Anomalous fluid emission of a deep borehole in a seismically active area of Northern Apennines (Italy)

J. Heinicke [(1)], F. Italiano [(2)], U. Koch [(3)] G. Martinelli [(4)], and L. Telesca [(5)]

(1) Sächsische Akademie der Wissenschaften zu Leipzig, Arbeitsstelle an der TU Bergakademie Freiberg, 09599 Freiberg (Germany)
(2) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Palermo, 90146 Palermo (Italy)
(3) Sächsische Akademie der Wissenschaften zu Leipzig, Arbeitsstelle Bad Brambach, 09599 Bad Brambach (Germany)
(4) ARPA Emilia Romagna, 42100 Reggio Emilia (Italy)
(5) Istituto Metodologie Ambientali Avanzate, CNR, 58100 Tito Scalo, Potenza (Italy)

Corresponding author: J. Heinicke, ***heinicke@physik.tu-freiberg.de***

In Press on Applied Geochemistry

Anomalous fluid emission of a deep borehole in a seismically active area of Northern Apennines (Italy)

J. Heinicke [(1)], F. Italiano [(2)], U. Koch [(3)] G. Martinelli [(4)], and L. Telesca [(5)]

(1) Sächsische Akademie der Wissenschaften zu Leipzig, Arbeitsstelle an der TU Bergakademie Freiberg, 09599 Freiberg (Germany) heinicke@physik.tu-freiberg.de
(2) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Palermo, 90146 Palermo (Italy)
(3) Sächsische Akademie der Wissenschaften zu Leipzig, Arbeitsstelle Bad Brambach, 09599 Bad Brambach (Germany)
(4) ARPA Emilia Romagna, 42100 Reggio Emilia (Italy)
(5) Istituto Metodologie Ambientali Avanzate, CNR, 58100 Tito Scalo, Potenza (Italy)

Abstract

The Miano borehole of 1047 m depth is located close to the river Parma in the Northern Apennines, Italy. A measuring station is installed to observe the discharge of fluids continuously since November 2004. The upwelling fluid of this artesian well is a mixture of thermal water and methane as main components. In non-seismogenic areas, we would expect a relative constant fluid emission perhaps overlaid with long term variations from that kind of deep reservoirs during the time. However, the continuously record of the fluid emission, in particular the water discharge, the gas flow rate and the water temperature, show periods of stable values interrupted by anomalous periods of fluctuations in the recorded parameters. The anomalous variations of these parameters are of low amplitude in comparison to the total values but significant in their long-term trend. Meteorological influences of rain and barometric pressure were not detected in recorded data probably due to reservoir depth and relatively high reservoir overpressure. Influences due to the ambient temperature after the discharge were evaluated by statistical analysis. We consider that recorded changes in fluid emission parameters can be interpreted as a mixing process of different fluid components in depth by variations in pore pressure as result of seismogenic stress variation. Local seismicity was analyzed in comparison to fluid's physico-chemical data. The analysis supports the idea of an influence to fluid transport conditions due to geodynamic processes exist. Water temperature data show frequent anomalies probably connected with possible precursory phenomena of local seismic events.

1 Introduction

Fluids in upper crust are strongly involved in geodynamic processes. Crustal fluids as natural strain sensors were studied by Kümpel (1992); Woith *et al.* (2003) and Koizumi *et al.* (2004). Variations in several parameters, in particular water level, water temperature or radon concentration were detected in many geological environments with fluid emissions in springs, mofettes or wells, e.g. Roeloffs (1998), Igarashi *et al*. (1993), Wang *et al.* (2004) or Itaba and Koizumi (2007). Relations to local earthquakes are a matter of study. Buntebarth and Chelidze (2005) observed microtemperature variations in deep groundwaters induced by seismic activity. In Southern Italy the monitoring of a 500 meters well discharging thermal water and methane evidenced gas flow and temperature variations induced by local earthquakes (Colangelo *et al*., 2005; 2007).

In the Northern Apennines a 1040 m deep well was monitored with the purpose to evidence possible variations in physico-chemical parameters due to local tectonic / seismic activity.

2 Geological setting

The Northern Apennines are a fold and thrust belt originating from by the convergence between European and African plates. As a result of the convergence all Northern Apennines and in particular the Parma province are subjected to vertical uplift (Argnani *et al*., 2003) horizontal and vertical movements are responsible for local seismicity characterized by frequent seismic events of small and moderate size magnitude. Focal solutions of the moderate seismicity affecting the Northern Apennines show the occurrence of extensional faults trending NNW-SSE (Frepoli and Amato, 1997). Northern Apennines seismicity is mainly located within the upper 20 km, although some events deeper than 50 km have been recorded (Selvaggi and Amato, 1992). In the period 1907-1911 a well for hydrocarbon researches was drilled close to the locality of Miano, in the Municipality of Corniglio, Parma province, Northern Apennines. The so called Miano well is located on an overthrusting basement (Boccaletti et al., 2004), which is seismically active. Main tectonic units recognizable in the area are the Caio unit, the Canetolo unit, the Falda Toscana unit, the Monte Piano unit and the Sporno unit. The Caio unit is of Cretaceous age and is composed by calcareous sandstones. The Canetolo unit is composed by carbonatic and argillitic sandstones of Cretaceous age. The Falda Toscana unit is composed of sandstones of the Macigno formation. The Monte Piano unit is composed by sandstones and marls while the Sporno unit is constituted by carbonatic sandstones.

The following rocks were encountered during drilling:

- interval 0-585 m sandstones with clays of the Canetolo unit
- interval 585-660 m carbonatic sandstones with clays of the Canetolo unit

- interval 660-850 m marls with sandstones of the Marra marls formation
- interval 850-1047 m sandstones with clays of the Pracchiola sandstones formation

During drilling, gas emissions were encountered in all geologic formations; traces of oil were encountered at the depths of 580, 790 and 850 m. Brackish water eruptions were noticed at the depths of 929, 977 and 985 m (Geogas srl., 1995).

After drilling, the well produced a mix of warm brackish water (39 °C) and methane. Methane was utilized in the period 1936-1957 after separation from water. In the period 1958-1990 warm water was utilized for thermal baths but in the present time all equipments are abandoned. Methane gas pressure is 0.3-0.5 kg/cm^2 while water flow rate is 1 L/sec.

3 Seismicity

The Northern Apennines are a seismically active region of the Mediterranean area. Geodynamic processes induce strain and stress variations and, in principle, can affect rock pore pressure values. Local seismicity is characterized typically by events characterized by M<3. We have selected all seismic events within a radius of approximately 12 km from the well. Correlation tests with events located at larger distances shown no effect on fluid emission variations. The frame is bounded by coordinates of 44.2 – 44.65N and 9.85-10.25E. Table 1 shows these events in the period 1/2006-4/2008. Running numbers indicate local seismicity in Figs. 8 to 10.

4 Fluid characterization and genesis

The Miano well water is characterized by a total salinity of 4.48 g/l and is of Sodium-Chlorine-type (Francavilla et al., 1982). Their $^{18}O/^{16}O$ ratio is -8.46 (δD= -58) on July 10, 2004; -8.1(δD= -56) on March 15, 2005; and -8.64 (δD= -58) on May 22, 2005.

Recent samplings evidenced the absence of Tritium (T.U.= 0.5 ±0.4) indicating residence time > 50 years. Thus the Miano hydrologic circuit is fed by meteoric waters enriched in salts in principle deposited in possible evaporitic layers. Since evaporitic layers were not significantly reported during drilling it's more probable that meteoric waters mix at depth with small amounts of fossil hypersaline water linked to hydrocarbon reservoirs. Hypersaline fossil waters were found in many deep hydrocarbon wells of Northern Apennines and of the Po valley. Thus the sensitivity to seismic events of the Miano well can be attributed to the size of the deep hydrologic circuit, to the semiconfined condition of the reservoir and to the mix with a deep non meteoric water component.

The mentioned features agree with those of the gas phase that are of deep origin and released because of vertical migration of the buried hydrocarbons (Borgia *et al*., 1988). Hydrocarbon generation and accumulation are the result of Neogene tectonics with Apennines orogenesis. Most of the gas released in the investigated area is biogenic, characterized by negative values of the isotopic composition of CH_4 (C1): $-76<\delta^{13}C<-60$; $-223<\delta D<-171$, and generally stored in Plio- to Pleistocene sediments. A minor gas amount is thermogenic (CH_4 isotopic composition in the range of $-50<\delta^{13}C<-30$; $-215<\delta D<-153$) and normally found in pre-Pliocene reservoirs (Novelli and Mattavelli, 1988).

The gas phase released from the well of Miano is CH_4-dominated with minor amounts of N_2, CO_2 and He. Oxygen is detectable only in negligible concentrations (see Table 2). The chemical composition clearly shows that the gas derives from the hydrocarbon reservoirs of the Northern Apennine, while the CH_4 isotopic composition ($\delta^{13}C$ and δD) (Tab. 2) displays a possible thermogenic origin. The ^3He-^4He-CH_4+N_2 triangular plot of Fig. 2 provides information on both the composition and the origin of the released gases. The gas phase of Miano is reported in Tab. 2 compared to other methane-dominated gases from dry vents and mud volcanoes in the same area of the Apennine chain (Tosco-Emiliano Apennine). A typical crustal gas (CO_2-dominated) and air are plotted on the graph for reference. The advantage of such a triangular plot is that binary mixing relationships can be easily recognized by linear trajectories. Almost all the samples fall on a binary mixing line between air and a crustal end-member marked by a helium isotopic ratio of 0.04 R_a that clearly represents the isotopic signature of the whole Northern sector of the Apennine chain. The gases from Miano show a further enrichment in crustal-type fluids: besides a similar content of CH_4 and N_2 the Miano gas phase exhibits higher helium content and a lower helium isotopic ratio (0.01R_a) compared to the other gases. This evidence can be interpreted as a consequence of

1) a deeper origin of the Miano gases or

2) the presence of a deep-originated component mixed to the hydrocarbon gas mixture.

5 Technical properties of the station and their recorded parameters

The Miano borehole was drilled for oil and gas exploration in 1911. The depth of around 1000 m was extraordinary for that region in that historical age. Temperature of thermal water of around 39°C gives indications of a slight local geothermal anomaly. Artesian flowing water enters in gas/water separator. The separated gas and water phases flow through plastic pipes of a few centimetres diameter to a house where the sensors for gas- and water flow and water temperature are installed. Figs. 3a and b show the location. The distance between the separator and the house is about 5 m.

A drum gas counter (Ritter) registered gas flow (Fig. 3a) continuously. Water flow was measured by a through flow turbine (Bürkert) in the range of mL/s.

The data of all probes were stored by means of two 16 bit data loggers, including the temperature of the data logger system (ambient temperature) and the battery voltage. The recording interval for the gas and water discharge was 10 minutes while the recording interval for temperature was 30 minutes. Long term recording periods are important constrains for a reliable data interpretation.

6 Variations of the recorded parameter

6.1 The gas flow data

Gas flow data show daily oscillations strongly correlated with the ambient temperature. Fig. 4 shows this effect in a detailed record during August 2007. Normal fluctuations are in the range of ± 3% of the average value. Anomalous periods can be well recognized by simultaneous comparison with ambient temperature data.

6. 2 The water flow data

Water flow through the pipe with a diameter of 6 cm is relatively constant. Frequent fluctuations are generated by the separation process of gas and water bubbles. Flow rate data were recorded every minute and stored as average value of a 10 min recording period.

6. 3 The water temperature data

Water temperature data are probably the most informative one. Data show a daily variation of water temperature. During the transport of thermal water through the pipeline to the house, water temperature was slightly influenced by typical day and night effects induced by direct sunshine on the pipe (heating effects) or rain/snow events (cooling effects). These influences can be identified by comparison with the simultaneous record of the ambient temperature. Therefore, a further temperature sensor was installed close to the pipe on the roof of the house to get optimal information about the daily variations of the ambient temperature since April 2006.

The two temperature probes of Pt100 sensors have an accuracy ± 0.2 K and temporal stability of 0.06%. Normal periodic fluctuations of the two probes can vary in 24 hours due to effects of environmental conditions: 0.5 K for the thermal water and up to 50 K for the temperature on the roof of the house. The limited daily excursion of water temperature allows to assume temperature as a constant parameter except during possible anomalous periods. The occurrence of an anomalous period can be detected by a divergent behaviour in temporal variation of temperatures during the night (e.g. an increasing of water temperature during the cooling night) and/or by an increased water temperature during the day in comparison to normal daily ambient variation. In both cases only positive anomalies can be recognized (Fig. 5). Rain events or snow which induce a short term negative anomaly due to cooling effect on the water pipe can be identified.

We have calculated a 24-hour running average for both temperatures. In this way the daily effect can be easily reduced and strong anomalies are detectable as an increasing in water temperature above the long term average (Fig. 5).
To improve the reliability of the anomaly identification a further statistical evaluation was carried out.

7 Statistical evaluation of data

In order to remove from water temperature data both meteo-climatic effects and influence of the ambient temperature, we applied a statistical procedure, mainly based on evaluation of the power spectral density (PSD) of the signals (Currenti *et al*., 2005; Telesca *et al*., 2005). Fig. 6b and Fig. 6e show PSD in water and ambient temperatures respectively. Several cyclic components (24 hours, 12 hours, 8 hours etc.) are observable and likely mostly linked with meteo-climatic effects. Tidal effects were not observed probably due to the smoothing role of water gas separator device. Periodicities were removed and after normalization a residual time series was obtained (Fig. 6c and Fig. 6f). Due to the dependence of the residual water temperature ($T_{w\text{-}res}$) on the residual ambient temperature ($T_{a\text{-}res}$), shown by a rather high correlation coefficient (R~0.6) (Fig. 6g), the regression line $T_{w\text{-}res\text{-}reg}$ = 3.10063E-8+0.56378$T_{a\text{-}res}$ was calculated and removed from the residual water temperature, obtaining the final residual water temperature $T_{w\text{-}res2}$ (Fig. 6h), whose distribution was fitted by a Gaussian function, obtaining a σ~0.93. To evaluate anomalies, which are defined as values of $T_{w\text{-}res2}$ above a fixed threshold, a 2σ threshold was assumed. The final result is presented in Fig. 6h. Fig. 7 shows the final result applied to the data set of Fig. 5 as example.

8 Results

The presented statistical analysis requires undisturbed long term time series of recorded data. Our available data set suitable for a statistical evaluation are:

- Water temperature: April 4 to June 3, 2006, June 14 to August 29, 2006, December 1, 2006 to September 12, 2007, October 9, 2007 to May 5, 2008;
- Gas flow: May to August 2007 and September 2007 to February 2008;
- Water flow: February to August 2006.

8.1 Water temperature records

A comprehensive analysis of all available water temperature data is shown in Figs. 8, 9 and 10. Anomalous periods above the confidence threshold of two sigma are marked by red triangles in the figures. A comparison with local seismicity is reported in Table 1. Local earthquakes are indicated by green triangles and their identification numbers.

8.2 Gas flow records

Gas flow records show typical daily variations. Anomalous gas emissions were recorded only in few periods. Fig. 11 and 12 represent the gas flow records in undisturbed periods. Only on June 23/24 and July 31- August 2, 2007, two significant anomalies were recorded.

8.3 Water flow records

The record of water flow rate is limited to the period February-August 2006. Statistical analysis by PSD and following residuals evidence interesting periods:

- a more or less constant period between February and June 2006;
- the increasing of flow rate on June 6, 2006 ;
- a peak on June 20;
- a decreasing of flow rate up to the beginning of August;
- an increasing at the end of August.

9 Discussion

Fluid parameters show different variations likely induced by meteorological effects and reservoir processes. In particular ambient temperature due to sunshine effects, can be evaluated in the final result of the thermal water variations so that geogenic induced signals can be well separated. Seismicity in the studied region expresses geodynamic processes which likely influence crustal fluids like the emission at the Miano well. Tidal effects, as typical for strain sensitive aquifers, were not detected in the time series analysis.

Variations in water discharge can be induced by stress perturbations in the reservoir. Correlation tests with local rain data and water discharge showed no indications. Fig. 13 shows water flow variations in connection with seismicity in the studied area related to seismic events listed in Table 1.

The opportunity to interpret a coincidence between single events and anomalous variations, for example on June 6 or August 6, is given but not proofed. The lack of a long term data sets complicates further interpretation.

Further information is obtainable from the analysis of water temperature anomalies.

Several short term anomalies of water temperature were observed. Water temperature can be changed due to variations of the mixing process between different water / gas reservoirs with different temperatures, and/or variations in transport velocity. Anomaly durations lasted from 15 hours up to three days. A comparison of these anomalies with the local seismicity could explain their occurrence.

Fig. 14 shows a geographic overview of the distribution of epicenters around the Miano well (M) listed in Table 1 within a frame of about 450 km^2.

To increase robustness of evaluation only anomalies greater than a 3 sigma threshold on residual time series were considered. This evaluation evidences anomalies in four periods showed in Fig. 15 and 16. In particular the comparison with seismic events close to Miano evidences:

- anomaly period of April 2006 - no seismic indication in the near field;
- anomaly period of June 16, 2006 - seismic events 35 and 37 (June 19 and 24);
- anomaly period of January 14, 2007 – seismic event 58 (February 24);
- anomaly period of June 18, 2007 – seismic events 70 and 71 (June 22 and 28).

Fig. 17 shows the geographic distribution of considered seismic events, the well of Miano and the fault segment of river Parma, probably responsible of observed anomalies.

An additional coincidence of anomalies was also recorded in June 2007. An anomaly in the gas flow was recorded 10 hours after the seismic event (Fig.18). The occurrence of a temperature anomaly on June 18-20, 2007, as a possible precursor effect of a local seismic event on June 22, followed by a post seismic gas flow anomaly on June 23/24 evidences that the strain process influenced both fluid reservoirs. Some hours after the shock gas emission increased from 50 to 53 l/min. The registration of anomalies on two different parameters was observed only one time. The epicenter of the seismic event no. 70 occurred on June 22 is located on the fault zone along the river Parma shown in Fig. 17. The seismogenic process characterized by a short distance between the epicenter and the borehole of around 4 km was able to influence both fluid reservoirs inducing an increasing of warm water output during the stress build up and by an increased gas release after the stress relaxation.

10 Conclusions

Monitoring of fluid emissions at the Miano well during three years evidenced some anomalous fluid emissions probably related to local geodynamic processes. Statistical analysis of data by using the power spectra density analysis supports the anomaly detection by sigma threshold analysis. Water temperature shows the largest number of recorded anomalous variations. Many seismic events in the region occurred within a radius of about 12 km to the location cannot be significantly related to all of the recorded water temperature anomalies. Further analysis, using a 3 sigma threshold for anomaly indication and events located within 8 km southeast of Miano station, revealed significant correlation between anomalous values in water temperature and narrow earthquakes. In particular some anomalous values occurred before seismic events. The fault zone indicated by the river Parma could be a preferential transport path of the pore pressure signal. Active geodynamic processes in Northern Apennines act as a permanent force able to influence deep fluid reservoirs and fluid filled fractures. Pore pressure perturbation can induce the observed anomalies and in particular an increased output of thermal water.

Acknowledgments

One of the authors, L. Telesca, acknowledges the financial support received in the framework of the bilateral agreement CNR/DFG.

References

Argnani, A., Barbacini, G., Bernini, M., Camurri, F., Ghielmi, M., Papani, G., Rizzini, F., Rogledi, S.,Torelli, L., 2003. Gravity tectonics driven by quaternary uplift in the Northern Apennines: insights from the La Spezia-Reggio Emilia geo-transect. Quaternary International 101, 13-26.

Boccaletti, M., Bonini, M., Corti, G., Gasperini, P., Martelli, L., Piccardi, L., Severi, P., Vannucci, G., 2004. Carta sismotettonica della Regione Emilia- Romagna - Note Illustrative, Consiglio Nazionale dlle Richerche, Firenze.

Borgia, G. C., Elmi, C., Ricchiuto, T., 1988. Correlation by genetic properties of the shallow gas seepages in the Emilian Apennine (Northern Italy). Organic Geochemistry 13, 319-324.

Buntebarth, G.,Chelidze, T., 2005. Time-dependent microtemperature and hydraulic signals associated with tectonic/seismic activity. Georgian Academy of Sciences, Tbilisi.

Colangelo, G., Heinicke, J., Koch, U., Lapenna, V., Martinelli, G., Telesca, L., 2005. Results of gas flux records in the seismically active area of Val d'Agri (Southern Italy). Annals of Geophysics 48, 55-63.

Colangelo, G., Heinicke, J., Lapenna, V., Martinelli, G., Mucciarelli, M., Telesca, L., 2007. Investigating correlations of local seismicity with anomalous geoelectrical, hydrogeological and geochemical signals jointly recorded in Basilicata Region (Southern Italy). Annals of Geophysics 50, 527-538.

Currenti, G., Del Negro, C., Lapenna, V., Telesca, L., 2005. Fluctuation analysis of the hourly time variability of volcano-magnetic signals recorded at Mt. Etna Volcano, Sicily (Italy). Chaos Solitons and Fractals 23, 1921-1929.

Etiope, G., Martinelli, G., Caracausi, A., Italiano, F., 2007. Methane seeps and mud volcanoes in Italy: Gas origin, fractionation and emission to the atmosphere. Geophysical Research Letters 34, doi 10.1029/2007gl030341.

Francavilla, F., Gorgoni, C., Magoni, G., Martinelli, G., Sighinolfi, G.P., Zecchi, R., 1982. Caratteri geologici e geotermici di alcune aree appenniniche. In " Caratteri Geoidrologici e Geotermici dell'Emilia-Romagna"- Regione Emilia Romagna-Consiglio Nazionale delle Ricerche, Pitagora Editrice, Bologna.

Frepoli, A., Amato, A., 1997. Contemporaneous extension and compression in the Northern Apennines from earthquake fault-plane solutions. Geophysical Journal International 129, 368-388.

Geogas srl., 1995. Permessi di ricerca Palanzano e Berceto, Parma.

Igarashi, G., Tohjima, Y., Wakita, H., 1993. Time-Variable Response Characteristics of groundwater radon to earthquakes. Geophysical Research Letters 20, 1807-1810.

INGV web catalogue: www.ingv.it.

Itaba, S., Koizumi, N., 2007. Earthquake-related changes in groundwater levels at the Dogo hot spring, Japan. Pure and Applied Geophysics 164, 2397-2410.

Koizumi, N., Kitagawa, Y., Matsumoto, N., Takahashi, M., Sato, T., Kamigaichi, O., Nakamura, K., 2004. Preseismic groundwater level changes induced by crustal deformations related to earthquake swarms off the east coast of Izu Peninsula, Japan. Geophysical Research Letters 31, doi 10.1029/2004gl019557.

Kümpel, H. J., 1992. About the potential of wells to reflect stress variations within inhomogeneous crust. Tectonophysics 211, 317-336.

Novelli, L., Mattavelli, L., 1988. Geochemistry and Habitat of Oils in Italy. Aapg Bulletin-American Association of Petroleum Geologists 72, 229-229.

Roeloffs, E. A., 1998. Persistent water level changes in a well near Parkfield, California, due to local and distant earthquakes. Journal of Geophysical Research-Solid Earth 103, 869-889.

Selvaggi, G., Amato, A., 1992. Subcrustal earthquakes in the Northern Apennines (Italy) - evidence for a still active subduction. Geophysical Research Letters 19, 2127-2130.

Telesca, L., Colangelo, G., Lapenna, V., Macchiato, M., 2005. Fractal approaches in investigating the time dynamics of self-potential hourly variability. International Journal of Earth Sciences 94, 285-300.

Wang, R. J., Woith, H., Milkereit, C., Zschau, J. C., 2004. Modelling of hydrogeochemical anomalies induced by distant earthquakes. Geophysical Journal International 157, 717-726.

Woith, H., Wang, R. J., Milkereit, C., Zschau, J., Maiwald, U., Pekdeger, A., 2003. Heterogeneous response of hydrogeological systems to the Izmit and Duzce (Turkey) earthquakes of 1999. Hydrogeology Journal 11, 113-121.

Tables

Table 1: List of all seismic events in the frame of a latitude of 44.2 to 44.65 and a longitude of 9.85 to 10.25 N, according the web catalogue of INGV.

#	Latitude	Longitude	Foci in km	Magnitude	Year	Month	Day
1	44,451	9,895	8,4	3,4	2006	4	1
2	44,237	10,202	9,5	1,5	2006	4	2
3	44,241	10,183	10	1,3	2006	4	2
4	44,227	10,238	7,8	1,4	2006	4	2
5	44,243	10,243	10,1	1,2	2006	4	2
6	44,219	10,145	5	1,7	2006	4	2
7	44,248	10,178	9,5	2	2006	4	2
8	44,244	10,158	9,4	1,7	2006	4	3
9	44,543	9,96	10	1,6	2006	4	14
10	44,583	10,043	8,5	2,7	2006	4	17
11	44,579	10,051	10,7	2,5	2006	4	17
12	44,564	10,046	10	1,7	2006	4	17
13	44,306	10,246	11,1	1,2	2006	4	27
14	44,303	10,216	10,9	1,6	2006	4	28
15	44,599	10,082	5	1,9	2006	4	28
16	44,63	10,096	10	1,2	2006	4	28
17	44,569	10,036	6	1,6	2006	4	28
18	44,588	10,07	5	1,8	2006	4	28
19	44,596	10,055	3,2	2,2	2006	4	28
20	44,626	10,033	10	1,5	2006	4	28
21	44,595	10,063	5,7	2,1	2006	4	28
22	44,603	10,071	2,4	1,9	2006	4	28
23	44,628	10,084	8,8	2,7	2006	5	1
24	44,545	10,01	10	1,8	2006	5	1
25	44,574	10,042	7,7	1,7	2006	5	1
26	44,611	10,083	10	1,7	2006	5	1
27	44,601	10,067	6,2	2,5	2006	5	1
28	44,582	10,036	10	1,6	2006	5	1
29	44,623	10,03	10	1,3	2006	5	2
30	44,512	9,985	10	1,8	2006	5	4
31	44,592	10,04	10	1,5	2006	5	7
32	44,582	10,059	6,7	2,3	2006	5	10
33	44,279	10,069	8,1	0,9	2006	5	29
34	44,288	10,212	11	0,9	2006	6	7
35	44,476	10,012	5,9	2,6	2006	6	19
36	44,424	10,002	5,2	1,3	2006	6	24
37	44,474	10,011	10	1,7	2006	6	24
38	44,301	10,09	5	2,7	2006	7	6
39	44,518	10,086	25,7	1,8	2006	7	13
40	44,401	9,96	9,1	1,5	2006	7	14
41	44,389	9,951	16,8	2,7	2006	7	14
42	44,648	10,165	10	1,9	2006	7	15
43	44,634	10,212	10	2	2006	7	16
44	44,511	9,856	10	1,7	2006	7	16
45	44,24	10,012	10	2,1	2006	7	20
46	44,425	9,997	10	1,3	2006	8	6
47	44,231	10,056	5	3,1	2006	8	10
48	44,55	9,916	10	1,8	2006	9	2
49	44,604	10,238	32,7	2,2	2006	9	7
50	44,251	10,046	10	1,1	2006	9	22
51	44,253	10,121	10	0,8	2006	9	30
52	44,354	10,162	9,3	1,1	2006	10	15
53	44,55	10,052	10	1,8	2006	10	21
54	44,507	10,203	22,9	1,8	2006	12	15
55	44,616	10,028	5,3	2,3	2006	12	30
56	44,214	10,054	10	1,3	2007	2	4
57	44,466	9,855	10	2,7	2007	2	11

58	44,473	10,04	10	2,3	2007	2	24
59	44,529	10,178	10,1	2,3	2007	2	24
60	44,54	10,113	10	1,8	2007	2	24
61	44,539	10,06	6,8	2,4	2007	3	7
62	44,603	10,158	23,7	1,2	2007	3	14
63	44,646	10,12	10	1,9	2007	3	25
64	44,358	10,204	9,9	1,3	2007	4	30
65	44,355	9,984	10	1,3	2007	5	7
66	44,254	10,101	8,3	1,6	2007	5	24
67	44,269	9,933	10,2	1,6	2007	6	1
68	44,525	10,124	10	1,9	2007	6	2
69	44,318	10,204	10,4	2	2007	6	4
70	44,485	10,053	8,2	3	2007	6	22
71	44,476	10,075	21,5	2,3	2007	6	28
72	44,215	10,21	6,3	1,8	2007	8	4
73	44,218	10,219	6,4	1,9	2007	8	5
74	44,237	10,243	12,8	1,2	2007	8	8
75	44,601	10,233	10,5	1,8	2007	8	11
76	44,312	10,205	10,3	1,7	2007	8	15
77	44,272	9,89	10	1,2	2007	8	27
78	44,271	10,117	6,4	1,1	2007	10	6
79	44,497	10,233	24,9	1,5	2007	10	20
80	44,212	10,082	10	1,3	2007	11	6
81	44,364	10,15	10	2,6	2007	12	16
82	44,209	10,08	10,8	1,6	2007	12	21
83	44,479	10,213	25,7	2,3	2007	12	24
84	44,512	10,176	3,9	4,1	2007	12	28
85	44,475	10,217	25,9	2,5	2007	12	28
86	44,518	10,216	20	1,7	2007	12	28
87	44,615	10,246	28,6	2	2007	12	28
88	44,466	10,197	28,3	2,1	2007	12	29
89	44,484	10,23	23,2	2,3	2007	12	30
90	44,507	10,245	22,8	1,8	2007	12	30
91	44,484	10,212	24,4	3,1	2007	12	31
92	44,484	10,241	26,5	2,8	2007	12	31
93	44,506	10,248	24,9	1,7	2007	12	31
94	44,492	10,202	10,5	2,1	2008	1	1
95	44,499	10,244	22,9	2	2008	1	1
96	44,489	10,228	22,6	2,3	2008	1	9
97	44,503	10,235	23,9	1,4	2008	1	25
98	44,529	10,236	17,2	1,8	2008	1	26
99	44,536	10,127	10	2	2008	1	31
100	44,203	10,228	9,3	2,5	2008	1	31
101	44,226	10,126	10,6	1,7	2008	2	9
102	44,553	10,241	24,4	1,6	2008	2	10
103	44,531	10,231	22,3	1,6	2008	2	14
104	44,528	10,221	23,6	1,7	2008	2	14
105	44,524	10,169	9,5	2,1	2008	2	17
106	44,567	10,224	23,3	1,6	2008	2	18
107	44,51	10,234	22,7	2,6	2008	3	29
108	44,64	9,982	18,3	3,2	2008	4	3
109	44,299	10,034	10	1,8	2008	4	22

Tab 2: see extra file

Figures

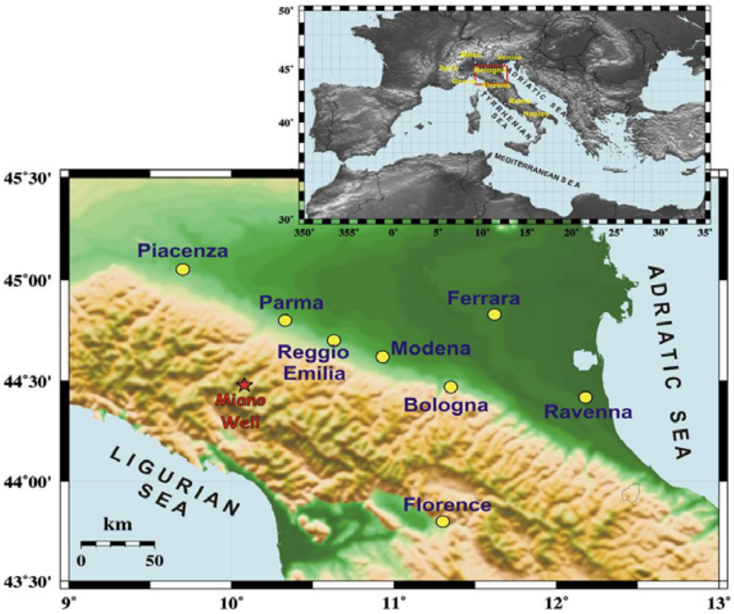


Fig 1: Location of the Miano well (red star) in the Northern Apennine belt.

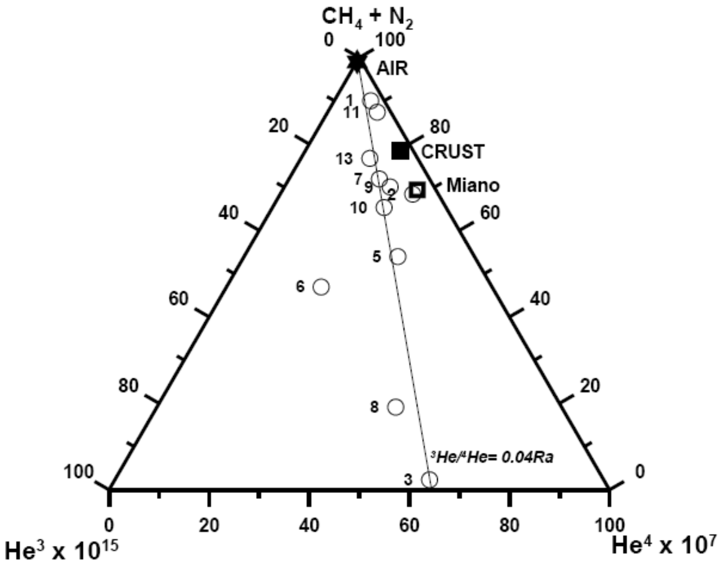


Fig. 2: ^3He-^4He-CH_4+N_2 triangular plot: CH_4 and N_2 are plotted together as they represent the typical gas species in crustal-hydrocarbon environment. The compositions of air and a crustal, CO_2-dominated gas, are reported. The plotted composition account for gases from mud volcanoes and wells of the Northern Apennine. Numbers indicating the sampling site are from Tab. 2.

a)  b) 

Fig. 3 a): The Miano station with the gas/water separator on the left site, the tube to the house and the drum gas counter on the right site. 3b): The water outlet at the house with the water temperature probe and the water flow sensor.

Fig. 4: Gas flow record compared to daily ambient temperature. Gas flow oscillations are limited when ambient temperature excursion is low.

Fig. 5: Records of water temperature (blue) and ambient temperature (black) show typical daily variations except on April 21/22, when water temperature increased during the night and following day. The 24-hours running average display this anomaly as a significant increase in water temperature (light blue) and a relative constant ambient temperature (brown).

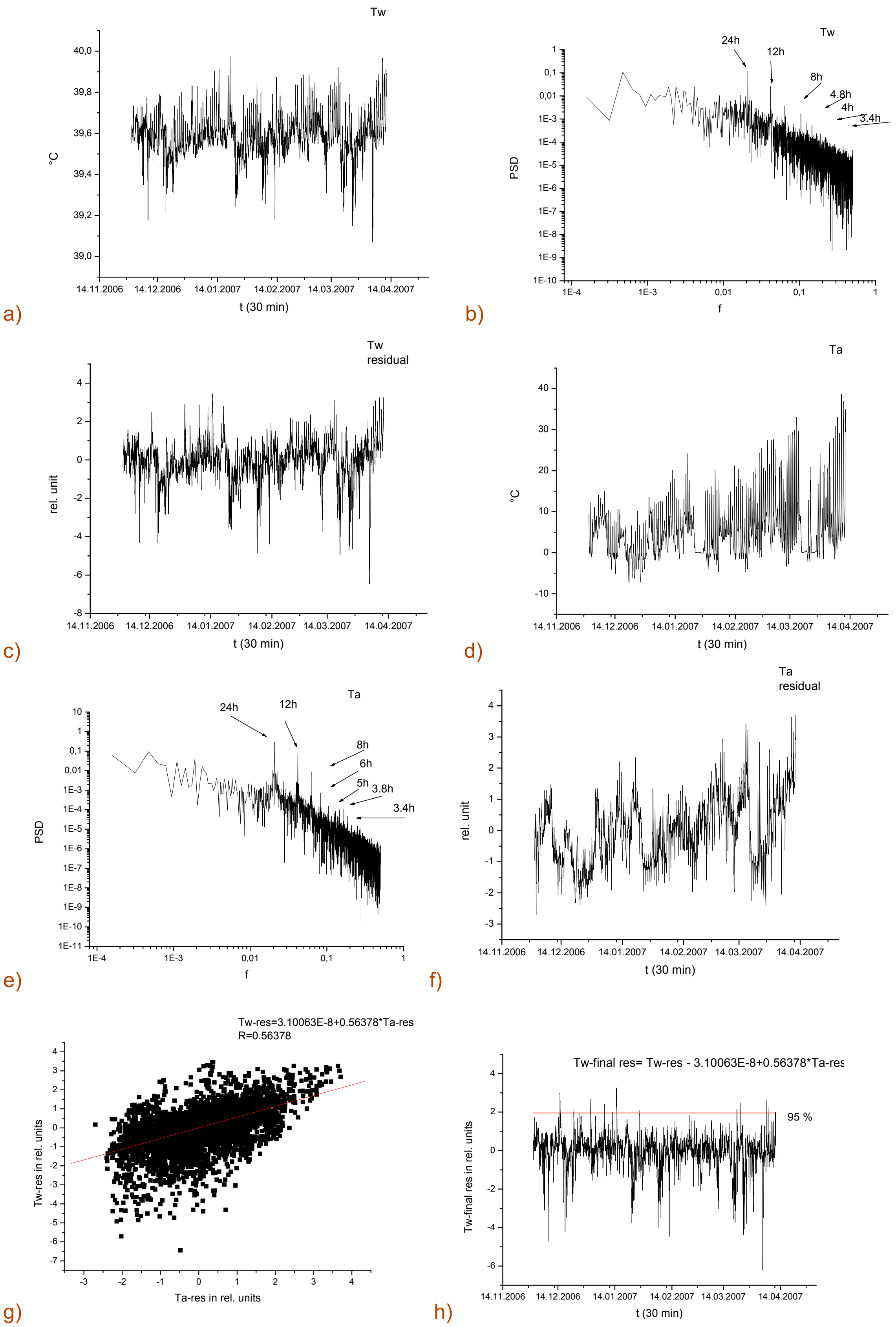
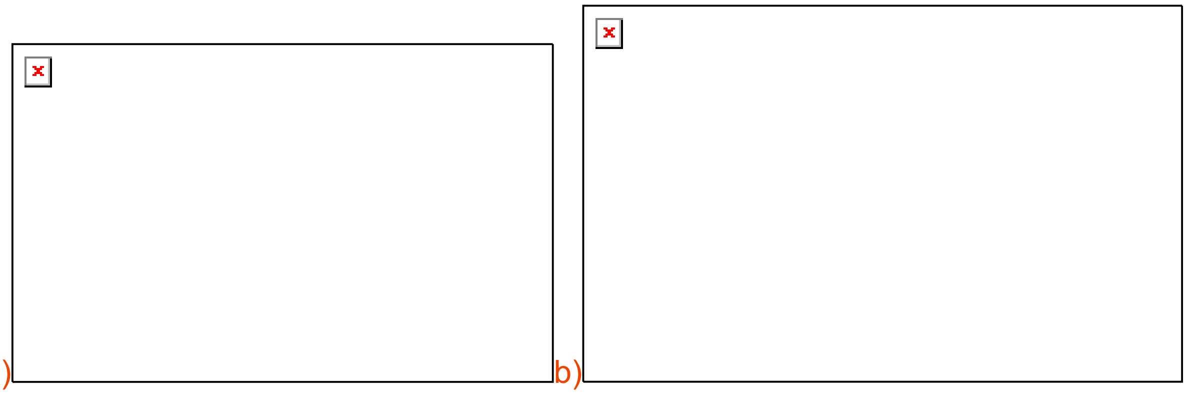


Fig 6a-h: Example of the recorded data sets of water and ambient temperature in the period of November 2006 to April 2007. The power spectra (b and e) were calculated from the original data of water temperature Tw (a) and ambient temperature Ta (d). The final residual data Tw-res (c) and Ta-res (f) display time series after the removed periodicities. The regression function of both Tw-res and Ta-res is used to calculate the difference between the recorded Tw-res and the calculated Tw-res from the ambient temperature. In that way we reduce the daily influence of the ambient temperature in the residuals. The result (h) is a time series of the final Tw-residual without ambient influence. An anomaly indication is possible by calculation of a threshold, for example the two sigma value. The 95% confidence threshold (2 σ) can separate anomalous high temperature data from "normal" variations. Periods with final residual values higher than the 2 σ value will be therefore considered as anomalous in comparison to all other data.

Fig. 7: Example of data evaluation by running average method (Fig. 5) and statistical analysis of residuals. The residual values (red line) above the 2 sigma threshold indicate an anomalous water temperature increase during one day.

Fig. 8: Part one of the original data of water temperature (blue), ambient temperature (black) (above) and the result of the statistical anomaly evaluation (below). The running average values (blue and black) and the anomalous residuals (>2sigma as red triangles) are presented for the period April-August 2006. A short technical data gap (storage overflow) in June is visible as straight data line. The numbers of seismic events are according to Table 1.



a) b)

Fig. 9: Part two of original data of water temperature (blue), ambient temperature (black) and the result of the statistical anomaly evaluation in the period November 2006-September 2007.

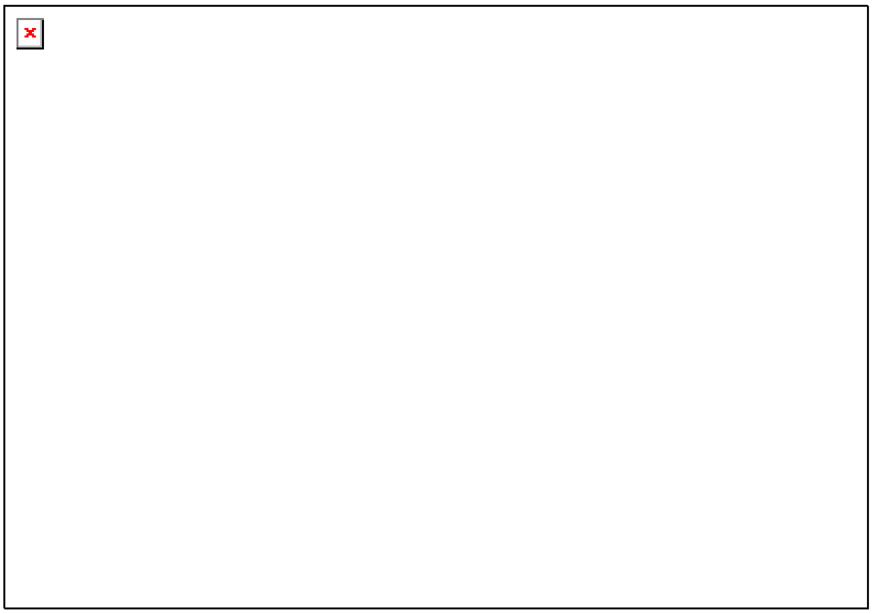


Fig. 10: Part three of the original data of water temperature (blue), ambient temperature (black) and the result of the statistical anomaly evaluation and seismicity in the period October 2007- May 2008.

Fig. 11: Gas flow records in the period May-August 2007. Two anomalous enhanced flow rates are visible: June 23-24 and July 31 - August 2.

Fig. 12: Gas flow record from September 2007 to February 2008.

Fig. 13: Water flow record from February to the end of August 2006. The calculated residuals (red) reflect different trends in the flow rate as well as minima and maxima values. The anomalous increasing at the beginning of June could be interpreted as result of seismic events on these days (no. 33 ,34) but could be also part of a seismic active period occurred since April 2006 (see Table 1).

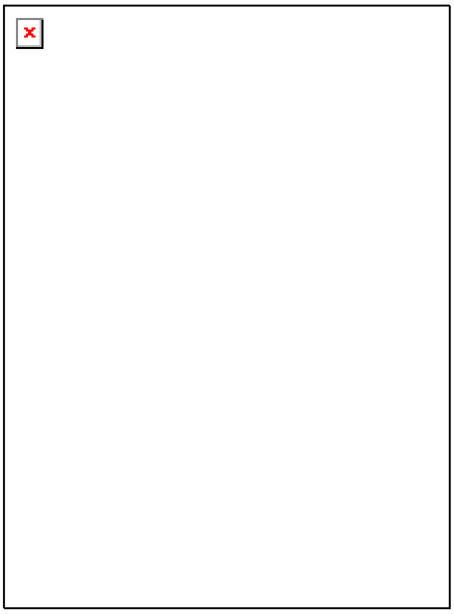


Fig. 14: Distribution of epicenters around the location Miano (M). Labels are according to labels in Figs. 8 to 10 and row numbers in Table 1. The red rectangle indicate the region of Fig. 17.

Fig. 15: Comparison of the running average temperature data (blue –water, black-ambient temperature, according to Fig. 8)with the indications of final residuals above the 3 sigma threshold (red) and their temporal vicinity of local events, shown also in Fig. 16.

Fig. 16: Comparison of the running average temperature data (blue –water; black-ambient temperature, according Figs. 9 and 10) with the indications of final residuals above the 3 sigma threshold (red) and their temporal vicinity of local events shown also in Fig. 17.

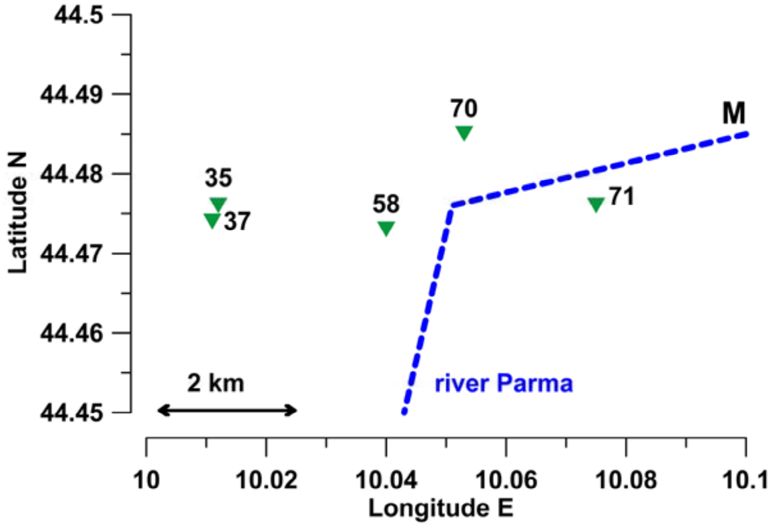


Fig. 17: Distribution of epicenters near Miano (M). The events occurred along the fault line of Parma river. The label numbers are according to Table 1.

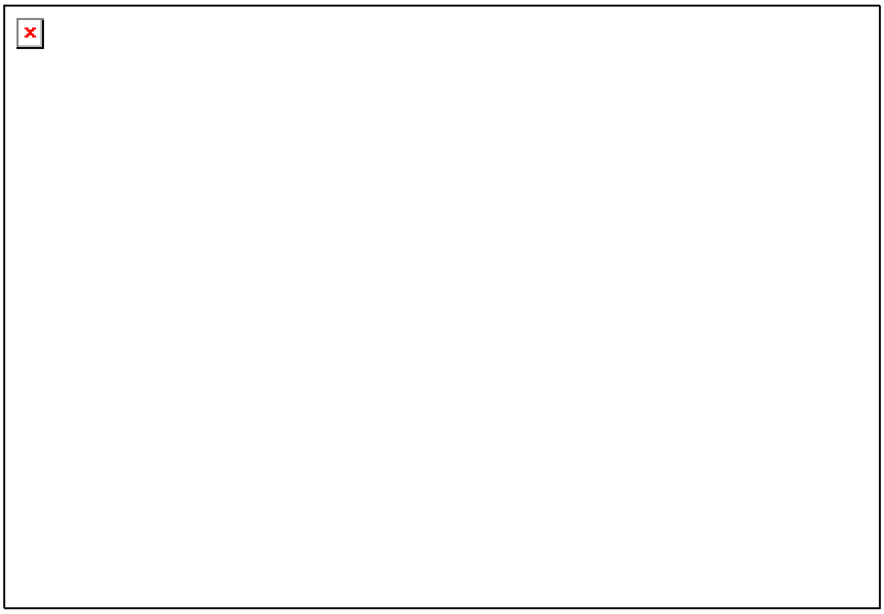


Fig. 18: Recorded anomalies in both water temperature and gas flow (pink). The comparison of the running average temperature data (blue –water; black-ambient temperature) with the indications of final residuals (red) shows an anomaly before the event no. 70. After this local event the gas flow increased significantly for two days.