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Micro-PIXE and micro-IBIL characterization of lapis lazuli samples from Myanmar mines and implications for provenance study

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Abstract The provenance of raw lapis lazuli used since the Neolithic Age for the realization of carved artefacts can be pivoting for the reconstruction of ancient trade routes. The role of main provider of this material in ancient times is generally attributed to the Badakhshan quarries (Afghanistan), although other deposits could have been exploited as well since antiquity. The systematic multi-technique analysis of lapis lazuli rocks coming from four known source areas (located in present-day Afghanistan, Tajikistan, Siberia and Chile) has led in the last years to the compilation of a protocol for provenance determination. The protocol is based on differences in the physical–chemical properties measured with non-invasive techniques (Ion Beam Analysis (IBA)), making it suitable also for precious ancient artefacts. In this work, 10 new reference samples from the Mogok quarry (Myanmar), previously subjected to a complete petrographic and mineralogical characterization, have been analysed employing μ-PIXE (Proton Induced X-ray Emission) and μ-IBIL (Ion Beam Induced Luminescence) techniques. The subdivision of Myanmar samples into three groups, previously suggested, is corroborated by diopside trace elements concentrations. The results also allow to include Myanmar as a new provenance in the analytical protocol, indicating that provenance markers such as presence/absence of wollastonite, altered pyrites and Sr content are still valid to discriminate also the Myanmar lapis lazuli from Chilean or Siberian ones. New weaker markers (Zn content in diopside, Se and Cu contents in pyrite) are proposed for the discrimination of Myanmar from Afghan or Tajik provenances; however, from the analysis it arose the need of investigating new mineral phases with IBA to find strong markers for a definitive discrimination with samples from Southwest Asia.

1 Introduction

Lapis lazuli is commonly classified as a metamorphic rock [1], although the mechanisms that lead to its formation are quite complex and up to now not completely understood. It is, however, certain that its generation requires precise geological conditions, occurring only in few places around the globe [2]. The Badakhshan region in Afghanistan presents the richest and most famous lapis lazuli quarries, but some other less exploited sources exist in the world, for example in Pamir Mountains (Tajikistan), near Irkutsk in the Lake Baikal area (Siberia, Russia), in the Coquimbo region (Chile), near Mogok (Myanmar) [3]. Lapis lazuli is a complex rock composed by a high number of mineral phases. The blue colour is provided by the lazurite phase ($(Na, Ca)_{7.5\text{-}8}$ $(Si, Al)_{12}$ $(O, S)_{24}$ $(SO_4, Cl)_{1.3\text{-}2}$), a member of the sodalite group where sulphur ions are enclosed in cage-like structures [4]. Other main phases are diopside ($CaMgSi_2O_6$), calcite ($CaCO_3$), wollastonite ($CaSiO_3$) and pyrite (FeS). In gemmology, lapis lazuli is defined as a semi-precious stone and its value is enhanced by its peculiar colour and rarity. In fact, it has been appreciated and used since the VII millennium BCE and can be found in glyptic art and inlays coming from ancient sites of different civilizations, such as Ancient Egypt and the Indus Valley Civilisation [5–8]. The interest of archaeologists in this stone resides particularly on the fact that such artefacts were found at a distance of thousands of kilometres from the known lapis lazuli quarries, posing a lot of questions on the ancient trade routes connecting the sites and on the economic and social structure in ancient societies. The possibility to associate the raw material to the place of geological origin by means of scientific analysis seems to be the optimal way to provide some

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