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Unusual geological phenomena in the Emilia-Romagna plain (Italy): gas emissions from wells and the ground, hot water wells, geomorphological variations. A review and an update of documented reports

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ABSTRACT Fifty-two unusual geological phenomena (up to November 2015) were reported during a three-year observation period after the seismic swarm that occurred in Emilia in May-June 2012. Here we show and discuss for the first time the data collected directly from wells with apparently abnormal temperatures. Most of the abnormal temperatures occurred in the areas struck by earthquakes, but others were located in the urban area of Bologna and in the eastern sector of the Ferrara province. No relationship between the temperature data and the earthquakes was observed. The Italian oil company AGIP (now ENI) has recorded a large number of hydrocarbon surface phenomena in Emilia-Romagna since the early decades of the 20th century. The phenomena were located both in the Po Plain and in the Apennines. This database was recently provided by ENI and, for the first time, utilized for research purposes following the 2012 Emilia seismic sequence. The emissions observed are due to the presence of methane gas mixed with groundwater, resulting from the decomposition of organic matter present in proximity to tapped aquifers, or gas rising from greater depths along tectonic discontinuities. Similar to the findings involving the well temperatures, no significant relationship was found between the geographic distribution of the hydrocarbon emissions and the earthquakes. Ground-shaking phenomena, however, have sometimes induced temporary increases in the gas flow rate.

Key words: earthquake, gas emission, groundwater abnormal temperature, ground settlements, sand, mud volcanoes.

1. Introduction

Since ancient times, unusual geological phenomena, observed both in concomitance with earthquakes and in periods of seismic quiescence, have been described in some areas of the Po Plain and the Emilia-Romagna Apennines (Italy).

The main bibliographical sources refer to the work of Boschi *et al*. (1995, 1997), Cordier (1996, 1999), and Centini (2003). In addition, recent investigations by Pancaldi and

Tampellini (2013) and Baldini (2014) have presented detailed descriptions of geological events.

Historical documentation has described luminous phenomena, changes in the characteristics of water from wells, and soil liquefaction following great seismic shocks (Boschi *et al.*, 1995).

In the recent past, springs characterised by significantly higher water temperatures than the local climatic average were reported in the towns of Bagno di Romagna, Bobbio, Ferriere, and Porretta (Fig. 1); in these locations, groundwater flows across well-known geothermal circuits (Martinelli *et al.*, 2014).

Albarello *et al.* (1991) and Ciancabilla *et al.* (2007) studied some changes of the characteristics of fluids at Porretta, in concomitance with seismic events.

Martinelli and Panahi (2005) and Mellors *et al.* (2007) described the presence of mud volcanoes due to the eruption of clay mixed with salty water and methane. In addition, Scicli (1972), Martinelli *et al.* (2012), and Sciarra *et al.* (2013) reported methane emissions of the dry type, small emissions of native oil, bubbling of methane gas in water from wells; Cremonini *et al.* (2008) described cases of *ignis fatuus* due to gas emissions. Furthermore, Spinelli (1893a; 1893b) wrote about areas where the ground was characterised by anomalous temperatures, and Scicli (1972) and Curzi (2012) reported sinkholes in the lowlands of the provinces of Bologna, Ferrara, Modena, and Parma, and degassing phenomena in a marine environment.

Many authors reported several co-seismic phenomena following the Emilia seismic swarm of May - June 2012, including changes in the chemical composition of groundwater and fluctuations

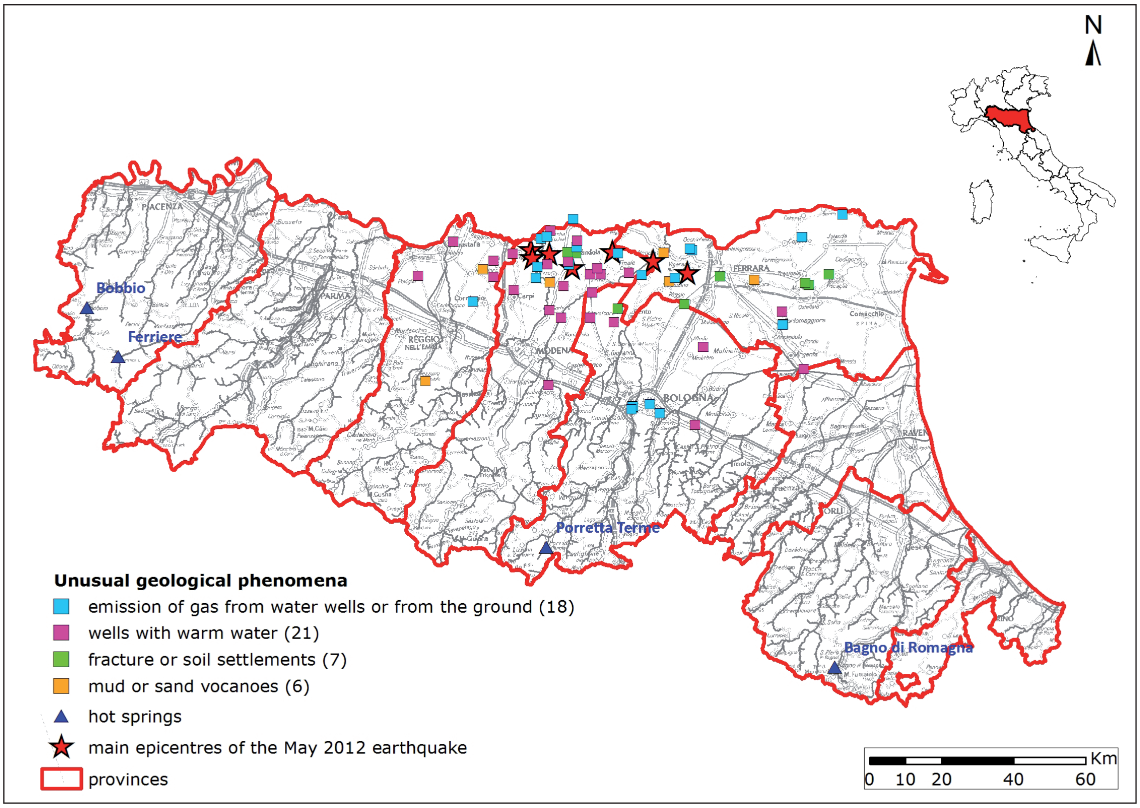

Fig. 1 - Specific geological phenomena in the regional territory following the May - June 2012 seismic swarm.

of the water table in many wells (Italiano *et al.*, 2012a, 2012b; Marcaccio and Martinelli, 2012). In addition, over 700 cases of soil liquefaction were reported (Bertolini and Fioroni, 2012; Sciarra *et al.*, 2012; Emergeo Working Group, 2013) quite similar to those already observed during the seismic sequence that struck the territory of Ferrara in 1570 (Baratta, 1901; Boschi *et al.*, 1995). Finally, some luminous phenomena were also reported, which are probably ascribable to the ionization of atmospheric gases in the epicentral zone. They included "mid-air" lights observed in the area of Massa Finalese, similar to the electrostatic phenomena previously described in the historical literature (Galli, 1910; Fidani, 2005).

2. Unusual geological phenomena following the Emilia May-June 2012 seismic swarm

Descriptions somewhat similar to those previously reported in the historical literature were given after the seismic sequence that struck Emilia in 2012 (Bonzi *et al.*, 2014) (Fig. 1).

These anomalous geological events can be grouped into four main categories: i) gas emission from water wells or from the ground, ii) wells containing hot water (with temperatures exceeding 50°C), iii) fractures and/or ground settlements, iv) sand and mud volcanoes.

After the May - June 2012 earthquakes in Emilia, 52 events were reported over a three-year observation period (up to November 2015). Most of them occurred in the areas struck by earthquakes, but others were located in the less damaged areas of Bologna and in the eastern sector of the province of Ferrara (Fig. 1).

All of the reports were put into in a database, which can be consulted online (http://ambiente.regione.emilia-romagna.it/geologia/temi/geologia/fenomeni-geologici-particolari). Within this database, various pieces of information have been collected, such as the location and the date of the report, the type of report, and any possible links to photographic or filmed evidence, scientific papers, and/or newspaper articles. A form has been prepared for each report containing the above-mention information, as well as descriptions of the geological and tectonic context of the area affected by a specific event and, sometimes, a possible interpretation of the event.

Most of the reports (21 out of 52, see Fig. 1) concern wells with warmer than normal water. The groundwater temperature in the Emilia-Romagna plain is well known, thanks to the large number of monitoring activities carried out since 1987 on over 500 wells, which make up the region's groundwater monitoring net (http://www.arpa.emr.it/dettaglio_generale.asp?id=216).

The results of monitoring show that the average temperature of groundwater is usually around 15°C, with no significant changes between summer and winter. In some of the cases reported in Fig. 1, the temperature exceeded 30°C. The wells which recorded anomalous increases of temperature were always less than 10 m down from the ground surface and drew from the phreatic aquifers of the Emilia-Romagna plain (Severi and Bonzi, 2015). The highest temperature recorded was 55°C, in a well at Medolla (province of Modena) in October 2015. After this anomalous increase, temperatures generally returned gradually to near normal values. This particular event has created great concern among the population owing to the high water temperature reached, and also because a few days later, a 3.5 magnitude quake struck the territory of Mirandola in the province of Modena (Fig. 2), not far from the area where the hot water had been reported (http://cnt.rm.ingv.it/event/6174121).

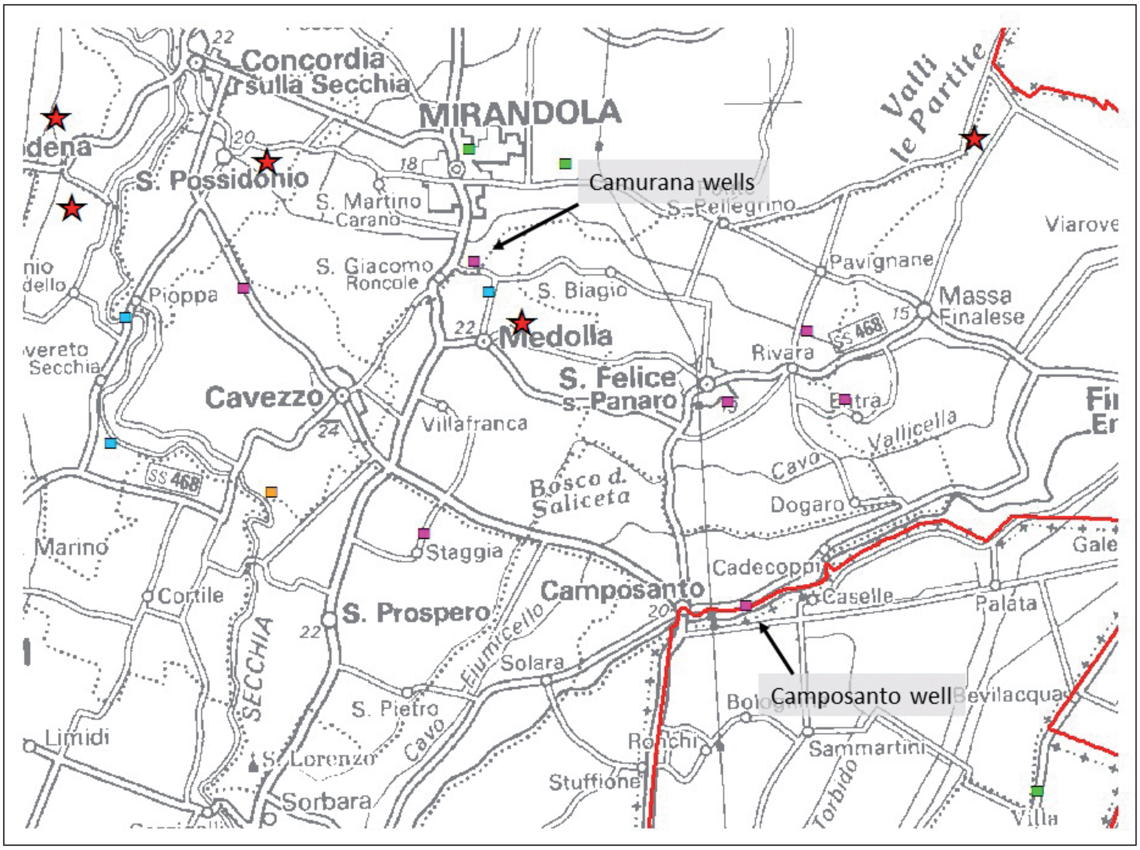

Fig. 2 - Position of the wells with warm water that were continuously monitored. Legend as in Fig. 1.

Frequently, the local press has considered these kinds of geological events as precursors of seismic activity. Nevertheless, it should be pointed out that none of the numerous sites of the regional monitoring network ever showed significant variations in the water table, temperature, or salinity of groundwaters prior to the May - June 2012 seismic swarm (Marcaccio and Martinelli, 2012; Bertacchini *et al.*, 2014; Nespoli *et al.*, 2015).

Here, we put forward two examples (Camurana and Camposanto, Fig. 2) of monitoring carried out after the May - June 2012 seismic swarm in wells in which an increase in water temperature was recorded (Fig. 2). In particular, we continuously monitored the piezometric level, the temperature, and the conductivity of the underground waters. The data collected are presented here and are commented upon for the first time.

Two wells about 20 m apart were analysed at Camurana, one 10 m deep with continuous monitoring (Camurana 1, with warm water), the other one 22 m deep (declared by the owner, not measured directly) with periodic measurements (Camurana 2, with normal water temperature).

The subsoil area of the zone is made up, in the first 14 m, of alternating silts and sandy silts/silty sands, from 14 m to 17 m the subsoil is sands, from 17 m to 24 m it is alternating silts and clayey silts, and down to 25 m it consists of sands, according to data available from the Geological Service of the Emilia-Romagna Region (http://ambiente.regione.emilia-romagna.it/geologia/cartografia/webgis-banchedati/webgis). The Camurana 1 well affects the superficial

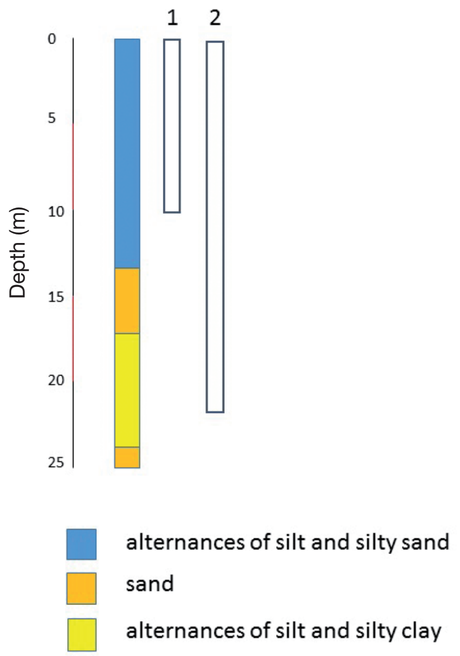

Fig. 3 - Lithology of the underground area in the zone of Camurana and the depth of the monitored wells. Well No. 1 intersects the phreatic aquifer; well No. 2 the semi-bordering aquifer.

phreatic aquifer, the Camurana 2 well affects the underlying semi-bordering aquifer (Fig. 3).

The continuous data in the Camurana 1 well indicate that in October 2016, the temperature reached 55°C, which represents the highest temperature known for a phreatic well in the Emilia-Romagna plain (Fig. 4). Subsequently, the temperature dropped quite fast and in January 2016, it stabilized at around 15°C (normal for the area) (Marcaccio and Martinelli, 2012).

Throughout 2016, the temperature had a completely normal evolution, varying between about 12 and 16°C, with a springtime low (corresponding to an increase in the piezometric level due to the heavy rainfall, Figs. 5 and 7), and a late-autumnal peak.

There is no apparent relationship between the temperature trend and the trend in the electrical conductivity or the well's piezometric level (Figs. 4 and 5).

The cause of such a strong rise in the temperature is still unclear.

As mentioned above, a malfunctioning of the pump could have overheated the water in the well.

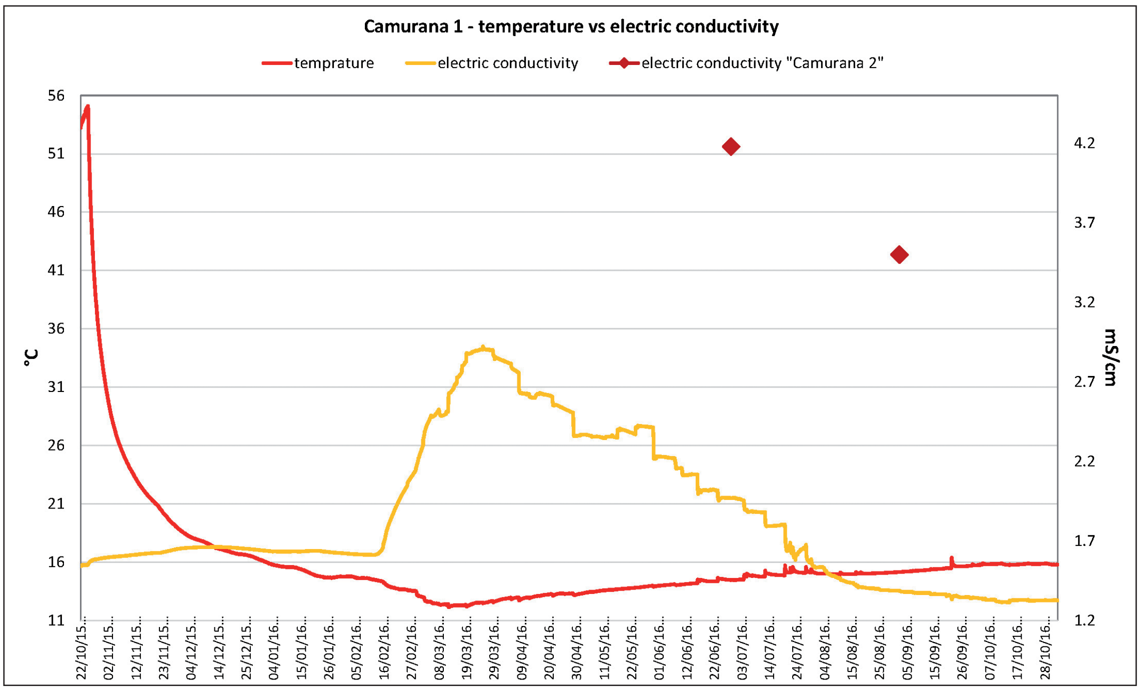

Fig. 4 - Temperature and electrical conductivity of Camurana 1, and the electrical conductivity of Camurana 2 (red rhombuses).

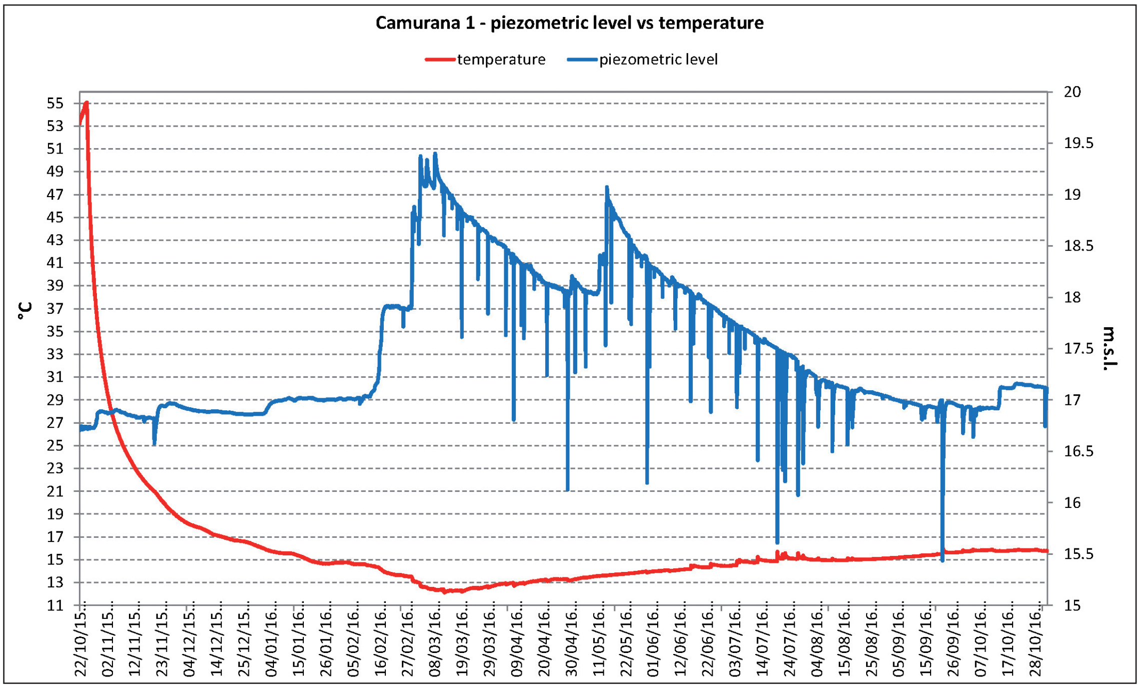

Fig. 5 - Temperature and piezometric level in Camurana 1.

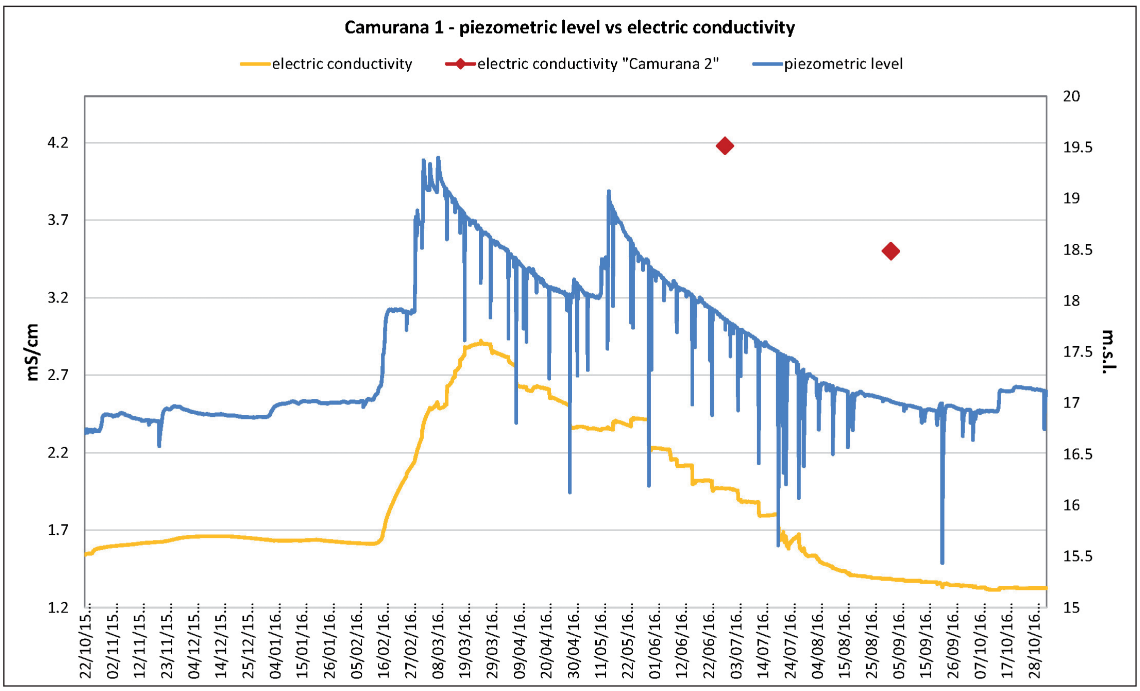

Fig. 6 - Piezometric level and electrical conductivity in Camurana 1 well, and electrical conductivity in Camurana 2 (red rhombuses).

In recently published research, increases in ground temperature have been explained by exothermal-type biochemical reactions affecting the shallow soil layers (Capaccioni *et al*., 2015) caused by bacteria capable of oxidizing methane. Until now, however, it has not been clarified whether this same phenomenon can cause increases in the temperature of aquifer waters.

Instead, it seems unlikely that the temperature increase is due to the arrival of warm waters from the marine formations present in the deepest underground levels of the plain through the presence of faults or fractures. The volume of deep warm waters needed to cause such a big rise in the temperature would be very large. As it is well-known, the deep waters present in the marine formations are characterized by very high salinity, and therefore the arrival of these waters should have visibly altered the conductivity of the Camurana 1 well, something that was not observed (Fig. 5).

The electrical conductivity of the Camurana 1 well from February to June 2016 saw a clear-cut increase, going from 1.6 to almost 3 mS/cm (Fig. 4).

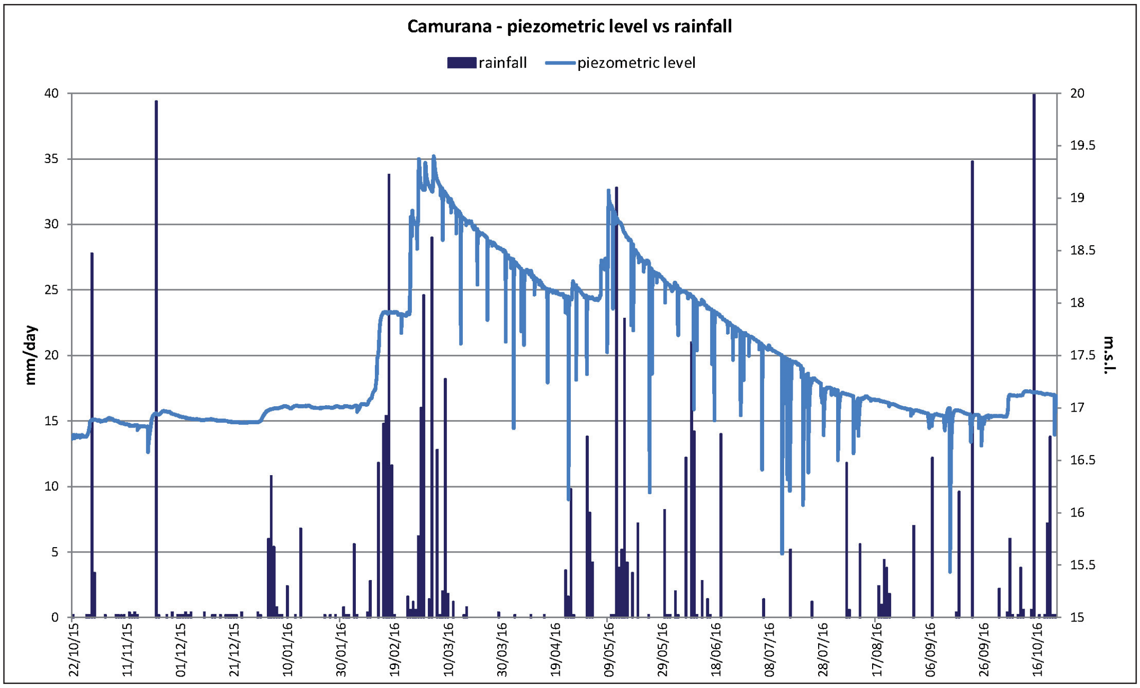

Fig. 7 - Piezometric level of Camurana 1 well and daily rainfall (ARPAE station at San Felice sul Panaro).

The arrival of these saltier waters might simply be due to the increase in the piezometric level of the semi-bordering aquifer, following the heavy rainfall as observed in the phreatic aquifer (Fig. 6).

The monitored well at Camposanto is 10 m deep and reaches the phreatic aquifer, made up of alternating silts and sandy silts, according to data from the Geological Service of the Emilia-Romagna Region (http://ambiente.regione.emilia-romagna.it/geologia/cartografia/webgis-banchedati/webgis).

This well has been the subject of continuous surveys of the temperature level and conductivity (the latter are not reported here because they have little significance), during two separate periods, i.e., from August 2012 to December 2013, and then from February to October 2016 (Figs. 8 and 9).

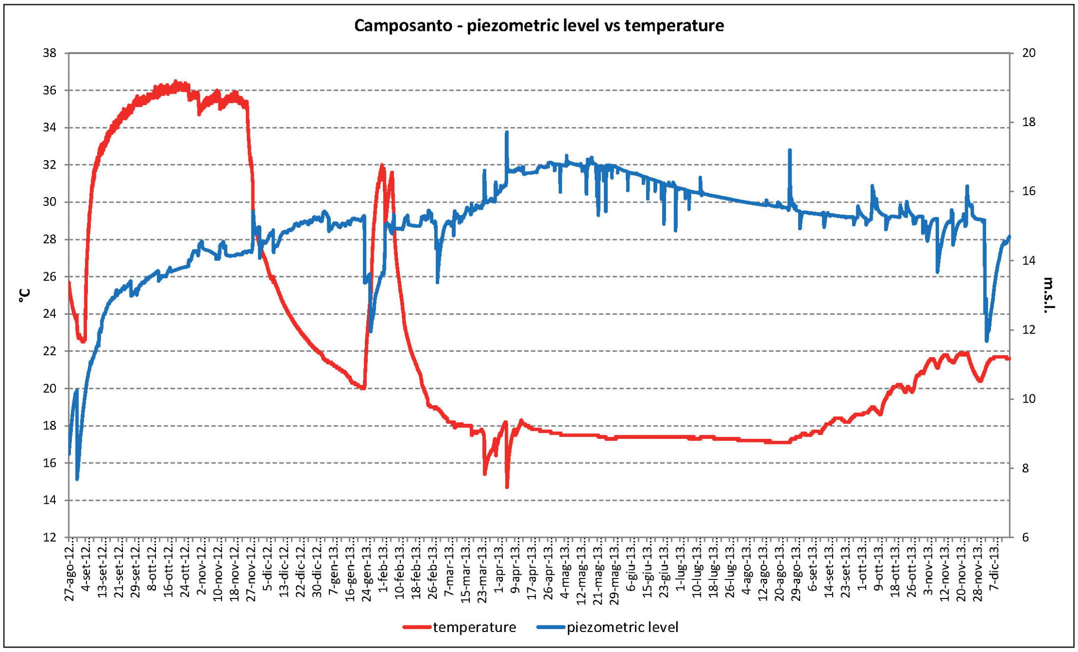

Fig. 8 - Piezometric level and temperature in Camposanto (August 2012 - December 2013).

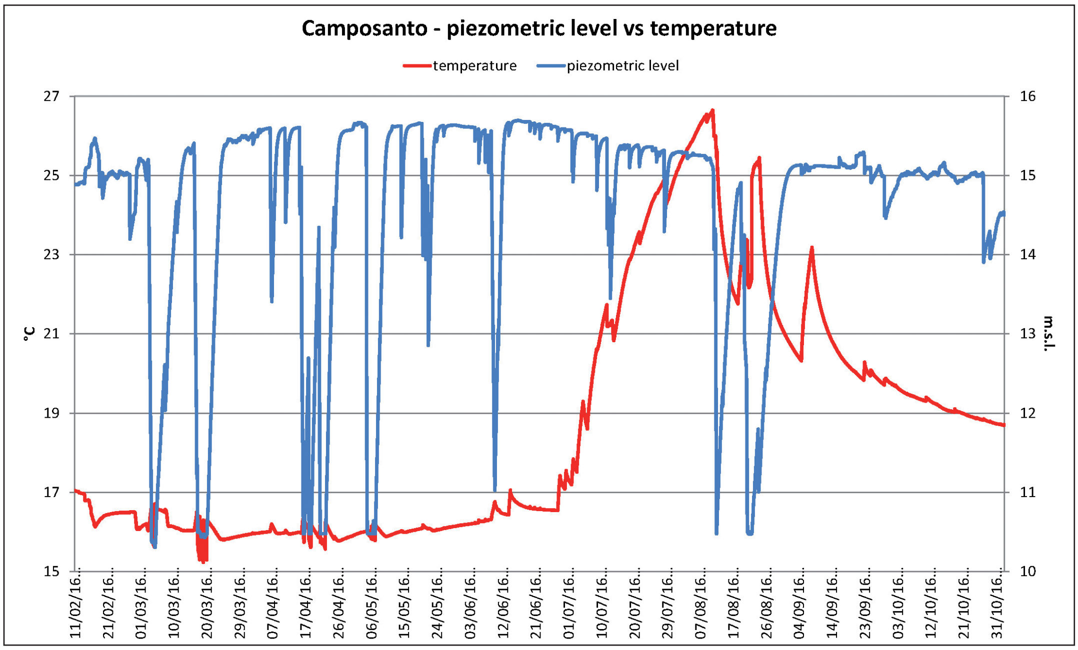

Fig. 9 - Piezometric level and temperature in Camposanto (February - October 2016).

In the first monitored period, we observed that the piezometric level and the temperature have a trend that can be correlated in some cases, albeit with an opposite tendency (Fig. 8). The large increase in temperature in September 2012 and in January 2013 occurred in correspondence with a decrease in the level of the well, which is likely related to a water withdrawal due to the starting of the pump. The cause of the increase in the temperature of the water in the well might, therefore, be the overheating of the pump, and in fact when it starts working, the water level goes down and at the same time the temperature rises.

In the second monitoring period, the well was often used, as demonstrated by the frequent drops in the piezometric level (Fig. 9). The decreases in the level (and thus the activation of the pump) in the period March - July 2016 are constantly accompanied by a slight (but very visible) temperature increase. This shows that the pump causes a rise in the temperature of the well water, albeit slight. The very evident increase in the temperature which occurs in July and continues throughout the monitored period appears to occur independently of the level trend, as also observed in the period September to November 2012.

It should be pointed out that for some of the reports sent to the Geological Service and verified each time and monitored, we are certain that the malfunctioning of the pumps was the cause of the overheating of the water of the wells even to above 30°C, because in these cases the turning off of the pump was accompanied by a concomitant lowering of the temperature.

Fig. 10 - 20 m ground fracture which appeared in Ferrara in August 2013 (courtesy of Doriano Castaldini).

Some residual uncertainties can be eliminated with the ongoing continuation of the monitoring.

Meanwhile, seven reports regard fractures or soil settlements and six describe the appearance of mud or sand volcanoes. Among these soil settlements, the fracture formed in the urban area of Ferrara in August 2013 should be mentioned (Fig. 10); it was interpreted as being due to differential ground settlement following the alternation of rainy and drought periods, and therefore not to be connected with the 2012 earthquakes (Caputo, 2013).

Eighteen reports concern the emission of gas from water wells or from the ground (Fig. 1). Some of these emissions, which usually consist of gas bubbling at varying intensities, were observed from old methane wells, which have not been in use for several decades.

Fig. 11 - Example of emission of gas mixed with salty water from an old methane well in the municipality of Copparo (FE) (courtesy of Carmela Vaccaro).

In these cases, the gas pressure, built-up in old disused plants, has caused the cement of the well heads to break and the consequent leakage of gas mixed with salty water (Fig. 11). This phenomenon is well-known in the Po Delta, where in the past many deep wells (several hundreds of metres) were drilled for drawing so-called "methane-rich waters" (e.g., Caputo *et al.*, 1970). It is relatively frequent, and was well documented before May 2012, that the sealing cement of these old wells is subject to deterioration, thus causing the leakage of gas and salty water from the subsurface (Italian National Mine Board for Hydrocarbons and Geothermal Energy - UNMIG of Bologna, 2014, personal communication). Hence, there is no good reason to believe that these events were linked to the 2012 seismic sequence.

Other reports regard gas emissions from water wells at a shallow depth (ten metres or so) observed in various areas of the Emilia plain (Fig. 1). Specific analyses have not been carried out on these gases, but in view of the specific literature (Mattavelli *et al.*, 1983) and the results of simple field tests, it is quite likely that most of this methane has a biogenic origin (Martinelli *et al.*, 2012, 2016; Sciarra *et al.*, 2013).

Similar methane emissions from water wells have been widely documented, in particular in the plain of the Ferrara and Ravenna provinces and in the northernmost sector of the Modena plain. These reports result from a very rich archive collected by AGIP (now ENI), which describes various types of hydrocarbon emissions (Mosca, 1983).

The frequency of reports describing anomalous geological phenomena has remained practically unchanged in time, corresponding to 1.25 reports per month (52 reports in 43 months, from May 2012 to November 2015). During the same period, the number of seismic events recorded by INGV has dropped drastically, as shown in the right-hand column of Fig. 12, which represents seismic events with magnitude ≥ 2.0 recorded within a 20-km radius from Finale Emilia (Fig. 12).

Hence, the reports of anomalous geological phenomena have not shown a temporal correlation with the recorded seismicity. It is also worth underlining that never in the world, outside of Italy, have pre-seismic temperature increases in groundwater been reported in layered aquifers hosted in sedimentary basins (Cicerone *et al.*, 2009; Martinelli and Dadomo, 2017, and references therein).

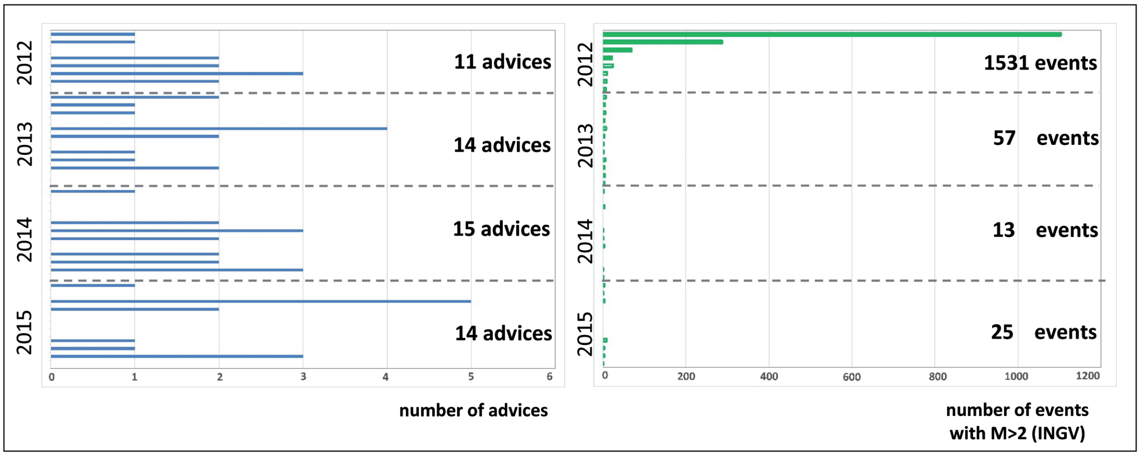

Fig. 12 - Temporal relationships between reports of anomalous geological phenomena and seismicity (iside.rm.ingv.it) in the area struck by the 2012 seismic swarm.

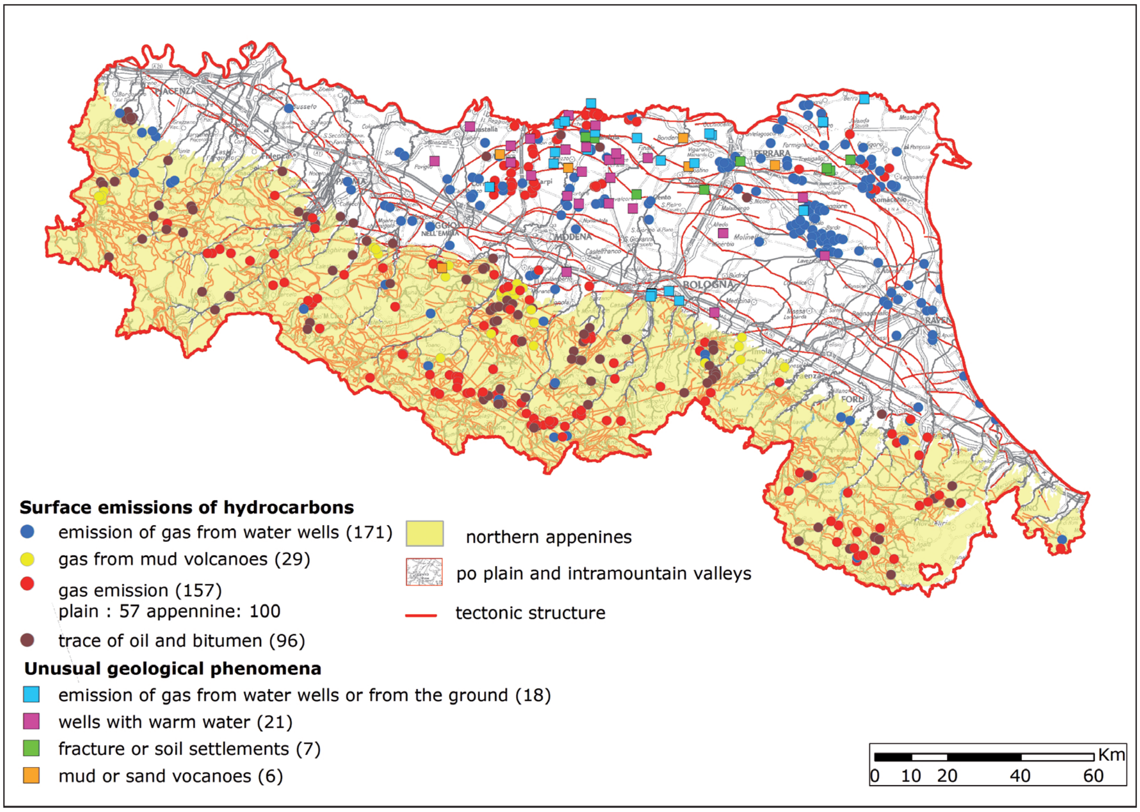

Fig. 13 - Surface emissions of hydrocarbons, anomalous geological phenomena (Mosca, 1983) and distribution of active faults in Emilia-Romagna (Boccaletti *et al.*, 2004).


AGIP MINERARIA
SEZIONE GEOLOGICA
REPARTO ESPLORAZIONE
UFFICIO MANIFESTAZIONI

PROVINCIA: MODENA COMUNE: MIRANDOLA
ALTRI RIFERIMENTI: 800 mt. a SE di "I Gazzi"
lungo il can.le "Cavo di Sotto"

N° 070404/7
F° 75 I NW

TIPO gas sup.le

DESCRIZIONE E SITUAZIONE GEOLOGICA

Il gas si manifesta alla superfice dell'acqua del Canale "Cavo di Sotto" in un tratto di 40 mt. con gorgoglio continuo, più intenso pochi mt. a monte del ponte sul canale.
I terreni ai lati del tratto di canale appartengono al sig. Giuseppe Bellodi di Mortissuolo(S.Felice Pana--ro) e sono di natura alluvionale.
(Sopr.: A. Scioli - I7-3-I927)

Fig. 14 - Detail of a report form concerning the description of gas at ground level (after Mosca, 1983). The report describes gas bubbling in a channel. Details concerning land properties are also given.

3. Emissions of hydrocarbons in Emilia-Romagna region

The spontaneous emission of hydrocarbons is a well-documented phenomena observed in many geological contexts of the world (e.g., Etiope, 2015, and references therein).

AGIP (now ENI) had collected a large number of sites where hydrocarbons emissions in Emilia-Romagna were reported (Mosca, 1983) (Fig. 13). These emissions were reported in the early decades of the 20th century and were subsequently verified by means of detailed field surveys and tests in the period 1955 -1959. Reports describe gas in artesian wells, gas emissions, traces of oil and bitumen, and gas erupting from mud volcanoes and have been disclosed for research activities linked to the Emilia earthquakes to be published for the first time in the present paper.

Each report is described in a specific form (for example in Fig.14).

The phenomena occurring in the Apennine areas (416) include superficial gas, traces of oil and/or bitumen, and presence of gas inside mud volcanoes hydrocarbon wells and unknown points (not included in Fig. 13). In the Po Plain area, the reports (455) concern gas emissions (often almost pure methane) from artesian wells (generally some 10 m deep) and/or gas emissions from the ground, ditches, or canals, hydrocarbon wells and unknown points (not included in Fig. 13).

In the Po Plain, these phenomena are found nearly exclusively in the provinces of Ferrara, Modena, Ravenna, and Reggio Emilia, where most of the anomalous geological phenomena were recorded after the 2012 seismic swarm (Fig. 13).

4. Degassing phenomena observed in water wells

The presence of methane in the subsoil of the Emilia-Romagna plain mainly results from the decomposition of organic matter (Martinelli *et al.*, 2012; Sciarra *et al.* 2013; Martinelli *et al.*, 2016) which is found in the subsurface at different stratigraphic layers, from a few metres down to several thousands of metres.

In the first hundred metres of soil, the distribution of organic matter is mainly linked to the sedimentation of the Po fluvio-delta deposits, which took place in the plain of Ferrara and Ravenna from the mid-upper Pleistocene to the Holocene (Amorosi *et al.*, 2004). In these areas, numerous levels of peat and organic clay are found in the subsurface (Panzani, 2015). Their decomposition may produce methane (Cremonini *et al.*, 2008).

Peat and organic clay (potential producers of methane) are also certainly widespread in the soil of the most superficial layers of the Emilia-Romagna Plain, although with volumes lower than those found in the Po Delta.

At lower stratigraphic levels, the decomposition of organic matter, and its subsequent migration from parent rocks into deep aquifers, has created the well-known methane reservoirs, which AGIP (now ENI) found and later exploited mainly from the 1950s onwards (Accademia Nazionale dei Lincei - Ente Nazionale Idrocarburi, 1959). The gas contained within these reservoirs is not subject to significant surface migration, since it is constrained by impermeable rocks.

Most of the reports collected by Mosca (1983) refer to places in the Ferrara and Ravenna plain, where there is an abundance of organic matter, which could generate the gas found in the surrounding aquifers (Fig. 13).

Most of the reports come from areas where important compressive tectonic structures are present in the subsurface, among which are the well-known “Ferrara Folds” (Pieri and Groppi, 1981). Some of these structures are considered tectonically active (Boccaletti and Martelli, 2004; Boccaletti *et al.*, 2004) and are depicted in Fig. 13. The faults affecting these geological structures could facilitate the rise towards the surface of traces of deep methane. At shallow depths, the latter could mix with biogenic methane and with the groundwater contained within the Pleistocene and Holocene aquifers (Cremonini *et al.*, 2008; Sciarra *et al.* 2013). Martinelli *et al.* (2016) sampled and analyzed local hydrocarbon emissions over time and concluded that temporary variations in the flow rate and the chemical composition of the bubbling gases were due to ground-shaking induced by the seismic swarm.

In the Apennine mountains, belt faults affect outcrops, and gas emissions occur in the fractured areas.

It needs to be pointed out that the reports collected by Mosca (1983) were written in the early decades of the 20th century, that is, in a period preceding the industrial era. They are the result of natural exfiltration phenomena and cannot be correlated to the exploration or exploitation activities of subsurface mineral resources.

5. Conclusions

The particular geological phenomena described in Emilia after the 2012 seismic swarm have affected an area that is historically characterized by many similar reports, well documented in

Mosca (1983). The frequency of these reports has considerably increased since May 2012. It is possible that the higher frequency of these reports results from a greater attention to phenomena of this kind by the local residents of the earthquake-struck areas and by local press. No relationship with earthquakes was found regarding the apparent warming of the groundwater. Detailed studies demonstrated the artificial origin of the water temperature increase. These phenomena are somehow correlated with a sort of readjustment in the subsurface sediments after the seismic sequence.

The degassing phenomena observed in the water wells of the Emilia-Romagna plain, collected by Mosca (1983) and included in the census of the Regional Geological Survey after the 2012 earthquakes, are entirely natural. They are due to the presence of gas (usually methane) mixed with groundwater and resulting from the decomposition of organic matter present in proximity to the tapped aquifers, or from gas rising from greater depths along tectonic discontinuities. The observed phenomena are somehow correlated to a sort of readjustment of the subsurface sediments after the seismic sequence. The reports collected by Mosca (1983) refer to a period of substantial seismic quiescence in the Emilia-Romagna plain (first half of the 20th century); therefore their geographic distribution is linked to tectonic activity during geological times rather than to contemporary seismicity. Similarly, hydrocarbon emissions reported after the 2012 earthquakes did not change the geographic distribution reported by Mosca (1983). Ground-shaking due to the seismic swarm may have brought about some short-lived flow rate variations.

Acknowledgements. Thanks are due to ENI S.p.A for permission to utilize unpublished data related to hydrocarbon seepage phenomena collected in: AGIP S.p.A., Serv. GERS, Vol. II, Manifestazioni di idrocarburi nella regione Emilia - Romagna, L. Mosca, S. Donato Milanese 1955 - 1983.

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