



Water Flows and Water Accumulations on Bedrock as a Structuring Element of Rock Art

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Abstract

The paper proposes a new method to quantify the flow of water and water accumulation zones on bedrock panels. This can be used to investigate how water influences the placement of rock art. The analysis is based on photogrammetric models on which water flows and accumulations were modelled using a NetLogo simulation and the SAGA hydrology package. To test the hypothesis that water was a structuring element in the creation of rock art, case studies of Bohus-granite panels from south-western Sweden were used. The described approach should be possible to use on most rock art placed on bedrock panels regardless of rock type, its state of cleaning, or present microfauna. The modelling of water flows and accumulations is a powerful tool to compare the image placement and image density in relation to water even on widely separated panels on which such observations cannot be made directly.

Keywords Rock Art · Waterflow · Agent-Based Modelling · Topography · Hydrology · Scandinavia

Introduction

Rock art in southern Scandinavia is mostly applied by engravings which form a negative relief on the bedrock panels. This rock art is typically dated to the Nordic Bronze Age (ca. 1700–500 BC) and its figurative images mostly depict boats and warriors. It has been shown that this rock art was often closely associated to the ancient coastline and was often carved next to the water in bays and fjords.

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Numerous authors have commented on the close relationship between Nordic Bronze Age rock art and a maritime setting in which the depicted warriors were characterised as maritime warriors (Coles, 2008; Goldhahn, 2002; Ling, 2014; Nimura, 2015; Wrigglesworth, 2011). To modern visitors, this maritime character of the rock art may be lost, as after the ice masses melted at the end of the last Ice Age, the Scandinavian landmass rebounded and lifted upwards. This caused the coastline to recede further, and the former coastline—including the rock art, to be located further inland today. Recent work has highlighted that rock art also follows other water bodies such as rivers and lakes (Nimura et al. 2020).

It has variously been commented how water on the panels themselves may have been a structuring element for the placement of images. However, such work has been hampered by field observations dependent on certain events, like rainfall, the disparate placement of the carved surfaces in the landscape, their immovable nature, and other factors. This paper suggests a new methodology which introduces an accurate way of analysing the flow of water across the rock art panels in a systematic way. The approach opens for a comparative perspective on how rock art was positioned in relation to water, and it enables this comparison to be made. It is hoped that this will eventually lead to a better understanding of Scandinavian rock art and the influence of various waterbodies and maritime practices of Nordic Bronze Age societies. The proposed method is based on surface topography and gravitational forces. Therefore, it can also benefit the study of other rock art located on bedrock panels.

Previous Research

Early on, Carl Georg Brunius noticed that rock art was often found on panels which had water running down causing a black discoloration (Brunius, 1868; see also Malmer, 1989). Since then, several authors have commented on waterflows across rock art panels (Coles, 2008; Fredell, 2004; Hauptman Wahlgren, 1998). Tilley (2016) theorized that the rock carvings at Nämforsen could have been periodically submerged during flooding in the past. On the example of carvings in Vingen, Tilley showed how rock art panels were demarcated by flowing water, observing that the largest water puddle coincided with the largest concentration of rock art on the panel in Brattebakken (Tilley & Bennett, 2008). Lise Nordenborg Myhre (2004) provided the most in-depth analysis of the phenomenon observing water “overrun[ing] the images from springs above or sources from the interior of the rock” on several examples from Norway. She mostly analysed the relationship between such waters and images of boats, footprints, and abstract motifs, arguing that the water increased the dynamism of the scenes and hinted at (mystical) boat journeys (Bradley et al., 2002; Nordenborg Myhre, 2004). Earlier, Knut Helskog observed that melting snow, rain, and other water would enliven rock art, with bears being a central figure of a journey to the underworld where water collected on the panel (Helskog, 1999). Magnus Tangen (2018) observed natural features and the microtopography influencing rock art panels’ placement. Similar discussions have also begun in other rock art regions, for example, in the context of alpine rock art (Fossati, 2015).

The aforementioned work mostly rests on qualitative observations based on photos or field observations of discolorations through microfauna or actual flowing water. The lack of a quantitative approach has variously been remarked upon (Goldhahn, 2008; Tangen, 2018). To accommodate such a study a new way of displaying rock art documentation has been suggested to show topography. The work conducted so far has often relied on impressive cases like Revheim (Bradley et al., 2002; Nordenborg Myhre, 2004), Bergbukten (Helskog, 1999), on relatively constant water flow through springs, or by splashing water on the panels (Goldhahn, 2002; Tilley, 2016; Tilley & Bennett, 2008). Although many panels indicate flowing water through discoloration, this cannot be taken for granted since while many panels, especially in tourist regions, are cleaned (Bottna 88:1), others are completely or mostly black from microfauna (Bottna 1:1) making it impossible to distinguish water accumulations. Lastly, the waterflow on panels in disparate locations cannot be compared directly, and researchers have had to rely on static notes and photographs. These issues impeded comparative and quantitative research on the relationship of rock art and water on the panels themselves.

The approach put forward in this paper is based on new 3D documentation, creative use of GIS, and Agent-Based Modelling seeking to investigate the flow and accumulation of water on rock art panels, independent of surface colour and current location. It takes the subtle topography of the panels into account which may not be immediately obvious to modern observers. The case studies used herein are all within the Bottna and Tanum communities, southwestern Sweden, and from rock panels of a homogenous monzogranite called Bohus granite (Fig. 1). The panels discussed below are identified by the number designated to them by the Swedish National Heritage board.

Material and Method

Bohus Granite

The majority of the carvings in the investigated area are engraved on relatively flat rock panels of Bohus granite (Fig. 1). The late Sveconorwegian (Grenvillian) granite intruded ~920–890 Ma in an extensional stress regime, and along a gently easterly dipping fault zone (Bingen et al., 2021; Eliasson et al., 2003). The intrusive body mainly consists of granitic and fewer intermediate to mafic rocks (Fig. 1). Most of the rock art can be found on the homogenous, medium grained phase of the monzogranitic granite, with quartz, k-feldspar, plagioclase, and biotite being the main mineral phases. The dominant granitic landscape in the investigated area represents a Sub-Mesozoic etchsurface with a pronounced structural control (Johansson et al., 2001). Ice movement overprint during the last glacial maximum (~22 ka; Kleman et al., 1997) led to glacial forms such as roches moutonnées, p-forms, crescentic gouges, crescentic fractures, and striae (Johansson et al., 2001; Ljungner, 1930). All the investigated sites are post glacial, flat, and mainly polished granitic surfaces, which were often used by the Bronze Age carvers for their artwork.

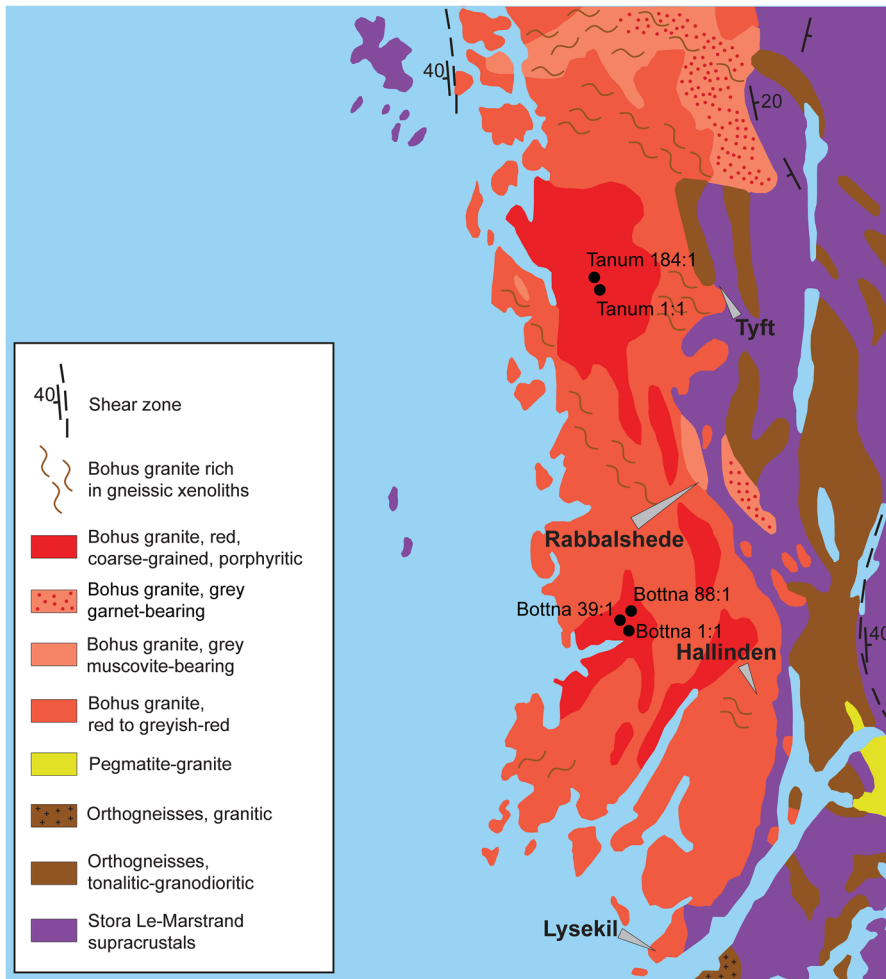


Fig. 1 Geological map of main rock types in Bohuslän with case study sites indicated

The Bohus granite is a mechanically strong rock (Åkesson et al., 2004), and the majority of near-surface weathering of the granite was removed during this last glacial overprint meaning that the recent surface topography has mainly been affected by Holocene weathering after the Late Weichselian deglaciation (c. 12 ka; Swantesson, 1992). However, Swantesson (1985; 1992) has shown that microweathering phenomena in southern and central Sweden during the Holocene have only changed the surface topography by a few centimetres and involves a complex interaction of several processes. He relates larger breakdown of the granitic structures to the geological history of the rocks. The surface topography of the rock panels in the Bohus granite, which were used by the Bronze Age carvers, has only changed by up to a centimetre, and even less where the polished, glacially derived surface is

still preserved. Pre-glacial, tectonic fractures, and joints may have been widened and deepened since the carvers were active on the panels, but this mostly leads to a pronouncement of the overall segmentation of the panels and not to a general change in its topography.

Photogrammetry

For this research, three-dimensional models of rock art were produced using photogrammetry involving Structure from Motion with Agisoft Metashape[®], which is capable of reconstructing highly precise 3D surface models (Micheletti et al., 2015). Before taking the photos, the surfaces were cleaned using a broom and moss patches were removed manually. Low growing lichens were left in place since they do not impede the flow of water and to reduce the risk of accidentally damaging the surface. The models were georeferenced by measuring coordinates in situ using a Leica Viva[®] GS15 GPS system to guarantee that the models had the correct orientation, and each point had the correct height relative to every other point, which was a requirement to model the actual water flow across the surface. From the 3D model, we calculated digital elevation models (DEM) that were used to create visualizations (see Horn et al., 2019) and to model the waterflow. Two of the case studies are panels from the Tanum world heritage area (1, 184) and the other three panels are located further to the South outside the protected area in Bottna parish (1, 39, 88; Fig. 1). All panels, except for Bottna 39, can be considered as large panels with over 50 figurative motifs each. The sample includes panels with dramatic (Tanum 184, Bottna 88; Sects. 3.3, 3.5) and more subtle topographies (Tanum 1:1, Bottna 39; Sect. 3.2). These panels were selected because they had a varied topography, differing numbers and types of motifs, and because they were representative of other panels. While it would have been ideal to be able to have collected areas of bare rock connected to panels to observe how water flowed onto them, this was unfortunately not possible as only the areas with visible rock art are uncovered; the areas outside of the panels are covered in vegetation, trees, and grass which we could not remove. As such this study relies on looking at the panels which all included some areas of uncarved rock surface across which water moved on to the engraved surfaces.

Agent-Based Modelling (ABM), SAGA Hydrology, and the Location of Rock Art

To calculate water flows and accumulations, NetLogo, the SAGA hydrology package, and ArcGIS were used. These packages also allowed us to compare the water-flow relationship to the motif distribution. The agent-based modelling (ABM) approach used herein complies with the theoretical-methodological framework for ABM (Wurzer et al., 2015), but it must be stressed that in this case it is not the actions of conscious actors (Banitz et al., 2015; Cortier et al., 2019; Jaxa-Rozen et al., 2019), but of a physical process.

After several iterations fine-tuning the ABM model, the DEMs were used in NetLogo to program actors (turtles) to react to parameters stored in patches, *i.e.* segments of the DEM below them (Fig. 2). For the following, it is important to

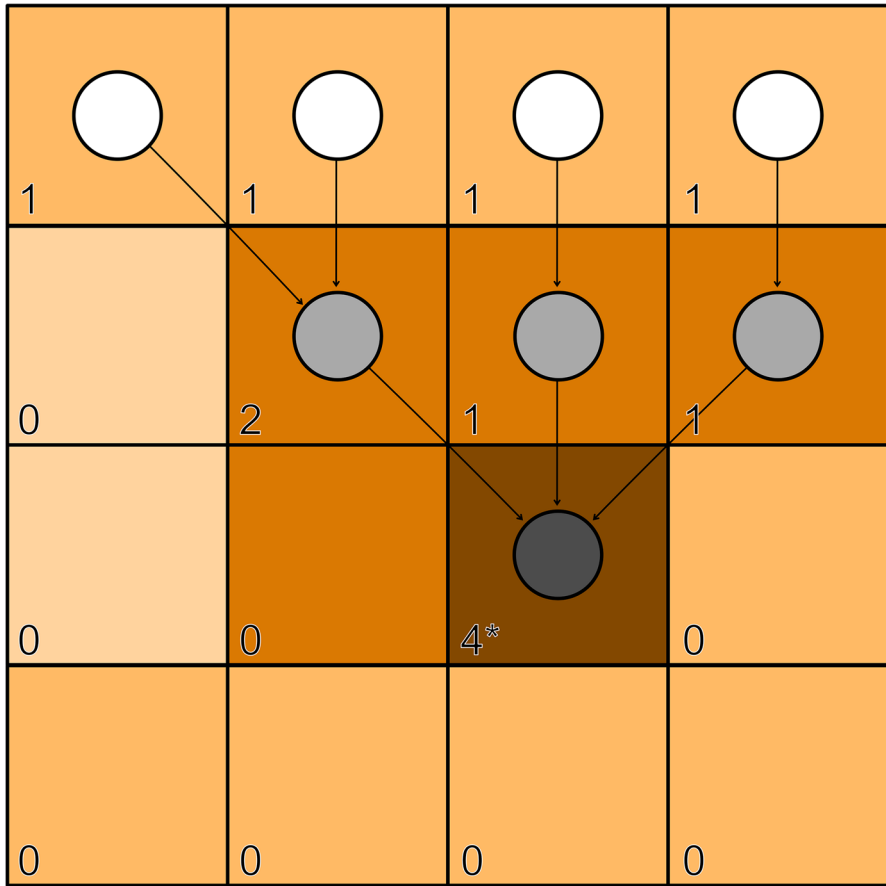


Fig. 2 Schematic representation of the ABM to visualize water flow and accumulations. Circle: turtle, darker colors subsequent step. Square: patch, darker colors lower down. Number: accumulated turtles in this patch. Star: lowest laying patch from which the turtles cannot escape any more, and thus, will be eliminated

note that while we speak of rainfall, this is a theoretical assumption that water could be deposited on the panel through rainfall. Another potential water source could be snowmelt. Furthermore, the turtles do not represent a single rain drop, rather they could be conceptualized as an amount of water sufficient to overcome the “light rain, micro topography” limitation, and to run from where it first touches the panel to where it will come to rest and eventually evaporate. There are few detailed regional studies on prehistoric precipitation in the Nordic sphere, but the data seems to indicate a fluctuating climate with long periods of increased rainfall with extreme rain events during the earliest part of the Bronze Age (Scholz, 2012). The time between the wetter climatic phases was not rain-free, and we can, therefore, assume that there was regularly enough water on the panels for it to run down and accumulate.

Turtles were placed on each patch that had a value, *i.e.* had a grayscale value that was neither black nor white (null values) simulating rainfall that would affect the entire panel. The turtles were instructed to move downhill one patch at the time based on the grayscale value in the same direction in order to limit the amount of turtles that became stuck in small chips or bumps on the surface. Once turtles had stopped moving or were massing in one area, the simulation was stopped. Every time a turtle moved across a patch, a variable called “value” was increased by one showing how often this patch was crossed at the end of the simulation. This was then visualized with a heatmap dividing the value by two to create a good colour spread. After cross-checking with photos of the panels taken following rainfall, we verified that the results indicated water accumulation zones very well.

The turtles were also instructed to draw multicolored lines indicating the direction of each step. Their accumulation shows in which direction water flows down the surface, highlighting channels. Eight colours were used, each representing a direction within a range of 45°. The ability to place turtles on the highest points of the panel (top 30% grayscale value), to spawn them along the outermost edges, and to draw them interactively on patches were added. With this, it was possible to investigate water flows seeping on the panel from the surrounding soil cover, during various precipitation events (with the possibility to increase and decrease the amount of rain that was calculated on the panel), and from specific points of interest.

To increase the resolution and as a control, we used the topographical wetness index in SAGA which visualises water flow and collection based on surface characteristics including slope and relative position. The output confirmed the results of the NetLogo model. While the SAGA outputs do not visualize flow directions or accumulations, they are a quantitative representation of the water flows across the panels. SAGA also outputs an aspect visualization which indicates the compass direction the topography is facing with radiance further highlighting slope effects. This offers a better understanding of the topographic structure of the panels as it emphasises three-dimensional topographic features in a 2D visualization. Therefore, these images were included for all panels.

To complement the analysis of the relationship of rock art motifs and water, the most prevalent motifs were marked on the outputs and a kernel density estimate was calculated, discarding the lowest two values to show location of the highest concentrations on the panels. The outputs were then compared to investigate how water flow and accumulation matched up with the overall distribution of motifs.

Applicability to Other Rock Art Regions

Although the case studies focus on Scandinavian panels, this approach can be used on most rock art panels regardless of location or geology, since it models gravitational forces on surface topography, such as shape, gradients, and orientation. However, one exception is the combination of light rain and a high rock-surface roughness (highly irregular micro-topography), which impede weaker waterflows. The surfaces should not be entirely vertical or horizontal, because water would either fall straight down or would not flow. Although in the latter

case, water accumulation, for example in puddles, may still be of interest. Thus, few regions and some materials may be excluded, like the painted vertical rock faces in Finland or the stelae in Iberia. From this discussion, we expect that the proposed method works best on bedrock outcrops with a gradient in regions at least with occasional rainfall or other sources of water running across the surface. Examples of this could be the bedrock panels in northwest Iberia, the Alps, or the Lake Onega seashores. The input data should be the same as for the Scandinavian examples which means a DEM derived from a georeferenced 3D model should be created for NetLogo and SAGA.

Surface Topography, Water, and Images—Case Studies

Bottna 1:1

The rock art panel Bottna 1 is relatively flat and extends at least 10×11 m. In the NW, it falls sharply towards a shallow valley which was filled with water during the Early Bronze Age. In the SE, a higher part of the panel is separated by a ridge running for ca. 9 m SW–NE and flattening out towards the NE (Fig. 3a). Some of the rock art in the northern part is partially covered by a large block of earth and vegetation which had to remain in place. The motifs surrounding this area were visible. Water accumulates around the area which probably forms a deeper puddle (Fig. 4a).

Water flows from the elevated part of the panel above the ridge, and curves down at its NE ending into a wide channel that crosses the entire panel along a SW–NE axis, roughly splitting the panel in half (Fig. 4a–c). This flow is the strongest into the channel (Fig. 4a, c) with the highest water accumulation (Fig. 4b). The channel runs from one edge of the bedrock panel to the other and through the vegetation spot that was not removed, emptying into the valley in the N. (Fig. 4a–b).

The panel contains 114 cupmarks, 69 boats, 21 humans, and 7 foot-soles (Fig. 3). Only one motif could tentatively be an animal, for that reason it was left out of the analysis. Generally, rock art accumulates in the waterflow areas in the large channel, especially at the confluence with the NE ending of the ridge and in the SE of the channel (Figs. 3a–b, 4–5). Another carved area lies between the puddle and the edge of the panel (Figs. 3a–b, 4–5). The only exception is a cluster of cupmarks at the western edge of the panel (Fig. 5b). The kernel density estimates for boats and cupmarks closely follows the curved flow at the confluence at the NE ending of the ridge (Fig. 5a). Boats are less densely distributed in the area at the northern edge of the puddle, while cupmarks and humans are stronger. Conversely to boats and cupmarks, humans are more densely distributed in the higher part above the ridge (Fig. 5c).

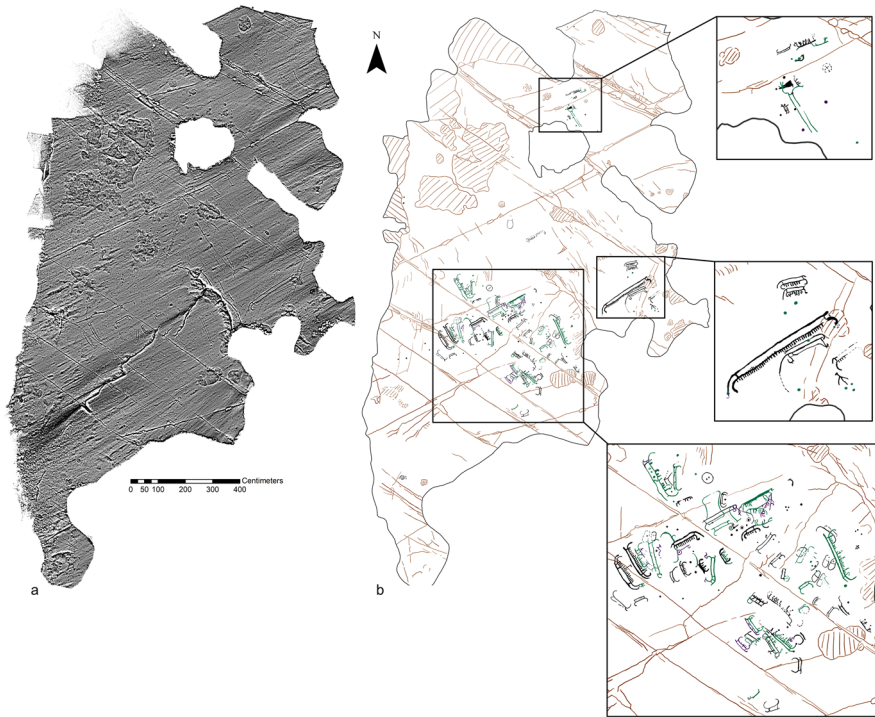


Fig. 3 Bottna 1: **a** DEM visualisation, **b** interpretation squares with enlarged sections of the panel

Bottna 39:1

Bottna 39 is a relatively small rock art panel at 8.5×3 m (Fig. 6a). Apart from cupmarks, there are very few motifs on this panel; as such, it was analysed without kernel density estimates. Overall, the panel slopes weakly with a noticeable downward incline at the western edge of the panel facing NW (Fig. 6a-b). Here water does not accumulate and runs off quickly (Fig. 7). A channel runs E-W in which water accumulates and clearly flows in a W direction widening slightly to the NW (Fig. 7a-c). This channel also widens at the centre of the panel and flows a short distance south (Fig. 7c-d). Rather than an extension, this could also be a second channel. In the NW, there are two weaker water accumulation channels (Fig. 7a, c).

There are 134 cupmarks on the panel, but only 4 footsoles, 2 or 3 boats, and 1 wagon (Fig. 6). Cupmarks seem to accumulate along the smaller channel in the eastern end of the panel. The cupmark distribution follows in and next to the channel where there is a weaker water accumulation area. However, the remaining cupmarks on the panel are generally in drier areas (Fig. 7b). The smaller boat is located in an area where water accumulates and begins to flow into the smaller channel. Its long axis is oriented horizontally along the downslope of the panel (Fig. 7b).

A very large boat (2.45 m long) is located right on the border where the panel falls towards the NW (Fig. 7b-d). Water flows strongly in this direction and the boat

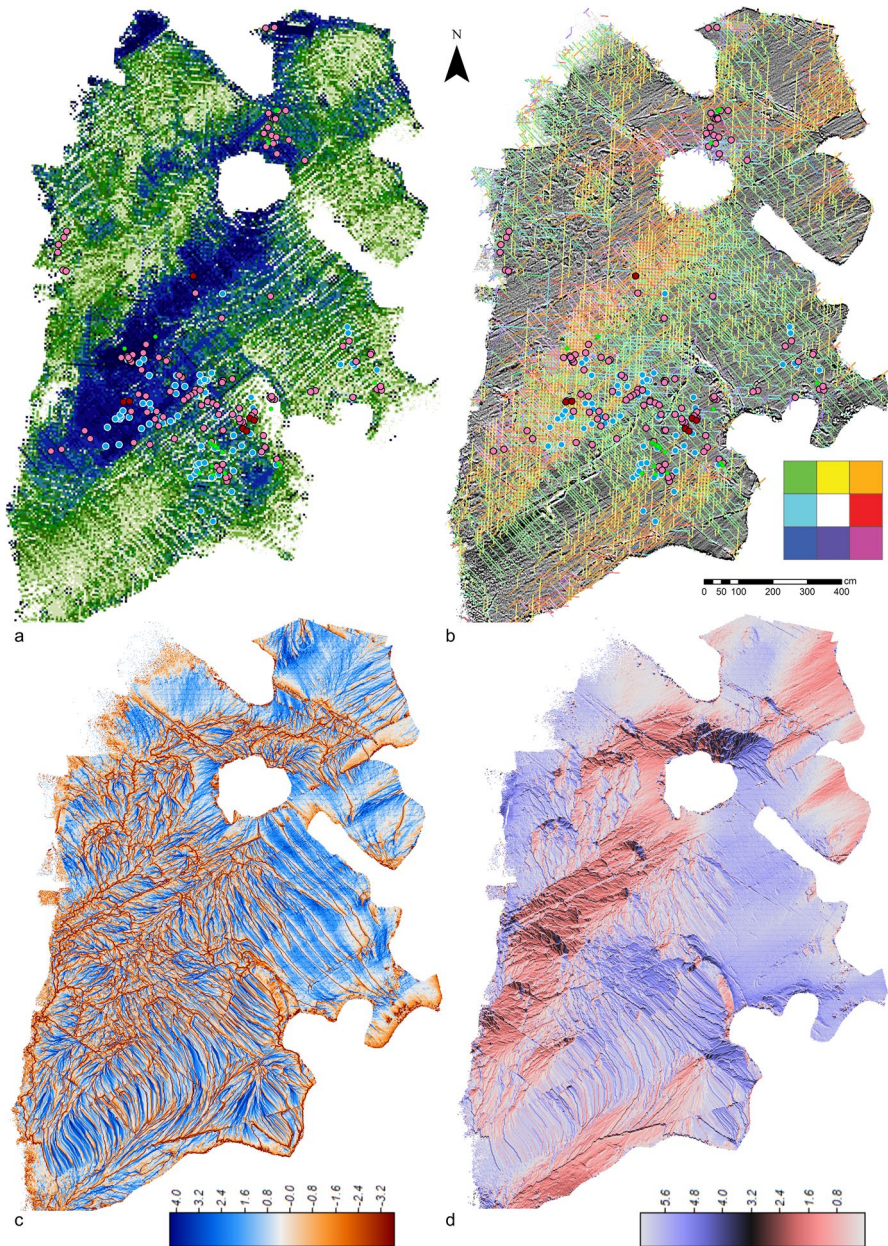


Fig. 4 Bottna 1: **a** water accumulation, **b** water flows, **c** topographical wetness index, **d** aspect

is oriented along the area where the flow originates with a NE-SW longitudinal axis (Fig. 7b). The southern prow of this boat, which was updated at least once (Milstreu, 2017), ends in the southern water accumulation channel. The prow in the N does not lie in a water accumulation, but the northern end of the boats hull is placed in the

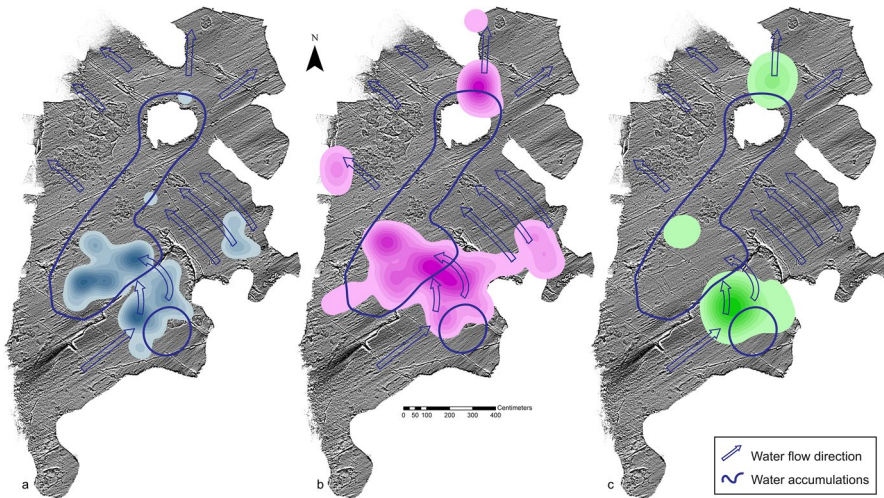


Fig. 5 Bottna 1 heatmaps: **a** boats, **b** cupmarks, and **c** humans

weaker water accumulation zone in the centre W of the panel (Fig. 7a-b). The large wagon and one footprint are carved next to the channel carrying water in a western direction. Both are aligned with the axis of this channel. The SW wheel lies within the water stream (Fig. 7b).

Bottna 88:1

The rock art on the Bottna 88 panel extends 8.4×4 m (Fig. 8). In the NW of the documented area, there is a water flow running down towards the S which is a stronger water accumulation zone (Fig. 9a-b). This stream meets roughly at the centre of the documented area with a stream flowing northwest (Fig. 9a-c). A prominent fracture runs through the panel (Figs. 8, 9d). One larger water accumulation zone is located below the fracture, a smaller one above (Fig. 9). There are further water accumulation zones below the puddle where the two flows meet. At the southern extent of the panel towards the east, there is an upwards sloping surface with a slight crest which bears no images. Water flows down across the entire surface toward N and SE depending on which side of the crest the turtles were placed.

There are 91 cupmarks, 33 boats, 18 humans, and 17 animals (Figs. 8, 10). The densest distribution of boats is within the central puddle which is the strongest water accumulation zone. Other boats are located on drier parts in the confluence zone at the centre of the rock art panel (Fig. 10a). Cupmarks accumulate south of the central puddle including the water flow. However, they seem to avoid the lowest parts of the panel where most water accumulates (Figs. 9ab, 10b). The densest distribution of human figures follows the NW flow closely in a S–SE direction (Fig. 10c). The largest and most obvious humans, which could be mythical figures with wings, are in a channel in which water

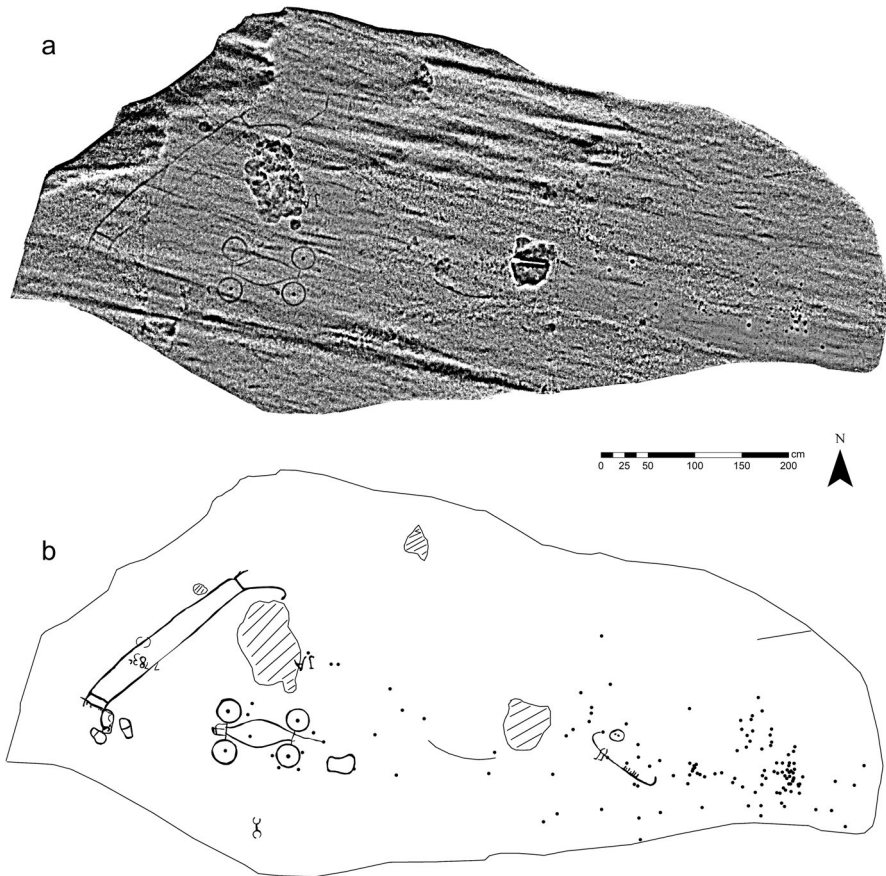


Fig. 6 Bottna 39: **a** DEM visualisation and **b** interpretation

accumulates (Figs. 8, 9a-b). However, other human figures are rather located next to the wettest part to the SE. They also reach lower into the water agglomeration zones than the cupmarks (Figs. 9a, 10c).

There is an interesting pattern for the animal figures on this panel. The densest area is in a relatively dry zone (Fig. 10d). This seems to be a herd or procession of animals that begins in the wettest area of the SE-E flow and is depicted as walking to the central puddle (Figs. 8, 9a). The front animals' heads end right in the puddle (Figs. 8, 9c-d). All animals except for a horseback rider are facing the lower puddle.

Tanum 1:1

The panel Tanum 1, also known as the Vitlycke panel, is the largest Bronze Age rock art panel currently known. It has an extent of ca. 21×6 m (Fig. 11). The panel itself is relatively steep with a shallow depression in its centre (Fig. 12d). This

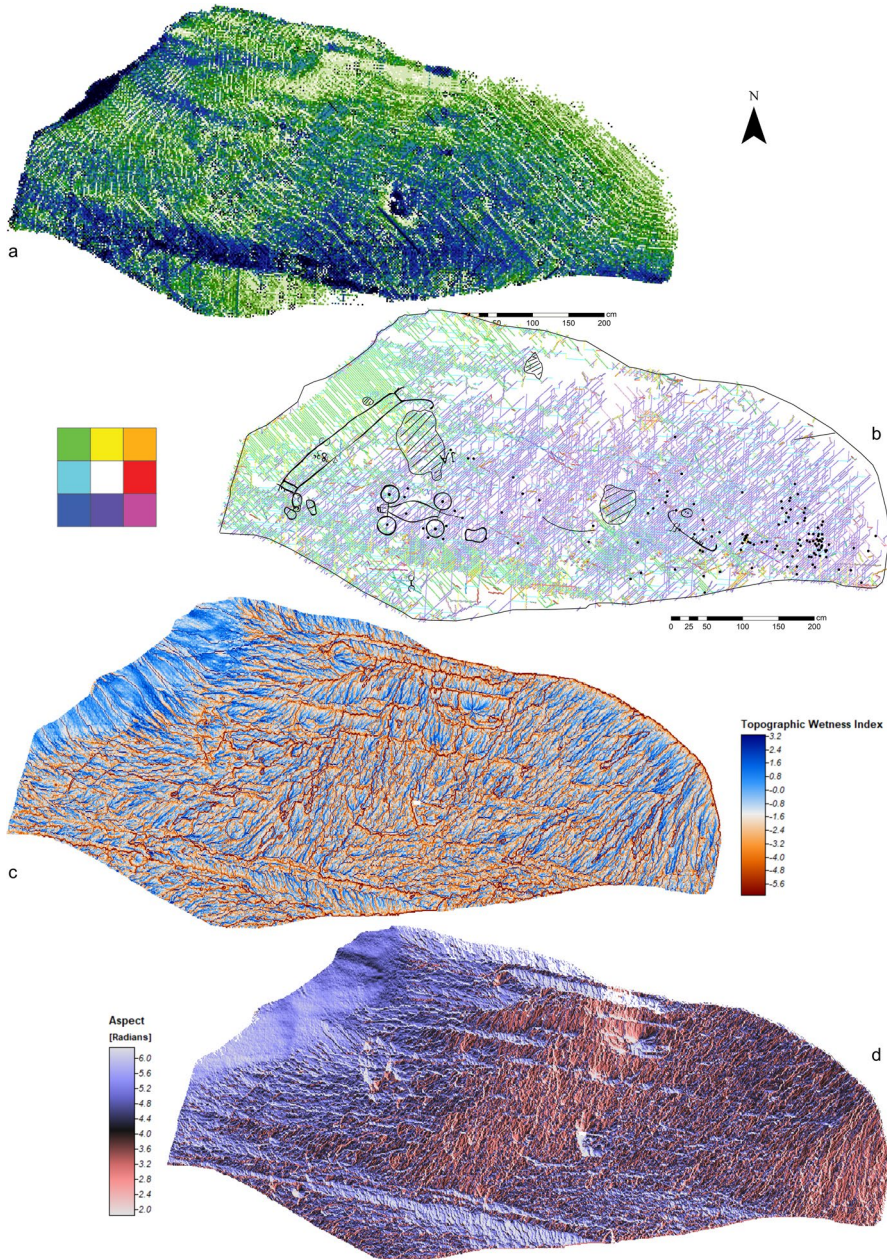


Fig. 7 Bottna 39: **a** water accumulation, **b** water flows, **c** topographical wetness index, **d** aspect

depression has two wider channels in which water accumulates (Fig. 12a). Water from the N runs in a SE direction and from the S in a NE direction into this depression (Fig. 12a-c).

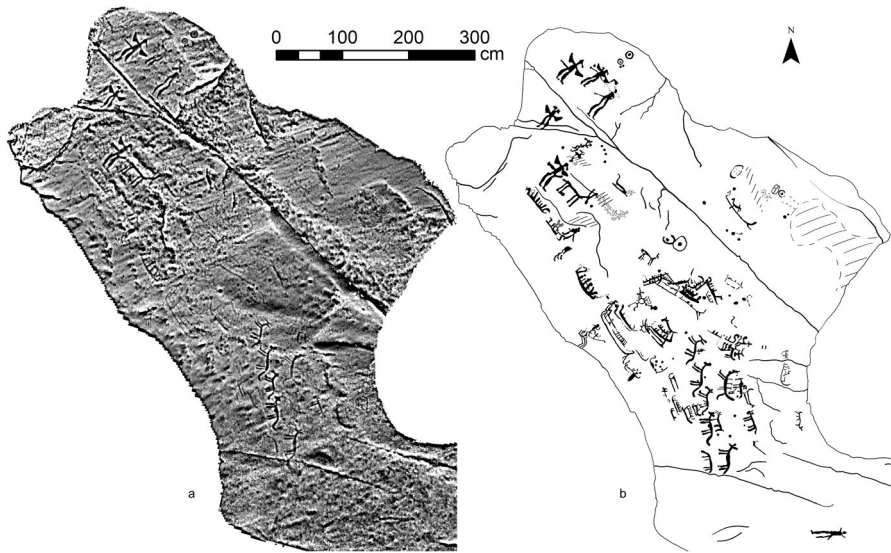


Fig. 8 Bottna 88: **a** DEM visualisation, **b** interpretation

The panel carries 281 cupmarks, 123 boats, 117 humans, and 52 animals. Overall, the highest densities of the rock art distribution on the panel correspond well with the two wide water accumulation channels (Figs. 11, 12a). Even the smaller hot-spots of all images are in zones where water streams accumulate (Figs. 12b-c, 13). The only exception is a procession of smaller human figures that seem to follow a comparatively large warrior located on a drier part of the panel (Figs. 11, 12a). The prominent vertical row of cupmarks on the panel was placed directly into the strongest water accumulation zone for the more northern of the two streams (Figs. 12a-b, 13b). There is another conspicuous row of cupmarks which is less obvious to the observer as it was reused as the heads of the crew of a very large boat (Horn, 2016). The row accurately mirrors the N-S extent of the more southern of the two water accumulation zones (Figs. 12a, 13b). The boat itself is over 3.5 m long and is oriented horizontally along the strongest water accumulation at the bottom of the wide depression. The densest distribution of boats also follows these wetter parts of the panel (Figs. 12a-b, 13a). Boats have a tendency to be lower down on the panel closer to the strongest water accumulation within the central depression, especially in the confluence of the two streams (Figs. 12a-b, 13a). Humans are on average higher up on the panel than boats, and while they are generally within water accumulation zones, they seem to avoid the wettest parts, being next to or between these (Figs. 12a-b, 13c). The densest animal distribution is linked to the more northern stream in which water accumulates. However, there is a second hotspot on a drier part higher up between the two large water accumulation zones (Figs. 12a-b, 13c).

Lastly, it should be noted that the kernel density estimates for boats, humans, and animals while being placed closely together, may occupy distinct zones (Fig. 13). Only higher up in the southern water accumulation zone, below a prominent crack

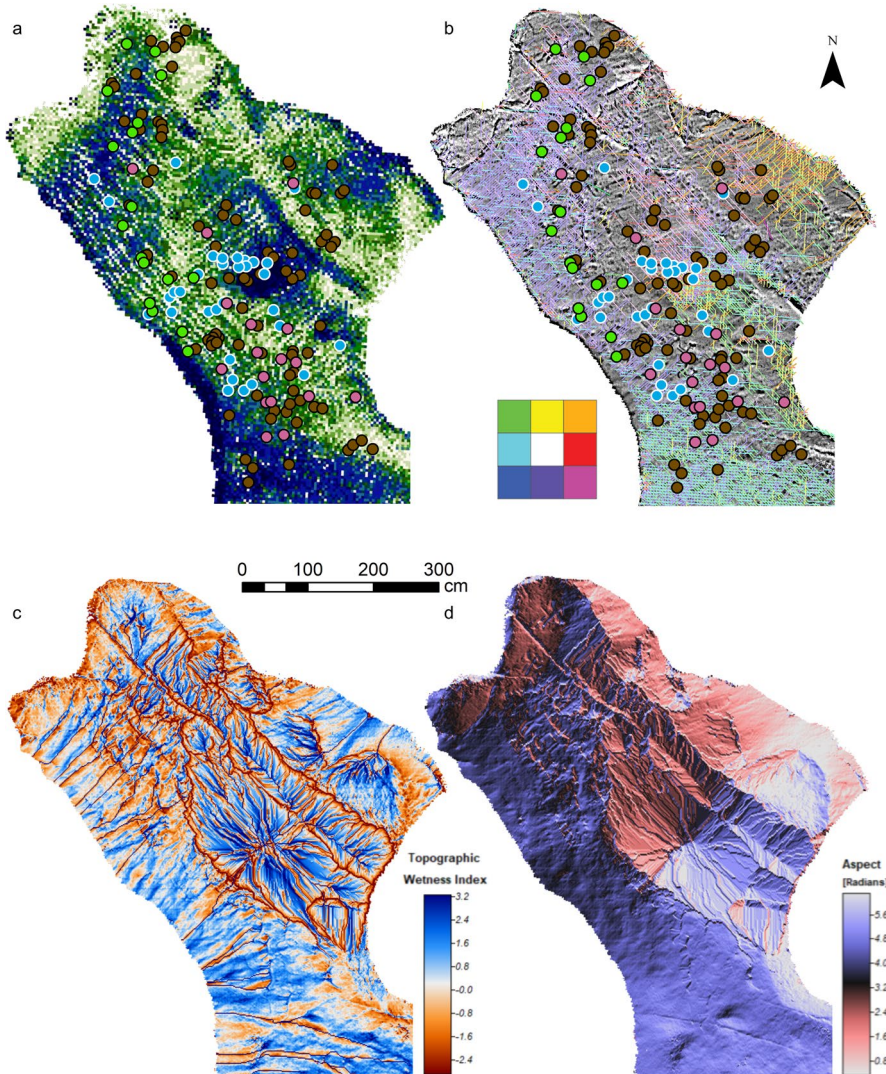


Fig. 9 Bottna 88: **a** water accumulation, **b** water flow, **c** topographical wetness index, **d** aspect

that propagates through most of the panel, do the higher densities of all three motifs overlap (Fig. 7e-f).

Tanum 184:1

At 45 m above sea level, Tanum 184 is one of the panels located higher up in the landscape. The rock art extends across a surface of roughly 4.8×3.9 m (Fig. 14). The bedrock has a flat part on top in which a puddle is located (Fig. 15). Below this the surface slopes down in a wide relatively steep area (Fig. 15d) where the

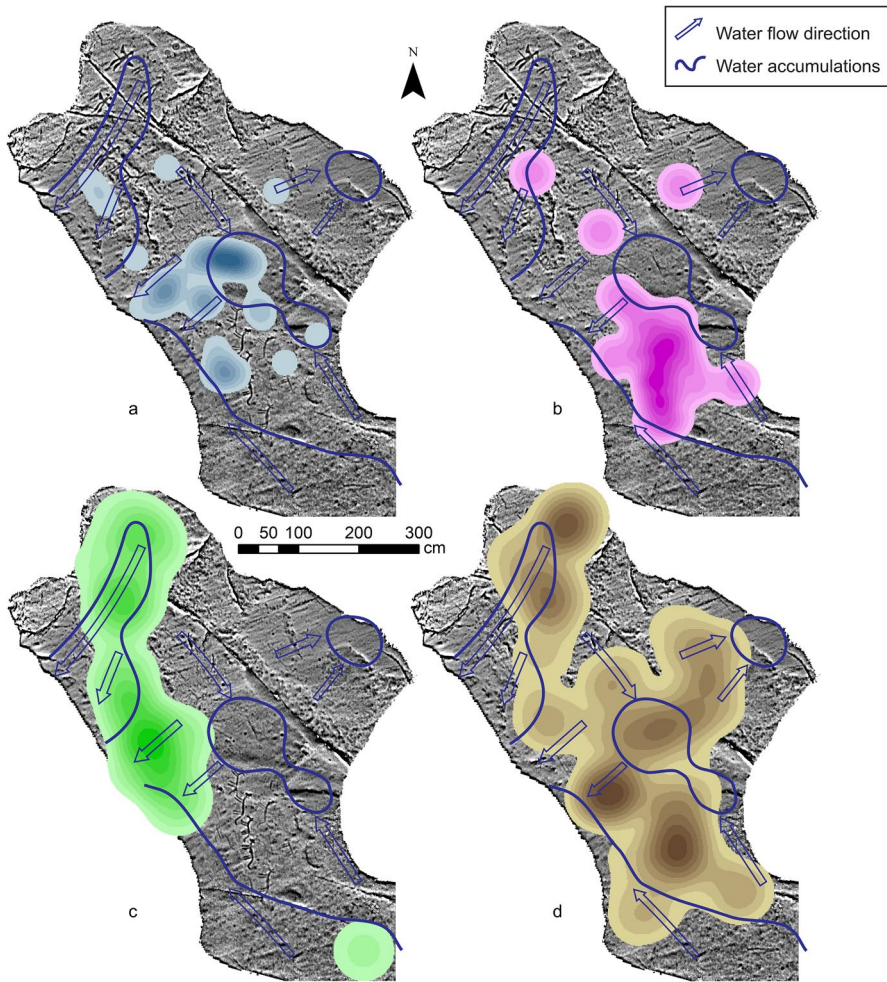


Fig. 10 Bottna 88 heatmaps: **a** boats, **b** boatscupmarks, **c** humans, and **d** animals

water flows SE in a ca. 2 m wide stretch (Fig. 15b, c). There is a gentle slope to the S and SE direction beyond which the water streams somewhat closer to a southern direction (Fig. 15b-d). The wide slope ends in a strong natural channel going from N-S. Adjacent to this in the E is a narrow flat part before the rock slopes down a small cliff (Figs. 14a, 15d). In the SE of the cliff area, there is a boat carved which has not yet been captured as the constant light moisture combined with the moss and lichen makes this part of the panel very slippery. The risk for injury was considered too high to stand and walk there to take images for photogrammetry. Instead, we compared our documentation to rubbings taken from that area and marked the boat in our model to include it in the calculation (Figs. 14, 15, 16a). Two cracks form an x shape across the entire panel



Fig. 11 Tanum 1: **a** DEM visualisation, **b** interpretation

propagating NW–SE and NE–SW respectively (Fig. 14a). How this additionally structures the rock art was discussed elsewhere (Horn & Wollentz, 2019).

On the panel there are 622 cupmarks, 16 humans, 12 boats, and seven animals (Fig. 14). Rock art is clearly most concentrated on the slope with the wide water flow (Fig. 15a, b). Boats are also densely distributed in the wide SE flow down the slope. However, their densest distribution extends across the channel at the bottom of the panel (Fig. 16a). Here two boats are located in opposition to each other on either side of the panel. They were applied to the rock in a way that they are right

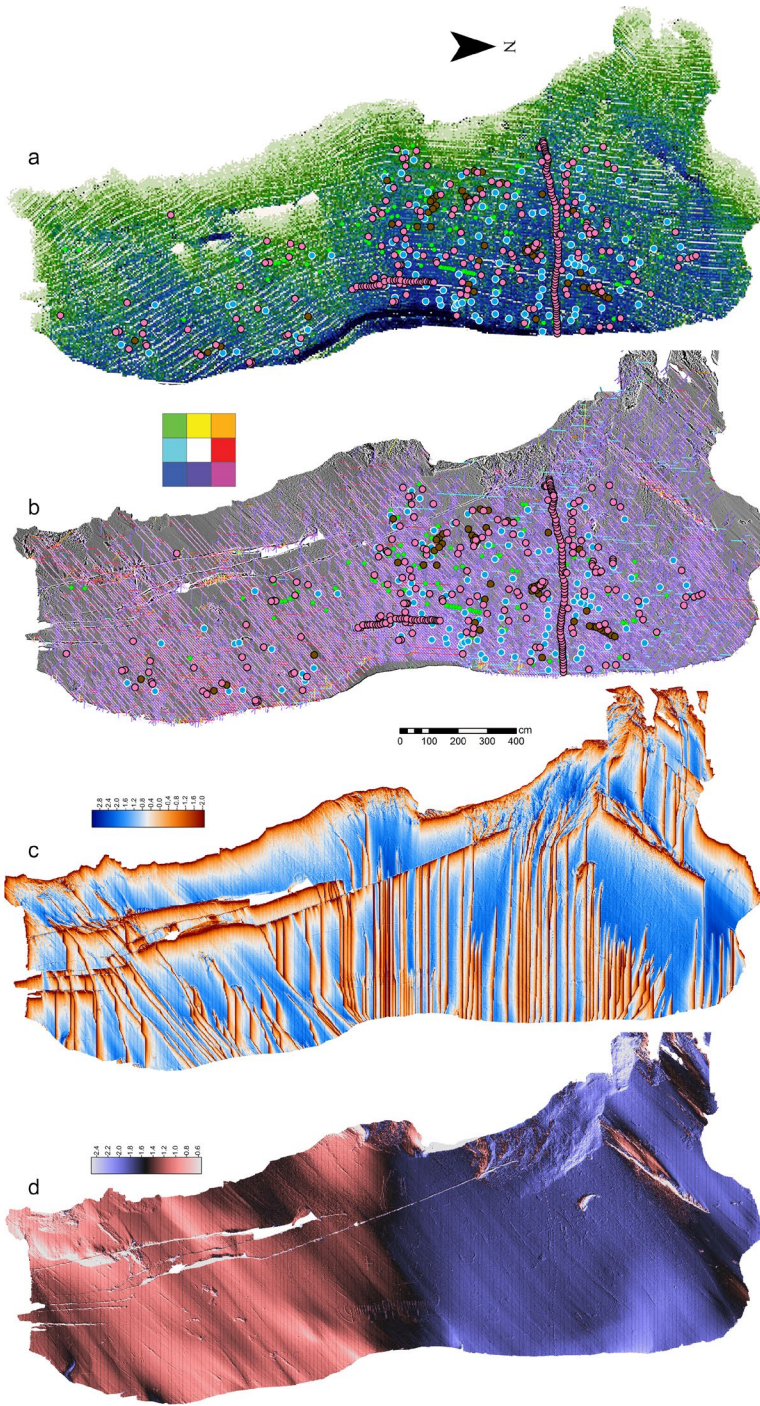


Fig. 12 Tanum 1: **a** water accumulation, **b** water flow, **c** topographical wetness index, **d** aspect

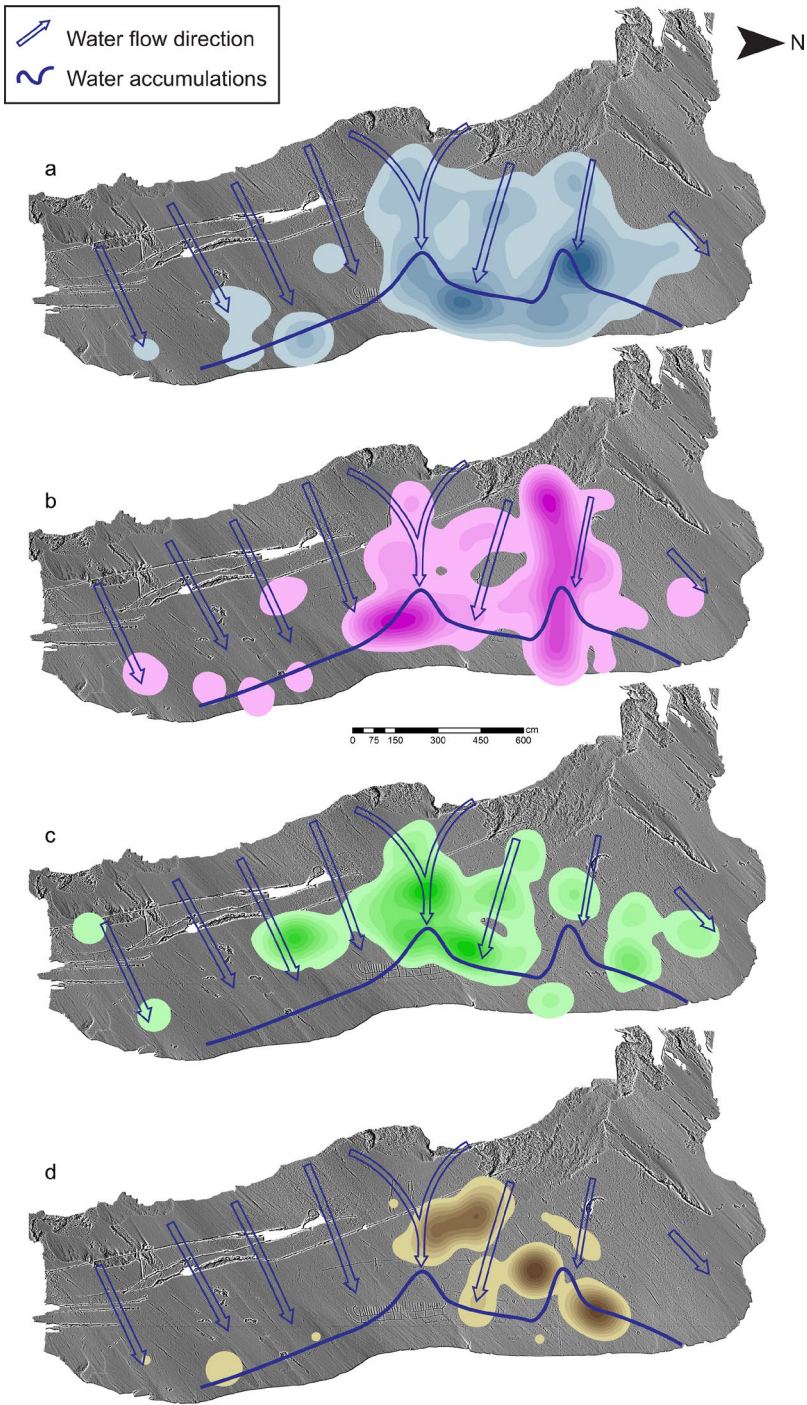


Fig. 13 Tanum I heatmaps: **a** boats, **b** cupmarks, **c** humans, and **d** animals



Fig. 14 Tanum 184: a DEM visualisation, b interpretation

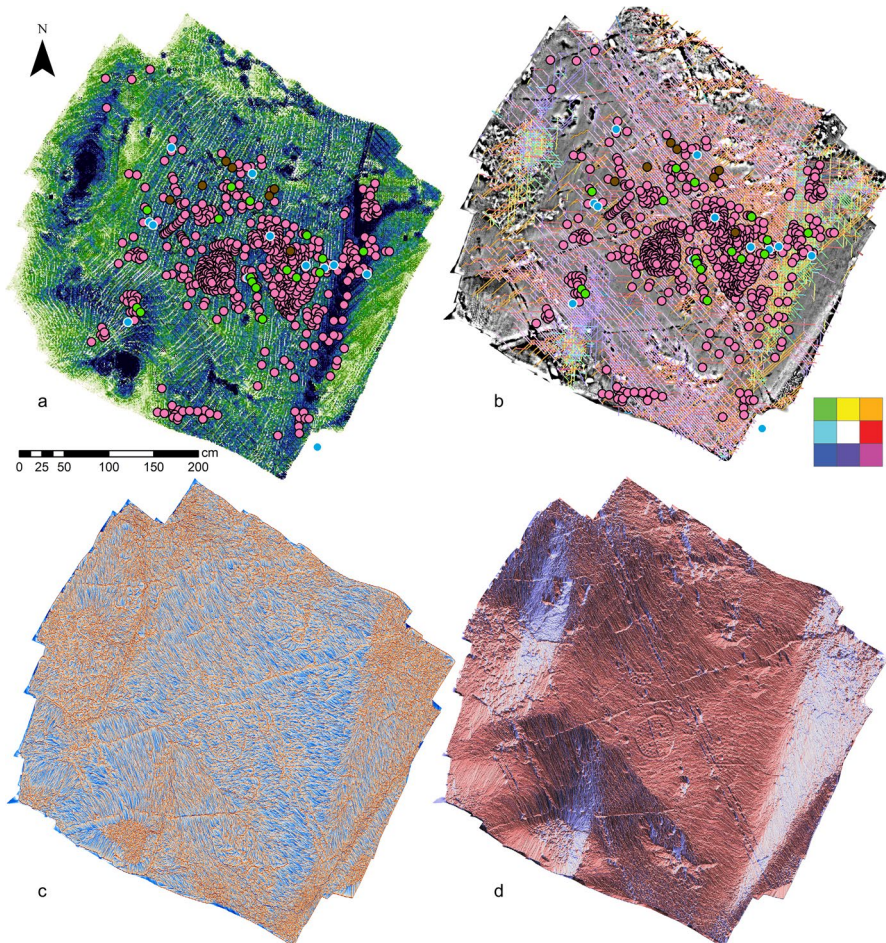


Fig. 15 Tanum 184: **a** water accumulation, **b** water flow, **c** topographical wetness index, **d** aspect

on the water's edge at different fill levels of the channel (Horn & Potter, 2020; Horn & Wollentz, 2019). The panel is dominated by the numerous cupmarks which concentrate in the wide flow down the slope and in the channel. However, cupmarks are also found on drier parts of the panel (Fig. 16b). The densest part of the kernel density estimate for humans mirrors the distribution of the boats, because they are the crews of the boats in this area (Fig. 16c). In the other areas, higher densities of humans and boats are in similar but distinct locations. Animals are not located in the channel area, but higher up on the panel in the wide water flow from the N (Fig. 16d).

On the panel, there is a large circle-cross that is filled with cupmarks in each quarter. In a sense, this resembles the overall structure of the panel with the large cross formed by the natural cracks. The circle and the deeper cupmarks seem to redirect some of the water at the edge of the central flow towards a general SE direction

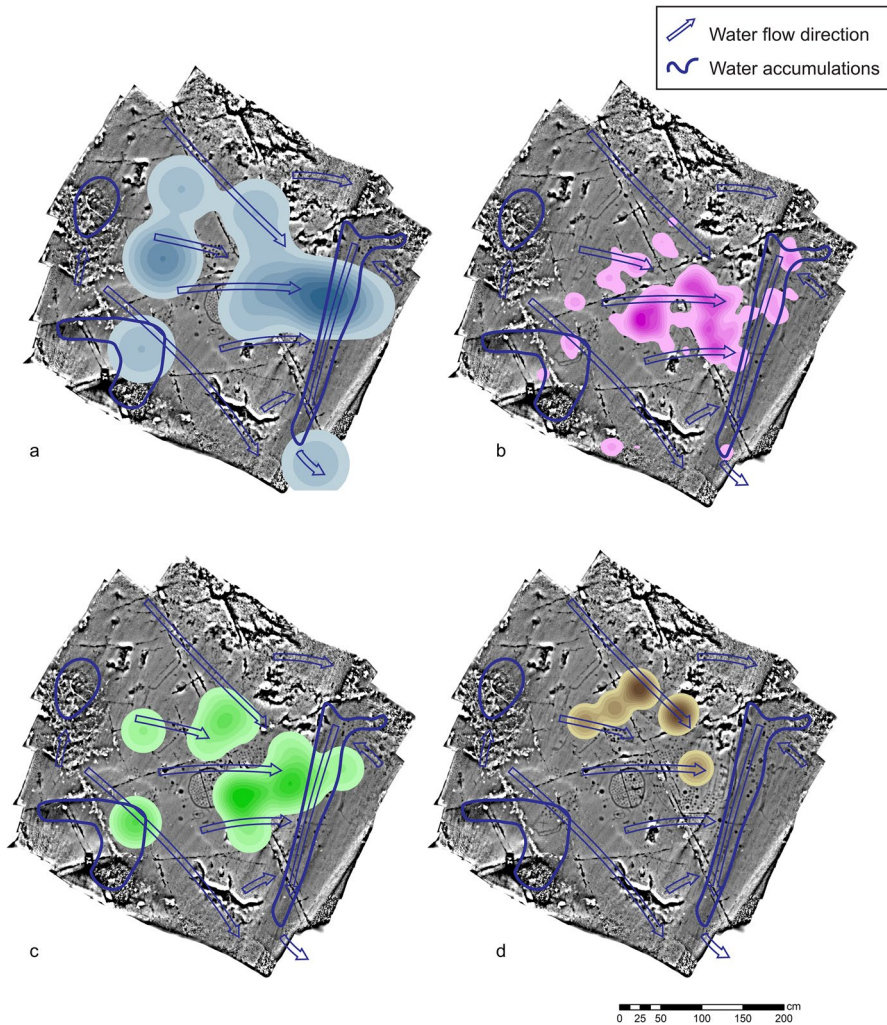


Fig. 16 Tanum 184 heatmaps: **a** boats, **b** cupmarks, **c** humans, and **d** animals

(Fig. 15b-c). Whether this is coincidence or whether rock art was perhaps deliberately placed to affect water flows across a panel is not the focus of this paper, but needs to be studied in the future.

Water as Structuring Element for Rock Art—Discussion

In all our case studies, there is a relationship between the placement of images on the rocks and water flows and accumulations on the rock art panels. This is based on quantitative and qualitative observations. Boats may be most directly

associated with water as their densest distribution often follow streams directly like in Bottna 1, Tanum 1, and 184, or water accumulation zones like in Bottna 88 and Tanum 1. The longitudinal orientation of some boats either within these zones or next to them may also be determined by water flows. In Bottna 39, the axis of the large boat follows the length of the area where it drops off and causes a strong water flow. In Tanum 184, the lower two boats are clearly oriented along the channel. The largest boat in Tanum 1 rides on top of the strongest water accumulation. This association to water streams has been noted at various places in Norway, for example Revheim (Bradley et al., 2002; Nordenborg Myhre, 2004). A very specific parallel to Tanum 184 has been discovered in Valle Søndre (Norway) where at least seven boat carvings were placed either side of a natural channel through which water runs. Like in Tanum, the boats are oriented along the channel with their bottom facing the water (Tangen, 2018; other examples in Nordenborg Myhre, 2004). More qualitative observations that were made during fieldwork in Tanum can also be added.

We first noticed that the boats in Tanum 184 are placed precisely on top of the water flowing through the small channel after a period of rain (Fig. 17a). On Panels in Lövsåsen (Tanum 321) and Litsleby (Tanum 75), several boats were also placed directly in the water flows (Fig. 17b-c). However, these two panels have not yet been documented in a way that quantitative analysis can be carried out.

Although humans are also often associated with water streams, for example in Tanum 1, they tend to be beside, but not in, the strongest water accumulation zones. In Bottna 1, for example, human figures were carved next to the puddle in the weaker water accumulation zone. Likewise, in Bottna 88:1, the most prominent human figures are in the northern stream flowing NE–SW. However, the densest distribution diverts SE following the waterflow and lies between the two strongest water accumulations. This could be the result of the association of human figures with boats when they have naturalistically articulated crews, because then the images are counted as humans and as boats (see Tanum 184). However, as the procession following the large warrior on Tanum 1 shows, humans also occupy areas that are dry and have no apparent position in relation to any water flow.

The interplay between animals and water on the panels is somewhat more difficult to assess. They are only present on four of the five panels, and on these, they are always the smallest class of motifs. From a qualitative viewpoint, Bottna 88 stands out since, much like in Tanum 184, the natural topography of the rock and water is used to tell a story. In this case, animals appear to walk from a stream to a pond. It is less clear on the other panels: on Tanum 1, there is a cluster of animals on a drier part, but it could be argued that they face both water streams to the left and right of them. The two other clusters on this panel are within the northern flow next to the cupmark line. Animals on Tanum 184 only have a generic relationship to the general broad central waterflow, and nothing more specific can be observed.

The wagon and foot soles on Bottna 39 are oriented along the waterflows. On Bottna 1, the situation appears to be similar, but here the densest distribution of foot soles is situated within the wide flow on the gentle downward slope. Despite their small number, this seems to suggest that placement of these motifs was also shaped by the presence of water flows and accumulations on the panels.

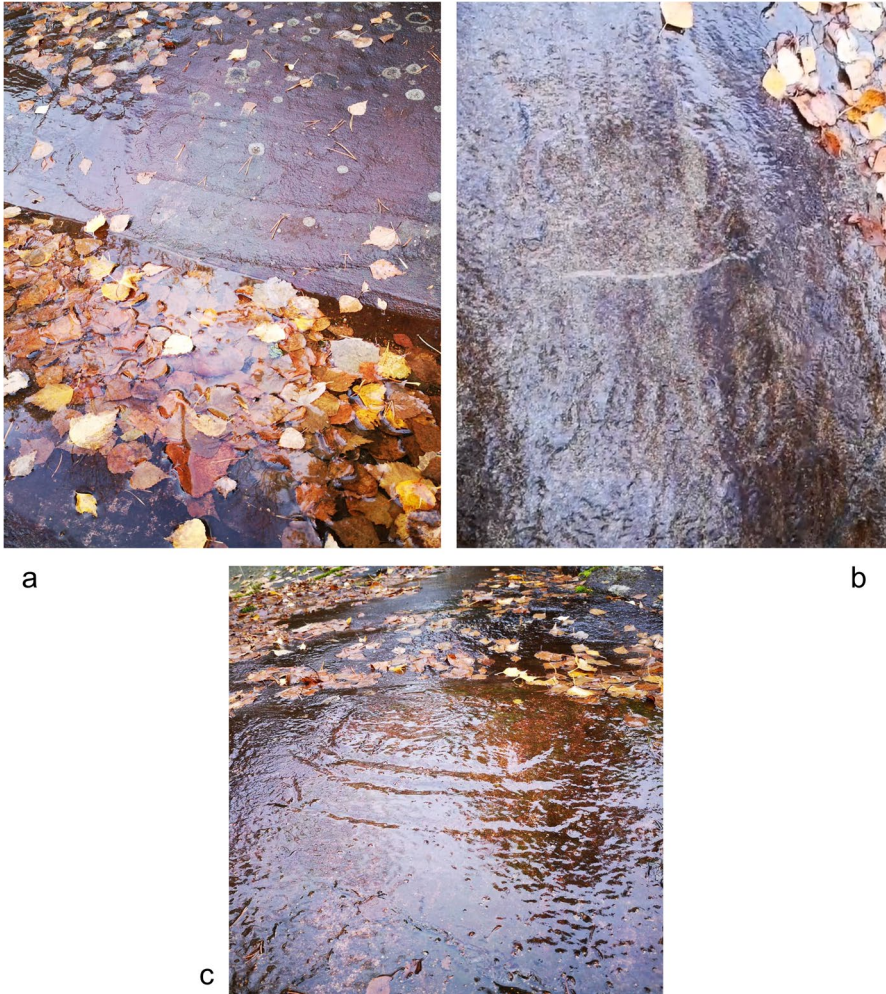


Fig. 17 Flowing water and accumulations after rainfalls in relationship to rock art boats: **a** Tanum 184, **b** Lövåsen, Tanum 321, **c** Litsleby, Tanum 75

Due to the generic nature of cupmarks, their position cannot easily be studied qualitatively in terms of orientation and directionality like for boats, animals, wagons, and foot soles. However, from the kernel density estimates, it is clear that they generally cluster in water flows and accumulation zones. Other than being merely placed in these streams, observations in Tanum 1, 184, and perhaps Bottna 39, suggest that in some instances their placement may be an attempt to actively influence the waterflow's direction or appearance. As previously mentioned, in Tanum 184, it appears that the cupmarks in and around the large circle cross may redirect some of the waterflow (see also Hauptman Wahlgren, 1998). Further down the panel, within the channel, the cupmarks may have been added to disturb the shallow waterflow.

This may have added motion and liveliness to the streams so that they appeared more life-like.

Water was, of course, not the only structuring feature on the panels—as has been noted previously. Other aspects like the physical closeness to water bodies, glacial lines, fractures, etc. also played important roles in the locations that were chosen to make rock art (see Nordenborg Myhre, 2004; Wrigglesworth, 2011).

Conclusion

In this article, we have explored the relationship between rock art, water flows and water accumulation zones in southern Scandinavia using case studies from Bohuslän, southwestern Sweden. Using agent-based modelling, we wanted to provide a quantitative means to study the flow and collection of water on bedrock panels using 3D models in order to enable a comparative investigation of panels that are cleaned, completely overgrown with microvegetation, or are in disparate locations. The case studies demonstrate this possibility.

Overall, carvers seem to have sought out waterflows and accumulations—even those which are more discrete, and thus, they appear to structure the placement of rock art. The results of the research presented in this article show that this is the case for both dramatic and more subtle sites. Furthermore, they indicate keen observational skills of the carvers, since features that mimic real-world water bodies, like puddles that could be lakes or water flows that could be rivers or fjords, were utilised to portray scenes that were probably observed in real life.

Together, the topography of the rocks, water flows, and accumulations formed a potent framework to support and empower Bronze Age narratives, rituals, and religious beliefs when carvers applied images to this canvas. Water was one of the structuring elements of rock art, it interplays with the other elements like perspective, position in the landscape, rock composition, other natural features, and the content of the linked narratives. Larger scale comparative analysis of these aspects may in the future bring us closer to an understanding of the content of Bronze Age narratives and the role carvers played in telling and shaping them. Future work should test and validate or falsify these findings for other Scandinavian and European rock art regions.

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Data Availability The models are part of the SHFA database and as such available under a creative commons license (CC BY-NC-ND 4.0). Since the models are too large to be shared online, it is necessary to request the models from the SHFA or directly from the authors.

The NetLogo code has been submitted with the supplementary material and will be made publicly available on the NetLogo website should the paper be accepted.

Declarations

Conflict of Interest The authors declare no competing interests.

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