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ORIGINAL PAPER

# Multitechnique characterization of lapis lazuli for provenance study

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**Abstract** Lapis lazuli is one of the oldest precious stone, being used for glyptic as early as 7,000 years ago: jewels, amulets, seals, and inlays are examples of objects produced using this material. Only a few sources of lapis lazuli exist in the world due to the low probability of geological conditions in which it can form, so that the possibility to associate the raw material to man-made objects helps to reconstruct trade routes. Since art objects produced using lapis lazuli are valuable, only nondestructive investigations can be carried out to identify the provenance of the raw materials. Ionoluminescence (IL) is a good candidate for this task. Similar to cathodoluminescence (CL), IL consists in the collection of luminescence spectra induced by megaelectronvolt ion (usually protons) irradiation. The main advantage of IL consists in the possibility of working in air while measuring simultaneously the composition of major and trace elements by means of complementary ion beam analysis techniques like particle-induced X-ray emission (PIXE) or particle-induced gamma-ray emission (PIGE). In the present work, a systematic study of the luminescence properties of lapis lazuli under charged particle irradiation is reported. In the first phase, a multitechnique approach was adopted (CL, scanning electron microscopy with microanalysis, micro-Raman) to characterize luminescent minerals. This characterization was propaedeutic for IL/PIXE/PIGE measurements carried out on significant areas selected on the basis of results obtained previously. Criteria to identify provenance of lapis lazuli from four of the main sources (Afghanistan, Pamir Mountains in Tajikistan, Chile, and Siberia) were proposed.

**Keywords** Lapis lazuli · Provenance · Ionoluminescence · Cathodoluminescence · Archaeometry · Ion beam analysis

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## Introduction

Lapis lazuli is one of the oldest precious stones, being used for glyptic as early as 7,000 years ago [1]. It was diffused throughout the Ancient East and Egypt by the end of the fourth millennium B.C. and continued to be used during the following millennia: jewels, amulets, seals, and inlays are examples of objects produced using this material. In more recent times, from the sixth century B.C. until the last centuries, finely grinded lapis lazuli was also used as pigment.

Only few sources of lapis lazuli exist in the world due to the low probability of geological conditions in which it can be formed [2, 3]. Thus the possibility to associate the raw material to man-made objects is helpful to reconstruct trade routes. This is especially true for ancient contexts where there is an absence or scarceness of written evidences [4]. Although the Badakhshan mines in Afghanistan (the more famous being Sar-e-Sang) are now widely considered as the only sources of the lapis lazuli in ancient times [4–7], other

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