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A Multidisciplinary Approach to Earthquake Research: Implementation of a Geochemical Geographic Information System for the Gargano Site, Southern Italy

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Abstract. A priority task for correct environmental planning is to evaluate Natural Hazards, especially in highly populated areas. In particular, thorough investigations based on different Earth Science techniques must be addressed for the Seismic Hazard Assessment (SHA) in tectonically active areas. Not only the management but also the multidisciplinary analysis of all the SHA-related data sets is best performed using a Geographic Information System. In this paper we show how a research-oriented GIS is built and used in a practical case. The Geochemical Geographic Information System (G^2IS) was developed and applied to the Gargano promontory (southern Italy) in the framework of an EC research project, the *Geochemical Seismic Zonation* (GSZ) Project. This multidisciplinary – multiscaling powerful tool is described in its structure, updating procedures and manipulation techniques. Preliminary results are presented on the detection of *geochemically active fault zones* and their correlation with remote sensing data and other evidences of seismogenic structures.

Key words: GIS management, seismogenic structures, fluid geochemistry, Gargano promontory (southern Italy).

1. Introduction

The modern concept of deterministic Seismic Hazard Assessment (SHA) involves the detection and parameterization of seismogenic sources. This task could be accomplished by means of different and independent observations and techniques: epicenter distribution of recent and historical seismicity, geological and geomorphologic field data, geophysical prospecting, analysis and monitoring of deformation by geodetic data, photo interpretation of aerial and satellite images and fluid geochemistry monitoring (e.g., Dall'Aglio *et al.*, 1995; Quattrocchi *et al.*, 1997a; Quattrocchi *et al.*, 1998; Salvi *et al.*, 1995).

In the framework of the *Environment and Climate Workprogramme* 1996, the European Commission decided to fund a research project called *Geochemical Seis-*

mic Zonation (GSZ), (EC Program 1996–1998, ENV4-CT96-0291; Lombardi *et al.*, 1998), whose objectives were both to refine the SHA using fluid geochemistry techniques and to increase the knowledge of the processes linking the stress-strain accumulation, seismicity and geochemistry of rising fluids from deep sources.

The fluid geochemistry methodology is proposed on the basis of the well known fluid bearing properties of active faults (Gold and Soter, 1985; Fournier, 1991; Torgersen and O'Donnell, 1991; Nur and Walder, 1992; Chester *et al.*, 1993; Linde *et al.*, 1994; Miller *et al.*, 1996) and the response of chemistry of discharged deep-seated fluids to the thermal and stress-field conditions (e.g., King, 1986; Thomas, 1988; Tsunogai and Wakita, 1995; Quattrocchi, 1998). In the last decades the study of the relationships between fluid geochemistry and active tectonics was enhanced by the earthquake prediction theories and by promising field work (Wyss, 1991).

The study of geochemical fluids, for seismotectonics applications, must take into account the processes by which the various geochemical species are produced, concentrated and released in the different Earth environments – from the mantle to the upper crust – during the tectonic stress accumulation along fault zones.

The thermodynamic and physic-chemical patterns of fluids are influenced by the stress-driven processes (i.e., dilatancy and related phenomena) during the seismic cycle; at the same time geochemical anomalies cannot be related only to active strain areas, but also to preexisting fractured zones. Both may act either as preferential fluid pathways or as fluid seals depending upon several parameters, including lithology, type of circulating fluids, rheology, fracture geometry, and the ongoing stress regime (Quattrocchi *et al.*, 1998; Lombardi *et al.*, 1998). In this frame, one of the main GSZ task is to refine the concept of *geochemically active fault zone*, and its relationship with the concept of *active fault* as defined by seismotectonic disciplines like paleo-seismology, neotectonics and seismology. To solve the possible ambiguities between "geochemically active" structures and seismotectonically active ones, it is very important to use a multidisciplinary approach for the analysis and for the interpretation and validation of the results; i.e., the largest possible number of independent data sets should be used to integrate the fluid geochemistry methods.

For this multidisciplinary approach, a powerful tool for the management of large multi-scaled data sets, geographically referenced and with continuous or discrete coverage, that is, a Geographic Information System (GIS), is required. The various data layers in the GIS can be easily compared and the results of the analysis can help develop site-specific models for the interaction between active tectonics and geochemistry (Figure 1). Given the temporal characteristics of the seismic stress buildup in the Earth's crust, the data sets must span a relatively long period of time to be representative of all the processes related to the seismic cycle, therefore a specific monitoring strategy must be planned. The GIS layers must be periodically updated and the analysis repeated each time new data are available ("dynamic analysis"), increasing the accuracy of the interpretation.

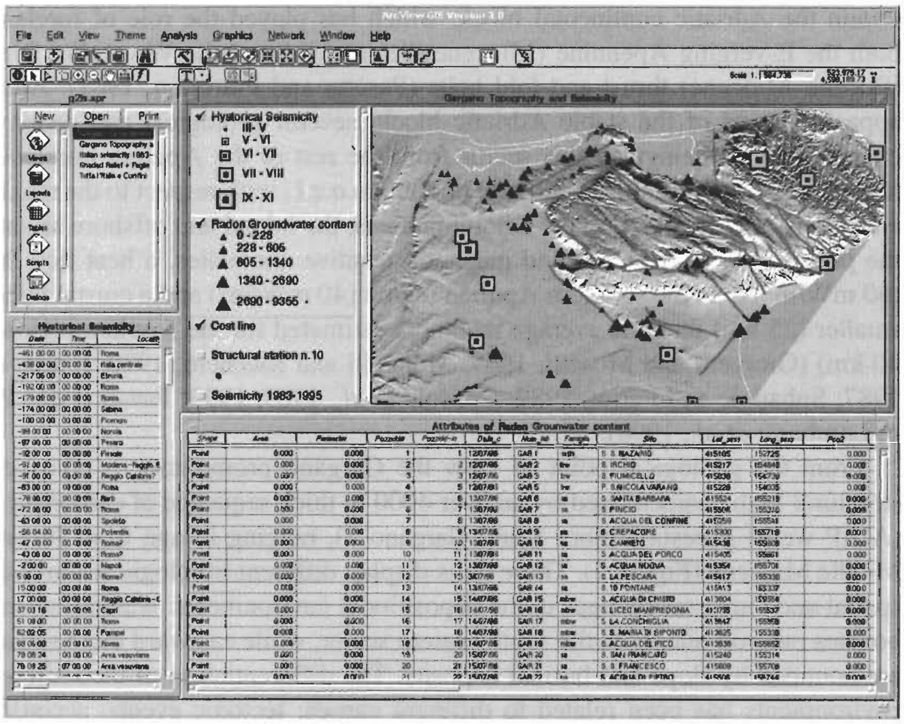

Figure 1. Example of the graphical user interface for the Geochemical Geographic Information System. The figure shows a typical window for the display of multiple data layers and for the querying of the data tables. Fault lines, Radon groundwater content, and historical seismicity are shown.

This paper describes the conceptual and practical development of a GIS which was intended to be the common software platform for the development of research in the GSZ project.

Among all the sites selected for the GSZ program, i.e., Sannio Matese, Umbria, Sardinia (Italy), Lesbo Island, Calcidica Peninsula (Greece), the Gargano promontory in southern Italy was chosen as a test bench for the GIS implementation, since a large number of good quality data sets were readily available for this area (Figure 1). In this paper we report some preliminary results which show that Geographical Information Systems can be effectively used not only for the data management and display but also for their analysis and interpretation in a research context.

2. The Gargano Site

The Gargano promontory is an ENE-WSW ridge (Finetti, 1982; Anderson and Jackson, 1987; Bosellini *et al.*, 1993; De Alteriis and Aiello, 1993) extending in the Adriatic Sea (central Mediterranean Sea). The geology of Gargano developed within the Adriatic continental block, which has played the role of foreland for both the E-verging Apennine (Miocene-Pleistocene) and the W-verging Dinaride (Eocene–Miocene) thrust-and-fold belts (Parotto and Praturlon, 1981). Although apparently part of the stable Adriatic block, several geological and geophysical characteristics distinguish this sector from the rest of the Apulian Foreland: the high relief, with a maximum altitude of 1000 m *a.s.l.*, with respect to the maximum elevations of 200–300 m in the adjoining areas, the inland and offshore seismicity, the presence of gravimetric and magnetic positive anomalies, a heat flow higher (60 mW/m^2) than the southern Apulian region (40 mW/m^2) and a crustal thickness smaller (25 km) than the average thickness estimated for the Apulian region (35–40 km) (Giorgetti and Mosetti, 1969; Mongelli and Ricchetti, 1970; Finetti *et al.*, 1987; Suhadolc and Panza, 1989; Console *et al.*, 1989, 1993; Favali *et al.*, 1993a, b; Lombardi *et al.*, 1998).

From the geological point of view the Gargano promontory is considered a structural high characterized by an over 4000 m thick sequence of carbonate rocks (AGIP wells: Foresta Umbra 1 and Gargano 1), ranging in age from Jurassic to Middle Miocene (Figure 2). These units display different lithologic features due to spatial and temporal changes in the depositional environments: shallow-water carbonates outcrop mainly in the southwestern sector, while eastward these sequences are bounded by slope and basinal deposits. The differentiation of the sedimentary environments has been related to different causes: tectonic events, according to Masse and Borgomano (1987) and Masse and Luperto Sinni (1987), and simple platform dismantling, according to Bosellini and Ferioli (1988) and Bosellini et al. (1993).

In the southern margin of the promontory two evident morphologic escarpments (the Candelaro and Rignano faults, Figure 3) separate the rugged landforms of the carbonate succession from the Foggia plain located south and south-west (Ciaranfi and Riccetti, 1980). The latter is filled by the terrigenous sediments of the Apennine foredeep basin, overlaid by recent continental and marine deposits.

The structural patterns of the Gargano are characterized by prevailing W–E and NW–SE trending strike-slip and normal faults (Figure 3). The most evident structure is the Mattinata Fault, a sub-vertical E–W fault, that cuts across the southern sector of the promontory. According to many Authors (Funiciello *et al.*, 1988; Favali *et al.*, 1993a, b) this fault experienced a complex kinematics history, the last and most evident movement being left-lateral strike-slip, which gave rise to a pull-apart basin (Pantano S. Egidio) and to contractional structures (S. Marco in Lamis area), related to a releasing and a restraining bend of the main fault, respectively. Faults cutting through the carbonate rocks of the Gargano promontory are typically 2–300 m wide sub-vertical damage zones, characterized by aligned NW–SE fractures.

The Gargano is well known as a seismically active zone (Peronaci, 1980; Suhadolc *et al.*, 1983). Destructive earthquakes are reported to have occurred in historical times, with felt effects in the area up to XI MCS (Guidoboni and Tinti, 1988;

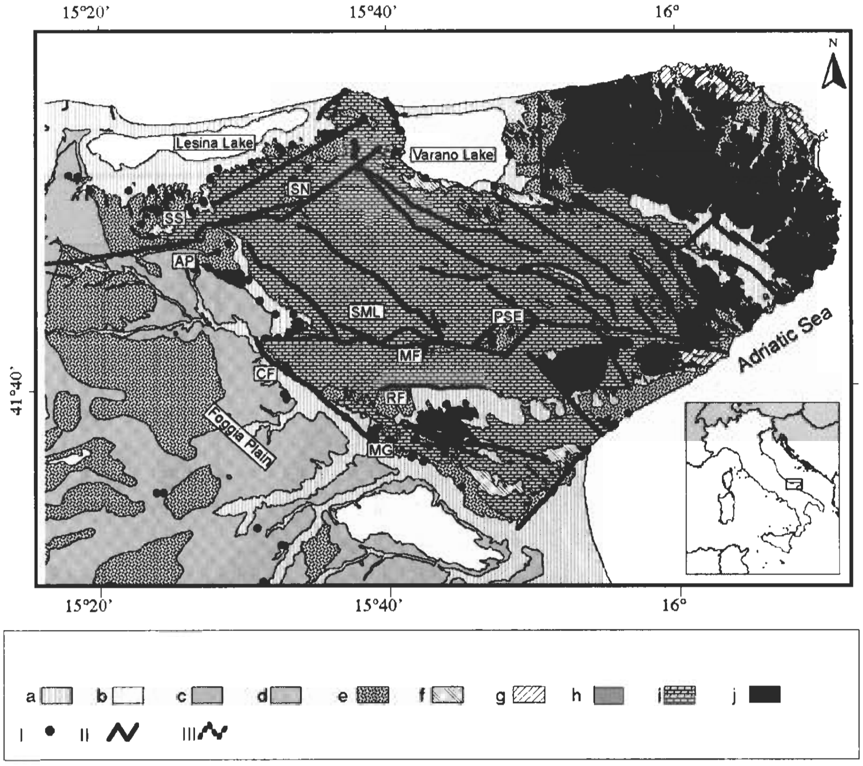

Figure 2. Geological map of the Gargano promontory showing the principal tectonic elements and lithologies. Legend: (a) Beach and recent deposits; (b) Montesecco clays (marls, clays); (c) Campomarino conglomerates (conglomerates and clays – Pliocene/Calabrian); (d) Marine and fluvial terraces (gravels, sands and clays – Olocene); (e) Fossiliferous sands and cemented gravels (Pliocene); (f) Daunia formation (cemented sands with polygenic elements – Lower Miocene); (g) Sandstones and limestones (Paleocene/middle Eocene); (h) Indifferentiated complex (clays, sand, with calcareous elements – lower Miocene); (i) Shelf limestones (dolomites and limestones – upper Cretaceous/Giurassic); (j) Transition facies (dolomites and limestones – upper Cretaceous/Giurassic), (MF) Mattinata Fault; (CF) Candelaro Fault; (RF) Rignano Fault; (PSE) Pantano S. Egidio; (SML) S. Marco in Lamis; (MG) Mt. Granata; (SS) S. Spirito; (AP) Apricena; (SN) Sannicandro.

Boschi *et al.*, 1997; Console *et al.*, 1993; Tinti *et al.*, 1995). Extensive damage and casualties were referred to these events but the exact location of their seismogenic and, in some cases, tsunamigenic sources (Tinti *et al.*, 1997) is still uncertain. More recent instrumental data show a moderate seismicity both offshore, with a maximum magnitude of 5.3 in 1988, and inland, with a maximum magnitude of 4.4 occurring in the central part of the promontory (Figure 3).

The offshore seismicity seems to indicate the presence of two active structures, also recognized on seismic profiles: one extending ENE–WSW and located about 50 km north of the promontory, i.e., the Tremiti Islands Deformation Belt, the other

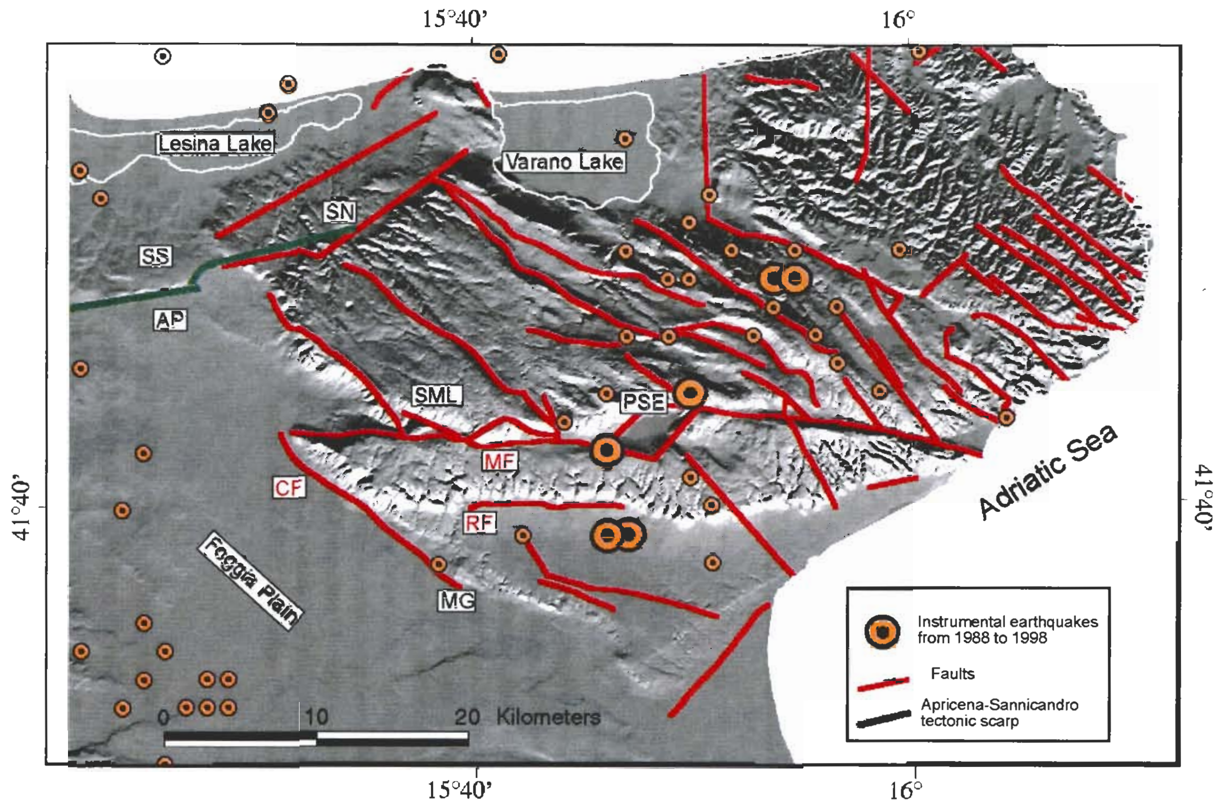

Figure 3. Faults and seismicity (small circles: $M \leqslant 3.5$; large circles: $M > 3.5$) of the Gargano promontory over a Shaded Relief topographic image. Also shown is the Apricena–Sannicandro mophotectonic structure. Geographical references as in Figure 1.

located SE of the promontory, i.e., the Southern Gargano Deformation Belt which might extend inland in the Mattinata fault zone (Argnani *et al.*, 1993).

Focal mechanism solutions are available for the 26/04/1988 event only, calculated using both the double-couple and CMT models. The double-couple solution displays strike-slip faulting with a small thrust component, while in the CMT solution the thrust component is more evident (Console *et al.*, 1993; Favali *et al.*, 1993a).

A detailed hydrogeological study of the Gargano promontory has been carried out by Cotecchia and Magri, (1966), while a few hydro-geochemical data exist throughout the area (Carlini *et al.*, 1966; Cotecchia and Magri, 1966; Brondi *et al.*, 1983).

3. Development of the GIS

A Geographic Information System (GIS) is typically composed of a data base and a software for the management of the data in a geographic reference frame (Aronoff, 1995). The first step in the development of the GIS is the definition of the user needs (Brunori *et al.*, 1997); for the *Geochemical Geographical Information System* (G^2IS), these were defined in a scientific discussion among the groups involved in the GSZ project and summarized in the following requirements: the effective storage and quick retrieval of the data sets; the management of both the geochemical time-series and the multicomponent chemical spatial trends; the comparison of continuous (raster format) data with discrete (vectorial format) information; the execution of queries on all the variables of the data base; a simple, user friendly interface for the analysis of the spatial and temporal relationships between the different data layers; the possibility to gather a real-time data acquisition in the GIS from the future (GMS II) monitoring stations (Quattrocchi *et al.*, 1996), to be used for natural hazard surveillance and earthquake prediction studies.

The various data sets have been analyzed for the type of variables and organization and the descriptive tables have been designed. Six thematic libraries containing spatial and descriptive data have been selected as the minimum number of fundamental layers (Table I). Derived layers can then be created by applying simple calculations to the fundamental ones (for instance a slope image from the DEM (Digital Elevation Model), a contour map from spot geochemical measurements, etc.).

We have used the *ArcInfo* software package for the creation of the libraries (Data Base) and their georeferencing. Given the limited extent of the area (60 × 40 km) we chose a UTM coordinate system for all the layers. A friendly user interface has been built under *ArcView* environment using the *Avenue* language (Figure 1). All the updates and modifications of the data sets are performed under control of a data base manager, while the users are only allowed to do data querying, analysis and printing.

Table I. Structure of the data layers

Layer	Description	Data
Geochemistry	It contains the chemical and isotopical data gathered during the areal surveying and time-series, measured in groundwaters gas emission points, and soils. The measurements have been pre-processed and checked before being inserted in the data base. The layer contains also ancillary information regarding the sampling site. *Point features*	For each sampling site: – Sampling date, type, name, basic information, photo, maps. – Electrical conductor, pH, Eh, temperature – ^{222}Rn, H_2S, CO_2, NH_3, etc. – Major, minor, trace elements (gaseous-liquid phase). – Isotopic ratios: He, C, O, H, S, Sr. – References
Lithology	It contains the extension of the various geological formations, digitized from 1 : 100,000 scale maps. Other detailed maps could be added or removed as layers. *Polygon features*	Codes, ages and description of series geological formations, permeability acquifers. – References
Tectonics	It contains the regional tectonic structures (faults lines, fold axes, etc.) digitized from the 1 : 100,000 scale maps, taken from published papers or directly mapped in the field. *Line features*	For each structure: – Type – Geometry – Kinematics – Age of inception – References
Structural geology	It contains the results of meso-scale structural analysis at various sites. *Point features, maps*	For each structural station: – Dip, plunge, slickensides, stria –Diagrams, plots
Seismicity	Contains instrumental seismic data recorded by the ING National Seismic Network. Historical seismicity information. *Point features*	For each event: epicenter location, source-depth, origin time, magnitude; macroseismic maps focal mechanisms.
Topography	It contains elevation data from 1 : 25,000 and 1 : 100,000 scale maps of the IGM. – Satellite images *Image data*	2 Digital Elevation Model at 30 meters and 400 meters per pixel.
Geography	It contains several geographic features at the scale 1 : 1,000,000 extracted from the Digital Chart of the World data base. *Point, line and polygon features*	Populated places, political boundaries, coastlines, main rivers. main roads.

4. The Data Sets

4.1. GEOCHEMICAL DATA

Since the GSZ project is aimed at the refinement of fluid geochemistry methods for active tectonic assessment and SHA studies, the geochemical data were considered fundamental for the G^2IS. They have been collected during field surveys, which involve a considerable logistic effort. The fluid sampling sites have been initially selected on the basis of known location of interesting spring and wells (i.e., thermal, gaseous, acidic or reducing groundwater, etc. ...), then, during the survey, on the basis of their location to increase the uniformity of the sampling distribution. Nevertheless, since the Gargano promontory is made up of carbonate rocks, the drainage is mainly karstic and spring occurrence is rather scarce in the central part. This clearly affects the distribution of groundwater sampling sites, which are limited to the boundaries of the limestone massif (Figure 2). We must keep this in mind when it is necessary to correlate the geochemical spatial anomalies, which are very discrete, with other more continuous information, as the distribution of geological units, for instance.

The measurements of soil gases can be performed in a more uniform pattern, since the sampling scheme is user-defined, despite the pre-requisite of an appropriate soil thickness. Three areas for high resolution soil gas surveys have been selected along the Mattinata Fault, namely Piana di Mattinata, Pantano di S. Egidio and S. Marco in Lamis (Figure 2). Soil gas analyses have yet to be included within the G^2IS strata, together with groundwater isotopical data.

4.2. GROUNDWATER GEOCHEMISTRY SURVEYS

Each survey has been accomplished in two steps: measurement in the field of some physico-chemical parameters as temperature (Figure 4(a)), pH, Eh, electrical conductance, radon activity (Figure 4(b)), HCO_3 (titration), CO_2 and H_2S content (ion-selective electrode potentiometry), as well as sampling for further chemical and isotopic analyses ($^3He/^4He$ by CNRS-CRPG Nancy; isotopes of H, O, C, Cl by University of Turin, Italy; $^{87}Sr/^{86}Sr$ by the University *"La Sapienza"* of Rome). Laboratory analyses for detection of major, minor and trace elements (e.g., Li, B, As, Hg, SiO_2, Fe, Mn, etc.), have been performed by ING Laboratory and by the ENEA-AMB-TEIN-CHIM Laboratory, using liquid chromatography; ICP-AES, FES, GFAAS spectroscopy; γ spectrometry (Rn by active charcoal canisters), α scintillation methods (Rn); ion-selective potentiometry.

For a subset of samples the dissolved gas composition (N_2, O_2, Ar, CO_2, He, CH_4) was also determined by mass-spectrometry and gas chromatography both at ING and at University "*La Sapienza*" gas-Laboratory. A total number of 118 samples have been collected since July 1996 up today, other surveys will be carried out over the eastern region and along the Fortore River, west from the Lesina Lake. The spatial groundwater surveying have been useful to select the most interesting

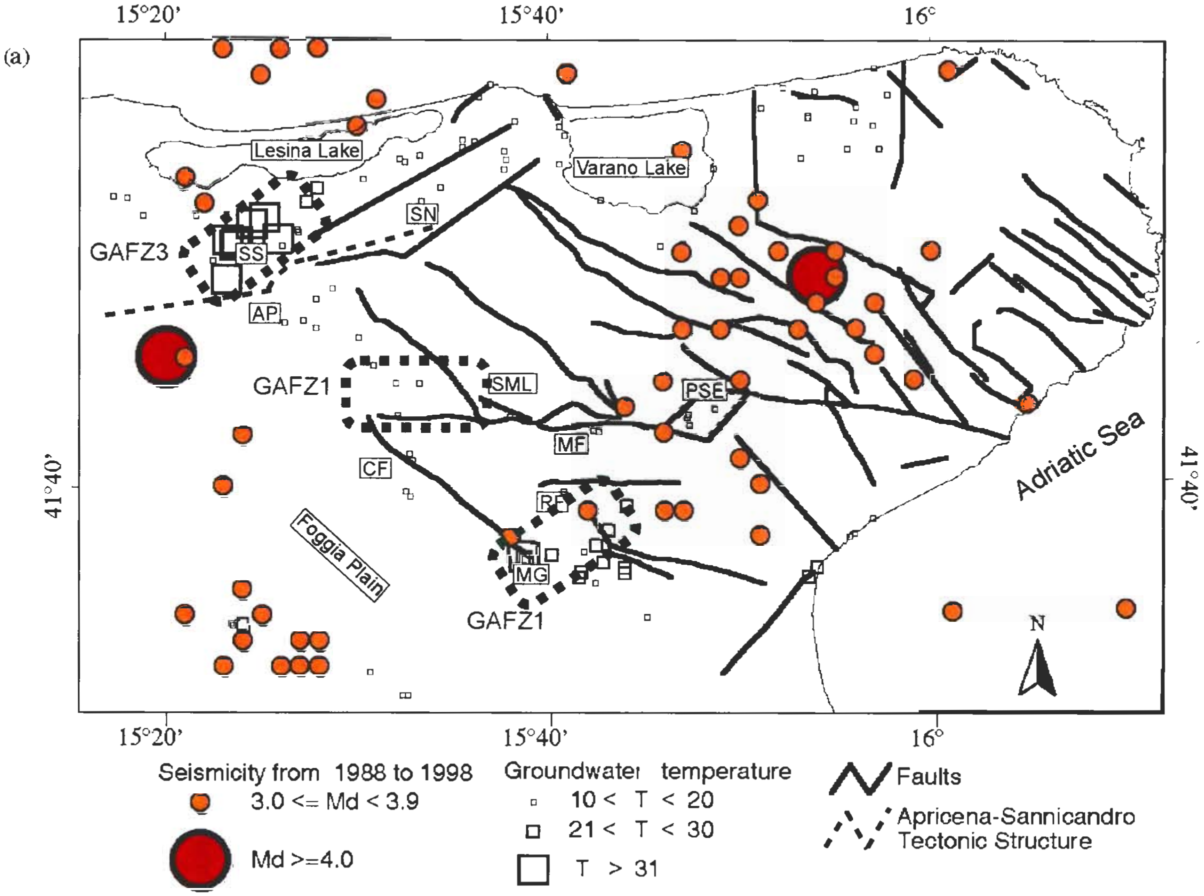

Figure 4a. Distribution of temperatures (a) and Radon content (b) in groundwater of wells and springs in the Gargano promontory. Also shown are the instrumental seismicity, the tectonic structures, and the location of the GAFZs discussed in the text.

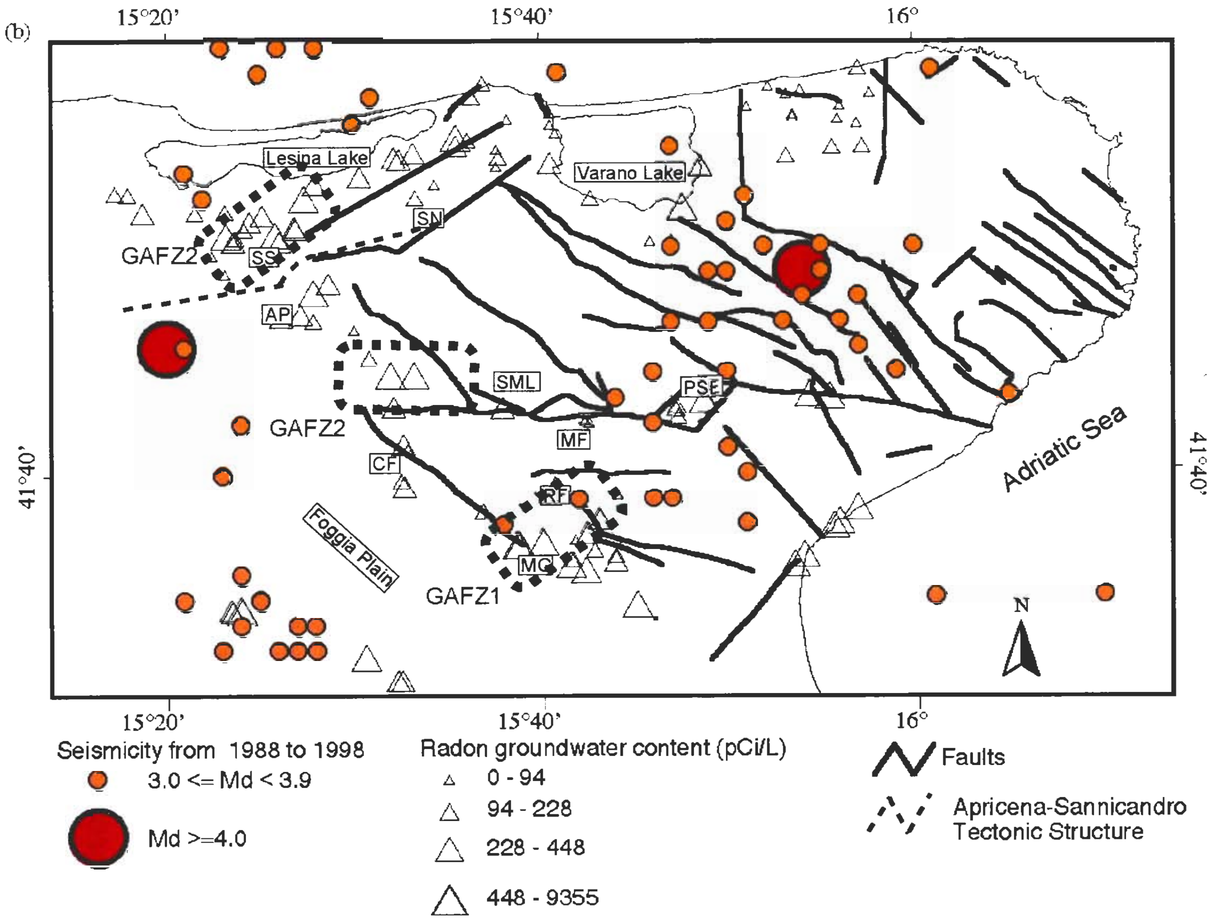
(b)
15°20'
15°40'
16°
41°40'
Lesina Lake
Varano Lake
SN
SS
AP
GAFZ2
SML
PSE
MF
CF
RF
MC
GAFZ1
Foggia Plain
Adriatic Sea
N
Seismicity from 1988 to 1998
3.0 <= Md < 3.9
Md >=4.0
Radon groundwater content (pCi/L)
0 - 94
94 - 228
228 - 448
448 - 9355
Faults
Apricena-Sannicandro Tectonic Structure

Figure 4b.

areas on which more frequent surveys should be achieved – i.e., Monte Granata site on weekly basis since October 1996 – (Figure 2) and eventually to select the soundest sites for the installation of continuously monitoring station of GMS II (Quattrocchi *et al.*, 1996). The GMS II is a station prototype that will provide measurements of selected parameters either geochemical or physical-hydrological (i.e., water temperature, Electrical Conductivity, pH, Eh, PCO_2, ^{222}Rn, H_2, H_2S, air temperature, barometric pressure, etc.), transmitted in real-time to the ING laboratories, processed and inserted in the G^2IS for immediate analysis, useful for earthquake prediction experiment and environmental risks surveillance.

Details about the geochemical data and their interpretation will be given in future paper specifically addressed to fluid geochemistry discussion, in which the "anomaly" for each parameter will be quantitatively evaluated by tables and diagrams (see also Lombardi *et al.*, 1998). We want to summarize here that the spatial distribution of the considered geochemical parameters indicates that anomalous values are clearly concentrated in proximity of well known regional fault systems as, for example, the Candelaro Fault and Mattinata Fault (Figures 3 and 4). The highest values of dissolved Rn (330 Bq/L), $^3He/^4He$ ratio (R/Ra = 1.10) and the Hg content were found at the Monte Granata well, where a roughly NE–SW alignment of anomalous groundwater temperatures and radon content, is present (Figure 4a, b). At this site relatively high heat flow, positive gravimetric and magnetic anomalies were also reported (e.g., Mongelli and Ricchetti, 1970; Finetti *et al.*, 1987).

Another area where apparent geochemical anomalies are concentrated (groundwater temperatures, Rn, Eh, CO_2, H_2S, B, Li and $^3He/^4He$), following a WSW–ENE direction, was found in the S. Spirito area, south of the Lesina Lake (Figure 4a, b), but here no heat flow anomaly is reported (Mongelli and Ricchetti, 1970).

As far as geothermal exploitation is concerned, the promontory deserved no special interest up to date, as a consequence of the very low enthalpy of the circulating fluids: the only thermal anomalies, detailed in this paper, seem to be linked either to the heat flow anomaly connected to a fault system (Candelaro fault) or to the presence of a buried fault without no evidence of heat flow anomalies (S. Spirito area), as discussed later.

4.3. GEOLOGICAL AND STRUCTURAL DATA

The lithology of the bedrock, its primary and secondary permeability, the fabric of the rocks, the mesoscopic structures (both sedimentary and tectonics), all represent important factors driving both the production, concentration, evolution and release of geochemical species in groundwater and the accumulation and release of deep-seated gases in soils. A detailed knowledge of the three-dimensional distribution of the various geological units and bodies and of their large and small scale structures would of course allow a straightforward interpretation of geochemical anomalies, unfortunately this is clearly unrealistic, and we must rely only to shallow data.

For our purposes lithological information is more precious than chronostratigraphic one, but simple lithological maps are not available for the area. The highest resolution geological maps are published at the scale 1 : 100,000 (SGN, 1965, 1969, 1970) and are based on stratigraphic columns where the lithological data are grouped into geological formations. They were digitized and simplified within G^{2}IS, ignoring outcrops with a dimension smaller than 300 meters (3 mm on the maps).

Data regarding the shallow tectonic structures were extracted from available published geologic and structural maps, after selection of the data reliability (Funiciello *et al.*, 1988) and from original field work. The regional faults are rather well described but their extension at depth cannot be determined, since deep well logs and seismic profiles are not available on land. The surface trace of regional faults may indicate the presence of high permeability zones, which should strongly influence the uprising of deep fluids.

Meso-scale structural surveys increase the detail of the information and allow a better characterization of the fault zones, so new structural surveys have been carried out within this project. In particular three major faults have been studied along the southern sector of the Gargano: the E–W Mattinata and Rignano faults and the NW–SE Candelaro fault. For each fault the survey has been divided into a series of structural sampling sites. At each site the following information have been recorded: location, altitude, lithology, bedding attitude, fault attitude and fault-related kinematic indicators, i.e., values of dip and plunge for all structures as fault, slickensides, riedels, etc.

The main results of the structural analysis in the southern Gargano can be summarized as follows:

- outcrops displaying fractures and cleaved rocks (limestones) are well aligned along the three major faults (Mattinata, Rignano and Candelaro faults); the overall E–W, 30° south dipping geometry of the bedding indicates that the faults are placed along the southern flank of a regional WNW-trending anticline, which affects the entire Gargano promontory.
- the pattern of meso-scale fault orientations along the major deformation zones is rather heterogeneous (as usual in strike-slip systems). However, four main prevailing orientations are shown by our data: (1) E–W left-lateral strike-slip faults; (2) N70°E left lateral strike-slip faults; (3) N20°E right lateral strike-slip faults; (4) N50°W left-lateral strike-slip faults. All these sets are consistent with a regional left-lateral strike-slip tectonics affecting the southern Gargano.
- the solution cleavage orientation along the major deformation zones is well clustered along the N50°W direction. This pattern, growing the solution cleavage perpendicularly to the maximum shortening axis, is consistent with a

left-lateral strike-slip kinematics of the major faults in the southern Gargano promontory. Since the area has been affected by strike slip tectonics, particular attention has been posed to meso-scale R- and P-shears (Riedel Model) which are a fundamental tools to reconstruct the geometry and the kinematics of the fault zones.

Solution cleavages characterized by an average spacing of few centimeters (between 2 and 6 cm) are the most common features throughout fault zones of the Gargano promontory. The wide diffusion of these surfaces and their patterned distribution (i.e., N50°W-striking, 2–6 cm spaced) may constitute a significant tool for predicting fluid migration pathways.

4.4. SEISMIC DATA

Since the beginning of a good instrumental monitoring of the area (in the 80's), the Gargano promontory has not experienced earthquakes as large as those felt in historical times, i.e., the destructive earthquakes of 1223, 1414, 1627, 1646, 1731, 1893 (Boschi *et al.*, 1997, fig. 1). From the isoseismal maps of historical earthquakes, that is, from the spatial distribution of their felt effects, the approximate location of the seismogenic sources can be inferred. The event occurred on 30th July 1627 is the best studied of the area (e.g., Molin and Margottini, 1985; Panza *et al.*, 1991; Tinti *et al.*, 1995; Tinti *et al.*, 1997). This earthquake produced a destructive tsunami and caused several thousands of victims. Numerical simulations of the 1627 tsunami have been carried out in order to constrain the location and geometry of the seismogenic/tsunamigenic fault (Tinti *et al.*, 1997). The result of this study is that the fault zone cannot be unambiguously determined and that possible orientations of the structure are either an E–W or a N–S fault crossing the northern part of the promontory close to the Lesina Lake. According to Panza *et al.* (1991) a NW–SE dip-slip fault would be responsible for this earthquake, but this interpretation was inferred only on a theoretical basis and by the analysis of ancient macroseismic field data.

As for the recent seismicity in the study area, we inserted in the G^{2}IS the seismicity from 1985 to 1998 (ING Seismic Bullettin, Figures 3 and 4).

The strongest instrumental sequence occurred in September 1995 (main shock magnitude = 4.4); however, from Figure 5, few alignments of earthquakes are evident that could suggest any relationship with possible seismogenic structures.

5. Geomorphological Data

Satellite optical images (Landsat TM) and digital topography (DEM) was used in this project to perform regional geomorphic analysis. The presence of recent morphotectonic structures is diagnostic of possibly active faults (Gold, 1980; Salvi, 1995) and a map of these elements, which integrate the structural elements meas-

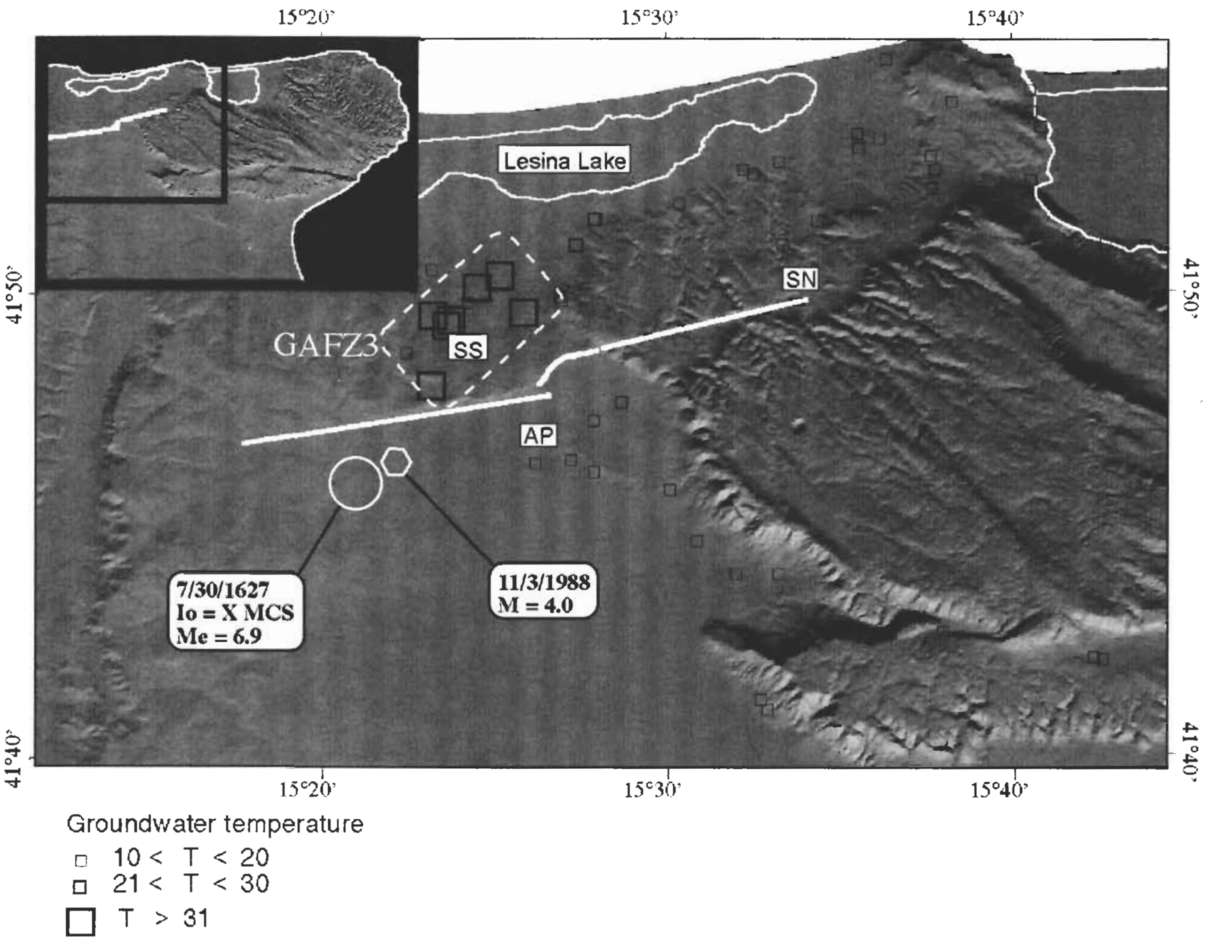

Figure 5. This figure shows a topographic Shaded Relief of the northwestern sector of the Gargano promontory, south of the Lesina Lake. The continuous white line shows the trace of the Apriicena–Sannicandro tectonic scarp. The small circle is the epicentral location of the largest instrumental earthquake and the large circle is the macroseismic epicenter of the largest historical earthquake for this area. Also shown is the location of GAFZ3, see discussion in the text.

ured at the meso-scale, was considered an important derived layer for the G^2IS. Their detection was performed through photo-interpretation and quantitative geomorphic analysis of the Landsat TM and Digital Elevation Model (DEM) images. A high-resolution DEM was generated by interpolation from digital vector data at the scale 1 : 25,000. The pixel dimension for the DEM was fixed to 30 m for compatibility with the LANDSAT data; the two images were then co-registered.

To perform the regional morpho-structural photo-interpretation a syntethic stereopair of a false colour LANDSAT image was created, merging spectral and elevation data (Salvi, 1995). The regional stereopair analysis was performed both directly on the computer screen by means of special glasses and on large-format colour films. Some regional morphotectonic landforms (straight valleys, escarpments and mountain fronts, uniform slopes, deflected drainage, regularly shaped basins, etc.) were mapped. The structural control on the geomorphic evolution is obvious in the Gargano where typical examples of strike slip tectonics are extremely prominent in the landscape (e.g., the Mattinata fault and the pull-apart basin of Pantano S. Egidio, figure shaded).

A few of the morphotectonic landforms did not correspond to known faults. The most interesting one is a complex morphologic lineament, stretching ENE for about 26 kilometers, along the alignment Apricena–Sannicandro, south of the Lesina Lake. It is a composite lineament, mainly represented by a scarp limiting an E–W ridge to the south. To the west, the scarp is about 80–90 m high and marks the limit between Miocene (Apricena Calcarenites) and Upper Pleistocene (alluvial plain deposits) formations. Further eastward, the lineament runs between the Miocene and the Giurassic limestones and then for the easternmost part it lies completely within the Giurassic limestones of the Sannicandro formation. It is clear from the air-photo interpretation that the area north of the lineament has been uplifted and displaced along the ENE scarp. The drainage channels coming from the inner mountains south of Sannicandro and flowing toward NNE, manage to cross the lineament, showing rejuvinated incisions on the uplifted northern side, and locally showing evidences of left-lateral offsets. All these features strongly suggest a post-Pleistocene uplift of the area north of the lineament, and an active tectonic origin for the Apricena – Sannicandro escarpment.

In addition to the typical morphotectonic structures associated to faults, throughout the Gargano promontory several low-dipping surfaces are visible both inland and along the coastline, exposed at different elevations. A detailed analysis of the latter has been started, following the hypothesis that they are relict erosion surfaces of marine or continental origin. First results clearly show that they have been originated by a considerable Quaternary uplift of the Gargano promontory. The analysis of the DEM raster image has provided a very fast and precise tool for the mapping of these planar surfaces, whose spatial relationships with the tectonic structures has yet to be investigated.

5.1. OTHER DATA

Several other data sets provided by the GSZ partnership are planned to be included in the G^2IS in the next future. The interpretation of pre-existing gravimetric data as Bouguer anomalies and magnetic data (Mongelli and Ricchetti, 1970; Toro, unpublished data, 1997) has been partially used to detect crustal discontinuities indicative of buried faults. Geodetic displacements measured at a GPS network across the Adriatic micro-plate (Argnani *et al.*, 1993) will show the strain rate affecting the area and help define sub-areas with stronger strain accumulation. An important derived layer will be the areal representation of the cumulative moment release, calculated from the instrumental seismicity, which will quantify the areal distribution of the strain (stress) release for the area. Hydrogeological information (Cotecchia and Magri, 1966) are partially inserted onto the lithology layer (Table I), despite the lack of information about piezometric data and recharge areas.

We also intend to include information about offshore topography and geology, when available.

6. Discussion

The main purpose of this paper is to show how the GIS tool may increase the effectiveness of research in the field of SHA. This is done by exploiting the inherent GIS capabilities of spatial data manipulation. The most important feature is the possibility to visually compare and jointly analyze several different layers of information. The analysis can be enhanced by using site specific empirical models for the comparison of the data.

For the Gargano area, one of the objectives was the detection and discrimination of seismotectonic structures. The latter are by definition active faults or fault zones. Given the general tectonic framework of this sector of the Italian peninsula (Parotto and Praturlon, 1980; Anderson and Jackson, 1987), we expected that active faults in this area were likely to show some amount of topographic expression. Impressive tectonic landforms are very clear along the Mattinata, the Rignano and the Candelaro faults, but many other geomorphic lineaments are present in the area (Figure 3). We must consider that the intensity of geomorphic expression alone is not diagnostic of a recent activity of a fault and that several landforms are probably due to exhumation of old tectonic structures, enhanced by the Pleistocene uplift of the promontory. One of the latter seems to be, for example, the high tectonic escarpment present along the NE side of the Foggia plain, which downthrows the inner platform limestones towards the SW, without affecting any Quaternary formation (Figures 2 and 3). In fact, no clear fault cutting through the Upper Pleistocene formations is mapped in the entire promontory (SGN, 1965, 1969, 1970).

The already discussed Apricena–Sannicandro morphotectonic landform, is located in the epicentral area of the destructive 1627, I_0 = X MCS, earthquake (Figure 5). It must be noted that no other large, mapped fault is present in this area and that the maximum intensity isoseismal of the 1627 earthquake (Molin and Margottini, 1985) shows an E–W elongation compatible with the direction of the Apricena–Sannicandro line. Field investigations carried out along the western sector of this structure confirmed the presence of an oblique-slip fault, downthrowing to the south the Pleistocene sediments of the upper Foggia Plain (M. Lenoci, unpublished seismic refraction data).

We used the G^2IS to compare the historical and instrumental seismicity to the fault map. Unfortunately, the distribution of moderate level instrumental seismicity does not show any clear alignment which can be attributed to a specific fault. This may be due to the limited accuracy of the earthquake location, or, more likely, to the type of fault activity in this area, which is expressed by frequent, but small, clusters of seismicity on minor faults and rare, but strong earthquakes on the larger structures.. Epicentral locations for the strong historical events which affected the area during the past centuries could be mapped with an accuracy of 20–25 km (Boschi *et al.*, 1997), while the strongest instrumental events were localized with an accuracy of 5–10 km. In general, on the basis of a purely spatial correlation, high magnitude earthquakes do not seem to have occurred on the same structure since the 13th century. This suggests that the average recurrence interval for large earthquakes along the active faults of the Gargano is longer than 7–800 years, in agreement with the recurrence intervals for apenninic earthquakes.

The results of the geochemical surveys were then analyzed within the above framework. The rationale for the interpretation of the geochemical data was based on the recently (Lombardi *et al.*, 1998) developed concept of the *Geochemically Active Fault (Fracture) Zone* (GAFZ). According to this concept, a GAFZ is "an area where an anomaly of one or more geochemical parameters, indicative of deep fluid uprising along a more permeable pathway of tectonic origin, is measured within a certain temporal framework". Given the essentially planar shape of faults and, at a larger scale, of deformation belts, the spatial surface pattern of geochemical anomalies linked to a GAFZ is usually linear. Moreover, since secondary permeability is generally related to fracture density and fracture network connectivity, the strongest anomalies are expected at the intersection of fault systems (Dall'Aglio *et.* *a*l., 1995; Quattrocchi *et al.*, 1997; Quattrocchi *et al.*, 1998; Lombardi *et al.*, 1996; Lombardi *et al.*, 1998), where differently oriented structural surfaces intersect and interact.

The temporal framework is included in the GAFZ definition because, in the case of an active structure, the tectonic processes of strain accumulation/release along the fault zone originates various time-dependent physic-chemical, water rock interaction, and thermodynamical processes. Most of the latter involve differential deep gas release to the surface (Holub and Brady, 1981; Kristiansson and Malmquis, 1982; King, 1986; Shi and Cai, 1986; Megumi and Mamuro, 1987; Torgersen *et al.*, 1990; Honkura and Isikara 1991; Varhegyi *et al.*, 1992; King, 1993, Quattrocchi *et al.*, 1997). For example, the reaction of fluids with wall-rock minerals may produce secondary or indirect anomalies related to the fault seepage, e.g., increase of emanation power of radon from rocks (Soonawala *et al.*, 1980, Quattrocchi *et* *al.*, 1998). Moreover, faults act as "geochemical barriers" (Perel'man, 1986) and should be considered as anomalous for concentration of tracer compounds as As, Hg, Fe, Mn, B, Li, an other metals.

On the basis of the above definitions, we used the G^{2}IS to detect the possible GAFZs within the Gargano area. We compared our geochemical data to the other data layers (geology, tectonics, seismicity, geomorphology, etc.) and evidenced the presence of three GAFZs (Figure 4(a, b)): one corresponds to the area between Mt. Granata and the Rignano Fault (GAFZ1), one corresponds to the western part of the Mattinata Fault (GAFZ2), and the third to the S. Spirito area (GAFZ3).

In the GAFZ1 area, anomalous values of Rn, ^{3}He/^{4}He ratio, Hg and temperature, were measured in the groundwater (Figure 4(a, b)). Along the GAFZ2, anomalous values of Rn content were measured in two wells located at both ends of a fault line (Figure 4(b)) but no other anomalies were found. The relationship to known faults is clear for these two GAFZs, and in fact, our structural survey revealed that the Mattinata and Candelaro faults are associated to discrete bands of very deformed rocks, encompassed by almost un-fractured limestone. The significant role of these bands of augmented permeability in the migration of deep fluids, is verified by our geochemical data. Other surveys will be needed to define the actual activity of the two tectonic structures.

While the first two GAFZs correspond to clear tectonic structures, for which some low seismicity is also reported, the third does not compare to any mapped fault. It must be noted that the anomalous groundwater temperatures measured throughout the wells of the GAFZ3 discharges are not correlated with anomalies of the geothermal gradient and heat flow (according to Mongelli and Riccetti, 1970). On the other hand, in this area there seems to be no other hydrogeological reason than a fault for the presence of the described anomalies. The most likely explanation resides in the up-welling of deep waters along a belt of increased permeability, allowing a possible heat-mass enhanced transport by convection, which minimizes the cooling by the shallow meteoric groundwater.

The anomalies in the fluid geochemistry data (groundwater temperature, Rn, Eh, CO_2, H_2S, B, Li and ^{3}He/^{4}He, Figure 4) suggest that the S. Spirito area (GAFZ3) is neither a typical thermal circuit driven by shallow hydraulic-thermal gradients, nor a higher heat flow zone in the vicinity of magmatic bodies, but simply an "open zone", in which the meteoric-shallow groundwater is less able to erase the deeper aquifers, deeper thermal field and deeper gaseous components. This hypothesis could be further stressed by the concept of "fault valve mechanism", as proposed by Sibson (1975, 1981, 1990, 1996, 1998), recently enhanced by other authors too (Gold and Soter, 1986; Kerrich, 1996; Parry and Bruhn, 1990; Bruhn *et al.*, 1990; Nur and Walder, 1992; Roberts *et al.*, 1996; Quattrocchi, 1998).

The observed ongoing process of deep fluid uprising, which defines the *geochemically active fault zone* GAFZ3, is probably a direct consequence of the activity (in the tectonic and seismic sense) of the fault, in the absence of which self-sealing processes should eventually "close" the fault. In the GAFZ3 area, the instrumental seismicity data show the occurrence of one seismic event of moderate magnitude (11/3/1989, $M = 4.0$) in a context of relatively low seismicity (Figure 5). This event is located within only 8 kilometers from the geochemical anomalies mentioned above. Moreover, the macroseismic epicentre of the 1627 earthquake (I_0 = XI MCS, Boschi *et al.*, 1997; Tinti *et al.*, 1997), is placed less than 10 km SW of the GAFZ3 (Figure 5), as well as the mentioned Apricena–Sannicandro morphotectonic structure.

The spatial correlation of the GAFZ3, the strong 1627 earthquake, the surface expression of a recent (at least post-Pleistocene) fault along the Apricena-Sannicandro line, strongly suggest a genetic link between these events. New measurement campaigns will be focused on this area to acquire more specific information regarding this hypothesis.

7. Conclusions

A large effort was made to create a really multidisciplinary GIS system for Seismic Hazard analysis. In the framework of the GSZ project original data sets have been acquired for the Gargano test site, geo-referenced, processed and archived; other data sets will be inserted in the next future (soil gases analyses, isotopical data).

The G^2IS represented for the Geochemical Seismic Zonation Project a powerful research tool. The joint analysis of all data layers of the G^2IS allowed us to integrate several independent pieces of information, confirming the activity of known faults and suggesting new evidences of active tectonics. In particular, we pointed out the likely occurrence of a seismogenic source in the area south of the Lesina Lake, along the Apricena–Sannicandro structure.

The concurrence (within 10 km) of geochemical anomalies, of instrumental seismicity and strong historical earthquakes, and of a clear, cumulated tectonic scarp, strongly suggests the presence of an active seismotectonic source in the area. Further geochemical and geological surveys in the Fortore –Lesina – S. Severo area will better clarify the relationships between the ENE Apricena–Sannicandro fault with the NE-trending GAFZ3.

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