DOI: https://doi.org/10.68732/29cbc2fe1cad71a9

ISBN: 978-9989-2053-6-1

Non-destructive Determination of Building Stone Provenance

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Abstract

In professional conservation practice, determining the provenance of building stone used in historic structures represents a frequent and methodologically complex task. Conventional analytical approaches capable of providing reliable answers are predominantly destructive, as they require sampling of the investigated material. Sample extraction is often unacceptable in the case of valuable architectural or artistic elements. For this reason, the present study focuses on the application of reflectance spectroscopy as a promising, efficient, and non-destructive analytical method. The paper introduces the fundamental principles of this technique, discusses its analytical potential, and evaluates its applicability to the study of historic building and decorative stone, including its limitations and the requirements for further methodological development.

Keywords

Non-destructive testing, Reflectance spectroscopy, Spectral characteristics, Spectral library.

1 Introduction

The question of the origin of building stone used in historical structures is frequently encountered in conservation practice, archaeology, and architectural history. Traditionally, its answer has relied on petrographic analysis, archival research, or visual expert assessment performed by experienced geologists. Petrographic analysis remains the most applied method, but it requires physical sampling and is therefore inherently destructive. This limitation becomes critical when the investigated objects are historically or artistically valuable, where any intervention may be restricted or strictly prohibited. Moreover, the interpretation of results depends heavily on the expertise of a trained petrographer whose judgement may vary depending on experience and available comparative materials.

Archival research, although valuable, is often insufficient due to incomplete or missing historical records, which frequently lack information about repairs or later interventions involving different stone types. Similarly, in situ visual assessment is based primarily on expert experience and visual

similarity, which may be significantly distorted by the presence of weathering crusts, surface deposits, or conservation treatments.

The importance of analytical methods for provenance determination has been emphasised, for example, by Dontová (2021), who discussed the use of trace element analysis, typically performed by destructive techniques such as LA-ICP-MS or neutron activation analysis. Přikryl et al. (2015) proposed a methodological framework for determining the origin of limestone and marble using laboratory-based approaches, which are likewise destructive in nature. Hopkinson et al. (2015) demonstrated the effectiveness of combining petrographic and spectroscopic methods to identify potential quarry sources, highlighting the strong potential of modern analytical techniques, but still requiring sampling.

These limitations underline the necessity of developing non-destructive methods based on objective and reproducible data analysis rather than expert judgement alone. Equally important is the possibility of applying such methods directly in situ, without the need for material sampling

2 Reflectance Spectroscopy

The methodology presented in this study assumes that the optical properties of surfaces allow for their identification (Pavelka Jr. et al., 2018). In the case of rocks, these properties are influenced by their mineral composition, internal structure, and conditions of formation, and are therefore characteristic of specific lithological types. Reflectance spectroscopy operates on the principle of the interaction between electromagnetic radiation and matter, measuring the proportion of incident radiation reflected from a material surface as a function of wavelength (Fig. 1). Different materials interact with radiation in distinct ways due to their chemical and structural properties, leading to selective absorption and reflection of specific wavelengths (Clark, 1999; Matoušková, Kovářová, 2021).

The resulting spectral reflectance curve represents a unique “spectral signature” of the investigated material and can be used for identification through comparison with reference datasets. Several factors influence the shape of these curves, including mineralogical composition, grain size and orientation, surface roughness, porosity, moisture content, and the degree of weathering. In the case of near- and mid-infrared measurements, the influence of colour and ambient lighting is significantly reduced due to the use of controlled illumination and contact probes, although proper measurement geometry remains essential for obtaining reliable results.

The identification process is based on comparing measured spectra with reference spectral libraries. Existing databases, such as those maintained by the U.S. Geological Survey (USGS Spectral Library) and NASA (NASA Spectral Library), provide extensive collections of spectral data; however, they are primarily designed for remote sensing applications and often do not include materials typical for specific regions such as Central Europe. For this reason, it is necessary to develop dedicated regional spectral libraries reflecting historically used building stones. Fig. 2 shows the acquisition of spectral data in situ (Matoušková et al., 2021).

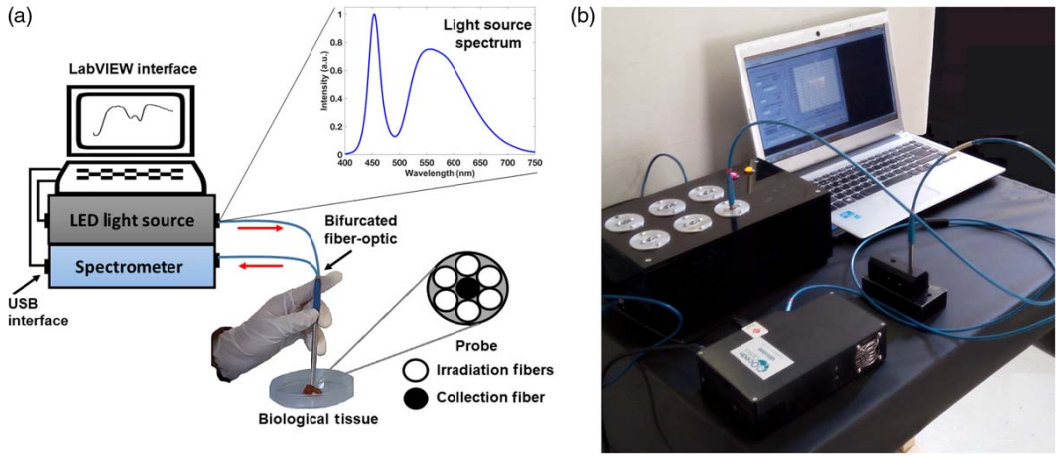


Fig. 1 Right: reflectance spectroscopy device; left: schematic representation of the application (Spie Digital Library).



Fig. 2 Examination of Petr Parléř's tombstone using reflectance spectroscopy, St. Vitus Cathedral in Prague.

The comparison of spectral curves is performed using mathematical algorithms. Among these, the Spectral Angle Mapper (SAM) has proven particularly effective, as it evaluates similarity based on the angle between spectral vectors, with smaller angles indicating higher similarity. Data processing requires averaging multiple measurements and evaluating statistical parameters, which often necessitates custom computational solutions due to the absence of specialised user-friendly software.

3 Results and Discussion

The construction of a comprehensive spectral library is essential for the successful application of reflectance spectroscopy in provenance studies. The present research focuses primarily on sandstones and marlstones, which are common materials in historical architecture in the Czech Republic. Samples were obtained from lithotheques, academic collections, and museum repositories, and measured under controlled laboratory conditions. Each sample was measured repeatedly, and the resulting spectral curve represents an average of multiple measurements to ensure statistical reliability. An example of sandstone CTU spectral library can be seen on Fig. 3, an example of marstone CTU library is shown on Fig. 4.

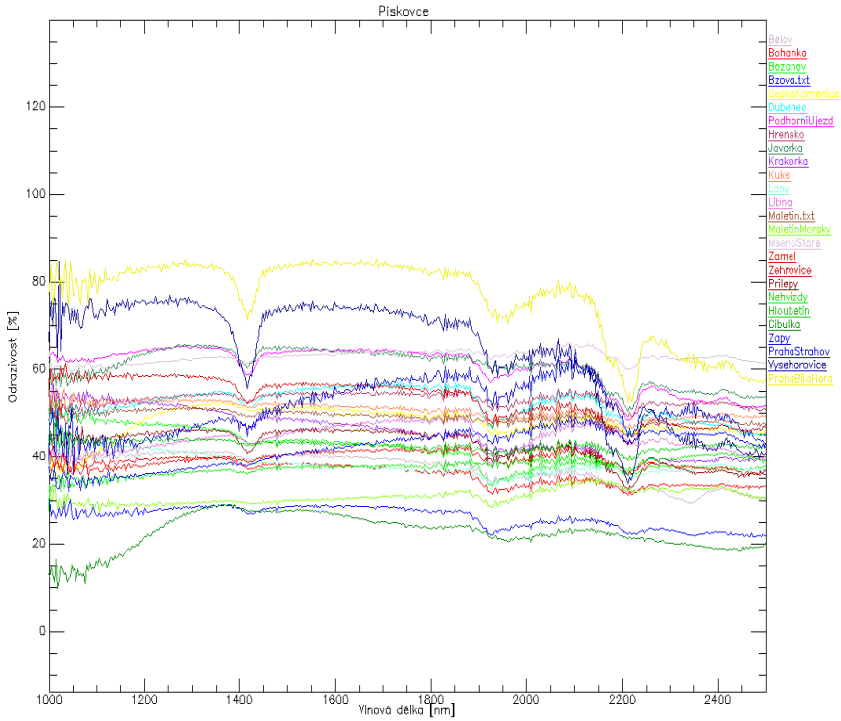


Fig. 3 Spectral reflectance curves of selected Czech sandstones, Spectral Data Library of the Faculty of Civil Engineering, Czech Technical University in Prague.

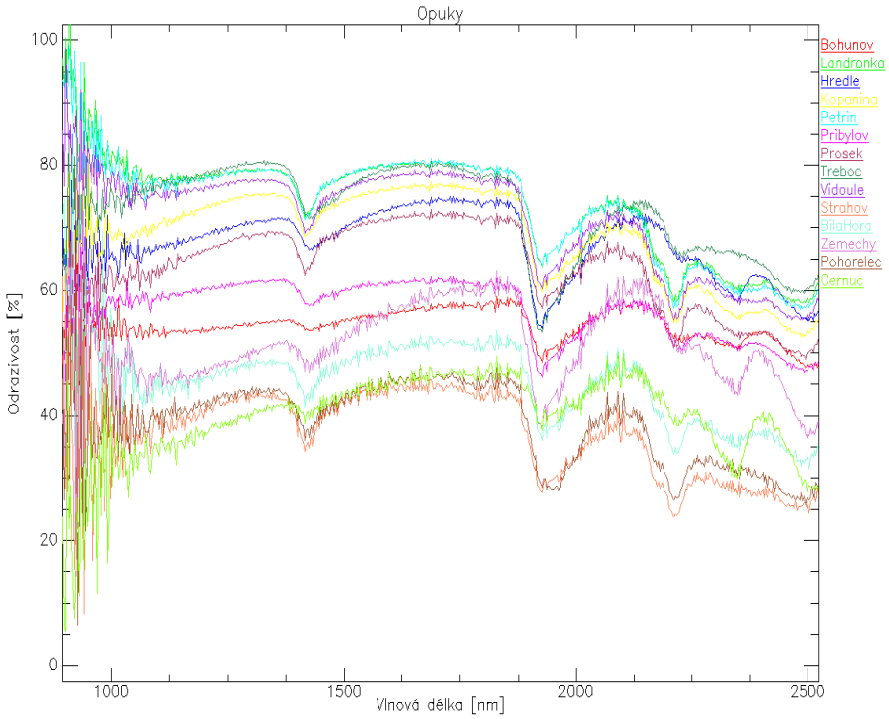


Fig. 4 Spectral reflectance curves of selected Czech marlstones, Spectral Data Library of the Faculty of Civil Engineering, Czech Technical University in Prague.

The practical application of the method can be illustrated by the analysis of a sandstone block from the base of the Wohlmut Gallery (Fig.5), which showed the highest similarity to sandstone from the Kuks locality. This result corresponds well with historical records indicating the use of sandstone from the Dvůr Králové region (Březinová et al., 1996), thereby confirming the validity of the method in this specific case (Kovářová et al., 2025).

Unknown: WK-sokl_prumer.txt:C2		
Library Spectrum	Score	SAM
Kuks.txt:C2	[0.933]:	{0.933}
Bohanka.txt:C2	[0.931]:	{0.931}
Maletin.txt:C2	[0.931]:	{0.931}
Hloubetin.txt:C2	[0.926]:	{0.926}
Hrensko.txt:C2	[0.926]:	{0.926}
Javorka.txt:C2	[0.922]:	{0.922}
Dubenec.txt:C2	[0.921]:	{0.921}
HoriceStare.txt:C2	[0.916]:	{0.916}
Zamel.txt:C2	[0.915]:	{0.915}
Lany.txt:C2	[0.914]:	{0.914}
Zehrovak10mereni.txt	[0.912]:	{0.912}
Bzova1.txt:C2	[0.912]:	{0.912}
MsenoStare.txt:C2	[0.910]:	{0.910}
Prilepy.txt:C2	[0.909]:	{0.909}
Belov.txt:C2	[0.903]:	{0.903}
Libna.txt:C2	[0.901]:	{0.901}
CeskaKamenice.txt:C2	[0.901]:	{0.901}
Bozanov.txt:C2	[0.892]:	{0.892}
Krakorka.txt:C2	[0.885]:	{0.885}
Nehvizdy.txt:C2	[0.880]:	{0.880}
MaletinMorsky.txt:C2	[0.877]:	{0.877}
zapy.txt:C2	[0.824]:	{0.824}
Cibulka.txt:C2	[0.792]:	{0.792}

Fig. 5 Ranking of the visual similarity of the sandstone block forming the base of the Wohlmut pulpit.

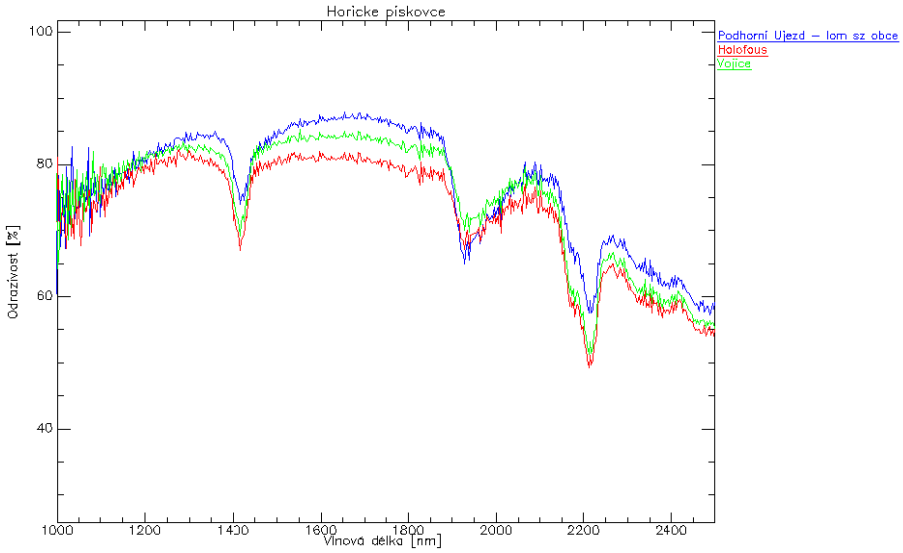


Fig. 6 Spectral reflectance curves of selected Hořice sandstones.

Despite these promising results, several limitations must be considered. One of the main challenges is the high degree of similarity between spectral curves of certain lithological types, such as Hořice sandstones or Prague marlstones, which cannot always be reliably distinguished using the current methodology (Fig.6). Another significant factor is the impact of surface conditions, including weathering processes, contamination, and conservation treatments (Fig.7). These factors can substantially alter the spectral response, often smooth characteristic features and reducing overall reflectance.

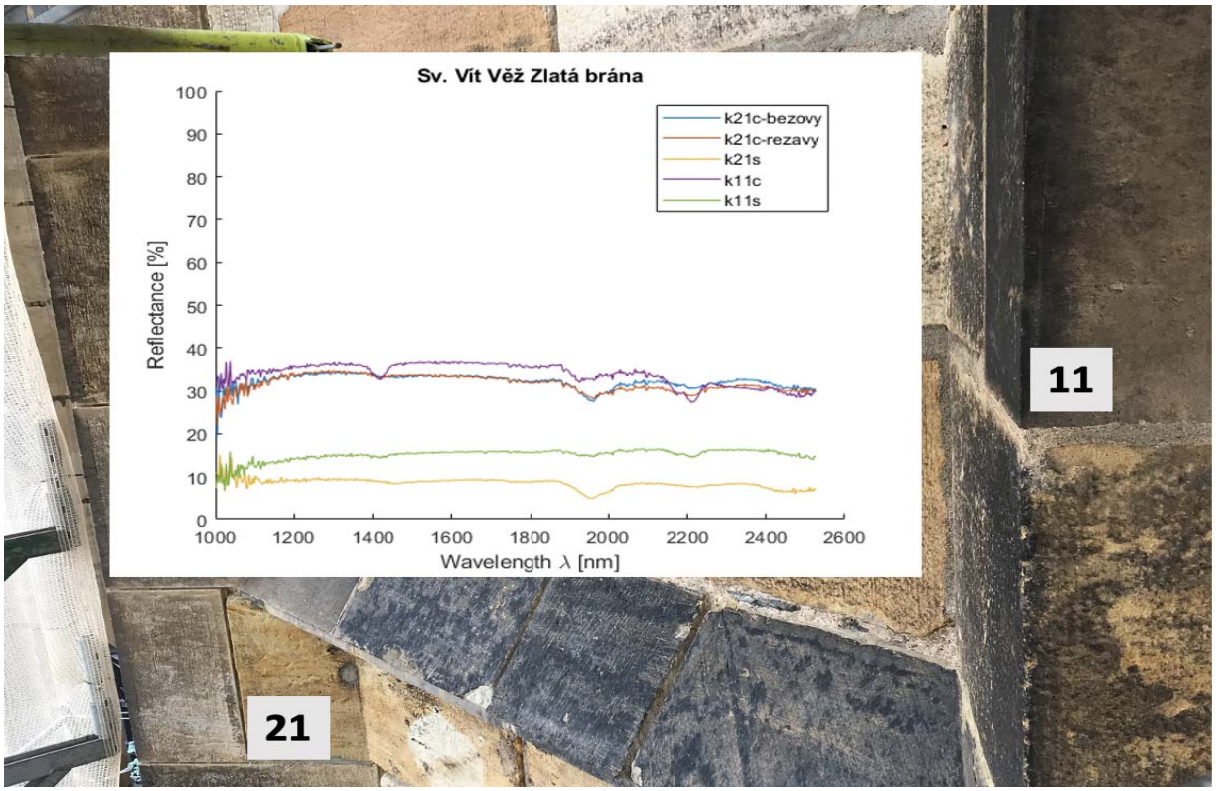


Fig. 7 Spectral reflectance curves for the blocks of the south staircase of St. Vitus Cathedral (samples labeled "c" after the numerical identifier indicate a clean surface; samples labeled "s" after the numerical identifier indicate a soiled surface).

The influence of conservation materials is particularly important. For example, alkoxysilane-based consolidants may result in the formation of silica phases that modify the spectral signature (Xu et al, 2019), while lime-based coatings lead to the formation of calcium carbonate, which also affects reflectance characteristics (Doehne, Price, 2010). These alterations may significantly complicate or even prevent the identification of the original material. In many cases, the complete history of conservation interventions is not known, which further increases uncertainty.

The reliability of the method may be improved by adopting a selective analytical approach, in which measured spectra are compared only with relevant subsets of the spectral library corresponding to specific historical periods. This approach requires independent dating of the studied objects, which may be achieved through archival research or traceological analysis (Cihla et al., 2022). The integration of such methods within a broader multidisciplinary framework significantly enhances the accuracy and interpretability of the results.

4 Conclusion

Reflectance spectroscopy represents a highly promising non-destructive method for determining the provenance of building stone used in historical architecture and artefacts. Its primary advantages include the possibility of in situ application, the absence of sampling, and relatively rapid data acquisition. However, the method also presents several challenges, particularly in terms of data processing, the similarity of spectral characteristics among certain materials, and the sensitivity of measurements to surface conditions and conservation treatments.

At the current stage of development, reflectance spectroscopy should not be considered a standalone tool but rather a complementary method that benefits from integration with other non-destructive analytical approaches. The accuracy of results may be significantly improved through interdisciplinary collaboration involving experts in geology, materials science, conservation, archaeology, and art history.

Future research should focus on expanding spectral libraries to include a wider range of historically used materials, developing more advanced data processing algorithms, and establishing international databases of spectral reflectance data. Such developments would considerably enhance the applicability and reliability of this method in the field of cultural heritage research.

5 Acknowledgement

This paper was supported by the Ministry of Education, Youth and Sport of the Czech Republic in the programme INTER-EXELLENCE II No. LUABA24083 Memory written in stone.

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