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# A multiscalar methodology for holistic analysis of prehistoric rock carvings in Scotland

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**Abstract**

Prehistoric rock carvings are one of Scotland's most enigmatic and poorly understood monument types. This article discusses the pioneering approach used by Scotland's Rock Art Project to enhance understanding of the abstract motifs through multiscalar computational analyses of a large dataset co-produced with community teams. The approach can be applied to suitable rock art datasets from other parts of the world and has international relevance for rock art reserach. Our analysis incorporates data from across Scotland in order to investigate inter-regional differences and similarities in the nature and contexts of the carvings. Innovative application of complementary analytical methods identified subtle regional variations in the character of the rock art and motif types. This variability suggest an understanding of the rock art tradition that was widely shared but locally adapted, and reflects connections and knowledge exchange between specific regions.

**Keywords** Prehistoric rock art, Multidisciplinary methodology, Geographical Information Systems (GIS), Computational analyses, Agent-Based Modelling (ABM), Multiple Response Permutation Procedure (MRPP), Multiple Component Analysis (MCA)

## Introduction

Rock art, defined as marks deliberately painted or engraved onto natural rock surfaces, is an important part of the global archaeological record that can provide valuable insights into how people perceived and interacted with their surroundings in the past. Interpretation of prehistoric rock art presents many challenges, however. Abstract (non-figurative) carvings created in the open air, found in many parts of the world, are especially problematic for research and public awareness, and therefore under-valued and poorly understood relative to other prehistoric monument types. The paucity of appropriate methodological tools for analysing such carvings has hindered research internationally. A key objective of our work was address this issue by developing a comprehensive computational approach that offers new insights into abstract motifs and their contexts.

Prehistoric rock art in Scotland forms part of a wider carving tradition known as Atlantic Rock Art (ARA), represented by thousands of examples in northern England, Wales, Ireland, Portugal, and north-west Spain, and also in some Scandinavian countries. The sheer volume of carvings suggests they were significant to the people that made and used them, yet their meaning remains elusive [1]. The chronology of ARA is uncertain due to an absence of direct dating methods, and limited associated archaeological contexts. Nevertheless, there is general consensus that rock art in Britain was created and used during the local Neolithic (c. 4000–2200 BCE), continuing into the Early Bronze Age (c. 2200–1800 BCE), after which carvings were occasionally used or re-used in

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**Fig. 1** Rock art in the landscape. Balmacnaughton 2, overlooking Loch Tay, Stirling. Image, Tertia Barnett

certain Bronze Age monuments, including burial cairns and standing stones [2, 3]. This view is based on excavations (e.g. [4, 5]), carvings in dated burial contexts [6], and comparisons with evidence from other countries where relevant work has been undertaken (e.g. [7]).

The abstract motifs comprising Scotland's rock art are carved on boulders and outcropping bedrock in the landscape, most frequently on horizontal surfaces flush with the ground (Fig. 1). These are typically situated in undulating or hilly terrain, in rough grazing and moorland. Over 3,000 carved rocks (or 'panels') are known across the country. They are not evenly distributed, with large concentrations in south-western regions, particularly Kilmartin in Argyll and Bute, around Kirkcudbright in Dumfries and Galloway, and in parts of central Scotland (Perth and Kinross, and Stirling) (Fig. 2a and b) [8]. The imagery is characterised by cupmarks (small circular hollows carved into the rock), often surrounded by single or multiple concentric rings, and frequently associated with linear grooves (Fig. 3). These basic motifs have numerous subtle variations, and occur either singly or in complex arrangements.

Interest in landscape-based investigations of the setting and context of rock art has grown internationally in recent decades, representing a shift away from traditional approaches focussing primarily on the meaning of the motifs. Largely inspired by Bradley's [1] seminal

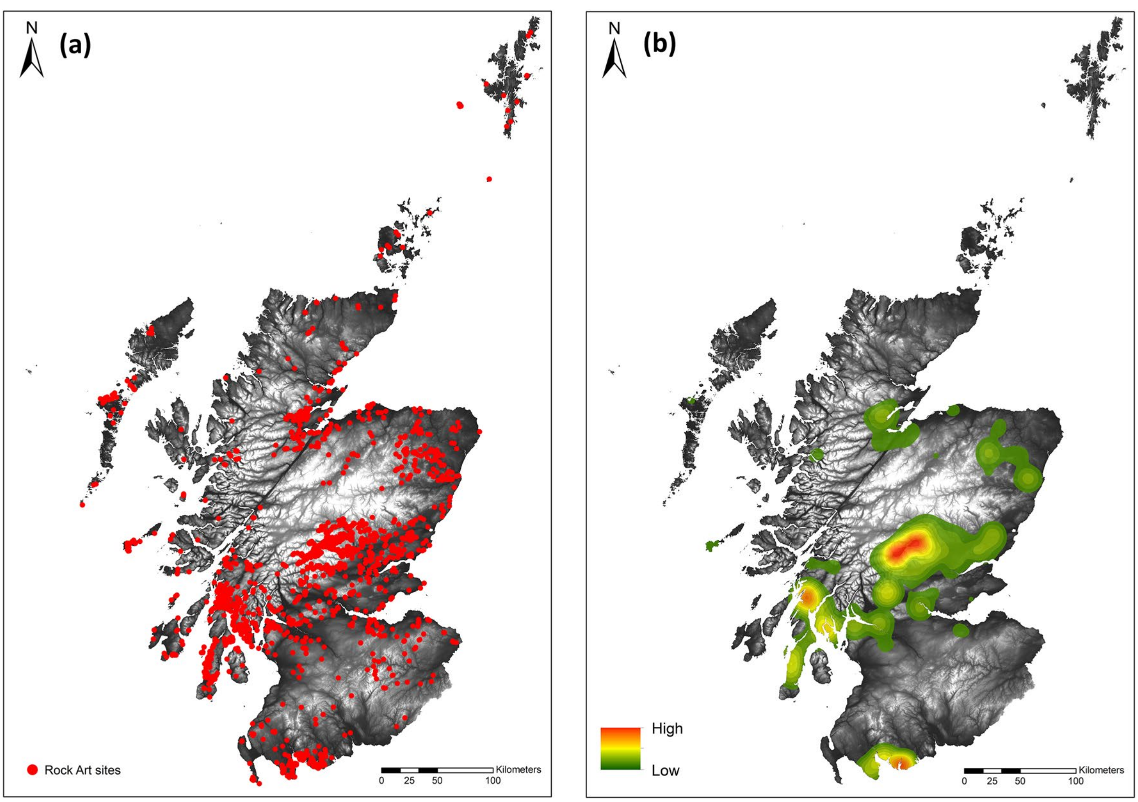


**Fig. 2** **a** Distribution map and **b** density map of known prehistoric rock art in Scotland based on the Scotland's Rock Art Project database

**Fig. 3** Typical carved motifs including cups with concentric rings and radial grooves at Cairnbaan 4, Argyll and Bute. Image, Tertia Barnett

work on ARA, in Europe these studies have developed in tandem with Landscape Archaeology and computational approaches, including Geographical Information Systems (GIS)-based analysis (e.g. [7, 9–12]). Landscape approaches, together with systematic and quantitative methods, have offered new insights into British rock art and placed it firmly within mainstream archaeology [1, p. 8]. Nevertheless, overemphasising the spatial context of rock art without addressing the motifs results in only a partial understanding [7, p. 2]. Despite recent advances in understanding ARA, many questions remain, not least concerning the character and variability of rock art at different scales, and its relationship to wider archaeological narratives.

In order to address certain gaps in current knowledge, our research aimed for a holistic approach using a multiscalar methodology. This allowed us to consider the motifs and design of Scotland's prehistoric rock carvings in relation to environmental and contemporaneous archaeological data. This article discusses the different stages of our research, including motif assessment, spatial analysis, statistical testing, and computational methods for modelling visibility and movement. The methodology was applied to carvings from across Scotland using data co-produced with communities during Scotland's Rock Art Project (ScRAP).[1] Investigating the rock art at different scales through a wide range of variables afforded a better understanding of the similarities and differences within and between local areas. This enabled us to test and challenge established interpretations through a 'critical and cautious approach' [7, p. 4]. Further details about the work and outcomes of ScRAP can be found in [8, 13] and [14] with an overview of the project available in [15].

## Research background

### Previous research

The earliest published account of prehistoric rock art in Scotland noted carvings around Cairnbaan in Kilmartin, Argyll and Bute (Fig. 3) [16]. Other discoveries soon followed, and the corpus of rock art grew steadily during the nineteenth century [8, 17, 18], with 204 sites noted by 1882 [19]. Many hundreds of sites have since been recorded by professional organisations, such as the Royal Commission on the Ancient and Historical Monuments of Scotland (e.g. [20]), community groups, and independent researchers. Today, the rock art database is curated by Historic Environment Scotland (HES) as part of the national record of Scotland's historic environment (accessible via Canmore[2]). As this database was constructed over two centuries by multiple authors with different techniques and observational skills, it contained numerous inconsistencies and anomalies that have constrained large-scale analyses. As a result, research primarily targeted a few specific sites or areas, and understanding of the bigger picture for Scotland as a whole was lacking.

Until the late twentieth century, rock art studies in Britain focused mainly on determining chronology, and classifying and interpreting the motifs [21, p. 181]. The challenging nature of the material and lack of appropriate theoretical and methodological tools served to marginalise rock art from mainstream archaeology. Despite the growing inventory of sites, academic research on the role of rock art in understanding past societies was negligible. Although certain individuals, such as independent researcher Ronald Morris [22, 23], broke with traditional thinking by beginning to consider rock art in relation to landscape setting, such notions were not firmly established until recent decades.

Towards the end of the twentieth century, the emergence of Post-Processual thinking and Landscape Archaeology heralded a new era in British rock art studies. Building on an already growing interest [23–26], Bradley's [1] ground-breaking work was influential in emphasising the importance of landscape contexts for ARA. Bradley's work has inspired many researchers and his ideas still shape the rock art discourse today.

[1] Scotland's Rock Art Project (2017–2021) was funded by the Arts and Humanities Research Council and hosted by Historic Environment Scotland, working in collaboration with the School of History, Classics and Archaeology (University of Edinburgh) and the School of Innovation and Technology (Glasgow School of Art). The project partners were Kilmartin Museum, Archaeology Scotland, and the North of Scotland Archaeological Society (NOSAS).

[2] https://canmore.org.uk/.

This paradigm shift prompted fresh research directions whilst focusing on the past social and cultural role of rock art. Bradley introduced interpretations inspired by Social Anthropology theory and Post-Processualism, despite his structuralist-based methodologies [1]. Landscape variables such as altitude, distance to water bodies, and soil types were among the first to be explored for ARA, with an emphasis on visibility and intervisibility (e.g. [1, 27, 28]). Following Ingold's [29] work, Bradley proposed a model of prehistoric landscapes organized around territories structured by trails and views, stressing the importance of long-distance visibility and pathways in the placement of carvings. He suggested that rock art defined routeways across lowland valleys or entrances to specific spaces, including fertile or ceremonial landscapes, and may have been encountered within the context of seasonal movements such as transhumance and hunting (e.g. [1, 10, 30]). Some complex rock art panels in marginal locations were thought to act both as threshold markers, intended to be seen by people entering the area, and as sites used by the local community [1, 4]. Rather than signposting routes through the landscape, the carvings were viewed as a means of controlling mobility and communicating information, expressed as boundary markers associated 'with paths leading through the landscape and certain significant places along their course' [1, p.217, 29]. Many of these assumptions have been extrapolated uncritically in later studies and, following on Bradley's work, visibility has been widely accepted as a determining factor in the location of ARA.

Landscape approaches developed in tandem with a growing interest in the use of Geographical Information Systems (GIS) in archaeology [7, 10, 31]. Although GIS has potential for promoting new lines of enquiry in rock art research, its use has been relatively limited and primarily focused on visibility [9, 11, 32, 33]. The majority of viewshed analyses are relatively simple, assessing visibility from or towards panel locations, and intervisibility between and sometimes in relation to other contemporaneous archaeological sites [9–11, 30, 33].

Despite the popularity of visibility studies and viewshed analysis, interpretations of results should be assessed cautiously. Although viewshed analysis can be useful for studying perceptions of the landscape, it has limitations. Visibility can be affected significantly by vegetation and weather conditions, which are seldom modelled, and by the acuity of the human eye, which loses precision over long distances ([12], p. 129). Overemphasis on visibility may also reflect modern values on perception of landscapes in our interpretations of the past. Indeed, there are recent suggestions that visibility and viewsheds may not have played a crucial role in rock art placement [12]. This is particularly pertinent when considering carved rocks as visible landmarks, since ARA is predominately carved on relatively small, low-lying panels that are often overgrown, and the motifs weather rapidly, fading from view unless frequently re-carved or enhanced ([12, p. 129]), [13].

GIS has more potential when used critically. It enables cross-referencing of multiple variables that may have affected the location of rock art, and engages creatively with the manipulation and simulation of space ([12], p. 108), [7, 34]. Although such methods have been criticized in Post-Processual and Post-Modern approaches for their Functional-Processual origin and over-reliance on environmental determinism [e.g. 35], these issues can be mitigated when used in combination with social and ideological variables to explore perceptions of the landscape ([12], p.108).

**Table 1** Chart showing frequency of rock art records investigated and validated during ScRAP, and a broad breakdown of validated records

| | |
|---|---|
| Total Panels January 2022 | 3210 |
| Total Validated | 1630 |
| Total Not Investigated | 1580 |
| Total Validated Panels | 1630 |
| Total Not Rock Art | 215 |
| Total Not Located | 305 |
| Total Detailed Records for Analysis | 1110 |

## Scotland's Rock Art Project

Within this context, Scotland's Rock Art Project (ScRAP) was established in order to enhance knowledge, understanding and awareness of prehistoric carvings across Scotland. Between 2017 and 2021, ScRAP trained and worked with community teams to revist and record known rock art. We co-produced a consistent rock art database using a standardised methodology that incorporated quantitative and descriptive recording, georeferencing, field drawings, photography, and 3D modelling. Over half (1630) of the 3210 rock art panels known in Scotland were investigated during the project. Of these, 1110 were located and verified as rock art, recorded in detail, and validated by the ScRAP team (Table 1). The data were compiled into a comprehensive digital database, publicly accessible via the project website,[3] and archived in HES's digital repository, available via the Canmore website.[4] The unprecedented volume and

[3] At the date of writing, the ScRAP rock art database is open access and available to search and download in CSV format at https://www.rockart.scot/rock-art-database.

[4] https://canmore.org.uk/collection/2219572.

scope of the ScRAP database provided a firm foundation for detailed investigation of prehistoric rock art for the entire country, enabling us to address old and raise new research questions.

The ScRAP database formed the basis of our inquiry. We formulated four interlinked research questions directed towards key gaps in current knowledge. First, in order to understand Scotland's rock art, we need to know when it was created and how it changed over time. Without a reasonable grasp of chronology, it is not possible to draw any meaningful conclusions or bridge the divide between rock art and its contemporary contexts. Determining an interval of time for the 'currency' of rock art, generally agreed as spanning the Neolithic and Early Bronze Age (c.4000–1800 BCE), enabled us to include the carvings within the narrative of prehistoric Scotland. Second, we aimed to define the character of Scotland's prehistoric rock art in order to identify and better understand common themes and regional variations. This led to our third question concerning the uneven distribution of the rock art across Scotland. As previously noted, there are significant concentrations of carvings in certain regions and virtual absences in others. Some suggestions for this imbalance emerged during our research. Finally, our fourth question considered the social and cultural role of the ARA tradition. The frequency and spread of rock art indicates its importance for people in the past, and clearer insights into its purpose are imperative for integration with the wider archaeological framework. These four research questions drove the development of our analytical methodology, discussed below.

**Table 2** Categorical scheme showing the different variables within the three scales of analysis, largely adapted from [7, 12]

| Categories | No. Sub-categories | No. attributes | Scale of analysis |
|---|---|---|---|
| Types of depiction | | 3 | Small Scale |
| Motif classification | 13 | 190 | Small Scale |
| Carving techniques | | 9 | Small Scale |
| Type of Media | | 6 | Medium Scale |
| Compositional sub-classes | | 7 | Medium Scale |
| Motif range | | 3 | Medium Scale |
| Structural variants | | 18 | Medium Scale |
| Motif behaviour | 8 | 13 | Medium Scale |
| Bedrock geology | 2 | 139 | Large Scale |
| Landscape character | | 390 | Large Scale |
| Soil type | | 29 | Large Scale |
| Peat depth | | N/A | Large Scale |
| Land use | 4 | 97 | Large Scale |
| Elevation | | N/A | Large Scale |
| Slope | | 5 | Large Scale |
| Aspect | | 10 | Large Scale |
| Visibility | | N/A | Large Scale |
| Mobility | | N/A | Large Scale |

## A multiscalar methodology

Multiscalar methodologies have proved valuable for rock art studies. Notably, those used by O'Connor [7] in Ireland and Valdez-Tullett [12] in Western Europe have introduced nuance and detail to our current knowledge of ARA and opened new avenues of investigation. Building on these studies, we developed a bespoke multiscalar methodology that aimed to investigate rock art holistically, and address our four research questions. Our approach aimed to advance understanding of the landscape character of rock art in Scotland, whilst also focusing on detailed motif analysis.

Our methodology comprised a Small, Medium and Large Scale of analysis, each broken down into several interlinked variables within a classification scheme composed of 18 categories (Table 2). Some of these variables have been studied previously [7, 12], but others, particularly the landscape features, were assessed for Scotland's rock art for the first time. The Small Scale analysis focused on motif types and carving techniques; the Medium Scale analysis examined the nature of the carved rock, the 'behaviour' of the motifs (e.g. their organisation and arrangements), and their relationship to the rock surface; the Large Scale analysis explored the spatial patterning of rock art in relation to natural and cultural attributes of the landscape. We investigated specific variables for each scale of analysis, then reviewed them relationally in order to generate a comprehensive picture of prehistoric rock art in Scotland.

As already mentioned, our dataset was co-produced with community teams trained specifically in using a standardised methodology. A crucial component of the recording was digital 3D modelling using Structure from Motion (SfM) photogrammetry [36], which captured the level of detail necessary for Small and Medium Scale analyses. Enhancement of the 3D models with a range of softwares and renders, including Meshlab's Radiance Scaling plugin [37] and Blender, enabled assessment of fine detail in the motifs and their relationship with the rock surface. The spatial investigation developed for the Large Scale analysis was carried out with GIS and NetLogo, and results were tested in R.

Different subsets of the data were used for each scale of analysis. For the Small and Medium Scale analyses, focusing more on the imagery, we incorporated all panels from across Scotland for which we had viable motif data and high-resolution 3D models for detailed interrogation. This included both in situ panels and those in secondary

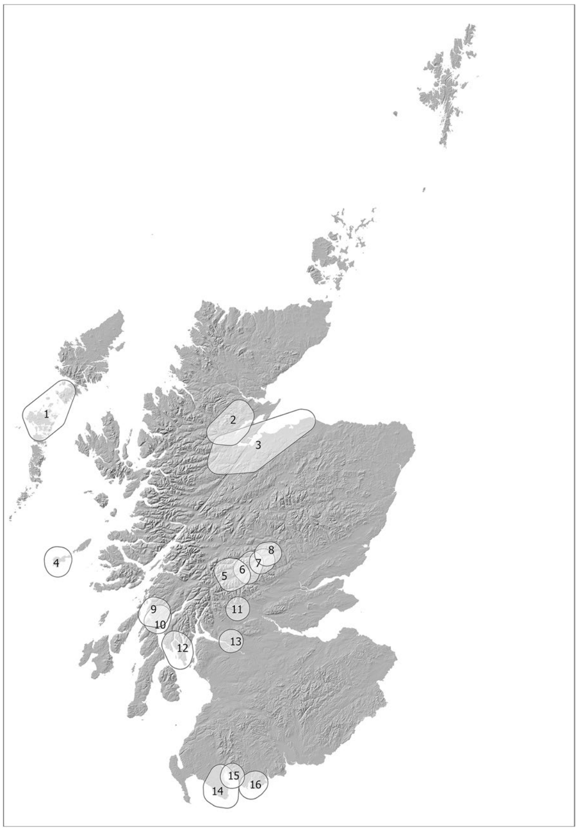


**Fig. 4** Case study areas used in the Large Scale analysis. 1. Western Isles; 2. Inverness North, Highland; 3. Inverness South, Highland; 4. Tiree, Argyll & Bute; 5. South Loch Tay, Stirling; 6. Mid Loch Tay, Perth & Kinross; 7. North Loch Tay, Perth and Kinross; 8. Strath Tay, Perth & Kinross; 9. Kilmartin I, Argyll & Bute; 10. Kilmartin II, Argyll & Bute; 11. Port of Menteith, Stirling; 12. Bute, Argyll & Bute; 13. Faifley, Dunbartonshire; 14. Machars, Dumfries & Galloway; 15. Cairnholy, Dumfries & Galloway; 16. Kirkcudbright, Dumfries & Galloway

locations. The Large Scale analysis demanded accurate georeferencing of each carved rock, so only in situ panels (i.e. outcrops and boulders unlikely to have been moved) were investigated. To ensure that the Large Scale analysis included rock art from the whole country, we identified 16 Case Study areas to represent Scotland's natural, historical and archaeological diversity (Fig. 4). Although the largest possible samples were selected for each scale of analysis, it should be noted that there are significant discrepancies between the number of validated records in each study area (Tables 3 and 4). This reflects the uneven distribution of rock art across the country, issues with relocating known panels, and historical inaccuracies in the previous dataset. For example, in the Western Isles, 14 of the 28 previously known panels were re-classified as natural or historic features by ScRAP. For the mobility analysis, we also piloted a simple Agent-Based Modelling (ABM) approach in one Case Study area (Kilmartin, Argyll), to test its viability for understanding rock art within the landscape.

For the purpose of uniformity, the rock art dataset was filtered and processed in-line with a set protocol. The data were classified according to their location (In Situ, In Monuments, Moved/Relocated, Not Located), the type of analysis for which they were used (In Situ for Large Scale analysis; In Situ, Moved/Relocated and In Monuments for Medium and Small Scale analyses), and whether they had been re-classified as 'Natural features' or 'Other' human-made features. In total, 1630 validated records from across Scotland were exported and filtered for the Small and Medium Scale analysis, of which 896 (55%) were viable for assessment (Table 3). For the 16 Case Study areas, 1080 validated records were exported and filtered, of which 631 panels (58.4%) were in situ and used for the Large Scale analysis (Table 4). The entire dataset can be freely downloaded as a CSV file from the ScRAP website, and filtered according to the different parameters used in our analysis. Details of the data and protocols that we used in our analysis are also provided with this article to ensure transparency and reproducibility.

## Small Scale analysis

In recent decades, the emphasis on Landscape Archaeology theory and methods in rock art research, together with criticism of Culture History approaches, have promoted critical re-evaluation of approaches for studying rock art motifs. Nevertheless, classification is a useful process in archaeology and the value of typologies for archaeological research, particularly when developed relationally, has been acknowledged [38]. Our approach included minute classification of motif types, grammar, compositions, and techniques using an established categorization system, adapted to our dataset, to ensure comparability with previous studies of ARA (see [12] for the original, following [7]).

The Small Scale analysis used data for every carved rock recorded across Scotland during ScRAP for which a viable 3D model had been created, totalling 896 panels and 16,088 individual motifs (Table 5). This represents the largest sample size ever analysed for ARA, offering unparalleled insights into the tradition. Following classification, the data were used in a Presence/Absence Matrix approach which determined regional preferences and relations between different areas of the country. These were explored further through a Multiple Response Permutation Procedure (MRPP) and a Multiple Component Analysis (MCA), discussed in section "The wider picture".

For the Small Scale analysis, the *Type of Depiction*, *Motifs*, *Carving Techniques,* and *Motif Behaviour* variables classify the fine details of the imagery. The *Type of Depiction* category assessed the relationship between the

**Table 3** Number of validated panels per Council area included in the Small and Medium Scale analysis

| Council area | Total validated panels | Total analysed | Total excluded (not located, not rock art, lost/destroyed) | % viable for analysis |
|---|---|---|---|---|
| Orkney & Shetland | 1 | 0 | 1 | 0.0 |
| Western Isles | 28 | 7 | 20 | 25.0 |
| Highland & Moray | 265 | 178 | 87 | 67.2 |
| Aberdeenshire | 85 | 12 | 73 | 14.1 |
| Angus | 50 | 22 | 28 | 44.0 |
| Argyll & Bute | 441 | 257 | 184 | 58.3 |
| Perth & Kinross | 160 | 125 | 35 | 78.1 |
| Stirling | 213 | 76 | 137 | 35.7 |
| Dunbartonshire | 27 | 15 | 12 | 55.6 |
| Lothians | 33 | 10 | 23 | 30.3 |
| Glasgow & Inverclyde | 28 | 0 | 28 | 0.0 |
| Renfrewshire | 8 | 0 | 8 | 0.0 |
| Lanarkshire | 3 | 2 | 1 | 66.7 |
| Fife | 16 | 3 | 13 | 18.8 |
| Ayrshire | 9 | 1 | 8 | 11.1 |
| Scottish Borders | 18 | 1 | 17 | 5.6 |
| Dumfries & Galloway | 245 | 187 | 58 | 76.3 |
| Total | 1630 | 896 | 734 | 55.0 |

**Table 4** Number of panels in each Case Study area used for Large Scale analysis after filtering

| Case study area | Total panel records exported | Total in situ panels for Large Scale analysis | Total panels excluded (not located, not rock art, not in situ) | % viable for analysis |
|---|---|---|---|---|
| Western Isles | 28 | 7 | 21 | 25.0 |
| Inverness North | 112 | 71 | 41 | 63.4 |
| Inverness South | 80 | 28 | 52 | 35.0 |
| Tiree | 32 | 20 | 12 | 62.5 |
| South Loch Tay | 40 | 25 | 15 | 62.5 |
| Mid Loch Tay | 53 | 45 | 8 | 84.9 |
| North Loch Tay | 40 | 22 | 18 | 55.0 |
| Strath Tay | 42 | 34 | 8 | 81 |
| Kilmartin I | 112 | 68 | 44 | 60.7 |
| Kilmartin II | 44 | 23 | 21 | 52.3 |
| Port of Menteith | 83 | 46 | 37 | 55.4 |
| Bute | 128 | 55 | 73 | 43.0 |
| Faifley | 25 | 13 | 12 | 52.0 |
| Machars | 79 | 65 | 14 | 82.3 |
| Cairnholy | 43 | 26 | 17 | 60.5 |
| Kirkcudbright | 139 | 83 | 56 | 59.7 |
| Total | 1080 | 631 | 449 | 58.4 |

carvings and the rock surface, and how responsive the motifs are to natural features (Table 6).

The *Motifs* category is the most extensive and complex of the classification system, comprising 13 sub-categories and 190 variants. These describe the main motifs and their range of variations (see Fig. 6). For example, the sub-category *Cupmarks* includes simple cups of average size (2-6cm diameter), mini-cups (less than 2cm diameter) and large cups (more than 6cm diameter). Cupmarks can be conjoined (carved adjacent to each other),

**Table 5** Total number of panels and motifs per Council area (listed geographically from north to south), assessed in the Small and Medium Scale analyses

| Council area | Number of panels | Number of motifs |
|---|---|---|
| Western Isles | 7 | 68 |
| Highland & Moray | 178 | 3100 |
| Aberdeenshire | 12 | 230 |
| Angus | 22 | 373 |
| Argyll & Bute | 230 | 5160 |
| Perth & Kinross | 125 | 1672 |
| Stirlingshire | 76 | 1271 |
| Dunbartonshire | 15 | 397 |
| Lothians | 10 | 140 |
| Dumfries & Galloway | 187 | 3622 |
| Lanarkshire | 2 | 15 |
| Fife | 3 | 26 |
| Ayrshire | 1 | 9 |
| Borders | 1 | 5 |
| Overall total | 896 | 16,088 |

**Table 6** Description of type of depictions (after [12])

| Type of depiction | |
|---|---|
| Planar | Carved motifs are unresponsive to geological features Please make all rows in this table beneath the 'Type of Depiction' heading the same, i.e. not bold and no line underneath the row |
| Plastic | Motifs and compositions incorporate some natural features such as solution holes and fissures |
| 3D Style | Motifs have a 3D appearance, being adapted to the micro-topography of the rock surface (e.g. Glassie 1, Fig. 5) |

represented as dumbbells (two cups connected by a short linear groove) or located in association with other motifs, such as along, adjoining or intersecting rings. Other variations include different numbers and types of concentric rings surrounding a central cupmark. Rarer motifs, such as rosettes (an arrangement of cupmarks in a circular shape), keyholes and spirals, have several versions across the country and in other regions with ARA, denoting connections within Scotland and with other countries. The *Motifs* category is particularly important in demonstrating numerous subtle variations, many of which co-exist in disparate areas of Atlantic Europe, suggesting a prehistoric network of exchange and cultural transmission that facilitated the spread of ARA [12].

Finally, the *Carving Techniques* category assessed the technology used to create the rock art, although this was based on close observation of the motifs and would benefit from systematic experimental archaeology studies. The majority of the carvings were created by pecking (repeatedly striking the rock surface with a pebble or other hard implement), which can be either fine and precise or rough and crude. Other methods can be identified in high-resolution 3D models of the carvings, including abrasion, incision, and a combination of techniques.

## Medium Scale analysis

The decisions underpinning the selection of specific rocks and motifs may shed new light on past values and perceptions. The Medium Scale analysis used the same number of carved panels as the Small Scale analysis (see Table 5). It assessed multiple features relating to the type of rock medium, the organization of motifs, and their interaction with natural features, using the sub-categories *Type of Media, Compositional Subclasses, Motif Range, Structural Variants* and *Motif Behaviour* adapted from [12], and inspired by [7]. Although landscape was important, the characteristics and features of the rock could be essential in attaining specific carving designs, so it is necessary to know them in detail.

The *Type of Media* category showed that ARA was predominantly created on boulders and outcropping rocks, but our study revealed a preference for the former in northern Scotland and the latter in southern and western Scotland (see section "Geology". for details). This category also includes carved rocks extracted and used in secondary contexts, incorporated either into prehistoric monuments (e.g. the Clava Cairns near Inverness, Highland) or into recent structures such as field walls.

The *Compositional Subclasses* (Table 7) category describes the distribution of motifs on the rock surface according to seven attributes, while the *Motif Range* assesses the frequency of representation of each symbol (Table 8). Although the repertoire of ARA motifs is extensive, this analysis demonstrated the monothematic and repetitive character of the tradition, which had already been identified by other authors [1, 12].

Aside from its main characteristics, the Medium Scale analysis aims for a more refined appreciation of motif structuring on the rock face and interactions with natural features. ARA has a strong relationship with the rock surface and often uses its contours to create motifs, as seen in the *Type of Depiction* category (see Table 6 and Fig. 5), as well as incorporating natural features in the

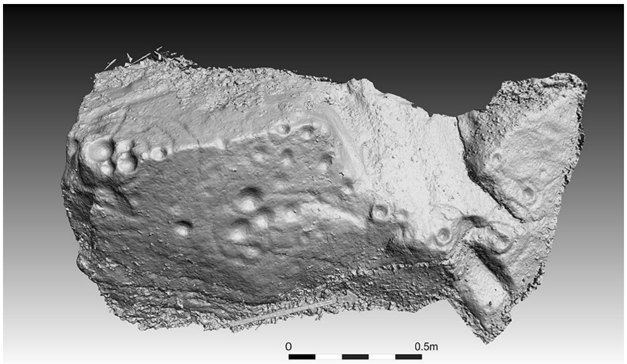


**Fig. 5** Screen-shot of an enhanced 3D model of Glassie 1, Perth and Kinross, showing how the carved motifs are moulded to the three-dimensional form of the rock. Created using 3D model data TM 001808 © Historic Environment Scotland

composition [4, 7, 12]. The *Structural Variants* category assesses these relationships by considering whether fissures truncate, divide, converge with, or are incorporated into motifs; whether natural features such as fissures or solution holes are enhanced, enclosed by, or intersect with motifs; and whether edges of the rocks are incorporated into the compositions. In addition, the *Structural Variants* category evaluates the relationship between motifs, such as whether they are conjoined, superimposed or connected by linear grooves. Until recently, superimposed motifs were thought to be virtually absent from ARA, despite being common to many other rock art traditions. Systematic use of 3D modelling to record ARA has revealed several examples of overlain motifs (Fig. 7) ([12], p. 98), [15, 36].

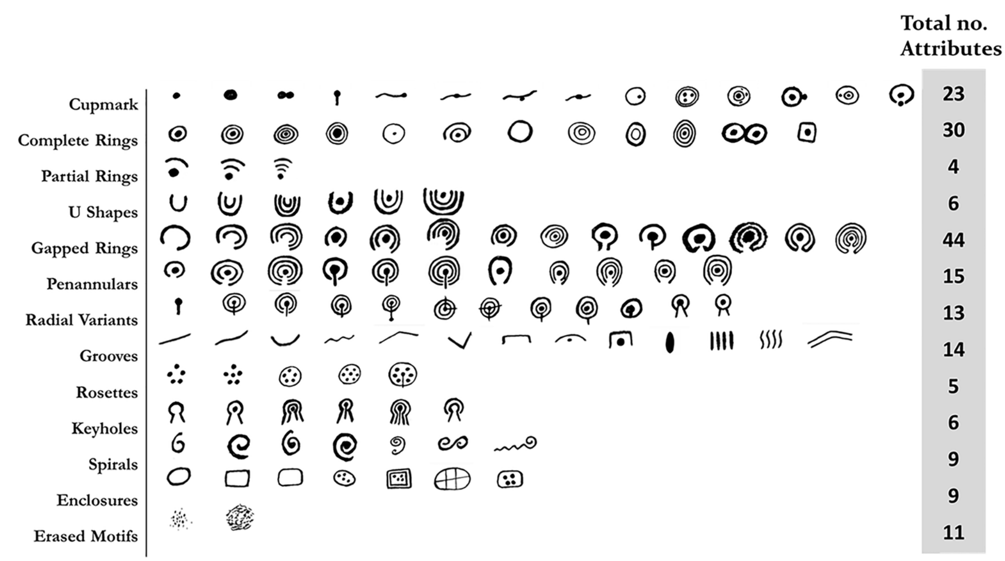


**Fig. 6** Categorical scheme of motif variants for the Small Scale analysis. Adapted from [12]. Drawings by Andrew Valdez-Tullett

**Table 7** Description of compositional subclasses (after [12], p. 100–101 & 218)

| Compositional subclasses | |
|---|---|
| Single | One only motif carved |
| Simple | Simple arrangement of a small number of motifs (between 1 and 2) |
| Clustered | Motifs are close together or arranged over a limited area (half or less) of the panel |
| Prominent Motif | A large motif occupies a central position on the panel due to location or size |
| Irregular | Motifs appear dispersed in a random or irregular fashion across the rock surface |
| Dispersed | Motifs are widely but evenly distributed |
| Dense | A series of motifs are closely located and/or interconnected, covering a large part of the rock surface |

**Table 8** Description of Motif Range types (after [12], p. 101–105 & 218)

| **Motif Range** | |
|---|---|
| Dominant Type | The panel is dominated by one frequent type of motif |
| Limited Type | Relatively high frequency of two to three types of motifs (no more than four represented simultaneously) |
| Varied Type | Five or more types of motifs are represented on the same panel |

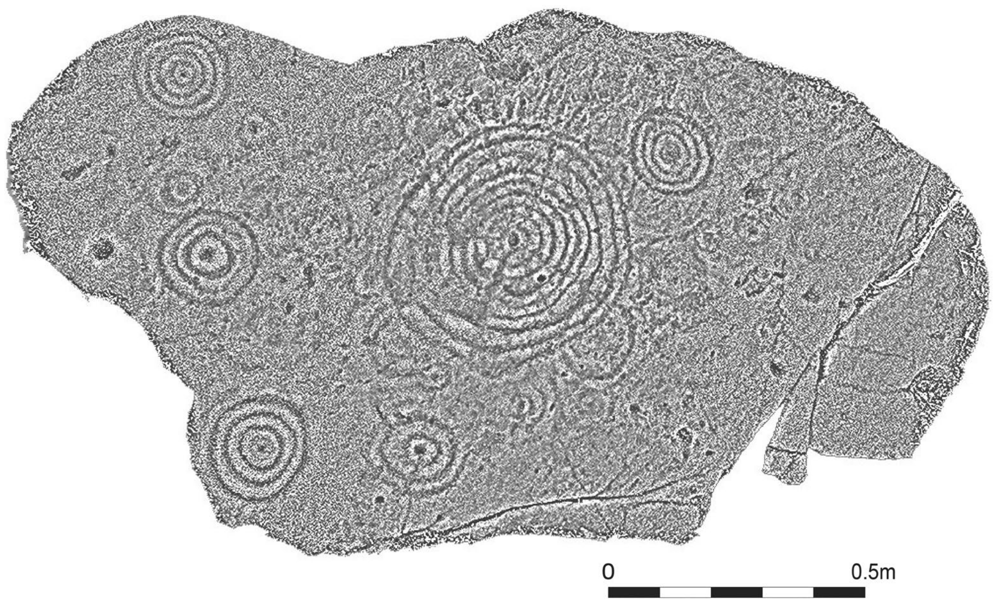


**Fig. 7** Castleton 3 (ScRAP ID 2070), Stirling, comprises a densely carved outcrop featuring a cup with nine concentric rings and multiple radials, superimposed over smaller cup-and-ring motifs. Created using 3D model data TM 001924 © Historic Environment Scotland

The last category of the Medium Scale analysis focuses on *Motif Behaviour* ([12], p. 96–100 & 225–6). This assesses how the motifs are organized on the panels, according to parameters such as linearity or convergence of motifs. For example, if a number of cupmarks are displayed in a row or a curve, or if there is a consistent direction in the radials of all the cup-and-ring motifs carved on the rock surface.

The Medium Scale analysis demonstrated that the ARA tradition privileges not only the motifs, but also the rock on which they are carved and the natural world by engaging with the rock surface. In order to achieve particular effects common to ARA, such as the 3D character of some motifs, it is likely that the compositions were conceived prior to execution. Certain rocks appear to have been deliberately selected for their particular attributes, which could explain at least in part why specific boulders and outcrops, and even landscape locations, were chosen for carving.

## Large Scale analysis

Our Large Scale analysis encompassed several computational approaches, including GIS, to explore spatial patterning in rock art contexts and how the landscape setting may have affected people's perceptions of the carvings in the past. We examined two categories of landscape variables. First-order characteristics are enduring features of the landscape upon which point patterns may depend, such as Elevation, Slope and Aspect, and may affect the distribution of rock art (e.g. [39], p. 959, [40], p. 192). Second-order characteristics include more nuanced variables that describe the interactions between points, and encompass reasons other than topographic or geomorphological that may have attracted people to these locations ([39], p. 959, [40], p. 192). Our analysis used a range of variables from both categories to identify potential natural and cultural constraints on and opportunities for human activity (e.g. settlement, subsistence, movement, and access). We explored the implications of these

**Table 9** Spatial datasets used in the Large Scale analysis

| Provider | Name | Type | Scale | Source | Open source |
|---|---|---|---|---|---|
| Scottish Natural Heritage | Landscape Character Assessment 2019 | Vector | 1:50,000 | www.spatialdata.gov.scot | Y |
| The James Hutton Institute | National Soil Map of Scotland 2011 | Vector | 1:250,000 | www.spatialdata.gov.scot | Y |
| The James Hutton Institute | National Peat Depth Map of Scotland 2011 | Vector | 1:250,000 | Not publicly available | N |
| Bluesky International Limited & Getmapping Plc | 5 m Digital Terrain Model | Raster | N/A | www.apgb.co.uk | N |
| Ordnance Survey | Inland water and coastline data from OS MasterMap® Topography Layer | Vector | 1:1 | www.ordnancesurvey.co.uk | N |
| British Geological Survey | Bedrock geology and linear faults | Vector | 1:625,000 | www.bgs.ac.uk | Y |
| Historic Environment Scotland | Historic Land-use Assessment 2015 | Vector | 1:25,000 | www.spatialdata.gov.scot | Y |
| Historic Environment Scotland | Canmore data 2021 | Vector | 1:1 | www.canmore.org.uk | Y |

elements on the location of carvings, whilst acknowledging known and unknown differences between prehistoric and modern landscapes. To gain a more comprehensive picture we also examined spatial relationships between the rock art and other types of monuments, artefact scatters, field systems and pathways.

### Variables and analytical approaches

As previously mentioned, we used 16 Case Studies from across Scotland, comprising a total of 631 validated rock art panels (see Fig. 4 and Table 4). The majority are concentrated in western and central areas since rock art in eastern Scotland is more sporadic, and Covid-19 restrictions limited data collection here in the final 2 years of the project. Each Case Study area comprised a minimum number of points (i.e. georeferenced carvings) defined by specific topographic features, such as a valley or island. A convex hull was created from each point and expanded by a 20 km buffer to encompass the immediate surroundings of the rock art.

Spatial analyses were largely conducted in GIS, modelled in ESRI ArcGIS Desktop 10.6 and QGIS Version 3.4.5-Madeira using the datasets described in Table 9, with licenses provided by HES. The Digital Terrain Models (DTM) used to derive variables such as Elevation, Aspect and Slope had a 5m resolution and were produced by Bluesky International Limited & Getmapping Plc. These basemaps were selected for consistency of results as comprehensive higher resolution LiDAR data coverage for Scotland was lacking at the time of our research. There is significant variance in the scale of these datasets, with some offering a detailed perspective of local features and others more general trends at a larger scale. A critical discussion of how scale affects the results is provided below.

Goodness-of-fit tests were carried out to establish the veracity of our results, namely the non-parametric Kolmogorov–Smirnov (K-S) test, which does not assume a normal distribution, and can be used to 'measure the deviation of one observed data distribution from another observed data distribution' ([41], p. 86). The null hypotheses determined whether the relationship between each tested variable and the rock art was relevant or a product of chance. The K-S test was run with the 'ks.test' function from the R Stats Package [42], R version 4.0.3 via RStudio [43] (Version 1.3.1093). Random points were generated with 'spsample' from the sp package [44] and 'extract' from the raster package [45]. In each Case Study area, the rock art values were compared to the values of 1000 randomly sampled points from within that Case Study area, and the process was performed 10 times. The probability values for the 10 runs were averaged to produce one p-value (see Table 10). Overall, the results show considerable diversity in the significance of the tested variables, and suggest regional patterns of engagements with the rock art. Further details of the spatial analysis and testing for significance are discussed below, and in the Additional Methods and Data (files 1, 2) provided with this article.

### Natural variables

The creation of motifs on boulders and outcrops in fixed places within the landscape is not random, but structured and meaningful [1]. In order to better understand why certain places were selected for carving, we analysed several natural variables that may have influenced decision-making: geology, soil type, peat depth, elevation, aspect, and slope. Modelling only represents the affordances of the terrain, however. While these analyses are useful to examine ways in which the landscape can be explored, we acknowledge the subjectivity of body cultural-specific

**Table 10** Average probability values (p-value) from K-S test for each variable. Shaded values are not significant

| Case study area | Elevation | Slope | Aspect |
|---|---|---|---|
| Bute | 5.28E−3$^{-}$** | 8.19E−5$^{5}$*** | 0.046* |
| Cairnholy | 8.89E−10*** | 4.1E−3** | 0.072 |
| Faifley | 1.81E−10*** | 0.101 | 0.0140* |
| Inverness North | 7.89E−12*** | 3.52E−3** | 1.39E−5*** |
| Inverness South | 0.012* | 0.289 | 0.036* |
| Kilmartin I | 5.82E−9*** | 0.012* | 0.014* |
| Kilmartin II | 8.59E−10*** | 0.012* | 0.106 |
| Kirkcudbright | 0.117 | 0.08 | 0.063 |
| Machars | 0.016* | 4.8E−3** | 0.4 |
| Mid Loch Tay | 1.4E−10*** | 3.05E−4*** | 3.45E5*** |
| North Loch Tay | 9.73E−8*** | 0.542 | 1.15E−7*** |
| Port of Menteith | 3.1E−14*** | 4.4E−5*** | 1.36E−3** |
| South Loch Tay | 1.04E−14*** | 1.35E−4*** | 0.6 |
| Strath Tay | 1.82E−7*** | 0.074 | 2.08E−5*** |
| Tiree | 6.42E−11*** | 6.24E−6*** | 0.223 |

*Probability value < 0.05 (significant)

**Probability value < 0.01 (very significant)

***Probability value < 0.001 (highly significant)

biases and the unpredictability of human behaviour. As such, our results and hypothesis were statistically verified with goodness-of-fit tests.

#### *Geology*

Rock type could have influenced the appearance of the motifs, and the time and tools required to produce them [46]. For example, the scarcity of rock art, generally limited to cupmarks, in the north-west of Scotland may be due to the local hard Lewisian Gneiss geology [8]. In addition, the Small and Medium Scales of analysis have shown that ARA is very responsive to natural rock surface features, and the micro-topography of the rock may have been considered more important than its hardness.

Overall, there is no obvious preference for a particular geology within Scotland. ARA was created on a variety of rock types, from gneiss and schists to sandstones and greywacke, with a few carvings on granites in the Inverness area. In general, the main bedrock type was used in each region. For example the majority of panels are schist in the Loch Tay and Kilmartin areas, while greywacke predominates in Dumfries and Galloway.

#### *Soils*

The complex geology and climate of Scotland have created variable soil types which support a diversity of ecosystems, human settlement and activities [47, 48]. Studies of soil types and taphonomic processes are useful in discerning the uneven distribution of prehistoric rock art in Scotland, and its preservation (e.g. [20], p. 8). In addition, when palaeoenvironmental data are available, soil types can inform our understanding of past vegetation conditions, human activities, and potential for arable farming and settlement in the immediate environs of the carvings. Palaeoenvironmental investigations of rock art sites are rare in Scotland, however, and could only be considered in our research in relation to certain Case Study areas (e.g. [48, 49]). Consequently, our analysis was based mainly on assessment of modern soil maps (Table 11), which may differ from prehistoric soil types.

A significant percentage (37%) of the panels included in this study is located in areas of infertile and acidic Podzols, notably Loch Tay, Inverness, Tiree and parts of Kilmartin. Podzols are generally poor in nutrients and support vegetation communities characterised by heather, moorland and native pinewood, although some types, such as Humus-Iron Podzols, can be improved for agriculture. A further 30% of the rock art is found within Brown Forest Soils or Brown Earths. These soils are mostly concentrated in southern Scotland, and the result is biased by the density of rock art in the Dumfries and Galloway study areas. Apart from this region, only a few panels in Kilmartin I, Strath Tay, North Loch Tay and Mid Loch Tay are currently located in Brown Forest Soils, while in Faifley the panels are distributed across Brown Forest Soils with Gleying. Finally, 29% of carved rocks are situated within different types of Gley soils (i.e. Non-calcareous Gleys to Humic and Peaty Gleys; Table 11), which can be found at various elevations in Scotland. These soils can be compact and associated with periodic or long-term waterlogged conditions, so require drainage for agricultural use. Other soil types include Rankers, which are more predominant in steep mountainous or hilly terrain, and comprised 2% of the rock art, mainly in Inverness North and North Loch Tay. Only in the Western Isles were panels associated with peat.

#### *Peat deposition*

Peats are formed in cool, wet climates, and predominate in upland areas of Britain and Ireland. Peats have been forming in Scotland for the past 10,000 years and occur in many locations from hillsides to valley floors ([50], p. 2097–8). Blanket peat formations developed after 6000 BP and typically occur in upland areas of southern and central Scotland [50]. Aside from their palaeoecological importance, peat deposits can preserve invaluable archaeological remains, including rock art. Several panels have been uncovered during peat cutting in Ireland, including the Kealduff Upper area of the Iveragh Peninsula, where rock art was associated with a prehistoric field system ([12], p. 117).

**Table 11** Number of panels and types of soils on which they are located in each study area

| Soil type | Western Isles | Inverness North | Inverness South | Tiree | Kilmartin I | Kilmartin II | Bute | Strath Tay | North Loch Tay | Mid Loch Tay | South Loch Tay | Port of Menteith | Faifley | Cairnholy | Kirkcudbright | Machars | Total | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Peat | 2 | | | | | | | | | | | | | | | | 2 | 0.3 |
| Peaty Podzols | 1 | 15 | 7 | | | | | 3 | | | | 41 | | 4 | | | 71 | 11.3 |
| Humus-Iron Podzol | 1 | 46 | 21 | | 9 | 6 | | 23 | 3 | 15 | 25 | 5 | | | | | 154 | 24.4 |
| Humus-Iron Podzol with Peaty Gleys | | | | 6 | | | | | | | | | | | | | 6 | 1.0 |
| Peaty Gleys | 3 | | | 13 | 5 | | 41 | | | | | | | | | | 62 | 9.8 |
| Humic Gleys | | | | | 40 | 13 | | | | | | | | | | | 53 | 8.4 |
| Calcareous Gleys | | | | | | | 13 | | | | | | | | | | 13 | 2.1 |
| Non-Calcar-eous Gleys | | 5 | | 1 | | 5 | | 6 | 6 | 26 | | | | 8 | | | 57 | 9.0 |
| Brown For-est Soils | | | | | 13 | | 1 | | 5 | 6 | | | | 14 | 76 | 54 | 169 | 26.8 |
| Brown Forest Soils with Gley-ing | | | | | | | | | | | | | 5 | | 7 | 11 | 23 | 3.6 |
| Rankers | | 4 | | | | | | | | | | | | | | | 4 | 0.6 |
| Brown Rankers | | | | | 1 | | | | 8 | | | | | | | | 9 | 1.4 |
| Built area | | | | | | | | | | | | | 8 | | | | 8 | 1.3 |
| Total Panels | 7 | 70 | 28 | 20 | 68 | 24 | 55 | 32 | 22 | 47 | 25 | 46 | 13 | 26 | 83 | 65 | 631 | 100 |

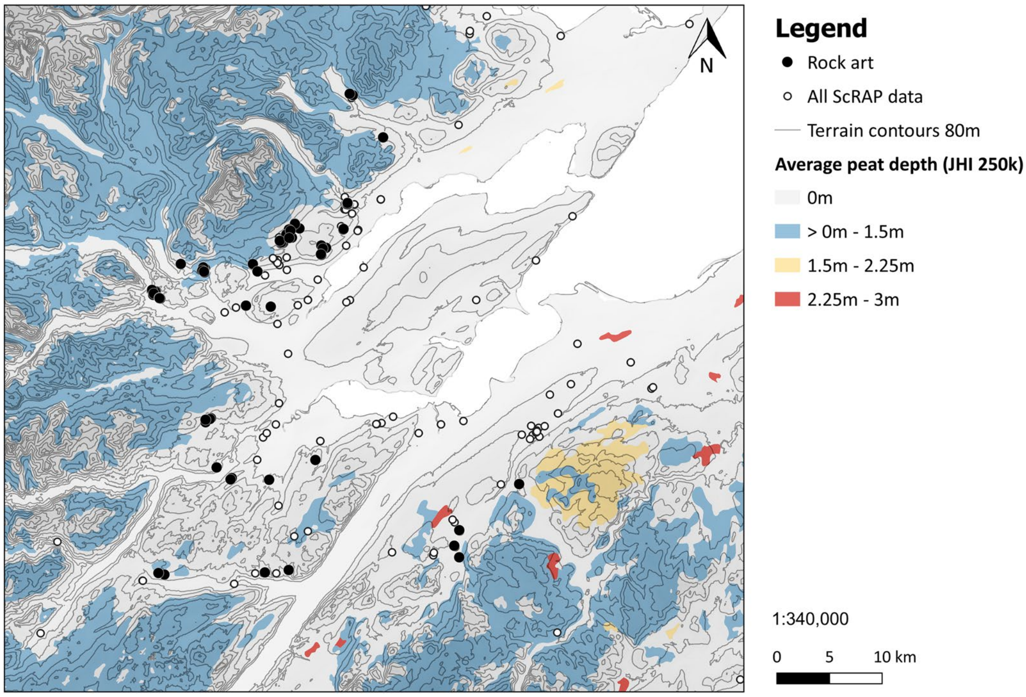


**Fig. 8** Map showing how rock art panels in Inverness avoid or lie on the edges of peat, determined by data from the James Hutton Institute

Peat deposition can obscure rock art panels, and may contribute to the uneven distribution of carvings across the country. There is a broad correlation between areas with low peat formation and high concentrations of rock art, such as Dumfries and Galloway, and areas with extensive, thick peat deposits and low frequency of carvings, including much of the Highlands and the Western Isles. In Inverness, the majority of panels lie at the edges of the peat blankets, raising questions about whether peat formations conceal carved panels or were deliberately avoided in prehistory (Fig. 8).

Our analysis of peat coverage in relation to rock art location would have benefitted from a higher resolution soil dataset combined with paleoenvironmental data. Nevertheless, it became clear that the majority of rock art is located in areas where peat is absent or in thin layers that are unlikely to cover the carvings.

### *Elevation*

Elevation has often been considered significant in both the location and the complexity of rock art. In his study of Ilkley Moor in Yorkshire (England), Bradley ([1], p. 96) proposed that cup-marked rocks are found more often on sheltered, lower grounds, and that complex carvings occur at higher elevations (c. 250–400 m), but not exceeding 500 m OD. While differences in elevation may relate to the local ecology [1, p. 129 & 170], they could also denote visibility preferences. In their viewshed analysis of rock art in GIS, Gaffney et al. [9] confirmed that mid-slope locations were preferred, and suggested that elevation served a particular function within the landscape.

Our analysis encompassed Scotland's diverse geomorphology and elevations ranging from high mountains to lowlands. Despite this variability, our results confirmed a consistent preference for the location of rock art at mid-slope elevations in relation to the local topography. In coastal areas such as Kirkcudbright, Kilmartin, Tiree and the Western Isles, the majority of panels lie at 0–100 m OD. In the Cairnholy Case Study area close to the south coast, most carvings are located at 150–200 m OD, with a few up to 250 m OD. Panels are only situated at higher altitudes in the more mountainous area of Loch Tay, although here they are also predominately in mid-slope locations within the generally raised elevation of this area.

Overall, in all areas rock art is located at accessible elevations rather than high altitudes, despite the availability of suitable rock surfaces at different elevations. Interestingly, with the exception of Kirkcudbright, Elevation was the only variable returning a consistent significance test result, indicating that mid-slope placement of rock art was deliberate rather than simply reflecting the affordances of the local topography.

### Aspect

The Aspect analysis derives from the elevation data and determines the orientation of slopes on which rock art is situated. Slope orientation may be significant in the relationship between rock art and other cultural and natural elements in the landscape, and/or in privileging visibilities ([12], p. 111). Aspect may have been relevant also for the amount and direction of sunlight striking the carvings, which can be calculated through a Hillshade analysis. Light conditions have a dramatic effect on rock art visibility. Shadows cast by oblique sunlight in winter or at the start and end of the day bring the motifs into sharp relief. North-facing slopes receive less sunlight than those facing south, especially in the winter, which may have affected seasonal visibility of the carvings. The amount of sunlight on a slope can also influence local vegetation, which may impact on perceptibility and accessibility of panels, especially since ARA was characteristically created on low-lying rocks that easily become overgrown. In addition to enhancing the effect of sunlight on rock art, southwards-facing terrain would have been more conducive for settlement and farming in Scotland than northwards-orientated slopes, with implications for human activities associated with rock art.

In our analysis, aspect was calculated in degrees, and results were classified in eight equal numerical intervals, with a flat option for areas lacking specific orientation ([51], p. 120–1). Further details of the analysis are provided in the Additional Methods and Data (files 1, 2) published with this article. Excepting some regional disparities, panels in all case studies were overwhelmingly located on south-facing slopes, with slight variations towards the southeast (22%) or southwest (14%), but rarely facing north. The significance of this result was confirmed in some areas by the goodness-of-fit K-S test, but the null hypothesis was rejected in other areas. Thus, despite the apparent southwards-facing trend, there is seemingly no common pattern across our study areas, implying that reasons other than orientation also dictate the location of the rock art.

Furthermore, we assessed the aspect of the carved panels themselves using fieldwork data to establish whether this offered different insights from slope aspect. No clear patterns were identified, suggesting that this micro-orientation played no specific role in carving practice.

### Slope

Like Aspect, Slope—a first-order derivative of the surface that can be used to assess changes in the terrain—is calculated from elevation data. In our analysis, terrain steepness was calculated in degrees, then reclassified according to five classes of slope intervals in percentages, following Butzer's [52] principles (see Table 12), used for rock art studies elsewhere [12]. Estimating the inclination of the terrain may provide insights into potential human activities developed in proximity to rock art. For instance, it has been suggested that optimal arable farming areas are typically located between 0 and 12% of inclination, whereas terrain with slopes greater than 20% are more appropriate for grazing and forestry activities [10]. Slope steepness would also affect movement across the landscape and access to the rock art, as well as opportunities for people to gather near panels [12].

**Table 12** Slope intervals of inclination (after [52])

| | Slope type | Inclination |
|---|---|---|
| 1 | Flat/Gentle | < 2% |
| 2 | Soft/Smooth | 2–5% |
| 3 | Medium | 5–15% |
| 4 | Accentuated | 15–40% |
| 5 | Very Accentuated | > 40% |

The majority of panels assessed fall within the classes of medium and accentuated slopes (Fig. 9 and Table 13). Carvings are overwhelmingly located in areas with medium slopes in Cairnholy (81%), Kirkcudbright (58%), Machars (60%), Faifley (77%), Kilmartin II (74%), Strath Tay (65%), Inverness South (57%), and Tiree (75%). The rock art is preferentially located in terrain with accentuated incline in Bute (53%), North Loch Tay (68%) and Mid Loch Tay (68%), while Inverness North, Kilmartin I and South Loch Tay have similar proportions of panels on both medium and accentuated slopes, and small percentages (2–4%) in very accentuated terrain. Probably due to their coastal location, the Machars, Inverness South and Tiree are the only case studies with panels on soft/smooth slopes. The Western Isles have the highest percentage of rock art on very accentuated slopes, although the sample here comprises only seven panels and is statistically unreliable.

Significance testing of these results using the K-S test indicated that slopes with specific inclines were deliberately selected in ten case studies (Inverness North, Tiree, Kilmartin I and II, Bute, Mid and South Loch Tay, Port of Menteith, Cairnholy and the Machars). In the remaining case studies of Inverness South, Strath Tay, North Loch Tay, Faifley and Kirkcudbright, the distribution of rock art on specific slopes of the terrain was not intentional.

In essence, the results suggest that rock art is generally located in relatively accessible areas of the landscape where the inclination of the terrain would not significantly restrict people's movements and, as testified during fieldwork, would allow gatherings of several individuals. This is particularly relevant when viewed in

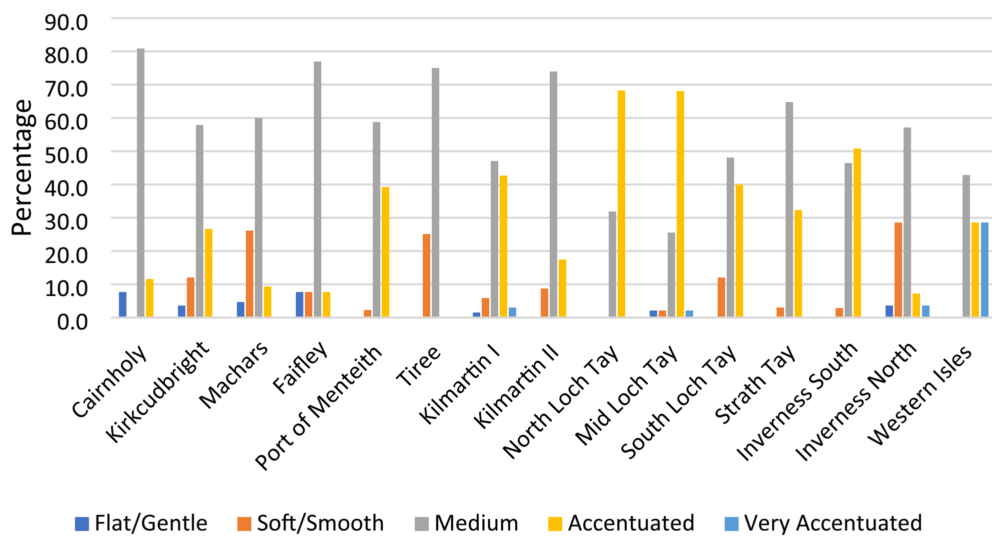


**Fig. 9** Percentage of panels per Case Study area according to slope

**Table 13** Percentage of panels per Case Study area according to slope

| | Flat/Gentle | Soft/Smooth | Medium | Accentuated | Very Accentuated |
|---|---|---|---|---|---|
| Cairnholy | 7.7 | 0.0 | 80.8 | 11.5 | 0.0 |
| Kirkcudbright | 3.6 | 12.0 | 57.8 | 26.5 | 0.0 |
| Machars | 4.6 | 26.2 | 60.0 | 9.2 | 0.0 |
| Faifley | 7.7 | 7.7 | 76.9 | 7.7 | 0.0 |
| Port of Menteith | 0.0 | 2.2 | 58.7 | 39.1 | 0.0 |
| Tiree | 0.0 | 25.0 | 75.0 | 0.0 | 0.0 |
| Kilmartin I | 1.5 | 5.9 | 47.1 | 42.6 | 2.9 |
| Kilmartin II | 0.0 | 8.7 | 73.9 | 17.4 | 0.0 |
| North Loch Tay | 0.0 | 0.0 | 31.8 | 68.2 | 0.0 |
| Mid Loch Tay | 2.1 | 2.1 | 25.5 | 68.1 | 2.1 |
| South Loch Tay | 0.0 | 12.0 | 48.0 | 40.0 | 0.0 |
| Strath Tay | 0.0 | 2.9 | 64.7 | 32.4 | 0.0 |
| Inverness South | 0.0 | 2.8 | 46.5 | 50.7 | 0.0 |
| Inverness North | 3.6 | 28.6 | 57.1 | 7.1 | 3.6 |
| Western Isles | 0.0 | 0.0 | 42.9 | 28.6 | 28.6 |

combination with the results for Elevation and Aspect. In addition, the slope would determine the potential types of activities around the rock art, with the majority of panels situated in terrain best suited for farming or grazing.

### Lived landscapes: cultural variables

Over 3000 rock art panels are known in Scotland today, and at least 3500 elsewhere in the UK, although this is probably only a fraction of their original number. The sheer volume and spread of prehistoric carvings signifies their importance to past societies. Research in recent decades has prioritised understanding the social and cultural contexts of their creation and use (e.g. [1, 4, 12, 28]).

Within our Large Scale approach, we developed a series of spatial analyses to assess patterning in the location of rock art and choices underpinning those patterns. Producing rock art did not simply involve carving motifs; deciding where to carve was an important step in the creative process, and reflects how people perceived rock art and its surroundings. As we have seen, certain physical elements of the landscape appear to have been significant in the placement of rock art. What we are concerned with now is whether particular cultural or intangible features were also relevant, and what these features might be.

This section discusses our analysis of variables affected by people's behaviour and perceptions that shape a 'lived landscape'. While there are countless possible culturally-specific variables that may have influenced where rock art was placed, we focused on a range of relatively measureable characteristics that inform our understanding of past human activities and preferences. These primarily explore land-use in the surrounding area, relationship with other contemporary monuments, and visibility and mobility in relation to rock art and other features in the landscape.

**Table 14** Historic land use around rock art panels

| Historic land-use type | No. of panels |
|---|---|
| Unenclosed Improved Pasture (Late 20th Century–Present) | 1 |
| Recreation Area (19th Century-Present) | 1 |
| Planned Rectilinear Fields and Farms (18th–20th Century) | 1 |
| Holdings (20th Century) | 1 |
| Opencast Site (Late 20th Century-Present) | 2 |
| Urban Area (19th Century–Present) | 3 |
| Designed Landscape (17th–20th Century) | 3 |
| Smallholdings (19th-20th Century) | 8 |
| Military Site (20th Century–Present) | 8 |
| Managed Woodland (18th–20th Century) | 14 |
| Crofting Township (18th–19th Century) | 19 |
| Sub-rectangular Fields and Farms (18th–19th Century) | 35 |
| Plantation (20th Century–Present) | 60 |
| Rough Grazing (Late 20th Century–Present) | 203 |
| Rectilinear Fields and Farms (18th Century–Present) | 272 |

### *Historic land use*

The land-use analysis aimed to investigate the biographies of rock art landscapes, and the processes of preservation and destruction that may have shaped current distribution of the rock art. The nature and intensity of human intervention in the landscape varies across the country, and has implications for survival rates of carvings in different areas.

Previous studies have discussed the impact of land-use patterns on rock art in Scotland (e.g. [8, 20, 53]). We built on these studies using Historic Landuse Assessment (HLA) data. HLA was developed by HES through systematic assessment of Ordnance Survey topographic maps, vertical aerial photographs, and archaeological and historical data in the National Monuments Record of Scotland and the Land Cover of Scotland 1988 [54]. In this context, 'Historic' denotes current land-use types whose origin 'may stretch back hundreds of years' ([55], p. 1); 'Relict' refers to past land-uses with identifiable surviving traces, organized chronologically ('Relict 1', most recent to 'Relict 3', the oldest). Mapping both historic and relict landscapes created a digital record of changing land-use across Scotland over time.

The HLA data demonstrates that land-use is a key factor in preservation and the diversity of survival of archaeological remains across Scotland, particularly Neolithic and Bronze Age features. Most rock art analysed in relation to HLA data are located on historic arable or rough grazing land (Table 14), suggesting that other land-use practices pose greater threats to its survival or visibility. For instance, only a small proportion (9.5%) of panels are situated in modern forestry plantations where rock art is at considerable risk from deep ploughing and felling. Our study demonstrated that rock art is more likely to have been preserved in areas which today are indicated as medieval or post-medieval settlements and have evolved into rough grazing, rather than on land that was improved in the nineteenth century. Land-clearance associated with large-scale farming is likely to have removed significant numbers of smaller carved stones and outcrops. For example, there are proportionately fewer carved stones and small outcrops in Dumfries and Galloway, an area that has been intensively farmed for hundreds of years, relative to Loch Tay which has been predominately under rough grazing since the nineteenth century Improvements.

Although the HLA dataset offers a broad overview of landscape evolution and the impact of changing land-use patterns, detailed appreciation of prehistoric land-use around rock art requires localised palaeoenvironmental investigation and archaeological excavation. Prehistoric land-use practices also need to be correlated chronologically with rock art production and use. This presents further challenges due to imprecise dating of rock art. For example, dates from excavations and palaeoenvironmental studies around carved rocks at Torbhlaren in Kilmartin indicate human activity at the site over 7000 years, from the Mesolithic to the medieval period (e.g. [4]).

Nevertheless, the few such studies conducted in Scotland have demonstrated the potential for a more comprehensive landscape contextualization of the carvings [4, 32, 49]. For instance, pollen analysis of two soil cores obtained during archaeological excavations of carved rocks above Loch Tay revealed that the panels were originally situated in an open landscape characterized by upland grazing and moorland habitats similar to today [32]. The open nature of the landscape would have afforded clear views to the sky and across the loch, which offers possible insights into Neolithic belief systems ([32], p. 52–6). In Kilmartin, palaeoenvironmental studies in the environs of two carved outcrops on the valley floor at

Torbhlaren demonstrated that the rock art was located in arable land where domestic wheat and barley were grown from 3200 and 3400 BCE respectively [48]. Managed woodland and grazing in the surrounding hills indicate a vibrant 'lived landscape' with visible and accessible rock art at its centre [4].

In the absence of more extensive palaeoenvironmental research, we cannot decipher the nature of land-use associated with rock art creation and use across Scotland. What the HLA data do show, however, is how historic land-use has contributed to the preservation and destruction of rock art, which may in part explain gaps in its distribution.

#### *Relationship to other contemporaneous sites*

While it is acknowledged that rock art needs to be integrated with the wider archaeological context, such discussions are still relatively infrequent. Studies that have addressed the relationship between carvings and the cultural landscape explore the physical and/or visual interplay between rock art and monuments [7, 23, 27], the nature of human activity in the vicinity of panels [4, 7, 32], and the process of material engagement with rock [3, 56]. Part of our analysis aimed to situate rock art within the archaeological diversity of Neolithic and Early Bronze Age Scotland. This section describes our approaches, working within the parameters of relevant datasets.

In order to investigate the social and cultural context of rock art, we examined its relationship with other broadly contemporaneous monuments and artefacts using three datasets curated by HES: (i) the National Record of Scotland's Historic Environment (Canmore database) containing spatial and descriptive information for Neolithic and Bronze Age domestic and ritual sites; (ii) the Historic Land-use Assessment (HLA) data, discussed in section "Historic land use", providing a chronological overview of the character of the historic environment containing rock art, illustrating landscape changes from prehistory to modern times; (iii) the Scottish Radiocarbon Dating Index comprising precise dates for a number of sites and locations which, although rarely directly related to rock art panels, were important in constructing a narrative of human activity in the surrounding landscape, and contributing to more effective chronological contextualization of the carvings. The three datasets were assessed spatially within a 10 km buffer of the rock art.

It should be noted that available data for prehistoric sites vary across the country. Current distribution patterns may in part reflect spatial inconsistencies in prehistoric population and activity, but are also shaped by research biases and heterogeneous patterns of survival and visibility. For these reasons, relationships identified between the rock art and other contemporaneous sites, and conclusions drawn from these observations, need to be measured and cautious. In general, our approach indicated no clear correlation between the distribution of rock art and other monument types. For reasons of space, it is only possible to provide a few examples of the outcomes of our analysis here. A more detailed account is provided in [14].

In some Case Study areas, such as Port of Menteith (Stirling), rock art is situated in contexts that appear removed from areas of more intensive human activity, where pursuits like grazing were perhaps more common. No archaeological remains are known in the immediate surroundings of the rock art here, and the closest monuments (the Wester Torrie stone circle and Auchenlaich chambered cairn) are located about 8 km away near Callander, an area with several other Neolithic features, including the Claish Farm timber hall [57] and the potential pit-defined cursus at Keltie Bridge [58]. This dichotomy between the apparent absence of prehistoric sites associated with rock art at Port of Menteith and the wealth of prehistoric sites but lack of rock art around Callander raises interesting questions that invite further investigation.

Conversely, in Case Study areas such as Faifley (West Dunbartonshire) the rock art is situated within more dynamic landscapes with evidence of varied prehistoric activities. The Early Neolithic site of Douglasmuir Quarry, located 500 m northeast of the Law Farm panels, contains buried land surfaces, pits, pottery and organic materials, while a stone circle lies around 1.5 km northwest of the Edinbarnet 1 panel, and 500 m beyond this is the Cairnhowit Neolithic chambered cairn.

The Western Isles are rich in prehistoric sites, including Neolithic chambered cairns. Interestingly, however, there are few examples of rock art, and the majority comprise single or small clusters of cupmarks. The paucity of rock art here may be due partly to the very hard local rock, Lewisian Gneiss, which may be less conducive to carving, and the growth of thick peat deposits since the Bronze Age that may obscure rock art panels in many areas. It may also reflect differences in Neolithic traditions in the Western Isles relative to mainland Scotland. Although many cupmarks were effectively re-classified as modern bait holes during ScRAP, the authenticity of prehistoric carvings here is supported by the presence of motifs on the capstone of the Coir Fhinn Neolithic chambered cairn, 3 km north-northeast of other panels.

The combination of these three datasets—Canmore, HLA data and radiocarbon dates—provided an overview of possible human activities in the vicinity of rock art panels. Many of our Case Study areas reveal a spatial relationship between rock art and Neolithic chambered cairns, as well as other monuments of probable Neolithic

**Table 15** Details of visibility analyses

| Type of analysis | Number of case studies | Software | Tool | DTM | Observer height | Target height | Radius |
|---|---|---|---|---|---|---|---|
| Individual viewshed | 16 | ESRI ArcGIS Desktop 10.6 | Viewshed (Spatial Analyst) | 5 m | 1.6 m | None | No limit |
| Cumulative viewshed | 16 | ESRI ArcGIS Desktop 10.6 | Viewshed (Spatial Analyst) | 5 m | 1.6 m | None | No limit |
| Intervisibility | 11 | QGIS Version 3.4.5-Madeira | Visibility Analysis plugin Version 1.4 | 5 m | 1.6 m | None | 50 m, 100 m, 500 m and 1 km |
| Reverse viewsheds | 16 | QGIS Version 3.4.5-Madeira | Visibility Analysis plugin Version 1.4 | 5 m | Height of panel | 1.6m | 100 m, 500 m and 1 km |

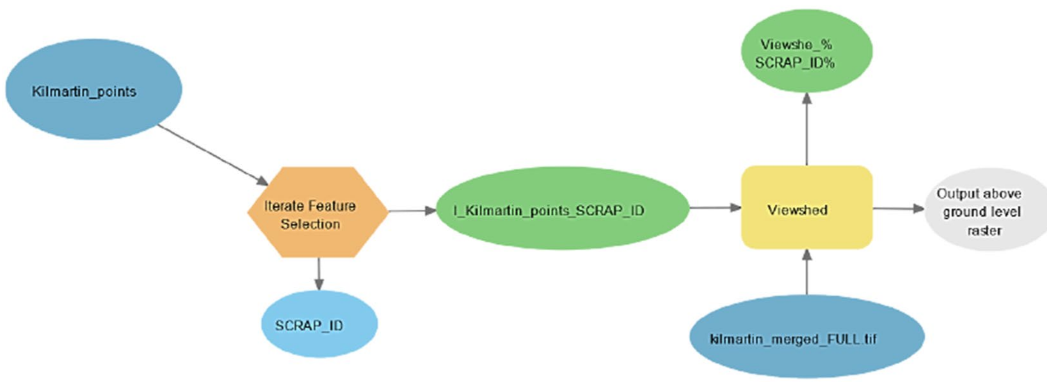


**Fig. 10** Workflow developed in ModelBuilder (ESRI ArcGIS Desktop 10.6) to automate the calculation of individual viewsheds, shown here with the data from Kilmartin. Each output was named with the individual SCRAP ID

date, including standing stones and stone circles. The incorporation of rock art within funerary monuments is also relatively common across all parts of Scotland, but prehistoric monuments often have complex biographies and it is unclear at what stage carved panels were integrated into their lifecycles. It would appear that, although the principles underpinning ARA are shared between different prehistoric communities across Scotland, each community adapted the tradition according to their own social and cultural character and beliefs [12]. The variability of associations between prehistoric monuments and rock art reflects the heterogeneity of Scotland's Neolithic, where significant differences can exist between neighbouring communities [59].

#### *Visibility*

As discussed in section "Previous research", visibility is arguably the most frequently studied variable in landscape approaches, with GIS tools popularising viewshed analyses in archaeological and rock art research [60–65]. The suggestion that wide vistas are paramount for rock art location has been generally accepted and has become an assumption in many studies.

Considering the emphasis on visibility for ARA, we explored this variable from a number of perspectives in order to confirm or refute its importance. We employed four types of viewshed analysis in order to develop a more complete understanding of what could be seen from the panels, and, in turn, how rock art could be perceived visually, including how perceptibility changes with distance (see also Table 15):

- individual viewsheds: visibility from each rock art panel
- cumulative viewsheds: combined visibility from all rock art panels
- intervisibility: visual connection between all rock art panels
- reverse viewsheds: visibility towards the rock art panel from surrounding landscape.

Viewsheds were calculated from the Digital Elevation Model (DEM). Individual and cumulative viewsheds were calculated with ESRI ArcGIS Desktop 10.6 using the 'Viewshed' tool ('Spatial Analyst' toolbox). A simple ModelBuilder was developed to automate the calculation

**Table 16** Distance ranges used in visibility analyses

| Range | Distance | Characterization |
|---|---|---|
| Identification | 0–50 m | Potential to identify motifs and/or the panel |
| Recognition | 50–100 m | Potential to recognise the rock and/or other identifiable features surrounding it |
| Detection | 100–500 m | Potential to detect the approximate location of the panel |
| Observation | 500–1000 m | Potential to observe the wider area in which the panel is situated |
| Beyond visual detection | > 1000 m | Probably no visual perception of the panel or its location in the landscape |

of individual viewsheds (Fig. 10). Intervisibility and reverse viewsheds were calculated with QGIS Version 3.4.5-Madeira using the Visibility Analysis plugin Version 1.4, developed by Zoran Čučković [66], which specifically addresses more advanced viewshed analysis. Following Wheatley and Gillings' reasoning ([51], p. 204–5), an observer height (OFFSETA) of 1.6 m was used for all visibility analyses, except the reverse viewsheds (Table 15). For these, OFFSETA was used to simulate the real height of the rock art panels, documented during fieldwork, and a target height (OFFSETB) was set to 1.6 m.

Whilst the individual and cumulative viewsheds were only limited by the extent of the extracted elevation data, the intervisibility analysis and reverse viewsheds were generated at different distance ranges inspired by Higuchi's principle (1983) (Table 16). This aimed to introduce more nuance to the viewsheds and consider variance, for example the acuity of human vision, by determining what can be identified at specific distances. Using different ranges for the radius also provided an appreciation of how perception changed with distance, and how rock art may have been experienced. The definition of distances was informed by similar approaches [12, 67, 68] and empirical evidence from our fieldwork.

The results provided a comprehensive insight into the visual properties of the rock art panels. A key outcome was the difference between the various case studies. Some places did not demonstrate any particular trends, whilst others had targeted and focused visual characteristics. In the Port of Menteith Case Study area, for example, both the individual and cumulative viewsheds were clearly oriented towards the south, channelling the observer's gaze from the largest concentration of panels (Fig. 11). This focus on a southwards visibility seems deliberate, and was confirmed through statistical testing, discussed below.

The reverse viewshed analysis indicated that many rock art panels had to be approached from specific directions in order to be visible, particularly at longer distances (500 m away). Many panels do not become fully perceptible (i.e. visible from most directions) until less than 100 m away. This can be a product of the terrain, particularly in more rugged and mountainous regions. Visibility can also alter with distance. The Ormaig panels in Kilmartin, for example, are visible at shorter distances when approaching inland from the north/northeast and south/southeast, but at a long distance (1 km) the location of the panels is more perceptible from the sea to the west. The analysis also demonstrated that rock art locations are best observed from hill slopes leading into valleys, and panels are often more perceptible looking downhill rather than up.

The intervisibility analysis did not prove particularly revealing for our research as panels tended to be either very dispersed or very clustered. Results from 11 study areas showed that, at smaller scales, generally only pairs or small clusters of panels are intervisible, and this pattern did not alter significantly at different scales. Interestingly, certain panels, such as Eurach in Kilmartin and Ceosabh in Tiree, appear to act as bridging nodes in intervisibility networks, connecting different parts of clusters, particularly at greater distances. The overall results indicate that intervisibility was not a key characteristic of the majority of Scotland's prehistoric rock

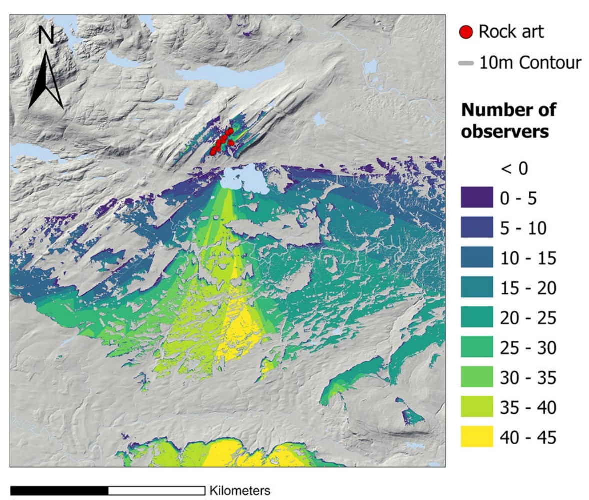


**Fig. 11** Cumulative viewshed for rock art at Port of Menteith, Stirling, channelling visibility southwards from the panels across the Flanders Moss, an ecologically important wetland

**Table 17** Results of significance testing for viewshed analysis for relevant Case Study areas

| Case Study Area | Panels (Count) | Mean rock art | Mean random | Kolmogorv-Smirnov test (p value) | Significance? Y/N |
|---|---|---|---|---|---|
| Mid Loch Tay | 45 | 0.024 | 0.024 | 0.612 | No |
| Bute | 55 | 0.098 | 0.116 | 0.067 | No |
| Faifley | 13 | 0.078 | 0.059 | 0.037 | Significant |
| Kilmartin I + II | 91 | 0.007 | 0.011 | 0.019 | Significant |
| Kirkcudbright | 83 | 0.074 | 0.051 | 0.012 | (Very) significant |
| Inverness South | 28 | 0.015 | 0.067 | 6.36E-4 | Highly significant |
| Strath Tay | 34 | 0.029 | 0.033 | 2.01E-4 | Highly significant |
| Port of Menteith | 46 | 0.066 | 0.037 | 5.7E-6 | Highly significant |

Probability (p) value < 0.05 (significant)

Probability (p) value < 0.01 (very significant)

Probability (p) value < 0.001 (highly significant)

art, which aligns with similar conclusions drawn from previous work in Dumfries and Galloway ([12], p. 134).

The viewshed analyses of eight Case Study areas were measured for statistical significance. Fifty randomly distributed sites were generated within the minimal bounding extent for the panels in each Case Study, and individual viewsheds were generated for each random site using the same parameters as for the rock art panels (i.e. 1.6 m observer height, same elevation data and no radius). The mean values of the individual viewsheds for each panel in a particular area were then compared to the mean value of the viewshed outputs from the random sites in that area. A higher mean value indicates that more cells are visible from that point (or the site is visible from more cells); a lower mean value denotes less visible cells. A two-sample Kolmogorov–Smirnov (K-S) test was then employed to confirm the relative significance of rock art and random viewsheds (Table 17). Constraints on time and computer-power made it possible to test only nine Case Study areas, including Kilmartin I and II which were analysed in combination.

Statistical testing demonstrated that in areas such as Strath Tay and Inverness South the visual properties of the rock art were intentional and, in these cases, panels were intended to be 'tucked away' in the landscape. Most striking was the confirmation of visual significance for the Port of Menteith carvings. These do not derive from a random distribution and have higher mean viewshed values than random sites, indicating that their visual properties are significant and important. Conversely, panels in Bute and Mid Loch Tay seem to follow a random distribution, and visibility did not seem to have any particular significance. Kirkcudbright, Kilmartin and Faifley have p-values just under 0.05 and can be interpreted as significant or, in the case of Kilmartin, possibly very significant. In sum, if we are being cautious, visibility appears to be a statistically significant factor in location choice for only three out of eight tested Case Study areas, and the data overall show very mixed significance values, in-line with the results for the other variables.

### *Mobility*

Mobility and migration are growing themes in archaeological research [69–71], particularly fuelled by recent ancient DNA studies which are providing tangible evidence for large-scale prehistoric mobility in the 3rd millennium BCE [72–76]. Movement has been a consistent theme in ARA interpretations since Bradley's work in the 1990s, however, despite the lack of systematic studies (e.g. [1, 27]).

Our approach aimed to use innovative computational techniques to test and explore possible relationships between rock art and mobility. We analysed movement potential within the 16 Case Study areas on the premise that, if rock art panels were intentionally associated 'with paths leading through the landscape and certain significant places along their course' ([1], p. 217), they would be located in areas more likely to be travelled. This enabled us to assess, first, whether rock art was located in spatial proximity to computer-generated optimal paths and, second, whether the study areas displayed obvious differences in how their rock art related to these paths. In addition to this wider study of movement, we also tested the viability of Agent-Based Modelling (ABM) as a comparative tool for understanding mobility in relation to prehistoric rock art within the landscape. Although this technique has been used successfully in archaeological research [83–85] there has been limited application to rock art studies. As the computer power and time required to run this approach in all our Case Study areas exceeded our resources, our pilot study focused only on the Kilmartin area. Kilmartin contains the densest concentration of prehistoric rock art and monuments of all the areas we studied, and was considered most appropriate for this test.

*Least coast path analysis with R (LCP-R)* Scotland's prehistoric rock art was probably created over centuries, if not millennia, and it cannot be assumed that people travelled between specific carving locations, or that particular panels formed the start or end points of journeys. Given these constraints, we applied a From-Everywhere-to-Everywhere (FETE) approach to explore mobility across the landscape [77]. Rather than determining the points between which movement occurs, this method calculates the shortest path from all points to all points in a dataset. In our analysis, the spatial environment was prepared in GIS,[5] with a 10 km buffer established from the boundaries of each Case Study area, and random points were generated at 12.5% evenly spaced distances along this outline. The FETE calculation was processed to and from each of these points. Optimal pathways were then modelled with the 'leastcostpath' (LCP) package in R [78], considering various slope-based cost surfaces, as well as barriers to movement. Non-tidal waterbodies, such as large rivers and lochs, were not included in the model since movement across them would have varied relative to land travel. Coastlines were considered, however, as sea travel is likely to have facilitated mobility in prehistory, although a full sea-land movement approach was not developed in this study. The 'leastcostpath' algorithm was calculated for 15 Case Study areas across Scotland, excluding the Western Isles where the rock art is separated by lochs, lochans and other forms of tidal inlets, and where the terrestrial travelling model would not be relevant. For subdivided study areas (Dumfries and Galloway, Inverness, Kilmartin and Loch Tay), the process was developed both for each subarea and for the larger region in order to construct a more comprehensive and comparative picture of movement.

Despite the limitations of the approach, our pilot study produced a range of local networks of optimal paths, based on a series of definable topographical features, illustrating which parts of the landscape were more likely to be traversed ([77], p. 2687). Although these calculations were based on modern topographic basemaps, our multivariate approach and consideration of sea level changes in prehistory [59] revealed interesting patterns. For instance, during the Neolithic, tidal areas separated the eastern side of Tiree, which lacks rock art, from the rock art-rich western side of the island. Similarly, in Bute, higher relative Neolithic sea levels effectively split the island into three, with the rock art concentrated in the two northern-most parts. In Kilmartin, the Moine Mhòr bogland would have been seawater [59] and, consequently, many rock art panels that are now well inland would have been located on the coast during the Neolithic. This has important implications for understanding how rock art was approached, encountered and perceived in prehistory and also, potentially, for dating rock art relative to ancient sea levels [79]. There is a need for more detailed reconstructions of prehistoric landscapes and coastlines, and integration of complex models for travelling via land and sea [80, 81].

**Table 18** Probability values from K-S test of LCP output from R

| Case study area | Probability value | Significance? Y/N |
|---|---|---|
| Kirkcudbright | 0.846 | No |
| Kilmartin I | 0.444 | No |
| Tiree | 0.265 | No |
| Bute | 0.214 | No |
| Inverness South | 0.076 | No |
| Cairnholy | 0.056 | No |
| *Kilmartin II* | *0.040* | *Significant* |
| *Machars* | *5.92E−3* | *Very Significant* |
| *Mid Loch Tay* | *2.34E−4* | *Highly Significant* |
| *Faifley* | *1.25E-4* | *Highly Significant* |
| *Strath Tay* | *1.81E−6* | *Highly Significant* |
| *North Loch Tay* | *7.78E−9* | *Highly Significant* |
| *Port of Menteith* | *2.46E−9* | *Highly Significant* |
| *South Loch Tay* | *2.88E−12* | *Highly Significant* |
| *Inverness North* | *2.2E−16* | *Highly Significant* |

The values are the average p-value of 10 × K-S tests performed on rock art panels and 1000 randomly sampled points. Significant values are in italics

Probability value < 0.05 (significant)

Probability value < 0.01 (very significant)

Probability value < 0.001 (highly significant)

The overall results of the LCP analyses demonstrated that the spatial relationship between randomly generated pathways and rock art varied across Scotland. Variation became particularly apparent when considered in relation to viewsheds and spatial relations with contemporaneous archaeological sites such as standing stones, funerary monuments and known settlements. In order to achieve a more tangible measure, we calculated the statistical significance of these relationships for the 15 Case Study areas, testing the goodness-of-fit of the LCP calculations with a K-S test. In practice, the test compared the outcomes of the mobility analysis with those obtained through a similar process using a dataset of random points. For each raster (1 per Case Study area), 1000 random points were sampled and their distance from optimal pathways was tested for significance against the values obtained for rock art.

[5] ESRI ArcGIS Desktop 10.6.

**Table 19** Mean mobility values for LCP output from R of rock art sites with significant values where K-S test indicates statistical significance

| Case study area | Mean rock art | Mean random | Min–max rock art | Min–max random |
|---|---|---|---|---|
| North Loch Tay | 6.432 | 2.159 | 0.05–13.5 | 0–27.9 |
| South Loch Tay | 5.160 | 1.504 | 2.7–7.4 | 0–12.85 |
| Faifley | 4.283 | 2.157 | 2.2–5.61 | 0–16.3 |
| Kilmartin II | 2.629 | 1.913 | 0–7.02 | 0–21.7 |
| Inverness North | 2.386 | 0.957 | 0–4.06 | 0–18.05 |
| Mid Loch Tay | 2.384 | 1.737 | 0–3.99 | 0–16.31 |
| Port of Menteith | 2.249 | 1.852 | 1–3.31 | 0–11.9 |
| Machars | 0.716 | 1.648 | 0–8.01 | 0–25.57 |
| Strath Tay | 0.406 | 2.182 | 0–1.81 | 0–18.08 |

This procedure was repeated 10 times for each Case Study area (Table 18).

Variations in the spatial relationship, or proximity, between rock art panels and optimal pathways observed in each study area are reflected in the K-S test results. For six Case Study areas (Cairnholy and Kirkcudbright in Dumfries and Galloway, Bute, Tiree, Kilmartin I, and Inverness South) the K-S test showed no statistical significance, indicating that the rock art follows a random distribution. The remaining eight case studies (italics in Table 18) revealed a statistically significant relationship between rock art and pathways. To better understand this significance, we looked more closely at the average mobility values in the different areas for the rock art and the random points where the K-S test highlighted statistical significance. These are the values that reflect how easily the landscape would be traversed, considering its topographical characteristics and barriers, such as waterbodies, input in the modelling process (Table 19).

The rock art panels in North and South Loch Tay appear to be located in particularly dynamic areas, with average mobility values substantially higher than those of the random points. The panels in Faifley, Kilmartin II, Inverness North, Mid Loch Tay and Port of Menteith also have higher average mobility values than random points, but their values tend to be at the lower end of the scale (maximum mobility value = < 5), therefore indicating that these areas probably had lower levels of movement across the landscape. In the case of Port of Menteith, these results seemingly corroborate the notion of minimal activity in this area, evident from other variables. Finally, the Machars and Strath Tay have significantly lower average mobility values than random points, placing the rock art in remote locations away from the simulated pathways, possibly intentionally.

*Least cost path analysis with NetLogo (LCP-NL)* We further investigated mobility with an Agent-Based-Modelling (ABM) method developed with the software NetLogo [82]. ABM is a form of computer simulation used to explore and understand the characteristics of a system, and how the simulation of actions, interactions and behaviour of artificial agents lead to patterns that shape the dynamics of that system. This approach can inform multiple theoretical perspectives ([83], p. 247, [84], p. 7). In archaeological ABM, the agents typically represent individuals or other types of social unit, although certain studies have increased the realism of these simulations by incorporating elements of social interaction, such as knowledge exchange, exchange of goods, decision-making, and environmental change [83, 85]. ABM has seldom been applied to rock art studies (but see [86]).

As noted in section "Mobility", our aim was to pilot the suitability of this study as a tool for understanding mobility in relation to rock art. For the purpose of this analysis we used only the Kilmartin study area due to its density of rock art and prehistoric monuments, and because it was the largest of our datasets. The ABM exercise developed for Kilmartin was relatively simple, but allowed further explorations by introducing more complex variables. This initial approach facilitated a dynamic investigation of mobility that considered several features which potentially influenced formation of patterns or, in this case, networks of paths calculated with the 'leastcostpackage' (LCP) package.

This study modelled the From-Everywhere-To-Everywhere (FETE) approach, incorporating 92 rock art panels. The same method to calculate the LCP was used, but here with 16 defined points equidistant in 6.25%.


**Fig. 12** Different parameters and settings selected for the various simulations. Speed optimisation has nine individual combinations of settings, whereas the Distance and Exploration optimisation each have three (15 in total)

The same 16 points were included in the 'least-cost path mobility' version 2.0.0 model [87]. This algorithm simulates human behaviour within a topographic environment which is not entirely familiar to the agent, but allows them to make decisions regarding the best route to follow when considering the need to (a) minimize speed, (b) minimize distance or (c) explore the surroundings[6] [87]. In this simulation the agent evaluated the best path at each step within a cone of vision, since their visibility ahead is limited. Fifteen simulations, with five runs per simulation, were set up to explore different parameters, such as optimisation mode (how the agent chooses a path); visibility threshold (how

**Table 20** Average density values for LCP output from NetLogo

| | Rock art | Funerary monuments | Standing stones | Random points | Potential cells | Min–max of raster output |
|---|---|---|---|---|---|---|
| Speed; Low fitness; No vis-threshold | 1.116 | 2.188* | 1.151 | 0.735 | 2.153 | 0–36.6 |
| Speed; Medium fitness; No vis-threshold | 1.057 | 2.559* | 1.049 | 0.832 | 2.384 | 0–38.8 |
| Speed; High fitness; No vis-threshold | 1.075 | 2.582* | 1.355 | 0.818 | 2.437 | 0–40.8 |
| Speed; Low fitness; Medium vis-threshold | 0.587 | 2.335* | 1.169 | 0.792 | 1.696 | 0–41.4 |
| Speed; Medium fitness; Medium vis-threshold | 0.798 | 2.353* | 1.000 | 0.651 | 1.921 | 0–42.6 |
| Speed; High fitness; Medium vis-threshold | 1.204 | 2.976* | 1.613 | 0.620 | 1.966 | 0–43.6 |
| Speed; Low fitness, High vis-threshold | 0.767 | 2.153* | 1.191 | 0.678 | 1.687 | 0–41.8 |
| Speed; Medium fitness, High vis-threshold | 0.859 | 2.523* | 0.987 | 0.738 | 1.891 | 0–43.2 |
| Speed; High fitness, High vis-threshold | 1.376 | 2.924* | 1.591 | 0.763 | 1.993 | 0–44.4 |
| Distance; No vis-threshold | 0.470 | 1.094 | 0.635 | 0.686 | 1.419 | 0–30 |
| Distance; Medium vis-threshold | 0.657 | 1.306* | 0.964 | 0.709 | 1.191 | 0–30.2 |
| Distance; High vis-threshold | 0.727 | 1.347* | 0.867 | 0.768 | 1.194 | 0–31.2 |
| Exploration; No vis-threshold | 0.811 | 1.182* | 1.111 | 0.791 | 1.176 | 0–28.4 |
| Exploration; Medium vis-threshold | 0.716 | 1.441* | 1.244* | 0.807 | 1.153 | 0–28.6 |
| Exploration; High vis-threshold | 0.793 | 1.759* | 1.124 | 0.874 | 1.159 | 0–28 |
| Average | 0.867 | 2.048 | 1.137 | 0.751 | 1.695 | N/A |

**Table 21** Overview of the parameters involved in the Mobility analysis

| | Approach 1 | Approach 2 |
|---|---|---|
| Type | Spatial modelling | Spatial and temporal modelling |
| Case Study area | Kilmartin | Kilmartin |
| Software | R (version 4.0.3) | NetLogo (version 6.1.1) |
| Elevation data | APGB DTM 5m | SRTM 90m |
| Tool | Leastcostpath [78] | 'Least cost path mobility' (version 2.0.0) [87] |
| Runs | 1 | 5 per simulation (15 simulations) |
| Number of random points | 16 | 16 |

[6] Further details about the 'least cost path' mobility NetLogo model used in this analysis are available in https://www.comses.net/codebases/5782/releases/2.0.0/.

**Table 22** Average density values for LCP output from R

| Monument type | Sample size | Mean | Min–max of raster output |
|---|---|---|---|
| Rock art | 91 | 11.797 | 0–79.359 |
| Funerary monuments | 34 | 24.478 | 0–79.359 |
| Standing stones | 45 | 19.802 | 0–79.359 |
| Random points | 1000 | 9.151 | 0–79.359 |
| Potential cells | N/A | 10.589 | 8.627E–05–79.359 |

obstructed the agent's vision is in mountainous areas); and fitness (fitness of the agent, only in 'Speed optimisation') (Fig. 12). The average of these runs was calculated producing one raster per simulation. These rasters show how popular each cell raster is, with popularity being the number of times a path crosses a cell in the elevation model. Similar simulations were carried out to other types of contemporary archaeological sites such as funerary monuments (n = 34), standing stones (n = 45), as well as 1000 random points (Table 20).

The LCP-NL results were compared with those obtained through the LCP-R calculation in order to understand variations between these approaches, and establish if the paths considered more popular were significantly different from one method to another (Table 21). In general, both approaches revealed that there was no significant relationship between the rock art and the simulated paths in Kilmartin, since panels tend to follow the signature of random points and have a lower than average popularity. In contrast, funerary monuments scored significantly higher than other categories, being systematically located on cells with significant high popularity throughout all simulations. While the popularity of standing stones is situated between that of rock art and funerary monuments, they are particularly popular in the exploration mode and are generally more popular than random values (Table 22). The Distance optimisation seems to produce low popularity scores compared to the other optimisation modes. Furthermore, a higher visibility threshold tends to increase the average popularity of cells, but this is not a rigid rule.

The results of LCP analysis with NetLogo were also tested with a K-S test in order to assess the data variability and overall distribution of values. For each raster, 1000 random points were sampled and tested against the rock art. The results confirmed the observations from the mean values, both of the LCP-R and the LCP-NL. In essence this demonstrates that rock art follows a random distribution in almost all scenarios, while funerary monuments and standing stones do not. Funerary monuments have stronger statistical significance than standing stones, and tend to be located in more popular cells.

*Overview* The combination of two different methods (in R and NetLogo) in the application of Least Cost Path analysis, together with the statistical testing, provided a new perspective on local mobility patterns. This demonstrates that Kilmartin rock art is not necessarily located in areas of high movement, in contrast to previous arguments. On the contrary, it occupies places that people were less likely to pass when travelling through the landscape. The simulation was slightly sensitive to the selected variables. For example, choosing the shortest route was deemed less optimal than choosing the quickest route or exploration mode, perhaps due to the nature of the local terrain. Nevertheless, the various approaches produced similar results. The mobility patterns identified for funerary monuments and standing stones suggest that they were perhaps meant to be encountered more frequently or to be more accessible than rock art. Overall, differences in popularity between these monuments relative to the simulated mobility network may signify deliberate structuring of the ceremonial landscape, with implications for how people perceived and experienced specific types of monuments.

## The wider picture

Using a multiscalar methodology has enabled us to focus in great detail on particular rock art features, including motif morphology, carving techniques, rock surface characteristics, and landscape variables. Although the ARA tradition appears relatively standardised in the nature of motifs and rock surfaces selected for carving, these similarities disguise subtle local and regional diversity across Scotland. Our study has potential for shedding new light on these nuances, based on assessment of a dataset comprising hundreds of panels and thousands of individual motifs.

Having establishing the local characteristics of the rock art, we investigated inter-regional relationships following a methodology which has previously suggested that ARA spread across the Atlantic through networks of exchange and connectivity [12]. A presence/absence approach first provided an overview of the differences and similarities between the 16 Case Study areas. We then applied two statistical methods in order to assess the datasets relationally, including data produced by each scale of analysis, without geographical constraints or biases. The Multi Response Permutation Procedure (MRPP) and the Multiple Correspondence Analysis (MCA) methods were used to analyse categorical data and compare motif co-presence, as well as identify shared characteristics between the panels in our samples. The aim was to determine how and to what extent the different scales of analysis influenced clustering and patterning within the data. The

**Table 23** Results from the MRPP for landscape variables only

| Case study area | Class mean (δ) | Number of panels |
|---|---|---|
| Kilmartin I & II (Argyll & Bute) | 0.657 | 91 |
| Bute (Argyll & Bute) | 0.560 | 55 |
| Cairnholy, Machars, Kirkcudbright (Dumfries & Galloway) | 0.549 | 174 |
| Faifley (Dunbartonshire) | 0.435 | 13 |
| Inverness North & South (Highland) | 0.678 | 99 |
| Mid & North Loch Tay, Strath Tay (Perth & Kinross) | 0.701 | 101 |
| South Loch Tay, Port of Menteith (Stirling) | 0.592 | 71 |
| Tiree (Argyll & Bute) | 0.390 | 20 |
| Western Isles | 0.703 | 7 |

methods were applied three times, with slight variations depending on the data requirements of the analysis:

1. Using data generated by the landscape analysis only, comprising panels in their original location with secure geospatial data (n = 631);
2. Using data generated by the motif analysis only, comprising all panels with detailed records and 3D models (n = 896);
3. Using a combination of data from 1 and 2, but only in situ panels (n = 631).

#### Multiple Response Permutation Procedure (MRPP)

The Multiple Response Permutation Procedure (MRPP) offers interesting potential for archaeological analysis as it takes into account sample size and can incorporate a range of heterogeneous data types [88]. It was initially designed to investigate ecological datasets which, like archaeological data, present a range of issues such as fragmentation or sampling biases ([88], p.8) and, in the case of our rock art datasets, accept a varying number of sites per sample. This method calculates the null hypothesis by comparing average distance for the entire dataset against the distance of elements of each group with similar sizes. It assesses the changes in distance between elements through the performance of random permutations. The p-value results from the percentage of permutations with lower or equal δ than those observed in the calculations described in step 3 below ([88], p. 8).

Our first step was to transform the rock art datasets from categorical to binary data using the 'dummy_cols' function from the fastDummies package in R,[7] followed by the calculation of a Jaccard coefficient. This is a similarity measure defined, as 'the intersection of shared motifs between two sites divided by their union' ([89], p. 6), and used in rock art studies as a clustering metric. The Jaccard distance matrix was created using the function 'vegdist' in R, then applied to perform the MRPP with the function 'mrpp' [90], with council area as the grouping factor. Further details of the analysis are provided in the Additional Methods and Data (files 1, 2) published with this article.

Tables 23, 24 show the mean dissimilarities within each council area for the three calculations noted above, and the number of panels used for each calculation. The function 'meandist' [90] identified the average distance within and between these groups, which simplifies the

**Table 24** Results from the MRPP for motif variables only

| Area | Class mean (δ) | Number of panels |
|---|---|---|
| Aberdeenshire | 0.775 | 12 |
| Angus | 0.814 | 22 |
| Argyll | 0.8 | 142 |
| Ayrshire | NA | 1 |
| Borders | NA | 1 |
| Bute | 0.720 | 74 |
| Dumfries & Galloway | 0.851 | 187 |
| Dunbartonshire | 0.889 | 2 |
| East Lothian | 0.969 | 3 |
| Faifley (West Dunbartonshire) | 0.770 | 13 |
| Fife | 0.780 | 3 |
| Highland | 0.741 | 178 |
| Kintyre | 0.786 | 2 |
| Lanarkshire | 0.812 | 2 |
| Midlothian | 0.734 | 3 |
| Perth & Kinross | 0.790 | 125 |
| Stirlingshire | 0.812 | 76 |
| Strachur (Argyll) | 0.721 | 19 |
| Tiree (Argyll) | 0.583 | 20 |
| West Lothian | 0.813 | 4 |
| Western Isles | 0.716 | 7 |

[7] https://cran.r-project.org/web//packages//fastDummies/vignettes/making-dummy-variables.html.

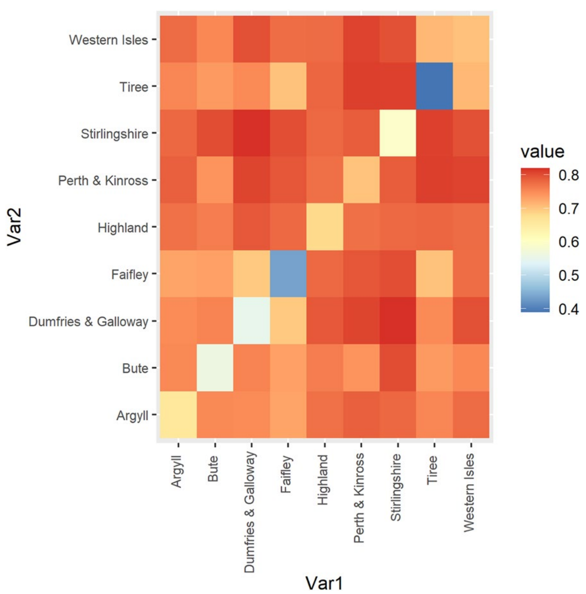


**Fig. 13** Heatmap visualization of the Mean Dissimilarity Matrix for landscape variables only. Smaller value (blue) means more similarity; higher value (red) means more dissimilarity

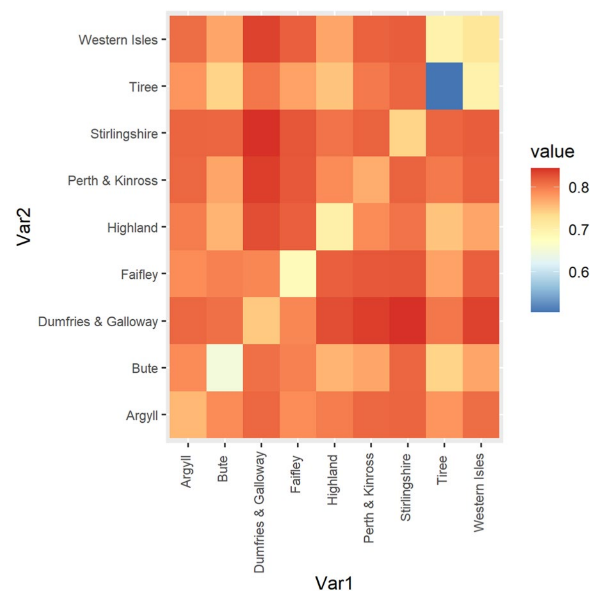


**Fig. 15** Heatmap visualization of the Mean Dissimilarity Matrix for both motif and landscape variables. Smaller value (blue) means more similarity; higher value (red) means more dissimilarity

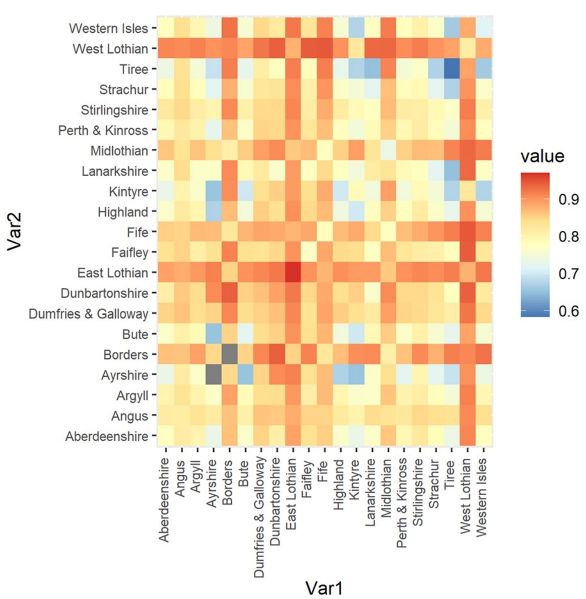


**Fig. 14** Heatmap visualization of the Mean Dissimilarity Matrix for motif variables only. Smaller value (blue) means more similarity; higher value (red) means more dissimilarity

visualization of similarity/dissimilarity (Figs. 13, 14, 15). The probability value of all three MRPP tests was 0.001, showing that the results are significant.

1) Considering the landscape variables only, the rock art data appears to express patterning within specific areas (Table 23). The observed δ (i.e. the overall mean of group dissimilarity) is 0.609892977, whereas the expected δ (i.e. the overall mean under the null hypothesis of no group structure) is 0.748957715. This indicates a certain group structure. Based on the average distances expressed generated with the Jaccard distance matrix, some areas emerge as more similar than others (Fig. 13).

2) When considering the motif variables only, the observed δ is 0.784820113, whereas the expected δ was 0.811352191 (Table 24). This seems to indicate a lack of apparent geographic (expressed through regions) group structure within the rock art data. If a clear group structure existed, we would expect the lowest values (i.e. dark blue) to be displayed horizontally in Fig. 14.

3) When combining the motif and landscape variables, the results lie somewhere between the previous results (Table 25). The observed δ is 0.726322459 and the expected δ was 0.798801618, implying less group structure than the landscape only results, but more group structure than the motifs only. Whilst a group structure does appear, it is slightly weaker than that for the landscape only (Fig. 15). Across all three MRPP calculations, Tiree expresses a particularly strong group patterning that differs from all other Case Study areas.

#### Multiple Correspondence Analysis (MCA)

The datasets generated throughout this research are composed mainly of counts and categories, so Correspondence Analysis provides an ideal framework for summarizing the data. This symmetrical analysis can create biplots which summarizes the results of a projection of observations into a space defined by variables

**Table 25** Results from the MRPP for both motif and landscape variables

| Area | Class mean (δ) | Number of panels |
|---|---|---|
| Kilmartin I & II (Argyll & Bute) | 0.760 | 89 91 |
| Bute (Argyll & Bute) | 0.648 | 55 |
| Cairnholy, Machars, Kirkcudbright (Dumfries & Galloway) | 0.747 | 174 |
| Faifley (Dunbartonshire) | 0.681 | 13 |
| Inverness North & South (Highland) | 0.702 | 99 |
| Mid & North Loch Tay, Strath Tay (Perth & Kinross) | 0.767 | 102 |
| South Loch Tay, Port of Menteith (Stirling) | 0.739 | 70 |
| Tiree (Argyll & Bute) | 0.505 | 20 |
| Western Isles | 0.719 | 7 |

(like principal components), or the opposite, in which variables are projected into the space defined by observations ([91], p. 279). MCA assesses correlation between variables, and highlights factors which contribute to variance without predetermining groupings. The method has been employed successfully in zooarchaeogical research [92, 93]. The application of MCA is particularly interesting given the nature of our datasets and research questions. It can be developed in R using the FactoMineR package [94]. Further details of the analysis are provided in the Additional Methods and Data (files 1, 2) published with this article.

In practice, the data were adjusted according to the three types of analysis conducted (i.e. landscape, motifs, and all data combined), and standardized to a comparable measure in order to be projected into a multidimensional variable space. An 'MCA' function [94] was used to run the algorithm, generating a list containing the measures of association between individuals (rock art panels) and variables. Furthermore, we utilised the 'HCPC' function [94] to produce a hierarchical clustering of the results from the MCA. This would allow us to see how the entire dataset could be organized in different groupings determined by their similarity. Based on the variance within the dataset, the rock art can be divided into different clusters, shown in a factor map. This output identifies panels that contribute particularly to variability. We used the same input as for the MRPP, and ran the MCA analysis three times.

(1) Fig. 16 visualizes the relative distribution of rock art panels according to the clusters when considering landscape variables only. This indicates four main clusters, which correspond roughly to geographic regions: Cluster 1. Largely confined to Dumfries and Galloway; Cluster 3. Mainly around Loch Tay; Cluster 4. Mostly Perth & Kinross and Highland; and Cluster 2. Widely distributed (Fig. 17).

(2) Two main clusters emerge when we look at motif variables only (Fig. 18). These are not regionally defined, so panels from both clusters occur in the same areas (Fig. 19). Cluster 1 is more widespread than Cluster 2. There are two visible outliers, one is classified as its own cluster (Braes of Balloch 1: ScRAP ID 2251), the other belongs to Cluster 2 (Townhead 1: ScRAP ID 1392) (Fig. 20).

(3) Lastly, we combined the motif and landscape variables. This produced a more dispersed plot (Fig. 21). Compared to motif variables only, the clusters are less contained but still expressed as two main groupings. Again, the clusters are not regionally defined (Fig. 22), although the regional character clearly contributes to the unique character of rock art in each area. Interestingly,

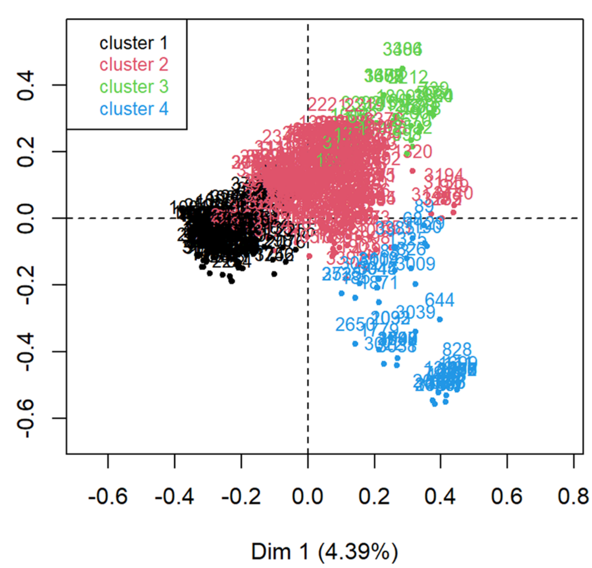


**Fig. 16** Factor map showing the hierarchical clustering on principal components as determined by the MCA for landscape variables only. Numbers correspond to the unique panel ScRAP ID

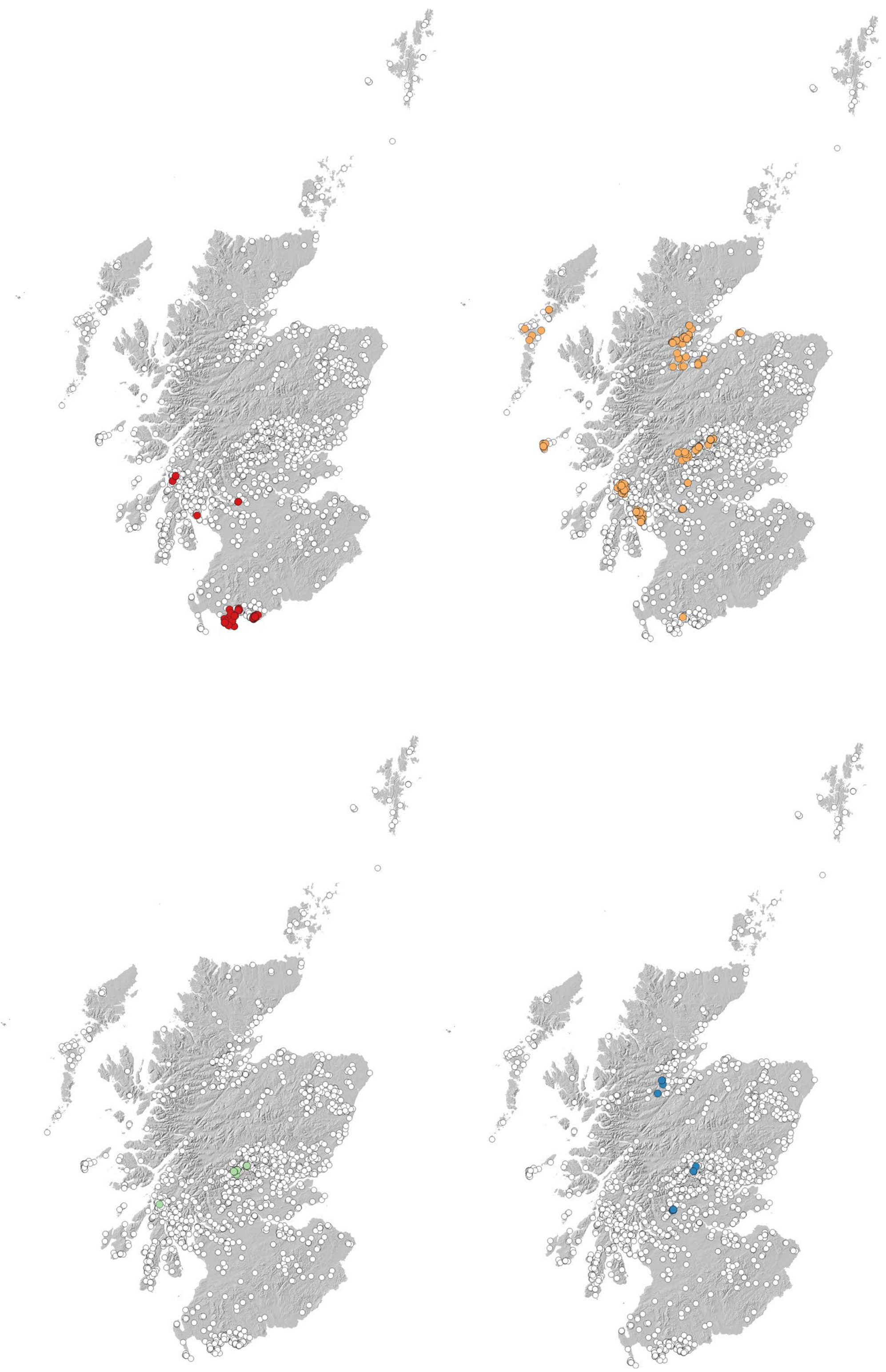

**Fig. 17** Hierarchical clustering on principal components as determined by the MCA for landscape variables only; Cluster 1 (red), Cluster 2 (orange), Cluster 3 (green) and Cluster 4 (blue)

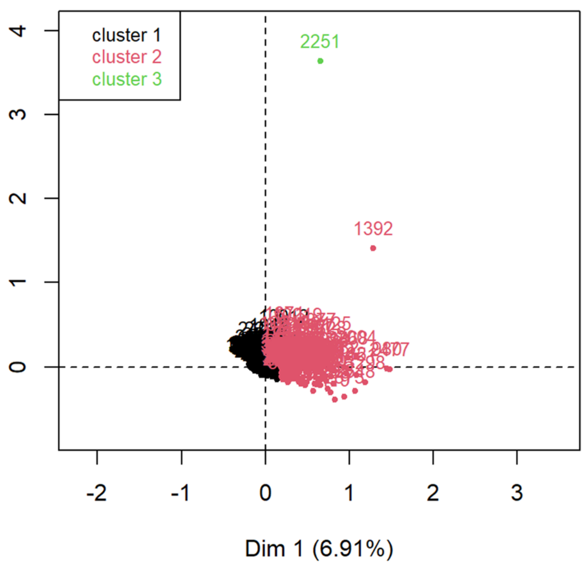


**Fig. 18** Factor map showing the hierarchical clustering on principal components as determined by the MCA for motif variables only. Numbers correspond to the unique panel ScRAP ID

the MRPP still identifies Braes of Balloch 1 (Fig. 20) as an outlier and a unique panel.

Spatial mapping of the clusters in a GIS environment has helped us to further understand the composition within each Case Study area. Bearing in mind that the MCA does not group the panels according to council area, it is interesting that most Case Study areas show a relatively homogenous cluster composition. The homogeneity we see within the motifs is diminished by the heterogeneity of the landscapes. Running the MCA has therefore been useful to further inspect the clusters already identified by the MRPP, and highlight the implications for understanding differences and connections between the regions.

## A new view of Scotland's rock art

Since the early nineteenth century, the quest to understand Scotland's prehistoric rock art has been shaped by prevailing perspectives and techniques. Interpretations have ranged widely, with varying degrees of subjectivity, while working within the constraints and idiosyncrasies of the database. In this study, we aimed to minimise

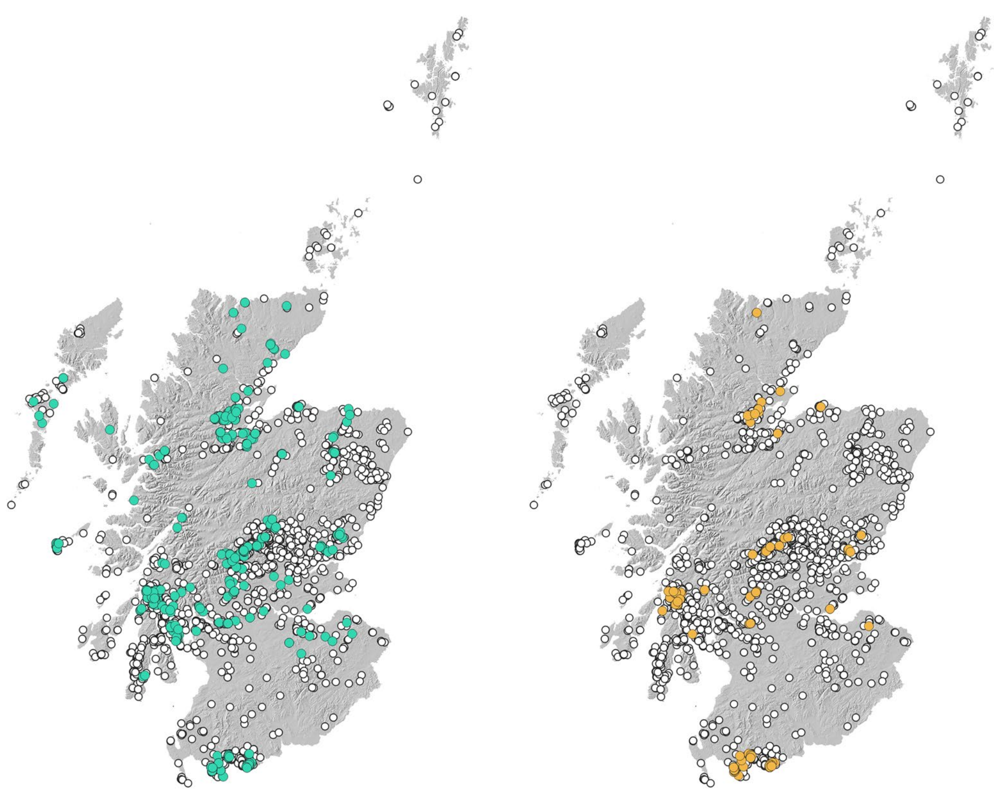

**Fig. 19** Hierarchical clustering on principal components as determined by the MCA for motif variables only; Cluster 1 (green) and Cluster 2 (orange)

**Fig. 20** Top: Braes of Balloch 1, North Loch Tay, Perth & Kinross, DP 370526 © Historic Environment Scotland Bottom: Townhead 1, Kirkcudbright, Dumfries & Galloway, DP 365302 © Historic Environment Scotland

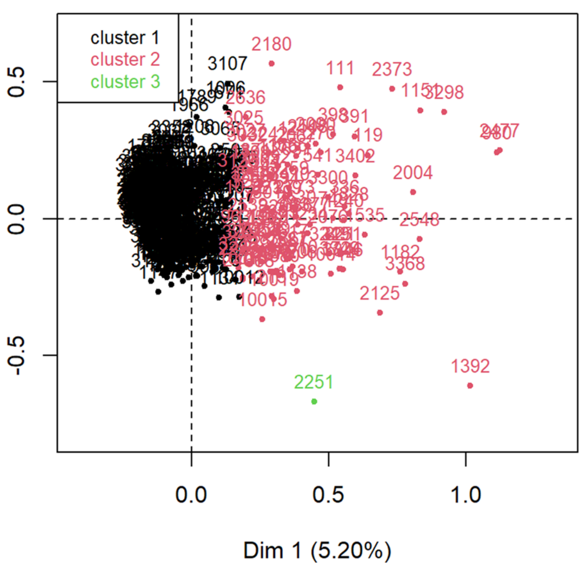


**Fig. 21** Factor map showing the hierarchical clustering on principal components as determined by the MCA for both landscape and motif variables. Numbers correspond to the unique panel ScRAP ID

subjectivity and bias by, first, compiling a very large, consistent, and objective dataset containing hundreds of detailed records and, second, applying a range of computational approaches that explored multiple dimensions of the data and tested the results for significance. We sought to break from site- and area-specific investigations that have dominated rock art research in Scotland, and develop a comparative framework of nuanced rock art for the whole country. Our intention, also, was to pioneer the use of digital techniques applied in other fields, and establish their potential for rock art studies internationally, thus creating quantifiable and reproducible methodologies that could be applied widely.

This article has described our multiscalar, multivariate approach in some detail. While there has not been scope here to discuss every result, by highlighting specific examples and key outcomes we aimed to demonstrate how innovative techniques can generate a more comprehensive insight into Scotland's prehistoric rock art. Nevertheless, we acknowledge the limitations of our approach, not least the incomplete nature of our dataset which excluded many previously recorded panels not located during our fieldwork. Consequently, the rock art sample in certain Case Study areas does not fully reflect the known corpus, with implications for the results. Additionally, although using multiple datasets was beneficial, in some cases their resolution was too crude to permit close scrutiny of the landscape-rock art relationship. This is one area that could certainly be improved upon in future analysis of prehistoric rock art in Scotland, and more widely. Another would be to incorporate further attributes that may have affected how people perceived and encountered rock art in the past, including detailed spatial reconstructions of vegetation patterns and prehistoric sea levels, as well as specific material qualities of the rock, such as colour, texture and glittery-ness.

One of the principal outcomes of our analysis was the absence of consistent relationships between rock art and landscape variables across the country. While this could be interpreted in terms of localised preferences for and adaptations of specific aspects of the ARA tradition, we should also consider that more prosaic undercurrents of survival and discovery may shape this diversity. Rather than assuming that rock art today mirrors its past distribution, contexts, and content, our analyses and interpretations need to be critically informed by detailed modelling of the potential impact of changing land-use and human activities on the rock art database. For instance, one interesting pattern that emerged from our study indicated that rock art is preferentially located on relatively poor soils. This could be interpreted either as a reflection of past decision-making, i.e. rock art was deliberately located away from fertile land, or the inverse,

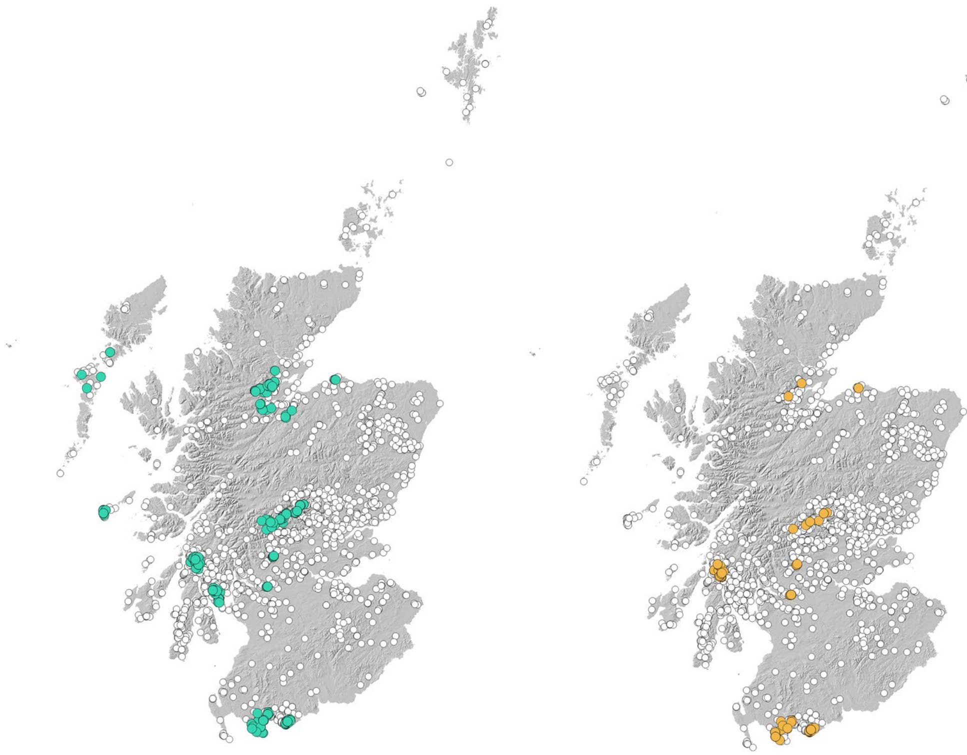

**Fig. 22** Hierarchical clustering on principal components as determined by the MCA for both motif and landscape variables; Cluster 1 (green) and Cluster 2 (orange)

i.e. rock art is far less likely to survive on good farm land that has been used intensively for millennia, and will be best preserved in more marginal areas. We touched on this theme in our Large Scale analysis, but it requires greater in-depth, localised assessment than our resources allowed.

Despite these limitations, our analysis revealed some important trends that challenge certain established notions about ARA, reinforce various empirically-based ideas, and progress our understanding of the tradition. In particular, our simulations of visibility and mobility in relation to rock art within the landscape indicate that, contrary to popular opinion, prehistoric carvings in Scotland tend to be relatively obscure and situated 'off the beaten track.' Although they are generally located in accessible places, conducive to human domestic and ritual activity, they are neither especially evident, nor likely to be frequently encountered by people moving around the landscape. In contrast, other Neolithic ritual monuments, specifically chambered cairns and standing stones, are often located on obvious routeways and can almost be considered as 'public' landmarks. This raises interesting questions about whether isolation was fundamental to how most rock art was 'used' (e.g. [95]) or whether the significance of rock art lay principally in its creation (e.g. [4]). Finally, when considering the combined results from all the variables and scales of analysis, a picture emerges of a shared understanding of the ARA tradition across Scotland, in which certain areas appear to share more attributes than others—a view that was confirmed by both the MCA and MRPP. These regional commonalities and differences may indicate networks of connectivity through which the idea of rock art spread across Scotland [12].

Rock art is a global phenomenon, and the analytical model discussed in this article has potential for application in many parts of the world with adequate sample sizes and consistent datasets. As digital techniques evolve, there will be significant opportunities for further computational analysis of ARA, and Scotland's rock art in particular, building on the foundations that we have constructed. By making our dataset and 3D models publicly accessible, we hope to inspire and facilitate more extensive research and an enhanced understanding of ARA, and encourage similar data-sharing internationally.

**Abbreviations**

| | |
|---|---|
| ABM | Agent-Based Modelling |
| GIS | Geographical Information Systems |
| HES | Historic Environment Scotland |

| | |
|---|---|
| HLA | Historic Landscape Assessment |
| MCA | Multiple Component Analysis |
| MRPP | Multiple Response Permutation Procedure |
| ScRAP | Scotland's Rock Art Project |

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-024-01183-8.

**Additional file 1:** Additional methods.

**Additional file 2:** Additional data.

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**Author contributions**
The analysis and interpretation of data detailed in this article, and drafting of the manuscript were conducted by TB, JVT and LMB. All authors made substantial contributions to the design of the work, and data acquisition, and revised the manuscript critically for important intellectual content. All authors approved the manuscript version submitted for publication and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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**Availability of data and materials**
The datasets generated and analysed during the current study are available to search and download from the Scotland's Rock Art Project database and webite: https://www.rockart.scot/rock-art-database and Historic Environment Scotland's digital archive, accessible via the Canmore website: https://canmore.org.uk/collection/2219572.

## Declarations

**Competing interests**
The authors confirm that they have no competing financial or personal interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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