

# Hydrogeologic and geochemical precursors of earthquakes: an assessment for possible applications

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**ABSTRACT** Groundwaters and gaseous emissions have been analyzed in the past with the purpose to contribute to earthquake prediction researches. Main test sites were Japan, U.S.A., former U.S.S.R., China and Turkey. Catalogues of presumed precursory episodes have been compiled over the years and allowed to reach preliminary conclusions about site selection techniques. Controlled experimental sites have recently given the opportunity to better investigate the physical mechanisms originating recorded pre-seismic anomalies. Main characteristics and limitations of hydrogeologic and geochemical parameters are discussed. An in-depth review of results obtained in most relevant test site areas allow to project future instrumental networks oriented to hazard reduction policies.

**Key words:** earthquake precursors, groundwaters, gaseous emissions.

## 1. Introduction

Hydrogeologic and geochemical parameters have been considered in past the 50 years for researches oriented to earthquake prediction. A relatively high amount of spot data has been collected by manual techniques in various geological contexts while a much lower amount of automatically recorded data was collected in some experimental areas in Japan, U.S.A., former U.S.S.R., China, Turkey, Iceland, etc. Considered parameters include oil flow rate, water level, water temperature, water dissolved ions, CO<sub>2</sub>, CH<sub>4</sub>, radon, helium. Possible geochemical and hydrogeologic precursors have been observed hours to months before some strong earthquakes in “sensitive” monitoring sites among many insensitive sites (Thomas, 1988; King and Igarashi, 2002). Sensitive sites are usually found along active faults, in thermal springs or in deep wells reaching confined deep reservoirs able to act as natural strain meters (Bodvarsson, 1970; Wang and Manga, 2010) and have been considered in search of earthquake precursors. Worldwide collected data were reviewed by previous researchers (Hauksson, 1981; Friedmann, 1985; Roeloffs, 1988; Kissin and Grinevsky, 1990; Toutain and Baubron, 1999; Hartmann and Levy, 2005; Cicerone *et al.*, 2009; Matsumoto and Koizumi, 2011) who attempted to find general laws of deep fluids behavior before earthquakes in order to better constrain possible time and location of a forthcoming seismic event. The present paper reviews the actual state of the art of the topic

with the purpose to identify well assessed findings in non-volcanic areas in view of possible experimental application.

## 2. Mechanisms for earthquake hydrologic and geochemical precursors

Groundwaters, hydrocarbons and gases are pervasive fluids which fill deep seated geological formations where porosity values allow fluid's accumulation or circulation (Fyfe *et al.*, 1978). Usually hydrocarbons fill porous sedimentary anticlines while groundwaters can be of meteorologic or of marine origin.

Marine originated waters (formation waters) fill sedimentary geological formations often in association with hydrocarbons while meteorologic originated groundwaters can fill all kinds of rocks. Formation waters are very old and characterized by ages similar to hydrocarbons with which are associated, while meteoric water ages are in the range of 1-100,000 years. Young groundwaters (1-100 years old) are usually hosted in phreatic aquifers and linked to present hydrologic cycles, while confined aquifers and geothermal circuits host relatively old groundwaters characterized by low circulation velocities and scarce or no link with present hydrologic cycles. Geothermal systems can be faulted and generate thermal springs and carbon dioxide dominated gas emissions. Carbon dioxide is chiefly generated by thermo-metamorphic reactions in the crust (Frezzotti *et al.*, 2009 and references therein) or by mantle degassing in particular in volcanic systems (Chiarabba and Chiodini, 2013 and references therein). Further gas emissions represented in particular by methane may affect hydrocarbons faulted accumulations.

Geochemical anomalies observed before earthquakes include stable isotopes of water (Skelton *et al.*, 2014), dissolved ions, dissolved gases and soil gases (Thomas, 1988; Segovia *et al.*, 1989; King and Igarashi 2002). Main gases involved in the Earth's degassing activity are CH<sub>4</sub> and CO<sub>2</sub> which are considered responsible for water-gas-rock interaction processes able to induce chemical variations in groundwater composition. Great part of the geochemical variations in the chemical composition of groundwaters were attributed to aquifer mixing processes (Thomas, 1988) in particular when accompanied by temperature variations of fluids. Precursory variations observed in radon, helium and hydrogen in soil gases have been accompanied by carrier gas CO<sub>2</sub> or CH<sub>4</sub> flow rate variations. Generation mechanisms of hydrologic and geochemical precursors have been reviewed by Roeloffs (1988), Thomas (1988), King and Igarashi (2002), Matsumoto and Koizumi (2011) and about all geochemical anomalies observed before earthquakes have been retained directly or indirectly attributable to deep fluids pressure variations induced by crustal deformative processes since fluid pressure is proportional to stress and volumetric strain (see also Perrini *et al.*, 2012). The stress-strain relationship for an isotropic, linearly elastic porous medium was studied, among others, by Rice and Cleary (1976 and references therein) and by Roeloffs (1996). In particular, the stress tensor  $\sigma_{kk}$ , the volumetric strain  $\varepsilon_{kk}$  and the fluid pressure  $p$  under undrained conditions can be described as:

$$p = -B\sigma_{kk}/3 \quad (1)$$

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

where  $G$  is the shear modulus,  $B$  is the Skempton coefficient, and  $\nu_u$  is the Poisson's ratio under undrained conditions. As a consequence the fluid pressure is proportional to stress and

volumetric strain. Thus, groundwaters can be, in principle, utilized as natural strainmeters being water nearly incompressible and monitorable by large scale networks. To better constrain the candidate area eventually identified by anomalous signals detected from large scale networks attempts have been carried out to detect areas affected by maximum amplitude signals (Popov and Vartanyan, 1990; Vartanyan *et al.*, 1992).

### 3. Experiments carried out in the world

Geochemical prospections and hydrologic studies have been widely utilized in past and present researches to locate faults and to characterize tectonically active areas. Part of the identified areas was subjected to monitoring during time of one or more parameters in one or more sites. Most relevant results were obtained in places where manual or instrumental networks monitored wells or springs for periods longer than 5 years in particular in the former U.S.S.R., China, U.S.A. and Japan.

Observational networks of wells (depth range of 0.2-2.9 km) or of thermal spring sources constituted by about 100 sampling points (1 sampling site every 10,000 km<sup>2</sup> and higher density in the so called experimental “polygons”) were utilized in the period 1970-1990 in Tadjikistan, Uzbekistan, Kazakhstan, Caucasus and Kamchatka. Asimov *et al.* (1984), Sidorenko *et al.* (1984) and Sidorin (2003) reported that some local strong seismic events were preceded some hours or days before by precursory water level variations although with a bias in epicentral localization which could reach 100 km. Further networks for groundwater monitoring were also set up in China where water level and gaseous content have been analyzed in about 400 thermal springs or wells (depth range of 0.1-2.0 km; 1 sampling site every 3000 km<sup>2</sup> and higher density in “polygons”) and precursory variations in water level were observed before some strong earthquakes. Most of findings in the former U.S.S.R. and China were published in local languages and complete time series of water recorded data were scarcely published: anyway Roeloffs (1988), Thomas (1988), and King and Igarashi (2002) retained reliable the precursory character of observed anomalies. In the period 1984-1989 groundwater level (6 monitoring stations) and radon (5 monitoring stations) were recorded together with other geophysical parameters in Turkey (Zschau and Ergunay, 1989). The lack of strong earthquakes during the observation period hampered definitive conclusions, but significant methodological improvements were reached in groundwater monitoring techniques and in data interpretation (Woith *et al.*, 2013). A network of 12 wells was set up in California and water level data recorded and compared to other geophysical parameters (Bakun, 1988). A precursory variation in groundwater level was detected in 1985 (Roeloffs and Quilty, 1997) but the fluid monitoring network was partially dismantled in following years due to successive missed anomalies before local earthquakes. Many research groups recorded hydrologic and geochemical data in single spring sources or in small networks of wells in Japan (Matsumoto and Koizumi, 2011) and some precursory anomalies were detected together with no reliable signals (King *et al.*, 2000). Recently, a network of 14 equipped deep wells (depth 0.6 km) started a monitoring activity in the area of Nankai, Tonankai and Tokai (Taba *et al.*, 2010) in view of a possible expected local strong earthquake. Further observations characterized by relatively shorter time series (<5 years) have been carried out in France, Italy, Spain, Greece, India, Germany, Iceland, Bulgaria,

Afghanistan, Iran, Israel, Mexico and Taiwan. About all available data were considered in review works by Hauksson (1981), Friedmann (1985), Kissin and Grinevsky (1990), Toutain and Baubron (1999), Hartmann and Levy (2005), and Cicerone *et al.* (2009).

#### 4. Evaluation of assessed precursory fluid related anomalies

Hauksson (1981) reviewed all available radon precursory anomalies occurred all over the world, published in the period 1971-1981, and argued that time duration of anomalies increases with magnitude. He observed that radon anomalies reflect small changes in the local stress intensity factor which control the velocity of crack growth.

Friedmann (1985) reviewed all available radon precursory anomalies published in the period 1969-1982 and reached the conclusion that faster spike-like anomalies are more frequent close to the epicentral area while bay-shaped anomalies are more frequent far from the epicentre.

Toutain and Baubron (1999) reviewed gaseous anomalies (chiefly radon) published in the period 1980-1995 and observed that amplitudes of anomalies are independent by magnitudes and epicentral distances of related earthquakes while time and duration of anomalies increase with magnitudes and epicentral distance.

Hartmann and Levy (2005) reviewed gaseous and water related anomalies (level and geochemistry) published in the period 1978-1997 reaching the conclusion that signal duration is proportional to the magnitude of seismic event.

Kissin and Grinevsky (1990) reviewed available anomalies in water level data occurred in the period 1948-1980 finding that precursory time and signal amplitude are proportional to magnitude. In particular, most of groundwater variations occurred within 50 km from epicentre and in areas characterized by intense deformative processes.

Cicerone *et al.* (2009) reviewed geochemical, hydrologic and geophysical anomalies occurred in the period 1948-2001. The authors found that the signal amplitude is proportional to earthquake magnitude. Most of the observed precursory anomalies have been found in the region in the Earth where the largest deformations occurred.

All considered review publications directly or indirectly conclude that a deformative process is responsible for observed anomalies in fluids. Most scrutinized works are related to "a posteriori" identified precursory signals while official alarms were issued before the 1975 Haicheng shock (Wang *et al.*, 2006) and before the 1978 Pamir earthquake (Asimov *et al.*, 1984) but exact time and locations of forthcoming shocks were not appropriately constrained. Roeloffs (2006) reviewed data about deformative processes before earthquakes and found that in at least 10 seismic events for which data were available an aseismic deformative change characterized by time durations in the range 10 of minutes -15 years occurred. Not all earthquakes seem to be preceded by detectable crustal strain changes in the epicentral area and this could explain the lack of fluid related precursors observed in many cases. Anyway, being water about incompressible, water level can be considered as the signal of a natural sensitive ( $10^{-7}$ - $10^{-8}$ ) strainmeter if a deformative process occur in the candidate area of an earthquake. Furthermore, signal characteristics of a forthcoming anomaly could be anticipately calculated as in the last generation groundwater monitoring network set up in the Tokai area (Matsumoto *et al.*, 2007). Popov and Vartanyan (1990) proposed the utilizations of large scale water level networks able to monitor

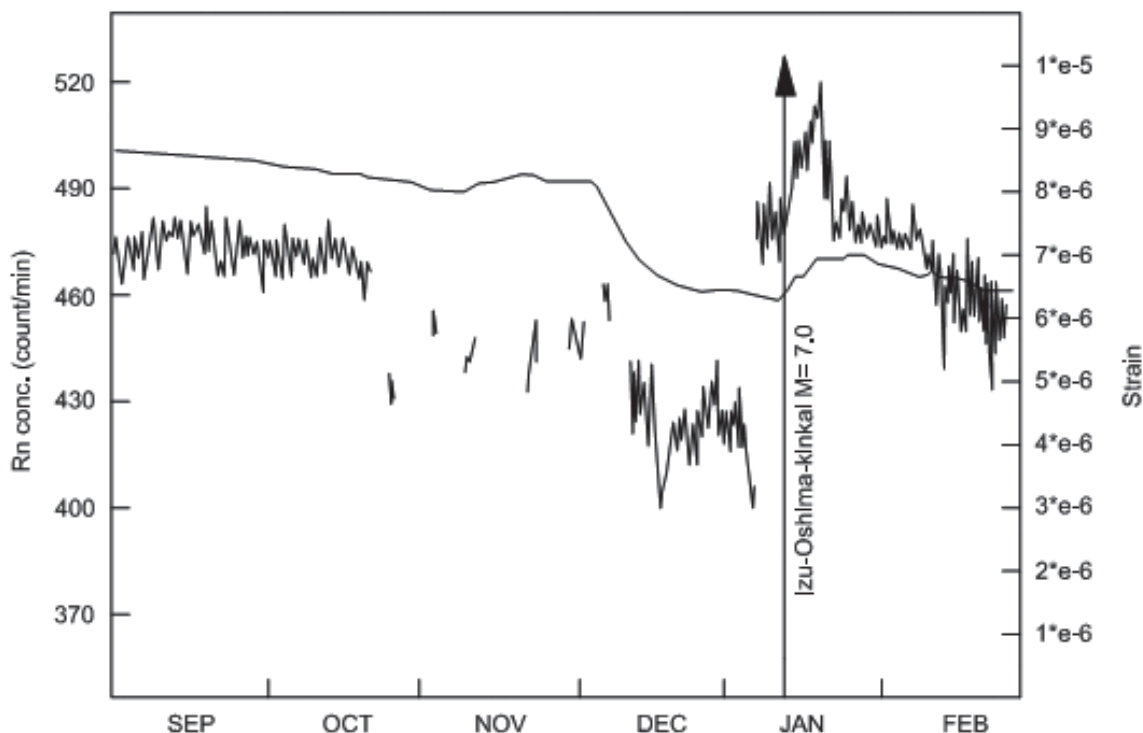


Fig. 1 - Radon and strain data simultaneously recorded in concomitance with the Izu-Oshima-kinkai earthquake in 1977-1978.

hydro-geo-deformation fronts with the purpose to better constrain candidate epicentral areas. The non compressibility character is lacking in gases, thus radon data compared with strainmeters data, when available, did not give unambiguous results (Roeloffs, 1999) (Fig. 1), while progress in time series analysis have been achieved (Finkelstein *et al.*, 1998). The calculation of a stress tensor from radon data is still an unsolved problem but radon or helium data could be still utilized in next future to monitor semi-quantitative signals of tectonic reactivation in faulted areas. A sub-commission of the International Association for Seismology and Physics of the Earth's Interior reviewed available precursory anomalies and added radon and water level to a list of possibly significant precursors (Wyss, 1991; Wyss and Booth, 1997).

## 5. Possible experimental applications

Epicentres of earthquakes often migrate towards a non-random direction being the results of wide large scale crustal deformation processes (Kasahara, 1979). Experimental indirect confirmations on the role of regional strain on possible precursory fluid anomalies were collected by Vartanyan *et al.* (1992), Facchini *et al.* (1993), Silver *et al.* (1993), Albarello and Martinelli (1994), Buntebarth and Chelidze (2005). Migration of a deformation front may trigger earthquakes and is characterized by velocities in the range of 10-100 km/yr. These phenomena are linked to the rheologic stratification of the lithosphere (Rice, 1980) and may play a fundamental role in medium- and long-term earthquake prediction (Mantovani *et al.*,

2010). Groundwater monitoring of well networks may strongly contribute to better understand these processes for researches oriented to earthquake forecasting.

Recent most relevant networks on water level or fluid monitoring include China, Taiwan, Turkey, Japan, Russia and U.S.A. while about no systematic researches are carried out in Europe. Most seismically active areas of Italy, France, Germany, Czech Republic, Greece, Slovenia, and of the Balkan area hosted short experimental monitoring researches in the past and no conclusive results were reached due to short monitoring time over too small areas during not relevant seismic periods. The idea to monitor large scale hydro-geo-deformation fronts induced by possible crustal deformative processes, with the purpose to identify most relevant areas in condition to host one or more forthcoming shocks, seems in present times more effective than the monitoring of a single site with the purpose to exactly predict time and location of a forthcoming shock. Hydro-geo-deformation fronts were monitored in various areas of the former U.S.S.R. (Vartanyan *et al.*, 1992) and of Italy (Albarello and Martinelli, 1994). The availability of a significant number of thermal springs, of gaseous emissions, and of wells in Italy, Greece, Spain, Albania and in the former Yugoslavia in areas characterized by a relatively high frequency of strong earthquakes (see also Martinelli and Albarello, 1997) make possible the set up of monitoring networks in a near future possible. Most suitable technologies include sensors for water level, temperature, electric conductivity and gas components in selected wells or thermal springs. Most of the continuous precise measurement of tectonic motions by strainmeters and tiltmeters is not easily detectable (Agnew, 1986). Kumpel (1992) reviewed data summarized by Roeloffs (1988) and by Kissin and Grinevsky (1990) and underlined that the weakness of conventional wells as stress sensors results from the fact that the process of fluid flow often lacks a sufficient control on possible inhomogeneities of the reservoir and on fluid circulation modalities. To better constrain experimental conditions and reduce troubles due to natural geological formations, Swolfs and Walsh (1990) experimented a sort of “artificial confined aquifer” emplacing in a cavity drilled in a rock formation a liquid-filled pressurized cell. A precursor of a local shock was detected confirming the need of advanced networks able to continuously monitor crustal deformative processes. The advantage of a natural aquifer, if appropriately chosen, is represented by the size dependent sensitivity not reachable by artificial devices. Recent advantages in monitoring techniques were increased by advances in electronics and informatics. Automatic monitoring was utilized by Woith *et al.* (2006), who observed possible non-random phenomena in confined aquifers of Turkey linked to crustal deformative processes. Their monitoring activity demonstrated that transient phenomena in confined aquifers may be characterized by relatively short time duration (hours or days). The possible existence of short duration transient phenomena was evidenced by Roeloffs and Quilty (1997) in Parkfield monitoring and by further authors (e.g., Sidorenko *et al.*, 1984) in various geological contexts. Short-term possible precursory phenomena in groundwaters or in gas emissions may be observed only by automatic monitoring equipments. In the past 15 years, short-term possible fluid related precursory signals in southern Europe (Greece, Italy, Spain and Slovenia), Turkey and Israel were automatically recorded by Contadakis and Asteriadis (2001), Steinitz *et al.* (2003), Lapenna *et al.* (2004), Colangelo *et al.* (2005, 2007), Riggio and Sancin (2005), Cioni *et al.* (2007), Richon *et al.* (2007), Perez *et al.* (2008), Heinicke *et al.* (2010), Torkar *et al.* (2010), Yuce *et al.* (2010); in central Europe by Heinicke *et al.* (1995) and Stejskal *et al.* (2009), while further automatic monitoring activities were carried out in Taiwan (Walia *et*

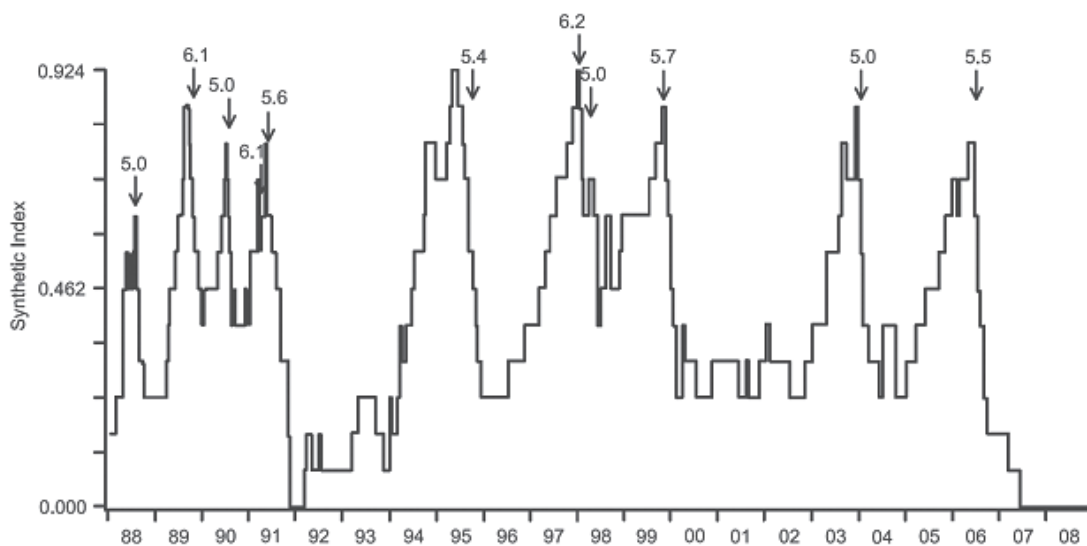


Fig. 2 - Record of the synthetic index obtained for the Beijing area by Zhang *et al.* (2013) in the period 1988-2007 by means of multiparametric measurements.

*al.*, 2013), Kamchatka (Firstov *et al.*, 2007) and Mexico (Taran *et al.*, 2005). In spite of a relatively high sampling rate and encouraging data, no completely definitive results were reached by the above mentioned authors since the number of false alarms or of missed alarms is relatively high for practical purposes probably due to inadequate array density, to inadequate site selection or for simple elusivity of the task, being eventual pore pressure change at seismogenic depth  $< 0.1$  MPa (Johnston and Linde, 2002). The groundwater monitoring could contribute to reveal hydro-geo-deformation fronts useful to lower seismic hazard in the medium term as evidenced by Vartanyan *et al.* (1992), Albarello and Martinelli (1994) and Vartanyan (2014). It is unclear if aseismic precursory crustal deformative processes always accompany earthquakes since experimental data are still lacking; anyway, lateral migration of the stress field after dislocation events has been recognized as responsible for the generation of further earthquakes. Tectonic pumping phenomena able to generate groundwater and gas anomalies could be easily explained in this view. Great part of the recorded geochemical and hydrologic anomalies reported in the cited review papers were detected in Tadjikistan, Uzbekistan, Kazakhstan, Caucasus, Kamchatka, Yunnan Province (China), Hebei Province (China), Iceland and Japan. These areas are characterized by anomalous ( $> 60$  mW/m<sup>2</sup>) heat flow values (IHFC, 2011) which implies the existence of hydrothermal circuits where earthquakes similar to volcanic seismic events can occur. In this sense the observed short-term precursory anomalies could have been generated by fluid kinetic related processes which are typical of volcanic areas. In volcanic areas fluid kinetic is the driver of seismicity while fluids have a secondary role in plate tectonic earthquake generation. In geothermal areas the brittle-ductile transition can be shifted to shallower depths (Zencher *et al.*, 2006) enhancing the effects of crustal deformative processes due to a more effective deformability of ductile layers induced by temperatures  $> 300$  °C (e.g., Ranalli, 1995). For this reason dilatancy processes are scarcely invoked to explain earthquake triggering in volcanic areas. In volcanic areas precursory geochemical and

hydrological phenomena have been often observed and fluid monitoring is presently part of the Civil Defense routine control for volcanic eruption risk reduction. Thus, observed geochemical and hydrological short-term earthquake precursors could have been generated in hydrothermal areas, whose seismicity could be similar, in principle, to the one observed in volcanic areas. These features could explain the apparently encouraging results obtained in central Asia, China and Japan and the low scores obtained in low heat flow seismic active areas. In this sense, volcanic fluid monitoring is in the scientific maturity stage while earthquake fluid precursor monitoring is still in the first steps stage. Zhang *et al.* (2013) recently reported encouraging results obtained in the area of Beijing. In particular, over 10 local seismic events were apparently preceded by 1-2 years lasting anomalous signals related to geophysical and geochemical parameters (Fig. 2). The monitoring system considers about 19 different parameters. In this way, a more multidisciplinary approach is adopted and a sort of comprehensive super index is evaluated every three months in the attempt to forecast earthquakes at least in the medium term. Authors did not reach yet a true alarm system but rather presume that a multiparametric approach could be more suitable than a single parameter monitoring, at least in medium-term forecasting. No definitive results were reached in short-term earthquake precursors monitoring since possible precursors are not detectable for all earthquakes and for the relatively high number of missed alarms. Hydrogeologic and geochemical monitoring could, anyway, better contribute to constrain time and location of occurrence of earthquakes eventually forecasted by different methods (e.g., Peresan *et al.*, 2005; Mantovani *et al.*, 2010; Bragato, 2014) since the existence of possible short-term precursory signals could be, in principle, not ruled out in particular if the monitored aquifer, as evidenced in previous review works, is directly fed by a deep geothermal system. This is the case of thermal springs and deep wells which should be considered as priority monitoring sites. Data obtained, although incomplete, look encouraging for future more in depth researches oriented to hazard reduction. Furthermore, data obtained by satellite based thermal and gas sensors could contribute to a more comprehensive deep fluid monitoring oriented to earthquake forecasting (Tramutoli *et al.*, 2013) over large areas.

## 6. Short summary of analyzed data

Experimental data on possible earthquake precursory geofluids collected by the Civil Defense, research centres and single researchers indicate that:

- 1) groundwaters may act as natural strainmeters due to the peculiar characteristic of non compressibility of water;
- 2) physical characteristics of water are enhanced by confined conditions of aquifers;
- 3) gaseous components are a consistent part of geofluids but cannot allow, at present, a clear definition of stress tensor;
- 4) short-term earthquake forecasting reached interesting results at scientific level by monitoring sensitive subvertical deep aquifers but no practical applications have been reached so far;
- 5) medium-term seismic hazard reduction by geofluids is presently experimented in some areas by networks of wells drilled in sub-horizontal aquifers. More definitive results will be evaluated in next future;



- 6) geofluid possible precursors could be reasonably experimented only jointly with other geophysical parameters measured on the ground or by space techniques.

## 7. Conclusions

The existence of crustal deformative front migration processes induce the need to monitor crust topography and crustal volumes subjected to stress induced strain. Thermal springs and deep wells in confined aquifers could be monitored as high resolution natural strainmeters. Automatic devices able to monitor water level, temperature and electric conductivity in main 3-4 seismically active areas of Italy (or of Spain, France, Greece, Portugal, Balkan area, Turkey, Israel and former Yugoslavia) could effectively contribute in short and medium-term earthquake forecasting experiments. Gaseous component monitoring could be jointly carried out in selected degassing areas with the same purposes, specifically in areas characterized by relatively high heat flow values. Available data on geofluids indicate the possible task of a medium-term earthquake forecasting activity over large areas (regions); some short-term precursors detected in past 15 years confirm the possible utilization of the same networks for short-term earthquake prediction experiments. Instrumental arrays should be improved with respect to past pioneeristic experiences and characterized by at least 1 observational point (piezometer or thermal spring or gas emission) every 500 km<sup>2</sup>, approximately equivalent to about 60-100 sampling points for a territory like Italy, similarly to best monitored areas of Japan, China and former U.S.S.R. Lower densities could limit short-term constraint possibilities in short-term earthquake forecasting surveys. Geofluid monitoring networks should be finally embedded in existing GPS, tiltmeter and strainmeter networks and in satellite based monitoring activities. Data interpretation should be comprehensive and take account of all geophysical monitored parameters.

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