ANNALI DI GEOFISICA, VOL. XL, N. 6, December 1997

Main constraints for siting monitoring networks devoted to the study of earthquake related hydrogeochemical phenomena in Italy

Giovanni Martinelli (1) **and Dario Albarello** (2)
(1) *Servizio Cartografico e Geologico, Regione Emilia-Romagna, Bologna, Italy*
(2) *Dipartimento di Scienze della Terra, Settore di Geofisica, Università di Siena, Italy*

Abstract
Criteria and data useful to select test sites in Italy suitable for monitoring earthquake related fluctuations in geofluid natural emissions are given. For this purpose, a catalogue of thermically anomalous natural springs was compiled on the basis of recent and old documentary sources. This catalogue, reporting more than 1200 localities, can be used to identify those sites where gas-fluid emissions are presumably representative of deep water circulation. A catalogue of CO_2 gas reservoirs exploited in the past and at present for industrial extraction was also compiled to identify all the areas where strong degassing activity may affect spring sources and generate enhanced water-rock interaction processes. To complete this review, data were also collected on natural springs characterized, on the basis of documentary sources, by «anomalous» behaviour during past earthquakes. An independent constraint to select the most interesting test sites was obtained by the analysis of seismic activity in this century. In this way, a number of sites were identified where it is likely to observe at least one significant earthquake (with magnitude ≥ 3.5 within 20 km) during a 3 year monitoring interval. These pieces of information were matched and three areas, respectively located in the Central Apennines, Southern Apennines and Sicily were identified as the most promising test sites for monitoring geofluid emissions as markers of active seismogenic processes.

Key words *earthquake prediction – applied geochemistry – Italy*

1. Introduction

In principle, it is reasonable to hypothesize that transient physical phenomena affecting crustal structures involved in seismogenic processes may also influence the circulation of deep-seated underground fluids (Scholz *et al.*, 1973; Mjachkin *et al.*, 1975). Thus, despite the hypothetical character of the physical models so far proposed as responsible for such fluid/rock coupling and the lack of satisfactory knowledge on pre-seismic/co-seismic phenomena in the focal area, monitoring of deep circulating fluids has been widely used for phenomenological studies devoted to earthquake prediction (Sultankhodjaev, 1984; Wakita *et al.*, 1988).

However, only in a restricted number of cases have efforts devoted to such monitoring been corroborated by short-cut experimental results and recent literature on this topic abounds in preliminary results. This is probably also due to the fact that these kind of researches require quite long observational periods (of the order of several years) and, as a

---

Mailing addresses: Dr. Giovanni Martinelli, Servizio Cartografico e Geologico, Regione Emilia-Romagna, Viale Silvani 4/3, 40122 Bologna, Italy; e-mail: g.martinelli@mo.nettuno.it – Dr. Dario Albarello, Dipartimento di Scienze della Terra, Settore di Geofisica, Università di Siena, Via Banchi di Sotto 55, 53100 Siena, Italy; e-mail: dario@ibogfs.df.unibo.it

consequence, great logistic efforts have to be sustained for operating sophisticated monitoring networks over relatively large areas. If monitoring is carried out in areas where strong earthquakes are relatively rare events (as in Italy) it becomes difficult to justify the financial support required for this kind of studies in the short-medium term. This implies that in most cases, monitoring has been carried out for relatively short time intervals, only sufficient to support preliminary conclusions. A possible solution to the problem came from Nicolaysen (1992), who proposed monitoring an old gold mine in South Africa recording possible precursory phenomena attributable to local induced earthquakes. In this way, the gold mine was considered as a semi-controlled source of seismic events, but collected data were obviously connected to artificial environmental conditions and their extrapolation to natural conditions could be unreliable.

The only way to tackle these problems is to concentrate experimental (and financial) efforts in areas with a maximum probability to obtain, during a relatively short observational period (1-3 years), satisfactory results concerning the reliability (or the irrelevance) of geofluid emissions as markers of deep-seated processes associated with seismogenesis. Thus, the optimization of financial and technical resources, obtained by a careful choice of sites where experimental equipment has to be placed assumes strategic importance. A first attempt to select Italian areas to be used as natural laboratories for the study of the seismogenic process from the seismological point of view was made by Mulargia and Tinti (1985). The aim of the present work is to make a similar attempt from the hydrogeochemical point of view, suggesting some criteria and data useful to select test sites in Italy suitable for monitoring gas-fluid emissions representative of potential seismogenetic activity.

2. Geochemical and seismological constraints

Two main features were considered for the definition of the most promising sites for location of a monitoring network devoted to the validation of hydrogeochemical markers of the seismogenic process:

a) Presence of gas-fluid emissions presumably representative of deep-seated circuits (hydrogeochemical constraints).

b) A relatively high local seismicity rate such as to increase the probability that at least one significant earthquake occurs during a time span of a few years (1-3) considered a «realistic» period for monitoring research programs (seismological constraints).

The study for both of these features would require detailed analyses and careful data collection specific for each possible site. Thus, if a large scale survey is of interest, both these requirements cannot be realistically satisfied. However, in the frame of an exploratory analysis devoted to supplying first order indications over large areas to orientate specific studies, a number of simplified assumptions can be made and useful indicators can be deduced from the available literature. The following sections describe the information used to define possible geochemical and seismological constraints for exploratory test site selection over the Italian territory.

2.1. *Hydrogeochemical constraints*

The confined or at least semi-confined character of the fluid reservoir responsible for observable earthquake related phenomena, can be considered a necessary pre-requisite due to the capability of confined fluids to act as natural strainmeters (Bodvarsson, 1970; Kümpel, 1991, 1992). This kind of information can be obtained by a careful chemical-isotopic analysis to select spring sources characterized by geochemical indicators of long path circulation circuits. Furthermore, fluid emissions characterized by geochemical pathfinders ($^3He/^4He$, $^{12}C/^{13}C$) indicative of deep tectonic processes are also suitable (Carapezza *et al.*, 1980; Dall'Aglio *et al.*, 1992; Martinelli, 1995). Minissale (1991) reviewed the analyses of 66 springs located in carbonatic reservoirs and characterized by temperatures ranging from 24 to 99 °C and completeness in oxygen and hydrogen isotopic data. Other recent papers refer to specific areas (see, *e.g.*, Belloni *et al.*, 1979; Chiodini *et al.* 1995; D'Alessandro *et al.*, 1997) which are not fully representative of the variety of geochemical and geophysical features of fluids occurring in the whole Italian area.

Thus, simplified criteria should be defined for a more exhaustive exploratory regional survey of the entire Italian territory.

For this purpose, a criterion can be found in the «anomalous» temperatures of spring emissions. In fact, when ground fluids are characterized by temperatures significantly greater than the ones typical of phreatic fluids, it is likely that gas-fluid-rock interactions in reservoirs occur in approximately adiabatic conditions typical of confined or semi-confined deep environments. Deep-seated waters are, in principle, more suitable with respect to phreatic ones to transmit toward the surface first hand information on deep physicochemical processes. Furthermore, meteorological noise can have a relatively limited effect on long path deep circulating thermically anomalous waters. Due to its economic and social importance, information on the location of thermically anomalous springs can be easily found in the wide literature devoted to hydrothermal/thermomineral springs exploited both for medical and industrial purposes since the last century (Tioli, 1894; Vinaj and Pinali, 1923; Touring Club Italiano, 1936; Fanelli, 1972; Fanelli *et al.*, 1982). Tioli (1894) quoted about 1800 localities in Italy characterized by chemically and thermically anomalous springs. Each locality hosted more than one source, thus about 5000 sites were mentioned. Vinaj and Pinali (1923) mentioned about the same number of sites considered by Tioli (1894), with the addition of more analytical details. During the period 1925-1935 many springs were caught and fewer than 170 localities were mentioned by Touring Club Italiano (1936). In fact in the period 1925-1935 all the uncaught springs were progressively abandoned and poorly considered by scientific literature. A consistent and valuable informative recovery attempt was made by Fanelli (1972) who listed 214 localities where 692 thermal springs characterized by temperatures above 20 °C were present. Fanelli *et al.* (1982) also listed 347 springs and 138 wells characterized by water temperature above 20 °C. Only 200 thermically anomalous sites ($T \geq 20$ °C) chosen from the list compiled by Fanelli *et al.* (1982) were mapped by Cataldi *et al.* (1995) in a review paper devoted to geothermal energy in Italy. In conclusion, in the period 1894-1995 much information about deep fluids in natural conditions was lost due to urban and economic development.

In this situation, the role of the oldest compilations is to provide information on deep terrestrial fluids in environmental conditions characterized by low anthropic noise. Many fluid emissions, in fact, have been artificially caught at present or simply cancelled by roads. Merging old and modern catalogues allows to correctly understand and describe deep fluid circulation patterns. In this sense a complete catalogue represents the first step of geochemical prospection.

According to Waring (1965) all spring sources characterized by temperature «... above the mean annual temperature of the air at the same locality may be classed as thermal ...». In 80% of the Italian peninsula mean annual temperatures below 15 °C have been recorded (Mennella, 1967) while greater values have been recorded in coastal areas (Macchiato *et al.*, 1995), where practically no interesting spring sources are present. Thus, natural springs characterized by temperatures ≥ 17 °C were considered as «thermically anomalous» sources. Data concerning 1274 of such kind of emergencies widely distributed over the Italian area (fig. 1) were collected and organized in the data base described in Appendix 1.

A second geochemical criterion for site selection is suggested by the proximity of strong CO_2 natural emissions exploited for industrial purposes. Both historical and recent documentation demonstrate the persistence of industrial interest in CO_2 extraction in areas where spring sources are strongly affected by CO_2 bubbling activity. These emissions are representative of regional «anomalous» composition of shallow waters contamined by fluids upwelling from confined deep-seated gas reservoirs (Panichi

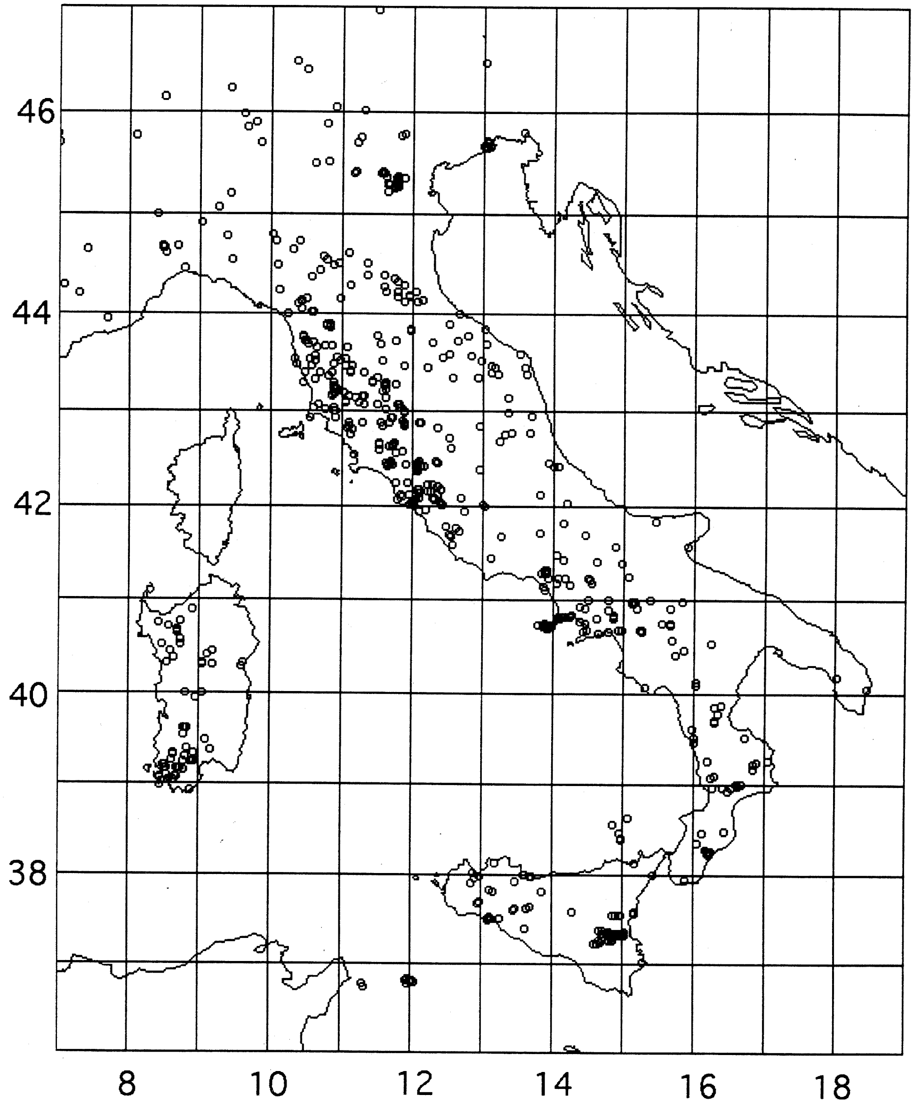

Fig. 1. Locations of thermically anomalous ($T \geq 17$ °C) spring sources deduced from the relevant literature (Tioli, 1894; Vinaj and Pinali, 1923; Touring Club Italiano, 1936; Fanelli, 1972; Fanelli *et al.*, 1982).

and Tongiorgi, 1975; Gianelli, 1985; Chiodini *et al.*, 1995). Furthermore, CO_2 can strongly affect water-rock interaction processes making earthquake-related geochemical phenomena more easily detectable (Dall'Aglio, 1976; Irwin and Barnes, 1980).

A list of CO_2 mine exploitation and exploration licences was compiled after a check of the Official Bulletin of the Italian Ministry of Industry and Mine Corps by 1897 up to 1987 with contemporary updates. The corresponding data base is described in Appendix 2 and in-

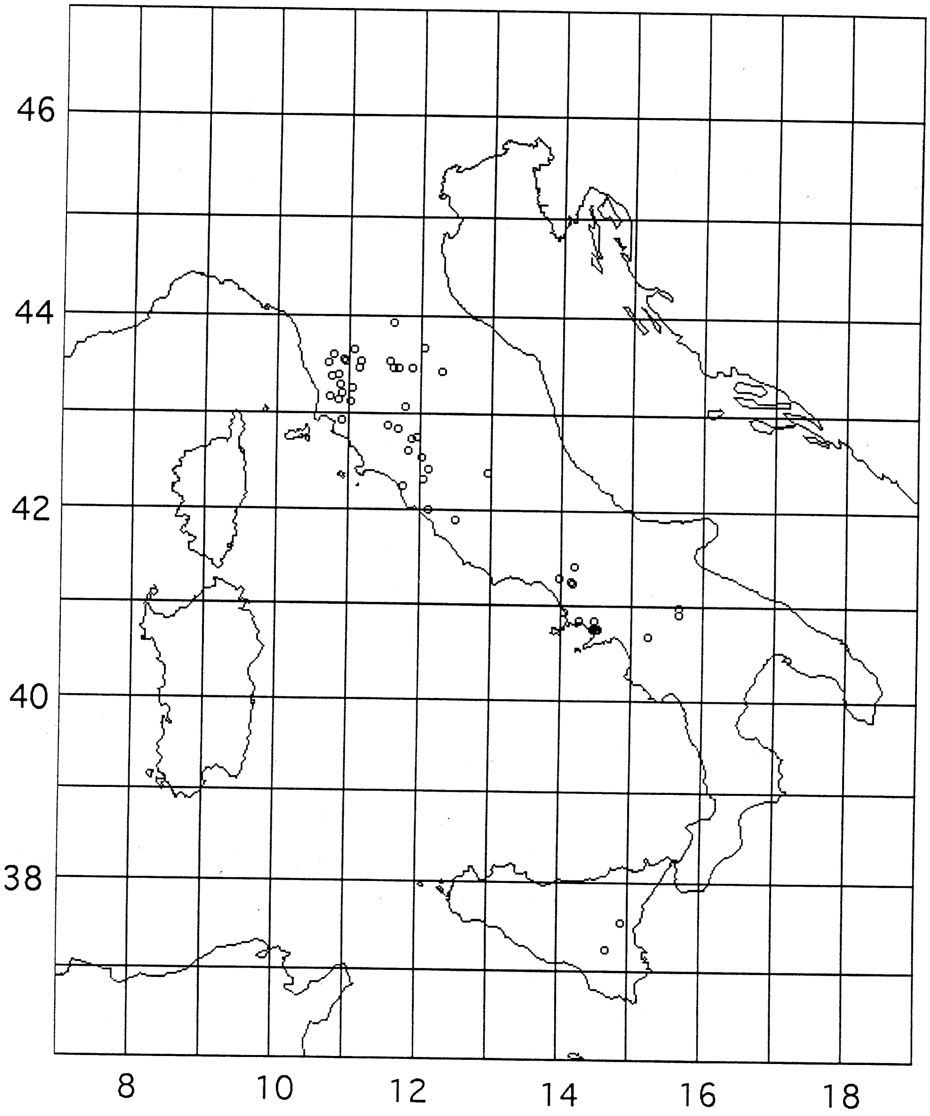

Fig. 2. Locations of mineral permits for industrial exploitation of natural CO_2 ground emissions (Official Bullettins of the Italian Ministry of Industry and Mining Corps).

cludes 380 sites (fig. 2): each of them represents one or more gas accumulations generally discovered on the basis of surface manifestations, geophysical surveys and drillings. Gas pressure values can reach some hundreds of atmospheres.

A third, and probably less reliable criterion, is the presence of information on the «anomalous» behaviour of underground fluid in association with past earthquakes. The reliability of such information, widely present in documentary descriptions of old earthquakes, is probably compromised by the lack of objective check of the available witnesses (in most cases provided by occasional observers) always collected after the earthquakes. Furthermore, in most cases, the «anomalous» character of the observed event is not well defined and only qualitatively assessed. Despite these limitations, this kind of information might suggest useful indications oriented to more detailed analyses and can corroborate site selection performed on the basis of other pieces of information. For this purpose, a catalogue of seismic-

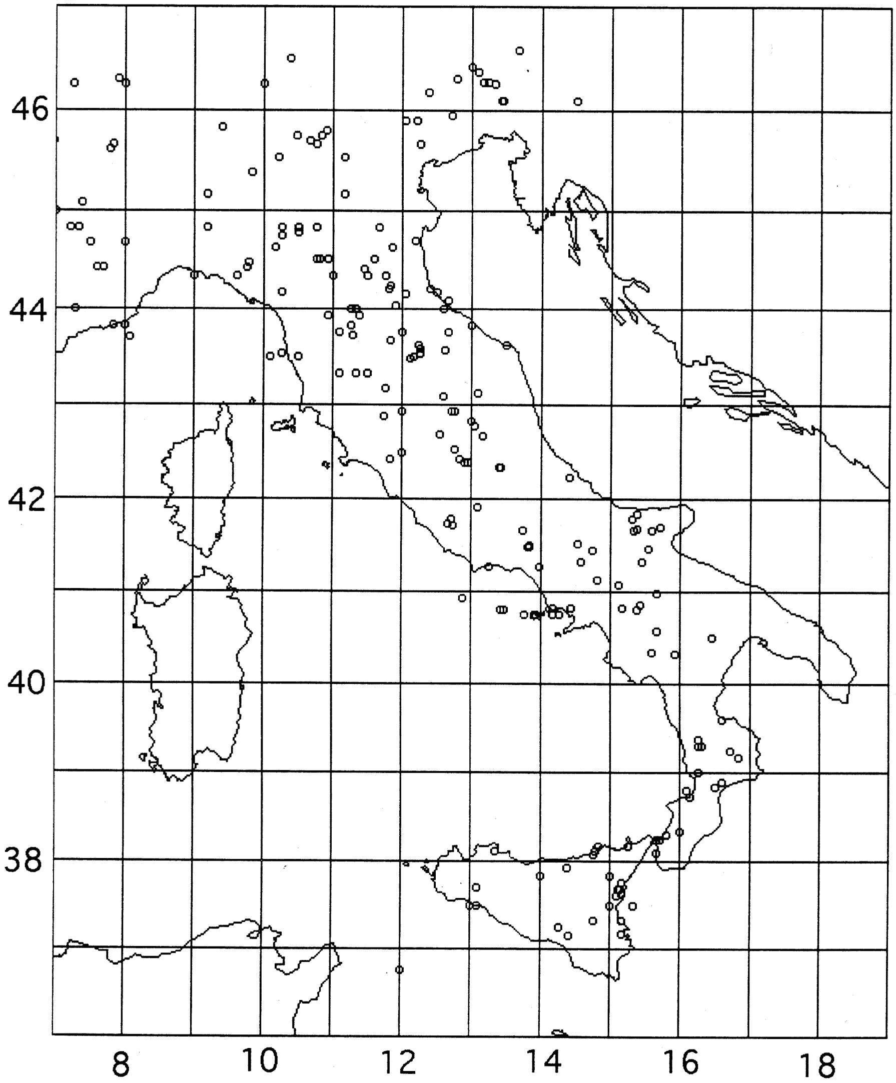

Fig. 3. Locations of sites where earthquake related anomalies in ground fluid emission are documented in the historical record (Bonito, 1691; Mallett, 1862; Mercalli, 1883; Baratta, 1901; Dall'Aglio, 1976; Balderer and Martinelli, 1995; Boschi *et al.*, 1995).

related phenomena reported in old documentary sources was compiled (see Appendix 3) after a check on the important historical reports on earthquakes and related phenomena in Italy published in the last centuries by Bonito (1691), Mallett (1862), Mercalli (1883) and Baratta (1901). Data quoted by Boschi *et al.* (1995) and Martinelli (1997) on precursory phenomena connected with the strongest events which have occurred in Italy in the past 1000 years were also included. In this way, 223 events accompanied by «anomalous» phenomena were identified in Italy (fig. 3).

2.2. *Seismological constraints*

The importance of such constraints, to be defined on the basis of a statistical analysis of local seismicity, is in general underestimated. In most cases, this criterion is simply ignored in the assumption that earthquakes occur almost everywhere in Italy. In other cases, surveys were carried out in areas where in the past large earthquakes have occurred. In the latter case, the underlying assumption is that seismogenic sources responsible for the strongest earthquakes are also responsible for more frequent minor seismic activity. In general, this assumption is not checked by an adequate statistical analysis of recent seismicity. This implies that, since the expected return times of such larger earthquakes are in general much longer than geochemical/hydrological routine surveys (several hundreds years *vs.* a few years) sites chosen in this way prove almost «quiescent» from the seismic point of view. In these «unlucky» cases, expensive surveys of gas-fluid ground emissions cannot be correlated with relevant seismic activity and no conclusive result can be obtained. A better knowledge of «minor» but relatively frequent seismicity could be considered helpful for geochemical monitoring purposes, and thus, an explorative statistical analysis of seismicity in the whole Italian area was performed.

The aim of the procedure is to evaluate, for each site, the probability that at least one earthquake, able to produce significant effects on fluid emission at the site, is expected to occur within a fixed time span (seismic hazard).

The estimate of this probability for the area under study was made in the framework of a number of simplifying assumptions. In order to make available for statistical analysis a sufficient seismic sample, a relatively low magnitude threshold was chosen ($M \geq 3.5$).

Theoretical/experimental considerations (Dobrovolsky *et al.*, 1979; Hauksson, 1981) allowed us to roughly estimate from the magnitude of the expected event, the maximum useful range between the seismic source and the monitoring sites where possible hydrogeochemical phenomena induced by the seismogenic process are in principle observable (range of detectability).

In the case of events characterized by the minimum magnitude here considered (3.5) the range of detectability results in the order of 20 km (Hauksson, 1981).

A second major assumption concerns the statistical model to be chosen for the estimate of the seismic hazard as a function of seismic history. In general, seismic events cannot be considered mutually independent (earthquakes swarms, mainshock-aftershock sequences, etc.) and thus simple Poissonian models (see, *e.g.*, Lomnitz, 1974) are ruled out when relatively low magnitude events (as in the present case) are considered. On the other hand, more complex approaches (see, *e.g.*, Hong and Guo, 1995) are beyond the scope of the present explorative survey. To overcome this problem, a simple robust approach was applied.

For each possible site, the time dependent stocastic variable E was considered. It was defined over discrete time intervals of length Δt and assumed value 1 if at least one earthquake with magnitude ≥ 3.5 occurred within 20 km from the monitoring site during the considered time interval and 0 otherwise. It is assumed that for suitable choices of the time span Δt (1 year in the present study) realizations of the binary random variable E can be considered mutually independent.

Given the probability F that in the generic elementary time interval E is 0 (no earthquake occurs with magnitude ≥ 3.5) it is assumed that F does not depend on the particular time interval considered.

In this case it holds that

$$P = 1 - (F)^q \tag{2.1}$$

where P is the probability that at least one earthquake with magnitude ≥ 3.5 is expected to occur in the time span $\Delta T = q\Delta t$. The probability F can be empirically estimated for each site taking into account the past seismic activity during a time span $T \gg \Delta T$. A possible estimator of F can be given by

$$F = n\,\Delta t/T \tag{2.2}$$

where n is the number of non overlapping time intervals of length Δt covering the time span T and such that $E = 0$.

The key point of the proposed approach is the definition of the time span T to be used for the estimate of F by eq. (2.2). Of course, the longer the span T the more reliable is the final estimate of F. However, seismic catalogues to be used for F estimates are affected by incompleteness (see, *e.g.*, Lee and Brillinger, 1979; Mulargia *et al.*, 1987a). In particular, the «apparent» seismicity rate generally decreases back in time as an effect of worsening of available information on past seismicity. This apparent decrease may produce significant biases in F estimates performed using «incomplete» catalogues. A further bias can also be introduced by variations in the monitoring network which could significantly affect earthquake parameterization. An example of this kind of effect was recently pointed out in the Italian region (Wyss *et al.*, 1997).

In order to reduce these problems, a number of approaches have been proposed so far to identify the stationary («complete») segments of the catalogues which can be safely used for hazard estimates (Stepp, 1971; Caputo and Postpischl, 1974; Bath, 1983; Tinti and Mulargia, 1985a,b; Mulargia *et al.*, 1987a,b).

The approach here adopted represents a more quantitative version of the CUVI semi-qualitative technique proposed by Mulargia *et al.* (1987a,b) and is based on the Cox and Stuart distribution-free stationarity test (Rock, 1988). It is assumed that at the present time (T_f) seismicity overcoming the threshold of interest ($M \geq 3.5$) is satisfactorily monitored and that incompleteness increases back with time. Given a possible starting point T_i for the catalogue to be used for the estimate of F, the probability can be computed that in the time span $[T_i, T_f]$ the catalogue is «complete» or, in more correct terms, that the seismicity rate in the considered time span «appears» stationary. For this purpose, the time interval $[T_i, T_f]$ is divided into M elementary non overlapping sub intervals of equal length δt (1 year in the present analysis). The number of earthquakes N_j which occurred within each j-th sub interval is thus computed from the seismic catalogue. The binary random variable R_j is defined to assume value 1 when $N_j > N_{j+M/2}$ and 0 otherwise. If M is equal to $(T_f - T_i)/\delta t$, we have $M/2$ realizations of the binary variable R_j in the considered time interval: K out of them correspond to the case $R = 1$. If the seismicity rate is stationary, probabilities for each realization to be $R_j = 1$ or $R_j = 0$ should both be equal to 0.5. By using the binomial distribution it is possible to compute the probability that K (or more) out of $M/2$ realizations of R result equal to 1 in the case of stationarity. If this probability results higher than a fixed threshold (assumed equal to 0.1 in the present analysis) the hypothesis of stationarity (here equivalent to the assumption of completeness) for the time interval $[T_i, T_f]$ is accepted. Each possible choice of T_i can be explored and possible «completeness» intervals can be checked.

This approach was applied to the data set represented by the Italian Catalogue of Earthquakes (Postpischl, 1985) extended to 1994 by using data from ING bulletins. The analysis suggests that the catalogue can be considered «complete» for magnitude $\geq$ 3.5 since 1960. The distribution of earthquakes which occurred in Italy with $M \geq 3.5$ and reported in the «complete» part of the catalogue is shown in fig. 4.

Thus, the Italian territory was divided into 20 × 20 km cells overlapping each other for a 10 km strip on each side. Earthquakes which occurred within each cell since 1960 until 1994 were considered for hazard estimates by using

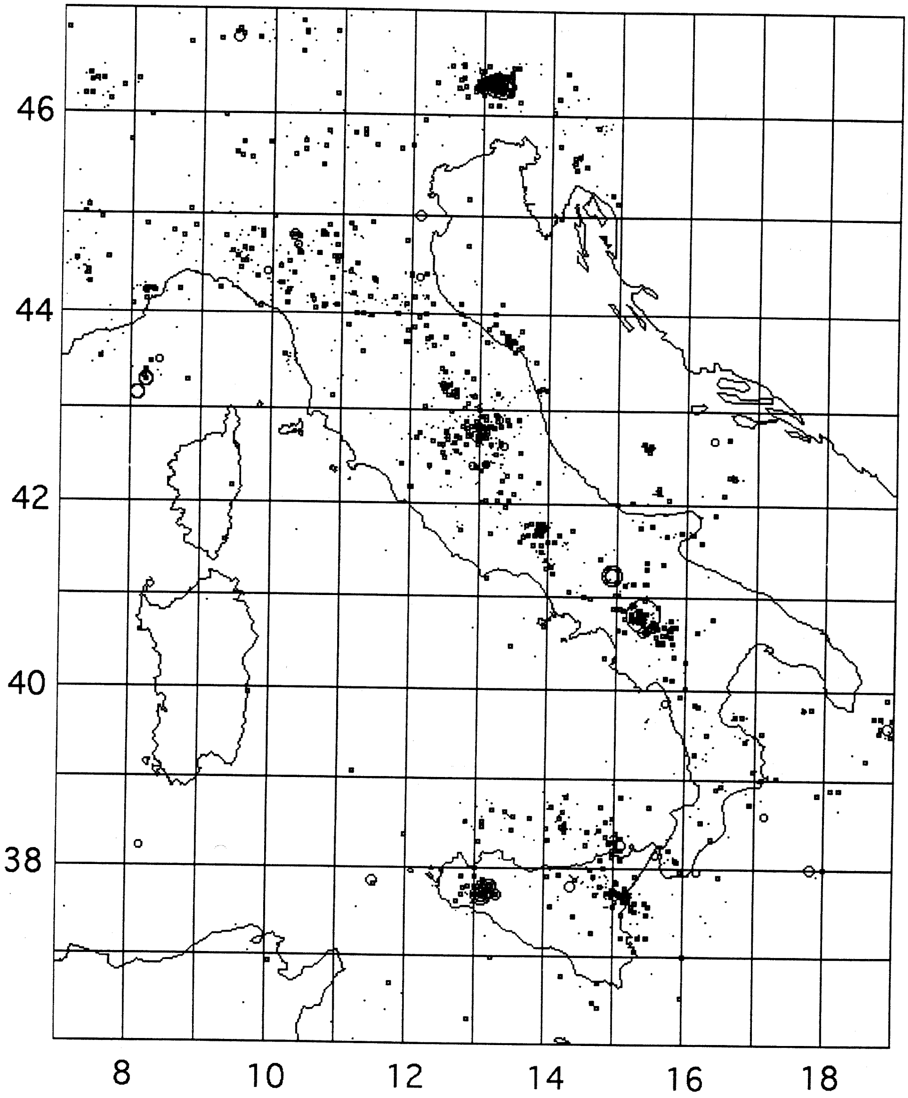

Fig. 4. Distribution of earthquakes occurred in Italy in the period 1960-1994 with magnitude ≥ 3.5 (Postpischl, 1985; ING bullettins). Circle locate seismic epicenter and its size is representative of the focal volume deduced from magnitude following Bath and Duda (1964).

eqs. (2.1)-(2.2) with ΔT equal to 3 years ($q = 3$) and Δt equal to 1 year. Figure 5 reports the locations of cells where the probability of observing at least one earthquake with magnitude ≥ 3.5 in a 3 year time span resulted ≥ 50% (white cells) and ≥ 60% (black cells). In order to show to what extent the choice of ΔT affects the distribution and the extension of areas where future seismic activity is expected, fig. 6 reports the location of cells where the probability of observing at least one earthquake with magnitude ≥ 3.5 in a 5 year time span results

≥ 50% (white cells) and ≥ 60% (black cells). The comparison between figs. 5 and 6 indicates that the number of sites suitable for monitoring earthquake related phenomena critically depends on the choice of the time interval considered economically realistic for the experimental survey to be performed.

3. Site selection

Data shown in figs. 1, 2 and 3 and results reported in fig. 5 allow a first selection of sites of potential interest.

The most restrictive criteria are supplied from the analysis of seismicity. In fact, despite

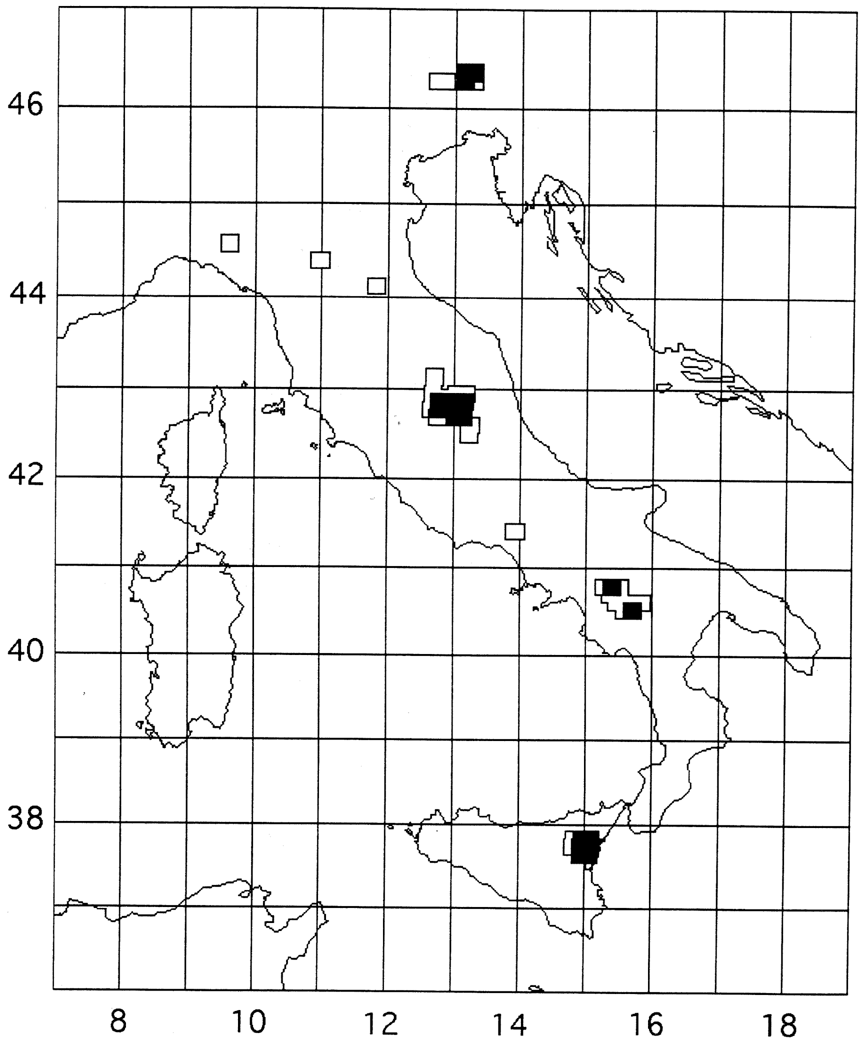

Fig. 5. Results of the seismic hazard analysis. Polygons include areas characterized by a probability ≥ 50% to generate at least one earthquake with magnitude ≥ 3.5 in a time span of 3 years (see text for details). Black areas are the ones where the probability is ≥ 60%.

the widespread distribution of seismicity in the Italian area (see fig. 4) sites where the probability of observing at least one event within 3 years with magnitude ≥ 3.5 is significant are few (fig. 5). Maximum probability over the whole territory does not exceed 75%, but in the peculiar area of the Etnean volcanic district where a probability of 81% is reached. Results in fig. 5 disclose 8 areas where the probability of observing at least one earthquake during a three year time span exceeds 50%. Each of these areas has been conventionally identified by the denominations reported in fig. 7. In order to further select among these areas the

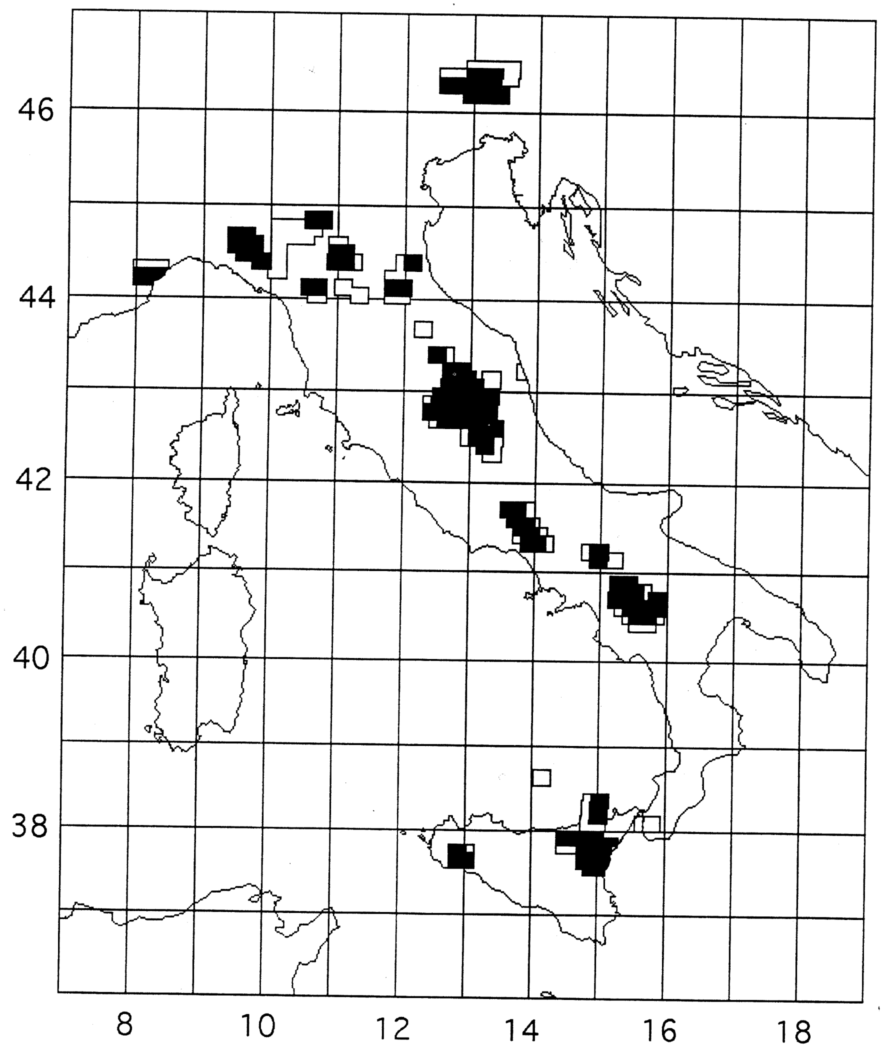

Fig. 6. Results of the seismic hazard analysis. Polygons include areas characterized by a probability ≥ 50% to generate at least one earthquake with magnitude ≥ 3.5 in a time span of 5 years (see text for details). Black areas are the ones where the probability is ≥ 60%.

most promising ones for geochemical monitoring experiments, data concerning the presence of hot spring sources, CO_2 exploitation, hydrogeochemical activity associated with past earthquakes have been considered.

The Friuli area – This area is located along a well recognized compressional belt which most probably accommodates the continental collision occurring between the Adriatic microplate, moving roughly N to NNW, and the Alpine belt (see, *e.g.*, Mantovani *et al.*, 1996 and references therein). The recent/present compressional activity of the belt is testified by neotectonic observations and by the occurrence of intense seismic activity which is characterized by compressive fault plane solutions (see *e.g.*, Slejko *et al.*, 1989).

The analysis of recent seismicity in the zone suggests that the probability of observing at least one earthquake with $M \geq 3.5$ within 3 years is greater than 70%. The interest of this test site for studies on precursory phenomena is also reinforced by the fact that at least 4 strong earthquakes ($I_{\max} \geq$ IX) have been generated in seismogenic sources located within 50 km from the considered area in 1348, 1511, 1928, 1976 (Boschi *et al.*, 1995).

However, from the hydrogeological point of view, the most represented rocks are karst calcareous complexes which inhibit the development of confined aquifers due to their high hydraulic conductivity and absence of aquitards. This feature makes it difficult to identify spring sources suitable for the study of earthquake-related phenomena. Few attempts to relate water level variations with earthquakes have been made (Riggio and Sancin, 1995; Braitemberg *et al.*, 1997). No CO_2 mining licences and no anomalous spring sources are known within the considered area. The nearest «anomalous» spring source of our catalogue is Arta Terme (close to the city of Udine), a relatively cold spring source fed by a short path hydrologic circuit. According to Belloni *et al.* (1979) no significant geochemical anomalies were detected in Arta Terme spring source in the seismic period of 1976. The absence of CO_2 gas emissions in the area and the lack of phenomena related to past earthquakes confirm the relatively scarce interest of Arta Terme water for the study of deep-seated phenomena. In any case, monitoring activity on Arta Terme water could be possibly informative about strong but poorly probable local seismic events. Drillings at depth ranging 500-1000 m could be useful to reach more informative local chemically and thermically anomalous fluids (ENI, 1972; Bellani *et al.*, 1995).

Parma, Bologna and Forlì – Detailed scientific literature is available on the seismotectonic of Northern Apenninic belt where the three areas indicated as «Parma», «Bologna» and «Forlì» in fig. 7 are located (see, *e.g.*, Boccaletti *et al.*, 1985; Castellarin and Vai, 1986). The area represents a large accretionary complex characterized by thrust structures to the north (outer Apenninic border) and coeval tensional features to the south (inner Apenninic border). These tectonic structures are presently active as indicated by neotectonic data and seismic activity. The three sub-areas considered in the present analysis are characterized by a relatively low hazard, the probability of observing at least one event with $M \geq 3.5$ within 3 years being less than 60% for each sub-area. This relatively low seismicity level is also confirmed by the analysis of the strongest earthquakes ($I_{\max} \geq$ IX) reported in a recent seismic catalogue (Boschi *et al.*, 1995). No strong earthquake is known to be generated near (less than 50 km away) the westernmost sub-area («Parma») while, as concerns the central sub-area («Bologna»), only relatively old earthquakes (1501 and 1542) are reported in the catalogue with maximum observed intensity ≥ IX MCS. The easternmost area («Forlì») is the most active one and at least 5 strong seismic events ($I_{\max} \geq$ IX) have been recorded (1542, 1661, 1768, 1781 and 1919).

Some potentially interesting spring sources are known in the areas of «Parma» (S. Stefano d'Aveto in Genova Province) and «Bologna» (Castelvetro and Torre Maina spring sources in Modena Province and Vergato-Cavacchio in the Bologna Province). All the mentioned groundwaters are characterized by short path hydrologic circuits. No salinity anomaly has been pointed out until now except at S. Stefano

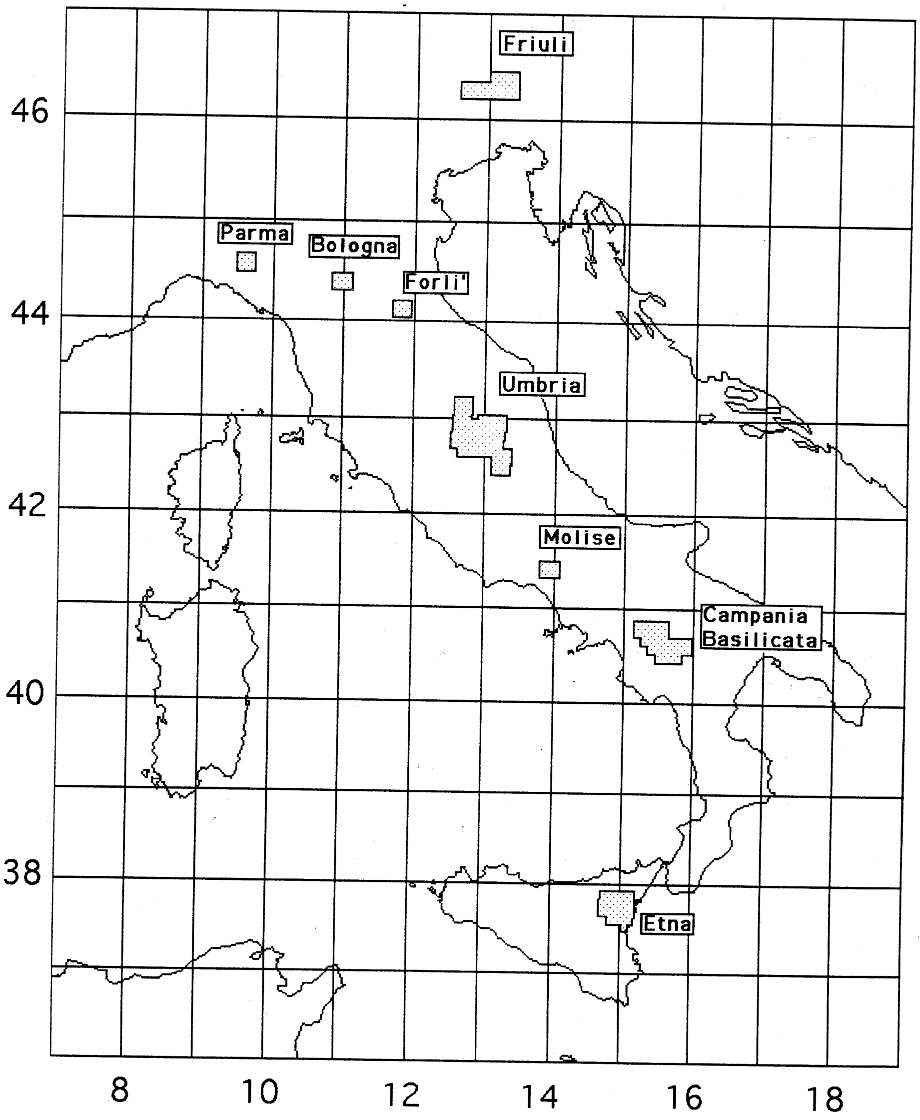

Fig. 7. Locations and adopted conventional denominations of possible test areas suitable for the study of hydrogeochemical earthquake related phenomena on the basis of seismic hazard results in fig. 5.

d'Aveto for which spot past information refers to a slight Na-Cl character. The springs of the Modena Province are now abandoned or not caught. The absence of CO_2 in all the mentioned fluids strongly discourages further possible monitoring activity.

As concerns the Forlì area, which represents the most interesting sector of the Northern Apennines due to the relatively strong seismicity recorded in the past, no high temperature or CO_2 bearing water is present in the nearby areas. The Castrocaro Terme, Dovadola and

Modigliana spring sources are the only relevant ones in the identified sector. Castrocaro Terme spring sources could be considered interesting for geochemical monitoring of seismic activity due to its anomalous salinity with respect to the regional geochemical framework.

In 1661 the close localities Galeata and Pondo (Monte Steragia) were affected by some degassing activities (Bonito, 1691; Boschi *et al.*, 1995) however, the absence of CO_2 degassing in the area makes these springs poorly suitable for geochemical monitoring. Some local spontaneous CH_4 emissions could be the object of future research.

Umbria – From the tectonic point of view this area (fig. 7) is located close to the Olevano-Antrodoco (or Ancona-Anzio) line, an old lateral ramp which accommodated the relative displacements between different segments of the Apenninic belt (see, *e.g.*, Ghisetti and Vezzani, 1991). Present activity of tectonic structures of this area is testified by the significant seismic activity observed both in historical and recent times (Cello *et al.*, 1997). Following Boschi *et al.* (1995), this area has been characterized by intense seismic activity with at least 10 strong earthquakes ($I_{\max} \geq$ IX MCS) since 1000 A.D. (1279, 1328, 1349, 1639, 1703, 1730, 1741, 1751, 1799, 1832). Recent seismic activity suggests that the probability of observing in the area at least one event with $M \geq 3.5$ within three years reaches 68%.

In this sector of the Apenninic belt, many springs are present and have been described by Chiodini *et al.* (1982). The Triponzo-Cerreto di Spoleto (29 °C), Parrano (27 °C) warm springs, the Massa Martana, the Monte Castello di Vibio, and the Umbertide CO_2 gas emissions are the most interesting sites.

The CO_2 signature clearly recognized in most local springs makes the Umbria Region a challenging test site. In May 1997 in concomitance with a $M = 4.5$ seismic event close to Massa Martana some chemical parameters (CO_2, electric conductivity, Cl) slightly fluctuated in the Massa Martana «San Faustino» springs (courtesy of C. Petrucci). In connection with the seismic sequence in September 1997 which occurred 20-25 km far away from the Triponzo-Cerreto di Spoleto spring, a slight fluctuation (~ 1 °C) of water temperature was observed. Gas activity variations were also observed in some spring sources and gas emissions (Parrano, Monte Castello di Vibio, etc.).

In the 1703 (Norcia) earthquake, coseismic fluid related phenomena were recorded (Mercalli, 1883; Baratta, 1901).

Molise area – From the tectonic point of view this zone, roughly coincident with the Isernia Province, is located near the Ortona-Roccamonfina line, a major deformation belt which separates the two tectonic domains of the Abruzzi-Latium platform (to the north) and Southern Apenninic arc (to the south). This structure, which probably represents the surface expression of a lithospheric discontinuity, played an important role in the evolution of the Apenninic belt and surrounding regions (see, *e.g.*, Patacca and Scandone, 1989; Patacca *et al.*, 1990).

Present seismic activity of this area is relatively low with a probability of observing at least one event with $M \geq 3.5$ within 3 years equal to 54%. However, in the past, this region experienced a number of strong earthquakes (1361, 1456, 1688, 1702, 1732, 1805, 1962, all with $I_{\max} \geq$ IX MCS) probably generated within 50 km from the considered site (Boschi *et al.*, 1995).

No high temperature waters are present in the area. Only the Venafro spring source is characterized by a slight chemical anomaly (CO_2 bubbling). Direct observations demonstrate that temperature values of Venafro springs do not exceed 13 °C. However, at least part of the springs are affected by CO_2 presence (Cotugno, 1824; G. Iannacone, 1997, personal communication). Strong CO_2 springs were caught by a well in modern times in Roccaravindola, close to Venafro, and abandoned in 1995 due to water level lowering. In correspondence with the 1231 Montecassino earthquake (Mercalli, 1883; Baratta, 1901), coseismic and postseismic phenomena were recorded. No recent scientific literature is available about anomalous springs active in this selected site.

Campania-Basilicata – The identified sector of the Southern Apennines consists of a pile of thrust sheets forming a complex system orogenically transported over the flexured southwestern margin of the Apulia foreland. In very recent times (Patacca and Scandone, 1989; Patacca *et al.*, 1990), due to the suture of the Apenninic/Apulian front, the previous compressional regime was substituted by a more complex tectonic pattern which involves complex block rotations and bending of pre-existing belts (Cinque *et al.*, 1993). Present tectonic activity is testified by the occurrence of large earthquakes mostly related to tensional structures (see, *e.g.*, Westaway and Jackson, 1987). At least 7 strong earthquakes ($I_{\max} \geq$ IX MCS) have originated within 50 km from the considered area (1561, 1694, 1851, 1853, 1857, 1930, 1980).

From the hydrogeochemical point of view, spring sources and gas emissions located in the Province of Salerno (Contursi Terme and Oliveto Citra), and the spring sources of Tito and Bella (both in the Province of Potenza) are suitable for monitoring deep-seated hydrologic circuit fluids due to their relatively high temperature ranging between 20 and 40 °C and CO_2 intense bubbling, probably related to deep faults which can be pathways for anomalous fluid flow of deep origin (Balderer and Martinelli, 1995). The interest in the area for monitoring activity is also confirmed by the presence of the nearby CO_2 mine licences located in Riardo, Teano, Rocchetta, Oliveto Citra and Rionero in Vulture. Encouraging information also comes from past hydrogeochemical coseismic activity: in 1694 (Basilicata), in 1826 (Tito), 1980 (Irpinia-Basilicata) coseismic and precursory phenomena were locally recorded also in the Avellino Province (Mercalli, 1883; Baratta, 1901; Balderer and Martinelli, 1995) where a strong CO_2 gas emission (Mefite D'Ansanto) characterized by a marked $^3He/^4He$ signal occurred (Balderer and Martinelli, 1995; Doglioni *et al.*, 1996).

Mt. Etna area – Intense seismic activity has been observed in the area both in connection with volcanic and tectonic activity (see, *e.g.*, Romano, 1982; Chester *et al.*, 1985). Following Boschi *et al.* (1995), at least 9 strong earthquakes ($I_{\max} \geq$ IX MCS) occurred within 50 km from this area (1169, 1693, 1786, 1818, 1865, 1879, 1894, 1911, 1914). Minor seismicity is characterized by relatively high occurrence rates and the probability to observe at least one event with $M \geq 3.5$ in the area results the highest of the whole explored region (up to 81%).

Interesting scientific literature is available on fluids and spring sources in the Etna area (Anzà *et al.*, 1989; Dall'Aglio *et al.*, 1994; Parello *et al.*, 1995; D'Alessandro *et al.*, 1997; Giammanco *et al.*, 1997). The mine licences of Paternò and Mineo confirm the intense regional CO_2 flux. Water temperatures and chemical compositions confirm significant water-rock interaction processes for local fluids. The most promising identified fluids of the area occur in Acireale spring sources. Furthermore, in 1169 (Mar Jonio – Mt. Etna), 1329 (Mt. Etna), 1818 (Catania Province), 1865 (Mt. Etna), 1879 (Mt. Etna), 1879 (Acireale), 1880 (Giarre) precursory phenomena occurred (Mercalli, 1883; Baratta, 1901).

3.1. *Most promising test sites*

On the basis of the exploratory screening performed above, it results that among the 8 areas shown in fig. 7 only three priority areas are recognizable because of the contemporary convergence of the adopted indicators: relatively high seismic rates, emergencies of deep-seated circulating fluids. In fact, thermically anomalous spring sources and large CO_2 emissions are lacking in «Friuli», «Parma», «Bologna», «Forlì» and «Molise» areas. On the other hand, relatively high seismicity rates along with the presence of significant ground fluid emergencies representative of deep-seated circulation in the areas of «Umbria», «Campania-Basilicata» and «Etna» indicate these areas as the most promising ones for monitoring hydrogeochemical anomalies possibly related to seismic activity. Furthermore, since in the past these areas have been characterized by damaging earthquakes, studies of seismic precursory activity could also be of interest for civil defence purposes.

Among these three most promising sites, particular caution should be associated with monitoring projects in the «Etna» area where the presence of major volcanic activity is likely to produce strong perturbations in gas-fluid-rock interaction processes. This feature could make it difficult to separate hydrogeochemical manifestations induced by seismogenic processes from phenomena related to impending volcanic activity (see also Bonfanti *et al.*, 1996). Intense joint geophysical and geochemical monitoring could help to solve interpretative problems deriving from complex local geological features.

4. Conclusions

Three data bases, useful to select possible Italian locations for monitoring experiments devoted to the study of earthquake related hydrogeochemical phenomena have been compiled on the basis of available literature. The first concerns more than 1200 hydrothermal/thermomineral springs exploited both for medical and industrial purposes and presumably representative of deep-seated fluid circulation. The second reports data on more than 350 sites where industrial exploitation of CO_2 emissions has been active. The third concerns those sites (more than 200) where anomalous behaviour of local springs has been documented in association with past earthquakes.

In order to select areas where medium-term (3 years) monitoring projects can be developed without unnecessary time lost, recent seismicity was analyzed to identify sites where the probability that at least one earthquake with magnitude ≥ 3.5 will occur within 20 km during a 3 year time interval is greater than 50%.

The most constraining results were supplied by the seismic hazard analysis and only a few places in the Italian territory seem to provide a seismic activity suitable for precursor research monitoring. Among these sites, three areas only, respectively located in Central Italy («Umbria»), Southern Italy («Campania-Basilicata») and Sicily («Etna»), were identified. In these areas, the presence of warm natural springs presumably representative of deep-seated fluid circulation, large CO_2 emissions, the recorded occurrence of seismicity-related anomalies and the proximity to significant seismogenic sources are promising for successful monitoring experiments.

REFERENCES

ANZÀ, S., G. DONGARRÀ, S. GIAMMANCO, V. GOTTINI, S. HAUSER and M. VALENZA (1989): Geochimica dei fluidi dell'Etna: le acque sotterranee, *Mineral. Petrogr. Acta*, **32**, 231-251.

BALDERER, W. and G. MARTINELLI (1995): Geochemistry of groundwaters and gases occurring in the 23 November 1980 earthquake area (South Italy), *Environ. Geochem. Health*, **16** (suppl), 147-164.

BARATTA, M. (1901): *I Terremoti d'Italia*, anastatic reprint (A. Forni Ed., Bologna, 1979), pp. 951.

BATH, M. (1983): Earthquake data analysis: an example from Sweden, *Earth Sci. Rev.*, **19**, 181-303.

BATH, M. and S.J. DUDA (1964): Earthquake volume, fault plane area, seismic energy, strain deformation related quantities, *Ann. Geofis.*, **17**, 353-368.

BELLANI, S., C. CALORE, S. GRASSI and P. SQUARCI (1995): Flusso di calore superficiale in presenza di acquiferi in bacini sedimentari e anomalie termiche profonde: due esempi, in *Atti 14° Convegno GNGTS*, CNR, vol. 2, 911-923.

BELLONI, S., A. CAVALLIN, M. MANCUSO, B. MARTINIS and G. SFONDRINI (1979): *Le Acque Solfuree di Arta (Carnia) ed il loro Ambiente Geologico*, CNR, Udine, pp. 179.

BOCCALETTI, M., M. COLI, C. EVA, G. FERRARI, G. GIGLIA, A. LAZZAROTTO, F. MERLANTI, R. NICOLICH, G. PAPANI and D. POSTPISCHL (1985): Considerations on the seismo tectonics of the Northern Apennines, *Tectonophysics*, **117**, 7-38.

BODVARSSON, G. (1970): Confined fluid as strain meters, *J. Geophys. Res.*, **75**, 2711-2718.

BONFANTI, P., W. D'ALESSANDRO, G. DONGARRÀ, F. PARELLO and M. VALENZA (1996): Medium term anomalies in ground water temperature before 1991-1993 Mt. Etna eruption, *J. Volcanol. Geotherm. Res.*, **73** (3/4), 303-308.

BONITO, M. (1691): *Terra Tremante*, anastatic reprint (A. Forni Ed., Bologna, 1981), pp. 822.

BOSCHI, E., G. FERRARI, P. GASPERINI, E. GUIDOBONI., G. SMRIGLIO and G. VALENSISE (1995): *Catalogo dei Forti Terremoti in Italia dal 461 a.C. al 1980*, Istituto Nazionale di Geofisica, Roma, pp. 973.

BRAITEMBERG, C., M. GARAVAGLIA, S. MAGNONI and M. ZADRO (1997): Radon and crustal deformation continuous monitoring in the seismic area of Friuli, North-East of Italy, in *Proceedings of the 3rd International Colloquium on Rare Gas Geochemistry*, Amritsar, 143-157.

CAPUTO, M. and D. POSTPISCHL (1974): Contour mapping of seismic areas by numerical filtering and geological implications, *Ann. Geofis.*, **27**, 619-640.

CARAPEZZA, M., P.M. NUCCIO and M. VALENZA (1980): Geochemical precursors of earthquakes, in *High Pressure Science and Technology*, edited by B. VODAR and P.H. MARTEAU (Pergamon Press), 90-103.

CASTELLARIN, A. and G.B. VAI (1986): South Alpine *versus* Po plane Apenninic area, in *The Origin of Arcs*, edited by F.C. WEZEL (Elsevier, Amsterdam), **19**, 253-270.

CATALDI, R., F. MONGELLI, P. SQUARCI, L. TAFFI, G. ZITO and C. CALORE (1995): Geothermal ranking of Italian territory, *Geothermics*, **24**, 115-129.

CELLO, G., S. MAZZOLI, E. TONDI and E. TURCO (1997): Active tectonics in the Central Apennines and possible implications for seismic hazard analysis in peninsular Italy, *Tectonophysics*, **272**, 43-68.

CHESTER, D.K., A.M. DUNCAN, J.E. GUEST and C.R.J. KILBURN (1985): *Mount Etna* (Chapman and Hall Ltd., London), pp. 404.

CHIODINI, G., S. GIAQUINTO and A.R. ZANZARI (1982): Relazione tra il chimismo delle sorgenti Umbre e le caratteristiche litologiche degli acquiferi, in *Energia Geotermica: Prospettive Aperte dalle Ricerche del CNR*, CNR, Progetto Finalizzato Energetica, Roma, 30-47.

CHIODINI, G., F. FRONDINI and F. PONZIANI (1995): Deep structures and carbon dioxide degassing in Central Italy, *Geothermics*, **24**, 81-94.

CINQUE, A., E. PATACCA, P. SCANDONE and M. TOZZI (1993): Quaternary kinematic evolution of Southern Apennines. Relationships between surface geological features and deep lithospheric structures, *Ann. Geofis.*, **36** (2), 249-260.

COTUGNO, G. (1824): *Memorie Istoriche di Venafro*, Stamperia della Società Filomatica, anastatic reprint (A. Forni Ed., Bologna, 1976), pp. 353.

D'ALESSANDRO, W., S. DE GREGORIO, G. DONGARRÀ, S. GURRIERI, F. PARELLO and B. PARISI (1997): Chemical and isotopic characterization of the gases of Mount Etna (Italy), *J. Volcanol. Geotherm. Res.*, **78**, 65-76.

DALL'AGLIO, M. (1976): Earthquake prediction by hydrogeochemical methods, *Rend. Soc. It. Min. Petr.*, **32**, 421-436.

DALL'AGLIO, M., F. QUATTROCCHI, A. BENCINI, V. DUCHI and M. BRONDI (1992): Selecting proper sites for the automatic monitoring of geochemical premonitory events of earthquakes: case histories from Italy, in *Proceedings of 7th Water-Rock Interaction International Symposium*, Park City, 371-374.

DALL'AGLIO, M., F. PAGANI and F. QUATTROCCHI (1994): Geochemistry of the groundwaters in the Etna region before and after the paroxysmal phase of the eruption of December 1991: implications for the geochemical surveillance of Mt. Etna, *Acta Vulcanologica*, **4**, 149-156.

DOGLIONI, C., P. HARABAGLIA, G. MARTINELLI, F. MONGELLI and G. ZITO (1996): A geodynamic model of the Southern Apennines accretionary prism, *Terra Nova*, **8**, 540-547.

DOBROVOLSKY, I.P., S.I. ZUBKOV and V.I. MIACHKIN (1979): Estimation of the size of earthquake preparation zone, *Pure Appl. Geophys.*, **117**, 1025-1044.

ENI (1972): *Acque Dolci Sotterranee*, Roma, pp. 914.

FANELLI, M. (1972): Acque calde Italiane, CNR, Istituto Internazionale Ricerche Geotermiche, *Internal Technical Report.*

FANELLI, M., L. BELLUCCI and F. NACHIRA (1982): *Manifestazioni Idrotermali Italiane*, App. vol. R.F. 13 «Contributi alla conoscenza delle risorse geotermiche del territorio italiano», PF Energetica, pp. 191.

GASPERINI, P. and F. MULARGIA (1989): A statistical analysis of seismicity in Italy: the clustering properties, *Bull. Seism. Soc. Am.*, **79** (4), 973-988.

GHISETTI, F. and L. VEZZANI (1991): Thrust belt development in the Central Apennines (Italy): northward polarity of thrusting and out-of-sequence deformations in the Gran Sasso chain, *Tectonics*, **10** (5), 904-919.

GIAMMANCO, S., S. GURRIERI and M. VALENZA (1997): Soil CO_2 degassing along tectonic structures of Mount Etna (Sicily): the Pernicana fault, *Appl. Geochem.*, **12**, 429-436.

GIANELLI, G. (1985): On the origin of geothermal CO_2 by methamorphic processes, *Boll. Soc. Geol. It.*, **104**, 575-584.

HAUKSSON, E. (1981): Radon content of groundwater as earthquake precursor: evaluation of worldwide data and physical basis, *J. Geophys. Res.*, **86**, 9397-9410.

HONG, L.L. and S.W. GUO (1995): Nonstationary Poisson model for earthquake occurrences, *Bull. Seism. Soc. Am.*, **85**, 814-824.

IRWIN, W.P. and I. BARNES (1980): Tectonic relations of carbon dioxide discharges and earthquakes, *J. Geophys. Res.*, **85**, 3115-3121.

KÜMPEL, H.-J. (1991): Poroelasticity: parameters reviewed, *Geophys. J. Int.*, **105**, 783-799.

KÜMPEL, H.-J. (1992): About the potential of wells to reflect stress variations within inhomogeneous crust, *Tectonophysics*, **211**, 317-336.

LEE, W.H.K. and D.R. BRILLINGER (1979): On Chinese earthquake history – an attempt to model an incomplete data set by point process analysis, *Pure Appl. Geophys.*, **117**, 1229-1257.

LOMNITZ, C. (1974): Global tectonics and earthquake risk, in *Developments in Geotectonics* (Elsevier, Amsterdam), vol. 5, pp. 320.

MACCHIATO, M., C. SERIO, V. LAPENNA and L. LA ROTONDA (1993): Parametric time series analysis of cold and hot spells in daily temperature: an application in Southern Italy, *J. Appl. Meteorol.*, **32** (7), 1271-1281.

MALLET, R. (1862): *Great Neapolitaner Earthquake of 1857: the First Principles of Observational Seismology*, London, 2 vols.

MANTOVANI, E., D. ALBARELLO, C. TAMBURELLI and D. BABBUCCI (1996): Evolution of the Tyrrhenian basin and surrounding regions as a result of the Africa-Eurasia convergence, *J. Geodyn.*, **21** (1), 35-72.

MARTINELLI, G. (1995): Sulla scelta di aree test per la misura di precursori geochimici e geofisici in Italia Meridionale, in *Proceedings of the Meeting «Terremoti in Italia: Previsione e Prevenzione dei Danni»*, Roma, Accademia Nazionale dei Lincei, 271-277.

MARTINELLI, G. (1997): Non seismometrical precursors observations in Europe: steps of earthquake prediction research, in *Proceedings of the Workshop «Historical Seismic Instruments and Documents: a Heritage of Great Scientific and Cultural Value»*, edited by G. FERRARI, Conseil de l'Europe, Cahiers du Centre Européen de Géodynamique et de Séismologie, Walferdange, Luxembourg, vol. 13, 195-216.

MENNELLA, C. (1967): *Il Clima d'Italia* (EDART), pp. 1243.

MERCALLI, G. (1883): *Vulcani e Fenomeni Vulcanici in Italia*, anastatic reprint (A. Forni Ed., Bologna, 1981), pp. 376.

MINISSALE, A. (1991): Thermal springs in Italy: their relation to recent tectonics, *Appl. Geochem.*, **6**, 201-212.

MJACHKIN, V.I., W.F. BRACE, G.A. SOBOLEV and J.H. DIETERICH (1975): Two models for earthquake forerunners, *Pure Appl. Geophys.*, **113**, 169-181.

MULARGIA, F. and S. TINTI (1985): Seismic sample area defined from incomplete catalogues: an application to the Italian territory, *Phys. Earth Planet. Inter.*, **40**, 273-300.

MULARGIA, F., P. GASPERINI and S. TINTI (1987a): A procedure to identify objectively active seismotectonic structures, *Boll. Geofis. Teor. Appl.*, **29** (114), 147-164.

MULARGIA, F., P. GASPERINI and S. TINTI (1987b): Contour mapping of Italian seismicity, *Tectonophysics*, **142**, 203-216.

NICOLAYSEN, L.O. (1992): International semi controlled experiment on seismic event: a review of the background and proposal, IASPEI Sub-Commission Earthquake Prediction, Bernard Price Institute of Geophysical Research, Witwatersrand, *Technical Report*, pp. 17.

PANICHI, C. and E. TONGIORGI (1975): Carbon isotopic composition of CO_2 from springs, fumaroles, mofettes and travertines of Central and Southern Italy: a preliminary prospection method of geothermal areas, in *Proceedings 2nd UN Symposium on Development and Use Geothermal Research*, San Francisco, 815-825.

PARELLO, F., W. D'ALESSANDRO, P. BONFANTI and G. DONGARRÀ (1995): Subsurface gases in selected sites of the Mount Etna area (Sicily), *Acta Vulcanologica*, **7** (1), 35-42.

PATACCA, E. and P. SCANDONE (1989): Post-Tortonian mountain building in the Apennines. The role of passive inking of a relic lithospheric slab, in *The Lithosphere in Italy*, edited by A. BORIANI, M. BONAFEDE, G.B., PICCARDO and G.B. VAI, *Proc. Accad. Naz. Lincei*, Roma, **80**, 157-176.

PATACCA, E., R. SARTORI and P. SCANDONE (1990): Tyrrhenian basin and Apenninic arcs: kinematic relations since late Tortonian times, *Mem. Soc. Geol. It.*, **45**, 425-451.

POSTPISCHL, D. (Editor) (1985): Catalogo dei terremoti Italiani dall'anno 1000 al 1980, *Quad. Ric. Sci.*, **114** (2B), pp. 239.

RIGGIO, A. and S. SANCIN (1995): Analysis of some physical and seismological parameters as earthquakes precursors, in *Scientific Meeting on the Seismic Protection*, edited by V. SPAGNA and E. SCHIAVON, Regione Veneto, 114-118.

ROCK, N.M.S. (1988): *Numerical Geology* (Springer-Verlag, Berlin), pp. 427.

ROMANO, R. (Editor) (1982): Mount Etna Volcano, *Mem. Soc. Geol. It.*, **23**, pp. 205.

SCHOLZ, C.H., L.R. SYKES and Y.P. AGGARWAL (1973): Earthquake prediction: a physical basis, *Sciences*, **181**, 803-809.

SLEJKO, D., G.B. CARULLI, R. NICOLICH, A. REBEZ, A. ZANFERRARI, A. CAVALLIN, C. DOGLIONI, F. CARRARO, D. CASTALDINI, V. ILICETO, E. SEMENZA and C. ZANOLLO (1989): Seismotectonics of the Eastern Southern Alps: a review, *Boll. Geofis. Teor. Appl.*, **31** (122), 105-136.

STEPP, J.C. (1971): An investigation of earthquake risk in the Puget Sound area by the use of the type I distribution of largest extreme, *Ph.D. Thesis*, Pennsylvania State University, pp. 131.

SULTANKHODJAEV, A.N. (1984): Hydrogeoseismic precursors to earthquakes, in *Earthquake Prediction*, UNESCO, Paris, 181-191.

TIOLI, L. (1894): *Le Acque Minerali e Termali del Regno d'Italia*, Milano, pp. 552.

TINTI, S. and F. MULARGIA (1985a): Completeness analysis of a seismic catalogue, *Ann. Geophys.*, **3**, 407-414.

TINTI, S. and F. MULARGIA (1985b): An improved method for the analysis of the completeness of a seismic catalogue, *Lett. Nuovo Cimento*, **42**, 21-27.

TOURING CLUB ITALIANO (1936): *Guida Pratica ai Luoghi di Soggiorno e di Cura d'Italia*, part III, pp. 223.

VINAJ, G.S. and R. PINALI (1923): *Le Acque Minerali e gli Stabilimenti Termali, Idropinici ed Idroterapici di Italia* (Grioni Ed., Milano), 2 vols.

WAKITA, H., Y. NAKAMURA and Y. SANO (1988): Short-term and intermediate-term geochemical precursors, *Pure Appl. Geofis.*, **126**, 267-278.

WARING, G.A. (1965): Thermal springs of the United States and other countries of the world: a summary, USGS, Washington, *Professional Paper*, pp. 383.

WESTAWAY, R. and J. JACKSON (1987): The earthquake of 1980 November 23 in Campania Basilicata (Southern Italy), *Geophys. J. R. Astron. Soc.*, **90**, 375-443.

WYSS, M., R. CONSOLE and M. MURRU (1997): Seismicity rate change before the Irpinia ($M = 6.9$) 1980 earthquake, *Bull. Seism. Soc. Am.*, **87** (2), 318-326.

(received January 20, 1997;
accepted October 3, 1997)

Appendix 1.

The data base of thermally «anomalous» ($T \geq 17$ °C) spring sources is constituted by 1274 records. Each record reports data deduced for each spring source from the available literature (Tioli, 1894; Vinaj and Pinali, 1923; Touring Club Italiano, 1936; Fanelli, 1972; Fanelli *et al.*, 1982). Documentary sources used for each piece of information are reported in coded form (CNR = Fanelli *et al.*, 1982; FAN = Fanelli, 1972; MIC = Michelin map of Italy; 1:400 000; TCI = TCI, 1936; TIO = Tioli, 1894; VIP = Vinaj and Pinali, 1923). The resulting data set is currently available in the form of a digital ASCII file (AG-APPENDIX1.TXT) available on the «anonymous» ftp site IBOGFS.DF.UNIBO.IT/ALBARELLO and on the ING web page (http://io.ingrm.it/precursors). «TAB» characters separate pieces of information distributed over 21 numerical and alphanumerical fields whose contents are described below:

Field 1 (numerical): progressive number of the record in the catalogue;

Fields 2-5 (alphanumerical): denomination of the major administrative partitions where the spring is located («Regione», «Provincia», and «Comune»), name of the spring and in parenthesis the documentary source of the adopted toponym;

Fields 6-11 (numerical): geographic co-ordinates (latitude and longitudes in degrees, minutes and seconds);

Field 12 (alphanumerical): documentary source of the adopted co-ordinates; the presence of the symbol $ indicated that the co-ordinate have been deduced from the toponym;

Field 13 (numerical): water temperatures expressed in °C or coded (– 1 = cold; – 2 = medium cold; – 3 = environmental; – 4 = slightly warm; – 5 = warm; – 6 = hot) when only qualitative information is available;

Field 14 (alphanumerical): documentary source of temperature data and other estimates supplied by different authors;

Field 15 (numerical): dry residual expressed in g/l;

Field 16 (alphanumerical): documentary source of data concerning dry residual and other estimates supplied by other authors;

Field 17 (alphanumerical): chemical characterization of fluid emissions in coded form (A = acid; al = alcaline; Ar = Arsenic; Bic = bicarbonate; Bo = boron; Br = bromide; C = carbon; Cl = cloride; CO_2 = carbon dioxide; Fe = iron; S = sulphide; Hca = hydrocarbon; H_2S = sulphidic acid; J = iodine; K = potassic; Me = methane; Mg = magnesium; N_2 = nitrogen; Se = selenium; Si = silicic; sl = saline), documentary data source and other information provided by different authors;

Field 18 (alphanumerical): – data concerning eventual gases with relevant documentary source and other information provided by different authors; chemical characterization is given in the form adopted for data on fluid emissions reported in field 17;

Field 19 (numerical): flow rate expressed in l/s or coded (– 1 = low flow rate; – 2 = high flow rate);

Field 20 (alphanumerical): documentary sources of data concerning flow rate and other estimates supplied by different authors;

Field 21 (alphanumerical): other pieces of information on the considered spring (radioactivity, etc.).

Appendix 2.

The data base of mineral licences for industrial exploitation of CO_2 natural ground emission concerns is constituted by 380 records. Each record concerns information on a single mining permit deduced from Official Bullettins of the Italian Ministry of Industry and Mining Corps. The resulting data set is presently available in the form of a digital ASCII file (AG-APPENDIX2.TXT) available on the «anonymous» ftp site IBOGFS.DF.UNIBO. IT/ALBARELLO and on the ING web page (http://io.ingrm.it/precursors). «TAB» characters separate pieces of information distributed over 12 numerical and alphanumerical fields whose contents are described below:

Field 1 (numerical): progressive number of the record in the catalogue;

Fields 2-4 (alphanumerical): denomination of the major administrative partitions where the spring is located («Provincia», and «Comune») and the name of the site where the extraction is performed;

Fields 5-10 (numerical): geographic co-ordinates (latitude and longitudes in degrees, minutes and seconds);

Fields 11-12 (numerical): beginning and end of the mining permit (when the second field is empty, exploitation is still underway).

Appendix 3.

Tentative list of possible earthquake-related phenomena deduced from available literature (Bonito, 1691; Mallett, 1862; Mercalli, 1883; Baratta,1901; Dall'Aglio, 1976; Boschi *et al.*, 1995; Balderer and Martinelli, 1995; Martinelli, 1997). The data base concerns effects documented in correspondence of 219 earthquakes which occurred between 1000 A.D. and 1980. Each record of the data base includes pre-co-post seismic «anomalous» effects documented for each earthquake. Six kind of effects have been considered: on springs and wells, on geochemistry of ground fluids, on springs flow rates, on animals, and eventual presence of lightning and electric phenomena. For each kind of effect, the degree of belief estimated for the reported information (empty = no effects; 1 = minor uncertainty; 2 = major uncertainty) along with the relevant documentary sources (BAM = Balderer and Martinelli, 1995; BAR = Baratta, 1901; BON = Bonito, 1691; BOS = Boschi *et al.*, 1995; DAL = Dall'Aglio, 1976; MAL = Mallett, 1862; MER = Mercalli 1883) are given. The resulting data set is presently available in the form of a digital ASCII file (AG-APPENDIX3.TXT) available on the «anonymous» ftp site IBOGFS.DF.UNIBO.IT/ALBARELLO and on the ING web page (http://io.ingrm.it/precursors). «TAB» characters separate pieces of information distributed over 46 numerical and alphanumerical fields whose contents are described below:

Field 1 (numerical): progressive number of the record in the catalogue;

Fields 2-4 (numeric): time location of the earthquake responsible for documented effects (year, month and day);

Field 5 (alphanumeric): epicentral locality;

Fields 6-10 (numeric): epicentral coordinates (latitude and longitude in degrees and minutes) following the Italian Catalogue of Earthquakes (Postpischl, 1985) and number of the considered seismic event in the same catalogue;

Field 11-12 (numeric/alphanumeric): pre-seismic effects on springs and wells;
Field 13-14 (numeric/alphanumeric): geochemical pre-seismic effects;
Field 15-16 (numeric/alphanumeric): pre-seismic effects on springs flow rates;
Field 17-18 (numeric/alphanumeric): pre-seismic effects on animals;
Field 19-20 (numeric/alphanumeric): pre-seismic lightning and electric effects;
Field 21-22 (numeric/alphanumeric): other pre-seismic effects;
Field 23-24 (numeric/alphanumeric): co-seismic effects on springs and wells;
Field 25-26 (numeric/alphanumeric): geochemical co-seismic effects;
Field 27-28 (numeric/alphanumeric): co-seismic effects on springs flow rates;
Field 29-30 (numeric/alphanumeric): co-seismic effects on animals;
Field 31-32 (numeric/alphanumeric): co-seismic lightning and electric effects;
Field 33-34 (numeric/alphanumeric): other co-seismic effects;
Field 35-36 (numeric/alphanumeric): post-seismic effects on springs and wells;
Field 37-38 (numeric/alphanumeric): post-seismic geochemical effects;
Field 39-40 (numeric/alphanumeric): post-seismic effects on springs flow rates;
Field 41-42 (numeric/alphanumeric): post-seismic effects on animals;
Field 43-44 (numeric/alphanumeric): post-seismic lightning and electric effects;
Field 45-46 (numeric/alphanumeric): other post-seismic effects.