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# Weathering and decay

## Breakdown rates of rock carvings in the southern part of Sweden

### Introduction

During the last decades it has been recognised by many that several of our Bronze Age rock carvings have suffered damage and that there is a risk that they finally will disappear. However, fairly little is known about how fast the decay proceeds or about the reasons for the weathering we see today. It must be remembered that weathering is a natural process and rock carvings and other heritage objects in rock never can have an eternal life. It is furthermore often said that several environmental factors might increase breakdown rates of rocks, but it is not proved to what extent. This article is a contribution to a better knowledge of how fast the breakdown proceeds at present and comparisons are made with other areas without rock carvings. To assess downwearing rates 24 sites with rock carvings were selected, with the help of regional authorities, in southern and south central Sweden. Between 1994 and 2003 accurate repeated measurement with laser scanner were made at these sites. This allowed recent downwearing rates to be calculated precisely. The investigated sites are listed in table 1 and their locations are seen on the map in figure 1. The sites are chosen in order to represent different environments and rock types. Swantesson (2005) describes all investigated rock carving sites, referred to in this article, in great detail. In that report the sites are treated separately, the surrounding is described, all measurement results are presented as well as how to interpret them. An opinion about how weathering and erosion might proceed in the future is also given for each site.

### The measurement device

A laser scanner was especially constructed for the purpose of measuring rock carving sites (figure 2). Its construction, as well as advantages and limitations of the device, is described in detail by Williams et al. (2000), Swantesson (2005) and Swantesson et al. (2006), which is why a brief overview only is given here. In the latter two articles it is also described how measurement data is treated and how to calculate downwearing rates from repeated laser scans at the same site. The central part of the measurement device is a commercially available laser gauge probe of the so-called tri+angulation type. This means that a laser beam is emitted from the probe and its reflection at the rock surface is detected through an optical lens by an electronic detector. Since there is a certain angle between the laser beam axis and the optical detector axis, measurements at very steep edges are unfortunately not detected correctly. Some parts where the laser beam hits the surface can be hidden for the detector and in other cases unwanted reflections can arise. Measurements are thus always most reliable from surfaces without any abrupt height changes while errors tend to occur near, for example, joints. The probe

**Table 1.** Sites where repeated micro-mappings have been performed. The numbers correspond to those on the map in figure 1. **A** is the number of measurements made during the period 1994-2003. **B** is the range of calculated surface lowering at different time intervals at the micro-mapped sites in mm per 1000 years. The sign – means that the results are inconclusive. How the calculations were made and how to interpret them is described in the main text.

| County and site | | Rock type | A | B |
|---|---|---|---|---|
| **Blekinge län** | | | | |
| 1. | Torhamn 11 (Hästhällen, Möckleryd) | gneissic intrusive | 3 | 0.47 – 0.65 |
| **Kalmar län** | | | | |
| 2. | Gamleby 54 (in built up area) | red to grey metasediment | 3 | 0.18 – 0.20 |
| 3. | Lofta 353 (Vittinge) | red to grey metasediment | 2 | 0.04 |
| **Skåne län** | | | | |
| 4. | Gryt 1 (Frännarp) | porphyritic red-grey granite | 3 | 0.21 – 0.42 |
| 5. | Järrestad 13 (Dansarenhällen) | quartzitic Cambrian sandstone | 3 | - |
| **Stockholms län** | | | | |
| 6. | Ösmo 622 (Nynäshamn municipality) | Precambrian marble | 3 | - |
| **Södermanlands län** | | | | |
| 7. | Nicolai 340 (Släbro, Nyköping) | gneissic granodiorite | 4 | 0.04 – 0.28 |
| **Uppsala län** | | | | |
| 8. | Boglösa 138 (Rickeby) | Svekofennian supracrustal | 7 | 0.00 – 0.71 |
| 9. | Litslena 194 (Ullstämma) | Svekofennian supracrustal | 3 | 0.10 – 1.11 |
| 10. | Vårfrukyrka 192 (cup marks) | Svekofennian supracrustal | 3 | - |
| **Västra Götalands län** | | | | |
| 11. | Brastad 141 (man with hand) | Bohus granite | 4 | 0.00 |
| 12. | Brastad 18 (deer figure) | Bohus granite | 3 | 0.01 – 0.10 |
| 13. | Foss 6 (Lökeberg) | grey veined orthogneiss | 3 | 3.73 |
| 14. | Husaby 70 (Flyhov) | Lower Cambrian sandstone | 5 | 2.46 – 60.83 |
| 15. | Skee 619 (Jörlov) | Bohus granite | 4 | 1.79 – 2.13 |
| 16. | Tanum 12 (I) (Aspeberget) | Bohus granite | 5 | 0.02 – 1.12 |
| | Tanum 12 (II) (Aspeberget) | Bohus granite | 3 | < 0.01 – 0.03 |
| | Tanum 12 (III) (Aspeberget) | Bohus granite | 2 | 0.01 |
| 17. | Tanum 255 (Fossum) | Bohus granite | 4 | 0.01 – 0.03 |
| 18. | Tisselskog 11 (Högsbyn, the meadow) | marly clay slate | 4 | 0.13 – 1.56 |
| 19. | Tisselskog 15 (Högsbyn, Ronarudden) | marly clay slate | 3 | < 0.01 – 0.30 |
| **Östergötlands län** | | | | |
| 20. | Borg 51 (Herrebro) | fine-grained granite | 3 | 0.00 – 0.93 |
| 21. | St. Johannes 14 (Egna hem) | biotite-rich veined gneiss | 3 | 0.22 – 0.25 |
| 22. | Västra Tollstad 21 (Hästholmen) | acid porphyritic volcanic | 3 | 0.00 – 0.07 |
| 23. | Östra Eneby 1 (Himmelstalund) | Svekofennian supracrustal | 5 | 0.06 – 0.21 |
| 24. | Östra Eneby 8 (Fiskeby) | Svekofennian supracrustal | 4 | 0.01 |

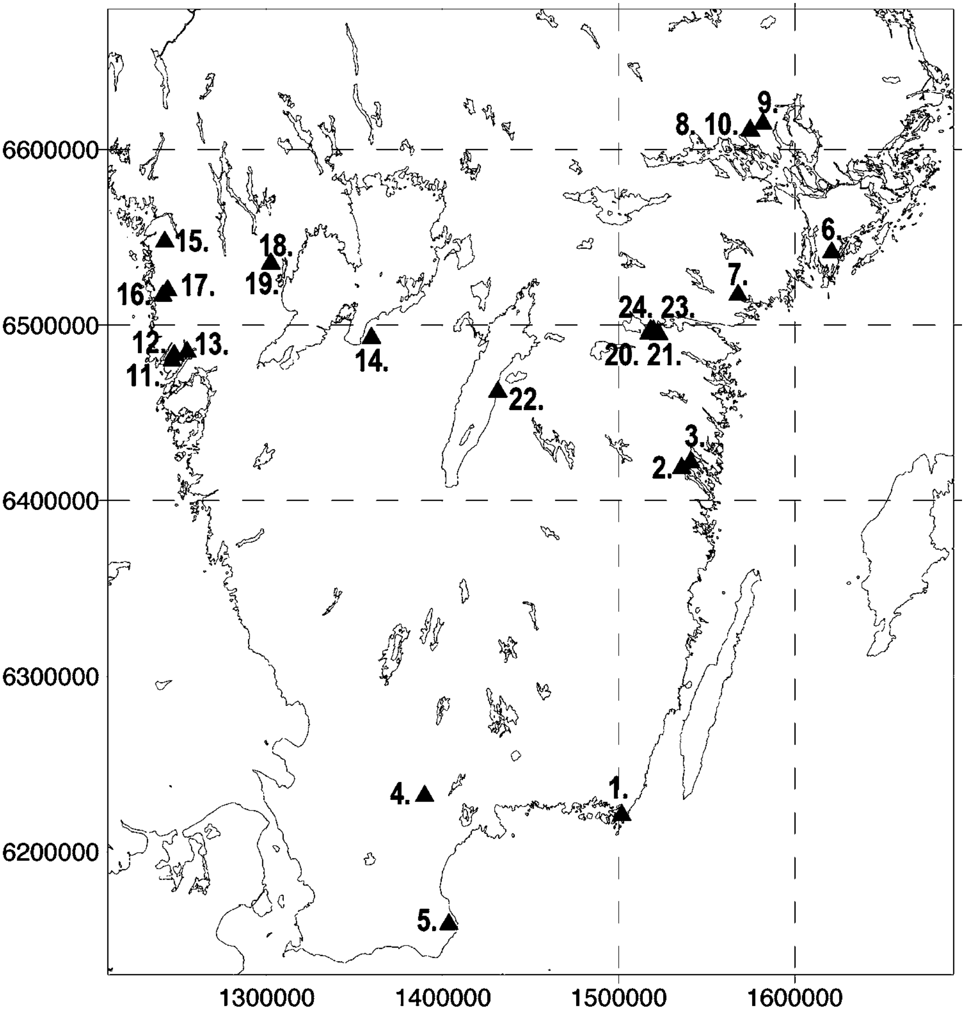


*Fig. 1. Outline map showing the location of rock carving sites where micro-mappings have been made on more than one occasion during the period 1994-2003. The numbers correspond to those in table 1. The co-ordinates in the margins are in 'Rikets Nät' (RT90). The distance between the grid lines is 100 km.*

used can measure heights with a resolution of 0.025 mm within a measurement range of 100 mm.

For movements of the probe in the x- and y-directions two stepping motors are mounted on a specially designed aluminium frame with four adjustable legs. Control cards for the laser and for the measurement process were constructed and are together with control cards for the two stepping motors housed in a separate box. All recorded data are stored on a portable computer directly in the field. The software for controlling the measurement process and data collection is developed especially for the purpose of measuring rock carvings and works in the Windows® environment. The laser scanner device needs a power of 24 V, which is accomplished by two motorcycle batteries. The total weight of all parts of the apparatus, including the batteries, is less than 30 kg. Two

*Fig. 2.The laser scanner during measurement at site 13 (Foss 6, Lökeberg) in the province of Bohuslän. There is a dense lichen growth on the veined gneiss. The two motor cycle batteries used as power source are not seen in the picture.*

people, or one person in turns, can therefore carry it in the field. The fairly small size of the complete laser scanner also makes it easily transportable in an ordinary car.

**Field measurement procedure**

When measurements are made the stability of the frame of the scanner has to be controlled. Likewise it has to be made sure that the distance from the laser gauge probe to the surface is appropriate. For repeated measurements at the same site some kind of studs are necessary to be able to replace the device accurately. Large studs such as those usually used when geodetic measurements are made, can for obvious reasons not be applied at rock carving sites since they themselves would damage the appearance of the ancient art. Instead a special type of very small stud has been used. It is made of stainless steel and is about 20 mm long and has a head with a diameter of six mm. Holes are drilled and four of these studs are glued into these holes in the rock at each measurement site, within the area to be laser scanned. The studs are always, when possible, placed where damage already has occurred. The exact positions of the studs are recorded in connection with each scan, since it usually is not possible to relocate the device exactly. In most cases one height measurement is taken for each $mm^2$ when a scan is made. It is also possible to choose other distances between recordings. The size of the scanned surfaces with rock carvings varies between 0.06 $m^2$ and 0.12 $m^2$, resulting in between 60 000 and 120 000 height values being recorded. The time needed for a complete measurement varies between 1½ and 2 hours. The same accuracy of measurements as in the laboratory can never be achieved in the field. It has, for example, not been possible to remove the lichen cover from the rock at all measurement occasions completely. Ants walking on the measurement area were sometimes hit by the laser beam and caused erroneous readings. These problems are minor when only a single measurement is taken at a site but reduces the reliability of the calculations of breakdown rates.

**How measurement data is treated**

Since all data is stored on the computer as a sequential file directly in the field, different forms of visualisations and statistical treatments can be made instantly. Among others, contour maps, 3D-figures and digital shadow images can easily be made. One type of statistical treatment is the calculation of rock surface roughness. The roughness or unevenness of a surface is often a measure of how far weathering has reached and can be used when different places are compared to each other. Swantesson (2005) uses roughness indexes for descriptions and comparisons of the sites also treated in this article.

If the laser scanner could be replaced at exactly the same position between consecutive measurements calculations of material losses would be easy to perform. In this case the height data from the first scan could simply be subtracted from the second scan to obtain the amount of rock that had eroded away. There is, however, always a small discrepancy in how the laser scanner was placed at different measurements at the same site. This makes it necessary to make a so-called affine transformation of one of the data files. This type of transformation allows rotation, translation and scale changes, while parallelism, projective properties and topology are always preserved (Hauska & Harrie, 1999). The subtraction of the first scan from the second can now be made to obtain, for example, a contour map of where changes have taken place, but all recalculations unfortunately introduce inaccuracies. Furthermore a smoothing of the resulting image is usually needed to reduce the amount of single erroneous values at sharp edges of the rock. Due to these inaccuracies we can only be sure of material losses to depths of more than 0.5 mm. The calculations of the downwearing rates refer to depths greater than this, which means that the results ought to be regarded as a minimum amount of deterioration. At places where there is a slow downwearing it is estimated that real rates might at the most be almost twice as high as the calculated ones. The computations are, however, nearly correct at places exhibiting faster erosion.

**Rock carvings in granite areas**

Many of the known rock carvings in Sweden lie within granite areas. This is, for example, the case with the UNESCO world heritage area around the parish Tanum in the province of Bohuslän where the rock carvings are made in Bohus granite. Bertilsson (1987) considers it as the main rock art area of all Scandinavia, and perhaps even of Europe. There are more than 1 000 panels with in all more than 40 000 individual carvings. The majority of the carvings are Bronze Age and there is a rich variety of figure types. Among them are, for example, ships, humans, footprints, animals, circles, ring-crosses and cup marks. The Bohus granite covers an area of 2 000 $km^2$ in Sweden and Norway. Its petrography and chemistry varies only slightly while there are great differences in colour and texture (Eliasson et al., 2003). The most common rock type is a red to greyish-red, medium-grained, biotite granite. Pegmatite dykes and other dykes are fairly common. Usually joints are fairly far apart from each other giving excellent panels for the rock art. Weathering and hardness tests reveal that the rock is strong and durable (Moses et al., 2006).

As seen in table 1, seven sites have been investigated for the assessment of downwearing rates in the Bohus granite. When the area is visited it is striking to see the contrast between in some places rock carvings in a nearly original state and others where the weathering has gone so far that the rock carving figures are under threat of disappearance. This is also revealed by the calculated downwearing rates at the different sites varying from 0.00 mm to 2.13 mm in 1 000 years. Three of the sites (11, 12 & 17) show almost negligible results. These sites should, however, not be considered as safe.

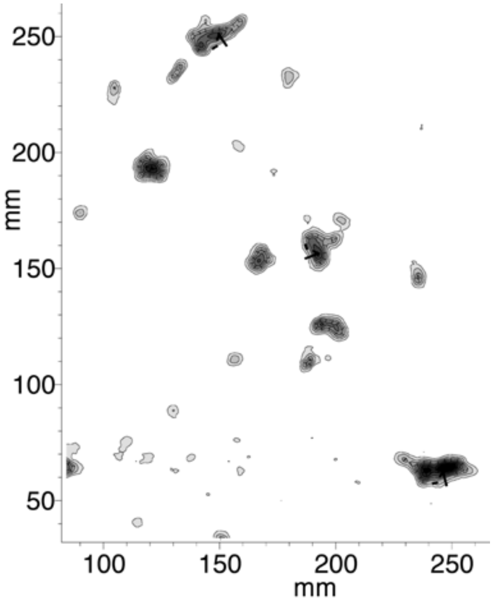


*Fig. 3. Surface lowering to depths of more than 0.5 mm at Jörlov in the parish of Skee (site 15) between 1995 and 2002. The contour interval is 0.25 mm. The downwearing mainly proceeds by detachment of thin rock fragments of a few cm in size. The rates have been similar throughout the entire period.*

At two places (Brastad 141, site 11 & Tanum 255, Fossum, site 17) there is clear evidence of minor granular disintegration that could not be detected with the measurement method. Granular disintegration means that single mineral grains or parts of them are detached from the rock surface.

At Tanum 12 (Aspeberget, site 16) and at Skee 619 (Jörlov, site 15) the breakdown is much more severe. At these sites granular disintegration also plays an important part in the breakdown but there is also some kind of "micro exfoliation". Flakes about one mm thick and around one cm in size weather away, leaving whitish scars that are easily recognised macroscopically. When a flake has disappeared from one place, the weathering usually continues at another place. At Skee 619 the measured rock carving figure is hardly recognisable any more. Places where material losses have taken place here between 1995 and 2002 are shown in figure 3. During the beginning of the monitoring period, until 1995 a shelter covered the measured sites at Aspeberget. It was built in order to protect the rock carvings from weathering, but its effect was doubtful. Trickle water could still flow across the panel and organic material could be accumulated. In 1996 the shelter was dismounted and since then the area is temporarily covered during winter seasons, to minimise frost weathering. Drainage water from vegetated areas above the locality is also prevented from trickling over the rock carvings. Almost all indicated decay at Tanum 12 (I) took place between 1994 and 1996, while material losses were minimal during the rest of the monitoring period. Tanum 12 (II & III) are situated in the immediate vicinity but have no rock carving figures. At these two sites the first measurements were made 1996 and the last 2002. Calculated downwearing rates during this period are almost zero. It is difficult to tell whether the winter covering caused the downwearing to decrease or if it is due to natural variations in the strength of weathering processes during different time intervals. On an obviously already weathered rock surface it might well be that the covering really prevents rock fragments from being detached and material losses being caused. Signs of ongoing "micro exfoliation" are, however, still seen adjacent to the three laser scanned areas.

A digital shadow image of a rock carving in coarse-grained granite at Frännarp in the parish of Gryt in the northern part of the province of Skåne (site 4) is shown in figure 4. The downwearing is fairly small and varies from 0.21 to 0.42 mm in 1 000 years depending on the period over which the calculations were made. Almost all material loss occurred between 1998 and 2002. It mainly proceeds by granular disintegration. The rock carving of a network figure at Borg (Herrebro), near the town Norrköping (site 20) lies only twenty m away from a motorway. The rock is grey, fine-grained granite. Although the indicated downwearing rates in table 1 cannot be considered as disastrous, the site is at great risk. This is mainly due to salt weathering that is considered to be ef-

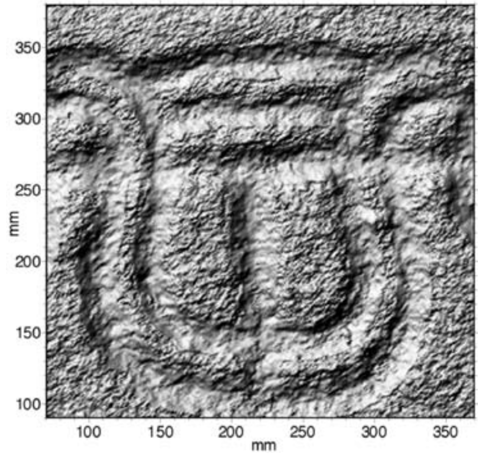


*Fig. 4. Digital shadow image of a carriage made in coarse-grained granite at Frännarp in the parish of Gryt, province of Skåne (site 4). The imaginary light comes from the Northwest.*

fective in causing rock breakdown (Kwaad, 1970 and Goudie et al., 1970). When the motorway is salted during winter, to prevent skidding, salt spray is spread over the outcrop by passing cars.

**Carvings in other Precambrian rocks**

Investigations of the decay of rock carvings in a wide variety of rock types of Precambrian origin other than granite have been made. As seen in table 1 the rates are highly variable with calculated downwearing rates ranging from 0 mm to almost 4 mm in 1 000 years. The ways by which the decay occurs are also variable and can usually not be attributed to the specific rock type. A discoloured surface, that is an early sign of weathering is, however, seen at almost all studied places. Material loss has not yet taken place here but some alteration of the rock is obvious. This phenomenon is also common in the granite areas.

The calculated downwearing rates at two of the investigated sites in Precambrian rocks are considerably higher than elsewhere. At both Vårfrukyrka 192 (site 10) and Foss 6, Lökeberg (site 13) the decay proceeds at present mainly by granular disintegration although the rock types are contrasting. At Vårfrukyrka 192 the rock is of Svekofennian supracrustal origin and can be described as gneissic mica schist. The measurements were made over a number of cup marks (figure 5) and the calculated downwearing amounted to 12.98 mm in 1 000 years between 1994 and 1996. The result is somewhat inconclusive since it was difficult to get a good overlap between measurements from consecutive occasions, but it is clear that decay is fast. It could be that such features as cup marks are preserved for a long time even at places with rapid rock breakdown. There is a possibility that they weather, and deepen faster than the surrounding surfaces are lowered. If other rock carvings have ever been present at this site they would already have disappeared due to the intense weathering. The grey, veined gneiss at Foss 6, with a calculated downwearing rate of 3.73 mm in 1 000 years between 1996 and 2002, has a soft and porous surface and the lichen growth on the rock carvings is extensive. The figures on the panel are often cut to a depth of more than one cm but their contours are not very distinct due to the severe recent decay. When the character of the rock with its surface alteration is taken into consideration it can be expected that the lifetime of the rock carvings at Foss 6 is limited.

At some of the investigated sites the breakdown mainly takes place by flaking, also called exfoliation. Sheets, with a fairly uniform thickness of maybe one cm, at the surface of the rock lose contact with the main rock body. The phenomenon is reported from all areas of the world and there are several reasons why it occurs. One explanation that is plausible in many places is chemical alteration near the surface of the rock that causes a slight volume increase and arching up of exfoliation sheets, followed by failure (Swantesson, 1992). At Gamleby 54 (site 2) in red to grey metasediment the extension of exfoliated areas is easily detected by the laser scanning method, but decay rates are at present low. At Litslena 194, Ullstämma (site 9) in mica schist of Svekofennian supracrustal origin the laser scanned ship figure is, how-

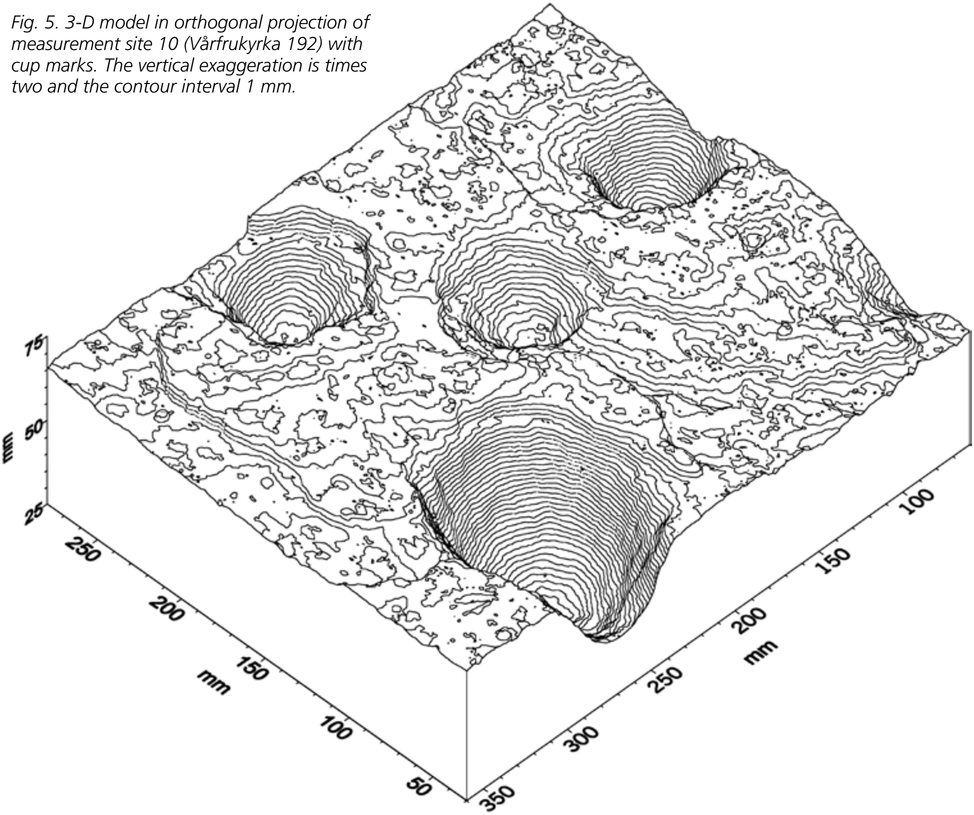


*Fig. 5. 3-D model in orthogonal projection of measurement site 10 (Vårfrukyrka 192) with cup marks. The vertical exaggeration is times two and the contour interval 1 mm.*

ever, under a state of current destruction. Further enlarging of the flaking will make the figure disappear completely. At Boglösa 138, Rickeby (site 8), also in mica schist of Svekofennian supracrustal origin, failure of exfoliation sheets has not yet taken place. About one third of the measured area displays initial flaking. The surface layer of the rock is bulging up, leaving a hollow space between the uplifted sheet and the rock below. Simple knocking can easily reveal the phenomenon. Although calculated downwearing rates are fairly limited the site is at great risk, since the uplifted exfoliation sheet on the measured ship carving might collapse very suddenly. Trampling or even vandalism can make this happen earlier than natural processes alone.

At Torhamn 11, Möckleryd (site 1) in the province of Blekinge there is a gneissic, acid intrusive rock. The schistosity is dense and lies parallel to the surface where the measurements were made. Downwearing rates varies between 0.47 and 0.65 mm in 1 000 years, depending on the period over which the calculations were made. The individual layers of the rock are hard and durable but due to the dense schistosity and weak support between the layers there is a constant tearing of parts of the rock carvings. It can, however, not be considered as alarming at present.

The rock at the two measured places in Högsbyn, Tisselskog 11 & 15 (site 18 & 19) is a marly clay slate that often has been altered to a slightly folded phyllite. It belongs to the so called Dalsland group that is a Precambrian, mainly sedimentary sequence nearly 2 000 m thick (Lundqvist, 1979). The surfaces of the fine-grained rock are smooth and significant recent micro weathering could not be detected. Some higher values are

*Fig. 6. Photograph of the micro mapped rock carving at Fiskeby in the parish of Östra Eneby, Norrköping (site 24). The measured area includes the man with a spear in the right part of the ship. The protruding andalusite crystals are a characteristic of the rock at this place.*

most probably due to unwanted reflections at sharp edges and joints that easily occur when a laser of the triangulation type is used. There is, however, evidence of breakdown on larger scales, than the micro scale, near the sites. Cuneiform scars, sized from about one cm and upwards, are fairly often seen in the rock. In this rock type there is a much greater risk that larger rock fragments will be lost causing destruction of large parts of the rock carving figures instantly than deterioration by micro weathering.

At some places hardly any downwearing at all can be detected by the repeated measurements with the laser scanner equipment. There are also very few macroscopically visible signs of present weathering, except some discolouring of the rock surfaces. This is, for example, the case at Lofta 353, Vittinge (site 3) in red to grey metasediment. The site lies on a small summit surrounded by farmland. Even if dramatic changes in breakdown rates most probably will not take place in the near future there are always some risk factors. Weathering might eventually widen a joint going through the measured ship figure. A number of triangular rock fragments, about one cm in size, are found on the outcrop, indicating that some deterioration is taking place in the vicinity of the laser-scanned area. Also the two investigated places in the town Norrköping, Östra Eneby 1 & 8 (site 23 & 24) in Svekofennian supracrustal rock show limited signs of weathering. Östra Eneby 8, Fiskeby is in an almost perfect state. The reason might be that it has been covered until a few decades ago (figure 6). At Östra Eneby 1, Himmelstalund some limited material loss could be detected by the repeated laser scans (table 1). Most of it took place between 1996 and 2000.

At least three of the investigated sites display more or less severe damage, but calculated downwearing rates are at present very low.

The reason is man-induced damage while natural weathering processes are not very active in these places. At, for example, Nicolai 340, Släbro (site 7) in the town Nyköping large parts of the original rock carving in gneisic granodiorite have most probably been destroyed by fire. It can sometimes be difficult to distinguish destruction by fire from natural exfoliation. Usually exfoliation sheets have a fairly uniform thickness while damage by fire is thicker in the centre than at the edges and thus leave more discus-shaped scars. At Västra Tollstad 21, Hästholmen (site 22) a post for a previous fence was once placed in the middle of a rock carving, destroying its appearance completely. At St. Johannes 14, Egna hem (site 21) in biotite-rich veined gneiss holes from previous fence posts are also seen, but not within the measured area of a circle-cross. There is a damage of unknown origin within a part of the figure. Calculated downwearing rates are at present, however, low and there are no signs that the damage is extending.

The weathering at Ösmo 622 (site 6) in the county of Stockholm differs from all other investigated places since the breakdown for the most part takes place by solution as is common in various types of limestones. The rock is a medium-grained Precambrian crystalline marble that can be partly dolomitic. According to analyses by Stålhös (1979), from a place near the investigated carving, it consists of 88.2% $CaCO_3$, 0.5% $MgCO_3$, 0.1% iron and aluminium oxides and 11.0% insoluble components. Granular quartz inclusions varying in size from a few mm up to half a meter are significant. In the area there are some signs of solution weathering in the form of, for example, small runnels. It was not possible to make any detailed calculations of downwearing rates at Ösmo 622. Due to the unusually high slope of 40° the laser scanner equipment could not be relocated with enough precision for consecutive measurements. Manual comparisons of images from the different occasions, however, reveal clearly visible changes. The downwearing at the site is believed to be high. When dissolved $Ca^{2+}$ disappears in rainwater draining the area, even the insoluble components of the rock lose support and weather away. It seems that the figures are deepened and at the same time widened, thus obscuring them before they finally disappear, by the weathering processes acting at this site.

**Carvings in Cambrian rocks**

Only two sites with sedimentary rocks of Cambrian or later origin have been investigated. The reason is that the areal extent of such rocks is fairly limited in Sweden, but also that they usually are softer and less durable than most crystalline Precambrian rocks. Eventual rock carvings might already have disappeared and modern man has never known about them. The Hardeberga sandstone at Järrestad 13, Dansarenhällen (site 5) forms a massive and very hard quartzite with filled pore spaces between the sand grains. The shallow rock carvings are easily seen in the quartzite despite them not having been painted as is the case at most other investigated sites. The carvings are excellently preserved, but there is a fairly dense spacing between joints of 20 to 30 cm. No downwearing could be detected between 1995 and 2002 on the carvings themselves. Calculations over the same period, however, gave a denudation rate of 1.47 mm in 1 000 years, all of which occurred along the sides of the joints. It is unclear whether this rate is true or if the value is due to unwanted reflections from the laser scanner at the sharp edges of the joints. Even if the panel at present is in a good state there is a risk that breakdown can take place here.

In contrast to the Hardeberga sandstone the Lingulide sandstone at Husaby 70, Flyhov (site 14) on the mesa hill Kinnekulle, is fairly soft and has a porosity of more than 10%. Calculated downwearing rates are also higher than at any of the other rock carving sites that were investigated. For the period between 1994 and 2003 results point to a rate of 60.83 mm in 1 000 years, but if only the period from 1996 to 2003 is considered the calculated downwearing rate falls to 2.46 mm in 1 000 years. The very high rate between 1994 and 2003 is difficult to explain. It might be erroneous and caused by variations in the

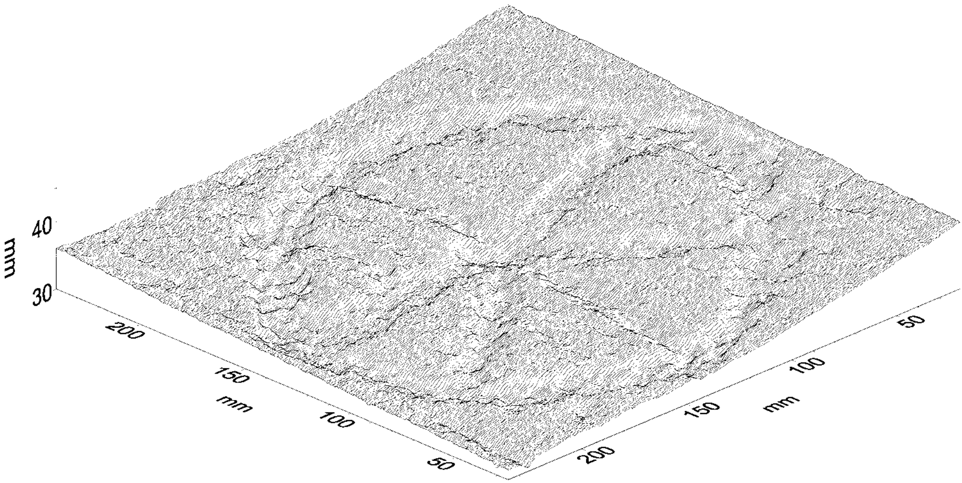


*Fig. 7. 3-D model in orthographic projection of a well preserved circle-cross in Cambrian sandstone at Flyhov in the parish of Husaby, province of Västergötland (site 14). The vertical exaggeration is 2.5 times.*

lichen growth on the rock during different measurement occasions since the lichens were difficult to remove completely. They are very firmly attached to the porous rock. It can, however, be considered that downwearing is fast and that it mostly proceeds by the loss of single sand grains when the support between them is lost. It is necessary to take precautions to expand the lifetime of this panel that was discovered in1889. On an adjacent more recently cleansed part of the outcrop the rock carvings are still very well preserved since they have been covered by a thick enough layer of soil for a prolonged period. Glacial microforms shaped by the land-ice are also seen here. In figure 7 a circle-cross from this part is shown. Cut marks indicating how the figure was created are clearly visible.

**Other measurements of downwearing rates in Scandinavia**

Indirect measurement methods have earlier been used to estimate downwearing rates during the Holocene in Scandinavian crystalline rocks by, for example, Dahl (1967) and Rudberg (1970). They measured the height of quartz veins and nodules protruding above the rest of the rock. This assumes that the land ice left a smoothly polished surface and that the quartz only has weathered to a very limited extent during the Holocene. They arrived at downwearing rates between 1.05 and 1.50 mm in 1 000 years. As the data presented in this article the figures are to be regarded as minimum values. More recently, André (1996) presents deterioration rates between 0.1 and 1.3 mm in 1 000 years in quartzite, quartz phyllite and amphibolite from the Abisko area in northern Sweden.

Between 1999 and 2001 measurements with exactly the same device as used for the rock carvings were made at four coastal localities in Sweden (Swantesson et al., 2006). The calculations of downwearing rates were also made in an identical way. At five coastal sites in Bohus granite on Ramsvikslandet, about 30 km south of the Tanum area, the average denudation rate was 0.53 mm in 1 000 years. This is almost the same as the average of 0.45 mm in 1 000 years for the seven sites with carvings in the same rock type. At the other coastal localities in crystalline rocks breakdown was faster. Average downwearing rates from six sites in gneissic rock at Hovs Hallar was calculated to 8.04 mm in 1 000 years. The location lies at the northern fault line of the Hallandsås horst, about 100 km north of Malmö, and is heavily dissected by joints in varying directions with spacings of only a few cm. There are several signs of alterations and the joints are often filled with soft clay minerals (VIAK AB, 1990). Due to its structure it can be concluded that the rock at Hovs Hallar never has been suitable for making rock carvings. At Rotsidan, Höga Kusten, between the city of Härnösand and the town Örnsköldsvik at 63° N facing the Bothnian Sea average downwearing rates were calculated to 5.92 mm in 1 000 years. The rock is dolerite and the mineral plagioclase is always present while high augite content corresponds to low olivine content and vice versa (Larsson, 1980). For comparison it can be mentioned that the calculated downwearing in Upper Silurian limestone at the coast of the island Fårö, just off Gotland, was as high as 25.28 mm in 1 000 years.

When the average downwearing of 1.10 mm in 1 000 years for all measured crystalline rocks with carvings are compared with results achieved by other methods and at other places it is seen that it is of approximately the same order of magnitude. There is maybe even a tendency that the breakdown is somewhat less intense at the rock carving sites than elsewhere.

## Discussion

The use of modern technology in the form of laser scanning has made it possible to make accurate micro maps of rock surfaces that were not possible with older purely mechanical devices. Other types of images and statistical treatments of measurement data are also readily produced. By repeated measurements at the same site it has been possible to make calculations of average downwearing rates. There have, however, been some difficulties in arriving at exact values, since there were problems of relocation of the laser scanner frame at consecutive measurements. As mentioned earlier all reported downwearing rates in this article ought for this reason to be regarded as minimum values. Although the device used was up to date when the monitoring of rock carvings started in 1994 there are now commercially available laser scanners that can perform the measurement task considerably faster, without any loss of precision. For documentation purposes of entire rock carving panels this type of equipment is excellent. For repeated measurements at the same site for assessing exact downwearing rates the relocation problem needs, however, still to be solved more satisfactorily.

Perhaps more important than making downwearing rates possible to calculate are the laser scans for knowledge of how the micro weathering proceeds. From overlays of consecutive measurements it is clearly seen that material losses, within a time span of maybe a few years, only occur from restricted parts of the laser scanned areas. The influenced parts are usually not larger than a few percent of the total measured area, while major parts remain unaffected. There is thus a great spatial variability in where rock breakdown takes place even within small areas of a few $dm^2$. The downwearing is also episodic in time. At many of the investigated sites almost all breakdown took place between the first and second measurement, while no detectable changes were seen later, or vice versa. Due to the variability of the weathering and erosion both in time and spatially, measurements at more sites or during a longer monitoring period would have yielded valuable additional information.

Downwearing rates vary considerably between the investigated sites. It is also a fact that they are not faster at places with rock carvings than elsewhere. On the contrary higher rates are often calculated from other areas. This inevitably leads to speculation about how many rock carvings there once might have been. At many places they were probably already weathered away before modern man became interested in rock art. This means that maybe only the carvings made in hard and durable rock or at protected places are still well preserved. Especially the number of rock carvings in softer sedimentary rocks such as limestones and some sandstones can be expected to have been much greater than what we still can see today. Also the distribution of rock carvings in the terrain might have been different from our view at present. If this were true, theories about where and why ancient Scandinavian people created carvings might eventually change somewhat.

In the research presented in this article only the micro weathering has been considered. Breakdown can, however, also occur on a meso- and macro scale. The meso scale downwearing involves losses of rock fragment with sizes between one cm and one m while even larger rock parts are withdrawn on the macro scale. Such erosion will instantly destroy rock carvings, and we can often not see exactly where it has happened in the past. It is, however, believed that events on these scales take place fairly seldom in the southern part of Sweden and that the micro weathering is responsible for most of the total downwearing of rock carvings. For a better understanding of the processes behind weathering and erosion of our cultural heritage co-operation between several scientific disciplines are of importance. Experts in earth sciences, chemistry, biology, archaeology and other relevant subjects need to work together. It is also important to carefully examine the interactions between natural factors and those induced by man.

**Conclusions**

- Weathering is a natural phenomenon that ultimately breaks down rocks by chemical, physical and biological processes. The speed of it can, however, be altered by various environmental factors that in many cases are induced by man.
- Downwearing rates at the investigated sites vary considerable. Some places are in an excellent state while, at other places protective measures are needed to extend the lifetime of the rock art.
- The breakdown proceeds in a number of different ways at the investigated sites. Some common phenomena are, for example, discoloured rock surfaces, granular disintegration, exfoliation at different scales and widening of already existing joints. In limestone there is also solution of the rock by water.
- The downwearing is episodic. Significant deterioration might take place within a relatively short time span, while almost nothing happens during other periods.
- The downwearing is also highly variable spatially. Usually only small parts of the investigated sites are influenced, while the most part is left unaffected by breakdown.
- There is no indication that weathering and erosion proceed faster at the investigated sites with rock carvings than elsewhere. On the contrary the downwearing is in many cases faster at many of the places where no carvings are detected. This can indicate that many areas in Scandinavia where rock art once existed already are destroyed. Modern man had never a chance to know about them.
- Modern technique in the form of laser scanning has made it possible to study the course of micro weathering on heritage objects in stone at a level of detail that was not previously possible to achieve.

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