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Interdisciplinary Data Base of Marble for Archaeometric, Art Historian and Restoration Use

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Abstract

Marble material is widely used for artistic, sculptural and architectural work all over the history of Europe. Marble masterpieces are known from Greek temples, busts of Roman noblemen, and baroque figures to modern facade material, to mention only a few examples. The multitude of raw material and the various creation techniques raise several questions concerning the analysis, provenance, restoration of the objects. A number of proposals have been recently published to unify the data content of data bases concerning marble artefacts and samples. Our approach is similar to the previous workers, however, we renew our earlier concept that a common interface is needed for the data management and query. In this paper we give an account on the state of the art of our project that intends to provide an integrated, scalable and extendable data management and analysis system.

The project aims to characterise historic and recent marble quarries, as well specific marble objects, and makes the information available to all other people involved in the field of research and preservation of marble artefacts. We have developed a software solution for the problem based on client/server architecture. The server-side engine can be installed both on Windows and Linux systems, while the client software is Windows-based. The client software connects to the server via internet connection in a way that the user does not need to install any additional software. The client-side software can be easily updated: the user receives a message to automatically update the software and the update is done by a single mouse click.

The data content of our data base follows the principles laid down previously. Beside of the sample description (geographic location and catalogue data) the data base includes information on colour and fabric, physical properties, chemical composition, mineralogical composition (both macroscopic and instrumental), isotopic data, and textural analyses like fractal analytical and quantitative textural properties. Most of these properties are suitable as filtering criteria to provide query tools and data grouping possibilities. Furthermore there is a sophisticated geographical hierarchy defined in the system, so the samples can be organised into a logical geographic context as well. This context later can be used for larger scale studies, e.g., for provenance determination.

Introduction

During each archaeological research project a lot of data are compiled by literature research, evaluation of resources, field studies, surveys, measurements and simulations. After the termination of the project the vast majority of these data typically remains unpublished. The data themselves are stored by the research institutions often decentralised, analogously or digitally, using various media and in databases of different formats. All these data would be, in principle, ready for dissemination for any scientific purposes on request; however, only the author has the information about the storage and code system of the data. This makes it difficult to verify the conclusions of the publications in the light of the gathered data; and this makes it almost impossible to prepare the data for later use in other projects to answer other research-related questions involving third research parties. Sometimes unnecessarily repeated work is done; consequently the resources of the applied research equipment are needlessly used. To avoid duplicated research, the researchers are expected to publish the data together with the scientific contributions to provide public access to the original information.

Nevertheless, it is often difficult to fulfil this demand. The standards for raw data publication are quite different from the requirements for research publications. Most of the editorial boards discourage the publication of voluminous raw data; only some journals provide data repository functions. Even if such a repository is provided, the storage must be organised in such a way that the structure and format are conceivable for the researchers worldwide. Furthermore, the data must be filed in reliable data centres where they are maintained and are put into archives for long time and remain available even if the IT solutions change.

There is a general agreement in the scientific community that the co-ordinated and free availability of the research data serves all scientists fosters interdisciplinary studies and helps international efforts. Via the availability of the raw data the original research results gain also importance and become valuable.

The demand for data integration generated by provenance studies

Determining the source area of white marbles used in antiquity for sculptures and buildings is still an important problem in archaeology and art history. Deciphering the source of an artefact is a multidisciplinary–multi-method approach whereby disciplines like art history and archaeology have to supply from stylistic characteristics and the original location the most likely time frame and place of fabrication, but also locations of quarries in use at this time period. Natural science disciplines such as physics, chemistry or earth sciences, on the other hand, have to apply physical, chemical, mineralogical and petrographical analysis techniques which unequivocally assign the artefact’s marble to comparable material from a unique quarry. Simply based on individual parameters, however, reliable determinations are questionable and only a multi-method approach may reach a high confidence level. Moreover, almost all techniques applied to date are destructive for the artefact, i.e., they consume material. Thus, the size extractable from an archaeological artefact sets limits on the quantitative use of certain techniques. Therefore, it is important to apply a set of techniques which encompass the whole characteristics of the extracted material, i.e., not only the bulk chemical fingerprint, but also chemical, mineralogical and petrological heterogeneities as well as preferred orientations/accumulations. From this viewpoint a combination of cathodoluminescence texture, fabric analysis and geochemical parameters such as stable isotopes, is an ideal, low cost multi-method approach which satisfies the demand for 2D characterization of the material.

Still, large uncertainties exist on the assignment to a source as not all ancient quarries are known; certain quarries used in antiquity were reopened later or are still in use and thus the exact location of the ancient quarry is unclear; often only small, randomly oriented chips from ancient dumps are available which are not necessarily representative for the quarry and the marble in the quarry is heterogeneous. Thus, the knowledge at quarry level is limited and depends on the quality of the sampling method, i.e., random extraction/collection or well defined location and orientation. Therefore, any substantial improvement in the determination reliability of the source area of white marble used for a specific artefact needs detailed studies of the 3D variability at each ancient quarry site. Furthermore, a search for still unknown sites is required.

The provenance approach

The marble provenance studies have a long tradition in the archaeology; for science historic reasons the roots of marble provenance studies lay in the Mediterranean (e.g., Herz & Waelkens 1988; Waelkens *et al.* 1992; Maniatis *et al.* 1995; Schvoerer 1999; Herrmann *et al.* 2002; Lazzarini 2002). Beyond studies on the famous occurrence of Carrara marble, there are studies on the Aegean marbles, however, only a few investigations of other European marble occurrences have been carried out. These studies typically are of pure geological or petrographical nature, systematic interdisciplinary investigations are often lacking. Some new initiative exists from several authors and research groups, dealing first of all with the stable isotope characteristic of the white marbles from Austria (e.g., Müller & Schwaighofer 1999; Unterwurzacher 2005; Zöldföldi *et al.* 2004a, 2005) and Romania (e.g., Benea et al. 1995; Müller *et al.* 1995; Benea 1996; Benea *et al.* 1998).

Previous comprehensive systems

Restorers, researchers working in various fields of humanities, museologists and specialists managing collections, are basically interested in the construction of data retrieval system of primary data. Thus, the storage, access and safety of scientific data can be assured via co-ordinated activity of the data producers. Summarizing the users' requirements, in our previous work (Zöldföldi *et al.* 2004b, Zöldföldi & Weigele 2007) we laid down some principles that we found necessary to follow in designing such a system. A list of properties that the data base necessarily should contain was also provided. Although some design elements were previously set, this conceptual paper can be considered as the launch date of our current project.

Somewhat later, Cramer (2004) developed an expert system "MarbExpert" for marble provenance determination. A wide range of analytical techniques has been included: Macroscopic and microscopic petrographic analysis including thin-sections, calcite/dolomite characterization by means of XRD, quantification of the acid-soluble carbonate-hosted Mg, Fe, Sr and Mn by means of ICP-OES, and of Sr and the REE by means of ICP-MS, isotopic composition ($\delta^{13}C$ and $\delta^{18}O$), cathodoluminescence spectra, EPR-spectra and gas chromatographic analysis of the volatile phases. The database and a set of questions were implemented into an easy-to-use expert system shell which on one hand forces the user to "ask the right questions" – i.e. to make precise observations –, on the other hand, it allows him/her to get hints for a marble provenance determination with a high degree of reliability. The Knowledge Acquisition with a database of actually 17 marble quarry districts together with the Question Editor are capable of processing 30 questions on petrographic, geochemical and archaeologically relevant properties. The use of "fuzzy logic" also allows the processing of "diffuse" answers. The whole "MarbExpert" system may be modified and completed by the user according to specific marble quarries or characteristics.

In his recently published book Attanasio *et al.* (2006) using case studies, extends the scope of the data introducing a new isotopic, EPR and petrographic database of Mediterranean white marbles which includes 1346 samples from 20 different historical quarrying sites. 12 variables from three different techniques (isotope analysis, EPR, and petrography) were measured for each sample. This conceptual framework, depending on the specific problem under investigation and on the user's experience, can be used at various levels of complexity, from simple bidimensional graphs to full multi-method statistical analysis.
Attanasio *et al.* (2006), concerning the general issue, wrote: "*Although future work in this direction is already planned, it seems important to point out once again that the establishment of a truly comprehensive collection of data relies critically on the possibility to share results and samples within the archaeometrical community*".

A short review of common data types in marble analysis

The first attempts to apply scientific methods to the study of marble go back to the work of G.R. Lepsius, which was published in 1890. He introduced the methods of petrography into the field and in particular the microscopic study of thin sections (Lepsius 1890). This was the only method utilised until the mid 20th century and it still remains important today. In the first half of the twentieth century it was gradually accompanied by the use of X-ray diffraction spectra, with which the identification of the most significant mineral phases could be made. Spectroscopic techniques for the identification of trace elements, those with a presence of the order of 0.1% or below, then began to be introduced. Chemical fingerprinting of different materials and samples is possible with this technique, and for this reason it has become the most commonly used analytical method in archaeological research.

The determination of the type and quantity of trace elements is one of the most frequently used analytical methods in archaeometry. Without going into the technical details many different methods have been developed for trace analysis. They include optical emission spectroscopy (OES), atomic absorption spectroscopy (AAS), X-ray fluorescence (XRF), electron microprobe (EMP) and neutron activation analysis (NAA). More recently techniques using a torch of argon plasma to ionize samples in solution have became more common. The most important of these techniques are inductively coupled plasma spectroscopy (ICPS), inductively coupled plasma atomic emission spectroscopy (ICP-AES) and inductively coupled plasma mass spectroscopy (ICP-MS). Leaving aside older and less frequently used methods, the various techniques obviously have different levels of sensibility and accuracy. This means that the comparison of data obtained by different methods is often problematic, as can also be the case when the same techniques are used by different laboratories.

The quantitative study of texture (Quantitative Textural Analysis or QTA) is in essence the numerical analysis of microscopic images obtained with thin sections evaluating the textural properties on the marble samples by means of quantitative fabric analysis (QFA) and fractal analysis (FA). Fractal analysis is a mathematical approach to the quantification of structural information on natural object. When applied to marble textures the method enables rigorous characterisation of textural relationships of calcite grains, and makes it possible to incorporate the spatial interconnections among grains and the geometrical features of the single grain in the fractal dimension calculation. In combination with quantitative fabric analysis (QFA), fractal analysis is a powerful tool in the discrimination of marbles from various occurrences given its high capability to resolve the convolution of the grain boundaries, which is a distinguishing textural feature of marbles.

The isotope geochemistry of carbon and oxygen applied to the study of marble provenance commenced in 1970s (Craig & Craig 1972). The method was proposed as the most powerful among the techniques already in use, which were, essentially, chemical and petrographic. The isotopic compositions of carbon and oxygen measured in marble samples collected from four different quarry areas of Greece (Naxos, Paros, Mt. Pentelicon and Mt. Hymettos) were remarkably different. The initial results were very promising and encouraged many other researchers to take the same route. The new data, plotted on the usual $\delta^{18}O/\delta^{13}C$ diagram, already gave a more confused frame for the growing database of marble isotopic compositions. Herz (1985) presented much new data and summarized the existing results. About the same time the most important subsequent contribution was a more detailed investigation of the marbles of the Carrara and Seravezza (Herz & Dean 1986). These authors also noticed the possibility of distinguishing the two sites isotopically, while intra-site discrimination was found to be difficult. After the above mentioned studies the marble isotopic reference diagram has been enlarged and updated several times, in the last two decades. A comprehensive account was published by Moens *et al.* (1992). More recently Gorgoni *et al*. (2002) published an extensive diagram of the Greek quarries and Zöldföldi & Satır (2003), Zöldföldi & Székely (2004; 2005b) of the white marble quarries in Anatolia.

On examination of the more recent diagrams the main limits of isotopic analysis become quite evident. Owing to the ever growing number of sampled sites, as well as to the growing number of samples available per quarry, site superposition has become almost a rule, with the results that multiple provenances are a common outcome of isotopic assignments.
The $\delta^{18}O$-$\delta^{13}C$ plots are widely used today to determine provenance but, unfortunately, with so many quarries in the data bank, many quarry fields overlap in values. Clearly ancillary data banks are needed to obtain a more certain determination of provenance. Because of great advantage of isotopic ratio analysis, principally the need for only small samples and homogeneity over large areas, we decided to include the $^{87}Sr/^{86}Sr$ isotopic ratios along with $\delta^{18}O$ and $\delta^{13}C$ and to do a trivariate analysis to improve the discriminating powers of the $\delta^{18}O$-$\delta^{13}C$ plot.

In the last twenty years the already existing methods have been accompanied by a further series of even more sophisticated techniques, these include magnetic resonance, cathodoluminescence, laser reflectance and the quantitative analysis of texture.

Recently a new database of white marbles, based primarily on EPR (Electron Paramagnetic Resonance or ESR) spectroscopy and including some of the most important Greek, Turkish and Italian historical quarrying sites, has been introduced (Armiento *et al.* 1997; Attanasio 1999). In the field of marble provenance the use of ESR spectroscopy, which detects, among others, the Mn^{2+} impurity ubiquitously present in marbles, dates back to the early 1980s (Cordischi *et al.* 1983). Since then much more work has been carried out (Lloyd *et al.* 1988; Maniatis *et al.* 1988, Maniatis & Polikreti 1998), but the use of EPR spectroscopy has remained relatively limited.
This is partly due to the intrinsic characteristics of the method which is not particularly suited for quantitative analytical determinations, but also to the fact different variables have been measured and used by different authors and to the lack of generally accepted standards for both signal intensity and magnetic field strength. In spite of these difficulties the amount of information that EPR spectroscopy of marbles may provide is remarkable.

In addition, and being aware of the fact that reliable assignments may be often obtained only by the combined use of different analytical methods. (Matthews *et al.* 1995; Moens *et al.* 1992), the database was conceived from the beginning as a starting data set to be extended to other measuring techniques. It is obvious, in fact, that the data processing step and the statistical analysis of the experimental information require the various measurements to be carried out on the same quarry samples.

Since its first introduction the marble database has been considerably enlarged and updated. New samples, mainly from Anatolian quarries, have been collected and measured. New, more suitable, standardization procedures have been adopted and also the measuring process has been modified and improved, particularly in the case of the petrographic or morphological variables, which were previously estimated simply on a qualitative basis and given as categorical variables (Attanasio *et al.* 1999). The classification rule, based on discrimination function analysis and taking into account the new experimental results, has been optimized and validated using standard statistical techniques, as well a set of test samples. This last point, i.e. the validation step, is particularly important in that development of a reliable classification method depends upon the ability to estimate realistically its error bar. Extension of the database to other techniques was introduced in the paper of Attanasio and Platania (2003), where morphological variables have been included, but more substantially reported elsewhere, where isotopic data have been taken into account to improve discrimination within a single, large quarrying site (Attanasio *et al.* 2000) or among a properly selected subset of sites (Attanasio 2003). On the basis of the above outline, an updated account of the EPR and petrographic marble database, covering all aspects of data collection, standardization and analysis seemed appropriate and is given in Attanasio (2003).

It is important to remark on the combined use of different methods. This is because all previous studies have unequivocally revealed that no single analytical technique is capable of resolving all the problems related to provenance. Quite frequently one of the techniques, although extremely sophisticated, will produce data that does not discriminate some of the possible provenance sites, which are instead easily distinguished by using a different technique, and vice versa. It is commonly agreed that an approach that integrates two or three different methods and measures is necessary to determine reliable provenances.

The results produced using integrated methods, or occasionally with single techniques, go far beyond simply assigning the provenance of artefacts. Most known marble localities, including renowned sites such as Dokimeon, Proconessos, or Carrara, are extensive regions that include numerous districts and quarries. In favourable conditions particular areas of the locality can be distinguished, at least partially, and further analyses may sometimes reveal the district or even the exact quarry of provenance. The data can also be utilised to determine whether different parts or fragments of a work originate from the same quarry and even if they originate from the same single block of marble.

This is of great interest since such information, when available, may allow us to recognise forgeries (Polikreti 2007) and later restorations, detect different stages of the manufacturing process, and monitor the reassembly of large artefacts. Furthermore, if a number of samples from the same large work are available; the use of disparate or homogeneous materials can be verified, providing information regarding the building history and manufacturing process of the artefact. The former result would suggest that the construction material had been acquired at different times or from different places, whereas homogeneous materials can originate only from a single quarrying project, which may have planned specifically within the context of a single construction project.

Motivation of our project

In accordance with Attanasio's (2006) cited opinion, we intended to create a common interface to collect, share and, possibly to comment or criticize the existing results. Similarly to other authors, we have collected a number of own measurement data especially in Anatolia (Zöldföldi & Székely 2003; 2004; 2005a; 2005b) and in Austria (Zöldföldi *et al.* 2004a; 2005). These data and the requirement of comparison to other marbles with different provenance involved an imminent need for such an approach. Since the informal replies to our requests to the community were positive, the development has been started.

The aim of this project was to develop a scientifically and technologically interdisciplinary and easily accessible data base management system with user friendly interfaces for data entry, quality control, storage, continuous dissemination, and exchange. This is needed to develop innovative, efficient and practical ways of processing, archiving, and disseminating the large volume of data. Furthermore, the system should provide practical hints to understand the techniques applied on various samples and relate them to other literature data.

Conceptual elements and general properties of the system

The rapid pace of information technology development in the last years makes it possible to create a general information system including already existing analyses and results not only of marble occurrences but of archaeological objects and architectural elements. Conceptually we intend to manage the results of analyses of both type of material together to handle the data in the same manner. It enhances the overlaps and the gaps in the analytical results defining the further analyses to be done. On the other hand the integration makes it possible to spare expensive and time consuming measurements, if the data are already available from the material with the same provenance.

General properties

As any such software (or IT) solution, the system should fulfil the following criteria:
- User friendliness: the typical (trained) user should be able to use the system effectively, including, among others, data input, retrieval and update.
- Scalability: the system should provide means for the extension in scope, number of users, increasing access, and amount of data.
- Data security: the system should be tailored to prevent unwanted, incidental data loss as well as intruder attacks or malicious access.

Our system provides a user-friendly interface for those users who are familiar with the principles of the sampling and various types of marble investigations. The menu structure follows the logic of the sample identification, processing and measurements, therefore it is easy to understand and use. The system is designed to be scalable, especially extendable to include new methods that are developed. The data base from the server side can be extended to include new fields for each record; the client-side application can be easily updated by the user if the system administration sends a message to do so. The access is password protected, however, there no need for more protection since major attacks are not expected.
And last but not least the system is designed to perform user defined filtering operations practically on any combination of logical “AND” criteria, i.e., restricting the selection set by multiple selection.

Conceptual issues

The goal of the developed system is to provide help for data comparison, provenance analyses and to reveal missing analytical results. It integrates data on raw material (hereafter referred to as geological samples) and results on archaeological (art historical and/or architectural) objects (referred to as archaeological samples). The system manages both type of data using the same concept, and most of the data entries are the same for both object types. However, because of the nature of the stored data, in some aspects the two data structures differ.

The data entries are organized in the following scheme. All records contain the following entries: Sample identification; Methods applied on the sample; Colour and fabric; Mineralogical composition; Textural properties; Chemical composition; Isotope geochemical data; Electron paramagnetic resonance; Engineering physical properties. Dependencies on the type of the sample are the following. (a) in case of *geological sample*: geological classification (age, facies); (b) in case of *archaeological samples*: Archaeological description of the objects; Probable provenance if determined; Conservational and restoration experience.

The system is designed so that further amendments and extensions are possible without data loss. It will be updated and tailored according to the experience gathered during its use. It is planned to revise the system functionalities, data structure and data content regularly according to the requirements of the users and data providers. However, the amendments should be done so that the changes do not hamper the comparisons with the previous data and applied methods.

The design of the system

Implementation

From the point of view of the implementation our software solution is based on client/server architecture. The server-side engine is based on the freeware PostgresSQL-technique that can be installed both on Windows and Linux systems, while the client software is Windows-based. The client software connects to the server via a standard internet connection layer in a way that the user does not need to install any additional software. (A firewall-protection may be an issue, but can be solved by an experienced user.) The client-side software can be easily updated: the user receives a message to automatically update the software and the update is done by a single mouse click. This solution ascertains that the whole community has the same interface and no outdated access tools exist.

The data content

The data content of our data base follows the principles laid down previously. The data base is designed so that it should form an effective means of data exchange between (a) the data producers and (b) the data users.

(a) From our point of view the data producers are those researchers, who carry out any type of measurements on marble material regardless of its purpose, e.g., geoscientific, physical, chemical, material scientific, archaeological and art historical analyses;
(b) The data users are expected to be interested in any type of comparison, classification, query of the aforementioned data set.

The development of the data base had two major aspects. At the first place the structure of the records had to be defined; the structure is expected to be basically unchanged, though the feedback of the users should be taken into account continuously. To foster the exchange of ideas and experiences a notice board is included in the system.

In the following the data base structure is outlined. The structure is determined by all possible features of marbles which may be useful in the distinction of their different types.

The data entries are organized in the following scheme:

1. Sample identification
2. Methods applied on the sample
3. Colour and fabric

4. Mineralogical composition
5. Textural properties
6. Chemical composition
7. Isotope geochemical data
8. Electron paramagnetic resonance
9. Engineering physical properties
10. Depending on the type of the sample
    a. In case of geological sample: geological classification (age, facies)
    b. In case of archaeological or art historical samples : archaeological description of the objects; probable provenance if determined
11. Conservational and restoration experience

(a) Sample identification
In order to be able to handle the archaeological and geological samples in the same manner, the data of the sample and the locality/artefact properties are stored in separate relational data base. However, they are connected via unique key field entries. Each sample is assigned to one of the categories; consequently the samples inherit properties from the ancestor category. Some of the identifying properties are compulsory, to avoid any indetermination in the data base. These properties basically belong to the identification data block (Figure 2), so the analytical result can be added later.

(b) Geographic identification
It is important to emphasize that the data of the localities and the artefacts are entered and managed separately to allow any number of samples in the data base for a given locality/artefact. To this end a nesting concept has been applied for the determination of the geographic location (somewhat sloppily, hereafter referred to as georeference). It is assumed that the sample (whatsoever it is) has an approximate localization (e.g., continent). This is then the top level of georeference; consequently, all samples must have this property. (In the vast majority of the cases the continent of origin can be determined. If the artefact is found e.g., in a shipwreck and the provenance cannot be determined, then a special "region" can also be introduced.)

Having defined the region of origin, the user may define deeper level of georeference. It is possible to give any level of geographic identification (region, country, locality, mountains, island, quarry, etc.) without any restriction. The logical structure is maintained by the property named "upward nesting" that is, the geographic entity that completely contain the entity to be defined (Figure 1). Since all samples have the continent property defined, all sampling localities can be assigned to at least one higher geographic entity. As it was mentioned above, the geographic entities are managed separately from the samples, since the geographic context does not depend on the actual sample.

This way a geographic structure pyramid can be built. This structure is collected dynamically as the data base grows, and the users do not have to do extra effort for its maintenance, since all new entries are defined by their first occurrence. Even if the geographical assignment has an error, later it can be corrected, and the samples themselves should not be modified.

The structure allows to store unlimited nested features, e.g. within in a quarry several raw materials can be present, and the system allows this separation, e.g., western wall, NE pit, etc. If the user later decides to split up a locality, it can be done by introduction of new geographic level, and the samples belonging to the new geographic units can be reordered accordingly.
Similarly the buildings/artefacts can be handled in this manner. The larger unit (e.g., a sculpture) can be later divided into sampling units. In this sense the artefact is the geographical entity, which can be split according to the needs

(c) Method summary sheet

In this part of the data base the measurement history of the sample is summarized. Beside of the date and type of the carried out measurements and related information (e.g. laboratory, instrument type), the external references (sample identification) of the measuring laboratories are stored. Ample space is provided for further investigation types and other bookkeeping information.

Of course, the different measurements can be summarized on the very same sheet only if the measurement was made on the very same specimen. If not, the measurements will be separated to different samples with their own sample ID. This approach assures that artefacts mosaicked of various materials can be separately stored in the scheme.

(d) Macroscopic properties

This sheet summarizes all the observations which are done without instrumentations, made during field work or in the lab, for example colour and smell, distinguishing between calcitic and dolomitic marble (reaction with HCl), fabric, foliation, minerals detected by naked eyes.

(e) Microscopic properties

This group sums up the results of different observations methods:

1. Microscopic and microprobe investigation;
2. Quantitative Textural Analysis (QTA) including quantitative Fabric Analysis (QFA) and Fractal Analysis (FA) for statistical evaluation of grain size analyses. Additional to the conventional grain size determination, the statistical distribution (histogram) of other grain size-properties, like axial difference (long axis – short axis), ratio perimeter/surface, shape factor etc., Fractal Analysis (FA, mass dimension method) is used to extract pattern related parameters in order to characterise the different samples (Zöldföldi & Székely 2005b);
3. Staining technique;
4. Cathodoluminescence imaging.

(f) Instrumental data

Detailed description of samples is given based on instrumental studies, which include:

1. X-ray diffraction (XRD) in order to determine the mineralogical composition;
2. X-ray fluorescence (XRF), inductively coupled plasma mass spectrometry (ICP-MS), instrumental neutron activation analyses (INAA), and prompt gamma activation analyses (PGAA) in order to determine the chemical composition of the sample;
3. Carbon and oxygen isotope geochemistry;
4. $^{87}Sr/^{86}Sr$ isotope geochemistry.

Examples of applications

This internet accessible database forms the scientific basis and background of provenance analyses of historical monuments and marble masterpieces. Here a few application examples are provided.

(a) Authenticity of "antique" marble objects

In one of our projects the authenticity of some marble artefacts said to be authentic Cycladic Neolithic sculptures had to be determined. Conceptually the decision was made based on several factors, including macroscopic, microscopic, cathodoluminescence investigation, isotopic analyses. First of all the results measured on the raw material were compared to the data base values. In a part of the cases this comparison immediately showed that the assumed provenance can be excluded because of several discrepancies in the mineralogical and stable isotopic composition.

One of the sculptures showed almost identical values in all analysed aspects with the assumed raw material of Naxos, i.e., we could conclude that the material is very probably Cycladic marble. On the other hand this study proved the importance and necessity of the weathering studies of the material because despite of the similarity of the bulk rock material the surface of the analysed sculpture did not show the weathering properties which would be expected of an artefact with the corresponding age. This way it was possible to conclude that this piece is also a modern forgery, though of original material.

(b) Provenance determination of building material in Troy (Turkey)
Marble is an important building material in Troy, from the Greek period, Ilion (Troy VIII, shortly before 700 BC - 85 BC) and Roman period, Ilium (Troy IX, 85 BC - c. 500 AD). These phases of construction left their fingerprints on the buildings and monuments of Troy. The materials of the monuments could have been shipped from various areas because of the occupation history of Troy and the surrounding area. This example has already been published in detail (Zöldföldi & Satir 2003; Zöldföldi & Székely 2005a), here we summarize it briefly as a successful application example to identify geographic locality of quarries of possible provenance.

There are abundant marble material resources in the near vicinity and in the farther surrounding of Troy (Zöldföldi & Satır 2003): various white marble occurrences can be found in Asia Minor (Sakarya Zone tectonic unit: Marmara, Orhangazi, Bergaz, Mustafa Kemalpasa, Altınoluk; Menderes Massif tectonic unit: Muğla, Afyon, Uşak, Babadağ). Furthermore archaic quarries are well-know in the archipelago of the Aegean: Naxos, Paros, Thasos, Lesbos etc. Because of the extended commercial connection in the Roman times other marble sources come into consideration. On the other hand, the recycling of the already readily available material cannot be excluded. This wide variety of white marble material sets up a challenging problem of the origin(s) of the architectural and sculptural stone-works. The analysis of the building material can explain the commercial and political connections via the determination of the possible shipment sources.
In this study the following architectural elements were considered: Athena Temple (280 BC), Athena Temple Portico (230 BC), Sanctuary of "Roman Altar" (3rd century BC), Bouleuterion and Bath moulding (both 2nd century BC), Odeion (2nd century AD).

The textural analysis of the fabric (maximum grain size and fractal properties) excludes most of the occurrences of the Menderes Massif and some of the Aegean Islands like Thasos and Naxos. Based on microscopic investigation and stable isotopic geochemistry the material used for construction of the Athena Temple dated at 280 BC could have come from the Marmara and/or Orhangazi area. Some samples of the Temple (PBA1-2) can be clearly referred to Marmara and/or Orhangazi, based on their $^{87}Sr/^{86}Sr$ ratios, but the rest of them fall also into the $^{87}Sr/^{86}Sr$ ranges of Marmara and/or Orhangazi. More specific reference to provenance cannot be made presently, because the geological samples from these areas, Marmara and Orhangazi are indistinguishable. The investigation of the Athena Temple Porticoes shows that, in part, the same building material has been used such as for the Athena Temple (new shipping from the same quarries or recycling). However, a new group of material, certainly from Pentelikon, Greece was also found. According to the stable isotopic geochemistry the "Sanctuary" of Roman Altar dated from the 3rd century BC, was built of marble from Serhat or Altınoluk, but Marmara and/or Orhangazi can not be excluded. The building material of Bouleuterion dated from the 2nd century BC was derived from Marmara, which is proved based on microscopic, cathode-luminescence investigation, stable isotope geochemistry, and Sr-isotope ratios. Concerning the next construction period (Troy IX) fragments of several architectural elements and columns of Odeion were investigated. Based on microscopic investigation and isotopic geochemical constrains, the marble for this construction phase came from Marmara/Orhangazi, Serhat, Ayazma, or Altınoluk.

The fragments of the Bath moulding dated from the late 2nd century BC can be sharply separated into three groups. One of them stems from Marmara and/or Orhangazi, the second from Bergaz, while the 3rd one shows affinity to Paros (Greece) on the basis of stable isotope geochemistry and cathode-luminescence features. This complex provenance pattern demonstrates that this architectural feature was constructed of material from various shipments (including marble from Greece) or, more probably, partly of recycled material already present at Troy. In summary the majority of marbles used for construction of the Trojan architectural elements is derived from Marmara and/or Orhangazi areas, with minor percentages of other Northwest Anatolian and Greek shipment at various historical periods.

(c) Importance of provenance analyses in restoration

It has been shown by Recheis et al. (2001) that in certain cases the *in situ* analytical techniques may fail to provide appraisable results in the lack of provenance information. These authors analysed the portals of Schloss Tirol (Tyrol, Austria) dated to the 12th century.

The two marble portals of "Schloss Tirol" show differences, both in material and in weathering state. As the building history of the portals is still not clear – historians suppose that some parts of the portals are older and completed by different masters – it is of significant interest whether the differences are due to a different weathering history or due to marble materials of different provenance. Based on isotopic analysis, trace element analysis and grain size determination, Recheis *et al.* (2001) conclude that there is a difference between the two portals in the whole and a difference between some parts of the palace portal in particular.

Furthermore these authors draw the conclusion that "*for a reliable interpretation of ultrasonic results with respect to weathering effects the knowledge of the exact origin of the marbles is necessary*". Our data base is intended to serve for such purposes.

Conclusions

A data management system has been developed for storage and manipulation of various properties of marble rock samples and artefacts. The system applies the client-server architecture, allowing multiuser access. A novel conceptual approach, to handle the geological samples similarly to the archaeological artefacts, has been found advantageous to manage the data records and to make provenance decisions using various filtering criteria.

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Entity	Upward nesting
Tectonic unit Z	[Continent]
Locality C	Tectonic unit Z
Quarry R	Tectonic unit Z
Formation Y	Tectonic unit Z
Formation W	Tectonic unit Z
Locality A	Formation W
Locality B	Formation W
Locality D	Formation Y
Quarry Q	Locality B
Quarry P	Locality B

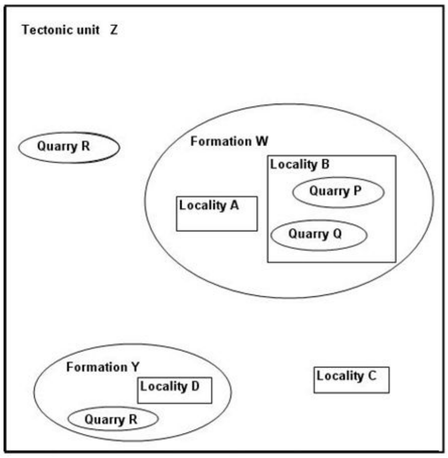

Figure 1: The logical structure is maintained by the property named "upward nesting" that is, the geographic entity that completely contain the entity to be defined.

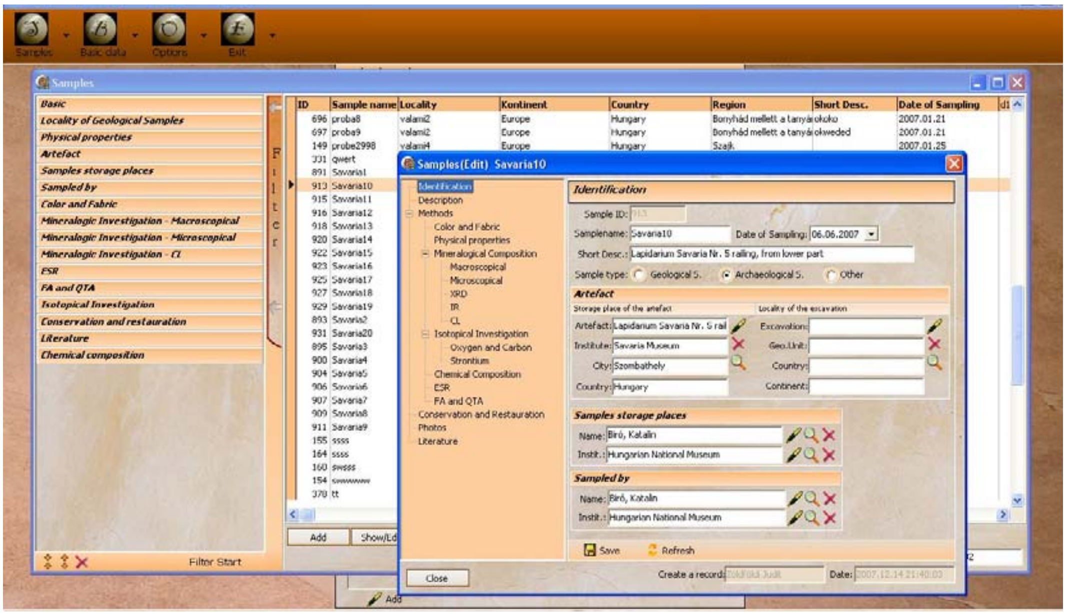

Figure 2: Each sample is assigned to one of the categories (archaeological/geological/other); consequently the samples inherit properties from the ancestor category. Some of the identifying properties are compulsory, to avoid any indetermination in the data base. These properties basically belong to the identification data block, so the analytical result can be added later.