

New insights into dating rock art in the arid carbonate terrain of the Negev Highlands, Israel

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Abstract

This study examines the challenges of dating petroglyphs in the arid Negev Highlands, Israel, focusing on rock art carved on carbonate rocks. Utilizing portable X-ray fluorescence technology, we measured manganese (Mn) concentrations in desert varnish coatings as a potential nondestructive method for relative dating. The results reveal a statistically significant correlation between Mn concentrations and chronological phases, enabling the categorization of the petroglyphs into five distinct periods, from the Intermediate Bronze Age (2500–2000 BCE) to the present. The study introduces a reliable nondestructive approach to dating petroglyphs, contributing not only to rock art research but also to a broader understanding of cultural development in arid regions.

1. Introduction

Petroglyphs, a form of rock art found worldwide, represent some of the earliest expressions of human creativity (Andreae et al., 2021; Whitley, 2005: 11–13). They are made by removing material from the rock surface using techniques such as pecking, engraving, or abrasion. Differences in microtopography or color between the rock surface and the newly exposed area render the petroglyphs visible to the naked eye.

Given the potential of petroglyphs to enhance our understanding of cultural development, there is a strong need for reliable noninvasive dating techniques. Numerous methods have been applied to date these artifacts, such as radiocarbon and cation-ratio dating; microlamination, varnish thickness, and micro-erosion measurements; and colorimetric analysis. However, most are unreliable for petroglyph dating, and those that have proven reliable are destructive to the artifacts

(Dorn et al., 1992; Watchman, 2000; Bednarik, 2007: 129–132; Dietzel et al., 2008; Liu and Broecker, 2008; Liu et al., 2025). Recent advances have utilized portable X-ray fluorescence (pXRF) to address this issue (Lytle et al., 2008; McNeil, 2010; Macholdt et al., 2018; Macholdt et al., 2019; Andreae et al., 2020; Andreae et al., 2021).

Desert varnish, a thin coating that often serves as a substrate for petroglyph engraving, is common in hyper-arid to semiarid regions and has been studied for dating purposes (Lytle et al., 2008; McNeil, 2010; Goldsmith et al., 2014; Macholdt et al., 2018; Macholdt et al., 2019; Otter et al., 2020). The thickness of maturely developed varnish ranges from 1 μm to 200 μm . Varnish typically consists of approximately 70% clay minerals and amorphous silica, and it is notably enriched in manganese (Mn), which may constitute 10–20% of its composition (e.g., Reneau et al., 1992; Liu and Dorn, 1996; Liu

et al., 2025). Desert varnish develops on a wide variety of rock types, including limestone, sandstone, basalt, and chert. However, the oxidation mechanisms behind its formation remain unresolved. Evidence indicates that rain or fog leaches trace elements from clay minerals, which are subsequently redeposited into the varnish through atmospheric moisture (Otter et al., 2020; Liu et al., 2025). It is widely accepted that rock varnish forms primarily from airborne dust (Potter and Rossman, 1977; Krinsley, 1998; Fleisher et al., 1999; Bao et al., 2001; Goldsmith et al., 2014; Otter et al., 2020). Varnish layers are composed of alternating black and yellow microlaminations correlating to high and low Mn and iron (Fe) oxides ratios, respectively, which are associated with wet and dry climatic conditions. These microlaminations reflect past climatic fluctuations on a millennial scale (Liu, 1994; Liu and Dorn, 1996; Liu et al., 2000; Broecker and Liu, 2001; Dietzel et al., 2008; Liu and Broecker, 2008; Otter et al., 2020: 2). In the Negev Highlands, Israel, the carbonate host rock contains high proportions of calcite; however, its influence on the geochemical composition of the fine dust and varnish is limited (Goldsmith et al., 2014: 101; Otter et al., 2020: 9–10).

Prior research utilizing pXRF has been integrated into rock art studies across various substrates. This technique is particularly relevant in arid and semiarid regions, where desert varnish coats rock surfaces, such as in the Negev Highlands, the focus of this study. At the Coso petroglyphs site in Nevada, USA, researchers measured Mn concentrations in desert varnish that developed on basalt and observed that they increased with varnish age (Lytle et al., 2008). Similar studies on sandstone conducted elsewhere yielded comparable results. For example, in eastern Utah, USA, Mn concentrations measured in graffiti and adjacent rock art enabled to reconstruct the chronology of the local rock art (McNeil, 2010). In the Ha'il Region of Saudi Arabia, a correlation was found between Mn surface densities and the petroglyph age (Macholdt et al., 2018). Additional research in the Al-Quwaiyah Governorate in Saudi Arabia combined iconographic data with Mn density measurements, revealing multiple phases of rock art creation (Andreae et al., 2021). Despite these contributions, no detailed research has yet examined petroglyphs engraved into carbonate substrates such as limestone.

Dietzel et al. (2008) note that fewer varnish layers accumulate on petroglyphs than on non-engraved surfaces. They further found that younger petroglyphs host fewer varnish layers than older ones. Deeply carved petroglyphs remove existing desert varnish, exposing a pristine rock surface on which a new varnish lamina accumulates. This new varnish layer covers both the new petroglyph and the surrounding preexisting varnish. Liu et al. (2025) dated the varnish microlamination sequence from the Dead Sea area to determine maximum-limiting surface exposure ages and found it to be similar to that of the Negev varnish. While microlamination dating is a reliable tool to evaluate past climatic conditions and can indirectly assist in petroglyph dating, it requires invasive sampling, which limits its applicability to preserving the integrity of the rock art.

The rock art of the Negev Highlands is a cultural heritage asset with both historical and archaeological significance. It comprises a fairly homogeneous rock art assemblage that evolved over approximately eight millennia on Eocene limestone covered by Holocene varnish (Eisenberg-Degen and Rosen, 2013; Liu et al., 2025). Alongside the Negebite tradition, dominated by abstract elements, zoomorphs, anthropomorphs, inscriptions, and foot/sandal prints, there are some intrusive traditions representing the movement of people into and through the region (Eisenberg-Degen and Rosen, 2013). These differ in subject matter and style from the Negebite petroglyphs, making them easily distinguishable (Schwimer and Yekutieli, 2021).

Rock art is seldom discovered in archaeological contexts that provide clear stratigraphic information, as is the case in the Negev. Stratigraphy, along with related material finds, underpins archaeological interpretation, providing the basis for dating and determining cultural affiliation. Only a limited number of studies have addressed the chronology for rock art in the Negev Highlands, most notably those by Anati (1954, 2015) and Eisenberg-Degen and Rosen (2013).

Anati's groundbreaking studies suggested a relative chronological sequence that may reflect a progression in social complexity, as indicated by stylistic changes in the petroglyphs. In contrast, Eisenberg-Degen and Rosen (2013) constructed a relative chronology of engraving phases based on petroglyph color and superimposition and anchored by datable attributes such as

inscriptions and the depiction of specific weapons and domesticated animals.

The dates associated with rock art are approximate and may extend over long periods, possibly even two millennia. Panels (engraved rock surfaces) displaying numerous petroglyphs with similar desert varnish coloration (as observed by the naked eye) are unlikely to have been created on one occasion; rather, they probably represent cumulative engraving activity over time. When engraved motifs recur across multiple periods, unlike inscriptions in distinct dialects, Christian crosses, or specific weapon types, it may be nearly impossible to date them on the basis of style or typology.

By combining empirical data with traditional archaeological methods, this study aims to shed light on some of the uncertainties regarding cultural and historical aspects of Negev rock art. We seek to construct a detailed timeline for the Negev petroglyphs grounded in empirical parameters, highlighting the potential of desert varnish on carbonate terrain to establish a

relative yet measurable chronological framework of this rock art. Utilizing pXRF enables a fast, nondestructive method applicable on a broad scale, providing a tool for future studies of petroglyphs in the Negev and other regions with comparable geological settings.

2. Materials and methods

2.1 Field survey of the study site

The study site, Ramat Matred, is located on the Avedat-Matred Plateau (Fig. 1) in the Negev Highlands. The plateau's elevation ranges from 400 to 1,000 m above sea level and lies about 170 km south of Jerusalem. This terrain is rocky and composed primarily of marine sediments consisting of limestone, dolomite, marl, chalk, and chert beds dated from the Late Cretaceous to the Tertiary period (Arkin and Braun, 1965; Avni, 1991). These sediments are affiliated with Avedat Group formations from the Eocene epoch (Braun, 1967; Benjamini and Reiss, 1979).

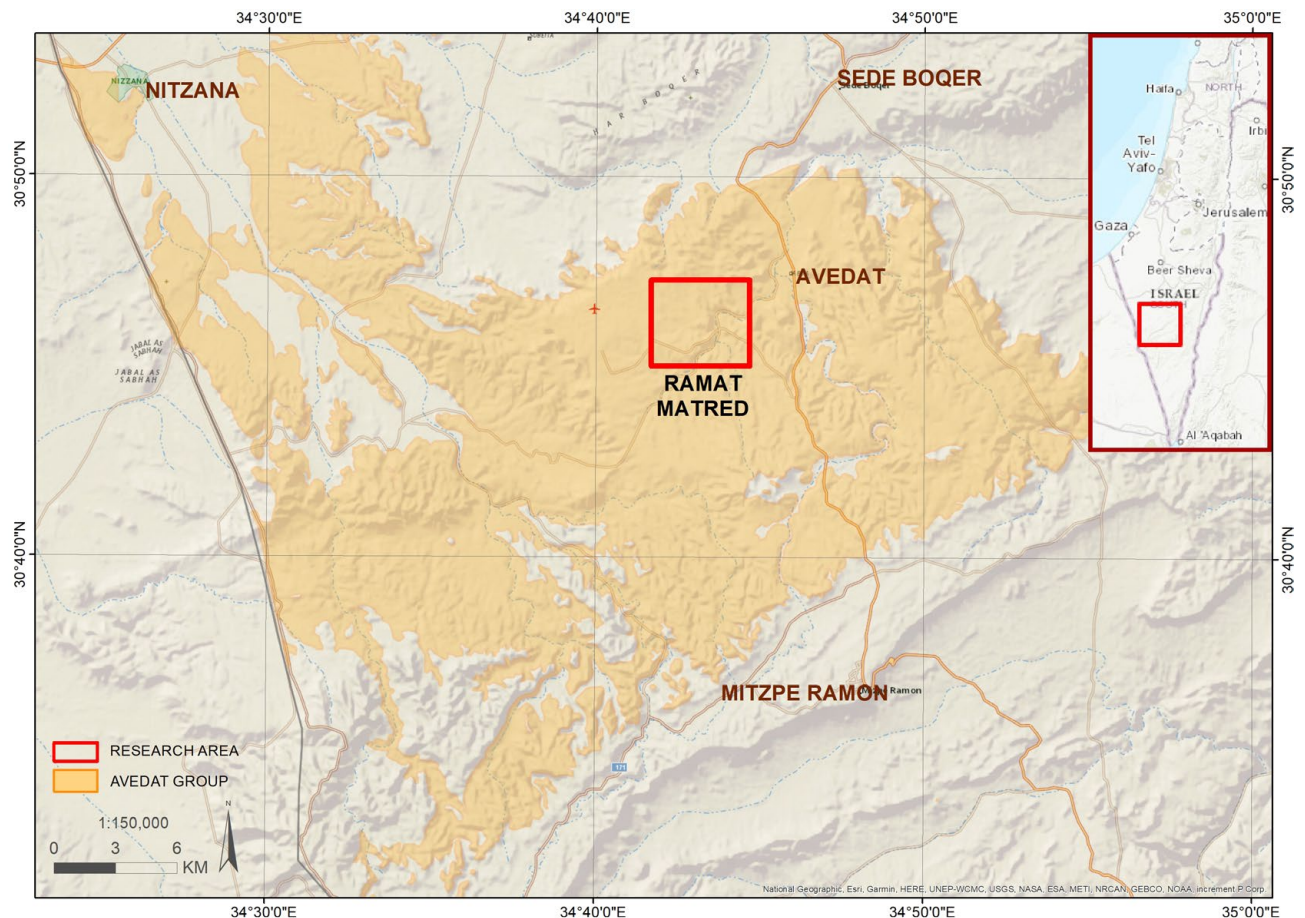


Figure 1. The Negev Highlands and the study site Ramat Matred.

The site experiences an arid climate, as it lies within the hot Sahara–Arabian desert belt of the Northern Hemisphere. Average annual precipitation varies, ranging from 130 mm in the northern regions to less than 90 mm in the south. Dew and fog occur over 50% of the late summer and fall mornings, with an average yield of 0.1 mm on cloth attached to glass plates. The annual dew amount averages approximately 1400 h/yr (Kidron et al., 2002; Bruins, 2012; Goldsmith et al., 2014: 104).

A survey of the Avedat-Matred Plateau produced a comprehensive database from which six representative rock panels (Panels A–F; Fig. 2) were selected for this research (Schwimer, 2015; Shapira, 2018). Selection criteria included the presence of inscriptions, motifs associated with a limited time frame, evidence of superimposition, and variations in varnish color. All selected panels feature petroglyphs carved into dark desert varnish coating carbonate rocks. These outcrops contrast sharply with the surrounding bright, bare carbonate landscape, making them a prime canvas for engraving.

Environmental data were documented for each panel, including spatial location, aspect, and size.

Upon arrival at the field, the following procedures were carried out for each panel (Table 1, Fig. 2):

1. The panel was gently cleaned with distilled water to remove dust accumulation, using no mechanical tools. The color of each panel and petroglyph was then identified using Munsell soil-color charts—specifically the Hue 7.5YR diagram—and recorded after the rock surface had dried.
2. Each petroglyph underwent elemental analysis of its mineral composition using pXRF (as detailed below).

2.2 Portable X-ray fluorescence (pXRF)

PXRF measures chemical composition, making it an effective method for identifying and analyzing Mn and Fe in and over petroglyphs. Additionally, pXRF is a non-destructive technique, which enables numerous on-site measurements.

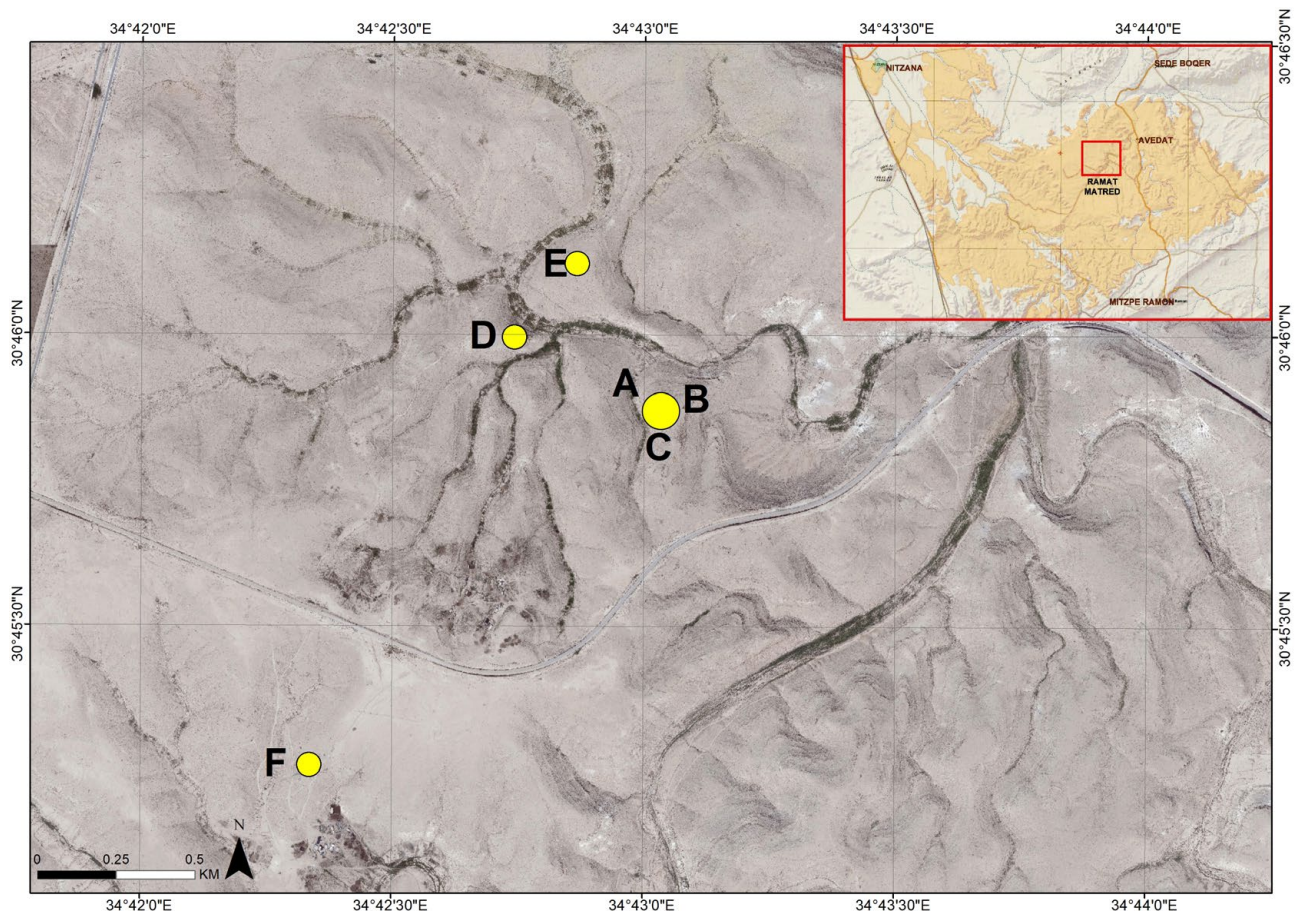


Figure 2. The research area and panel location.

Panel	X	Y	Panel length (cm)	Panel width (cm)	Panel gradient	Panel aspect	No. of petroglyphs per panel	No. of activity phases	No. of patina shades	Chronological anchor petroglyphs	Period of chronological anchors
A	172869	519471	95	61	180	None	39	5	4	Thamudic inscription	Hellenistic–Roman periods 3rd c. BCE–3rd c. CE
										Arabic inscription	Early Islamic period mid-7th–10th c. CE
										Bedouin <i>wusum</i>	Ottoman period–present 1825–1960 CE
B	171760	518353	120	75	45	SE	40	4	5	Arabic inscription	Early Islamic period 735 CE
										Bedouin <i>wusum</i>	Ottoman period–present 1825–1960 CE
C	172414	519708	187	41	30	W	30	3	4	Arabic inscription	Early Islamic period 737/738 CE
D	172612	519940	106	53	12	E	64	4	5	Crescent-head figures	Intermediate Bronze Age 2500–2000 BCE
E	172867	519470	48	36	50	W	7	1	1	None	Unknown
F	172868	519471	99	57	180	None	8	2	2	Nabatean inscription	Hellenistic–Byzantine periods 3rd c. BCE–3rd c. CE

Table 1. Panel location and physical characteristics

The pXRF apparatus used in this study was a Thermo Scientific™ Niton™ XL3t GOLDD+ XRF Analyzer, equipped with a 50 kV X-ray tube and a Geometrically Optimized Large Area Drift Detector (GOLDD), and featuring 80 MHz real-time digital signal processing and dual embedded processors for efficient computation and data storage. As the Niton pXRF is set to use several company-preset calibrations, “mining” mode was employed, which includes the relevant elements for this study (i.e., Fe, Mn, Ca). To reduce the screening time, measurements focused on Fe and Mn using only the main filter with an irradiation time of 30 seconds and the device’s factory-set calibration program. The irradiation area is circular, with a diameter of either 3 or 8 mm, making it efficient for analyzing relatively nonhomogeneous surfaces. The results were recorded in ppm.

Marks and lines forming petroglyphs and inscriptions vary in width, with some as narrow as 1 mm. Inscriptions and figures with very fine lines were excluded due to the limitations of the pXRF device. Sampling spots were selected in the wider and deeper areas of each petroglyph. For Panels A, B, E, and F (Figs. 2, 3), we initially

used an 8 mm diameter collimator for small-spot measurements. To ensure the readings reflected the engraved surface rather than the surrounding intact varnish, we repeated measurements on four of the six panels using a 3 mm diameter collimator.

For Panels C and D (Figs. 2, 3), readings were taken using only the 3 mm collimator. In total, we conducted 550 pXRF measurements: 237 from petroglyphs and 100 from uncarved intact surfaces of desert varnish utilizing the 3 mm collimator, and 150 measurements from petroglyphs and 63 from uncarved varnish using the 8 mm collimator. The ratio of uncarved varnish to petroglyph measurements, 1:2.3, remained consistent for both the 3 mm and 8 mm spots.

A statistical analysis of the pXRF data was conducted to examine the correlation between Fe and Mn. For Panel E we analyzed also calcium (Ca) concentrations. This analysis was based on the assumption that both Mn and Fe accumulate in microlaminations over time, albeit at different rates. Mn and Fe values from petroglyphs of various periods were plotted in box and whisker plots, using Microsoft Excel software, enabling comparison

across different time periods and highlighting the minimum, maximum, and average Mn values for the petroglyphs.

3. Results

Establishing a chronology based on empirical data for the Negev Highlands petroglyphs requires defining a specific range of Mn and Fe concentrations that correspond to defined time periods. Each panel may contain up to five petroglyph engraving phases, identifiable by their color and superimposition. The earliest engraving phase in each panel is designated as Phase 1. Petroglyphs that can be dated within these phases serve as chronological anchors forming a foundation for a traditional rock art sequence and enabling the construction of a relative timeline.

3.1 Panels and petroglyphs description

(Fig. 3, Table 1)

Panel A features five engraving phases, with datable petroglyphs identified in Phases 1, 3, and 5. Engraving Phase 1 includes a Thamudic inscription dated to the Hellenistic–Roman periods, approximately between the 3rd century BCE and the 3rd century CE (Halloun, 1990: 37; Macdonald, 2000). Phase 3 features an

Arabic inscription dated to the mid-7th to 10th century CE (Sharon, 1990), while Phase 5 contains a *wusum*, Bedouin tribal symbol, dating from the early 19th century to the mid-20th century CE (Shapira, 2018).

Panel B includes four engraving phases, with datable petroglyphs in Phases 2 and 3. Engraving Phase 2 contains an Arabic inscription dated to 735 CE (Sharon, 1990), and Phase 3 features a *wusum* from the early 19th century to mid-20th century CE (Shapira, 2018).

Panel C presents three engraving phases, with a datable petroglyph observed only in Phase 1. This phase contains an Arabic inscription dated to 737/738 CE (Sharon, 1990).

Panel D (Fig. 3, Table 1) contains four engraving phases, with datable petroglyphs only in Phase 1. This phase features “crescent-headed figures” dated to the Intermediate Bronze Age (2500–2000 BCE, Schwimer and Yekutieli, 2021).

Panel E comprises a single engraving phase featuring seven motifs but provides no archaeological anchor and cannot be dated. This panel was selected for control, as its petroglyphs have the darkest documented desert varnish in the Avedat-Matred Plateau. By sampling this panel, we aim to compare the values of the petroglyphs to the similarly dark non-engraved varnish surrounding them.

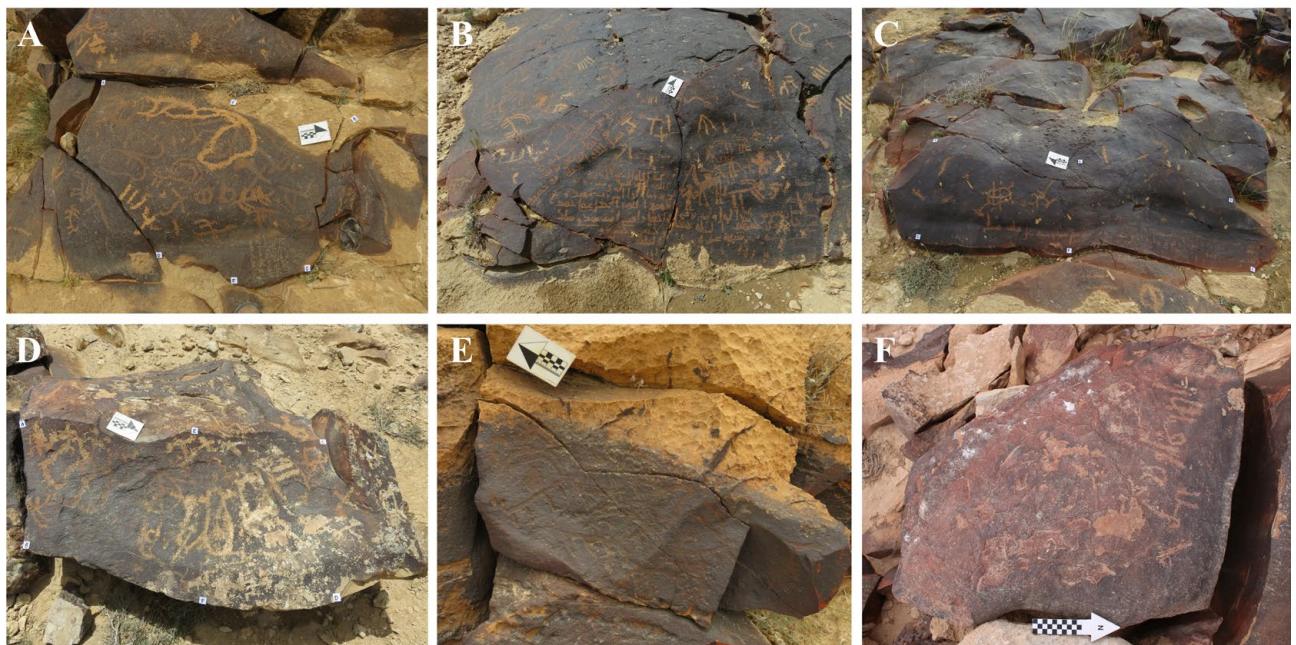


Figure 3. Rock Panels A–F.

Panel F contains a single Nabatean inscription, dated to the Roman period (1st–4th centuries CE) based on the dialect and letterform (J. Norris, pers. comm.).

3.2 Fe and Mn concentrations in petroglyphs

The pXRF measurements for all petroglyphs and intact desert varnish samples demonstrate a strong correlation between Mn and Fe (Fig. 4a, Table A.1), with a very high correlation coefficient ($R^2 = 0.86$) and significance level ($p < 0.01$). Mn concentrations in the petroglyph samples range from 0 to 18,588 ppm, whereas those

from uncarved varnish surfaces range from 3033 to 34,647 ppm (Fig. 4b). Fe concentrations in petroglyph samples range from 941 to 49,613 ppm, while higher concentrations were recorded for uncarved desert varnish surfaces, ranging from 28,225 to 73,872 ppm (Fig. 4b, Table A.1). The lower Mn and Fe concentrations on petroglyph surfaces result from carving that removed the original varnish layers; these reduced values reflect fewer laminae while maintaining the Mn–Fe correlation.

We further examined Mn and Fe values in relation to the size of the pXRF collimator. This analysis revealed a strong correlation between the two elements for both

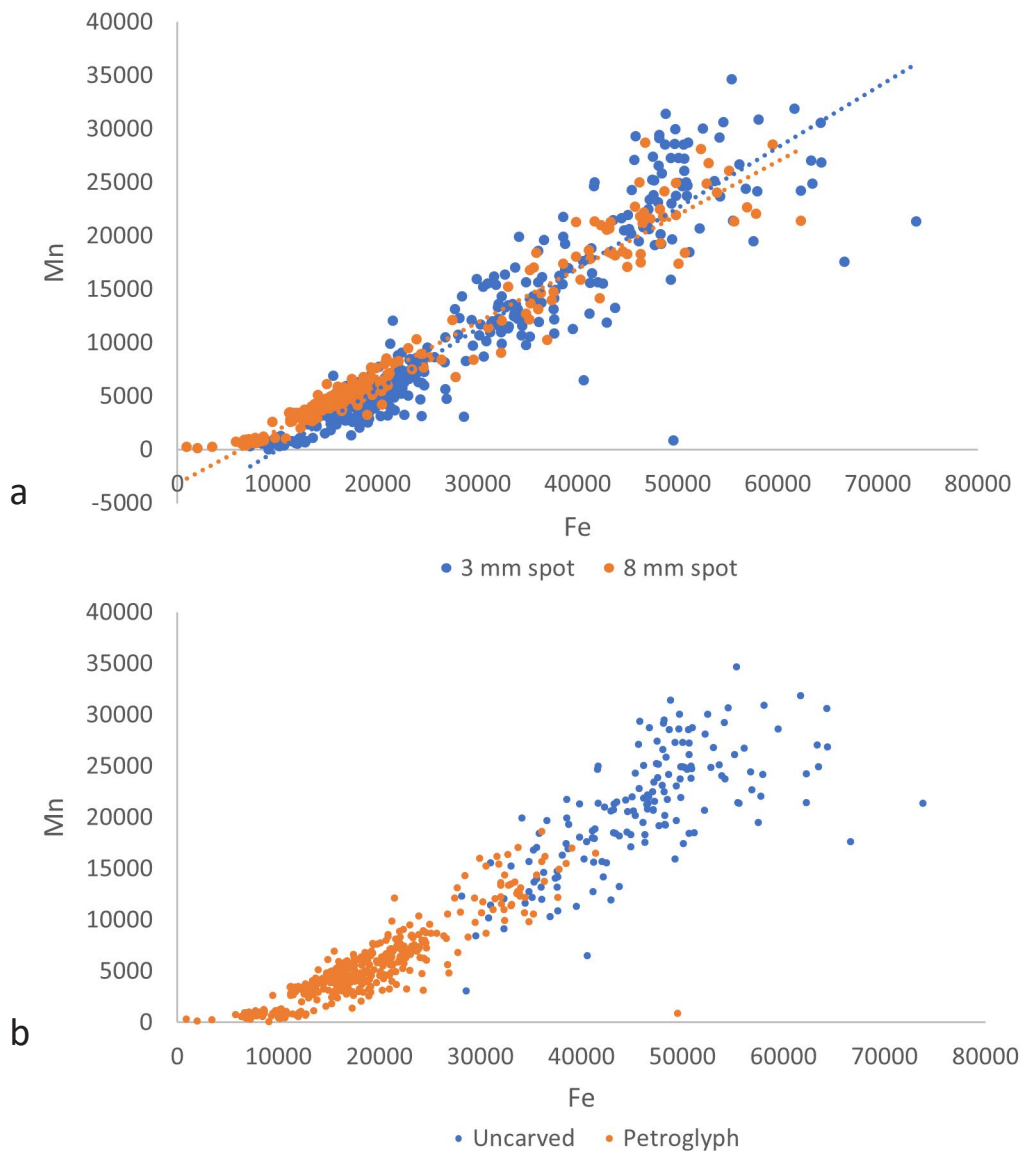


Figure 4. Correlation between Mn and Fe as seen on Panels A, B, E, and F, with 3 and 8 mm collimators (a); Mn and Fe concentrations in petroglyphs and uncarved surfaces (b).

the 8 mm and 3 mm collimators. In both datasets, a linear relationship between Mn and Fe was observed, with correlation coefficients exceeding 0.9 (3 mm: $R^2 = 0.924$; 8 mm: $R^2 = 0.950$). The p-values for the Mn/Fe ratios were below 0.01 in both cases (3 mm: $p = 3.53E-55$; 8 mm: $p = 1.26E-37$; Fig. 4, Table A.1), indicating a high level of statistical significance. These results demonstrate that measurements taken with either collimator size are statistically robust and reliable, supporting the conclusion that both diameters can be used effectively for this type of geochemical analysis. Accordingly, data collected using both the 3 mm and 8 mm collimators were combined to create a unified dataset.

Alongside increased Mn concentrations in petroglyphs relative to uncarved surfaces, an opposite trend was observed for Ca values, with higher Ca concentrations in petroglyphs and lower ones in uncarved surfaces (Fig. 5). Ca values measured for Panel E range from 12,287 to 19,309 ppm for the uncarved surfaces and from 13,351 to 24,331 ppm for the petroglyphs.

We observed that measured Fe values for datable anchor petroglyphs from different periods overlapped (Fig. 6). The Fe values for the crescent-headed figures in Panel D, dated to the Intermediate Bronze Age, overlap with those of the Thamudic inscription from the Hellenistic–Roman periods, covering a time span

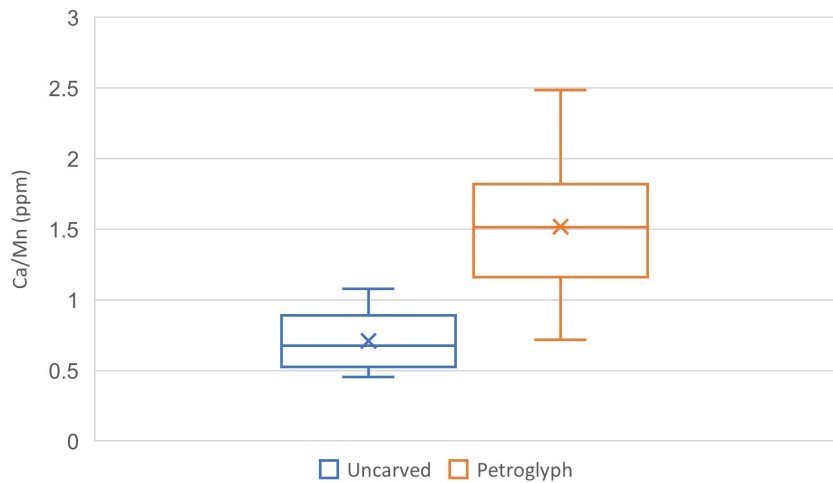


Figure 5. Ca/Mn concentrations (ppm) in Panel E.

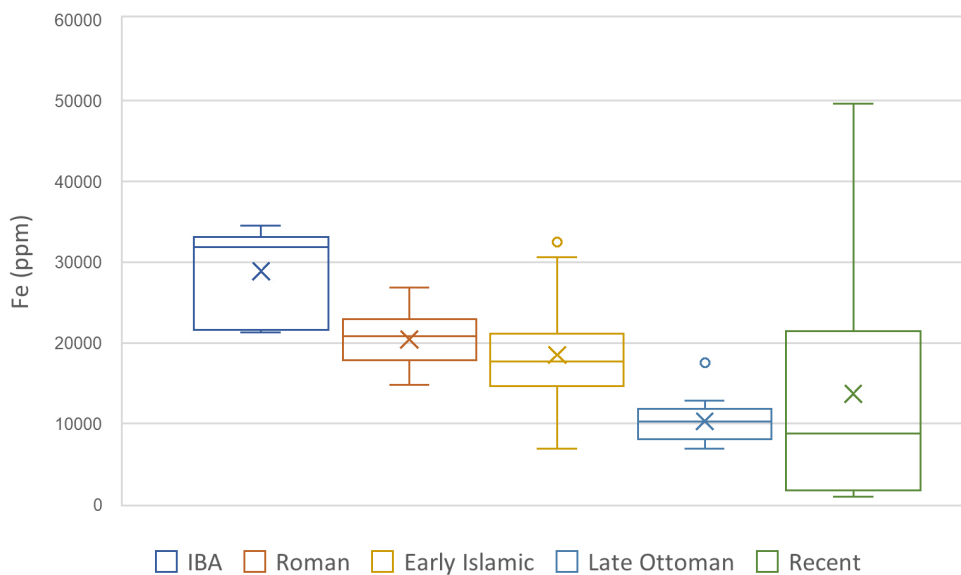


Figure 6. Fe concentrations (ppm) of datable petroglyphs.

of approximately 2500 years. Both petroglyphs exhibit Fe values ranging from 21,286 to 26,835 ppm (Table A.1).

In contrast to Fe values, Mn values allow for clearer chronological differentiation, showing a narrower range of element concentrations (Fig. 7). Mn concentrations in the Intermediate Bronze Age petroglyphs range from 9857 to 15,421 ppm, while those from the Hellenistic–Roman periods fall between 3904 and 10,505 ppm. Petroglyphs from the Early Islamic period exhibit Mn concentrations ranging from 1799 to 7787 ppm; those from the Late Ottoman period–present (up to the 1960s) range from 309 to 780 ppm, and the latest engravings (from the 1990s onward) show Mn concentrations between 0 and 862 ppm (Table A.1). These results indicate that Mn values increase over time, a trend that aligns well with the traditional chronological framework established for the sampled petroglyphs on the basis of typological and stylistic criteria, superposition, and varnish color differences.

4. Discussion

Rock varnish in the Negev forms as alternating microlaminations that reflect shifts in Mn/Fe ratios, which are linked to past climatic conditions (e.g., Liu, 1994; Liu and Dorn, 1996; Liu et al., 2000; Broecker and Liu, 2001; Dietzel et al., 2008; Liu and Broecker, 2008; Otter et al., 2020: 2). Although the local carbonate bedrock is rich in

Ca, its influence on the geochemical composition of the varnish and dust is minimal (Goldsmith et al., 2014: 101; Otter et al., 2020: 9–10). Since Ca is depleted in both varnish and fine dust in the Negev yet present on uncarved surfaces and enriched in petroglyphs, we infer that the elevated Ca concentrations originate in the underlying host rock. While pXRF-derived Mn values represent the cumulative signal of multiple varnish layers and are therefore unsuitable for precise quantification, they are effective for comparative analysis. These values enable them to distinguish uncarved varnish from petroglyphs and potentially also petroglyphs created during different climatic periods, on the basis of differences in varnish development.

Datable petroglyphs serve as chronological anchors due to their content (such as inscriptions and depicted weapon types), superposition, and color. The Mn concentrations of the datable examples provide a reliable foundation for establishing a timeline of petroglyph production in the Negev Highlands. Our findings enable correlation of dated petroglyphs with those yet undated based on their Mn concentrations, thereby offering a new method for dating and interpreting rock art on carbonate terrains. Ibex petroglyphs, along with Arabic and Nabatean inscriptions, serve as representative case studies for this new approach, demonstrating both its potential and limitations.

The Mn concentration results align with the traditional chronological framework of Negev rock art.

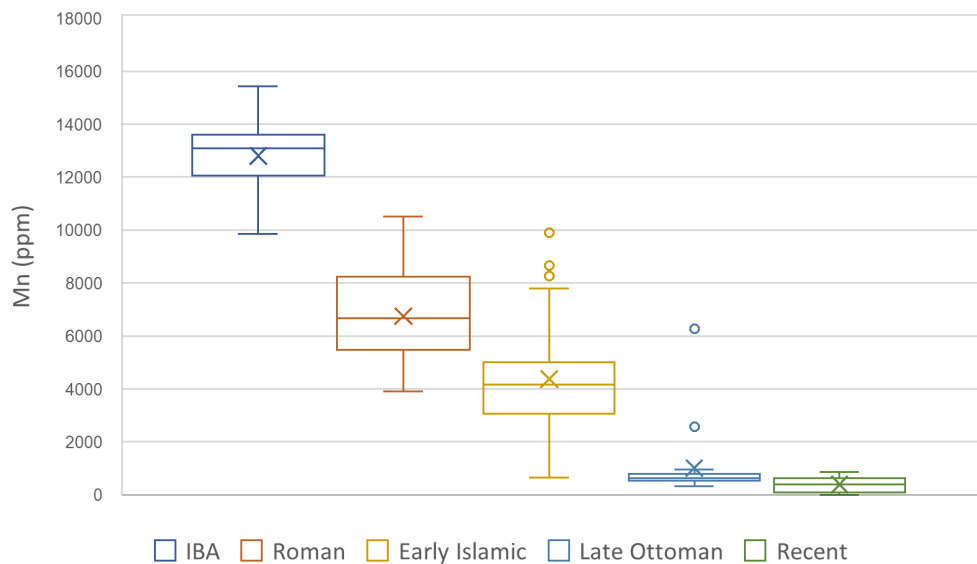


Figure 7. Mn concentrations (ppm) of datable petroglyphs.

Higher Mn concentrations are associated with earlier petroglyphs (Fig. 6). This relationship provides a relative dating tool, enabling comparison of Mn ratios of petroglyphs that were previously difficult or impossible to date. In contrast to Fe, Mn values display clearer distinctions between different time periods, even across a few decades. Although current data are insufficient for high-resolution differentiation of Mn concentrations over short time periods, a larger database may enable finer chronological resolution in future studies.

4.1 Ibex petroglyphs

Ibexes, engraved over roughly eight millennia, are a common motif found in Negev Highlands petroglyphs. Varnish color, along with stylistic characteristics, has helped categorize these petroglyphs into relatively broad time periods; however, precise dating has not been achieved until now. The ibex depicted in Panel E (Fig. 8) belongs to the Negebite tradition (Eisenberg-Degen and Rosen, 2013; Fig. 3). This example, rendered in linear style, is distinguished by its dark desert varnish, closely matching the color of the surrounding uncarved surface. Linear-style ibexes have been engraved continuously through several millennia. The Panel E ibex exhibits Mn values of 9728–14,891 ppm, overlapping with the range recorded for the crescent-headed figures in Panel D, thereby dating them to the mid-3rd

millennium BCE, during the Intermediate Bronze Age (Schwimer and Yekutieli, 2021; Fig. 3). The results from Panel E demonstrate both the effectiveness of the methodology used and the validity of the pXRF-based chronological framework.

For the first time, we propose an analytical protocol for dating the ibex motif. It remains to be determined whether ibex images were also engraved in earlier periods, as suggested by the traditional chronology of Negev rock art (Anati, 1954; Eisenberg-Degen and Rosen, 2013; Avner et al., 2017).

4.2 Retouched petroglyphs

Retouching refers to the modification or renewal of a petroglyph by removing the varnish that had accumulated on it, thereby reexposing the underlying rock. This action introduces additional challenges for interpreting and dating engravings using traditional methods, particularly when there is no clear superimposition or color contrast between the original and retouched engravings. Investigating Panel D, we suspected that a petroglyph had undergone retouching; pXRF analysis enabled us to identify and date this intervention.

One of the crescent-headed figures in Panel D (Fig. 9) showed evidence of less refined pecking, displaying desert varnish of inconsistent coloration. The pXRF results confirmed that this figure had been retouched after its original engraving, involving re-pecking of the original

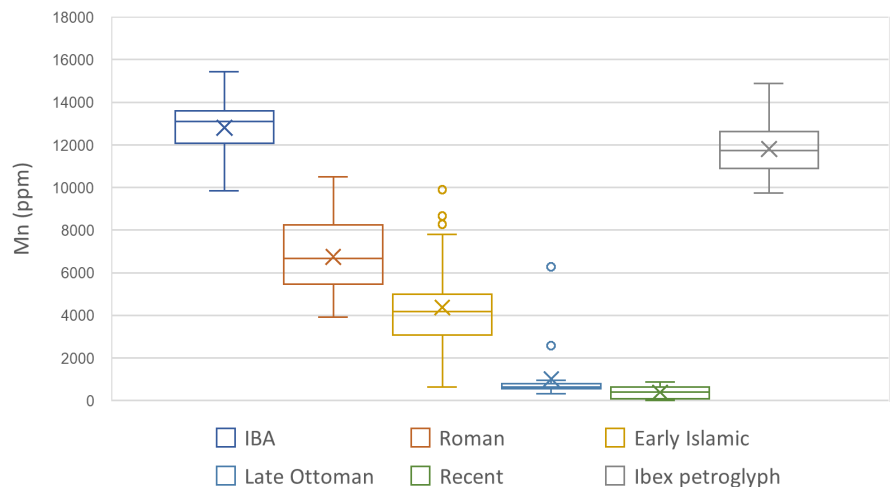


Figure 8. The Negebite ibex petroglyph of Panel E and its Mn concentrations (ppm).

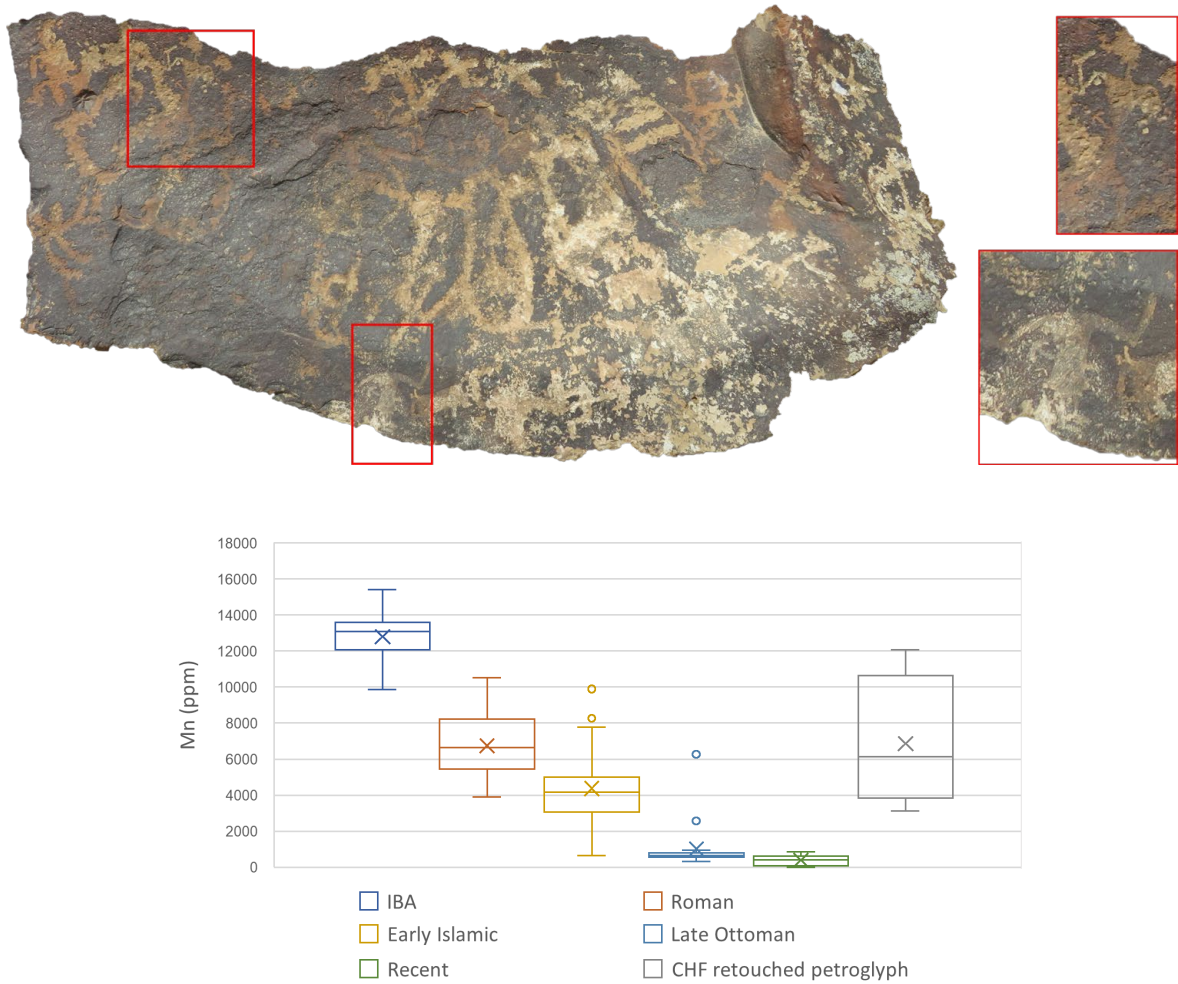


Figure 9. Crescent-headed figures and the Mn concentrations (ppm) of the retouched petroglyphs: retouched petroglyph (top); original carving (bottom).

design. Consequently, while the figure conforms stylistically to the Intermediate Bronze Age, it features desert varnish of a lighter color.

The Mn values suggest that the original image was created contemporaneously with the untouched crescent-headed figure dated to the mid-3rd millennium BCE. In contrast, the Mn values associated with the lighter pecking correspond to those of the Hellenistic–Roman periods anchors, indicating that the retouching occurred during these later periods.

4.3 Arabic inscriptions

Arabic inscriptions that include precise dates provide clear calibration points for correlating Mn

concentrations with known chronological markers. We identified two Arabic inscriptions that date back to the mid-8th century CE, engraved on panels situated under different environmental conditions, such as inclination and aspect (Panels B and C in Figs. 2 and 3, Table 1). We hypothesized that these environmental factors may have influenced Mn concentrations; however, the results indicate that, despite their differing settings, the inscriptions display similar Mn concentrations. This finding suggests that Mn concentrations are not significantly affected by the inclination or aspect of the panels.

The Mn values of the Arabic inscription on Panel A (Fig. 10; 4694–9899 ppm) overlap with those of the petroglyph from the Hellenistic–Roman periods

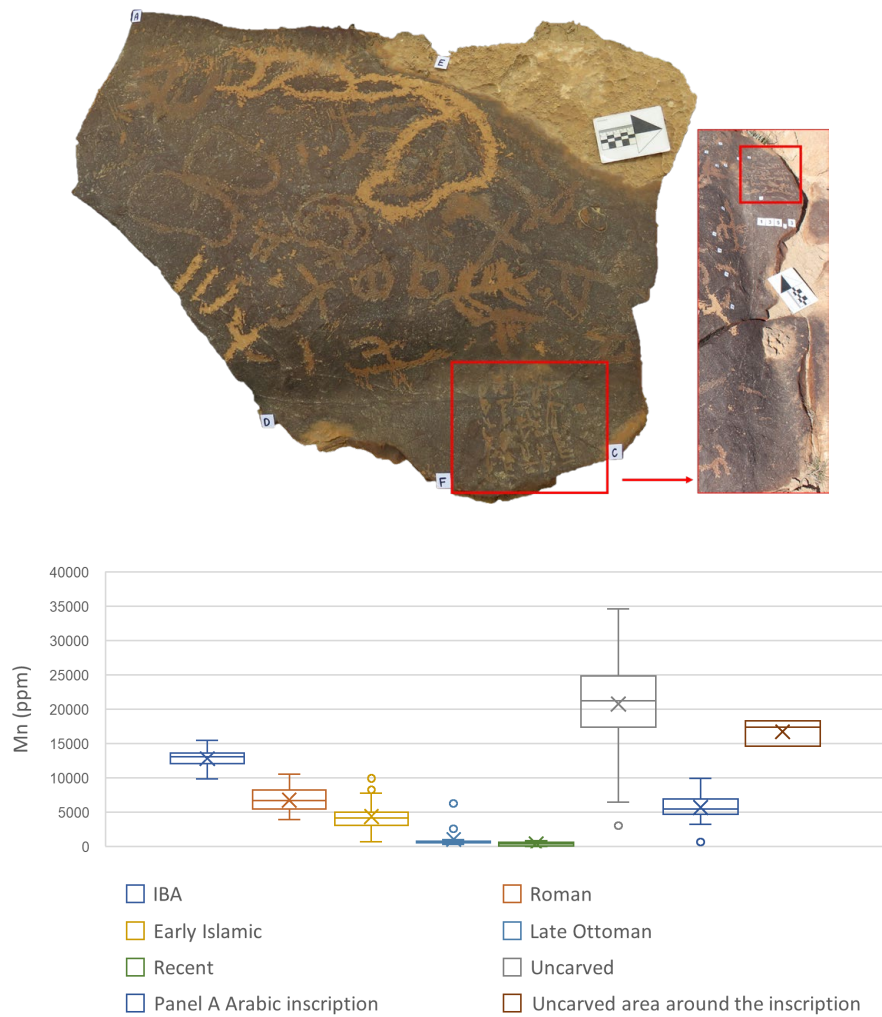


Figure 10. The Arabic inscription of Panel A and the Mn concentrations (ppm) of the inscription and the surrounding uncarved surface.

(3904–10,505 ppm). Only a few readings align with the defined mid-8th-century CE range, suggesting that the Panel A inscription may antedate the dated Arabic inscriptions in Panels B and C. Though possible, we consider this unlikely.

The Panel A inscription illustrates the effect of micro-topography. While the convex panel is slightly tilted, facing east, the inscription is positioned on its lower eastern fringe, which forms a more horizontal, flat surface (Fig. 3). A comparison of the Mn values from the panel's convex uncarved surface with those from the eastern flat surface, bearing the inscription, revealed inconsistencies. The Mn concentrations on the flat surface averaged $13,601 \pm 294$ ppm (8417–18,405 ppm), whereas those on the convex surface averaged $19,525 \pm 349$ ppm (9058–30,866 ppm). The latter values are

consistent with the overall average Mn concentrations recorded across all panels in this study (Panels A–F; $20,769 \pm 439$ ppm).

The convexity of the panel's larger, upper section hinders retention of rainwater and dew, which instead drain eastward toward the lower section, where the inscription was engraved. During the initial survey, this lower section contained loess deposition, particularly within the depressions of the inscription. This regolith indicates that water had accumulated and remained there longer than on the rest of the rock surface before evaporating.

The Mn values suggest that precipitation affects accumulation of varnish layers. This pattern accords with Goldsmith et al.'s (2014) conclusion that desert varnish develops primarily in micro-basins on exposed rock

surfaces, and that its formation is influenced directly by precipitation, humidity, and dew. Consequently, we conclude that Mn concentrations reflect directly the panel's micro-topography and the amount of moisture it retains.

4.4 Nabatean inscription

The Nabatean inscription on Panel F (Fig. 11) raises an intriguing archaeological question. The Mn concentrations of this inscription do not correspond to the Roman period, as expected; instead, they align with the Early Islamic period, ranging from 2038 to 6174 ppm. Panel F is located on a local hilltop, an area susceptible to increased erosion. Furthermore, the inscription was engraved on a convex surface parallel to the ground and lacks a distinct aspect.

Epigraphic evidence identifies the inscription's paleography as "classical" Nabataean, and it was likely engraved between the end of the 1st century BCE and the mid-3rd century CE. A later development, Nabatean-Arabic, was used in northern Arabia, with a few isolated examples found in the Eilat region (approximately 200 km to the south) as late as the 6th century CE (Jérôme Norris, pers. comm.).

It is possible, albeit unlikely, that the inscription on Panel F represents a late survival of this tradition into the late Byzantine period, which would suggest a date close to the mid-8th century CE, during the Early Islamic period. It appears more likely that the Nabatean inscription was retouched during the Early Islamic period. We would expect some of the measurements to reflect the original engraving phase; however, in this case, the

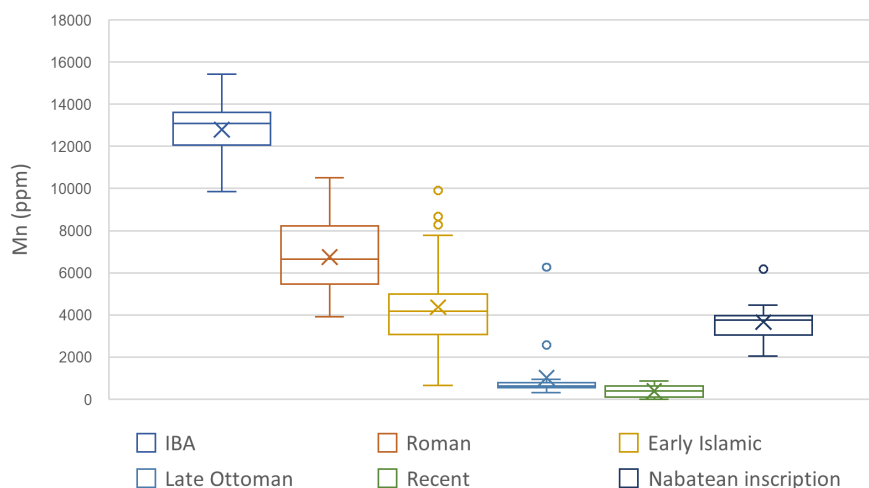


Figure 11. The Nabatean inscription of Panel F and its Mn concentrations (ppm).

Mn values all correspond to the Early Islamic period. A larger dataset will be required to clarify these anomalies in future analyses.

5. Conclusion

This study presents a nondestructive and fairly rapid method for the relative dating of varnish-covered petroglyphs in arid carbonate terrains. By measuring Mn concentrations on engraved and uncarved rock surfaces, we demonstrate the potential to assign rock art to specific historical periods, while acknowledging transitional phases. Our results show that Mn concentrations provide a reliable framework for distinguishing four chronological phases: the Intermediate Bronze Age (2500–2000 BCE, Mn = 9857–15,421 ppm), the Hellenistic–Roman periods (3rd century BCE–3rd century CE, Mn = 3904–10,505 ppm), the Early Islamic period (mid-7th–10th centuries CE, including two precisely dated inscriptions from 735 and 737/738 CE, Mn = 1799–7787 ppm), and the Late Ottoman period–present (1825–1960 CE, Mn = 309–862 ppm).

Several factors must be considered when applying this method: the laminated nature of varnish as a proxy for paleoenvironmental change, the influence of microtopography on varnish accumulation, the variability in carving practices, and the resolution limits of pXRF instruments. Expanding the comparative database is essential for improving temporal resolution and enhancing the precision of this method, especially for distinguishing shorter or overlapping chronological phases.

The Mn concentration results correspond closely with traditional rock art dating methods and provide a reliable foundation for placing additional, unsampled petroglyphs from arid environments within a chronological framework. By offering a measurable and replicable

geochemical basis for dating, this approach enhances chronological accuracy, especially in cases where motifs recur across long periods or where petroglyphs have been retouched, rendering conventional typological or stylistic methods less effective.

Contribution statement

The study was conceptualized by IS and YG. Archaeological survey investigation was performed by IS, DED, and LS. Analytical measurements and data curation were conducted by YG and IS. Statistical analysis was performed by IS and NW. YG acquired funding and supervised the project. All authors contributed to reviewing and editing the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that may appear to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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