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# A geo-spatial data management system for potentially active volcanoes—GEOWARN project

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**Abstract**

Integrated studies of active volcanic systems for the purpose of long-term monitoring and forecast and short-term eruption prediction require large numbers of data-sets from various disciplines. A modern database concept has been developed for managing and analyzing multi-disciplinary volcanological data-sets. The GEOWARN project (choosing the ‘‘Kos–Yali–Nisyros–Tilos volcanic field, Greece’’ and the ‘‘Campi Flegrei, Italy’’ as test sites) is oriented toward potentially active volcanoes situated in regions of high geodynamic unrest. This article describes the volcanological database of the spatial and temporal data acquired within the GEOWARN project. As a first step, a spatial database embedded in a Geographic Information System (GIS) environment was created. Digital data of different spatial resolution, and time-series data collected at different intervals or periods, were unified in a common, four-dimensional representation of space and time. The database scheme comprises various information layers containing geographic data (e.g. seafloor and land digital elevation model, satellite imagery, anthropogenic structures, land-use), geophysical data (e.g. from active and passive seismicity, gravity, tomography, SAR interferometry, thermal imagery, differential GPS), geological data (e.g. lithology, structural geology, oceanography), and geochemical data (e.g. from hydrothermal fluid chemistry and diffuse degassing features). As a second step based on the presented database, spatial data analysis has been performed using custom-programmed interfaces that execute query scripts resulting in a graphical visualization of data. These query tools were designed and compiled following scenarios of known ‘‘behavior’’ patterns of dormant volcanoes and first candidate signs of potential unrest. The spatial database and query approach is intended to facilitate scientific research on volcanic processes and phenomena, and volcanic surveillance.


*Keywords:* Spatial database; GIS; Volcanic hazards; Data modeling; Query tools

## 1. Introduction

### 1.1. The ‘‘GEOWARN’’ project

The major aim of the European-funded project GEOWARN was the development of a multimedia-based geo-spatial warning system (a modular web-based

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Atlas Information System) which comprises graphical and numerical geo-spatial data, visualizations, derived satellite images (e.g. infrared thermal imaging), real time monitoring of surface movements (interferometric analysis), seismic activity, heat and gas fluxes and chemical changes in fumarolic gases and hydrothermal waters. The software system consists of a set of customized components that facilitate analysis and visualization of this huge amount of data. Integration of these parameters in a geospatial database has led to development of modeling techniques that are suitable to detect dynamic processes such as reactivation of a quiescent volcano and the occurrence of earthquakes related to fluid pressure changes in magmatic-hydrothermal systems. Deep crustal seismic soundings have provided a regional volcano-tectonic and structural model derived by tomographic processing. All relevant data were set up in a Geographical Information System (GIS).

As is typical for volcanological research, the different data sets have various spatial resolutions and are often collected in diverse time periods. In our database, however, they are unified in a common, four-dimensional data representation in space and time. Despite large differences in data acquired by different methods, groups, and instruments, and over varying time scales, the data-sets nevertheless keep a good degree of accuracy.

During the three and a half year project, the proposed multiparametric approach has been applied to Nisyros (Greece) and to Campi Flegrei (Solfatara volcano, Italy). The volcanological and geochemical differences between the two areas proved the transferability to other active volcanic systems.

### 1.2. The volcanic field of Kos–Yali–Nisyros–Tilos

The volcanic field of Kos–Yali–Nisyros–Tilos is situated in the Eastern Aegean Sea, part of the Dodecanese archipelago near the Turkish coast (Fig. 1). It belongs to the eastern limb of the Quaternary South Aegean volcanic arc, spanning from Nisyros/Kos via Santorini, Milos, into the Saronic Gulf (Aegina, Poros, Methana, Crommyonia). Magmatic activity in the current arc started about 10 MA as a result of northeastward-directed subduction of the African plate underneath the Eurasian Aegean continental microplate. The volcanic field of Kos–Nisyros constitutes the largest volume of volcanic products in the Aegean Arc.

The unique situation of Nisyros island as a test site can be based on the complexity of the volcanic and related hazards and the increasing impact of tourism on the island. The Nisyros volcano and its hydrothermal craters are visited daily by hundreds of tourists (Fig. 2).

Although the last magmatic eruption on Nisyros dates back at least 15,000 years, the present geodynamic activity encompasses high seismic unrest and widespread fumarolic activity. Violent earthquakes and steam blasts accompanied the most recent hydrothermal eruptions in 1871–1873 and 1887, leaving large craters behind. Mudflows and hydrothermal vapors rich in $CO_2$ and $H_2S$ were emitted from fracture zones that cut the Nisyros caldera and extend north-northwest through the vicinity of the village of Mandraki into the island of Yali and toward Kos. In 1996 and 1997, seismic activity started with earthquakes up to M 5.5 with hypocenters down to 10 km depth, damaging 30 houses in Mandraki.

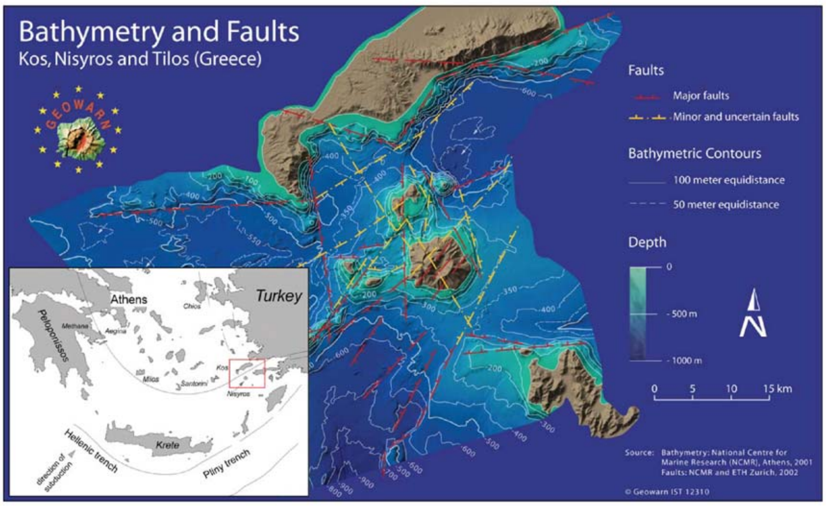


Fig. 1. Nisyros Island and Kos–Nisyros–Tilos volcanic area.

Fig. 2. Stephanos crater, Nisyros caldera.

*Five different kinds of natural hazards are possible:*

- gas and steam hydrothermal eruptions within the Nisyros crater field;
- seismic activity due to the regional tectonic movements;
- magmato-tectonic seismic activity related to magmatic unrest in the crust;
- a volcanic eruption;
- landslides and Tsunami hazards subsequent to earthquakes, magmatic and volcanic activity.

## 2. The GEOWARN geo-spatial database concept

### *2.1. Data management*

A well-organized database with accurate procedures of data retrieval can provide the basis for reliable interdisciplinary research in active volcanic environments. The purpose of developing a comprehensive volcanic database concept was to integrate the main data and information that volcanologists typically use when investigating *dormant* volcanoes that may show future unrest. The objectives for the final database were (1) to provide an organized scheme for capturing, storing, editing, and displaying geographically referenced volcanological data and information, (2) to process and analyze spatially distributed data, (3) to support hazard and risk assessment, (4) to create various thematic maps.

### *2.2. The geo-spatial database design*

The GIS database developed in this study contains large sets of volcanological data compilations, regrouped and structured following the *Geodatabase model* (Zeiler, 1999), and based on the GEOWARN researchers' expertise on historical eruptive behavior of dormant volcanoes.

The GEOWARN data types have been structured accordingly and grouped into main information layers. Different schemas of attribute data related to the geographic representation (points, lines, polygons, raster layers) were analyzed and optimized in order to meet the following criteria:

- Provision of a better representation of data to enhance optimal information retrieval and enable designs of complex query and analysis scenarios;
- Diminution of data redundancy;
- Establishment of a good platform for analysis and correlation for the highly heterogeneous data;
- Support the data for the modular web-based atlas information system.

The general database archive composition is shown in Fig. 3. Three main parts can be distinguished: *attribute data*, *geometric vector and raster data layers*, and *cartographic data*. These are complemented by supplementary data consisting of descriptions, audiovisual material, field orientation sketches, literature references, links, and others.

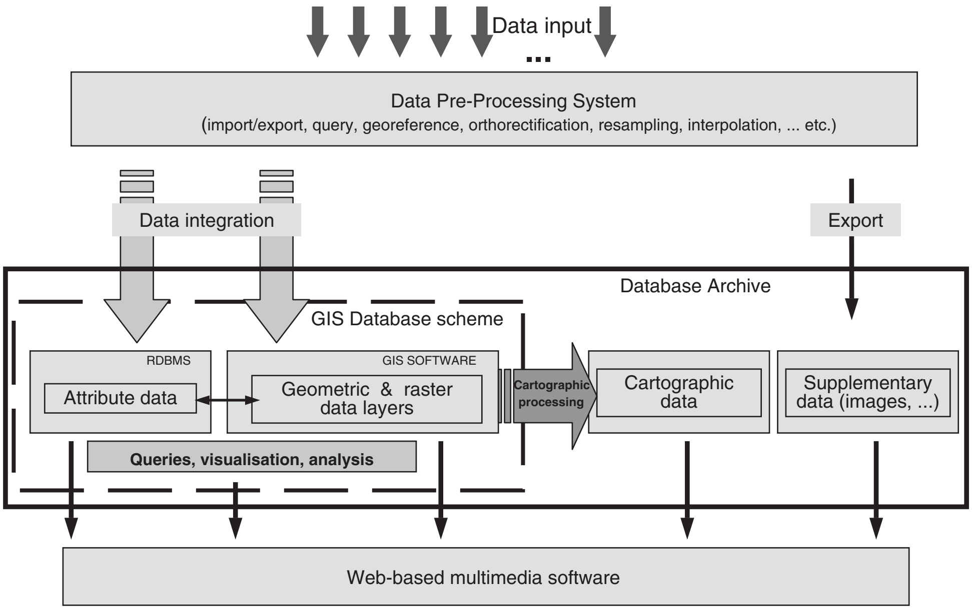


Fig. 3. Overview on data-flow and data-organization system.

### 2.3. The layers

A simplified version of the database layers and its content for the Kos–Yali–Nisyros–Tilos volcanic field is shown in Table 1. The information is divided into several groups. Each group of data is composed of one or several layers and optional additional data.

The *Topography* group contains topographical features as class layers, such as contour lines, roads, buildings, churches, etc. *Land-use* consists of a single polygon layer and a simple related attribute table describing the land-use characteristics. The *digital elevation models* (DEM) group local and regional models of different resolutions. The DEM for Kos, Yali, and Tilos islands were acquired using the topographical paper maps of a scale of 1:50,000 of the Hellenic Military Topographic service. For Nisyros island, a 2 m cell size DEM was produced using paper maps of the same source of scale 1:5000. The procedure of deriving the land DEM is described by Vassilopoulou et al. (2002). The regional DEM including the bathymetry data was produced by the National Center of Marine Research of Greece after several data acquisition cruises during the year 2000.

The *Geology* group comprises the geological maps of the studied area. *Volcanological structure* regroups simple lithological units, tectonic structural features (faults, cracks, fissures), fissures with fumarolic or effusive phenomena, eroded fissures, and the crater rims. They are modeled by polygons and lines with an attached attribute table. Tectonic features of the regional Kos–Yali–Nisyros–Tilos volcanic field and Nisyros island, together with the lithologic units, are represented within the *Tectonic* group. *Neotectonic* data, based on the regional tectonic map, regroups morpho-tectonic features (landslides, rock-falls, debris) and active tectonic features (active faults, cracks, and others).

*Seismic data* are represented by three distinct layers of information: position of the local seismic stations during the project period (2000–2002), hypocenters of a magnitude $M<4.0$ registered during the project period (2000–2002), and historical hypocenters (1911–2003) of important regional earthquakes with magnitudes $M>3.0$.

*Gravity and magnetic data* are both structured in a similar way: a point layer relates to a table where their coordinates are specified, the date and time, and the corresponding gravity or magnetic value registered at each station. The raster grid data-sets derived by interpolation from the above mentioned layers of points, representing Bouguer anomaly and magnetic data, respectively, are also stored in the database.

Earth's *Density* was derived from Bouguer gravity data constraining the density values by the registered *Vp* velocities as well as using the Nafe–Drake curves for sediments and the Birch empirical functions for the crust and the upper mantle (Makris et al., 2001). It contains three groups of information: the three-dimensional density model, a set of equal velocity surfaces as grids characterizing the interpreted limits between the various rock type units, and the interpreted density cross-sections.

Table 1
Simplified version of database schema content for Nisyros–Kos–Tilos (Greece) volcanic area (main layers)

| | Group of data | Characteristics represented | Details |
|---|---|---|---|
| 1 | Topography | Topographical map | |
| 2 | Land-use | The land-use map | |
| 3 | Digital elevation models | Digital elevation models—regional and local | |
| 4 | Geology (*Geology & Volcanology*) | Geological maps of the areas of interest | |
| | | Sea floor geological map | |
| | | Geological cross-sections | |
| 5 | Volcanological structure | Fumarolic fissures, flow structure features, crater rims | |
| 6 | Tectonic | Lithologic units, tectonic features | |
| 7 | Neotectonic | Morphotectonic features (landslides, rock-falls, debris), active tectonic features (active fault, cracks, …) | |
| 8 | Seismic | Position of seismic stations | |
| | | Regional hypocenters of $M<4.0$ (link to seismic stations) | |
| | | Historical hypocentres $M\geqslant 4.0$ | |
| 9 | Gravity | Location of the gravimetric stations + measurement points on land and sea | |
| | | Grid of interpolated gravity | |
| 10 | Density | Three-dimensional voxel density cube—not in GIS (model output) | ASCII file |
| | | Surfaces, delineating the rock types (equal velocity values) interpolated from the model output | |
| | | Cross-sections of density model | |
| 11 | Magnetic | Location of the magnetic stations + measurement points on land and sea | |
| | | Grid of interpolated magnetic values | |
| 12 | Velocity model | Cross-sections of velocity model | |
| 13 | Tomography | Three-dimensional voxel tomography cube—not in GIS (model output) | ASCII file |
| | | Surfaces, delineating rock types (equal velocity values) | |
| | | Cross-sections of tomographic model | |
| 14 | Technological data | Ship tracks, shooting points, active seismic stations (land, sea) | |
| 15 | Degassing process | $CO_2$ flux, heat flux, soil temperature—measured and processed | |
| 16 | Geochemistry | Geochemical measurement points (geothermal wells, springs, gas emissions, …) | |
| 17 | GPS | Location of the GPS stations—link to measured and computed displacements | |
| 18 | Thermal | Ground temperatures—points (used in thermal images calibration) | |
| | | LANDSAT and ASTER thermal images and surface temperature differences derived from LANDSAT | |
| 19 | Interferometric | Interferograms | ERDAS raster dataset |
| 20 | Satellite image | Satellite image—orthorectified | IKONOS—1 m resolution |
| 21 | Weather | Weather parameters measurements | |

Geometric features and attribute table.
Point features and attribute scheme.
Point features and attribute table.
Line features and images for each cross-section.
Line features and attribute table.
Grids (raster data)—various resolutions.
Geometric features and attribute scheme.

The seismic *Velocity model* is represented by various cross-sections (images) linked to a layer of lines that follow the surface trace directions of the cross-sections. The tomographic data is represented within the group of layers called *Tomography*. Even though it is not directly accessed by the GIS software, the derived tomographic three-dimensional model cube is also a part of the database. Surfaces of equal velocity (horizontal and vertical cross-sections) can automatically be derived as a set of grids, for instance, representing the interpreted limits between the various geological units (e.g. soft sediments, magmatic rocks, etc.). Interpreted tomographic cross-sections are also represented as images, linked to a layer of surface traces.

*Technological* data includes the seismic station locations on land and on the seafloor (ocean bottom seismographs), as well as the shooting points and ship tracks for the active seismicity experiments. This group provides information about the geophysical campaigns performed within the Kos–Yali–Nisyros–Tilos volcanic field in 1997 and 2000 as part of the GEOWARN project.

*Degassing process* refers to data resulting from the study of diffuse degassing at the southern Lakki plain (within the Nisyros caldera), and Stephanos hydothermal crater in particular. The main goals of the study of diffuse degassing processes in hydrothermal areas are both the mapping of the process and the computation of the amounts of gas and energy released. The diffuse degassing measurements at Stephanos crater were performed during several field campaigns between 1997 and 2003. Each campaign consisted of the direct measurement of $CO_2$ flux by the accumulation chamber method (Chiodini et al., 1998), heat flux (conducting plate method (Geowarn, 2003)), and soil temperature in about 80–100 temporary measuring stations regularly arranged in a rectangular grid of 20 m cell width. Systematic $CO_2$ flux and soil temperature measurements covering the southern Lakki plain were performed during 1997–2003. About 2900 measuring sites consistently covered the area. A Sequential Gaussian simulation was applied to soil flux data (gas and heat) and soil temperature data, respectively (Brombach et al., 2001). Modeling the degassing process affecting the Lakki plain was performed in order to derive a detailed map of $CO_2$ soil degassing of this area. The resulting grid was integrated into the spatial database. At Stephanos crater, several grids were derived, each of them corresponding to one measurement campaign (nine campaigns during 1997–2003).

*Geochemistry* is a group of layers representing almost all point features with time-dependent geochemical information: fumaroles, springs, geothermal wells, and wells. Each type of feature has its layer, and the point features are linked to an attribute scheme. The attribute scheme of each entity differs slightly from each other. In Fig. 4, the scheme for geothermal springs is shown as an example. *Geothermal springs* is the main table where the scheme is linked to the geographical location of the point in the GIS software. The relationships "*one to one*" and "*one to many*" between the *Geothermal springs* table and the connected tables are defined using the same indicator. As shown in Fig. 4, the table *Geothermal springs* contains information concerning the geographical position (coordinates), type of represented entity, name (or official names), system of codes (used by several experts in order to identify the entity), altitude, locality (description in words), and remarks. The local geology of a geochemical sampling site is described within the *Geology* table. Note that rock chemistry is not included in the *Geochemistry* group since it contains data of static nature with respect to time scales of the monitoring activities and is therefore included in the *Geology* table. The *Sample* table is designated for registering individual water or gas samples. The *Parameters* table contains time-dependent data series for various physical parameters (temperature, pH, and others) and chemical composition parameters (including isotope data). The number of geochemical parameters is relatively large compared to the physical ones due to their extensive analytical data, although the number of entries (samples) is smaller. Among the geochemical parameters, gaseous samples and aqueous samples differ slightly in terms of their list of parameters; similarly, well parameters differ slightly from spring parameters.

*GPS* represents geodetic measurements using *Global Positioning System* with horizontal ($X$, $Y$) and altitude ($Z$) data. The main reference layer of points is made up of GPS station locations from the first establishment of the network (June 1997). Two tables are related to this table, both following a "*one to many*" relationship. The first one contains horizontal ($X$, $Y$) and altitude measurements at various campaign dates, and the second table contains horizontal, azimuthal and vertical displacements between different campaigns. Related estimates of horizontal and vertical standard deviations of each set of values are attached as well.

The *Thermal* group contains three sets of raster grids representing the thermal images acquired by the LANDSAT satellite system, the grids of surface temperature differences between the satellite passes (derived from LANDSAT 7 ETM), and the thermal images recorded by the ASTER satellite system. Both sets of thermal grids (LANDSAT and ASTER) were acquired at different dates (day and night time), orthorectified, and corrected for atmospheric influences. In addition, all satellite thermal images were corrected by measuring soil temperatures at specific points and various depths (2, 4, 7, and 10 cm) at the time of the satellite overpass.

The images resulting from the application of interferometric synthetic aperture radar (InSAR) are part of the *Interferometric* group. This technique was applied to study the regional deformation of the island in conjunction with GPS measurements and morphological corrections using the orthorectified DEM. Two interferograms of Nisyros island are currently in the database. They cover the 1996–1999 and the 1999–2000 time periods.

The *satellite image* layer contains a satellite image of Nisyros island with 1 m resolution. The image taken by the IKONOS satellite was orthorectified using the before

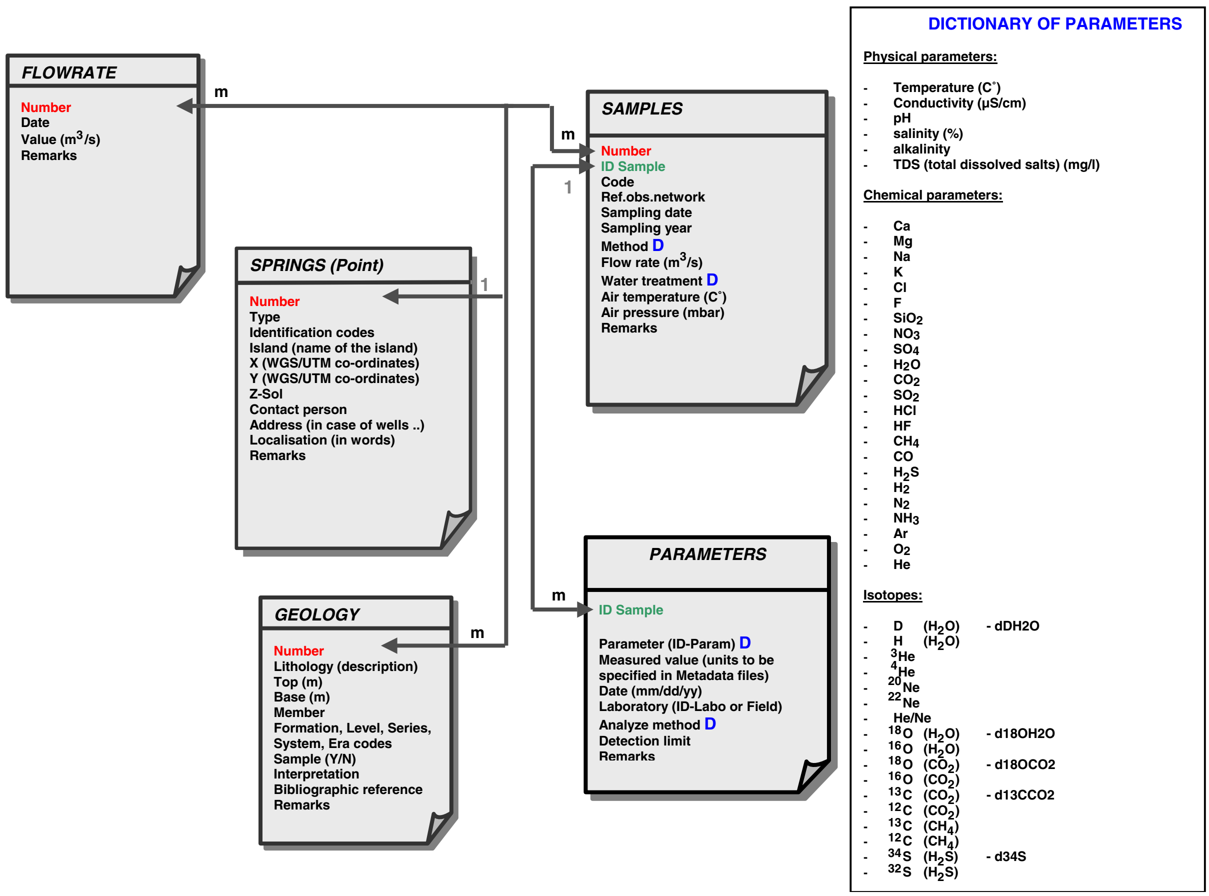


Fig. 4. Simplified version of attribute data schema for *Geothermal springs*.

mentioned 2 m cell size DEM. The entire orthorectification procedure has been described in Vassilopoulou et al. (2002).

Meteorological data are embodied within the *Weather* group. The only deployed weather station, represented as a point, is linked to tables where time-dependent data is registered. The collected weather parameters are air temperature, humidity, atmospheric pressure, wind speed, and a brief weather description. The acquired data cover the GEOWARN project duration (2000–2003).

### 2.4. Technical aspects: data types, coordinates, metadata, and software

After the database schema has been developed and its layers have been defined, it has to be optimized. A thorough analysis of the existing, expected and incoming data types and formats, as well as data quantity and quality, is an important consideration to ensure an optimal data representation in a volcanological database.

To compare and correlate spatial data-sets, the entire set of data for a particular volcanic field must use a single coordinate system. In the case of the "GEOWARN early warning system", the national Hellenic reference system (HGRS 87) was used for the pilot site in Greece.

One concern in the database design was the inevitable simplification of data-sets. This is necessary in order to achieve maximum information retrieval, while attempting not to lose data resolution or precision. The inclusion of error estimations for some time-series data was thus necessary to allow for the distinction between artifacts, noise, and "real" deviations from background data trends that may represent a change in subsurface processes.

A useful method for metadata generation is to follow widely accepted standards. For the described data-sets, we adopted the US Federal Geographic Committee's Content Standard for Digital Geospatial Metadata (FGDC). The chosen GIS software offers tools to comfortably handle metadata using this standard. This standard was customized according to the individual projects needs and requirements.

As a software solution, ArcGIS-Arc/Info™ 8.1. (Zeiler, 1999) embedding MS Access™ (Microsoft) was considered satisfactory for expert-level GIS operability of the database. The database itself can easily be transferred to other database systems (e.g. Oracle™). MS Access was chosen simply for its wide distribution and low cost. It soon appeared necessary to combine the main GIS package (GIS expert software and the access—Relational Database Management System) with complementary software and to develop new data exchange interfaces (Hurni et al., 2004). This arises from the broad requirements of general user skills, uses, and needs encountered in volcano observatories.

## 3. Examples of visualization, and spatial analysis

Spatial analysis is feasible once the database is established. The needs and knowledge of volcano monitoring activities define the types of query, visualization and data analysis tools required. Much of this depends on the monitoring tasks and technical capabilities of volcano observatories. However, personnel, access, usage and knowledge base to design, program, customize and operate query strategies and tools on large relational databases in an GIS environment is to date still a rare occurrence. GIS technology is still used mainly to generate maps.

### *3.1. Crustal structure and tomography*

In the GEOWARN project, scientific query interfaces were designed and implemented following different query scenarios. These query scenarios are currently used for deductions from the data sets and for the purpose of visualization. For example, various analyses of the DEM, of seismic data represented by the locations of the hypocenters, and of the three-dimensional tomography were done using the ArcScene™ module (ArcGIS™ software package). As a result, the relation between the calculated hypocenters and the tomographic model of the underground has been generated (Fig. 5). It gives an overview of the greater Yali–Nisyros volcanic field represented by the DEM (view to north, Kos island in the background), the subsurface crustal structure (iso-velocity surfaces of unconsolidated volcanoclastic sediments, the deeper metamorphic rock formations, and magmatic intrusive bodies), and the earthquake hypocenters registered during 2001 with a magnitude $<4$. Clearly, both the tomographic results and the earthquake hypocenters testify geodynamic activity concentrated underneath Nisyros island.

Similar query interfaces allowing for data manipulation, analysis and visualization are

- earthquake hypocenter queries in time and space (3.2),
- a grid analysis tool for diffuse soil degassing and heat flux data (3.3),
- and query interfaces for analyzing geochemical data (3.4).

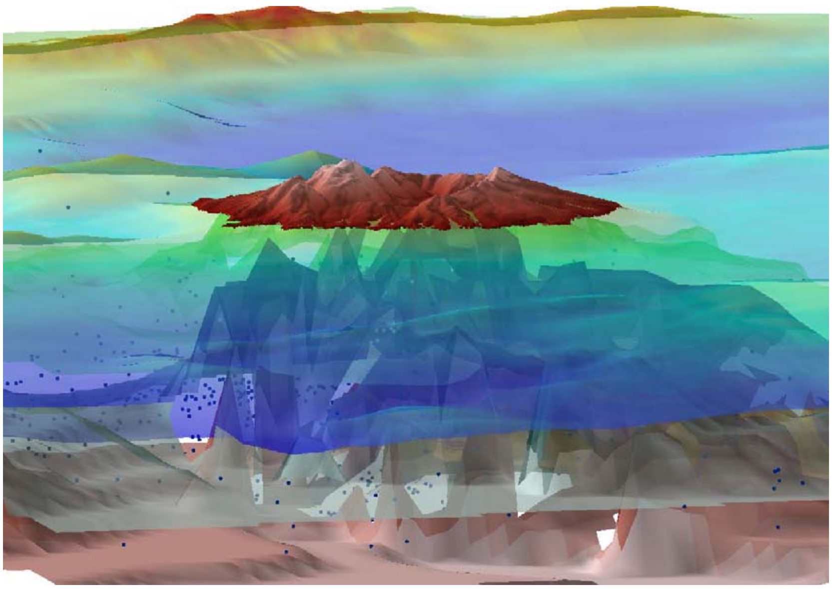

Fig. 5. Visual correlation between calculated hypocenters and interpreted limits between various geological strata resulting from tomographic model.

### 3.2. Earthquake hypocenters in time and space

A tool was developed for queries of earthquake hypocenters in time and space. Used in the ArcScene™ module, it allows temporal and spatial (*x*, *y*, and depth) dependent queries on point features. The tool is specifically designed to assist the analysis of earthquake hypocenters. However, it also allows 3D time-dependent animations. The script operates in the background by sequentially selecting and then displaying the points using a customizable time-step (day, hour).

### 3.3. Grids of the temperature, diffuse soil degassing, and heat flux

To achieve a better representation for grids of the temperature, diffuse soil degassing, and heat flux datasets, several interpolation procedures were tested. One example is given in Fig. 6. It shows an approximate image of the apparent $CO_2$ flux distribution of the southern part of the Nisyros caldera. The resulting multi-dimensional grid represents the $CO_2$ flux values as heights and the temperatures as colors. The orthorectified satellite image of Nisyros Island is overlaid on the DEM and serves as a spatial reference. Temperature or $CO_2$ flux values can be queried simply by selecting any point on the grid with the cursor.

### 3.4. Time series of physical and chemical monitored parameters

Time series consisting of physical and chemical parameters related to fumaroles, springs, geothermal wells, and wells can easily be retrieved, visualized, statistically treated, and displayed on charts.

Query interfaces for analyzing geochemical data were programmed using the Visual Basic and SQL programming languages as well as the Arc/Object™ library (Object-Oriented modules library, by ESRI). These query tools complete and combine the existing GIS package functions. The tools were designed to query, display, calculate time-dependent statistics, and show graphs of the physical and chemical parameters related to volcanic point features such as springs and fumaroles. Fig. 7 shows the $H_2S$ variation measured during August 02, 1997 and January 02, 2002 at a fumarole coded as PP9N ("Polyvotes Micros" hydrothermal crater). Minimum, maximum, mean, and the standard deviation for the selected period is automatically computed and displayed. These tools can be used to process and display time series data related to other geometric entities (line or polygon) representing other features (faults, fractures, etc). For instance, if separate overlapping consecutive grids of diffuse degassing campaigns are considered, a time series of individual $CO_2$ flux

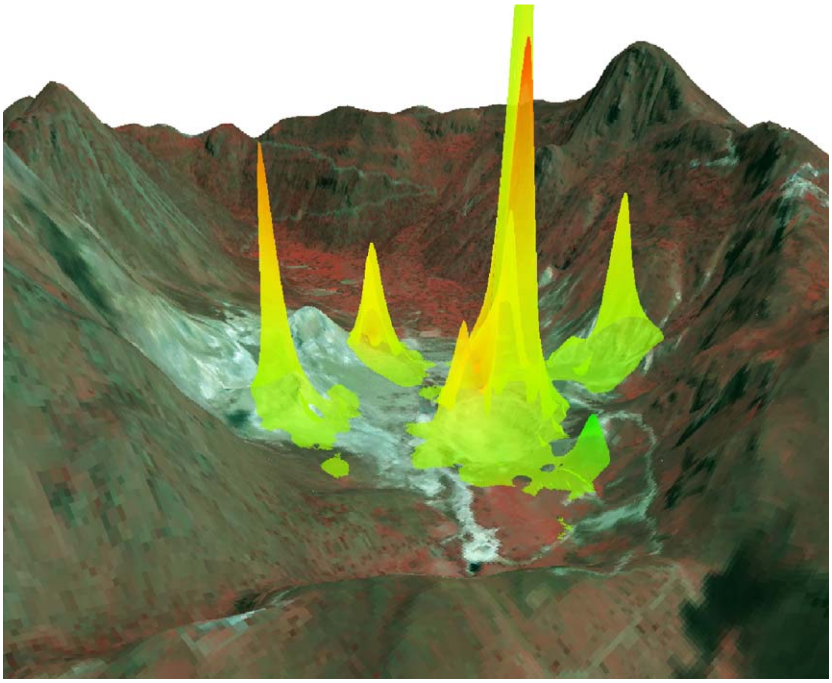

Fig. 6. Three-dimensional representation of exuded $CO_2$ flux distribution in Nisyros caldera. Heights represent modeled $CO_2$ grid flux values and colors represent temperature.

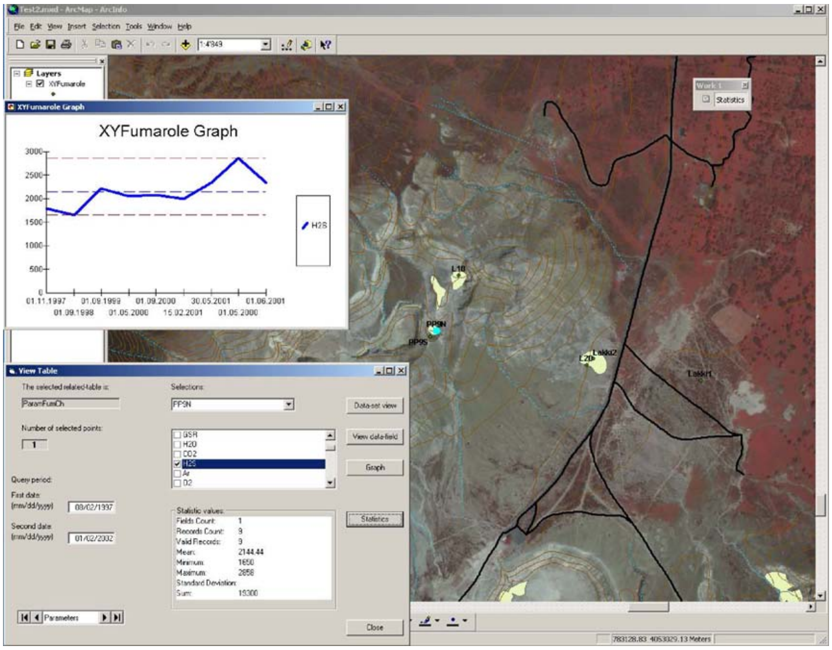


Fig. 7. Spatial database query menu for fumaroles chemical parameters.

values can be computed at any given point location within the areal coverage of these grids.

### 3.5. Hazard assessment

Quantification of volcanic and related hazards can easily be derived. The slope stability map (Fig. 8) demonstrates a complex example, which has been derived following an overlay and indexing method. The method combines the classified slopes, the geotechnical behavior of lava flows and unconsolidated pyroclastic rocks as well as steep cliffs of loose rock material in order to delineate zones of fragile stability.

Power lines, streets and settlements may show an increased vulnerability due to a highly exposed position in a valley that would serve as the transport bed for a rock fall event, as could be triggered by increased local earthquake activity.

## 4. Discussion

The following chapter is devoted to the problems that have arisen during the three-year GEOWARN project in particular, during the design of the GIS database handling complex data provided by all partners of different scientific fields and from different European countries. In addition, a new development has been undertaken, the programming of user-friendly, web-based multimedia software. The design and programming of these interfaces required continuous communication, the use and understanding of a common "scientific" language, and the full understanding of the entire GEOWARN work and its final goals among volcanologists, geophysicists, geochemists, cartographic designers, GIS specialists, and informatic engineers.

### 4.1. DEM of volcanic landscapes

Any volcanic environment shows major differences in morphology. The volcanic landscape exhibits various landforms created by a variety of eruptive scenarios and any subsequent erosional processes. These processes generate specific landforms that have to be reproduced with accuracy by the DEM. As a consequence, the operator creating the DEM of a volcanic landscape has to understand the geomorphology of a volcanic environment to be able to interpret singularities, heights, depressions, steep escarpments and fractures that could appear to the unwary operator. Vents, collapsed flanks, domes, necks, spines, lava and pyroclastic flows, ash and pumice deposits generated during eruptive phases, as well as craters and large calderas and their erosional products, could appear as DEM errors for an unskilled operator. To better discriminate the volcanic landscape singularities from possible modeling errors, a careful examination of the DEM versus volcanic and other geomorphological features is necessary. Furthermore, a good knowledge of the specific volcanic field, careful field examinations, and an interpretation of existing

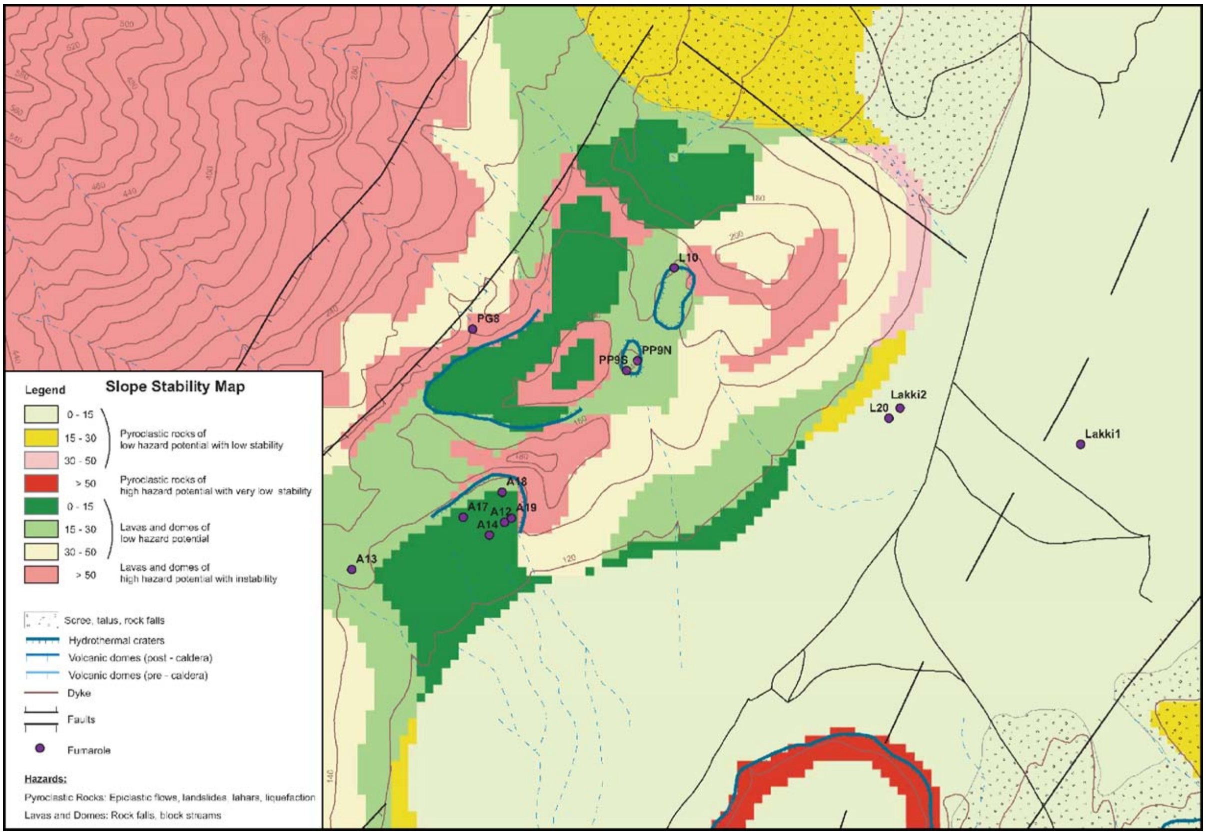


Fig. 8. Slope stability map of Nisyros island derived by performing an overlay and index method on spatial database (as a combination of GIS based functions).

geological maps are essential prior to the creation of a DEM.

### 4.2. Data modeling

A data model represents a methodical approach to classify information and their relationships. A geographic data model represents the real GIS world in order to create maps, perform queries, and support analysis. It is the basis for modeling the system behavior describing how the various features of the landscape interact with each other.

Within the GEOWARN project, it was necessary to generate an appropriate way to explain data-modeling issues to all scientific experts. Because of the myriad of volcanological, geophysical, geodetic, and geochemical monitoring procedures, this task helped in finding a proper common language necessary for optimizing the data representation.

Finding an optimal spatial and temporal database representation for various phenomena is essential. The solution to this task is not obvious, when dealing with complex features like volcanic fumaroles or thermal springs. Fumaroles, vents from which volcanic gases (like sulfur vapor) escape, can occur along small cracks or long fissures. At the land surface, they show a frequent displacement in time, because soil fills some of the vents while others open at the same time. Scientists are sampling the fumaroles belonging to the same field but coding differently various superficial soil holes. Following their experience, they will identify easily the samples belonging to the corresponding location. Representing this within a spatial database needs a clear understanding of the phenomena and of the field, as well as the sampling procedures and measured parameters of various research teams.

### 4.3. Visualization of seismic data and test tomographic models

Data visualization allows surveying data quality and avoids unfitting between data delivery and database capture. To recognize data errors, data visualization has to include time and spatial data query facilities. For data related to the location of hypocenters of earthquakes, a three-dimensional visualization within the GIS package

(ArcScene) offered a good understanding of the seismic phenomena and avoided in several cases, error propagation. The visualization procedure enabled the three-dimensional hypocentres to be observed from various angles, simultaneously with the geology, tomography, gravity, and magnetic models.

## 5. Conclusions

The GEOWARN GIS database offers capabilities for data modeling as well as for other volcanic studies, such as

- *Data verification and validation,* essential for accurate and precise data representation. Using an advanced database supported by GIS, these operations can be done in a simple way. For example, anomalies in chemical time-series data for fumaroles, springs, and geothermal wells can be inspected on graphs as a result of a query.
- *Automatic data treatment* is required before input to any process-based model and for data to be stored from continuous data streams. Because of the huge amount of work required to prepare the data used by various modeling procedures, a GIS-supported database is absolutely essential.
- *Maps of various parameters* can be generated. Paper and screen maps, as well as other graphical spatial screen representations (e.g. four-dimensional-animations of data correlations) can be created starting from existing point data using statistical procedures (including geostatistics) supported by the GIS software. Anomalies indicating unrest in volcanic behavior can be detected using these maps.
- *Correlations among parameters* can be detected and displayed using programmed interfaces or already existing GIS software procedures. For instance, geochemical parameters, lithology, morphotectonic features, and hypocenters distribution can be compared.
- Using the entire set of spatial data and having the described tools available "at a mouse click", the user is able to have a *complete view of the entire data-set*.

The database described in this paper is an integral part of the GEOWARN project, a pilot study of geospatial data management of dormant volcanoes. It still has certain limitations, which were considered in the previous sections. Changes, updates, or further developments of the schema are expected to be incorporated in the future. Furthermore, experts using only a Relational Database Management System (RDBMS) in the absence of a GIS tool can handle the attribute data.

Starting from this schema, new developments have been undertaken. One of them consists of web-based cartographic multimedia software having GIS tools, designed for spatio-temporal volcanological data analysis (interactive maps, stations, and time-dependent data-series; Hurni et al., 2004). This "GEOWARN software" accesses the described database.

## 6. Outlook

A comprehensive geo-spatial database concept for data management of dormant volcanoes is still lacking in the daily operations in many observatories. Such a concept should be the very basis for any analysis and visualization efforts that help observatory scientists to extract the most out of their data in times of crisis, and for scientific work for the purpose of expanding the body of scientific process knowledge. Efforts are currently under way by IAVCEI to accelerate the process of implementing such improvements in individual observatories (the "bottom-up" approach) by creating a world-wide standard for a database structure of volcanic unrest (Venezky et al., 2002).

The volcanological geo-spatial database presented here gives volcanologists a modern and versatile research tool. Query, visualization, and analysis tools such as the ones presented here are useful for other observatories. Furthermore, observatories facing a volcanic crisis can easily store, share, visualize, correlate, and analyze various sets of monitoring data in space and time. GEOWARN represents an important step toward more efficient integrated monitoring and hazard assessment procedures for potentially active volcanoes.

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## References

Brombach, T., Hunziker, J.C., Chiodini, G., Cardellini, C., 2001. Soil diffuse degassing and thermal energy fluxes from the southern Lakki plain, Nisyros (Greece). Geophysical Research Letters 28, 69–72.

Chiodini, G., Cioni, R., Guidi, M., Raco, B., Marini, L., 1998. Soil $CO_2$ flux measurements in volcanic and geothermal areas. Applied Geochemistry 13, 543–552.

GEOWARN consortium, 2003. GEOWARN, Geo-spatial Warning System—Synthesis Report. Athens (Greece) and Zurich (Switzerland), 57pp. (http://www.geowarn.ethz.ch).

Hurni, L., Jenny, B., Terribilini, A., Freimark, H., Schwandner, F.M., Gogu, R.C., Dietrich, V.J., 2004. GEOWARN: ein Internet-basiertes multimedia-atlas-informationssystem für vulkanologische anwendungen. Kartographische Nachrichten 54 (2), 67–72.

Makris, J., Papoulia, J., Papanikolaou, D., Stavrakakis, G., 2001. Thinned continental crust below northern Evoikos Gulf, central Greece, detected from deep seismic soundings. Tectonophysics 341, 225–236.

Vassilopoulou, S., Hurni, L., Dietrich, V., Baltsavias, E., Pateraki, M., Lagios, E., Parcharidis, I., 2002. Orthophoto generation using IKONOS imagery and high-resolution DEM: a case study on volcanic hazard monitoring of Nisyros Island (Greece). ISPRS Journal of Photogrammetry & Remote Sensing 57, 24–38.

Venezky, D.Y., Malone, S.D., Newhall, C.G., 2002. WOVOdat: a new tool for managing and accessing data of worldwide volcanic unrest. EOS Transactions on AGU (Fall Meeting Supplementary) 83 (47), F1501 (abstract V22C-08).

Zeiler, M., 1999. Modeling Our World—The ESRI Guide to Geodatabase Design. Environmental Systems Research Institute, Redlands, CA 195pp.