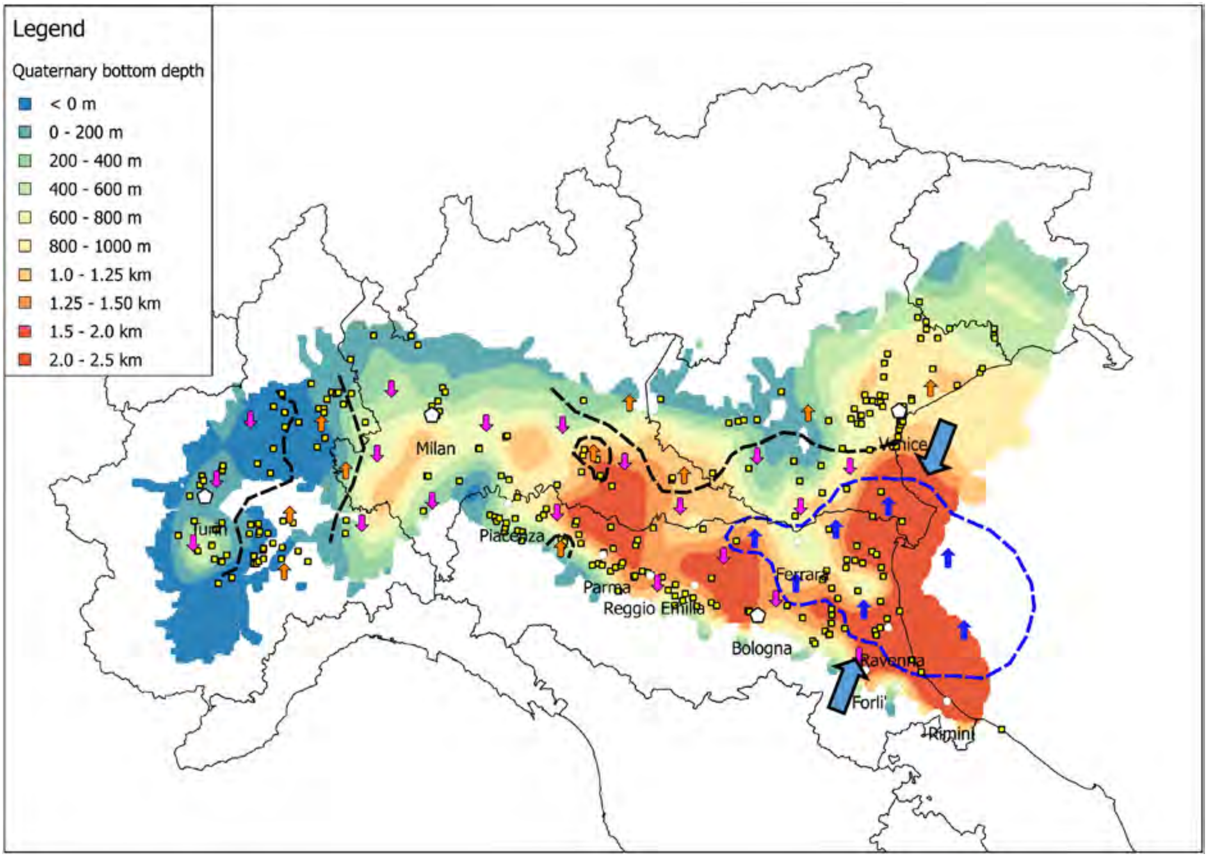


Fig. 13. Distribution of water level in wells during the period 1910–1932 according to Sacco (1912, 1924, 1933) and Quaternary bottom depth (Molinari et al., 2015; depth is positive below sea level). Blue arrows indicate gushing groundwaters while magenta arrows indicate groundwater levels below the topographic surface. Orange arrows indicate wells in which water level grazes the topographic surface. The areas of present-time gushing groundwaters are similar to the areas described in previous catalogues by Sacco (1912, 1924, 1933) (original data in Table 2 in Supplementary material). Blue arrows in the sea on the right side indicate gushing groundwaters intercepted by offshore hydrocarbon drillings in the period 1959–1976 (Idroser, 1977). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

excluded, an almost continuous compressive period probably affected the Eastern part of the studied area in the period 1982–2012, while the same stress field conditions affected the Western area in the period 1990–2012. In the period 2013–2015 water level data in both areas indicate a relative lowering in the velocity of the increasing trend probably due to the Emilia seismic swarm and to possible following stress field relaxation (e.g., Bragato, 2014 and references therein). Hence, the shortening of the Po Valley (2 mm/year) and the uplift of the anticlines involved in the 2012 seismic swarm (1 mm/year) induced significant variations in size and shape of local confined aquifers which behaved as natural strainmeters (Bodvarsson G., 1970; Rice and Cleary, 1976) and water level increased at a rate of 150–170 mm/year in the two or three decades before the 2012 seismic swarm. Such an increase cannot be continuous during geological time since present-day maximum values of groundwater gushing over the topographic surface are in the range 1–4 m in the blue arrows area of Fig. 13 and similar values were found by Sacco (1912, 1924, 1933) while higher values were never reported. The increasing rate of 150–170 mm/year could virtually have induced an increase of 12–13.6 m in the past 80 years since the last report on groundwaters compiled during the pre-industrial period (Sacco, 1933). These values were never found in gushing wells of the Southern Po Valley. Furthermore both graphs shown in Fig. 15 indicate increasing and decreasing periods. Thus a possible periodic multi-decadal signal in groundwater levels could be possible (see also Albarello and Martinelli, 1994 and references therein; Vartanyan et al., 2014 and references therein). Similar periodicities were recently found in the seismicity rate of the southern Po Valley by Bragato (2014) who considered earthquake occurrence in the studied area in the period 1890–2012. Thus, crustal deformative processes are associated with seismic events and groundwater level fluctuations in confined aquifers. A medium-sized seismic event (Ml = 4.8) that occurred on 17 July 2011 (blue star in Fig. 1 and blue arrow in Fig. 15) slightly to the north of the 2012 seismic sequence could also be tentatively considered as a possible seismic precursor of the seismic swarm (see also Peresan et al., 2015).

7. Conclusions

No short-term geochemical or hydrogeologic precursors were observed before mainshocks of the 2012 Emilia Romagna seismic sequence, whereas coseismic phenomena were clearly observed. Sediment compaction due to the seismic swarm induced significant variations in chemical composition of groundwaters and of gases in the area where the Emilia 2012 seismic swarm occurred. An almost continuous long-term water level increase trend was observable in confined aquifers of the studied area. This trend could be linked to the ongoing compressive motion of the Adriatic microplate. The 2012 seismic swarm could have lowered the velocity of the water level increase trend indicating a possible stress field relaxation in the Po Valley and an ensuing seismic hazard fluctuation. The pattern of seismic occurrence in Italy following available water level data will better clear a possible seismic hazard reduction in the Po Valley. While no short-term

Please cite this article as: Martinelli, G., et al., Geochemical monitoring of the 2012 Po Valley seismic sequence: A review and update, Chem. Geol. (2016), http://dx.doi.org/10.1016/j.chemgeo.2016.12.013

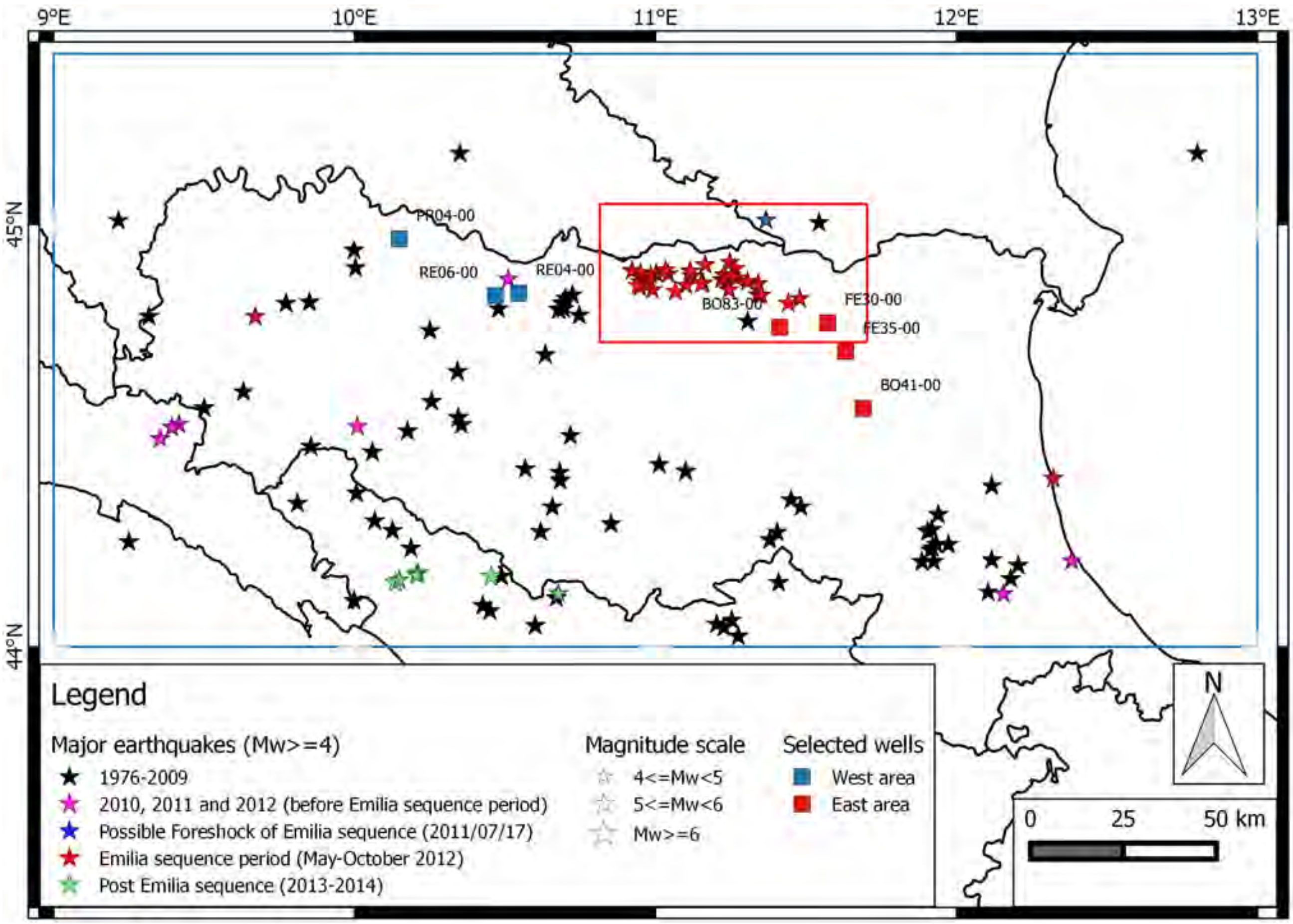


Fig. 14. Selected wells (eastern part = red squares; western part = blue squares) utilized for long time series monitoring of water level data. The seven wells indicated by squares were chosen among the 17 wells shown in Fig. 5 (see text). Relevant seismic events are also indicated as in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fluid-related precursory phenomena were observed before mainshocks, huge medium-term water level variations were detected before the Emilia seismic swarm and confirm the sensitivity of confined fluids as natural strainmeters.

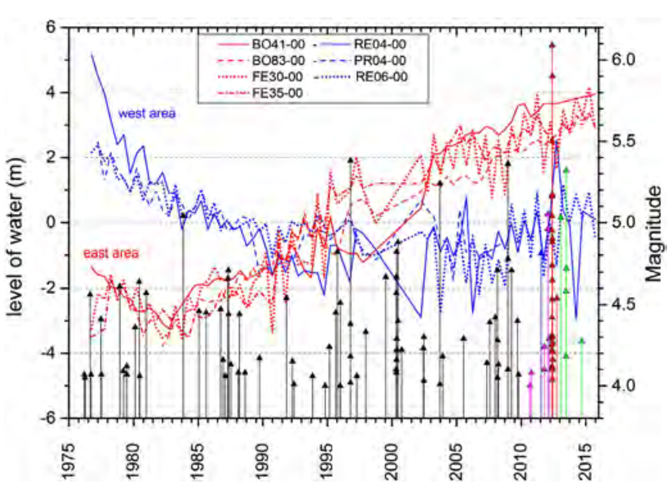


Fig. 15. Water level data (1976–2015) recorded in selected wells in the eastern (red colour) and in the western (blue colour) areas of the southern Po Valley. Colours of seismic events are as in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Acknowledgments

Thanks are due to two unknown Reviewers which contributed to improve the quality of text, Claudio Colognesi (Municipality of Mirandola), Daniela Corradini and Franca Bottazzi (ARPAE, Dept. of Modena) for kind suggestions and support during Mirandola (M) well monitoring. Thanks are also due to Luigi Poletti for kind permission of monitoring the Bellentani (B) well. This study has benefited from funding provided by the Italian Presidenza del Consiglio dei Ministri-Dipartimento della Protezione Civile (DPC), Projects S3-2012 and S3-2014-2015. This paper does not necessarily represent the DPC's official opinion and policies. This paper was presented at 13th International Conference on Gas Geochemistry, Chengdu (China), 2015.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.chemgeo.2016.12.013.

References

Albarello, D., Martinelli, G., 1994. Piezometric levels as possible geodynamic indicators: analysis of the data from a regional deep waters monitoring network in northern Italy. Geophys. Res. Lett. 21:1955–1958. http://dx.doi.org/10.1029/94GL01598.

Bennett, P.C., Hiebert, F.K., Roberts Rogers, J., 2000. Microbial control of mineral groundwater equilibria: macroscale to microscale. Hydrogeol. J. 8:47–62. http://dx.doi.org/10.1007/s100400050007.

Bertacchini, M., Castaldini, D., Tosatti, G., 2014. Rumours related to the 2012 Emilia seismic sequence. Engineering Geology for Society and Territory-Education, Professional

Ethics and Public Recognition of Engineering Geology Vol. 7:pp. 97–102. http://dx.doi.org/10.1007/978-3-319-09303-1_19.

Bertolini, G., Fioroni, C., 2012. Aerial inventory of surficial effects induced by the recent Emilia earthquake (Italy): preliminary report. Annals of Geophysics 55:705–711. http://dx.doi.org/10.4401/ag-6113.

Bianchi, E., Borgatti, L., Vittuari, L., 2014. The medium- to long-term effects of soil liquefaction in the Po Plain (Italy). In: Lollino, G., Giordan, D., Thuro, K., Carranza-Torres, C., Wu, F., Marinos, P., Delgado, C. (Eds.), Engineering Geology for Society and Territory Vol. 6. Springer:pp. 421–425. http://dx.doi.org/10.1007/978-3-319-09060-3_73.

Bodvarsson, G., 1970. Confined fluids as strain meters. J. Geophys. Res. 75:2711–2718. http://dx.doi.org/10.1029/JB075i014p02711.

Bonini, M., Rudolph, M.L., Manga, M., 2016. Long- and short-term triggering and modulation of mud volcano eruptions by earthquakes. Tectonophysics:672–673 http://dx.doi.org/10.1016/j.tecto.2016.01.037.

Boschi, E., Ferrari, G., Gasperini, P., Guidoboni, E., Smriglio, G., Valensise, G., 1995. Catalogo dei forti terremoti in Italia dal 461 a.C al 1980. Istituto Nazionale di Geofisica, Storia Geofisica Ambiente, Bologna (973 pp.).

Bragato, P.L., 2014. Rate changes, premonitory quiescence, and synchronization of earthquakes in northern Italy and its surroundings. Seismol. Res. Lett. 85:639–648. http://dx.doi.org/10.1785/0220130139.

Burrato, P., Ciucci, F., Valensise, G., 2003. An inventory of river anomalies in the Po Plain, Northern Italy: evidence for active blind thrust faulting. Ann. Geophys. 46:865–882. http://dx.doi.org/10.4401/ag-3459.

Buttinelli, M., Procesi, M., Cantucci, B., Quattrocchi, F., Boschi, E., 2011. The Geo-database of Caprock Quality and Deep Saline Aquifers Distribution for Geological Storage of CO_2 in Italy. http://dx.doi.org/10.1016/j.energy.2011.02.041.

Capaccioni, B., Tassi, F., Cremonini, S., Sciarra, A., Vaselli, O., 2015. Ground heating and methane oxidation processes at shallow depth in Terre Calde di Medolla (Italy): observations and conceptual model. J. Geophys. Res. B 120:3048–3064. http://dx.doi.org/10.1002/2014JB011635.

Caputo, R., Poli, M.E., Minarelli, L., Rapti, D., Sboras, S., Stefani, M., Zanferrari, A., 2016. Palaeoseismological evidence for the 1570 Ferrara earthquake, Italy. Tectonics 35. http://dx.doi.org/10.1002/2016TC004238.

Carannante, S., Argnani, A., Massa, M., D'Alema, E., Lovati, S., Moretti, M., Cattaneo, M., Augliera, P., 2015. The May 20 (Mw 6.1) and 29 (Mw 6.0), 2012 Emilia (Po Plain, northern Italy) earthquakes: new seismotectonic implications from subsurface geology and high-quality hypocenter location. Tectonophysics 655:107–123. http://dx.doi.org/10.1016/j.tecto.2015.05.015.

Carella, R., 1995. EC funded reservoir testing — Casaglia (Ferrara, Italy). Proceedings of the World Geothermal Congress, International Geothermal Association Vol. 3, pp. 1819–1824.

Carminati, E., Scrocca, D., Doglioni, C., 2010. Compaction-induced stress variations with depth in an active anticline: Northern Apennines, Italy. J. Geophys. Res. Solid Earth 115:2. http://dx.doi.org/10.1029/2009JB006395.

Cenni, N., Mantovani, E., Baldi, P., Viti, M., 2012. Present kinematics of Central and Northern Italy from continuous GPS measurements. J. Geodyn. 58:62–72. http://dx.doi.org/10.1016/j.jog.2012.02.004.

Cenni, N., Viti, M., Baldi, P., Mantovani, E., Bacchetti, M., Vannucchi, A., 2013. Present vertical movements in Central and Northern Italy from GPS data: possible role of natural and anthropogenic causes. J. Geodyn. 71:74–85. http://dx.doi.org/10.1016/j.jog.2013.07.004.

Cenni, N., Viti, M., Mantovani, E., 2015. Space geodetic data (GPS) and earthquake forecasting: Examples from the Italian geodetic network. Boll. Geofis. Teor. Appl. 56: 129–150. http://dx.doi.org/10.4430/bgta0139.

Chapelle, F.H., Knobel, L.R.L., 1985. Stable carbon isotopes of HCO_3 in the Aquia Aquifer, Maryland: evidence for an isotopically heavy source of CO_2. Ground Water 23: 592–599. http://dx.doi.org/10.1111/j.1745-6584.1985.tb01507.x.

Chiarabba, C., De Gori, P., Improta, L., Lucente, F.P., Moretti, M., Govoni, A., Di Bona, M., Margheriti, L., Marchetti, A., Nardi, A., 2014. Frontal compression along the Apennines thrust system: the Emilia 2012 example from seismicity to crustal structure. J. Geodyn. 82:98–109. http://dx.doi.org/10.1016/j.jog.2014.09.003.

Ciancabilla, N., Ditta, M., Italiano, F., Martinelli, G., 2007. The Porretta thermal springs (Northern Apennines): seismogenic structures and long-term geochemical monitoring. Annals of Geophysics 50 (4):513–526. http://dx.doi.org/10.4401/ag-4436.

Conti, A., Sacchi, E., Chiarle, M., Martinelli, G., Zuppi, G.M., 2000. Geochemistry of the formation waters in the Po plain (Northern Italy): an overview. Appl. Geochem. 15 (1): 51–65. http://dx.doi.org/10.1016/S0883-2927(99)00016-5.

Elliot, T., Ballentine, C.J., O'Nions, R.K., Ricchiuto, T., 1993. Carbon, helium, neon and argon isotopes in a Po Basin (northern Italy) natural gas field. Chem. Geol. 106:429–440. http://dx.doi.org/10.1016/0009-2541(93)90042-H.

Emergeo Working Group, 2013. Liquefaction phenomena associated with the Emilia earthquake sequence of May–June 2012 (Northern Italy). Natural Hazards Earth Syst. Sciences 13:935–947. http://dx.doi.org/10.5194/nhess-13-935-2013.

Etiope, G., Martinelli, G., Caracausi, A., Italiano, F., 2007. Methane seeps and mud volcanoes in Italy: gas origin, fractionation and emission to the atmosphere. Geophys. Res. Lett. 34, L14303. http://dx.doi.org/10.1029/2007GL030341.

Fontana, D., Lugli, S., Marchetti Dori, S., Caputo, R., Stefani, M., 2015. Sedimentology and composition of sands injected during the seismic crisis of May 2012 (Emilia, Italy): clues for source layer identification and liquefaction regime. Sediment. Geol. 325: 158–167. http://dx.doi.org/10.1016/j.sedgeo.2015.06.004.

Frepoli, A., Amato, A., 1997. Contemporaneous extension and compression in the Northern Apennines from earthquake fault-plane solutions. Geophys. J. Int. 129 (2): 368–388. http://dx.doi.org/10.1111/j.1365-246X.1997.tb01589.x.

Giuliano, G., 1995. Ground water in the Po basin: some problems relating to its use and protection. Sci. Total Environ. 171:17–27. http://dx.doi.org/10.1016/0048-9697(95)04682-1.

Gorgoni, C., Tosatti, G., 2004. Emissioni di metano e fanghi salmastri da un pozzo dismesso in Comune di Concordia (Provincia di Modena). Atti della Società dei Naturalisti e Matematici Modenesi Vol. 135, pp. 155–174.

Gorgoni, C., Martinelli, G., Sighinolfi, G.P., 1982. Radon distribution in groundwater of the Po sedimentary basin (Italy). Chem. Geol. 35 (3–4):297–309. http://dx.doi.org/10.1016/0009-2541(82)90007-9.

Gresse, M., Vandemeulebrouck, J., Byrdina, S., Chiodini, G., Bruno, P.P., 2016. Changes in CO_2 diffuse degassing induced by the passing of seismic waves. J. Volcanol. Geotherm. Res. 320:12–18. http://dx.doi.org/10.1016/j.jvolgeores.2016.04.019.

Herczeg, A.L., Torgersen, T., Chivas, A.R., Habermehl, M.A., 1991. Geochemistry of ground waters from the Great Artesian Basin, Australia. J. Hydrol. 126:225–245. http://dx.doi.org/10.1016/0022-1694(91)90158-E.

Hilton, D.R., 1996. The helium and carbon isotope systematics of a continental geothermal system: results from monitoring studies at Long Valley caldera (California, U.S.A.). Chem. Geol. 127:269–295. http://dx.doi.org/10.1016/0009-2541(95)00134-4.

Idroser, 1977. Progetto di piano per la salvaguardia e l'utilizzo ottimale delle risorse idriche in Emilia Romagna. Relazione generale. Poligrafici Luigi Parma, Bologna (360 pp.).

Italiano, F., Liotta, M., Martelli, M., Martinelli, G., Petrini, R., Riggio, A., Rizzo, A.L., Slejko, F., Stenni, B., 2012a. Geochemical features and effects on deep-seated fluids during the May–June 2012 southern Po Valley seismic sequence. Annals ofGeophysics 55 (4): 815–821. http://dx.doi.org/10.4401/ag-6151.

Italiano, F., Martinelli, G., Petrini, R., Slejko, F., Stenni, B., 2012b. Fluids geochemistry and faulting activity during the Emilia seismic sequence. Gruppo Nazionale Geofisica Terra Solida, pp. 99–103.

Italiano, F., Bonfanti, P., Ditta, M., Petrini, R., Slejko, F., 2009. Helium and carbon isotopes in the dissolved gases of Friuli region (NE Italy): geochemical evidence of CO_2 production and degassing over a seismically active area. Chem. Geol. 266:76–85. http://dx.doi.org/10.1016/j.chemgeo.2009.05.022.

Italiano, F., Yuce, G., Uysal, I.T., Gasparon, M., Morelli, G., 2014. Insights into mantle-type volatiles contribution from dissolved gases in artesian waters of the Great Artesian Basin, Australia. Chem. Geol. 378/379:75–88. http://dx.doi.org/10.1016/j.chemgeo.2014.04.013.

Lasagna, M., De Luca, D.A., Franchino, E., 2016. Nitrate contamination in the western Po Plain (Italy): the effects of groundwater and surface water interactions. Environ. Earth Sci. 75:1–16. http://dx.doi.org/10.1007/s12665-015-5039-6.

Ludwig, K.R., 1994. Analyst. A computer program for control of a thermal-ionization single-collector mass-spectrometer. U.S.G.S. Open-file report, 92-543. U.S.G.S, Denver CO (96 pp.).

Marcaccio, M., Martinelli, G., 2012. Effects on the groundwater levels of the May–June 2012 Emilia seismic sequence. Annals of Geophysics 55:811–814. http://dx.doi.org/10.4401/ag-6139.

Martinelli, G., 1979. Caratterizzazione geochimica di acque chimicamente e termicamente anomale della Pianura Padana. (M.Sc.Thesis). University of Modena (77 pp.).

Martinelli, G., Vaccari, S., 2007. Il radon nelle acque sotterranee della Regione Emilia-Romagna. In: Gaidolfi, L., Angelini, P., Mignani, R. (Eds.), "Il radon ambientale in Emilia-Romagna" 51. Regione Emilia-Romagna, Servizio Sanitario Regionale, Bologna, pp. 51–56.

Martinelli, G., Chahoud, A., Dadomo, A., Fava, A., 2014. Isotopic features of Emilia-Romagna region (North Italy) groundwaters: environmental and climatological implications. J. Hydrol. 519:1928–1938. http://dx.doi.org/10.1016/j.jhydrol.2014.09.077.

Martinelli, G., Cremonini, S., Samonati, E., 2012. Geological and geochemical setting of natural hydrocarbon emissions in Italy. In: Al-Megren, H. (Ed.), Advances in Natural Gas Technology. InTech:pp. 79–120 http://dx.doi.org/10.5772/37446.

Martinelli, G., Dadomo, A., Heinicke, J., Italiano, F., Petrini, R., Pierotti, L., Riggio, A., Santulin, M., Slejko, F.F., Tamaro, A., 2015. Recovery and processing of hydrological and hydrogeochemical parameters for researches on earthquake short-term precursors in Italy. Boll. Geofis. Teor. Appl. 56:115–128. http://dx.doi.org/10.4430/bgta0147.

Martinelli, G., Minissale, A., Verrucchi, C., 1998. Geochemistry of heavily exploited aquifers in the Emilia-Romagna region (Po Valley, Northern Italy). Environ. Geol. 36: 195–206. http://dx.doi.org/10.1007/s002540050335.

Mattavelli, L., Ricchiuto, T., Grignani, D., Schoell, M., 1983. Geochemistry and habitat of natural gases in Po Basin, Northern Italy. Am. Assoc. Pet. Geol. Bull. 67, 2239–2254.

Mayer, A., Sultenfus, J., Travi, Y., Rebeix, R., Purtschert, R., Claude, C., Le Gal La Salle, C., Miche, H., Conchetto, E., 2013. A multi-tracer study of groundwater origin and transit-time in the aquifers of the Venice region (Italy). Appl. Geochem. 50:177–198. http://dx.doi.org/10.1016/j.apgeochem.2013.10.009.

Mellors, R., Kilb, D., Aliyev, A., Gasanov, A., Yetirmishli, G., 2007. Correlations between earthquakes and large mud volcano eruptions. J. Geophys. Res. 112:1–11. http://dx.doi.org/10.1029/2006JB004489. doi:10.1029/2006JB004489.

Minissale, A., Magro, G., Martinelli, G., Vaselli, O., Tassi, G.F., 2000. Fluid geochemical transect in the Northern Apennines (central-northern Italy): fluid genesis and migration and tectonic implications. Tectonophysics 319 (3):199. http://dx.doi.org/10.1016/S0040-1951(00)00031-7.

Molinari, I., Argnani, A., Morelli, A., Basini, P., 2015. Development and testing of a 3D seismic velocity model of the Po Plain Sedimentary Basin, Italy. Bull. Seismol. Soc. Am. 105:753–764. http://dx.doi.org/10.1785/0120140204.

Montone, P., Mariucci, M.T., Pondrelli, S., Amato, A., 2004. An improved stress map for Italy and surrounding regions (central Mediterranean). J. Geophys. Res. 109, B10410. http://dx.doi.org/10.1029/2003JB002703.

Nespoli, M., Todesco, M., Serpelloni, E., Belardinelli, M.E., Bonafede, M., Marcaccio, M., Rinaldi, A.P., Anderlini, L., Gualandi, A., 2015. Modeling earthquake effects on groundwater levels: evidences from the 2012 Emilia earthquake (Italy). Geofluids:1–12 http://dx.doi.org/10.1111/gfl.12165.

Orange, D., Garcìa-Garcìa, A., Lorenson, T., Nittrouer, C., Milligan, T., Miseriocchi, S., Langone, L., Correggiari, A., Trincardi, F., 2005. Shallow gas and flood deposition on the Po Delta. Mar. Geol. 222:159–177. http://dx.doi.org/10.1016/j.margeo.2005.06.040.

Ori, G.G., 1993. Continental depositional systems of the Quaternary of the Po Plain (northern Italy). Sediment. Geol. 83:1–14. http://dx.doi.org/10.1016/S0037-0738(10)80001-6.

Peresan, A., Gorshkov, A., Soloviev, A., Panza, G.F., 2015. The contribution of pattern recognition of seismic and morphostructural data to seismic hazard assessment. Boll. Geofis. Teor. Appl. 56 (2):295–328. http://dx.doi.org/10.4430/bgta0141.

Petrini, R., Pennisi, M., Vittori Antisari, L., Cidu, R., Vianello, G., Aviani, U., 2014. Geochemistry and stable isotope composition of surface waters from the Ravenna plain (Italy): implications for water resources in agricultural lands. Environ. Earth Sci. 71: 5099–5111. http://dx.doi.org/10.1007/s12665-013-2913-y.

Pezzo, G., Merryman Boncori, J.P., Tolomei, C., Salvi, S., Atzori, S., Antonioli, A., Trasatti, E., Novali, F., Serpelloni, E., Candela, L., Giuliani, R., 2013. Coseismic deformation and source modeling of the May 2012 Emilia (Northern Italy) earthquakes. Seismological Research Letters 84:645–655. http://dx.doi.org/10.1785/0220120171.

Pilla, G., Sacchi, E., Zuppi, G.M., Braga, G., Ciancetti, G., 2006. Hydrochemistry and isotope geochemistry as tools for groundwater hydrodynamic investigation in multilayer aquifers: a case study from Lomellina, Po plain, South Western Lombardy, Italy. Hydrogeol. J. 14:795–808. http://dx.doi.org/10.1007/s10040-005-0465-2.

Rice, J.R., Cleary, M.P., 1976. Some basic stress diffusion solutions for fluid-saturated elastic porous media with compressible constituents. Rev. Geophys. Space Phys. 14 (2), 227–241.

Rovida, A., Camassi, R., Gasperini, P., Stucchi, M., 2011. CPTI11, la versione 2011 del Catalogo Parametrico dei Terremoti Italiani. Milano. http://emidius.mi.ingv.it/CPTI. http://dx.doi.org/10.6092/INGV.IT-CPTI11.

Sacchi, E., Acutis, M., Bartoli, M., Brenna, S., Delconte, C.A., Laini, A., Pennisi, M., 2013. Origin and fate of nitrates in groundwater from the central Po plain: insights from isotopic investigations. Appl. Geochem. 34:164–180. http://dx.doi.org/10.1016/j.apgeochem.2013.03.008.

Sacco, F., 1912. Geoidrologia dei pozzi profondi della Valle Padana. Annali della Regia Accademia d'Agricoltura di Torino Vol. 55. Tipografia Vincenzo Bona, Torino (387 pp.).

Sacco, F., 1924. Geoidrologia dei pozzi profondi della Valle Padana. Ministero dei Lavori Pubblici-Servizio Idrografico, Tipografia Luigi Checchini, Torino (180 pp.).

Sacco, F., 1933. Geoidrologia dei pozzi profondi della Valle Padana. Ministero dei Lavori Pubblici – Servizio Idrografico, Istituto Poligrafico dello Stato, Roma (532 pp.).

Saccon, P., Leis, A., Marca, A., Kaiser, J., Campisi, L., Bottcher, M.E., Savarino, J., Escher, P., Eisenhauer, A., Erbland, J., 2013. Multi-isotope approach for the identification and characterization of nitrate pollution sources in the Marano lagoon (Italy) and parts of its catchment area. Appl. Geochem. 34:75–89. http://dx.doi.org/10.1016/j.proeps.2013.03.019.

Sciarra, A., Cantucci, B., Buttinelli, M., Galli, G., Nazzari, M., Pizzino, L., Quattrocchi, F., 2012. Soil-gas survey of liquefaction and collapsed caves during the Emilia seismic sequence. Annals of Geophysics 55 (4):803–809. http://dx.doi.org/10.4401/ag-6122.

Sciarra, A., Cinti, D., Pizzino, L., Procesi, M., Voltattorni, N., Mecozzi, S., Quattrocchi, F., 2013. Geochemistry of shallow aquifers and soil gas surveys in a feasibility study at the Rivara natural gas storage site (Po Plain, Northern Italy). Appl. Geochem. 34: 3–22. http://dx.doi.org/10.1016/j.apgeochem.2012.11.008.

Tassi, F., Bonini, M., Montegrossi, G., Capecchiacci, F., Capaccioni, B., Vaselli, O., 2012. Origin of light hydrocarbons in gases from mud volcanoes and CH4-rich emissions. Chem. Geol. 294–295:113–126. http://dx.doi.org/10.1016/j.chemgeo.2011.12.004.

Toth, J., Almasi, I., 2001. Interpretation of observed fluid potential patterns in a deep sedimentary basin under tectonic compression: Hungarian Great Plain, Pannonian Basin. Geofluids 1:11–36. http://dx.doi.org/10.1046/j.1468-8123.2001.11004.x.

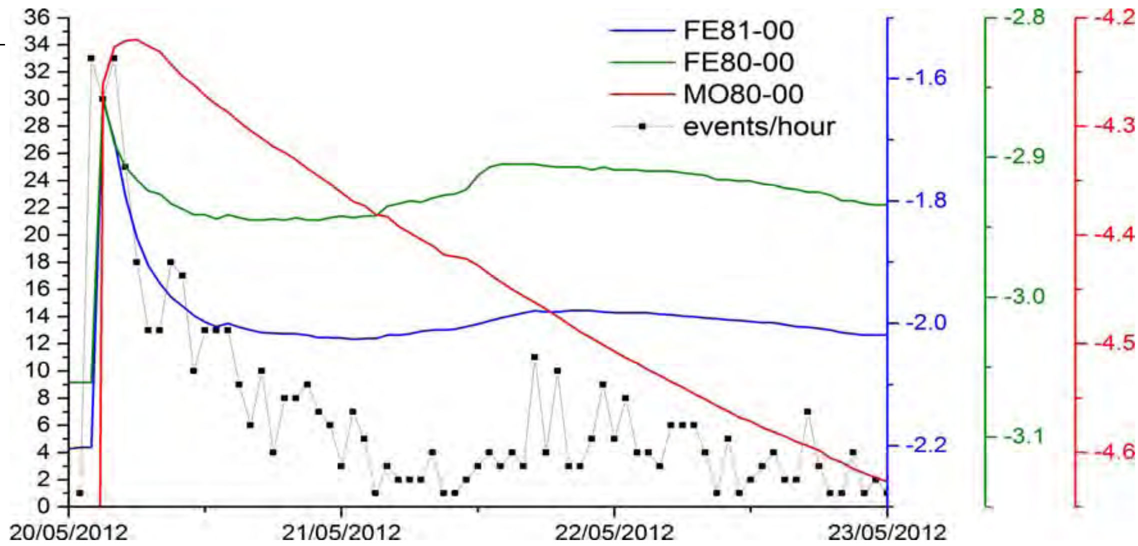
Vannoli, P., Burrato, P., Valensise, G., 2014. The seismotectonics of the Po Plain (Northern Italy): tectonic diversity in a blind faulting domain. Pure Appl. Geophys. 172 (5): 1105–1142. http://dx.doi.org/10.1007/s00024-014-0873-0.

Vartanyan, G., Stazhilo-Alekseev, S., Zaltsberg, E., 2014. Hydrogeodeformation monitoring: prospects of earthquake prediction. Environ. Earth Sci. 71:3039–3047. http://dx.doi.org/10.1007/s12665-013-2681-8.

Please cite this article as: Martinelli, G., et al., Geochemical monitoring of the 2012 Po Valley seismic sequence: A review and update, Chem. Geol. (2016), http://dx.doi.org/10.1016/j.chemgeo.2016.12.013

Figure S.1 Water level in FE-80-00, FE-81-00 and MO-80-00 wells. A) detail of the period May 20-May23, 2012. Seismic events are indicated as events/hour. b) events/hour in the period May 20-May 23, 2012. Classes of magnitude are indicated.

a)



b)

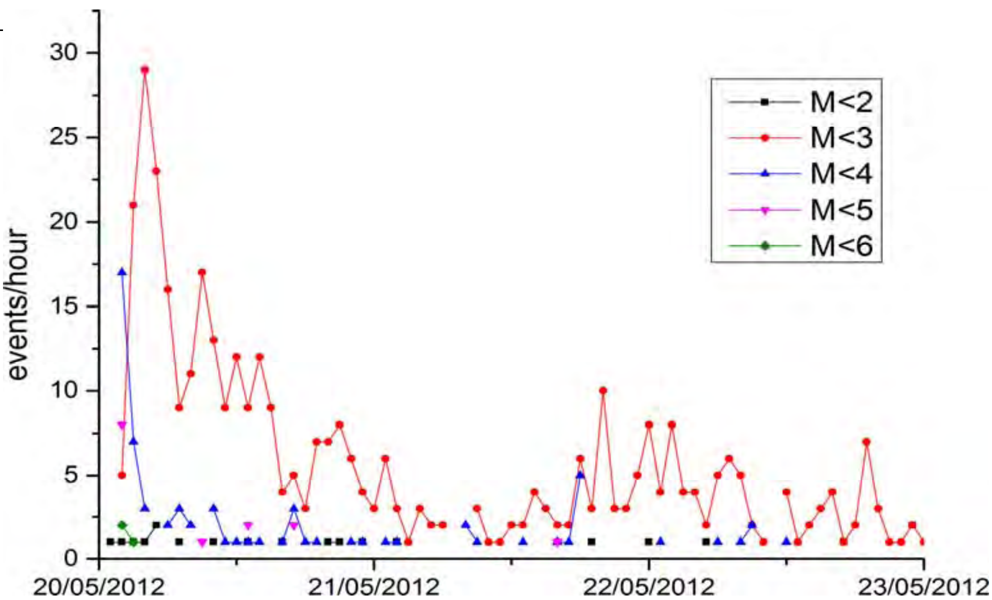


Figure S.2 Geographic distribution of geochemical families of groundwaters of the southern Po Valley (Martinelli et al., 2014). Top of salt waters is also indicated. Trace section refers to Fig. 4.b.

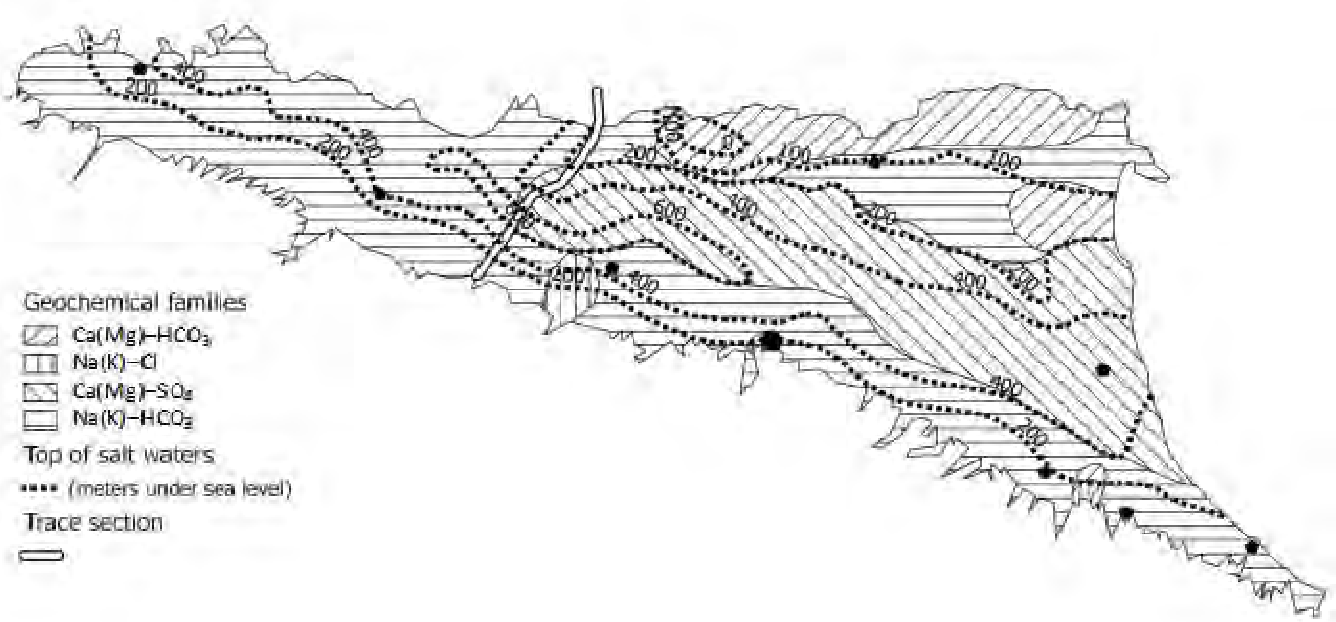
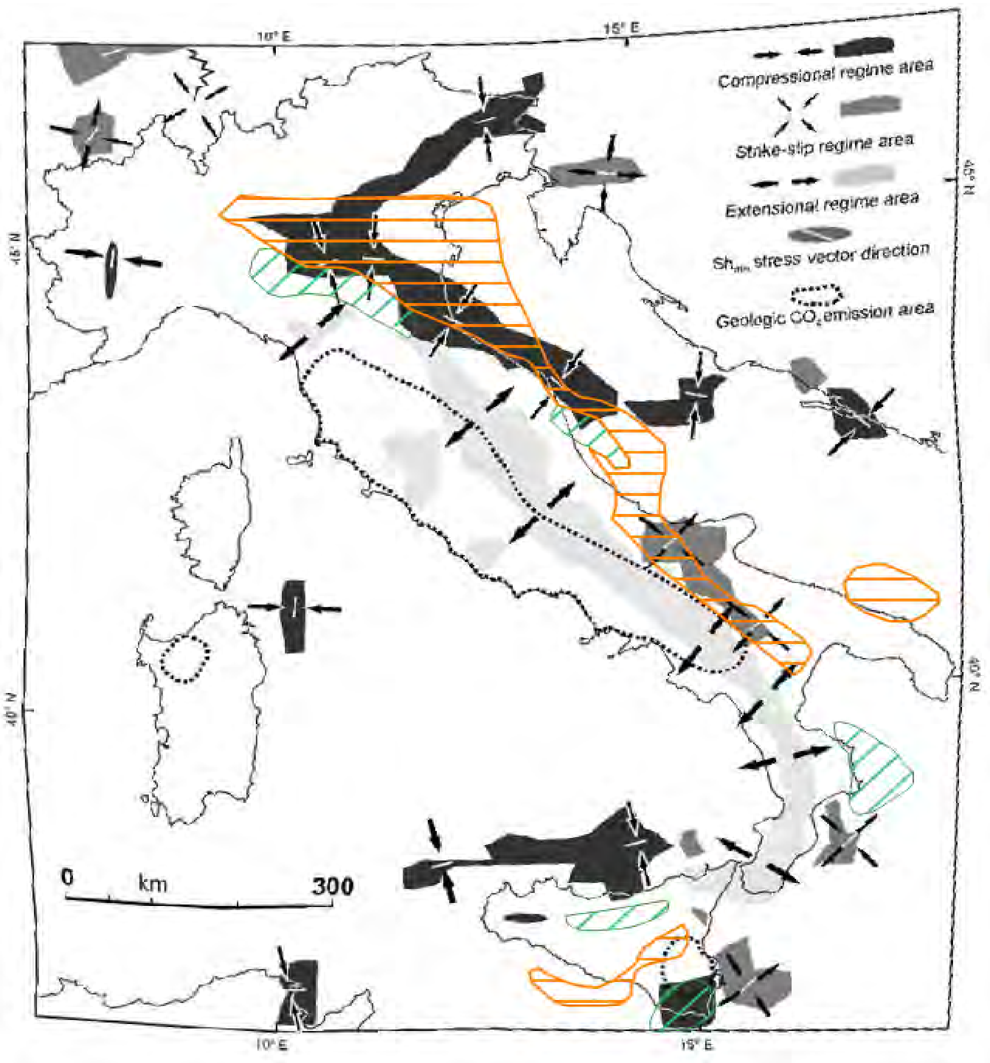


Figure S.3 Thermogenic and biogenic methane in natural gas seepages of Italy. Stress field of Italy and CO_2 gas emission area are also indicated. After Martinelli et al. (2012) and Etiope et al. (2007), modified.



Thermogenic and biogenic methane in natural gas seepages of Italy. Stress field of Italy and CO_2 gas emission area are also indicate. After Martinelli et al. (2012) and Etiope et al. (2007), modified.

Green areas: Thermogenic methane
Orange areas: Biogenic methane

Table S.1 Chemical and isotopic composition of sampled groundwaters

Site	data	T_w (°C)	T_{air} (°C)	EC (mS/cm)	pH	Eh (V)	$\delta^{18}O$	δD	87/86 Sr	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	F (mg/L)	Cl (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	NO_3 (mg/L)
V well	29/05/2012	18.1	26.0	7.79	7.77		-10.68	-73.81	0.70908	1502.8	9.5	106.1	68.7	nd	2428	0	567	nd
V well	01/06/2012	17.8	26.2	6.39	7.54		-10.70	-74.96		1490.6	8.1	105.1	65.7	nd	2265.1	0	561	nd
V well	07/06/2012	17.9	29.5	7.62	7.73		-10.69	-74.99		1487.5	8.6	105.5	67.0	nd	2232.4	0	561	nd
V well	13/06/2012				7.6	0.160	-10.68	-74.33		1499.0	9.0	107.0	66.8	nd	2189.1	0	580	nd
V well	20/06/2012				7.6	0.110	-10.70	-73.99		1524.8	10.6	108.2	68.5	nd	2183.8	0	567	nd
V well	26/06/2012			6.26	7.68					1575.0	11.2	113.5	68.2	nd	2372.2	0	567	nd
V well	03/07/2012			6.25	7.7					1614.6	10.8	117.0	70.3	nd	2195	0	579	nd
V well	13/07/2012			6.25	7.69					1586.1	10.1	114.7	68.5	nd	2333.6	0	567	nd
V well	18/07/2012			6.31	7.55	0.158	-10.67	-74.08		1555.9	10.5	112.2	66.3	nd	2318.7	0	561	nd
V well	25/07/2012			6.42	7.66	0.155	-10.69	-73.57		1572.8	12.4	112.9	66.8	nd	2312.5	0	567	nd
V well	01/08/2012						-10.58	-74.12		1547.5	14.0	110.0	64.2	nd	2304.5	0	537	nd
V well	09/08/2012						-10.74	-74.41		1548.9	9.4	110.3	64.3	nd	2326.9	0	543	nd
V well	16/08/2012						-10.70	-74.00		1548.1	8.4	110.0	63.4	nd	2256.4	0	543	nd
V well	30/08/2012						-10.89	-75.00		1510.9	8.2	106.2	60.5	nd	2295	0	543	nd
V well	06/09/2012						-10.68	-73.91		1524.6	8.2	106.8	60.7	nd	2300.1	0	494	nd
V well	13/09/2012						-10.67	-74.09		1544.1	6.9	107.7	60.4	nd	2231.5	0	488	nd
V well	20/09/2012						-10.52	-74.85		1517.1	6.8	105.4	59.1	nd	2310	0	476	nd
V well	27/09/2012						-10.67	-74.33		1485.7	5.9	102.5	56.8	nd	2281.5	0	500	nd
V well	04/10/2012						-10.52	-74.62		1529.0	5.9	105.8	58.6	nd	2281.1	0	500	nd
V well	11/10/2012						-10.59	-74.59		1514.0	6.2	104.3	12.6	nd	2286.5	0	500	nd
V well	20/10/2012						-10.57	-75.43		1523.1	5.6	104.7	63.7	nd	2288.7	0	494	nd
V well	24/10/2012						-10.61	-66.86		1452.8	8.1	106.1	61.5	nd	2188.9	22.12	366	nd
V well	05/11/2012						-10.55	-74.12		1461.6	8.7	108.1	68.9	nd	2229.3	0	360	nd
V well	14/11/2012						-10.57	-73.19		1461.6	8.9	107.7	70.7	nd	2266.8	14.96	360	nd
V well	24/11/2012						-10.59	-73.31		1506.5	9.9	111.7	74.8	0.41	2212.1	0	354	nd
V well	19/12/2012						-10.56	-74.58		1465.9	8.6	109.6	73.6	0.36	2275.9	0	360	nd
V well	24/01/2013						-10.56	-74.46		1473.5	8.7	116.7	85.9	nd	2242.5	0	354	nd
V well	23/02/2013						-10.51	-73.40		1469.9	8.0	115.1	81.1	nd	2280.2	0	354	nd
V well	23/03/2013									1484.6	9.0	116.7	80.0	nd	2224.1	0	445	nd
V well	27/04/2013									1463.0	13.8	115.4	83.5	3.91	2229.2	0	458	nd
V well	21/05/2013									1487.8	8.7	116.8	81.3	nd	2186	0	451	nd
V well	06/08/2014									1477.2	9.0	116.2	82.0	nd	2226.5	0	447	nd
M well	29/05/2012	15.5	25.0	31.3	7.6		-7.71	-52.99	0.70882	6480.5	27.0	507.3	283.6	nd	11163.8	0	439	nd
M well	01/06/2012	15.8	28.2	28.5	7.48		-8.12	-55.73	0.70879	5812.7	26.6	444.8	259.4	nd	9735.9	0	458	nd
M well	07/06/2012	16.0		23.3	7.55		-8.68	-60.29	0.70885	4860.8	23.3	354.2	202.8	nd	7988.5	0	488	nd
M well	13/06/2012				7.4	0.100	-8.63	-59.99		4769.6	24.5	346.3	200.6	nd	7856.2	0	494	nd
M well	20/06/2012				7.5	0.055	-8.71	-60.41		4688.2	23.2	339.9	198.5	nd	7729.3	0	500	nd
M well	26/06/2012			16.85	7.5					4719.2	23.5	343.1	183.4	nd	7880.8	0	494	nd
M well	03/07/2012			16.67	7.55					4564.2	22.9	329.8	175.9	nd	7759.8	0	488	nd
M well	13/07/2012			16.4	7.52					4448.0	20.3	320.6	169.9	nd	7808.5	0	488	nd
M well	18/07/2012			16.82	7.5	0.132	-8.74	-60.46		4579.2	22.1	331.0	176.2	nd	7780.4	0	488	nd
M well	25/07/2012			16.93	7.52	0.107	-8.78	-60.82		4622.6	21.4	334.4	177.8	nd	7671.2	0	488	nd
M well	01/08/2012						-9.02	-61.45		4529.5	23.5	326.7	176.3	nd	7591	0	445	nd
M well	09/08/2012						-8.72	-60.98		4583.0	21.0	331.0	176.9	nd	7569	0	470	nd
M well	16/08/2012						-8.98	-61.83		4543.3	21.8	327.9	175.7	nd	7460.7	0	464	nd
M well	30/08/2012						-8.83	-60.98		4466.1	21.7	322.2	172.9	nd	7470.6	0	464	nd
M well	06/09/2012						-8.63	-61.90		4360.0	21.0	314.1	168.1	nd	7218.7	0	451	nd
M well	13/09/2012						-8.83	-61.15		4462.3	20.3	323.0	172.5	nd	7490.7	0	451	nd
M well	20/09/2012						-8.59	-61.67		4508.5	24.1	327.2	176.9	nd	7481	0	451	nd
M well	27/09/2012						-8.87	-61.60		4500.7	21.4	317.6	174.2	nd	7163.6	0	458	nd
M well	04/10/2012						-8.65	-61.73		4419.9	20.5	321.3	172.7	nd	7415.9	0	439	nd

M well	11/10/2012						-8.66	-61.98		4480.9	21.2	322.8	173.2	nd	7183.3	0	439	nd
M well	20/10/2012						-8.77	-60.99		4470.5	21.9	324.0	174.3	nd	7291.4	0	439	nd
M well	24/10/2012						-8.83	-61.09		4424.2	19.1	307.8	161.5	nd	7117.7	0	390	nd
M well	05/11/2012						-8.70	-59.70		4488.3	20.1	316.5	165.1	nd	7379.7	0	384	nd
M well	14/11/2012						-8.85	-62.26		4314.8	18.2	303.1	157.9	nd	7051.9	0	390	nd
M well	24/11/2012						-8.81	-59.89		4313.3	18.4	305.4	160.7	nd	7216.1	0	390	nd
M well	19/12/2012						-8.91	-58.62		4311.6	19.8	304.8	161.4	nd	7217.4	0	390	nd
M well	25/01/2013						-8.71	-61.23		4295.7	18.6	321.6	199.8	nd	7227.1	0	317	nd
M well	23/02/2013						-8.68	-60.27		4227.7	17.6	317.7	196.1	nd	7481.5	0	317	nd
M well	23/03/2013									4316.6	22.3	337.7	223.1	nd	7339.8	0	384	nd
M well	27/04/2013									4405.7	37.9	341.4	222.5	8.96	7526.2	0	384	nd
M well	21/05/2013									4508.6	26.4	352.7	217.5	nd	7670.2	0	390	nd
M well	06/08/2014									4321.6	29.1	344.3	220.5	nd	7548.2	0	401	nd
B well	29/05/2012	16.9		1.385	7.66		-10.81	-74.09	0.70876	209.3	7.8	45.3	102.3	nd	314	0	415	nd
B well	01/06/2012	16.5	27.1	1.42	7.36		-10.81	-74.63		207.7	8.0	44.9	102.7	nd	319.5	0	421	nd
B well	07/06/2012	16.6	28.0	1.31	7.35		-10.79	-74.93		195.4	6.3	41.0	89.6	nd	309.1	0	421	nd
B well	13/06/2012				7.5	-0.080	-10.77	-73.94		186.7	7.0	40.9	89.2	nd	307	0	415	nd
B well	20/06/2012				7.5	0.002	-10.76	-73.96		203.9	7.3	45.2	101.2	nd	306.9	0	427	nd
B well	26/06/2012			1.428	7.5					204.9	9.0	44.5	93.7	nd	318.7	0	415	nd
B well	03/07/2012			1.41	7.55					194.2	7.6	44.1	93.7	nd	311.4	0	421	nd
B well	13/07/2012			1.425	7.55					193.7	9.3	45.0	93.3	nd	308.4	0	427	nd
B well	18/07/2012			1.447	7.55	0.165	-10.74	-74.97		192.7	10.4	44.9	92.7	nd	309.2	0	421	nd
B well	25/07/2012			1.433	7.55	0.158	-10.76	-74.69		193.2	10.4	44.6	92.1	nd	306.4	0	421	nd
B well	01/08/2012						-10.93	-74.61		191.7	7.5	44.1	91.5	nd	302.7	0	390	nd
B well	09/08/2012						-10.76	-74.88		189.6	7.8	42.9	90.5	nd	310.7	0	403	nd
B well	16/08/2012						-10.94	-74.54		194.2	8.1	42.9	89.8	nd	307.6	0	390	nd
B well	30/08/2012						-10.78	-75.69		187.7	7.3	44.9	90.9	nd	303.1	0	390	nd
B well	06/09/2012						-10.86	-73.40		183.7	7.1	41.9	87.6	nd	297.8	0	384	nd
B well	13/09/2012						-10.73	-75.88		183.4	6.9	41.6	86.9	nd	295.8	0	378	nd
B well	20/09/2012						-10.57	-75.60		183.4	6.8	41.6	87.4	nd	291.9	0	378	nd
B well	27/09/2012						-10.65	-75.27		183.0	6.9	41.5	86.8	nd	293.6	0	396	nd
B well	11/10/2012						-10.77	-74.55		182.0	7.3	41.2	86.4	nd	293	0	378	nd
B well	20/10/2012						-10.64	-74.94		182.2	7.5	40.9	85.8	nd	292.1	0	378	nd
B well	24/10/2012						-10.68	-73.68		181.7	6.2	40.7	85.4	0.85	286.6	0	336	nd
B well	05/11/2012						-10.68	-74.97		180.7	6.2	40.6	85.3	nd	298.2	0	329	nd
B well	14/11/2012						-10.56	-74.27		175.0	6.1	39.3	82.4	nd	295.7	0	329	nd
B well	24/11/2012						-10.70	-74.97		182.3	6.5	40.9	85.9	nd	297.3	0	323	nd
B well	19/12/2012						-10.72	-72.94		181.3	6.7	39.8	84.7	nd	298.1	0	336	nd
B well	25/01/2013						-10.68	-74.79		175.6	6.2	42.2	97.6	nd	300.7	0	262	nd
B well	23/02/2013						-10.65	-74.15		167.5	7.2	40.3	92.8	nd	308	0	262	nd
B well	23/03/2013									179.7	5.9	42.9	98.0	0.99	286.9	0	336	nd
B well	27/04/2013									173.7	6.0	42.5	98.6	nd	285.2	0	336	nd
B well	21/05/2013									181.8	6.1	43.2	99.4	nd	284.4	0	336	nd
B well	06/08/2014									177.6	6.0	42.2	97.5	nd	279.1	0	331	nd

Table S.2 Water level depth to groundwater according to Sacco (1912), Sacco (1924) and Sacco (1933) in the Po Valley.

ID	ID_well	Reference	Pag.	Year	Well depth	Depth to ground water (*)	East (UTM32-WGS84)	Nord (UTM32-WGS84)	UTM Zone	Municipality	Other geographic information
333	201	Sacco (1924)	67		117	15	420857	4960828		Canale	Fornace Ferrero
574	367	Sacco (1933)	443		71	10.25	685639	5032356		Almisano	
445	272	Sacco (1933)	99	1933	85	10	423848	4973762		Villafranca d'asti	C.a Bonoma
331	199	Sacco (1924)	65			10	425704	4963958		Val Blesio	nord S. Damiano
338	203	Sacco (1924)	74	1922		9.5	425906	4959422		Priocca	
180	155	Sacco (1912)	174	1912	112	9	628276	4952177		Reggio Emilia	Villa Cella
344	208	Sacco (1924)	80	1910	120	9	435721	4965473		Isola d'Asti	
307	182	Sacco (1924)	44	1923	143	9	437256	5028637		Carisio	Cascina Masino
204	163	Sacco (1924)	17		102	8.5	381036	4971731		Scalenghe	C. Prese
337	202	Sacco (1924)	70	1913	178	8.2	420857	4960828		Canale	Piazza Torino
129	116	Sacco (1912)	108		76	8	308663	5076937	33T	Mansué	
511	314	Sacco (1933)	244		76	8	583113	4966329		Fidenza	Lodesana
335	202	Sacco (1924)	70	1913	178	8	420857	4960828		Canale	Piazza Torino
336	202	Sacco (1924)	70	1913	178	8	420857	4960828		Canale	Piazza Torino
322	191	Sacco (1924)	57			7.5	423321	4972433		Cantarana	
381	239	Sacco (1924)	139	1917	113	7	322573	5046343	33T	Grisolera	Revedoli-Foce Piave
374	233	Sacco (1924)	112		74.4	7	503667	5076569		Maslianico comense	Cartiera Maraino
372	231	Sacco (1924)	111			7	507207	5071750		Como	
479	286	Sacco (1933)	157		130	6.9	457705	5038108		Mondello Vitta	
323	192	Sacco (1924)	57			6.7	423321	4972433		Cantarana	
55	48	Sacco (1912)	28-29		81	6.55	512512	5003065		Pavia	Porta Nuova
412	253	Sacco (1924)	154	1913	151	6.5	270633	5034024	33T	Dolo	Ospedale Civile
146	127	Sacco (1912)	139		216	6.5	289876	5034463	33T	Venezia	Santa Marta
464	282	Sacco (1933)	141	1929	57	6.5	444415	5031009		Formigliana	Tenuta Bussonengo
202	162	Sacco (1924)	13		160	6.5	381036	4971731		Scalenghe	
203	162	Sacco (1924)	14		160	6.5	381036	4971731		Scalenghe	
201	162	Sacco (1924)	13		160	6.3	381036	4971731		Scalenghe	
405	248	Sacco (1924)	150		182	6	281646	5040229	33T	Mestre	Stazione ferroviaria

(*) Positive values are related to levels above topographic surface. Negative values are related to levels below topographic surface.

145	127	Sacco (1912)	139		216	6	289876	5034463	33T	Venezia	Santa Marta
385	241	Sacco (1924)	140	1916	222	6	291060	5028838	33T	Venezia	Isola di Poveglia
325	193	Sacco (1924)	58		51	6	425879	4964821		Molino S. Damiano	S. Pietro dei Cavoli
475	285	Sacco (1933)	151		162.25	6	457741	5036118		Vicolungo	Cascinone
449	276	Sacco (1933)	105			6	425866	4964990		San Damiano d'asti	
540	339	Sacco (1933)	332		78.8	5.5	723798	4919600		Mordano	BO
328	196	Sacco (1924)	61			5.5	423813	4973652		Villafranca	
398	247	Sacco (1924)	147		181	5.4	293236	5032849	33T	Venezia	Isola San Servolo
152	131	Sacco (1912)	147	1911	197.8	5.3	292668	5029215	33T	Venezia	Lido
144	127	Sacco (1912)	138		216	5	289876	5034463	33T	Venezia	Santa Marta
583	375	Sacco (1933)	456		238	5	290398	5025324	33T	Alberoni	Venezia
128	115	Sacco (1912)	107			5	305362	5072388	33T	Oderzo	
410	251	Sacco (1924)	153			5	268923	5030029	33T	Fossò	Loc. Chiesa
411	252	Sacco (1924)	153			5	270841	5029728	33T	Camponogara	
373	232	Sacco (1924)	111	1923	66	5	503667	5076569		Maslianico comense	
51	47	Sacco (1912)	27-28	1901	80	5	511993	5002914		Pavia	Borgo Ticino
329	197	Sacco (1924)	64	1923	174	5	430882	4967594		Celle Enemondo	
563	358	Sacco (1933)	370		259.7	5	517002	5034640		Milano	Viale Piceno
564	358	Sacco (1933)	371		259.7	5	517002	5034640		Milano	Viale Piceno
579	371	Sacco (1933)	449		264	5	723279	5031820		Padova	deposito locomotive
276	177	Sacco (1924)	34	1922	114	4.85	404004	5005949		Volpiano	
277	177	Sacco (1924)	34	1922	114	4.8	404004	5005949		Volpiano	
384	240	Sacco (1924)	140	1915	204.5	4.5	292267	5035336	33T	Venezia	Ospedale Civile
143	127	Sacco (1912)	138		216	4.5	289876	5034463	33T	Venezia	Santa Marta
268	176	Sacco (1924)	32	1922	115	4.5	404004	5005949		Volpiano	
474	285	Sacco (1933)	150		162.25	4.5	457741	5036118		Vicolungo	Cascinone
482	288	Sacco (1933)	160		250	4.4	467976	5040617		Caltignaga	
407	249	Sacco (1924)	151		168.5	4.24	265612	5032879	33T	Stra	Villa Nazionale
395	247	Sacco (1924)	146		181	4.2	293236	5032849	33T	Venezia	Isola San Servolo
403	248	Sacco (1924)	149		182	4	281646	5040229	33T	Mestre	Stazione ferroviaria
428	264	Sacco (1933)	50	1926	75	4	400613	4975059		Villastellone	C.a Vernetta
57	49	Sacco (1912)	29	1902	91.54	4	511867	5003206		Pavia	Porta Pertusio
444	271	Sacco (1933)	95	1929	94	4	422115	4956825		Castagnito	Riazzolo
486	290	Sacco (1933)	162		100	4	459295	5043161		Briona	
294	179	Sacco (1924)	37	1904	105	4	404471	5008477		S. Benigno Canavese	Morizzo
184	156	Sacco (1924)	2	1913	135	4	409284	4949411		Brà	
473	285	Sacco (1933)	150		162.25	4	457741	5036118		Vicolungo	Cascinone
525	324	Sacco (1933)	293		1193	4	621038	4949751		Cavriago	Borgata Cella
447	274	Sacco (1933)	101			4	418479	4972696		Valfenera	
451	278	Sacco (1933)	120			4	435664	5046249		Cossato	
596	380	Sacco (1933)	476		152.35	3.8	310429	5055861	33T	San Donà di Piave	caserma pontieri

393	246	Sacco (1924)	145		180.2	3.8	293513	5034582	33T	Venezia	San Pietro di Castello
189	158	Sacco (1924)	5	1910	79	3.8	398690	4966457		Carmagnola	Ospedale di S. Lorenzo
590	378	Sacco (1933)	466		199.7	3.5	288313	5016941	33T	Pellestrina	ve
142	127	Sacco (1912)	138		216	3.5	289876	5034463	33T	Venezia	Santa Marta
585	377	Sacco (1933)	460		230	3.5	298129	5040060	33T	Burano	ve
465	283	Sacco (1933)	141	1915	74	3.5	458214	5022835		Borgo Vercelli	Asilo
111	98	Sacco (1912)	65	1891	109	3.5	640713	5000893		Mantova	
110	97	Sacco (1912)	62		123	3.5	641147	5002207		Mantova	Piazza Dante (Broletto)
298	180	Sacco (1924)	39	1915	164	3.5	422737	5009652		Saluggia	C.na Giarrea
200	162	Sacco (1924)	12		160	3.42	381036	4971731		Scalenghe	
593	379	Sacco (1933)	469		188.7	3.3	274245	5041807	33T	Mirano	ve
392	245	Sacco (1924)	144		183	3.2	291528	5032022	33T	Venezia	Isola San Clemente
130	117	Sacco (1912)	108		64	3	308770	5080983	33T	Portobuffole	Villa Frova
416	257	Sacco (1924)	162		136.5	3	266106	4956938	33T	Ostellato	San Giovanni
170	147	Sacco (1912)	163		140	3	263704	4966217	33T	Massafiscaglia	
592	379	Sacco (1933)	469		188.7	3	274245	5041807	33T	Mirano	ve
383	240	Sacco (1924)	140	1915	204.5	3	292267	5035336	33T	Venezia	Ospedale Civile
387	243	Sacco (1924)	142			3	289867	5035258	33T	Venezia	Gazometro
463	282	Sacco (1933)	141	1929	57	3	444415	5031009		Formigliana	Tenuta Bussonengo
356	217	Sacco (1924)	94	1923	66.5	3	583101	4966382		Borgo S. Donnino	Lodesana
365	225	Sacco (1924)	105	1920	106.4	3	724673	4925469		Massa Lombarda	Fabbrica Esperia di pomodoro
183	156	Sacco (1924)	2	1913	135	3	409284	4949411		Brà	
484	289	Sacco (1933)	161		135	3	465350	5046788		Momo	
485	289	Sacco (1933)	161		135	3	465350	5046788		Momo	
432	265	Sacco (1933)	52	1925	156	3	391302	4963625		Casalgrasso	
526	325	Sacco (1933)	295		195	3	621791	4966637		Poviglio	piazza comunale
562	358	Sacco (1933)	370		259.7	3	517002	5034640		Milano	Viale Piceno
330	198	Sacco (1924)	64	1910		3	425879	4964821		S. Damiano	
468	284	Sacco (1933)	149			3	464119	5046089		Agnellengo	Momo
409	250	Sacco (1924)	153		180	2.85	290351	5034016	33T	Venezia	Molino Stuky
293	179	Sacco (1924)	37	1904	105	2.85	404471	5008477		S. Benigno Canavese	Morizzo
553	352	Sacco (1933)	345		125	2.7	262523	4942442	33T	Longastrino	
437	267	Sacco (1933)	77	1928		2.7	404137	5006058		Volpiano	
151	131	Sacco (1912)	147	1911	197.8	2.67	292668	5029215	33T	Venezia	Lido
267	176	Sacco (1924)	32	1922	115	2.6	404004	5005949		Volpiano	
316	186	Sacco (1924)	48	1912	131.9	2.6	454133	5018373		Vercelli	Ospedale
458	281	Sacco (1933)	137	1928	170	2.6	437094	5036233		Villanova biellese	C.a Grangia
138	125	Sacco (1912)	131		60	2.5	335092	5052011	33T	Caorle	
547	346	Sacco (1933)	340		126	2.5	270423	4918451	33T	Ravenna	Villanova
141	127	Sacco (1912)	137		216	2.5	289876	5034463	33T	Venezia	Santa Marta
70	59	Sacco (1912)	36	1896	150	2.5	539384	5017959		Lodi	spalto com. la Siberia

472	285	Sacco (1933)	150		162.25	2.5	457741	5036118		Vicolungo	Cascinone
459	281	Sacco (1933)	138	1928	170	2.5	437094	5036233		Villanova biellese	C.a Grangia
460	281	Sacco (1933)	138	1928	170	2.5	437094	5036233		Villanova biellese	C.a Grangia
461	281	Sacco (1933)	138	1928	170	2.5	437094	5036233		Villanova biellese	C.a Grangia
462	281	Sacco (1933)	138	1928	170	2.5	437094	5036233		Villanova biellese	C.a Grangia
436	267	Sacco (1933)	77	1928		2.5	404137	5006058		Volpiano	
286	178	Sacco (1924)	35	1923	112.5	2.15	404004	5005949		Volpiano	
546	345	Sacco (1933)	339		160	2.1	277011	4922203	33T	Ravenna	Mercato coperto
443	270	Sacco (1933)	94	1929	178	2.1	420712	4956795		Vezza d'alba	
125	112	Sacco (1912)	106		60	2	314245	5071797	33T	Motta di Livenza	
153	132	Sacco (1912)	148		60	2	282664	5038038	33T	Venezia	Bottenigo
134	121	Sacco (1912)	128		80	2	343889	5071125	33T	Latisana	
155	134	Sacco (1912)	149	1910	140	2	289620	5021556	33T	S. Pietro in Volta	Forte
551	350	Sacco (1933)	343		146	2	276832	4926760	33T	Ravenna	Stabbiale
382	240	Sacco (1924)	140	1915	204.5	2	292267	5035336	33T	Venezia	Ospedale Civile
366	226	Sacco (1924)	105			2	288457	4904264	33T	Cervia	Piazza Garibaldi
388	244	Sacco (1924)	143			2	292718	5034675	33T	Venezia	Arsenale
346	210	Sacco (1924)	83	1912	65	2	444114	4963511		Mombercelli	
571	364	Sacco (1933)	427		123	2	594312	5042537		Brescia	
483	289	Sacco (1933)	161		135	2	465350	5046788		Momo	
448	275	Sacco (1933)	102		140	2	428217	4972846		Baldichieri	Caserma Carabinieri
300	181	Sacco (1924)	42	1923	212	2	431070	5017506		Bianzè	
327	195	Sacco (1924)	60			2	423279	4977919		Val Triversa	Roatto
339	204	Sacco (1924)	74	1921		2	423338	4958103		Castellinaldo	
342	207	Sacco (1924)	79			2	436226	4979392		Callianetto	
414	255	Sacco (1924)	158			2	722291	4953189		Portomaggiore	
446	273	Sacco (1933)	101			2	419270	4977463		Solbrito	
466	284	Sacco (1933)	149			2	464119	5046089		Agnellengo	Momo
467	284	Sacco (1933)	149			2	464119	5046089		Agnellengo	Momo
174	151	Sacco (1912)	169		155.75	1.9	275670	4953841	33T	Valle di Comacchio	S. Carlo
595	380	Sacco (1933)	475		152.35	1.85	310429	5055861	33T	San Donà di Piave	caserma pontieri
224	167	Sacco (1924)	21	1913	98	1.8	394270	5000763		Borgaro	
92	79	Sacco (1912)	51		100	1.8	601370	5011864		Gambara	Borgata Corvione
102	89	Sacco (1912)	51	1909	136	1.8	594032	5014010		Milzano	
573	366	Sacco (1933)	440		150.8	1.8	698305	5047111		Vicenza	
199	162	Sacco (1924)	12		160	1.8	381036	4971731		Scalenghe	
404	248	Sacco (1924)	150		182	1.775	281646	5040229	33T	Mestre	Stazione ferroviaria
285	178	Sacco (1924)	35	1923	112.5	1.75	404004	5005949		Volpiano	
161	140	Sacco (1912)	151	1903	100	1.7	271196	5034233	33T	Dolo	Stabilim. Marinoni concimi
188	157	Sacco (1924)	4	1924	90.3	1.7	403628	4958119		Sommariva Bosco	
453	280	Sacco (1933)	132		91.25	1.7	450994	5051346		Gattinara	

113	100	Sacco (1912)	70	1909	140.5	1.7	662235	5004648		Nogara	piazza
211	165	Sacco (1924)	19	1912	82.7	1.65	392464	4998322		Venaria Reale	
157	136	Sacco (1912)	150		70	1.5	284318	5043409	33T	Mestre	
159	138	Sacco (1912)	150		80	1.5	277575	5041408	33T	Spinea	
160	139	Sacco (1912)	151		90	1.5	280309	5040674	33T	Chirignago	
149	130	Sacco (1912)	144	1909	95	1.5	293017	5037301	33T	Venezia	Murano
121	108	Sacco (1912)	92		108	1.5	267787	5037943	33T	Pianiga	
140	127	Sacco (1912)	137		216	1.5	289876	5034463	33T	Venezia	Santa Marta
576	369	Sacco (1933)	446		317	1.5	288411	4977385	33T	Ariano Polesine	Po di Gnocca
433	266	Sacco (1933)	57	1929	55	1.5	389438	4979339		Candiolo	C.a Ceppea
275	177	Sacco (1924)	34	1922	114	1.5	404004	5005949		Volpiano	
308	183	Sacco (1924)	46		118.57	1.5	454883	5038184		Landiona	fuori Albano
423	262	Sacco (1933)	22		122	1.5	400129	4959290		Caramagna	
478	286	Sacco (1933)	156		130	1.5	457705	5038108		Mondello Vitta	
558	356	Sacco (1933)	362		209	1.5	555090	5001080		Codogno	Filandone
320	189	Sacco (1924)	55			1.5	419063	4977532		S. Paolo	val Traversola
150	131	Sacco (1912)	146	1911	197.8	1.47	292668	5029215	33T	Venezia	Lido
397	247	Sacco (1924)	147		181	1.45	293236	5032849	33T	Venezia	Isola San Servolo
396	247	Sacco (1924)	147		181	1.4	293236	5032849	33T	Venezia	Isola San Servolo
380	238	Sacco (1924)	128		54	1.4	554191	5023916		Crema	Stazione ferroviaria
422	261	Sacco (1933)	22		90	1.4	404027	4957832		Sommariva Bosco	Ponte due acque
230	168	Sacco (1924)	23	1914	99.5	1.3	394270	5000763		Borgaro	
557	356	Sacco (1933)	362		209	1.25	555090	5001080		Codogno	Filandone
173	150	Sacco (1912)	166		156.5	1.2	276366	4949175	33T	Valle di Comacchio	
76	64	Sacco (1912)	41	1898	60	1.2	551052	5003208		Casalpusterlengo	Piazza Maggiore
541	340	Sacco (1933)	332		86.4	1.2	721495	4921274		Mordano	Loc. Bubano
179	154	Sacco (1912)	172		104	1.2	724805	4932979		Conselice	Lavezzola
292	179	Sacco (1924)	36	1904	105	1.2	404471	5008477		S. Benigno Canavese	Morizzo
406	249	Sacco (1924)	151		168.5	1.195	265612	5032879	33T	Stra	Villa Nazionale
274	177	Sacco (1924)	34	1922	114	1.15	404004	5005949		Volpiano	
136	123	Sacco (1912)	130		122	1.13	344187	5069543	33T	S. Michele al Tagliamento	
594	380	Sacco (1933)	475		152.35	1.125	310429	5055861	33T	San Donà di Piave	caserma pontieri
471	285	Sacco (1933)	150		162.25	1.1	457741	5036118		Vicolungo	Cascinone
177	152	Sacco (1912)	171		170	1.1	732889	4958857		Ostellato	
122	109	Sacco (1912)	99		80	1	273796	5044844	33T	Salzano	
413	254	Sacco (1924)	156		94	1	278487	4993744	33T	Loreo	
552	351	Sacco (1933)	344		152	1	272816	4922253	33T	Ravenna	Fornace Zarattini
171	148	Sacco (1912)	164	1887	177	1	273749	4960884	33T	Lago Santo	
591	379	Sacco (1933)	468		188.7	1	274245	5041807	33T	Mirano	ve
575	368	Sacco (1933)	445		250	1	273177	4981115	33T	Ariano Polesine	
598	382	Sacco (1912)	162		52	1	732439	4954718		Bonifiche ferraresi	

609	393	Sacco (1933)	332		77	1	723352	4919408		Mordano	
97	84	Sacco (1912)	51		81	1	594748	5017092		Pavone Mella	
91	78	Sacco (1912)	50		83	1	603106	5003336		Isola Dovarese	
421	261	Sacco (1933)	22		90	1	404027	4957832		Sommariva Bosco	Ponte due acque
187	157	Sacco (1924)	3	1924	90.3	1	403628	4958119		Sommariva Bosco	
309	184	Sacco (1924)	46		92	1	454883	5038184		Landiona	piazzetta Chiesa
539	338	Sacco (1933)	331		118	1	701476	4934853		Budrio	BO
420	260	Sacco (1933)	21		144	1	403242	4958221		Sommariva Bosco	Stazione ferroviaria
326	194	Sacco (1924)	59		180	1	423321	4972433		Borgata Scaglia	Cantarana
314	185	Sacco (1924)	47		230	1	431143	5039328		Verrone biellese	piazza comunale
345	209	Sacco (1924)	80	1916		1	435322	4959404		Costigliole d'Asti	
348	212	Sacco (1924)	86			1	469378	4979806		Valmadonna	
172	149	Sacco (1912)	164		63.72	0.9	271458	4962637	33T	Valle Gallare	
158	137	Sacco (1912)	150		74	0.9	281822	5044046	33T	Zelarino	
163	142	Sacco (1912)	154		100	0.9	274323	5016220	33T	Codevigo	Laguna di Chioggia
135	122	Sacco (1912)	129		103	0.9	343889	5071125	33T	Latisanotta	
233	169	Sacco (1924)	23	1914	99.2	0.9	394270	5000763		Borgaro	
301	181	Sacco (1924)	43	1923	212	0.9	431070	5017506		Bianzè	
408	250	Sacco (1924)	152		180	0.8	290351	5034016	33T	Venezia	Molino Stuky
147	128	Sacco (1912)	141	1896		0.8	291839	5032963	33T	Venezia	Isola delle Grazie
93	80	Sacco (1912)	51		89	0.8	601370	5011864		Gambara	Borgata Corvione
297	180	Sacco (1924)	39	1915	164	0.8	422737	5009652		Saluggia	C.na Giarrea
560	357	Sacco (1933)	369		302	0.8	513747	5035812		Milano	Viale Byron
127	114	Sacco (1912)	107		95	0.7	305362	5072388	33T	Oderzo	
450	277	Sacco (1933)	112		110	0.7	449245	4958010		Nizza Monferrato	
515	316	Sacco (1933)	261		131	0.7	605037	4962656		Parma	Stazione
516	316	Sacco (1933)	261		131	0.7	605037	4962656		Parma	Stazione
582	374	Sacco (1933)	453		160	0.7	719342	5008578		Pozzonovo	pd
132	119	Sacco (1912)	108	1893	70	0.6	306062	5091648	33T	Sacile	
175	152	Sacco (1912)	171		170	0.6	732889	4958857		Ostellato	
299	181	Sacco (1924)	42	1923	212	0.6	431070	5017506		Bianzè	
131	118	Sacco (1912)	108		50	0.5	304598	5083593	33T	Gajarine	
154	133	Sacco (1912)	148	1909	60	0.5	293629	5037323	33T	Burano	
139	126	Sacco (1912)	131	1890	67	0.5	336502	5054158	33T	Valnuova Vaina	Valli di Caorle
137	124	Sacco (1912)	130		75	0.5	344246	5074562	33T	Ronchis	
124	111	Sacco (1912)	102		84	0.5	287309	5065519	33T	Lancienigo	
162	141	Sacco (1912)	152		91	0.5	275685	5034996	33T	Mira	Oriago
156	135	Sacco (1912)	149	1902	104.5	0.5	270821	5029636	33T	Camponogara	
167	144	Sacco (1912)	158	1888	124	0.5	278477	4993744	33T	Lorèo	
549	348	Sacco (1933)	342		129	0.5	270055	4920925	33T	Ravenna	San Michele
599	383	Sacco (1912)	170		132	0.5	266084	4956991	33T	San Giovanni Ostellato	

548	347	Sacco (1933)	342		143	0.5	273948	4936139	33T	Ravenna	San Alberto
584	376	Sacco (1933)	459		154	0.5	298081	5041372	33T	Burano	Torcello
386	242	Sacco (1924)	140	1915	190	0.5	291509	5027702	33T	Malamocco	Forte degli Alberoni
123	110	Sacco (1912)	100			0.5	284407	5053602	33T	Preganziol	
126	113	Sacco (1912)	106			0.5	320817	5076385	33T	Pravisdomini	
148	129	Sacco (1912)	141			0.5	292573	5034500	33T	Venezia	Cà di Dio
572	365	Sacco (1933)	435		74	0.5	640834	5001660		Mantova	
195	160	Sacco (1924)	9	1915	82	0.5	400904	4974952		Villastellone	incrocio C. Verna
108	95	Sacco (1912)	58		91	0.5	675696	5031568		Soave	Ospitale
555	354	Sacco (1933)	346		110	0.5	724836	4925456		Massa Lombarda	
597	381	Sacco (1933)	479		113	0.5	285280	5060785		Treviso	
358	219	Sacco (1924)	98	1914	114.5	0.5	614851	4957391		S. Ilario d'Enza	
417	258	Sacco (1924)	163	1913	122	0.5	724997	4929891		Conselice	fraz. San Patrizio
107	94	Sacco (1912)	57		126.25	0.5	670807	5030718		Caldiero	Terme romane
72	60	Sacco (1912)	38	1905	126.5	0.5	539075	5017622		Lodi	tra Porta Stazione e Porta Milano
513	316	Sacco (1933)	260		131	0.5	605037	4962656		Parma	Stazione
514	316	Sacco (1933)	260		131	0.5	605037	4962656		Parma	Stazione
317	186	Sacco (1924)	48	1912	131.9	0.5	454133	5018373		Vercelli	Ospedale
605	389	Sacco (1933)	307		140	0.5	651988	4938913		San Martino di Mugnano	MO
306	182	Sacco (1924)	44	1923	143	0.5	437256	5028637		Carisio	Cascina Masino
544	343	Sacco (1933)	336		146	0.5	720114	4948411		Consaldolo	
69	59	Sacco (1912)	36	1896	150	0.5	539384	5017959		Lodi	spalto com. la Siberia
71	59	Sacco (1912)	37	1896	150	0.5	539075	5017622		Lodi	tra Porta Stazione e Porta Milano
431	265	Sacco (1933)	52	1925	156	0.5	391302	4963625		Casalgrasso	
415	256	Sacco (1924)	159	1921	157	0.5	723515	4974999		Copparo	
530	329	Sacco (1933)	311		166	0.5	674753	4968809		Massa Finalese	
506	308	Sacco (1933)	241		167	0.5	582500	4969678		Fidenza	S. Faustino
378	236	Sacco (1924)	125		176	0.5	539479	5017469		Lodi	
543	342	Sacco (1933)	336		193.5	0.5	731783	4922850		Lugo	Podere Passetto
527	326	Sacco (1933)	295		200	0.5	622752	4969298		Poviglio	verso Po
581	373	Sacco (1933)	453		200.4	0.5	730577	5017683		Bovolenta	pd
561	358	Sacco (1933)	370		259.7	0.5	517002	5034640		Milano	Viale Piceno
578	371	Sacco (1933)	449		264	0.5	723279	5031820		Padova	deposito locomotive
608	392	Sacco (1933)	311		283	0.5	661721	4949277		Nonantola	
559	357	Sacco (1933)	369		302	0.5	513747	5035812		Milano	Viale Byron
402	248	Sacco (1924)	149		182	0.4	281646	5040229	33T	Mestre	Stazione ferroviaria
505	307	Sacco (1933)	240		165	0.4	584294	4968413		Fidenza	Ospedale
509	311	Sacco (1933)	244			0.4	591864	4972312		Fontanellato	Paroletta
176	152	Sacco (1912)	171		170	0.35	732889	4958857		Ostellato	
364	224	Sacco (1924)	103		151	0.3	292665	4897455	33T	Cesenatico	piazza municipio
243	171	Sacco (1924)	26	1915	99.3	0.3	394270	5000763		Borgaro	

178	153	Sacco (1912)	171	1877	101.35	0.3	724927	4943944		Argenta	
489	291	Sacco (1933)	163		153.35	0.3	461846	5046905		Barengo	
389	245	Sacco (1924)	144		183	0.2	291528	5032022	33T	Venezia	Isola San Clemente
168	145	Sacco (1912)	159		50	0.2	732743	4996338		Cà Tron	Cà Emo
507	309	Sacco (1933)	242		63.5	0.2	589849	4977629		Soragna	Ardenga
244	171	Sacco (1924)	26	1915	99.3	0.2	394270	5000763		Borgaro	
520	320	Sacco (1933)	272		150	0.2	609981	4964848		San Lazzaro Parm.se	Chiozzola
554	353	Sacco (1933)	345		256	0.2	728158	4938522		Lavezzola	Alfonsine
401	248	Sacco (1924)	149		182	0.17	281646	5040229	33T	Mestre	Stazione ferroviaria
457	281	Sacco (1933)	137	1928	170	0.1	437094	5036233		Villanova biellese	C.a Grangia
341	206	Sacco (1924)	77	1923		0.1	441471	4978458		Portacomaro	Stazione ferroviaria
504	306	Sacco (1933)	239		68.5	0	559735	4974370		Carpaneto	Case Nuove
223	167	Sacco (1924)	21	1913	98	0	394270	5000763		Borgaro	
182	156	Sacco (1924)	2	1913	135	0	409284	4949411		Brà	
362	223	Sacco (1924)	103		140	0	709621	4928288		Medicina	loc. Forni
430	265	Sacco (1933)	52	1925	156	0	391302	4963625		Casalgrasso	
377	236	Sacco (1924)	125		176	0	539479	5017469		Lodi	
524	324	Sacco (1933)	293		1193	0	621038	4949751		Cavriago	Borgata Cella
266	176	Sacco (1924)	32	1922	115	-0.15	404004	5005949		Volpiano	
273	177	Sacco (1924)	33	1922	114	-0.3	404004	5005949		Volpiano	
265	176	Sacco (1924)	32	1922	115	-0.3	404004	5005949		Volpiano	
194	160	Sacco (1924)	8	1915	82	-0.4	400904	4974952		Villastellone	incrocio C. Verna
186	157	Sacco (1924)	3	1924	90.3	-0.4	403628	4958119		Sommariva Bosco	
272	177	Sacco (1924)	33	1922	114	-0.45	404004	5005949		Volpiano	
418	259	Sacco (1933)	20	1932	102	-0.5	402151	4946407		Marene	verso Bra
419	259	Sacco (1933)	20	1932	102	-0.5	402151	4946407		Marene	verso Bra
441	269	Sacco (1933)	87	1932		-0.5	429523	5004661		Crescentino	C.a Favorita
512	315	Sacco (1933)	255			-0.5	592932	4967558		Fontevivo	
234	169	Sacco (1924)	24	1914	99.2	-0.65	394270	5000763		Borgaro	
209	165	Sacco (1924)	19	1912	82.7	-0.75	392464	4998322		Venaria Reale	
210	165	Sacco (1924)	19	1912	82.7	-0.75	392464	4998322		Venaria Reale	
88	75	Sacco (1912)	49			-0.8	593255	5005217		Pescarolo ed Uniti	
235	169	Sacco (1924)	24	1914	99.2	-0.85	394270	5000763		Borgaro	
470	285	Sacco (1933)	150		162.25	-0.9	457741	5036118		Vicolungo	Cascinone
369	228	Sacco (1924)	106	1923	40	-1	332634	4864263	33T	Pesaro	
550	349	Sacco (1933)	343		208	-1	283653	4930349	33T	Ravenna	Porto Corsini
510	312	Sacco (1933)	244		76	-1	583113	4966329		Fidenza	Lodesana
54	48	Sacco (1912)	28-29		81	-1	512512	5003065		Pavia	Porta Nuova
545	344	Sacco (1933)	337		120	-1	737139	4958574		Migliarino	
166	143	Sacco (1912)	156	1908	140	-1	719954	4994240		Rovigo	Manicomio prov.
586	378	Sacco (1933)	466		199.7	-1.1	288313	5016941	33T	Pellestrina	ve

271	177	Sacco (1924)	33	1922	114	-1.1	404004	5005949		Volpiano	
517	317	Sacco (1933)	265		119.8	-1.2	608711	4976305		Colorno	
85	72	Sacco (1912)	49		40	-1.25	609242	4997871		Vho	Cascina Caselle
570	363	Sacco (1933)	403		137	-1.3	471724	5064191		Sesto Calende	
400	248	Sacco (1924)	149		182	-1.35	281646	5040229	33T	Mestre	Stazione ferroviaria
588	378	Sacco (1933)	466		199.7	-1.4	288313	5016941	33T	Pellestrina	ve
291	179	Sacco (1924)	36	1904	105	-1.4	404471	5008477		S. Benigno Canavese	Morizzo
587	378	Sacco (1933)	466		199.7	-1.45	288313	5016941	33T	Pellestrina	ve
394	246	Sacco (1924)	145		180.2	-1.5	293513	5034582	33T	Venezia	San Pietro di Castello
589	378	Sacco (1933)	466		199.7	-1.5	288313	5016941	33T	Pellestrina	ve
493	295	Sacco (1933)	222		72	-1.5	570999	4980882		Cortemaggiore	Paullo
245	171	Sacco (1924)	26	1915	99.3	-1.5	394270	5000763		Borgaro	
379	237	Sacco (1924)	127		139	-1.5	553326	5023553		Crema	Linificio e Capanificio Nazionale
192	159	Sacco (1924)	7	1912	220	-1.5	398690	4966457		Carmagnola	Tenuta Casanova
399	248	Sacco (1924)	149		182	-1.52	281646	5040229	33T	Mestre	Stazione ferroviaria
193	160	Sacco (1924)	8	1915	82	-1.6	400904	4974952		Villastellone	incrocio C. Verna
488	291	Sacco (1933)	163		153.35	-1.6	461846	5046905		Barengo	
236	169	Sacco (1924)	24	1914	99.2	-1.7	394270	5000763		Borgaro	
318	187	Sacco (1924)	51	1922	36.65	-1.8	479444	5030980		Trecate	
242	171	Sacco (1924)	26	1915	99.3	-1.8	394270	5000763		Borgaro	
476	286	Sacco (1933)	156		130	-1.8	457705	5038108		Mondello Vitta	
315	186	Sacco (1924)	48	1912	131.9	-1.8	454133	5018373		Vercelli	Ospedale
39	38	Sacco (1912)	18	1888	146	-1.8	513935	5035777		Milano	Arena
284	178	Sacco (1924)	35	1923	112.5	-1.85	404004	5005949		Volpiano	
264	176	Sacco (1924)	32	1922	115	-1.9	404004	5005949		Volpiano	
357	218	Sacco (1924)	97	1917	57	-2	604128	4956015		Vigatto	Fontanini
50	47	Sacco (1912)	27-28	1901	80	-2	511993	5002914		Pavia	Borgo Ticino
196	161	Sacco (1924)	10	1915	81	-2	404011	4978465		Sansalvà	Castello del Conte di Sambuy
222	167	Sacco (1924)	21	1913	98	-2	394270	5000763		Borgaro	
114	101	Sacco (1912)	74	1889	111	-2	681307	5007101		Legnago	contrada Mura
283	178	Sacco (1924)	35	1923	112.5	-2	404004	5005949		Volpiano	
508	310	Sacco (1933)	243		126	-2	590566	4979344		Soragna	Diolo
164	143	Sacco (1912)	156	1908	140	-2	719954	4994240		Rovigo	Manicomio prov.
30	30	Sacco (1912)	9-13	1907	206	-2	520141	5049255		Monza	vicino Macello
311	185	Sacco (1924)	47		230	-2	431143	5039328		Verrone biellese	piazza comunale
481	288	Sacco (1933)	159		250	-2	467976	5040617		Caltignaga	
577	370	Sacco (1933)	447		250	-2.15	705649	4982000		Fiesso Umbertiano	
263	176	Sacco (1924)	32	1922	115	-2.18	404004	5005949		Volpiano	
305	182	Sacco (1924)	44	1923	143	-2.4	437256	5028637		Carisio	Cascina Masino
469	285	Sacco (1933)	150		162.25	-2.4	457741	5036118		Vicolungo	Cascinone
117	104	Sacco (1912)	80			-2.43	705052	5011011		Ospedaletto Euganeo	

262	176	Sacco (1924)	32	1922	115	-2.5	404004	5005949		Volpiano	
304	182	Sacco (1924)	44	1923	143	-2.5	437256	5028637		Carisio	Cascina Masino
435	267	Sacco (1933)	77	1928		-2.5	404137	5006058		Volpiano	
56	49	Sacco (1912)	29	1902	91.54	-2.6	511867	5003206		Pavia	Porta Pertusio
440	268	Sacco (1933)	81	1916		-2.6	394261	5000690		Borgaro	
116	103	Sacco (1912)	80			-2.7	705052	5011011		Ospedaletto Euganeo	
238	170	Sacco (1924)	25	1915	94	-2.8	394270	5000763		Borgaro	
240	170	Sacco (1924)	25	1915	94	-2.8	394270	5000763		Borgaro	
220	167	Sacco (1924)	21	1913	98	-2.8	394270	5000763		Borgaro	
251	173	Sacco (1924)	28	1915	80	-2.85	394270	5000763		Borgaro	
439	268	Sacco (1933)	81	1916		-2.85	394261	5000690		Borgaro	
556	355	Sacco (1933)	348		100	-3	263629	4900871	33T	Forlì	
532	331	Sacco (1933)	315		100	-3	653841	4934442		Castelnuovo Rangone	
289	179	Sacco (1924)	36	1904	105	-3	404471	5008477		S. Benigno Canavese	Morizzo
290	179	Sacco (1924)	36	1904	105	-3	404471	5008477		S. Benigno Canavese	Morizzo
538	337	Sacco (1933)	330		122	-3	686263	4930684		Bologna	Stazione Ferroviaria
477	286	Sacco (1933)	156		130	-3	457705	5038108		Mondello Vitta	
165	143	Sacco (1912)	156	1908	140	-3	719954	4994240		Rovigo	Manicomio prov.
490	292	Sacco (1933)	209			-3	510029	4984717		Casteggio	
391	245	Sacco (1924)	144		183	-3.1	291528	5032022	33T	Venezia	Isola San Clemente
565	359	Sacco (1933)	376		120	-3.1	518530	5036861		Milano	Lambrate
221	167	Sacco (1924)	21	1913	98	-3.15	394270	5000763		Borgaro	
239	170	Sacco (1924)	25	1915	94	-3.2	394270	5000763		Borgaro	
219	167	Sacco (1924)	21	1913	98	-3.35	394270	5000763		Borgaro	
218	167	Sacco (1924)	21	1913	98	-3.5	394270	5000763		Borgaro	
604	388	Sacco (1933)	305		105	-3.5	638863	4942951		Rubiera	San Donnino
227	168	Sacco (1924)	22	1914	99.5	-3.55	394270	5000763		Borgaro	
228	168	Sacco (1924)	23	1914	99.5	-3.65	394270	5000763		Borgaro	
229	168	Sacco (1924)	23	1914	99.5	-3.65	394270	5000763		Borgaro	
568	362	Sacco (1933)	391		300	-3.7	521506	5046971		Monza	Via Ghilini
115	102	Sacco (1912)	79		147.34	-3.71	705052	5011011		Ospedaletto Euganeo	
118	105	Sacco (1912)	81			-3.74	705052	5011011		Ospedaletto Euganeo	
368	227	Sacco (1924)	106	1923	41	-3.8	332634	4864263	33T	Pesaro	Manicomio
112	99	Sacco (1912)	68	1912	87.23	-3.9	631040	4975725		Guastalla	Piazza G. Bruno
498	300	Sacco (1933)	225		53	-4	559496	4991908		Mortizza	
376	235	Sacco (1924)	124		66	-4	528988	5000451		Corteolona	piazza comunale
109	96	Sacco (1912)	59	1903	71	-4	678731	5032140		Monteforte d'Alpone	
351	215	Sacco (1924)	93	1914	79	-4	553733	4978373		Podenzano	
500	302	Sacco (1933)	226		150.5	-4	561755	4968923		S. Giorgio P.	Rezzano
429	265	Sacco (1933)	52	1925	156	-4	391302	4963625		Casalgrasso	
313	185	Sacco (1924)	47		230	-4	431143	5039328		Verrone biellese	piazza comunale

80	67	Sacco (1912)	44		237	-4	580393	4998438		Cremona	Via Gonzaga
566	360	Sacco (1933)	382		94	-4.2	514550	5039632		Milano	Niguarda
226	168	Sacco (1924)	22	1914	99.5	-4.35	394270	5000763		Borgaro	
303	182	Sacco (1924)	43	1923	143	-4.5	437256	5028637		Carisio	Cascina Masino
521	321	Sacco (1933)	272		80	-5	608581	4952920		San Lazzaro Parm.se	Marano
533	332	Sacco (1933)	317		111	-5	646494	4937385		Formigine	
38	38	Sacco (1912)	18	1888	146	-5	513935	5035777		Milano	Arena
40	38	Sacco (1912)	18	1888	146	-5	513935	5035777		Milano	Arena
602	386	Sacco (1933)	298	1925	147	-5	625233	4952891		Villa Pieve di Modolena	RE
452	279	Sacco (1933)	128			-5	437094	5036233		Villanova biellese	
250	173	Sacco (1924)	28	1915	80	-5.2	394270	5000763		Borgaro	
569	362	Sacco (1933)	391		300	-5.4	521506	5046971		Monza	Via Ghilini
438	268	Sacco (1933)	80	1916		-5.45	394261	5000690		Borgaro	
603	387	Sacco (1933)	298		110.3	-6	629919	4950803		Setificio	RE
529	328	Sacco (1933)	310		131.5	-6	657229	4975278		Concordia	
82	69	Sacco (1912)	47			-6	580393	4998438		Cremona	
347	211	Sacco (1924)	86			-6	469015	4972846		Alessandria	Stazione Ferr.
442	269	Sacco (1933)	87	1932		-6	429523	5004661		Crescentino	C.a Favorita
491	293	Sacco (1933)	217			-6	550025	4980820		Piacenza	Ciavernasco
497	299	Sacco (1933)	225		64	-6.5	574721	4985767		San Pietro in Cerro	
496	298	Sacco (1933)	224		79	-6.6	548571	4979221		Gossolengo	Palazzina Caratta
601	385	Sacco (1933)	291		94	-6.7	620713	4950163		Cavriago	Cà Monte di Pietà
455	281	Sacco (1933)	137	1928	170	-6.75	437094	5036233		Villanova biellese	C.a Grangia
518	318	Sacco (1933)	267		75	-6.85	598995	4956064		San Martino Sinzano	
355	216	Sacco (1924)	93	1923	100	-7	562204	4973668		Carpaneto	
487	291	Sacco (1933)	162		153.35	-7	461846	5046905		Barengo	
580	372	Sacco (1933)	452		169	-7	708130	5000468		Sant'Urbano	pd
390	245	Sacco (1924)	144		183	-7.4	291528	5032022	33T	Venezia	Isola San Clemente
531	330	Sacco (1933)	315		69	-7.5	642213	4934950		Sassuolo	
536	335	Sacco (1933)	326		110	-7.5	664414	4934797		Piumazzo	
456	281	Sacco (1933)	137	1928	170	-7.5	437094	5036233		Villanova biellese	C.a Grangia
360	221	Sacco (1924)	101		60	-7.6	680965	4932067		Borgo Panigale	
607	391	Sacco (1933)	308		82.7	-7.75	647818	4941081		Baggiovara	
119	106	Sacco (1912)	81			-7.8	705052	5011011		Ospedaletto Euganeo	
502	304	Sacco (1933)	234		142	-8	558347	4980735		Podenzano	San Polo
567	361	Sacco (1933)	383		170	-8	517779	5042203		Sesto San Giovanni	
537	336	Sacco (1933)	328		195.5	-8	681776	4931468		Borgo Panigale	
312	185	Sacco (1924)	47		230	-8	431143	5039328		Verrone biellese	piazza comunale
503	305	Sacco (1933)	236		73	-8.4	552694	4973507		Vigolzone	Villò
495	297	Sacco (1933)	224		104.5	-8.5	547766	4981533		Gossolengo	Rossia
454	281	Sacco (1933)	137	1928	170	-8.7	437094	5036233		Villanova biellese	C.a Grangia

600	384	Sacco (1933)	290		74	-8.8	621379	4950360	Cavriago	Case Nuove
534	333	Sacco (1933)	319		100	-9	642461	4939889	Formigine	Magreta
480	287	Sacco (1933)	158		87.5	-9.5	472084	5046184	Bellinzago	
523	323	Sacco (1933)	284		96	-9.5	614162	4955784	S. Ilario d'enza	Loc. Gazzaro
519	319	Sacco (1933)	269		101	-9.5	602272	4957003	Gaione	Vigatto
535	334	Sacco (1933)	325		128	-9.8	661591	4936321	San Cesario sul P.	
255	174	Sacco (1924)	29	1921	70	-10	393524	5003008	Caselle Torinese	Lanificio Basilio Bona
81	68	Sacco (1912)	47	1907	100	-10	580393	4998438	Cremona	
499	301	Sacco (1933)	226		102	-10	559496	4991908	Mortizza	Torre della Razza
191	159	Sacco (1924)	7	1912	220	-10	398690	4966457	Carmagnola	Tenuta Casanova
256	174	Sacco (1924)	29	1921	70	-10.3	393524	5003008	Caselle Torinese	Lanificio Basilio Bona
606	390	Sacco (1933)	308		71	-10.6	642742	4945834	Marzaglia	
492	294	Sacco (1933)	222		89	-10.6	573324	4982672	Cortemaggiore	
494	296	Sacco (1933)	223		52.5	-11	545138	4982613	Gragnano	Casaliggio
216	166	Sacco (1924)	21	1913	106	-11.15	392464	4998322	Venaria Reale	
501	303	Sacco (1933)	233		110	-11.4	553149	4975874	Grazzano Visconti	
214	166	Sacco (1924)	20	1913	106	-11.95	392464	4998322	Venaria Reale	
359	220	Sacco (1924)	98		74.5	-12	612813	4942373	S. Polo d'Enza	
215	166	Sacco (1924)	20	1913	106	-12	392464	4998322	Venaria Reale	
528	327	Sacco (1933)	297		198	-12	635728	4949797	Villa Masone	RE
213	166	Sacco (1924)	20	1913	106	-12.5	392464	4998322	Venaria Reale	
610	394	Sacco (1933)	333		62	-12.8	715031	4916109	Imola	Ponte Santo
257	174	Sacco (1924)	29	1921	70	-13	393524	5003008	Caselle Torinese	Lanificio Basilio Bona
258	174	Sacco (1924)	29	1921	70	-13	393524	5003008	Caselle Torinese	Lanificio Basilio Bona
542	341	Sacco (1933)	334		119	-13	716139	4914853	Imola	
522	322	Sacco (1933)	273		70	-13.4	611112	4954898	Malandriano	Pecorile
206	164	Sacco (1924)	17	1913	92	-19	387025	4992640	Collegno	Ricovero provinciale c/o Manicomio
426	263	Sacco (1933)	42	1930	124	-22	406542	4961441	Ceresole d'alba	C.a Verona
425	263	Sacco (1933)	42	1930	124	-23.5	406542	4961441	Ceresole d'alba	C.a Verona
371	230	Sacco (1924)	110	1913	39	-24.8	483894	5076779	Velate	
424	263	Sacco (1933)	41	1930	124	-27	406542	4961441	Ceresole d'alba	C.a Verona
32	32	Sacco (1912)	16		61.2	-51.5	551286	5059391	Bergamo	Manicomio provinciale

Table S.3 Manual values of water level recorded in long time series utilized in Fig. 15.

Time	08/BO83-00	08/BO41-00	08/FE30-00	08/FE35-00	08/RE04-00	08/RE06-00	08/PR04-00
set-76		6.59	-4.07	-5.39	24.27	30.32	
mar-77		6.37	-2.98	-5.28	23.62	30.54	30.50
set-77		6.31	-3.17	-5.14	23.09	30.06	29.26
mar-78		6.00	-2.39	-3.62	22.26	30.23	30.17
set-78		5.94	-3.21	-4.16	21.50	29.49	29.62
mar-79		5.68	-2.57	-3.84	21.80	29.53	29.35
set-79		5.63	-3.46	-4.46	20.62	29.07	28.98
mar-80		5.24	-2.79	-4.61	21.25	29.62	29.68
set-80		5.23	-3.56	-5.35	21.46	28.83	28.98
mar-81		5.35	-3.27	-4.86	20.30	29.42	28.54
set-81		5.17	-4.03	-4.88	20.32	29.33	29.00
mar-82	1.95	4.87	-4.33	-4.54	20.66	29.40	28.40
set-82	2.28	4.70	-4.21	-4.78	20.01	28.37	28.20
mar-83	2.78	5.16	-3.35	-4.98	20.04	29.33	28.88
set-83	2.74	5.44	-4.35		18.90	28.37	28.59
mar-84	3.07	5.74	-2.99	-5.42	19.48	28.49	28.09
set-84	3.10	6.04	-3.53	-4.71	19.40	28.60	28.50
mar-85	3.41	6.06	-2.76	-4.80	19.79	29.18	29.04
set-85	3.31	6.03	-2.58	-4.76	18.90	28.25	28.40
mar-86	3.35	6.21	-2.16	-4.55	19.39	28.77	28.18
set-86	3.32	6.27	-2.56	-3.98	18.97	27.91	28.39
mar-87	3.76	6.17	-2.58	-4.28	19.17	28.23	27.76
set-87	3.76	6.25	-3.08	-3.96	18.89	27.94	27.86
mar-88	4.23	6.49	-2.71	-4.16	18.98		28.19
set-88	3.95	6.24	-3.41	-4.49	18.39	28.18	28.16
mar-89	4.37	6.32	-2.69	-4.24	18.61	28.27	27.47
set-89	4.04	6.42	-2.36	-3.96	18.92	27.88	26.43
mar-90	4.52	6.58	-1.76	-4.21	18.34	28.13	26.75
set-90	4.37	6.32	-4.20	-4.42	17.50	27.11	26.45
mar-91	5.26	6.88	-1.05	-2.57	18.15	28.02	26.80

set-91	5.17	6.83	-3.24	-3.28	17.59	27.53	26.83
mar-92	5.11	7.25	-1.03	-2.17	18.10	28.20	26.85
set-92	5.21	6.93	-2.11	-2.40	17.49	28.06	27.16
mar-93	6.04	6.48	-1.99	-1.78	17.66	28.12	27.67
set-93	5.21	6.27	-2.07	-2.34	17.60	27.86	27.58
mar-94	5.85	7.78	0.08	-1.38	17.59	28.37	27.82
set-94	5.18	7.15	-2.51	-2.08	16.90	28.12	
mar-95	4.83	8.11	0.74	-0.76	18.41	27.63	27.62
set-95	4.71	7.17	-0.23	-1.08	18.41	27.90	27.71
set-96	6.29	6.97	0.15	-0.83	17.32	28.24	28.31
mar-97		7.00	1.21	-0.43	18.91	27.82	27.39
set-97	6.47	6.74	0.21	-0.83	18.77	27.17	27.17
set-98	5.94		-0.83	-0.68	18.28	27.17	26.86
mar-02	6.67	8.39	1.26	-0.69	16.22	27.87	28.70
set-02	6.99		0.11	-0.34	18.57	27.67	28.40
mar-03		10.05	1.90	0.16	18.98	28.00	28.20
set-03	6.81	10.07	0.65	-0.34	18.21	25.39	27.44
mar-04	7.17	10.29	1.65	0.46	18.65	27.47	27.45
set-04	6.91	10.32	0.85	0.71	18.08	26.75	26.25
mar-05	7.12	10.41	1.95	1.11	18.51	27.78	28.40
set-05	7.18	10.65	0.95	0.51	19.89	26.32	27.07
mar-06	6.97	10.70	2.05	0.81	16.33	27.75	27.45
set-06	6.97	10.70	0.65	0.46	18.08	25.97	26.90
mar-07	7.22	10.90	1.85	0.01	18.20	27.49	
set-07	7.69	10.83	-0.05	0.41	18.01	26.33	
mar-08		10.63	1.75	0.41	18.84	27.04	27.33
set-08		10.81	0.05	0.21	18.29	26.22	27.35
mar-09	7.97	11.03	2.15	0.81	19.08	28.74	
set-09		11.53	1.35	0.71	18.19	27.52	
mar-10	7.93	11.60	2.55	1.01	19.17	28.54	
set-10	8.16	11.20	1.85	0.81	18.57	27.08	
mar-11	8.28	11.35	3.10	1.41	19.46	29.10	
set-11	8.11	11.60	0.75	0.96	17.95	26.53	

mar-12			2.28	0.69	19.37	28.11
set-12	8.43	11.60	0.85	0.41	21.65	26.87
mar-13	8.77		2.65	1.21	19.47	29.32
set-13	8.45		1.95	0.91	19.03	28.17
mar-14	8.82	11.75	3.05	1.41	16.16	29.02
set-14	8.72	11.80	2.45	1.21	19.46	28.29
mar-15	9.03	11.85	3.35	1.51		29.10
set-15		11.90	2.05	1.01	19.21	27.66

Vallalta well

-

Photographs during sampling activities

27/05/2012

P1040140.JPG

27/05/2012

P1040141.JPG

27/05/2012

P1040142.JPG

27/05/2012

P1040143.JPG

27/05/2012

P1040144.JPG

27/05/2012

P1040145.JPG

29/05/2012

P1040164.JPG

29/05/2012

P1040165.JPG

29/05/2012

P1040167.JPG

29/05/2012 – ≈9:00
Mw 5.66 - coseismic effects

P1040168.JPG

16/08/2012

P1040293.JPG

16/08/2012

P1040294.JPG

06/09/2012

P1040462.JPG

17/11/2012

17/11/2012

19/12/2012

P1040603.JPG

19/12/2012

P1040604.JPG

06/11/2013

P1000353.JPG

06/11/2013

P1000354.JPG