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Georchaeology - Reconstructing our early history

Contents

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Foreword

EurGeol. Vítor Correia, EFG President

I must start by saying I found the theme of this edition of *European Geologist* fascinating. I don't say it because I have a special interest in archaeology but because, reading the articles enclosed, I found myself surprised by the glimpses from the past the authors are offering to us by blending – with large doses of research and knowledge involved – geology and archaeology. The themes are vast, from the Neolithic to the Bronze Age, or from Petra to Roman monuments (and thermal baths), passing by the Greek Acropolis, and the methods of study range from magnetic susceptibility to geomorphology or micromorphology.

This reminds me that one of the most interesting facts about geological processes and their study is its scale[1]: from the atoms to the stars, geoscientists encompass all sizes. And by combining scale with the huge number of existing physical and chemical processes (and also the aims of investigation), geology becomes a greatly diversified science.

But the distinctive aspect of geology is, in my opinion, its reasoning. I fully agree with Robert Frodeman, an American philosopher, who wrote[2] *"Facing the difficulties of modeling the geologic past because of problems of temporal and spatial scale and the singularity and complexity of geologic events, the geologist turns to other types of explanation, such as reasoning by analogy, the method of hypothesis, and eliminative induction"*. Frodeman stated that geological reasoning combines logical procedures, some shared with the experimental sciences, while others are more typical of the humanities in general and Continental Philosophy in particular. Naturally this combination of techniques is not utterly unique to geology and such a combination is present to one degree or another in most types of thinking, scientific or otherwise. But Frodeman claimed (and I trust all geoscientists will agree) that such a combination is especially characteristic of geological reasoning.

In the same article Frodeman concluded *"geological reasoning offers us the best model of the type of reasoning necessary for confronting the type of problems we are likely to face in the 21st century"*. In his opinion the "engineering or physics envy" that geology sometimes seems to suffer from (i.e., the sense of inferiority concerning the status of geology as compared with other "harder" sciences) is misplaced.

The articles about Geoarchaeology published in this issue support Frodeman's claim, illustrating how combining geological reasoning with the methods used in historical sciences to explain human behaviour and its consequences proves to be a powerful tool. And geological reasoning is now being used in fields as varied as space exploration, geoforensics, deep sea exploitation or natural hazards response.

Imagine what would happen if geological reasoning was also used in economics or politics. You're probably smiling, thinking I'm advocating for geoscientists making governmental decisions. I'm not. I'm just standing up for the advantages to modern societies of teaching geology to school kids. It's time for *mente et malleo.*

1 It affects both space and time. I'm not giving examples on time because it is not in the scope of this article. But the importance of geological time matches the paradigm shift from the Ptolemaic model of the heavens to the heliocentric model started with the publication of Copernicus's *De revolutionibus orbium coelestium*.
2 Frodeman, R. 1995. Geological reasoning: Geology as an interpretive and historical science. *Geological Society of America Bulletin* 1995, 107(8). 960-968. DOI:10.1130/0016-7606(1995)107<0960:GRGAAI>2.3.CO;2

Reconstruction of agrarian practice and land impact in the drylands: A geoarchaeological approach

M. M. Sampietro Vattuone, J. L. Peña Monné, J. Roldán and M. G. Maldonado*

Mankind is an important factor for landscape and soil change. The reconstruction of past human activities in agricultural lands is a challenge in itself because in these archaeological areas, evidence of artefacts is normally scarce or missing. This challenge must be met with a geoarchaeological methodology that goes beyond usual archaeological approaches. In this paper, we develop a step-by-step proposal for the reconstruction of agrarian behavior of dryland environments, considering geosciences, biogeochemistry, biology, and archaeology.

L'espèce humaine joue un rôle important dans les changements affectant les paysages et les terrains superficiels. La reconstitution des activités humaines du passé concernant les terres agricoles représente un défi en lui-même parce que, pour ces secteurs archéologiques, l'évidence d'objets façonnés est normalement rare voire absente. On doit répondre à ce défi par une méthodologie géo-archéologique qui va au-delà des approches archéologiques conventionnelles. Dans cet article, nous décrivons une proposition par étapes, pour la reconstitution des pratiques agraires dans un environnement de sols arides, prenant en compte les géosciences, la biochimie, la biologie et l'archéologie.

El hombre es un factor importante de cambio para los paisajes, así como para los suelos. La reconstrucción de las actividades humanas pasadas sobre las tierras agrícolas es un desafío en sí misma. Esto se debe a que en estas áreas arqueológicas la evidencia artefactual es escasa o nula. El desafío debe ser afrontado con metodologías geoarqueológicas que exceden las aproximaciones arqueológicas usuales. En este trabajo desarrollamos paso a paso una propuesta para la reconstrucción del comportamiento agrario en ambientes áridos considerando aportes de las geociencias, biogeoquímica, biología y arqueología.

The reconstruction of past agricultural practice is a challenging archaeological task. In the drylands, humans have implemented different kinds of activities to make lands adequate for crop production. Some of the most evident features include the construction of different kinds of irrigation systems, earth benches, stone lines, and terraces. Even though crop parcels are often easily identifiable in landscapes, archaeological artefacts are scarce or missing. There are normally some ceramic potsherds on the surface or stratigraphy but agricultural tools were not typically discarded in the fields. In this way, prevailing activities were related to (a) adequacy and maintenance of the fields for crop production; (b) tillage, which left behind specific features in soils according to the technical capacities of the people and the environmental conditions; and (c) extraction, given by the effect of continued harvests on soil nutrients. Each of these activities left its own footprint, which is not accessible through traditional archaeological methods, constituting an exceptional field of research for geoarchaeology.

In this context, the objective of this paper is to propose a step-by-step methodology to study agricultural lands established in world drylands. This proposal is the results of 30 years of experience as a research team working in the drylands of SW Spain and NW Argentina (Peña-Monné *et al.*, 2004; Sampietro Vattuone *et al.*, 2011, 2014, among others).

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Methodological approach

It is recognised that agricultural activities produce positive and negative effects on lands and landscapes on different scales. To a large degree, the weight of one or another depends on management abilities, the technological capacity of the people, and the environmental stability of the place where the activity took place.

Considering the most relevant subjects related to cropland management in a decreasing scale, it is possible to identify changes as follows (***Fig. 1***): (1) on the ecosystemic/landscape/basin scale, there are changes in the distribution of erosion patterns and vegetation; (2) on the scale of crop parcels, it is possible to identify a local decrease in slope gradient as well as fine sand and clay accumulations; the presence of structures could affect normal superficial runoff and produce concentrate fluxes that form rills and gullies, and piping; (3) on the scale of the internal characteristic of croplands (soil horizons or sediment layers), superficial horizons could be deepened or eroded, and changes in the capacity to retain water are also possible as a consequence of tillage and irrigation; (4) on the micromorphological scale, agricultural lands could produce structure degradation and porosity loss, reflected by land compaction (impeding the correct aeration and growth of roots); it is possible to observe changes in colour (normally related to changes in organic matter contents), and texture (clay translocation); (5) finally, on the scale of physicochemical and biological properties, changes in the bioavailability of nutrients as well as in organic carbon presence in lands are common (Homburg and Sandor, 2011).

Results

Considering that the variables implied on the agrarian activities are diverse and that the analytical results could change over time, we propose the following research steps:

Step 1 – Landscape and ecosystem scale analyses

These analyses require understanding the geomorphological, paleoenvironmental, archaeological, and edaphic characteristics at a regional level. The construction of geoarchaeological models is a very useful tool in this step of research (see Peña Monné and Sampietro Vattuone, 2014, in this issue).

These models make it possible to know the environmental characteristics prevailing before the first human settlements occurred in a region. This knowledge is gained by putting together the natural and cultural formation processes that affected agrarian archaeological sites. Thus, these models constitute the basic evolutionary landscape unit to work on. It is useful to construct thematic maps, including geological, geomorphological, archaeological, pedological, hydrographical, and morphodynamical data.

On this scale it is possible to observe features related to the construction of agricultural terraces, earth benches, stone lines, and irrigation structures. In several cases these structures look like steps in the slopes. These steps decrease inclination and shorten slopes, thus minimising agricultural erosion hazards (*Fig. 2*).

Where these agricultural techniques and land management were inadequate, it is possible to observe macro-scale negative effects, such as gullies and ravines developed over slopes and deep fill in the bottom valleys as a product of runoff. In the presence of agricultural terraces, it is common to find a high number of rapid fill upslope walls that could have affected cultivars in the past. The elimination of vegetative cover due to changes in land use for agricultural purposes produced massive erosive slope processes, increasing bottom valley sediments (*Fig. 3*).

Step 2 – Soil scale analyses

Within the framework of crop parcels or agricultural terraces, it is necessary to consider that the objective of landscape transformation for agricultural purposes is to generate steps for slope stabilisation. These steps are generally contained by walls or earth benches that tend to favor the retention of fine sediments and to promote soil development by water infiltration. To have an idea of the general state of conservation, and of the positive/negative features associated with positive/negative features associated with these steps, it is useful to plan pedestrian surveys over the area. The state of conservation of fills and walls is a good indicator of the general state of soil/land crop bodies. The degree of infill inside agricultural structures constructed along slopes is a good index of the general stability of the surrounding landscape. Normally, the older and/or the more unstable the agricultural area is, the more filled the retaining wall body terraces tend to be (*Fig. 4*). Among the negative effects that could be detected after slope and bottom valley interventions on this scale, it is possible to detect local erosion processes, ranging from rill wash erosion to gullies and piping.

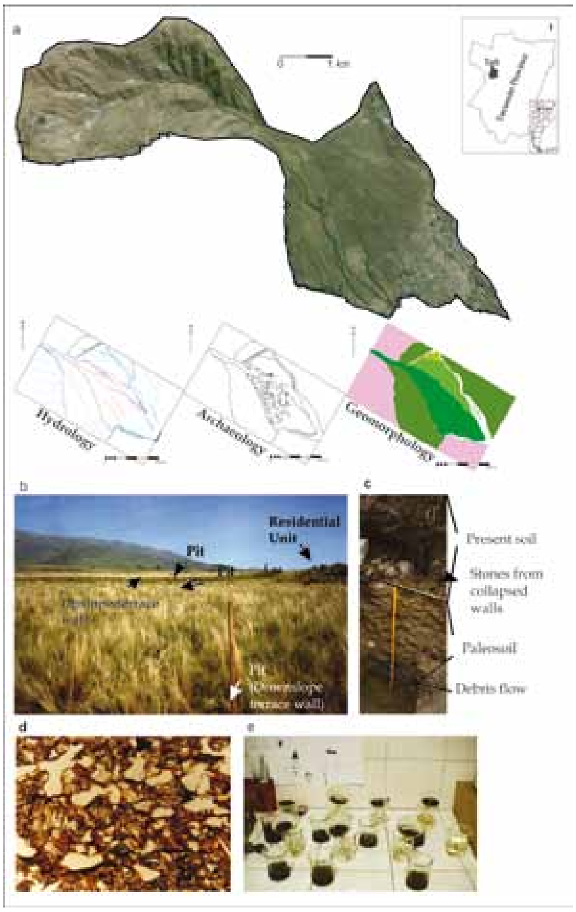

Figure 1: Different scale of analyses: (a) ecosystemic/landscape/basin scale; (b) crop parcels; (c) internal characteristics of cropland profiles; (d) micromorphological evidence; (e) physicochemical analyses.

Previously suggested pedestrian surveys have made available the scarce archaeological materials dispersed over surface and in exposed profiles. These materials are useful in providing an idea of the chronological background of the area. Given the extended surface of productive areas, it is almost impossible to apply full coverage strategies, so we suggest selecting sampling areas, taking into account the most representative sections of the agricultural fields which were detected in the previous research step. On the other hand, it is necessary to survey and identify the areas with similar environmental history (i.e., inside the same geomorphological unit) and without anthropic impact, in order to compare them. This provides a real comparative background to know if there was anthropic impact and in which sense (positive or negative). Drawing detailed maps and sketches of sampling sectors is necessary to determine local inclination and the present distribution of natural and cultural features (*Fig. 5*).

From a biological point of view, it is necessary to take samples of pollen rain in the area together with samples of superficial sediment to characterise local vegetation from pollen and microfossil evidence.

Step 3 – Analyses of horizons and layers of croplands

To evaluate the physical and morphological characteristics of layers and/or soils from the agricultural areas, it is necessary to dig pits and make pedological descriptions. Increasing thickness of the A horizons and improvement of textures (which tend to be loamy) are among the most relevant features of positive effects of cropland management. In addition, texture changes improve water availability. A horizons and texture, as well as colour change (good index of organic matter contents), are easily observable (*Fig. 6*). In the case of bad management, lands tend towards compaction and porosity loss limits soil air circulation and root growth. Crusting is also common. In these cases, the general cropland structure decays, tending to look massive and compact. In several cases, A horizon erosion is evident. Normally, the Andean foot plow is less land aggressive than the Roman plow. As a result, the identification of Ap horizon, which is usual in areas where sustained agriculture has taken place, is variable. Ap horizons are formed because original aggregates are broken up by plow, promoting vertical downward movement of fine particles and upward movement for big particles and materials (including also archaeological artefacts). In this way, at the maximum penetration depth of the plow, a loamy-clayey layer could be accumulated (Porta Casanellas, 2008).

At this research stage, bulk samples for laboratory soil analysis, pollen, microfossils and archaeobotany must be taken. Pollen analysis makes it possible to know the evolution of the local vegetation over time. It is also possible to find over-representation of those specimens belonging to cultivated taxa. Isolating and identifying microfossils (phytoliths and starch grains) as well as archaeobotanical remains provides knowledge of exploited species. Bulk sam-

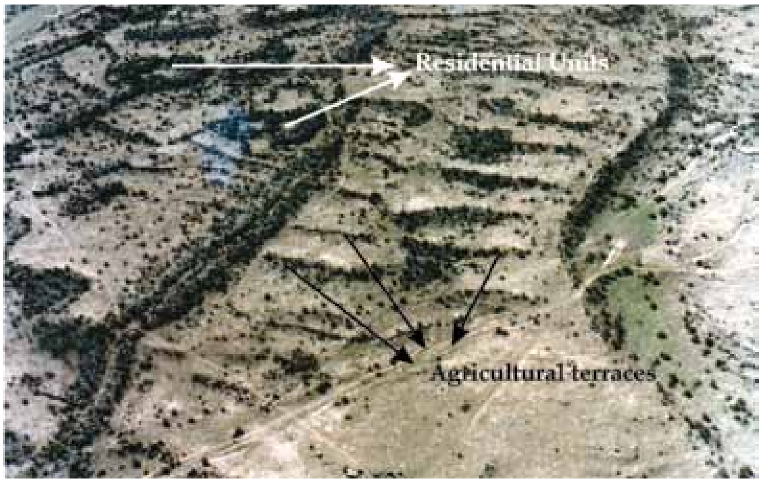

Figure 2: Aerial view of agricultural terraces in Tafí valley (Northwest Argentina).

Figure 3: Bad land management results. Filled bottom valleys at Alfocea (Spain).

Figure 4: Filled and unfilled terraces at (a) Molleyaco (AD 0 – 1000) and (b) Yasyamayo (AD 1000 – 1500) archaeological sites (Northwest Argentina).

ples could be taken following natural stratigraphy or at regular sampling intervals.

Step 4 – Micromorphological scale of analysis

The success or failure of land management is also observable through the degree of compaction and alteration of land aggregate structures. Micromorphological studies of soil thin section analyses of unaltered blocks are very useful in this sense (Sampietro Vattuone *et al.*, 2005). They make it possible to observe different degrees of pedoturbation introduced by several agents, such as worms, roots, rodents, and man, among others (***Fig. 7***).

One relevant aspect to be taken into account when estimating the productive capabilities of an agricultural area is to know what plants were cultivated, through pollen, archaeobotany and/or microbotany (phytoliths and starch grains). On the other hand, each species has its own nutritional needs and leaves behind particular fingerprints on soils. Due to the fact that continued harvests imply a sustained extractive activity, nutrient restitution is necessary. A common Andean practice used for generating interpretation problems to infer productive capacities is intercropping, as reflected by the microfossil record. Intercropping is the practice of cultivating several species in the same parcel and at the same time, achieving soil nutrient complementarity and nutrient restitution. It is also used for plague control. An example of this practice is the association of kidney beans with maize. Bean has nodules with nitrogen-fixing bacteria in their roots, which provide much-needed soil nitrogen to maize, while beans demand a large amount of phosphorus. The maize straw left after harvest restitutes the phosphorus taken by beans (Tapia and Fries, 2007). Examples like this are abundant in traditional Andean agriculture.

Step 5 – Physicochemical analyses of croplands

For the evaluation of anthropic impact on agricultural lands we propose the implementation of several nutrient availability tests. From experience, we know it is highly recommended to test organic matter content and different phosphate species, and that the behaviour of available micronutrients such as iron, copper, and manganese is more complex to elucidate (***Fig. 8***) (Sampietro Vattuone *et al.*, 2014). Well-managed lands that benefitted from addition of the organic matter in different ways (runoff, irrigation, manure, and/or straw) could have been even more enriched over time. Water use practices could have increased contents of organic carbon as well as nitrogen and phosphorus by taking advantage of periodical floods (like the Zuni Indians in the SW United States) (Homburg *et al.*, 2005), besides the use of fertilizers and straw. However, permanent harvests without reposition produce nutrient deficits, with the lack of organic matter, nitrogen, and phosphorus being especially important.

Another factor is that intensive use of irrigation systems in drylands may entail salinity problems (i.e., increasing sodium and calcium salts). These features are easily investigated by conductivity and cation exchange capacity tests.

Biological changes related to agricultural practices are even less known. Among beneficial biological changes we can mention

Figure 5: Detail of fine sediments accumulated upslope terrace wall (Hualfín, Northwest Argentina).

Figure 6: Profile colour changes at El Paso agricultural site (Northwest Argentina).

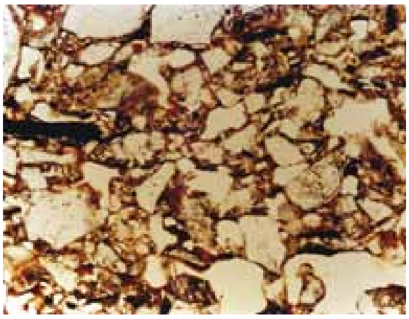

Figure 7: Soil thin sections from El Tolar agricultural site showing unaltered clay coatings (Northwest Argentina).

nitrogen fixation in the case of specific crops and increase of mycorrhizae, while negative agents are the concentration of pathogenic fungi (Homburg and Sandor 2011).

Conclusions

As demonstrated in this paper, the reconstruction of agrarian practices in drylands is a multiscale and interdisciplinary task. Geoarchaeology offers the ideal tools to gain a broad and thorough perception of the set of variables. It makes it possible to focus gradually on landscape as a whole and then on physicochemical variations of croplands considering crop nutrient consumption. Through geoarchaeology it is possible to fluently integrate geological, geomorphological, edaphic, biogeochemical, biological and archaeological parameters.

As a corollary, we must clarify that the abandonment of croplands often produces land degradation at first. This is due to the lack of maintenance, accelerated runoff erosion, erosion behind walls by concentration of superficial runoff, piping, and aeolian erosion due to the lack of native plant and rock cover. However, landscapes tend to reach a new equilibrium over time, thus favouring the development of native vegetation due to the improvement of the local lands. This process makes it possible to reconstruct past agricultural practices and their environmental impact.

Acknowledgements

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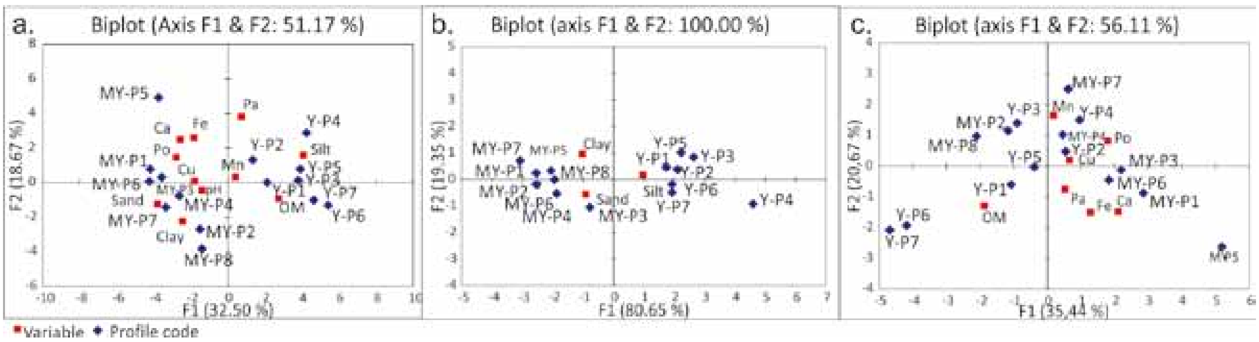

Figure 8: Biplot graphics showing soil chemical responses to agricultural use from Yasyamayo profiles (Northwest Argentina): Y1, Y6 and Y7 control profiles; Y2 – Y5 agricultural profiles. (A) response to all variables; (B) response to texture; (C) response to nutrients.

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Earth sciences in Walloon archaeology: Four examples of co-operation

O. Collette, E. Goemaere , D. Pacyna , S. Pirson and P. Spagna*

In Wallonia, Earth Sciences specialists contribute to the mission of the archaeologists of the Walloon administration. Four short examples illustrate the diversity of activities: sourcing pottery artefacts by several analytical techniques, building stratigraphic tools with mineralogy, identification of old mining traces by processing archives and databases and working out a continuous cartography of archaeological potential by assembling geomorphological elements with archaeological sites. Each of the examples lead to similar conclusions: interdisciplinary networking and improving reciprocal knowledge are in the interests of all parties involved.

En Wallonie, les spécialistes des Sciences de la Terre apportent leur contribution aux missions archéologiques dépendant de l'Administration wallonne. Quatre courts exemples illustrent la diversité des activités entreprises: la recherche de l'origine des tessons de poterie, à l'aide de plusieurs techniques d'analyse, l'établissement d'outils stratigraphiques à partir de la minéralogie, l'identification de vestiges d'anciennes mines en analysant les archives et les bases de données et la réalisation en continu de la cartographie des sites potentiels archéologiques en confrontant ces derniers aux données géomorphologiques. Chaque exemple conduit à des conclusions semblables : le travail en réseau interdisciplinaire et l'amélioration des connaissances entre tous sont bénéfiques pour chaque partie impliquée.

En Valonia , los especialistas de las Ciencias de la Tierra contribuyen a la misión de los arqueólogos de la administración valona. Cuatro breves ejemplos muestran la diversidad de las actividades realizadas: conseguir objetos de cerámica mediante distintas técnicas analíticas, la construcción de columnas estratigráficas con la mineralogía, la identificación de huellas mineras antiguas mediante el procesamiento de archivos y bases de datos, y la elaboración de una cartografía continua del potencial arqueológico mediante el montaje de elementos geomorfológicos en emplazamientos arqueológicos. Cada uno de los ejemplos lleva a conclusiones similares: construir redes interdisciplinarias y mejorar el conocimiento recíproco son en interés de todas las partes involucradas.

In Wallonia, a French-speaking region in south Belgium, archaeologists employed by the public administration study, evaluate and preserve the archaeological heritage. Their main tasks consist of doing site inventories, identifying threats due to town and country planning, and leading preventive excavations. Several specialists from Earth Sciences regularly provide valuable contribution during their missions. Their knowledge and techniques are used before the intervention to assist decision making project planning, during the intervention as expertise in concrete applications, and afterward for study and evaluation. The following examples illustrate a great diversity of contributions and reciprocal interests of earth scientists and archaeologists.

1. **Sourcing archaeological pottery artefacts (E. Goemaere)**

As pottery is virtually indestructible, once produced, ceramic sherds are among

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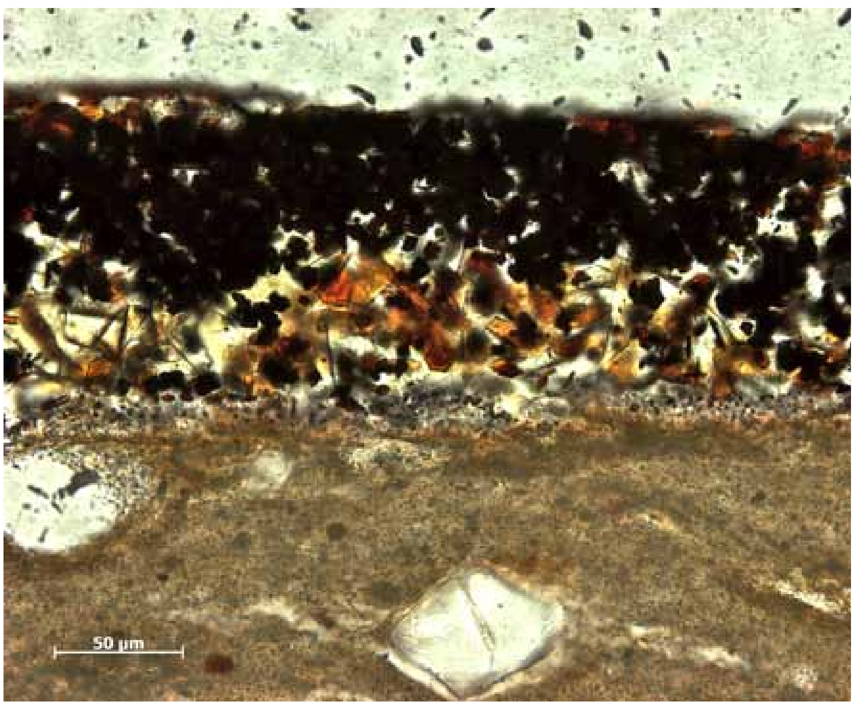

Figure 1: Thin section in an blackish stained iron-glazed medieval pottery from Dinant showing the hematite micrometric hexagonal-shaped red-black flakes in a transparent lead-glass, covering the clay matrix (+ quartz grains in very fine sand fraction) of the ceramic body. Polarised light.

Table 1: Examples of collaboration (from the 2 last years) between geologists and archaeologists resulting in collaboration with the Walloon Region, the Geological Survey of Belgium, and Belgian, French and American university research teams.

			Analytical methods						
Archaeological site	***Epoch***	***Place***	***Optical***	***Image analysis***	***SEM***	***EDS***	***Raman Spectroscopy***		***S.Mag***
LBK of Hesbaye	*Lower Neolithic*	*Hesbaye area*	*X*					*X*	*In progress*
Workshop of Tourinnes-St-Lambert	*Roman*	*Tourinnes*	*X*		*X*			*X*	
Germanic settlement	*4th century*	*Nereth*	*X*		*X*				
Lead-glazed pottery from Dinant-Bouvignes	*Medieval*	*Dinant & Andenne*	*X*		*X*	*X*	*X*		
Pottery from Andenne	*Neolithic to Middle Ages*	*Andenne*	*X*					*X*	
Workshop of Autelbas	*Medieval*	*Autelbas*	*X*	*X*	*X*	*X*	*X*	*X*	*X*

the most common artefacts to be found at archaeological sites dating from the Neolithic period onwards. As a consequence they play a major role in archaeology for understanding the culture, technology and behaviour of peoples of the past, but also serve as a chronological tool to date assemblages. Their study is an important focus of archaeometric sciences (Tite, 2008) requiring co-operation between geologists-mineralogists and archaeologists both from the Geological Survey of Belgium and the Walloon Region (Goemaere *et al.*, 2014). Done by specialised archaeologists, the first analysis concerns the typology and involves sorting ceramic sherds into specific types based on style, nature of the paste, presence of temper, manufacturing and morphology. By creating these typologies it is possible to distinguish between different cultural styles and to determine the purpose of the ceramic and the technological state of the people.

Provenance studies required the contribution of the physical-chemical sciences and are based on a number of combined techniques such as thin-section petrography (classical), X-ray diffractometry, electron microscopy, Raman spectroscopy, magnetic susceptibility and chemical analysis by LA-ICP-MS. The geologist-mineralogist is familiar with all these tools, which often are available in mineralogical laboratories. More specific tools (e.g. image analyses) can require calling on the network of researchers in archaeometry.

The geologist also provides the reference collections in order to compare fired products and raw clays. The geologist helps the ceramologist to identify the mineralogical content of the paste and the tempering agents made of quartz, feldspars and lithic pieces in order to determine the geological and geographical source of the material (clay + natural or added temper). Temper is a material added to the clay during the initial production stage and used to help the subsequent drying process. The best situation concerns artefacts associated to their manufacturing workshops, where sometimes raw clays are found, while the clay pits are unknown and presumed located in a small area around the workshop. But generally, sherds occur in consumption sites totally unlinked to the pit and the workshops, especially for small regional production. Microscopic examination is the first tool to characterise both the temper and the fired clay matrix, sometimes completed by a granulometric analysis performed by image analyses. Further analyses are made on the fired matrix by different analytical methods. X-ray diffractometry allows identifying the mineral components that are stable after firing in the kiln and giving a good approximation of the firing temperature. Recently, Rasmussen *et al.* (2012) presented a new method for determining the maximum firing temperature of ceramics and burnt clay based on the measuring of the magnetic susceptibility on a step-wise re-fired ceramic. This new methodology is in progress in our research team. More specifically, LA-ICP-MS data are acquired on the fired clay matrix and compared with the raw material picked in the field (outcrop or low-deep boreholes) and clay lumps found in the workshops. Chemical analyses were fruitfully used to make the distinction between the products of different workshops, though mesoscopic observations could not discriminate the different groups. The Scanning Electron Microscope (SEM) along with Energy Dispersive Spectrum (EDS) not only allows us to study the microstructure (sintering, vitrification, pores, etc.) of the clay matrix, but combined with EDS and associated with the Raman spectroscopy, the composition of the micrometric to mm-sized inclusions can also be identified and the study of glazed pottery can be achieved. The choice of the available methods is driven by the mineralogist as a function of the results acquired after the petrographic investigation, which remains the master tool. By estimating both the clay and temper compositions, and locating a region where both are known to occur, an assignment of the material source can be made. From the source assignment of the artefact further investigations can be made into the site of manufacture. To achieve these goals, extensive and stimulating collaboration is required.

2. Mineralogy as a stratigraphic tool for the study of archaeological sites (Paul Spagna (RBINS) and Stéphane Pirson (SPW))

Using the mineralogical composition of the sediments as a stratigraphic tool (i.e. "mineralostratigraphy") can be interesting in an archaeological context. Two specific applications of this tool are regularly used by the Service public de Wallonie in the study of prehistoric sites. The first one deals with the green amphibole stratigraphic distribution in loessic sediments; the second one focuses on the tracking and identification of characteristic volcanic fallouts (tephra).

Green amphibole distribution has been studied for more than 60 years in loessic sediments from Middle Belgium and surrounding countries. Firstly related to green hornblende, it has been used in ratio with epidote, then in the "mineralogical index" (see synthesis in Meijs, 2002) together with garnet, zircon and rutile. Nowadays the green amphibole content is used as a parameter on its own (e.g. Meijs, 2002).

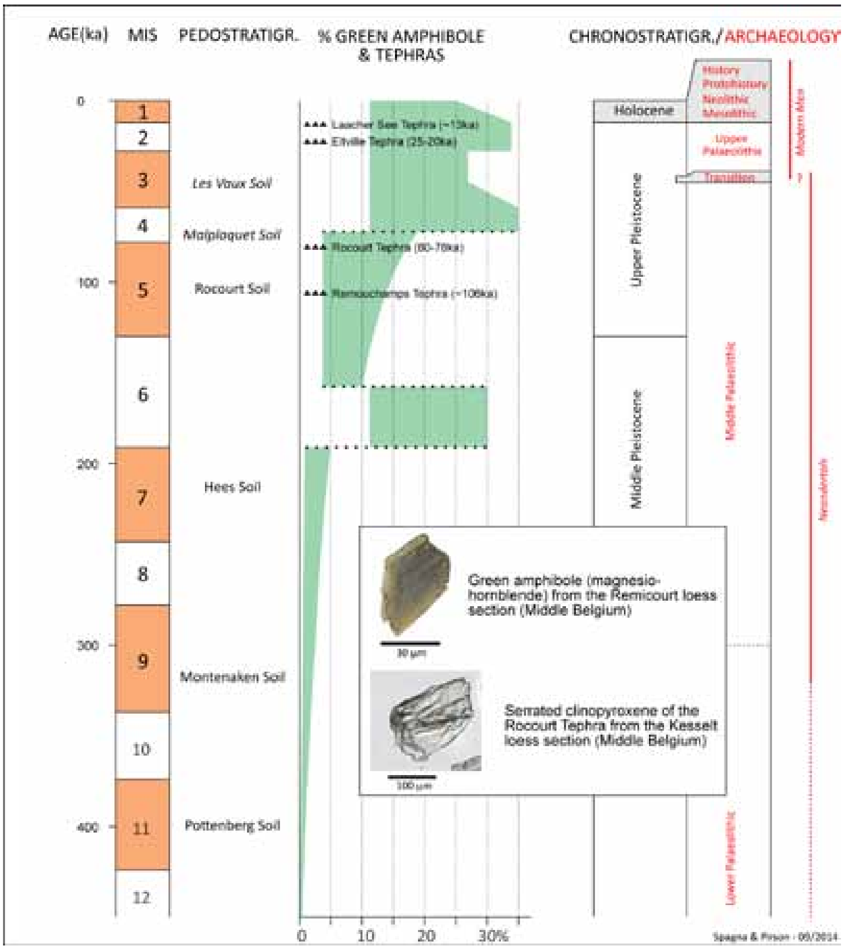

Figure 2: Synthesis of the green amphibole stratigraphic distribution in the loess belt from Belgium (data sets: see Meijs, 2002; Pirson, 2007). The four tephra layers identified in the Upper Pleistocene are also shown (Juvigné, 1999; Pouclet et al.*, 2009; Pirson & Juvigné, 2011; Juvigné* et al.*, 2013), as well as the main archaeological periods.*

Their variations through time, whose origin has not been clearly established yet, have been synthesised in the Middle Belgium lœss reference sequence (Pirson, 2007). Moreover, the recent re-evaluation of the green amphibole content of several regional loess deposits has shown a remarkable consistency in their stratigraphic distribution (Spagna *et al.*, in preparation). Those encouraging results validate the use of this mineralogical tool in cave deposits. This can be very useful in this kind of sedimentary environment, rich in prehistoric remains but where chronostratigraphic markers are often missing. As an example, the green amphibole stratigraphic distribution recently studied in the Walou and Scladina cave sequences – in conjunction with other disciplines – allowed researchers to refine the chronostratigraphic context of the Middle Palaeolithic assemblages of the two cave sites as well as the age of the Scladina Neandertal child (Pirson, 2007, 2011; Pirson *et al.*, 2012, in press).

Tephra are also used as stratigraphic benchmarks inside geological deposits. During the late Quaternary of Belgium, four tephra layers of different mineralogical compositions have been observed (Juvigné, 1999; Pouclet & Juvigné, 2009; Pirson & Juvigné, 2011; Juvigné *et al.*, 2013): the Remouchamps Tephra (ca. 106 ka), the Rocourt Tephra (80-78 ka), the Eltville Tephra (between 25 and 20 ka) and the Laacher See Tephra (ca. 13 ka). The two oldest tephra layers are contemporary with Middle Palaeolithic while the two youngest settled during Upper Palaeolithic. Therefore, these tephras provide precious chronostratigraphic markers in the archaeological sites where they are identified. For example, the presence of the Rocourt Tephra in some sequences, together with data sets from other disciplines, allowed refinement of the age of some Middle Palaeolithic occupations, such as in Remicourt (Juvigné *et al.*, 2013) or at Walou cave (Pirson & Juvigné, 2011).

The value of these two methods, which are very similar in terms of methods, is that they reinforce each other. In conjunction with other chronostratigraphic tools, they contribute to refining the age of the analysed sediments, and therefore the age of the associated archaeological assemblages.

3. Intensive underground mining: traces to assess (D. Pacyna)

The great diversity of rocks in Wallonia was the reason for ancient and intensive mining and quarrying activity. Surface excavations cannot be distinguished through the ages, unlike underground operations, which have left many traces on the land underground.

All of this activity began during the Neolithic, through flint exploitation in Spiennes and in Hesbaye, and after that with iron ore mining, since the Gallo-Roman era. Coal has been extracted continuously since the 13th century and probably even earlier, from the mid-10th century (Demelenne, 2013). Metallic ores (lead, zinc) have been exploited since the Middle Ages. The Celts and the Prussians extracted alluvial gold in the Upper Ardennes.

Slate quarries have been numerous in the Ardennes since the 18th century. The underground quarrying of tuffeau (soft calcareous stone) in Lower Meuse and of visean limestones near Namur probably began in the 17th century; quarrying of black marmor, sandstone, flint or refractory clays was characteristic of the 19th and 20th centuries. Farmers opened hundreds of marl pits in the cretaceous chalk of Hesbaye or in the cenozoic calcareous sands of Brabant. About one hundred chalk quarries were fueled lime kilns. Between 1874 and 1945, more than 3,800 phosphate underground quarries (known as "phosphate pits") were officially recorded in Hesbaye and a few dozen phosphatic chalk around Mons (La Malogne, on 80 hectares).

A total of 15,000 mine shafts (coal, metallic ores) have been identified. Their number exceeds certainly 50.000. Around 5,000 underground quarries are known, as well as about a thousand exploited iron ore deposits. More than 2,000 dumps and "terrisses" (small or very small dumps, around or beside a shaft) have been mapped, mainly linked to coal mining, or collieries.

The more significant remains are these colliery dumps. But, thousands of "terrisses" are still waiting in forests to be mapped and dated. Associated mine shafts – aligned on coal seam heads – are confused with "bomb craters". The gold mines have left dumps on the field. Underground quarries and marl pits are offered to the attention of searchers after collapsing. The traces of iron ore

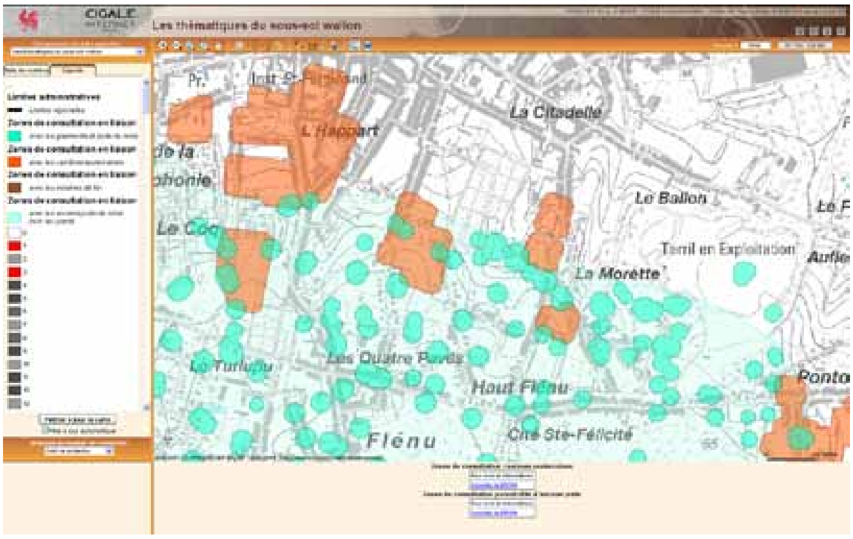

Figure 3: Example of mining data available on website **http://carto1.wallonie.be/CIGALE.**

mines are worthy of more attention, along with investigations and studies on the sites of ore processing. The same attention would be required for the metallic ore deposits, in order to link them to the local industries (such as brassware).

Mines (coal, metallic ores, gold) and iron deposits are well documented after 1790. However, few data exist on the underground quarries. On the base of these archives and field observation, the Geological Survey of Wallonia has been identifying and examining these ancient exploitations since 1997. The results are available on its website (***http://geologie.wallonie.be***). These data are particularly useful in the mapping of archaeological zoning (Guillaume *et al.*, 2013).

Moreover, in case of discovery of underground workings, as part of a multidisciplinary approach in recent years there has been collaboration among the GSW (DGO3 – the General Directorate of Agriculture, Natural Resources and Environment), the "Cellule Mines" (DGO3), the Directorate of Geotechnics (DGO1) and the Directorates of Archaeology and of Regional Planning (DGO4) of the Public Service of Wallonia, as well as some mining firms. Since 2010, the accessible underground quarries are being surveyed and their access maintained. New typological and technical data have thus been collected.

The Geological Survey of Belgium has conducted studies linking geology and mining history, which meets with the interest of archaeologists, especially in their search for remains and material studies. Examples are the exploration of collapsed chalk quarries (Vrielynck *et al.*, 2012) or work on the analysis of cement (Demelenne, 2013).

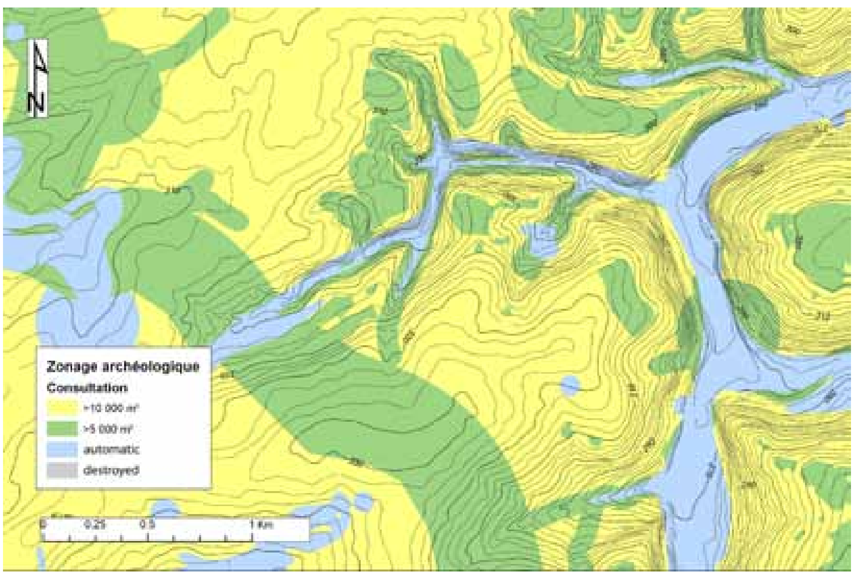

Figure 4: Detail of the archaeological zoning map with the three levels of interrogation (consultation).

From the heritage point of view, more than 1,500 mine shafts, concrete-covered and marked, would benefit from being listed in the inventory of archaeological sites and to be given a protection status as a testimony of centuries-old activity. Some underground quarries are also worthy of such a status. And while many dumps are classified, there is still only one set of "terrisses" and mine shafts that has been well studied and evaluated (in Blaton).

This leaves a lot of opportunities to be seized for mining archaeology, for improving knowledge of our past through the investigation of mining relics. In this sense, the flow of information between services can only be beneficial.

4. Archaeological zoning: geomorphology in the service of risk mapping (O. Collette)

Geomorphological data used in geographical data systems are particularly useful in archaeology. They can guide the way to land prospecting, to assisting excavating and to bring valuable knowledge during studies. The use of such data is generalised and systematised on the Wallonia scale in the frame of "archaeological zoning" (Guillaume *et al.*, 2013). This is a project led by the archaeological directorate of Wallonia which involves setting up cartography of highly sensitive areas. The final result is intended to guide consultations in case of land settlements.

The project associates the archaeological inventory with the geomorphological approach. It includes a selection of areas subject to various human activities. This approach supplements the limited data of the archaeological inventory with continuous cartography and covers the whole area of Wallonia.

The main basic data come from a numerical earth model and its practical applications (slopes map, flow axis, etc.), the geological and pedological maps. The data selection was developed with the setting up of criteria formed with archaeological knowledge. Among them, the presence of some land elements: reliefs, edges of plateaus, alluvial plains, or differences of height on chalky substrate, giving possible areas of flint extraction. Some of the criteria are useful on a regional scale while others were applied locally, for instance sandy mounds in the Flemish plain.

The translation of criteria into spatial analysis allowed the automated production of environmental layers. About twenty layers were produced by geo-processing. They were compared with the archaeological inventory and subjected to review by archaeologists. The comparison assisted by statistical process allowed researchers to moderate the weight of each layer. The combination of the archaeological sites and the moderated layers produced a map with three levels of intervention.

The zoning project was a risky gamble given the short deadline (one year) and the limited means. Through the integration of geomorphological data, continuous cartography was completed for the whole of Walloon. Its use contributes to heritage conservation during modern land settlement.

Conclusions

The scientific purposes described in this article reflect particular cases. In fact, they are extremely diversified and can be adapted to numerous archaeological situations. When archaeologists work on sourcing, setting up stratigraphic tools, supplying archaeological inventories or developing information for decision making assistance, the expertise, reference collections and techniques of geologists are necessary to reach their goals. To guarantee such operation it is essential to maintain dynamic cooperation between concerned players.

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Unraveling geological and geographical provenances of lithic materials during Roman times in Belgium: a fruitful collaboration between geologists and archaeologists

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Comparative petrographical, mineralogical and geochemical analysis allowed an international team of archaeologists and geologists to identify the raw materials used for the manufacturing of millstones, whetstones, building stones and decorative stones found in the capital and agglomerations of the civitas Tungrorum *(Eastern Belgium) as well as in less urbanized areas of Roman period Belgium. Moreover, geological and geographical provenance areas have been inferred, suggesting probable transport routes and cross-border economical-cultural exchanges. The large-scale use of lithic building materials can be considered as a direct consequence of Roman urbanisation and the incorporation of the area into the Roman Empire. Mapping of provenance areas, workshops and consumption areas of the various lithic raw materials demonstrate the integration of the objects within the Roman economic system and allow the reconstruction of trade routes inside the Roman Empire and their evolution throughout the Roman period.*

Une analyse comparée au niveau pétrographique, minéralogique et géochimique a permis à une équipe internationale d'archéologues et de géologues d'identifier les matières premières utilisées pour la fabrication de meules, d'aiguisoirs, de pierres à bâtir et ornementales, rencontrées dans la capitale et les agglomérations de la Civitas Tungrorum *(Belgique Est). De plus, on a pu en déduire les aires d'origine géologique et géographique des matériaux avec mention des voies probables de transport ainsi que des échanges économiques et culturels, transfrontaliers. L'utilisation à grande échelle de matériaux rocheux de construction peut être considérée comme la conséquence directe de l'urbanisation romaine et de l'incorporation de cette région dans l'empire romain. La cartographie des aires de provenance des matériaux, les lieux utilisés comme ateliers et ceux de consommation des matières premières minérales démontrent l'intégration de ces matériaux à l'intérieur du système économique et permettent la reconstruction de routes commerciales au sein de l'empire romain et leur évolution tout au long de l'époque romaine.*

El análisis comparativo anivel petrográfico, mineralógico y geoquímico permitió a un equipo internacional de arqueólogos y geólogos de identificar las materias primas utilizadas para la fabricación de piedras de molino, piedras de afilar, piedras de construcción y piedras decorativas encontradas en Tungrorum *(en el este de Bélgica). Por otra parte, la procedencia geológica y geográfica se hadeducido, lo que sugiere probables rutas de transporte y los intercambios económico-culturales transfronterizos. El uso a gran escala de materiales de construcción líticos puede ser considerado como una consecuencia directa de la urbanización romana y la incorporación de esta zona al Imperio Romano. La cartografía de las zonas de procedenciay áreas de consumo de las distintas materias primas líticas demuestra la integración de los objetos dentro del sistema económico romano y permite la reconstrucción de las rutas comerciales dentro del Imperio Romano y su evolución a lo largo del período romano .*

Introduction

Geologists meet archaeologists or vice versa when it comes to unraveling geological nature and geographical provenances of lithic materials, be it building stones, millstones or whetstones used during the Roman period in Belgian territory. By means of "classical" investigating techniques (e.g. petrography or geochemistry) geologists not only can determine the exact mineralogical composition and geological origin of the archaeological finds but they can also corroborate exact, or suggest probable geographical provenance areas. Lithic materials can reveal commercial networks and they represent excellent markers for transport routes, inferring socio-economic exchange paths. Their study helps also to understand the functional and cultural biography of stone objects and of their re-use in different functions and places during and after Roman times. On the other hand, archaeologists provide geologists with the exact chronological context and add extra sociocultural dimensions. Moreover, the importance of particular mineralogical composition and rock fabrics for specific uses can be clearly demonstrated. Obviously, because of long-distance exchanges of the lithic materials, the set-up of international networks of specialists is required. The elaboration of specific databases (e.g. for millstones & whetstones), the setup of reference collections of raw materials, the use of digital petrographic atlases (e.g. for building & ornamental stones) and the cross-border exchange of data and rock specimens are essential to fill the numerous gaps in our knowledge. Case studies from Belgian archaeological sites illustrate the

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use of a broad spectrum of specific local, regional or even exotic rock types in the Roman period. These case studies clearly demonstrate that the way geologists and archaeologists work and think are complementary, allowing us to forward reliable arguments regarding provenance, use and distribution of the lithic materials.

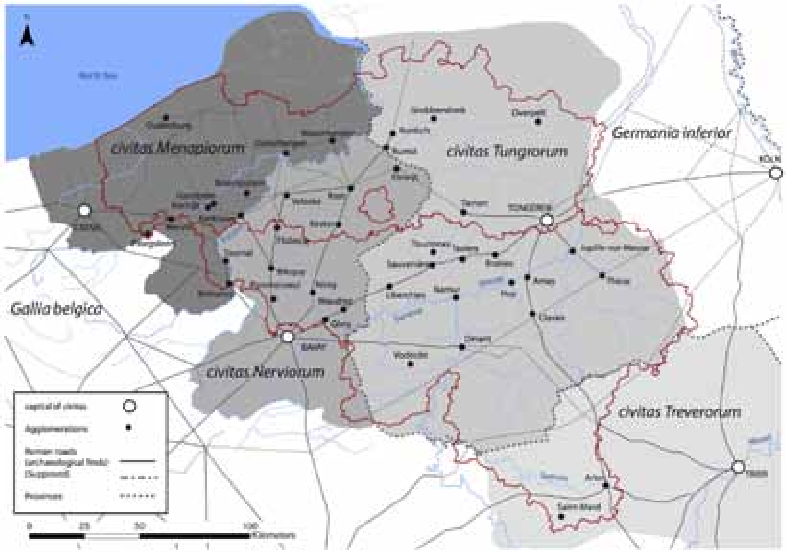

Figure 1: Civitates *covering the actual Belgian territory (Roman High Empire, 1st-3rd century AD). (Apis - CRAN - Université catholique de Louvain).*

The Roman context

Due to its durability, natural stone bears testimony of some important aspects of the profound cultural change that occurred in some parts of the native society after the Roman conquest of Gaul. Indeed, since almost no contemporary written documents have survived, it is in stone that a major part of the few remaining written sources (in epigraphic form) have been conserved. This allows the unravelling of part of the history of the northern Roman Empire, more specifically that of the elite residents, who could afford to erect or dedicate the inscribed monuments that also acted as billboards for displaying their social status. During Roman times, the current Belgian territory was located at the northern fringes of the Roman Empire, constituting the most northern part of the province of *Gallia Belgica* and part of *Germania Inferior*. The provincial territories on Belgian lands were subdivided into four *civitates*[1] (***Fig. 1***). During the Early and Mid-Roman period, the west was covered by the *civitas* of the Menapians and the civitas of the Nervians with Cassel (France) and Bavay (France) as their respective capitals. The *civitas* of the Trevires, with Trier (Germany) as its capital, stretched partially into the SE part of today's Belgium. Finally, the *civitas* of the Tungri, which covers almost the complete eastern half of Belgium, was administrated by the *municipium* (town) of Tongeren. Consequently, scientific studies of Roman urbanisation not only focused on the capital (Tongeren) but also on a large number of agglomerations distributed over the territory of the four *civitates*, governed by other capitals located in adjacent countries.

In northern Gaul, urbanisation was virtually absent before the Roman period, since the core distribution area of the phenomenon of the so-called *oppida* (Iron Age strongholds with proto-urban clustered occupation patterns) was located more to the south, in France. Urbanisation involving the large-scale use of lithic building materials therefore can be considered as a direct consequence of the incorporation of the area into the Roman Empire. Tongeren was created as a new town probably by an intervention of the Roman army, during the years 12–9 BC. It developed according to the standards of imperial urbanism and included a certain number of public buildings that were huge consumers of raw materials: a forum (not yet discovered), sanctuaries, granaries, public baths, etc., all symbols of the Roman cultural influence on architecture and the development of urbanism. Decorative stones originating from quarries situated in *Gallia Belgica* or in *Germania Inferior* and even some imported from Mediterranean provinces were devoted to this public architecture. Moreover, prestigious sanctuaries such as the Northern temple of Tongeren or the sanctuary of the Clavier-Vervoz agglomeration displayed luxurious interior stone decorations (pavements or panels in coloured marbles). Furthermore, the divinities had to be honoured within a magnificent environment, resulting in the creation of outside decorations in white stones, including colonnades or porticos and a variety of lapidary ornaments. In some Gallo-Roman rural villas and rich urban houses of the *civitas*, stone decorations reflect the cultural aspirations or wealth of their owners.

Parts of the stone collection of the Tongeren museum and a major part of the stone collection of Arlon (*civitas Treverorum* territory) point to another use: *mausolea*, funerary pillars or simple graved steles for honouring the deceased, mainly manufactured in local white limestones. Beside the above architectural objects, attention has also to be paid to one of the most common uses of stone: the lithic daily tool-kit. This gear was used in all daily life activities and in the work of craftsmen, especially that of blacksmiths.

White Jurassic limestone, a favourite building stone for public buildings and funeral sculptures

It can be assumed that because of the lack of the prestigious white (metamorphic) marbles in the Low Countries (today's Belgium and the Netherlands) such as those found in the Mediterranean, social or political elites in local Roman society favoured the quest for similar white stones in the provinces of *Gallia Belgica* and *Germania Inferior*. In the cuestas of Lorraine and the French Ardennes (Northern France), vast reserves of white or cream-colored oolitic, pseudo-oolitic and bioclastic Jurassic limestones were available: these could be easily worked and transformed into large columns or blocks for prestigious public buildings. Moreover, their overall fine grain size and relative softness allowed fine sculpture work, challenging the skills of the Roman craftsmen. Numerous funeral sculptures were manufactured in these white limestones, many of which travelled long distances before reaching the military and other settlements in the Roman provinces covering large parts of Belgium, the Netherlands, Germany and even the United Kingdom. Most probably, the semi-finished building materials (and sculpture works) were transported by ship, using the extensive water networks of the Meuse, Moselle and Rhine rivers.

Inspired by the pioneering work of

1 The term *civitas* refers to vast administrative subdivisions of the provinces. They each had a capital (*caput civitatis*) in which the administrative and political functions were grouped.

Figure 2: Fragment of Roman religious monument (GRM-2831) made of Norroy limestone (Photo: Gallo-Roman Museum Tongeren).

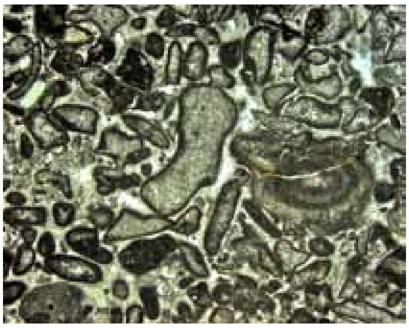

Figure 3: Norroy limestone, micrograph of thin section: detail of cortoid grainstone (Photo: R. Dreesen).

Panhuysen (1996) on the Roman settlement of Maastricht (*Mosae Trajectum*), a detailed comparative analysis was carried out of Roman artefacts and samples taken from known Roman quarries of the Côtes de Moselle (e.g. the Norroy quarries between Metz and Nancy) and in former extraction areas located on the Côtes de Meuse (e.g. Chémery-sur-Bar, Euville). As a result, Coquelet *et al.* (2013) were able to corroborate the provenances already suggested by Panhuysen and petrographically differentiate between the various white soft limestones found as architectonic elements or funeral sculptures within the *civitas Tungrorum*. The bulk of the white limestone material (probably a huge volume) must have disappeared in this *civitas* as a result of important post-Roman destruction or recycling, even during the Roman period and then in Medieval times: either fired for lime production or re-used as *spolia* (Dreesen *et al.*, 2001). Carbonate microfacies analysis of small cores drilled in the large architectonic elements exposed in the Gallo-Roman Museum of Tongeren and of pieces of architectonic elements found in other Roman agglomerations of the same *civitas* (e.g. Liberchies, Jupille-sur-Meuse) allowed their proper identification. After comparison with reference material sampled in situ, the geological and geographical provenance of the latter has now been scientifically proven.

The Norroy limestone is a badly sorted pseudo-oolitic limestone (cortoid grainstone) of Middle Bajocian (Middle Jurassic) age, belonging to the Calcaires à Polypiers Supérieurs Formation (***Figs. 2, 3***). The Roman origin of the (still visible) quarry face is proven by the discovery of several steles (ancient upright stone slabs bearing markings) dedicated by legionnaires to Jupiter and Hercules Saxanus (god of the quarry workers) as well as by the presence of numerous semi-finished architectonic elements in the immediate surroundings (Laffite, 2015). The Chémery limestone (***Figs. 4, 5***) is a relatively softer white oolitic limestone with a rather chalky appearance: it is a badly sorted oolitic grainstone with micritized ooids, peloids, oncoids and intraclasts, containing also numerous small foraminifera. It belongs to the Late Bathonian (Middle Jurassic) Chémery Formation. The Euville Limestone was (and still is) extracted from quarries in the neighbourhood of Commercy (Meuse Department). It is a relatively coarse-grained and well-sorted crinoidal grainstone belonging to the Middle Oxfordian (Upper Jurassic) Entroquite d'Euville Formation.

Interestingly, based on the geographical distribution of the mineralogically characterised architectonical elements and funeral sculptures throughout the northern Roman provinces, and by assuming that heavy rocks were transported by water, two main transport routes have been identified: the Moselle river for the Norroy Limestone and the Meuse river for the Chémery and Euville limestones. The Dom-le-Mesnil Limestone was imported as well but is much less frequent than the limestones mentioned before. It has been extracted in quarries located in the Meuse river basin, between Charleville-Mézières and Sedan. It is a soft, fine-grained orange-yellowish bioclastic grainstone composed of echinoderms and bivalves debris, belonging to the Lower Bajocian (Middle Jurassic) "Calcaires à débris" Formation. Other small fragments of "white" and mostly fine-grained limestones have been found in archaeological excavations within the *civitas*. Petrographic analysis points to the likely presence of limestone types analogous to the Pierre de Caen (Middle Bathonian bioclastic limestone from the Calvados area), the Pierre de Marquise (Upper Bathonian oolitic-bioclastic grainstone, from the Boulonnais area) and the Lutetian limestone (Middle-Eocene foraminiferal grainstone from the Paris area; Fronteau *et al.*, 2010). The latter fine-grained white or cream-coloured limestones are mainly used for decorative purposes, including floor tiles, floor mosaics (*tesserae*) or small encrustations (*opus sectile*) in temples and luxurious houses.

Roman rotary querns and millstones – provenance, use and socio-economics

The study of milling equipment covers different research areas within archaeology, the history of technology and geology. From a pure technological point of view, this equipment is the result of a long production chain, from extraction through processing, involving reflections on the choice of raw materials and on stone craftsmanship. When considering querns and millstones as commercial and consumer products, we have the opportunity to understand the circumstances of their distribution, thus treating natural and human constraints dominating the ancient economic systems. When considering them as transformational tools, they may help to assess the crafts practiced at rural or urban sites. But these objects also reveal crucial factors of cultural transformation in every-

Figure 4: Roman composite capital (GRM-2844) made of Chémery limestone (Photo: Gallo-Roman Museum Tongeren).

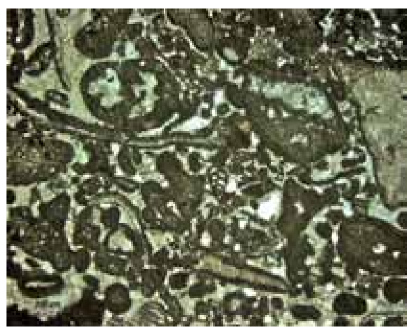

Figure 5: Chémery limestone, micrograph of thin section: detail of peloidal-oolitic grainstone (Photo: R. Dreesen).

day life within the territories conquered by Rome. New or improved stone technology (e.g. the wider spread of rotary quern technology instead of grinding in some areas; evolving dressing patterns) or simply the better quality of stones used could affect the often centuries old traditions for treating the different species of cereals and hence influence how food was prepared.

By its essential nature, this domestic tool requires great care during manufacturing and maintenance. Since the sixth or fifth century BC, a whole series of technical innovations probably originated in the Ibero-Punic area and in Greece, improving the milling methods. The first rotary mills appeared in the northeast of the Iberian Peninsula. However, new technical constraints required a choice of rocks with specific mechanical properties, resulting in mass production by specialised craftsmen on selected outcrops. It took several centuries and the end of the Iron Age to see this innovation reaching northern Gaul.

The possible relation between the introduction of the rotary mill and the colonisation by Roman military troops must be taken into consideration. It may lead us to understand the origin of the economic systems governing production and distribution of querns and millstones throughout the *civitates* composing *Gallia Belgica* and *Germania Inferior* during the Early and Middle Roman Empire. Ongoing studies therefore not only aim at investigating their provenance, supply or distribution networks, but also to understand their use within a spatial, technological, typological and chronological framework. This will provide further insights into the socio-economics of the local 'Gallo-Roman' communities and into their networks within the northern Roman Empire. Hence a multidisciplinary approach is required, combining classical context-based typo-chronological studies and archaeometrical analyses (e.g. petrography, geochemistry). Collaboration between archaeologists and geologists is therefore essential in order to identify the different rock types of which the querns and millstones are composed, to define their stratigraphical positioning and to locate their original deposits.

Furthermore, linking quarries to archaeological sites helps to trace their transport routes. This is particularly interesting for stone artefacts found in stoneless landscapes such as those of northern Belgium and the Netherlands. Some extraction sites are already known, especially in France and in Germany (the Eifel area). However, they are less well known from Belgium because raw materials were mined in quarries/mines over very long periods, often destroying previous exploitation traces.

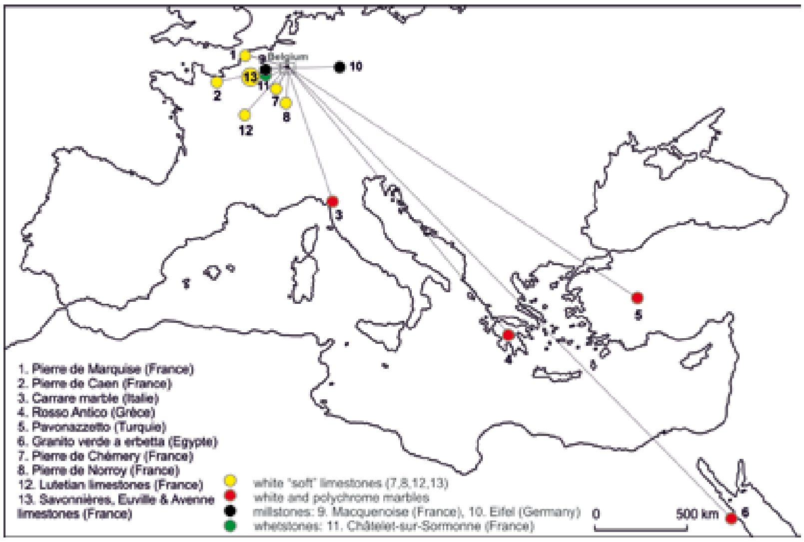

Figure 6: Provenances of main rock types identified in Roman constructions and decorations in the civitas Tungrorum *(modified after Coquelet* et al.*, 2014).*

The authors of this paper have focused mainly on the Roman period because exchanges of goods were very important during that time throughout the whole Roman Empire. Furthermore, the discoveries of millstones in Belgium are numerous and their lithological composition quite varied. They are made of a whole spectrum of detrital sedimentary rocks (fine- to coarse-grained sandstones, arkoses and conglomerates), of low-grade metamorphic rocks (quartzites, metamorphic arkoses and conglomerates) and of basic volcanic rocks. The material was successfully characterised using classical petrography in combination with geochemistry (especially for the volcanic rocks). All the samples have been compared with reference collections for which geological and geographical provenance areas are well known or with rock samples directly taken from Roman millstone quarry sites. Additionally, x-ray diffraction may help in unravelling the mineralogical composition of the finest rock types, whereas the precise identification of key mineral species (e.g. the exact nature of tourmaline grains, particular heavy minerals, feldspar grains or phyllites) requires the use of Raman Micro-Spectrometry and Energy Dispersive X-Ray Spectroscopy.

The long-distance transport of the above materials necessitates the setup of cross-border networks and collaborations between geologists and archaeologists. In this way experience, knowledge, reference collections and analytical equipment can be shared. Preliminary results of ongoing projects by several of the authors show that two major rock types (finished millstones) were imported from adjacent countries in Belgium (***Fig. 6***). One came from the east and consists of vesicular basaltic lava (mainly phono-tephrites or tephritic foidites) (***Figs. 7, 8***) extracted from several Roman quarries in the *Vulkan-Eifel* area (Germany). Due to the properties of the rocks, which make them the ideal raw material for milling tools, this area was one of the most important production places of millstones in Central Europe (Gluhak & Hofmeister, 2011). The quarries of the Bellerberg volcano in Mayen were the larg-

Figure 7: Roman rotary handmill made of vesicular Eifel lava, preserved in the collections of the Gallo-Roman Museum, Tongeren (12-476 AD) (Photo: G. Schalenbourg).

Figure 8: Micrograph of thin section (Roman rotary quern). Detail of a characteristic phono-tephrite of the Eifel area (Photo: R. Dreesen).

est Roman millstone production sites in the Eifel region. Identical millstones have been found in Northern France (Picavet *et al.*, 2011) as well. The second type comes from the south and consists of the Macquenoise "arkosic" sandstone or conglomerate (located in Northern France, close to the Belgian border) (Hartoch, 2014; Picavet *et al.*, 2011) (***Figs. 9, 10***). This rock type has been extracted from open-air quarries between Macquenoise and Hirson (France). However, several other "local" sedimentary rock types (sandstones, quartzites, conglomerates, limestones) have been used for manufacturing millstones as well. They were derived from either Lochkovian formations bordering the Lower Palaeozoic Belgian inliers, or from younger (Eifelian, Famennian, Visean and Westphalian) formations outcropping along a W-E axis formed by the Sambre and Meuse rivers and their tributaries.

Roman whetstones… the right tool for the right job

Whetstones are meant for sharpening metal gear such as knives, scythes and weapons, and have been used since the Bronze Age up to today. Used in the context of a particular profession or as objects of daily life, they are often discovered in

Figure 9: Millstone made of Lower Devonian sandstone. Gallo-Roman villa of Neuville, Malgré-Tout Museum, Treignes (B) (Photo: P. Picavet).

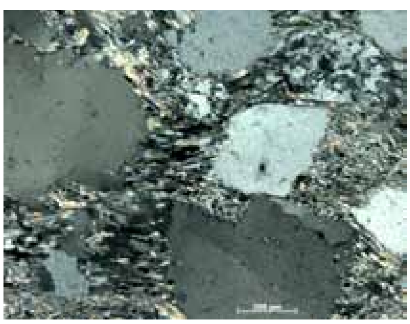

Figure 10: Micrograph of thin section (Roman quern16LP3). Detail of "arkosic" Macquenoise sandstone. Collection of Gallo-Roman Museum Tongeren (Photo: R. Dreesen).

archaeological excavations, sometimes in great number. However, they have received relatively little attention in reports and publications. Nevertheless, pioneering petrographic work on the nature and provenance of lithic material (including whetstones) of Northern Belgium has been carried out by the University of Ghent (De Paepe & Vermeulen, 1988). Current research in Belgium aims to characterise manufacturing processes, uses, trade roads and raw material sources: this results in fruitful collaborations between archaeologists and geologists. These tools testify to the knowledge and skills of past societies and help us to better understand the role of the tools in the operative chains of domestic activities.

Ongoing research projects at the Liège and Ghent universities are now focusing on Roman whetstones discovered in *Germania Inferior* and *Gallia Belgica*, covering the area between the Seine and the Rhine rivers, including Belgian territory. Characterising the raw materials is the most important goal, besides locating their probable mining areas and unravelling their cultural meaning. Mapping of provenance areas, workshops and consumption areas is in progress and the first results are in press. These mappings are being used to demonstrate the integration of the objects within the Roman economic system and to reconstruct their trade routes inside the Roman Empire and their evolution throughout the Roman period.

A major part of the raw materials consists of detrital sedimentary rocks, generally well-sorted siltstones and sandstones (***Fig. 11***). Both the Belgian and Northern France sandstone artefacts are dominantly Lower Paleozoic in age, derived from Caledonian inliers (Rocroi, Stavelot-Venn and Brabant Massifs). The sandstones vary from poorly cemented sandstones to real low-grade quartzites. The poor cementation in the former leads to faster wear but makes new grains appear. In contrast, the siliceous cement and grain imbrication in the quartzites generate a mirror-polished surface, progressively reducing their sharpening properties. Besides pebbles found on riverbanks, the majority of the raw materials is collected in quarries and transformed afterwards by cutting or sawing in different workshops. Three Roman workshops have already been identified in situ: Buizingen (Belgium) (Thiébaux *et al.*, 2013), Nereth (Belgium) (Hanut *et al.*, 2012) and Châtelet-sur-Sormonne (France) (Thiébaux & Goemaere, 2014).

As an example, Thiébaux *et al.* (2013) studied the manufacturing of whetstones found in a cellar of the Roman workshop

Figure 11: Whetstones of different shape and lithology, discovered in the vicus of Arlon (Province of Luxembourg, Belgium). SPW Collection ("Les Experts" exhibition, Arlon, 2012).

of Buizingen (near Halle, Flemish Brabant, Belgium). The authors found the source of the raw material after a comparative petrographical study. The hones are composed of very fine- to coarse-grained pale-green quartzitic sandstones, arkosic sandstones, arkoses and greywackes. Magnetite is present in most samples, providing a key element for their identification and provenance. This has been achieved by measuring magnetic susceptibilities (using pocket-size magnetic susceptibility metres) of the whetstones and of reference samples. The highest values (0.98 to 58.5E-6 kg/m^3) are characteristic of the Rogissart Member (Early Cambrian Tubize Formation). The lowest values (<1E-6 kg/m^3) correspond to a poorly outcropping member of the same formation in the Senne valley, near Buizingen.

White and coloured marbles – the Mediterranean connection

The Romans were very fond of coloured stones or "marbles", as can be seen in the numerous polychrome floor and wall decorations of their temples and villas (e.g. in Pompeï or Herculanum). These were used either as tesserae (coloured stones cut into small cubes and arranged into representational designs and geometric patterns – floor and wall mosaics), as *opus sectile* (encrustations or coloured stone cut and inlaid into walls and floors to make a picture or pattern) or as marble veneering (thin pieces of marble attached to another surface, e.g. walls). The Roman colonisers imported this tradition from Rome to our regions and decorated their private and public buildings with various local, regional and more "exotic" coloured stones, emphasising their social status or prestige. The term "marble" not only refers to true metamorphic, crystalline rocks, mainly composed of calcium carbonate, but also to a whole suite of white and often coloured rock types (including different kinds of igneous, metamorphic and sedimentary rocks, however mostly limestones) that have a dense structure,

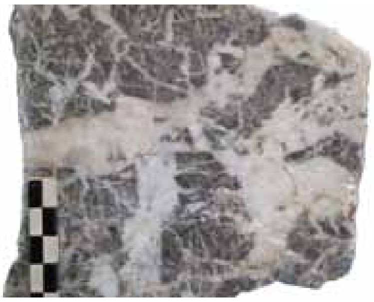

Figure 12: Slab of Belgian grey "marble": calcite-veined Frasnian mudmound facies. Basilica excavations, Tongeren. Collections of Agentschap Onroerend Erfgoed, Brussels (Photo: R. Dreesen).

display lively colours or hues and – most importantly – can be polished.

The Romans did find suitable local "marbles" in *Germania Inferior* and in *Gallia Belgica*: macroscopic and petrographic studies allowed corroboration of the nature and provenance of black, grey and red "Belgian marbles" found on Roman sites. The latter are in fact polish-prone, dense fossiliferous limestones of Upper Devonian and Lower Carboniferous age. They were presumably extracted from small underground quarries (black marble) and open quarries (grey and red marbles) in the area between the Sambre and Meuse rivers (Belgium). In the Roman town of Tongeren, many relicts of wall decorations have been found in the large Roman temple as well as in private houses, including fragments of black, grey and red marbles. Based on their morphology and the exact nature of the materials used, it can be demonstrated that each stone variety has been chosen according to its required colour and specific use. Carbonate microfacies studies unravelled the provenance of the grey and black "marbles": these are bioclastic wackestones belonging to the Lives Formation (Visean) found along the Meuse river banks between Namur and Liège (Coquelet *et al.*, 2014). The grey and white-veined limestones belong to the so-called "Gris des Ardennes", a variety of grey Belgian marble related to Frasnian carbonate mudmounds (***Fig. 12***). The majority of the "marbles" are of local origin, obviously because of the availability of good stone quality in the direct neighbourhood (within the same *civitas*), and hence minor transport costs.

Figure 13: Detail of Roman floor mosaic with various coloured tesserae. *Roman house, Hondsstraat Tongeren (Photo: A. Vanderhoeven* et al.*, 1992).*

However, for the manufacturing of more prestigious decorative elements, such as the luxury *opus sectile*, materials from adjacent *civitates* and even from remote areas such as the Mediterranean realm have been imported. In a floor mosaic found in a private house of Tongeren (Vanderhoeven *et al.*, 1992), cream-coloured, black and red tesserae have been used (***Fig. 13***). The cream-coloured pieces are Jurassic oolitic limestones, the black pieces are black Belgian marble (Visean age) and the red pieces are fragments of *terra sigillata*, imported fine ware pottery. In the collection of architectonic fragments found in archaeological excavations of the great Northern temple in Tongeren, several relicts of more luxury internal decorations have been identified: these include fragments of prestigious and expensive coloured Mediterranean marbles, most probably used in *opus sectile* objects (Coquelet *et al.*, 2014), including brick-red Rosso Antico, grass green Granito verde a erbetta, and variegated breccia Pavonazzetto (***Figs. 14-16***). Presumably, the latter thin marble slabs travelled long distances from their original provenance areas in Greece, Egypt and Turkey using transport by boat, e.g. over the extensive Rhone-Saône river networks (see ***Fig. 6***). Moreover, a much broader spectrum of coloured Mediterranean marbles is present in collections from other excavations of Gallo-Roman residential houses, bathing houses, temples and agglomerations within the *civitas Tungrorum* and is the object of ongoing research.

The accurate identification of such materials was only possible through international collaboration and exchanges allowing comparative macroscopic and petrographic studies, e.g. of the collection of polychrome marbles from different buildings (the harbour temple, *capitolium*, baths, forum, etc.) in Xanten (*Colonia Ulpia Traiana*; Ruppiene, 2014). Also, the availability of catalogues or image databases is quite helpful for macroscopically identifying ancient marbles (e.g. Lazzarini, 2004). Finally, numerous examples in the literature point to the necessity of an integrated approach for identifying the geological and geographical provenance of "true" white crystalline Mediterranean marbles used in antiquity: a combination of petrographical techniques, automated image analysis and geochemical tools (stable C-O isotope analysis) is required here.

Figure 14: Thin slab of green porphyry-type "marble" macroscopically assigned to the granito verde a erbetta *(metagabbro) originating from ancient Egypt. Kielenstraat excavations in Tongeren (Photo G. Schalenbourg).*

Figure 15: Thin slab of brick-red marble (GRM18783) petrographically identified as Rosso antico, *originating from ancient Greece. Kielenstraat excavations in Tongeren (Photo: G. Schalenbourg).*

Figure 16: Slab of marble breccia with purplish matrix macroscopically assigned to the Marmo Pavonazzetto, *probably originating from ancient Turkey. Basilica excavations, Tongeren. Collections of Agentschap Onroerend Erfgoed Brussels (Photo: R. Dreesen).*

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Geoarchaeology of "anthropogenic" travertine: a story of water and life etched in stone

Julien Curie and Christophe Petit*

The notion of "anthropogenic" carbonate deposits takes into consideration human impact on continental limestones precipitated from hot (travertine) or cold (calcareous tufas, speleothems) waters. It is documented here by a geoarchaeological study of the Roman site of Jebel Oust, Tunisia, where the exploitation of a hot spring is attested from the first century AD to the end of Late Antiquity. Petrographical and geochemical analyses performed on travertine deposits offer evidence of the anthropisation of the hot spring and its associated deposits, and reveal new elements of water management and bathing practices during Roman times.

La notion de dépôts carbonatés "anthropiques" prend en compte l'influence des activités humaines sur la précipitation des calcaires continentaux issus d'eaux chaudes (travertins) ou froides (tufs calcaires, spéléothèmes). Elle est ici illustrée par une approche géoarchéologique du site antique de Jebel Oust, en Tunisie, où l'exploitation d'une source chaude est attestée depuis le début de notre ère jusqu'à la fin de l'Antiquité tardive. L'analyse pétrographique et géochimique des dépôts de travertin a permis de mettre en évidence une anthropisation majeure des dynamiques sédimentaires associées à la source chaude et de fournir des éléments inédits à la question de la gestion des eaux chaudes pour des pratiques thermales dans l'Antiquité romaine.

La noción de depósitos de carbonato "antropogénicas" toma en cuenta el impacto humano sobre calizas continentales precipitados a partir de aguas calientes (travertino) o fríos (tobas calcáreas, espeleotemas) . Está documentado aquí por un estudio geoarqueológica del yacimiento romano de Jebel Oust, Túnez, donde la explotación de una fuente termal está atestiguada desde el siglo I dC hasta el final de la Antigüedad tardía. Los análisis petrográficos y geoquímicos realizados en los depósitos de travertino ofrecen evidencia de la antropización de las aguas termales y sus depósitos asociados, y revelan nuevos elementos de gestión del agua y las prácticas de baño durante la época romana .

Terrestrial carbonates are very widespread on Earth's surface, offering a great diversity in origin, development, morphologies and lithologies. Known as *Lapis Tiburtinus* ("Tibur Stone") and named after the volcanic precipitating spring of Bagni di Tivoli (about 25 km from Rome, Italy) during Roman Times, travertine is a type of terrestrial carbonate precipitated by hot waters. Travertines usually differ from (calcareous) tufas, which form from cool waters under ambient temperature (for a complete definition of fresh water carbonates, see Capezuolli *et al.*, 2014). These two kinds of rocks, and their associated processes and features, were well known during Antiquity, as writings of several ancient authors reveal (e.g. Pliny the Elder, Strabo, Vitruvius). And both of them have been used extensively for construction by ancient societies, first by the Greek civilization (e.g. the ancient Greek town of Paistos, later to become the Roman town of Paestum, Italy; the Segesta temple, Sicily), then by the Romans for many public monuments (e.g. the Colosseum, Rome).

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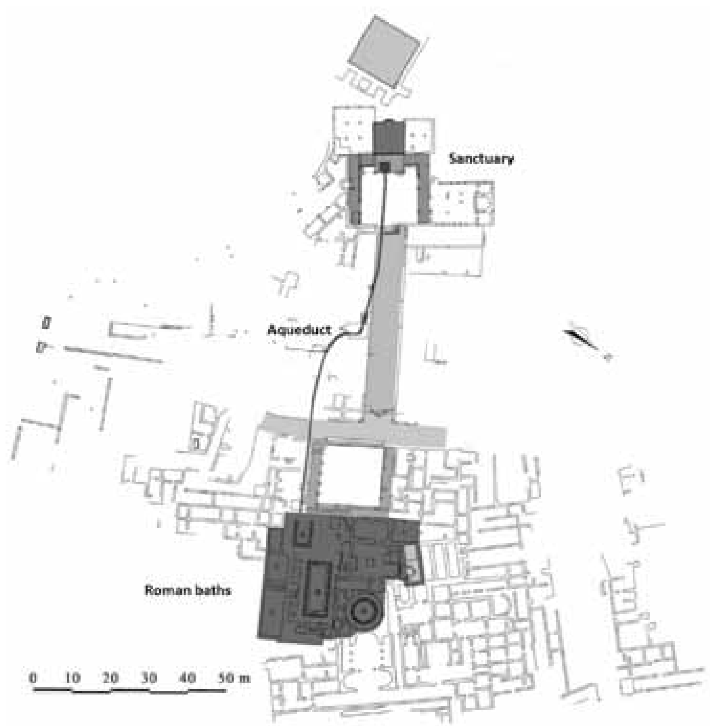

Figure 1: Plan of the archaeological Roman site of Jebel Oust, Tunisia, and locations of the three downstream sections (sanctuary-aqueduct-Roman baths) and travertine's sedimentary facies defined in the Roman Baths (A, B, C, D).

Figure 2: A pool incrusted with travertine, Roman baths of Jebel Oust, Tunisia.

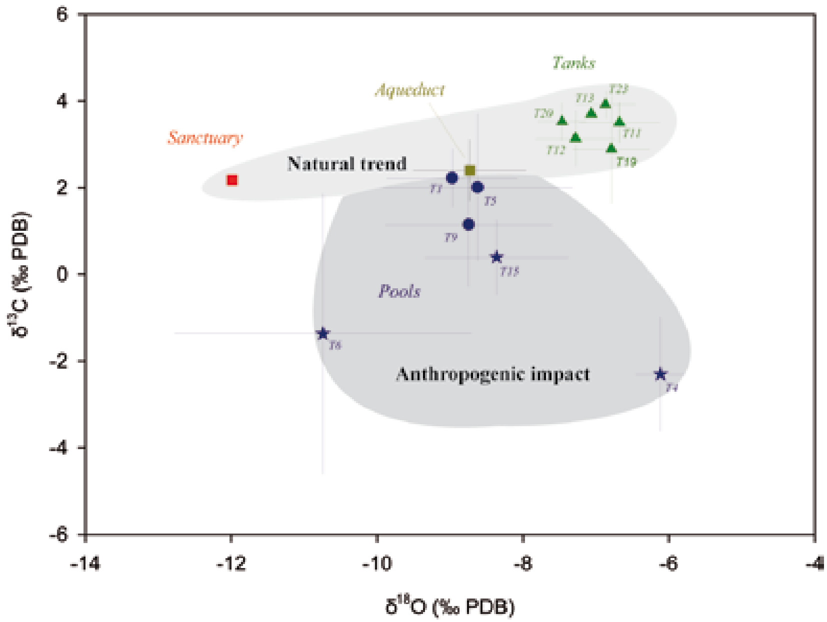

Figure 3: Oxygen and carbon isotopic compositions of travertine samples collected from the downstream sections of the archaeological site of Jebel Oust, Tunisia.

Continental limestones are of great interest due to their natural depositing conditions and climate reconstructions, and have been used for many years as reliable palaeoenvironmental indicators. Thus, they have been the subject of a recent and complete review (Pentecost, 2005). For a few decades now, some studies have integrated the impact of human activities on carbonates development (Goudie *et al.*, 1993). Furthermore, a new research area (sometimes called *Carbonate Geoarchaeology*) involved with the interactions between anthropogenic processes and carbonate environments has developed in the last decade. "Anthropogenic" carbonates are sediments precipitated under both natural conditions (climate and regional tectonics) and due to anthropogenic factors derived from human activities like exploiting waters of a spring, controlling water flow, quarrying former deposits, etc.

Figure 4: Puff-pastry travertine filling the aqueduct at Jebel Oust, Tunisia. The black arrow indicates an archaeological element encrusted in the precipitated sediment; the channel is about 1 m wide.

"Anthropogenic" carbonates: a question of water management and human engineering

Since the pioneer work performed on the aqueduct of Nîmes, in South-East Gaul (Guendon and Vaudour, 2000), some studies dealing with anthropogenic carbonates preserved in archaeological structures have been performed, mostly dealing with deposits preserved in Roman aqueducts, like the Gallo-Roman aqueducts of Arles (Guendon and Leveau, 2005) and Fréjus (Bobée *et al.*, 2010), or in other hydraulic structures like the water tower (*castellum aquae*) of the antique city of Ostia (Carlut *et al.*, 2009). Through these studies, archaeological carbonates are truly seen to represent a "memory of water". Advances in laboratory analytical techniques allowing the collection of high resolution signals offer great perspectives to understand Roman hydraulic engineering and water management, as has been shown in a study of several ancient aqueducts (Sürmelihindi *et al.*, 2013). In this article we present the case of exploitation of a hot carbonate-rich spring (hydrothermal waters) in antique Tunisia, an exemplary site illustrating a geoarchaeological study of "anthropogenic" travertines. Our geoarchaeological approach on the site of Jebel Oust aims to define the morphologies and sedimentary facies (petrography and geochemistry) of travertines precipitated throughout the ancient site, including human structures and anthropogenic features.

The "anthropogenic" travertine of the Roman site of Jebel Oust, Tunisia

The site of Jebel Oust, located 25 km south-east of Tunis, Tunisia and dating from the 1st century AD to the end of Late Antiquity, is the subject of fieldwork by a Tunisian and French cooperation directed by A. Ben Abed[1] and J. Scheid[2] (for a review of the preliminary results of first investigations,

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Figure 5: An alternate black/white laminated travertine (Facies A) from Roman baths, Jebel Oust, Tunisia.

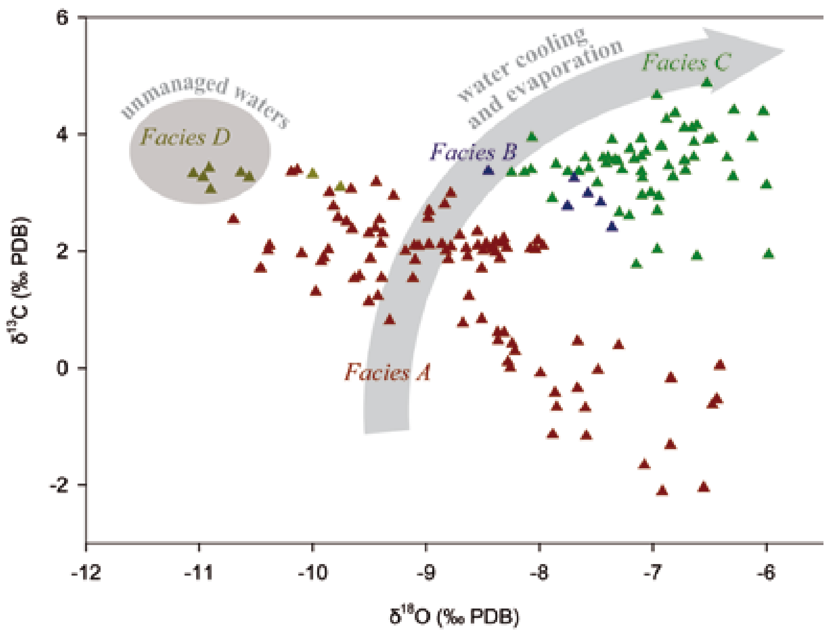

Figure 6: Oxygen and carbon isotopic compositions of travertine samples collected from the Roman baths of Jebel Oust, Tunisia.

see Ben Abed and Scheid, 2005). The site is characterised by a temple settled around the vent of a hot spring, associated with Roman baths located about 100 m downstream and supplied with hot water via an aqueduct (***Fig. 1***). The carbonate-rich waters of the spring precipitated considerable carbonate travertines where waters used to flow during Antiquity, covering the structures of the site (e.g. the Roman baths, ***Fig. 2***) with travertine deposits.

Samples were collected from the sanctuary (upstream part of the site), from the aqueduct (proximal slope) and from the Roman baths (downstream section). Petrographical analyses by optical microscopy and geochemical analyses were performed on the samples. The analyses of the stable isotope (C and O) composition of travertine show valuable results reported in a $\delta^{13}C$/ $\delta^{18}O$ diagram (***Fig. 3***). The $\delta^{13}C$ and $\delta^{18}O$ values increase from the proximal part of the site (i.e. the sanctuary: $\delta^{13}C$= 2.17 and $\delta^{18}O$= -12.0‰ PDB) and the middle part (i.e. the aqueduct: $\delta^{13}C$= 2.40 and $\delta^{18}O$= -8.73‰ PDB) to some of the rooms of the Roman baths (i.e. the distal part of the site) used as tanks ($\delta^{13}C$ values around 3.44‰ and $\delta^{18}O$ values around -7.02‰). The downstream change of stable isotope shows a “natural trend” reflecting progressive water cooling and evaporation (CO_2 degassing), a phenomenon previously described for the famous Pamukkale travertines, Turkey (Kele *et al.*, 2011). But at Jebel Oust, this phenomenon is not typical of all of the travertine deposits. Indeed, some stable isotope values of travertine from the distal part of the site, preserved in some of the pools of the Roman baths, differ significantly from this natural trend (see *Pools* in ***Fig. 3***). This fact highlights the anthropogenic impact on travertine development due to water management by Roman engineers.

Beside this anthropogenic impact on travertine development, our geoarchaeological study also deals with the petrographical and geochemical analysis of travertine sedimentary facies in relation to their depositional environment. This aims to bring new insights of ancient hydraulic engineering at Jebel Oust. The travertine deposit precipitated in the aqueduct is entirely controlled by the morphology of the channel (***Fig. 4***). It is a puff-pastry travertine with presence of encrusted stones (detrital material) and a few archaeological elements (see the fragment of an arch tube, ***Fig. 4***). This facies is due to the precipitation of microbial mats growing at the water surface (*hot water ice*), which suggests relatively still waters flowing in this aqueduct.

The anthropogenic travertines preserved in the Roman baths show a great variety in their morphology and their petrographical and geochemical features. Four sedimentary facies (see ***Fig. 1***) have been defined relating to different depositional environments directly linked to the nature and function of the room where they precipitated. First, an alternate laminated travertine (*Facies A*, ***Fig. 5***) shows a regular lamination of black/white laminae and average values of 1.44‰ for $\delta^{13}C$ and of -8.71‰ for $\delta^{18}O$ (see the data of each facies reported in a $\delta^{13}C$/ $\delta^{18}O$ diagram, ***Fig. 6***). This travertine precipitated in warm pools (*natatio*) regularly provided with hot spring water and covered by a roof (preventing water cooling and evaporation). A second facies (*Facies B*) is characterised by a regularly and alternating dense/porous lamination (***Fig. 7***) and by higher average values ($\delta^{13}C$= 2.93 and $\delta^{18}O$= -7.71‰) than Facies A, reflecting cooler and evaporated waters. It precipitated in an open-air lukewarm pool which used to play a major part in ancient thermal practices, in association with warm pools (*Facies A*). A third facies (*Facies C*) is characterised by a spongy fabric (***Fig. 8***) and by the highest $\delta^{13}C$ and $\delta^{18}O$ values (3.49 and -7.05‰ PDB, respectively), reflecting more evaporated and cooler waters than those precipitating Facies A and B. This travertine precipitated in open-air places used as tanks where standing waters from the hot spring cooled down. These cooling tanks represent a major element of antique water management, according to Seneca, the famous natural philosopher and tutor to Emperor Nero, who recommended this process when using hot waters[3]. Finally, the

Figure 7: An alternate dense/porous laminated travertine (Facies B) from Roman baths, Jebel Oust, Tunisia.

3 *Natural Questions*, III, 24.

Figure 8: A spongy fabric travertine (Facies C) from Roman baths, Jebel Oust, Tunisia.

Figure 9: A crystalline crust travertine (Facies D) forming a small cascade, Roman baths of Jebel Oust, Tunisia.

fourth and last facies is defined by a dense orange layered crystalline crust (*Facies D*) found in localised and small travertine cascades (***Fig. 9***) with micro-terraces forming at their surface. Due to low values of $\delta^{18}O$ (around -10.60‰, reflecting the highest temperatures of water), to their stratigraphic position (covering Facies A) and to the presence of a number of encrusted archaeological elements from the thermal architecture, this facies is interpreted as a phase of decay of the Roman baths, where water still flowed but was not being managed. The study of the "anthropogenic" travertines enable us to identify a management of water in the ancient Roman baths of Jebel Oust, with the association of hot, warm and cold waters simultaneously used for a classical thermal circuit during Roman Antiquity.

A geoarchaeological approach to read the "anthropogenic" travertines

The question of "anthropogenic" travertines deals with the interactions between anthropogenic processes and carbonate environments. A geoarchaeological study of these deposits offers new issues of importance, such as water management (exploitation of carbonate-rich waters), thermal baths organisation and management (nature and function of the thermal rooms), water temperature, and *geaoarchitectural* approaches (including both architectural engineering and carbonate deposits). Earlier studies on anthropogenic carbonates and our work at Jebel Oust (see Curie, 2013) show the great interest of developing interdisciplinary programs to decipher these sedimentary archives of human water management and thus to read, with a geoarchaeological approach, the interactions between nature and humans, as recorded in these carbonate sediments.

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The vitrified Bronze Age fortification of Bernstorf (Bavaria, Germany) – an integrated geoarchaeological approach

Astrid Röpke and Carlo Dietl*

"Vitrified forts" are phenomena which appear throughout Europe during prehistoric times. The burnt 1.6 km rampart of the vitrified Bronze Age fortification of Bernstorf is an invaluable example for studying burning temperatures, because it displays temperature zoning with various heating features that are recognisable in thin section and suitable for the development of micromorphological criteria to identify burning processes such as reddening, vitrification and melting. We use semi-quantitative mineral analytical methods (XRD, EDS and magnetic susceptibility) and compare our results with those of Gebhard et al. *(2004). Combining these data we get a broader picture of the burning conditions and are able to relate micromorphological burning features to temperature regimes, information which can be used to reconstruct past human fire activities.*

Les "Forteresses vitrifiées" sont des curiosités qui apparaissent en Europe pendant les temps préhistoriques. La fortification vitrifiée de Bernstorf, datant de l'Age de Bronze, est l'une des plus imposantes, en partie nord des Alpes. Elle fut complétement brûlée et détruite sur une longueur de 1.6 km. Le rempart calciné constitue un exemple inestimable pour l'étude des températures de combustion parce qu'il offre une zonation de températures avec différentes caractéristiques de chauffe. Cette zonation au sein de sédiments altérés structurellement est reconnaissable en lame mince et permet la mise en valeur de critères micro-morphologiques pour identifier les processus de combustion tels que le rougissement, la vitrification et la fusion. Ces informations peuvent servir pour reconstituer les activités humaines liées au feu. Nous appuyons et confirmons nos résultats à partir de méthodes semi- quantitatives d'analyse des minéraux, appelées XRD, EDS et mettant en œuvre la susceptibilité magnétique. Dans une étape suivante, nous comparons nos résultats avec les études plus anciennes de Gebbard et al. *(2004). La mise en commun de ces données permet d'obtenir une perception plus large des conditions de combustion et de relier les caractéristiques micro-morphologiques de combustion aux régimes thermiques.*

"Fortalezas vitrificadas" son fenómenos que occurrieron en toda Europa durante la época prehistórica. La muralla quemada del fuerte vitrificado de Bernstorf es da la Edad de Bronce y tiene un dide Bro de 1,6 km. Es un ejemplo muy valioso para estudiar las temperaturas de combustión de lso terraplenes, porque la fortaleza expone una zonificación de rasgos de calentamiento. Del exterior al interior se percibe una zona de enrojecimiento, una de vitrificación y una de fusión. En cortes delgados observábamos características micromorfológicas para estas tres zonas. Con herramientas avanzadas, tales como DRX (difracción de rayos X), SDE (espectroscopia dispersiva para energía) y la susceptibilidad magnética, podrla su definir temperaturas y procesos de combustión. Nuestros resultados están de acuerdo con los de Gebhard et al. *(2004). Nuestros datos completados con los textos (de la literatura) dan informaciones importantes para poder reconstruir el uso (y abuso) del fuego en tiempos prehistóricos.*

Vitrified forts are phenomena which appear throughout Europe during early- and pre-historic times. According to Youngblood *et al.* (1978) these ramparts were burned and due to high temperatures were vitrified (partly molten). They were first described by Pennant (1771) in Scotland. For a long time it was supposed that they were peculiar to Scotland; but they also occur in Ireland, France, Germany, Hungary and Sweden, built out of different geological rocks such as calcite, sandstone or even igneous rock. Kresten (1996) published a compilation of all existing structures, more than 1,000 of them in Sweden.

Since the late 18th century vitrified forts have been under discussion concerning the causes of vitrification. Kresten & Ambro-

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Figure 1: Map of the study site including excavation areas (Bayerische Denkmalpflege, Goethe University, Frankfurt) (Bernstorf-Project, Goethe University).

Figure 2: Section III3 burnt sediments of the rampart in Bernstorf (Bavaria, Germany) (Bernstorf-Project, Goethe University).

siani (1992) summarise the best established theories for burning of defense constructions: (1) incidental by natural causes, (2) constructive to make it more durable and (3) destructive by warfare. In addition Bähr *et al.* (2012) suggest ritual reasons for the Bernstorf fortification.

The Bernstorf rampart was discovered in 1904 by the local historian Josef Wenzel and recently rediscovered in 1990 (***Fig. 1***). According to dendrochronological and radiocarbon data the ca. 1.6 km long rampart was constructed during the Middle to Late Bronze Age. Its construction is based on sandy loam and wood. The fortification enclosed a settlement area. Preserved remnants of building structures are also burnt (Bähr *et al.*, 2012). The vitrified fortification of Bernstorf is an invaluable example for studying burning temperatures, because the construction is almost preserved *in situ* and displays a temperature zoning with various heating features.

Previous studies have investigated other parts of the fortification and made assumptions about their burning temperatures. Kresten (1998) using electron microprobe analysis and Unger (2001) by macroscopic inspection postulate burning temperatures around 1300 °C. Gebhard *et al.* (2004), using Mössbauer spectroscopy and X-ray powder diffraction analysis (XRD), suggest a temperature regime around 1200 °C. In this respect, Bernstorf is already well investigated and therefore an unusual case, because normally fire-affected soils and sediments are a neglected by-product of archaeological investigations (Berna *et al.*, 2007).

In this study we use this favourable situation of the Bernstorf fortification to extend the research with further methods and to try to create a "geoarchaeological thermometer". To receive more detailed information about the burning conditions, heat-affected changes and observable features in thin section we applied a multi-methodological approach using micromorphology, X-ray powder diffraction analysis (XRD), energy dispersive spectroscopy (EDS) and magnetic susceptibility (MS). Not only samples from the rampart itself but also samples of experimentally heated loam from the Bernstorf site were included in the reconstruction.

The site of Bernstorf and the Bronze Age fortification

The fortification of Bernstorf is situated on a hill site above the valley of the river Amper north of Munich (Germany). The Bernstorf rampart is the largest middle Bronze Age fortification north of the Alps, with a total length of 1.645 km which encompasses an area of 12.8 hectare (Bähr *et al.*, 2012). A substantial part of the rampart was destroyed by gravel quarrying during the last 50 years. Geologically the Bernstorf hill site consists stratigraphically of rocks from the Upper Freshwater Mollasse, namely of fine to coarse sand underlain by marl and silt (Unger, 2001). The geomagnetic survey (carried out by Terrana Geophysik) and archaeological excavations by the Bayerisches Landesamt für Denkmalpflege (Bavarian Monument Conservation) and the Goethe University Frankfurt document that the fortification was burnt along its entire length (Bähr *et al.*, 2012) (***Fig. 1***). Apart from that, Bronze Age and Iron Age archaeological sites were excavated within the fortification.

Materials and methods

To study burning conditions and thermal zoning of the fortification we applied a two-fold approach: we collected burnt archaeological samples from different zones of the rampart and compared them with untreated samples from the vicinity of the fortification, which we used for burning experiments (***Fig. 2, Table 1***). According to grain size distribution the texture of Bernstorf samples consists of sandy loam. Four samples were taken from the rampart of Section III3 (Goethe University, 2010). Samples DS 3 and DS 4 come from the rim and DS1 and 81 belong to the centre. As archaeological reference, B-M34 and B-M44 from Section 1 (Bayerisches Landesamt für Denkmalpflege) were included. The experimental samples (BT2-23, BT2-42, BT2-04) were heated in a muffle furnace for 24 hours in oxygen atmosphere at 600 °C, 1000 °C, 1200 °C and 1400 °C. In the latter case three hours

Table 1: Archaeological and experimental sample description from Bernstorf (Bavaria, Germany).

Sample	*Material*	*Location*	*Micromorphology*	*XRD*	*EDS*	*MS*	*κ(T)*
BT-EW06	*Reference, unburnt soil material*	*Section III3*	*x*	*x*	*-*	*x*	*x*
DS3	*Reddened rampart material, outer part*	*Section III3*	*x*	*x*	*x*	*x*	*x*
DS4	*reddened rampart material, outer part*	*Section III3*	*x*	*-*	*-*	*-*	*-*
DS1	*Slightly vitrified rampart material, centre*	*Section III3*	*x*	*x*	*x*	*x*	*x*
81	*Vitrified rampart material*	*Section III3*	*x*	*x*	*x*	*x*	*x*
B-M34	*Vitrified rampart material*	*Section 1*	*-*	*x*	*-*	*-*	*-*
B-M44	*Vitrified rampart material*	*Section 1*	*-*	*x*	*-*	*-*	*-*
BT-600	*Experimentally weakly reddened (at 600 °C)*	*Section III3*	*x*	*x*	*-*	*-*	*-*
BT2-23	*Experimentally intensively reddened (1000 °C)*	*Section III3*	*x*	*x*	*x*	*x*	*x*
BT2-42	*Experimentally vitrified (at 1200 °C)*	*Section III3*	*x*	*x*	*x*	*x*	*x*
BT2-04	*Experimentally melted (at 1400 °C)*	*Section III3*	*x*	*x*	*x*	*x*	*x*

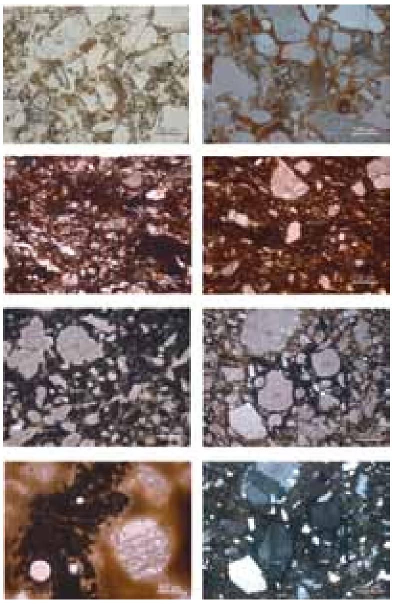

Figure 3: Micrograph: (A) Untreated sediment (BT-EW06) showing porphyric cf (cf denotes coarse vs.fine) with sand (mainly quartz = qu) as coarse fraction, voids are filled with dusty and limpid layered clay coatings (PPL). (B) BT-600 (600 °C) consisting of porphyric cf with sand as coarse fraction (quartz and mica = mc) mainly clay coatings in voids are reddened (PPL). (C) BT2-23 (1000 °C) is the experimental counterpart of DS3 consisting of a dense reddened groundmass with few voids, porphyric cf with sand as coarse fraction (mainly quartz) (PPL). (D) DS 3 with porphric cf showing complete reddening of the dense groundmass, mica is still present (PPL). (E) BT-42 (1200 °C), analogue of DS1, has a greyish groundmass with many vesicles. The former fabric has been modified by vitrification (PPL). (F) DS1 greyish groundmass with many vesicles und vitrified sediment. (H) Same sample as F in XPL. The vitrified groundmass in the vicinity of the vesicles appear isotropic. (G) BT2-04 (1400 °C) almost entirely molten sample. Only quartz with microcracks is left. Finely dispersed material (magnetite according to MS) forming schlieren.

were sufficient to melt the entire sample. BT-EW06 remained unheated.

Micromorphology

Nine samples were prepared according to micromorphological standards: freeze-dried, impregnated by epoxy-resin, made into thin section and polished at the preparation laboratory of the Earth Science Department of Goethe University. They were investigated under a polarising microscope at a magnification of up to x 800. The description mainly follows the terminology of Stoops (2003), MacKenzie *et al.* (1982) and Tröger (1982) form the base for the geological description.

X-Ray powder diffraction analysis (XRD)

Since clays are the most temperature sensitive components in sediments, samples were sieved and merely the clay fraction was used for analysis. In particular, Al-bearing silicates are of interest to our study, because they are very sensitive to temperature changes. These minerals can be identified by characteristic X-ray diffraction patterns in pulverised samples. Six powdered samples (DS3, DS1, 81, BT2-23, BT2-42) were investigated as to their mineralogical composition within the two-theta range from 2.5 to 90. The clay fraction was used for analysis. XRD helps to identify mineral phases in fine material.

Energy dispersive spectroscopy (EDS)

EDS analyses were applied to six samples (thin sections) with a Cameca SEM (EDS by Oxford Instruments) at the Archaeology Department of University College London. We focussed on the oxide phases as well as the matrix composition of the very fine grained material. EDS, in contrast to WDS, is very suitable for area scans.

Table 2: Micromorphological description of archaeological and experimental samples of Bernstorf.

Sample	*Micromorphological description*
DS3/4	*DS3/4 consists of porhyric cf (cf denotes coarse vs. fine) with few pores, reddened matrix with an anthropogenic flow fabric, probably the result of brick making. Quartz and feldspar are the two main phases within the reddened matrix; mica is also present (Fig 3D).*
DS1	*DS1 is rich in vesicles and of grey colour. Vitrified material, appearing isotropic under crossed polarisers, indicates the presence of sintered or even melted material (Figs. 3I, 3G). Quartz is the only visible silicate phase.*
81	*81 is rich in vesicles. The bridges between the vesicles consist mainly of glass, i.e. former melt, plus some quartz.*
BT-EW06	*BT-EW06 consists of a porphyric cf-related distribution with clay coatings. The coarse fraction is sand-sized quartz, mica and feldspar (Fig. 3A). Charcoal is evidenced.*
BT 600	*BT 600 is weakly reddened with a similar composition. Mainly clay coating in pores and around grains were ferruginised. Mica was not yet affected by heat (Fig. 3B).*
BT2-23	*BT2-23 shows strong reddening. Clay minerals within the matrix mostly vanished. Chlorite is evidenced (Fig. 3D).*
BT2-42	*BT2-42 shows vitrification and partial melting. The sample is stained gray. Besides quartz with some microcracks almost no other minerals can be identified within the vesicle-rich glassy matrix (Fig. 3E).*
BT2-04	*BT2-4 was entirely molten. Finely dispersed iron oxide (probably magnetite according to XRD and MS) forms schlieren within the glass. Quartz with microcracks is the only remaining mineral (Fig. 3H).*

Table 3: Data of XRD measurements of archaeological and experimental samples of Bernstorf.

Sample	*Quartz*	*Albite*		*Calcite/ dolomite*	*Three-layer Mica*	*Clinochlor / chlorite*	*Sillimanit / mullite*	*Cordier-ite*	*Indialite*	*Cristo-balite low*	*Spinel group*	*Hema-tite / ilmenite*
BT-EW 06	*48,5*	*12,1*	*9,1*	*7,1*	*15,2*	*8*	*0*	*0*	*0*	*0*	*0*	*0*
DS3	*62*	*5*	*18*	*0*	*15*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
DS1	*90,9*	*4*	*0*	*0*	*0*	*0*	*0*	*1*	*0*	*0*	*4,1*	*0*
81	*76,8*	*5,1*	*2*	*0*	*2*	*0*	*2,9*	*1*	*5,1*	*0*	*5,1*	*0*
B-M34	*87*	*5*	*4*	*0*	*3*	*0*	*0*	*0*	*0*	*1*	*0*	*0*
B-M44	*92*	*0*	*0*	*0*	*0*	*0*	*4*	*1*	*1*	*1*	*0*	*1*
BT- 600	*74,2*	*10,5*	*7,1*	*0,5*	*7,7*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
BT2-23	*51*	*9*	*24*	*0*	*0*	*0*	*6*	*0*	*0*	*0*	*5*	*5*
BT2-42	*33,3*	*0*	*0*	*0*	*0*	*0*	*42,4*	*12,1*	*5,1*	*1*	*0*	*6,1*
BT2_04	*68*	*0*	*0*	*0*	*0*	*0*	*23*	*0*	*0*	*5*	*4*	*0*

Table 4: Description of XRD measurements of archaeological and experimental samples of Bernstorf.

Sample	Description of the mineralogical composition measured by XRD
DS3	DS3 is rich in quartz and contains high amounts of mica (15 weight %) as well as both the feldspars (23 weight %). Clay minerals have already vanished (Fig. 5).
DS1	DS1 is very rich in quartz (91 weight %) which points to inhomogeneity of the starting material. More intense heating is reflected by cordierite and spinel replacing mica. Moreover, between θ angles from ca. 18° to 32° the XRD spectra arches up to form a so-called "glass bulge" (Fig. 6).
81	81 displays similar features as the other sintered and vitrified samples. It is rich in quartz (77 weight %) showing a distinct "glass bulge" as evidence for vitrification (Fig. 7).
B-M34	B-M34 is very rich in quartz (87 weight %) and contains typical HT minerals such as mullite, cordierite, indialite and cristobalite.
B-M44	B-M44 is very rich in quartz (93% by weight). The only measured HT mineral is cristobalite.
BT-EW06	BT-EW06 is rich in quartz (almost 50 weight %) and feldspar (20 weight %). XRD identifies mica and clinochlor as the main phyllosilicates. Carbonate minerals are present as dolomite (6 weight %) and calcite (1 weight %).
BT 600	BT 600 still contains calcite and dolomite and is rich in quartz (74 weight %). No chlorite was measured. Feldspar reaches nearly 18 weight % and mica (ca. 8 weight %).
BT2-23	BT2-23 includes 51 % quartz. Both feldspars are frequent (K-feldspar 24 weight % and albite 9 weight %). Mullite (6 weight %) is the Al-bearing silicate and together with the Al-bearing oxide spinel (5 weight %) the mineral which incorporates the Al from the yet vanished phyllosilicates. Both these minerals are, moreover, indicators for quite intense pyrometamorphism, probably directly below partial sintering. Hematite, responsible for the red staining, only reaches 5 weight %.
BT2-42	BT2-4 is the sample with the lowest quartz content (33 weight %) although coming from the same charge as the starting material for experiments. Besides hematite (6 weight %) - but no staining effect and quartz all other phases are of HT nature: mullite (23 weight %), sillimanite (20 weight %), cordierite/indialite (17 weight %).
BT2-04	BT2-04 is very rich in quartz (63 weight % plus 5 weight % christobalite) and the HT-Al2SiO5 polymorph sillimanite (28 weigth-%). The only detectable oxide is the Mg-Fe spinel magnesioferrite (i.e. a Mg-magnetite)

Table 5: Description of EDS measurements of archaeological and experimental samples of Bernstorf.

Sample	Description of the mineralogical composition measured by EDS
DS3	The matrix of the reddened sample DS 3 has K-feldspar composition as shown by area EDS scans. In addition, it is rich in Fe. The staining oxide hematite was also identified by an EDS point measurement (Fig. 8).
D1	DS1 is also of K-feldspar composition plus Fe. Ilmenite (FeTiO2) was the only detected oxide phase.
81	In 81 again, the matrix has K-feldspar plus Fe composition. Rutile or ilmenite and magnetite wuestite (depending on Fe2+/Fe3+ stoichiometry) are the main oxide phases. Numerous vesicles are visible under SEM, as well as quartz with microcracks.
BT2-23	BT2-23 has K-feldspar composition, however contains less SiO2 (55 weight %) and slightly more Fe. Ilmenit is the measured oxide phase.
BT2-42	BT2-42 has a more silica-rich matrix with almost 70 weight % SiO2. The main oxide phase is magnetite, hematite or ilmenite.
BT2-04	BT2-04 contains again a K-feldspar and Fe-rich glassy matrix. Cordierite was identified as well as quartz.

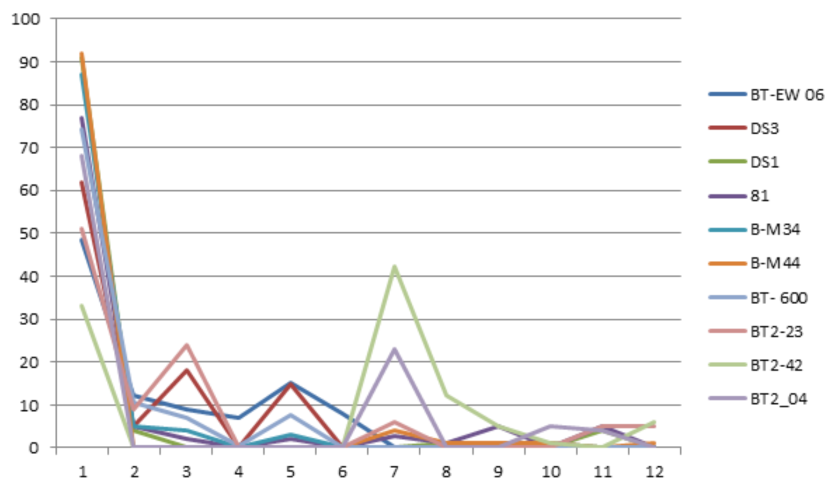

Figure 4: Mineralogical composition of archaeological and experimental samples of Bernstorf measured by XRD.

Magnetic susceptibility (κ / χ)

Measurements of κ and χ are frequently used in a geoarchaeological context to evidence burning conditions (Macphail & Goldberg, 2006). We measured κ and calculated the mass dependent susceptibility χ in order to evaluate the magnetic character of the individual samples (paramagnetic: χ in the range of 10-7 to 10-8; ferrimagnetic: χ in the range of 10-6). Moreover, we carried out thermomagnetic measurements to decipher the main carrier of κ. Six samples were investigated (see ***Table 1***). Measurements were undertaken at the magnetic laboratory of the Department of Geology and Geosciences of Friedrich-Alexander-Universität Erlangen-Nürnberg

Results

Micromorphology

The micromorphological descriptions of the archaeological and experimental samples are presented in ***Table 2***. In the micrograph (***Fig. 3***) photographs of substantial features regarding reddening, vitrification and melting are documented.

XRD measurements

The data of the XRD measurements are shown in ***Table 3***, their visualisation in ***Fig. 4*** and the description in ***Table 4***.

EDS measurements

The EDS descriptions of the archaeological and experimental samples are shown in *Table 5*.

Magnetic susceptibility measurements (MS)

The data of the MS measurements are shown in *Table 6*, their visualisation in *Fig. 9* and the description in *Table 7*.

Discussion

The Bronze Age Bernstorf fortification shows characteristic thermal zoning with a reddening of the rim and sintering/partial melting in its centre. This zoning was identified by micromorphological features, mineralogical composition and redox-pattern. The results are compared to the former excavation of Section 1 by Gebhard *et al.* (2004).

Reddening: micromorphological features, mineralogical changes and temperature regime

According to our experiment, weak and strong reddening can be distinguished. The sample heated at 600 °C is weakly reddened and mainly the clay fraction was affected (*Fig. 3B*). No comparable archaeological example was documented, either in Section 3III or Section 1 (Gebhard *et al.*, 2004), although such findings were described by Unger (2001). It is very likely they were not preserved due to high porosity leading to low stability. Strong reddening is omnipresent in Section III3. In the experimental and archaeological samples a decrease in porosity and masking by hematite is visible. The samples still include mica and feldspar – as evidenced also by Gebhard *et al.* (2004) – which can be used as a temperature signal.

In general, the formation of hematite is caused during the oxidation of $Fe2+$ to $Fe3+$ and/or the loss of water of iron

Table 6: Data of MS measurements of archaeological and experimental samples of Bernstorf.

Sample	Kappa	weight [g]	Kappa/g
DS1	6,89E-003	17,7	3,89E-004
DS3	2,02E-002	12,44	1,62E-003
DS4	2,36E-002	18,06	1,31E-003
81	4,89E-004	11,67	4,19E-005
BT-EW06	2,13E-004	21,64	9,83E-006
BT2-23	8,22E-004	12,28	6,69E-005
BT2-42	9,60E-004	9,67	9,93E-005
BT2-4	2,54E-003	7,54	3,36E-004

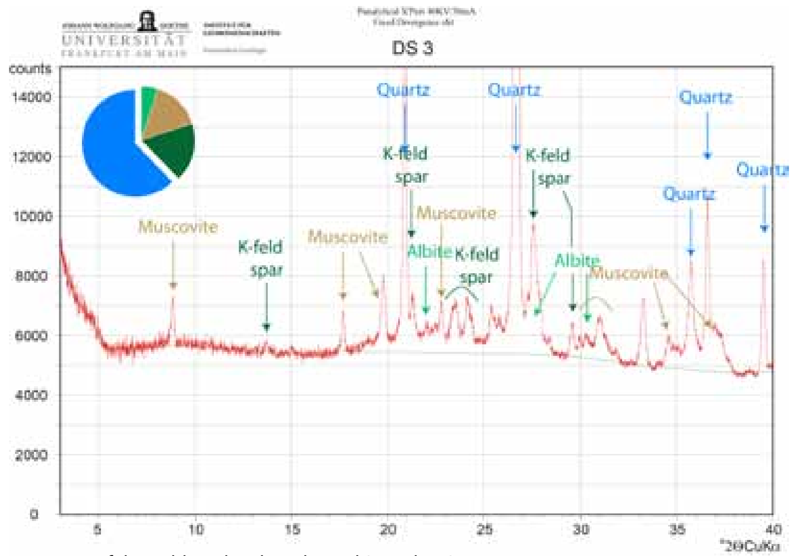

Figure 5: XRD of the reddened archaeological Sample DS3.

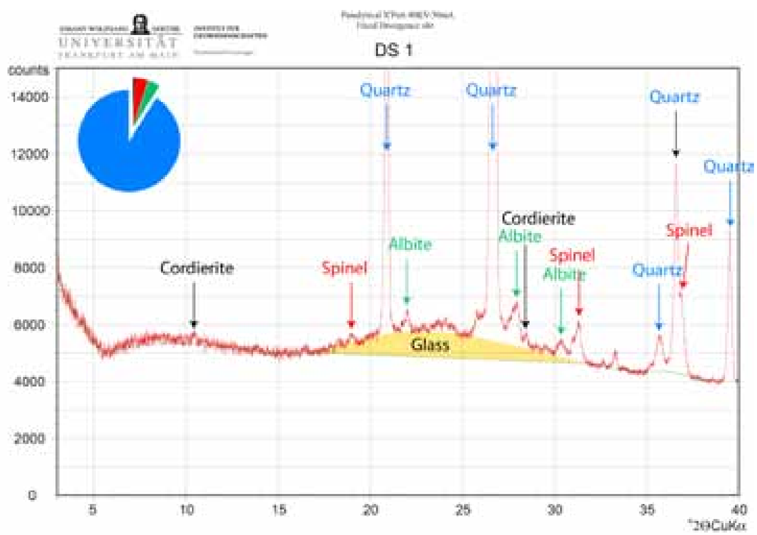

Figure 6: XRD of the vitrified archaeological Sample DS 1. In contrast to DS3 a "glass bulge" was formed showing vitrification.

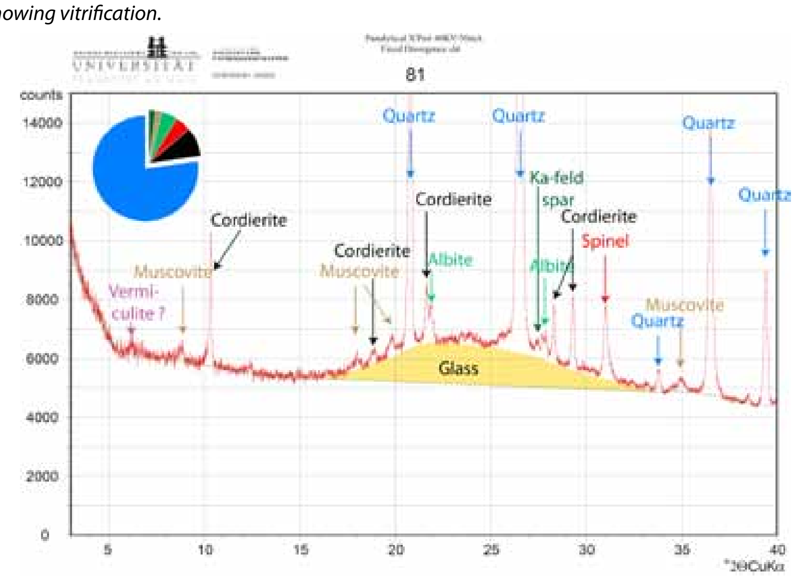

Figure 7: XRD of the vitrified archaeological sample 81. High temperature phases (HT) are shown by cordierite/indialite and spinel. The broad bulge between 18 und 32° of the X-ray spectra is due to the presence of glass. Vermiculite is the result of glass decay.

Table 7: Description of MS measurements of archaeological and experimental samples of Bernstorf.

Sample	*Description of MS measurements*
DS3	*Heating and cooling curve of DS3 (Fig. 9) show the presence of magnetite (Curie temperature T_C of 580° /Hopkinson peak at 490 °C). No hematite (T_C = 700°C) is displayed in the κ(T) curve. MS values χ in the range of 10-6 (1.62*10-6 and 1.32*10-6), clearly indicating ferrimagnetic behaviour, probably due to the presence of magnetite or titanomagnetite.*
DS1	*DS1 has the thermomagnetically detectable phase magnetite with typical TC of 580°C and a lower susceptibility than DS3 of only 3.89*10-7, typical for paramagnetic minerals such as the micas and clay minerals.*
81	*81 contains magnetite. The cooling curve is flatter than the heating curve in the range of 500 to 600 °C pointing to the formation of a new titanomagnetite. The magnetic susceptibility decreases from the rim of the rampart towards its centre, probably due to decreasing magnetite contents. It has the lowest χ value of all archaeological samples: 4.19*10-8, also in the range of paramagnetism.*
BT-EW06	*BT-EW06 has a very low paramagnetic in the core $^{-9}$. Samples used for the experiments were heated under a free oxygen atmosphere and χ increases with rising temperature.*
BT2-23	*BT2-23 (analogue to DS3 and 4) has a very low susceptibility. χ increases with^{-8}, typical for paramagnetic minerals.*
BT2-42	*The same applies for BT2-42 (analogue for DS1) with $9.93*10^{-8}$.*
BT2-04	*The entirely molten BT2-4 has a slightly higher susceptibility of $3.36*10^{-7}$. However, the sample is still paramagnetic.*

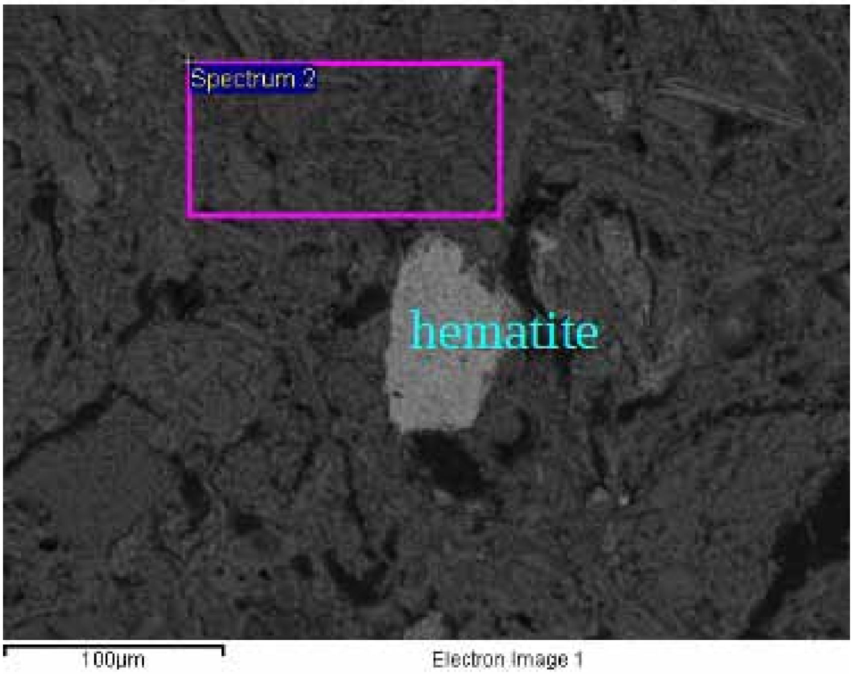

Figure 8: BSE image of the hematite rich matrix of DS3. Its bulk composition corresponds to K-feldspar..

hydroxides (mainly goethite FeO(OH)). Although reddening is distinctly visible, it is not feasible to identify the small amounts of hematite necessary for reddening using XRD. According to Muchez *et al.* (1992), less than 3% by volume is sufficient to cause complete reddening of sandstone, so not much hematite is needed for staining. Only EDS measurements on thin sections proved its existence. As shown by Gebhard *et al.* (2004), Mössbauer spectroscopy might here be a helpful tool, too. Magnetic susceptibility, widely used in archaeological record to identify burning conditions (e.g. Goldberg & Macphail, 2006), primarily yielded important hints for redox conditions during burning. MS decreases from the border of the rampart towards its centre, probably due to a diminished amount of magnetite. This may be caused by a decline in oxygen fugacity, i.e. the fire was oxidising at its rim and reducing within the centre.

Although reddening of soil and sediments is one of the most common heating features in an archaeological context (e.g. Goldberg & Macphail, 2006; Mentzer, 2012) estimations about the beginning of this process are still open to debate. In our experiment the sample turned dull reddish at under 600 °C and up to 1000 °C no vitrification is observable. This fits in well with the results of Berna *et al.* (2007) showing reddening above 500 °C in their experiments. Referring to Gualtieri & Venturelli (1999) and Gebhard *et al.* (2004) (by Mössbauer spectroscopy) transformation from goethite to hematite already takes place around 200–250 °C, whilst Mathieu & Stoops (1972) assume that it starts around 800 °C. Reddening probably strongly depends on the local material and its clay fraction, therefore results are not exactly transferable to other archaeological sites (Berna et al., 2007). Our results reveal an estimated temperature regime of the reddened archaeological samples between 900–1000 °C. The archaeological material did not experience more than 1000 °C, as shown by the presence of mica, which has vanished in the experiment. This is in good accordance with Gebhard *et al.* (2004) who assume temperatures between 900-950 °C, based on the assumption that muscovite disappears at 950°C. We expect a rather long ongoing burning process which caused the intense reddening of this part of the rampart, taking into account that sediments are generally good insulators (Berna *et al.*, 2007). This is contradictory to Gebhard *et al.* (2004), who expected a short exposure to heat, as in Section 1 heated and unheated material were located in close proximity. One possible reason could be the fact that the different amounts of wood were used for the construction of the rampart. In Section 1 distinctly higher amounts of wood were found, which might have led to a more chaotic collapse than in Section III3. Apart from that, the collapse of the fronts at different times could have affected the burning conditions of the core of the rampart (Childe & Thorneycroft, 1930).

Vitrification: micromorphological features, mineralogical changes and temperature regime

The main micromorphological features of the sintered sediments in Bernstorf are the greyish colour and ubiquitous vesicles which are situated within the vitrified matrix. Under crossed polars vitrified material appears isotropic/opaque. Microcracks in quartz grains known as the high temperature (HT) pattern are evidenced in the experimental sample but not in the archaeological counterpart. We therefore assume a slightly lower temperature regime for the archaeological samples. The change in colour from red to grey is the result of processes under reducing conditions. Hematite is replaced by magnetite. The reducing atmosphere is also well reflected by magnetic susceptibility. XRD measurements suggest that a sample heated at 1000 °C evidences a transitional state from reddening to vitrification. It still shows reddening but it also contains HT minerals such as mullite, indicating vitrification.

All vitrified archaeological samples match very well in mineralogical composition with the experimental sample heated at 1200 °C. They all include some of the common HT minerals such as mullite, cordiertite, indialite and cristobalite. Additionally they display a glass bulge, indicating incipient melting. This is in good agreement with the results of Gebhard *et al.* (2004), who observe a first appearance of mullite and cristobalite in the experimental sample at 1100 °C and a distinct increase at 1200 °C accompanied with indialite. Their archaeological analogies also include indialite. The major difference between the two sections lies in the higher amount of vitrified material in Section 1. One reason could be the varying amount of wood used for the construction. Section 1 reveals distinctly more wood beams, causing reducing conditions and high temperatures during the process of charcoal formation, whereas in Section III3 only the inner part was affected by reducing conditions.

According to our experiment, sintering of Bernstorf sediment starts at temperatures above 1000 °C with distinct occurrence at 1200 °C. This can be very well applied to our archaeological samples, which resemble a similar micromorphological and mineralogical composition; the results correspond to those of Gebhard *et al.* (2004). Comparable results can be found in the literature: Kresten & Ambrosiani (1992) report partial melting of amphibolite from the Broborg fort (Sweden) at 1130 °C; Baitinger and Kresten (2012) describe melting of basalt from the Glauberg fortification (Germany) at around 1200 °C; and Mathieu and Stoops (1972) report sintering form a Carolingian kiln at 1100 °C.

Melting: micromorphological features, mineralogical changes and temperature regime

Heating to 1400 °C led to melting. The former structural composition was completely dissolved, only quartz remained. The melt turns isotropic in XPL. Later alterations might lead to the growth of tightly intergrown minerals at the expense of an unstable glass phase, a phenomenon well known from volcanic glasses (e.g. Velde, 1995). Newly-crystallizing phases form dendritic individuals. They contain dendritic magnetite grains overgrown by fayalite, features which are often described within the context of production processes (Goldberg & Macphail, 2006). No archaeological analogy has been identified from Section 1 so far, coinciding with the study of Gebhard *et al.* (2004). Only Kresten (1998), using a microprobe, postulates a higher temperature from the Bernstorf rampart of around 1300 °C. As demonstrated before, local inhomogeneities of the 1.6 km long rampart are to be considered.

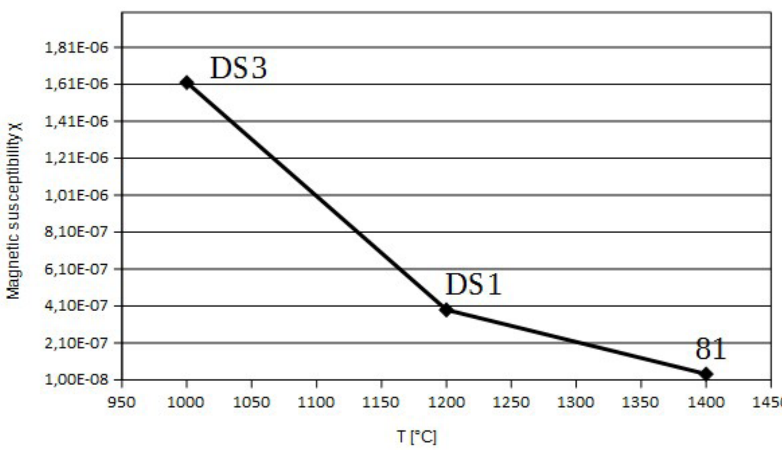

Figure 9: MS decreases from the border of the rampart towards its centre probably due to a diminishing amount of magnetite.

Conclusion

The Bronze Age fortification of Bernstorf is a good site to study heat affected archaeological remains, because it shows characteristic thermal zoning with a reddening of the rim and sintering/partial melting in its centre. Micromorphology proved to be useful in differentiating reddened, sintered and melted materials in an archaeological context. XRD turned out to be a helpful method to determine temperature-sensitive phases (e.g. cordierite, indialite) and to document burning temperatures: the rim of the rampart was exposed to less than 1000 °C whereas the centre was subject to temperatures up to 1200 °C. Without EDS the reddish matrix could not be detected, because low hematite contents are able to mask the coarse fraction. MS was not very useful for temperature estimations; increasing temperature does not always imply higher MS, but it was able to provide important information in regard to redox conditions.

It emerges from this second extensive study in Bernstorf that it is not only complicated to transfer temperature estimations from one archaeological site to another, but also distinct differences in burning conditions and temperature regime can occur within one fortification. We assume that in this case variation in construction details, in particular the amount of wood, was essential to the processes of burning and collapse.

Acknowledgements

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From historical hydrogeological inventory through GIS mapping to problem solving in urban groundwater systems

Helder I. Chaminé, Maria José Afonso and Liliana Freitas*

Water resources have had a huge impact on the socioeconomic sustainability and development of urban areas. The close relationship between water and human society has been important throughout the history of civilization. The water supply for early urban settlements included mainly the use of river canals, rainwater-harvesting systems, wells, aqueducts and underground cisterns. The industrialisation period in Europe promoted an increase in population and expansion of urban areas. Furthermore, several epidemics devastated European urban areas in the period between the18th and 19th centuries. Unhygienic conditions caused by polluted water, human and animal waste and excreta were among the main causes. This study discusses the importance of historical hydrogeological inventories in a large urban area, such as Porto city (NW Portugal), to better comprehend the evolution of urban water supply systems. In that approach urban geosciences need to advance towards a smart urban geoscience concept.

Les ressources en eau ont toujours été fondamentales pour la durabilité et le développement socio-économique des zones urbaines. La relation eau et société humaine a joué un rôle important tout au long de l'histoire des civilisations. L'approvisionnement en eau des agglomérations urbaines primitives comprend l'utilisation de canaux fluviaux, des systèmes d'eau de pluie-récolte, puits, aqueducs et citernes souterraines. La période d'industrialisation en Europe a favorisé une augmentation de la population et l'expansion des zones urbaines. En outre, plusieurs épidémies ont dévasté les zones urbaines européennes entre les 18e et 19e siècles. Mauvaises conditions d'hygiène dues à la pollution de l'eau, aux déchets humains et animaux et autres excréments en sont quelques-unes des principales causes. Cette étude analyse l'importance des inventaires hydrogéologiques historiques dans une grande région urbaine, telle que la ville de Porto (NO du Portugal), afin de mieux comprendre l'évolution des systèmes d'approvisionnement d'eau en milieu urbain. Dans cette approche les géosciences urbaines ont besoin d'évoluer vers le concept de géosciences urbaines soutenues par une technologie intelligente.

Los recursos hídricos han tenido un enorme impacto en la sostenibilidad socioeconómica y en el desarrollo de las zonas urbanas. La estrecha relación entre el agua y la sociedad humana ha jugado un papel importante a lo largo de la historia de las civilizaciones. El suministro de agua para los primeros asentamientos urbanos incluyó principalmente el uso de cursos fluviales, sistemas de siembra de agua de lluvia-cosecha, pozos, acueductos y cisternas subterráneas. El período de la industrialización en Europa promovió un aumento de la población y la expansión de las áreas urbanas. Por otra parte, varias epidemias devastaron zonas urbanas europeas entre los siglos 18 y 19. Entre las principales causas estuvo la contaminación, y los residuos y excrementos humanos y de animales. Este estudio analiza la importancia de los inventarios hidrogeológicos históricos en una gran área urbana, como la ciudad de Porto (NO de Portugal), para comprender mejor la evolución de los sistemas de abastecimiento de agua en medios urbanos. En ese enfoque las geociencias en medio urbano necesitan avanzar hacia el concepto de geociencias en medio urbano apoyadas con tecnología inteligente.

Urban geoscience, water, and mapping: towards a smart urban geoscience concept

Urban areas, independently of the socioeconomic development and administrative importance of their parishes, villages, towns or cities, play a key role in the lives of most populations. Nowadays cities face challenges like being innovative, competitive, creative, sustainable, inclusive and resilient. The newest goal for urban areas is to be smart. So, the cities of tomorrow are presently a reality (EU, 2011). That pioneering approach includes the integration of numerous data about all features of the urban areas – transport, environment, economy, housing, culture, science, population, health, history, architecture, heritage, etc. – through a series of interactive graphs, maps and digital technology. In that perspective urban geoscience needs to evolve to a new paradigm of a smart urban geoscience, particularly related to geology, hydrology, groundwater, rock and soil geotechnics, natural resources, environment, geohazards, geoheritage and geoarchaeology issues (***Fig. 1***). A core aspect for the smart urban geoscience concept necessarily includes Geographic Information Systems (GIS) as a tool for digital mapping (e.g., Chaminé *et al.*, 2010; Petitta, 2013; Freitas *et al.*, 2014).

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Since water is an essential part of the environment, the hydrology of urban areas should be seen as a vital key in all successful urban planning and management tasks and in the sustainability of ecosystems. A Chinese saying states this vital issue: *"when you drink the water, remember the spring"*. This inspirational quotation is the basis for the key role of water resources for drinking purposes. Throughout the ages, supplying water from rivers, lakes, wells or springs has been a regular task for mankind. The supply network for fresh water emerged alongside the construction of cities, towns or villages.

There are reports of water supply to the urban settlements from the Bronze Age

Figure 1: Cloud diagram based on keywords about the smart urban geoscience concept.

(2800–1100 BCE), that comprise the use of river canals, rainwater-harvesting systems, wells, aqueducts and underground cisterns (e.g., Wittfogel, 1956; Bono and Boni, 1996; Angelakis *et al.*, 2012, Freitas *et al.*, 2014). In the past, public fountains were a social meeting place, while people collected water for drinking or bathing (Chaminé *et al.*, 2010). The Romans established an organised system of aqueducts, fountains, siphons, cisterns and sewers, channelling water to create public bath sites and temples dedicated to gods of healing (e.g., Wittfogel, 1956; Bono and Boni, 1996; Angelakis *et al.*, 2012; and references therein). In the Middle Ages, water was distributed often by private water carriers. With the empirical methods of the 19^{th} century, modern societies began addressing issues of water supply more carefully. By the mid-20^{th} century water usage issues like availability, management and competition were becoming increasingly relevant due to pressing environmental and resource concerns (Angelakis *et al.*, 2012). One method for understanding the complexity of Earth systems (lithosphere, hydrosphere, and atmosphere) is the use of ground models, in which the basic approach is the observation, description, analysis, assessment and modelling of the natural systems. Thus, urban geology or more broadly the so-called urban geoscience, is an interdisciplinary field encompassing geology, engineering geosciences, environmental sciences and socioeconomic sciences addressing Earth-related problems in urbanised areas (McCall *et al.*, 1996). That overall framework is related to the impact of humans as geologic agents, predominantly in urbanised regions.

Man-made excavations on rock masses are often reported in old settlements, villages, towns or cities. These constructions sometimes consisted of an intricate network of tunnels or galleries, which were excavated to facilitate transportation, drainage, sewerage and a water supply system for the population (e.g., Gray, 1940; Wittfogel, 1956; Bono and Boni, 1996; Afonso *et al.*, 2010; Chaminé *et al.*, 2010; and references therein). Therefore, the underground in urban areas today frequently contains a complex system of dug spaces and buried

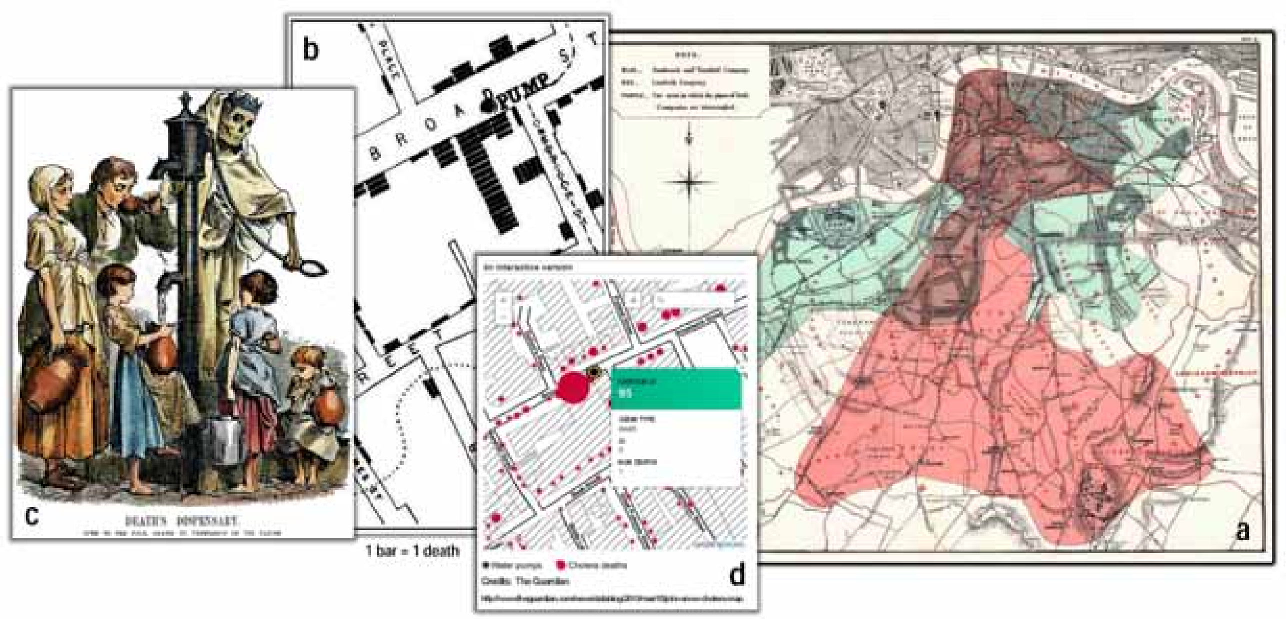

*Figure 2: Snow's maps of cholera outbreak in the London region; a) the map describes the so-called grand experiment of 1854 comparing cholera mortality among persons consuming polluted water (Southwark and Vauxhall Company: blue-green on the map) versus cleaner water (Lambeth Company: red). The overlapping area (grey-reddish on the map) represent where the pipes of both companies are intermingled (Snow, 1855); b) an extract of Snow's map showing a pump exactly at the corner of Cambridge Street and Broad Street (adapted from Snow, 1855 and Brody et al., 2000); c) a drawing of the contaminated water pumps by George J. Pinwell, entitled "Death's Dispensary", published in the Victorian magazine "Fun" during the cholera epidemic of 1866; d) presently the use of interactive maps published in "The Guardian Data Blog" section: cholera deaths and pump information from John Snow's 1854 map of the cholera outbreak in London (adapted from "The Guardian", **http://www.theguardian.com/news/datablog/2013/mar/15/**).*

structures, where anthropogenic materials are used to cover, hide or change the natural environment (Freitas *et al.*, 2014). However, these underground conduits regularly have obstructions and leakages which affect the urban water cycle (e.g., Afonso *et al.*, 2010; Chaminé *et al.*, 2010). In addition, the knowledge of aquifer characteristics in large urban areas is still scarce and there are several issues to assess, like uncontrolled exploitation and/or indiscriminate sewage and bad waste disposal practices which contribute to groundwater resources degradation.

In this study, the importance of historical groundwater inquiries and/or inventories in ancient urban areas is discussed to better understand the evolution of water supply systems. Presently, the use of GIS-based mapping on urban hydrogeology is essential for the assessment of water resources. In addition, the cross-checking of reliable hydrohistorical studies with current hydrogeological investigations contributes decisively to the resolution of problems in urban groundwater systems and to the comprehension of the urban water cycle. Last but not least, the use of a multidisciplinary and transdisciplinary approach (e.g., historical documentation, archaeological hydraulic structures, subterranean geology, groundwater ecotoxicology, geomicrobiology, and urban groundwater studies) leads to an accurate assessment and protection of aquifers in urban areas, as well as contributes definitively to a reliable understanding of the impact of climate variability on water resources.

Water supply, sanitation and urban areas: hydrohistorical issues

Presently, over one half of the global population lives in urban areas (particularly, cities and towns), and this proportion is likely to grow rapidly. Moreover, nearly 70% of the European population lives in urban areas (EU, 2011). Urban areas are shaped by complex systems that use inputs such as water, energy, materials and nutrients. Groundwater is of particular concern, as it represents over 95% of the world's freshwater reserves, and supplies over 1.5 billion city inhabitants for drinking and sanitation purposes (Howard, 2014). So, abstracting freshwater from a surface or groundwater source will not be possible in the near future, since it will affect the sustainability of the resource. Urban development requires new approaches that reduce water resource consumption and focus on resource recovery. According to Howard (2014) the fundamental principles of sustainable groundwater management in urban areas are very recent and, in some cases, still growing. Consequently, all involved agents (municipalities, decision makers, stakeholders, scientists, practitioners and individuals) are still learning about those values. Petitta (2013) argues that a blueprint vision should be highlighted and developed with the collaboration of hydrogeologists.

Interest in the relationship between urban epidemics and water dates back to the early 1800s, particularly during many severe pandemics (cholera and typhoid fever) spanning 1826 to 1866 (e.g., Lardner, 1833, 1855; Snow, 1855; Gray, 1940; Jackson, 2013; Freitas *et al.*, 2014; and references therein). Cholera and typhoid fever are bacterial diseases that are acquired by the consumption of water and food that has been contaminated by sewage. It was in the middle of the 19th century that the waterborne nature of cholera was first argued by the anaesthesiologist John Snow (Snow, 1855), contrary to prevailing theory that diseases were spread by miasma in the air.

The created cholera maps and the urban inquiry survey were important tools to confirm Snow's theory (***Fig. 2***). Afterward, two others key studies were published: Flint (1873) confirmed the typhoid fever was related to drinking polluted groundwater and Orton (1874) noticed the close relationship between geology and contaminated groundwater could lead to human diseases. Epidemics and pandemics are spatial phenomena (Koch, 2011). Mapping them is a great challenge and embedding in the map several basic and specific types of information (e.g., congested housing, fetid local waste site, marshy swamp, dug wells, and springs) was a great improvement (Koch, 2011; Jackson, 2013).

Brody *et al.* (2000) argue that Snow's map of the epidemic area was simply the visual representation of a deduction from a theory of transmission developed earlier, which in turn was grounded in a theory of the pathology of cholera as primarily a disorder of the gastrointestinal tract. However, the scientific legacy of Snow's

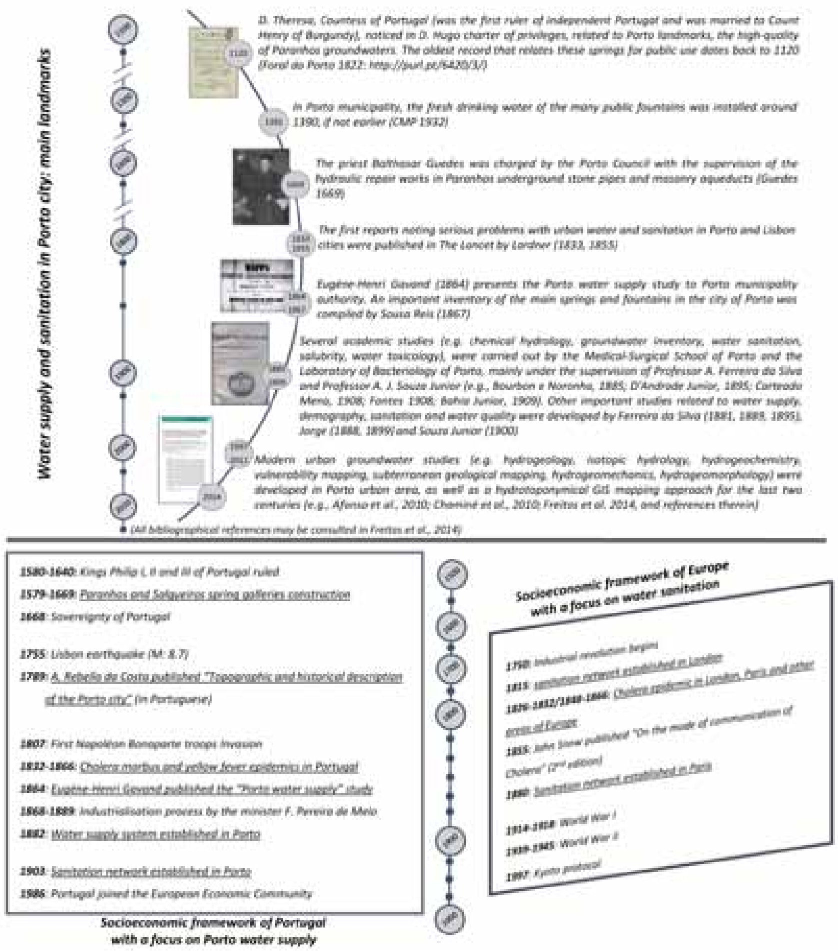

Figure 3: Outline of historical landmarks related to the water supply and sanitation in Porto urban area, as well as a comparative socioeconomic framework and landmarks in water sanitation in Portugal and Europe (revised and updated from Freitas et al.*, 2014).*

Table 1: Groundwater and water toxicology key studies in Porto urban area developed by the Medical-Surgical School of Porto and the Laboratories of Bacteriology and Hygiene of Porto, in the early 20th century, under the guidance of Professor A. J. de Souza Junior.

Date	*Groundwater key studies in Porto urban area (in portuguese)*	*Original cover*	*Publisher*	*Type of documentation Historical repository source*	*Biographical note*
1908, May	***Adriano Fontes:** Contribuição para a hygiene do Porto: analyse sanitária do seu abastecimento em agua potável. I: estudo dos mananciaes de Paranhos e Salgueiros / **Contribution to the study of Porto city hygiene: sanitary analysis for the potable water supply. I. Study of Paranhos and Salgueiros springs.** 172 p.*		*Escola Médico-Cirúrgica do Porto, Laboratório de Bacteriologia do Porto* *Medical-Surgical School of Porto, Laboratory of Bacteriology of Porto* *Typographia Encyclopedia Portugueza, Porto*	*Dissertação Inaugural* ***Graduation Dissertation*** ***http://hdl.handle.net/10216/17066***	***Adriano de Figueiredo Fontes** earned the Bachelor of Medicine in 1908; served as a military physician (Lieutenant) in the Portuguese army; was appointed 2nd provisional trainee teacher (8th course) in 1912 in the Faculty of Medicine, University of Porto (DR Nº89-16.Fevereiro.1912, p.646). He also practiced medicine during his career.*
1908, July-November	***José Carteado Mena:** Contribuição para o estudo da hygiene do Porto: analyse sanitaria do seu abastecimento em água potável. III: estudo sobre os poços do Porto / **Contribution to the study of Porto city hygiene: sanitary analysis for the potable water supply. III. Study about Porto dug-wells.** 270 p.*		*Laboratórios de Bacteriologia e Hygiene do Porto* ***Laboratories of Bacteriology and Hygiene of Porto*** *Typographia Encyclopedia Portugueza, Porto*	*Relatório Técnico-Científico* ***Technical-Scientific Report***	***José Casimiro Carteado Mena** (1876-1949) obtained the Bachelor of Medicine in 1902; served as a military physician in the Portuguese army, reaching the rank of Major; was appointed Head of Institute Pasteur, in Porto. He developed pioneering radiological studies in medical applications.*
1909, February	***José Bahia Junior:** Contribuição para a hygiene do Porto: analyse sanitaria do seu abastecimento em agua potavel. II: Mananciaes do Campo Grande, Bispo e Freiras, Cavaca, Camões, Virtudes, Fontainhas, Praça do Marquez de Pombal e Burgal; fontes suas derivadas e fontes de nascente privativa / **Contribution to the study of Porto city hygiene: sanitary analysis for the potable water supply. II. Study of the Campo Grande, Bispo e Freiras, Cavaca, Camões, Virtudes, Fontainhas, Praça do Marquez de Pombal and Burgal springs; related fountains and private springs.** 111 p.*		*Escola Médico-Cirúrgica do Porto, Laboratório de Bacteriologia do Porto* ***Medical-Surgical School of Porto, Laboratory of Bacteriology of Porto*** *Typographia Encyclopedia Portugueza, Porto*	*Dissertação Inaugural* ***Graduation Dissertation*** ***http://hdl.handle.net/10216/17030***	***José da Silva Ferreira Bahia Junior** (1882-1968) received the Bachelor of Medicine in 1909. He practiced psychiatry during his career and he was the director of the "Conde Ferreira" psychiatric hospital in Porto.*

approach was indeed the use of rigorous deductive method and field inquiry surveys. Moreover, he proposed that spatial data and topographic terms were the basis to relate cholera outbreaks to the source of water and at the end of his approach he created useful illustrative maps (see Snow, 1855). Sanitary research in the 18th and 19th centuries was related to medical hydrology and engineering, which played a key role to the development of urban disease maps and the protection of water supply systems (see details in Koch, 2011).

Selected site: example from Porto urban area, NW Portugal

In 1833, the British physician William Lardner, the appointed director of the Foz Hospital, reported in the journal *The Lancet* several concerns about the malignant cholera in Porto city. In his own words: *"(...) The next evidence of the disease spreading, was the fact of several of the Portuguese and French soldiers, and the poor inhabitants of the village of Foz [do Douro], being at attacked; and, finally, it insinuated itself. Into the heart of the city, where it certainly committed less mischief than might have been anticipated; for poverty, foul air, and filth, universally prevailed."* (Lardner, 1833: 301). This impressive quotation illustrates the violence of the cholera outbreak and the unsanitary conditions in Porto urban area in the early 19th century. Lardner (1855) noted new cholera epidemic outbreaks in Lisbon and Porto cities. Several studies about the epidemics on the ground (like cholera, yellow and typhoid fevers) were reported throughout the 19th century by eminent Portuguese academics such as A. Bernardino Gomes, A. J. Ferreira da Silva, R. Jorge and A. J. de Souza Junior (details in Pires de Almeida, 2012; Freitas *et al.*, 2014).

Porto city is the second largest urban area in Portugal and has been developed in a discontinuous way, mainly related to the processes of city building and urban morphology dynamics. The city was settled on the granitic hill slopes close to the Douro river mouth (Carríngton da Costa, 1938). Porto city has been an important conurbation since the 12th century, being one of the oldest cities in Europe, and its old neighbourhoods in the historical centre were recognised by UNESCO as a World Heritage Site in 1996. Earlier settlements date back at least to the 5th century BC, in the days of Visigoths and Suevians, followed by Romans in the 1st century BC, who established an administrative and trading centre. The so-called Portus Cale (later Portucale and, in its non-Latin form, Portugal) was the previous designation for the Porto and Gaia settlements. Although this region changed hands more than once during the Moorish occupation in the Iberian Peninsula, the invaders were evicted definitively in AD 868, after which it remained Christian (Afonso *et al.*, 2010; Chaminé *et al.*, 2010; Freitas *et al.*, 2014; and references therein).

Over more than six centuries, groundwater was supplied to the Porto urban area, mainly through springs and fountains, and fresh water was conducted through lead, ceramic or stone pipes by an intricate network of underground aqueducts (Afonso *et al.*, 2010). The use of these natural springs dates back to AD 1120. The main water galleries (Paranhos and Salgueiros springs), with a length of 3.289 km and a maximum depth of 21 m b.g.l., were dug out of a heterogeneous granitic rock mass under the densely populated urban area of Porto (Carríngton da Costa, 1938; Chaminé *et al.*, 2010). Nowadays, these underground galleries are a good example of geoarchaeological and geoheritage sites to preserve.

Porto municipality, the Laboratory of Chemistry of the municipality of Porto, Laboratories of Bacteriology and Hygiene of Porto, and the Polytechnic Academy of Porto have supported numerous pioneering studies highlighting groundwater inventorying, water supply, water toxicology, sewage and sanitation issues in the period between 1830 and 1930 (e.g., J.E.G. Leite, H.D. Souza Reis, E.-H. Gavand, A.J. Ferreira da Silva, R. Jorge, T. Bourbon e Noronha, A. D'Andrade Junior, C. Coelho, A. Antas, C.B. Champalimaud, A. Fontes, J. Carteado Mena, J. Bahia Junior, A. Sá, A.G. Lemos, A.M. Guedes; see references to these studies in Freitas *et al.*, 2014). Porto city achieved high standards of water supply and sanitation in the early 20th century. ***Figure 3*** outlines the evolution of the foremost historical issues concerning the water supply and sanitation in the Porto urban area, as well as the overall framework in Portugal and Western Europe.

Porto's urban groundwater systems were seriously degraded, both in quantity and quality, by very poor sanitation infrastructures and hygiene practices beginning in the early 19th century. In addition, urban sewage arrangements were poor and often fetid water was fed into the water supply system. ***Table 1*** shows at a glance an outstanding set of key studies developed during the years 1908-1909 related to sanitary investigations for the potable water supply. These scientific studies were designed by A. J. de Souza Junior, head of the Laboratory of Bacteriology of Porto and a distinguished professor of medicine of the Polytechnic Academy of Porto. In this overall framework the urban fieldwork, the water inquiry bulletins and the hydrological mapping (surface and/or shallow underground water tunnels surveys) played a key role in the development of reliable groundwater and water toxicology studies (***Fig. 4***).

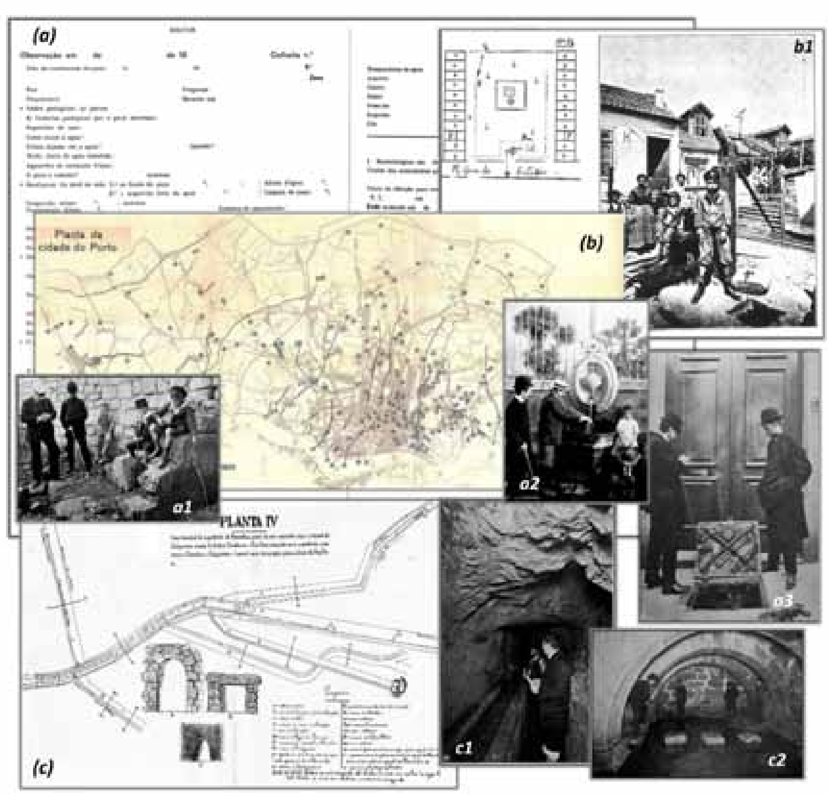

Figure 4: Several aspects of the urban fieldwork and mapping published in the Porto groundwater and water toxicology key-studies developed by A. Fontes (1908), J. Carteado Mena (1908) and J. Bahia Junior (1909), under the supervision of Professor A. J. de Souza Junior (see Table 1). (a) an excerpt of an original field hydrological inquiry bulletin created by J. Carteado Mena, 1908 [a1, a2: springs and fountains surveys – J. Bahia Junior, 1909; a3: sewage survey – A. Fontes, 1908]; (b) Porto dug wells map by J. Carteado Mena, 1908 [b1: dug-well survey and sketch framework of the surveyed well – J. Carteado Mena, 1908]; (c) underground water gallery map (Salgueiros spring) by A. Fontes, 1908 [c1, c2: water gallery with stone aqueduct and Arca d'Água masonry reservoir – A. Fontes, 1908].

The reports were unusual because each constituted a unique set under the main theme *"Contribution to the study of Porto city hygiene: sanitary analysis for the potable water supply"* (***Table 1***), with three interrelated parts making up a comprehensive description about topographic, geologic and hydrological conditions, hydro-sanitary and water toxicology analysis and hydrological mapping (I – underground water tunnels of Paranhos and Salgueiros springs; II – other springs and fountains; III – dug wells) of more than 550 pages, 445 images, 75 tables, 179 sketch maps and 10 survey maps. The set of volumes is outstanding regarding the design of the scientific approach, i.e., understanding problems in the field encompassing urban topography (surface and underground surveys), geology and hydrogeology, with careful data collection and field description, followed by exhaustive hydro-sanitary and water toxicology laboratorial analyses, as well as desk studies generating a set of valuable hydrological maps and a proposal for several sanitary and engineering actions. It still remains a remarkable achievement in the present day because of the high standards applied and is an amazing source for scientific, historical, archaeological and geoheritage studies (e.g., Afonso *et al.*, 2010; Chaminé *et al.*, 2010; Pires de Almeida, 2012; Freitas *et al.*, 2014; and references therein).

Recently several groundwater and hydrohistorical inventories have been performed in Porto's urban area, supported by field and desk techniques for urban hydrogeology and GIS-based mapping (e.g., Afonso *et al.*, 2010; Chaminé *et al.*, 2010; Freitas *et al.*, 2014; and references therein). These studies were supported by a comprehensive cross-check and analysis of historical sources and old mapping related to groundwater use (see ***Table 1***). In addition, more than 410 water sites were inventoried and over 100 sites are currently being monitored for field hydrogeology, hydrogeochemistry, groundwater ecotoxicology, geomicrobiology, engineering geosciences, subterranean geology, and radiological studies regarding a smart urban geoscience approach (***Fig. 5***).

Concluding remarks

Mapping has extensive applications, such as military operations, water resources, geosciences, engineering, environment, urban planning and heritage. This study points out the importance of coupling an historical groundwater inventory and GIS-based mapping to better understand the evolution of urban water supply systems. New challenges are emerging related to the assessment, abstracting and modelling of the urban water cycle. In this approach, urban geoscience studies assume greater importance in contributing to the concept of smart cities, particularly in urban areas with an extensive history and geoheritage.

Thus, innovative approaches are needed in the collection, analysis and integration of urban data, like groundwater ecotoxicology, geomicrobiology, urban speleology, subterranean geology, hydrogeomorphology and historical hydrotoponymy (e.g., Afonso *et al.*, 2010; Chaminé *et al.*, 2010; Freitas *et al.*, 2014). This study highlights the importance of the use of ancient urban groundwater systems, namely to assess the groundwater supply that might be available for non-potable practices, such as irrigation of parks and lawns, street cleaning and firefighting.

In recent years, a new focus on the scientific community has emerged, addressing issues on integrated studies on urban water supply systems, mainly in the largest old cities. In addition, urban hydrogeology, groundwater ecotoxicology, hydraulic and sanitary engineering, and geoarchaeological studies are fundamental to achieve a correct understanding of the overall outlook of the urban water systems. This integrative approach is far from being concluded, and research is still taking place. The sanitary and hydraulic engineer Harold F. Gray summarised this perspective in a remarkable way: *"If our progress today is so much less than what we know is possible, let us not be disheartened. Even though in four thousand years we have accomplished relatively little in sanitation, remember that after all that is but a small sector of time in man's history."* (Gray, 1940: 946).

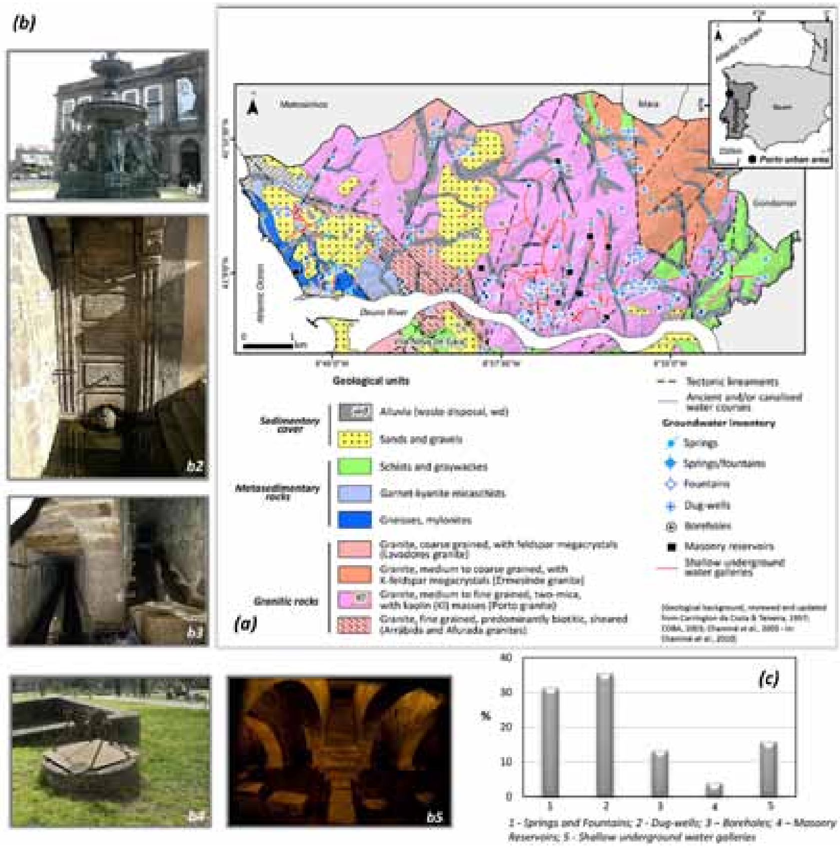

Figure 5: Current-day hydrogeological inventory in Porto urban area (GIS-mapping updated from Chaminé et al., 2010) (a) and several aspects of the water sample sites (b): b1 Leões fountain, b2 – Colher spring/fountain, b3 – Paranhos and Salgueiros underground water galleries; b4 – dug well, b5 – Arca d'Água masonry reservoir (photo kindly shared by Armando Bento); (c): groundwater inventory from the early 20th century to present (over 410 water sites).

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Geoarchaeological and paleoenvironmental reconstructions through evolutionary models: dryland applications

J.L. Peña-Monné and M.M. Sampietro-Vattuone*

Dryland archaeological sites are usually affected by erosion/accumulation processes that substantially alter their original features. Reconstructing the original positions and dimensions of archaeological sites requires the application of geoarchaeological techniques to create evolutionary regional models.
In this paper we present several evolutionary models developed in Spain and Northwest Argentina linking geomorphological processes of slopes, valleys, and alluvial fans. Given that, in many cases, these processes are the result of climate changes, evolutionary reconstructive models are also important for paleoenvironmental reconstruction.

Les sites archéologiques en terre ferme sont d'habitude affectés par des processus d'érosion et/ou de dépôt qui altèrent leurs caractéristiques originales de façon substantielle. Reconstituer les situations d'origine et les dimensions des sites archéologiques requiert l'application de techniques géo-archéologiques pour créer des modèles régionaux évolutifs.
Dans cet article, nous présentons plusieurs modèles évolutifs développés en Espagne et au Nord-Ouest de l'Argentine, associant les processus intéressant les pentes, les vallées et les cônes alluviaux. Au-delà, dans nombre de cas, ces processus sont le résultat de changements climatiques ; les modèles évolutifs de reconstitution sont aussi déterminants pour une reconstitution paléo-environnementale.

Los yacimientos arqueológicos de medios áridos y semiáridos están habitualmente afectados por procesos de erosión/acumulación que pueden modificar de forma importante sus características originales. La reconstrucción de la posición y dimensiones de los yacimientos necesita de la aplicación de técnicas geoarqueológicas para la elaboración de modelos evolutivos regionales.
En este trabajo presentamos diferentes modelos evolutivos desarrollados en España y el Noroeste de Argentina, relacionando procesos geomorfológicos en laderas, valles y conos aluviales. Dado que, en muchos casos, estos procesos son la consecuencia de cambios climáticos, los modelos reconstructivos tienen también un valor para la reconstrucción paleoambiental.

Dryland archaeological studies have several problems. One of them is the considerable modifications that archaeological sites have suffered over time due to geomorphological processes. These modifications could occur during and/or after human occupation, and they have specific characteristics depending on the preeminent geomorphological processes of these regions (e.g., fluvial, slopes, aeolian, among others). In many cases, climatic changes play an important role in these processes (especially due to dry/wet fluctuations). In other cases, human activity could be identified as the principal agent of change, or at least as a factor contributing to the modifying processes, especially during the Late Holocene. Archaeological research must address these kinds of problems, especially considering that they affect site conservation. Knowledge of process of change also makes it possible to obtain information about the original landscape, socio-economic context, and paleoenvironmental evolution on different scales.

In this paper, we propose some geomorphological evolutionary reconstruction models for different dry environments and occupational periods, for Northeast Spain (***Fig. 1.1***) and Northwest Argentina (***Fig. 1.2***). The purpose of any model of this kind is to establish the most representative stages of landscape changes in a given region. This kind of model is useful for improving survey archaeological work and archaeological maps that help to better select excavation areas and reconstruct settlement systems.

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Objectives and methodology

The objective of this paper is to show the applied value of geoarcheological interpretative models using examples from the drylands of Spain and Argentina. Producing these models requires previous geomorphological, edaphic, and archaeological knowledge about the region to be modelled. It is then necessary to test their validity following a hypothetical-deductive methodology, and to check their possible generalisation. The following examples are the result of several test cases, and the development of the interpretations is based upon the environmental changes recognised on global and local scales.

From a strictly methodological point of view, the first step involves making geomorphological maps. These maps are useful for setting the present context of the archaeological settlements, but including also sedimentary and morpho-sedimentary records, thus allowing deeper understand-

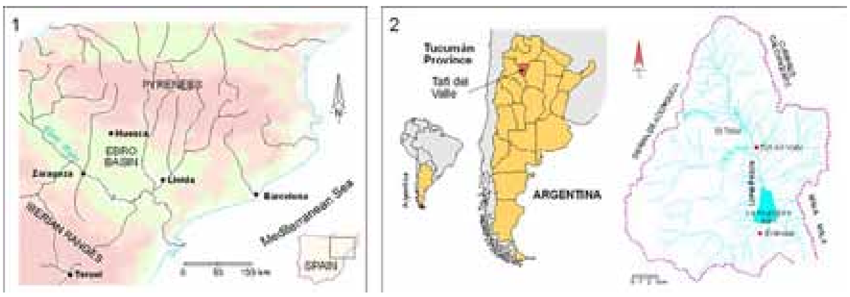

Figure 1: Study area locations: (1) Ebro Basin and Iberian Ranges (Northeast Spain); (2) Tafí Valley (Northwest Argentina).

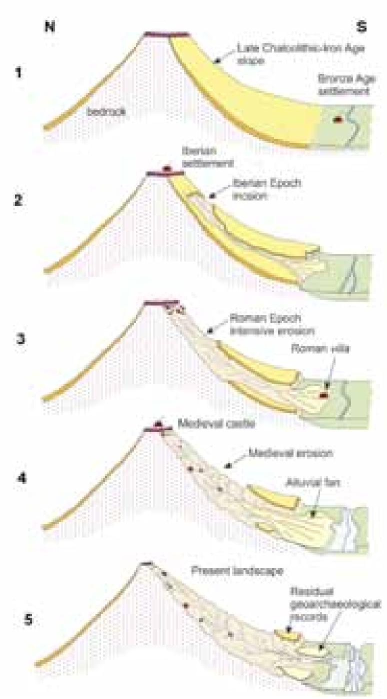

Figure 2: Evolutionary reconstruction of the Holocene slopes in the Northeast Spain.

ing of the evolution of these landscapes. The presence of archaeological materials involved in the erosion/sedimentary processes as well as elements that can be dated through different techniques (^{14}C, TL, OSL) make it possible to create the chronological framework of such processes. The next step entails creating basic evolutionary stages that include general cultural stages for the region. Finally, this information may be represented as reconstructive models that include several characteristics, with high explicative value, that could be applied to the reconstruction of land use patterns, paleoenvironmental reconstruction and the prediction of archaeological site location, among other uses.

Results

Ebro Basin and the Iberian Ranges (NE Spain)

These regions (***Fig. 1.1***) are characterised by their continental Mediterranean and semiarid conditions (precipitation between 330-550 mm). The Ebro Basin is a Tertiary tectonic depression, with an altitude ranging from 150 to 700 m above sea level (masl). The Iberian Ranges form a mountainous unit of middle altitude, reaching 2000 masl in the central-eastern part. The stages of highest human population density during the Holocene started during the Neolithic. This period was followed by the Chalcolithic (4400-3800 BP), Bronze Age (3800-2700 BP), Iron Age (2700-2500 BP), Iberian Period (2500-2200 BP) and the Roman Epoch (2200-1600 BP). Environmental changes and human impact have had great influence on the modification and changes of archaeological sites of those times; we hereby present two evolutionary models that could be generalised for the study of other semiarid areas.

Slopes are the landforms of highest environmental fragility. They also have rapid response to environmental changes. Accordingly, they must be considered among the best paleoenvironmental recorders in the presence of minor climate fluctuations. Geoarchaeological studies from NE Spain show that there was a phase of high development of slope accumulations under wet and cold climatic conditions between the Late Chalcolithic and the Iron Age (4200-2500 BP). This stage generated a period of slope stabilisation (***Fig. 2.1***) that allowed soil development (Pérez-Lambán *et al*., 2014). This soil was covered by vegetation that protected it from erosion. However, it must have suffered the effects of deforestation for agropastoral purposes. This situation lasted several centuries, until the maximum demographic growth of the Iberian and Roman Epochs (***Figs. 2.2 and 2.3***). These stages coincided with a drier climate that favoured intensive rill wash erosion and gully formation over stabilised slopes (***Fig. 3***). At a regional level, these slopes never recovered, whilst the erosion processes would continue during the Middle Age. However, slopes and ample alluvial fans would locally develop during brief, wetter Little Ice Age (LIA) periods. They would cover the middle and lower part of landscapes (***Fig. 2.4***) (Pérez-Lambán *et al.*, 2014). At present, morphological and sedimentological records tend to be reduced to fragmented elements in the landscape (***Figs. 2.5 and 3***), and it is very difficult to recognise and interpret them without an appropriate evolutionary model.

Sometimes, these landscape fragments could be the only archaeological remnants of the old archeological settlements of the Bronze and Iron Ages, and of the Iberian culture, originally located in the upper areas. On the other hand, these sediments could be covering archaeological sites such as the Roman *villae*, which used to be settled in alluvial bottom areas.

The valleys are also involved in the geomorphological dynamic previously described for slopes. In the Ebro Basin,

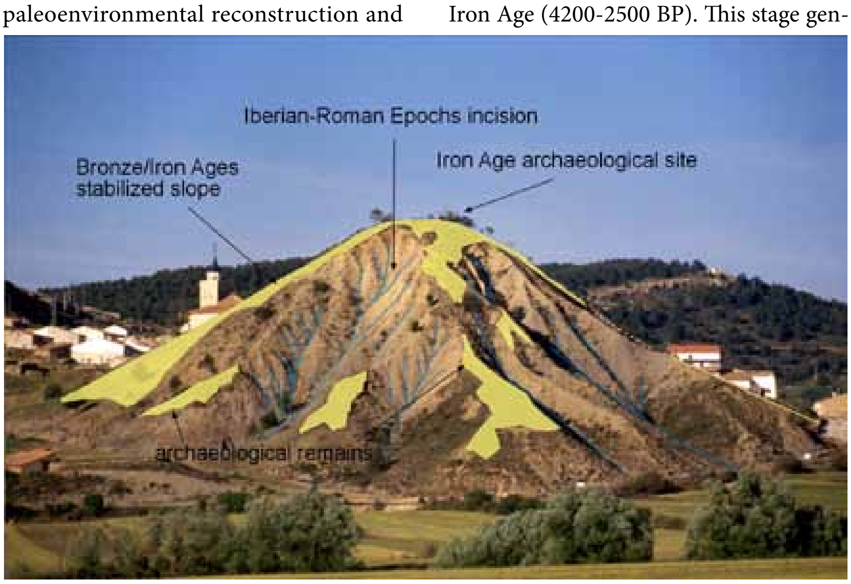

Figure 3: Residual hill of the Iron Age archaeological site of the Frías de Albarracín (Iberian Ranges). Iberian/Roman incision degrading older slopes.

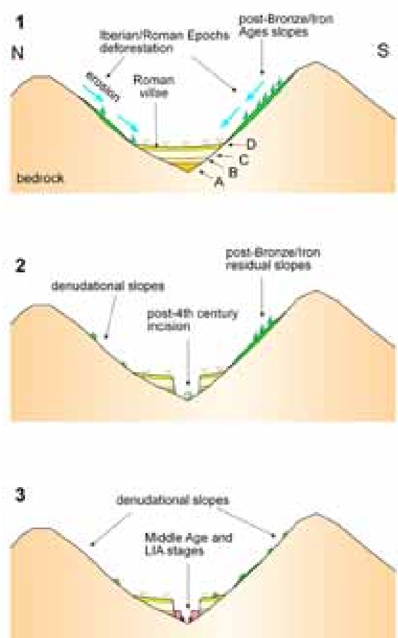

Figure 4: Evolutionary reconstruction of the Holocene infilled valleys in Northeast Spain.

the most important phase of infilled valleys developed during the Holocene (regionally named N3), and began during the Neolithic; lower levels (***Fig 4.1: A***) are chronologically located ca. 7000-6000 BP. However, due to their correlation with the slope erosion of posterior periods, sedimentary packages reach 15 m thickness, increasing through the Iberian and Roman Epochs (***Fig. 4.1: C and D*** levels). On these accumulations it is possible to find archaeological remains coming from the up-slope erosion. This accumulative phase had a regional impact, characterised by the disappearance of several archaeological sites originally located in the upper relief, as well as the preservation of others settled in valley bottoms (***Fig. 5***). An intense incision process following the Late Roman Epoch (4th century) exposed profiles of these accumulations (***Figs. 4.2 and 6***) (Peña-Monné, 1996; Peña-Monné *et al.*, 2004; Constante *et al.*, 2010). During the Medieval Climate Anomaly (MCA) and LIA, new cumulative phases were formed (named N2 and N1) (***Fig. 4.3***). These accumulations had less thickness and were separated by incision periods (Peña-Monné *et al.*, 2004; Constante *et al.*, 2011). However, these morpho-sedimentary stages are more visible in the extensive alluvial fans developed in the confluence with the main rivers of the region. From a paleoenvironmental point of view, these late stages were the result of climate events, while stage N3 had a considerable human influence, due to the intense deforestation made over slopes.

Tafí Valley (Northwest Argentina)

Tafí Valley is located in Northwest Argentina (Tucumán Province), covering 450 km^2, altitudinally reaching between 1800 and 2200 masl. The surrounding mountains are higher than 4000 masl. Among the most important mountains are the Cumbres de Mala Mala, Cumbres Calchaquíes, and Sierra de Aconquija (***Fig. 1.2***). The climate is semiarid with precipitation of 450 mm per year.

From an archaeological point of view, it is possible to identify features of agropastoral cultures after 2300 BP. The first settlements belong to the Tafí culture, dating between 2300 and 1000 BP (Formative Period). It is possible to identify subsequent Santa Maria settlements between 1000 and 500 BP (Regional Developments Period). Although some Inca Period ceramics were found dating after 1492 AD, no Inca settlement has been discovered in the area to date. In 1535 AD the Spaniards arrived in Northwest Argentina, introducing several disruptive changes in the local sociocultural processes.

As stated above, there are no records of settlements or archaeological features of any kind prior to the Tafí culture. For this reason, we made a general landscape evolution model from the Early Holocene to the present (***Fig. 7***), applying the methodology exposed above in order to plan specific surveys in the future.

This model is representative of the eastern slope of Loma Pelada. The geological bedrock is composed of Paleozoic granitoids and metamorphic rocks that suffered a long and intense pre-Quaternary weathering process. The tributaries of the Tafí River have developed a sedimentary record that covers the whole Holocene in the form of slopes, infilled valleys, and alluvial fans. The most important accumulation is the result of an intensive erosive process established from Early Holocene to *ca.* 4000 BP (Sampietro Vattuone & Peña-Monné, in press). Sediments from slopes (S4) and valleys (L4) were from the coarse sand and clay (*grus*) resulting from the weathering mentioned above. At present, *grus* is observable only in residual deposits. ***Fig. 7.1*** shows the formation of the L4 level that ends with the accumulation of volcanic ashes (***Fig. 8.1***), whose age is around 4000 BP (***Fig 7.2***) (May *et al.*, 2011; Fernández-Turiel *et al.*, 2012). There are no human-related features in these first evolutionary stages. The environmental conditions reflected by these deposits were arid.

An incision process developed after 4000 BP (***Fig. 7.3***), and inside the incision a new

Figure 5: Iron Age and Iberian houses covered by the N3 level accumulations. Los Castellazos (Mediana de Aragón, Ebro Basin).

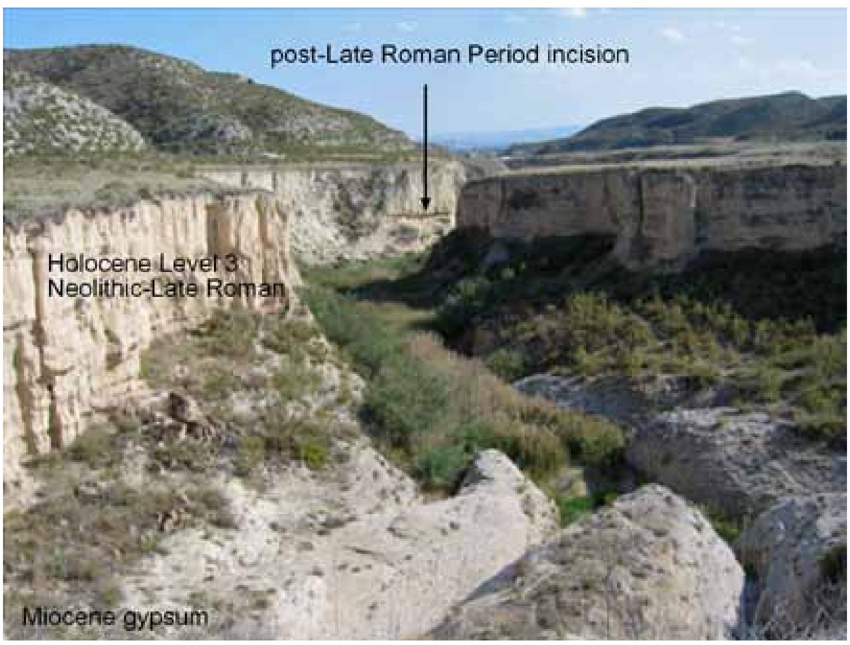

Figure 6: Incised Level N3 in Alfocea Valley (Ebro Basin).

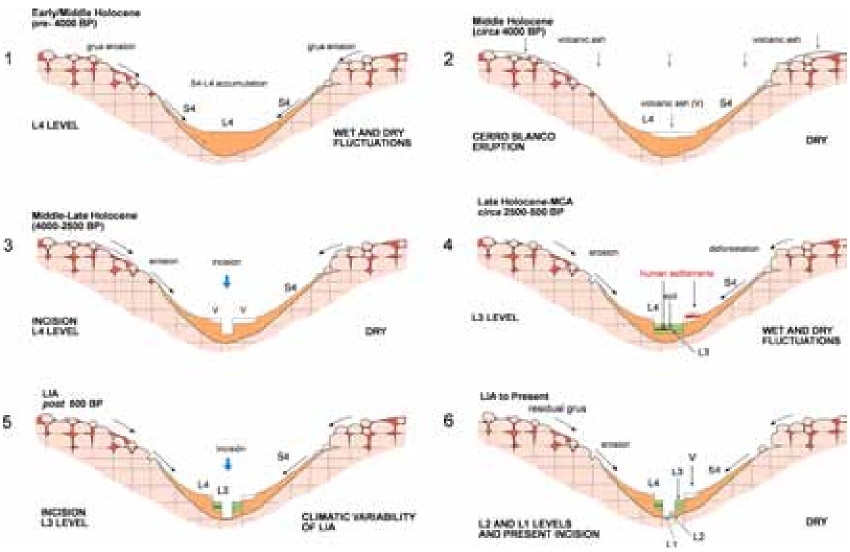

Figure 7: Evolutionary reconstruction of the Holocene valleys in the eastern slope of Loma Pelada (Tafí Valley).

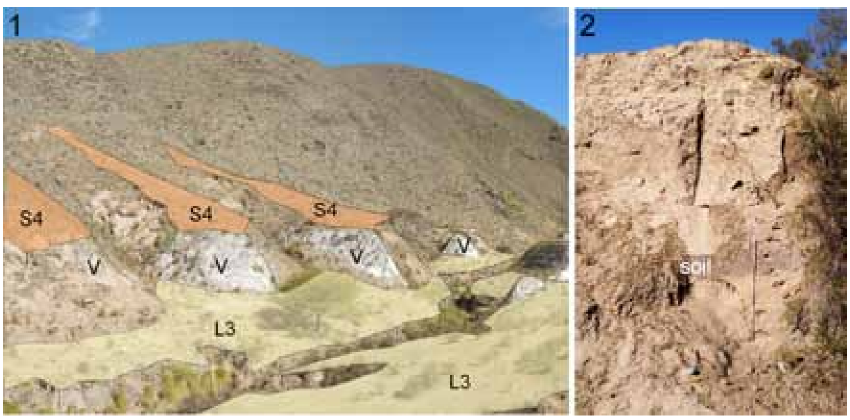

Figure 8: (1) General view of Holocene levels from Loma Pelada, Tafí Valley; (2) L3 Level section with interstratified soil.

Figure 9: (1) El Tolar archaeological site: (1) General view; (2) Archaeological site detail.

sedimentary cycle started; it was named the L3 level (***Fig. 7.4***). The sedimentary record of this level showed a buried soil (***Fig. 8.2***) containing ceramic potsherds belonging to the Tafí Culture (*ca.* 2300-1000 BP), as well as upper levels with ceramic potsherds typical of the Regional Development Period (*ca.* 1000-500 BP). The first human settlement was coincident with high population density in the entire valley. This phenomenon necessarily affected the environment, favoring erosive processes of high magnitude. These erosive events are reflected inside the valleys by the thick accumulations of the profiles made in a short time. They also generated extensive alluvial fans in the confluence with the Tafí River. Paleoenvironmentally, the L3 level reflects wet and dry fluctuations. In the last 500 years, which includes the climatic variability of LIA, stages of accumulation and incision occurred (***Figs. 7.5 and 7.6***) resulting in two new levels (L2 and L1) separated by incision phases.

According to this model, human settlements prior to the Tafí Culture must be located in the S4 slopes and the L4 infilled valleys.

During the Formative Period, one of the most relevant characteristics of this valley was the presence of large surfaces transformed for food production by the construction of agricultural terraces. Given the antiquity of the settlements and the cultural development already described, knowledge of the local and traditional agricultural practices was lost. In this context, we developed a geoarchaeological occupational and agricultural model for the El Tolar archaeological site, Tafí valley (Tucumán – Argentina) (***Fig. 9***).

The landform evolution that started under semiarid climatic conditions became established during the Middle Holocene with debris flow deposits (***Fig. 10.1***), which formed the alluvial fan identifiable at present. This fan had several alluvial cycles that favoured the migration of the Blanco River through the north to its present situation until it developed its active alluvial fan. After the stabilisation of the alluvial fan surface, wetter environmental conditions were established, developing a soil dated *ca.* 2500 BP. This soil presents the evolution of B horizon with clay translocation and intense biotic activity (***Fig. 10.2***). Such conditions favoured the settlement of one of the earliest agrarian societies in Northwest Argentina, as evidenced by the presence of an extensive agrarian terrace system in the alluvial fan surface. Several archaeological digs made in the fan made it possible to demonstrate that terrace walls were constructed without foundations on the fan surface. Soil labor introduced physicochemical changes, such as B horizon compaction and loss of organic matter contents and quality (***Fig 10.3***). After 1000 BP drier conditions were established on a regional level; these affected the social dynamic of the Tafí people and the site was abandoned (***Fig. 10.4***). Given the lack of maintenance and the agricultural practices applied during almost one millennium, the A horizon was eroded and terrace walls gradually collapsed (***Fig. 10.5***). Finally, sheet flood processes that affected the surface gradually buried the collapsed structures. The establishment of the present

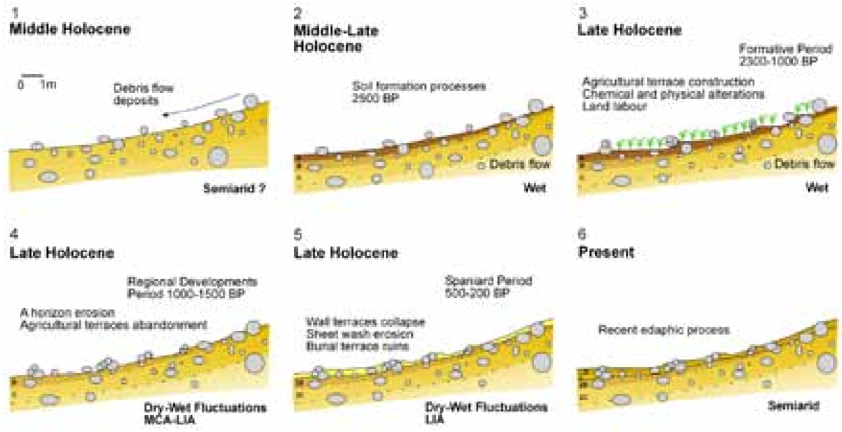

Figure 10: Evolutionary reconstruction of the agrarian settlement of El Tolar, Tafí valley.

environmental conditions made possible the incipient edaphization of the materials transported during the previous erosion/ sedimentation period (***Fig 10.6***). Today, the alluvial fan looks like a stepping surface with small elevations resulting from the collapsed stone wall terraces that are still visible on the surface (***Fig. 9.2***) (Sampietro Vattuone *et al.*, 2011).

Conclusions

The application of appropriate techniques from earth sciences (geology, geomorphology, edaphology, etc.) for archaeological studies supplies potentially useful information for the paleoenvironmental reconstruction of highly fragile and sensitive landscapes. These environments are sensitive not only to climatic changes but also to human activity impacts. Geoarchaeological information could be presented as evolutionary models of the utmost importance for regional planning of archaeological studies and for understanding the changes produced over landscapes throughout different occupational stages.

Despite the fact that the models presented are from two spatially and culturally distant areas, the application of the proposed methodology makes it possible to obtain equally valid results aimed at deepening the study of archaeological site formation processes in world drylands.

Acknowledgements

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The geology of the Acropolis (Athens, Greece)

M. Regueiro, M. Stamatakis**, K. Laskaridis****

The famous Acropolis is an ancient temple site located high up on a rocky cliff in the middle of Athens. The hill is formed of a lowermost Upper Cretaceous (100 My) limestone resting on younger rocks of the Athens Schist Formation (72 My). Overthrusting, marked by the brecciated character of the lower part of the limestone, must have occurred during continental collision in the Upper Eocene orogenic phase; erosion and faulting produced the klippe that we can observe today. The contact between the lower Athens schist and the upper limestone has traditionally been a place of numerous springs and karstic caves. We describe the main characteristics and history of several springs and some caves used for worship.

L'Acropole renommé est le site d'un ancien temple, localisé au sommet d'une falaise rocheuse, au centre d'Athènes. La colline est formée par un calcaire de la base du Crétacé supérieur (100 millions d'années) reposant sur des niveaux rocheux plus récents de la Formation des Schistes d'Athènes (72 millions d'années). Le chevauchement, caractérisé par le caractère bréchiforme de la partie inférieure des calcaires, a dû se produire pendant la collision continentale qui a eu lieu lors de la phase orogénique, à l'Eocène supérieur. Les processus d'érosion et de fracturation sont à l'origine de la klippe que nous observons aujourd'hui. Le contact entre les schistes inférieurs d'Athènes et les calcaires supérieurs fut traditionnellement à l'origine de nombreuses sources et cavités karstiques. Nous décrivons les caractéristiques principales et l'historique de plusieurs sources et de quelques cavités servant de lieux de culte.

*La famosa Acrópolis es un antiguo lugar de ubicación de templos, situado en una colina rocosa en el medio de Atenas. **La colina** está compuesta por una caliza de la base del Cretácico Superior (100 Ma) que descansa sobre rocas más jóvenes de la formación Esquistos de Atenas (72 Ma). El cabalgamiento, que se evidencia por el carácter brechoide de la parte inferior de la caliza, debe haberse producido durante la colisión continental de la fase orogénica del Eoceno Superior. La erosión y la fracturación han producido el klippe que observamos hoy. El contacto entre los Esquistos de Atenas inferiores y las calizas superiores ha sido ubicación tradicional de numerosos manantiales y cuevas kársticas. Se describen en este trabajo las características y la historia de varios de esos manantiales y cuevas utilizadas como lugares de culto.*

The famous Acropolis in Athens is an ancient temple site located high up on a rocky cliff in the middle of Athens. Its turbulent history is long - in human life-span terms - and dates back to 6000 BC. It has been the focus of a myriad of texts written by all types of authors, but oddly enough, the rock that bears the site has scarcely been mentioned.

This paper intends to fill that gap, to provide readers and visitors alike with a view of another much longer history, dating back to the Upper Cretaceous age, some 70 million years ago, when the rocks that underlie the rocky crest of the sacred hill were deposited in the delta of a mighty river.

How much the geological composition and geological structure of the hill affects its human-related history, and why this particular hill has been – and for some, still is – considered sacred, might be a matter of intense debate. So first let us briefly address that glimpse of time. After all, a rock is only a rock, at least for us geologists.

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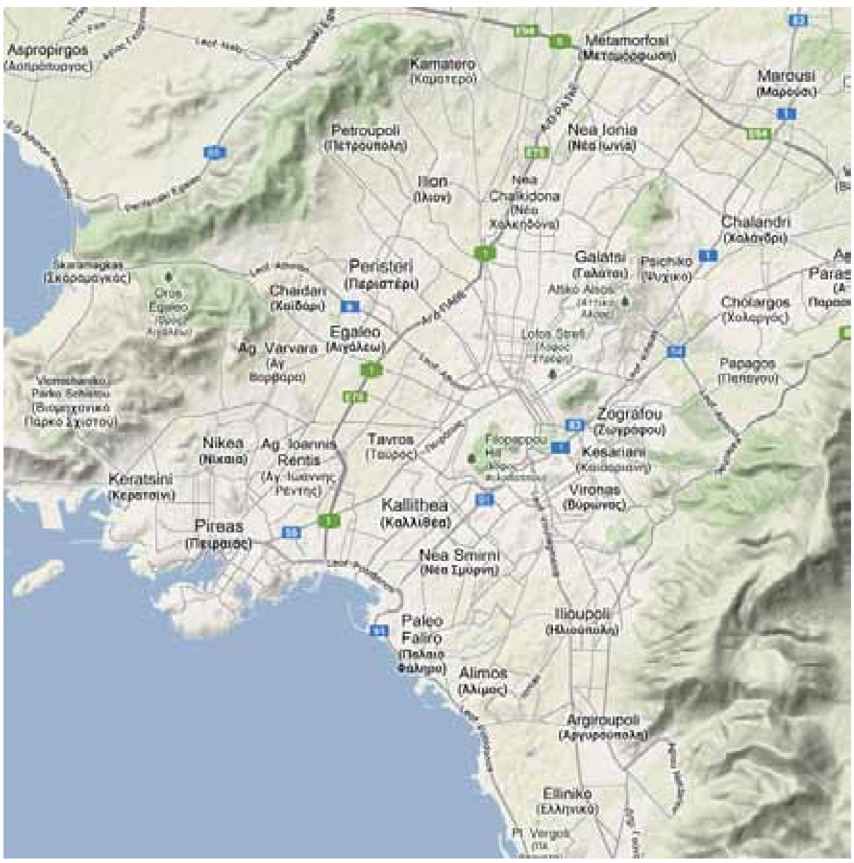

Figure 1: Geographic map of Athens showing its main physiographic features.

A brief history of a piece of rock

The Acropolis might have looked quite odd for our relatives 8,000 years ago, since the whole territory around it was more or less flat, except for this 70 m high, 300 m long and 150 m wide flat mound, along with the taller Likavitos to its north-west (***Fig. 1***) and Tourkovounia further north. There were probably some trees on the top of the Acropolis but not many, since the marble was probably outcropping exactly as it is today, forming high unassailable walls of rock. In fact the rock was a natural fortress because it was quite inaccessible from all sides (***Fig. 2***). This was probably the reason why the place was used to host a safe city, and this is why its name is *acropolis*, a Greek word meaning "city on the top" or "upper city".

In Greek mythology, the first king and founder of Athens was *Cecrops*, quite a nice chap who is said to have unified all the tribes of the region. He apparently came from Egypt and wisely married *Aglauro*, the daughter of *Acteo*, the King of Attica. Cecrops was also a knowledgeable man, as it is said that he taught the Athenians important things, such as marriage (before him, they probably lived promiscuously), reading and writing, and ceremonial burials; he also initiated the cult of Zeus. In fact, Acropolis is also named Cecropia in his honor. Cecrops was half man and half dragon, which in geological terms might means that he was a dinosaur-man...

It was Cecrops who gave the Athenians their name, as in the competition for the Acropolis he was the referee that decided that Athena came first over Poseidon; thus, Athena became the goddess patron of the city. Poseidon was not very happy with the result of the race so he decided to destroy the city with what today we would call a tsunami. Luckily enough he was not successful, apart from the fact that he probably managed to link the – at that time – island of *Piraeus* to land. In true prehistoric times Piraeus was a rocky island consisting of the steep hill of *Munichia* (today *Kastella*) and was connected to the mainland by a low-lying stretch of land that was flooded with sea water most of the year, and used as a salt field whenever it dried up. Poseidon apparently also used his trident to try to make a salt water fountain on the top of the Acropolis, but he failed because Athena had planted an olive tree first. Maybe the salty isthmus of prehistoric Piraeus was the place that Poseidon´s trident hit, and so there seems to be again quite an interesting connection between myth and geology.

Another example of this relation is the case of *Deucalion*. In Greek mythology

Figure 2: A probable look of the Acropolis from the south (left) and from the north (right) 8,000 years ago has been imagined from today's look.

Deucalion was the equivalent of *Noah* in the Bible. He was the son of *Prometheus* (the creator of humankind), king of *Phthia* in Thessaly, and husband of *Pyrrha*; he was also the father of *Hellen*, the mythical ancestor of the Hellenic race. When *Zeus*, the king of the gods, resolved to destroy all humanity by a flood, Deucalion constructed an ark in which, according to one version, he and his wife rode out the flood and landed on Mount Parnassus. According to a story found first in the Roman poet Ovid's *Metamorphoses, Book I*, upon offering a sacrifice and inquiring how to renew the human race, they were ordered to cast behind them the bones of their mother. The couple correctly interpreted this to mean they should throw behind them the stones of the hillside ("mother earth"), and they did so. Those stones thrown by Deucalion became men, while those thrown by Pyrrha became women. In early Greek versions *Hermes* told the couple directly to cast stones behind them. So the human race, according to Greek mythology, was destroyed by a flood and was then renewed from the stones thrown by Deucalion and Pyrrha, all of which is very geological.

If we go back to real history, many human inhabitants have made constructions in or on the Acropolis since the Mycenaean era, thanks to its flat top table and the abundance of spring waters and caves. The place was deemed perfect for human habitation.

There is ample evidence of a Bronze Age Mycenaean palace or *megaron* on the hill, with a defensive Cyclopean 3.5 to 6 m thick massive 10 m high circuit wall around the whole mound, whose remains still exist. The main gate was a ramp located to the

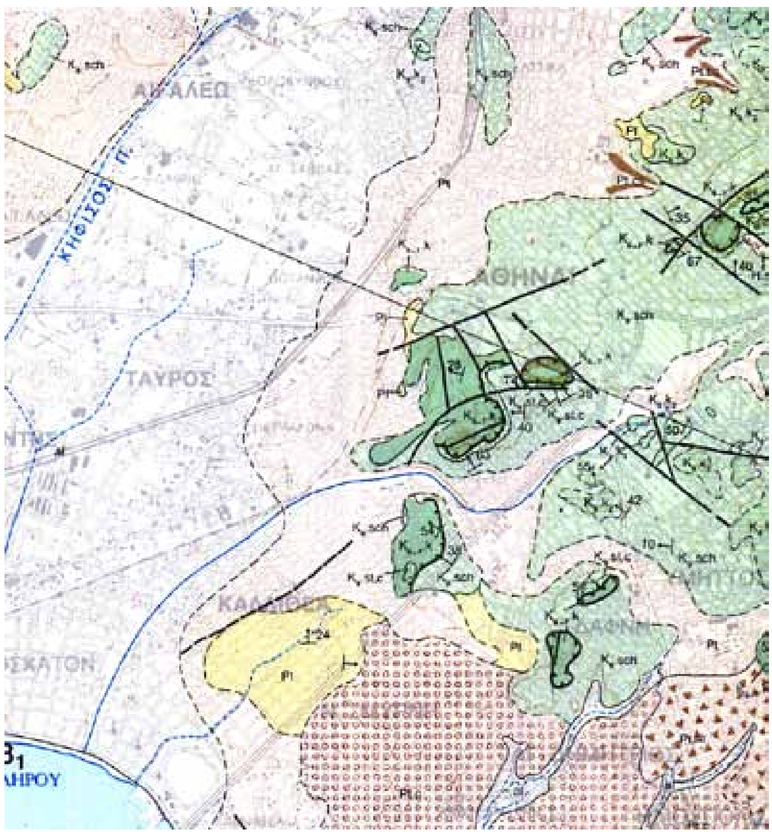

Figure 3: Geological map of Athens 1:50000. Gaïtanakis (1982).

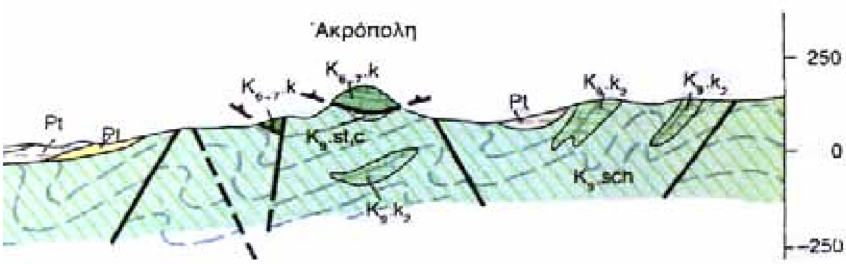

Figure 4: Cross section NW-SE of the Acropolis. Gaïtanakis (1982).

southwest (where later the Erection was located) and there were steep, narrow flights of steps cut in the rock in the north. Geologically a noted earthquake before the 13th century BC caused a 35 m long fissure in the marbles near the northeastern edge of the Acropolis which sliced the marble down to the red schist underneath. The fracture probably helped in the development of a cave and a karstic spring, which was discovered in the second half of the 13th century BC during the works for the fortification of the Acropolis. A well called the *Clepsydra* was then dug here in the soft schist with an elaborated set of stairs, an invaluable source of fresh water for the city, but we will develop the topic of the underground water of Acropolis later on. To protect the spring a nine-gate wall, the *Enneapylon*, was built at the northwestern foot of the Acropolis.

What the archaeologists tell us now is that the Acropolis became a sacred place in the 6th century BC, when the northeastern side of the hill (near the current position of the Parthenon) hosted a temple dedicated to *Athenia Polias*, the *Hekatompedon*. Later in the same century, another temple known as the *Archaios Naos* or Old Temple was built in the Acropolis near the Hekatompedon, by the tyrant *Peisistratos* (527/528 BC). He also built a monumental entrance to the site of *Propylaea*. Peisistratos was not a dictator, as unfortunately we know them today, but a sort of constitutional leader (as even Aristotle wrote), because he was voted in as tyrant by the Athenian assembly in 561. He will be remembered by the Athenians because he instituted the famous *Panathenaic Festival*.

The Old Temple was destroyed by the Persians in their invasion of 480 BC, rebuilt in 454 BC, and finally probably succumbed to a fire in 405 BC. A huge new building was started before the invasion, which is known as the *Older Parthenon* or *Pre-Parthenon*. To build this temple, the southern part of the Acropolis was leveled using blocks of limestone and earth, all of which was held in place by a wall. First they employed limestone from Piraeus although construction remained unfinished because of the invasion, and, when the Athenians defeated the Persians at the Battle of Marathon (490 BC), they decided to use marble instead.

After the war, the northern walls of the Acropolis were built using parts of the destroyed temples, and the devastated site was cleared of debris. The surroundings of the current Parthenon were again leveled to create an artificial plateau and many religious objects were buried ceremoniously by the Athenians in pits dug on the hill or in surrounding caves. This incredible archaeological deposit was discovered and excavated in 1885 and is called the "Persian debris". The new walls were known as the Wall of Themistokles and the Wall of Kimon.

During the Golden Age of Athens (460 BC to 430 BC) most of the remains we see today of buildings and temples of Acropolis were constructed under the leadership of *Pericles* over almost half a century by workers who received a pay of 1 drachma a day, which apparently, according to Aristophanes, was decent pay for the daily subsistence of a family of three. The *Parthenon*, the *Propylaia*, the *Erechtheion* and the temple of *Athena Nike*, whose remains we can behold today, were built during this time.

Later, during the advent of Christianity, the monuments were converted into churches. All the structures were renamed and served as churches and cathedrals.

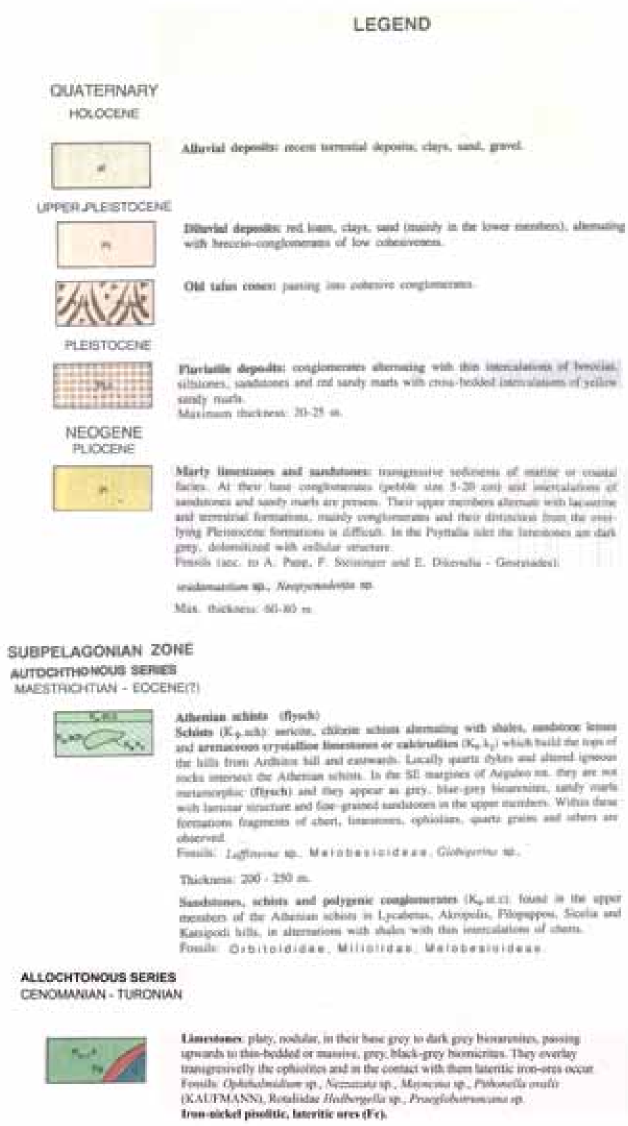

Figure 5: Legend of the geological map and the cross section. Gaïtanakis (1982).

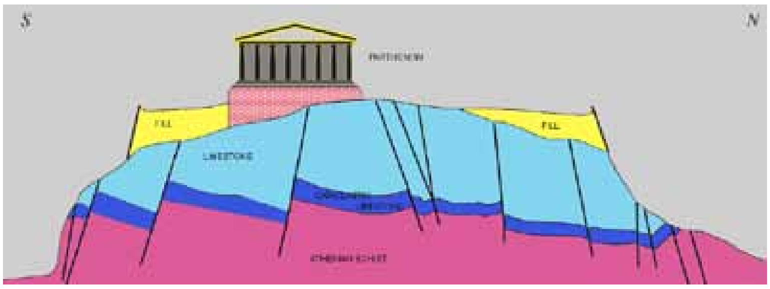

Figure 6: Cross section of the Acropolis. Adapted from Higgins & Higgins (1976).

During the medieval period, some of the structures became residences or headquarters for kings such as the Frankish or Turkish rulers. Wars, invasions and attacks destroyed important structures such as the Parthenon, leading to a tragic historical loss. It was only during the late 20th century that the Acropolis was properly excavated and the demolition of Ottoman buildings was decided upon.

Geology of the Acropolis

The geological history of Acropolis is much older than what we human beings can easily understand. The geological setting of the Athens area has been studied by several researchers since the middle 18th century (Lepsius, 1893; Kober, 1929; Marinos & Petrascheck, 1956; Tataris, 1967; Niedermayer, 1971a; Marinos *et al*., 1971; Trikkallinos, 1955; Paraskevaidis & Chorianopoulos, 1978). In spite of that, our knowledge about the lithostratigraphic structure of Athens is still incomplete.

But let us first review where the city of Athens is located. Athens lies in a great topographic basin surrounded by Mts Parnes, Aigaleos, Penteli and Hymettos (***Fig. 1***). The basin was formed by the erosion of the soft Upper Cretaceous (72 My) Athens Schist, which outcrops or underlies the veneer of younger sediments in much of this area.

The hills in the eastern part of the Athens basin, such as Lykabettos, Areopagus, Acropolis and Philopappos, are all made of a lowermost Upper Cretaceous (100 My) limestone called locally "Tourkovounia Formation" (Karfakis & Loupasakis, 2006). All these hills form what in geology is called a nappe or thrust sheet, that is, a sheet-like body of rock that has been moved several kilometers above a thrust fault from its original position (Gaïtanakis & Dietrich, 1992). In this case the oldest Upper Cretaceous limestone that was formed 30 My before the formation that now lies under the limestone, has been brought up and travelled from the south to finally end up resting on younger rocks of the Athens Schist Formation (72 My) (***Figs. 3–5***). The time of emplacement of the Cenomanian limestones over the Pellagonian tectonic units is given by the minimum ages at the Athens schist. Overthrusting must have occurred during the Upper Eocene orogenic phase as result of continental collision.

After the Alpine compression ended, erosion and faulting produced a series of smaller Neogene basins in the main basin which were flooded by the sea and filled with transgressive or coastal facies with rocks such as sandstone, shale, clay and limestone. These rocks can still be seen exactly where they were deposited, except that recent tectonic movements have raised them above sea level. Many of the clay deposits were used by the ancient Athenian pottery industry, and some are still exploited today.

During the Quaternary much of the central and western parts of the basin were covered with a layer of alluvium up to 20 m thick as a result of infrequent floods in the recent past.

The Acropolis klippe

The Acropolis site has two main geological units from its lowermost part to the top of the rock (***Fig. 6***):

1. Athens schist
2. Crest limestone

Both units are not only lithologicallly very different – a difference that has affected very much the geological and historical evolution of the rock – but also both have a dissimilar geological history. In fact the lower Athens schist is what is called an autochthonous terrain, that is, the rocks are located more or less where they were formed (in this case the same place where they were deposited), whilst the upper limestone, as mentioned above, is an alochthonous terrain, that is, it was formed in another place and is located where it is today due to extraordinary orogenic events. In geology, a structure like this is called a klippe, that is, the remnant portion of a nappe after erosion has removed connecting portions of the nappe. This process results in an outlier of exotic, often nearly horizontally translated strata overlying autochthonous strata.

And this is the most extraordinary and less known fact about the geology of Acropolis; the limestone rock has travelled from far away to finally stop where it is today, like a huge rock vessel that has run aground far inland after a terrible geological storm. In geological terms the limestone was thrust over the schist by the effect of the Alpine compression movements. In fact the limestone of Acropolis is 30 My older than the schist it lies upon.

The physical proof of this abrupt journey is reflected in the lowermost part of the limestone, in the contact with the schist, where the limestone shows a very distinct sheared texture. Instead of a normal limestone, what we see is a rock made up of fragments of limestone. This is called a cataclastic rock, that is, a rock that has been dragged along many kilometers not on the surface of the land, but down below the Earth at a certain temperature and pressure. The faulting, granulation, and flowage of the original limestone produce a new rock called cataclastite (***Fig. 7***). After this process ended, erosion did the rest.

Athens schist

This formation has a very distinct reddish color and is in general a soft rock. In fact the huge open-air theatre of *Dionysus Eleuthereus* (with an original capacity of 17,000 spectators, built in the 4th century BC) and the smaller *Odeion of Herodes Atticus* (for 5,000 spectators, built in AD 161) are both located on the southern slope of

Figure 7: Outcrop of limestone cataclastite near the Propylea and on the southern slope of the Acropolis.

the Acropolis, and were directly excavated in these rocks.

The Athens schist represents quite heterogeneous formations of low-grade metamorphic and relatively soft rocks (***Fig. 8***). The name of the stratigraphic formation was given because it extends over a great part of the ground of the city of Athens.

In the area of the Acropolis, the formation is composed of alternating beds of sericite sandstone, shales and phyllites, locally with intercalations and lenses of crystalline, usually microclastic, limestones. The Athens Schist bedrock shows remarkable weathering and intense folding, shearing and extensional faulting, which completed the structural "downgrading" of the rock mass.

Very complex folding, shearing and cataclastic phenomena can be observed within the flyschoid formation. Cataclastic deformation is certainly the most dominant feature in the more incompetent silty and sandy layers. Ductile deformation is weak in the slates. The occurrence of chlorite and crystallinity of illite/sericite transformation suggest burial temperatures around 200 °C. An overburden of 2 to 5 km rock pile on top of the Acropolis klippe is quite feasible. According to Marinos *et al.* (1971), the Athenian schist represents a flyshoid phase of delta-type deposit of the Upper Cretaceous (Maastrichtian, 70 My), that is, what we see today was once the talus of the delta of a huge river.

Acropolis limestone

The Acropolis limestone horst is fractured and block faulted by steeply inclined N-S, E-W and NW-SE trending faults. The cataclastic deformation increases towards the base as expressed by the occurrence of classical riedel•shear systems. The contact zone consists of several metres of strongly folded reddish and greyish cherts, fine-grained siliceous limestones and slates. An Upper Jurassic age for this formation is suggested by the occurrences of Radiolaria and Tintinidae. The slate-chert formation changes its deformational features rapidly along a few tens of metres towards east and west. As a result of displacement and heterogeneity of strain gradients, the schistosity (s-structure) has become uneven and shear banding (c-cisaillement) appeared. In the east, close to the Dionysos Theater, the same formation is developed as a homogenous "brecciated conglomerate" (Geitenekis & Dietrich, 1992).

According to most researchers (Megris, 1913; Kober, 1929; Marinos & Petrasceck, 1956; Trikallinos, 1955; Niedermayer, 1971a and others) the upper calcareous horizons overthrust the marly horizon and the hilltops of the city of Athens were deposited in form of big olistoliths. According to that interpretation, the breccio–conglomerate beds located along the base of the limestones are tectonic mylonites.

Hydrogeology of Acropolis

It is quite clear that the first inhabitants of the Acropolis selected this place for their residence due to the natural protection of the rock, but also because there were many natural springs, with the Clepsydra spring being its most famous representative. Thus, fresh water was another important clue for the historical development of the site (Chiotis & Chioti, 2012).

The contact between the Athens schist and the overlying upper limestone is a typical place where geologists might expect to find springs. The reason for that is that limestone can easily become a good groundwater container via its fractures and its caves, whilst the schist is a relatively impermeable formation due to its clayey content. The result of this combination is that the water often flows in the contact of both formations (***Figs. 9, 10***) in what can be considered a hanging aquifer, discharging regularly by three small springs with a discharge of 0.5 to 1 l per minute in the dry season, which can increase considerably during rainfalls. The quantity of penetrating water amounts to 4,500 m^3 per year (Andronopoulos & Koukis, 1976).

Even today, we can see the contact in the growth of fig trees and in karstic formations that provide evidence of ancient water flows (***Fig. 11***).

The HYDRIA Project (***http://www.hydriaproject.net/en/cases/athens/acropolis_hill/asklipios.html***), a multinational project on the history of the use of water, has made several case studies from Mediterranean countries, including the Acropolis springs. A summary of its findings follows.

Figure 8: Contact between the cataclastite and the Athens schist on the southern slope of the Acropolis (above) and detail of the contact (below).

Northern springs

On the northern slope of the Acropolis, inside the cave of *Ersis* (until recently attributed to the nymph *Aglauros*), an impressive structure exists for a spring that was probably discovered during the fortification works of the Acropolis (Pelargikon or Pelasgikon wall, second half of 13th century BC) for the protection against imminent

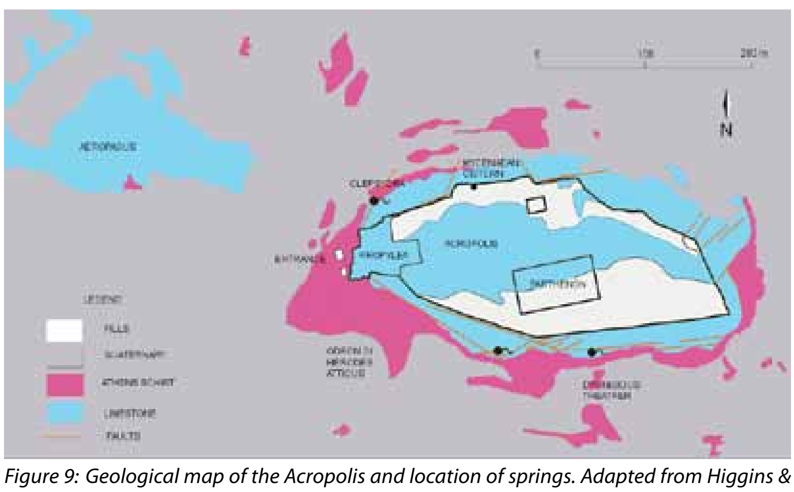

Figure 9: Geological map of the Acropolis and location of springs. Adapted from Higgins & Higgins (1976).

invasion by the Dorians.

The spring construction, in use only for a short time during the Mycenaean period, is believed to be one of the first technical works to ensure water supply to the city. Mycenaean pottery found in it, dating from the second half of the 13th century BC and not later, indicates that the period of use was no longer than 30-40 years. A landslide or earthquake must have blocked it.

The entrance to the cave is at the level of the Parthenon, west of the *Arrhephorion*, a small square building where young women (*Arrhephoroi*) used to weave the mantle/veil of the goddess (Athena) for the Panathenaic festival and other rituals.

The cave is an impressive, almost vertical fissure, 35 m deep, with a series of stairways. In the upper part the rock was carved in order to support wooden steps; while in the lower part the stairways were made using large schist slabs placed on rubble, which was supported by wooden beams. The stairway ended at the boundary between the upper layer of limestone rock and the underlying layer of marl rock. In this lower part of the cave there was a well, 9 m deep, that provided access to an underground vein of water. The diameter of the well was ~ 2 m at the surface and 4 m near the bottom.

The spring ceased to be in use, as its lower part was covered with soil, probably due to an earthquake or landslide. However, the upper part of the cave remained intact and was used during antiquity, and in subsequent periods, as a secret passage, since it has a second exit to the north slope of the rock. Actually, this passage is linked to a heroic moment in recent Greek history. During the Nazi occupation in 1941 two students, Manolis Glezos and Apostolos Santas, used this passage to reach the Acropolis and take down the Nazi flag.

Clepsydra

Clepsydra, the most important fountain and spring of the Acropolis, is located inside a cave on the northwest of the Acropolis at the point where the ancient streets *Panathenaic Way* and *Peripatos* met (***Fig. 12***). Its name gives us an important clue about the nature of this spring, since the word κλεψύδρα in Greek means *"stolen water"* and was given to the spring because its water appeared and disappeared from time to time. This is what we would expect from a karstic spring whose main source is the infiltration of rainwater in the limestone.

Although the cave spring was rediscovered in the second half of the 13th century BC during the works for the fortification of the Acropolis, it is well known that during the Neolithic period, the inhabitants of Athens were aware of the underground water vein in the area. In fact they opened 22 wells (3–5 m deep) to exploit it. The area was originally named after the nymph *Empedo*, who was related to water.

During the cited fortification works it was ensured that this cave spring, along with the *Asklepieion* spring house on the other side of the Acropolis, were located inside the walls, as these would provide protection and easy access to the valuable resource within the walls.

Kimon, who ruled Athens in the period 470–460 BC, transformed the spring into a fountain, including rectangular 56 m^2 flooring and a deep reservoir inside the cave with a staircase for access. There were frequent rock falls and landslide affecting the spring, but particularly in the 10th century BC a rock fall severely affected the fountain. Protection works were then carried out in the fountain against potential collapse of the overlying rock using wooden braces. Landslides in the 1st century AD compelled the Athenians to change the entrance to the fountain, but this entrance was also blocked by yet another landslide in the late 2nd century AD, depriving access to the spring from the Panathenaic Way. Then a well was opened in order to draw water through the fallen rock and above it a solid vaulted construction was created for protection. From this point an ascending vaulted corridor (70 steps) led to the foot of the bastion below the Propylaia, this being the only way to access the spring-house. During the Christian era the church of *St. Apostoloi* was built in the fountain.

The Clepsydra spring was used throughout the Byzantine period (4th–15th century AD) and was again repaired during the Frankish occupation (mid-13th century). The spring was completely abandoned during the Turkish occupation until it was rediscovered in 1822 by the Greek archaeologist Kyriakos Pittakis.

Southern springs

On the southern slope of the Acropolis stand the remains of the temple of *Asklepios*, god of healing for Ancient Greeks. To the west of the *Ionic stoa*, one of the auxiliary buildings of the temple, a small fountain house has been discovered, dating from the end of the 6th century BC. The width of the fountain house must have been about 3 m internally and therefore about 4bm externally. It is believed that the entrance to the fountain was through a kind of porch, which was demolished in the 4th century BC, when the well was covered with earth and was no longer used.

In the early Christian period, around AD 450, the temple of Asklepios was demolished to be replaced with a Christian temple that was built using the same building material. Interestingly this new church was devoted to the saints Anargyroi (two brothers who were doctors), considered also saints of healing, and the spring was used for its "holy" water. This is a common phenomenon in the transition from idolatry to Christianity in Greece, that the ancient Gods are replaced with Christian saints who are considered "protectors" of the same characteristic, i.e. health, travel, family, crops, etc.

Caves of Acropolis

The cave of Clepsydra has already been mentioned above, but there are other caves in the slopes of the Acropolis worth mentioning.

Apollo's altar in the cave: near Clepsydra is the altar-cave of Apollo. After the election of the nine archons of Athens, it was usual for them to take an oath in the altar of *Apollo Patroos* and then to come here to take a second vow. Among other things they vowed that if they did not govern correctly or if they became embezzlers of public property they would create a golden statue of Apollo Pythiou-Patroou inside the altar. When their service was finished they offered a marble plaque with sculpted laurel and myrtle wreaths in memory of their successful service for the public good. An abundance of such plaques were found inside the cave and the area around it.

Cave of Zeus Astrapaios: right next to the cave of Apollo there is a second, more

Figure 10: Aerial view of Acropolis. Google Earth 2013.

Figure 11: Old karstic conduction on the Acropolis limestone.

impressive cave, dedicated to Zeus. Every spring the *Pythaists* waited inside the cave for a bolt of lightning, a sign from Zeus appearing on the top of Arma hill in Parnitha Mountain, in order to begin their course towards Delphi. The Pythaists were chosen Athenian citizens who represented the city during the Delphic celebrations of the Pythians. When the Pythaists returned from the Delphic altar they brought back fire, "new light", to purify the altars of Athens. Recent geological investigations have started a controversy on whether gas emissions from a geologic chasm in the earth could have inspired the Delphic Oracle to "connect with the divine". (Piccardi *et al.*, 2008; Spiller *et al.*, 2008); this is another interesting relation of Ancient Greece mythology and geology.

Cave of Pan: next to the cave of Zeus Astrapaios and a bit to the east another small cave was found, dedicated to the god of woods and shepherds, Pan. The worship of Pan came to Athens late, after the victory of Marathon in 490 BC. Tradition has it, according to the sayings of Herodotus, that Pan appeared in the battlefield of Marathon, spread terror to the Persians and helped the Athenians win even though they were fewer. The Athenians, grateful for this victory, decided to honour Pan here and also organised a torchlight procession. They carved small niches into the rock and placed their oblations, statues, flutes and even delicacies there. The cave of Pan is known to us from the work of Aristophanes, *Lysistrati*. During the Christian years the sacred cave of the goat-legged god became Saint Athanasios' church.

Mycenaean Drinking Fountain - Ersis's Cave: an impressive cave is situated a bit to the east and is attributed to *Aglavros*, the daughter of Cecrops. Recent research has shown that this was the altar of Ersis. This cave is in fact a drinking fountain, formed when the Mycenaeans surrounded the Acropolis with walls during the second half of the 13th century BC. Its entrance was found on the Acropolis near the Erechtheum. The Mycenaean drinking fountain was barely used (for only 30 years), as is obvious from the vases that were found. It is probable that a landslide covered the fountain and as a result its bottom section was forgotten, while the upper part was used as a secret exit of the Acropolis.

The altar of Aphrodite in the garden: here, the worship of Aphrodite replaced that of the Mycenaean goddess with the doves worshipped as the goddess of fertility near the Mycenaean entrances of the Acropolis. In this shrine of the goddess of love and fertility a group of *Arrifores* performed a ceremony one summer evening, a revival of an old agricultural custom whose purpose was to reinforce the fertility of the ground. Here also on the ancient worshippers placed their oblations in carved niches in the rock of the shrine. At the same location many dedicative signs for Aphrodite and love were found.

Moving on, towards the northeastern side of the Acropolis we can see the neighbourhood called *Anafiotika*, outside the walls. Small white-washed houses with narrow alleys remind us of the villages of the Cycladic islands. This picturesque quarter was built in the middle of the 19th century by craftsmen from Anafi Island.

Conclusions

The sacred Acropolis hill, along with its famous monuments, has a long human-related story linked to its obvious morphological and geological features such as its hydrogeology and its karstic caves, and the mighty consortium also has a close relation with Greek mythology.

But the rock, aside from its incredible historical antecedents, also hides a spectacular geological secret: the limestone underlying the temples – dated from the Upper Cretaceous (more than 100 my ago) – was initially a soft mud sediment, deposited 120 km south of its current location. Later on the calcareous mud consolidated and transformed into a limestone by diagenetic processes. Then a colossal but extremely slow continental collision of the Alpine orogeny during the Upper Eocene moved the recently created rock over the overlying schist of the Athens Schist Formation by a process called thrusting and brought the limestone to where it is today. Such geological structure in geological terms is called a klippe. The evidence of that long journey can be observed in a special type or rock called cataclastite in the foot of the hill. Erosion did the rest and left the limestone hill isolated and surrounded by the younger schist, as found by the first dwellers of Athens.

Sacred land and geology meet in the rocky heights of Athens. Understanding both features is probably the door to sustainable use of the archaeological site.

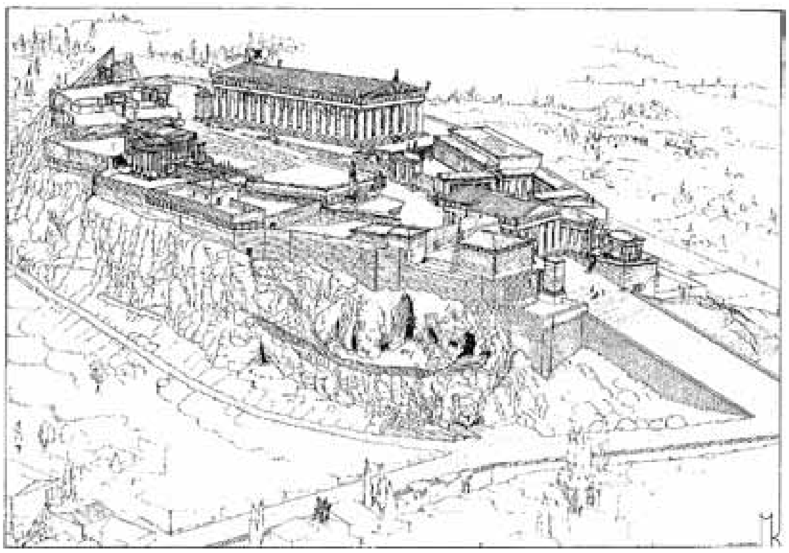

Figure 12: View of the Acropolis from the north west. The Clepsydra fountain is seen in the front. Source: Hurwit (2004).

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How rocks were used: an archaeopetrographic history of the Middle Dnipro Area, Ukraine

*Ihor Nikitenko**

On the basis of petrographic research of stone artefacts the means of usage of rocks by the population of the Middle Dnipro Area from the Neolithic Age to the Medieval Times were identified and major mining centres and trade routes were determined. Mining in the region started in the Neolithic Era, when people began to use rocks of the Ukrainian Shield for the production of stone tools. In the Bronze Age the region exported stone tools and talc casting moulds to neighbouring areas. In the Early Iron Age rocks were mainly used to produce sculptures and millstones. With the advent of stone architecture in the Middle Ages the centres of building stone mining were founded.

Sur la base de recherche pétrographique de pierres taillées, les diverses utilisations des roches par les populations de la région du Moyen Dnipro, depuis le Néolithique jusqu'au Moyen Age, ont été reconnues et les principaux centres miniers et routes commerciales, déterminés. Les travaux miniers dans la région commencèrent au Néolithique quand la population commença à utiliser les roches du Bouclier Ukrainien pour fabriquer des outils en pierre. A l'Age de Bronze, la région exporta, dans les régions voisines, des outils en pierre et des moules à talc. Au début de l'Age de Fer, les roches furent utilisées pour la sculpture et la fabrication de meules. Avec l'arrivée de l'architecture à base de pierres, au Moyen-Age, les carrières d'extraction de pierres à bâtir ont été créées.

Sobre la base de la investigación petrográfico de los objetos de piedra se identificaron los usos de las rocas por la población de la Zona Oriente Dnipro desde el Neolítico a la época medieval, y se determinaron los principales centros mineros y las rutas comerciales. La minería en la región se inició en la era neolítica, cuando la gente comenzó a usar rocas del Escudo de Ucrania para la producción de herramientas de piedra. En la Edad de Bronce la región exportó herramientas de piedra y moldes de fundición talco a las áreas vecinas. En la Edad de Hierro temprana las rocas se utilizaron principalmente para producir esculturas y piedras de molino. Con la llegada de la arquitectura de piedra en la Edad Media se fundaron los centros de minería de piedras de construcción.

The usage of mineralogical and petrographic methods in archaeology began as early as the 19th century, when in 1863 French mineralogist Alexis Damour carried out the first analysis of Neolithic stone tools. Since then these methods have been widely used for the research of stone artefacts and the determining of their origin. Nowadays archaeological petrography is considered as a sub-discipline of archaeological science, or archaeometry. It helps archaeologists to get more information about the usage of rocks in different times and even to reveal ancient trade routes.

The most interesting region for the archaeopetrographic research in Ukraine is the Middle Dnipro Area (***Fig. 1***). Firstly, it is connected to the location of the Ukrainian Shield outcrops in the valleys of the river Dnipro (Dnieper) and its feeders. The region is also rich in sedimentary rocks, which are spread throughout the territory of the Ukrainian Shield and outside of this zone in the southern and northern parts in the Left Bank Area.

The archaeopetrographic research of the Middle Dnipro Area was started in the 1950s by Petrun. His research work was focused on the Kryvyi Rih district (***Fig. 2, site 7***), which was considered by him as a Bronze Age centre of diabase, talc schist and other rocks mining (Petrun, 1969). The research of talc artefacts was continued by Sharafutdinova, who supposed that talc schists could have been mined both in the Kryvyi Rih district and in the area of the Dnipro rapids (***Fig. 2, site 8***) (Sharafutdinova, 1985). My petrographic study of stone artefacts from the Kryvyi Rih district showed that many stone tools were not of local origin (Nikitenko, 2009). Therefore, outcrops throughout the Middle Dnipro Area could be potential places of mining and all the region could be regarded as a stone-mining province.

Besides the Bronze Age stone artefacts, systematic archaeopetrographic studies were carried out of Chernyakhov culture tuff millstones (Khavliuk, 1980) and medieval pyrophyllite spindle whorls. To this entire list we can add numerous random

Figure 1: Location of the Middle Dnipro Area.

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Figure 2: The main ancient mining centres of the Middle Dnipro Area with their main stone raw materials: 1 – Ovruch (pyrophyllite schists and quartzites); 2 – Novhorod-Siverskyi (quartz and glauconite-quartz sandstones); 3 – Yemilchyne (dolerites); 4 – Fastiv (granitoids); 5 – Kaniv (quartz and glauconite-quartz sandstones); 6 – Hirskyi Tikych valley (amphibolites); 7 – Kryvyi Rih (dolerites, metadolerites, diabases, amphibolites, talc schists, granitoids, limestones, ferruginous quartzites, metasandstones); 8 – Dnipro Rapids Area (amphibolites, dolerites, metadolerites, granitoids, talc schists, limestones); 9 – Southern Left Bank Area (sandstones, granitoids).

petrographic studies of different artifacts.

Thus, today we have numerous evidence of the development of mining in the Middle Dnipro Area in ancient times; however, this information is fragmentary and it is not always based on petrographic analysis. During the last five years a number of archaeopetrographic studies have been carried out to form the overall picture of the stone mining development in the region from the Neolithic Age to the Middle Ages. Today we can already draw some conclusions about the main features of raw stone materials usage in this area during the period.

Figure 3: Talc atlatl weight.

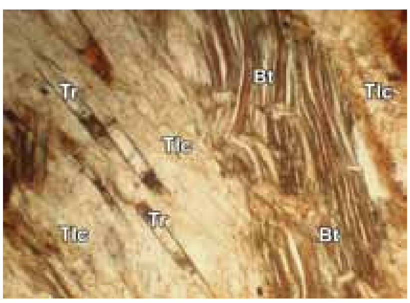

Figure 4: Tremolite-biotite-talc schist (talc vessel). Tlc – talc, Bt – biotite, Tr – tremolite. Transmitted light, nicols (–), 90ˣ.

The purpose of the work is to build a historical model of the usage of raw stone materials of the Middle Dnipro Area from the Neolithic Era to the Middle Ages. Current research is based on petrographic analyses of more than 350 artefacts and numerous specimens from outcrops and collections. The artefacts were taken from the collections of museums, archaeological scientific institutions, expeditions, and private collections of different regions. The petrographic method is destructive because of the need to produce a thin section. Therefore, only damaged or less important artefacts were investigated. The methods of x-ray structural and chemical analyses were also used when it was necessary and possible.

Neolithic Age

The Neolithic Era is the time of the invention of agriculture and mining. The Neolithic culture expanded to the Middle Dnipro Area in the 6th millennium BC. Partially because of the lack of flint, which was imported to the region, the Neolithic population of the river Dnipro valley actively used local stone materials for the production of different tools such as polished axes, hammers, hoes, abrasive stones, etc. A specific peculiarity of the Neolithic Age was the usage of talc schists for the production of atlatl stone weights (***Fig. 3***); besides this, talc rocks were used as a material for vessels. For the production of axes, hammers and similar tools people mainly used dolerites, metadolerites and amphibolites, which form outcrops among granitoids of the Ukrainian Shield. The discoid hoes were produced of gneisses, granites, diorites, epidosites, amphibolites and vein quartz. The abrasive stones were made of sandstones, metasandstones, tremolite-chlorite schists and tonalites (Nikitenko and Kutsevol, 2012). The petrographic research of some talc artefacts from different places showed that their raw materials can be of the same origin because of similar petrographic features and a tremolite-biotite-talc mineral association that is rare for the Ukrainian Shield (***Fig. 4***). This fact can prove that the mining of talc rocks was specially carried out for exchange (Nikitenko, 2012).

Eneolithic-Bronze Age

The Eneolithic-Bronze Age (5500–900 BC) was a period of the most active usage of raw stone in the history of the Middle Dnipro Area. This was caused by the high price of metal, which was imported from other regions. Similar to the Neolithic Age, in the Eneolithic–Middle Bronze Age stone was used for the production of axes, hammers and maces, and in addition carved stone sceptres appeared. In the Middle Bronze Age these tools, with the exception of big hammers, turned into symbols of power. They were smaller and more decorative, sometimes with carving (***Fig. 5***). In the Late Bronze Age the mining of talc rocks was renewed as a material for metallurgical casting moulds. The Bronze Age was a period of wide usage of rocks as a material for steles.

The main raw materials for the production of axes, hammers and maces were dolerites, metadolerites, amphibolites and diabases. The production of such tools was carried out in special workshops located near the outcrops. The highest concentration of such centres was in the area of the Dnipro rapids (***Fig. 2, site 8***). Evidence of the delivering of stone tools from this zone to the steppe territories is provided by the analysis of a stone axe that was found in the

Left Bank Area in Mezhyrich (Dnipropetrovsk region). The tool was made of dolerite, and from the content of micropegmatite (***Fig. 6***) and chemical properties, it is similar to the dolerites from the Dnipro valley. Particularly, this type of dolerite was used in the Strilcha Skelia workshop. Also, according to petrographic research, stone axes and similar tools were supplied to the northern part of the Middle Dnipro Area and beyond.

Also, the petrographic research of conventional tools and goods such as hammerstones, burnishers, pestles, grain grinders, different abrasive stones (grindstones), hoes, altars, etc. from different places was carried out. For their production people used such rocks as granites, gneisses, dolerites, diabases, amphibolites, schists, epidosites, diaphthorites, tectonoblastites, ferruginous quartzites, aplites, metasandstones and quartz sandstones with different cements and limestones. Craftsmen mainly used local stone materials, but exchange also occurred. Left bank tribes received igneous and metamorphic rocks from the right bank of the river Dnipro; at the same time they sent sandstone to some parts of the Right Bank Area where there was a lack of such rocks. The population of the northern part of the Middle Dnipro Area mainly received amphibolite tools from the valley of the Hirskyi Tikych river (***Fig. 2, site 6***) and dolerites from Yemilchyne district (***Fig. 2, site 3***) (Nikitenko and Lysenko, 2014).

In the Late Bronze Age (1800–900 BC) the southern part of the Middle Dnipro Area, notably its right bank, turned into a centre of talc rocks mining. Talc workpieces for casting moulds and production of other goods were delivered to other regions. Talc moulds have been found in Central, Eastern and Southern Ukraine, and outside the country. The intensive mining and export of talc rocks was connected to the heat resistance of these rocks; besides, they are very easy to carve. Petrographic research of talc moulds and goods from the Donbas and Kyiv region confirmed their origin from the southern part of the Middle Dnipro Area.

Figure 5: Stone axes.

Figure 6: Dolerite (stone axe from Mezhyrich). Pl – plagioclase, Cpx – clinopyroxene, Mcp – micropegmatite, Mgt – magnetite. Transmitted light, nicols (+), 37^x.

Stone materials were widely used in sculpture. Stone steles were widespread in the steppe zone – the southern part of the Middle Dnipro Area. The material of the steles is presented by granites, gneisses, migmatites, quartzites, metagravelites, sandstones, shell and oolitic limestones. It was determined that people used local stone materials for the production of statues. In the Left Bank Area they used sandstones, in the zone of the Ukrainian Shield masters carved local igneous and metamorphic rocks, while in the southern part of the region they took local limestones. Also, stone materials were used in building, especially in burial construction, where plates of gneiss, schist, limestone and other rocks were applied.

Early Iron Age

In the Early Iron Age (900 BC – AD 500) iron started to replace raw stone as a material for the production of tools. The main directions where stone materials retained their positions were sculpture, building, production of different abrasive stones and grain grinders.

During the first centuries of the Iron Age people continued to use stone tools similar to those of the Late Bronze Age. The changes are connected to the Scythian culture (700–300 BC). The main Scythian monuments in the Middle Dnipro Area are concentrated in the south of the region, where the Scythians kings lived and the richest Scythian burials are located.

According to petrographic research, for the production of abrasive stones Scythians used sandstones and granites. The analysis of grain grinders showed that the main materials for their production were local sandstones with different cements, granites and limestones. One of the analysed granite grain grinders was delivered from the area near the Sea of Azov. Also Scythians used stone materials such as amphibolites, dolerites, limestones and quartzites for the production of rounded sling stones.

Scythians had a developed sculpture. Most Scythian sculptures were anthropomorphous (***Fig. 7***). The analyses showed that in the Middle Dnipro Area Scythian craftsmen used granites and limestones for their production; furthermore, as in the previous epoch, all the statues were made of local raw stone.

Figure 7: Scythian statue made of plagiogranite. Height – 2.25 m.

The cultures of the Early Iron Age, which replaced Scythians, left far fewer stone artefacts. They continued to use the same rocks for the production of abrasives, grain grinders and sculptures. In the 1^{st} millennium AD the population of the Middle Dnipro Area started using rounded millstones. The most widespread materials for their production were sandstones and limestones. Also, during the period of Chernyakhov culture (AD 250–450) there was an import of tuff millstones from the territory of Vinnytsia region in the west (Nikitenko *et al.*, 2013).

Middle Ages

At the beginning of the Middle Ages the usage of stone materials in the Middle Dnipro Area was similar to the Early Iron Age. Significant changes began at the end of the 1^{st} millennium AD. They were connected to the development of stone building in the state of Kyivan Rus and to the bloom of stone sculpture in the steppe zone inhabited by Turkic tribes.

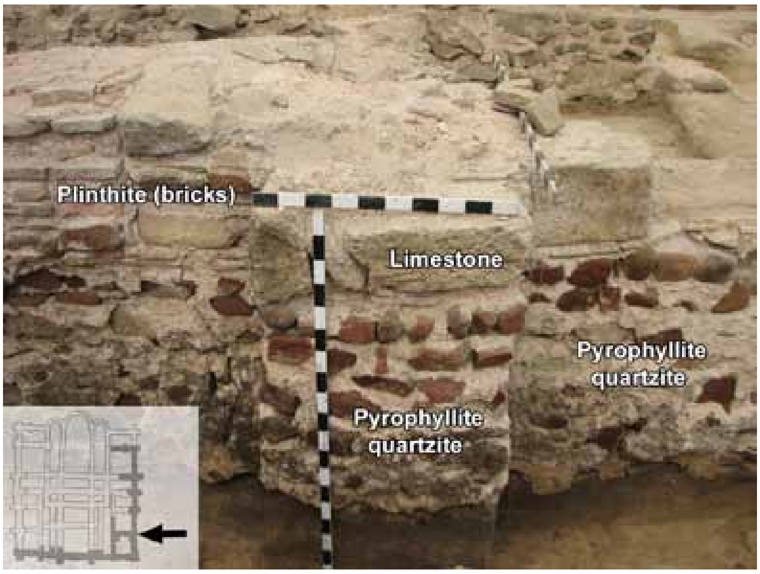

Figure 8: Foundation of the Church of the Tithes in Kyiv (Photo: D. Yolshin).

The new direction of stone usage was a development of pyrophyllite schist deposits around the city of Ovruch (***Fig. 2, site 1***). These soft rocks were used for the production of spindle whorls, which were widely distributed in Eastern Europe. Later these rocks were also used in architecture and plastic art.

The development of stone mining in Kyivan Rus was connected to the adoption of Christianity in AD 988, when the construction of stone cathedrals began. The first stone building was the Church of the Tithes (Desiatynna) in Kyiv (AD 996). There only the foundation of the church remains nowadays. The foundation can be divided into the two parts: the first was mainly built of quartz and glauconite-quartz sandstones from the Kaniv district (***Fig. 2, site 5***) and the other part was built of pyrophyllite quartzites from Ovruch (***Fig. 8***). The local rocks are presented by ferruginous, argillaceous sandstones and calc tuff. The rocks of the Ukrainian Shield such as granites, quartz diorites, quartz monzonites and cataclasites were also used. These rocks could have been delivered from the Fastiv district (***Fig. 2, site 4***). Surviving elements of the floor, walls and columns are presented by quartz-pyrophyllite schist from Ovruch, shell limestone from the Crimea, and marble from the Mediterranean (Nikitenko and Yolshin, 2009).

Figure 9: Outcrop of quartz sandstone in the former quarry in Novhorod-Siverskyi.

The second stone temple that was founded in Kyivan Rus was the Savior's Transfiguration Cathedral in Chernihiv. Its foundation was built of quartz and glauconite-quartz sandstones from the area around the city of Novhorod-Siverskyi (***Fig. 2, site 2***) (Nikitenko and Chernenko, 2013). Subsequent research of the other ancient buildings in Chernihiv region showed the same origin of the building stone. Conclusions were also confirmed by the petrographic research of the extant outcrops (***Fig. 9***). This fact permits us to consider the area around Novhorod-Siverskyi as a mining centre of the 11th–13th centuries.

The southern part of the Middle Dnipro Area was inhabited by nomadic Turkic tribes. The main stone artefacts that are left from the steppe nomads are their stone statues. The majority of surviving statues belong to the people of Polovtsians. Their statues were mainly made of sandstones with argillaceous, ferruginous and siliceous cements, granitoids, shell and oolitic limestones. Similar to the previous epochs, the statues with known origin were usually made of local raw stone.

Conclusions

From the Neolithic Age to the Middle Ages the Middle Dnipro Area was a territory with developed stone mining, which met most of its needs in raw stone and exported stone materials and goods to neighbouring regions. From the Neolithic to the Bronze Age the region was a centre, producing polished stone tools and weapons such as axes, hammers, maces, etc. made of dolerites, metadolerites, diabases, amphibolites and other igneous and metamorphic rocks of the Ukrainian Shield. All the main outcrops of these rocks throughout the Shield's territory were exploited by ancient miners. The most developed mining occurred in the Late Bronze Age in the southern part of the region, where talc schists were mined as a material for casting moulds.

From the Neolithic Age to the Middle Ages stone materials were widely used in sculpture. For the production of statues craftsmen mainly used local stone materials of different genesis. Also, within all the considered period people used raw stone materials of different origin for the production of grain grinders, millstones and abrasive stones.

With the development of stone architecture in Kyivan Rus in the 10th–13th centuries a number of mining centres appeared which produced building stones such as sandstones, quartzites, schists and granitoids. The majority of them were located in the areas around Ovruch, Kaniv, Novhorod-Siverskyi and Fastiv.

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Geoarchaeology at the microscale

L-M. Shillito*

One of the challenges of geoarchaeology is working with deposits that are created by both natural and cultural processes. Such anthropogenic deposits may be in the form of large, homogenous strata, but frequently they occur as thin lenses of material, subject to complex formation processes and depositional histories. A popular method for investigating the formation processes of anthropogenic deposits is thin section micromorphology. Originally developed as a tool for understanding the formation and structure of soils, micromorphology is now applied most extensively in archaeological contexts. Here we review the ways in which micromorphology is contributing to our understanding of early human history, from reconstructing the use of fire by early hominids, to understanding the origins of animal domestication and agriculture in the early Holocene.

L'un des défis de la géo-archéologie est la prise en compte des dépôts créés, à la fois, par les processus naturels et culturels. De tels dépôts anthropogéniques peuvent apparaître sous la forme de couches homogènes et de grande extension mais fréquemment, elles n'existent qu'en tant que minces lentilles de matériau, liées à un passé de formation et de dépôt complexes. La méthode en vogue d'investigation des processus de formation des dépôts anthropogéniques est l'examen de lames minces en micromorphologie. Développée à l'origine comme un outil pour comprendre la formation et la structure des sols, la micromorphologie est maintenant appliquée beaucoup plus extensivement aux contextes archéologiques. Ici, nous examinons de quelles manières la micromorphologie contribue à notre perception des premiers temps de l'histoire humaine, depuis la reconstitution de l'utilisation du feu par les premiers hominidés jusqu'à la compréhension des origines de la domestication animale et de l'agriculture, au début de l'Holocène.

Uno de los retos de la geoarqueología es de trabajar con los depósitos creados tanto por procesos naturales como culturales. Tales depósitos antropogénicos pueden estar en la forma de grandes estratos homogéneos, pero con frecuenca se producen como capas delgadas de material, sujeto a procesos de formación complejos e historias de deposición. Un método popular para la investigación de los procesos de formación de depósitos antropogénicos es la micromorfología de sección delgada. En un principio se desarrolló como una herramienta para comprender la formación y la estructura de los suelos, sin embargo actualmente la micromorfología se aplica más frecuentemente a contextos arqueológicos. En este artículo revisamos las formas en las que la micromorfología está contribuyendo a comprensión de nuestra historia humana temprana, a partir de la reconstrucción del uso del fuego por los primeros homínidos, a la comprensión de los orígenes de la domesticación de animales y la agricultura a principios del Holoceno.

The study of formation processes is an essential step in being able to interpret human activity in the past, and it is here that geoarchaeology has an incredibly important role to play. There are some activities that leave visible traces in the archaeological record, such as building architecture and other structures. However many anthropogenic sediments, created by human action rather than natural processes, can be a challenge for the geoarchaeologist. This is because many of the deposits that arise from human activity leave only microscopic traces, and are difficult to detect using macroscale methods. Even in the case of large, visible deposits, such as hearths, there is more to the deposits than meets the naked eye, and the picture is complicated further by the possibilities of post-depositional processes modifying the record. How then can we approach these deposits? Thin section micromorphology lends itself particularly well to such investigation, as it enables the researcher to look simultaneously at the deposit microstructure, the microscopic inclusions within it, and the associations between these inclusions *in situ*.

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Thin section micromorphology is a technique whereby an intact block of soil or sediment is collected from a stratigraphic section, set in resin, and turned into a thin section slide so that the characteristics can be viewed under the microscope (***Figure***

Figure 1: Sediment block set in resin and sliced (left) and the final slide (right). Images courtesy of Earthslides.com. Micrographs show close ups of these floor layers from the Neolithic settlement of Kamiltepe, Azerbaijan, showing layers of dust that accumulated underneath a reed mat (1), fine layers of domestic debris including bone fragments and charcoal (2) and the transition between a packed earth floor and overlying layer of domestic debris, with lenticular gypsum crystals from post-depositional drying out of the sediments (3). Kamiltepe is excavated by a team from the German Archaeological Institute.

1). As with petrographic thin sections these are finished to a standard thickness of 30 microns. Sediment micromorphology applies the methods and concepts of soil science to archaeological sediments to describe the depositional characteristics of deposits, based on standardised descriptive criteria (Stoops 2003, Bullock *et al.* 1989). These characteristics in turn can be in interpreted to reconstruct human activity, through comparison with known materials, experimental samples and ethnographic analogues. Characteristics of materials deposited by human action are very different to those deposited by natural processes. For example, sediments laid by water or wind action tend to have degree of sorting, seen most clearly in varved lake sediments. Human action on the other hand, such as the discard of domestic debris, tends to create unsorted, highly mixed deposits. Taphonomic studies have identified micromorphology linked to trampling, such as fragmentation and dip in the orientation of bone inclusions.

The beginnings of soil micromorphology are traced back to the publication of Micropedology in 1938 by Walter L. Kubiena, where the technique became central to understanding the formation of soils and their classification. Although it has fallen out of fashion in soil science, the past two decades have seen a rapid surge in applications in archaeological contexts for the study of ancient soils and agriculture, as a tool for understanding the formation processes of anthropogenic 'sediments', and to provide a microstratigraphic framework in which to interpret analyses such as geochemistry. The major applications and advances in this area now arguably come from archaeology rather than soil science (Stoops 2010). Much like the wider discipline of geoarchaeology, archaeological sediment micromorphology has been applied to a wide variety of site 'types', from open air, cave sites, early settlements and urban sites, each of which present their own challenges. Micromorphology is providing important contributions in identifying deposits and addressing some of the key questions about the human past such as the earliest use of fire, animal domestication, the creation and use of settlement space, and resource exploitation.

Investigating the earliest use of fire

Understanding how and why our early ancestors' first manipulated fire is one of the key questions in archaeological research. The use of fire in the archaeological record may be recorded in the form of charcoal, but

Figure 2: Hearth deposit at Qesem Cave (image courtesy of Ruth Shahack-Gross).

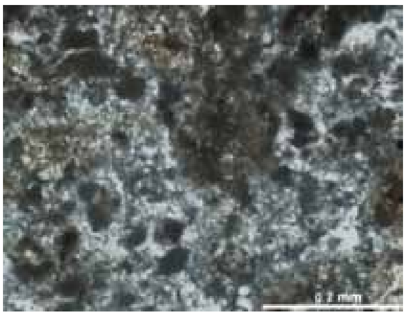

Figure 4: Micrograph showing detail of ash deposits

the preservation of this material depends largely on the context and preservation environment. Charcoal only preserves in fires of low temperature or short duration so in many cases charcoal is completely burnt away, leaving only ash residues behind. The rise of microscopic geoarchaeological techniques has completely changed the level of information that can be gained from ash deposits (Braadbaart *et al.* 2012). From the earliest use of fire to the increasing sophistication of pottery production, and eventually metal production, in later prehistory, early cultures became aware of the properties of different types of fuel for different activities. Geoarchaeological approaches have played a key role in understanding these processes. Microscopic and geochemical analysis of ash deposits can reveal the type of fuel that was used, as the crystal morphology and composition of ash varies between different fuels. Wood based fuels leave ash residues that are high in calcium carbonate, with distinctive rhomb-like crystals (Canti 2003). Grass based fuels on the other hand are high in biogenic silica, which lacks birefringence

Figure 3: Thin section slide through hearth deposits

under cross polarised light, and forms silica 'casts' of plant tissues or phytoliths, which can help identify the genus or species. Animal dung has a high carbonate component, and may also be high in silica if the animals were consuming grasses. The presence of calcareous spherulites and dung pellet pseudomorphs in undisturbed thin sections can distinguish between these different depositional pathways. Calcareous spherulite particles form within the guts of certain animals, and are used frequently in archaeology to identify the presence of animals. Under cross polarised light they have a distinctive extinction cross. Often we can see a mix of different fuel types, or even evidence of 'refuelling' episodes within one ash deposit.

Using a combination of thin section micromorphology and FT-IR (Fourier-transform infra-red) spectroscopy, Shahack-Gross *et al.* (2014) have uncovered evidence for some of the earliest habitual human use of fire at Qesem Cave, Israel. Infra-red spectroscopy uses infra-red energy to study the chemical structure of molecules. Molecules absorb specific frequencies characteristic of their structure, producing vibrations linked to molecular bonds or groups. An FT-IR spectrum shows the absorbance or transmittance of IR light against frequency or wavelength. When combined with thin section microscopy, this technique can distinguish between different crystalline forms of ash, and the spectra of clay deposits on which a fire has been built can also give an estimation of the temperature of a fire, due to alterations in these minerals during heating.

Organic geochemical approaches to detecting early animal domestication

Combining geochemical techniques such as FTIR is a common approach to augment visual data from micromorphology. Inorganic techniques are now well established, and organic methods are beginning to show promise. One of the big questions that archaeology seeks to understand is the process by which animals were first domesticated. By studying morphological changes in animal bone assemblages, it is possible to distinguish between wild and domestic varieties of species such as cattle, sheep and goats. However it can take centuries, if not longer, for these morphological indicators to appear. Preceding this is a long transitional period of time where it is impossible to distinguish between 'wild' and 'domestic'. Geoarchaeology can address this question from an alternative perspective. It is not only their bones that animals leave behind, they also leave their dung. If wild animals were hunted and then brought to a site for food, we would not expect to see animal dung on a site. However, if wild animals were being kept on site during the process of early animal management, prior to true domestication, we would expect to see accumulations of dung on a site. This is the hypothesis that was tested by Matthews *et al.* (2013) as part of the Central Zagros Archaeological Project. Researchers from the University of Reading have identified the earliest evidence of animal management, prior to domestication, in the form of compressed layers of animal dung within an enclosed area of Sheik e Abad, a small Neolithic settlement in the Central Zagros region of Iran. The layers of animal dung were initially thought to be fine plaster floors, but thin section analysis under the microscope revealed dense accumulations of amorphous and fibrous organic material along with small calcareous spherulite particles. By careful sub-sampling of the sediment blocks prior to resin impregnation this hypothesis was further tested by GC/MS analysis of the preserved lipid residues, which showed that the amorphous organic material contained high quantities of coprostanol and bile acids, consistent with human and animal faecal material (Shillito *et al.* 2013), lending further support to the identification as animal dung.

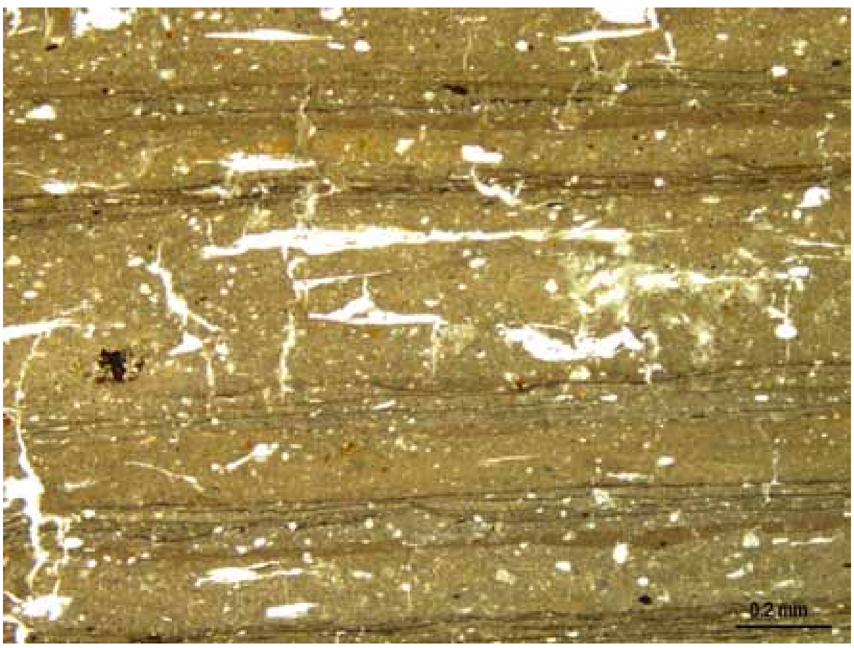

Figure 5: Thin section of wall plasters from Çatalhöyük Building 1 showing thicker wall surface and multiple finer 'painted' layers.

Building and decorating a Neolithic home

The rise of micro-geoarchaeological methods has led to an increased understanding of the ways that sediments can be used to understand human activity in the past. Analysis of the microscopic characteristics of sediments and sediment based artefacts, such as mudbricks and pottery, enables researchers to make inferences about human behaviour. For example, Love (2012) used a combination of geochemical and microscopic analyses to identify the composition of mudbricks at the Neolithic site of Çatalhöyük in Turkey. By looking at the spatial distribution of different mudbrick 'recipes', it was observed that the source materials used for making mudbricks remained the same for different houses, however variations in the texture and organic content was attributed to the addition of different mixing materials, suggesting independent manufacturing processes between households rather than a centralised production system.

Within prehistoric houses, thin section micromorphology of floors can reveal different activities that were occurring in different parts of the building. Microscopic 'dust' layers for example in floor layers at the site of Kamiltepe, Azerbaijan, indicate that these areas were once covered by reed matting. The layer of fine material is all that remains of domestic debris that escaped the sweeping seen in other rooms. ***Figure 1*** shows how we can observe multiple layers of floors that demonstrate household maintenance, with evidence of different activities occurring over the lifetime of the building. In the earliest layers we see relatively clean floors, whereas later we see the build-up of finely trampled bone and charcoal. The floors are re-laid, and accumulation begins again.

Not only do these type of studies help understand the social habits of the people, but they also give insights into the landscape that they inhabited. Analysis of geological materials used for wall and floor plasters at Çatalhöyük (***Figure 5***) has shown that several different sources of sediment were used, and specially selected for particular activities. These sediments have been sourced on the basis of their micromorphology and geochemistry to different parts of the landscape, and show how far people were willing to travel to acquire these resources.

Viking trade and medieval ruins

Geoarchaeology has a particularly important role to play in the archaeology of historic periods in addressing research questions that are difficult to tackle using historic documentary sources, for example in understanding the relationships between people and their environments, and the exploitation of natural resources in the past. At the site of Biała Góra in Poland, thin section micromorphology of soils indicated a high quantity of micrososcopic anthropogenic debris including bone, mortar and brick fragments (Pluskowski *et al.* 2014), indicating the presence of human activity when no architectural remains were present. The transition from the Viking Age to the Medieval period around AD 1050 is associated with the expansion of trading activities in the North Atlantic region, associated with increased exploitation of marine resources and agriculture. Thin section micromorphology has been used in Orkney to understand the timing and nature of these processes. Analysis of midden sediments demonstrated that intensification of fishing activities occurred prior to increased agricultural activities (Simpson *et al.* 2005). Historic studies can act as an important frame of reference for geoarchaeological analyses in earlier periods. By applying thin section micromorphology to abandoned turf buildings in Iceland from the 19th and 20th centuries, Milek (2012) was able to make comparisons between this analyses and detailed descriptions of construction materials and methods, and use of space within the buildings, provided by a former resident. The analyses showed that only a limited range of daily activities produce signals which can be detected under the microscope, however more infrequent building maintenance events, such as the laying of fresh turf, were highly visible.

Acknowledgements

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Archeogeology, Conservation Challenges, and Contemporary Lessons of the UNESCO World Heritage Site at Petra, Hashemite Kingdom of Jordan

*Barney Paul Popkin**

The UNESCO World Heritage Site at Petra, Jordan, has long intrigued and been investigated by both ancient and modern peoples from Nabataeans, Greeks, Romans, and Crusaders to modern Europeans and Americans. The Site's intimate relationships between rocks and tectonics, architecture and engineering, agriculture and trade, water resources and management, and human settlement and restoration has implications for contemporary planners, architects, engineers, and managers. This article summarizes published studies and notes personal observations from a practicing hydrologist/ geologist privileged to have attended Jordanian Archeology Conferences and Smithsonian Associates' short courses, and have visited the Site several times to develop its water resources for irrigation of medicinals and forage. In brief, Nabataeans produced awesome art, architecture, and water-resources civil works, from which modern societies may learn how to collect, treat, store, convey, and use limited water resources.

Le Site de Petra, en Jordanie, site du Patrimoine Mondial de l'Humanité (UNESCO), a pendant longtemps intrigué puis a été étudié à la fois, par les populations anciennes et modernes, depuis les Nabatéens, les Grecs, les Romains et les Croisés jusqu'aux Européens et Américains d'aujourd'hui. Les relations étroites entre la nature des roches et la tectonique, l'architecture et l'ingénierie, l'agriculture et le commerce, les ressources en eau et la gestion, et entre le peuplement humain et la restauration du Site, offrent des implications utiles pour les urbanistes, les architectes, les ingénieurs et les gestionnaires contemporains. Cet article résume les études publiées et les notes et observations personnelles émanant d'un praticien hydrologue/géologue privilégié puisqu'il a assisté aux Conférences Archéologiques de Jordanie et aux cours intensifs des « Associés du Smithsonian Institute » et visité le Site plusieurs fois pour développer ses ressources en eau pour l'alimentation de bains médicinaux et pour le forage. En bref, les Nabatéens ont fait montre d'un talent artistique impressionnant, et créé une architecture, des travaux civils pour l'aménagement en eau, connaissances que les sociétés modernes pourraient utiliser pour savoir comment on collecte, traite, stocke, distribue et utilise des ressources limitées en eau.

Petra, UNESCO Patrimonio de la Humanidad en Jordania, ha intrigado mucho y fue investigado tanto por los pueblos antiguos comomodernos, desde nabateos, griegos, romanos, cruzadas, a los modernos europeos y americanos. La intima relación entre rocas, y tectónica, arquitectura e ingeniería, agricultura y comercio, recursos hídricos y su gestión, y asentamientos humanos y restauración, tienen implicaciones para los planificadores contemporáneos, arquitectos, ingenieros y gerentes. Este artículo resume los estudios publicados y toma nota de las observaciones personales de un hidrólogo/geólogo privilegido de haber asistido a conferencias de Arqueología de Jordania y cursos cortos de Smithsonian Associates, y de haber visitado el sitio en varias ocasiones para desarrollar sus recursos hídricos para el riego de las plantas medicinales y de forraje. Resumiendo, los nabateos producieron arte, arquitectura, y sistemas hídricos impresionantes, de los cuales las sociedades modernas pueden aprender a recoger, tratar, almacenar, transmitir y utilizar los recursos hídricos limitados .

A vision

It was early in the first lunar month, Nisan, in mid-spring, Before the Common Era. The snowy and wet winter had passed along with the annual census. The census of course is performed annually to make a head county, pay taxes, and ransom the people for being enrolled in the Supreme God's protection and covenant and to support the army. Praise be Hamelach Haolam!

Ali was proud to have paid so much to his annual tax on his agricultural profits, especially his aged wine and his wife's sweet jams, and on his share of caravan-trading tariffs. He knew the funds from his and others assure the archery cavalry that protects his charming and hidden cracked-rock Petra City. Their taxes also support the major canal constructions as they expand from where the Supreme Unnamed God told Mousa to strike the rock and bring forth the eternal spring so many full moons ago. Mas boot, 'very good.'

Dawn in the Kingdom's capitol found Ali planning the week's tasks. He and his older sons Abdul and Nehustan would repair the winter storm damages to the glassed terra cotta pipes. They would raise the pipes higher in the main aqueduct canal to heighten the aeration fountains which purify the runoff-rain. They would lift up the smoothly crafted pipes to refresh the lateral canals with life-given water to irrigate the communal fields. The fields were routinely fertilized with the rich animal droppings which his wife Leah and daughters Dima and Wala'a, and his brothers' wives and daughters, collected from their communal grazing shoats. These practices the Nabataeans had learned and passed on for countless generations.

Once done with the pipes, Ali would remove the sediment from the wide and shallow, sloped settling basins forward to their communal rock-hewn cisterns. With the help of the whole family and his brothers' families, they would replace the now spent crushed crop-residue filters. The replaceable natural filters remove the runoff waters' rosy-red color and flour-like turbidity after leaving

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the settling basins before entering the water-storage cisterns. All would be well. Miya fil miya, '100 percent.'

As he recounted the family's winter food stocks stored in the rock catacombs, Ali was grateful to the Supreme Unnamed God who ruled the universe and brought forth the seasons and its bounties, and the female god who controlled the waters. Beseder, all is 'in order.' Another good year ahead, Baruch Hashem, 'Blessed be the name.'

Introduction

Water and rocks have indeed been *the foundations of life* for generations of nomads, settlers, traders, and tourists in the Jordanian desert. Petra's ancient practices of water resources-harvesting, and water and wastewater use, reuse, and management are of course rediscovered as contemporary practices of rooftop and surface harvesting, subgrade covered storage reservoirs. No doubt the ancient peoples of Petra and environs irrigated with wastewater as well, as Petra-area wastewater is now used for meadow and medicinal plants. ***Figure 1*** shows a location map of Jordan.

Information sources and limitations

This brief article is based on several site visits to Petra over the past 12 years, attendance to and participation in the Smithsonian Associates' short courses on Petra, and on the Archeology of the Syrian Desert and ACOR's Crossing Jordan 10th International Conference thereafter at Georgetown University in Washington, DC, and several articles, books and personal communication noted in References below. Sections from the cited articles and books are summarized, paraphrased, or quoted, with this author's interpretation.

There is much unknown about Petra.

Figure 1: Location map of Jordan.

Were elephants corralled there and used for labor or in caravans? Elephant sculptures were found in Petra, indicating a likely connection to India in Southeast Asia. Was bungee jumping practiced in Petra's steep cliffs? Were trapeze artistes popular on ropes from cliff to cliff? There are certainly steep cliffs at Petra and likely ropes of some sort. Was the main road, the Siq (*shaft*), used for donkey and camel races with on-track and off-track wagering? It certainly is suitable for animal races.

Did its resident farmers leave crop cuttings and such for grazing shoats (sheep and goats), donkeys and camels to leave their nitrogen- and nutrient-rich manure to fertilize their fields? Did they collect their food waste, human waste, and animal waste to make compost for fertilizers or soil amendments to add to their agricultural soils? They certainly had crops, shoats, donkeys and camels, and surely needed to add nitrogen and nutrients to their farmlands.

What did they interpret and how did they use the occasional winter snow for a water source? They surely experienced the uncommon winter snow and may have realized its very low salt content which would be suitable for leaching accumulated salts from farmland soils. Did they filter their collected and distributed water supply through sand, crop residues, hay or charcoal to remove its color, turbidity, and sediment, along with microorganism attached to clay particles? They surely noticed the red and yellow colors, turbidity, and sediment in their delivered water. Did the Nabataeans run a command-and-control environmental policy or use social marketing to promote sound environmental behavior? At present, these intriguing queries remain just that.

International conferences bring together experts who exchange research and push knowledge and insights forward. Such conferences, as this one organized by the American Center of Oriental Research (ACOR) with The Department of Antiquities of Jordan, nearly always evoke more questions. What were climatic and weather conditions, crops, cropping patterns, and soil and land modifications? Did farmers mix clay or loam into sandy soils so their crops would demand less water? Did they cover them to protect them from the sun to prevent burning and excessive evapotranspiration and crop consumptive use? What were there water harvesting and irrigation practices? Did they have knowledge and records for consumptive water demands for crops? Did they have Qantas? Did they have real wells, that tapped groundwater, like Jacob's well? Did they know the relationships between river (okay, Wadi) stage and discharge, even as nilometers of Egypt? Were the "wells" really man-made vertical shafts into the ground penetrating aquifer or were they really buried or open cisterns or tanks? Why so many? Were they lined?

How much hydrology did they know and manipulate and engineer? Was it based on trial-and-error, divine guidance, folklore, rigorous field testing, theory? Did their large surface reservoirs silt-up, evaporate much and concentrated salts? Were they used for artificial groundwater recharge? Were the dwellings or *qasrs*, etc. for year-round use or seasonal, and if so, under what circumstances? What caused "the end," drought, earthquake, conquest? Were some "splash pools," "fish farms," "clothing wash basins," "Jewish *mikvahs,*" "Christian baptismal baths?" How would one tell one from the other? Were the cisterns, tanks, pools, baths, etc., lined with impermeable barriers to reduce seepage losses? Did they understand mass water balance and the relationship between water flow rates and slopes, pipe hydraulics, water and wastewater treatment? How did they pressurize water pipes? How did they pump or lift water? How come we get little or no written words? Was water supplied for drinking and irrigation and wastewater treated at no charge as a public good, or was there a charge to manage demand and pay for capital and operations and maintenance? Were their bathrooms and pools clearly separated for "male" and "female," were there markings to so indicate?

How did they enforce their water-management practices? Through rigorous rules, regulations, monitoring and punishment, or through social marketing campaigns?

Background

The World Heritage Site at Petra, Jordan, established in July 7, 2007, is a major tourist attraction to this largely desert and regional politically stable and relatively safe country with its popular, democracy-leaning, authority- and tradition- respecting, socially tolerant, constitutional monarchy. The Hashemite Kingdom of Jordan is an ancient bridge and trade route to Europe, Africa, and Asia – a land of countless armies of Assyrians, Persians, Israelites, Greeks, Romans, Muslims, Christian Crusaders, Ottomans and refugees seeking shelter from Palestine, Lebanon, Egypt, Iraq, and now Syria.

Jordan's economy depends on Dead Sea phosphates and potash production, tourism, agriculture, and international donors. Tourism generates about 13 percent of its Gross Domestic Product (Teller, 2009, p.

8), much appreciated where the average annual income as GPD per capita is only about $6,100 in 2013 (CIA, 2014).

Jordan, which is 85 percent desert and about the size of Portugal or Indiana (Teller, 2009, p. 111), is among the most water-poor countries with an annual renewable water supply of less than 110 cubic meters per year as estimated in 2011 (World Bank Water Indicator, 2014), nearly a tenth of the Falkenmark Water Stress Indicator of 1,000. More alarming, its annual rainfall has been declining since the 1960s and its refugee population has been exploding. Jordan's water crisis is now well beyond "a race against time." It can only get more water-scarce until and if there are transnational water transfers, massive desalination, and extensive wastewater reuse program which would be funded by generous donors (USAID, 2008).

Petra, at 1,100 meters above mean sea level (AMSL) and 250 km south of Amman, 120 km north of Aqaba, and 100 km south of the Dead Sea, is an extraordinary architectural and inspiring tourist destination. As Jordan's prime tourist attraction, the several thousand year old city was carved from brown to red, friable to compact and hard Nubian Sandstone cliffs and hidden craggy mountains in a remote rift valley basin. Because of its several hundred years of occupation, modern planners and engineers can learn much from Petra's ingenious water management systems. At Petra, the Cretaceous and older age Nubian rests unconformably over crystalline rocks (Wikipedia, 2013).

Set in the north-south trade route and scene of countless prehistoric battles, the Nabataean Kingdom centered in Petra used the "King's Highway" to trade luxury goods between Arabia and Syria. When the Romans annexed the Kingdom, Emperor Trajan renovated the ancient road to improve travel and communication. Earlier, Moses was denied permission to travel the road by the Edom King. ***Figure 2*** shows the Nabataean Kingdom.

Some insights to Nabataean Culture

Looking at the mass of as well as the crevices and gaps between the large fingers which dominate the Nabataean Kingdom' map, there are few sources offering insight to Nabataean culture. Literary sources from Greeks, Romans and Jews are second hand. Art and architecture do not speak. Epigraphics, or rock carvings, were written by the Nabataeans themselves, so there study can be most revealing (Graf, 2014). From them, it's deduced that the Nabataeans were not a single people with a single culture, religion or languages, but a politically diverse umbrella of culture.

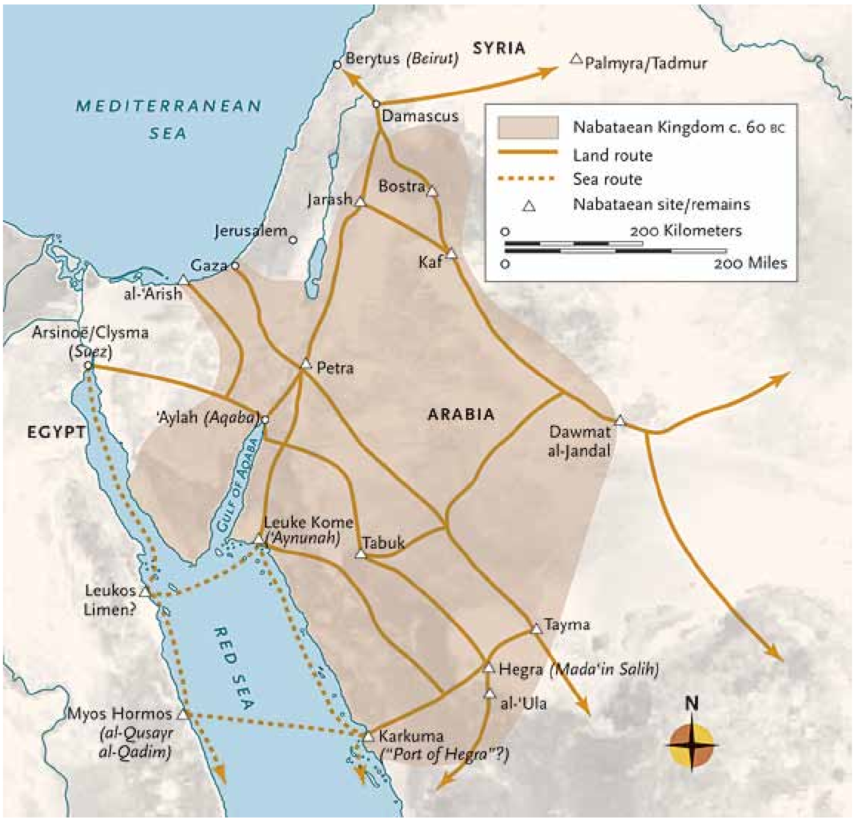

Figure 2: The Nabataean Kingdom.

They have many more horse inscriptions and figurine fetishes around their cities rather than camels. They used their horses for arrow-shooting cavalry for security and their camels as beasts of burden for desert caravans. Their alphabetic and ideographic script can be more-or-less read by readers of Aramaic and Hebrew. These people designed, built and operated a 26-km long aqueduct from three springs to two large rock-hewn reservoirs with 57 cisterns and terracotta pipes over bridges with culverts in the 1st century BCE. Some of their more ancient dried-ups springs they converted to cisterns. The seemed to have many Egyptian Isis statues, the Egyptian god who controls the Nile, from the 100 years BCE and earlier.

Their rock-cut ledges seem to be where religious ceremonies took place, especially during the beginning of their lunar year in the month of Nisan. A largely Aramaic people, but the names of their deities are not written, and their slaves seem to have had tattoos. Petra had a pottery kiln center at Wadi Mousa, and an archery armed, horse mounted cavalry at Petra. In Sinai and likely elsewhere, there are records indicating taxes paid and census taken for agricultural purposes.

Nabataean script is teaming with Aramaic and Hebrew letters. Nabataeans gathered year in Petra during early Nison from all over their Kingdom for religious services. Their scripts do not reveal the name of their gods. Only their slaves had tattoos. They were world class agriculturalists, traders and horseback warriors.

Petra Rocks

Petra is incredible, a breathtaking and during architectural and hydraulic masterpiece. Tucked in the Shura Mountains and shielded from the world by an impenetrable rock barrier, this fabled ancient city of ornate classical facades is steeped in a sense of mystery and drama. Since a Western adventurer stumbled on the site in 1812, it's fired the imagination. Two millennia of wind and rain blurred the once sharp edges of the facades and rubbed away its soft hematite-red and limonite-yellow russet sandstones.

Petra history brief

Its history is well documented by de Vries and Bikai (1993), ACOR (2007), Lawler (2007), Taylor (2007), Scheltema (2009), Ossorio (2009), (2009), and others, though has no living descendants or first-hand accounts to clarify it.

Early mention of the Nabataeans was in 647 BCE when they were listed as one of the enemies of the last Assyrian King Ashurbanipal. Then, the Nabataeans were a pastoral Bedouin or nomadic tribe inhabiting northern and western Arabia. They migrated from the arid Arabian Desert to the lush and temperate mountains of Edom, especially to the naturally well-watered and easily defended prize at Petra. They quickly developed their hidden village to become at first irrigated farmers and wine makers and then on to regional traders from Rome and the coastal Arabian Red Sea in the West and India and China in the Far East. By the first centuries BCE and CE, Petra had perhaps 30,000 residents. By 106 CE, it peacefully passed into Roman hands.

By the 1820s and 1830s, two British Royal Navy Commanders brought engravings and drawings of the "red-rosy city" to Europe. It induced a trickle of visitors. By 1890, Thomas Cook Travel Company offered tent or cave accommodations. The progressive Jordanian government ordered the Bdul Tribe to vacate Petra. UNESCO began to consider Petra for its List of World Heritage Sites in 1985. By 1990, the Petra National Trust began protecting Petra's environment, antiquities, and regional cultural heritage.

Today, a 900-square kilometer buffer zone protects the Petra site, while its 264-square kilometer core is defined as the strictly regulated Petra Archeological Park (PAP). Recent years have seen a host of new projects ranging from ongoing digs at several locations, major engineering works to repair the Siq road, upgrading tourist facilities and authorized guides, and beautifying Wadi Mousa town. In addition, substantial water supplies and wastewater collection, treatment and reuse systems for meadow irrigation and landscaping were developed with international donor funding. Much of Petra has been carefully mapped with three-dimensional laser precision technology for with Geographic Position Systems and populated to Geographic Information Systems, and surface geophysical surveys have been run to discover a network of dual staircases (BBC, 2014).

Petra current climatic conditions

Table 1 shows the current climatic conditions at Petra with respect to air average air temperature and rainfall.

During March-May (spring) and September-October (autumn), Petra is pleasantly warm, with highs around 25-30 °C and virtually no rain. In late May-early September (summer), it can be blistering hot during the day, even exceeding 40 °C. In November-December (winter), Petra can be cold, often below 10-15 °C during the day and below freezing at night; rain is expected and snow is not uncommon. Deserts, because of their aridity, may have a day-to-night time temperature range of tens of degrees.

Table 1. Petra climate at 1,100 meters above mean sea level.

Average Monthly	*January*	*April*	*July*	*October*
Air Temperature, °C	*4-12*	*11-22*	*18-36*	*14-24*
Rainfall, mm	*43*	*14*	*0*	*0*

Source: Teller, 2009, p. 15.

Petra monuments

The Nabataean Kingdom covered a roughly diamond-shaped area of about 200 by 250 kilometers. It included Sinai, Negev, much of modern Jordan, about half of northwestern Saudi Arabia, and a small part of southern modern Syria. Its trade linked and extended west to Rome, Athens, Rhodes, Cyprus, Antioch, Gaza, Alexandria and Cyrene, and south along the Red Sea coastal towns, and seaward east to India and China. The Nabataeans left extensive monuments and structures throughout their domain. These include, among other things, the Petra iconic Treasury, High Place of Sacrifice, the Monastery, the Colonnaded Street, the Great Temple, and numerous households, walls, walkways, staircases, border markers, temples, tombs, funeral chambers, and sundials. The recent decade uncovered aspects of the 11,000-sq m Great Temple at Petra and found elegant splash pool, six-stall bathroom with running water, various pools and well room, a 600-capacity amphitheater, an underground 103,000-gallon Great Cistern, an above-ground 19,600-gallon Cistern-Reservoir, an elaborate buried dual stairway promenade, and numerous rock-carved elephant heads decorating if not protecting columns. ***Figure 3*** show Petra's iconic Treasury Building.

The area was inhabited since the most ancient times, first by nomadic hunters and after by groups of farmers alongside shepherds who moved in search of pastures (Ossorio, 2009, p. 102). She notes (2009, p. 32-33):

The Nabataeans settled in the area of Transjordan in approximately 1000 BCE. Many aspects relating to their history prior

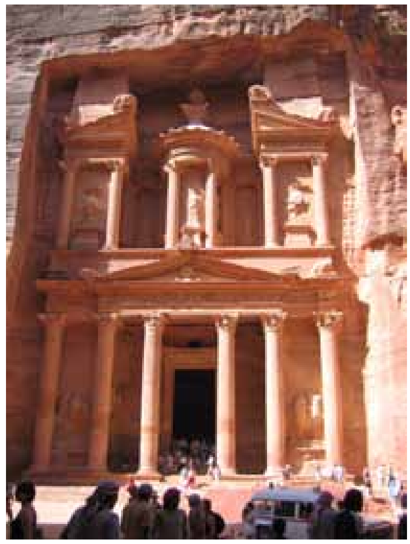

Figure 3: Petra's Treasury Building.

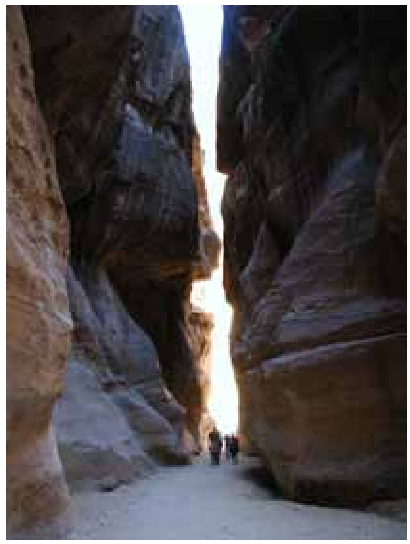

Figure 4: Siq (main road and flood drainage way) - entrance through rock to city.

to this date, as well as their precise origins and the borders of the territories they came to control, remain unknown. It is certain that between the 6th and 5th century BCE, the region passed from one dominion to another, with a swiftness indicating political and military instability as well as a strong intent in territories that were already at the center of a dense network of trade. Various evidence, written as well as material culture, demonstrates that during the period of Persian political rule there was also an Arab population existing alongside of Edomites who had remained in the territory that was previously the Kingdom of Edom (11th to 7th century BCE approximately), as well as Jews and Phoenicians; together these groups comprised the people who defined themselves as 'NBTW' – the Nabataeans.

Hydraulic features

Petra, of course, has been the center of much archeological interest, where Arab lore says Moses struck the rock and God brought forth water for the Children of Israel. They say that Miriam, Moses' sister, and Aaron, his brother, are buried nearby. Entry into the Petra Capitol is through the Siq (see ***Figure 4***)

The Nabataeans produced numerous hydraulic engineering structures and features, especially at their capital city, Petra. These include, for example, water structures such as aqueducts, main and lateral channels or canals, water cisterns or tanks, check dams and storage dams or barrages and reservoirs, pipelines to raise water above open-channel height from up gradient water pressure, flood and release sluice gates, and gardens and pool complexes, bath houses, and irrigated farmland. They designed, installed, operated, repaired, maintained, and upgraded an integrated water, drainage, and flood management network to meet their demand for domestic, livestock, and arable land to crop crops and fruits. Nabataean planners, engineers, and managers optimized hidden rock galleries and developed their springs, natural topography and hydrologic resources.

Figure 5 shows a Petra cistern and water channel. ***Figure 6*** shows a surprise Petra complete elephant. ***Figure 7*** shows current Bedouin meadow irrigation using Wadi Mousa wastewater.

Table 2 shows selected Nabataean hydraulic features. Many of the rock cisterns dug by Nabataeans have a small influent entry cistern which likely served as a sediment settling basin. After settling, there may have been some water-filtration media such as crop residue, grasses or hay to remove water turbidity and color.

The gifted Nabataean control of water facilitated freedom of movement, secrecy and security. They became wealthy through spice (frankincense, myrrh), perfume, oil, other luxury goods and Dead Sea bitumen (for Egyptian embalming), silver and copper trade, tribute and trade tariff collection, caravan guiding, and agricultural products including vegetables, fruits, grades and wine. They received wealth from tributes and duties received to protect caravans as they knew the safe desert trails and hidden water resources.

Although water is an incompressible fluid, it can give the illusion otherwise. This hydraulic feature can be put to good use as the Nabataeans knew when they inserted and adjusted water pipes within their open channel canals. Water flowing horizontally in a full pipe has more pressure than water flowing in its surrounding open water channel with the same slope as the pipe. This hydraulic phenomena comes about because water pressure in the downgradient pipe is determined the elevation of the water in the upgradient pipe inlet,

Figure 5: Petra cistern and water channel.

Figure 6: First Petra complete elephant.

Figure 7: Wadi Mousa wastewater reclamation and meadow irrigation.

Table 2. Selected Nabataean hydraulic features at Petra.

Hydraulic feature	*Description and function*
Aqueducts	*Ground-level water conveyance from 3 km north of the Petra center and carried across a rock-cut ravine by an arch to deliver water to the north end of Petra*
Ceramic pipe or tubes	*Increased water pressure and lift in the northern, natural canals*
Channels or canals	*Rock-grooved or carved rock structures to divert water from the two springs to reservoirs, or to direct the maximum runoff water to cisterns from winter rains for storage for dry season use; rock-cut gravity flow canals on the southern cliff were covered with stone slabs to keep water clean and reduce evaporation losses or unaccounted-for-water*
Cisterns	*Carved from in-place native rock, often lined with stucco, in every Petra neighborhood and most households to provide stored potable water; often mislabeled on maps as "wells"*
Dams	*Rock features at wadis end to control flows*
Nymphaeum	*Monumental fountain as water display of the city aqueduct*
Pools, fountains and baths	*Provide aesthetic water monuments to enhance their pleasure and prestige, as well as improving health and sanitation*
Reservoirs	*Large capacity, rock-cut water storage tanks for winter runoff control and water storage from the two eastern springs to release water when needed downstream; subterranean reservoirs carved from in-place native rock, often stucco-lined, each side up to 30-m wide; the openings were closed and made level with the ground and secret signs were left to help locate them*
Siq, *or main road*	*The graded main road served as a flood control canal as well; since antiquity, this long natural corridor flanked by 100-m high cliffs*
Sluice gates	*Controls served as valves to send water along raised canals to distribution points, then through intricate networks of irrigation canals to crop fields*
Springs	*Developed springs at 'Ain Mousa and 'Ain Braq on the eastern hills*
Wadi	*Intermittent or seasonal creeks, to the east of Petra at Wadi Mataha and Wadi Mousa which flowed west to Petro City*

Sources: Taylor (2007), Ossorio (2009), and Teller (2009).

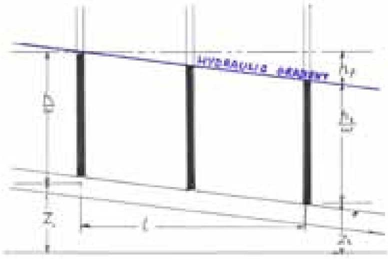

Figure 8: Hydraulic gradient in a closed pipe.

less pipe friction losses, assuming the pipe is continuous and has no leaks or other inflows. However, water pressure in the downgradient canal is determined by the elevation of the upgradient canal inlet, less canal friction losses and energy dispersion from the canal's free or unconfined surface, assuming the canal is continuous and has no leaks or other inflows.

Therefore, at any given cross-sectional of the full-water pipe within an open water channel of flow, the water pressure in the full pipe will be higher than the water pressure in the canals free surface. Nabataean engineers recognized this feature and used it to make aeration fountains from the pipes within the canals and to pipe water above the canal surface to lateral canals. Upon first seeing this in action, it must have appeared miraculous!

Figure 8 shows a sketch of the hydraulic gradient in a closed pipe.

One might visualize how a full pipe in an open channel has more pressure than the channel by blowing air through a tube or straw and then blowing air with the same force into the open air. The outflow at the straw will produce noticeably more pressure than the open air the same distance from one's mouth if the blowing forces are the same. Roughly speaking, the ratio of outflow straw pressure to outflow free-air pressure would be approximately the ratio of the cross-sectional area of an open cut the length of the straw to the cross-sectional area of the straw, or on the order of 30 to 50 fold.

In addition, it must have been magical to observe colorful turbid- and sediment-rich runoff enter a cistern, pass through a filter trap, and come out colorless, clear and sediment free. ***Figures 9 and 10*** show sketches of a simple settling basin and a rapid sand filtration, respectively.

Most likely the Nabetaeans also knew how to make and routinely use hand-piston, wind, bladder, bucket, wheel, and screw pumps, and siphons and U-tubes to transfer water and grind grain into flour for bread, grits, or meal, though their artifacts are not apparent. Most likely, their flimsy materials as wood, hemp, animal hides and organs, and pottery would not survive the centuries.

There are several reasons for not finding anticipated artifacts. Among these are: they never existed; looking in the wrong places or misdirection; weathering, erosion and deterioration; stolen or vandalized beyond recognition; buried or moved; recovered for reuse, recycling or destroyed.

In addition, artifacts may be misinterpreted. For example, Roman portable toilets for wheat thrashers, Egyptian power wands and fetishes for ear cleaners, and Amman ball valves for marbles, and Petra cisterns for wells.

Probably, the Nabataeans had stone hammers, chisels, wedges, drills, files, plumbs, ropes, pulleys, wheels, oil-levels, triangles, compasses, lathes, wheel grinders, measuring rulers, and stadia markers.

Although there is no explicit evidence that the Nabataeans knew the governing water flow equations, they clearly demonstrated a practical skill through their physical hydraulic works unrivaled until later Romans.

Success and lessons learned

The Nabataeans were successful. They were effective, sustainable, and learned from their lessons to make improvements, scale-ups, and replications in their hydraulic structures. The passed the common architectural first-tier screening criteria of effectiveness, implementability, and cost effectiveness. They passed the second-tier criteria of: 1) overall protection of human health and the environment; 2) compliance with applicable or relevant and appropriate criteria; 3) long-term effectiveness and permanence; 4) reduction of toxicity, mobility or volume through treatment; 5) short-term effectiveness; 6) constructability; 7) cost; 8) state acceptability; and 9) community acceptability.

Perhaps Nabataean water engineers would recommend today several water conservation, harvesting, distribution, and treatment strategies, technologies and equipment (Popkin, 2014), such as:

- Use native and locally available materials
- Reduce water demand by pipe-flow restrictors and aerators on faucets and taps, and low-flow, low-tank and duel-flush toilets
- Turn off the tap when not in immediate use
- Capture rooftop, gray, and street runoff water for treatment, storage and use

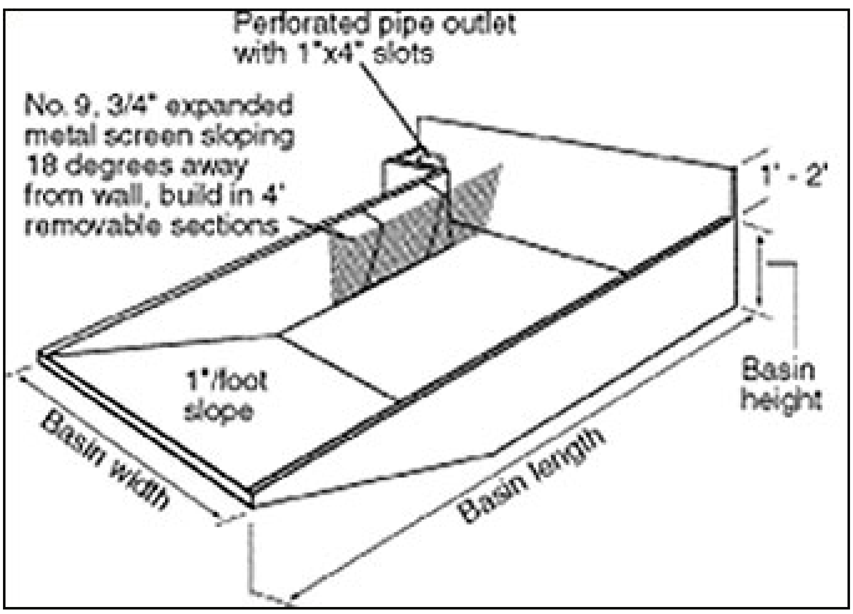

Figure 9: Simple settling basin system.

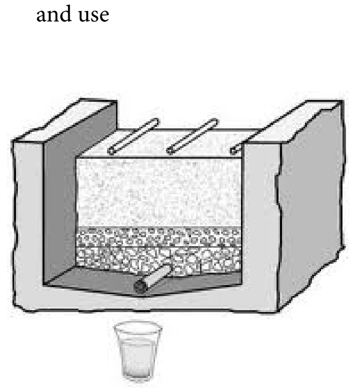

Figure 10: Simple rapid sand filtration system.

- Enhance groundwater recharge through wide and scarified groundwater basins, dry reservoirs and wadis
- Carefully design, operated, maintain, repair and adjust water collection, conveyance, storage, distribution and treatment systems
- Treat water by aeration, settling basins, sand and organic filtration media, and sunlight
- Capture, treat and reuse wastewater for crop irrigation
- Use water-saving irrigation methods such as drip irrigation on trees and subsurface irrigation on row crops; incorporate greenhouse for high-value crops
- Use command-and-control and make-the-polluter-pay strategies as well as social marketing aimed at children, youth, students, householders, bill payers, large-water users, and water purveyors
- Teach your children well

Acknowledgements

The author gratefully acknowledges the wonderful network of cadres of archeological, engineering, geological, and hydrological friends and colleagues and his happy opportunities to have visited Petra in admiration of Nabataean architects and hydraulic engineers. As my NYU Petrology Professor, Leslie E. Spock, was fond of saying, "May he who cares for such things, carry away from here, something apart from the hardness of rock; may he cherish the bones of mother earth!'

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Primary geological education in Ukraine

Ganna Liventseva and Marina Krochak*

Extracurricular activities

The student geology movement in Ukraine became very popular in the second half of the 20th century; young geologists joined geological groups and teams of young geologists took part in professional competitions from regional to state levels. Strong centers have been established in cities where there were great exploration and mining companies. In the early 1990's, after the collapse of the Soviet Union, the student geology movement began to decline and in most regions of Ukraine this direction of extracurricular activities ceased to exist. In some Ukrainian cities – Zhytomyr, Rivne, Kharkiv, Cherkasy, Odessa, Kramatorsk, Ivano-Frankivsk and Kalush – the youth geological movement has survived to present days; it has long-term achievements, traditions and is gradually developing. However, all children's centers of geological study are developing thanks to mentors-enthusiasts who do not rely on government assistance and independently resolve all financial, organisational and methodological issues. Let us focus on the activity of children's geological centers, which cooperate with the All-Ukrainian public organisation "Ukrainian Association of Geologists" (UAG).

An interactive form of communication dominates in the classroom of geological circles. Much time is spent conducting workshops where the students independently identify samples of minerals, rocks and fossils, or paint or sculpt works on a given subject. An integral part of the geological circles of any level has always been expeditionary activity in the field.

An important attraction to geology is the participation of senior pupils (ages 14-17) in a competition of scientific-research works of Junior Academy of Science. During preparation, senior pupils were familiarised with the main features of the geological structure of the area where they live, developed geological routes around native land, studied the local rocks, minerals and organic remains, and described interesting geological objects that they found during trips and geological routes. At the meeting of their section they present the results of their research in the form of research papers and defend them. Half of the participants win the certificates I, II or III degree, which is an advantage in entering higher educational institutions.

No less fascinating was the first Kyiv Competition on Geology among Ukrainian pupils in 2013. The initiators of the contest were Ukrainian Association of Geologists, the Geological Department of the National Museum of Natural History at the National Academy of Sciences of Ukraine, and the Geological Faculty of Taras Shevchenko National University of Kyiv. In addition to testing and advanced theoretical tasks, participants visited the Geological Museum and educational laboratories, and had the opportunity to communicate with teachers. After summarising, participants were awarded with certificates.

It's no secret that the geological industry of Ukraine is going through tough times and the prestige of the geologist's profession in society is low. The process of restructuring of the industry is necessary and natural, and without skilled well-trained young professionals a way out of the crisis will be impossible to find. Nine higher educational institutions of Ukraine are preparing geologists of different specialisations. The level of preparation of applicants entering the geologic profession currently is unsatisfactory due to lack of information for pupils about the geologist's profession.

Educational project "Geology - the profound sanctity"

The Ukrainian Association of Geologists (UAG) and the "Tutkovsky Institute" have been working together for fourteen years. Their activity is aimed primarily at preserving the achievements of the Ukrainian Geological School with its ex-Soviet and world professional relationships, and at enhancing and promoting its glorious traditions.

In order to properly understand the place of humanity in life of the planet and to have a comprehensive understanding of the scientific picture of the world, it is essential for a young person who begins the process of learning science to get an idea of geology as a system of fundamental Earth Sciences, along with knowledge of other sciences. Today in the Ukrainian schools, as in other

Ukrainian Association of Geologists (UAG)

The Ukrainian Association of Geologists is an All-Ukrainian Public Organisation established in 2000 on the initiative of leading Ukrainian geological enterprises and organisations.

The membership consists of geologists, geophysicists and petroleum engineers as well as other specialists of the geological industry of Ukraine. The total number of regular members is about 4,000. The Association consists of 22 branches in Ukrainian regions, Kyiv and the Republic of Crimea. There are 46 geological societies, associations and institutions among the collective members of the Association, including the state service of geology and mineral resources of Ukraine and all its enterprises, affiliate companies of NJSC Naftogaz of Ukraine (JSC Ukrnafta and JSC Chornomornaftogaz), and scientific institutions of the National Academy of Sciences of Ukraine. The Association has its own registered logo.

UAG is working on raising the prestige of geological science in Ukraine, with its rich mineral resources and comprehensively gifted professionals involved in expansion of public influence (NGOs). We aim to promote: the expansion of opportunities to exchange professional experience with experts from other countries; joint participation in scientific and practical conferences, workshops and lectures; involvement in specific scientific publications, including the journal *Ukrainian Geologist*. The Association has introduced a system of awards to honour outstanding achievements and special merit in exploring mineral resources, including gold and silver badges, a geological hammer engraved with the awardees' name, a medal "For Merit" of I, II and III degree, and the medal "For contributions to mineralogy" named for E.K. Lazarenko.

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countries of the former Soviet Union, geology is not included in the curriculum. This lack of basic knowledge leads to the fact that society misunderstands the meaning of geology, thinking it is just an industry that searches for minerals.

Taking into account the situation in Kyiv, public and private geological organisations together with educational institutions are developing a series of educational programs and projects which promote geological education at different age levels – from teaching "Fundamentals of Geology" in secondary school to higher professional trainings.

The private Higher Educational Institution "Tutkovsky Institute" is the only organisation in the Ukraine Institute of Postgraduate Education which systematically and consistently provides educational activity in geological science and practice in the following areas: geology, mining and environmental safety. Among the main activities of the Tutkovsky Institute are: professional development of specialists in exploration and oil and gas sectors, organising and conducting lectures and workshops with leading scientists and geologists from Ukraine and the world, organising and conducting conferences, issuing publications for the general public as well as research reports and journal articles. The educational activity at pre-university level is highlighted as a separate direction. The Institute publishes the professional journal *Ukrainian Geologist*, which includes not only scientific articles, but also materials about the geological youth movement, the activities of the Association of Geologists in the field of education, and stories about heads of children's geological circles, teachers-enthusiasts that prepare pupils to work in the Junior Academy of Sciences.

The educational activity is conducted in partnership with community organisations, educational institutions and private companies related to geology. The main project "Geology - the profound sanctity" is focused on an audience of children and teens. It includes the following components:

1. Children's conferences and readings dedicated to outstanding Ukrainian scientists and geologists
2. Geological lectures in the Kyiv Palace for Children and Youth
3. Conducting city geological quizzes
4. Contests for pupils on geology
5. Excursions to modern geologically-related enterprises, educational institutions and museums
6. Seminars for teachers, methodologists and heads of regional associations of geography teachers

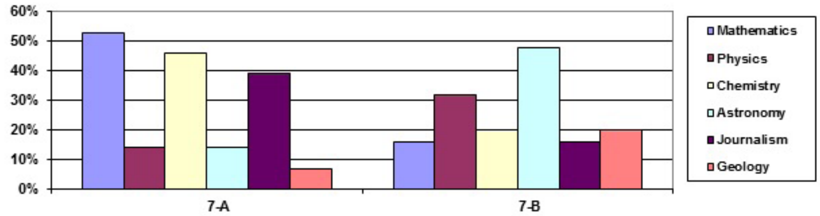

Figure 1: Results of the "Interest Map" survey in 7-A and 7-B classes in the spring of 2012 before the special course "Depths of the Earth (Fundamentals of Geology)".

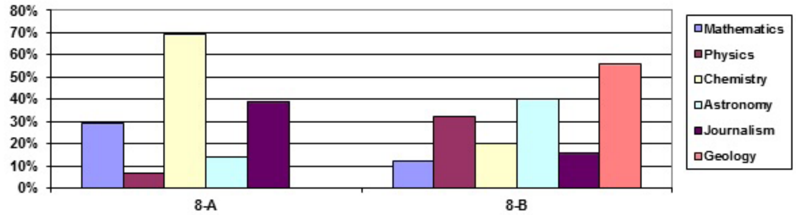

Figure 2: Results of the "Interest Map" survey in classes 8-A (control group, no geology instruction) and 8-B (experimental group, one year of studying the special course "Depths of the Earth (Fundamentals of Geology)"), spring of 2013.

7. Teaching the experimental specialised course "Depths of the Earth (Fundamentals of Geology)" in Kyiv schools.

Geology at school: "Depths of the Earth (Fundamentals of Geology)"

This is a major direction in the project because it gives children systematic knowledge. It has been carried out regularly for the last two years. The necessity of teaching geology at school has been discussed for a long time. Geology is an interdisciplinary body of knowledge that can combine all the other natural sciences in the pupil's imagination of the world, to show how physical laws operate within our planet in its surface and depths, and how chemical reactions that are reproduced in the school laboratory occur in the geological environment. Geology gives an idea of the scale of actions of all processes, whether they are at the atomic and molecular level or in planetary space, whether they last a fraction of a second or take billions of years. Geology is not restricted to description and identifying objects and natural phenomena, it tries to describe the causes and course of geological processes which have formed the modern face of the planet. Therefore, in comparison with geography, which only describes natural phenomena and objects, geology requires to us to build a logical chain, to see cause and effect.

Within the project, the course "Fundamentals of Geology" started to be taught in one of the schools of Kyiv in the 8th and 9th grades in 2012-2014. The teacher is M. Krochak, an associate professor of the Geology Faculty in Taras Shevchenko National University of Kyiv. The content of the school course is designed for two years with two academic hours per week within the main teaching load, and is made in accordance with the course "General Geology" in higher education institutions, with a significant simplification and reduction of material.

The program of the course was developed in the Geological Faculty of Shevchenko National University, approved by the Institute of Postgraduate Education of Hrinchenko University and adopted by the Academic Council of the "Tutkovsky Institute". The syllabus for "Depths of the Earth (Fundamentals of Geology)" for secondary schools (grades 8 and 9, ages 13-14) contains the following sections:

8th grade:

1. Introduction. Geology - science, profession and lifestyle - *2 hours*
2. Earth in outer space - *8 hours*
3. Internal structure and age of the Earth - *16 hours*
4. Minerals - inorganic compounds of the crust - *8 hours*
5. The main rock-forming minerals of the crust - *36 hours*

9th grade:

1. Introduction. Geological processes that shape the Earth - *2 hours*
2. External (exogenous) geological processes - *44 hours*
3. Internal (endogenous) geological processes - *24 hours*

Before the creation of the course a sociological survey was carried out in two groups of 7th grade pupils about their inclinations to certain areas of expertise. Analysis of the results of the "Interest Map" survey (by the Fedoryshyn method) has shown that pupils in class 7-B are more interested in geology, astronomy and physics more than pupils in 7-A, so that led us to choose 7-B as the experimental class and 7-A as the control one. Results of the survey are shown in ***Fig. 1***.

The survey was repeated after the successful completion of the first year and shows that geology as a subject and as a prospective job significantly increased its rating in the "Interest Map" (***Fig. 2***). Pupils of the test group of 8-A class, without information replenishment, have completely lost any interest in geology.

In September 2013 the children who passed into the 8th grade joined to the project. And the experimental, now 9-B class, moved on to mastering the second-year program.

Pupils of the 8th and 9th grades study geology in the school and from the 10th grade once a week they attend classes in the Geological Faculty of National University. An agreement has been made between schools and the Geological Faculty, and all teachers of the faculty are involved in the 10th grade teaching.

The syllabus for "Depths of the Earth (Fundamentals of Geology)" for secondary schools for 10th grade contains the following sections:

SECTION I. Fundamentals of Crystallography

1. Main information about structure, properties and crystal growth - *3 hours*
2. Crystal symmetry - *7 hours*
3. Crystal system - *3 hours*
4. Doctrine about crystallographic symbols - *4 hours*
5. Simple forms of crystals - *8 hours*
6. Crystal growth - *6 hours*
7. Basis of crystal chemistry - *4 hours*

SECTION II. Principles of Paleontology

1. Development stages of land and biosphere - *2 hours*
2. Kingdom of ancient plants - *2 hours*
3. Kingdom of ancient animals - *13 hours*

SECTION III. Distant study of the Earth from space

1. General information about studying the Earth from space - *2 hours*
2. Processing and interpretation of digital satellite images - *5 hours*
3. Applications and objectives of Earth remote sensing - *10 hours*

Considering child psychology, from each topic the main and bright information has been selected, lectures alternate with practical tasks, and much of the information comes through computer presentations, drawings on the board or thematic videos, but learning is still systematic and consistent.

Project achievements, problems, suggestions

Analysing our two-year experience of teaching children the basics of geology, one could argue that limited time makes it impossible to familiarise them with the range of all areas of the geological sciences. This task should be performed by optional modular courses for senior pupils who have successfully learned the two-year course of principles of geology and expressed a desire to deepen their knowledge in specific areas. This provided a reason to expand the curriculum of the course to three years. The authors of the project have developed a program for the third year of study for pupils of 10th grade that includes sections that had proven to be most interesting for pupils, in particular sections of the foundations of crystallography, paleontology and distant study of the Earth from space.

The first successful experience resulted in increased interest of pupils in geology, as is seen from the survey results shown in ***Fig. 2***, as well as improved success with other natural sciences. Therefore an experiment has been launched to transfer the course to other schools of the city. The project is being implemented thanks to the coordinated efforts of people who care about geology. Unfortunately, there is no system of state support for the project and it continues to develop only through sponsors and school funds.

For further implementation of the project, funds are necessary for:

1. Drafting the project of a comprehensive programme for the introduction of Earth Sciences into the curriculum by the collective of experienced geology and geography teachers;
2. Creating advanced training courses for teachers of geography to study the principles of geology;
3. Organisation of pedagogical training courses for expert geologists who temporarily are out of the profession to qualify them to teach geology (Earth Science) in secondary schools;
4. Conducting geological student practice and field trips (routes have been chosen, estimates have been made);
5. Establishment of school geological laboratories;
6. Assembling full mineralogical and petrographic collections;
7. Publication of children's literature on geology; there is an obvious need to create new educational, science books and terminology guides for pupils and students;
8. Purchase of specialised children's literature on geology and modern literature for teachers;
9. Financial encouragement for teachers-enthusiasts.

Today, when the second year of studying geology at school has finished, we can say that the experiment is already successful. Teachers noted that pupils not only are going on well with the planned program, but also improve their scores in physical and economic geography, physics, astronomy and chemistry. Moreover, the topics of the experimental course are in good agreement with the educational sections of standard natural sciences. And most importantly, through the geology training children began to realise the unity of all natural processes and the relationship between the natural sciences. Since 2013 geology has been taught at two schools in Kyiv (secondary schools № 13 and № 256); it is now planned to add other schools of the city and a rural school in Zhytomyr.

Our activity and efforts of other organisations have led to the fact that children's interest in Earth Sciences is increasing. This is evidenced by the substantially increasing number of works on geology submitted in recent years to the Junior Academy of Science contest. Ten years ago in Kyiv there were fewer than 10 works on geology in the city competition, while in 2012 there were 34, in 2013 there were 69, and in 2014 there were 49 geology-related works.

We have discussed our achievements and problems at many national and international conferences, where our beginnings have attracted the interest and approval of professionals in the geological and education field. Our experience of teaching geology at school and the main results have also been discussed in the pages of the Ukrainian and foreign press.

It is our hope that geology training will spread throughout the schools of Ukraine, and that this will lead to increased participation in geology-related research and careers, to the benefit of Earth Sciences and the nation.

Bringing Earth Sciences to the public through actions designed to raise interest in geosciences

*Balazs Bodo and Adrienn Cseko**

People have been fascinated by volcanoes ever since the dawn of mankind and have treated them with utmost respect. Our modern life has brought a change to our perception of volcanism, and there are no longer superstitious elements associated with volcanoes in Western societies. The connection between plate tectonics, earthquakes, and volcanoes has been studied and understood. Four-dimensional models are being developed to simulate eruptions, cutting edge equipment is used to record even the tiniest seismic events and a broad array of remote sensing sensors are used on a routine basis to monitor volcanic activities from space. At the same time a dramatic gap has formed between the professionals and the public. Research and studies on volcanism use more and more specialised language, which does not translate into popular science or public communications. The media often delivers inaccurate information, going for sensational facts when they should be factual, and failing to report findings, when they should use their power to disseminate information. It seems that in our world there is no longer time for explanations, only for some quick quotes in the news if some exciting developments need to be broadcast. As a result, in today's world, the work of volcanologists is nearly as mythical as the work of volcanoes in ancient times.

"La Noche de los Volcanes III (i.e. Volcanoes' Night) – Researchers' Night of the Canary Islands" is a Marie Skłodowska-Curie Action financed by the European Commission's Horizon 2020 programme.

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The project and the Night followed up on the successes of the previous initiatives La Noche de los Volcanes I and II, both financed under the EC's FP7 Programme. On 26 September 2014 the Night was organised for the third time, this time simultaneously on all seven islands of the Canary archipelago (Fuencaliente, Puerto de La Cruz, La Frontera, Hermigua, Ingenio, Yaiza and Pajara and also in Almagro, Ciudad Real, mainland Spain), where the volcanic environment is part of the local heritage and culture, but at the same time represents a potential hazard as well. Although the islands' population (around 2 million) lives in volcanic areas, the gap between geoscientists/volcanologists and the public is huge. At the same time, the science of volcanoes can be used to mobilise the public: a survey[1] conducted in 2013 during Volcanoes' Night II indicated high public interest in the topic of geology, volcanology and the work of geo-scientists. About two-thirds of the survey responders marked high or very high interest initial interest for the topic, and this was raised further during the event. Similarly, initial public interest in the work of geoscientists is also high as a baseline; the absolute majority, three quarters of the respondents, stated that they consider their work *"Useful for society"*. Yet, according to the past surveys, the daily work of geoscientists still appears to be somewhat of a mystery to the public. Volcanoes' Night I (La Palma) and II (La Palma, Tenerife, El Hierro, Lanzarote) already addressed this challenge, with almost 60% of the participants indicating that their understanding about the work of geoscientists substantially improved as a direct outcome of the Night.

The objective of Volcanoes Night III was to address the still remaining gaps between geosciences and society. During the event participants were provided access to research facilities, and a complementary scheme of workshops, science cafés, excursions, presentations and challenge games were arranged to fuel the public's curiosity, interest and understanding of research activities. Participating scientists not only talked about their field of research, but also shared their experience on how students can approach science and research institutions, providing a perfect scenario to attract young people to science careers. As a backdrop to the Night volcanoes were used not only to explain the work of volcanologists but also to explain what science is about and what scientists and researchers do during their daily work. Activities during Volcanoes Night III attracted over five thousand participants this year, and as such, this action remains a successful example of raising public awareness about the work of geoscientists in Europe. Detailed evaluation of the surveys conducted during the Night is underway, and will be made available for download on the project website, together with photos and other documents of interest. ***http://www.nochedevolcanes.es***

1 Evaluation was based on 479 collected questionnaires (282 online and 197 on paper).

Book review:
A Quarry Design Handbook
*Isabel Manuela Fernández Fuentes**

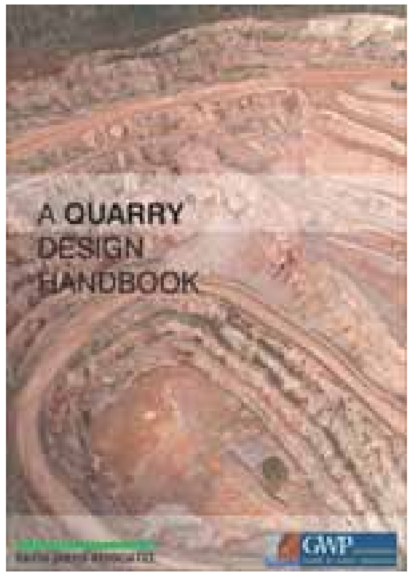
A Quarry Design Handbook
by GWP Consultants LLP and David Jarvis Associates Ltd. The principal authors of the Handbook are Ruth Allington (GWP Consultants) and David Jarvis (David Jarvis Associates Ltd)

Copyright: 2014
Price: free
More information: http://www.gwp.uk.com/research.html. The Quarry Design Handbook is available as linked PDFs that can be read online or it can be downloaded in its entirety.

The Handbook is about the design of new quarries, quarry extensions or revised quarry working schemes. The primary objectives of good quarry design are the safe, efficient and profitable extraction of the maximum usable material from the available land whilst causing the minimum environmental disturbance and resulting in beneficial final restoration and land-uses. The Handbook sets out to provide a source of reference and guidance to those involved in designing and operating quarries in the UK or elsewhere. In particular, it should assist them in preparing good quality mineral planning applications for new and extension sites, which also incorporate compliance with all legal and regulatory requirements (notably, in the UK, the Quarries Regulations, 1999) and demonstrate effective mitigation of environmental impacts.

The 2014 edition of the Handbook is a completed and updated version of the pre-publication draft Handbook first produced in 2007 as the output of a project funded from the Aggregates Levy Sustainability Fund (ALSF) and managed by the Mineral Industry Research Organisation (MIRO). Research and writing carried out by GWP Consultants LLP and David Jarvis Associates Ltd.

The Handbook should assist in promoting common understanding of the process of quarry design and provide support to effective communication and negotiation between all relevant stakeholder groups. In order to be accessible to a wide range of readers, wherever possible it avoids technical jargon and defines terms where these have to be used. The Handbook is structured to allow it to be used in a number of ways: as a readable general introduction; as a source of guidance on specific techniques



or aspects of quarry design; or as a reference source to lead the reader to other sources of information and advice (e.g. primary legislation, regulation, guidance, data, technical and scientific reports, papers and books). It is structured to allow accessible presentation in a variety of paper, electronic and combined formats.

News corner:
Compiled by Isabel Fernández Fuentes and Anita Stein, EFG Office

EFG/PERC conference - MIN WIN-WIN: Establishing Europe-wide minerals reporting standards – the key to reducing risk and increasing opportunity

Date: *20-21 November 2014*
Venue: *Belgian Institute of Natural Sciences, Rue Vautier 29, B-1000 Brussels*
Organisers: *European Federation of Geologists (EFG) and Pan-European Reserves & Resources Reporting Committee (PERC)*
Supporting organisations: *Committee for Mineral Reserves International Reporting Standards (CRIRSCO), Euromines, Geological Survey of Belgium – Royal Belgian Institute of Natural Sciences, Geological Society of London (GSL), Institute of Geologists of Ireland (IGI), Industrial Minerals Association (IMA), Institute of Materials, Minerals and Mining (IOM3), International Union of Geological Sciences (IUGS) Task Group on Global Geoscience Professionalism, United Nations Economic Commission for Europe (UNECE).*

This conference, jointly organised by the European Federation of Geologists and the Pan-European Reserves & Resources Committee (PERC), aims to promote the adoption of a common reporting standard in the EU. Such an approach will contribute to the convergence of terminology and the comparability/compatibility of data, thus facilitating the creation of a solid European Knowledge Database on mineral resources and to the successful delivery of the Raw Materials Initiative. Such harmonisation is equally important to government policy-makers and to companies within the minerals industry – the users and the providers of data on mineral resources and reserves. The conference provides a unique opportunity to learn about and discuss concrete steps regarding mineral reporting in a cross-disciplinary environment, including EU policy makers, national government officials, academics, minerals company executives, and finance and industry experts.

More information: ***http://eurogeologists.eu/min-win%E2%80%90win/***

New EFG members

EFG is glad to welcome two new members, the Polish Association of Mineral Asset Valuators (***http://www.polval.pl***) and the Czech Association of Economic Geologists (CAEG) (***http://www.calg.cz/***). The EFG Council approved both associations as new full members during the summer Council meeting in Palermo on 31 May and 1 June 2014. EFG now counts 24 national association members from all over Europe. More information: ***www.eurogeologists.eu/members***

Obituary – Floriano Villa, a geologist who loved nature and fought against natural disasters.

Floriano Villa was born in 1930 in Seregno, close to Milano, and died at home in Milano on 22 August 2014. A serious illness confined him to bed for the last three years of his life.

After the Classic High School, he obtained his degree in Geological Sciences at Milano University in 1954. He was an appreciated lecturer at the Universities of Milan, Pavia and Venice. He was first Secretary and then President of ANGI (Associazione Nazionale Geologi Italiani) and had a fundamental role in creating CNG (Consiglio Nazionale Geologi) in 1968. In 1980 he was one of the founders of EFG and took part in several Council Meetings of the Federation.

For several years, Floriano Villa was also President of "ITALIA NOSTRA", an association whose purpose is the saving of Italy's natural heritage and the conservation of the environment. He carried out many professional assignments in this field. He also wrote some books and several papers concerning hydrogeological risks.

Each of us who had the chance to meet Floriano and spend some time with him will surely remember a special person, with great humanity and a sincere sense of friendship.

Carlo Enrico Bravi

GEOTRAINET

On 2 April 2014 the GEOTRAINET international not-for-profit association under Belgian law (aisbl) was officially established. The funding members of this new association are:

European Federation of Geologists (EFG), European Geothermal Council (EGEC), ANIG (Italy), RGS (Romania), BWP (Germany), GEOPLAT (Spain), SGC (Sweden), APG (Portugal), HHPA (Hungary).

On 9 October GEOTRAINET AISBL held its first General Assembly organised in collaboration with APG, LNEG and the Platform for Shallow Geothermal Energy in Lisbon, Portugal. During the meeting two new members of the association were approved: BRGM (France) and the Ground Source Heat Pump Association (UK). The association currently has 11 members.

During the assembly two training courses for 2014 were approved: a training course on 7 and 8 October in Lisbon and the training course organised by GEOPLAT on 5 and 6 November in Madrid. The training programme is aimed at GSHP installers and designers and will provide the market with trained experts in the field of shallow geothermal technology who can design, install and operate efficient systems.

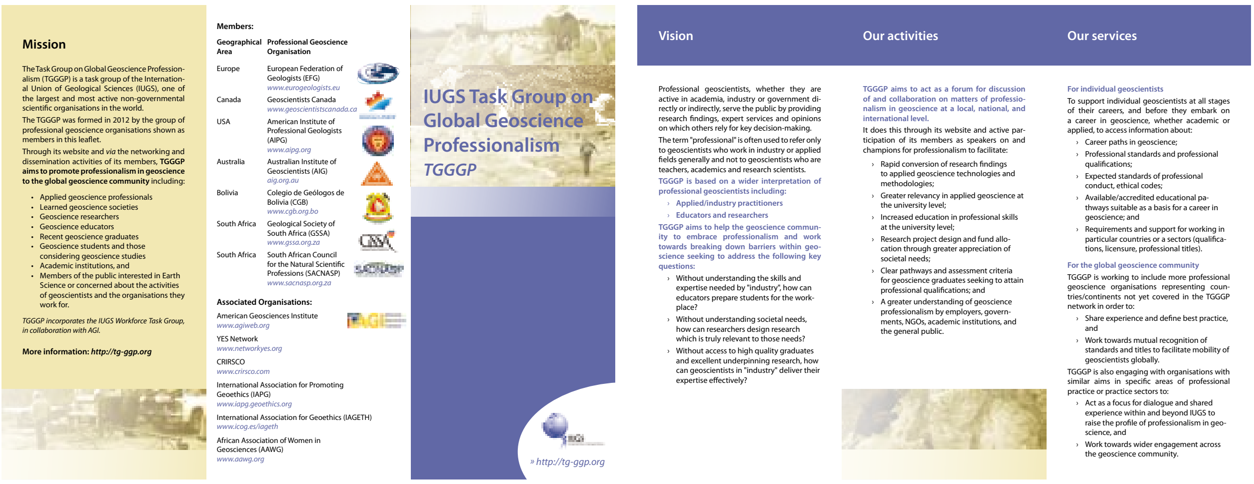
More information: ***www.geotrainet.eu***

IUGS Task Group on Global Geoscience Professionalism

Formed by the International Union of Geological Sciences (IUGS) at the 34th International Geological Congress in Brisbane, Australia, in August 2012, the Task Group on Global Geoscience Professionalism ("TG-GGP") provides a single global forum for interchange on professional affairs in geoscience worldwide. Its main purpose is to ensure that geoscientists, active in all areas of geoscience, are fully engaged in the transformation of their profession – a profession that is increasingly relied upon by the public to provide expert opinions and service, and to safeguard the public interest. The European Federation of Geologists is one of the sponsoring organisations of this Task Group and backs its activities through administrative support.

In autumn 2014 the Task Group produced a leaflet outlining its mission, vision and activities to the wider public. The leaflet was presented at the GSA 2014 meeting in Vancouver, Canada (19-22 October 2014).

More information: ***http://tg-ggp.org/***



Mission

The Task Group on Global Geoscience Professionalism (TGGGP) is a task group of the International Union of Geological Sciences (IUGS), one of the largest and most active non-governmental scientific organisations in the world.

The TGGGP was formed in 2012 by the group of professional geoscience organisations shown as members in this leaflet.

Through its website and *via* the networking and dissemination activities of its members, **TGGGP aims to promote professionalism in geoscience to the global geoscience community** including:

- Applied geoscience professionals
- Learned geoscience societies
- Geoscience researchers
- Geoscience educators
- Recent geoscience graduates
- Geoscience students and those considering geoscience studies
- Academic institutions, and
- Members of the public interested in Earth Science or concerned about the activities of geoscientists and the organisations they work for.

TGGGP incorporates the IUGS Workforce Task Group, in collaboration with AGI.

More information: *http://tg-ggp.org*

Members:

Geographical Area	Professional Geoscience Organisation
Europe	European Federation of Geologists (EFG) *www.eurogeologists.eu*
Canada	Geoscientists Canada *www.geoscientistscanada.ca*
USA	American Institute of Professional Geologists (AIPG) *www.aipg.org*
Australia	Australian Institute of Geoscientists (AIG) *aig.org.au*
Bolivia	Colegio de Geólogos de Bolivia (CGB) *www.cgb.org.bo*
South Africa	Geological Society of South Africa (GSSA) *www.gssa.org.za*
South Africa	South African Council for the Natural Scientific Professions (SACNASP) *www.sacnasp.org.za*

Associated Organisations:

American Geosciences Institute *www.agiweb.org*

YES Network *www.networkyes.org*

CRIRSCO *www.crirsco.com*

International Association for Promoting Geoethics (IAPG) *www.iapg.geoethics.org*

International Association for Geoethics (IAGETH) *www.icog.es/iageth*

African Association of Women in Geosciences (AAWG) *www.aawg.org*

IUGS Task Group on Global Geoscience Professionalism

TGGGP

» *http://tg-ggp.org*

Vision

Professional geoscientists, whether they are active in academia, industry or government directly or indirectly, serve the public by providing research findings, expert services and opinions on which others rely for key decision-making.

The term "professional" is often used to refer only to geoscientists who work in industry or applied fields generally and not to geoscientists who are teachers, academics and research scientists.

TGGGP is based on a wider interpretation of professional geoscientists including:

- Applied/industry practitioners
- Educators and researchers

TGGGP aims to help the geoscience community to embrace professionalism and work towards breaking down barriers within geoscience seeking to address the following key questions:

- Without understanding the skills and expertise needed by "industry", how can educators prepare students for the workplace?
- Without understanding societal needs, how can researchers design research which is truly relevant to those needs?
- Without access to high quality graduates and excellent underpinning research, how can geoscientists in "industry" deliver their expertise effectively?

Our activities

TGGGP aims to act as a forum for discussion of and collaboration on matters of professionalism in geoscience at a local, national, and international level.

It does this through its website and active participation of its members as speakers on and champions for professionalism to facilitate:

- Rapid conversion of research findings to applied geoscience technologies and methodologies;
- Greater relevancy in applied geoscience at the university level;
- Increased education in professional skills at the university level;
- Research project design and fund allocation through greater appreciation of societal needs;
- Clear pathways and assessment criteria for geoscience graduates seeking to attain professional qualifications; and
- A greater understanding of geoscience professionalism by employers, governments, NGOs, academic institutions, and the general public.

Our services

For individual geoscientists

To support individual geoscientists at all stages of their careers, and before they embark on a career in geoscience, whether academic or applied, to access information about:

- Career paths in geoscience;
- Professional standards and professional qualifications;
- Expected standards of professional conduct, ethical codes;
- Available/accredited educational pathways suitable as a basis for a career in geoscience; and
- Requirements and support for working in particular countries or a sectors (qualifications, licensure, professional titles).

For the global geoscience community

TGGGP is working to include more professional geoscience organisations representing countries/continents not yet covered in the TGGGP network in order to:

- Share experience and define best practice, and
- Work towards mutual recognition of standards and titles to facilitate mobility of geoscientists globally.

TGGGP is also engaging with organisations with similar aims in specific areas of professional practice or practice sectors to:

- Act as a focus for dialogue and shared experience within and beyond IUGS to raise the profile of professionalism in geoscience, and
- Work towards wider engagement across the geoscience community.

EFG strategy and Horizon 2020 projects

Horizon 2020 is the biggest EU Research and Innovation programme ever, with nearly €80 billion of funding available to secure Europe's global competitiveness in the period 2014-2020. In its recently released document ***Initiative Looking Forward*** the EFG Board drafted the reasons why EFG is paying so much attention to the European Commission's Horizon 2020 programme. This initiative is framed by several Action Plans of EFG's 2014-2017 strategy: AP1 EFG Members; AP2 European Network; and AP6 Projects. More information on EFG's strategic plan: ***http://eurogeologists.eu/strategy/***.

EFG is glad to report that its efforts in participating in several calls for project proposals have been fruitful: from the beginning of 2015 on, the Federation will be involved in four Horizon 2020 projects. More information will follow soon.

PERC

The Pan-European Reserves and Resources Reporting Committee (PERC) has been very active since our last paper in May.

Our Training sub-committee, led by Ed Sides of AMEC, has produced a 1-day Workshop on the reporting of exploration results, reserves and resources specially adapted for PERC Standard 2013. This was presented on 21st October in London preceding the FINEX '14 conference, and will also be presented on the 19th November in Brussels, ahead of the MIN WIN-WIN Conference. Steve Henley led a half-day reporting standards Masterclass for a group of Russian candidate members of IOM3 in London on 17th October.

Our PERC Standard 2013 sub-committee, led by former Chair Steve Henley, has drafted proposals for additional clauses on mining and demolition waste, as well as dimension stone. Work also continues on integration of the FRB reporting code into PERC. Some extension of the PERC standard will be needed for governmental use in the context of the INTRAW project, and initial consideration of the requirements has begun.

In June 2014, Chair Eddie Bailey presented on the work and principles of PERC, and on our relationship with European and international regulators and standards authorities, at the UK Extractive Industry Geologists Conference held in Scotland.

In September, Secretary Carlos Almeida and Treasurer Ruth Allington, together with Steve Henley, successfully established PERC as a core participant of the EU Horizon 2020 INTRAW Project. This is a large project aimed at developing international co-operation on raw materials with Australia, Canada, Japan, South Africa and the USA. Aligned to existing EU initiatives, MINVENTORY, and another small project MINATURA in which PERC is also a participant, INTRAW will create databases based on PERC Standard 2013 and establish a permanent European Raw Materials Observatory securing raw material strategy and development for decades to come.

October 2014 saw the CRIRSCO AGM at Ulaanbataar in Mongolia. The event was attended by the PERC representative on CRIRSCO, Eddie Bailey, and Deputy Chair Neil Wells (kindly standing in for PERC 2nd CRIRSCO representative Carlos Almeida, who was unable to attend due to important company project commitments). Eddie Bailey presented an update on the work of PERC and our intentions to outreach more directly to our European members and neighbours, including the translation of PERC Standard 2013 into other European languages through the INTRAW project. The event was an enormous success and Mongolia was formally ratified as the 8th member (and first Asian member) of CRIRSCO.

The CRIRSCO delegation then travelled to Beijing to meet with representatives of the Chinese Government (Ministry of Land and Resources, PRC), major Chinese mineral extractive companies, geological surveys, and mining exchanges, and presented on the CRIRSCO family of Codes and Standards, including PERC and NAEN, at the China Mining Expo 2014. There was great enthusiasm shown by our various hosts for embarking on CRIRSCO membership and this was exemplified by a presentation ceremony involving the formal translation of the JORC Code into Chinese.

Finally, the next PERC AGM has been scheduled to take place in Helsinki, Finland in March 2015, hosted by Geologiliitto, and kindly arranged by PERC committee member Markku Iljina. Details to follow. More information: ***www.percstandard.eu***

EAGE/EFG Photo Contest 2014

The European Association of Geoscientists and Engineers (EAGE) and the European Federation of Geologists (EFG) again joined forces for the organisation of the 'Geoscientists at work' photo contest. The Top 12 pictures chosen through public online voting clearly reflect the diversity of the geoscientific profession: they not only cover different sectors of the profession such as natural hazards, minerals & mining or oil & gas exploitation, but they also depict the impressive and inspiring variety of geological features all around the Earth in general.

The winning pictures are displayed in a travelling exhibition visiting several geosciences events this autumn. If you do not have the opportunity to visit the exhibition, you may also take a glance at the Top 12 pictures at ***www.houseofgeoscience.org.***

Electronic voting for the best three photos closed on 1 September. First prize is a Samsung Galaxy Tab S, second prize is the book Earth from Space and an EAGE book¬shop voucher of €100, and third prize is a copy of Earth from Space and an EAGE bookshop voucher of €50.

The winners of this year's Photo Contest are:

- First prize: 'Svalbard + Students' by Filip Bielicki
- Second prize: 'Seismic Testing in Morocco' by Lisa Ashari
- Third prize: 'Call of the Mountains' by Julia Krullikowski

Congratulations to all winners!

EAGE and EFG publish an exclu¬sive 2015 wall calendar containing the 12 best 'Geoscientists at Work' photographs of this year's contest. You can order the calendar in the EAGE Online Bookshop for €10. Please go to ***www.eage.org/bookshop*** for more information.

‘Svalbard + Students’ by Filip Bielicki

‘Seismic Testing in Morocco’ by Lisa Ashari

‘Call of the Mountains’ by Julia Krullikowski

Submission of articles to European Geologist magazine

Notes for contributors

The Editorial Board of the European Geologist magazine welcomes article proposals in line with the specific topic agreed on by the EFG Council. The call for articles is published twice a year in December and June along with the publication of the previous issue.
The European Geologist magazine publishes feature articles covering all branches of geosciences. EGM furthermore publishes book reviews, interviews carried out with geoscientists for the section 'Professional profiles' and news relevant to the geological profession. The articles are peer reviewed and also reviewed by a native English speaker.
All articles for publication in the magazine should be submitted electronically to the EFG Office at info.efg@eurogeologists according to the following deadlines:

- Deadlines for submitting article proposals (title and content in a few sentences) to the EFG Office (***info.efg@eurogeologists.eu***) are respectively 15 July and 15 January. The proposals are then evaluated by the Editorial Board and notification is given shortly to successful contributors.
- Deadlines for receipt of full articles are 15 March and 15 September.

Formal requirements

Layout
- Title followed by the author(s) name(s), place of work and email address,
- Abstract in English, French and Spanish,
- Main text without figures,
- Acknowledgements (optional),
- References.

Abstract
- Translation of the abstracts to French and Spanish can be provided by EFG.
- The abstract should summarise the essential information provided by the article in not more than 120 words.
- It should be intelligible without reference to the article and should include information on scope and objectives of the work described, methodology, results obtained and conclusions.

Main text
- The main text should be no longer than 2500 words, provided in doc or docx format.
- Figures should be referred in the text in italic.
- Citation of references in the main text should be as follows: 'Vidas and Cooper (2009) calculated…' or 'Possible reservoirs include depleted oil and gas fields… (Holloway *et al.*, 2005)'. When reference is made to a work by three or more authors, the first name followed by '*et al.*' should be used.
- Please limit the use of footnotes and number them in the text via superscripts. Instead of using footnotes, it is preferable to suggest further reading.

Figure captions
- Figure captions should be sent in a separate doc or docx file.

References
- References should be listed alphabetically at the end of the manuscript and must be laid out in the following manner:
- Journal articles: Author surname, initial(s). Date of publication. Title of article. Journal name, Volume number. First page - last page.
- Books: Author surname, initial(s). Date of publication. Title. Place of publication.
- Measurements and units
- Measurements and units: Geoscientists use Système International (SI) units. If the measurement (for example, if it was taken in 1850) was not in SI, please convert it (in parentheses). If the industry standard is not SI, exceptions are permitted.

Illustrations
- Figures should be submitted as separate files in JPEG or TIFF format with at least 300dpi.
- Authors are invited to suggest optimum positions for figures and tables even though lay-out considerations may require some changes.

Correspondence

All correspondence regarding publication should be addressed to:
EFG Office
Rue Jenner 13, B-1000 Brussels, Belgium.
E-mail: ***info.efg@eurogeologists.eu***

Note

All information published in the magazine remains the responsibility of individual contributors. The Editorial Board is not liable for any views or opinions expressed by these authors.

Subscription

Subscription to the Magazine:

15 Euro per issue

Contact

EFG Office
Rue Jenner 13, B-1000 Brussels, Belgium.
E-mail: ***info.efg@eurogeologists.eu***

Advertisements

EFG broadly disseminates geology-related information among geologists, geoscientific organizations and the private sector which is an important employer for our professional members, but also to the general public.

Our different communication tools are the:
- EFG website, *www.eurogeologists.eu*
- GeoNews, a monthly newsletter with information relevant to the geosciences community.
- European Geologist Magazine, EFG's biannual magazine. Since 2010, the European Geologist Magazine is published online and distributed electronically. Some copies are printed for our members associations and the EFG Office which distributes them to the EU Institutions and companies.

By means of these tools, EFG reaches approximately 50,000 European geologists as well as the international geology community.

With a view to improving the collaboration with companies, EFG proposes different advertisement options. For the individual prices of these different advertisement options please refer to the table.

Prices for advertisements

EGM	**One Insertion**	**Two Insertions**
Full page (colour)	820 Euro	1320 Euro
Half page (colour)	420 Euro	670 Euro
Quarter page (colour)	220 Euro	350 Euro
Full page (black and white)	420 Euro	670 Euro
Half page (black and white)	220 Euro	350 Euro
Quarter page (black and white)	120 Euro	200 Euro
Business card size	90 Euro	150 Euro
Preferential location	25% plus	
Price for special pages:		
Outside back cover (colour)	1200 Euro	1900 Euro
Second page (colour)	1000 Euro	1600 Euro
Second last page (colour)	1000 Euro	1600 Euro
Geonews	**Annual Price**	
Ad and regular newsfeed	1500 Euro	
EFG Homepage		
Ad and regular newsfeed	1500 Euro	
University ad		
Ad for training opportunities in the job area of the homepage	500 Euro	
Annual package		
Business card size ad in EGM, GeoNews and homepage.	3000 Euro	

FÉDÉRATION EUROPÉENNE DES GÉOLOGUES
EUROPEAN FEDERATION OF GEOLOGISTS
FEDERACIÓN EUROPEA DE GEÓLOGOS

EFG - the voice of European Geologists

The EUROPEAN FEDERATION OF GEOLOGISTS, EFG, is a non-governmental organisation that was established in 1981 and today includes 24 national association members. It is the representative body for the geological profession in Europe.

EFG contributes to protection of the environment, public safety and responsible exploitation of natural resources by promoting excellence in the application of geoscience, by supporting research and teaching that underpins it, and also by creating public awareness of the importance of geoscience to society.

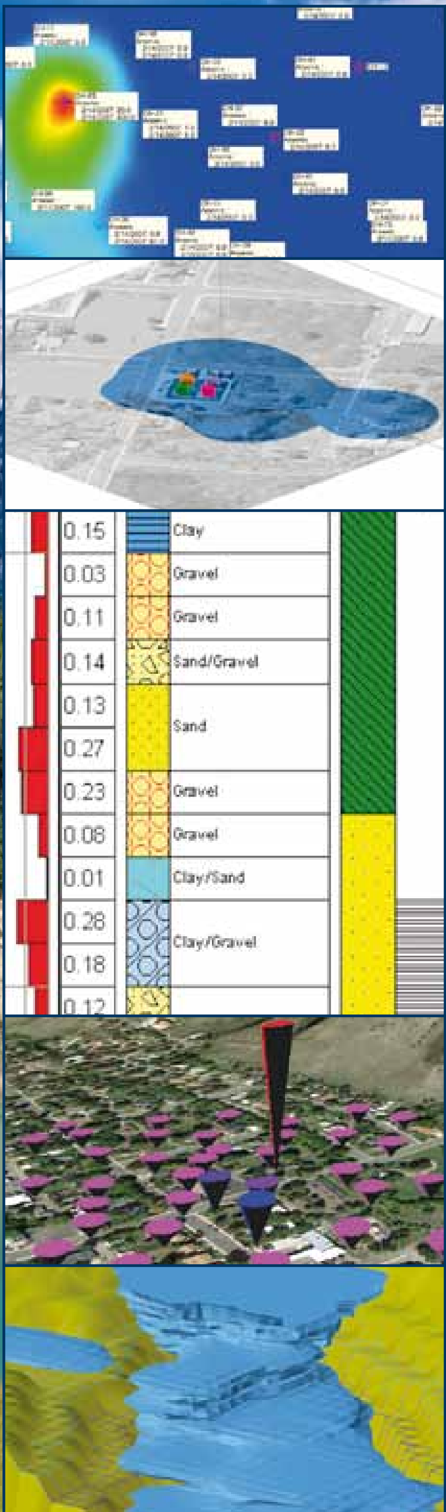
EFG encourages professional development by promoting training and Continuing Professional Development and offers validation (certification) through its internationally recognised title of European Geologist (EurGeol).

The EFG delivers its objectives through activity relating to:

- EU policies & environmental protection
- Education & outreach
- Free movement & professional titles
- Professionalism & ethics
- Supporting EFG Members

UBLG – Belgium-	SGF – France	KNGMG – Netherlands	SGD – Slovenia
Luxembourg	BDG – Germany	PAMAV - Poland	ICOG – Spain
CGS – Croatia	AGG – Greece	APG – Portugal	SN – Sweden
CAGME – Cyprus	MFT – Hungary	NAEN – Russia	CHGEOL – Switzerland
CAEG – Czech Republic	IGI – Ireland	SGS – Serbia	UAG - Ukraine
YKL – Finland	CNG – Italy	UGAS – Slovakia	GSL – United Kingdom

www.eurogeologists.eu



0.15 Clay
0.03 Gravel
0.11 Gravel
0.14 Sand/Gravel
0.13
0.27 Sand
0.23 Gravel
0.08 Gravel
0.01 Clay/Sand
0.28
0.18 Clay/Gravel
0.12