GEOSCIENCE CANADA
JOURNAL OF THE GEOLOGICAL ASSOCIATION OF CANADA
JOURNAL DE L'ASSOCIATION GÉOLOGIQUE DU CANADA

Our Stone Age: From the Neolithic to the New Millennium

Keeping up with appearances in the stone repair business

Encounter some tough but polished Italians, Brazilians and Slovenians

The granites in Spain are anything but plain

Nice Neoarchean Nubian anorthositic gneiss

Wonderful Whitehorse 2016: Field Trip Preview

2016 VOLUME 43

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Cover Photo: This life-size statue of King Chephren was fashioned around 2500 BCE, from anorthositic gneiss quarried in the remote desert of southwestern Egypt. This same stone, known as the Chephren gneiss, was also used to create thousands of funerary vessels. The beauty of these artifacts attests to the skills of these ancient artisans, but also to the innate qualities of this heritage stone. The statue now resides in the Egyptian Museum, Cairo; the bowls reside in museums in Brussels (top) and Turin (bottom).

Photo credits: Jon Bodsworth (left) and Tom Heldal (right).

EDITORIAL

GEOSCIENCE CANADA – The Road Ahead

It is my pleasure to welcome you to volume 43 of *Geoscience Canada* as its new scientific editor, and also on behalf of the greater team that makes this journal a reality. In the year since I became the 'editor-in-training,' many of my preconceptions about the publishing process have been demolished, but I have gained some new and valuable perspectives. I am keenly aware that there is much left to learn, but thanks to the efforts of Brendan and Cindy Murphy, the road ahead now seems much clearer and a little less steep. I would also like to thank Chris White and Sandra Barr of Geological Association of Canada (GAC) Publications for their encouragement to take on this role, and for their advice and assistance.

My first task is to thank our outgoing editor, Brendan Murphy of St. Francis Xavier University in Nova Scotia. There have been many significant changes in the format and content of *Geoscience Canada* under his stewardship. In 2011, we moved to a digital and online format – a move dictated in part by the growing cost of producing a printed journal. However, this transition went beyond dollars and cents, as freedom from the constraints of the printed page opened many new possibilities. The size of individual issues – and the length and complexity of individual articles – is no longer strictly limited by printing costs. Colour illustrations and eye-catching photographs are now standard accessories for any article, and links to other sources and articles can be embedded in the text. We are indebted to the University of New Brunswick in Fredericton for hosting the online journal, and we owe particular thanks to James Kerr and Michael Nason for assistance with this vital aspect of today's *Geoscience Canada*.

The leap from printed page to PDF was just the first of the many changes. In 2013, *Geoscience Canada* became a stand-alone journal, meaning that access to our content was decoupled from membership in the GAC. This does not sever links between the journal and GAC, nor does it indicate that we no longer serve GAC's objectives, but it has given us greater visibility and impact on national and international levels. This has broadened our readership, widened the scope of contributions and encouraged more submissions. In time, we hope that it will bring increased visibility and membership growth for GAC itself. These changes in *Geoscience Canada* can be directly measured. Our last pre-digital volume (2011) contained 164 pages; this grew to 204 pages in 2012, to 382 pages in 2013, to 584 pages in 2014 and to 492 pages in 2015. This trend reflects increasing numbers of papers, and longer papers, covering an increasingly wide range of topics. We are indebted to Brendan for his energy and enthusiasm, his ability to connect with scientists in many different fields and his legendary talent for persuading authors to write! It has been said that there are good editors and there are popular editors, but being both of these at once can be a challenge. Brendan managed it with great skill and insight, and will continue to do so as one of the science editors of *Geology*. I hope also to continue to benefit from his advice from time to time.

Encouraging papers, and seeing them through peer review, is only the first step in a lengthy process. Our managing editor, Cindy Murphy, looks after the downstream part of the editorial pipeline, where text, references, figures, photographs and other things all come together into a final seamless product. It takes a great deal of work and communication with authors to bring articles to this stage. I am enormously grateful that Cindy will continue this role in the years to come, and thank her sincerely for orienting me to my tasks and keeping me on time as this issue developed. We also owe great thanks to hard-working volunteer copy editors who take the time to ensure that the authors' work is represented in a clear and accurate manner, with the style consistent to the journal's format. Last but not least, we also owe thanks to Bev Strickland in St. John's, whose skills with the layout and formatting of articles are indispensable. Karen Dawe at GAC Headquarters in St. John's will continue her important work to promote the journal and manage subscriptions, and devise initiatives to enlarge our readership base. In the last twelve months, I have come to understand that I am just the newest member of a well-established and very efficient team, and that team effort and coordination are essential in everything that we do. I have no doubt that we can continue our record of timely assembly and production of each issue throughout volume 43 and beyond.

Geoscience Canada has now served the diverse Canadian Geoscience Community for over 40 years. Our founding editor Gerry Middleton envisaged a mission to publish articles about diverse topics in the Earth Sciences that would inform non-specialist readers, rather than simply mystify them. Our science is increasingly specialized, and sometimes it seems that each sub-discipline now has its own language and incomprehensible

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vocabulary. Over the years, *Geoscience Canada* has sought to create a bridge to connect those who should be in communication but often are not. This intersection of ideas from diverse disciplines is truly at the heart of the Earth Sciences, and it depends upon specialists understanding the relevance of ideas and advances in other areas that are less familiar to them. The highly successful *facies models* and *ore-deposit models* thematic paper series of the past provide great examples of this philosophy, and have seen wide use as instructional materials, but they are not the only ones. You can find illuminating and readable treatments of complex topics in most issues of *Geoscience Canada*. This guiding principle – that the science we present should be understandable in general terms by a wide cross-section of our community – is one that I firmly believe in, and I will do everything possible to uphold it.

Over the years, our content has diversified, notably through thematic paper series in which invited and submitted papers combine to address specific problems or topics in Earth Science. In the last year, compiled papers from the Hank Williams Series and the Paul Hoffman Series were published as books, and we anticipate that the popular Igneous Rock Associations series will result in a similar product of lasting value. The current issue contains the first contributions in a new thematic series dedicated to Heritage Stone, intended to give readers insight into the origins and special features of rock types that are widely used by human society, or which have played important roles in human history and culture. The Andrew Hynes Series directed at tectonic processes will have several new contributions in Volume 43, as will other existing thematic series. The 'GAC Medallist' paper series provides overview papers by leading Earth Scientists, which integrate established concepts with new developments. These will continue, and we hope to expand boundaries to include medallists from associated Canadian geoscience societies. Finally, some long-running thematic paper series will come to an end in the coming years, so we will need to replace them with new ideas. If you have such thoughts, or are interested in taking a valuable role as a series editor, please get in touch with us. We will also continue to publish scientific articles that are independent of thematic paper series, and bring you columns, book reviews and conference reports. Suggestions on all of these topics from the readership are encouraged and welcomed.

Geoscience Canada has indeed evolved, but we need to think about its further development and growth, and what our objectives should be in the coming years. There remain fundamental challenges that we cannot ignore, even with an online format, and with much of our effort aided by volunteers, the costs of running a quality journal remain significant. We have been awarded continued funding through the Canadian Geoscience Foundation that will support our activities over the next two years, but in the long run the journal needs to become self-sufficient. It is critical that we retain our subscription base, and expand it whenever and wherever we can. We need to raise the profile of *Geoscience Canada* as widely as possible through GAC's agreements with organizations such as the Geological Society of America and the Geological Society of London. A wider awareness of *Geoscience Canada* will expand our readership, which will bring in more article submissions, and in turn raise our profile even more. We must also endeavour to broaden the scope of the journal – we are very diverse already, but there remain active areas of Earth Science that are rarely featured in our pages. Over the years, we have published many papers that have proved invaluable as instructional tools. We must continue to emphasize this vital role, with the idea that undergraduates become familiar with *Geoscience Canada* at an early stage, and remain with us throughout their professional careers.

I believe, as does Brendan, that there is no reason why Canada cannot produce a multidisciplinary journal of the highest stature. I am struck by the great progress that has been made towards this goal over the last few years. We need to maintain this momentum, even as we venture into some uncharted waters, such as the growing movement towards open-access publishing. It goes without saying that we will need your support in order to continue and complete this journey. We need your support as readers – not only to use what we publish, but to raise awareness of the journal with colleagues and collaborators. We need your support as interested volunteers – to review papers and provide advice to authors, to be series editors for thematic papers, or to assist us with copyediting. We need your support as teachers and educators – to use the resources of *Geoscience Canada* in the classroom, and to use it to bring your own insights to the students of others. Above all, we need your support as researchers and writers – to submit the well-written and thought-provoking papers that are the hallmark of this journal. *Geoscience Canada* has a mandate that extends throughout our Geoscience Community and it is in many respects *your* journal. Its continued success depends on you as much as it does upon the efforts of its editorial and production team.

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SPECIAL ISSUE

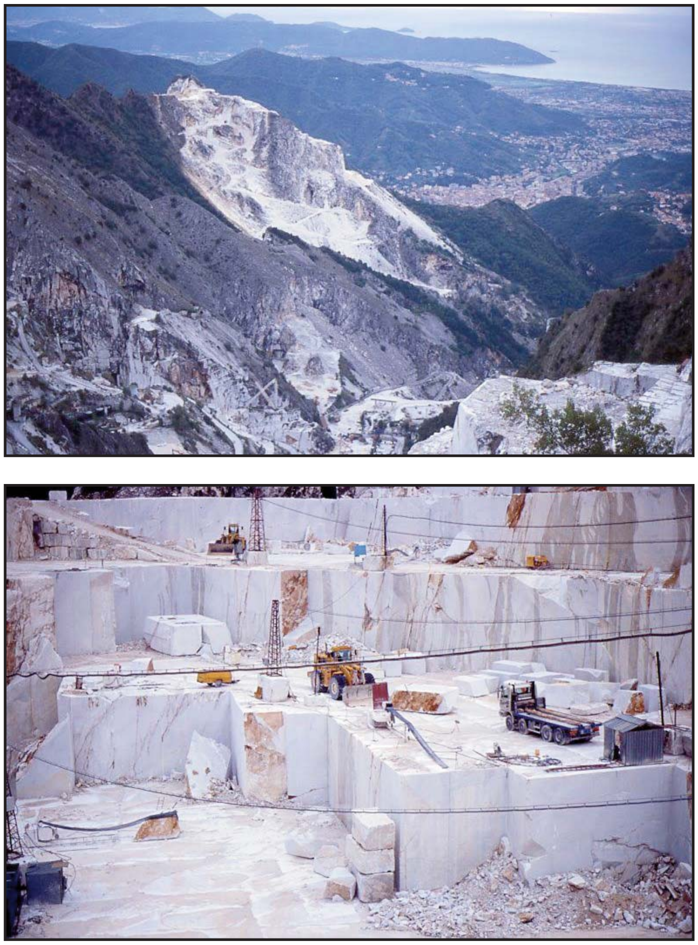
Heritage Stones of the World: Introduction to the New Series

Heritage stones are those stones that have special significance to human culture, especially in the construction of historical buildings and monuments. The mandate of the Heritage Stone Task Group (HSTG) of the International Union of the Geological Sciences is to draw attention to such stones, for many are no longer extracted but their historical quarries are linked to regional culture and local society, and should be preserved for conservation and restoration. The objectives of the HSTG are:

- To facilitate formal designation of natural stones that have achieved widespread recognition in human culture (i.e. heritage stones).
- To create the 'Global Heritage Stone Resource' (GHSR) and Global Heritage Stone Province (GHSP) as internationally recognized heritage stone designations.
- To promote the adoption and use of heritage stone designation by international and national authorities.

The intent of recognizing a GHSR or GHSP arises from the value of:

- Promoting increased community, national and international awareness of natural stone and its widespread utilization in human culture.
- Gaining additional professional recognition for, and understanding of, natural stone amongst professional workers, primarily in geology, engineering, architecture, archaeology and stone/building conservation.
- Highlighting the significant positive attributes of natural stone in terms of sustainability and regional economic development.
- Safeguarding and protecting heritage stone resources from subsequent sterilization by alternative human endeavour.
- Raising the profile of many natural stone materials to greater prominence through researching GHSR and GHSP citations.
- Encouraging proper management of well-known existing natural stone extraction operations in order to ensure future availability and utilization.



Carrara Marble quarries, Tuscany, Italy. Photo credit: D. Pereira.

- Offering a means or mechanism, operating on a worldwide basis, to formalize selected characteristics of natural stone material, for professional purposes and otherwise, in an internationally accepted context.
- Enhancing international co-operation in the research and utilization of natural stone resources.

This, then, is a special issue of *Geoscience Canada* dedicated to heritage stones from the world, and our objective is to spread awareness of the architectural heritage and the variety

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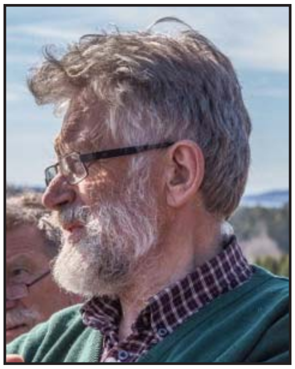
Geoscience Canada, v. 43, http://www.dx.doi.org/10.12789/geocanj.2016.43.089 pages 3–4 © 2016 GAC/AGC®

of natural stones that have been utilized. It comprises papers mostly arising from a session on heritage stone during the *General Assembly of European Geosciences Union*, held in Vienna in April 2015, supplemented with additional contributions from members of the task group. The volume is introduced by the discussion on the need of using original stones in repairing and maintenance of historical buildings and structures, explaining the concept of Global Heritage Stone Resource that will be applied in the following papers on natural stones from Spain, Slovenia, Italy, Brazil and Egypt. This issue also complements two recently published collections on heritage stones: a special publication of the Geological Society of London entitled "*Global Heritage Stone: Towards international recognition of building and ornamental stones*" and the special issue in Episodes, "*Global Heritage Stone Resource: an update*." It is our hope that this publication in *Geoscience Canada* will be a further step in appreciating heritage stones and will trigger the contribution of future papers on heritage stones from North America and elsewhere.

We greatly appreciate the work of the reviewers, as well as IUGS and IGCP 637 support for the on-going work of the Heritage Stone Task Group. This issue is dedicated to the memory of Anders Wikström (1937–2015), who was a dedicated member of the task group and enthusiast of heritage building stones.

Dolores Pereira and Brian R. Pratt, Guest Editors

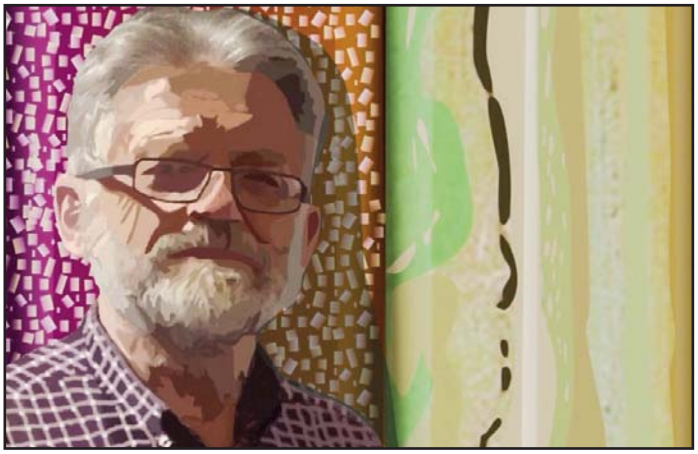
In Memory of Anders Wikström (1937–2015)



Anders Wikström was born in 1937. He studied at Uppsala University, in Sweden, graduating in Mathematics, Chemistry and Geology in 1961 and obtaining his Doctoral degree in 1968 in Mineralogy and Petrology with a thesis dealing with retrograde reactions in eclogites. Between 1968 and 2000 Anders was employed as a state geologist and senior state geologist at the Geological Survey of Sweden. Anders was very active in the study of granites and metamorphic rocks from Sweden. During the last years he became involved with the Heritage Stone Task Group with the purpose of bringing to light very important natural stones from Sweden that had been used in construction for centuries, but for which little information was available. He authored two papers on this subject, one on the serpentine marble from Kolmården and another one on the Dala porphyries from Älvdalen. Both papers were published in June 2015 and they were very much appreciated by museums from Sweden and Russia, which have pieces made from these stones, and requested scientific information on them. Anders helped to accomplish this important part of disseminating science for the scientific community but also for the general public. He was very active in writing and discussing science until he was diagnosed with ALS this past summer. On the 8th of November he passed away. We have lost a colleague and a friend.

Portrait of Ms. Shaeffer, by artist Mateo Hernández. Museum of Mateo Hernández, Béjar, Spain. Red Granite from Aswan, Egypt. Sculpture size: 55x30x30 cm. Photo credit: D. Pereira.

SERIES



Heritage Stone 1. Repair and Maintenance of Natural Stone in Historical Structures: The Potential Role of the IUGS Global Heritage Stone Initiative*

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SUMMARY

Natural stone has been used for millennia in many historically and culturally important structures. It inevitably undergoes weathering from natural processes and damage from human activities. Deterioration affects both ornamental features and main structural members of constructions, ultimately requiring repair and maintenance, or causing loss of the structure altogether. Stone similar to the original should generally be used for repairs, but if that is impossible, a closely similar material is required. Use of inappropriate stone or treatment with incompatible mortars can be aesthetically unsightly or have structurally and financially damaging consequences. Such use typically arises because of a lack of information and awareness among commissioners and specifiers of works, along with budget constraints leading to selection of cheaper alternatives. Even some World Heritage Sites have suffered. Selected examples from Western Europe illustrate these problems. The Global Heritage Stone initiative has been launched to improve recognition of the internationally most important heritage stones, promote their proper use in construction, maintenance and repair, and to stress the need to safeguard important stone resources for future use.

RÉSUMÉ

La pierre naturelle a été utilisée depuis des millénaires dans de nombreuses structures importantes historiquement et culturellement. Inévitablement cette pierre s'altère sous l'effet de processus naturels et de dommages causés par les activités humaines. Cette détérioration affecte aussi bien les éléments ornementaux que les principaux éléments structuraux des constructions, ce qui, éventuellement nécessite réparation et entretien, ou alors peut entraîner la perte de la structure. Une pierre semblable à l'originale doit généralement être utilisée pour des réparations, ou alors un matériau très similaire est requis. L'utilisation d'une pierre inappropriée ou un traitement avec des mortiers incompatibles peut être esthétiquement disgracieux ou avoir des conséquences structurellement et financièrement préjudiciables. Cette utilisation erronée est typiquement le résultat d'un manque d'information et de sensibilisation des commissaires et des rédacteurs du cahier des charges, ainsi que de contraintes budgétaires conduisant au choix d'options moins coûteuses. Et même, certains sites du patrimoine mondial en ont souffert. Des exemples choisis de l'Europe de l'ouest illustrent ces problèmes. L'initiative du patrimoine mondial de la pierre de taille lancée pour améliorer la conscience à l'échelle internationale des principales pierres du patrimoine, promouvoir leur utilisation correcte dans la construction, leur entretien et leur réparation, et souligner la nécessité de préserver les ressources importantes en pierre pour les besoins à venir.

Traduit par le Traducteur

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*This article is part of a set of papers dedicated to the memory of Anders Wikström published in Geoscience Canada Special Issue: Heritage Stone; a new series that is guest edited by Dolores Pereira and Brian R. Pratt.

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Figure 1. Examples of war damage: a) Cathedral in Ciudad Rodrigo (Salamanca, Spain) showing cannon ball impacts from the siege during the Peninsular War between French and Anglo-Portuguese and Spanish forces in the early 19th century. b) and c) parts of the façade of the Victoria and Albert Museum in London showing damage to the Portland Stone from casing fragments when bombs were dropped nearby. The damage was deliberately left unaltered when the façade was cleaned and repaired in 1985.

INTRODUCTION

Natural stone has been used in construction for thousands of years but is affected by the same processes of weathering by water, wind, frost, heating and biological activity as bedrock exposures of the same rocks. Inevitable progressive deterioration reflects the nature and properties of the stone, the passage of time and the ambient conditions, both natural and anthropogenic, to which it is exposed. Causes of deterioration of stone are varied, and include cracking and deformation, detachment, loss of material through erosion and mechanical damage, effects of discolouration and surface deposits, and biological colonization (e.g. algae, bacteria) (ICOMOS-ISCS 2008). Many stone-built structures are in urban areas. Particularly since large-scale industrialization, these structures have been exposed to aggressive attack by pollutants, accelerating the rate of decay. Because of early industrialization and large numbers of historically important structures, western Europe is an instructive area for observing causes of decay and possible approaches to reducing future damage to the historical, cultural and architectural heritage.

Article 4 of the UNESCO 'Convention concerning the protection of the World cultural and natural heritage' states that "*Each State Party to this Convention recognizes the duty of ensuring the identification, protection, conservation, presentation and transmission to future generations of the cultural and natural heritage*" (whc.unesco.org/en/conventiontext). This can help to protect national heritage and can contribute to income from tourism. Governments address this obligation in different ways depending on their national priorities and provisions for protecting heritage. However, positive efforts can be undermined by political instability and loss of control. Wars and vandalism have endangered historical areas and sites for centuries, causing damage or, in some cases, complete destruction (Fig. 1). Recent and current political instability in some places, including some UNESCO World Heritage sites, is a matter for continuing concern but can only be solved by conflict resolution.

More widely, anthropogenic deterioration, whether conscious or unconscious, or caused by climate and weather (http://whc.unesco.org/en/danger/), can be addressed by good practices for repair and maintenance (Pereira et al. 2015a).

DETERIORATION, MAINTENANCE AND REPAIR

Inappropriate maintenance and repair, development projects, inadequate management systems, and insufficient legal protection can threaten either important structures or groups of individually less important buildings that, together, constitute significant conservation areas. The rate of deterioration of stone depends on the initial quality and can progress to a condition in which only replacement can secure the future of the building or monument.

Intervention at the right time can preserve, or extend the life of, the cultural heritage but technically and aesthetically appropriate materials must be selected to retain both visual appearance and the structural integrity of constructions. It is recommended that original types of stone be used for maintenance and repair, but that may be impossible if resources have been exhausted, built-over, or have otherwise become inaccessible. In that case, detailed and readily accessible technical information is needed to identify the most appropriate alternatives.

SOME EXAMPLES FROM EUROPE

Inappropriate actions in the repair and maintenance of buildings occur widely, even in parts of UNESCO World Heritage cities and sites. Some examples of problems in these and other locations in western Europe serve to illustrate the salient issues.

Palace of Westminster, London, UK

Original selection of stone was not always good, even in the case of some prestigious buildings. An example is the Palace of Westminster (often referred to as the Houses of Parliament) in London, UK, which has World Heritage status (Fig. 2). The original medieval buildings were largely destroyed by fire in 1837. A replacement was commissioned in the then popular Gothic Revival style and was completed in stages between 1847 and 1852 (www.parliament.uk/about/living-heritage/building/palace/architecture/palacestructure/the-stonework). The stone selected for the new building was *Anston Stone* (Cadeby Formation, late Permian), a dolomitic limestone from Nottinghamshire (Anonymous 2012a). A variety called 'Mansfield White' was selected because it could be easily carved and was available at a favourable price. However, it performed badly from the outset because of rapid weathering exacerbated by acidic rainfall and fog resulting from the predominant use of coal as a fuel in London until the mid-20th century and, subsequently, pollutants mainly from road traffic. By the 1930s it was necessary to begin replacing the Anston Stone with Clipsham Stone (Middle Jurassic), a pale ooidal to bioclastic limestone similar in colour to Mansfield White but with different physical properties (Anonymous 2012b). After suffering bomb damage in the 1940s that program was completed in the 1950s and thus most of the present façade is in Clipsham Stone. But, by the 1960s, damage was again evident, leading to further works from 1984 to 1991. However, in 2012 it was again necessary to begin extensive repair work, which is likely to last for many years but at a cost of several billion £GB. Although the Anston Stone had proved to be inadequate, significant amounts still remain in the structure. But as the Clipsham Stone has also deteriorated badly, this raises the issue of whether newly quarried Clipsham Stone should be used for partial compatibility, or whether a more durable stone might replace it even though that could affect the future performance of older parts of the structure. This illustrates the need to select good stone at the outset, taking into account the environmental conditions that it will be exposed to and the dilemma that can face the repairer after an alternative replacement stone has been used.

Figure 2. The Palace of Westminster showing pale-coloured Clipsham Stone from recent repairs, contrasting with Clipsham Stone from previous repairs and Anston Stone.

Clerecía Church, Salamanca, Spain

Originally known as the Royal College of the Company of Jesus, construction of the Clerecía Church began during the 17th century in Baroque style, using Salamanca sandstone in the lower part and Villamayor sandstone in the upper part of the building. This church is part of the Salamanca World Heritage site. The lower part deteriorated unevenly as a result of water adsorption through the more porous parts of the stone, as well as several inappropriate actions such as covering some parts with mortar and replacing blocks in the frontage of the church. Limited understanding of natural stone led the architects in charge of the restoration of the Clerecía Church to use various igneous rocks to replace the sandstone (Fig. 3). The result is a poor aesthetic effect that could have been easily avoided by awareness of available local material (Pereira and Cooper 2014).

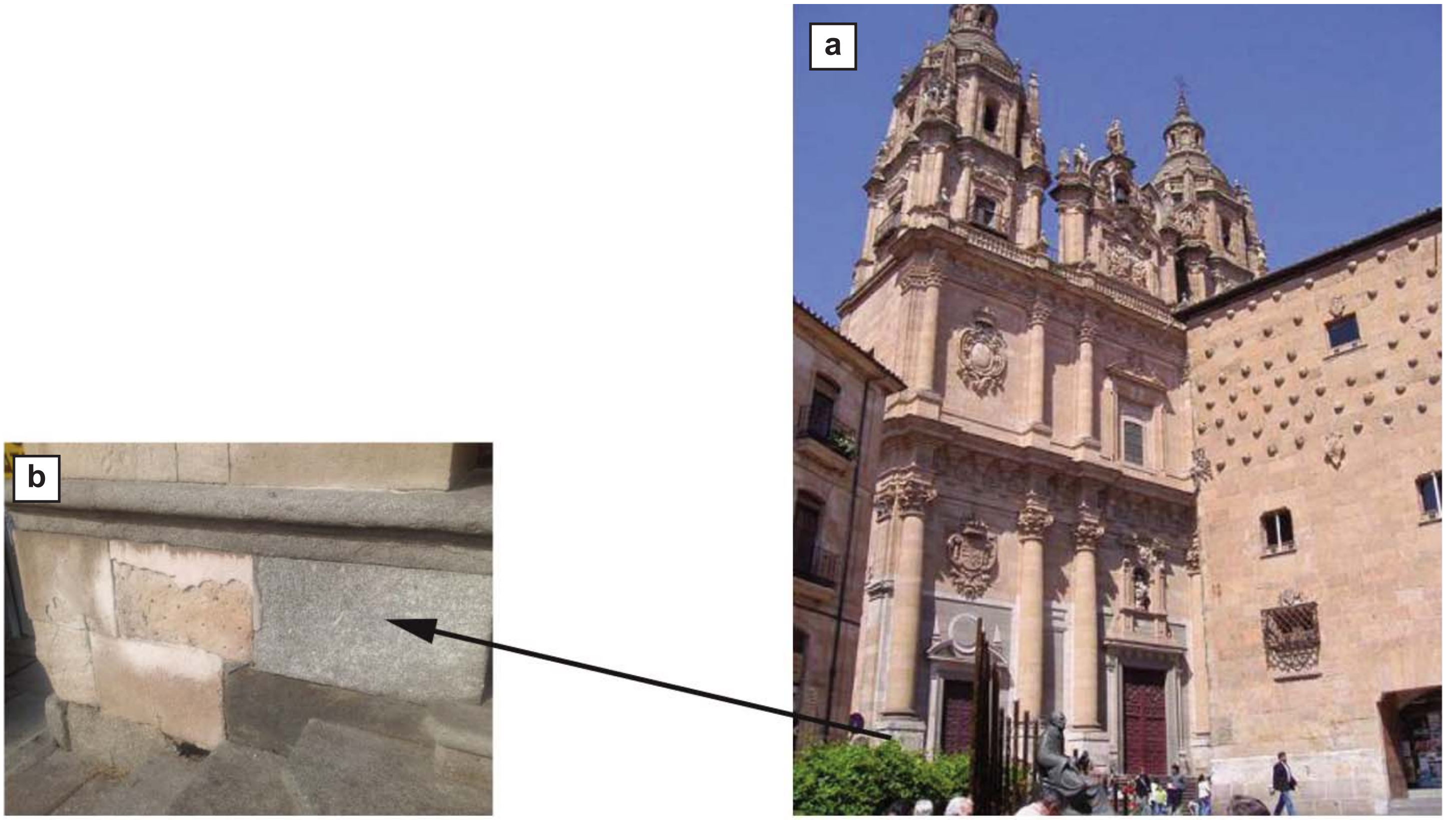

Figure 3. a) Clerecía Church, Salamanca; b) replacement of sedimentary stone (Villamayor sandstone) by various igneous rocks.

British Museum, London, UK

The British Museum was founded in 1753 as the world's first national public museum. The present building on the site was constructed in stages between the 1820s and 1850s using granite for the base courses and *Portland Stone* (Tithonian, Upper Jurassic) for the main body of the structure (http://www.britishmuseum.org/about_us/the_museums_story). In 2000, an internal courtyard was roofed over to form the Queen Elizabeth II Great Court, expanding visitor space by some 40%. The original Ionic portico of the courtyard had been demolished in the late 19th century. It was to be replaced (Fig. 4a) and the specification stated that the work should use 'stone from Portland.' In the event, Middle Jurassic stone imported from France (via Portland) was used, causing a major controversy in which some people considered that the stone was inappropriate while others praised the major architectural achievement (www.theguardian.com/the observer/2000/nov/12/2). The colour and texture do not match and, since this part of the building is sheltered from weathering, the contrast is unlikely to decrease over time. This illustrates the importance of precise specification of stone but also raises the question of whether some changes should be allowed for architectural reasons.

Lincoln Cathedral, Lincolnshire, UK

Lincoln Cathedral is regarded as one of the most important historic buildings in England. Building commenced in 1088 and continued in stages for several hundred years, and it was reputedly the tallest building in the world between 1311 and 1549 (Pevsner 1989). Like many other medieval cathedrals, it is under a continuous process of maintenance and repair. Current repair and maintenance work employs appropriate stone but the building shows evidence of 19th and early 20th century interior work that is aesthetically unpleasing. Parts of the interior walling were originally built with red sandstone (Triassic) but some repairs were made with white limestone (Lincolnshire Limestone; Bajocian, Middle Jurassic) (Ashton 1980), of a type used extensively elsewhere in the cathedral. This resulted in an irregular patchwork of contrasting colours (Fig. 4b) that some consider undesirable.

Chipping Norton, Oxfordshire, UK

Many buildings in the town of Chipping Norton date from the 18th century and were constructed mainly with *Hornton Stone* (bioclastic ferruginous limestone; Pleinsbachian–Toarcian, Lower Jurassic). This stone is susceptible to spalling. Chipping Norton Limestone (oolitic limestone; Bajocian, Middle Jurassic) (Horton and Edmonds 1987; Radley 2003, 2009) was used for detailing around windows in the structure illustrated in Figure 4c, providing a pleasing contrast. That colour pattern was disrupted by later repairs that used Middle Jurassic limestone in place of some of the darker Hornton Stone (Fig. 4c); the result is not likely to become visually compatible even after a period of weathering.

Salamanca, Turin and Oxford

Salamanca (Spain) was recognized as an UNESCO world heritage site in 1988, mainly because of the homogenous construction of the old town using local natural stone and the optimum state of conservation. Buildings in central Salamanca were constructed using Villamayor sandstone (García Talegón et al. 2015) and Salamanca sandstone (Nespereira et al. 2010;

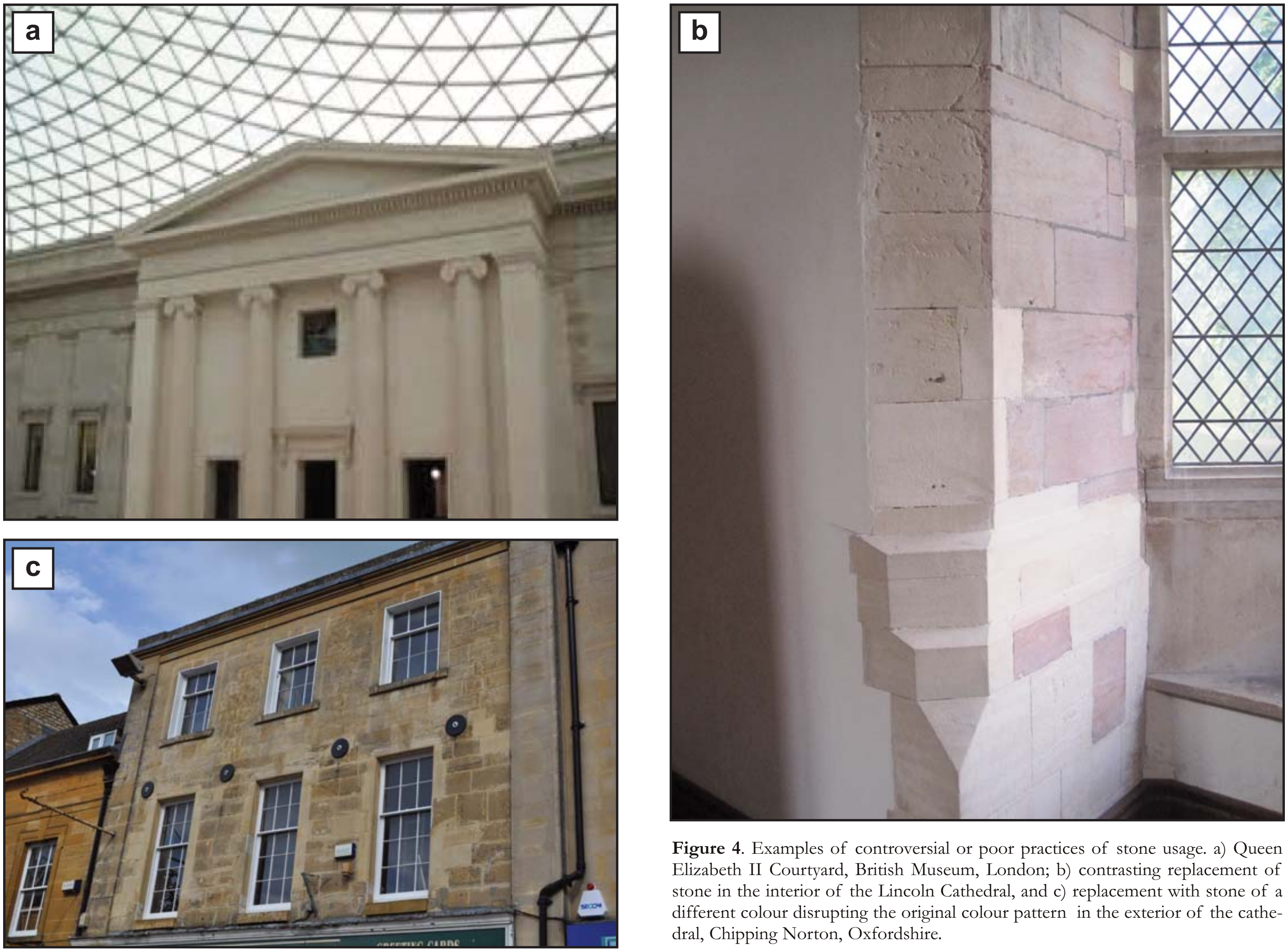

Figure 4. Examples of controversial or poor practices of stone usage. a) Queen Elizabeth II Courtyard, British Museum, London; b) contrasting replacement of stone in the interior of the Lincoln Cathedral, and c) replacement with stone of a different colour disrupting the original colour pattern in the exterior of the cathedral, Chipping Norton, Oxfordshire.

Pereira and Cooper 2014) for most of the structures. However, granite was used in the lower parts of the buildings after it was realized that the sandstones were not resistent to water absorption and became weak under critical conditions (Pereira et al. 2015a). Humidity and contamination have had negative influences on the sandstones, leaving some buildings in a very poor state. Mortar was used to disguise the deterioration, a common mistake because it can react chemically with minerals in the stone, especially where the stone has a high water absorption coefficient. The reactions cause accelerating deterioration as the mortar continues reacting with the sandstone matrix and cement, and can lead to complete destruction of the stone (Fig. 5a). Similar circumstances occurred in, for example, Turin (Italy), where attempts were made to obscure deterioration of the *Floresto Marble* by covering it with mortar (Fig. 5b) and Oxford (UK), where mortar has been used to 'repair' limestone (Fig. 5c). Granites can also be affected adversely by inappropriate coverings (Fig. 6); although the result is less dramatic than in the case of sandstone and limestone, at least in the short term; it is nevertheless aesthetically undesirable.

Hampstead, London, UK

An extreme example of inappropriate repair, presumably because it was undertaken at the lowest possible cost, can be observed at the front of a bank in Hampstead, London. The façade was constructed with *Doulting Stone* from Avon (crinoidal biosparite; Bajocian, Middle Jurassic), which contains numerous large *Thalassinoides* burrows (Richardson 1915). The infilled burrows are more porous than the body of the rock, and weather more quickly. During 'repair,' the hollows associated with these burrows were simply cemented over but some red bricks were also used to replace seriously weathered stone blocks, producing a poor visual result (Fig. 7). While this is a minor building, these repairs detract from the late 19th century terrace of which it is a part.

THE GLOBAL HERITAGE STONE RESOURCE AND GLOBAL HERITAGE STONE PROVINCE CONCEPTS

Poor practice can, therefore, involve poor initial selection of stone. But inappropriate replacement of stone is widespread, often because of a lack of technical information and understanding among some architects, contract specifiers of stone, and commissioning bodies such as local government and private companies. Even if technical information is available, less desirable but cheaper stone or inappropriate use of mortar or cement, may be selected to fit project budgets, without consideration of the longer term consequences in cost and further damage. Materials that are incompatible with the original fabric

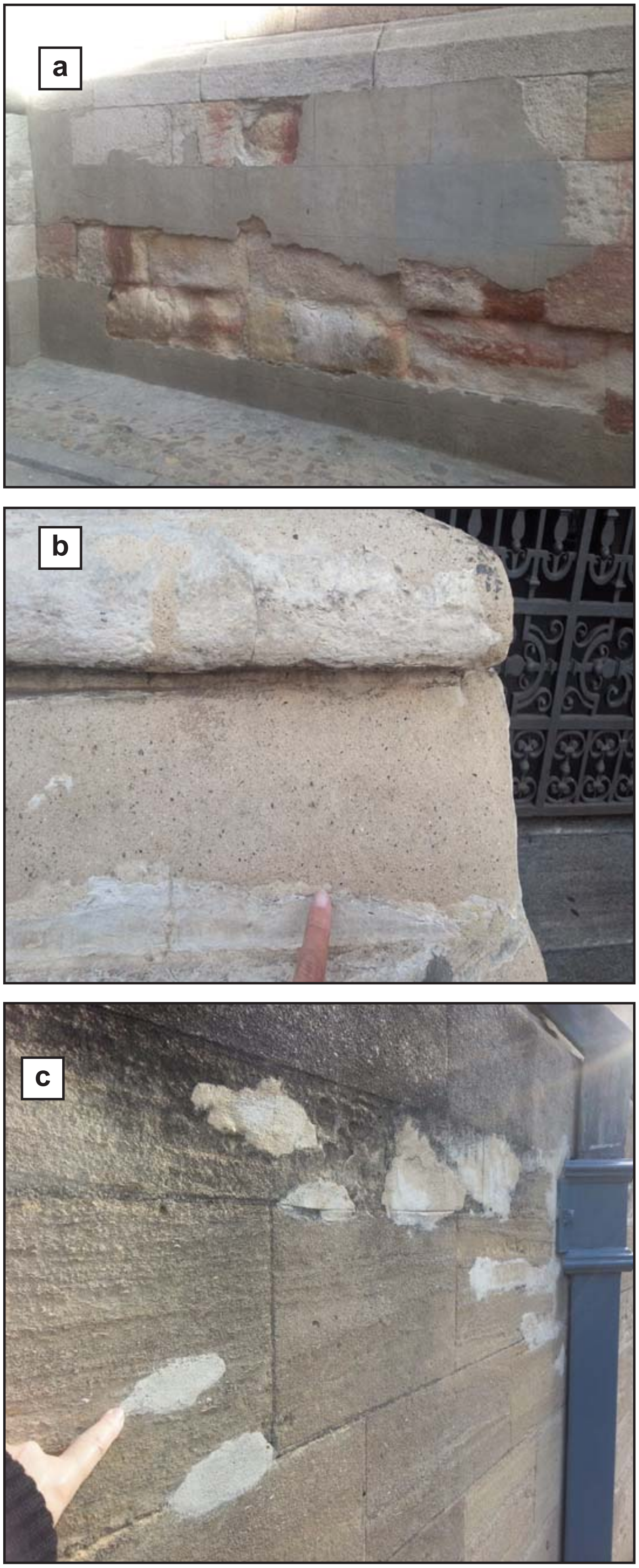

Figure 5. Inappropriate use of mortar in repairs. a) Use of mortar on an opal-cemented conglomerate (Salamanca sandstone) in an historic building in Salamanca; b) use of mortar on limestone (Floresto Marble) in an historic building in Turin; c) use of mortar on limestone in a building in Oxford.

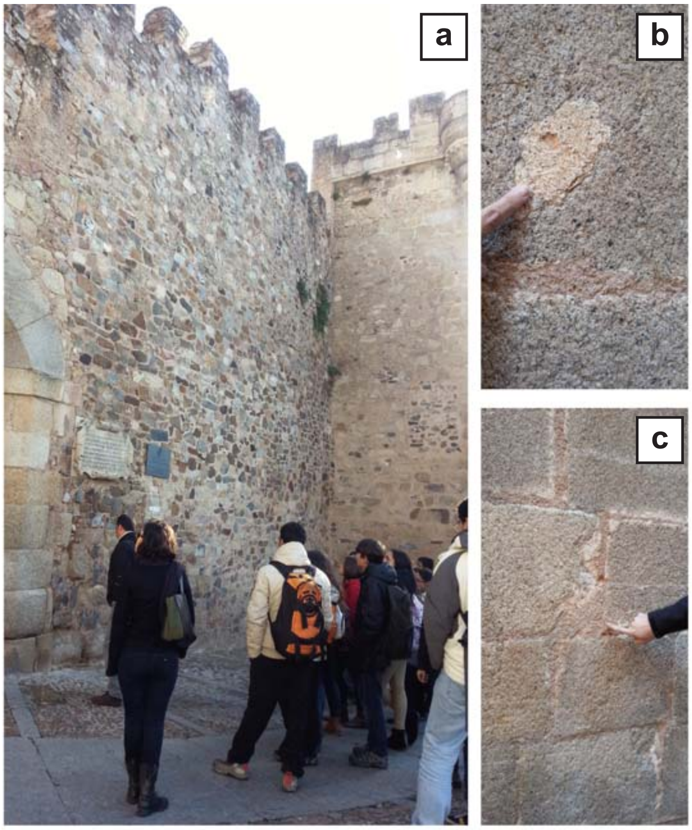

Figure 6. The Roman Wall around the World Heritage City of Cáceres, Spain, and use of mortar that contrasts markedly with the original colour of the granite forming the wall.

of the structure can either cause further or accelerated deterioration of the original stone and can be visually and aesthetically undesirable.

There is a need, therefore, to raise awareness and understanding of the importance of good practices for the maintenance and repair of the natural stone heritage. The Global Heritage Stone Resource (GHSR) and Global Heritage Stone Province (GHSP) concepts were developed by the Heritage Stone Task Group (a working group within the International Union of Geological Sciences) at the 33rd International Geological Congress of 2008 in Oslo as a step towards improving the situation. The initiative aims to establish new, formal, international geological designations for important types of natural stone that have been widely used and/or have widespread cultural and architectural recognition (GHSR), and of areas (GHSP) that contain more than one type of stone that would qualify for GHSR status (Cooper et al. 2013). It also aims to develop internationally accepted standard approaches to the reporting of technical and aesthetic characteristics of natural stones used for repair and maintenance of historic buildings, monuments and structures as well as for new construction. Formalization should help to increase awareness of the potential uses of various GHSR and provide important information for those engaged in using stone for repair and maintenance. Stones that have been used in heritage construction and sculptural masterpieces, as well as in utilitarian (yet culturally important) applications are obvious candidates for GHSR status. To achieve these aims, the GHSR and GHSP designations must

Figure 7. Part of the façade of a bank in Hampstead, London, showing inappropriate use of cement and brick in repairs to Doulting Stone.

be promoted and adopted by international and national authorities (Cooper et al. 2013).

Adoption of the GHSR and GHSP designations can have long-term benefits. Formalized reporting of the characteristics of natural stone for professional purposes, whether geological or in contractual specification of types of stone to be used in repair and maintenance, will help ensure that appropriate materials are used. Within the European Union there are three legally binding schemes in the agricultural sector: the protected designation of origin (PDO); protected geographical indication (PGI); and traditional speciality guaranteed (TSG), particularly for regionally important foodstuffs and wines (ec.europa.eu/agriculture/quality/schemes/index_en.htm). The aim is to prevent other areas from marketing produce purporting to be from the original place of production. The possibility of a similar approach to designation of stone has been raised to prevent imported materials from being substituted improperly for original types of stone.

The heritage stone designation can, if properly disseminated, create increased awareness of available and appropriate natural stone among professional workers in geology, engineering, architectural and artistic work, in stone/building conservation, and the general public. In addition, the designation can enhance international cooperation for research on, and documentation of, natural stone resources. This has already been demonstrated by the enthusiastic response and numerous contributions to specific sessions at international meetings and publications dedicated to this topic (e.g. Pereira et al. 2015a, b). Success of the GHSR and GHSP designations should also help to encourage proper management of natural stone resources, including future protection of important dimension stone resources from sterilization by other forms of development (Cooper et al. 2013; Pereira and González-Neila in press).

The Heritage Stone Task Group has formally considered whether Portland Stone (Hughes et al. 2013) from the UK should be the first Heritage Stone Resource to be designated. A decision is expected soon. The Group has promoted numerous papers describing selected natural stones from many parts of the world that might become candidate stones for formal designation (e.g. Pereira and Cooper 2013; García-Talegón et al. 2015; Pereira et al. 2015a) in the coming years. But it remains to be seen how many will be formally proposed and whether the designation will be fully recognized by international and national bodies.

CONCLUSIONS

As far as possible, natural stone similar to the original source should be used in repair and replacement so that adverse consequences for the historic and architectural heritage can be minimized. If that is impossible, a closely similar material is required. Use of inappropriate stone or treatment with incompatible mortars can have structurally and financially deleterious consequences, and can be aesthetically unsightly. Inappropriate use usually arises from a lack of information and awareness amongst commissioners and specifiers of works, and from budget constraints leading to selection of cheaper alternatives. Initial selection of suitable stone is important but inappropriate attempts at repair have exacerbated problems even in some World Heritage Sites. Selected examples from western Europe illustrate inappropriate use of mortar and replacement of stone. The Global Heritage Stone initiative has been launched to encourage standard reporting of technical data on, and to improve recognition of, the internationally most important heritage stones, as well as to promote their proper use in construction, maintenance and repair, and to stress the need to safeguard important stone resources for future use.

ACKNOWLEDGEMENTS

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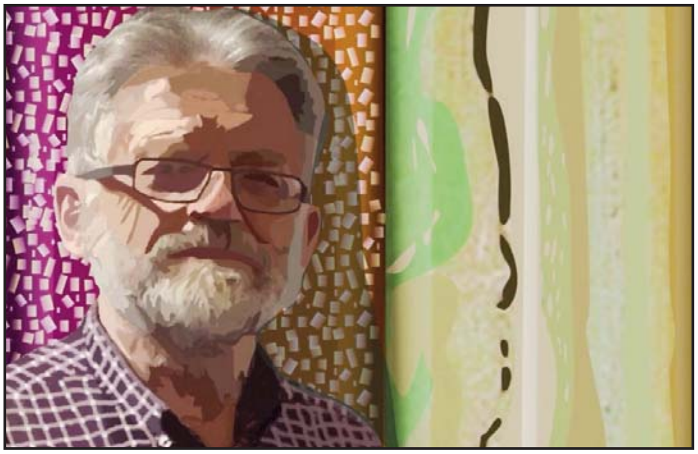

Heritage Stone 2. The Dora-Maira Unit (Italian Cottian Alps): A Reservoir of Ornamental Stones Since Roman Times*

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SUMMARY

The Dora-Maira Unit is a geological unit cropping out in the inner part of the Cottian Alps and belonging to the Penninic Domain of the Western Alps (northwestern Italy). It consists of a Paleozoic basement and its Mesozoic carbonate cover, metamorphosed under eclogite facies conditions in the Cenozoic. Due to the complexity of the rock associations and the textural-metamorphic transformations, the Dora-Maira Unit has been a source of ornamental stones over the centuries, and still represents a reservoir of material locally employed for historical and contemporary buildings. Several varieties of orthogneiss, quartzite and marble, derived from the Paleozoic basement and Mesozoic cover, are known by different local names (e.g. *Luserna Stone, Borgone* and *Vaie Stone, Perosa Stone, Bargiolina Quartzite, Foresto* and *Chianocco Marble*). These stones were largely employed during the 17th and 18th centuries for some of the most famous and important monuments in Turin (capital of Piedmont region, northwestern Italy), as well as in the countryside, since Roman times. Some of the materials exploited in the Dora-Maira Unit were also exported to foreign countries: Borgone and Vaie Stone were used for the paving of the Louvre Museum, and Perosa Stone was employed for the construction of the monument of Independence in Lagos, Nigeria. Consequently, the Dora-Maira Unit can be designated as a Global Heritage Stone Province.

RÉSUMÉ

L'Unité Dora-Maira est une unité géologique affleurant dans la partie interne des Alpes Cottiennes; elle appartient au Domaine Penninique des Alpes occidentales (Italie du Nord-Ouest). Elle se compose d'une croûte continentale d'âge Paléozoïque supérieur et de sa couverture carbonatique Mésozoïque, métamorphosées en faciès éclogite pendant le Cénozoïque. En raison de la complexité des associations lithologiques et des transformations métamorphiques et structurelles, l'Unité Dora-Maira a été une source de pierres ornementales au cours des siècles, et encore il représente un réservoir de matériau employé localement pour des bâtiments contemporains et historiques. Plusieurs variétés de gneiss, de quartzite et de marbre, provenant du socle paléozoïque et de la couverture mésozoïque et connues sous différents noms locaux (par exemple Pierre de Luserna, Pierre de Borgone et Vaie, Pierre de Perosa, Bargiolina, marbres de Foresto et Chianocco), étaient largement utilisées pour certains monuments les plus célèbres et importants à Turin (capitale de la région Piémont), au cours des 17ème et 18ème siècles, et dans les alentours de la ville depuis l'époque romaine. Certains des matériaux exploités dans l'Unité Dora-Maira ont été également exportés aux pays étrangers: la Pierre de Borgone et Vaie a été utilisée pour le pavage du Musée du Louvre, et la Pierre de Perosa a été employé en Afrique, à Lagos, au Nigéria, pour la construction du monument de l'indépendance. Par conséquent, l'Unité Dora-Maira peut être indiquée comme une Pierre Province du patrimoine mondial.

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INTRODUCTION

Stone has always been a major source of material in the Italian construction industry and an important cultural element for the creation of masterpieces of sculpture and architecture, thus constituting a significant part of Italy's cultural heritage. Knowledge of stone resources, their mineralogic and petrographic characteristics and their use, can provide a broad overview of the historical relevance of these materials, emphasizing the importance of a significant economic activity that is fundamental to the understanding of the history and the traditions of different Mediterranean cultures (Cooper 2015; Marker 2015).

Every Italian region is represented by artistic creations and historic buildings often made of historic heritage stone. In particular, in the Piedmont region (northwestern Italy), stone has always been the most widely employed building material characterizing, for example, the architectural identity of the city of Turin (capital of Piedmont). Here, stones have been used in historical and contemporary buildings, monuments and urban art, showing the close link between an urban area and natural stone resources, and emphasizing the role that stone has played in the culture and economic wealth of the Piedmont region (Borghi et al. 2015).

From the Roman age to the 18th century the easily workable materials (e.g. marble and sedimentary rocks) were exploited and used for valuable infrastructures and sculptures. Lately, during the 19th century, with the development of new technologies for dimension stone exploitation and processing, granite and other silicate rocks have been progressively employed. The knowledge of stone resources (mineralogical and petrographic features, their use and exploitation techniques, etc.), therefore enhances the historical and cultural significance of such materials. The great variety of ornamental and building stones used for architectural elements is certainly a result of the complex geological nature of the region (Borghi et al. 2014). In Piedmont, indeed, many different geological units occur, in particular, the western part of the metamorphic Alpine Chain, the sedimentary Tertiary Piedmont Basin, and a small sector of the Northern Apennines.

This paper illustrates the most important lithological varieties of cultural stone coming from the Dora-Maira Unit, which extends more than 1000 km^2 in the inner part of the Western Alps (Fig. 1). A lithological and textural characterization and an overview of the main applications are provided for the selected rock types.

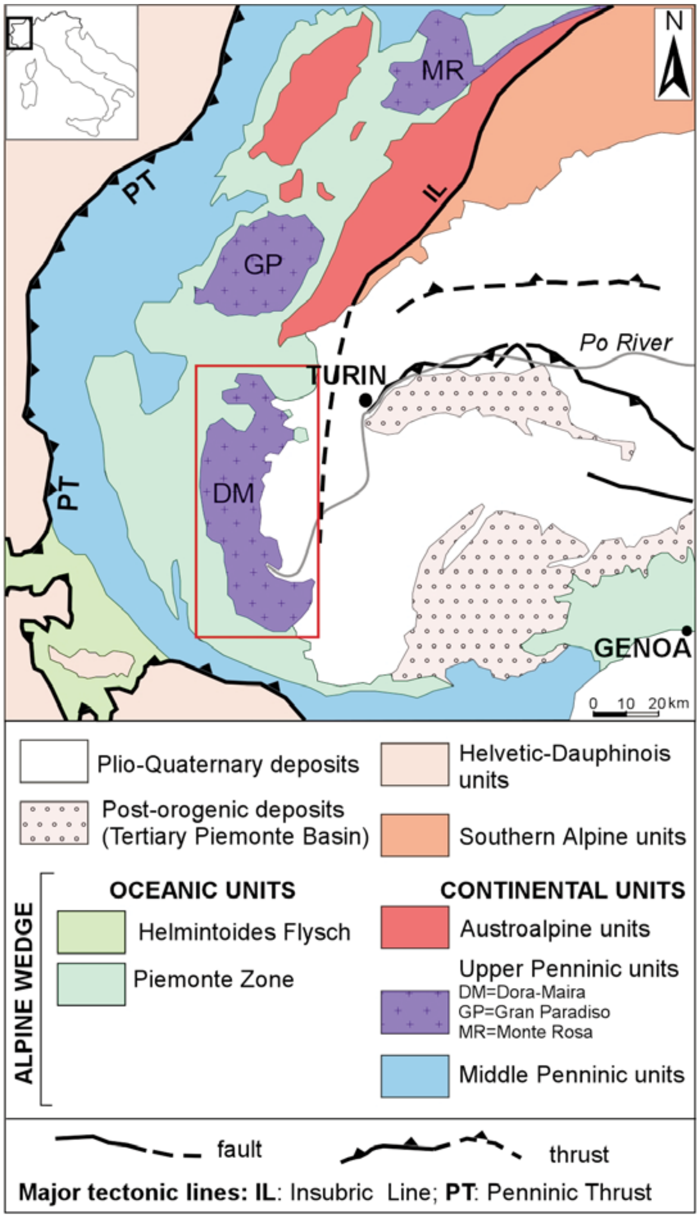

Figure 1. Geological map of the Western Alps (modified after Fusetti et al. 2012). The red rectangle points out the area represented in Figure 2.

GEOLOGICAL SETTING

The Western Alps represent a collisional orogenic wedge where both continent- and ocean-derived tectonic units are currently exposed. It consists of three main structural domains: (1) the internal domain, belonging to the upper plate of the collisional system, which corresponds to the Southern Alps; (2) the external domain, representing the European foreland and consisting of the Helvetic–Dauphinois domain; and (3) the axial sector of the chain, included between the Penninic Front to the north, and the Insubric Line to the south (Fig. 1) (Dal Piaz et al. 2003). The axial portion represents a composite nappe pile consisting of the Austroalpine and Penninic domains separated by oceanic units of the Piemonte Zone.

The Dora-Maira Unit, together with the Monte Rosa and the Gran Paradiso Massifs, represents the basement nappe of the inner Penninic Domain (e.g. Schmidt al. 2004) and consists of various tectonic slices of pre-Triassic basement and metasedimentary successions of Permo–Mesozoic cover. This unit underwent a strong Alpine tectono-metamorphic overprint characterized by high (HP) to ultra-high pressure (UHP) metamorphic assemblages and greenschist re-equilibration in Cenozoic time (Sandrone et al. 1993; Compagnoni et al. 2004). Because of the complexity of the rock associations and the textural-metamorphic transformations, the Dora-Maira Unit was, and still is, the object of extensive exploitation (Fig. 2; Table 1).

The pre-Triassic basement is represented by poly- and monometamorphic complexes, both intruded by late Variscan granitoids. The polymetamorphic complex (9 in Figure 2), mainly consists of garnet–chloritoid micaschists, minor metabasites, impure dolomitic marble, and granodioritic

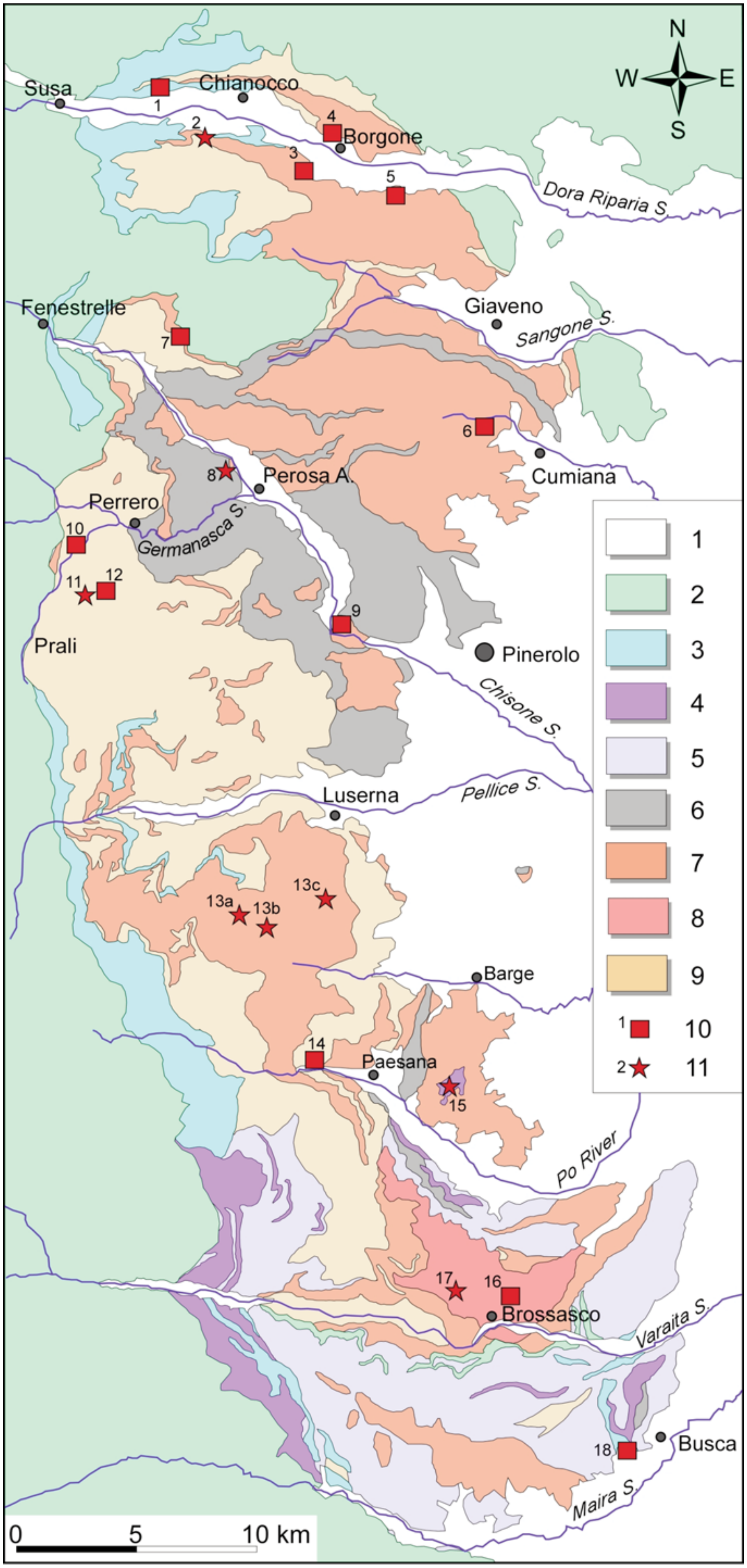

Figure 2. Geological map and quarry location of the most representative ornamental and building stones exploited in the Dora-Maira Unit. Map legend: 1) undifferentiated Quaternary deposits; 2) Piemonte ophiolite nappe (undifferentiated) and minor slices within the Dora-Maira Unit; 3) Mesozoic cover (marble, metadolomite and calcschist); 4) impure quartzite ('Bargiolina'); phengite-quartzite grading into quartz micaschist and phengite-schist (Permian?); 5) fine-grained gneiss and micaschist, including thin lenses of quartzite and rare bodies of blueschist facies metabasite (Permian?); 6) graphite-bearing micaschist, meta-arenite, and meta-conglomerates ('Pinerolese Graphitic Complex,' Carboniferous?); 7) meta-intrusive rocks of different age and composition; 8) orthogneiss and meta-granitoid, coarse-grained garnet micaschist, pyrope-coesite quartzite, silicate marble and metabasite with ultra-high pressure re-equilibration (Brossasco−Isasca Complex); 9) polymetamorphic garnet-chloritoid micaschist, impure marble, eclogite facies metabasite (mostly re-equilibrated into greenschist facies), and relics of pre-Alpine high temperature assemblages (pre-Carboniferous?); 10) historical quarries; 11) quarries still active in the last decade. The description of each quarry site is in Table 1. Geological map after Vialon (1966), Sandrone et al. (1993), Balestro et al. (1995), Bussy and Cadoppi (1996), Carraro et al. (2002), and Compagnoni et al. (2012).

Table 1. Location and description of the main lithotypes exploited in the Dora-Maira Unit.

Quarry site in fig. 2	Name	Lithology	Paragenesis	Fabric	Age
1	Foresto and Chianocco Marble	Dolomitic marble	Dol - Cal - Wmca	Foliated	Triassic
2 3	S. Basilio Stone Villar Focchiardo Stone	Leucocratic orthogneiss	Qtz – Ab – Kfs – Wmca – Tur	Gneissic layering	Late Variscan
4 5	Borgone Stone Vaie Stone	Metagranite-augengneiss	Qtz – Ab – Kfs – Wmca – Bt	Gneissic layering to poorly foliated	Late Variscan
6	Cumiana Stone	Orthogneiss	Qtz – Ab – Kfs – Wmca – Bt – Ep	Gneissic layering	Late Variscan
7	Luserna type Stone	Orthogneiss	Qtz – Ab – Kfs – Wmca ± Bt ± Chl	Tabular foliation	Late Variscan
8 9	Perosa Stone Malanaggio Stone	Dioritic- to granodioritic gneiss	Pl – Am – Ep – Chl – Bt – Wmca ± Qtz ± Kfs	Gneissic layering	Late Variscan
10 11 12	Salza di Pinerolo Marble Prali Marble Prali Marble	Impure to layered marble	Dol – Cal – Tr ± Chl ± Ep ± Wmca	Foliated	Paleozoic
13a 13b 13c	Luserna Stone Basin (Luserna S. Giovanni, Rorà and Bagnolo municipalities)	Orthogneiss	Qtz – Ab – Kfs – Wmca ± Bt ± Chl	Tabular foliation	Late Variscan
14	Paesana Marble	Impure to layered marble	Dol – Cal – Wmca – Tr	Poorly foliated	Paleozoic
15	Bargiolina	Quartzite	Qtz – Wmca – Ab	Tabular foliation	Permo-Triassic
16	Brossasco Marble	Silicate marble	Cal ± Dol ± Cpx ± Ph ± Ep ± Grt ± Phl	Isotropic to poorly foliated	Paleozoic
17	Gilba Stone	Orthogneiss	Pl + Qtz + Kfs + Ph ± Bt	Strongly foliated	Late Variscan(?)
18	Busca Alabaster	Speleothem	Cal	Columnar and fibrous	Quaternary

Ab=albite, Am=amphibole, Bt=biotite, Cal=calcite, Chl=chlorite, Cpx=clinopyroxene, Dol=dolomite, Ep=epidote, Grt=garnet, Kfs=K-feldspar, Ph=phengite, Phl=phlogopite, Pl=plagioclase, Qtz=quartz, Tur=tourmaline, Tr=tremolite, Wmca=white mica

orthogneisses of pre-Variscan age (457 ± 2 Ma; Bussy and Cadoppi 1996). Pre-Alpine relics, attributed to Variscan metamorphism, are represented by garnet–muscovite–sillimanite pseudomorphs after cordierite, spinel, andalusite and staurolite in the micaschists (Cadoppi 1990; Compagnoni et al. 1993); red biotite in the orthogneiss; and diopside in the marble (Cadoppi 1990). An important talc mineralization, presently exploited in the Germanasca Valley, is hosted in this complex. The polymetamorphic complex was metamorphosed under eclogite facies conditions at 15−20 kbar and 500−550°C (Borghi et al. 1985; Pognante and Sandrone 1989; Cadoppi 1990; Chopin et al. 1991; Borghi et al. 1996; Gasco et al. 2011), though a diffuse re-equilibration to greenschist facies affects the Dora-Maira Unit as a whole. During the past and in the last decade, the only rock type exploited in this complex has been dolomitic marble cropping out in metre-sized lenses within the micaschist (quarry sites 10, 11, 12 and 14 in Figure 2).

A coesite-bearing polymetamorphic complex, the so-called Brossasco−Isasca Complex (8 in Figure 2; Kienast et al. 1991), occurs in the southern Dora-Maira Unit. It has been distinguished, from all the other basement complexes, thanks to its peculiar metamorphic assemblage (Chopin 1984; Chopin et al. 1991). This complex consists of orthogneiss and subordinate metapelite, silicate marble and metabasite that underwent UHP metamorphism at 35 Ma (Gebauer et al. 1997; Compagnoni et al. 2004). In the Brossasco−Isasca Complex, two dimension stones are exploited: the *Brossasco Marble* and a mylonitic orthogneiss called *Gilba Stone* (quarry sites 16 and 17 in Figure 2).

Among the monometamorphic complexes, the 'Pinerolo Graphitic Complex' is noteworthy (Vialon 1966; Borghi et al. 1984; Henry et al. 1993). It is exposed in the innermost sector of the unit and represents the deepest tectonic element. It consists of locally graphite-rich metapelite, fine-grained gneiss, and metaconglomerate, probably of Carboniferous age (6 in Figure 2). Pressure-temperature ($P-T$) estimates for this complex are scarce but suggest a re-equilibration stage at 530−550°C and 6.0−7.5 kbar in the metapelite (Avigad et al. 2003) and development of blueschist facies assemblages (Borghi et al. 1985; Wheeler 1991). Another monometamorphic complex is present in the central-southern sector of the Dora-Maira Unit (partly corresponding to the Dronero and Sampeyre complexes of Vialon 1966); it is mainly represented by fine-grained micaschist and gneiss, chloritoid-rich micaschist, quartzite, and rare basic rocks (4 and 5 in Figure 2). Among these lithotypes, a variety of quartzite known as *Bargiolina* in the Monte Bracco area (Barge and Sanfront municipalities) is still exploited (quarry site 15 in Figure 2).

Various meta-intrusive rock types of granitic to dioritic composition, mainly attributed to the late-Variscan magmatic

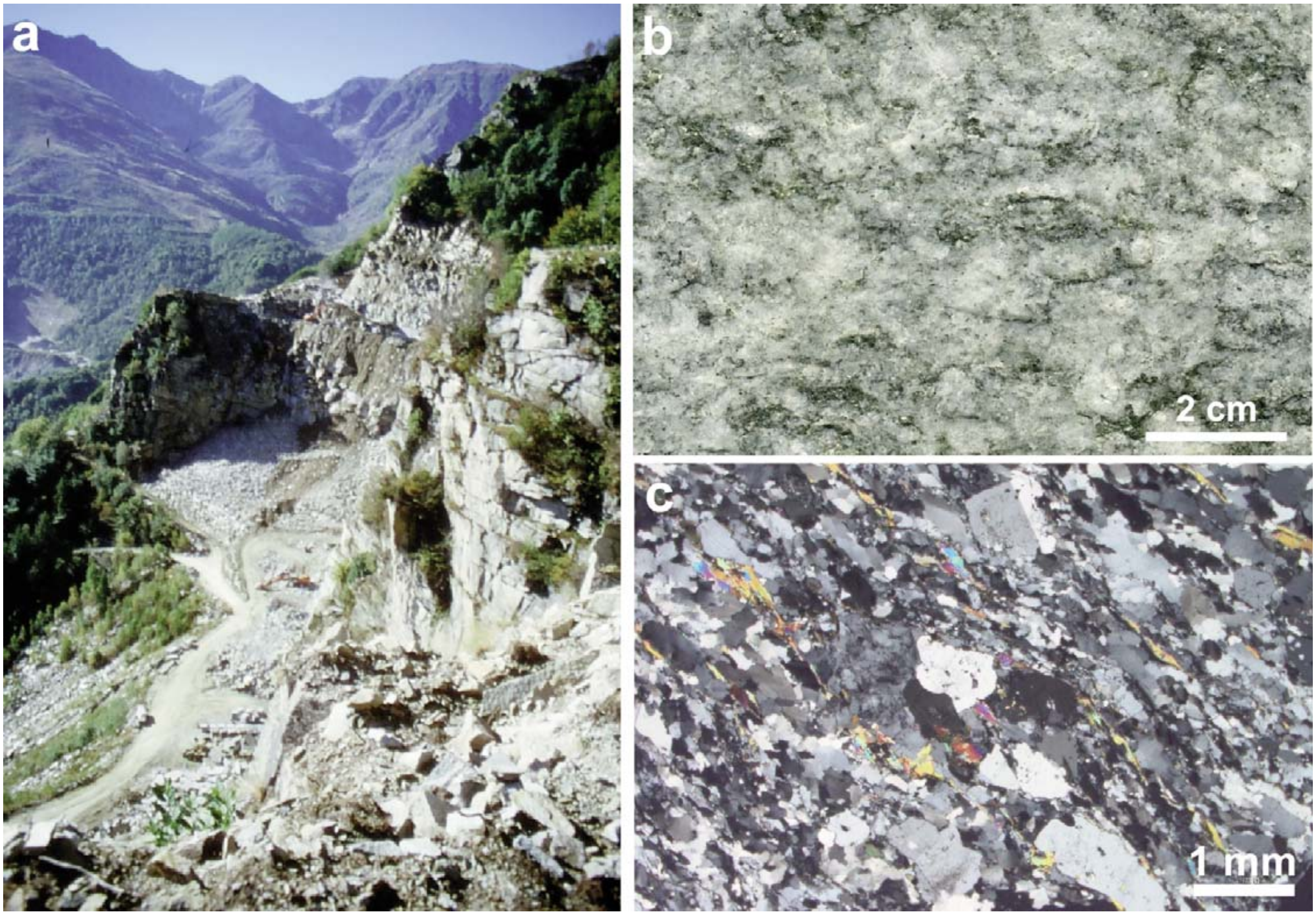

Figure 3. Luserna Stone: a) Quarry site in the Pellice Valley, Rorà municipality (site 13a in Figure 2); b) macroscopic aspect of the rock, characterized by a natural split surface defined by white mica, chlorite and biotite; c) microscopic aspect (crossed-polarized light), marked by the presence of magmatic K-feldspar porphyroclasts, enveloped by Alpine tectonic foliation.

event (Bussy and Cadoppi 1996), intruded both the polymetamorphic and monometamorphic complexes (7 in Figure 2). Since these orthogneisses have been in the past and are still the most widely exploited rock types (see quarry sites 2, through 9, 13a, b, c, and 17 in Figure 2), their detailed description is presented.

On top of the poly- and monometamorphic complexes, slices of the Permo–Mesozoic cover succession are preserved (3 in Figure 2). These are characterized mainly by quartzite or other siliciclastic layers in the lower part and carbonate sequences represented by dolomitic marble and calcschist in the upper part (Cadoppi and Tallone 1992; Cadoppi et al. 2002). In the Susa Valley (Dora-Riparia basin), dolomitic marble (*Foresto* and *Chianocco Marble*) is the exploited rock type (quarry site 1 in Figure 2).

Lastly, in the Mesozoic carbonate cover in the southern part of the Dora-Maira Unit (quarry site 18 in Figure 2), the *Busca onix* is present. It represents a Quaternary speleothem of calcite composition (Marengo et al. 2014) that fills narrow fractures in a dolomitic marble. This material was employed between the 16th and 17th centuries exclusively as ornamental stone and is not described here.

STONE DESCRIPTION

The ornamental and building stones quarried in the Dora-Maira Unit are grouped into two main categories: 1) silicates, which include all the orthogneisses and the quartzites; and 2) carbonates, which consist of all the marble varieties present in the region.

Silicate Stones

The most representative and most employed silicate stone in historical and current applications is the Luserna Stone, an orthogneiss derived from leucogranite of Permian age. It crops out over a large area (approximately 50 km^2) in the Cottian Alps, on the border between Turin and Cuneo Provinces (locations 13a, b, and c in Figure 2). The Luserna Stone quarries are located in the Bagnolo Piemonte, Rorà and Luserna S. Giovanni municipalities, at altitudes that range between 900 and 1500 m above sea level (a.s.l.) (Fig. 3a). At present, the Luserna Stone is the most important dimension stone quarried from the Dora-Maira Unit. Its overall annual production is nearly 330,000 t (≅125,600 m^3) of 'workable stone' and about 512,000 t (≅194,000 m^3) of rip-rap and armour stone (Sandrone et al. 2004). At the hand sample level, *Luserna Stone*

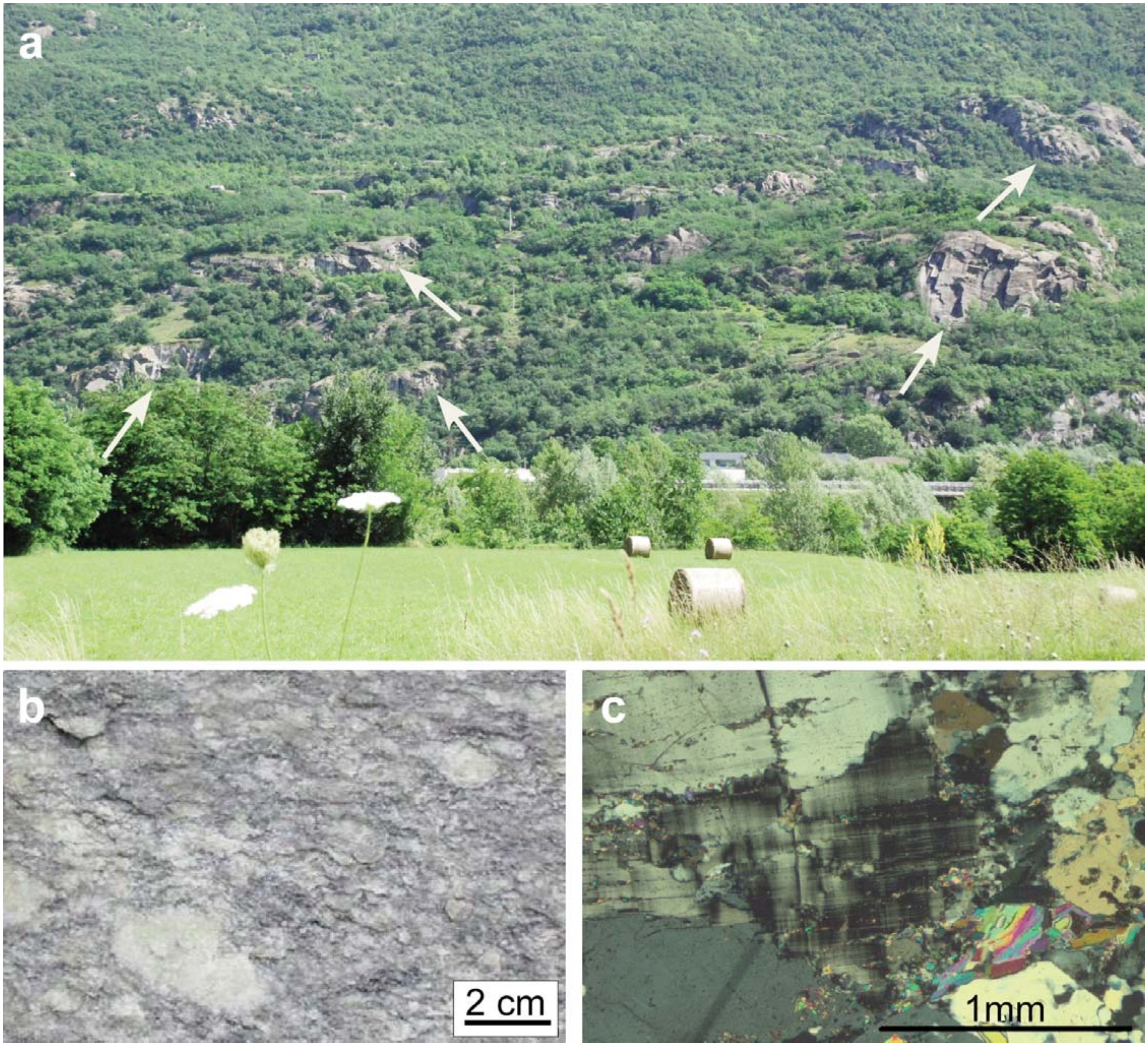

Figure 4. Borgone Stone: a) Ancient quarry sites along the northern slope of the lower Susa Valley (site 4 in Figure 2); b) macroscopic aspect of the rock, characterized by large K-feldspar porphyroclast of magmatic origin: c) microscopic aspect (crossed-polarized light), marked by the occurrence of microcline porphyroclasts.

shows a light grey colour; it is fissile and easy to split along schistosity planes defined by the iso-orientation of phyllosilicates (Fig. 3b). The phyllosilicates are mainly represented by white mica crystallized under high pressure conditions and, in smaller quantities, biotite and chlorite (Fig. 3c). Magmatic porphyroclasts, represented by K-feldspar, in addition to quartz and albite, partially recrystallized during the Alpine metamorphic event, impart a micro-augen texture to the rock (Sandrone et al. 2000).

In the past, the lower Susa Valley was characterized by the presence of numerous quarries, important for the exploitation of gneisses, namely the *Borgone* (Fig. 4a), *Vaie* and *Villar Focchiardo stones* (quarry sites 3, 4, 5, respectively, in Figure 2) (Barisone et al. 1992). The discovery of prehistoric objects near the Vaie quarry site suggests that this material was employed during the Bronze Age; it was certainly used during the Roman age (Fiora and Gambelli 2003). At present only the *San Basilio Stone* quarry, located in Bussoleno (west of Chianocco and 50 km northwest of Turin), is active (quarry site 2 in Figure 2; Fig. 5a). This rock, corresponding to the historic Villar Focchiardo Gneiss, consists of a tourmaline-rich leucocratic orthogneiss, and is light grey in colour. It is characterized by a granitic composition and shows a foliation defined by mica lamellae and the orientation of tourmaline blasts (Fig. 5b, c). Typical production is about 10,000 m^3/yr (Sandrone et al. 2004). Borgone and Vaie stones are represented by a metagranite having a porphyritic, slightly foliated texture (Fig. 4b, c). K-feldspar porphyroclasts are embedded in a recrystallized

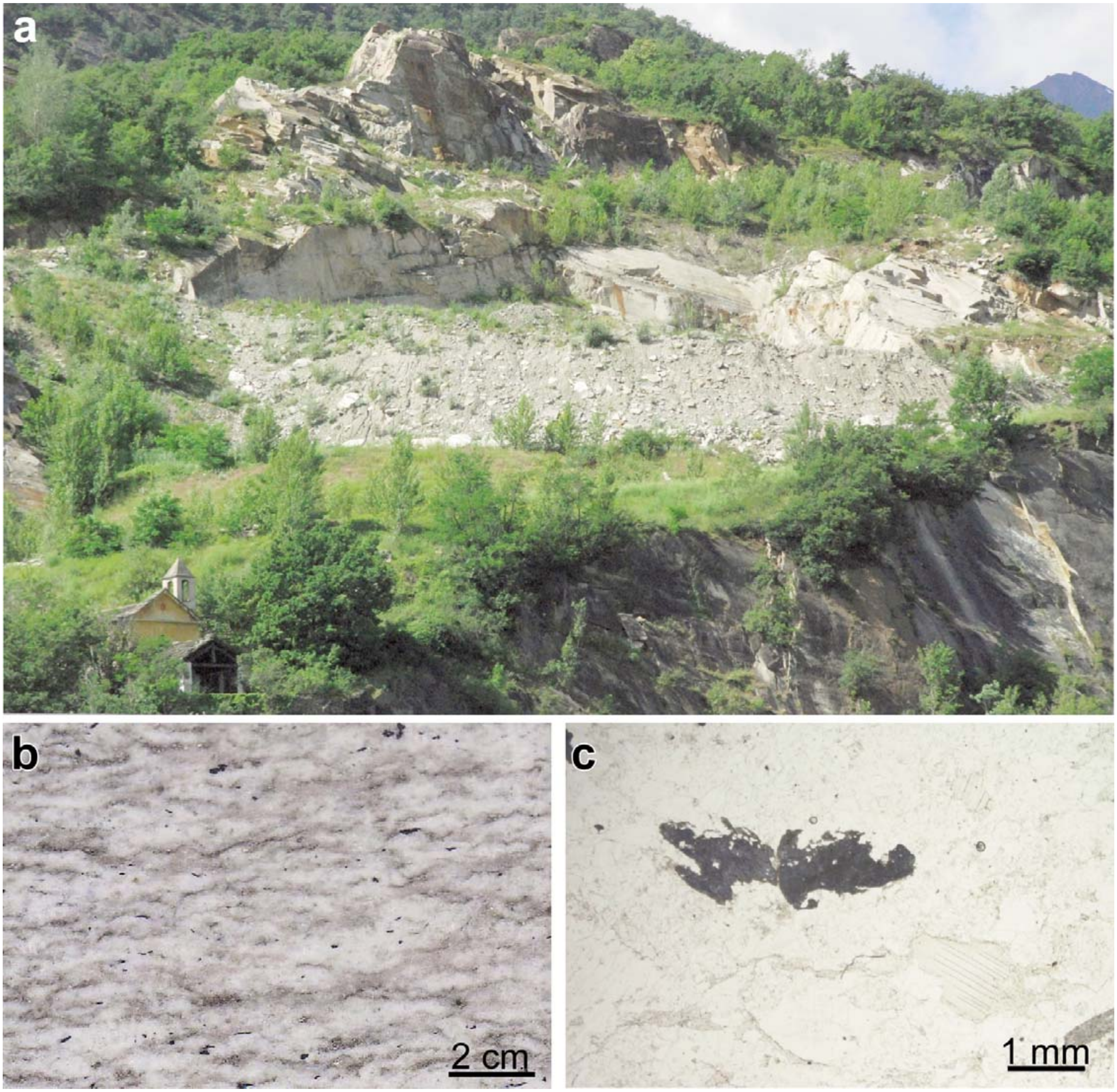

Figure 5. San Basilio Stone: a) Active quarry located along the southern slope of the lower Susa Valley (site 2 in Figure 2); b) macroscopic aspect of the rock, characterized by a mineralogical lineation defined by tourmaline; c) microscopic aspect (plane-polarized light), marked by the presence of pleochroic tourmaline crystal.

matrix mainly consisting of quartz and albite, in addition to white mica and minor biotite. Epidote and rare garnet, representing the metamorphic products of magmatic plagioclase, are also present. Allanite, zircon, monazite and apatite occur as accessory minerals. The main difference between these two stone varieties is the presence of primary muscovite (partially replaced by phengite) in the Vaie Stone (Cadoppi 1990).

Another important orthogneiss exploited in the Dora-Maira Unit is the *Cumiana Stone* (quarry site 6 in Figure 2). It consists of millimetre-sized K-feldspar porphyroclasts surrounded by a foliated matrix of quartz, white mica, biotite, albite and epidote (Fig. 6a, b). This variety of rock is no longer quarried and can be observed only in historical monuments.

The so-called *Malanaggio Stone* is an amphibole–biotite orthogneiss of quartz-dioritic composition that intruded the Pinerolo Graphitic Complex ca. 288−290 Ma (Bussy and Cadoppi 1996). Quarrying activities began in the early 19th century with the opening of five quarries located in the Porte and Perosa Argentina area (Chisone Valley); after World War II, because of the low demand for stone materials and the

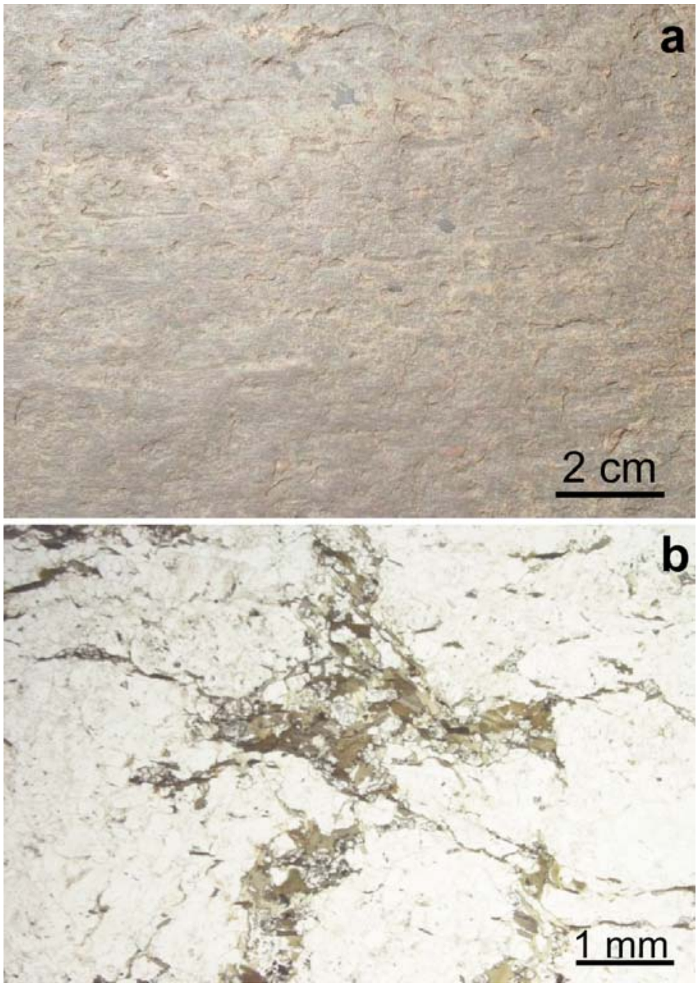

Figure 6. Cumiana Stone: a) Macroscopic aspect of the rock, characterized by alteration of feldspars; b) microscopic aspect (plane-polarized light), marked by the occurrence of biotite flakes.

decreased availability of manpower, some of these quarries were closed (quarry site 9 in Figure 2). At present only the quarry of the so-called *Perosa Stone* is active; it is located in the Brandoneugna village near Perosa Argentina (Chisone Valley) (quarry site 8 in Figure 2; Fig. 7a). The Perosa Stone is similar to the Malanaggio Stone and is distinguished mainly by the presence of white mica (which is absent in the historic variety) defining the main schistosity. The rock consists primarily of quartz, plagioclase, chlorite, biotite, hornblende, zoisite and clinozoisite; garnet, apatite and titanite occur as accessory minerals (Fig. 7b, c). The microstructure is weakly foliated; in places, the original sites of magmatic amphibole and plagioclase (mainly oligoclase/andesine) can still be recognized. Bargiolina Quartzite is another important dimension stone quarried in the Dora-Maira Unit, and it is exploited along the western slope of the Monte Bracco (in the Barge and Sanfront municipalities east of Paesana village), in the lower Po Valley (quarry site 15 in Figure 2). Geologically, it represents Permo–Triassic quartzarenites deposited during the post-Variscan marine transgression and subjected to Alpine-age metamorphism (Vialon 1966). It is a micaceous, fine-grained quartzite that displays a tabular and homogeneous appearance (Fig. 8a). The Bargiolina – known and used since prehistoric times as a substitute for flint, and celebrated by Leonardo da Vinci (Fiora et al. 2002) – has been intensely exploited since the early 20th century. There are different colour varieties of the Bargiolina: golden yellow, pale yellow, olive-grey, grey and white (marmorina variety). The quartzites, several metres thick, have been quarried as dimension stone by different companies, both in the Barge and Sanfront areas (Dino et al. 2001). At present, its market is much reduced by competition from Brazilian quartzite, and thus it is now exploited only in small quantities (5000 t of 'workable stone' in 2002) at a single quarry in Barge village (Province of Cuneo) (Sandrone et al. 2004). The Bargiolina contains thin layers of phengite that impart a regular schistosity, and consequently splits into very thin slabs (1–2 cm) (Fig. 8b, c).

Carbonate Stones

The Alpine marbles (both white and coloured) were widely employed in Turin for indoor as well as outdoor prestigious applications, especially until the end of the 18th century, when the carbonate stones, albeit easier to work, were gradually replaced by silicate rocks. Most of the marble from Piedmont have been exploited in the Western Alps. They generally crop out as small lenses intercalated in schist and gneiss belonging to various geological units and characterized by different metamorphic conditions. Four historical marbles, named *Foresto*, *Chianocco, Prali* and *Brossasco*, can be recognized in the Dora-Maira Unit. The Prali and Brossasco Marble belong to the polymetamorphic basement, whereas the Foresto and Chianocco Marble come from the Permo–Mesozoic metasedimentary succession, only affected by Alpine metamorphism.

The most important white marbles are Triassic−Early Jurassic dolomitic white marbles from Susa Valley (Foresto and Chianocco Marble), known and used since Roman times (quarry site 1 in Figure 2; Fig. 9a, b). The marble is finely crystalline, has a planar fabric, and is white to ice-grey in colour (Fig. 9c). It consists mostly of dolomite, although calcite crystals occur. White phengitic mica and chlorite define the anisotropy of the rock (Fiora and Audagnotti 2001) (Fig. 9d).

The Prali Marble has been quarried in the Germanasca Valley (quarry sites 10, 11 and 12 in Figure 2) since the 14th century and was also known as Perrero or Faetto Marble (Peretti 1938). The Rocca Bianca quarry (quarry site 12 in Figure 2; Fig. 10a, b), with exploitation beginning in 1584 and lasting until 1968, was the most important one in terms of quantity of exploited material. Since 1981, the marble has been occasionally extracted in the Maiera Quarry (western slope of the Rocca Bianca, quarry site 11 in Figure 2; Fig. 10c); its production has been several hundred cubic metres per year. Prali Marble has a banded structure characterized by white to grey layers and local occurrences of green veins formed by phyllosilicates (Fig. 10d). It is a predominantly finely crystalline calcitic marble forming several transposed layers (up to a few metres thick) embedded within garnet- and chloritoid-bearing micaschist (Cadoppi et al. 2008). In dolomite-rich domains it is locally characterized by centimetre-thick tremolite-rich layers (Fig. 10e).

Last, the Brossasco Marble, crops out in the middle Varaita Valley (quarry site 16 in Figure 2) and was intensively exploited from about 1600 to 1700. It lies within the Brossasco Isasca Complex in the southern part of the Dora-Maira Unit. It is a coarsely crystalline isotropic marble consisting of calcite and

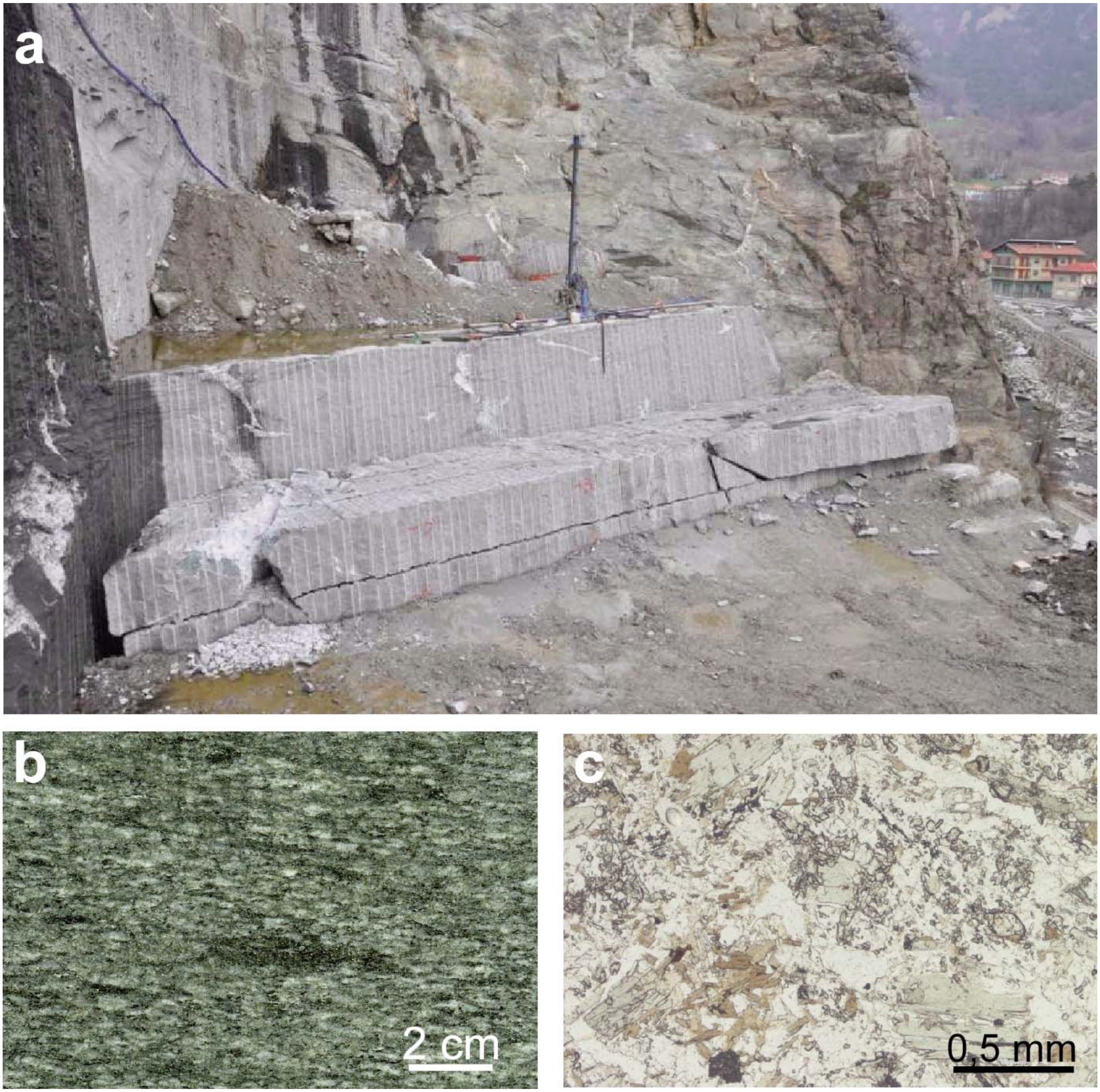

Figure 7. Perosa Stone: a) Active quarry located along the eastern slope of the Chisone Valley (site 8 in Figure 2); b) macroscopic aspect of the rock, characterized by tectonic foliation underlined by melanocratic inclusions; c) microscopic aspect (plane-polarized light), marked by the association of plagioclase, amphibole, epidote, chlorite and biotite.

minor dolomite, and formed under high-grade metamorphic conditions (over 700°C). The marble has a massive, largely saccharoidal texture (Fig. 11a, b). Also present are garnet (reddish brown), omphacite (light green), amphibole (dark green), white mica, and locally phlogopite (brown) associated with carbonate phases.

HISTORICAL EMPLOYMENTS

Because of the different varieties of rock present, the Dora-Maira Unit can be considered a reservoir of ornamental and building stones, employed locally since Roman times for military and religious buildings. Furthermore, these materials were used in the Piedmont region for the construction of important historical palaces (especially in the 17th and 18th centuries).

Countryside

One of the more striking examples of Dora-Maira stone applications during the Roman age is the Arch of Augustus at Susa, built by King Cozio to celebrate the return of the Roman emperor from Gallia in 9 BC (Fig. 12a). It was built using

Figure 8. Bargiolina Quartzite: a) Quarry site located on Mount Bracco (site 15 in Figure 2); b) macroscopic aspect of the rock, characterized by a natural split surface defined by thin mica layers; c) microscopic aspect (crossed-polarized light), marked by a strong dimensional preferential orientation of quartz crystals.

Foresto and Chianocco Marble, exploited in the immediate area of the Arch; indeed, looking through the Arch it is possible to see the remains of the original quarry. These materials were also employed for part of the Roman aqueduct of Segusium (present-day Susa).

During Medieval times, the most salient heritage building, partly constructed using Dora-Maira stones, was the Sacra di San Michele. It is standing on the peak of Mount Pirchiriano at 962 m a.s.l., near Sant'Ambrogio village, on the southern slope of the Susa Valley (Fig. 12b), and was one of the most important fortified monasteries in southern Europe. Construction of the Sacra di San Michele lasted several centuries and, at present, it stands out against the sky as a huge stone edifice. The first sanctuary probably dates before 1000 AD,

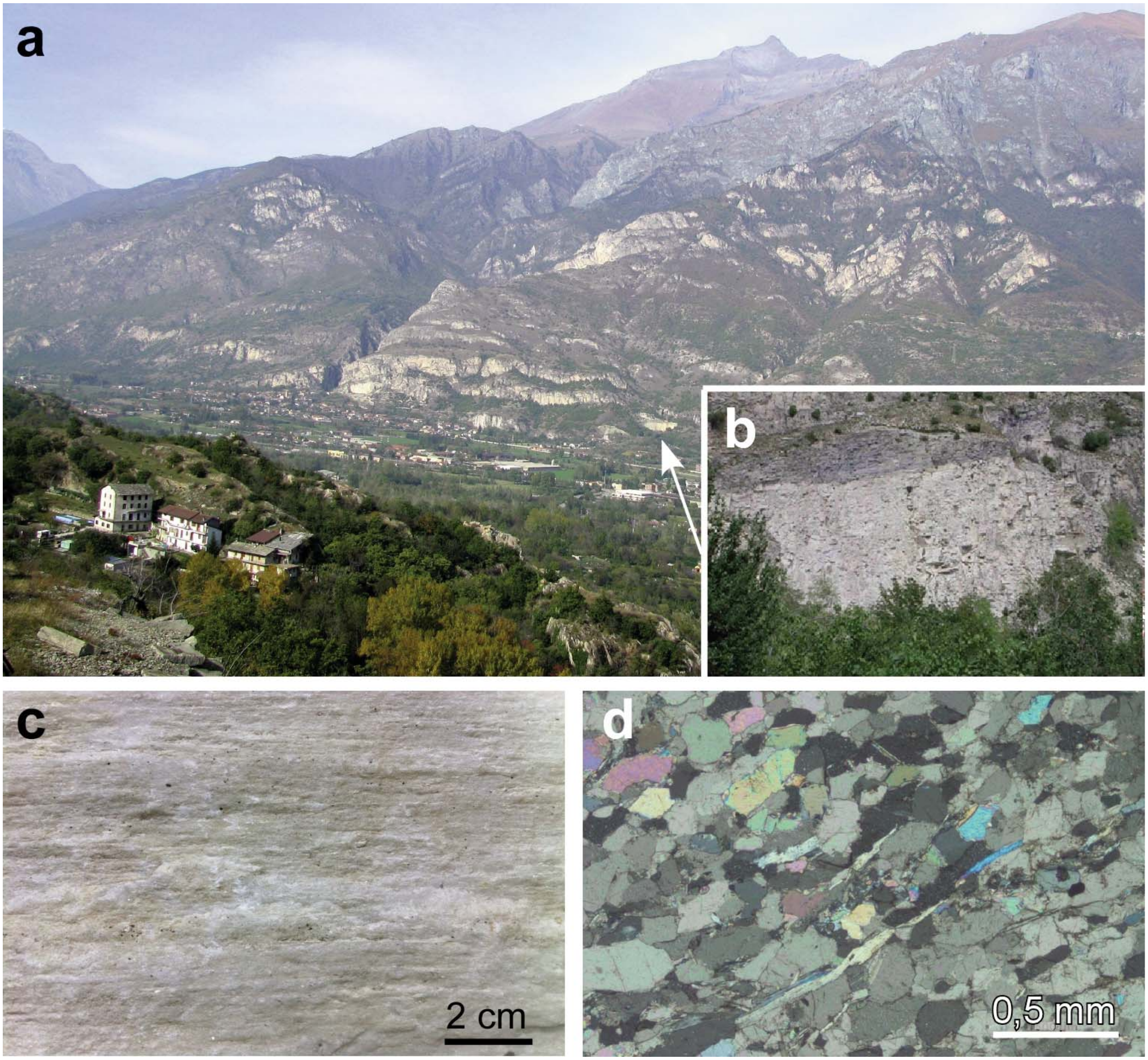

Figure 9. Foresto Marble: a) The northern slope of the lower Susa Valley, where the historic marble quarry b) is located (quarry site 1 in Figure 2); c) macroscopic aspect of the rock, characterized by a natural split surface defined by white mica; d) microscopic aspect (crossed-polarized light), marked by granoblastic texture and oriented lamellae of white mica.

and it was finally completed at the end of 1100 AD. In the 11th century the monastery was enlarged with the construction of the large church, characterized by the Scalone dei Morti (Staircase of the Dead). Because of its strategic position it was an important presidium of the Via Francigena, one of the most ancient communication routes in Europe. Over the centuries, different variety of stones from the Dora-Maira Unit were exploited to build the Sacra di San Michele: Borgone Stone was used for the steps of the Scalone dei Morti; the garnet-bearing micaschists of the polymetamorphic basement are visible at the entrance gate of the Sacra; and the Chianocco and Foresto Marble were used for the construction of the Portal of the Zodiac, a striking expression of Romanesque art of the 12th century (Fig. 12c). The Luserna Stone was used to build the access pathway to the monastery during the recent restoration for the XX Winter Olympic Games.

Dora-Maira stones were also employed in the Fenestrelle Fortress, a group of military buildings and infrastructures built between the 18th and 19th centuries in the Chisone Valley (80 km northeast of Turin) (Fig. 12d). This fortified complex covers an area of 1.3 million m^2 on the northern side of the middle Chisone Valley, between 1150 and 1750 m a.s.l. It consists of three core areas, one beside the other in chronological order: Forte Valli, Forte Tre Denti and Forte San Carlo. The fortress is entirely made of stone: the walls and the blocks constituting the pillars, columns and portals. The Scala Coperta

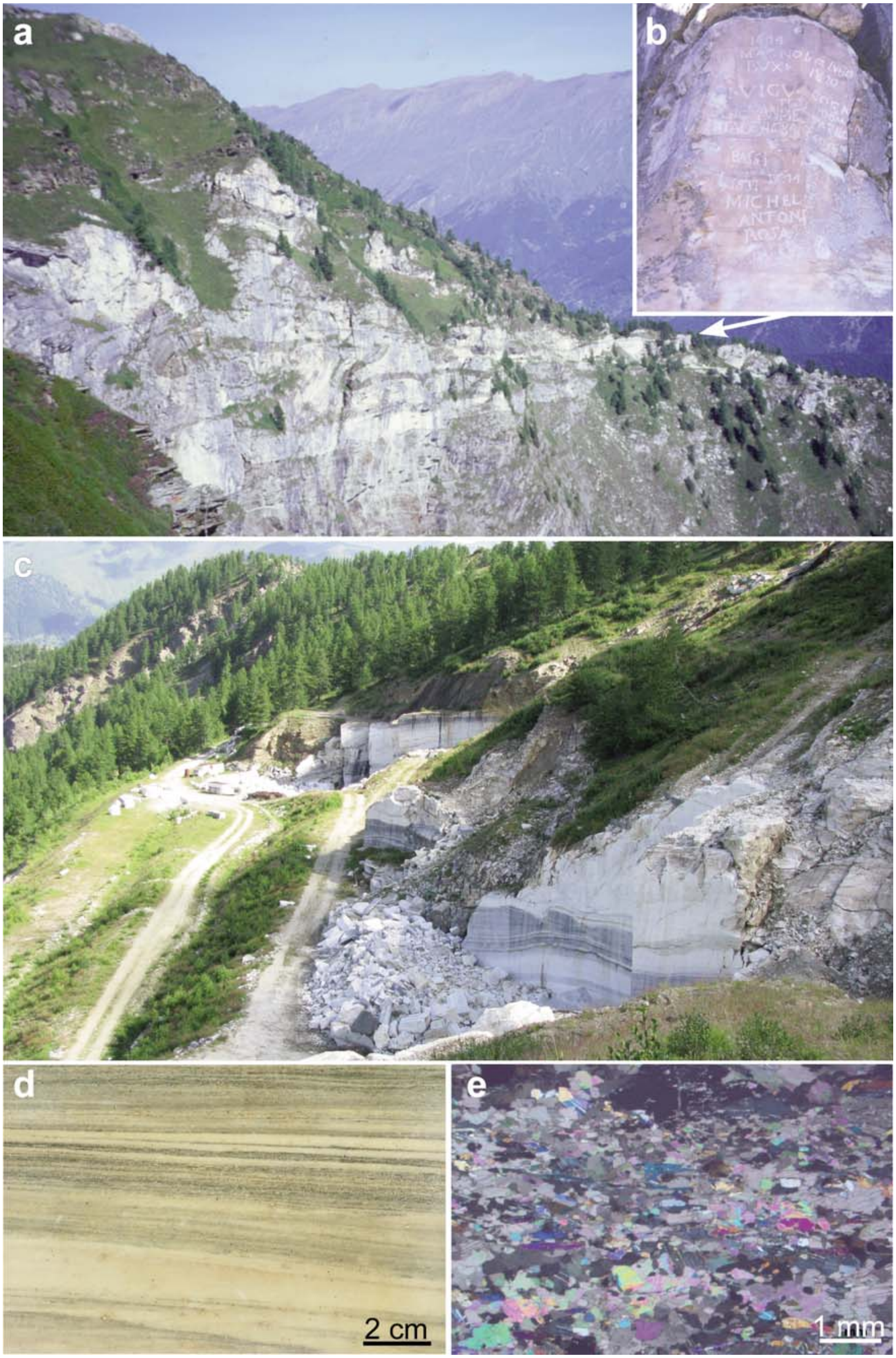

Figure 10. a) The eastern slope of the Rocca Bianca Mount (Germanasca Valley), where traces of the historic quarry of Prali Marble are still visible (quarry site 12 in Figure 2); b) graffiti dating back to the end of 1500 carved on a quarry face; c) Maiera Quarry, located along the western slope of the Rocca Bianca Mount (quarry site 11 in Figure 2), where the marble was exploited as recently as 2005; d) macroscopic aspect of the marble, characterized by regular intercalation of carbonate (light) and phyllosilicate layers; e) microscopic aspect (crossed-polarized light), marked by oriented crystals of tremolite and white mica, which define the anisotropy of the rock. Photo credits a) and b): Alessandro Ghelli and Cadoppi et al. 2008, respectively.

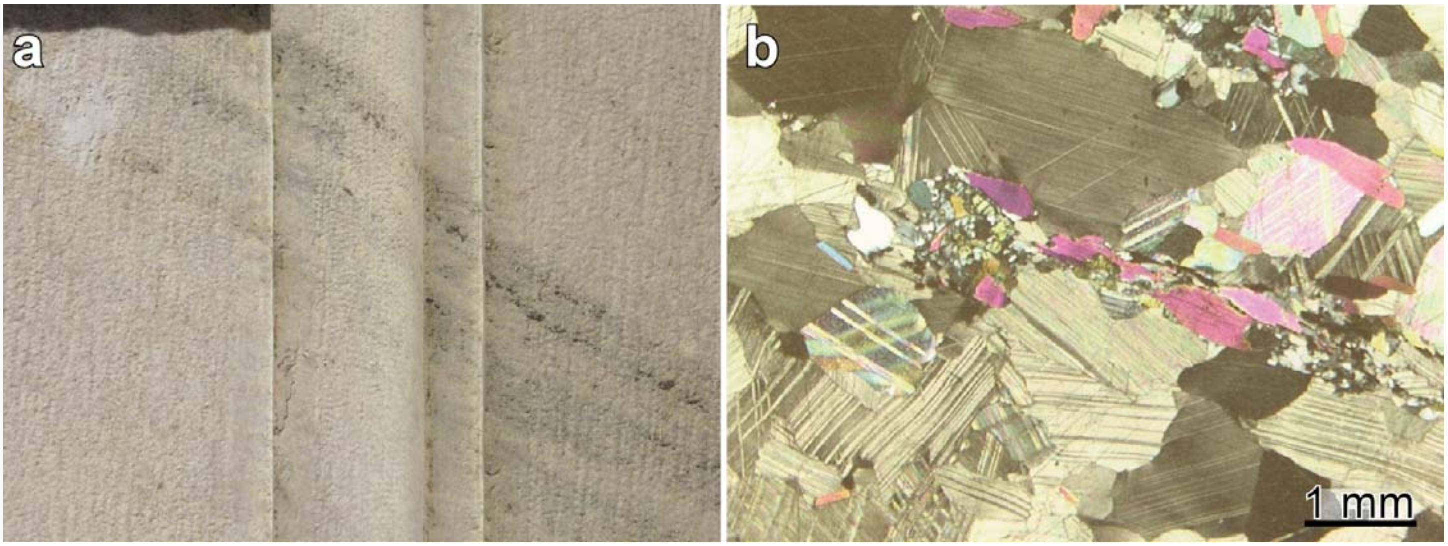

Figure 11. Brossasco Marble: a) Macroscopic aspect of the rock in an architectonical element of the San Filippo Neri Church; b) microscopic aspect (crossed-polarized light), characterized by the coarse and heterogeneous size of the carbonate grains and the occurrence of phlogopite lamellae.

(Covered Staircase) is worthy of note: it is the longest stone staircase in Europe, consisting of 3996 steps. Linking 28 bastions, it looks like a great wall connecting the upper and lower part of the fortress; the first 1250 steps are made of Malanaggio Stone (Fig. 12e) (Fiora et al. 2006). This material was also employed for the plinths of the Porta Reale, which is the ancient entrance to the Forte San Carlo, reserved for personages of the royal courts of Europe who visited the fortress. Luserna Stone and other gneisses extracted in the Chisone and Susa valleys were employed for the roofs of the Governor's Palace, the church of the Forte San Carlo, and the Officers' Palace. Finally, the garnet-bearing micaschist of the polymetamorphic basement was employed in the highest part of the fortress (Forte Valli) and in the last 1046 steps of the Scala Coperta.

Some of the historical stones quarried in the Dora-Maira Unit were also used for the construction of the Exilles Fortress, located in the middle Susa Valley, and dating back to the early 1800s in its present form; the original one was built during the Medieval Period (Fig. 12f). This is a typical example of a building made of stone that crops out on site. The walls consist of blocks of strongly schistose, easily splittable rock types. In particular, Villar Focchiardo Stone was employed for embrasures that overlook the French side, whereas Borgone and Vaie stones were used in the masonry and for the fountain of the main parade ground.

Historic Centre of Turin

Turin can be described as a 'stone city,' because most of the historical buildings, roads and squares are made of stone of local, national and international provenance. In particular, it is possible to appreciate the use of Dora-Maira stones in some interesting and historical buildings, such as the Gran Madre church, San Giovanni Cathedral, Palazzo Madama, the Royal Palace and Mole Antonelliana, along with infrastructure such as stone bridges. San Giovanni Cathedral (Turin cathedral) is the only Renaissance building still preserved in the city (Fig. 13a). Its façade is made of Foresto and Chianocco Marble. The marble blocks are creamy white to light grey and have a metamorphic foliation defined by centimetre-thick layers of varying colour. These blocks, randomly placed on the façade of the Dome, produce a 'checkerboard effect,' which was popular at the time. Foresto and Chianocco Marble were preferred to other contemporarily exploited materials because the blocks were easily transported from quarries to the cathedral yard by means of barges along Dora Riparia River. Stones from the Dora-Maira Unit were widely employed during the time of the Savoy kingdom. One of the most representative heritage buildings from this period is the Royal Palace, where there is a great deal of Malanaggio Stone and Prali Marble used for the inner court and gate pillars, respectively.

Chianocco and Foresto Marble have also been employed for columns of the façade of Palazzo Madama (1718–1721) (Fig. 13b), which hosted the Senate of the royal house during the Savoy period and where the Albertine Statute, progenitor of the Italian constitution, was approved. Here, it is also possible to appreciate several kinds of stones from the Dora-Maira Unit, including Prali Marble, used for capitals and bases of the columns of the façade; Brossasco Marble, for statues and vases that sit on the top of the façade; and Vaie Stone, used for the basement.

Vaie Stone was employed for construction of the columns of the 18th century façade of Santa Cristina Church (Piazza San Carlo; Fig. 13c), designed by Filippo Juvarra (one of the main architects at the Savoy court). Also used for the capitals and portal of the façade were Perosa Stone and Chianocco and Foresto Marble. Dora-Maira stones were also utilized in two other important churches in Turin: San Filippo Neri Church (1650–1891) and Gran Madre Church (early 19th century), both characterized by typical neo-classical elements such as the *pronao* (colonnade entrance). In particular, in the San Filippo Neri Church, the largest religious building in Turin (Fig. 13d), the atrium is made of Bargiolina Quartzite and the eight grooved columns consist of Brossasco White Marble. Malanaggio Stone and Prali Marble are present in the Gran Madre Church (Fig. 13e), the former for the columns and the latter for the sculptures and statues at the entrance of the church.

Figure 12. Main examples of employment of Dora-Maira dimension stones in historic buildings: a) Arc of Augustus at Susa (Roman Age, 9 BC); b) Sacra di San Michele Abbey located at the mouth of the Susa Valley; c) 'Portale dello Zodiaco,' one of the great expressions of Romanesque art of the 12th century; d) external features of the Scala Coperta of the Fenestrelle Fortress along the northern slope of the Chisone Valley; e) steps and internal appearance of the Scala Coperta; f) Exilles Fortress located along the Susa Valley.

Last, Luserna Stone was employed in the Mole Antonelliana (1863–1904), particularly in the slabs covering the dome (Fig. 13f). This was the tallest masonry building in the world when it was inaugurated in 1889.

Other important civil infrastructures were made of Dora-Maira stones: e.g. the six stone bridges over the Po River in Turin, three of which are entirely made of stone: King Vittorio Emanuele I Bridge (1803–1813), Princess Isabella Bridge (1876–1880) and King Umberto I Bridge (1903–1907) (Fig. 14). King Vittorio Emanuele I Bridge is the tangible sign of the acme of Napoleonic power; the architecture is of high quality and it stands as a prototype for the resurgence of stone building in Piedmont. Furthermore, it represents the first modern stone bridge built in Italy after the Renaissance, and thus has an important historical role. The exclusive use of Cumiana Stone for the construction of the bridge is documented at Turin State Archives; Cumiana Stone was preferred to the others because of its characteristics and the short distance between the quarry and bridge yard. Cumiana Stone was also employed in the slabs of the sidewalk (now replaced), and

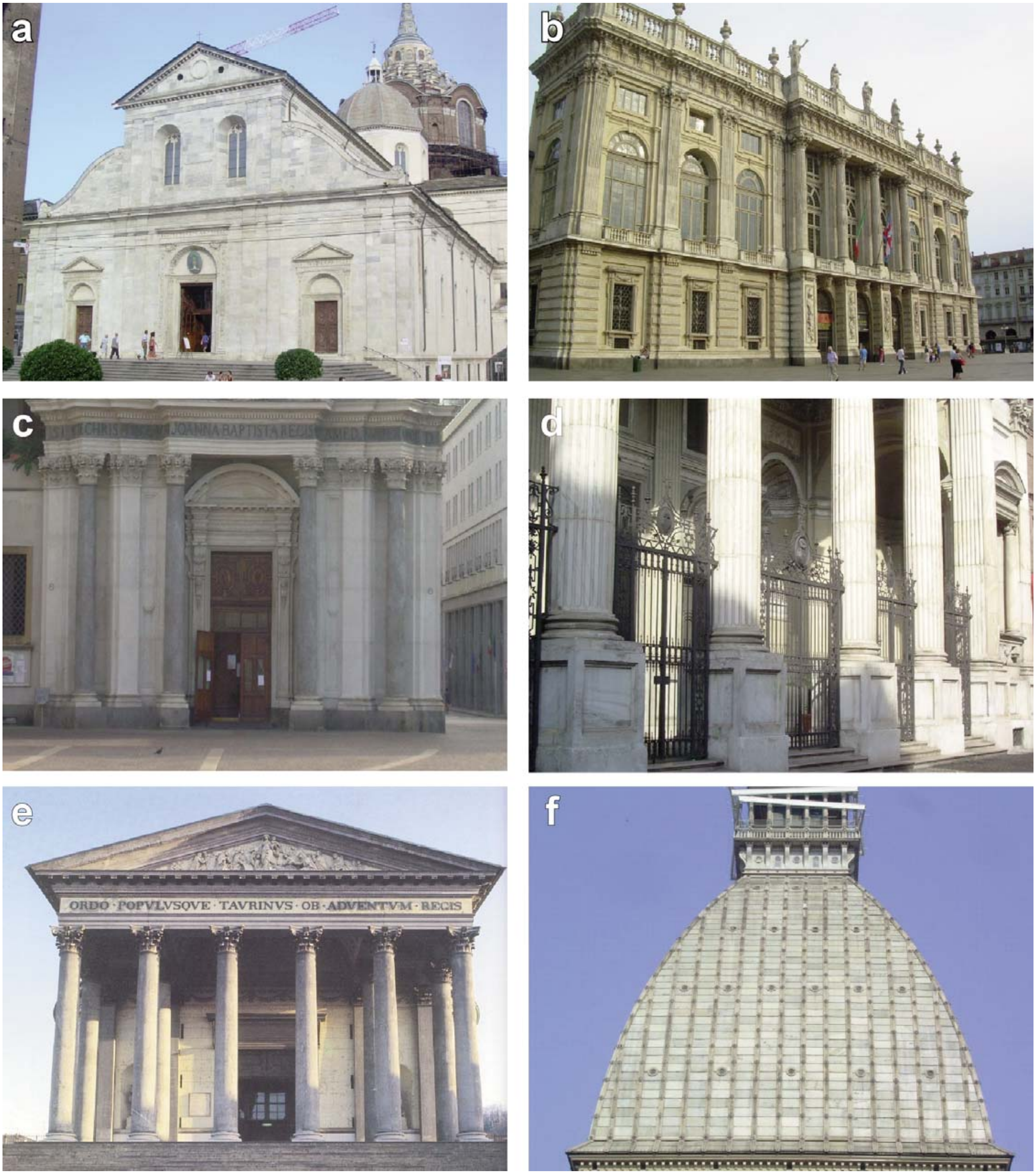

Figure 13. Representative examples of historic buildings in Turin, mainly made of Dora-Maira dimension stones: a) Façade of San Giovanni Battista Church, made of Chianocco and Foresto Marble; b) façade of Palazzo Madama, seat of the Savoy Senate, made with Chianocco and Foresto Marble and the Vaie Stone; c) façade of Santa Cristina Church, with columns made of Vaie Stone; d) San Filippo Neri Church, with the colonnade built of Brossasco Marble; e) colonnade of the Gran Madre Church made of Malanaggio Stone; f) Mole Antonelliana, symbol of the city of Turin, built in the late 19th century with material from the Alpine valleys. The dome is covered by the Luserna Stones slabs.

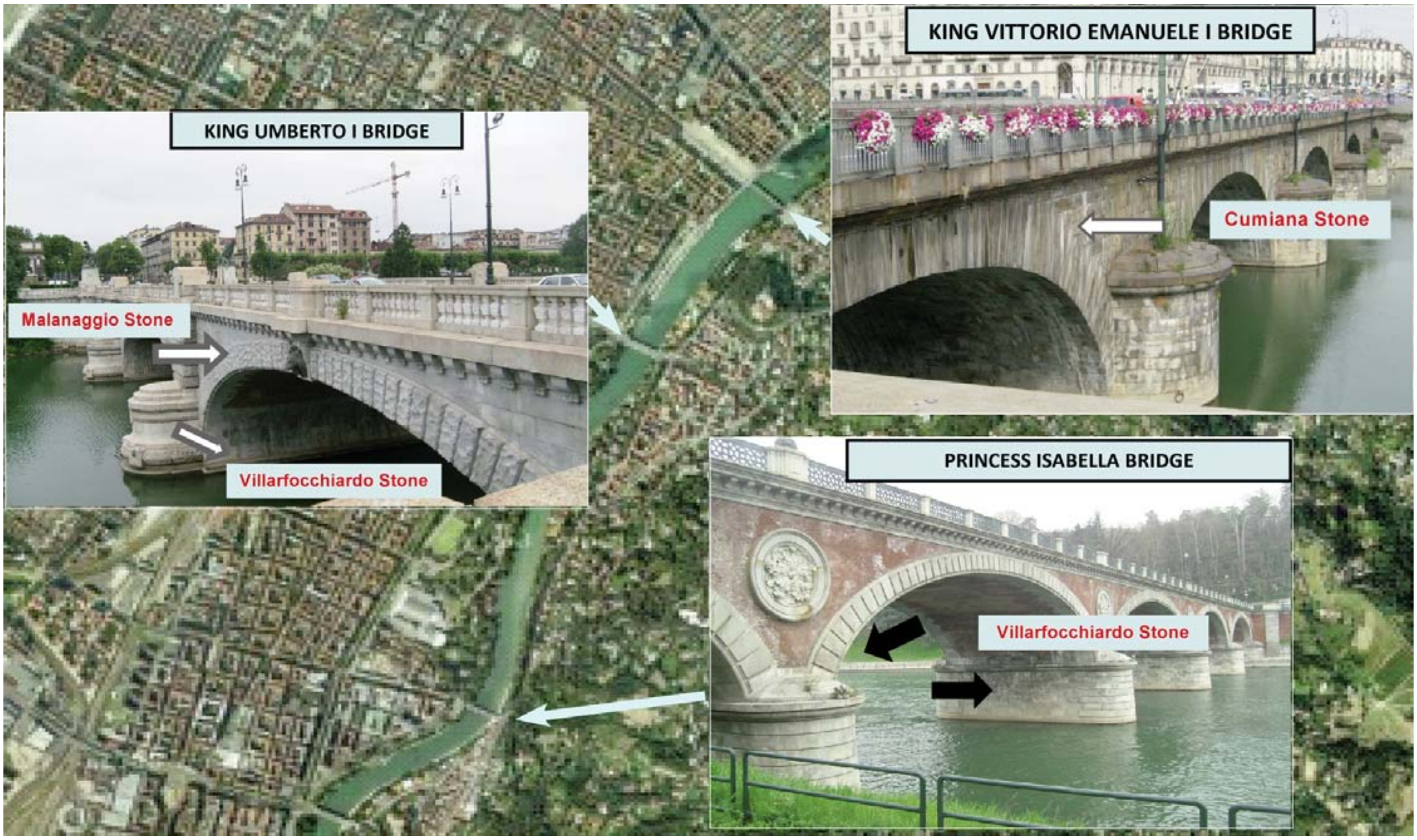

Figure 14. Satellite map of Turin (from Google Earth®, 22/03/2015), showing the location of the Po River bridges built with Dora-Maira stones.

in the wedges of the archways. The original railings were made of Malanaggio Stone, but in 1876 they were removed and replaced by cast iron railings.

Princess Isabella Bridge was built between 1876 and 1880; it has 24 metres of span and five semi-elliptical arches entirely made of brick and resting on tall pillars of Villar Focchiardo Stone. The paving consists of slabs of Luserna Stone confined by curbs of Villar Focchiardo Stone. The newer King Umberto I Bridge (1903–1907) is made of bricks as well as stone. It has three semi-elliptical arches on pillars, each characterized by a semi-circular rostrum. Several kinds of Dora-Maira stones, including Malanaggio, Villar Focchiardo and Vaie stones, were employed. The coating of the pillars is made of Villar Focchiardo Stone, whereas the part of the structure in plain sight, including the arches, is coated by Malanaggio Stone, worked with various techniques (Fig. 14).

Dora-Maira stones can be seen in two comparatively modern components of Turin's infrastructure: the Automobile Museum and the Metro stations. Both Luserna Stone and Perosa Stone have been used for the recently restored outer coating of the Automobile Museum.

The international application of Dora-Maira stones is noteworthy. For example, Borgone and Vaie stones have been used for the paving of the Louvre Museum, and Perosa Stone was employed in Lagos for the Monument of Independence.

CONCLUSIONS

Ornamental and dimension stones extracted from the Dora-Maira Unit have been used for important buildings from Roman times up to the present day. In the 16th and 17th centuries, with the establishment of the kingdom of Savoy, stone was widely employed in Turin, the capital. From the second half of the 19th century to contemporary times, these ornamental stones continued to be employed in public buildings, including the Mole Antonelliana, which is the major landmark building in Turin, and other important infrastructural elements such as the stone bridges over the Po River. Some of these stones are still quarried and exported to foreign countries, such as the Luserna Stone, San Basilio Stone, Perosa Stone and the Bargiolina Quartzite.

The Dora-Maira Unit is almost unique in the number and variety of ornamental and building stones exploited over the centuries from a relatively small area. For this reason, it can be considered a Global Heritage Stone Province. Moreover, active and historical quarries that occur in this geological unit are interesting sites in terms of geo-tourism. The quarries can also be used to stage cultural events such as concerts and plays. In turn, this can introduce the general public to quarries as a vital industrial activity in contrast to the negative way in which they are often portrayed (Dino and Cavallo 2015). For example, cultural events staged in locales of past mining activity, such as those hosted in abandoned galleries of the talc mine in Germanasca Valley (Scopri Miniera and Scopri Alpi; www.scopriminiera.it), could be extended to other quarries in the Dora-Maira region (e.g. Luserna Stone quarries).

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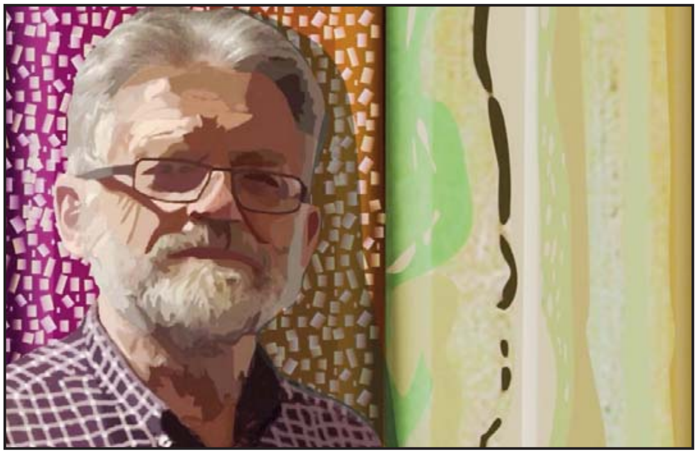
SERIES



Heritage Stone 3. Degradation Patterns of Stone Used in Historic Buildings in Brazil*

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SUMMARY

Brazil's heritage buildings were built using different types of natural stone, including sandstone, limestone, quartzite, granite, gneiss, steatite (soapstone) and schist. Historic buildings are located in cities such as Recife, Olinda, Salvador, Rio de Janeiro, Congonhas and Ouro Preto; some are over 300 years old. They show evidence of different alteration and decay processes, with the latter leading to a loss of value because of physical and chemical modifications in intrinsic properties of the natural stones used. Consequently, these buildings function as open-air laboratories, and contribute to the study of deterioration in such monuments. On going investigation of alteration and decay reveals that they are affected by a diverse group of processes that are, in part, influenced by lithological factors. This understanding will contribute to the choice of preservation methods that will be applied in order to arrest degradation.

RÉSUMÉ

Les édifices classés brésiliens ont été batis en roches variées. On a employé des grès, des calcaires, quartzites, granites, gneiss, ainsi que la stéatite et des schistes. Les bâtiments historiques, dont certains ont plus de 300 ans, se trouvent dans des villes comme Recife, Olinda, Salvador, Rio de Janeiro, Congonhas et Ouro Preto. Ils présentent les marques de différents processus d'altération et de deterioration, ce dernier conduisant à une perte de valeur, en raison de modifications physiques et chimiques dans les propriétés intrinsèques des pierres naturelles utilisées. De la sorte, ces bâtiments fonctionnent comme des laboratoires à ciel ouvert et contribuent à l'étude des modalités de dégradation des monuments. L'étude en cours des phénomènes d'altération et de décomposition révèle la diversité des processus en cours et leur relation avec la lithologie. La reconnaissance de ces phénomènes aidera à choisir les méthodes de conservation destinées à bloquer la dégradation.

INTRODUCTION

There are currently few studies in Brazil that describe the rocks that make up its built cultural heritage, or provide information on where they come from and how the stone was used in the construction of many monuments. Based on a detailed survey of these materials and other issues related to this heritage (Costa 2009), we present descriptions of the most common alteration processes and forms of decay observed for monuments located in a number of areas of Brazil. Given the variety of stone used for heritage buildings, this is the first step toward recommending adequate preservation methods for each case of observed deterioration.

THE USE OF STONE IN THE CONSTRUCTION OF BRAZIL'S CULTURAL BUILT HERITAGE

Brazil's territory features a diverse geology. Therefore, from north to south, east to west, different types of rocks (Fig. 1) have been used in the construction of the religious, civil, administrative or military buildings that currently constitute the assets of Brazil's Cultural Heritage (Costa et al. 2008; Costa 2009, 2014, 2015). Other rocks can be added to that list of

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Figure 1. Major regions of Brazil showing the location of its most important historical cities and the distribution of different types of natural stone used in monuments built between the 16th and the late 19th century.

materials, especially those brought or imported from Portugal and Italy, particularly in the 17th and 18th centuries.

With regard to timing, a considerable number of these buildings, notably those in Minas Gerais, were constructed between the mid-16th century and the late 19th century, with most in the first half of the 18th century. However, access to and use of rock materials was limited, and not always adequate. Broadly, such restricted rock use to the end of the 19th century, whether in masonry or stonework, was the result of multiple factors: variable rock distribution; a near-total absence of suitable stone in some regions; and lack of a work force skilled in stonework techniques. The people in charge of those constructions frequently found themselves forced to resort to other methods and to use less resistant materials, such as wood, mud or clay (Costa 2013).

Following the colonization of the Brazilian coast, inland Brazil was conquered in the late 17th century, the Portuguese focused their efforts on settling a region endowed with abundant gold and diamond mines, which became known as Minas Gerais (General Mines) (Fig. 1). This area later became part of the Brazilian Empire and is currently the State of Minas Gerais. With its rich mines, including iron deposits, it was very important to the economy of 18th and 19th century Brazil, becoming its richest captaincy. Located in the country's interior, it was also the region where the largest number of historic buildings was constructed with the use of natural stone.

The first half of the 18th century, during which Minas Gerais was developed, saw the rise of the state's most important constructions, even in the face of difficulties. Resources became progressively rarer, especially for projects belonging to religious orders, insofar as gold and diamonds were no longer produced in large quantities. In addition, the colonizers themselves lacked interest in spending their resources on very expensive buildings, as they eagerly hoped to return to their homeland with their newly acquired wealth. However, these reasons did not prevent Brazil, and especially Minas Gerais, from producing the beautiful baroque and rococo monuments typical of the 18th century. Eventually, that scenario contributed to the rise of a peculiar, typically mineira constructive art (mineiro being the adjective designating things or people from Minas Gerais).

BUILDING STONES USED IN BRAZILIAN HERITAGE BUILDINGS

The historical buildings were constructed with sedimentary rocks such as limestone and sandstone, metamorphic rocks such as quartzite, schist, steatite (soapstone), marble and gneiss, and igneous rocks such as granite, gabbro and basalt (Fig. 2).

Several types of limestone, sandstone and calcarenitic reef deposits were used during both colonial Brazil — in the north and in villages and towns of northeastern captaincies and provinces — and the imperial period (Carvalho 1942; Costa 2009). These materials, when compared to granite, quartzite and marble, proved to be more suitable for the sculptural arts, inasmuch as the former are softer while the latter are more resistant, making these more suitable for construction in general, and crop out all along Brazil's northeastern coast, from Paraíba south to Bahia state. Within that area, the use of limestone was more frequent in the states of Bahia, Sergipe and Paraíba, whereas sandstone and calcarenite were more widely used in the regions of Pernambuco and Alagoas states (where they could be easily extracted from reefs and beaches). Another type of sandstone, very ferruginous, was widely used in old buildings of Amapá state, located in the extreme north of Brazil.

Gneiss, plutonic igneous rocks such as granite, gabbro (mistakenly called black granite) and several kinds of volcanic rocks were used secondarily in buildings of those old historical centres. In his study on the use of stone in northeastern religious architecture, Carvalho (1942) indicated that "*a great amount of rock used in the adornments of Pernambuco's churches*" might have been extracted from volcanic Santo Aleixo Island, which lies near the coast of Pernambuco.

In João Pessoa (Paraíba state), São Francisco's Convent, Santo Antônio's Church and its fountain, all property of the old Third Order of Saint Francis, were built a few metres away from the quarry that provided the limestone used both in their masonry and for several decorative elements. In Lucena, also in the region of João Pessoa, Nossa Senhora da Guia's Church (Our Lady Who Guides), built between 1763 and 1778 to replace an old chapel dating from the late 16th century, features on its frontispiece an exquisite arrangement of fruit carved out of local limestone, which was likewise used in the construction of the church arches and portals.

In Recife, Pernambuco state, the calcarenitic rock found in coastal reefs and beaches was used in the masonry, stonework and sculptures of its innumerable churches, such as the Igreja dos Prazeres (Church of Pleasures), in São Pedro dos Clérigos' (Saint Peter of Clergymen), in Rosário dos Pretos' (Black People's Rosary), in the Igreja Matriz de Santo Antônio (Mother Church of Saint Anthony), and in the Igreja de Nossa Senhora do Carmo (Church of Our Lady of Carmo).

In the city of Olinda, also in Pernambuco, limestone was more frequently used in the construction of its older buildings. Partly brought from the area of João Pessoa, limestone was employed, among other rocks, in the construction of arches and lateral altar pieces in the Igreja Nossa Senhora das Graças (Our Lady of the Graces Church), located in the city's seminary and built between 1551 and 1592. Limestone from that region was also used in the production of several elements of the Capela de Nossa Senhora do Carmo (Chapel of Our Lady of Carmo), built around 1580. Later, sandstone began to be more frequently employed, as it provided higher resistance compared to limestone, as is the case with Basilica de São Bento (Saint Benedict's Basilica), reconstructed with stone and lime-based mortar between 1688 and 1692. Documents found with the Order of Saint Benedict (Carvalho 1942) in Olinda's Monastery, dedicated to Nossa Senhora dos Prazeres dos Montes Guararapes (Our Lady of Pleasures on the Guararapes Hills), indicate expenses concerning the extraction of sandstone from reefs nearby for the construction of quoins, arches, jambs and cartouches of the chapel. In Igarassú, limestone was used both in masonry and in stonework. In some buildings in Goiana, another important historical site in Pernambuco, calcareous rocks, varying from limestone to calcareous sandstone, were used. Both Carvalho (1942) and Costa (2009) noted that in Serinhaém, Pernambuco, sandstone was also used in the construction of arches, jambs and cyma moldings in the chapel of Santo Antonio's Convent, whereas granite was applied to the so-called ordinary masonry in the same building.

In Santo Amaro das Brotas, as well as in other coastal towns in Sergipe state, limestone was used in the production of quoins, cyma moldings, staircases, sills and transept arches. However, in the city of Gerú, located in the countryside, gneissic rocks crop out more frequently and were thus used by Jesuit priests both in the construction of their church and in elements of the doorway of another important historical site called Engenho Retiro.

In the town of Penedo, Alagoas state, sandstone appears along the bay of the Rio São Francisco, and was also used in the production of ornaments and stonework. In the Igreja de São Gonçalo Garcia (Church of São Gonçalo Garcia), in addition to its portals and quoins, tracery details made from arenitic sandstone are present. Despite the greater hardness of this material, these tracery details are identical to steatite tracery observed in Minas Gerais, as well as those produced in limestone at Santo Amaro.

In Salvador, Bahia state, the frontispiece at the Capela da Ordem Terceira de São Francisco (Chapel of The Third Order of Saint Francis) (Fig. 2a) is built partly of limestone, but also in sandstone. The frontispiece is covered from its base to its

Figure 2. Selected uses of stone in the construction of Brazil's cultural built heritage. a) Limestone and sandstone in the frontispiece at the Chapel of The Third Order of Saint Francis, Salvador, Bahia; b) gneiss in a building in the city of Rio de Janeiro; c) quartzite in the old Casa de Câmara e Cadeia (Chamber and Prison House), located in Ouro Preto; and d) quartzite and steatite in the frontispiece of the Chapel of The Third Order of Saint Francis, Ouro Preto, Minas Gerais.

ridge with countless figures and decorations which, according to Bazin (1956), resemble an architectural style typical of overly-decorated façades, associated with the Spanish Renaissance and known as 'Plateresco.'

After considering the use of soft or barely consolidated rocks, such as limestone and sandstone, widely used in historical buildings in northern and northeastern Brazil, our focus goes on to gneisses and granites. These rocks are aesthetically very similar, and constitute the bedrock on which several historical sites were established during the period of Portuguese America in the coastal zones of old captaincies and in the provinces of Brazil's southeastern and southern regions. They were widely used in several constructions, particularly those in the former Captaincy of Rio de Janeiro (Fig. 2b). Such frequent applications can be observed in buildings and monuments of cities such as Rio de Janeiro, Paraty, Cabo Frio and Angra dos Reis, as well as in the old Village of Nossa Senhora do Desterro in the Isle of Santa Catarina, currently Florianópolis, which at that time was part of the aforementioned captaincy. In the city of Rio de Janeiro, several churches, chapels, convents, residences, fortresses and palaces were built with different types of granite and, more commonly, gneiss. The latter, whether finely banded or not, normally contains fine- to coarse-grained crystals of feldspar and quartz, the latter resembling large eyes because of the difference in size between these grains and other minerals. Usually speckled with reddish garnet crystals in a whitish-grey matrix, these materials were worked by craftsmen who came mostly from Portugal. Examples can be found in cornices, portals, columns, quoins, jambs, lintels and sills installed in churches, such as those of São Francisco de Paula, Carmo and Nossa Senhora da Candelária. Gneisses were also used in the construction of different arches, such as the well-known Arco do Telles, in administrative buildings such as the Paço dos Vice Reis (Viceroy's Paço or Palace), as well as in the Santa Cruz Fort and the Fiscal Island palace.

As for Minas Gerais, also located in southeastern Brazil, its villages and towns, although inland, were established with the use of other materials, such as quartzite (Fig. 2c), a variety of schist, iron-rich rocks and steatite (Fig. 2d). In this captaincy, limestone, gneiss and even granite were also used, albeit infrequently. Minas Gerais features geological diversity and an abundance of stone occurrences, except for calcareous rocks, which were always rare and, in general, improper for the art of stonework. Nevertheless, the location of the mining areas, the extraction and processing technologies available at the time, and the geomorphic features of the mineiro territory, all influenced the choice of materials and construction techniques, and did not always favour the use of stone. The utilization of stone was, therefore, sometimes limited or even nonexistent.

Finally, in the southernmost area of the country, the abundance of basalt, as well as the occurrence of sandstone, determined the prominent use of these materials, as for example in the Jesuitical constructions in the territory of Sete Povos das Missões (Seven Peoples of the Missions).

In spite of this rock variety, limestone brought from Portugal, and, more rarely, from Italy, was also widely used in Brazilian constructions. Examples of such applications can be found in several villages and towns lying along the Brazilian coast, mainly those in the northern and northeastern regions, from the state of Pará to Bahia. In Minas Gerais, however, no significant quantity of rock from Portugal or other foreign regions was used in the construction of monuments, edifices, and sculptures between the early 18th century (when used in the construction of the city of Vila Rica), and the end of the 19th century (when used in the construction of the city of Belo Horizonte). This is likely because of the distance between the province's urban centres and the coast; that is, the great distances and lack of suitable roads meant higher transportation costs, forcing the use of local products.

STONE DEGRADATION AND DETERIORATION IN HERITAGE BUILDINGS OF BRAZIL

Based on the examination of various types of stone used in the production of Brazil's built cultural heritage, it has been possible to identify several forms of damage caused by processes leading to the decay or alteration of these materials. In some cases, the decay or alteration has resulted in a serious decline of the site's degree of preservation, as pointed out by the ICOMOS-ISCS (2008) Glossary. Some of these processes are natural and occur continuously at geological rates, starting with the actual genesis of the rocks that have been crafted into the architectural pieces, and influence the type of damage the stone may incur. Deuteric alteration occurs soon after crystallization of igneous rocks, and additional secondary changes include transformations related to weathering processes. However, other transformations can lead to the deterioration of historical monuments within a human time scale, affecting their use in architectural projects (Fig. 3). These transformations normally result from an interaction between factors related to the characteristics of the rock and those related to the environment. They can also be induced by extraction, processing and application methods at the time the monuments are constructed. There is consensus that extraction methods used in the past, such as impacts and vibrations inflicted by tools, have caused the appearance of cracks and microfissures. In addition, processing can equally contribute to rock alteration or decay, insofar as some methods allow the fixation and accumulation of particles, mainly from the atmosphere. Alteration processes have also been influenced by the action of fixation materials, such as mortars and cements, applied at the time of construction. Such materials have contributed to the emergence of stains and efflorescence that depend on the level of humidity or on significant evaporation.

An ongoing investigation of rocks such as steatite, quartzite, schist, gneiss and granite, all used in the construction of edifices belonging to Brazil's cultural heritage, especially in the state of Minas Gerais, indicates that the visual effects of such processes may compromise the aesthetics of heritage buildings to varying degrees. This may lead to a decrease in their value or prevent them from being used in some way, according to the indications in the illustrated glossary on deterioration patterns proposed by ICOMOS-ISCS (2008). Macroscopically, stone degradation may include: development of numerous fissures, swelling and detachment of outer layers in some rocks, separation of layers, disintegration of individual grains or grain aggregates, and loss of material. All of these lead to changes in the original stone surface, such as smooth shapes, resulting from partial or selective weathering, or to mechanical action. Missing parts, crumbling sculptures and the presence of

Figure 3. Examples of damage that attest to some of the processes responsible for decay or alteration of the stone in some historic monuments built in Brazil. a) Biological colonization and black crust on limestone in the São Francisco's Convent in João Pessoa (state of Paraíba); b) crack and alveolization of limestone in the Church of São Pedro dos Clérigos in Recife (Pernambuco); c) disintegration of calcarenite in São Francisco's Convent in João Pessoa (state of Paraíba); d) encrustation associated with gneiss in the Palacete Laje in Rio de Janeiro (state of Rio de Janeiro); e) missing part on one of the prophet statues at the Bom Jesus Sanctuary of Congonhas (state of Minas Gerais); f) graffiti on the Church of Santíssimo Sacramento in Rio de Janeiro (state of Rio de Janeiro); g) patina formed on quartzite in the old Chamber and Prison House in Ouro Preto (state of Minas Gerais).

cavities or alveoli formed on the rock surface have also been observed. Other degradation patterns were noted, such as fragmentation of the stone surface, blistering, presence of crusts associated with deposits of soot and dust (representing the accumulation of both foreign material and that produced by the rock itself), changes in colour, efflorescence, sub-efflorescence, encrustations interfering with surface morphology and with the colouration of the rocks involved, patinas, graffiti, and varying degrees of biological colonization by mold, lichen, algae and plants.

Some types of degradation were directly influenced by the textures and structures present in the stone employed. The presence or absence of a foliation, as well as variations in mineral content, are important factors. For example, where foliated rocks such as schist have been used, decay processes occur faster. Depending on the content of mica, planar structures may develop, and detachments ranging from delamination to exfoliation parallel to the stone structure demonstrate the strong influence of the rock's anisotropy.

Susceptibility is also associated with the type of rock-cutting method employed: blocks have been cut indiscriminately both parallel and perpendicular to rock foliation planes with concern for matching the type of cut with the requirements in each of those applications. Thus, in the parallel-cut blocks, where foliation planes lie vertically (Fig. 4), decay occurs rapidly as a result of surface delamination or exfoliation and separation of one or more layers. In some cases of detachment, separation involves submillimetric to centimetric elements such as flakes or scales parallel to the stone surface, although not following the stone structure. In such cases, as is observed at the external and flat wedges of the Capela de Nossa Senhora do Carmo (Chapel of Our Lady of Carmo) in Ouro Preto (Minas Gerais state), the process was identified as spalling (Fig. 5).

The presence of sedimentary structures inherited in metamorphic rocks may influence processes of degradation, such as in some of the quartzite used. Banding by compositional variation, or cross-bedding, occurring alone or in combinations, can lead to different degrees of degradation, and the effect of these structures may be enhanced by differential erosion. Some of the processes observed were strongly influenced by the mineralogical composition of the rocks employed, as in the case of steatite. Although prone to scratching because of the softness of its main mineralogical component, steatites contain a significant number of different minerals, and each mineral phase has its own coefficient of thermal expansion, contributing to the appearance of fissures and cracks. Broadly speaking, however, the main types of damage observed in steatite applications involve the appearance of cavities, because minerals formed from local enrichment of iron oxide or sulfide (pyrite) are easily removed by alteration/weathering. The common presence of carbonate crystals, usually dolomite, also contributes to the formation of such cavities through dissolution, accelerated in part by acid rain. An instructive example of the process of cavity or alveoli formation in steatite is seen in the statues of the prophets installed in the churchyard of the Santuário do Bom Jesus (Good Jesus Sanctuary) in Congonhas, Minas Gerais. Visual examination over the past 15 years has showed that, within the last 7 years, the process has accelerated. Throughout this period, it was noted that stains gave rise to cavities, some of which were 0.5 to 1.0 cm deep (Fig. 6).

In many of the applications studied, the stone consists almost exclusively of a single mineral, such as quartz in the case of the quartzite. But these stones may contain many different accessory minerals such as mica, kyanite and opaque minerals (iron oxides). The presence of iron-rich accessory minerals contributed, in some cases, to extensive oxidation, resulting in a great variety of rock hues. Because of these chromatic modifications (patina), quartzite and other rocks such as granite show colour variations ranging from white to yellow, red or orange tones. On the other hand, quartzite, consisting essentially of quartz grains, usually has a granoblastic texture, and contacts between the grains can be serrated, lobed or straight (polygonal arrangement). Depending on how these grains are juxtaposed, the type of degradation most frequently observed may consist of granular disintegration, the intensity and extent of which are quite variable. In several buildings, arenization (sand formation) and hydrolysis of varying amounts of micaceous material, if present, have occurred, as with the doors leading to the pulpit inside the Capela de Nossa Senhora do Carmo (Chapel of Our Lady of Carmo) in Ouro Preto.

Rock decay in monuments is also caused by differential erosion, such as that observed at the pillar bases in Mariana's Capitular House (Minas Gerais state), between parts constructed of quartzite and of schist, which respond differently to alteration processes. This decay was also seen in the wear found at the base of the old Casa de Câmara e Cadeia (Chamber and Prison House), located in Ouro Preto. Many of these irregularities and wear are a result of one or a combination of factors such as so-called eolian erosion and abrasive wear, including that caused by water erosion, for example, which is present on the stair steps of the Capitular House or on the stairway leading to the churchyard in the Congonhas Sanctuary, both in Minas Gerais state. Furthermore, the locations of some of the constructions in Minas Gerais, such as the Capela de Santo Antônio (Chapel of Santo Antonio) in the Itatiaia district, the Igreja de Santo Antônio (Church of Santo Antonio) in Tiradentes and the Santuário do Bom Jesus de Congonhas (Good Jesus Sanctuary), relative to wind currents, solar radiation and humidity levels, explains oxidation phenomena and differential development of patina and colonies of algae and lichen (Fig. 7). In the Congonhas complex, the increasingly common presence of orange-yellow patinas can be observed. They are concentrated in certain areas, especially those that are better protected from rain, and are difficult to remove. Biological colonization is equally frequent and has been the only reason for official interventions in recent years.

Fissures and oblique cracks, resulting in part from accidental ruptures or those caused by improper handling during application, are also present. Therefore, mechanical action might have contributed to the damage observed in some structures, as some blocks are both less resistant to compression effects and more prone to rupture. Pre-existing or induced microfissures were also observed to have evolved, causing parts of the same block to separate, with significant loss of mass, as shown in several of the Congonhas' prophet statues and in many of the sculptures set in innumerable medallions and portals of a variety of chapels. Examples include fissures and chipping in the winged seraphs and on the low-relief che-

Figure 4. Detachment processes observed in parallel-cut blocks in which surface exfoliation is parallel to vertical foliation planes (schistosity) in a) a sericite-quartzite application in Ouro Preto, Minas Gerais, and b) a garnet gneiss application in the city of Rio de Janeiro.

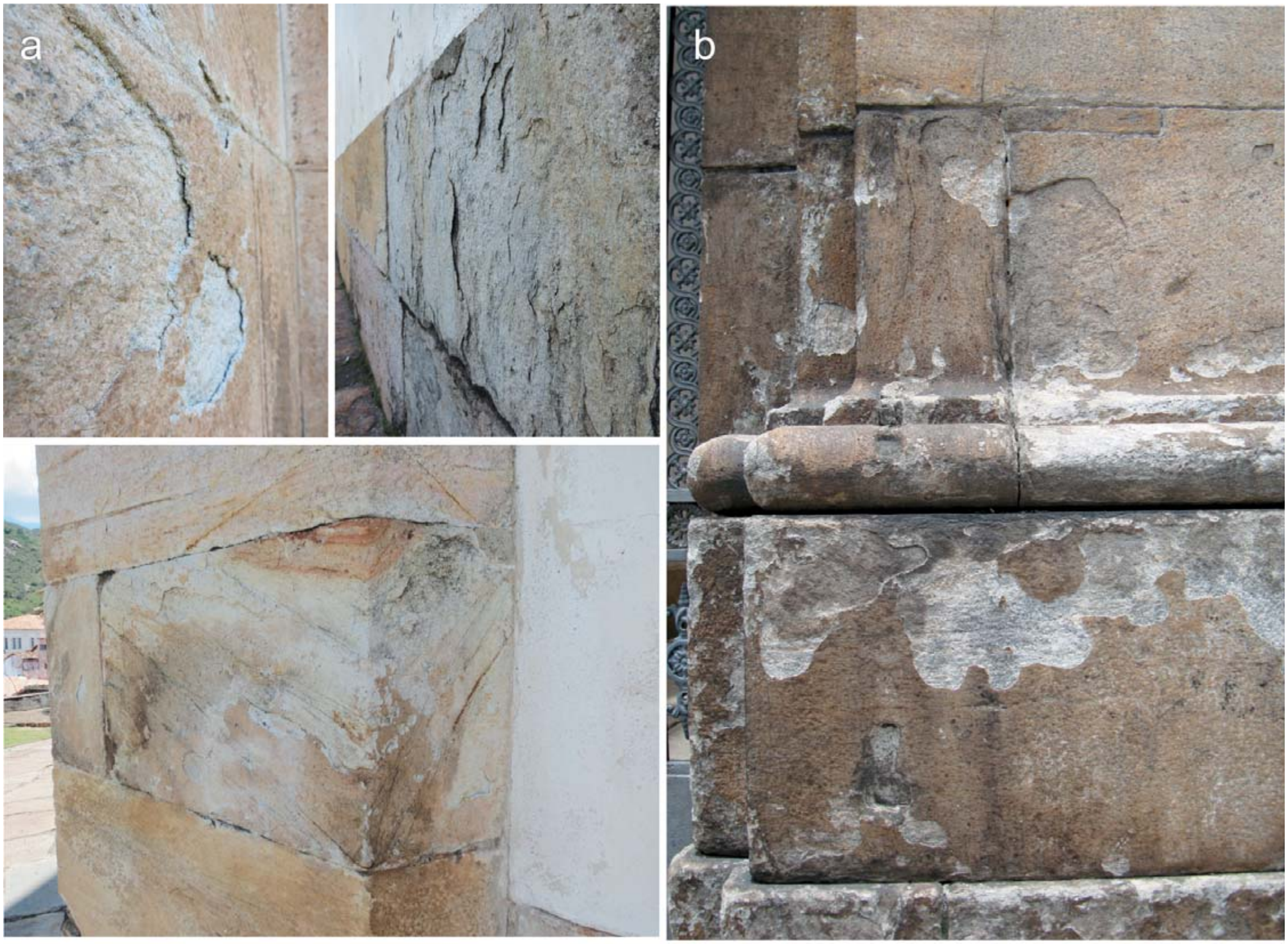

Figure 5. Example of stone detachment as flakes or scales (spalling). In this case, detachment is parallel to the block surface but not to the rock structure, as observed in a) the external and flat wedges of quartzite at the Carmelite Chapelin, Ouro Preto, Minas Gerais, and b) gneiss at the Carmelite Church in Rio de Janeiro.

rubim faces that compose the São Francisco de Assis Church frontispiece, in Ouro Preto.

Finally, in historic sites located in urban centres heavily affected by air pollution, such as in Rio de Janeiro and São Paulo, external surfaces are commonly covered by grey to black deposits of varying consistencies and degrees of adhesion to the substrate. In some cases, these deposits occur in areas protected from the rain; in others they are in areas exposed to open air and may be directly affected by rain water. The deposits differ in thickness and shape, ranging from inconsistent layers of pulverulent (powdery) material on horizontal surfaces, to surface deposits well adhered to the substrates. As black crusts, they are frequently associated with serious problems of stone degradation, manifested as exfoliation or blistering (Fig. 8).

Apart from these and other decay processes that have led to the deterioration of some of the monuments identified herein, many structures have been overlooked and left 'to their fate.' Some have been totally destroyed and others were affected by uncontrolled urban development, such as old constructions on Ouro Preto's hills, whereas others suffered intense and irreversible deterioration, especially in the past thirty years. Currently, they lie lost among new urban facilities, evidence of a lack of commitment towards the preservation of heritage and historical memory.

STEPS TOWARD CONSERVATION

Several technological characterizations of the physical and mechanical characteristics and petrographic features of the materials have been carried out. When possible, these investigations were made both in the quarry and on the monument. Accelerated weathering tests were carried out on all the rocks herein considered; more recently, these have been performed in the LABTECRochas laboratory at CPMTC/UFMG (Costa 2009), and involved simulation of natural processes including sharp drops in temperature, the influence of corrosive material, and variations in oxidation conditions, among others. Consequently, verification was obtained of the deleterious effects of several factors contributing to chromatic alterations, decrease in resistance and to compromised aesthetic standards.

The observations show that the most damaging activities were and still are: (1) interventions made without proper knowledge of rock characteristics and without regard to its texture and structure; (2) interventions that interrupted the

Figure 6. Deterioration of steatite (soapstone) works produced in the late 18th century, such as those shown here in Congonhas Sanctuary, mainly caused by weak rock resistance, and by biological and anthropological factors leading to cavity or alveoli formation.

history of some of these monuments in an unacceptable and irreversible way; (3) the abandonment and degradation of areas surrounding the monument that have been swollen by uncontrolled urban development/sprawl, as observed in almost all major historical sites both in Minas Gerais state and in the whole of Brazil; and (4) extensive vandalism, which remains unpunished in most cases and which arises from lack of information concerning the need for preservation of such rich heritage.

Figure 7. Example of patina formation (oxidation), deposition of particles, and biological colonization on the surface of granite blocks with whitish-grey original colour, on the frontispiece of the Congonhas Sanctuary of Bom Jesus church. The current brownish colour (patina) results from the position of these (outer) blocks facing the action of wind currents and variations in moisture content. In areas unaffected by such currents, the granite retains its original whitish-grey colour, although it is susceptible to intense biological colonization.

CONCLUSIONS

Stone decay increases over time because, from that moment of its installation and exposure in monuments, the rock finds itself in a foreign environment and is subject to thermodynamic conditions very different from those present where it was formed. Corrosion, disaggregation, crust formation and exfoliation of stone materials, among other forms of decay, can be kept under control or monitored, but can never be completely prevented. On the other hand, it is possible, via education, to reduce or eliminate the impacts of factors deriving from human influence.

It is recommended that cleaning processes using abrasive materials be avoided, especially on steatite, schist and limestone. As for the monuments that feature exposed stone or any stone sculptures kept outdoors, it is recommended that their respective patinas and crusts be preserved, in spite of it being possible to remove the original statues and replace them with copies. The presence of these coatings will probably not lead to further deterioration, nor aesthetically affect monuments or sculptures. Instead, they will function as protective elements and even consolidate their altered parts. Besides, their presence can prevent new losses or wear deriving from continuous attacks by external agents on the monuments. Because of this, removing the effects of alteration or decay is not always the best approach to conservation. Still, while patinas and crusts can prevent or reduce the absorption of fluid, whether or not carrying dissolved salts or other particles, they can also hinder or prevent the release of fluids through evaporation. Depending on climatic conditions, this can compromise the stone. In such cases, the recommended strategy is a gentle cleaning aimed at removing biological contamination and crusts. It is also worth noting that microbiological colonization, for example, does not always cause damage to the rocks used in monuments, especially if it is kept under control.

Each situation therefore deserves careful analysis, and any and all decisions, either towards maintenance or restoration, must be preceded by investigations aimed at collecting data on the environmental conditions affecting the monument, on the characteristics of the materials used in its construction, and on the types and extent of potential damage.

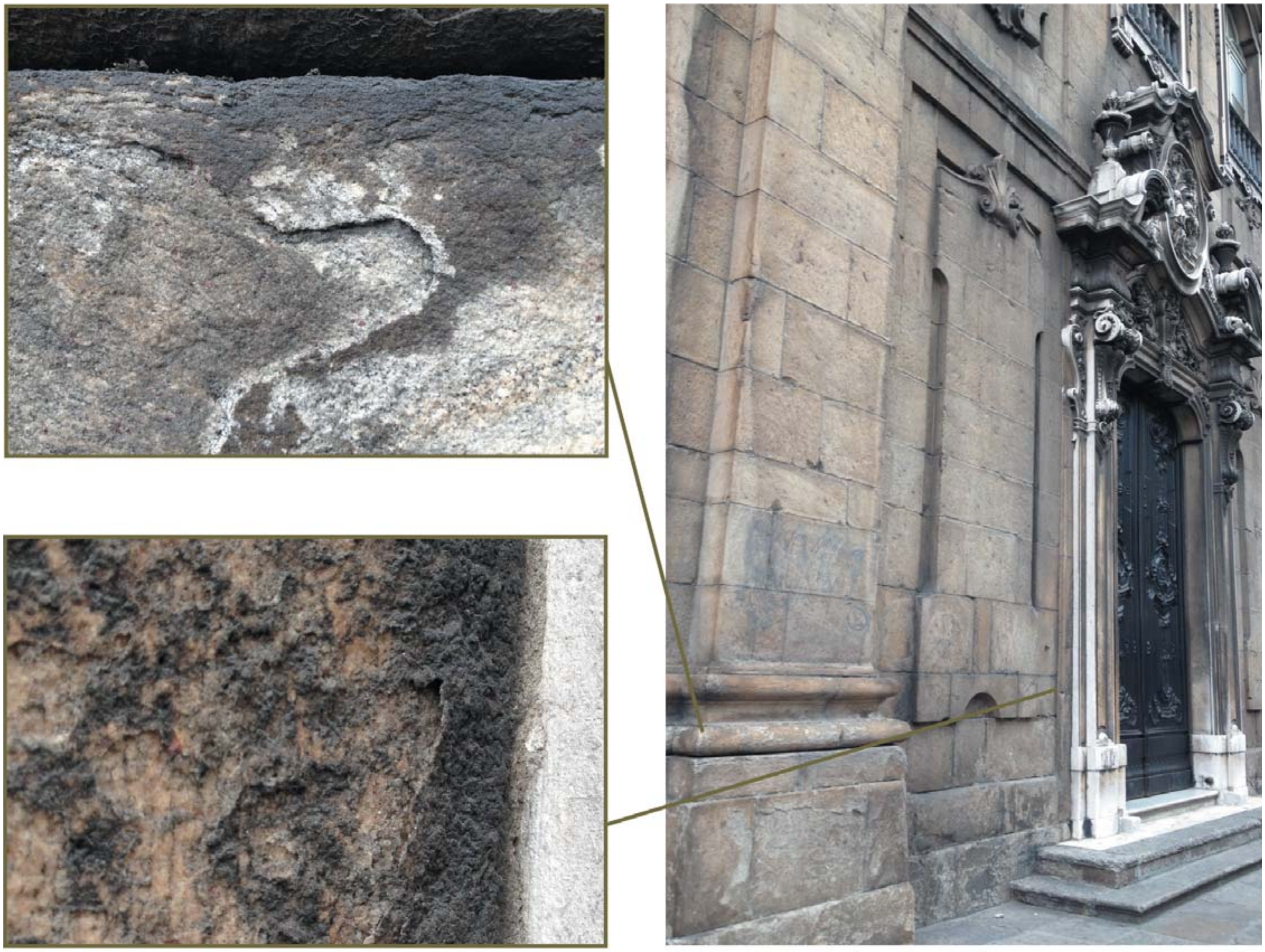

Figure 8. Degradation observed in historical buildings and identified as black crust. Formed by the accumulation of particles deposited on the flat surface of fine-grained garnet gneiss, the crust is associated with a blistering process on the façade of the Carmelite church, Rio de Janeiro.

It is hoped that, on the basis of the data collected for this study, it will be possible to indicate the most suitable preservation and maintenance methods for each case of alteration or decay observed in such stone monuments. On the other hand, considering that most of these monuments remain exposed and in direct contact with adverse conditions, all efforts in the area of preventive conservation will serve only to delay the impacts and minimize the effects of these degradation processes. These will, with time, inexorably cause the deterioration of the cultural heritage of Brazil, as they will elsewhere.

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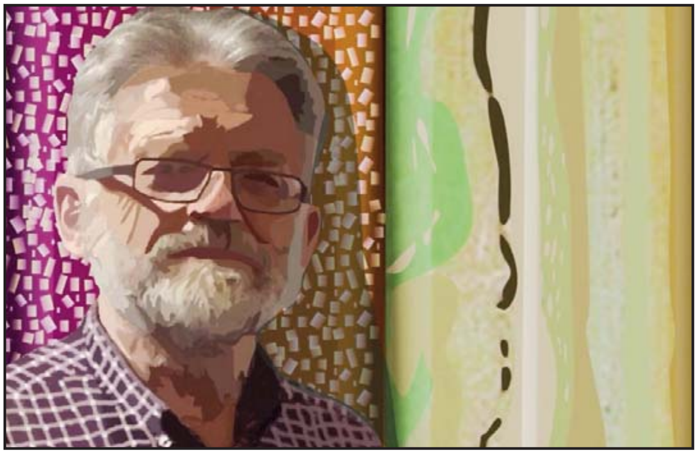

Heritage Stone 4.
The Piedra Berroqueña Region: Candidacy for Global Heritage Stone Province Status*

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SUMMARY

The Piedra Berroqueña region in the Guadarrama Mountains, part of Spain's Central Range, supplies most of the construction granite used in Madrid and surrounding provinces. The region's quarrying towns preserve their granite extraction and hewing traditions. Historic quarries form part of the landscape, as do current extraction sites with huge reserves that guarantee a speedy supply of variously finished dimension stone. *Piedra Berroqueña granite* has been in use as a construction material since long before Roman times. Many important monuments, including San Lorenzo Royal Monastery at El Escorial (1563−1584), Madrid's Royal Palace (1738−1764), the Alcalá Gate (1770−1778), the Prado Museum (1785−1808) and Puerta del Sol (one of Madrid's main squares), owe their good state of preservation to the stone's petrophysical characteristics and durability. The granite is also found in most of the city's housing and streets, as well as in modern buildings the world over, such as the airport terminals at Athens and Cork, and the British consulate at Hong Kong.

Four major types of monzogranite occur including: biotitic monzogranites containing some cordierite, biotitic monzogranites containing some amphibole, biotitic monzogranites having no cordierite or amphibole, and leucogranites. The petrological, petrophysical and chemical properties of Piedra Berroqueña, which afford it great durability, vary little from one variety to another and depend on the degree of alteration. Physical and chemical characteristics were determined for five granites representative of historic or active quarries in the Piedra Berroqueña region: Alpedrete (monzogranite containing cordierite); Cadalso de los Vidrios (leucogranite); La Cabrera (monzogranite containing amphibole); Colmenar Viejo (monzogranites containing cordierite); and Zarzalejo (monzogranites having no cordierite or amphibole).

The Piedra Berroqueña region meets the requirements of a Global Heritage Stone Province, and this paper supports the Piedra Berroqueña region's application for recognition as such. This distinction would enhance public awareness of an area committed to quarrying and working the local stone.

RÉSUMÉ

La région de Piedra Berroqueña dans les monts de Guadarrama, qui fait partie de la chaine centrale d'Espagne, est la principale source du granite de construction utilisé à Madrid et dans les provinces environnantes. Les agglomérations de la région qui exploitent une carrière conservent leur tradition d'extraction et de taille du granite. Les anciennes carrières font maintenant partie du paysage, comme les sites d'extraction actuels avec d'énormes réserves ce qui garantit un approvisionnement rapide en pierre de taille de fini varié. Le granite de *Piedra Berroqueña* a été utilisé comme matériau de construction bien avant l'époque romaine. De nombreux monuments importants, y compris le monastère royal de San Lorenzo à l'Escurial (1563–1584), le palais royal de Madrid (1738–1764), la porte d'Alcalá (1770–1778), le musée du Prado (1785–1808) et la Puerta del Sol (une des principales places de Madrid), doivent leur bon état de conservation aux caractéristiques

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pétrophysiques et à la durabilité de la pierre. Ce granite se retrouve également dans la plupart des habitations et des rues de la ville, ainsi que dans des bâtiments modernes du monde entier, tels que les terminaux de l'aéroport d'Athènes et de Cork, et le consulat britannique à Hong Kong. Il est constitué de quatre grandes classes de monzogranite : des monzogranites à biotite contenant un peu de cordiérite, des monzogranites à biotite contenant un peu d'amphibole, des monzogranites à biotite ne contenant ni cordiérite ni amphibole, et les leucogranites. Les propriétés pétrographiques, pétrophysiques et chimiques des granites de Piedra Berroqueña qui leur assurent une grande durabilité, varient peu d'une variété à l'autre et dépendent du degré d'altération. Les caractéristiques physiques et chimiques ont été déterminées sur cinq granites représentatifs des carrières historiques et actives de la région de Piedra Berroqueña : Alpedrete (monzogranite à cordiérite); Cadalso de los Vidrios (leucogranite); La Cabrera (monzogranite à amphibole); Colmenar Viejo (monzogranite à cordiérite); et Zarzalejo (monzogranite sans cordiérite ni amphibole). La région Piedra Berroqueña répond aux critères d'une Province pétrologique du patrimoine mondial, et le présent article documente la candidature de la région de Piedra Berroqueña à cet effet. Cette distinction permettrait d'améliorer la sensibilisation du public concernant une région spécialisée dans l'extraction et à la taille de la pierre locale.

Traduit par le Traducteur

INTRODUCTION

The Piedra Berroqueña region occupies an area of about 100 km by 40 km, and lies partly in the Guadarrama Mountains National Park, in the eastern branch of Spain's Central Range. The region is oriented southwest–northeast across the provinces of Madrid, Segovia and Ávila. 'Berroqueña' stone, a name that comes from the Spanish word 'berrueco' or outcrop of granite boulders, is the granite traditionally used in regional construction. Many towns in the Guadarrama Mountains, particularly in the province of Madrid, engage in quarrying, hewing and shipping granite. The mainstay of the area's economy for centuries, its importance is mirrored in the stone-related etymology of some of the local place names such as Alpedrete (stone in Spanish is *piedra*), Berrocal (in Spanish, a place where granite boulders outcrop) (Llorente 2011), Moralzarzal and Valdemorillo (based on the pre-Roman roots 'mor(r)' or 'mur(r)', meaning a pile of stones). Traditional quarrying in these towns forms part of the province of Madrid's intangible heritage, as attested by the many festivals honouring Saint Peter, the monuments to and courses on the stone trade, and quarrymen's competitions (Fig. 1). Most of the 2000 historic quarries in the province of Madrid are small and shallow because the stone was traditionally removed manually from the top of the outcrops (to depths of approximately 1 to 1.5 m). Whereas quarrying in the past consisted of removing only small whale-back formations (Fig. 2a), the gradual depletion of the latter has led to larger operations and quarrying at greater depths (Fig. 2b). Today, traditional family-run quarries co-exist with the mechanized variety (Fig. 2c, d).

Piedra Berroqueña began to be used internationally in the twentieth century. By mid-century, approximately 21,000,000 tonnes of Piedra Berroqueña had been removed from historic quarries and used as a construction material in Madrid (Martín 1994). In 2011, 5,573,450 tonnes were exported (AIDICO 2012). Cadalso de los Vidrios and Bustarviejo – La Cabrera are the two main quarrying areas presently in use. Their granite has been used in culturally significant buildings the world over (Tables 1, 2). This stone, along with other materials (Fort 2008), was used in key heritage buildings in the centre of the province (Table 1) and in nearly all the residential buildings in the capital city's historic quarters, as well as in pavement, cobblestones, manhole lids and urban furniture (Martín 1994).

Since Casiano de Prado y Vallo published his *Descripción Física y Geológica de la provincia de Madrid* (physical and geological description of the province of Madrid) in 1864, many scientific articles on Piedra Berroqueña have discussed its origin (Villaseca et al. 1998, 2009, 2012; Villaseca and Herreros 2000); petrological (Gómez-Heras et al. 2008) and petrophysical (Fort et al. 2011, 2013a) characteristics; durability (Gómez-Heras 2005; Fort et al. 2011; Freire-Lista et al. 2015a, b, c); and the buildings for which it has been used (López de Azcona et al. 2002; Fort González et al. 2004; Pérez Monserrat and Fort 2004; Menduiña and Fort 2005; Fort et al. 2010).

The granitoid plutons of the Piedra Berroqueña region (Brandebourger 1984) consist of Carboniferous to lower Permian, late- to post-orogenic monzogranite (De Vicente et al. 2007). Four major types of monzogranite occur: biotitic monzogranites containing some cordierite, biotitic monzogranites containing some amphibole, biotitic monzogranites with no cordierite or amphibole, and leucogranites. Monzogranite normally generates flat, braided, landscapes featuring boulders or tors. Leucogranites, having a smaller grain size, form more rugged landscapes characterized by subvertical fracturing, resulting in greater topographic relief. Piedra Berroqueña monzogranites have mafic inclusions of two types: xenoliths unrelated to granite magma (such as orthogneiss, metapelite or schist fragments) and igneous mafic microgranular nodules (Villaseca et al. 1998), for which the region's quarrymen have a number of terms: *gabarros, negrones* or *manchones* (smooth-edged nodules, black spots, or stains).

Global Heritage Stone Province (GHSP) status for the Piedra Berroqueña region is proposed in light of its quarrying tradition and history, and the use of its stone. This paper provides appropriate detail for GHSP assessment, including petrophysical and chemical descriptions of the granite, and the economic and cultural importance of quarrying this stone throughout history.

METHODOLOGY

Petrophysical data were compiled for five granites that are representative of historic or active quarries in the Piedra Berroqueña region and have been widely used in Madrid (Fort et al. 2013b). This includes granites from Alpedrete (monzogranites containing cordierite; Freire-Lista et al. 2015b), which has been proposed as a Global Heritage Stone Resource (Cooper 2010, 2013a, b; Hughes et al. 2013); Cadalso de los Vidrios (leucogranite); La Cabrera (monzogranite containing amphibole); Colmenar Viejo (monzogranite containing cordierite); and Zarzalejo (monzogranite having no cordierite or amphibole; Freire-Lista et al. 2015d) (Fig. 3), which was also proposed as a Global Heritage Stone Resource. To quantify the deterioration in the physical properties and strength of these granites, they were exposed to 280 freeze-thaw cycles (see

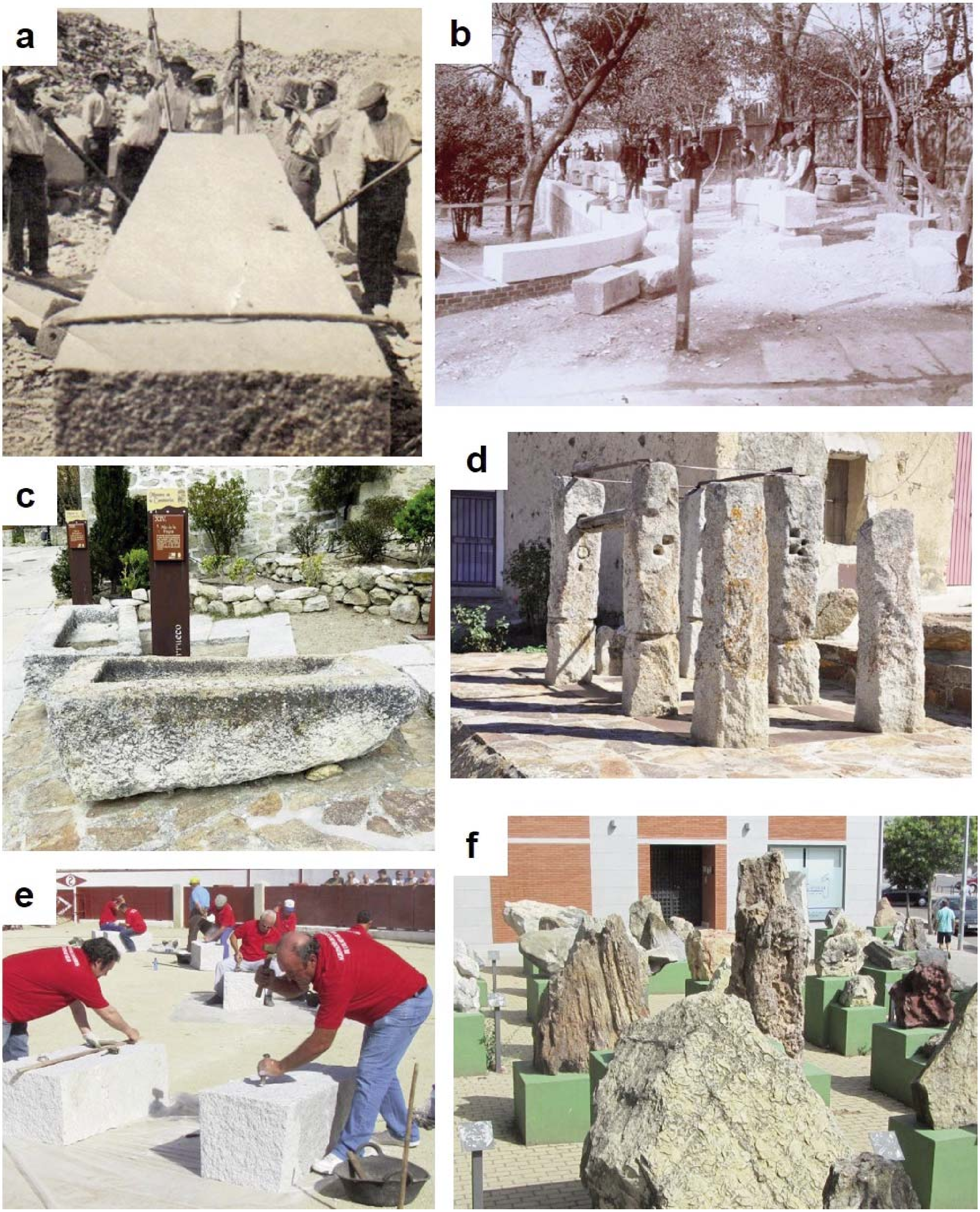

Figure 1. a) Lintel in historic quarry at Alpedrete; b) laying of Piedra Berroqueña at Madrid's Santo Domingo Square; c) outdoor Quarry Museum at El Berrueco; d) shoeing pen at Villavieja de Lozoya; e) quarrymen's competition at Colmenar Viejo; f) Geology Museum at Colmenar Viejo.

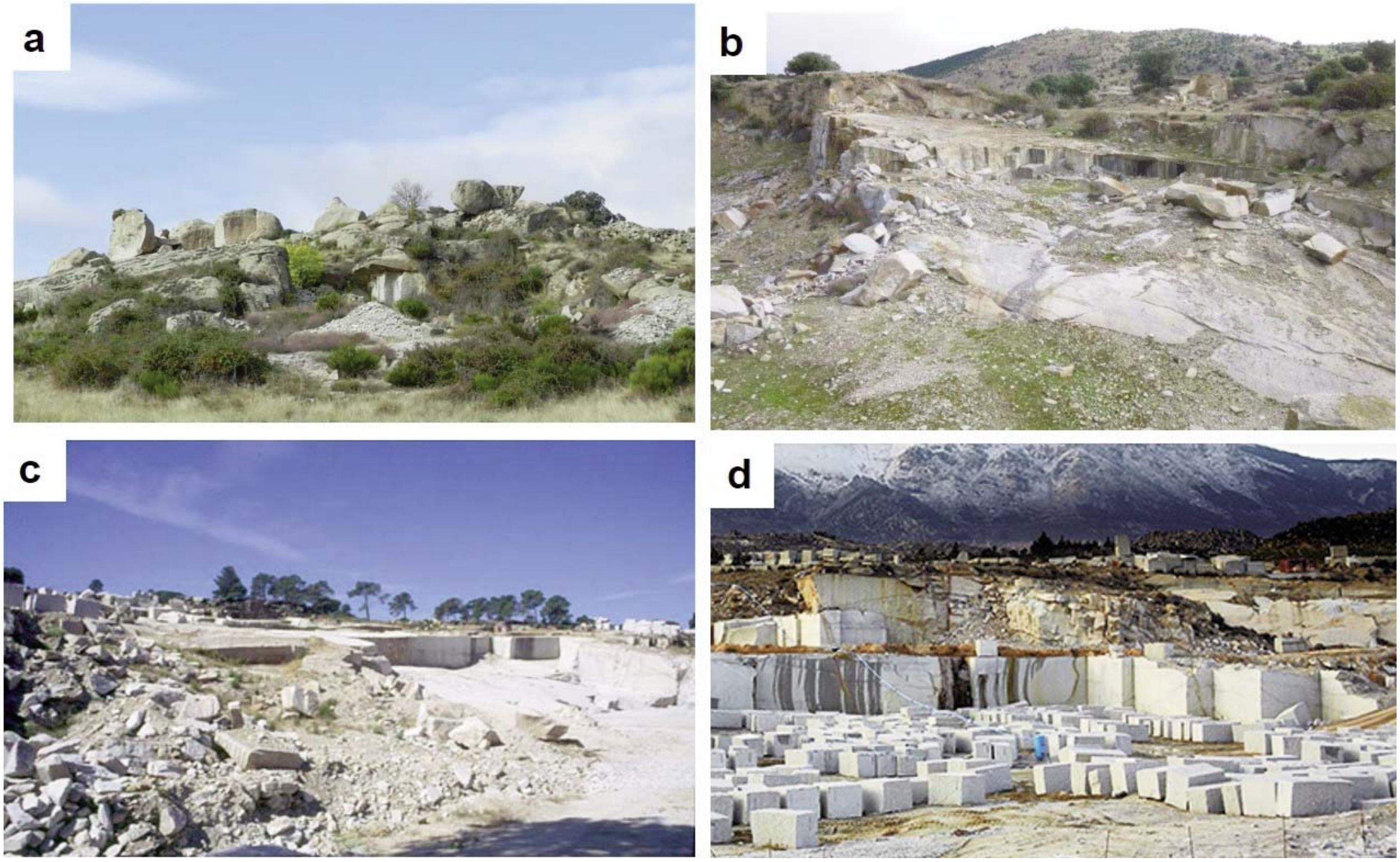

Figure 2. a) Historic quarry at Zarzalejo; b) historic quarry at Alpedrete; c) quarry in operation at Cadalso de los Vidrios; d) quarry in operation at La Cabrera.

below), as specified in European standard UNE-EN 12371 (2001) (Freire-Lista et al. 2015a).

HISTORIC USE OF PIEDRA BERROQUEÑA

The earliest artistic expressions in the Piedra Berroqueña region are found in a nook in the Aljibes cave (Priego 1991), where granite walls serve as a substrate for paintings that date from 1500−1200 BCE. The Neolithic dolmen at Entretérminos (Losada 1976) and the burial mound at Las Vegas de Samburiel (Gil 2013) are other examples of the pre-Roman use of Piedra Berroqueña. The Romans used it to build a road from Cercedilla to Segovia, remains of which have been preserved, as well as bridges at Colmenar Viejo and a building at Collado Mediano, now an archaeological site. The Colmenar Viejo Municipal District (Colmenarejo et al. 2005) hosts remains from the Visigoth period (4th to 8th centuries).

The mountains in the Piedra Berroqueña region form a natural barrier that has been the site of a number of important battles. For centuries, it was a frontier that divided the Christian and Muslim (Moorish) kingdoms to the north and south, respectively. In Muslim times, watchtowers were built in places such as El Berrueco and Buitrago de Lozoya. The latter town's historic centre was listed as a historic-artistic compound and its castle as a cultural heritage asset, both in 1993, and its walled enclosure has had national monument status since 1931.

It was not until the permanent conquest of Toledo by the Christians in 1085 that monastery-fortresses, churches and castles were built with Piedra Berroqueña. In the Middle Ages (7th through 15th centuries), the materials used were the ones closest to population centres. In 1475, work began on the Manzanares el Real castle (listed as a historic-artistic monument in 1931) using local leucogranite. Pedraza's historic core, built with Piedra Berroqueña, has had monumental compound status since 1951. Madrid's designation as the capital of the Kingdom of Spain in 1561 and the construction of the Royal Monastery at El Escorial between 1563 and 1584 marked the beginning of the widespread use of Piedra Berroqueña throughout the region of Madrid (Fort et al. 2011).

In 1749, work was completed on a newly paved road from the Guadarrama Mountains to Madrid. This improvement in communications increased the volume of granite shipments to the city. In the 18th century, nearly all the inhabitants of the Piedra Berroqueña region engaged in quarrying or shipping the stone (Marqués de la Ensenada 1752).

Royal architect Francisco Sabatini drafted a code, which was approved in 1761, that called for paving the streets of Madrid with Piedra Berroqueña. The municipal ordinance enacted that same year generated a growing demand for this dimension stone. After the city's Plaza Mayor (main square) burned down for the third time in 1790, it was reconstructed with Piedra Berroqueña, which was also used to build the Prado Museum (1785−1808). The Battle of Somosierra, fought and lost in 1808 during the War of Independence against the French, cleared the way for Napoleon's troops to enter Madrid. A small fort that was built on the battlefield with Piedra Berroqueña has been conserved and today is a cultural heritage asset. During and after the reign of Joseph (Bonaparte) I (1808−1813), a town planning ordinance required all

Table 1. Significant monuments built in the Madrid region with Piedra Berroqueña and other types of stone.

Works	Year built	References
Roman road, Caratrava, Cercedilla and Zarzalejo	Before 3rd century	Martín 1994
Batán and Grajal Roman bridges at Colmenar Viejo	Before 3rd century	Colmenarejo 1986
Archaeological site at Navalvillar	6th–7th centuries	López Sáez et al. 2015
Fuente del Moro archaeological site	6th–7th centuries	Colmenarejo 1986
Remedios' necropolis	After 7th century	Colmenarejo et al. 2005
El Paular Monastery	1086	López-Arce et al. 2011
Nuestra Señora de la Asunción Church at Alpedrete	12th-13th centuries	Menduiña and Fort 2005
Bernardos Monastery	12th century	Calero 1992
Church at Fuente el Saz del Jarama	13th century	Menduiña and Fort 2005
Castle at Manzanares el Real	1247	Menduiña and Fort 2005
El Paular Monastery (intervention)	1440–1486	López-Arce et al. 2011
Bishos Chapel	1520–1535	Guerra and Zapata 2010
Las Descalzas Reales Monastery	1559–1564	Martín 1994
San Lorenzo Royal Monastery at Escorial	1563–1584	Fort et al. 2013a
Segovia Bridge	1582–1584	Martín 1994
Plaza Mayor (main square)	1590, later reconstructions	Martín 1994
Agustinas Recoletas de la Encarnación Monastery	1611–1616	Bernabéu et al. 2004
Nuestra Señora del Carmen y San Luis Church	1611–1638	Menduiña and Fort 2005
Agustinas Recoletas de Santa Isabel Monastery	1640–1667	Tovar 1983
San Ginés Church	1641–1645	Martín 1994
San Andrés Church	1657–1669	Martín 1994
Concepción Real de Calatrava Church	1670–1678	Menduiña and Fort 2005
San Isidro Collegiate Church	1673–1675	Menduiña and Fort 2005
San Ildefonso de Trinitarias Descalzas Convent	1673–1688	Tovar 1983
Toledo Bridge	1719–1724	Menduiña and Fort 2005
Royal Palace at Madrid	1738–1764	Fort González et al. 2004
Palace of Prince Luis de Borbón	1763–1765	Fort et al. 1996
Prado Musesum	1785–1808	Martín 1994
Alcalá Gate	1770–1778	Martín 1994
Botanical Garden winter shelters	1779–1781	Martín 1994
Royal Theatre	1830–1850	Menduiña and Fort 2005
National Library	1862–1892	Martín 1994
Dam at El Villar	1870–1873	Unceta and Echenagusía 2005
San José Homeopathic Hospital	1874–1878	Merlos 2005
Veterinary School - Former Casino de la Reina	1877–1881	Del Corral 1972
Niño Jesús Hospital	1879–1881	Navascués 1993
Bank of Spain	1884–1891	Navascués 1993
Ministry of Agriculture, Fisheries and Food	1893–1897	Navascués 1993
Milagrosa Church	1900–1904	Menduiña and Fort 2005
La Concepción Church	1902–1914	Menduiña and Fort 2005
Former Maudes Street Workers' Hospital in Madrid	1909–1916	López-Urrutia, L. 1926
El Águila beer factory	1912–1914	Gutiérrez 1997
San Francisco de Sales Church	1926–1931	Martín 1994
Nuevos Ministerios	1933–1942	Maure 1985
Valle de los Caídos monument	1940–1958	Méndez 2009
Moncloa Palace reconstruction	1953	Menduiña and Fort 2005
IFEMA	1980	Blokdegal, S.A. Granite production company
Addition to the Reina Sofía Museum	2001–2005	Blokdegal, S.A. Granite production company
Addition to the Bank of Spain	2003	Blokdegal, S.A. Granite production company

buildings to have a dado (the lower part of a wall) consisting of three rows of Piedra Berroqueña ashlars, or finely dressed stone masonry (Cabello y Lapiedra 1901). The stone was also one of the materials used to build the network of optical telegraphic communication towers between Madrid and Burgos, undertaken in 1836 (Olivé 1990).

A substantial number of Piedra Berroqueña quarries were opened in the mid-19th century to build the Isabel II Canal that carries water from the Guadarrama Mountains to the city of Madrid. That project entailed the construction of a host of hydraulic infrastructures, such as the Amaniel aqueduct, a neo-Gothic tower, the reservoir at Manzanares el Real (Unceta and

Table 2. New buildings in other countries.

Atatürk Airport, at Istanbul, Turkey
Enfidha International Airport (Zine El Abidine Ben Ali Airport), Tunisia
Singapore Post Center
Mall Boulevard — Las Vegas, Nevada, USA
Cathedral Place — Vancouver, Canada
Sam Jung Building, Seoul, Korea
Cork Airport, Ireland
Magit Palace — Budapest, Hungary
Migdalot Tower — Tel Aviv, Isreal
Terra Park — Budapest, Hungary
Federal Deposit Insurance Corporation building — Washington, D.C., USA
Yayasan Sultan Hassanal Bolkiah — Brunei
Capval - Nouveau Berci — Paris, France
Istambul Airport, Turkey
Capitol East End Complex — Sacramento, California, USA
Granite Castle, English Channel Island, UK
US Embassy at Abidjan, Ivory Coast
Opera Tower, Tel Aviv, Israel
Zamert Tower, Tel Aviv, Israel
Platinum/Milenyom Towers, Tel Aviv, Israel
Great America Plaza, San Diego, California, USA
Migdalot Tower, Tel Aviv, Israel
Oceanus, Herzlelia, Israel
Herzelia Square, Herzklia, Israel

*Source: Granite production company: http://www.ingemargroup.com/.

Echenagusía 2005), and bridges. Improvement works were also conducted on the road between the quarries and the capital city.

Oxen were used to carry construction granite from the Piedra Berroqueña region as late as the 20th century, albeit less and less commonly, as the use of trains and trucks started in the 19th century. To meet such high demand, an 11 km railway line operated for 73 years (1883–1956), exclusively to ship Alpedrete granite from the quarry to Collado Villalba station (Aranguren and Lópes 1990). Railways lowered the cost of shipping the material, just at the time when most of Madrid's quarters were being built and summer homes were going up in the mountains. The dados on Madrid's municipal slaughterhouse (1910–25) and bullfighting ring (1920–29) are made of Piedra Berroqueña.

When the Sociedad de Sacadores de Piedra de la Sierra (society of stone extractors) and the Sociedad Construcciones Hidráulicas y Civiles (hydraulic and civil construction society) were founded in 1914, the Alpedrete region became the area's leading producer of Piedra Berroqueña. The harsh working conditions, in conjunction with the large number of workers engaging in quarrying Piedra Berroqueña, led to a strike in 1930 backed by over 1000 quarrymen. The economic importance of the Piedra Berroqueña region was symbolized by the 1932 unveiling of the Fountain of the Geologists, made of Piedra Berroqueña. The monument was a tribute to geologists Casiano del Prado, José Macpherson, Salvador Calderón and Francisco Quiroga, who had pioneered the study of this stone, fostered scientific research in the Guadarrama Mountains, and placed the region on the cultural map.

The building christened as 'los Nuevos Ministerios' (new ministries), one of Madrid's largest, was constructed with Piedra Berroqueña between 1931 and 1942 (Maure 1985). Although building construction, and therefore work in the quarries, waned during the Spanish Civil War (1936–1939), the war itself left a considerable heritage of trenches, shelters, observatories and forts scattered across the region. Alpedrete granite resisted the ravages of war, although bullet holes are still visible on the ashlars in some of Madrid's heritage buildings (Pérez-Monserrat et al. 2013; Fig. 4f). The granite quarried in 1940–50 was used to rebuild Madrid and erect the 'Valle de los Caídos' (Valley of the Fallen) monument (Méndez 2009). Beginning in 1960, output rose substantially to meet the city's huge demand for granite for buildings such as the National Mint, finished in 1964.

The stone quarried today is used primarily in flooring (García del Cura et al. 2008), paving, and funerary art, and for export, restoration and rehabilitation works in the region of Madrid. The key production centres are La Cabrera, which markets its stone under the trade name Blanco Perla, and Cadalso de los Vidrios, the home of Blanco Cristal. The granite is also quarried at Zarzalejo and trades under the name Blanco Rafaela, although output is much smaller. This stone was used to reconstruct Moncloa Palace (residence and office of the President of the Spanish Government), renovate the Royal Palace, build the entrance and buildings in the Institucion Ferial de Madrid (IFEMA) fairgrounds and erect the Queen Sofia Museum, among others. Historic Piedra Berroqueña quarries at Alpedrete and Zarzalejo supplied the granites used in many heritage buildings (Tables 1, 2).

HERITAGE ISSUES

Piedra Berroqueña has not only been used in art and building construction, but since the Middle Ages has also been cited in literature by travellers crossing the Guadarrama Mountains. Pinciano Hernán Núñez's 1555 compilation of sayings includes one on the durability of Piedra Berroqueña. The Piedra Berroqueña region was mentioned in the second half of the 19th and first quarter of the 20th centuries by authors such as Francisco Giner de los Ríos (1839–1915), Miguel de Unamuno (1864–1936), Pío Baroja (1872–1956), Antonio Machado (1872–1956) and José Ortega y Gasset (1883–1955).

Piedra Berroqueña has also been the subject of painters, e.g., 'Valle en la Sierra de Guadarrama' by Carlos de Haes (1826–1898), 'Arroyo de la Sierra de Guadarrama' by Martín Rico (1833–1908), 'Guadarrama, Picos de la Najarra' by Jaime Morera (1858–1927), and 'Tormenta sobre Peñalara' by Joaquín Sorolla (1863–1923). Guided tours have now been instituted (Perez-Monserrat et al. 2013) to enhance public awareness and to showcase significant buildings bearing Piedra Berroqueña.

PETROPHYSICAL PROPERTIES, CHEMICAL ANALYSIS AND DURABILITY OF PIEDRA BERROQUEÑA

The tectonic, petrological, petrophysical and chemical characteristics of Piedra Berroqueña are similar across the region

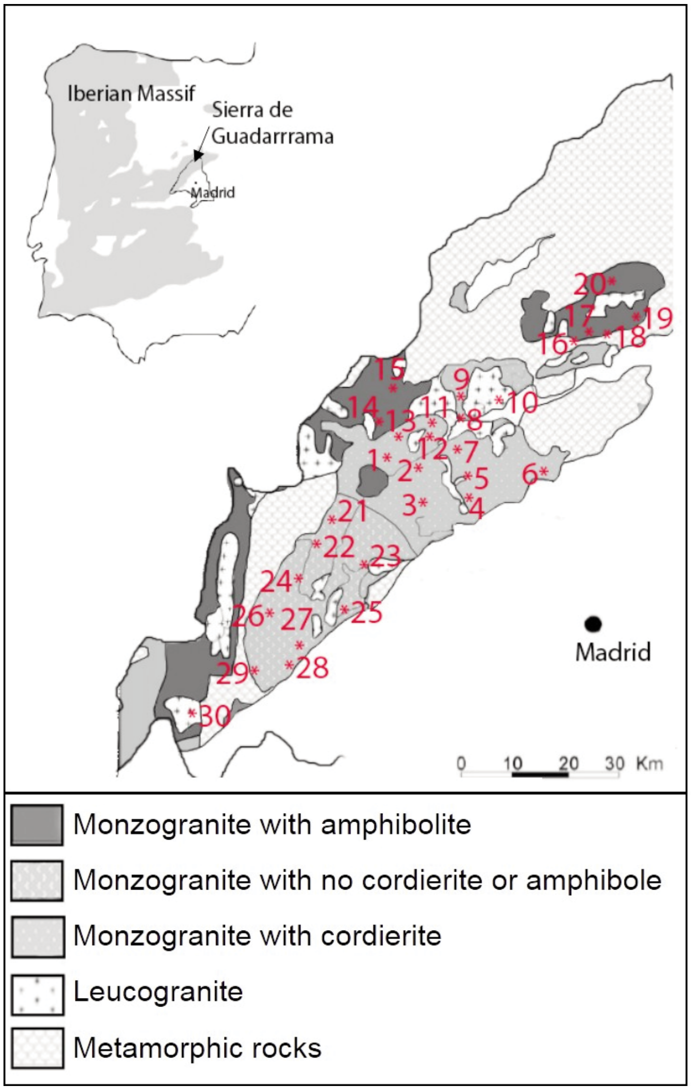

Figure 3. Towns with the highest density of historic quarries in the Piedra Berroqueña región. *Monzogranites with cordierite:* (1) Alpedrete, (2) Moralzarzal, (3) Galapagar, (4) Torrelodones, (5) Hoyo de Manzanares, (6) Colmenar Viejo, (7) Cerceda, (8) El Boalo, (9) Mataelpino, (11) Becerril de la Sierra, (12) El Berrocal, (13) Collado Mediano. *Monzogranites with amphibole:* (14) Los Molinos, (15) Cercedilla, (16) Bustarviejo, (17) Valdemanco, (18) La Cabrera, (19) El Berrueco, (20) Lozoyuela-Navas-Sieteiglesias. *Monzogranites with no cordierite or amphibole:* (21) San Lorenzo del Escorial, (22) Zarzalejo, (23) Valdemorillo, (24) Robledo de Chavela, (25) Navalagamella (26) Fresnedilla de la Oliva, (27) Colmenar de Arroyo, (28) Chapinería, (29) Navas del Rey. *Leucogranite:* (10) Manzanares el Real, (30) Cadalso de los Vidrios.

(Tables 3, 4). These characteristics are largely determined by a linear crack density (Wang et al. 1989; Sousa et al. 2005; Ismael and Hassan 2008; Vázquez 2010) that ranges from a high of 1.8 microcracks per millimetre in Zarzalejo granite to a low of 0.9 microcracks per millimetre in Colmenar Viejo granite (Freire-Lista et al. 2015a). The increase in linear crack density after exposing the Alpedrete, Cadalso de los Vidrios, Colmenar Viejo and Zarzalejo stones to 280 freeze-thaw cycles was similar in all the granites studied (Table 5).

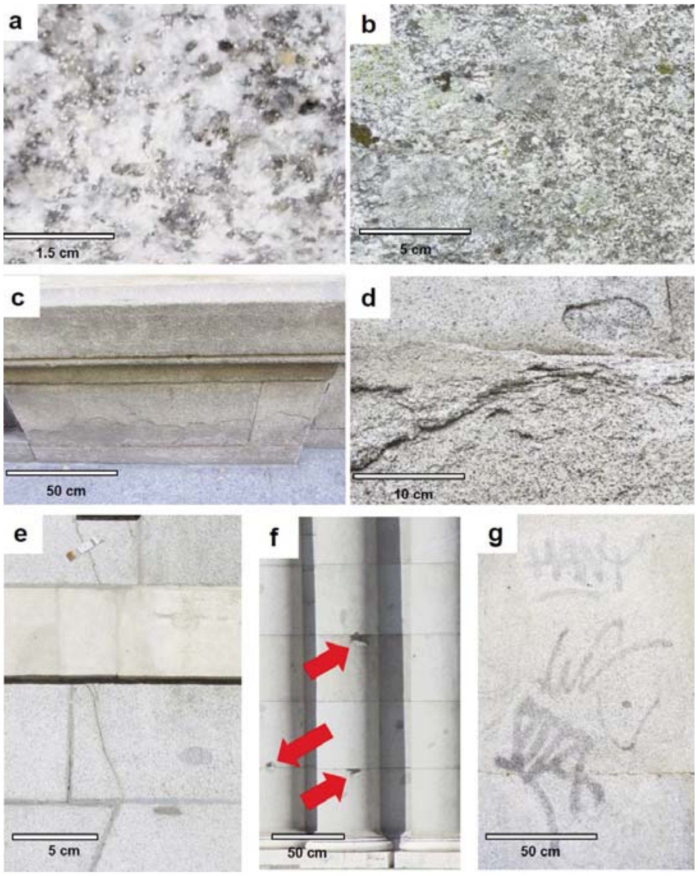

Figure 4. Decay in Piedra Berroqueña: a) salt efflorescence, indoor columns on Conde Duque Palace, Madrid; b) biodecay, Nuestra Señora de la Asunción church, Colmenar Viejo; c) scaling, Madrid; d) scaling and flaking, San Andrés Church, Madrid; e) cracking, Chamber of Deputies, Spanish Parliament, Madrid; f) bullet impact, Alcalá Gate, Madrid; g) graffiti, Madrid.

Piedra Berroqueña has resisted weathering for centuries. Its low anisotropy, capillary absorption, porosity, and high mechanical strength and durability protect it from damp and capillary rise. Ashlars hewn from this stone were traditionally used as pedestals for statues and on dados and building façades. Despite its resistance to alteration, it may be subject to decay in the form of salt efflorescence (Fig. 4a), biodecay (Fig. 4b), and surface scaling (Fig. 4c) or cracking (Fig. 4d), with a concomitant loss of volume. These forms of decay are primarily the result of climate, air pollution, and the presence of salts (Pérez-Monserrat et al. 2013), in conjunction with other factors. The occurrence of microgranular nodules in these granites may also expedite weathering resulting from the differential thermal behaviour associated with these inhomogeneities (Gómez-Heras et al. 2008). Stone with larger feldspar crystals, more biotite and no cordierite or amphibole is more vulnerable to decay than cordierite-bearing stone, which contains smaller crystals. Pre-quarrying decay, gloss (micro-roughness), finish, location on or within a building, and type of decay determine the type of maintenance or cleaning required; the methods used must not roughen the stone (Vazquez-Calvo et al. 2012). Old ashlars that have been quarried at the surface may contain altered feldspars and must be treated with particular care.

NEED FOR GHSP STATUS FOR THE PIEDRA BERROQUEÑA REGION

Towns in the province of Madrid are losing their traditional identity because of the increased use of stone from other regions as replacement or building stone. This change has had a heavy impact on the conservation of heritage buildings in historic urban cores. Action to reverse this trend is needed on

Table 3. Physical properties of five representative samples of Piedra Berroqueña.

Property	**AL**	**CA**	**CO**	**LA**	**ZA**
Impact strength (cm)	68±14 (2)68±14 (2)	-	-	44 (5)44 (5)	58.8 (1)58.8 (1)
Compressive strength (MPa)	136.9±41 (2)136.9±41 (2)	-	-	203 (5)203 (5)	160.0±49.0 (1)160.0±49.0 (1)
Bending strength (MPa)	8.88±3.69 (2)8.88±3.69 (2)	-	-	11.06 (5)11.06 (5)	8.21±2.25 (1)8.21±2.25 (1)
Bulk density (Kg/m^3)	2 636±18 (4)2 636±18 (4)	2 602±16 (4)2 602±16 (4)	2 629±13 (4)2 629±13 (4)	-	2 657±15 (4)2 657±15 (4)
Young's Modulus (MPa)	33 275 (4)33 275 (4)	35 377 (4)35 377 (4)	66 838 (4)66 838 (4)	-	26 882 (4)26 882 (4)
Water absorption (%)	0.29 to 0.31 (3)0.29 to 0.31 (3)	0.41 to 0.49 (3)0.41 to 0.49 (3)	0.28 to 0.41 (3)0.28 to 0.41 (3)	0.2 (5)0.2 (5)	0.54 to 58 (3)0.54 to 58 (3)
Water saturation (%)	0.5±0.2 (1)0.5±0.2 (1)	-	-	-	1.24 (1)1.24 (1)
Capillary absorption coefficient ($g \cdot m^{-2} \cdot s^{-0.5}$)	1.523 to 3.983 (3)1.523 to 3.983 (3)	3.502 to 4.706 (3)3.502 to 4.706(3)	0.969 to 1.437 (3)0.969 to 1.437 (3)	-	4.238 to 4.796 (3)4.238 to 4.796 (3)
Porosity accessible to water (%)	0.8±0.1 (4)0.8±0.1 (4)	1.2±0.2 (4)1.2±0.2 (4)	0.7±0.1 (4)0.7±0.1 (4)	-	1.7±0.06 (4)1.7±0.06 (4)
Porosity measured by HG intrusion (%)	0.44 (4)0.44 (4)	0.95 (4)0.95 (4)	0.59 (4)0.59 (4)	-	1.4 (4)1.4 (4)
Frost resistance (%)	0.01 (2)0.01 (2)	-	-	0.07 (5)0.07 (5)	0.005 (1)0.005 (1)
Ultrasonic P-wave velocity (m/s)	4 625±163 (4)4 625±163 (4)	3 687±300 (4)3 687±300 (4)	5 051±349 (4)5 051±349 (4)	-	3 219±204 (4)3 219±204 (4)
Ultrasonic S-wave velocity (m/s)	3 812±92 (4)3 812±92 (4)	2 596±110 (4)2 596±110 (4)	3 494±94 (4)3 494±94 (4)	-	2 2116±89 (4)2 2116±89 (4)
Total anisotropy (%)	5.8 (3)5.8 (3)	15.3 (3)15.3 (3)	3.5 (3)3.5 (3)	-	12.7 (3)12.7 (3)
LCD (microcracks per mm)	1.1 (5)	1.8 (5)	0.9 (5)	-	1.2 (5)

AL: Alpedrete; CA: Cadalso de los Vidrios; CO: Colmenar Viejo; LA: La Cabrera; ZA: Zarzalejo.
Sources: (1) Bernabéu et al. 2004; (2) Menduiña and Fort 2005; (3) Fort et al. 2011;
(4) Freire-Lista et al. 2015a; (5) ROC Máquina 2009.

Table 4. Chemical analyses for Alpedrete (AL), Cadalso de los Vidrios (CA), Colmenar Viejo (CO), La Cabrera (LA) and Zarzalejo (ZA) granites.

	Chemical analysis				
Major elements	**AL wt%** (1)wt% (1)	**CA wt%** (2)wt% (2)	**CO wt%** (3)wt% (3)	**LA wt%** (4)wt% (4)	**ZA wt%** (5)wt% (5)
SiO_2	69.6	76.94	74.15	76.02	68.97
TiO_2	0.4	0.08	0.14		0.55
Al_2O_3	15.02	12.83	13.5	12.99	15.17
Fe_2O_3	2.97	1.07	0.23	0.29	3.26
FeO	1.54		1.15	0.72	1.11
MnO	0.05	0.04	0.05	0.03	0.06
MgO	0.96	0.16	0.56	0.22	1.19
CaO	2.45	0.78	0.93	0.9	2.47
Na_2O	3.32	3.4	3.32	3.3	3.21
K_2O	3.89	4.48	4.79	4.58	4.07
P_2O_5	0.16	0.04	0.06	0.03	0.13

Sources: (1) Villaseca et al. 1998; (2) Martín-Serrano 2007; (3) Rodriquez-Fernández 2000; (4) Bellido 1979; (5) López de Azcona et al. 2002.

the local, regional, national and even international scale. Moreover, society at large should be made aware of the importance of construction materials in the local heritage and economy. To that end, the Group for Petrology Applied to Heritage Conservation, in conjunction with local quarries, conducts activities such as guided tourist routes to enhance public awareness of Piedra Berroqueña (http://www.madrimasd.org/). Popular cultural outings such as the tour of the 'Valle de los caídos' have been conducted in recent years under the umbrella of Madrid's Science Week. Another initiative, jointly backed by one municipality and the Region of Madrid, has led to the creation of a regional archaeological and geological interpretation centre (http://www.igeo.ucm-csic.es/en/igeo/noticias/588-risco). Similarly, a newly published history book for the general public contains a chapter dealing with quarries and their contribution to the construction of one of Madrid's historic quarters. Designation of the Piedra Berroqueña region as a Global Heritage Stone Province (GHSP) would help rally all stakeholders around a set of shared interests: to train local quarrymen, to further the use of traditional building stone, and to secure greater national and international visibility for Piedra Berroqueña.

Table 5. Linear crack density test results for Alpedrete, Cadalso de los Vidrios, Colmenar Viejo and Zarzalejo granites in freeze-thaw cycles 0 and 280.

Granite	Cycle 0	Cycle 280	Δ 0 to 280 (%)
Alpedrete	1.1	3.2	193
Cadalso de los Vidrios	1.8	3.7	107
Colmenar Viejo	0.9	2.3	150
Zarzalejo	1.2	3.9	228

CONCLUSIONS

Piedra Berroqueña, which forms part of the Region of Madrid's tangible and intangible heritage, is exported worldwide. Heritage buildings bearing this stone form part of Spain's history and culture, and as such must be conserved for future generations. Their restoration with material from the Piedra Berroqueña region will ensure more effective conservation of the tangible and intangible heritage.

The future supply of manually hewn Piedra Berroqueña in the homonymous region is not in doubt. Traditionally, Alpedrete and Zarzalejo monzogranites were the stones most widely used in heritage buildings in the city of Madrid, whereas Colmenar Viejo monzogranite was used primarily for paving and cobblestones. Although the properties of these granites are similar, the crystal size is larger in Zarzalejo granite. Although Cadalso de los Vidrios and La Cabrera granites were used as building materials in the villages near their respective quarries from before Roman times until the mid-late 20th century, neither was deployed in Spain's capital city. Today, however, output at Cadalso de los Vidrios and La Cabrera is greater than at Alpedrete, Zarzalejo or Colmenar Viejo. The existence of a considerable number of historical as well as mechanized quarries ensures that the demand for restoration and construction works can be met.

The physical properties of Piedra Berroqueña, which afford it great durability, vary little from one variety to another and depend on the degree of alteration. The petrographic, petrophysical, mechanical and aesthetic properties of Piedra Berroqueña, along with its durability and the large number of quarries still in operation, make the region eligible for designation as a Global Heritage Stone Province (Pereira and Cooper 2015). Such a designation will enhance public awareness of the past and present of this cultural asset and the features that are vital to its conservation, while ensuring fuller use of Piedra Berroqueña as a construction material.

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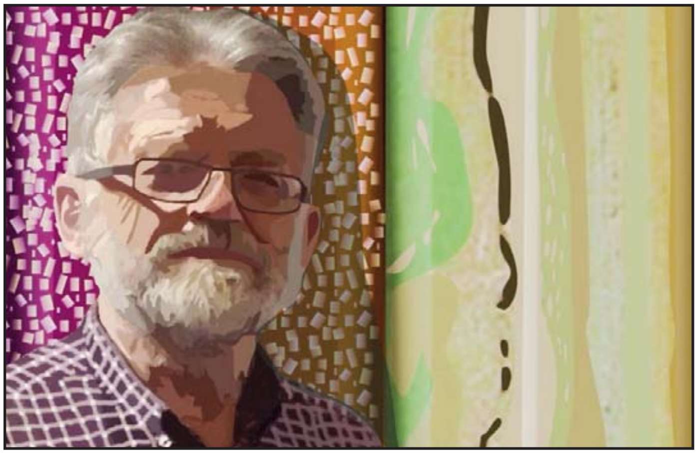
SERIES



Heritage Stone 5. Silicified Granites (Bleeding Stone and Ochre Granite) as Global Heritage Stone Resources from Ávila, Central Spain*

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SUMMARY

Silicified granites were used to build the Romanesque monuments in the city of Ávila, Spain. The building stones comprise two types of granite based on their technical properties and colour: *Bleeding Stone* (Piedra Sangrante) and *Ochre Granite* (Caleño). They were used as a facing stone in the city´s Romanesque monuments of the 12th century (e.g. the cathedral and church of San Pedro), and the famous city walls that constitute the best example of military Romanesque Spanish architecture. During the Gothic and Renaissance periods of the 13th and 15th centuries, silicified granites were used mainly to build ribbed vaults, the voissoirs of the arches, and elements of the windows in the monuments of Ávila.

Silicified granites are found in the intermediate and upper part of a complex palaeoweathering zone or mantle developed on the Iberian Hercynian Basement which underlies much of the western Iberian Peninsula. The silicification occurred during tropical conditions in the Mesozoic. The weathered mantle was truncated by Alpine tectonic movements during the Tertiary, and its remnants were unconformably overlain by more recent sediments in the western and southern part of the Duero Basin and along the northern edge of the Amblés Valley graben. The historical, and now protected, quarry is located in a village called La Colilla, about 5 km from the city of Ávila. Currently, this stone is exploited only for restoration work performed in the city, for example the Walls of Ávila, and the church of San Pedro. The resource is limited and being depleted, so the stone will be scarce in the near future. Consequently, these silicified granites should be recognized as a Global Heritage Stone Resource.

The specific technical properties of these stones and their historic use, decay patterns, durability, and suitability for conservation treatments combine to support its designation as a Global Heritage Stone Resource.

RÉSUMÉ

Des granites silicifiés ont été utilisés pour construire les monuments romans dans la ville d'Ávila, en Espagne. Les pierres de construction comprennent deux types de granite selon leurs propriétés techniques et leur couleur : *Bleeding Stone* (Piedra sangrante) et *Ochre Granite* (Caleño). Ils ont été utilisés comme pierre de revêtement de monuments romans du 12ème siècle de la ville (par exemple la cathédrale et de l'église de San Pedro), et pour les célèbres remparts de la ville qui constituent le meilleur exemple de l'architecture espagnole romane militaire. Durant les périodes gothique et Renaissance des 13e et 15e siècles, les granites silicifiés ont été utilisés principalement

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pour construire des croisés d'ogives, des voussoirs d'arcs et des éléments de fenêtres des monuments d'Ávila.

Les granites silicifiés se trouvent dans la partie intermédiaire et supérieure d'une zone complexe de paléo-altération ou de manteau développée sur le socle ibérique hercynien qui supporte une grande partie de la péninsule ibérique occidentale. La silicification s'est produite dans des conditions tropicales au Mésozoïque. Le matériau mantélique altéré a été tronqué par des mouvements tectoniques alpins au cours du Tertiaire, et ses restes ont été recouverts en discordance par des sédiments plus récents dans la partie ouest et sud du bassin de Duero, et le long de la bordure nord de la vallée en graben d'Amblés. L'ancienne carrière, maintenant protégée, est située dans un village appelé La Colilla, à environ 5 km de la ville d'Ávila. Actuellement, cette pierre est exploitée uniquement pour les travaux de restauration effectués dans la ville, par exemple les murs d'Ávila, et l'église de San Pedro. La ressource est limitée et en voie d'épuisement, de sorte que la pierre sera rare dans un proche avenir. Par conséquent, ces granites silicifiés devraient être reconnus en tant que pierre du Patrimoine mondial des ressources en pierre.

Les propriétés techniques spécifiques de ces pierres et leur valeur historique, leurs modes de désintégration, leur durabilité et leur pertinence pour la conservation patrimoniale justifient leur désignation en tant que roche du Patrimoine mondial des ressources en pierre.

Traduit par le Traducteur

INTRODUCTION

The Global Heritage Stone Resource program aims to emphasize the need for international agreements for the care of those natural stones and quarries that are recognized for their importance in architecture and historical heritage (Pereira et al. 2015). Ávila, located northwest of Madrid, is famous for its medieval city walls and historical stone buildings, and was designated a UNESCO World Heritage Site in 1985. Two types of silicified granite, *Bleeding Stone* and *Ochre Granite*, so-called because of their technical properties and colour, crop out in nearby hills where the quarries were developed. These granites were widely used to build the main Romanesque monuments during the 12th century, including the apse of Ávila Cathedral (Fig. 1a), and churches such as San Pedro (Fig. 1b) that were built into the interior and exterior of the Walls of Ávila. During the Gothic period in the 15th century they were used mainly to build ribbed vaults such as in El Real Monasterio de Santo Tomás (Fig. 1c) and Ávila Cathedral (Fig. 1d, e), and in the voissoirs (wedge-shaped stones that allow curvature in arches or vaults) of the arches and elements of the windows. The historical quarry, which is now a protected site, is located in a village called La Colilla, about 5 km from the city (Fig. 2a, b). Currently, this stone is exploited only for restoration work performed in the city, such as for the medieval walls (Fig. 1f–h) and for a few new buildings (Fig. 1i). Resources are limited and the stone will be depleted in the near future.

The aim of this work is to focus on the *silicified granite's* resources, technical properties, historic use, decay patterns (pathologies), durability, and suitability for conservation treatments. In view of these aspects, we urge its designation as a Global Heritage Stone Resource.

GEOLOGICAL SETTING OF BLEEDING STONE AND OCHRE GRANITE

Most of the western half of the Iberian Peninsula is underlain by the Iberian Hercynian Massif (IHM) in which granite outcrops are widespread (Fig. 2a). During the Mesozoic, the IHM underwent long periods of tropical weathering, giving rise to the development of an alteration mantle tens of metres in depth, accompanied by ca. 15–30% volume reduction. The following sequence of processes is evident at the top of these palaeoweathering zones (García-Talegón et al. 1994a; Molina-Ballesteros et al. 1997): 1) generation of clays by alteration of the parent minerals; 2) redistribution and concentration of oxyhydroxides released during alteration; 3) precipitation of silica as opal-CT (a variety of opal consisting of packed microscopic spheres made up of tiny microcrystalline blades of cristobalite and tridymite, and water content as high as 10 wt%) cementing the products of the weathered rock; and 4) generation of alunite–jarosite group minerals. These processes took place before the Alpine tectonism that affected the IHM during the Tertiary.

Three levels can be defined in the weathering profiles (Fig. 2a–f): 1) lower level (biotite granodiorite/porphyry and aplite dykes); 2) intermediate level (Ochre Granite; Caleño); and 3) upper level (Bleeding Stone; Sangrante). The lower level, Ávila Grey Granite, has been much used as a source of dimension stone from Roman ages until the present time, except for the Romanesque religious architecture. The porphyry and aplite dykes were mainly used to build the Walls of Ávila. The weathering that gave rise to Ochre Granite, (known as Caleño or Alterites), at the intermediate level produced petrophysical and mineralogical changes (in 2:1 and 1:1 layered phyllosilicates) and a decrease in the content of the most mobile cations. The Ochre Granite is several metres thick, and the parent minerals have released various elements (Ca, Na, Fe, K, etc.) during alteration to clay minerals (Fig. 2f). The upper level has received several names besides Bleeding Stone: Red Granite, White Granite, and Silcrete or Alterites. It was formed through a silicification process by precipitation of opal-CT, kaolinization, and remobilization of iron oxyhydroxides. The upper level is characterized by its hardness (a result of opal cementation), drastic changes in hues because of the mobilization of iron oxyhydroxides, and indistinct bioturbation at the top caused by pedological activity on the palaeosurface prior to cementation by opal-CT. It appears today as an undulating surface that is locally buried by younger sediments.

The generation of opal-CT, dissolution of clays (e.g. kaolinite) and precipitation of minerals of the alunite–jarosite group, all point to acidic conditions at the end of this evolution. Evidence for this is present both in the weathered Hercynian basement and the siderolithic sedimentary cover, whose outcrops are adjacent to many of the studied profiles and quarries (e.g. profiles I, II; Fig. 2e, f).

CONSERVATION OF BLEEDING STONE AND OCHRE GRANITE

Intrinsic Properties

Mineralogical and Chemical Characterization

Three varieties of silicified granite were analyzed: Ochre Granite and two types of Bleeding Stone, namely Red Granite and

Figure 1. Bleeding Stone and Ochre Granite used in monuments in Ávila. a) Apse of the Ávila Cathedral (Romanesque, 12th century); the fortress-like cathedral was built into the Walls of Ávila; b) apse of the church of San Pedro (Romanesque, 12th century) in the exterior of the medieval walls; c) El Real Monasterio de Santo Tomás (Gothic, 15th century); d) column of the cloister; e) roof of the central nave, Ávila Cathedral; f) panorama of Ávila; g) Roman elements reused for the Walls, including cists that once held cremated remains; h) restorations of the Walls of Ávila; i) new buildings.

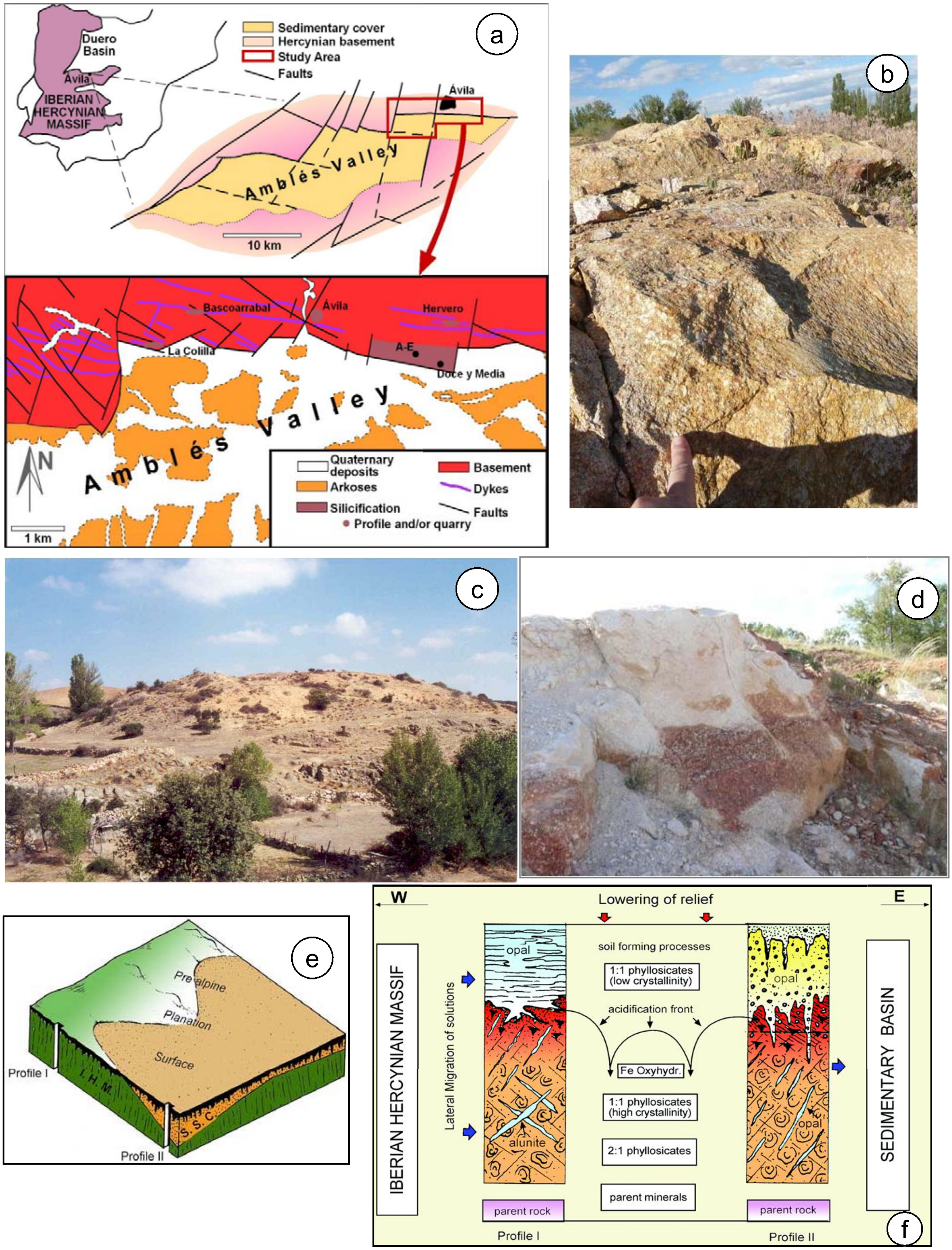

Figure 2. Geology and historical quarries of Bleeding Stone and Ochre Granite. a) Location and geological framework of the study area; b) middle level (Ochre Granite) of the main historical quarry, La Colilla; c) outcrop in the vicinity of La Colilla quarry; d) upper level (Bleeding Stone) of La Colilla quarry; e) 3D diagram showing the pre-Alpine planation surface on the Iberian Hercynian Massif (IHM), the overlying Tertiary siderolithic sedimentary cover (SSC), and location of profiles I and II; f) schematic representation of the main weathering processes that affected the Iberian Hercynian Massif.

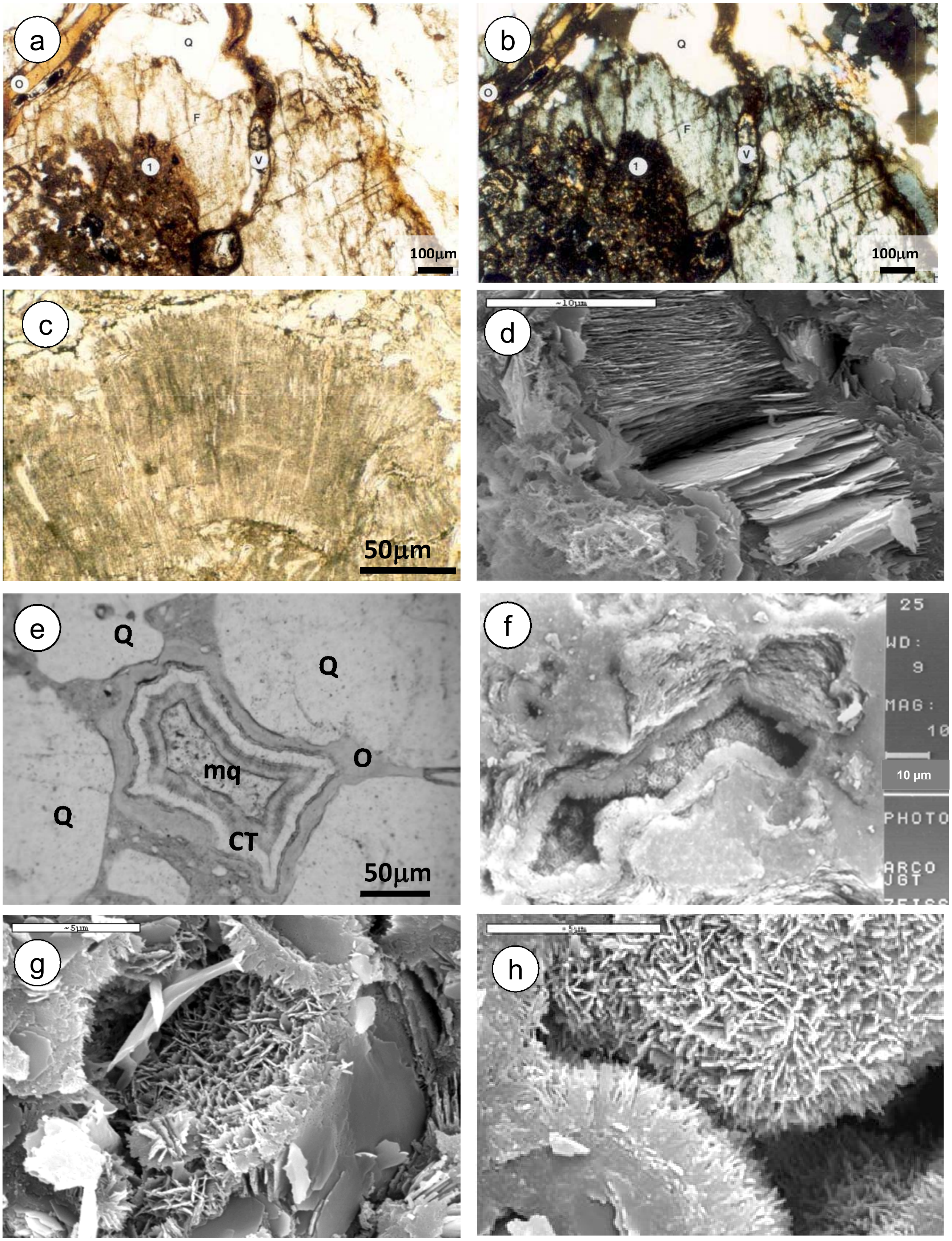

Figure 3. Mineralogical characterization of the Bleeding Stone and Ochre Granite. a) and b) Thin section photomicrographs (plane- and cross-polarized light, respectively) of a level in the middle of the palaeoweathered zone, Ochre Granite. Feldspar (F) is weathered and cracks are filled mainly by opal-CT (O) and clays (1); V= residual void space; Q = quartz; c) thin section photomicrograph of kaolinite; d) SEM photomicrograph of kaolinite; e) thin section photomicrograph of opal-CT (O) lining a cavity; CT= opal-CT lepispheres; mq = chalcedony microcrystalline quartz; Q = quartz; f) SEM photomicrograph of opal-CT lepispheres (spherical rosettes of authigenic silica formed during low-temperature diagenesis) lining a cavity; g) SEM photomicrograph of opal-CT and 1:1 phyllosilicates; h) SEM photomicrograph of opal-CT lepispheres.

White Granite. Transformation to Ochre Granite involved alteration of the most labile (unstable) mineral species of the basement granite, the disappearance of chlorite, biotite and feldspar (Fig. 3a, b), and the appearance of 2/1 layer silicates (interstratified illite/smectite) and iron oxyhydroxides (goethite). However, the texture of the fresh granite is conserved. The formation of Red Granite and White Granite involved kaolinization (Fig. 3c, d), the formation of opal-CT (Fig. 3e–h), and later the redistribution, under hydromorphic conditions, of iron oxides that were then concentrated in Red Granite. (Hydromorphy is a permanent or temporary state of soil water saturatuion associated with reducing conditions). The percentage of SiO_2 is high, followed by Al_2O_3 and Fe_2O_3; the content of Al_2O_3 does not vary appreciably among the varieties of quarry granites. Similarly, there are few significant changes in Fe_2O_3 except for its scarcity in White Granite, which in the quarry has undergone hydromorphic leaching of iron that was then concentrated in the Red Granite (García-Talegón et al. 1994b). Hence, in both the Ochre and Red granites, the greater quantity of iron is due to the presence of iron oxyhydroxides. Alkalis and alkaline earth elements decrease in abundance dramatically as the Grey Granite passes into the weathered versions in the quarry (Table 1). The trace element composition of Ochre Granite and Bleeding Stone (Table 1) differs among the silicified granite varieties, and is also specific to the location of the historical quarries (García-Talegón et al. 1999a).

Table 1. Major element (wt%) and trace element (ppm) composition of the Grey Granite (G), Ochre Granite (O), Red Granite (R) and White Granite (W).

	G	O	R	W
SiO_2	66.6	69.6	73.2	73.6
Al_2O_3	16.1	14.1	13.8	15.2
Fe_2O_3	3.7	5.7	3.1	0.9
CaO	3.4	0.1	0.1	0.1
MgO	1.2	0.1	0.1	0.1
Na_2O	3.1	0.1	0.2	0.1
K_2O	3.7	0.1	0.2	0.2
SO_3	0.1	0.1	0.1	0.1
TiO_2	0.5	0.4	0.4	0.5
MnO	0.1	0.0	0.0	0.1
P_2O_5	0.3	0.2	0.2	0.1
S	120	333	297	411
Zr	130	78	122	110
Cr	180	363	252	336
Sr	10	195	199	280
Zn	60	48	35	25
Ba	320	91	79	67
Nb	60	14	34	20

Table 2. Physical properties (measured in water) of Ochre Granite (O), Red Granite (R) and White Granite (W).

	O	R	W
Kυ	0.476	0.256	0.356
CI	12.78	7.92	8.25
n_t	28.40	20.13	21.04
DR	2.47	2.48	2.37
DA	1.77	1.98	1.87
n_o	74.31	66.70	60.48
CA	1.40	0.80	0.70

Kυ = permeability x 10^{-7} (kg/m^2s), CI = coefficient of imbibition by total immersion (%), n_t = total porosity (%), DR = real density (g/cm^3), DA = apparent density (g/cm^3), n_o = percentage of water absorbed present in free form (%), CA = capillary absorption coefficient ($g/cm^3/sec \times 10^3$).

Table 3. Physical properties (measured in mercury) of Ochre Granite O), Red Granite (R) and White Granite (W).

	O	R	W
n_t	19.55	17.45	13.18
n_o	11.49	9.94	9.18
n_a	8.06	7.51	4.00
S_e	18.09	8.04	7.51

n_t = total porosity (%), n_o = free porosity (%), n_a = trapped porosity (%), S_e = specific surface area 1st injection (m^2/g).

Physical and Mechanical Properties

The physical characteristics (measured in water) of three varieties of Bleeding Stone and Ochre Granite (Table 2) show that the permeability to steam, total porosity in water, and the coefficient of imbibitions (the absorption of water by porous rock, while totally immersed, under the force of capillary attraction and without pressure) are lower in the Bleeding Stone and higher in the Ochre Granite; furthermore, the Red Granite has lower values than the White Granite because of the infilling of pores in the former by iron oxyhydroxides. The porosity of all three varieties of granite is quite high, leading to sharp differences in real and apparent densities; this is most pronounced in the Ochre Granite. With respect to free porosity and capillary absorption coefficient, the Ochre Granite has the highest values, whereas Red Granite has intermediate values and White Granite the lowest values.

Mercury porosimetry measurements for Bleeding Stone and Ochre Granite (Table 3) show that the Ochre Granite has the highest porosity, followed by the red and white varieties; White Granite is least porous because it has undergone silicification that filled some of the pores. In the Ochre Granite, 58.77% of the porosity is free and the rest trapped, whereas in the red variety the percentages of free and trapped porosity are similar, and in the White Granite the free porosity is clearly predominant because the pores have not been filled by iron oxyhydroxides. Specific surface area (a property of solids defined by the total surface area of material per unit of mass, derived by Hg injection) is also much higher in the Ochre Granite.

Pore network characteristics of the three varieties of granite were also determined with the mercury porosimeter (Fig. 4a–c). The Ochre Granite has pores with a radius between 3 x 10^{-3} µm and 9 x 10^{-3} µm, and essentially no pores with a radius greater than 5 x 10^{-1} µm. In the White Granite, free porosity predominates, and there are two ranges of pore radius: 3–8 x 10^{-3} µm and 8–40 µm. In the Red Granite, there are three pore size ranges: 5–40 µm, 1–20 x 10^{-2} µm and 3–5 x 10^{-3} µm. There is a striking similarity between the white and red varieties of the rock in terms of pore radii greater than 5 µm; however, the

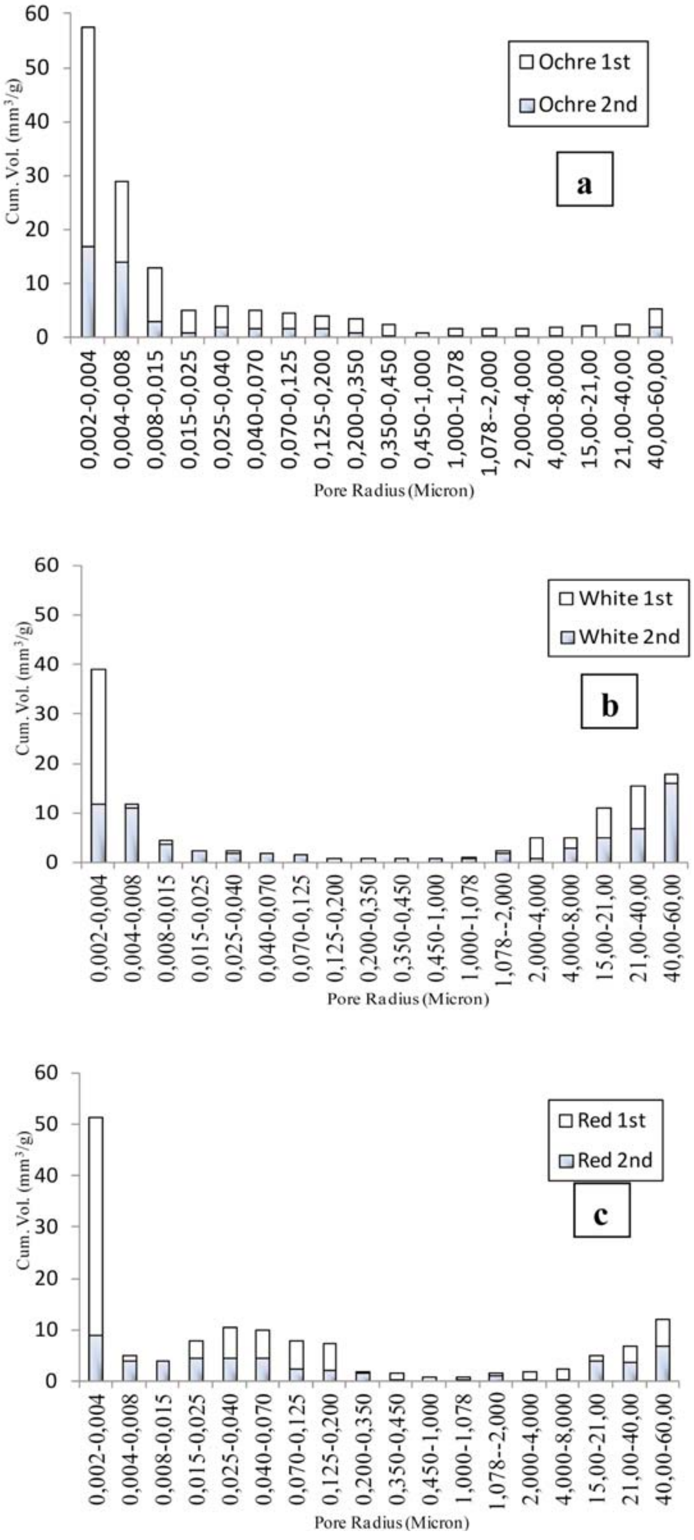

Figure 4. Pore characteristics determined by mercury porosimetry: a) Ochre Granite, first and second injection; b) White Granite, first and second injection; c) Red Granite, first and second injection.

Red Granite possesses greater trapped porosity in the medium (1–20 x 10^{-2} μm) and small (<5 x 10^{-3} μm) pore size ranges.

The Ochre Granite has a high but intricate porosity of a type referred to as 'bottle-neck' (referring to pore throat diameter, and the ease or difficulty of water flow), and has a high trapped porosity (Table 3). The Red and White granites possess a low percentage of macroporosity and, especially in the White Granite, the porosity shows more connection to the surface at atmospheric pressure (i.e. there is greater open porosity). Mechanical properties (Table 4) indicate that resistance to compression and to indirect traction is higher in the two Bleeding Stone granites than in the Ochre Granite. The variation in the velocity of ultrasound propagation is high in all three, but highest in the White Granite. It will be noted that the values for resistance to compression are always less than the theoretical values obtained directly from the velocity of ultrasound propagation.

Table 4. Mechanical properties of three varieties of granite employed in the Ávila Cathedral. O = Ochre Granite; R = Red Granite; W = White Granite.

	O	R	W
V_X	2585	3156	2985
V_Y	2633	3180	3412
V_Z	2497	3344	3350
T	281	485	428
f_{ti}	59	48	36
$T_{teórica}$	461	688	689

V_X, V_Y and V_Z = Velocity of ultrasound propagation (m/s); T = Resistance to compression (kg/cm^2); f_{ti} = Resistance to indirect traction (kg/cm^2); $T_{teórica}$ = Theoretical resistance to compression deduced from the velocity of ultrasound propagation (kg/cm^2).

Decay Patterns of Bleeding Stone and Ochre Granite

Building stones suffer decay processes, depending on intrinsic factors such as the composition of the material itself, and extrinsic factors like environmental conditions (climate and pollution), where the monument is located, and even the 'microclimate' produced by the specific architectural elements where it is employed (Rives and García-Talegón 2006; García-Talegón et al. 2015). The pathologies observed most often in the monuments of Ávila are plaques, scales and granular disintegration (Fig. 5a–f). Efflorescence of soluble salts is present locally, in places affected by damp, both from creeping and from filtrations from roofs and terraces (Fig. 5a). The most labile mineralogical component in the Bleeding Stone (Red and White granites) and Ochre Granite is opal-CT, followed by phyllosilicates (smectite and kaolinite) and iron oxyhydroxides, which show strong surface reactivity and susceptibility to change due to the conditions of the medium (pH, redox potential, etc.) and the pore network of the silicified granites (García-Talegón et al. 1999b). The decay of the outer and upper parts of monuments is the result of physical weathering caused by thermal processes (thermoclasty) and freezing and thawing (gelifraction). These processes lead to fissuring and granular disintegration, giving rise to the erosion of exposed areas (Fig. 5a–f).

Alteration by Freezing/Thawing and Thermal Shock

The city of Ávila is located on the Castilian plateau at an elevation of 1100−1200 m, with a semi-arid continental climate and low atmospheric pollution. The minimum and maximum annual temperatures are –20ºC and 39ºC, respectively; on average, there are 60 days of subzero temperatures and annual pre-

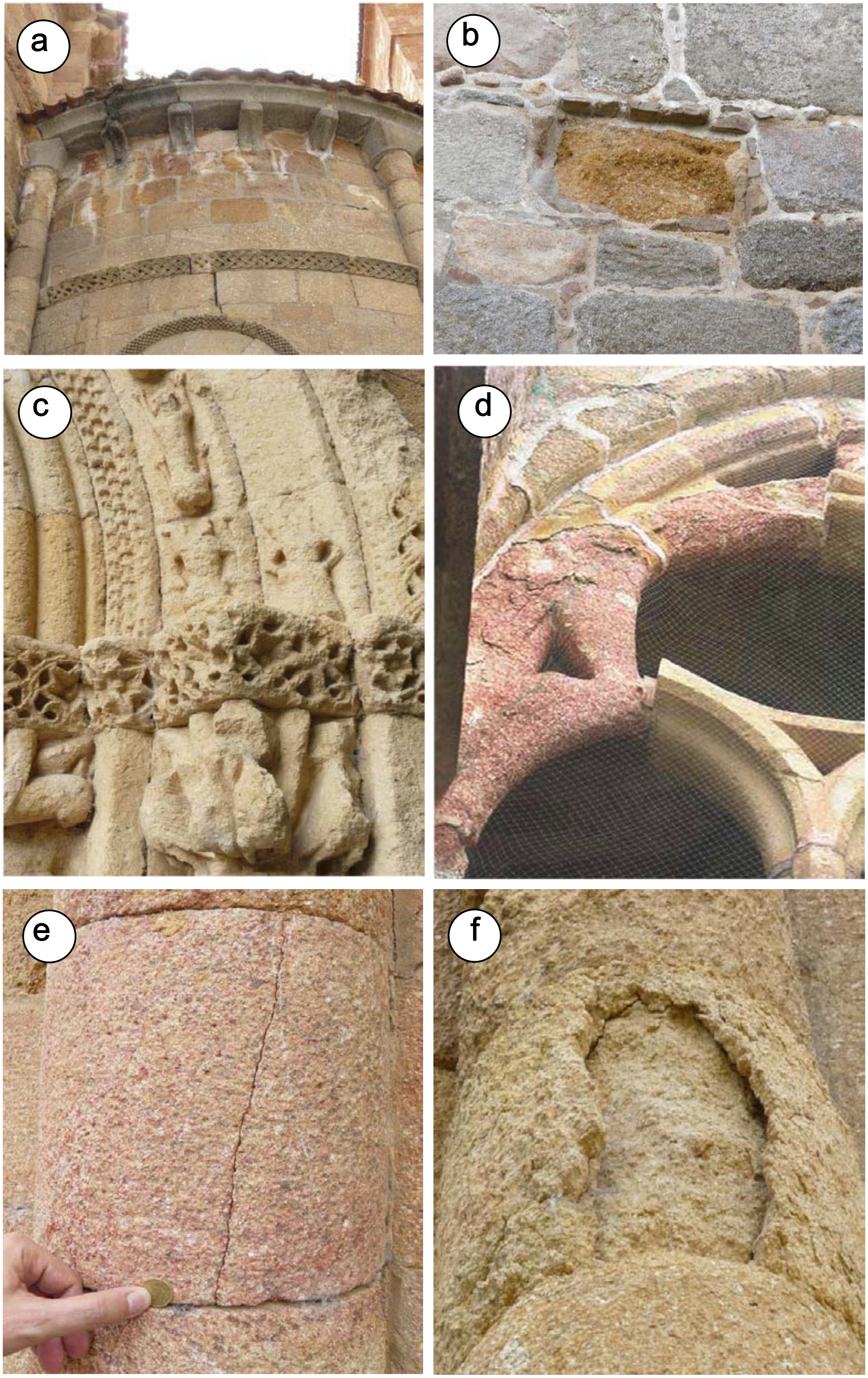

Figure 5. Pathologies of Bleeding Stone and Ochre Granite. a) Salt efflorescence in the upper part of the apse of the church of San Pedro (12th century); b) material loss of Ochre Granite in the Walls of Ávila; c) material loss of the main door of the church of San Mateo (12th century); d) scaling of Bleeding Stone in the cloister of Ávila Cathedral; e) crack in Red Granite; f) scaling of Ochre Granite.

cipitation of ~400 mm (Trujillano et al. 1995). Given this climate, the silicified granites are vulnerable to damage caused by frost weathering (gelifraction). Resistance to this kind of damage depends upon the porosity, pore size and pore connectivity to the surface.

Extreme changes in temperature cause differential expansion between mineral grains in building stones. This expansion, which may also occur when water freezes (about a 9% volume increase), induces tensile stresses that generate micro- and macroscopic discontinuities, allowing the circulation of fluids (water, dissolved salts, etc.). The intrinsic properties of the silicified granites (porosity, pore size distribution and mineral content) have a great influence on deterioration. It is well known that pores in the diameter range of microporosity (<7.5 μm by Hg injection) play an important role in degradation processes such as gelifraction and haloclasty (physical weathering caused by growth of salt crystals) (Camuffe 1996; Putnis and Mauthe 2001; Ruedrich and Siegesmund 2007; García-Talegón et al. 2015).

To quantify the resistance of the various stones to changes in temperature, 6 cm cubes were aged through 25 cycles of freezing/thawing and thermal shock (–20 to 100ºC) in a simulation chamber (Iñigo et al. 2013). Colour characterization before and after this artificial ageing (Table 5) was determined with a MINOLTA colourimeter (Chroma Metra) (Iñigo et al. 2014). The L* value refers to lightness (or darkness), while a* and b* are the chromaticity coordinates. The a* coordinate values range between positive, identified with red, and negative, identified with green. The negative values of the b* coordinate are associated with blue and the positive values with yellow. Changes in each of the chromatic coordinates for each of the tests are recorded as the difference in coordinate magnitude between the aged sample and the original sample (Table 5). Ochre Granite becomes less red (< a*) and yellow (< b*); Red Granite is clarified (> L*) and becomes more red and yellow (> b*); and White Granite darkens (< L*).

Table 5. Colour changes in silicified granite of Ávila when subjected to artificial aging caused by freeze/thaw cycles. O = Ochre Granite, R = Red Granite and W = White Granite.

	O	R	W
L*	67.30	63.88	73.14
a*	5.53	8.22	4.53
b*	22.16	19.85	16.68
$L_{F/T}$*	67.37	66.61	71.63
$a_{F/T}$*	4.92	7.26	4.41
$b_{F/T}$*	18.61	26.11	16.65

L*, a* and b* = Chromatic coordinates of silicified granite at quarry; $L_{F/T}$*, $a_{F/T}$* and $b_{F/T}$* = Chromatic coordinates of silicified granite aged by repeated freeze/thaw cycles.

Effectiveness and Sustainability of Conservation Treatments

The various granites were subjected to application of conservation treatments, which are meant to improve the durability and appearance of the stone. The conservation treatments used in this study were H224, RC70 and RC80 from Rhône-Poulenc, and supplied by Siliconas Hispania. H224 waterproofer is a colourless alkylpolysiloxane oligomer; RC70 consolidant is a colourless organic silicate having a viscosity of 0.86 mPa/s, a density of 0.890 g/cm^3, and a silicone content of 70%. RC80 consolidant and waterproofer is a colourless, catalyzed organic silicate with a methyl resin. It has a viscosity of 1.13 mPa/s, a density of 0.905 g/cm^3, and a silicone content of 68%. The solvent in all treatments is a white spirit. Two successive coats of the H224 waterproofer were brushed on to the surface of the stone, the second 24 hours after the first (Esbert et al. 1991). The application of the RC70 and RC80 products was carried out, with slight modification from the recommendations (García-Talegón et al. 1998; Iñigo et al. 2006), by immersing the sample in the consolidant fluid (instead of capillary absorption) and using different concentrations (instead of a single one) in order to facilitate penetration of the product inside the stone sample. Treatment was carried out by immersing the samples in white spirit for 30 minutes, followed by immersion in white spirit solutions of the conservation products at three levels of concentration: (i) 8 hrs in a 5% solution; (ii) 24 hrs in a 40% solution; and (iii) 40 hrs in a 75% solution. Table 6 shows that all treatments had a significant effect on the physical properties of the Bleeding Stone and Ochre Granite, producing a decrease in values of imbibition capacity, open porosity and capillary absorption coefficient, the main criteria used for evaluating treatment effectiveness and therefore the quality of the materials before and after treatment. Furthermore, the application of RC80, a combined consolidant and water repellency treatment, is more effective than when only a consolidant or waterproofing product (i.e. RC70 and H224, respectively) is used, at least in terms of the physical properties studied.

CONCLUSIONS

Bleeding Stone and Ochre Granite (silicified granites) have been used to build the Romanesque monuments in the 12th century city of Ávila (a 1985 UNESCO World Heritage Site). Silicified granites were used as facing stones in the city´s 12th century cathedral, other churches, and the city walls. During the Gothic and Renaissance periods, silicified granites were used mainly as an ornamental natural stone in the monuments of Ávila. Silicified granites are found in the intermediate and upper part of a complex palaeoweathering mantle developed on the Iberian Hercynian Basement. Three levels are defined; from bottom to top: 1) lower level (Grey Granite, including biotite granodiorite/porphyry and aplite dykes); 2) intermediate level (Ochre Granite, formed from the previous level through a tropical weathering process); and 3) upper level (Bleeding Stone, formed through an opal-CT silicification process, kaolinization, remobilization of iron oxyhydroxides, and later processes of hydromorphy).

A study of the physical properties (permeability to steam, total porosity in water, free porosity, the capillary absorption coefficient and the coefficient of imbibition by total immersion) of the respective stones demonstrates that the values of these parameters are lower in the Bleeding Stone (Red and White granites) and very high in the Ochre Granite. Mercury porosimetry data show that the Ochre Granite has a high porosity that is quite intricate ('bottle-neck') and includes significant trapped porosity, whereas the Red and White granites have lower values. The percentage of macroporosity in the

Table 6. Values of the physical properties of Ávila granites before and after application of conservation treatments H224, RC70 and RC80 (see text). O = Ochre Granite; R = Red Granite; W = White Granite.

Samples	TP	FP	AC	RD	AD	IC	CAC	WVP
O	27.20	20.70	75.55	2.46	1.84	13.70	0.001520	0.0000017
OH224	26.81	6.66	24.61	2.43	1.78	10.18	0.000705	0.0000011
ORC70	26.33	11.48	42.59	2.45	1.80	11.61	0.000730	0.0000013
ORC80	24.17	5.68	23.91	2.48	1.88	6.78	0.000396	0.0000011
R	24.03	10.95	45.59	2.32	1.99	7.64	0.000631	0.0000010
RH224	21.35	3.55	16.66	2.48	1.95	5.40	0.000443	0.0000006
RRC70	20.03	5.14	26.29	2.49	1.99	6.93	0.000510	0.0000009
RRC80	20.55	1.83	8.90	2.45	1.95	3.05	0.000395	0.0000007
W	22.51	13.36	59.60	2.42	1.88	10.12	0.001227	0.0000020
WH224	20.15	4.65	23.23	2.38	1.91	6.18	0.000582	0.0000012
WRC70	19.02	5.47	28.46	2.39	1.93	7.31	0.000620	0.0000014
WRC80	19.03	2.64	13.83	2.36	1.91	3.75	0.000438	0.0000011

TP = total porosity (%); FP = free porosity (%); AC = absorption coefficient (%); RD = real density (g/cm^3); AD = apparent density (g/cm^3), IC = imbibition coefficient (%); CAC = capillary absorption coefficient (g/cm^2/sec); WVP = water vapour permeability (Kg/m^2/sec).

Red and White granites is lower than in the Ochre Granite. Decay processes (salt crystallization, thermoclasty and gelifraction) occur in both the Ochre Granite and the Bleeding Stone, but are more pronounced in the former because of its high clay mineral content. Conservation treatments using H224, RC70 and RC80 produce a decrease in measured values for imbibition capacity, open porosity and the capillary absorption coefficient, vital parameters for evaluating treatment effectiveness and therefore the quality of the materials before and after treatment. The application of RC80 is more effective than when RC70 or H224 is used separately.

A historical and protected quarry is located in the village of La Colilla (Ávila, Spain). Currently, only silicified granite (Bleeding Stone and Ochre Granite) is used for restoration work in the city. Quarry reserves of the 'silicified granite' in the quarry are limited and being rapidly depleted. Taking such points into account, it is suggested that the Bleeding Stone and Ochre Granite of Ávila be recognized as a Global Heritage Stone Resource.

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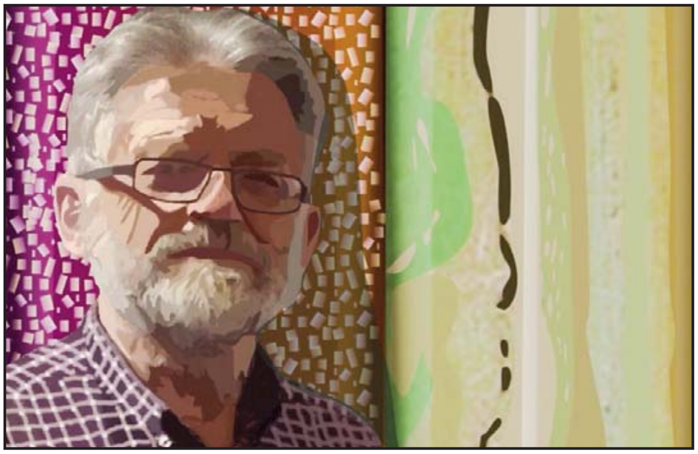

Heritage Stone 6.
Gneiss for the Pharaoh: Geology of the Third Millennium BCE Chephren's Quarries in Southern Egypt*

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SUMMARY

A remarkable campaign of decorative stone quarrying took place in the southwestern Egyptian desert almost 5000 years ago. The target for quarrying was Precambrian plagioclase–hornblende gneiss, from which several life-sized statues of King Chephren (or Khafra) and thousands of funerary vessels were produced. The former inspired George Murray in 1939 to name the ancient quarry site 'Chephren's Quarries.' Almost 700 individual extraction pits are found in the area, in which free-standing boulders formed by spheroidal weathering were worked by stone tools made from local rocks and fashioned into rough-outs for the production of vessels and statues. These were transported over large distances across Egypt to Nile Valley workshops for finishing. Although some of these workshop locations remain unknown, there is evidence to suggest that, during the Predynastic to Early Dynastic period, the permanent settlement at Hierakonpolis (Upper Egypt) could have been one destination, and during the Old Kingdom, another may have been located at pyramid construction sites such as the Giza Plateau (Lower Egypt). Chephren's Quarries remains one of the earliest examples of how the combined aesthetic appearance and supreme technical quality of a rock made humans go to extreme efforts to obtain and transport this raw material on an 'industrial' scale from a remote source. The quarries were abandoned about 4500 years ago, leaving a rare and well-preserved insight into ancient stone quarrying technologies.

RÉSUMÉ

Une remarquable campagne d'extraction de pierres décorative a été mené dans le sud-ouest du désert égyptien il y a près de 5000 ans. La roche cible était un gneiss à plagioclase–hornblende, de laquelle ont été tiré plusieurs statues grandeur nature du roi Khéphren (ou Khâef Rê) et des milliers de vases funéraires. C'est pourquoi George Murray, en 1939, a donné au site de l'ancienne carrière le nom de 'Chephren's Quarries.' On peut trouver près de 700 fosses d'extraction sur le site, renfermant des blocs de roches formés par altération sphéroïdale qui ont été dégrossis avec des outils de pierre pour la production de vases et de statues. Puis ils ont été transportés à travers l'Égypte jusqu'aux ateliers de finition de la vallée du Nil. Bien que la localisation de certains de ces ateliers demeure inconnue, certains indices permettent de penser que, de la période prédynastique jusqu'à la période dynastique précoce, l'établissement permanent à Hiérakonpolis (Haute Égypte) aurait pu être l'une de ces destinations; durant l'Ancien empire une autre destina-

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Figure 1. a) Statue of King Chephren (left) made from light-banded Chephren gneiss (Egyptian Museum, Cairo); b) at top, vessel made from speckled variety (Art and History Museum, Brussels), and at bottom, vessel made from a speckled, light variety (Egyptian Museum, Turin). Photo credits: Jon Bosdworth (left) and Tom Heldal (right).

tion aurait pu être située aux sites de construction de pyramides comme le Plateau de Giza (Basse Égypte). Les Chephren's Quarries l'une des plus anciennes exemples montrant comment la combinaison des qualités esthétiques et techniques remarquables de la roche ont incité les humains à consentir de si grands efforts pour extraire et transporter ce matériau brute à une échelle industrielle d'un site éloigné. Les carrières ont été abandonnées il y a environ 4500 ans, nous laissant une fenêtre rare et bien conservé sur des technologies anciennes d'extraction de pierre de taille.

Traduit par le Tracducteur

INTRODUCTION

Some of the greatest treasures of ancient Egypt were made from plagioclase−hornblende gneiss, including the life-sized sculptures of King Chephren (or Khafra; ca. 2500 BCE) and thousands of funerary vessels (Aston 1994; Fig. 1). The stone in question is a gneissic rock, essentially composed of varying proportions of bytownite plagioclase and hornblende, so that the appearance varies from almost white (anorthositic) to nearly black (gabbroic). The name '*Chephren gneiss,*' covering all the exploited varieties of the gneiss, was introduced by Klemm and Klemm (1993, 2008), partly to avoid confusion arising from the numerous names given to these rocks through time (Sultan et al. 1994; Harrell and Brown 1994). The only source of this stone had remained a mystery until a military patrol found it after getting lost in a sandstorm in 1932.

The quarries are located 12 km west of Gebel el-Asr in southern Egypt, 60 km northwest of Abu Simbel and just south of Wadi Toshka. Gebel el-Asr stands out as a natural landmark in the flat and hyper-arid desert, even though the sandstone hill is only 50 m higher than the surroundings. To the west of Gebel el-Asr, Precambrian basement rocks of the Gebel el-Asr Complex are exposed (Said 1962; Tawadros 2001; Fig. 2). Within this complex, almost all outcrops of hornblende−plagioclase gneiss were exploited by the ancient Egyptians (Fig. 3). The term 'Chephren's Quarries' is used for an extensive area with numerous extraction pits.

Vessel production had already started in the Late Neolithic (5100–4700 BC), given its presence in elite burials 50 km to the west at Nabta Playa (Schild and Wendorf 2001). However, it was during the Predynastic Period (ca. 4000−3100 BCE) that highly-crafted vessel production began in earnest, reaching a peak between the Early Dynastic Period (3100–2686 BCE) and the Fourth Dynasty (2613–2494 BCE) of the Old Kingdom (2686–2134 BCE). Production for objects such as life-sized statues of the pharaoh marked a significant transition towards much larger-scale appropriation and transport of the material

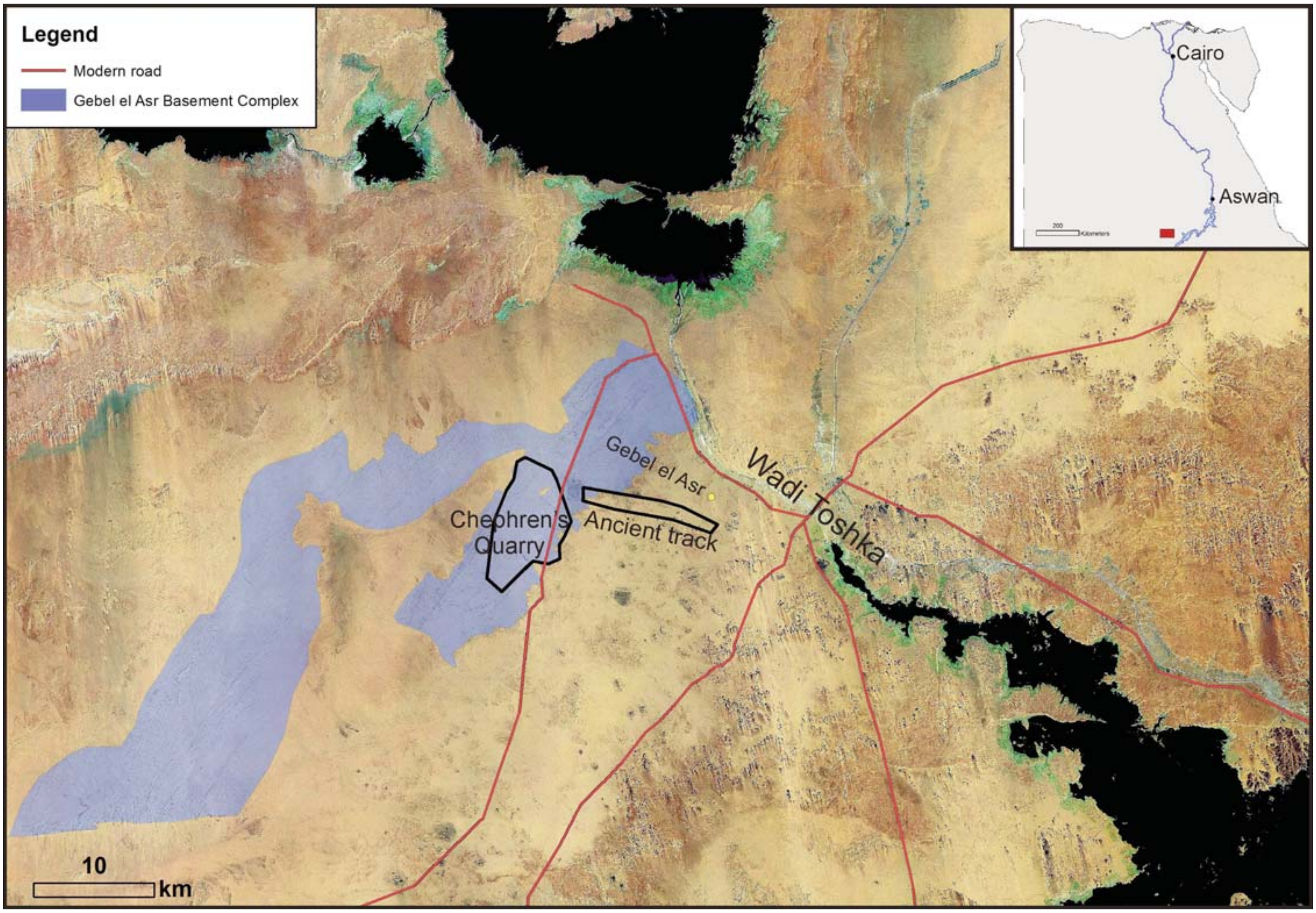

Figure 2. Map showing the location of the Gebel el-Asr basement inlier, Chephren's Quarry, and the ancient track to the Nile.

to sites over a thousand kilometres away (e.g. the Giza Plateau in Lower Egypt). We believe that appropriation of this particular rock is of global significance as it marks a turning-point in the large-scale production of a specific stone for purely ornamental purposes. Reginald Engelbach (1933) undertook the first survey at Chephren's Quarries, in the northern part of the area, discovering quarries, built structures and workshops at Quartz Ridge. Engelbach returned in 1938 with George Murray (Engelbach 1938; Murray 1939), discovering not only quarries, but also loading ramps, part of the transport route to the Nile, and several artefacts, such as inscribed stone stelae dating to the reigns of 4th, 5th and 12th Dynasty Egyptian rulers (including Khufu and Sahura). More recent geo-archaeological research was undertaken by Harrell and Brown (1994), and archaeological/geological surveys and excavations directed by Ian Shaw were carried out between 1997 and 2004 (Shaw and Bloxam 1999; Shaw 2000; Bloxam 2000, 2003, 2005, 2007; Shaw et al. 2001, 2010; Storemyr et al. 2002; Shaw and Heldal 2003; Heldal et al. 2009). This work revealed significant new information about the extent of quarrying, extraction technologies, and logistics, as well as settlement remains through which we could begin to understand the social organization and subsistence of a quarry work force operating 5000 years ago.

This paper presents a geological view of the quarries, including the ways in which geological processes formed this unique stone resource so that it became exploitable by the ancient Egyptians, and even how these processes resulted in a readily available 'tool kit' for working the stone. It builds on several field campaigns between 2003 and 2007. Some of the data presented have previously been published (Storemyr et al. 2002; Shaw and Heldal 2003; Heldal and Storemyr 2003; Bloxam 2007, 2011; Heldal et al. 2009; Shaw et al. 2010). However, this paper presents unpublished data on the geology of the area and seeks to engage a stronger geological perspective on the quarries than in previous publications. In this way, we hope to communicate the significance of this unique geological resource, exploited for only a brief period of time.

OUTLINE OF THE GEOLOGY

Between Lake Nasser and the Libyan–Sudanese border at Gebel Uweinat are three outcrop areas of Precambrian basement rocks (Richter and Schandelmeyer 1990): the Bir Safsat Complex to the west, and the Gebel el-Asr Complex and Gebel Umm Shâghir Complex to the east (Huth and Franz 1988). These form part of a large east-west trending system of basement uplifts, surrounded by Upper Cretaceous sedimentary rocks (Hendriks et al. 1984).

In the Gebel el-Asr area, the old metamorphic complex consists mainly of granitic rocks and patches of the Chephren

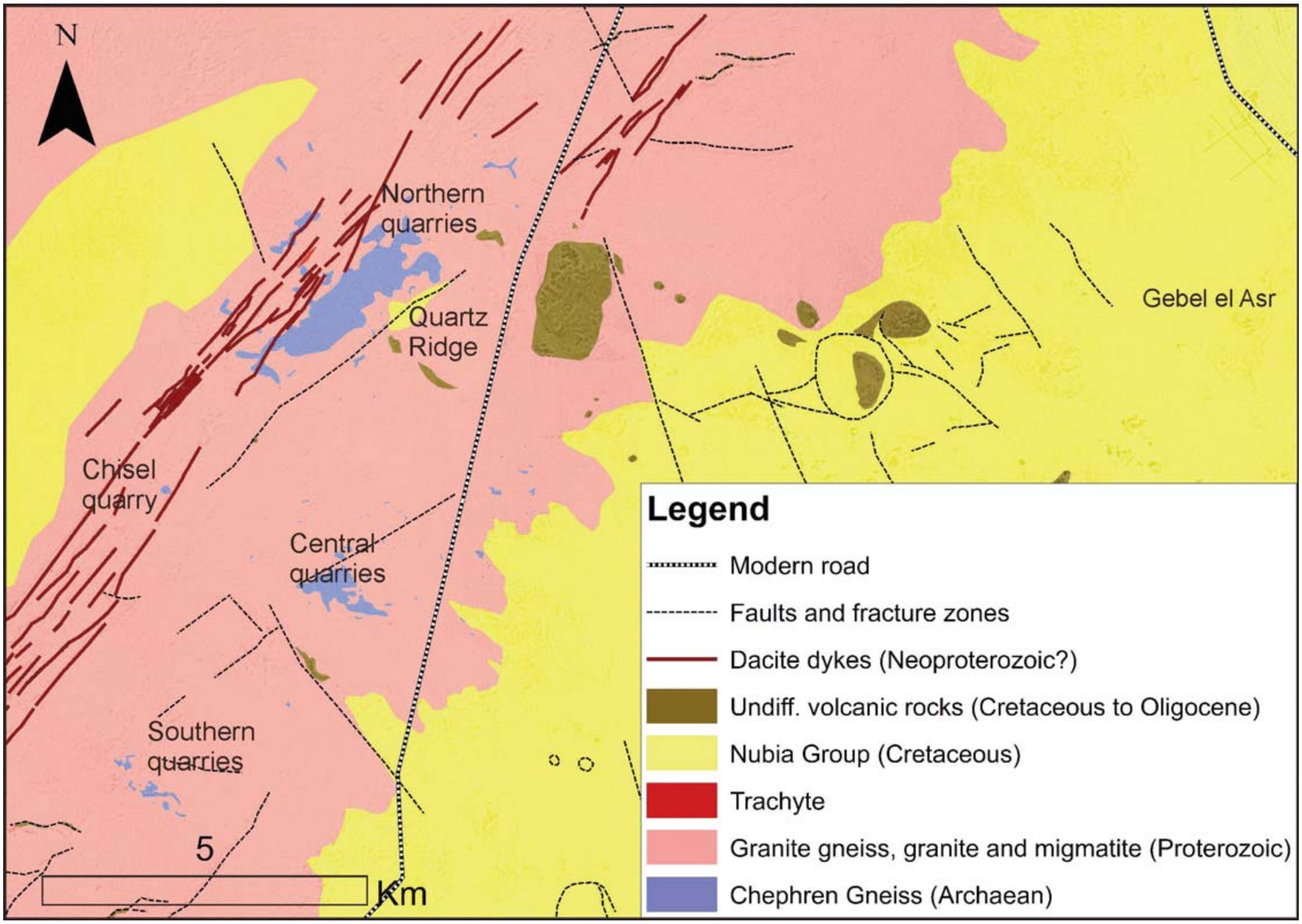

Figure 3. Geological map of the Chephren's Quarry area.

gneiss (Fig. 3). Hence, the outcrop pattern of the Chephren gneiss is highly irregular, displayed in numerous isolated outcrops of varying size. U–Pb zircon age-dating suggests that the gneiss is older than 1900–2100 Ma, and may well be Archean (Sultan et al. 1994). Schandelmeier et al. (1987) suggested that these rocks experienced granulite facies metamorphism around 2900 Ma, later retrogressive amphibolite facies metamorphism at 2650 Ma, and an anatectic event accompanied by granite formation around 1750 Ma. A new thermal event characterized by migmatization occurred by 680 Ma (Schandelmeier et al. 1987), corresponding to a metamorphic age of 690 Ma in the Chephren gneiss, and crystallization ages between 741 and 626 Ma in migmatites farther northeast (Sultan et al. 1994). Intrusive granitic bodies were linked to various stages of migmatitization.

The youngest rocks within the basement inliers are dykes of varying composition, but are predominantly dacitic. They probably relate to Late Proterozoic−Early Paleozoic extensional tectonics in the latter stages of subduction, and are commonly referred to as 'dyke swarms' and 'ring complexes' of felsic to mafic and locally alkaline composition (Richter and Schandelmeyer 1990; Pudlo and Franz 1994; Tawadros 2001). Mylonite zones are common in the basement inliers (Bernau et al. 1987), associated with Late Proterozoic retrogressive greenschist facies metamorphism that partly overprinted the previous high-grade fabrics of the basement rocks (Huth and Franz 1988). During the Late Cretaceous, the Precambrian rocks were exposed to weathering, and the Nubia Group (Whiteman 1970), consisting predominantly of fluvial and shallow marine sandstone and mudstone, was deposited on top of the then rather flat paleo-terrain. Shortly after (from around 80 Ma according to Bernau et al. (1987), and perhaps up to the Oligocene), the area experienced intense subvolcanic activity, corresponding to the Late Cretaceous volcanism described from other parts of Egypt, such as Wadi Natash (Mohamed 2001). Numerous volcanic plugs and dykes (basalt, trachyte and rhyolite) intruded the older rocks. The volcanic activity caused brecciation and deformation of the sandstone strata, as well as hydrothermal alteration (silicification). The hardening of the sandstone along faults, dykes, and above and around volcanic plugs made them resistant to weathering, resulting in a peculiar landscape of crater-like structures, fault ridges and sandstone hills. The origin of the crater-like structures has been subject to several studies in recent years, mainly because it was suggested that they were impact features (Paillou et al. 2004). More recently, however, doubts have been raised about such an origin; instead, it has been suggested that they represent an extensive, eroded hydrothermal vent complex (Orti et al. 2008).

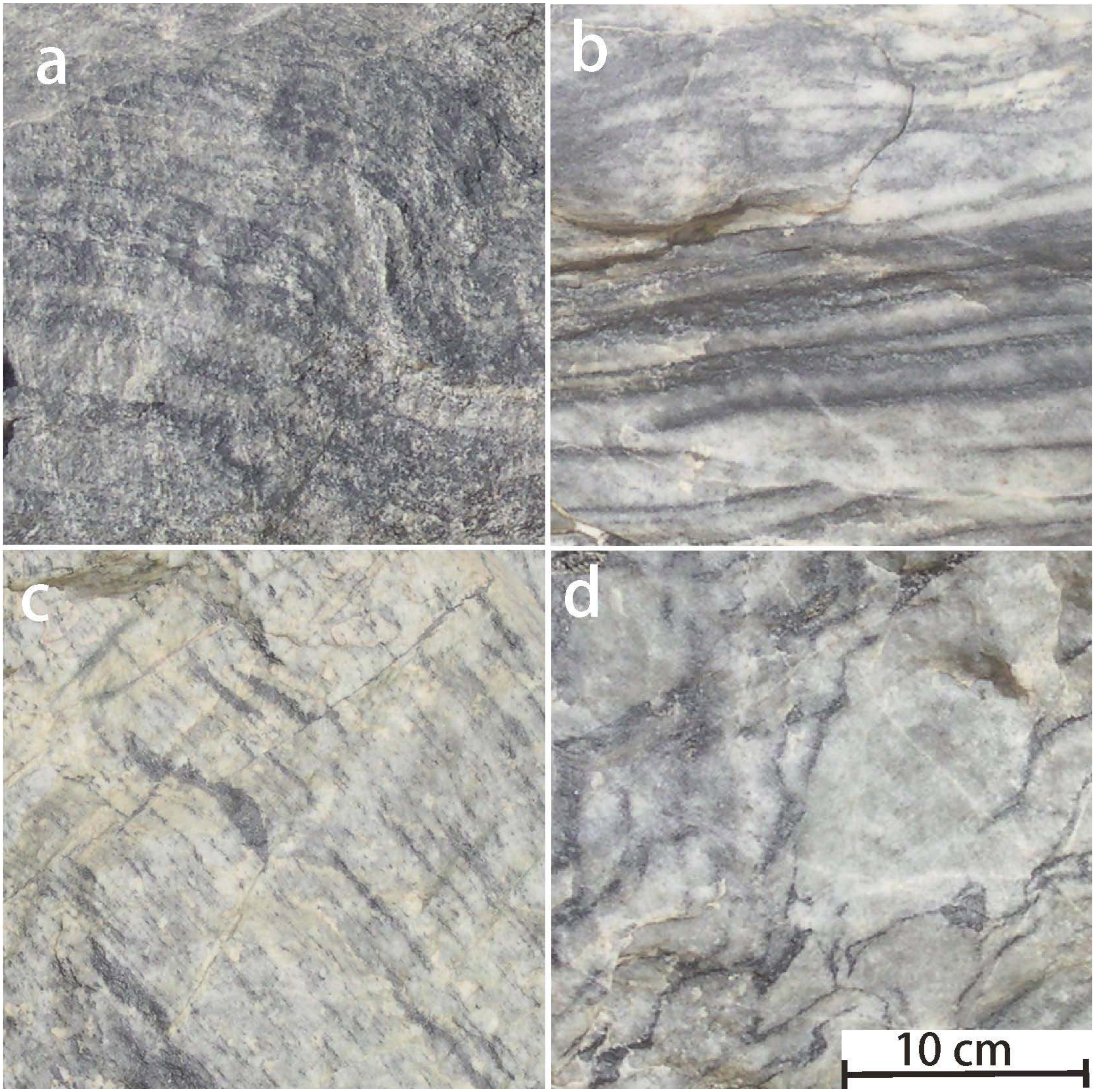

Figure 4. Varieties of the Chephren gneiss. a) Dark banded; b) light banded ('statue type'); c) light speckled ('vessel type'); d) light flame-structured.

PETROGRAPHY AND FABRIC OF THE ROCKS

High-An plagioclase (bytownite; An$^{78-83}$) and hornblende are the diagnostic and dominating minerals in the Chephren gneiss (Figs. 4 and 5a, b), and their proportions determine the subtypes described below. In addition, there are minor (less than one percent) quantities of quartz and zircon, and (in zones) minerals formed by retrograde metamorphism such as chlorite, sericite and uralite (Fig. 5c, d). The feldspar grain size varies between 0.1 and 1 mm. A characteristic aspect of the Chephren gneiss is its granoblastic texture (Fig. 5a, b), which is inherited from Archean to Palaeoproterozoic high-grade metamorphism ('granoblastite'). The granoblastic texture is one of the 'secrets' of the Chephren gneiss, since it makes the rock dense and strong, with extremely low porosity. This, in addition to the lack of quartz (resulting in less difference in hardness between minerals), may have been an important reason for the selection of the rock for funerary vessels and statues.

A field classification of four varieties of Chephren gneiss, based on its visual appearance, has been established, as follows (Heldal et al. 2009; Fig. 4a–d): light-speckled Chephren gneiss (main subtype for funerary vessels; Fig. 4c), light-banded Chephren gneiss ('statue' subtype, Fig. 4b), dark-banded Chep-

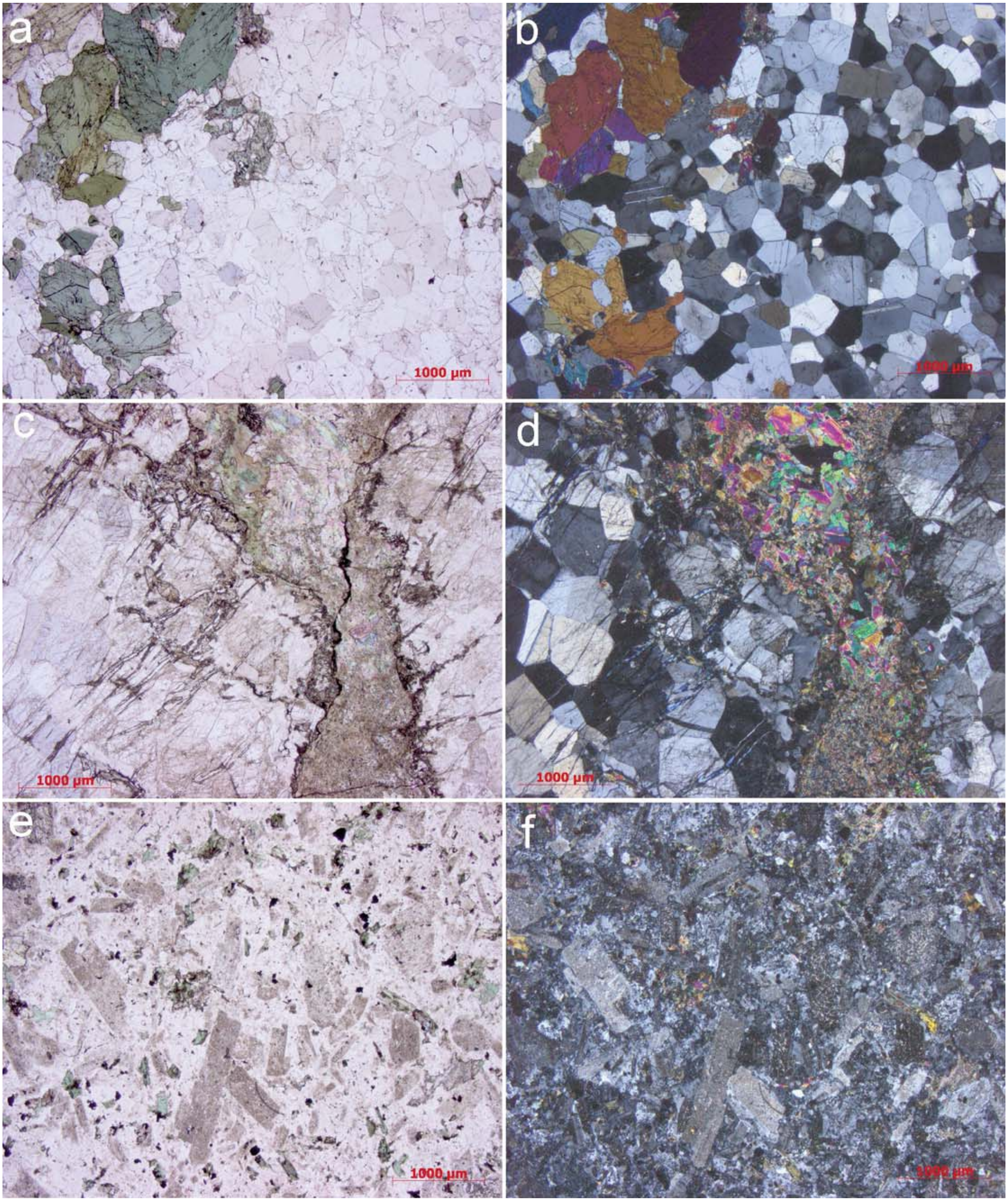

Figure 5. Photomicrographs of the Chephren gneiss and dacite. a) Typical speckled variety (plane-polarized light); green to bluish-green hornblende grains are seen on the left side, and the light coloured grains on the right side are predominantly bytownite and minor quartz; b) same image as a) with crossed Nicols; c) light-banded subtype displaying shear zones and microcracks (some filled with chlorite) related to Late Proterozoic mylonitization, which has a negative impact on the quality of the gneiss; d) same image as c) with crossed Nicols, also showing grain-reduction and uralitization of hornblende on the right side; e) porphyritic dacite showing plagioclase phenocrysts in a meshy groundmass of feldspar and quartz, locally forming a granophyric intergrowth, and alteration products; f) same image as e) with crossed Nicols.

hren gneiss (Fig. 4a), and light flame-structured Chephren gneiss (Fig. 4d); the latter two types were apparently not used.

Along shear zones, the granoblastic texture has been modified to display a more foliated to proto-mylonitic fabric; uralitization of hornblende, saussuritization of plagioclase, and chlorite-filling of extensional and shear fractures are commonly seen (Fig. 5c, d). Thus, the more foliated and sheared varieties have been subject to more alteration of the original granoblastic texture. The vessel-makers' preference for the less foliated varieties (light-speckled subtype) may perhaps be explained by the fact that it was simply better suited for the purpose than the other subtypes, although it is also possible that aesthetics and colour symbolism played a role (e.g. Grzymski 1999; Spence 1999). The composition of the feldspars and low density of microcracks may also be responsible for the translucency of the Chephren gneiss, and may have been another 'factor of preference' regarding its use for vessels. Moreover, the Chephren gneiss exhibits a blue glow in the bright desert sunlight and in the minds of the ancient Egyptians this may have imbued it with a magical quality.

The granitic rocks display a range of compositional and structural variations. The most common type is fine-grained, gneissic, microcline granite having a distinct biotite foliation, containing 'schlieren' and veins of more coarse-grained to pegmatitic granite, and aplitic veins. Also, non-foliated microcline granite and porphyritic granodiorite occur. The more fine-grained and aplitic varieties of granite were much used as tools (pounders) in the quarrying.

The dacite dykes are porphyritic and have a fine-grained groundmass (Fig. 5e, f). The plagioclase phenocrysts are partly zoned and rich in inclusions. The groundmass is composed of quartz, feldspars and pyroxene, but the low-grade metamorphic alteration has caused chloritization and uralitization of mafic minerals and sericitization of plagioclase, resulting in a meshy, dense texture (Fig. 5f). The dacite was also much used for tools (particularly pounders), possibly because metamorphic modification of the igneous texture made it a 'tougher' rock.

LANDSCAPE AND WEATHERING

The most striking aspects of the landscape in the Gebel el-Asr area are features related to the volcanic vents described above. In the area covered by the Nubia Group, hydrothermal hardening of the sedimentary rocks made them particularly resistant to weathering (compared to the poorly cemented surrounding rocks), leaving a pattern of linear, ring-shaped and circular hills and ridges. The volcanic rocks generally have low weathering resistance, and mostly occur in depressions in the terrain.

The outcrop area of the basement rocks does not display similar contrasts in weathering and is characterized by low relief. A characteristic feature of the weathering of hard, siliceous and feldspathic rocks in such an arid climate is the formation of rounded, *in situ* boulders. These boulders are produced by what has been called 'woolsack' or 'spheroidal' weathering (Fig. 6), the former term relating to the resulting boulder landscape, the latter to the process of weathering itself. Boulder-weathering can be described as a dynamic process involving chemical weathering of silicate rocks combined with mechanical fracturing caused by volume changes (thermal expansion and contraction) of the weathered rocks (Røyne et al. 2008). The chemical disintegration of the rock causes formation of a clay-rich mineral soil (saprolite). The chemical weathering initiates along pre-existing fractures, propagating outward from the fractures into the sound bedrock. Since the weathering occurs most rapidly at corners, the remaining parts of sound bedrock (corestones) take on a spherical shape. A zone of cm-scale rinds commonly occurs between the sound rock and the saprolite. Finally, the loose saprolite is eroded and the corestones exposed.

The landscape resulting from boulder-weathering typically consists of clusters of boulders formed where the density of natural fractures is low. Such is the case in the Gebel el-Asr area, where clusters of boulders from the basement rocks lay

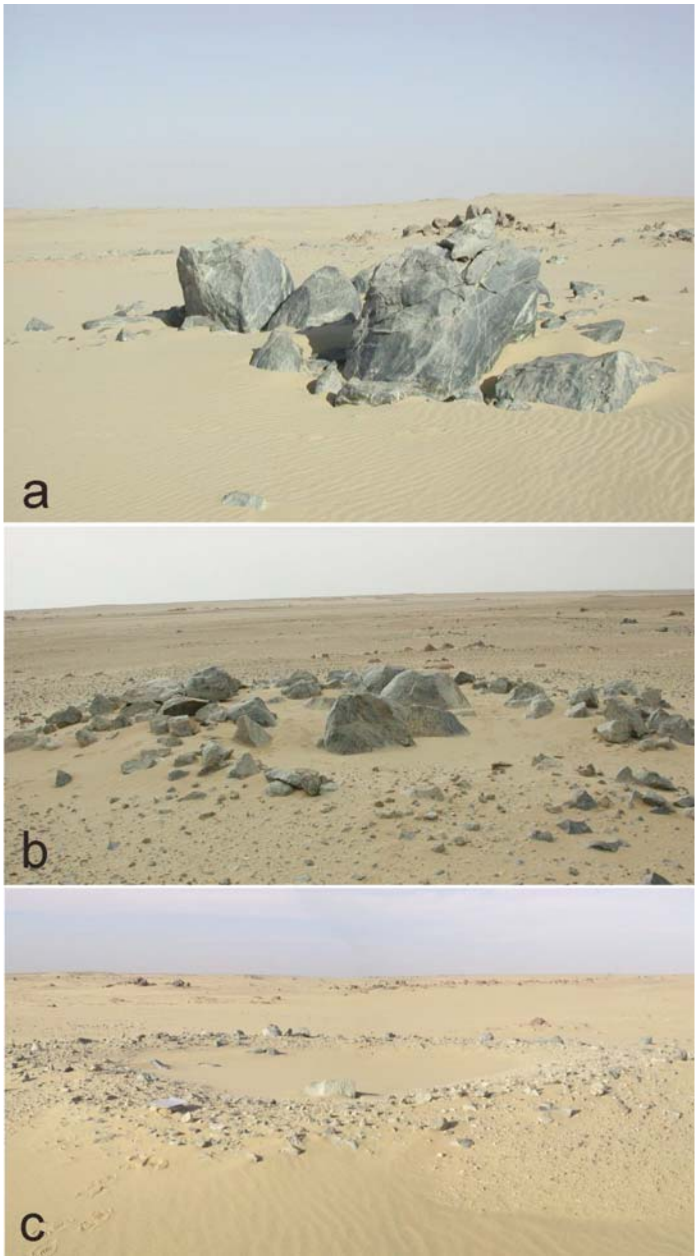

Figure 6. a) Cluster of gneiss boulders, shaped by weathering processes, not exploited; b) cluster of gneiss boulders that has been partly quarried; c) small quarry where the boulders once located in the center have been completely worked, forming a 'crater'-like structure enveloped by a circular spoil heap.

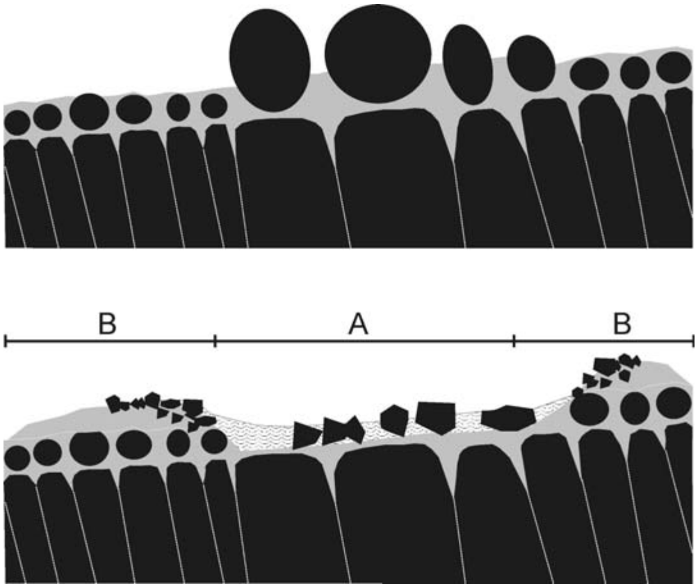

Figure 7. Before and after sketch of the quarrying of a cluster of gneiss boulders. A shows the extraction area, and B is where spoils from the working of blocks (work area) were deposited. Black = corestone or, if smaller and angular, work debris, and light grey = saprolite.

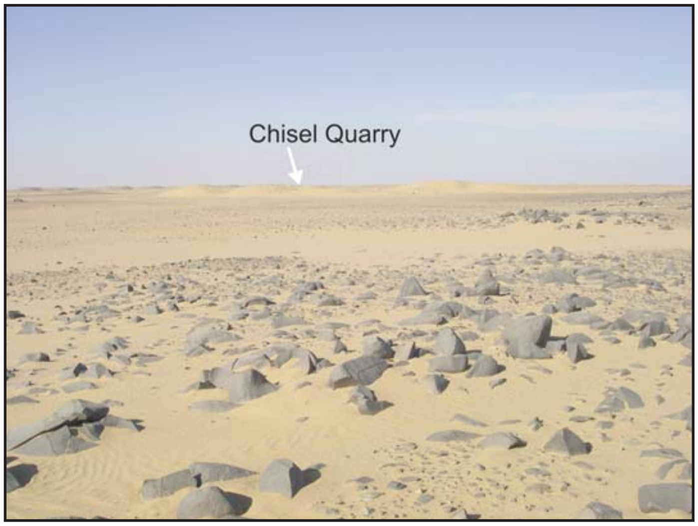

Figure 8. Outcrops of dacite dykes; the Chisel Quarry is seen in the background. Rounded cobbles suitable for tools can easily be found.

scattered on the surface within the outcrop area. It is interesting to note, though, that there is a clear difference in weathering between the granitic rocks and the gneiss: the former predominantly display thin-layered 'onion-skin' spalling, but the latter rarely does so, although the blocks are similarly rounded. The surface of the gneiss boulders is usually sound, eroded and polished by windblown sand. Because of the granoblastic texture described above, the gneiss is more resistant to weathering than the granitic rocks. In other words, the weathering process resulted in large and sound blocks, left ready for exploitation. Similarly, sound cobbles and boulders of dacite are found on the surface along the paths of the dykes. Such cobbles could be picked up and used directly as tools for working the gneiss boulders.

QUARRYING TECHNOLOGY

Before quarrying started, outcrops of the Chephren gneiss typically were seen as scattered, single boulders or clusters of boulders. Most of these had their upper part exposed, whereas the lower part was buried in the hard, clayey soil formed by *in situ* weathering of the rock (Fig. 7). During quarrying, the boulders were divided into smaller pieces of rock, which were worked into rough-outs for vessels or statues. The debris from the working was deposited concentrically around the boulders. Thus, the clusters of boulders were gradually transformed into concentric, 'crater-like' spoil heaps (Fig. 6). Large clusters of boulders resulted in large quarry pits with tall spoil heaps that had been worked for a long time; the smallest quarries reflect the work on a single boulder.

The Chephren gneiss was worked with stone tools, essentially pounders of varying size, as well as elongated hand-axes. All these tools came from local sources, the most apparent of which is the dacitic dyke rock (Fig. 8). The weathered cobbles and smaller boulders made perfect pounders and could be picked up from the ground and used without any reduction (Fig. 9). The dacite was also applied for making votive stelae, including the most famous one, the Khufu Stele (now displayed at the Cairo Museum, JE68572).

Cobbles of the Chephren gneiss itself were also used as pounders (Fig. 9), and, on the basis of a single find, it seems that the stone was also crafted into axe-heads. It is, however, difficult to quantify this use, since the tools (or fragments of tools) cannot be readily distinguished from spoil fragments. Pounders were also made from the granitic rocks. Since the granitic rocks are more porous than the gneiss and the dacite, they are not naturally found as rounded and sound cobbles, so these had to be manufactured (Fig. 10). Granite pieces were roughly hewn to irregular semi-spheres, which quickly became more spherical during use. Hand-axes were made from dacite and basalt, the latter from the volcanic plugs (Fig. 9).

Stone quarrying may generally be viewed as a four-step process (Heldal 2009): extraction from bedrock resulting in a rough block; reduction of the block to a core; semi-finishing of the core to a rough-out (or 'blank'); and finally, finishing to the final product. In Chephren's Quarries, quarrying started with the second step, since the boulders were already detached from the bedrock (see Figs. 6, 7 and 11). First, the soil and weathered rock fragments surrounding the boulders were removed. This is reflected in the lower part of the spoil heap stratigraphy, containing soil and deeply weathered rock fragments coated with white clay from the alteration of feldspar.

The second step was reduction of the blocks. In the case of vessel quarrying, the blocks were reduced to rough, squared fragments (cores) large enough to contain the shape of a vessel blank (Fig. 12). This part of the process seems to have been carried out mostly with large pounders up to 40 cm in diameter by first stripping off the weathered crust, then dividing the blocks into smaller pieces. Each piece was then worked with smaller tools, either small pounders or hand-axes, by splitting off small pieces (trimming) along the perimeter of the core until the vessel blank was finished.

The blocks destined for statues were worked differently. It is likely that fire-setting was involved in the first stages of 'peeling' layers from the block and, simultaneously, testing their soundness. There are two observed features that indicate the use of fire in quarrying: the sand and gravel beneath four

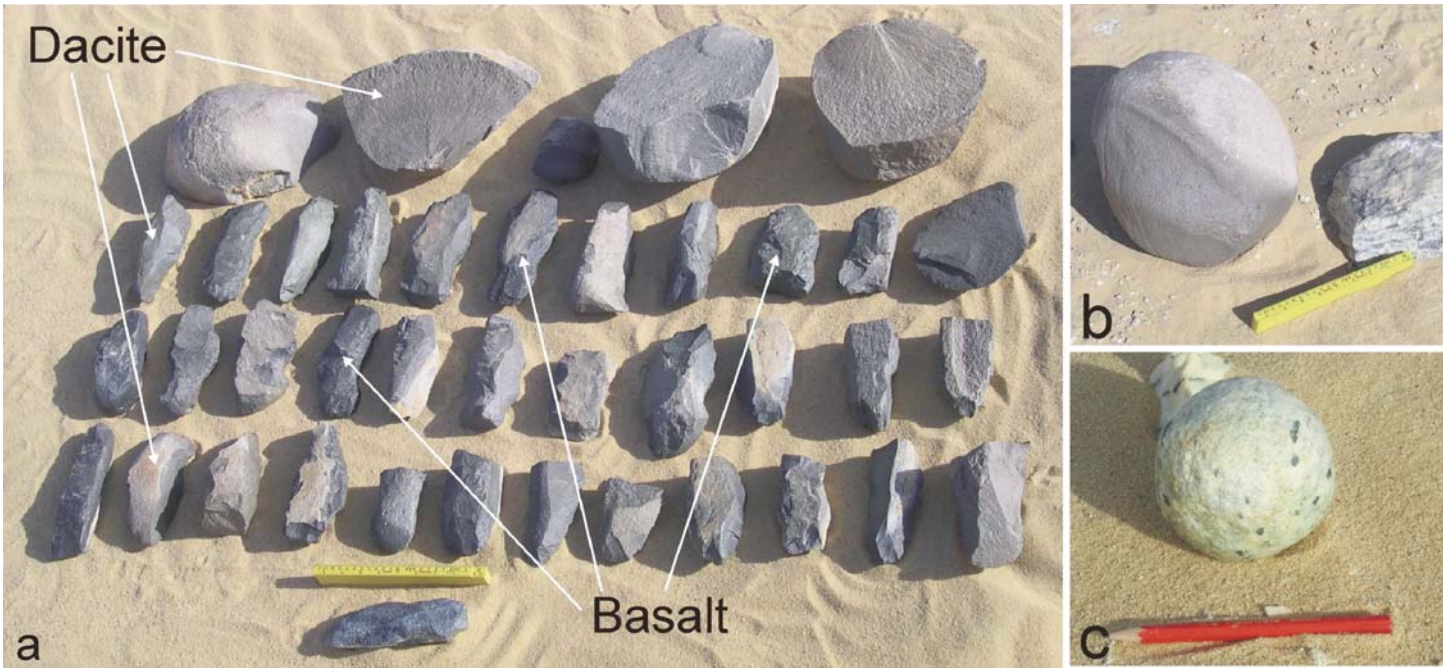

Figure 9. a) Tool collection, comprising discarded (split) pounders and hand axes; b) large dacite pounder for splitting blocks; c) well-used small pounder made from the Chephren gneiss itself. Scale: ruler = 21 cm; pencil ≈ 14 cm.

Figure 10. Manufactured granite pounders. These were made in the same way as vessel blanks, trimmed to a rough spherical shape.

of the blocks (including one of the dressed statue blocks) contain fragments of charcoal. Flaky 'potlid' rock fragments are seen beside one block (Fig. 13b), where they spalled off from the surface of the block following the application of heat. Such features are good indications of the use of fire (Heldal and Storemyr 2014). Fire-setting technology has also been recently observed in the large-scale quarrying of greywacke in the Wadi Hammamat, in Egypt's Eastern Desert (Bloxam 2015).

During production of vessels, the blocks were reduced by splitting. However, for making statue blocks, it would be necessary to remove thin flakes parallel to the surface rather than splitting off large pieces, both for reducing the block size and for changing its shape. Fire-induced spalling could have been the most efficient way of doing this, for this particular rock. Finally, dressing of the block surfaces (particularly the ones parallel to the gneissic banding) was carried out with pounders (Fig. 13d). Four discovered blocks of gneiss are leftovers from statue production. Two of these seem to be finished to the stage of transport readiness; they are wider at one end than the other, having a straight 'back' and a slightly curved 'front' (Fig. 14) − their shape would be perfect for some of the smaller statues of King Chephren. Other large blocks are found in many different shapes, and it is difficult to interpret their final purpose. Some may have been selected for statues and later discarded because of cracks or other flaws. Others may have been split up and worked to large vessels (e.g. a large vase in the Cairo Museum dating to the 5th dynasty reign of Unas).

LOGISTICS AND THE SOCIAL ASPECTS OF QUARRYING

As already mentioned, the only source of Chephren gneiss was 60 km away from the Nile Valley in the southwestern Egyptian desert, which, although seemingly remote to us today, was only 50 km east of the major Neolithic settlement of Nabta Playa and also close to later Old Kingdom habitations at Tushka. As we know from earlier evidence for the use of Chephren gneiss in Late Neolithic burial contexts at Nabta Playa, it is clear that the resource was well-known by local people for a long period. The exploitation and transport of this material on a much larger scale by the Early Dynastic and Old Kingdom was likely to be connected with intricate social networks involving local and regional specialists, such as stonemasons, who had knowledge of this resource and the ability to exploit it. Therefore, rather than scenarios that suggest large deployments of state-organized (unskilled?) labour to quarry the stone, we can argue for a much more nuanced picture in which the key contribution of central/state mechanisms involved the logistics of transporting the stone. Investments in logistical infrastructure such as constructing roads and ramps, as argued in the context of other quarry landscapes that witnessed similar transformations to larger-scale procurement, clearly present themselves in the

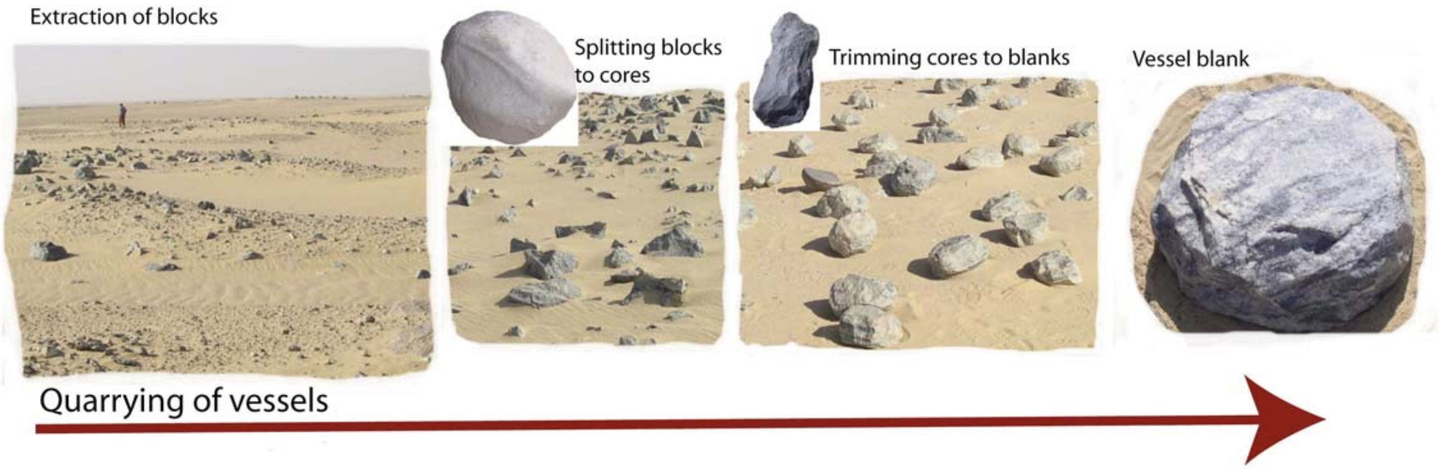

Figure 11. Overview of work process for vessel production.

Figure 12. Selection of vessel blanks showing the range of sizes and shapes.

archaeological record (Bloxam and Heldal 2007; Bloxam 2015; Bevan and Bloxam 2015). Significantly, it is along the transport route out of Chephren's Quarries that most of the settlement and subsistence evidence is found. This is in the form of two well-preserved small camps, a number of shallow groundwater wells, pottery and other domestic elements, and also the location of a single rock-cut inscription identifying an 'overseer of the craftsmen' (Bloxam 2003; Shaw et al. 2010).

The logistics of loading and transporting statue rough-outs weighing upwards of two tons from Chephren's Quarries is one of the most intriguing aspects of the whole quarrying operation. Tantalizing clues about the ways in which this may have been done remain well-preserved in the archaeological record. For example, three similar stone-built loading ramps associated with the large-block quarries were excavated, revealing two deep tracks in front that were artificially cut to accommodate the runners of a large vehicle (Fig 15). The height and dimensions of the vehicle implied by these tracks suggest something more substantial than a low-lying sledge, although nothing of this type has yet been found in the archaeological record (Bloxam 2000, 2003, 2007). Contrary to other quarries, where no large blocks seem to have been quarried, loading ramps are apparently unique to the quarries where one or several large blocks were ready for transportation.

As for small rough-outs intended for vessels, they would have been transported to workshops in the Nile Valley for finishing. Although tracing the precise locations of such workshops remains problematic, we can make some indirect suggestions because of the discovery of stone-vessel workshops at Elephantine and Hierakonpolis, as well as the recent discovery of Chephren gneiss debris associated with a workshop area on the Giza Plateau (Hoffman 1991; Kaiser et al. 1999).

DISTRIBUTION AND SIZE OF THE QUARRIES

In total, 667 individual gneiss quarries have been recorded (Fig. 16a), varying significantly in size (Table 1). The smallest ones, exploiting a single boulder only, measure approximately 2 metres in diameter, including the circular spoil heap. The largest quarries (up to 280 m along the longest axis) exploited either a large group of boulders or several in a row, resulting in tall, circular to elongated spoil heaps. In total, the quarries cover an area equal to 174,000 m^2. Most quarries range between 10 and 100 m^2 (542 quarries), 87 can be described as very small (less than 10 m^2), and 38 as large (more than 1000 m^2).

The northern area has the largest number of quarries (452) and also the largest quarried area (90,000 m^2) (Table 2). Although the central area hosts fewer quarries (180), the quarried area is almost as large as in the north (80,000 m^2) (Table 3), because most of the quarrying was concentrated in a few large quarries. Elsewhere, 'Chisel Quarry,' located northwest of the central quarries, is a single quarry covering almost 2000 m^2

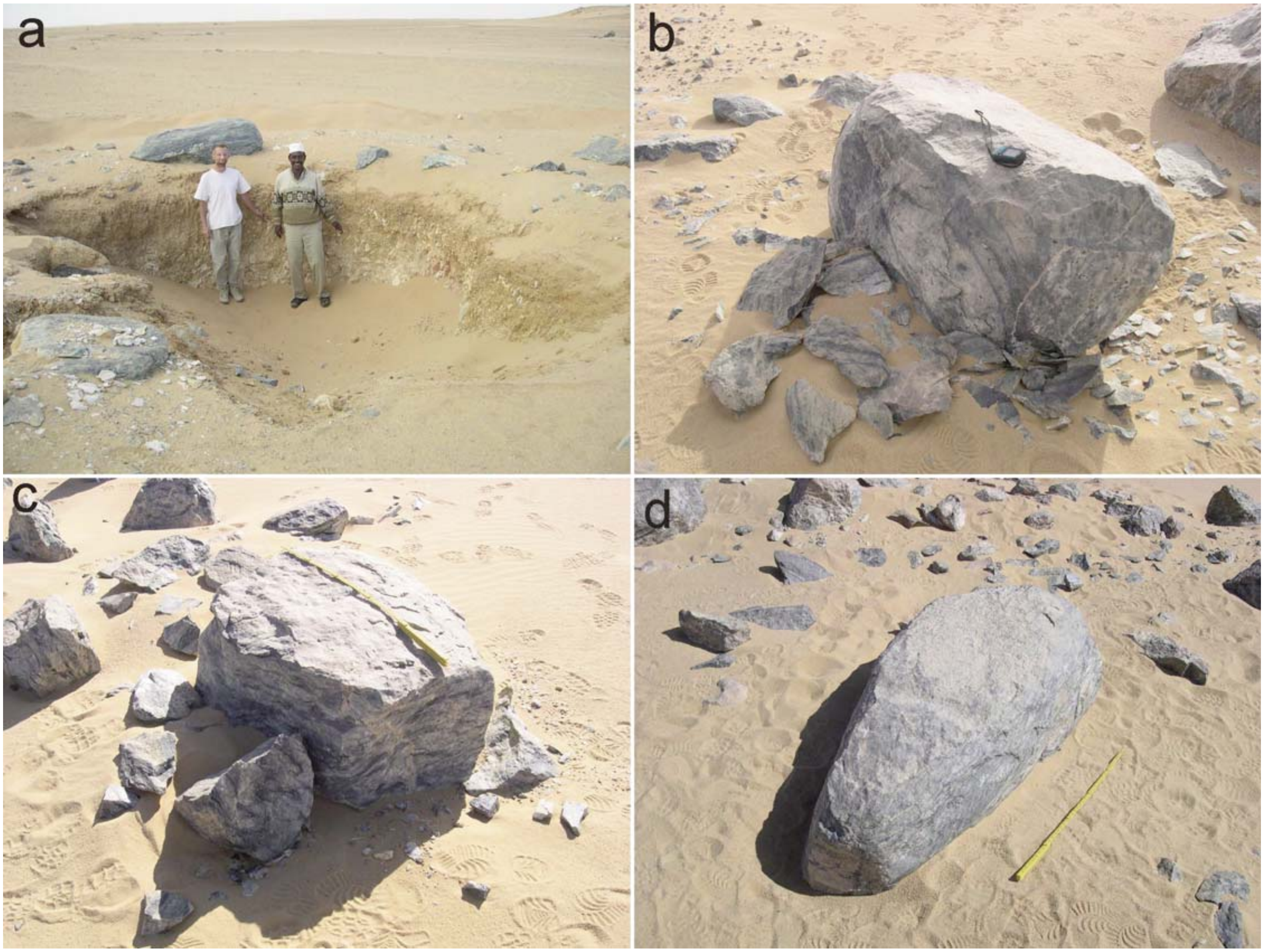

Figure 13. Overview of work process for statue blocks. a) Digging into the soil around a removed block; b) spalled surface on a gneiss block probably induced by heating; c) split rock pieces (made by pounding) around a partially worked block; d) dressed statue block (note the shape) ready for transport. Scale: ruler measures 80 cm.

Table 1. Number of quarries and their size.

m^2	Quarries
<10	87
10–50	259
50–100	186
100–500	85
500–1000	12
1000–1500	4
1500–2000	10
2000–3000	10
3000–10000	10
10000–20000	3
20000–30000	1
Total	667

(Figs. 16, 17), whereas the southern quarries, approximately the same area, comprise 34 very small quarries (Table 2).

Vessel blanks are found in many quarries. These are spherical to disc-shaped, trimmed rough-outs varying in size from 15 to 50 cm across. In some quarries, stockpiles of vessel blanks have been observed. The stockpiles have been recorded and, as shown in Fig. 16c, they are common in all the quarry areas. None, however, are found in the eastern part of the central quarries, and they are also less common in the central quar-

Table 2. Quarry areas, size and number of individual quarries.

	Area (m^2)	# of quarries
Northern quarries	90,000	452
Central quarries	80,000	180
Chisel quarry	2000	1
Southern quarries	2000	34

Table 3. Type of stone tools found in Chephren's Quarry.

Rock type	Cobble pounders	Manufactured pounders	Hand axes	Pounders with hafted necks
Dacite	X		X	X
Granitic rocks	X	X		X
Chephren gneiss	X			
Basalt			X	

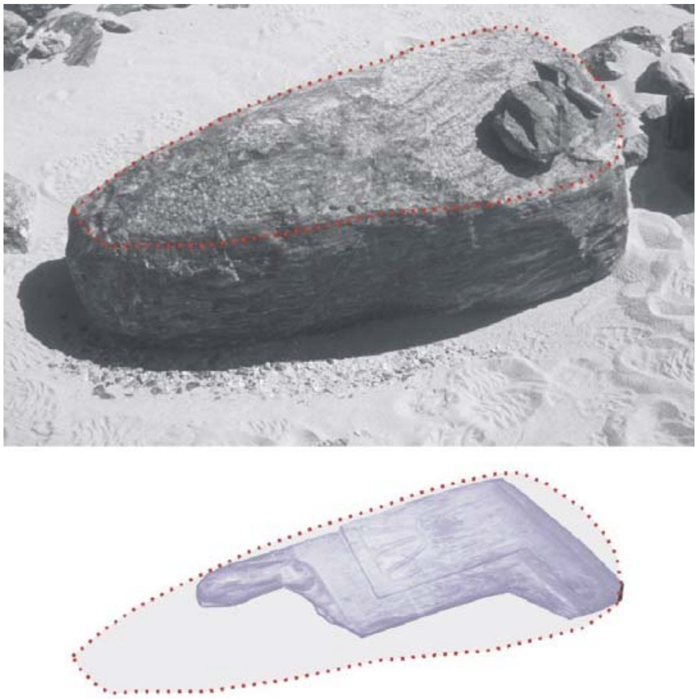

Figure 14. Statue block dressed to a shape suitable for making statues of a seated king (the block is approximately 150 cm long).

ries than in the northern ones. This pattern coincides with the distribution of gneiss subtypes: the evidence of vessel production is most commonly found within the occurrences of light-speckled Chephren gneiss.

The distribution of large blocks and loading ramps indicates that only small parts of the total quarry area were used for production of statues and, perhaps, very large vessels (Fig. 16d). There are few places with worked blocks and only one loading ramp in the northern quarries. In the central quarries, there are several statue-blocks and ramps, especially in the large so-called Khufu Stele Quarry and its vicinity. It seems that these quarries mainly produced large blocks, since no or few small vessel blanks have been found. The focus of large-block production in the central quarries coincides, interestingly, with the main occurrences of the light-banded subtype of gneiss.

Judging from evidence in the quarries, as well as from the archaeological records at pyramids and tombs, production of vessel blanks was virtually the only activity at the Chephren Quarries from the Predynastic Period through to the 3rd Dynasty. The number of produced vessels would have been very high. Given that the spoil deposition area is roughly the same size as the actual block extraction area, if each square metre within the extraction area produced one vessel, the number of vessels would be close to 90,000. This is not surprising, given the enormous numbers of stone vessels that have been found across Egypt. In the subterranean storerooms of Djoser's step pyramid, no less than 30,000 vessels have been found, of which 892 are made from Chephren gneiss (Firth and Quibell 1935).

Quarrying targeted the assumed best-quality rock for vessels, namely the speckled variety of the gneiss. Available blocks of this subtype may have been depleted when campaigns for larger statue blocks began during Chephren's reign in the Old Kingdom. Hence, the light-banded type was targeted. While this subtype is of poorer quality, it is still good enough for the production of large statues.

Figure 15. Loading ramp with dug linear depressions for fitting to a yet unknown type of transport vehicle.

Regarding the resources used for tools, there are some interesting patterns (Fig. 16b). Although the dacite seems to be the preferred tool rock, its use decreased away from the dykes. At a distance from the dykes, manufactured granite pounders and pounders from the Chephren gneiss were used. This strongly suggests that although dacite seemed to be the ideal pounder rock, it could be easily replaced by alternatives that did the job sufficiently well.

CONCLUSIONS

The landscape in the Gebel el-Asr area is remarkable, shaped by geological processes from the Archean to the present day. The geological landscape bears witness to repeated geological cycles: formation of layered igneous complexes; deep burial in the earth's crust; partial melting and high grade metamorphism; uplift and erosion; deposition of marine and fluvial sediments; volcanic eruptions; and finally uplift and erosion once more. All these events played a part in shaping a natural resource of such importance to the ancient Egyptians that they went to great lengths to exploit it. The Chephren gneiss is unique because its complex geological history and preservation of its high-grade metamorphic fabric through billions of years was the direct cause of its suitability for the production of beautiful vessels and sculptures.

In exploiting these resources, the ancient Egyptians created a unique cultural landscape that is testament to the ingenuity used not only in methods to extract it, but also in transportation over large distances. As a ghost-town of antiquity, we also get a sense of the people who worked there from the remains of their camps, food left on the hearth, pottery and other domestic artefacts that still remain. These all reveal to us the ways in which local knowledge of the subsistence resources, as well as stone resources of the region were key: from where to dig wells to access groundwater, to locating the best secondary resources to make tools. The quarrying activity is also a display of simplicity, a skilled and efficient production of a 'difficult'

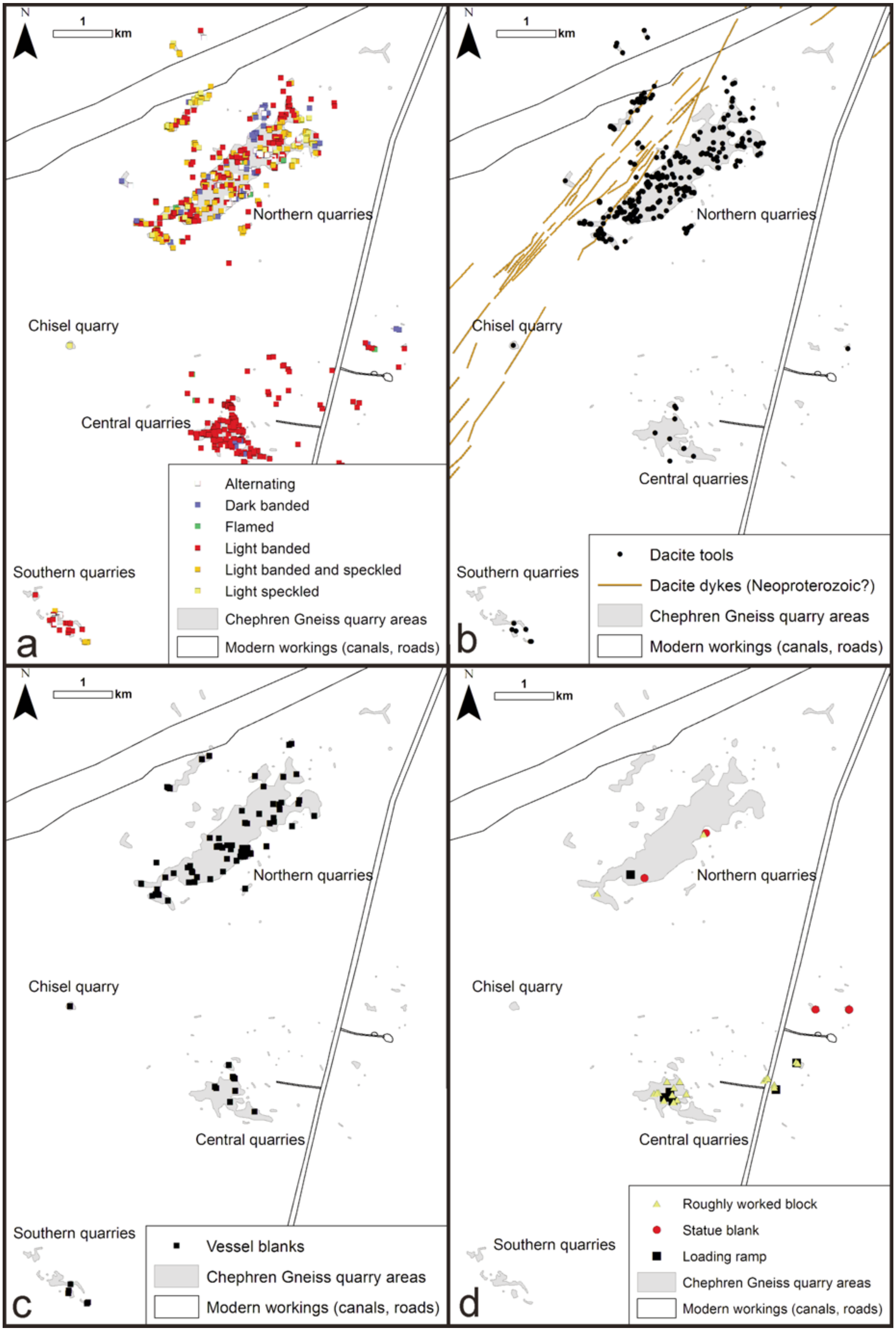

Figure 16. Spatial distribution of features in Chephren's Quarry. a) Recorded quarries and subtypes of gneiss; b) observations of dacite pounders and location of dacite dykes (source for the pounders); c) recorded collections of vessel blanks; d) observations of statue blocks and loading ramps.

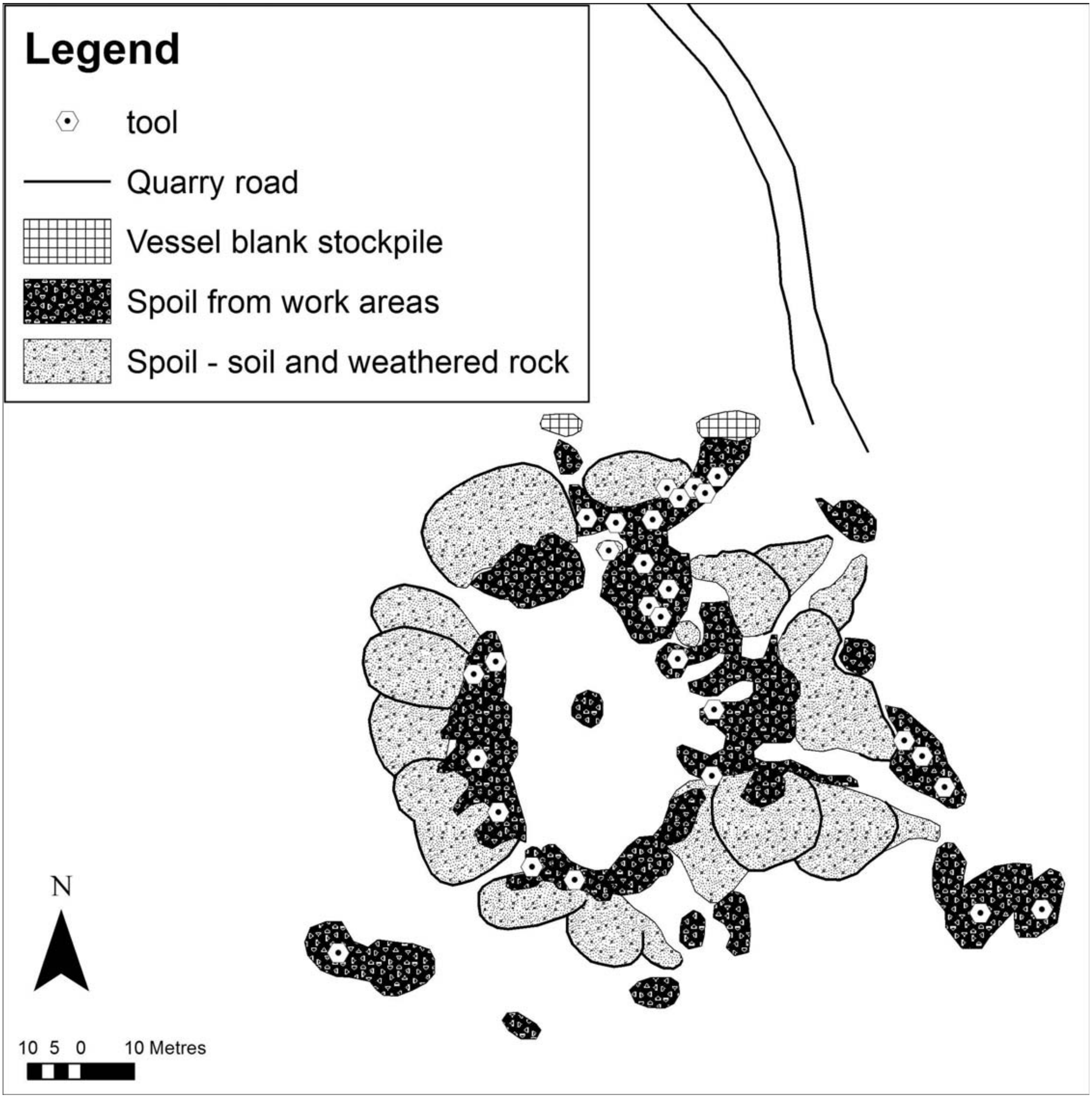

Figure 17. Map of Chisel Quarry, clearly showing the concentric layout and large spoil heaps.

rock with simple methods conducted by expert craftspeople. Although early vessels and statues were made from many stone types in ancient Egypt, Chephren's Quarries is an example of early industrial-scale excavation not only in Egypt, but globally. The beauty of the stone, combined with its unique physical properties, made it possible to make bowls and vases of extreme delicacy, and statues that are regarded as masterpieces of the ancient world. The quarries were abandoned more than 4500 years ago and, except for some limited use in the 12th Dynasty (about 500 years later), the stone never reappeared for large-scale use. Probably, the resource was considered depleted. Hence, the remains from quarrying display a frozen image of the vogue for beautiful stone during a rich period in human history. Moreover, it is the most remote cultural-natural landscape connected to the pyramid builders of the Old Kingdom, or in other words, an extended part of the pyramid landscapes almost 1300 km away, therefore adding more value to its significance. Modern development and irrigation mega-projects in this part of the Egyptian desert remain a constant threat and may easily destroy this unique site, as it already has in some parts (Storemyr 2009). But, if well managed and formally recognized as a heritage site of global significance, there will still be enough left to be enjoyed by future generations.

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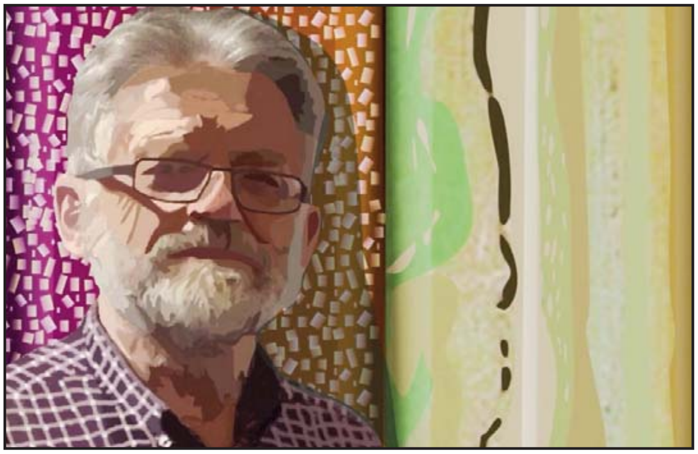

Heritage Stone 7.
Pohorje Granodiorite – One of the Most Significant Slovenian Natural Stones*

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SUMMARY

Granodiorite from the Pohorje Mountains (northeastern Slovenia) is considered the highest quality natural stone in Slovenia. *Pohorje granodiorite* is a grey, calc-alkaline igneous rock of Miocene age (18.7 Ma) that is distinguished by thick white aplite–pegmatite veins. It mainly consists of plagioclase, quartz, and K-feldspar, subsidiary biotite and a small amount of hornblende. It is characterized by high density, low water absorption, and low porosity, so that it exhibits high frost and salt resistance, as well as a high compressive strength and a very high flexural strength. It is widely recognized throughout the country for its durability and decorative white veins, and is the most frequently used natural stone in Slovenia today. It is mainly used as paving and cladding material for residential buildings, churches, and other structures, as well as in public areas, where it adds special character to many of the larger towns and cities. Several important buildings, some of which have been declared cultural monuments of national importance, are also decorated with this stone, including the Slovenian Parliament, the Republic Square business complex, and the Faculty of Law of the University of Ljubljana, all of which are located in Ljubljana. Since 1940, Pohorje granodiorite has also been widely used by sculptors in various monuments and fountains.

RÉSUMÉ

Le granodiorite des montagnes de Pohorje (nord de la Slovénie) est considéré comme la meilleure pierre naturelle de Slovénie. Le granodiorite de Pohorje est une roche ignée grise, calco-alcaline du Miocène (18,7 Ma) qui se distingue par la présence d'épais filons de pegmatites d'aplite blanche. Il se compose principalement de plagioclase, de quartz et de feldspath potassique, de biotite accessoire et d'une petite quantité d'amphibole. Elle est caractérisée par une densité élevée, un faible coefficient d'imbibition, et une porosité faible, de sorte qu'elle présente une haute résistance au gel et au sel, ainsi qu'une résistance élevée à la compression et une résistance très élevée à la flexion. Elle est très connue dans tout le pays pour

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*This article is part of a set of papers dedicated to the memory of Anders Wikström published in Geoscience Canada Special Issue: Heritage Stone; a new series that is guest edited by Dolores Pereira and Brian R. Pratt.

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sa durabilité et ses filons décoratifs blancs, et c'est la pierre naturelle la plus fréquemment utilisée en Slovénie de nos jours. Elle est principalement utilisée comme matériau de pavage et de revêtement pour les bâtiments résidentiels, les églises et autres constructions, ainsi que dans les espaces publics, où elle donne un caractère distinctif aux grands villages et aux villes. Plusieurs bâtiments importants, dont certains ont été déclarés monuments culturels d'importance nationale, sont également décorées avec cette pierre, y compris le Parlement slovène, le complexe d'affaires Place de la République, et la Faculté de droit de l'Université de Ljubljana, lesquels sont tous situés à Ljubljana. Depuis 1940, le granodiorite de Pohorje a aussi été beaucoup utilisé par les sculpteurs dans divers monuments et fontaines.

Traduit par le Traducteur

INTRODUCTION

This contribution proposes *Pohorje granodiorite*, a calc-alkaline igneous rock of Miocene age from Slovenia, as a candidate for international recognition as a Global Heritage Stone Resource, following the Terms of Reference of the Heritage Stone Task Group of the International Union of Geological Sciences (IUGS) (www.globalheritagestone.org; see also Cooper 2010; Pereira 2012; Cooper et al. 2013; Marker 2015). In required support of the nomination of Pohorje granodiorite as a Global Heritage Stone Resource (GHSR), this paper provides a comprehensive listing of the defining geological characteristics of the stone and its associated terminology. In addition, source quarries and petrophysical characteristics of Pohorje granodiorite are provided, as well as documentation of its use as a building stone.

GLOBAL HERITAGE STONE RESOURCE CANDIDACY REQUIREMENTS

Origin of Name

In Slovene, the Pohorje granodiorite is written as 'Pohorski granodiorit.' The name originates from the Pohorje Mountains (north-northeastern Slovenia), where the granodiorite crops out. The granodiorite has moderate quartz content (20–60%) and plagioclase predominates over K-feldspar by a factor of 2:1 or more. Biotite is relatively abundant, whereas hornblende is less common and augite is rare. The name 'granodiorite' originates from two geologically related rocks: granite and diorite, to which granodiorite is intermediate. The 'grano' root comes from the Latin word 'granum' meaning 'grain.' Diorite is named from the Greek verb 'diorizein' (διοριζειν) meaning 'to distinguish' (Le Maitre 2002). Commercial designations are also Tonalite, Pohorje tonalite, Pohorje granite.

In the past, the Pohorje igneous rock was named Pohorje granite (Benesch 1918) because of its mineral composition: quartz, feldspars and biotite. Later, the stone was classified as tonalite (Dolar-Mantuani 1938). According to the IUGS classification, the rock is a granodiorite, though local transitions to tonalite can be found (Zupančič 1994a). Despite apparent spatial relations, Faninger (1970, 1976) stressed that Pohorje granodiorite cannot be considered an eastern prolongation of the Železna Kapla (Eisenkappel) tonalite. Granodiorite differs from tonalite in its higher content of alkali feldspars – in this case, K-feldspar.

Principal Location of Extraction Sites

Pohorje granodiorite represents the largest occurrence of igneous rocks in Slovenia by area. It crops out in the Pohorje Mountains in the northern part of the country (Fig. 1). Two quarries are located in Pohorje granodiorite, both protected as valuable natural geological features. The only operating granodiorite quarry at present, and the largest igneous rock quarry in Slovenia, is situated at Cezlak near Oplotnica (Fig. 2). A second quarry at Josipdol (Fig. 3) is currently inactive.

Production Details and Manufacturing Information

In recent years, the total annual production of stone blocks at the Cezlak Quarry has varied greatly from 25,000 tonnes to 67,000 tonnes, depending on market demand. The stone is obtained by surface quarrying methods in 6 m-high benches, using a diamond wire for cutting. Raw blocks, approximately 1.6 x 1.8 x 2.9 m in size, are transported to a plant at Podpeč, near Ljubljana, for further processing. Using modern technology, raw blocks are then either cut into slabs of standard thickness and processed with different surface finishes, or manufactured into other products. Irregularly shaped large pieces that remain after removal of the raw blocks are processed into armour stone or paving setts (brick-sized dressed blocks of stone) at a production plant located at the quarry. The producer has plans to recycle part of the current quarry waste into an aggregate for asphalt course layers. The largest quarried block measured 1.9 m in width, 1.2 m in height and 6.6 m in length, and weighed about 40 tonnes.

Geological Age and Geological Setting

The area of Pohorje represents the south-easternmost exposed part of the Eastern Austroalpine metamorphic complex at the southwestern margin of the Pannonian Basin. The Pohorje tectonic block consists of polymetamorphic rocks, which were (in the central part) intruded by calc-alkaline magma at around 18.7 Ma (Trajanova et al. 2005, 2008; Fodor et al. 2008). The igneous body represents a strongly tilted batholith (Trajanova 2013), which extends continuously over more than 30 km in a northwest–southeast direction close to the Labot fault, north of the Periadriatic fault zone. The Pohorje pluton is surrounded by presumably Precambrian metamorphic rocks of the Pohorje Series (Mioč and Žnidarčič 1977, 1989; Mioč 1978). Gneisses and mica schists dominate, and contain numerous lenses of amphibolite, marble, quartzite, sparser pegmatite gneiss, eclogite, and serpentinite; their mineral paragenesis shows polyphase metamorphism (Hinterlechner-Ravnik 1971, 1973, 1982). The deepest easternmost part of the Pohorje metamorphic rocks (peridotites, eclogites, gneisses) were subjected to Cretaceous ultrahigh-pressure metamorphism (e.g. Janák et al. 2004, 2015a, b). The protolith radiometric age of these rocks has not been determined because they have been strongly rejuvenated in the Alpine orogenic cycle (e.g. Fodor et al. 2008). The northwestern part of the Pohorje tectonic block features a thrust and a partly imbricated structure; the primary overriding plate is the Remschnig thrust block (Mioč 1978), which consists of Ordovician to Carboniferous low-grade metamorphic sedimentary (lower part) and pyroclastic (upper part) rocks belonging to slates of the Magdalensberg Formation. Biostratigraphic investigation of lenses of marmorized limestone in this for-

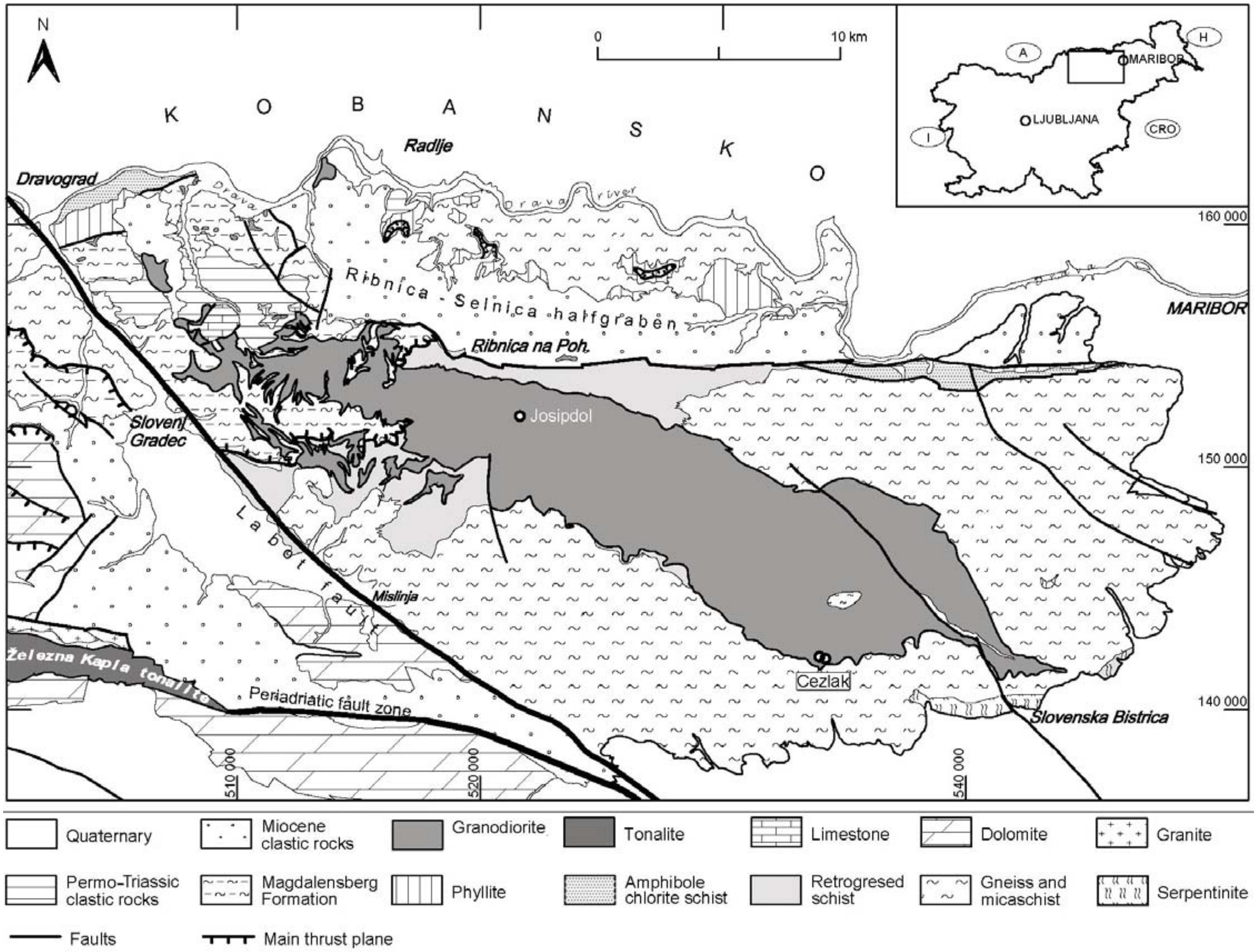

Figure 1. Simplified geological map the of Pohorje area (modified from Trajanova et al. 2008). Inset is a contour of Slovenia with the Pohorje area outlined.

Figure 2. Active quarry in granodiorite near the village of Cezlak. Photo: Samo Jenčič.

Figure 3. Josipdol granodiorite quarry during a period of active exploitation. Photo: Samo Jenčič.

mation has yielded sparse fossils indicating an Early Devonian age (Mioč and Ramovš 1973; Kolar-Jurkovšek and Jurkovšek 1996). The Magdalensberg Formation is discordantly overlain by, from oldest to youngest, Permo–Triassic clastic rocks, some patches of Triassic dolomite, relics of the Cretaceous Gosau Group rocks, and mid-Miocene sedimentary rocks. Granodiorite magma intruded the entire rock sequence, except for the mid-Miocene rocks, thus constraining its upper age limit. The northwestern part of the massif is considered to represent an apical part of the intrusion and of the entire Pohorje tectonic block lithological succession (Trajanova 2013).

Pohorje magmatic activity seems to be connected to the Miocene evolution of the Pannonian Basin (Trajanova and Pécskay 2006; Trajanova et al. 2008; Trajanova 2013) and not to the Oligocene Periadriatic intrusions, as believed by earlier researchers. Mid- to late-Miocene deformation, uplift and rapid unroofing affected the entire pluton and the host rocks, due to which they are tectonically and locally hydrothermally altered.

Petrographic Name and Characteristics

From an international perspective, the Pohorje granodiorite represents a classic calc-alkaline igneous rock. It forms a single, continuous, batholithic intrusion (Trajanova and Pécskay 2006; Trajanova et al. 2008; Trajanova 2013) of granodiorite and subordinate tonalite. Because of its petrographic similarities to the Periadriatic Železna Kapla tonalite, it was named tonalite, and this name remains in common use today. As reported by Zupančič (1994a), primary tonalite was altered to granodiorite as a result of strong potassic metasomatism. Later investigations confirmed metasomatic processes only for a limited area connected to the Remschnig thrust zone (Trajanova 2013).

The granodiorite is coarse- to medium-grained in the deeper, eastern part, and grades to fine-grained and porphyritic in the shallower, northwestern part of the pluton. Locally, gradual transitions to more mafic rocks of subvolcanic, andesitic composition can be observed. Their origin is considered a product of magma mixing (Trajanova 2013), which is indicated by geochemical parameters (Zupančič 1994b). Somewhat younger (about 18 Ma) are mafic dykes of basalt and andesite composition found in metamorphic host rocks near the south-southwestern margin of the pluton. They were previously identified as lamprophyres (e.g. Mioč and Žnidarčič 1977, 1989; Mioč 1978), but this determination has been rejected on petrographical and geochemical grounds. The youngest K–Ar cooling ages of about 16.5–16.0 Ma are associated with undeformed subvolcanic dacitic dykes of the same composition as the batholith. Their emplacement age is not confirmed yet, but geological evidence indicates that they are younger than the main igneous body.

The central part of the granodiorite commonly contains mafic inclusions. In addition, it is crosscut by white to very light grey aplite–pegmatite veins that are 1–50 cm thick. Syn-cooling tectonic activity has produced a fabric in the granodiorite, indicating ductile deformation. In addition to the foliation, a lineation is observed as a preferred orientation of phyllosilicates and sparse hornblende, and stretched, degraded, and recrystallized quartz. In the jargon of quarrymen in the Cezlak Quarry, the first is called *rast* (‘growth’) and the second *kolnost* (‘splitting’) (Vesel and Senegačnik 2004). Mylonitic to cataclastic shear bands formed locally. The upper part of the granodiorite body is strongly degraded, i.e. sub-horizontally brittle sheared and, therefore, unusable as natural stone.

The major mineral components of the granodiorite are plagioclase, quartz, K-feldspar, and biotite (Figs. 4 and 5). Hornblende occurs locally in the granodiorite, but is the dominant mafic mineral in subvolcanic andesitic and basaltic dykes. Opaque minerals, allanite, epidote, titanite, zircon, apatite, and traces of garnet and pyroxene are accessories. In places, the concentration of opaque minerals, garnet, and epidote is significantly higher, e.g. where the pluton intruded low-grade metamorphic rocks in the Remschnig thrust zone (Mioč 1978). The contact aureole is characterized by the presence of garnet, epidote, hornblende hornfels, and skarn. Magnetite–hematite mineralization in the contact aureole was discovered and exploited in the first half of the 20th century. Iron ore is accompanied by Fe-sulphides, predominantly pyrite, and some Pb and Zn mineralization; pyrite is sparser in the eastern parts of the granodiorite body. The Remschnig thrust zone is characterized by slight hydrothermal alteration, which is reflected as K-metasomatism, chloritization, sericitization and calcitization.

A peculiarity of the granodiorite is a large altered mafic xenolith (Trajanova 2013), locally called cizlakite (Nikitin 1939), included within the granodiorite on the southern rim of the pluton, close to the village of Cezlak. Cizlakite has been regarded as a mafic differentiate of granodiorite or as a prod-

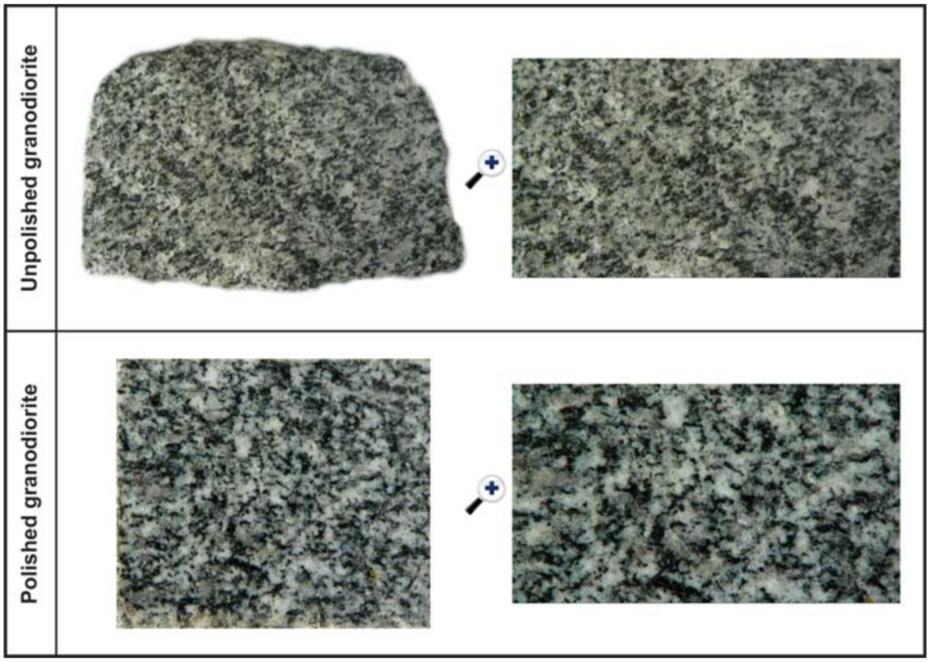

Figure 4. Unpolished and polished samples of granodiorite (left) with a magnified view (right). White – plagioclase, light grey – quartz, pale yellowish and pinkish grey – K-feldspar, black – biotite and amphibole. The width of the unpolished sample is 11 cm, and the width of the polished sample is 5.5 cm. Photo: Matej Dolenec.

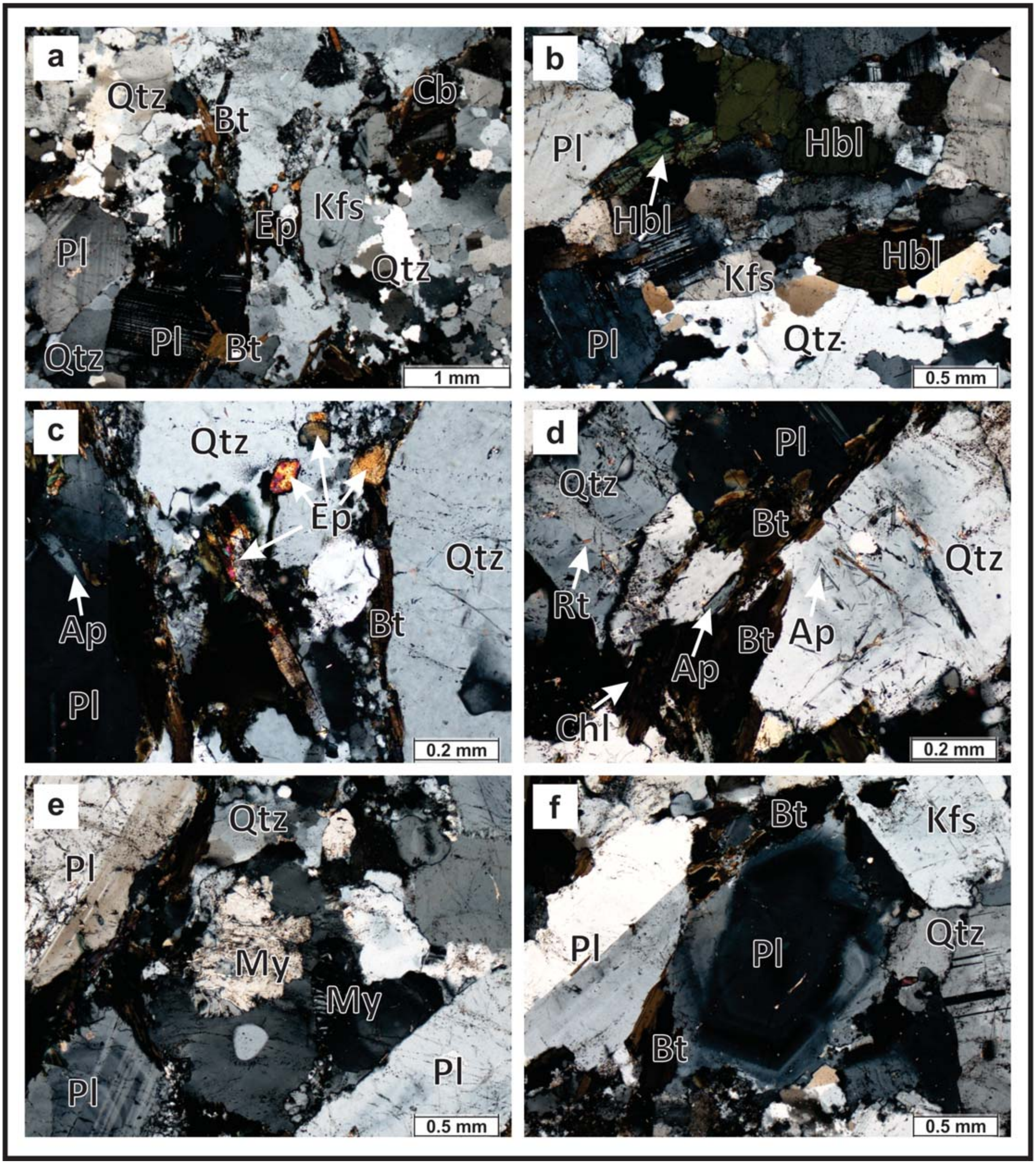

Figure 5. Photomicrographs of holocrystalline, hypidiomorphic, fine- to medium-grained Pohorje granodiorite (cross-polarized view). a) Granodiorite composed of euhedral to subhedral polysynthetic plagioclase, anhedral polycrystalline quartz grains, subhedral prismatic biotite, anhedral K-feldspar, idiomorphic accessory epidote and carbonate grains; b) euhedral hornblende twinned on Carlsbad law showing pronounced colour variations visible in plane-polarized light; twinned plagioclase; and polycrystalline quartz; c) accessory grains of epidote; poikilitic texture of small grains of apatite completely enclosed in large plagioclase; and anhedral grains of quartz with undulose extinction; d) chlorite replacing subhedral biotite at the rim and along cleavage planes, accessory grains of euhedral rutile in anhedral quartz, and prismatic euhedral laths of apatite in subhedral plagioclase grains; e) subhedral polysynthetic twinned and oscillatory zoned plagioclase grains, and myrmekitic textures of wormlike quartz at the boundary with subhedral plagioclase; f) oscillatory-zoned and polysynthetic-twinned euhedral to subhedral plagioclase with prismatic subhedral interstitial biotite, and anhedral grains of K-feldspar. Photo: Matej Dolenec. Ap – apatite, Bt – biotite, Cb – carbonate grain, Chl – chlorite, Ep – epidote, Hbl – hornblende, Kfs – K-feldspar, My – myrmeketic texture, Pl – plagioclase, Qtz – quartz, Rt – rutile.

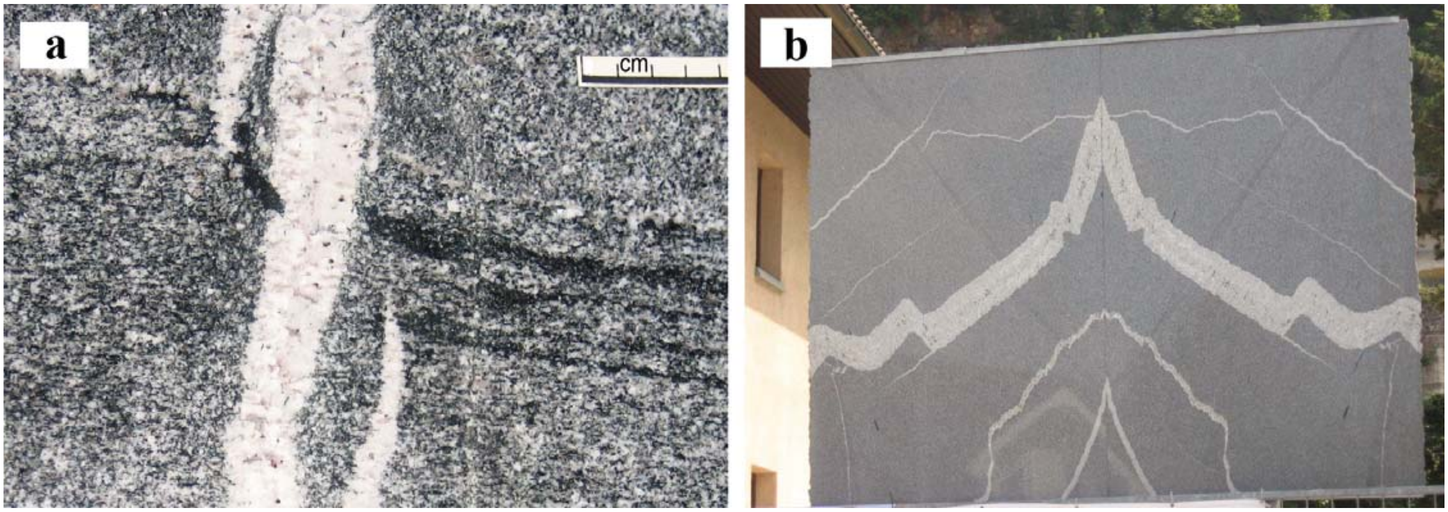

Figure 6. a) Foliated granodiorite with black schlieren and aplite−pegmatite veins at the Cezlak (active) Quarry. Photo: M. Trajanova. b) polished granodiorite panels in front of the company Mineral d.d. (Archive Mineral d.d.).

uct of stratification in the magma chamber (e.g. Zupančič 1994a, b), but most often has been referred to as diorite or gabbro, corresponding, respectively, to quartz monzogabbro and transitional diorite–pyroxenite (Trajanova et al. 2009) according to the classification of Le Maitre (2002). Faninger (1976) expressed doubt that cizlakite is a mafic differentiate of granodiorite, interpreting it instead as an older mafic to ultramafic rock that was partly assimilated by more felsic magma. This interpretation is supported by field and petrographic evidence (Trajanova 2013). The cizlakite lens is also crosscut by aplite−pegmatite veins.

The massive structure, coarse-grained texture, and variegated dark green and white colour of cizlakite were much admired in the past, and the rock was frequently used as an architectural stone. However, because of the small size of the lens, the reserves were limited and quarrying eventually ceased.

Primary Colour(s) and Aesthetics of Stone

Generally, Pohorje granodiorite is characterized by its grey colour and thick white aplite−pegmatite veins (Fig. 6). Major colours of the granodiorite mineral assemblage, as defined by the Munsell geological rock-colour chart, are as follows: N9 (white) for plagioclase, N8 (very light grey) and N7 (light grey) for quartz and K-feldspar, and N3 (dark grey) and N1 (black) for biotite and hornblende. Aplite−pegmatite veins are recognized as N9 (white). Aplite−pegmatite veins are up to 50 cm thick, but most do not exceed 25 cm. The veins mostly crosscut foliation, but are locally sheared together with the host rock. Foliation is developed unevenly, and is more pronounced in peripheral and shallower parts of the pluton.

Natural Variability

The Pohorje granodiorite and its porphyritic phases define the main textural varieties: equigranular granodiorite is a medium- to fine-grained rock, whereas porphyritic granodiorite comprises larger phenocrysts in a medium- to fine-grained groundmass. White veins consist of fine-grained aplite in the middle and coarse-grained pegmatite at the edge. Pohorje granodiorite has a relatively uniform structure, based on its appearance in active and abandoned quarries. Nevertheless, grain size and texture varies along the strike of the body from medium- to coarse-grained in eastern and central parts to porphyritic in its northwestern part. Aplite−pegmatite veins are more abundant in the central part of the granodiorite body and become sparser toward the east and west-northwest. Sporadic black schlieren and mafic inclusions impart a streaky appearance to the rock.

Technical Properties

Pohorje granodiorite is considered to be the highest quality natural stone in Slovenia. It is characterized by its high density, low water absorption, and low porosity, so that it exhibits high frost and salt resistance, as well as a high compressive strength and a very high flexural strength (Table 1).

Table 1. Physical properties of Pohorje granodiorite.

Parameter	Procedure	Result
Water absorption	EN 13755:2008	0.1 – 0.2% by mass
Real density	EN 1936:2007	2700 Mg/m$^{32700\ \mathrm{Mg/m3}}$
Apparent density		2670 Mg/m$^{32670\ \mathrm{Mg/m3}}$
Porosity (open)	EN 1936:2007	0.60%
Porosity (total)		0.90%
Compressive strength – dry	EN 1926:2007	190 MPa
Flexural strength – dry	EN 13161:2008	20 MPa
Resistance to salt crystallization	EN 12370:2000	0.00%
Frost resistance	EN 12371:2000	0.00%
Slip resistance		
Brushed surface		
SRV dry		63
SRV wet	SIST EN 14231:2003	39
Polished surface		
SRV dry		55
SRV wet		14
Thermal Expansion Coefficient	SIST EN 14581:2005	8.4 x 10^{-8}/K

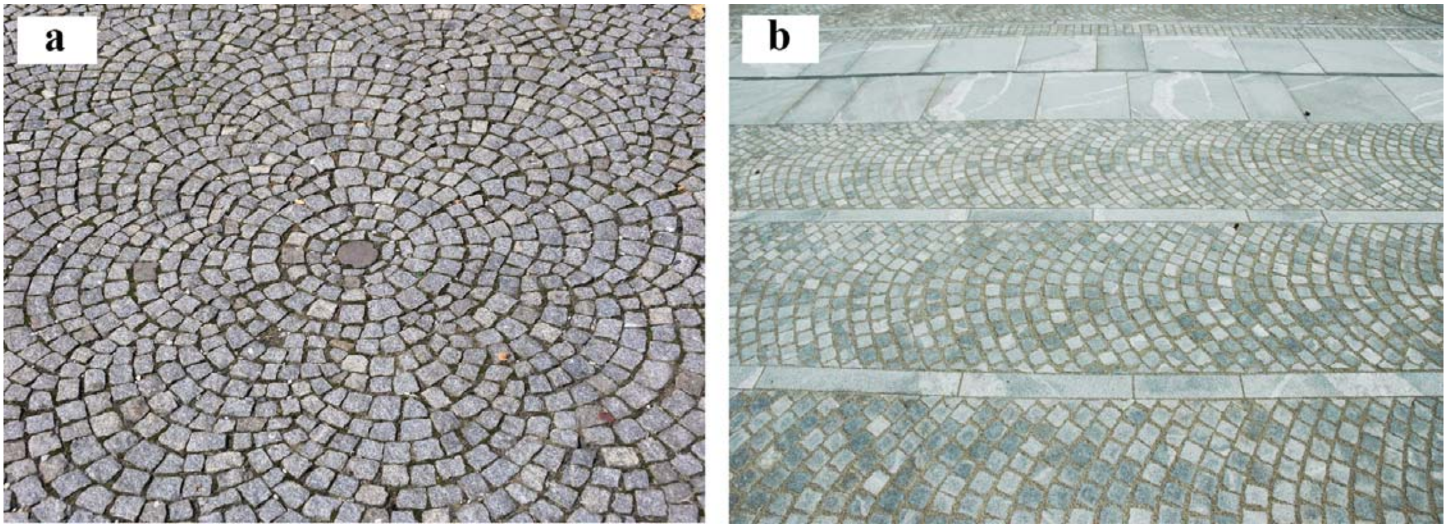

Figure 7. a) Pavement of granodiorite cobblestones. Photo: Samo Jenčič. b) pavement of granodiorite cobblestones and paving slabs. Photo: Miran Uddovč.

Suitability

Pohorje granodiorite is widely known throughout Slovenia for its durability and decorative white veins, and is currently the most frequently used natural stone in the country. It is mainly used as paving and cladding material for the interiors and exteriors of residential buildings, churches, and other structures, as well as for paving public squares, thus giving many of Slovenia's largest towns a unique character. Due to its high durability and artistic workability, this type of stone is excellent for various monuments and sculptures, which is shown by the existence of numerous historical and contemporary works. Pavements made of small cobblestones (Fig. 7) are common in the public squares of some towns. Until the recent past, many streets were entirely paved with cobblestones; some are still well-preserved and maintained. This type of paving was also common on some regional and local roads, where steep slopes can cause loss of traction in winter.

An unusual type of degradation of granodiorite cladding panels occurs in the form of bowing (Fig. 8). Despite being a common phenomenon with other natural stones, it was first detected with Pohorje granodiorite on the façades of the Maximarket department store in Ljubljana, which was constructed in 1971 (Mauko et al. 2006). This phenomenon is one of the very few documented cases of bowing of igneous rocks.

Pyrite has been considered to be a potentially problematic accessory mineral because of the possibility of limonitization. However, the presence of a small amount of arsenic in the pyrite makes it quite stable and not prone to alteration, hence minimizing its negative impact. Depending on exposure conditions, a slight limonitization may occur, but this phenomenon is much less extensive than in many other rocks containing pyrite.

Vulnerability and Maintenance of Supply

In the area of Pohorje, two localities are protected as valuable natural geological features, based on typicality, rarity, scientific research and evidential importance (decree on the designation and protection of valuable natural features; official gazette of the Republic of Slovenia, No. 111/04, 70/60, 58/09 in 93/10). The one-remaining operating quarry at Cezlak (Oplotnica, southern outskirts of Pohorje), is a valuable natural resource of national importance. Granodiorite in the non-active quarry in Josipdol (Ribnica na Pohorju, central Pohorje) was also

Figure 8. Bowing of granodiorite on a building façade. Photo: Ana Mladenović.

Figure 9. In the Cezlak granodiorite quarry, women also worked before World War II (Archive Mineral d.d.).

declared a valuable natural feature of local importance. Relevant data can be found on http://www.naravovarstveni-atlas.si/nvajavni/profile.aspx?id=NV@ZRSVNJ, under the identification numbers 4399 and 121. Stone reserves are estimated to be sufficient for future needs, and there is no question of the long-term availability of this valued material for cultural monument restoration.

Historic Use, Geographic Area of Utilization, Commercial Diffusion

According to historic records, exploitation of 'Pohorje granite,' the common name for the granodiorite among the general public, was started in 1891 by a farmer living in nearby Cezlak. This farmer began exploiting the resource with the permission of the landowner (Count Windischgrätz), cleaned up the hillside and started to cut the stone into smaller pieces. From 1905 to 1919, the quarry was operated by the owner. The following decades were marked by progress and expansion of the quarry (Fig. 9). Detailed geological exploration carried out to determine reserves of natural stone have been used as a base of production for several decades. From 1919 to 1941, the owner of the quarry was German Erlich (Vrečko 2012). In 1941, the quarry was nationalized by the Germans and handed over to the Austrian company SS Graz. After World War II, the quarry was managed and operated by Granite Industry Oplotnica (Vrečko 2012). During this period, setts of different sizes and blocks for building bridges were produced. The excellent quality of manual processing of the stone was recognized well beyond the borders of Slovenia, and much product was sold in Austria, Switzerland and Germany. In 1945, around 500 people were employed in the quarry (Curk 2004). The quarry also began co-ordinating with surrounding quarries in 1962, and until 1976 operated under the name INGMAG (Vrečko 2012). After 1975, new machinery and technologies allowed more rapid exploitation with a smaller work force. In 1984, the quarry was taken over by the company Mineral d.d. (Mineral podjetje za pridobivanje, predelavo in montažo naravnega kamna, delniška družba). Today, granodiorite is extracted by modern methods, including a diamond cutting wire. Granodiorite from the Cezlak Quarry is currently exported to Austria, Croatia, Italy, Serbia and Hungary. The second granodiorite quarry is at Josipdol (no longer active), located on the northern side of Pohorje. It is named after the village of Josipdol in the municipality of Ribnica on Pohorje. The quarry was opened in the second half of the 19th century and produced cobblestones. Five quarries, having 250 employees, were active between World Wars I and II (Vrečko 2012).

Figure 10. a) Granodiorite is used in the staircase of the Slovenian Parliament. Dark grey panels of the façade are made of cizlakite. Photo: Matjaž Zupanc. b) Maximarket department store with granodiorite façade. Photo: Miran Udovč.

Buildings

The major part of current production is used as paving and cladding material for residential buildings, churches, outdoor steps, and public squares, thus giving a unique character to many Slovenian towns and cities. Several important buildings are decorated with the stone, including the Slovenian Parliament (Fig. 10a), the Republic Square business complex (1962–1984), which houses the Maximarket department store (1971) (Fig. 10b), and the Faculty of Law of the University of Ljubljana (2000); all of the above are located in Ljubljana, and some have been declared cultural monuments of national importance.

Other significant buildings in Slovenia in which the stone has been used (listed chronologically) include:

- Old Bridge, Maribor, renovated with granodiorite during WWII

- hydro power plant Mariborski otok, during WWII
- business building Konus, Slovenske Konjice, 1985–1987
- Grajski Square, Maribor, 1993
- business building HIT, Nova Gorica, 1997
- Faculty of Social Sciences, University of Ljubljana, Ljubljana, 1999
- business skyscraper BTC-CITY, 2000
- business building, VO-KA, Ljubljana, 2001
- business building PKMG, Ljubljana, 2001
- congress hall − Hotel Habakuk, Maribor, 2002
- pavement of the old city centre, Kranj, 2012/2013
- pavement of the old city centre, Celje, 2013
- Faculty of Medicine, University of Maribor, Maribor, 2013

Since 1940, granodiorite has also been widely used by sculptors for various monuments, fountains, and sculptures exhibited throughout Slovenia (Brate et al. 2004). Among them:

- monument of Boris Kidrič, Maribor, 1961
- monument to the victims of fascism, Rogatec, 1964
- monument to the victims of WWII, Ormož, 1994
- monument of Rudolf Maister, Ljubljana, 1999
- monument to the victims of Frankolovo, Frankolovo, 2000
- Mobitel fountain, Ljubljana, 2001
- fountain in Postojna, 2009

Monuments abroad:

- monument to the victims of fascism, Graz, Austria 1961

One of the important Slovenian architects who used this stone was Edvard Ravnikar (1907–1993), who was a student of architect Jože Plečnik. Later, he led the new generation of Slovene architects, who are notable for developing the Slovene architecture field infrastructure.

Related Heritage Issues

Both granodiorite quarries lie within the Ecologically Important Areas, Pohorje (ID 41200) and Natura 2000, on the Pohorje site (ID 3000270). The largest square in Ljubljana, The Republic's Square, has been declared a cultural monument of national importance (Official Gazette RS, No. 44/2014-1813). The business complex in the square includes a central platform, two high buildings and a department store, Maximarket. Granodiorite has also been used for the façade and staircase of the Slovenian Parliament, a cultural monument of local importance (Official Gazette RS, No. 60/93-2193, 105/2008-4510).

Related Dimension Stones

Pohorje granodiorite is visually similar to the Železna Kapla/Eisenkappel tonalite. However, they are related geographically, not geologically. The main distinguishing characteristic of the granodiorite is its transition to porphyritic type and the presence of numerous aplite−pegmatite veins in the central part of the massif, where major exploitation is located. The veins are much sparser and thinner in the tonalite. Another specific feature related to the Pohorje granodiorite massif is the transitional diorite to pyroxenite lens referred to as cizlakite, located at the southern margin of the pluton. A small quarry operated there for a short period. Cizlakite is crosscut by aplite−pegmatite veins, which form a striking contrast to the dark green cizlakite. As reserves of this unique stone are very limited, exploitation has been stopped. At present, only Pohorje granodiorite is exploited as a natural stone resource from the Cezlak Quarry.

CONCLUSIONS

Pohorje granodiorite is a classic calc-alkaline igneous rock of Miocene age (18.7 Ma). It is spatially, but not geologically, related to other calc-alkaline intrusions along the Periadriatic fault zone and in the Pannonian Basin. It is medium- to fine-grained, and locally transitional to porphyritic granodiorite. The major mineral components and geochemical parameters identify the stone as a granodiorite rather than tonalite. Accessory minerals have no significant impact to the quality of the stone. White veins crosscutting the granodiorite consist of fine-grained aplite in the middle and coarse-grained pegmatite at the edges, adding a special character to the stone. The two localities in the Pohorje area are protected as valuable natural geological features.

Pohorje granodiorite is the only igneous rock exploited in Slovenia and is considered to be the highest quality natural stone, explaining its widespread use. It provides a special character to many of the larger towns and cities in Slovenia. Pohorje granodiorite is characterized by its high density, low water absorption, and low porosity. It exhibits high frost and salt resistance, as well as a high compressive strength and a very high flexural strength. These features facilitate a wide array of applications, mainly as paving and cladding material for the interiors and exteriors of residential buildings, churches, and other structures. Some buildings decorated with granodiorite have been declared cultural monuments of national importance, indicating the high regard in which the stone is held. The stone is also suitable and widely used by sculptors for various monuments and fountains.

The information given in this work will contribute to the international knowledge and recognition of Pohorje granodiorite as a natural stone that is part of our heritage. The authors believe that the granodiorite fulfils at least five of the criteria for a Global Heritage Stone Resource.

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GAC-MAC FIELD GUIDE SUMMARY

Whitehorse 2016: GAC-MAC Joint Annual Meeting Field Trips

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FIELD TRIPS SUMMARY

Nestled in the heart of the Northern Cordillera, Yukon's Capital Whitehorse is surrounded by diverse geology spanning the Proterozoic to present that is spectacularly exposed along our transportation system. This meeting is complimented by a full suite of field trips that will tour some of the best the Yukon and southeast Alaska has to offer geologists. Workshops include 'Indicator minerals in till and stream sediments of the Canadian Cordillera,' 'Ancient and Modern VMS deposits,' and an EdGEO Teacher Professional Development Workshop. For full details on the technical program, travel and accommodation information visit: www.whitehorse2016.ca.

The Whitehorse Copper belt provides a close to home tour through a historic mining district located only a few kilometres from the city centre. The 30 km-long belt hosts a number of mineralized occurrences and historic mine sites. The first discoveries were made during the stampede to the Klondike between 1897 and 1899; many of these deposits were mined intermittently during a first phase of mining until 1920. A modern phase of exploration and mining took place between 1967 and 1982. The trip will include stops at heritage sites where historical mine workings give you a glimpse into the past. Visits to more modern mining and exploration sites are sure to pique your interest, where uncommon skarn minerals such as thulite, valleriite and yellow serpentine may be found. This is a very affordable way of adding value to your conference experience!

If you are looking for a multi-day adventure there are several trips that cover a range of topics from placer gold to hardrock mining. A two day trip to Faro, located north of Whitehorse, focuses on the geology of the Anvil District and remediation of the Faro Mine Complex (FMC), which is Canada's largest Acid Rock Drainage (ARD) contaminated mine site. The geology portion of the trip will discuss the stratigraphy and structure of the Anvil pyritic massive sulphide deposits and their enclosing host rocks. The Cambrian Anvil deposits are situated in Selwyn basin, a lower Paleozoic marine shale basin southwest of carbonate platform rocks of northwest Laurentia. Open pit mining and on-site milling operations produced approximately 400 million tonnes of potentially acid-generating waste rock and tailings. Protecting the surrounding aquatic and terrestrial environment from these wastes and associated heavy metal-bearing seepage presents significant challenges in a mountainous, northern environment. This trip will take participants along the scenic Robert Campbell Hwy with a night's stay in the town of Faro 'Yukon's best kept Secret' located along the banks of the Pelly River.

Faro Mine Complex: Canada's largest Acid Rock Drainage contaminated mine site (will be explored during the trip titled, "SED-Exhumed: Catch a rare glimpse into the belly of the Faro Mine Complex, one of Canada's most prolific past-producers of lead and zinc").

Another two day trip will guide participants through the historic and active Keno Hill Mine, located 330 kilometres north of Whitehorse in one of the world's highest-grade silver mineralized districts. Field stops will examine host rock stratigraphy and mine sites in the district, view mineralized drill core samples and visit the historic community of Keno City. Between 1913 and 1989, the Keno Hill Silver District produced more than 214 million ounces of silver from over 4.8

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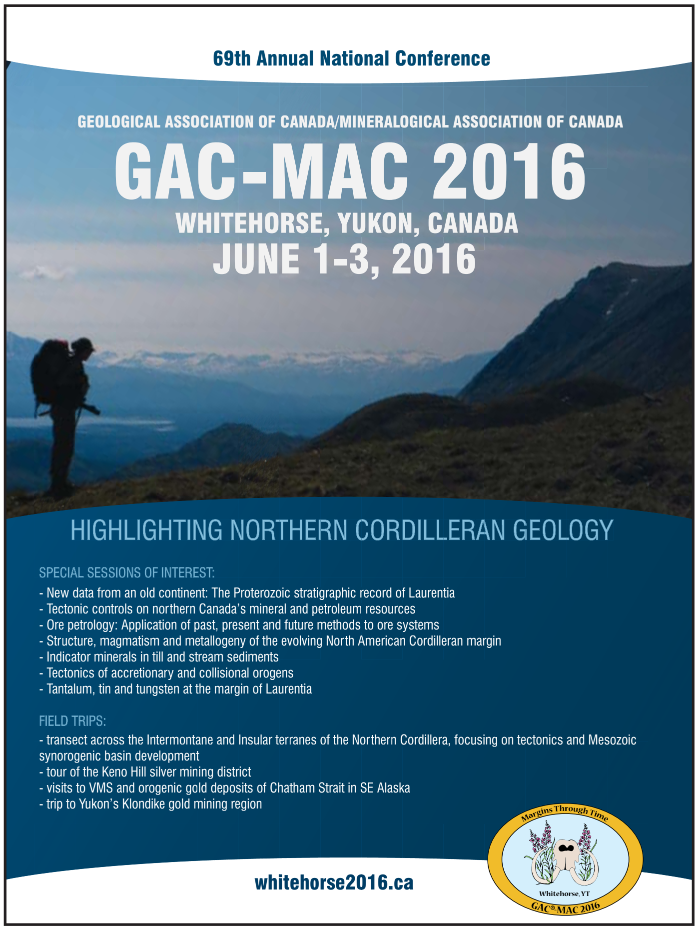
Kluane Range Mountains just north of Haines Junction: Kluane Lake in the background (will be viewed during trip titled, "Tectonics of the Intermontane and Insular terranes, and development of Mesozoic synorogenic basins in southern Yukon; Carmacks to Kluane Lake").

million tonnes of ore. There are over 35 mine sites that once contained some of the richest Ag–Pb–Zn vein deposits in the world. It provided the backbone of the Yukon economy from the 1920's until the 1960's and at one time supported up to 15% of the Territories' population. Two nights will be spent in the historic Keno city, where participants will have ample time to do the walking tour of Keno City, have a pint at the Keno City Hotel that was built in the early 1920's, or simply explore this mining ghost town.

The 'veins to valleys' field trip will take participants all the way to Dawson City and introduce them to the geology, structural evolution, geochemistry, placer deposits and Pleistocene palaeontology of the northern and central Klondike District. The route will take you into some of the most famous gold producing drainages in the world, including Bonanza and Hunker creeks, while exploring fascinating geology and modern placer mining methods. In the evenings we will stay in Dawson City and give you a taste of gold rush culture under the midnight sun. Sign up early and stake your claim on this rare field trip to the Klondike!

A five day field trip takes participant down the 'Trail of 1898' to Skagway, then onto Juneau and Haines via ferry, and ending with a drive through the spectacular scenery of the front ranges of the Saint Elias Mountains. This trip will expose participants to the best mineral deposits in southeast Alaska and is bookended by two days of highway stops that will put the deposits in a regional geological context. The focus will be split between volcanogenic massive sulphide deposits of the Late Triassic Alexander metallogenic belt and orogenic gold deposits of the Cretaceous Juneau Gold Belt. For a truly immersive VMS experience, this post-conference field trip can be paired with the pre-conference VMS workshop taught by world-class experts and emphasizing deposits from the northern Cordillera.

A 3-day field trip will examine the geology of the Intermontane and Insular terranes (mainly Stikinia and Wrangellia), the development of Mesozoic synorogenic basins (Whitehorse, Kluane, Dezadeash), and related Mesozoic–Cenozoic arc magmatism between Carmacks, Whitehorse and Kluane Lake in southern Yukon. The scenic roadside and river exposures will provide the backdrop for discussions of the tectonic evolution of the northern Cordilleran orogen and its resources, from Paleozoic to the Present. This trip will involve long-distance travel on major Yukon highways and end with two short hikes in the magnificent Kluane Ranges.



69th Annual National Conference

GEOLOGICAL ASSOCIATION OF CANADA/MINERALOGICAL ASSOCIATION OF CANADA

GAC-MAC 2016

WHITEHORSE, YUKON, CANADA

JUNE 1-3, 2016

HIGHLIGHTING NORTHERN CORDILLERAN GEOLOGY

SPECIAL SESSIONS OF INTEREST:

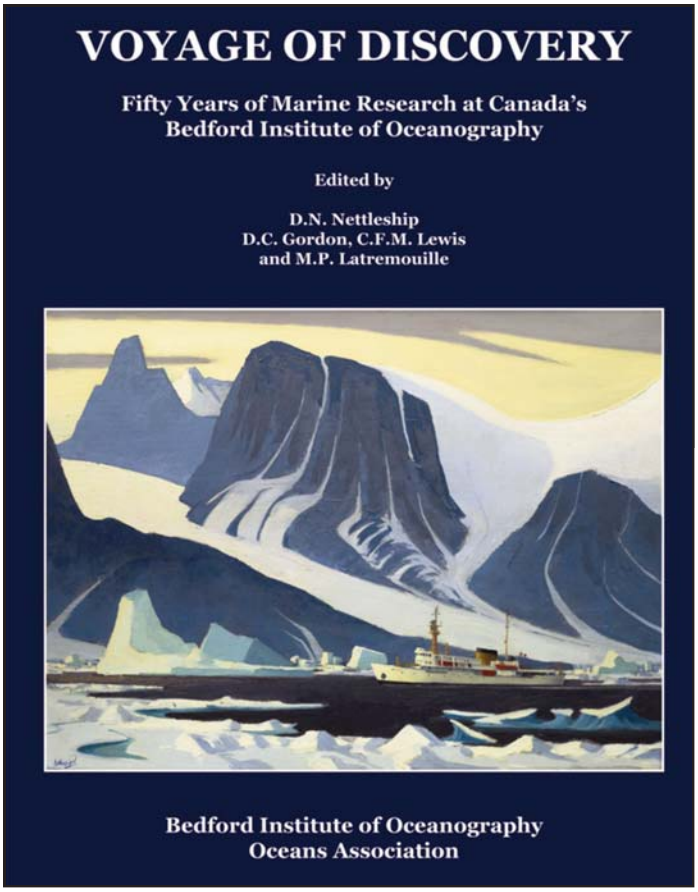
- New data from an old continent: The Proterozoic stratigraphic record of Laurentia
- Tectonic controls on northern Canada's mineral and petroleum resources
- Ore petrology: Application of past, present and future methods to ore systems
- Structure, magmatism and metallogeny of the evolving North American Cordilleran margin
- Indicator minerals in till and stream sediments
- Tectonics of accretionary and collisional orogens
- Tantalum, tin and tungsten at the margin of Laurentia

FIELD TRIPS:

- transect across the Intermontane and Insular terranes of the Northern Cordillera, focusing on tectonics and Mesozoic synorogenic basin development
- tour of the Keno Hill silver mining district
- visits to VMS and orogenic gold deposits of Chatham Strait in SE Alaska
- trip to Yukon's Klondike gold mining region

whitehorse2016.ca

REVIEW



Voyage of Discovery – Fifty Years of Marine Research at Canada's Bedford Institute of Oceanography

D.N. Nettleship, D.C. Gordon, C.F.M. Lewis and M.P. Latremouille (*editors*)

Publisher: Bedford Institute of Oceanography Oceans Association
(a non-profit organization)
Published: 2014; 460 p.
Price: $35 (CND); Hardcover
Available from the publisher at www.bio-oa.ca or www.amazon.com; there are plans for an e-book edition in the future.
Proceeds of the book sales are going towards public education about the oceans.

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It is a daunting task for one book to cover the past fifty years of activity of an eminent research organization such as Canada's Bedford Institute of Oceanography, and to do justice to the contributions by the past and present institute staff in their service to the Canadian Federal Government, to the Canadian public, as well to global science by being a responsible partner in the stewardship of the world's oceans. The book itself is also a physically daunting volume weighing in at 5 lbs (2.2 kg) and printed on high quality, coated, glossy paper with 460 pages in an 8.5 x 11 inch hardcover format. The book succeeds admirably on both counts, by providing a worthy heft as a testimonial to the research and activities of the organization, by being a comprehensive history of the institute to date and by providing concise 'scientific essays' written especially for this volume that address many topical issues of interest to a broad cross-section of the curiously minded. The book is intended for a broad readership from professional oceanographers to environmental and resource managers, decision-makers on ocean policy, marine-science educators and students, and any person interested in the oceans and in Canada's unique position as the country with the longest coastline in the world.

First, however, some brief background on the Bedford Institute of Oceanography or B-I-O as it is known to many. BIO was established in 1962 in eastern Canada on the shore of Bedford Basin, in Dartmouth, Nova Scotia by Dr. William van Steenburgh who was then Director-General for science in the Canadian Federal Government Department of Mines and Technical Services. The objective was to bring together different federal agencies that had, up until that time, overseen various aspects of oceanographic science and resource management that encompassed the relatively young sciences of physical, chemical and geological oceanography, as well as hydrography, fisheries and biological oceanography. The concept was to mirror the successful establishment of oceanographic research institutions in the United States like Scripps Institution of Oceanography in La Jolla, California and Woods Hole Oceanographic Institution in Woods Hole, Massachusetts, which brought together a diverse set of scientists, engineers and dedicated seagoing capabilities to address scientific questions in the inherently interdisciplinary field of oceanography. Unlike those independent research institutions, however, BIO was designed to be a federal research laboratory with the purview to serve the needs of the Federal Government in addressing important issues related to the oceans. Interestingly,

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an important area of concern at that time was the Arctic Ocean and, as we know today, the Arctic continues to be an important region environmentally, economically and strategically.

BIO was established by combining the Canadian Hydrographic Service, which brought ships to the table, the Atlantic Oceanographic Group, which was a research arm of the Fisheries Research Board of Canada and the Marine Services Branch, which was part of the Department of Mines and Technical Services overseen by van Steenburgh. The Federal Departments overseeing BIO have varied over the years and today BIO is comprised of the Federal Departments of Fisheries and Oceans Canada, Natural Resources Canada, Environment Canada and the Department of National Defence. BIO has become the largest and arguably the leading oceanographic research institution in Canada, respected around the world for its scientific contributions and its leadership on oceanographic issues.

The volume, *Voyage of Discovery – Fifty years of Marine Research at Canada's Bedford Institute of Oceanography*, as mentioned earlier, is a fitting testimonial to BIO's contributions both internationally, but also critically to national Canadian issues related to the oceans. The volume is arranged into 12 sections. The first section covers the historical aspects of the Institution's formation and evolution and is followed by a discourse on the 1970 circumnavigation of the Americas by the Institution's iconic research vessel CSS Hudson. This is followed by 10 sections that relate past and present research in 48 readable, easily accessible articles that are more like 'scientific essays' on topical subjects that demonstrate the breadth and relevance of ocean science to the modern world. The 10 sections cover the following themes: Arctic Studies, Ocean Life, Ocean Circulation and Chemistry, Hydrography and Seabed Mapping, Geological Oceanography, Fisheries, Ecosystems and Aquaculture, Marine Contamination, Technology and Instrument Development, Energy Developments, and BIO and the Law of the Sea. A final section is an Epilogue written by the editors of the volume who are all past research scientists from BIO. The book ends with a series of 10 appendices with a BIO time line, lists of annual reports, past directors, a campus history, awards, patents, and a list of authors.

Within each of the 10 main science sections are several articles written mostly in a clear and concise fashion for a broad readership and focused on the contributions of BIO in a national context, but often with global implications. These articles are informative and topical for today's world, even when discussing past historical events. I found them easily digestible, clearly articulated, copiously referenced and liberally documented with high quality images. The reader can pick and choose what to read either as a group of articles in a subject section, or by individual article, as each article gives a summary abstract of the content, and the content itself is written with sufficient background information to give the reader the appropriate context. As a practicing marine research scientist in geological oceanography, I found the Arctic Studies section and the following disciplinary sections on Ocean Life, Ocean Circulation and Chemistry, Geological Oceanography and Seafloor Mapping of most interest. The Fisheries section is interesting from a political background as important policy decisions have been made based on science as well as other factors – perhaps not in that order. The sections on Marine Contamination, Technology Development and Energy Resources will be of historical curiosity to those with interests in those areas. The final section on the Law of the Sea is a good example of why expert advice and in-depth knowledge of a subject area is often needed when it comes to Canada's role in the international arena of global ocean issues. Many of these essays would probably make great introductory material for undergraduate students in survey classes of oceanography, as well as for the interested public. Perhaps more importantly, the volume serves as an important snapshot of oceanographic research for decision makers and managers on how science can inform critical and strategic decisions. I am curious if there is any plan to make the book and or the articles available in digital or PDF format. This would ensure more widespread dissemination and possibly greater impact. Digital copy access would probably be more important for educators perhaps. The physicality of having the book on your desk or coffee table, however, is undeniable and the price of $35 Canadian is remarkably reasonable (although its shipping weight will cost you!).

In many of the conclusions to the individual articles, and recapitulated in the Epilogue, is the hope that those reading this volume not only gain an understanding and perspective on how valuable these contributions have been, but will also be motivated to act to encourage policy makers and government leaders both nationally and locally to support future science funding at the federal level. There are several activities such as long-term monitoring and national representation on global issues like the Law of the Sea, climate change and sea-level rise that only a national federal laboratory with the facilities and mandate of BIO can undertake on behalf of Canada's future. The *Voyage of Discovery* makes a good case for this.

In summary, the *Voyage of Discovery* will indeed take the reader to many places both geographically and intellectually, showcasing fifty years of Canadian oceanographic science and exploration, making new discoveries and expanding what is known so we can ask questions of where we go from here. The book superbly accomplishes its goal of documenting the first fifty years of the Bedford Institute of Oceanography. May the next fifty years be as productive.

Information on the book cover painting

The cover illustration is also worthy of note. The artist of the original oil painting, C. Anthony Law (Lt. Commander, DSC, RCN) was born in London, England in 1906 to Canadian parents and died in 1996. Commander Law was an accomplished artist and well known, both nationally and internationally, for his artwork and writings. He participated on several CSS Hudson research cruises in the eastern Canadian arctic and produced many sketches and paintings including this portrait of the Hudson surveying the East Baffin Land Current in Baffin Bay.
(additional information from David Nettleship)

COMMENTARY

OPEN ACCESS – PANACEA OR PANDORA'S BOX?

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The publishing industry has altered beyond all recognition in the first two decades of the 21st century, and scientific journals cannot evade the ever-shifting winds of change. There has been a fundamental leap from the expensive hardcopy printing of glossy scientific journals to online digital delivery of most content. Even for those journals that maintain print format, production is less, and many scientists now elect to do their reading and research from a laptop or a tablet. *Geoscience Canada* went 'digital only' about four years ago, and the advantages in terms of costs and flexibility are clear. I will admit that I personally miss the feeling of relaxing in a comfortable chair with my coffee and flipping through the printed pages, but there is no going back on this trend. Online publishing transforms access to scientific material on a global basis; readers on the other side of the world, where libraries would likely not archive printed copies of *Geoscience Canada*, can now easily read our scientific papers. Providing, that is, that they buy a personal subscription, or that their employer or institution (if they have one) holds an institutional subscription. Our annual subscription fee is amazing value (at less than $100 per year), but costs for some geoscience journals are hundreds or even thousands of dollars annually, and institutional subscriptions are even more expensive. Online publishing still requires subscriptions, because it depends on users paying for access, but such access does not come cheap. This seems a strange paradox, given the cost of digital publishing is so much less than printed media. Many universities now face severe challenges in maintaining these expenditures, and subscriptions to specialized journals are being discontinued, leading to protests from individual researchers.

However, those in the ivory towers remain the most favoured in terms of their access to online journals. Ironically, the online digital revolution has actually made access to this vital information more difficult for others within the research community. Those who work outside universities or select government institutions have more limited access, and it is becoming increasingly difficult to seek out such material at your local university library, if indeed one is available to you. Procuring a copy of some hard-to-find article can be a real challenge, and the cost of downloading a single paper is as much as buying a hardcopy book – in some cases the only recourse is to beg the assistance of academic colleagues or even students. Gone are the days when I would walk down Elizabeth Avenue on a nice day to browse some recent issues of journals in the periodicals reading room at Memorial University. Most of the journals that I used to look for are no longer even on the shelves, and hardcopy back issues are increasingly relocated to distant, dusty and inconvenient off-site storage. Papers that are published by scientists who are supported by government funding, in government institutions and at universities, now often appear in journals that the general public or unaffiliated researchers cannot freely or easily access. The online digital revolution makes the sharing of information easier for all of us, and the internet now connects us across the globe, but this new tree of knowledge has yet to fully blossom for scientific publishing. This again seems paradoxical, for commercial scientific publishing remains highly profitable even in times when most other parts of the sector confront serious fiscal challenges in maintaining their business models. Even before low-cost online publishing arrived, scientific publishers enjoyed lower costs, because the authors of papers are unpaid, as are the reviewers and most scientific editors. Given this backdrop, it is not surprising that discontent with access restrictions and increasing subscription costs has grown, and some in the research community have called for deliberate boycotts of prominent corporate publishers. It is also not surprising that research funding agencies, which mostly disperse public resources, are increasingly concerned that their investments are not rewarded by wide visibility and availability of their research.

The *Open Access* concept emerged as a possible solution to this growing dilemma, and it is now a persistent topic wherever scientists gather and talk, although opinions and viewpoints are understandably diverse. Three research funding agencies in Canada, including NSERC, which is the principal source for geoscience research funding, now require that peer-reviewed

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publications be made freely available to all within one year of their initial publication. Essentially, grant recipients must facilitate *open access* to the results of research funded by the public through NSERC. Broadly similar policies exist, or soon will exist, in most other western countries, including the United States and much of the European Union. Open access is a new reality that researchers and scientific journals must now address, but we do not yet fully understand the long-term implications of this latest paradigm shift. Nevertheless, I feel confident in predicting that open access will bring more irreversible changes in scientific publishing, and that it may also affect how *Geoscience Canada* functions in the future.

We are in many respects already an open access journal, because all of our content is available without subscription about two years after publication. Everyone agrees that complete 'open access' to the results of research benefits all of us in the long run, but there is little or no consensus about how this can be achieved on a sound fiscal basis. The costs of publishing online are indeed reduced, and many of us who participate in the process remain essentially unpaid, but the production of complex papers still requires money as much as it does time, dedication and effort. These financial resources presently come from subscriptions, and in the case of non-profit society journals such as *Geoscience Canada*, partly from other sources such as operating grants. For a journal to publish high-quality, peer-reviewed research on a long-term sustainable basis, it must have some reliable sources of revenue. For commercial publishers, these operations must also provide profits to the parent company and its shareholders. *Geoscience Canada*, like other society journals, redirects any profits into expanding publication activities, but we still have the need for long-term fiscal sustainability. If the money runs out, publishing the papers will be curtailed.

Open access is a complicated and controversial topic, and a short piece such as this cannot address all possible ramifications. A very good source for those interested in details and debates is an article published three years ago in *Elements* (Speer et al. 2013). There are presently two main 'flavours' of open access, which are referred to as *Gold* and *Green*. In the Gold Model, immediate unrestricted access is provided to the final published article on the publisher's website, following payment of an Article Processing Charge (APC) by the author(s) or their institution(s). In the Green Model*,* access to the final published paper on the publisher's website remains behind a subscription wall, but the author(s) are permitted to place an equivalent document (typically, the accepted manuscript) in an online data repository, or on a personal or institutional website. Clearly, the Gold Model has multiple advantages in terms of easily locating and accessing material, but is more costly to authors; the policies relating to the Green Model vary widely but some commercial publishers still do not permit authors to make their work available in any alternate fashion. The Gold Model spawned the interesting concept of *Open Access Journals*, which are funded almost entirely through APC payments – such journals support themselves (or generate profits) through a model that is in some respects reminiscent of the self-publishing industry. However, to be fair, it is not the same as prospective novelists quickly publishing their own unedited work, because some open access journals subject submissions to peer-review, and there is no guarantee of acceptance for any given manuscript. Nevertheless, there are growing concerns about the integrity of the peer-review process in circumstances where the rapid acceptance and publication of papers brings direct financial benefit. The open access journals generally also have lower 'impact factors' than established traditional journals, so they are not widely favoured by authors. Open access policies currently developed by Canadian agencies recognize APC payments as an eligible use of research funding, but not all authors have access to such funding, and their institutions or employers may not be willing to cover such costs. Open access journals operating on this funding strategy would thus not be available to all researchers or writers, and if they become the norm, their terms could suppress valuable work and thought by authors who lack financial resources. There is, however, a compromise between the status quo and fully open-access journals. Some scientific journals make open access possible through a more flexible policy where immediate access to papers is facilitated through an optional payment, following final acceptance of a paper for publication. Many recommend this hybrid model as the most prudent approach for society-managed, non-profit journals, and it forms the basis for the open access initiative that *Geoscience Canada* is introducing as of volume 43. We will become a *hybrid journal*, in which some content (such as this piece) is freely available, but other scientific articles will still require subscription access, unless the authors and/or their institutions have opted for open access. We term these optional charges Open Access Supplements (OAS) as they are not strictly related to processing of the articles.

I must here reiterate a very important point – *Geoscience Canada is already* an open access journal in many respects. The material that we have published over 40 years is for the most part freely available to all through our archives, as our modest annual subscriptions apply only to the current volume and the two previous years. In this respect, we differ from many other society-funded journals, in which all previous content remains behind a subscription wall. We are already a long way down the open access road, and we are very proud of this attribute. If you have an article in our editorial pipeline, or plan to soon submit a manuscript, you do not yet need to think about open access, in fact, we prefer not to discuss it prior to acceptance of a final revised manuscript. Our assessment of manuscripts and the comments and suggestions made by peer reviewers will remain impartial and uninfluenced by the prospect of OAS revenue. This is the core ethos of all scientific publishing: there must be no possibility of a bad paper being accepted simply because it will provide revenue. The integrity of our peer-review and assessment process will be faithfully respected. When a revised manuscript is finally accepted, the author(s) will be presented with options for gaining open access. The OAS is scaled to the length of the paper, and consists of a flat-rate charge of $1000, plus $100 per printed journal page; thus, a ten-page scientific paper will incur an OAS of $2000. We also offer a second option that provides open access one year from the publication date for a lesser rate of $500 plus $50 per published page. This latter option will satisfy policies now announced for research funding agencies in Canada. Decisions on open access do not have to be made upon acceptance of a paper; the OAS can be paid at a later time, after which the controls on access to the article will be removed.

These new open access policies are entirely *optional*; there is no requirement that an OAS be paid if authors or their institutions are content that access to the article will require a *Geoscience Canada* subscription for the first two years. Submission of an article, or its acceptance, will impose no obligation on authors to eventually provide OAS payments. The fee structure proposed for *Geoscience Canada* compares very favourably to those now in place for some other geoscience journals, and articles that are not open access upon publication will continue to become freely available after two years from issue publication.

Some of you will undoubtedly be asking why *Geoscience Canada* is making this choice, or why we even need to consider imposing charges for open access. You might also wonder if we plan to eventually become a fully open access journal. Funding agencies require that access to research become as wide and easily accessible as possible, and we have to respond to this reality. We have done so by implementing a reasonable and optional process that will allow us to continue publishing quality science, while meeting the journal's financial obligations. We cannot predict how many authors will ultimately opt for open access, but it is clear that should a large portion of our technical content become unrestricted, the incentives for personal and/or institutional subscriptions will diminish, and we will inevitably lose subscription revenue. Resources are needed to continue publishing because our long term goal goes beyond maintaining the *status quo* – we want to expand, diversify and increase our impact. Geoscientists should be very familiar with the necessity of change because the fossil record clearly demonstrates the fate of those who fail to adapt when environments shift. Some pundits have even suggested that the effects of open access on traditional scientific publishing could resemble a mass extinction. Should that be the case, *Geoscience Canada* has every intention of being amongst the survivors. It is not presently in our plans to become an open access journal funded *entirely* by OAS revenue, but if our strategy catches on with authors, it may be possible for us to eventually provide open access to more authors who lack the ability to meet OAS charges. We cannot predict where this road will lead us, but instead must just follow it and find out.

I will close with some thoughts that reveal my own advancing age. When I started submitting manuscripts over 30 years ago, the concept of *page charges* was common, and these still exist for some print-based journals. Upon acceptance of a paper, a request for settlement of page charges was made to authors, but final publication was not dependent upon payment. Page charges instead supported the operations and costs of the journal, and employers and institutions were generally agreeable to their payment. As a proud new author, I used to buy packages of glossy reprints for each article, and send them out to my colleagues and collaborators, or in response to 'reprint requests' that arrived on neat little cards in the mail. The sale of reprints to authors also helped journals meet their costs. Even today, some journals levy significant charges for 'clean' PDF-format files without watermarks that authors are allowed to send to colleagues, but *Geoscience Canada* will continue to give these to authors for free. At *Geoscience Canada*, we are fully aware that we are about to navigate some uncharted waters, and some might feel that our planned route is unwise. If you soon receive one of those welcome letters that confirms acceptance of your paper, but then suggests that you or your institution might wish to part with a few thousand dollars, just think back to those vanished days of page charges. Open access is really not so different in its overall concept. But then remember that open access, should you choose to pay for it, gives you something that page charges never could. It guarantees that the entire world has immediate access to the hard-won results of your scientific endeavours with the click of a mouse. I think you will agree that such impact has considerable value.

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