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Recovery and processing of hydrological and hydrogeochemical parameters for researches on earthquake short-term precursors in Italy

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ABSTRACT Hydrological and hydrogeochemical observations (piezometry, chemistry, electric properties, etc.) carried out in groundwaters in Italy in the past 40 years have been recovered and processed. Available data time series recorded by government agencies, scientific institutions and independent researchers in the field of groundwater and geochemical monitoring in 5480 different sites have been recovered, systematized and processed. Meteorological data useful for data evaluation have been recovered too. Some possible precursors have been identified but the relatively high amount of earthquakes not preceded by hydrologic or geochemical anomalies suggest the need to consider all together geophysical and geochemical parameters for future researches. Highest amount of data collected by manual sampling were found in the Lombardy, Veneto, and Emilia-Romagna regions, while most of automatically recorded data were found in the Tuscany region.

Key words: earthquake prediction, geochemical precursors.

1. Introduction

Italian Civil Defense offices (Dipartimento della Protezione Civile jointly with Istituto Nazionale di Geofisica e Vulcanologia or DPC-INGV) recently expressed the need to better understand if possible hydrologic and geochemical precursors are suitable for possible earthquake prediction procedures.

Thus, a wide recovery project on previously recorded time series of data was carried out with the

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purpose to set up a systematized data bank containing all useful data on fluids (Fig. 1). Data producers were identified by bibliographic researches and by institutional procedures able to help data mining activities. Data processing procedures were also carried out and allowed first evaluations.

2. Monitoring of terrestrial fluids in Italy

First ideas and data about spring sources and water well monitoring in Italy, oriented to study possible earthquake precursors, were reported by De Rossi (1879) and by Lorenzini (1898).

In 1975, after the Chinese prediction of the M=7.3 Hai-Cheng earthquake (Fengming *et al.*, 1984; Wang *et al.*, 2006), many research activities on geochemical earthquake precursors started in Japan, in the former U.S.S.R. and in the U.S.A. Most relevant international projects in Europe on earthquake precursors, including systematic monitoring of geochemical parameters, were held in Turkey (Zschau and Ergunay, 1989) and in Iceland (Stefansson, 2011) although the monitored Icelandic areas are chiefly located in a volcanic geological environment.

In Italy, Dall'Aglio (1976) promoted research activities in the field of earthquake precursors by geochemical methods. In 1977, the University of Calabria held a joint Italy-U.S.S.R. meeting devoted to earthquake prediction by geochemical methods and a scientific cooperation between Italian and Soviet researchers started (Carapezza *et al.*, 1980). Short geochemical time series were produced chiefly in volcanic geological environments (Dall'Aglio *et al.*, 1990; Valenza and Nuccio, 1993) and not in low heat flow seismically active areas. It is worth to mention that volcanic areas are also characterized by volcanic seismic activity generated by deep fluid expulsion. In a volcanic geological environment, fluid emissions are subjected to continuous variations while deep fluid emissions in tectonically active non volcanic areas are sensitive only to extremely small crustal deformative processes (see also Martinelli, 2015). The most relevant (M>5.5) earthquakes, which occurred after the Second World War in Italy, were located in the provinces of Udine (in 1976), Avellino (1980), Perugia (1997), L'Aquila (2009), and Modena (2012). No observations about geofluids were carried out during the 1976 Friuli seismic sequence while manual sampling monitoring activities were carried out after the 1980 seismic sequences of Avellino (e.g., Lombardi, 1981) and Perugia 1997 (e.g., Italiano *et al.*, 2001). Before and during the Perugia (1997) and L'Aquila (2009) seismic sequences, Heinicke *et al.* (2000, 2012) utilized geochemical automatic monitoring techniques. Before and during the Modena (2012) seismic sequence automatic water level monitoring techniques were utilized by Marcaccio and Martinelli (2012). Manual techniques were also utilized to monitor geofluids after the Modena (2012) seismic sequences (Italiano *et al.*, 2012) or to localize degassing areas (Chiodini *et al.*, 2011; Quattrocchi *et al.*, 2012) after the L'Aquila (2009) mainshock. Further monitoring activities by manual techniques started in concomitance with some minor magnitude events (Dall'Aglio *et al.*, 1995; Martinelli *et al.*, 1995; Favara *et al.*, 2007). Further time series obtained by automatic stations located in non-volcanic areas were obtained in 1988 in northern Apennines by Martinelli and Ferrari (1991) and in 1995 in the Friuli area by Riggio and Sancin (2005). A research group based at INGV obtained significant results in automatic geochemical monitoring of volcanic areas in 1995 (Quattrocchi and Calcara, 1998). Further results on automatic monitoring of geochemical parameters in non-volcanic areas were obtained by Facchini *et al.* (1993, 1995), Albarello *et al.* (2003) and Lapenna *et al.* (2004).

Tuscany Region jointly with Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse (CNR-IGG), started a geochemical monitoring activity on thermal springs of Tuscany accompanied by GPS monitoring managed by the University of Siena (Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente). Researches which include crustal deformation measurements and geochemical parameters are currently carried out in selected sites of Tuscany by CNR-IGG, Tuscany Region (Cioni *et al.*, 2007) and University of Siena, and in Friuli by OGS in cooperation with other scientific institutions (Vaupotic *et al.*, 2010; Petrini *et al.*, 2012). No geochemical or hydrologic anomalies were clearly observed before most significant earthquakes after the Second World War. The lack of systematic control during past decades of geochemical and hydrologic parameters in non-volcanic areas of great part of Italy, due to the prevalence of interest for volcanic systems, corroborated the interest of DPC-INGV for environmental measurements of groundwater parameters also if not designed for earthquake oriented studies.

3. Groundwater monitoring in Italy for environmental purposes

In Italy periodic measurements of groundwater level started in 1927 in phreatic wells chiefly located in railway stations by Servizio Idrografico Italiano which published data in "Annali del Servizio Idrografico" printed in Rome. The Servizio Idrografico Italiano collected also data on flow rate of most important spring sources but time series are unfortunately scarce. Measurements in phreatic wells, although often characterized by relatively high sampling rate (one data every 3 days), were not suitable for data collection due to low depth (10÷30 m) and unconfined conditions of aquifers. After the institutions of Regions in Italy in 1972, groundwater levels were collected by Regions or by Provinces or by Municipal Agencies chiefly for groundwater monitoring of waters utilized for human feeding. Spring sources monitoring lost importance after the Second World War except for most relevant springs located in the Alpine belt. Also some individual researchers monitored deep wells or spring sources in the past century but only short-term time series were obtained. An important role in groundwater managing is played in Italy by multiutility agencies, in particular for drinking water.

Usually their clusters of wells are monitored by automatic equipments but catchment areas are strongly disturbed by groundwater withdrawal which inhibits data significance. Usually, multiutility agencies also manage the most important cold springs located in mountain areas. In the great majority of cases, spring sources catchment areas are not equipped with automatic monitoring equipments and scarce or no data are available about eventual manual measurements. Groundwater civil consumption for drinking water is, thus, estimated by means of commercial parameters (cubic metre of water sold out) while agricultural and industrial groundwater consumptions are not systematically measured except for a few exceptions. At present, they only are estimated in the whole of Italy.

4. Groundwater monitoring by environmental agencies or by Regions

Since 1976, a network composed by 330 wells characterized by a depth usually larger than 100 m in confined aquifers is monitored in the Emilia-Romagna region. The network was

Fig. 1 - Data distribution stored in the database.

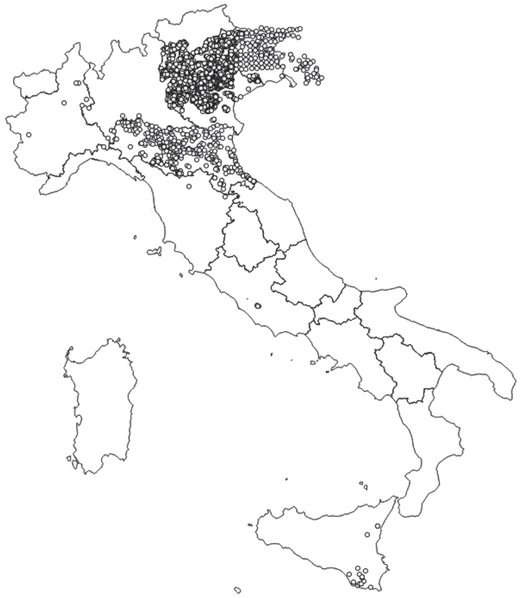

Fig. 2 - Radon monitoring sites.

improved during the years and presently is composed by over 600 wells (usual depth > 100 m). After 1987, a chemical periodic sampling was also carried out. Similar networks are presently utilized in other regions of Italy with smaller time series length. Usually, periodic water level monitoring and chemical water analysis are carried out by regional environmental protection agencies (ARPAs) but exceptions are relatively frequent like in Friuli-Venezia Giulia, Lazio, Piemonte, etc., where water level are monitored by offices belonging to Regions or to Provinces and not by ARPA agencies. Some Regions still do not have a proper data base obtained by a sampling network like Basilicata and Calabria. Long time series of water level data were obtained in northern and central Italy. Recording rate is in the range 0.5÷12 data per year on each monitoring point. These features strongly inhibit the utilization of data for short-term earthquake forecasting researches while medium-term forecasting researches could, in principle, benefit by longer time series in confined aquifers.

Automatic monitoring (1 data per hour) has been carried out by ARPA agencies in Emilia-Romagna, Piemonte, and Umbria regions. Networks are constituted by wells drilled in phreatic aquifers (Piemonte) or by wells located in confined and phreatic aquifers (Emilia-Romagna) or by springs (Umbria).

5. Groundwater monitoring by research agencies or by private institutions

Groundwater monitoring has been carried out also by independent researchers or by research agencies or by private institutions. In these cases, time series are relatively short but often characterized by high recording rate (1 data per hour). No flow rate data is presently recorded in both cold and thermal spring sources. Six advanced geochemical monitoring stations are

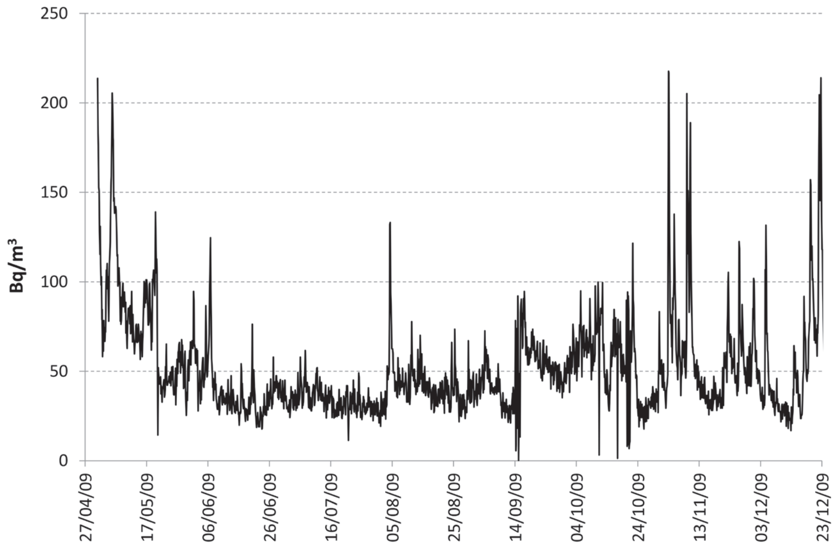

Fig. 3 - Radon in soil recorded in Friuli during 2009.

presently operated by CNR - IGG and Tuscany Region although no flow rate data is recorded. High frequency sampling rate and geochemical parameters (in particular dissolved gases in thermal waters) made time series suitable for short-term and medium-term earthquake forecasting researches. Water temperatures were recorded by individual researchers in some thermal springs of the Apenninic belt. High sampling rate and long time series allow researches on short-term earthquake forecasting.

6. Radon monitoring

Radon monitoring was chiefly carried out by ARPA agencies in indoor environment. The lack of long time series and the scarce significance of indoor locations inhibit the use of recorded data for earthquake related studies but make it possible to characterize large geographical areas in particular in northern Italy. Further radon measurement activities were carried out by INGV and by OGS in the Lazio and Friuli regions, respectively (Fig. 2). High sampling rate and multiyear length allow researches both in short-term and medium-term earthquake forecasting (Fig. 3). Other time series were obtained by single individual researchers and in some cases recording rate and length of time series allow eventual researches on short-term earthquake forecasting.

7. Gas monitoring

Gas flow rate monitoring was carried out by individual researchers in CH_4 and in CO_2 dominating emissions. CO_2 time series were collected in central Italy and sampling rate and time series length allow researches on short-term earthquake forecasting.

Fig. 4 - Data received by public agencies represented by Regions: a) chemical analysis and temperature; b) piezometric levels; c) cold spring sources flow rate. Black areas: no data.

8. Future monitoring trends

The lack of flow rate data in both cold and thermal springs will be partly mitigated by ongoing studies carried out by ARPA agencies on cold springs. Anyway, no automatic instruments are expected to be deployed apart from a few exceptions. Thermal springs, which are among the most suitable monitoring sites together with deep and confined aquifers, will be still not monitored by both environmental and scientific agencies although INGV and the Sicilia Region carry on a dense monitoring activity (data not available). In spite of interesting scientific results obtained in the past (Facchini *et al.*, 1993, 1995) no automatic monitoring activity in deep well (> 500 m) is planned by both environmental and scientific agencies except a few short duration experiments in the Alto Adige region by local geological surveys.

9. Obtained results: considered parameters and data sources

The obtained database considers water / gas points representative of deep fluid reservoirs seated at a depth greater than 100 m, approximately. Thermal waters and gaseous emissions have been considered too.

Main data sources have been: regional ARPA offices, environmental offices of Regions and of Autonomous Provinces, research agencies (CNR, INGV, and ISPRA) and single or independent researchers.

Sampling rate was found very variable. In automatically collected records, the sampling rate is in the range of 720-1 data per day. Discrete samplings are in the range of 12-1 data per year.

The investigated parameters are: water level in wells or in piezometers (piezometry), spring sources flow rate, gas flow rate, groundwaters chemical analysis, Eh, pH, electric conductivity, temperature, isotopic data in groundwaters, chemical analysis of free and dissolved gases, and self potential measurements.

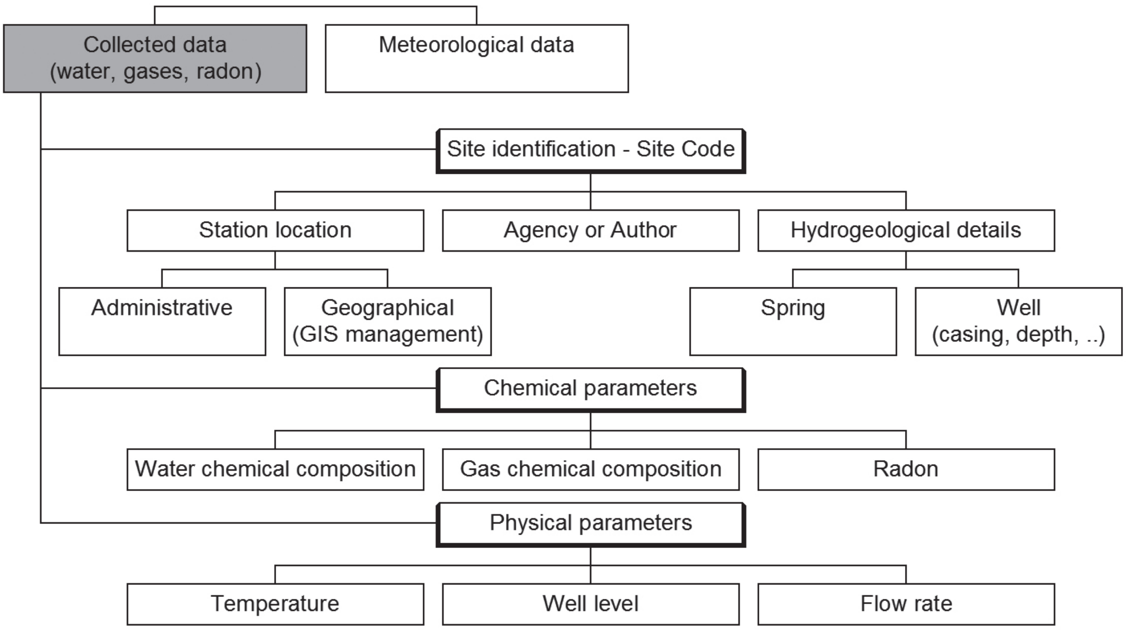

Fig. 5 - Relational network for the hydrogeochemical database.

When available, details on the wells (well depth, filter depth, altitude, properties) were recovered. Meteorological data have been recovered in selected areas to exclude possible external effects in eventually detected anomalous signals.

All hours have been converted into UTC code to allow data evaluation together with earthquakes. The data availability is summarized in Fig. 4.

10. The georeferenced database

A relational database software (DBMS) like Microsoft Access® was adopted and a number of tables equivalent to parameters or cluster of parameters have been created corresponding to: station location, well characteristic, fluid temperature, water level, spring source flow rate, gas emission flow rate, electric conductivity, redox potential, water pH, gas chemistry, water chemistry, ground self potentials. All tables are linked by query and through a relational network (Fig. 5).

Data analysis of the Excel® 1,048,576 produced lines has been carried out by commercial and open source softwares like: Microsoft Excel®, Origin Pro®, AutoSignal® (time series analysis) and Quantum GIS®, Google Earth®, gvSIG® (spatial analysis and georeferentiation).

Short-term anomalies identification and analysis have been carried out on high frequency time series (1 data every 2'< t <1440') while low frequency time series (1 data every 15 days < t < 180 days) have been excluded by short-term earthquake precursors research since more suitable for medium or long-term trend identification in wide areas.

Localization of available automatically recorded time series are shown in Figs. 6 and 7.

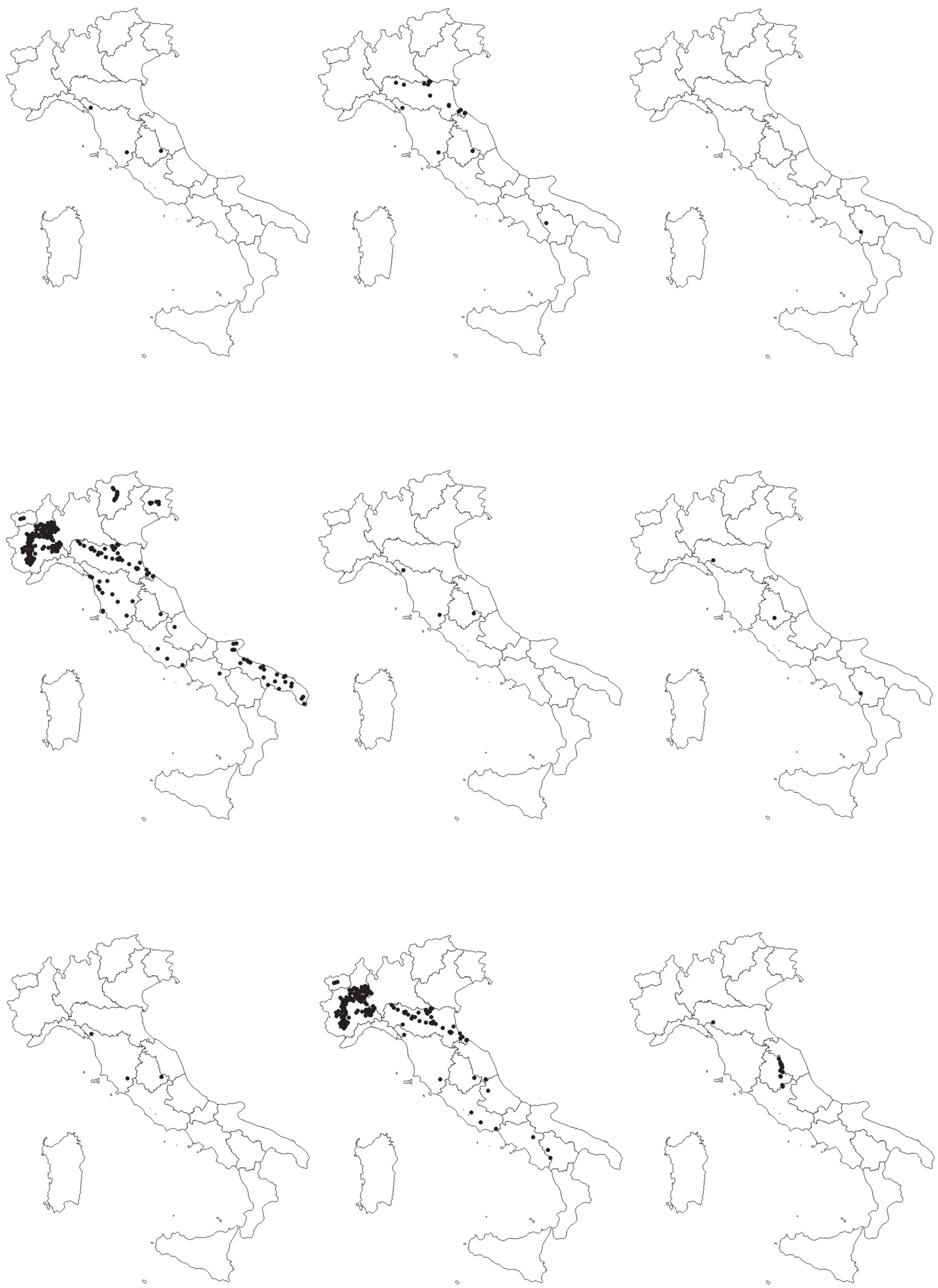

Fig. 6 - Distribution of automatic monitoring sites in groundwaters and in thermal waters. A self-potential in the ground monitoring site has been also considered.

Fig. 7 - Locations of automatic monitoring stations in thermal waters utilized to search short-term possible earthquake precursors.

11. An example of data analysis

The time series procedure carried out on the Miano di Corniglio [see Heinicke *et al.* (2010) for a general description] thermal water well data set is shown in Fig. 8.

Rough temperature data have been imported in the database (recording rate = 10') and averaged as hourly data. Meteorological data have been utilized to eliminate external signals. Daily and seasonal external temperature variations influence well water temperature through an external pipe catchment. Short and long-term environmental temperature changes can induce water temperature changes of about 0.6 °C.

Frequency distribution of water temperature in Miano well is Gaussian (Fig. 9) with mean value of 39.63 °C and standard deviation of 0.17 °C. The time series is not stationary and shows a linear trend with a slope equal to $-7.94 \cdot 10^{-5}$.

Air temperature effects have been subtracted to water temperature time series (Fig. 10) and a residual time series has been obtained (Fig. 11). Average values and standard deviation have been calculated and a threshold of ± 2 sigma has been adopted to evidence possible anomalous temperature fluctuations.

Only positive anomalous fluctuations (>2 sigma) have been considered due to possible effects of rain and snow on catchment pipes (blue dots). Earthquakes ($M \geq 2$) occurred within a radius of 20 km have been considered.

In some cases the identified anomalies apparently occurred before seismic events. Post seismic possible effects were equally identified. The time lapse of 7 days has been chosen as a possible pre- or post-seismic period allowing to evidence red (possible pre-seismic 7-day

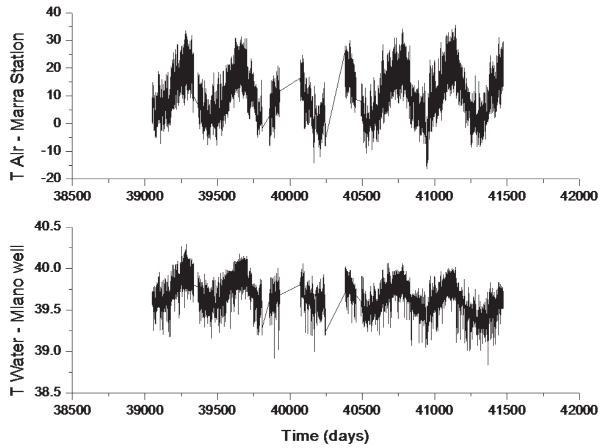

Fig. 8 - Original record of temperature in a warm 1-km deep water well and in atmosphere at Miano di Corniglio (Parma Province, northern Apennines).

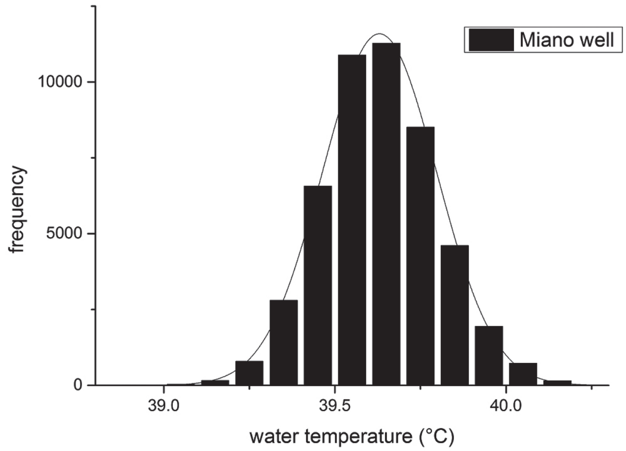

Fig. 9 - Normal distribution of water temperature in Miano well (Parma Province, northern Apennines).

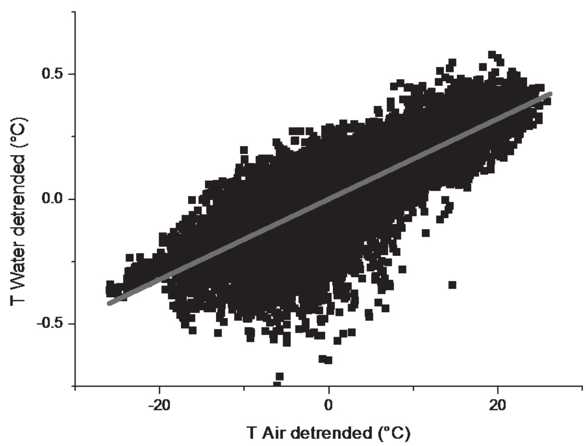

Fig. 10 - Correlation between detrended series of air and water temperatures (R2=0.75) in Miano well (Parma Province, northern Apennines).

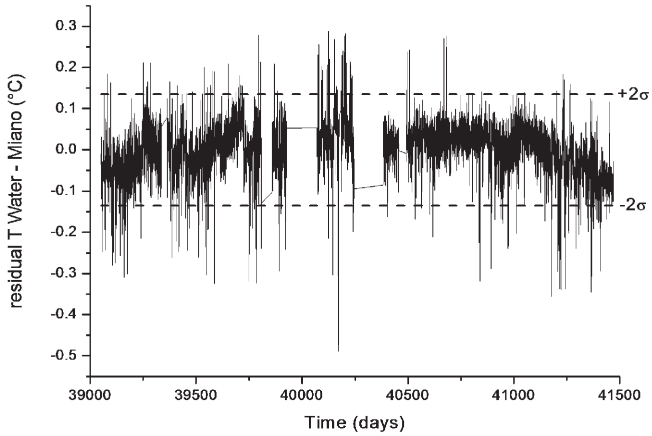

Fig. 11 - Time series of residuals relative to water temperature in Miano well (Parma Province, northern Apennines).

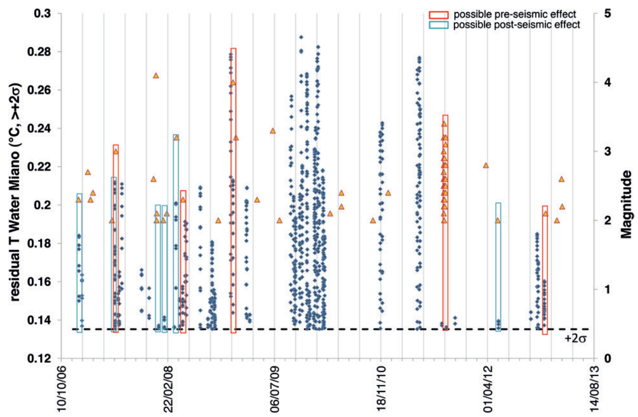

Fig. 12 - Anomalies exceeding +2 sigma (blue dots) and earthquakes (triangles) in Miano well (Parma Province, northern Apennines).

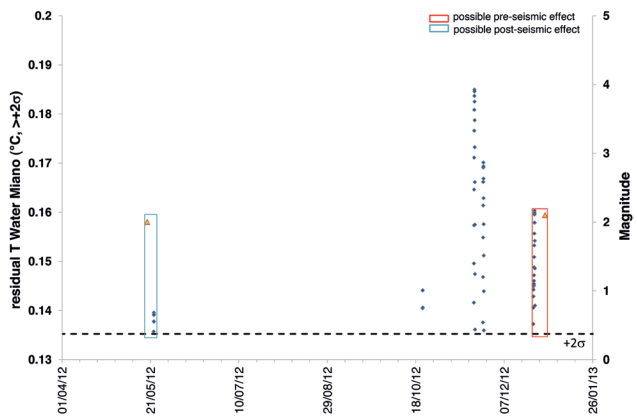

Fig. 13 - A zoom about two possible anomalies exceeding +2 sigma (blue dots in boxes) in Miano well (Parma Province, northern Apennines). Blue dots anomalous signals apparently not linked to previous or following earthquakes are also shown.

anomalous period) and blue boxes (possible post-seismic 7-day period) in Fig. 12. In the same figure, apparently unrelated anomalies (blue dots) are also reported while a zoom about identified phenomena is shown in Fig. 13.

12. Results

Twenty-one years of automatic recording data have been processed in total. The analysis of collected data allowed to state possible "*a posteriori* predictions" useful for further evaluations by means of following fields: progressive ID, toponym, latitude (WGS84), longitude (WGS84), parameter on which the anomaly was identified, method adopted for anomaly identification, anomaly (day/hour) starting period, anomalous (day/hour) ending period, anomalous time duration, sampling rate of analyzed time series, total duration of analyzed time series, starting time (day/hour) of time series, ending time (day/hour) of time series, magnitude of "predicted" seismic event, forecasted time, maximum radius of forecasting, maximum forecasting depth.

Hundred twenty-eight possible pre-seismic anomalous periods in 7 testing sites have been identified:

- northern Italy
  - Emilia-Romagna region, Parma, Corniglio, Loc. Miano, 85 anomalies;
  - Emilia-Romagna region, Modena, Mirandola, 4 anomalies;
- central Italy
  - Marche region, Ascoli Piceno, Acquasanta Terme, 2 anomalies;
  - Tuscany region, Massa Carrara, Fivizzano, Loc. EquiTerme, 4 anomalies;
  - Umbria region, Perugia, Cerreto di Spoleto, Loc.Triponzo, 14 anomalies;
- southern Italy
  - Campania region, Avellino, Rocca S. Felice, Loc. Mefite di Ansanto, 5 anomalies;
  - Basilicata region, Potenza, Tramutola, 14 anomalies.

Further 17 possible pre-seismic anomalous periods were also identified in a selected place for radon monitoring in the Friuli region.

The locations of all automatic monitoring stations, where recorded data were available, are shown in Fig. 12. Seven monitoring stations in thermal waters, where available data allowed *a posteriori* earthquake predictions useful for further evaluations, are also shown.

Radon data collected by public institutions or by independent researchers were collected too: radon in soil, in water, and in the air. Every ARPA of the national territory was contacted even if recorded data are mainly constituted of indoor radon measurements.

All received data have been reformatted and a georeferenced database was set up. It consists of 3961 sites and more than one million radon data. Available data can be grouped into two main categories: 1) measurements of radon in soil and in water (continuously and manually sampled) and 2) measurements of indoor radon.

Continuously recorded data were retained suitable for statistical analysis. Every values exceeding the limit of ± 2-sigma compared to the average value was considered anomalous and potential anomalies evidenced (see also Vaupotic *et al*., 2010).

13. Conclusions

A relatively high number of potential precursors have been identified together with post-seismic effects. Anyway, the relatively low number of correct earthquake predictions strongly inhibits the practical utilization of hydrologic and geochemical precursors for short-term earthquake forecasting. Medium-term forecasting could be furtherly developed according to data collected by discrete sampling on a long-term data set. A broader diffusion of automatic reliable stations is welcomed for future researches on possible earthquake precursors and for environmental purposes in general. The weak character of possible hydrologic and geochemical precursors suggests the need to jointly monitor various geochemical and geophysical parameters by different techniques to improve eventually more reliable earthquake forecasting procedures. Future possible test site areas could be placed in Lombardy (Rodigo deep warm water well), Friuli-Venezia Giulia (slow circulation spring sources and Monfalcone thermal springs), and in the whole Apenninic chain and adjoining plain areas (various thermal springs and confined aquifers insulated from recharge processes).

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