Radon measurements in Friuli (N.E. Italy) and earthquakes: first results

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ABSTRACT In 1995, a radon survey station was set up in the Friuli area (north-eastern Italy). Radon concentration is monitored with a sampling interval of 3 hours. In this work the data recorded from 1996 to 1999 are analysed in a search for a possible correlation between radon anomalies and local earthquakes. The minimum earthquake magnitude required to obtain a radon anomaly at a given distance from the radon recording device is determined. In this way, the selected earthquakes, especially if large, can have their epicentres up to many kilometres away from the radon site. Every datum exceeding the 2-sigma threshold has been considered as an anomalous value. Significant variations in radon concentration have been observed in relation to local events. The most interesting seismic events are characterized by epicentres that are less than 40 km from the radon station and with a magnitude greater than 3.0, followed by seismic series.

1. Introduction

Radon is a natural gas produced, in soil, by the radioactive decay of the radium element, produced in turn by uranium. Radioactive decay is a natural, spontaneous process in which an atom of one element decays or breaks down to form another element by losing atomic particles. Radon itself is radioactive because it also decays losing an alpha particle and forming the element polonium. The half-life of radon is 3.8 days.

Because radon is a gas, it has much greater mobility than uranium and radium, which are fixed in the solid matter of rocks and soils. Radon can leave the rocks and soils more easily by escaping into fractures and openings in rocks and into the pore spaces between grains of soil. It can travel a great distance before it decays and gathers, in high concentrations, also inside a building. Radon moves more rapidly through permeable soils, such as coarse sand and gravel, than through impermeable soils, such as clays. Fractures in any soil or rock allow radon to move more quickly. The spread of radon in water is slower than in air. Radon travels by diffusion or by convection through a gas carrier (as methane, carbon dioxide and nitrogen).

Radon measurements have shown to be useful in many sectors. Anomalous high values of radon concentration have been observed along active faults in many parts of the world. To test this radon behaviour, soil-air radon surveys across several faults in California have been carried out (King *et al.*, 1996). The results have confirmed the existence of this relationship and have pointed out that radon maps are useful to locate fracture zones and rocks with uranium. It is used as a natural tracer because it has been demonstrated (Semprini *et al.*, 2000) that radon decreases in the presence of residual NAPL (non-aqueous-phase liquids in the subsurface). The problem of radon indoors has become very popular in the last years because medical and environmental studies have pointed out that radon can be a health risk, primarily as a cause of lung cancer. Radon enters a home through cracks in floors and walls, construction joints, or can be contained in the building material and can reach high concentrations indoors (Nero and Nazaroff, 1984; Vaupotic *et al.*, 1994; Friedmann *et al.*, 1996). Finally, it is useful as a seismic precursor, which is the object of this work, because changes of the radon concentration in water and in soil were observed before earthquakes took place.

What happens exactly underground, some minutes or several months before an earthquake, is unknown and it is difficult to make deterministic predictions. There are, up to now, many difficulties in understanding the physics of earthquakes. Only interdisciplinary methods can contribute to the knowledge of the stress status of tectonic structures (Martinelli, 2000).

The purpose of this work is to contribute to the knowledge of the process of the earthquakes' preparation and to the study of the neotectonic characteristics through the possible relations between radon emission and earthquake occurrences. Since there is a correspondence between gas distribution through the soil and geomorphologic tectonic outlines, we suppose that the gas efflux towards the surface is controlled by the tectonic structures. The faults and the fractures are their preferential path and their identification can be facilitated by the gas concentration study.

The first radon changes in hot springs, used as precursors, were detected in Japan before the M 5.5 1966 Tashkent earthquake. The radon contents of water from a deep well in the epicentral region showed a quick increase, a stationary value until the earthquake took place and a return to its normal value soon after. Similar results, in agreement with the dilatancy model (Scholz *et al.*, 1973), have been detected also in other sites (Wakita *et al.*, 1980; Zmazek *et al.*, 2002; Richon *et al.*, 2003).

Later on, numerous studies, in China, Japan, USA, etc., suggested that the measurement of radon concentration in well water and soil gas could be an efficient tool for understanding the geodynamic process and the extent of the zone involved. Changes in radon concentration were considered as a seismic precursor also for the Haicheng earthquake of 1975, that was the best example of a successful forecast, while the Tangshan earthquake of 1976 was not predicted because the number of precursor phenomena were not considered statistically valid (Mogi, 1990; Che *et al.*, 1996). The earthquakes in Turkey, Taiwan and Parkfield can be considered prevision failures, especially using statistical methods (http://quake.wr.usgs.gov/research/parkfield/index.html; Dragoni, 1999). Before utilizing radon data to detect tectonic activity, it is necessary to locate the non tectonic influences on radon. Rainfall, pressure, and air and water temperatures can influence the radon datum, especially if it is recorded close the surface of the Earth.

Fluctuations of the underground water level are considered an earthquake precursor: many fluctuations in the water level have been observed before earthquakes. Before the M 7.8 1976 Tangshan earthquake, in China, the underground water level fluctuated for several years and then the average water level increased before the earthquake. Other fluctuations have been described in Japan, USSR, and USA (Rikitake, 1976). It is useful to verify the groundwater level in the well where the radon concentration is monitored.

At the present time, radon monitoring programs are operating in several tectonically active regions on Earth, such as Central America, China, Mexico, Japan, Philippines, Greece, etc. (Li and Li, 1996; Paparo and Gregori, 2003; Richon *et al.*, 2003).

In 1995, a radon survey station was set up in Friuli (north-eastern Italy) and it recorded continuously from 1996 to 1999. The first data (1996-1997) have already been published (Riggio *et al.*, 2001). The results have pinpointed the quality of the radon site and radon anomalies associated with earthquakes. Furthermore, the seasonal trend of the radon behaviour was evident. The other meteorological causes are uninfluential if the values over the 2-sigma (standard deviation) line are considered. The same data are analysed here with different methods and compared with the more recent data (1998-1999).

2. Seismotectonic outlines

The study region is constituted by Alpine and Dinaric structures (Fig. 1). The Italian sector is characterized by E-W trending overthrusts crossed by subvertical faults with N-S direction. To the east, the contact with NW-SE trending Dinaric structures occurs. These last are characterised, often, by trascurrent activity (Slejko *et al.*, 1989; Del Ben *et al.*, 1991). The study area is situated between the Periadriatic overthrust and the Gail river.

The radon station (marked by a black square in Fig. 1) is installed at Cazzaso, at 670 m above the sea level and a few kilometres to the north of Tolmezzo, an important crossing between the Alpine and Dinaric structures, and to the north of the most seismically active zone. Around Cazzaso, there is the thermal spring and other springs are also known in the Arta area, which is famous for its thermal baths. The water is cold and sulphurous and, the temperature and chemical contents are constant in the water. The flat behaviour of Ca^{2+}, HCO_3 and SO_4^{2-} with time is demonstrated (Cortecci *et al.*, 2000) as produced by the equilibrium of water with calcite and gypsum of the Werfen (Triassic) and Bellerophon Formation (Upper Permian).

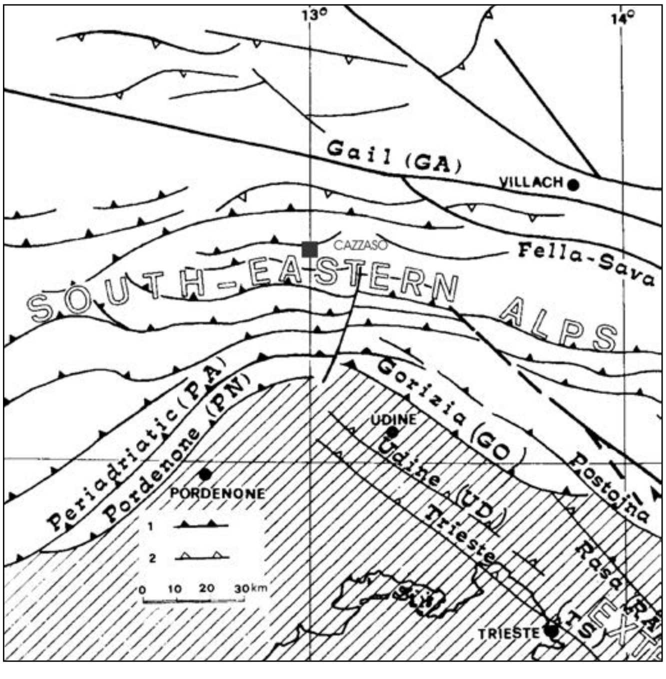

Fig. 1 - Seismotectonic outline of the study region (from Del Ben et al., 1991). The radon station is marked by the black square. 1 = Active thrust-faults and active transcurrent thrusts of the External Dinarides. 2 = Inactive thrust-faults and transcurrent thrusts.

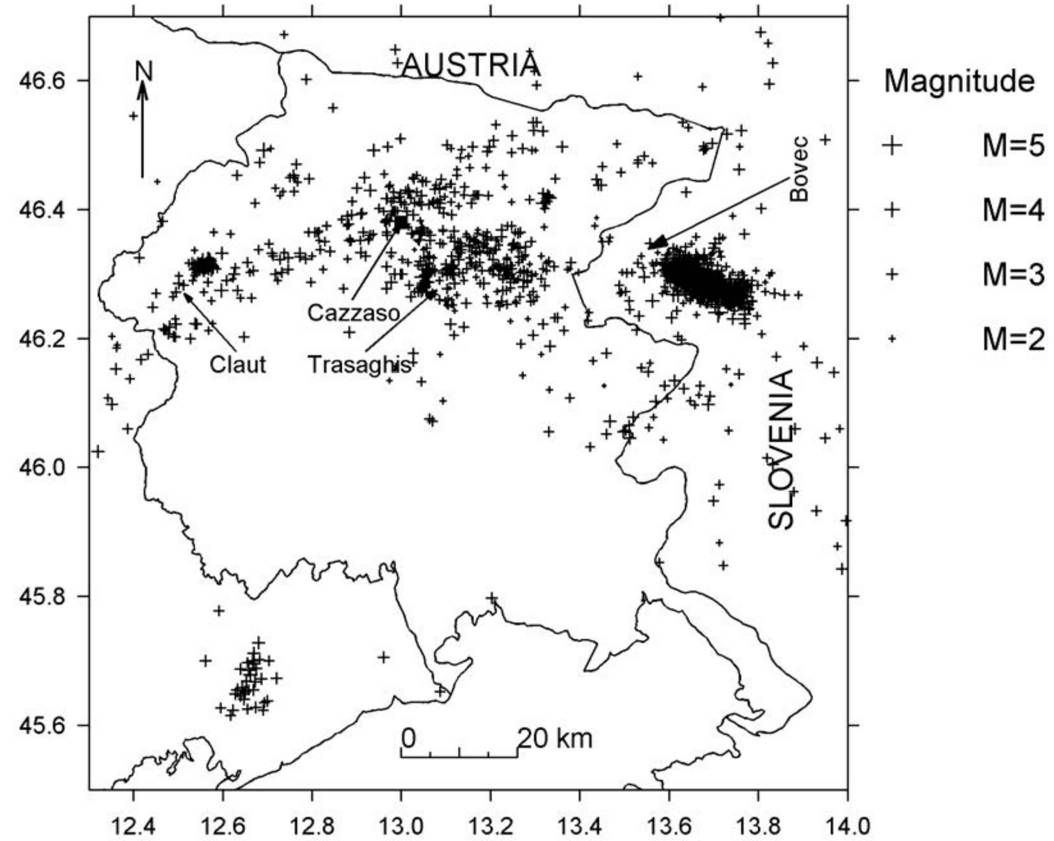

Fig. 2 - Epicentres of the earthquakes recorded during the period 1996-1999 in the studied area.

Large historical earthquakes occurred at Tolmezzo on October 20, 1788 and on March 27, 1928 both with maximum intensity VII-IX MCS. Westwards, the Raveo earthquake in 1700 was characterized by a maximum intensity of X degrees MCS, but its macroseismic area was very small. More recently, earthquakes happened on February 3, 1949 at Paularo and on April 26, 1959 at Arta, both with an intensity of VIII MCS (all the epicentral localities are less than 20 kilometres from Cazzaso). Present day seismicity is concentrated, prevalently, to the south of the survey site.

The epicentres of the earthquakes, recorded by the regional seismometric network (OGS, 1996-1999), during the period 1996-1999 are reported in Fig. 2. The symbol for the dimension is proportional to the magnitude. The Claut, Trasaghis, and Bovec seismic sequences can be seen moving from west to east.

3. Data acquisition and analysis

The survey site is equipped with a continuous radon recording, Lucas scintillation cell type. The operating modalities are continuous and grab sampling, the sensibility is of 4 Bq/m^3.

Batteries recharged by two solar panels provide the power. The air is inhaled by pumping, from a 40.5-m deep well with a 9 cm diameter, at a 7 m depth. The groundwater level is about 17 m deep from the top of the well. The well is closed by a gully-hole. Sampling intervals are of 3 hours.

The stratigraphy of the first metres from the ground level shows an alternation of sandy-clayey mud, gravel in the superficial 17 metres, and harder clays, sands, marn siltiti with calcite follow. The rainfall, the temperature and the groundwater level are controlled.

Unfortunately there were some breaks in the radon recording for technical reasons.

The radon data are related to the periods January 1996 - December 1997, February - October 1998, and June - November 1999.

The seismometric data used in the present study were recorded by the seismometric network of Friuli-Venezia Giulia, managed by OGS (OGS, 1996-1999), and by the Trieste broad band seismographic station, managed by OGS and Trieste University. In addition, the data from the NEIC database (www.NEIC.USGS.gov) were used for earthquakes not located by the regional network.

What earthquakes to investigate was done according to Hauksson and Goddard (1981), as already described by Dobrovolsky *et al.* (1979), taking all events that satisfy the condition

$$M \geq 2.4 \log_{10} D - 0.43$$

where M is the minimum magnitude required to obtain a radon anomaly at distance D (km).

In Fig. 3, the radon concentration (a), the daily sampled atmospheric pressure (b), the air temperature (c), and the daily sampled radon concentration with seasonal trend calculated by the linear best fit (d) are reported. One can see a particular shape of the radon concentration between February 22 and March 10, 1996. Between July and September 1997, high values of radon are evident in comparison with those of the 1996 summer period. In September 1997, the Umbria seismic series occurred and in April 1998 the Bovec earthquake (Slovenia) happened. The increase of the radon concentration from winter to summer and the following decrease in the second part of the year is evident.

The correlation coefficient between the radon concentration and the pressure is –0.14. The pressure data are referred to an aeronautical meteorological station located at 30 km from Cazzaso and at an elevation of 770 m above sea level (www.italian.wunderground.com). The correlation coefficient between the radon concentration and the air temperature is 0.59, showing that the two are strongly correlated, owing to the similar seasonal behaviour. To avoid the large oscillations of the radon concentration in this period, resampling to daily values (for each day the mean value is considered) has been introduced. This operation increases the correlation coefficient to 0.67. The reported trend lines are useful to avoid the proportional seasonal changes of the mean value and deviations.

In Fig. 4, the daily values of the radon concentration without the seasonal trend (a), the magnitude of earthquakes selected according to the Hauksson and Goddard (1981) criterion (b), the rainfall (c), and the groundwater behaviour above sea level in the same well during the period 1996-1997 (d) are reported. The correlation coefficient between the radon concentration and the air temperature without the seasonal trends is 0.11 confirming the seasonal influence. The correlation coefficient between the radon concentration and the groundwater is 0.01. From

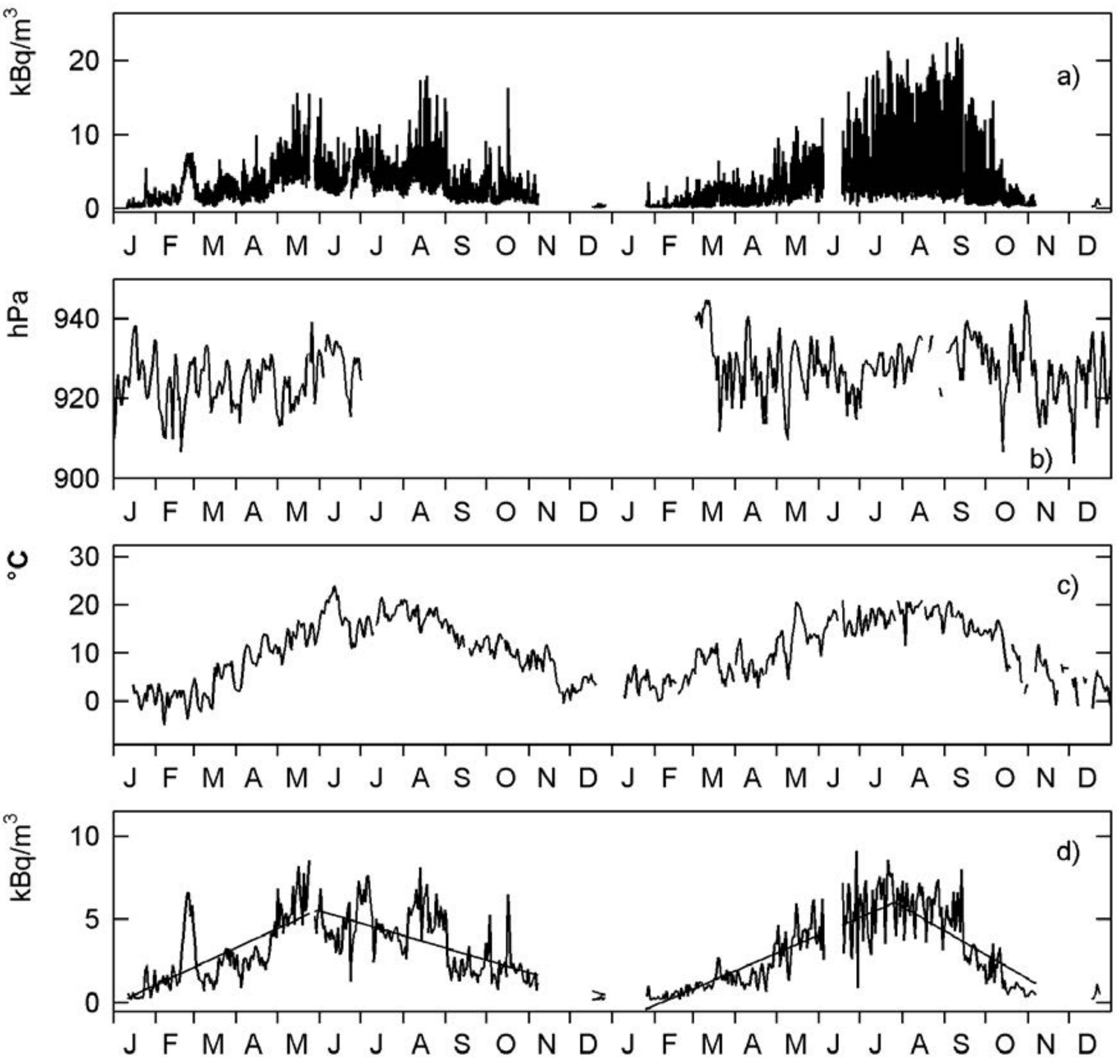

Fig. 3 - Period 1996-1997: a) the radon concentration, b) the daily sampled atmospheric pressure, c) the air temperature, and d) the daily sampled radon concentration with the seasonal trends calculated by the linear best fit.

February 25 to March 15 there was a decrement in the groundwater level and a following increment, of opposite sign to the radon concentration. The variation is about 30 cm.

For the radon variations to be considered “significant anomalies”, it is necessary to introduce a commonly accepted quantitative criterion, like the +/- 2 sigma limits (Box and Jenkins, 1976; Igarashi and Wakita, 1990). The +/- 2-sigma limit for the radon concentration daily values has been reported in Fig. 4a. One can see that the signals exceeding the 2-sigma lines precede all the strongest earthquakes within the previously selected group. The most evident anomalies are in January and February 1996. The last one, also, lasts the longest (16 days). In this period, a seismic series occurred at Claut, 35 km from the radon station. The three main shocks with magnitude

3.7, 4.0, and 4.3 occurred on January 27, February 27, and April 13, respectively. At that time, the radon concentration anomalies are exhausted and the radon value returned to its mean value. The anomaly began about 11 days before the February 27 earthquake and 45 days before the April 13 earthquake. From February to April there it did not rain in large quantities, confirming that the January and February anomalies were not produced by meteorological variations.

Other anomalies (values exceeding the 2-sigma line) can be seen in August and October. On August 28, an earthquake with magnitude 3.1 and on October 15 an earthquake with magnitude 5.8 occurred: they were respectively 16 km and 250 km from the radon station. Both October anomalies could be associated with the October 15 earthquake (the second anomaly is coseismic), or one of them could be associated with the earthquake of the following December.

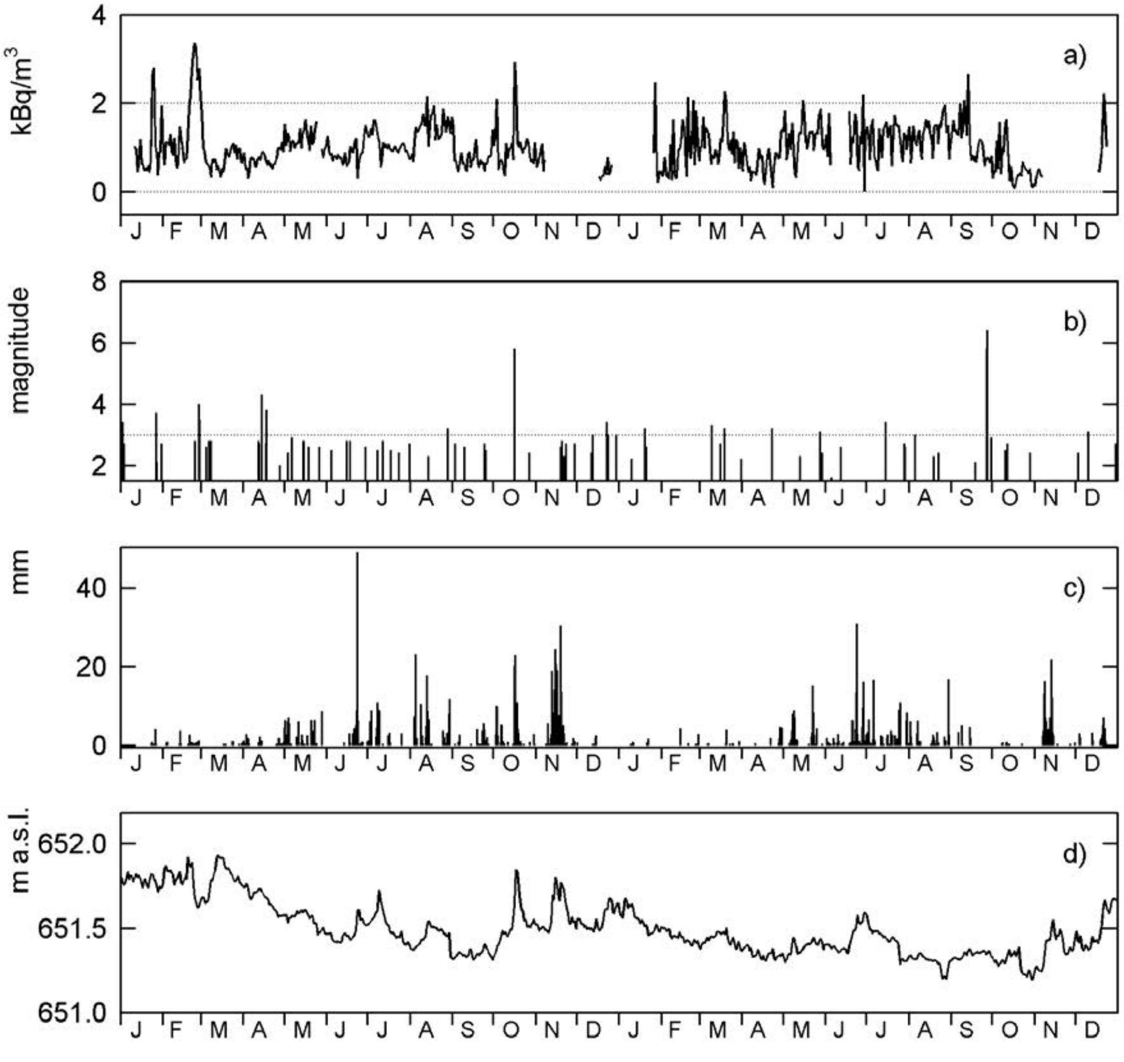

Fig. 4 - Period 1996-1997: a) the daily sampled radon concentration without the seasonal trend (the dotted lines mark the +/– 2-sigma limit); b) the earthquakes according to the Hauksson and Goddard (1981) criterion (the dotted line marks the magnitude value 3.0); c) the rainfall; and d) the groundwater level above the sea level, in the well.

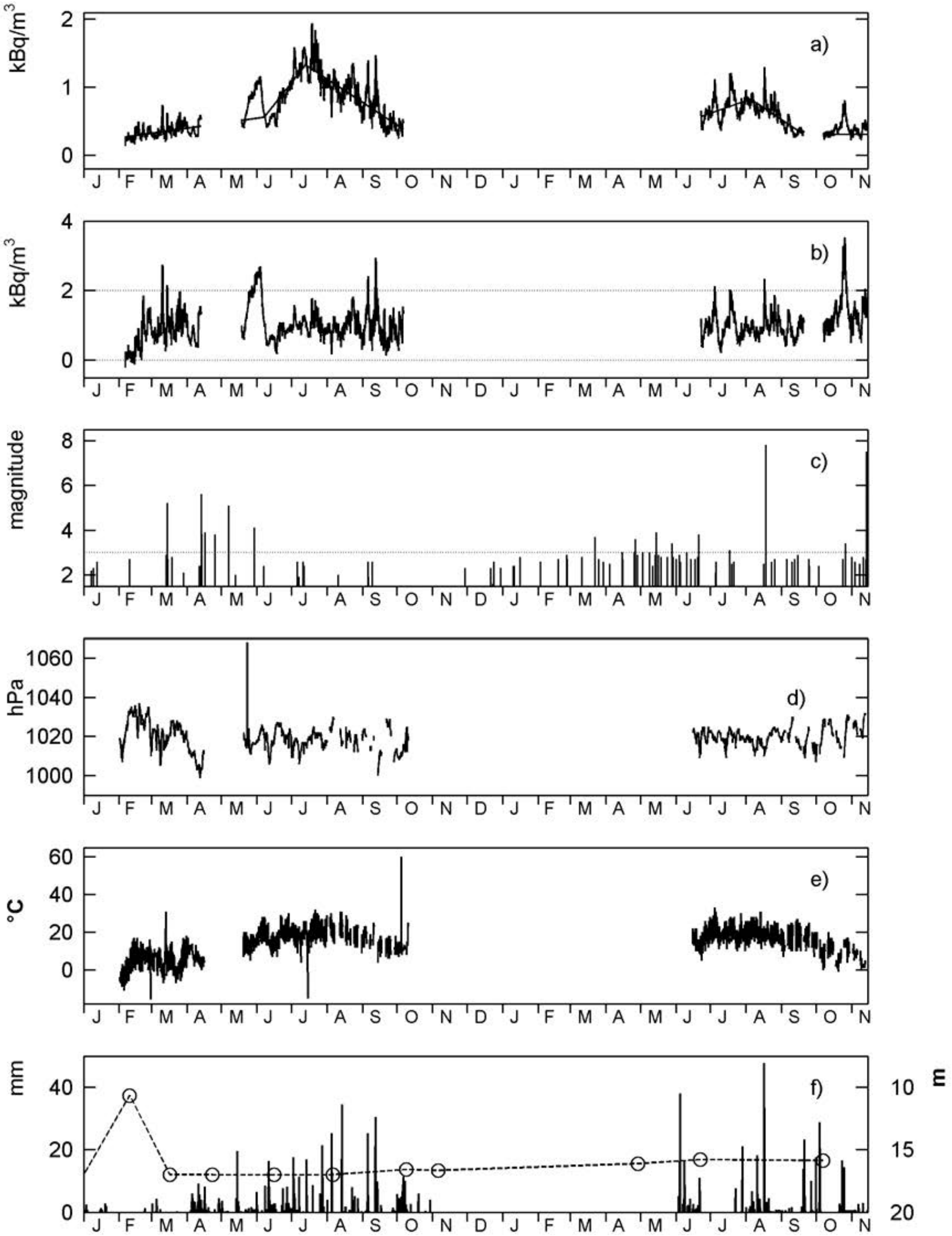

Fig. 5 - Period 1998-1999: a) the radon concentration with the seasonal trend; b) the radon concentration without the seasonal trends (the dotted lines mark the +/– 2 sigma limit); c) the earthquakes selected according to the Hauksson and Goddard (1981) criterion (the dotted line marks the magnitude value 3.0); d) the daily sampled atmospheric pressure; e) the air temperature; f) the rainfall and sporadic measurements of the groundwater level marked by white circles.

No influence of rain on the radon concentration was found because the most important anomaly, in February 1996, is not coupled with rain, while during the rainy periods there are no important anomalies, with the exception of the one in October. It must be pointed out, anyway, that 1996 and 1997 were not characterised by frequent and heavy rains.

The anomalies exceeding the 2-sigma line can be seen in January, February, March, June, September and December 1997. All these values precede earthquakes greater than magnitude 3.0. They happened on March 8 and 17, respectively at 2 and 4 kilometres from Cazzaso, on April 21, at a 6 kilometre distance, on July 14 with an 8 kilometre distance, and on September 26, 350 kilometres from the radon station but with a magnitude of 6.4 (the main shock of the Umbria seismic series) and in March and April strong earthquakes occurred in Slovenia, including the Bovec seismic series (Kobal *et al.*, 2003).

The data related to the period January 1998 - November 1999 are shown in Fig. 5, where the radon concentration with seasonal trends (a), the radon concentration without the seasonal variation with the +/– 2-sigma line (b), the magnitude of earthquakes selected according to the Hauksson and Goddard (1981) criterion (c), the atmospheric pressure (d), the air temperature (e), the rainfall and sporadic values of the groundwater level are reported (f). This period was very rainy. The ground water level data are sporadic, executed manually, but quite stable except for one value in February 1998.

The radon concentration values exceeding the 2-sigma line during 1998 can be seen in March, May-June, and September. The largest earthquake of March occurred in Slovenia, 143 km from the site, but there were also two earthquakes with epicentres less than 10 kilometres from Cazzaso

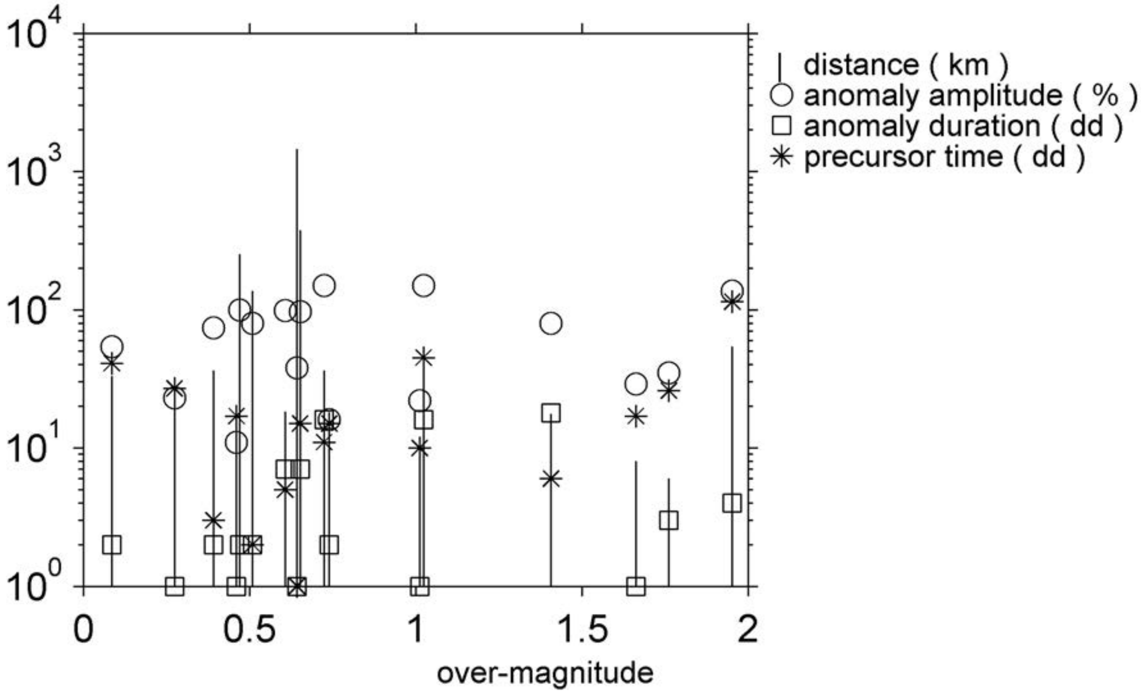

Fig. 6 - Radon anomalies, characteristic parameters versus over-magnitude.

and magnitude just under the line of 3.0. The large anomaly in May precedes the 4.1 magnitude earthquake at Trasaghis. Also this earthquake, as the Claut earthquake of 1996, had a long sequence with 17 aftershocks, not all reported in Fig. 5 because excluded by the Hauksson and Goddard (1981) selection. The anomaly lasted 18 days and started about 6 days before the main earthquake.

Other anomalies can be seen in September, when two earthquakes, about 5 kilometres from the site and with magnitude below 3.0, occurred.

The radon concentration values recorded through 1999 exceeded the 2-sigma line in June, July, August, September, and October. In the first days of July, the rain data are missing. In August and September there was a lot of rain, a little less in October. On July 16, a 3.1 magnitude earthquake happened at Trasaghis. The high magnitude reported in August is related to an earthquake in Turkey. On October 25, a 3.4 magnitude earthquake happened at Trasaghis and in November another strong earthquake hit Turkey. Also during the period reported in Fig. 5, the anomalies precede the events with magnitude greater than 3.0. Only in September 1998 did the earthquakes not follow the anomalies, there were only two small earthquakes contemporaneous to the anomalies.

Every anomaly is characterized by its duration in time, its amplitude above the 2-sigma line, and its precursor time (delay of the earthquake occurrence with respect to the anomaly start) and it is dependent on the distance from the earthquake epicentre and on its magnitude. The “over-magnitude”, that is the magnitude in exceedance with respect to the minimum magnitude of Hauksson and Goddard (1981), for events greater than 3.0, has been introduced to gather the influence of distance and magnitude. The characteristics of all the anomalies are shown in Fig. 6. In this figure, the over-magnitude is used as an independent variable but any proportionality between these quantities and the anomalies’ characteristics is not evident. The precursor times vary from 0 to 100 days.

The over-magnitude cannot substitute distance and magnitude because the dilatancy model turned out to be inadequate for earthquakes with a distance greater than 100 km. In these cases, the recorded anomalies are characterized by a short duration and brief precursor times. The variations of the wide-scale equilibrium strain are sensible at great distances only in the last paroxysmal period of earthquakes.

If we consider the whole period, the largest anomalies are connected with the two more consistent seismic series which happened within the zone of Claut (January-April 1996) and Trasaghis (May 28, 1998).

4. Conclusions

The results have pointed out a possible sensitivity of the fluids, picked up by a Cazzaso well, to the earthquakes with magnitude greater than 3.0, and particularly to the seismic series. For seismic sequences, the anomaly duration is longer than for single earthquakes. The two anomalies similar in shape are related to the only local earthquakes with magnitude greater than 4.0 in the zone of Claut and Trasaghis (Fig. 7).

In the light of these results, it is evident that the Hauksson and Goddard (1981) criterion does not hold for magnitude less than 3.0. For every earthquake, however, it is important a correct

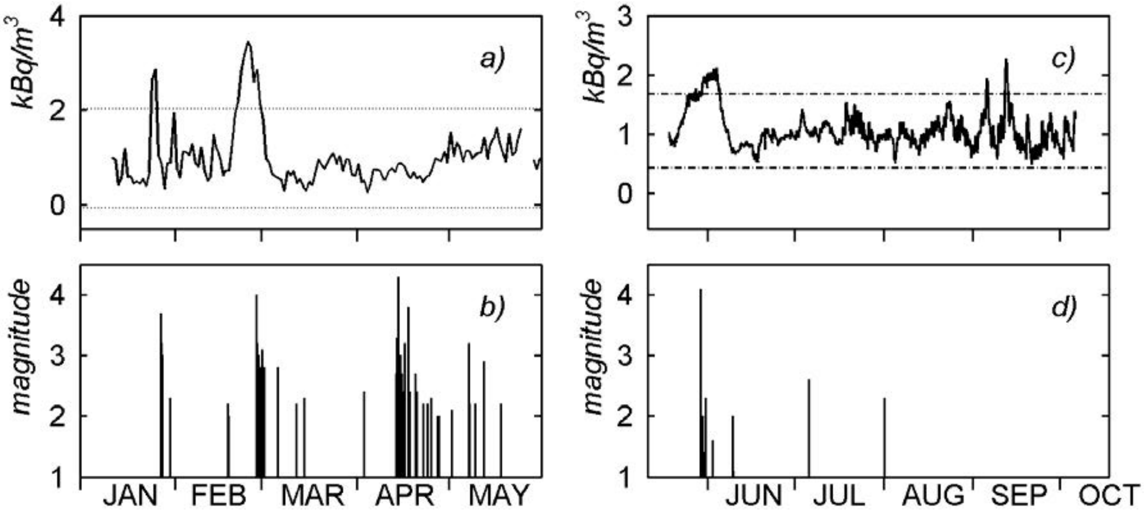

Fig. 7 - The radon anomalies on February 1996 and on May 1998 with the related seismic series.

hypocentral determination and a corrected evaluation of the magnitude. In the anomalies' evaluation, in addition to the 2-sigma threshold, the shape of the variation and its duration are important.

All earthquakes with magnitude greater than 3.0 show an anomalous value of radon and vice versa. Only the anomalous values in September 1998 are not related to earthquakes with magnitude larger 3.0.

The results obtained agree with the literature (Zmazek *et al.*, 2002; Richon *et al.*, 2003).

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REFERENCES

Box G.E.P. and Jenkins G.M.; 1976: *Time series analysis forecasting and control.* Holden Day, Oakland California, 350 pp.

Che Y., Huang Z., Wang A., Dong S. and Wan D.; 1996: *Evolution of precursory groundwater table anomaly field before Tangshan earthquake and its formation model.* In: GE Zhizhou (ed), The selected papers of earthquake prediction in China, Seismological Press, Beijing, pp. 139-146.

Cortecci G., Dinelli E. and Mussi M.; 2000: *Chemical and isotopic analyses of the "Acqua Pudia" groundwater from Arta Terme (Carnia, noorth-eastern Italy).* Miner. Petrogr. Acta, **XLIII**, 143-151.

Del Ben A., Finetti I., Rebez A. and Slejko D.; 1991: *Seismicity and seismotectonics at the Alps – Dinarides contact.* Boll. Geof. Teor. Appl., **33**, 155-176.

Dobrovolsky I.P., Zubkov S.I. and Miachkin V.I.; 1979: *Estimation of the size of earthquake preparation zones.* Pure and Applied Geophysics, **117**, 1025-1044.

Dragoni M.; 1999: *I meccanismi del terremoto? Dominati dal caos. Turchia, Grecia, Taiwan: ecco perché sarà sempre difficile prevedere le scosse*. Tutto Scienze, LaStampa.web 6 ottobre1999.

Friedmann H., Zimprich P., Atzmüller C., Hofmann W., Lettner H., Steinhäusler F., Hamernik E., Maringer F.J., Mossbauer L., Kaineder H., Nadschläger E., Sperker S., Karacson P., Karg V., Kralik C., Pock K., Schönhofer F., Breitenhuber L., Kindl P., Oberlercher G., Seiberl W., Stadtmann H., Steger F. and Tschurlovits M.; 1996: *The Austrian Radon Project*. Environment International, **22**, Suppl. 1, S677-S686.

Hauksson E. and Goddard J.G.; 1981: *Radon Earthquake Precursor studies in Iceland.* J. Geophys. Res., **86**, 7037-7054.

Igarashi G. and Wakita H.; 1990: *Groundwater radon anomalies associated with earthquakes.* Tectonophysics, **180**, 237-254.

Li X. and Li Z.; 1996: *The progress of the key problems in theories and methods for short-term and imminent earthquake predictions during the eighth five-year plan*. In: GE Zhizhou (ed), The selected papers of earthquake prediction in China, Seismological press, Beijing, pp. 3-8.

Kobal I., Martinelli G., Riggio A., Sancin S., Vaupotic J. and Zmazek B.; 2003: *Monitoraggio geochimico in una zona sismicamente attiva lungo il confine italo-sloveno.* In: Slejko D. (a cura di), Gruppo Nazionale di Geofisica della Terra Solida, Atti del 20° Convegno Nazionale, CD-Rom, Prospero, Trieste, file 01.18.

King C., King B. and Evans W.C.;1996: *Spatial radon anomalies on active faults in California.* Applied Geochemistry, **11**, 497-510.

Martinelli G.; 2000: *Contributions to a history of earthquake prediction research.* Seismological Research Letters, **71**, 583-588.

Mogi K.; 1990: *Earthquake prediction research in Japan.* In: Boschi E. and Dragoni M. (eds), Earthquake prediction. Il Cigno Galileo Galilei, Roma, pp. 11-31.

Nero A.V. and Nazaroff W.W., 1984: *Characteristing the source of radon indoors*. Radiat. Prot. Dosim, **7**, 23-39.

OGS; 1996-1999: *Bollettino della Rete Sismometrica del Friuli-Venezia Giulia*. OGS, Trieste.

Paparo G. and Gregori G.P.; 2003: *Multifrequency acoustic emissions (AE) for monitoring the time evolution of microprocesses within solids.* Review of Quantitative Nondestructive Evaluation, **22**, 1423-1430.

Richon P., Sabroux J.-C., Halbwachs M., Vandemeulebrouck J., Poussielgue N., Tabbagh J. and Punongbayan R.; 2003: *Radon anomaly in the soil of Taal volcano, the Philippines: a likely precursor of the M 7,1 Mindoro earthquake (1994)*, Geophysical Research Letters, **30**, No. 9, 1481, doi 10.1029/2003GL016902.

Riggio A., Sancin S., Gentile G.F., Zennaro P. and Belletti R.; 2001: *Misure di radon in Friuli e confronto con la sismicità.* In: Slejko D., Albarello D., Bernabini M., Carcione J.M., Cocco M., Cosentino P., de Franco R., De Natale G., Marson I., Mazzotti A., Neri G., Ranieri G. e Scarpa R. (a cura di), Gruppo Nazionale di Geofisica della Terra Solida, Atti del 18° Convegno Nazionale, CD-Rom, Prospero, Trieste, file 01.06.

Rikitake T.; 1976: *Earthquake prediction*, Elsevier, Amsterdam, 357 pp.

Semprini, L., Hopkins O.S. and Tasker B.R.; 2000: *Laboratory, field and modeling studies of radon-222 as a natural tracer for monitoring NAPL contamination.* Journal of Transport in Porous Media, **38,** 223-240.

Scholz C.H., Lynn R.S. and Aggarwal Y.P.; 1973: *Earthquake Prediction: a physical basis*, Science, **181**, 803-810.

Slejko D., Carulli G.B., Nicolich R., Rebez A., Zanferrari A., Cavallin A., Doglioni C., Carraro F., Castaldini D., Iliceto V., Semenza E. and Zanolla C.; 1989: *Seismotectonics of the eastern Southern-Alps: a review.* Boll. Geof. Teor. Appl., **31**, 109-136.

Wakita H., Nakamura Y., Notsu K., Naguchi M. and Asada T.; 1980: *A possible precursor of the 1978 Izu-Oshima-Kinkai Earthquake*. Science, **207**, 882-883.

Vaupotic J., Krizman M., Planinic J., Pezdic J., Adamic K., Stegnar P. and Kobal I.; 1994: *Systematic indoor radon and gamma measurements in kindergartens and play schools in Slovenia.* Health Phys., **66**, 550-556.

Zmazek B., Italiano F., Zivcic J.M., Vaupotic J., Kobal I. and Martinelli G.; 2002: *Geochemical monitoring of thermal waters in Slovenia: relationships to seismic activity*. Applied Radiation and Isotopes, **57**, 919-930.

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