PROTECTION OF SCANDINAVIAN ROCK ART USING MARINE CLAY

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Abstract. When a new highway in SE Norway was planned in 2003, five petroglyph sites, located in the immediate surroundings of the road, were to be permanently covered. The covers consist of c. 70-cm-thick layers of plastic Quaternary marine clay on the rock art, followed by a geotextile, a thin drainage layer of natural gravel and finally a rather thick top layer of cobble stones. The clay serves to sustain a stable temperature, humidity and circum-neutral pH at the rock surface and to prevent the establishment of plant roots. The purpose of the covers was to prevent increased deterioration rates of the rock art due to emissions from traffic and action from de-icing salts used on the road. This paper presents the cover design developed for this project, based on principles from the geotechnical, geochemical, biological and conservation fields. Subsequently, the paper demonstrates the success of a cross-disciplinary approach to rock art protection.

Introduction

The county of Østfold in south-east Norway contains numerous and various traces from pre-Historic times, among which are more than 400 petroglyph sites. Together with the neighbour county of Bohuslän, south-west Sweden, they represent the largest concentration of petroglyphs in northern Europe with more than 2700 sites altogether. This area comprises the famous Tanum, which is under protection by UNESCO as a World Heritage Site. The most common motif in this region is the cupule. The second common motif is the 'ship'. Other examples are anthropomorphs and zoomorphs. The Scandinavian petroglyphs are tentatively dated to the Bronze Age (c. 1750–500 BCE), based on iconographic identification and shoreline localisation.

The latest expansion of the main highway E6 through the Østfold County entailed conflicts and threats to several petroglyph sites in the region. Within the area of the regulatory plans for the road works, one of the sites was rescued and saved by an out-sawing-operation and the rock art is now exhibited in the regional museum at Borgarsyssel Museum, Sarpsborg (Bårdseth 2007: 75–79). This was not a preferred solution, but the course of action involving the fewest disadvantages for the petroglyphs. There was a choice to place the road expansion on the opposite side of the site; however, this would have affected a larger

panel. When the highway was first built 35 years ago, the cultural heritage authorities allowed removal of the panel. For unknown reasons this act never came to realisation. A final argument for the removal of the panel was that it was well suitable for this kind of operation, with low risk for failure.

However, five other sites came to be situated within the working zone for the road expansion, and after completion of the work the sites would be located on the edge of the new road. During the road work these five sites could be damaged or destroyed by rock blasting as well as heavy machinery, and after having finished the road construction the petroglyphs would still be exposed to salt and air pollution. Such contaminating elements are likely to increase weathering of the rock surface. This may lead to deterioration of the petroglyphs, and in the worst case total destruction. The fact that the rock art sites came to be situated on the edge of the new highway also made them unattractive as well as unreachable for future visitors. The five rock art sites were thus threatened by dangers in both a short-term and a long-term perspective. These scenarios led the Museum of Cultural History, University of Oslo, to request permanent covering of the sites as a method for preservation of the petroglyphs for the future. This initiative was accepted by the Norwegian Directorate for Cultural Heritage on the conditions of developing

Figure 1.   The Scandinavian peninsula. The area of research is within the county of Østfold, SE Norway, marked by the quadrangle. Graphics: Gro Anita Bårdseth.

a suitable covering method, and of the execution of documentation according to the guidelines given by the Norwegian rock art project, prior to the covering (Bergkunstprosjektet [online]). This article discusses the method developed for the covering of rock art sites in Østfold County, based on marine clay.

The discussions and fieldwork were conducted in the years 2004 to 2006 under the leadership of the 'E6-prosjektet Østfold' at the Museum of Cultural History, University of Oslo. An interdisciplinary team was established under the supervision of conservator Eva Ernfridsson, and included archaeologists, a geologist, a geo-technician, a landscape architect and a vegetation advisor. The goal was to develop a method for covering rock art sites that would last for a long time (100 years) by the use of natural materials. The covers applied had to be reversible and it should be possible to make future inspections. An important prerequisite for the design was to keep the need for annual maintenance to a minimum. In addition the method had to be operational as well as practical, and to be conducted according to the security demands related to the roadwork constructions. Documentation of the five rock art sites was conducted prior to the covering (Bårdseth 2007). This included copying of the figures onto transparent plastic and night photography in raking light. Surface roughness, discoloration, porosity, mineral alteration and adhesion between grains

was investigated visually and documented by photography.

An outline of rock weathering processes

The bedrock in Østfold consists mainly of late Precambrian granite called Iddefjord granite in Norway and Bohusgranite in Sweden. The mineral composition can vary a great deal. In general it is medium coarse (1–5 mm) and consists of quartz and plagioclase at similar proportions, a somewhat higher proportion of potassium feldspar and a smaller proportion of biotite, ore minerals and chlorite (Dahlin et al. 2000: 95). The rock was smoothed and sculptured during the last Ice Age. According to rates of isostatic uplift the elevation where most petroglyphs are situated emerged from the ocean about 5000 years ago (Påsse 2003: 50) and one can assume that people of the Bronze Age carved figures into softly rounded surfaces of *roche moutonnée*. Today weathering has increased surface roughness and developed a variably friable layer characterised by a higher intensity of micro-fissures and mineral alteration. The petroglyphs are depressions of a few millimetres to a maximum of 2 cm situated in this fragile weathered layer. During a survey, made in connection to the project INTERREG II A, cores from the test sites in nearby Begby, Fredrikstad municipality, Østfold County, showed that the weathering reaches 1 cm to 3.5 cm below the outer surface (Dahlin et al. 2000: 139). Microscopy showed that the degraded surface was characterised by an outer red-brown to yellow-brown weathering rind as seen in cross-section. Through light and electron microscopes it became evident that micro-fissures in the surface region had been opened up as a result of chemical dissolution. The colouring was a result of the presence of a higher amount of oxidised iron than the amount present in pristine rock. A similar study of Bohusgranite showed large loss of material in boundaries between some grains and deposition of iron hydroxide in microfissures. The iron oxide was interpreted as originating from biotite that was shown to be depleted of iron (Elfving 1997: 7–8).

Weathered rock is much more sensitive to weathering agents than fresh rock. That is because the strength of the adhesion between mineral grains has decreased and the surface area accessible for chemical attack has increased. That is why it was assumed that the degradation of the rock surfaces situated close to the highway through Østfold could be immensely increased, primarily by air pollution and salt weathering.

Chemical weathering

Glacially worked granite faces have a polished surface with interlocking and usually strong mineral grain boundaries. When chemical weathering has been at work over a period of time, the more easily weathered silicates (in this case plagioclase and bio-

tite; cf. Goldich 1938) dissolve or turn into secondary, weak mineral phases. As a result the surface becomes more textured. Chemical weathering of silicates is most efficient in contact with acid or basic waters, whilst being very slow or inefficient at pH about 7 ± 1, notably in a cool environment (cf. Appelo and Postma 2005). Entire mineral grains loosen as a result of focused weathering along the mineral grain boundaries. Thus, a small degree of weathering could result in major material loss within the outermost subsurface. The rate of weathering depends on temperature and the composition of dissolved substances in connection with the acid-induced weathering, a simplified explanation is that the positive ions in biotite and feldspars are exchanged with hydrogen ions dissolved in water, ultimately leading to dissolution of minerals (Kalinowski 1997: 2). Plants, bacteria and fungi use organic acids and chelating ligands with similar effects, to get access to nutrition substances.

Figure 2. Aerial view of the southernmost part of the research area, before the completion of the new highway. The rock art sites are located on rock exposures close to the road. Photograph: The Norwegian Public Roads Administration.

Air pollution

Car traffic produces sulphuric acids and nitric acid. Nitrogen oxide is produced when acid and carbon from the air react in the combustion engine. The nitrogen oxide then continues to react with water in the air (see formula) and produces nitric acid, which is a strong acid that contributes to further acidification of the environment (Elvingson and Ågren 1998: 35–45).

$$2\,NO_2\,(g) + H_2O\,(1) \rightarrow HNO_2\,(aq) + HNO_3\,(aq)$$
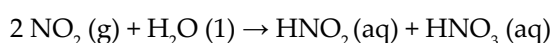
Sulphur in fuel reacts with oxygen in air during combustion and produces sulphur dioxide. The sulphur dioxide continues to react with water and produces sulphuric acid, which is also a strong acid. During recent years the amount of acid in the air has been reduced because of decrease of sulphur exhausts. Catalysts on cars have contributed to a decreasing amount of nitrogen oxide (NO_x) exhausts. The traffic on the highway through Østfold, however, will increase and presumably contribute to increase acidity of air in synergism with other corrosive processes, thus increasing the speed of the corrosion processes close to the road (synergetic effects; Rosvall et al. 1986: 197).

Physical weathering

Mechanical stress damaging the rock is usually called physical weathering (Löfvendahl 1996: 114). Several damaging processes cause a synergistic increase in weathering and the effect of single factors can seldom be quantified in a natural environment.

One could say that chemical weathering is a continually ongoing process while physical degradation is more incidental (incidental corrosion: Swantesson 2005: 90–91). When the weathering has reached a critical state, for example freeze-thaw expansion can cause material to fall off as flakes or grains. As a result a more intact surface is exposed and the weathering starts over again. Abrupt changes in temperature, caused for example by fire, can do great damage because they contribute to stress in the material. Major variations in temperature, such as the variation between day- and night-time in the summer, can presumably also cause material losses (Löfvendahl and Bertilsson 1996: 25).

Salt weathering

De-icing salts, most frequently in the form of NaCl, are used in huge amounts during winter in order to maintain traffic safety. It was considered likely that salt action could increase the deterioration rate of rock art near the highway. Salt action involves crystallisation pressure, hydration pressure and hygroscopic attraction of excess moisture (Swantesson 1989: 150).

Biological weathering

Depressions in rocks, such as petroglyphs, can act as a soil moisture reservoir containing water and plant nutrients. Plant roots growing and expanding into such recesses may inflict severe mechanical damage. As a step in plant nutrient uptake as well as by metabolic activity, living roots will release protons and other chemical weathering agents. This also applies for the organisms connected to the close neighbourhood of roots, the rhizosphere, of which a prominent part is played by mycorrhizal fungi. These

associates of plant roots are equipped with extremely fine filaments, hyphae, which may penetrate into even smaller fissures of minerals and rocks in order to remove phosphorous, potassium or other plant nutrients, and thus significantly break down mineral surfaces (Bonneville et al. 2009). Dittmer (1937) found that the roots of one single barley plant had a length of more than 500 m and a surface area of more than 500 m², which may give an impression of the possible extent of this problem.

Clay for protective cover

A promising method to prevent degradation of petroglyphs in Sweden and Norway has been the use of temporary protective covers during winter. Tarpaulin and insulating material has been tested, for example as a part of the INTERREG II project (Kallhovd and Magnusson 2000) and the national Norwegian Rock Art project (Riksantikvaren 2006). Winter covers reduce freeze-thaw cycles and keep the surface free from lichen and moss by blocking the light. Experience in long-term covers has been much sparser. An important inspiration for the E6-design was observation of rock surfaces that show smooth glacial surfaces after being naturally covered by clay for thousands of years before excavation. Clay has been put forward in the discussion about protective covers for a long time (for example by Löfvendahl and Bertilsson 1996: 25). In addition, to ensure that the petroglyphs would not come in contact with plant roots or connected organisms, the approach of the vegetation advisor was to look into methods which would prevent plant growth and, with that, organic activity. Danish research about street tree decay (Randrup 1996; Randrup and Dralle 1997) became inspiring. The investigations revealed how trees growing in clay soils were damaged by compression of their growing substrate. Further it was demonstrated that compacted clays were completely impermeable to plant roots, and that clay soils compressed between 15 and 35 years ago showed no signs of decompressing by natural geological processes.

The choice of marine clay as cover material

Marine clays in deeper layers are extremely stable with respect to chemical and physical characteristics (Scheffer 1998). If protected against mechanical erosion such layers are highly resistant to gas exchange and water movement. This finally led to the suggestion of using compacted marine clay in the protective cover design. The main challenge of the protective covering was to find a construction type and a construction material that could stop or reduce negative factors such as those mentioned above. Deliberations and analysis led us to marine clay from Borge, Fredrikstad municipality, Østfold, situated only 2–10 kilometres from the rock art sites.

Yet before reaching this final conclusion several other methods were discussed, among which crushed olivine and moraine materials were assessed. Olivine is available from west Norway. Although olivine weathers quite easily and buffers at pH c. 8–9, experience shows that the olivine gravel is a very good nutrient, which would very probably lead to undesirable effects. For this reason Norwegian olivine has been used with success in connection with golf greens. Soils from the south of Sweden, rich in clay and calcium carbonate (Baltic moraine), were also discussed. However, transportation costs were important and the focus was therefore on local deposits, being marine clays or moraine material. The geotechnical properties of Norwegian moraine materials are mostly very favourable and it was argued that such material should be utilised instead of marine clays, which sometimes contain sulphides that may produce acids when oxidised. However, moraines have some properties that make them rather unsuitable as primary protection material in direct contact with rock art:

1) Stones and finer materials occur in all size fractions. Hence big blocks could easily fall off and cause damage to the rock art.
2) It would seem difficult to avoid air pockets against the rock surfaces, since the finer grading is usually not well bound. This would facilitate entrance of both water and root systems in the long run.
3) Moraines represent the most inhomogeneous material, which due to its very high D_{max} (the size of largest blocks) would make it almost impossible to collect representative samples for chemical and mineralogical analyses. In reality one would not know the composition of the cover at each site.
4) Sources of acids may also occur in moraine material, notably due to rust deposits with ferrous iron as well as rare, long transported black shale fragments.

A decision was therefore made that local marine clay should first be characterised. Potential sources of marine clay were readily available in relevant quantities from several sites. The target quality was soft homogeneous plastic clay without harmful constituents.

Characterisation of the marine clay

The characterisation strategy itself was established after a thorough cross-disciplinary discussion, involving archaeology, botany, geotechnics and geology as well as landscape and conservation techniques. The main parameters to be investigated were mineralogy, pH response and geotechnical properties of the clay.

Samples

The samples were collected from an about 3–4 m vertical cross-section across layers of Quaternary marine clay at Borge. This occurrence had until recently been used as a raw material for lightweight aggregate and Leca. In 2006 the operator (Maxit

Samples	Depth below surface	Main minerals	Subordinate minerals
M1a (rusty-brown, stiff)	0.5 m	Quartz, plagioclase	Birnessite, micas, chlorite
M1b (dark, stiff)	0.5 m	Quartz, plagioclase	Birnessite, micas, chlorite
M2 (bluish-grey, plastic)	1.5–2 m	Quartz, plagioclase, hollandite	Birnessite
M3 (bluish-grey, plastic)	2.5–3 m	Muscovite, quartz, plagioclase	Birnessite

***Table 1.** Minerals identified by XRD. Iron sulphides such as pyrite and marcasite were not detected.*

Samples	C	Fe	S	Mn
M1	1.5–4.3	3–7	0.2–1.2	0
M1b	0.7–2.5	5.4–11	0–1.1	0–2.5
M2	2.5–3.5	4–12	0.02–0.9	0–2.6
M3	2.1–3.9	2–3.5	0–0.17	0–0.2

Samples for SEM were very carefully sliced off from intact clay lumps with a penknife.

***Table 2.** Semi-quantitative chemical compositional range from SEM (weight %), based on several point analyses in each sample.*

AS) was in the process of closing down the site for revegetation, and the time was restricted. The upper 0.5–1.0 m was characterised by oxidised clay with frequent occurrences of iron stain. This layer was relatively stiff. Beneath it the clay was bluish-grey and plastic, being characterised by a lack of oxidation. Just three samples were selected for further analysis, since records from the occurrence had proven the characteristics to be representative. In February 2005 one set of samples (M1, M2 and M3) were collected for mineralogical and water response analysis, whilst parallels (G1, G2 and G3) were collected for geotechnical testing. The entire cross-section was opened by a digger prior to final sampling.

The samples were regarded as representative for the variation across the section, as based on visual impression as well as the grain size. The sample volume was more than satisfactory with respect to the required laboratory investigations.

Mineralogical analysis and density of clay

The samples were investigated by x-ray diffraction (XRD) and scanning electron microscopy (SEM). The aim of this work was to establish the clay mineralogy and identify potentially harmful constituents. Most notably the possible presence of pyrite (FeS_2) or ferrous iron minerals was focused on, since these compounds may produce acids in contact with air and water. XRD is capable of identifying crystalline phases (minerals) whilst in SEM it was possible to observe the structure of the clay (using the back-scattered electron mode) as well as conducting micro-chemical analysis. Thus,

the combined effort gave an important insight into the composition of crystalline and possible amorphous constituents of the marine clay. The results are given in Tables 1 and 2. XRD indicated that, apart from the common minerals quartz, feldspars, chlorite and mica, also the manganese oxides birnessite and hollandite were present. In contrast to clays found in weathering profiles around the world, the marine clays do not contain significant contents of swelling clay minerals such as smectites. There was no sign of pyrite (FeS_2) on the XRD diffractograms. However, it should be emphasised that minor minerals may not easily be detected by XRD and therefore SEM chemical analysis was required.

The SEM results show that total sulphur contents varied from 0–1.2 weight %, whilst Fe was much more abundant than pyrite can account for. There was also a little chloride present, ranging from 0 to 0.02 and occasionally 0.35 weight per cent in single points analysed. Hence most likely both sulphur and chloride represent old seawater. SEM imaging showed that samples of plastic clay were in fact dense, occasionally containing voids <30 μm, which according to experience makes it very inaccessible to root penetration (Fig. 3).
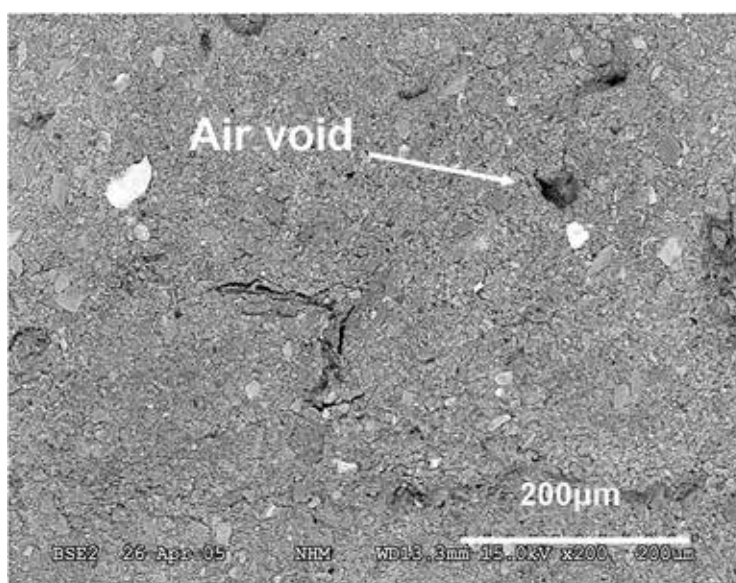

***Figure 3.** ESEM of the plastic clay sample M2. Notice the overall dense micro-structure with occasional non-connecting air voids reaching 30 microns. Photograph: Hans-Jørgen Berg.*
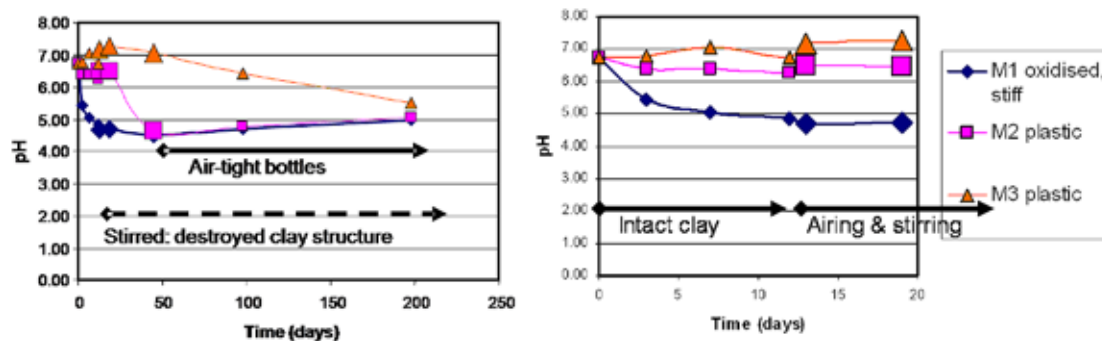
Figure 4. *Evolution of pH in the static leaching experiment under varied imposed conditions. The intact plastic clay levelled off at a circum-neutral pH while airtight, whilst oxidised stiff clay reacted with acidification. Later severe stirring and destruction of clay structure caused variable degree of acidification in the long run. Left: total experiment; right: first 20 days, representing the properties in final cover. Graphics: Per Hagelia.*

The pH reaction of clay in contact with water

Lumps of 100 ml from each clay sample were put into 500 ml plastic bottles and filled with about 400 ml of very low ionic tap water before capping (using an inner and outer lid). In the first part of this static leaching experiment the bottles were capped and airtight, and the clay lumps were kept intact by very careful treatment of the bottles during measurement. Under these conditions the aqueous pH of plastic clay (M2 and M3) levels off at circum-neutral values. In contrast, the oxidised and stiffer clay (M1) developed acidity, reaching pH = 4.7 after 12 days. After the measurements on day 12, all bottles were stirred very well several times and kept open to air for one month. This treatment involved disintegration of clay leaving much material in suspension. The motivation was to expose the clay to oxidised water and establish the ultimate potential effects in case of unwanted destabilisation of the protective layer. It was discovered that, although pH remained fairly constant in each bottle for at least one week after stirring and continuous airing (until day 19), also the initially plastic clays (notably sample M2) had a capacity to develop acidity. This was accompanied with quite heavy deposition of rusty iron compounds in all bottles (first M1, followed by M2, with extensive rust development also in M3 by day 45). Yet, after recapping and settlement of clay particles, pH started to rise gently in M1 and M2, converging with the still dropping M3 at pH about 5–5.5 on day 198 (see Figure 4). This was controlled on day 336 showing: pH (M1) = 5.4; pH (M2) = 5.5 and pH (M3) = 5.6 (not plotted).

Measurements of Eh showed a well-defined negative correlation with pH (cf. Bårdseth 2007: 49).
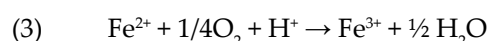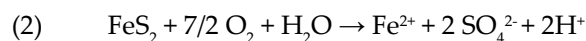
Chemical reactions involved

The leaching experiment indicated a somewhat complex behaviour. Plastic clay (M2 and M3) did not lead to a lower aqueous pH while bottles were sealed and clay lumps were relatively intact. In contrast, the oxidised rusty-brown sample (M1) developed acidity

in contact with water under the same conditions. It was also apparent that oxidation (open bottles), stirring and complete disintegration of the clay lumps were necessary requirements for acidification of water in contact with the plastic clays (M2 and M3). In this context it is important to realise that the pore space in undisturbed Norwegian marine plastic clays are usually close to 100% water saturated. Much of this water is adsorbed to the clay (Rosenqvist 1956) and is variably enriched in ions with internal pH 7–8 (Hilmo 1989). Hence the stirring and disintegration, involving extensive suspension of clay particles, appears to have led to an enhanced interaction between clay minerals/adsorbed water and the bottle water.

There was no evidence for presence of pyrite (FeS_2) in the clay material. Sulphide oxidation according to Reaction 1 cannot be regarded as the reason for acidification in the experiments.

(1) $FeS_2 + 15/4O_2 + 7/2H_2O \rightarrow Fe(OH)_3 + 2\,SO_4^{\,2-} + 4H^+$
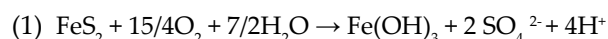
Fe greatly predominated over S in the clays (Table 2) and was most abundant in samples M1 and M2. There was no clear indication of goethite (FeOOH) or other crystalline iron mineral in any of the samples. Therefore the red rust (Fe^{3+}) in M1 most likely was bound to amorphous ferrihydrite ($Fe(OH)_3$). Fe^{2+} also likely occurred initially in all samples, being sorbed to negatively charged clay particles or amorphous iron (oxy) hydroxides, which contain both ferrous and ferric iron. The overall blue-grey colour may suggest that Fe^{2+} was predominating over Fe^{3+} in samples M2 and M3, which is likely in view of the relatively reducing conditions within the undisturbed clay at depth. Reaction 1 above represents a total reaction, which consists of three main steps (Reactions 2, 3 and 4).

(2) $FeS_2 + 7/2\,O_2 + H_2O \rightarrow Fe^{2+} + 2\,SO_4^{\,2-} + 2H^+$

(3) $Fe^{2+} + 1/4O_2 + H^+ \rightarrow Fe^{3+} + \frac{1}{2}\,H_2O$

(4) $Fe^{3+} + \frac{1}{2}\,H_2O \rightarrow Fe(OH)_3 + 3H^+$

It should be noticed that Reactions 3 and 4 might

take place wherever ferrous and ferric iron is available, being independent of sulphide oxidation. Therefore presence of dissolved iron should lead to acidification of waters. It seems very likely that loosely bound Fe^{3+} in sample M1 reacted directly with water to form ferrihydrite and acid according to Reaction 4. Similarly, Reaction 3 and subsequent Reaction 4 produce two moles of acid for each mole of dissolved iron.

This seems corroborated by the rust deposition, which developed along with acidification of the respective waters. Indeed, deposition was very extensive towards the end of the experiment. However, it is also very likely that the manganese oxide birnessite, being present in all clay samples, reacted with available ferrous iron according to the following reaction:

$$(5) \quad 2\,Fe^{2+} + MnO_2 + 2H_2O \rightarrow 2FeOOH + Mn^{2+} + 2H^+$$
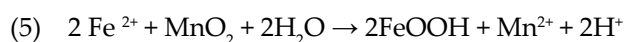
Acid-producing redox reactions of this kind have been reported in many different environments (Appelo and Postma 2005). In view of the predominance of total iron over manganese in the clays it may be argued that Reactions 3 and 4 were more important than Reaction 5. In view of the above discussion it was concluded that the overall effects of these acid-producing reactions will not be very effective in the present plastic marine clay, unless its structure is significantly disintegrated and exposed to air and water.

Interpretation of results and
consequences for handling of clay

The results confirmed previous analyses by suggesting that the Borge plastic marine clay responds with a circum-neutral pH. Bjørlykke (1933) reported pH within the 6.42–6.86 interval from similar clay. However, the present investigations also showed that under more extreme circumstances the pH might be susceptible to developing a somewhat more unwelcome acidic pH, notably if exposed to air and water for a long time after an event of severe disturbance. There was also an apparent risk for acid-producing reactions within plastic clay in a much shorter time, yet it was comparably difficult to rigorously establish the critical time factor for real life situations.

The time was short since the clay pit was about to be covered through the revegetation project. We were therefore faced with two alternatives: *either* to recover a huge amount of clay for later use after at least one year, thus risking oxidation and stiffening of the clay; *or* to place the clay on top of the rock art sites as soon as possible. Thus, based on pure geochemical arguments it was decided to dig out the clay, transport it and cover each petroglyph site on the same day. This was regarded as the least risky handling in view of the experimental results.

Geotechnical properties

Sieving of the three samples showed that the upper oxidised (G1) was silty clay whilst the plastic clays (G2 and G3) were true clays containing >30% grains < 0.002 mm (Bårdseth 2007: 56). This corresponds to permeabilities in the order of 10^{-7} m.sec^{-1}. Densities of pristine plastic clay at Borge were about 1810 kg/m^3, as obtained by a Troxler isotope probe. Measurements after deployment varied from 1820 to 1846 kg/m^3 suggesting transportation had not changed the properties to any significant degree.

Prospects for long-term pH development within the clay

The cover was designed for 100 years of maintenance-free durability. Yet a number of factors may potentially lead to disturbance and shorter lifetime. It was evident that as long as the clay remained undisturbed its plasticity and geochemical properties should be retained. These properties had in fact been preserved within the clay since the end of the Pleistocene about ten thousand years ago. The leaching experiment also suggested that in the worst case pH should be stabilised at about 5.5 ± 0.1. The effect on weathering rate at such pH is not significantly different from pH =7 (cf. Appelo and Postma 2005).

Design and construction
Frost penetration and thickness of layers

One of the desired results from permanent covering was to reduce the number of freeze-thaw cycles and frost bursts within the outer thin weathering rinds with petroglyphs. According to statistics for the local climate in Østfold, frost may penetrate nearly two metres into gravelly ground, or about 0.7 metres into clayey ground. Yet frost penetration of two metres is very rare, and we decided that a cover thickness of one metre should be sufficient. Frost penetration into rock does not extend notably further than it does in looser composites. In order to prevent frost penetration from the sides it was decided to cover the surrounding areas with a minimum of two metres of clay outside the petroglyph-covered areas.

Geotextile

A point of discussion was whether a geotextile should be placed between the rock surface and the clay to help separate the clay from the rock art in the future. Discussions led to the agreement that a geotextile could create air pockets on the rock surface, and that this would be an unfavourable situation as it could attract water as well as roots. However, by placing a geotextile above the clay layer it would contribute to decreasing the risk of the clay drying out. Further, it would function as protection for sudden and large rainfalls and thus prevent erosion of the clay surface. By giving the covers a convex shape, the water should follow the geotextile along the sides of the convex construction.
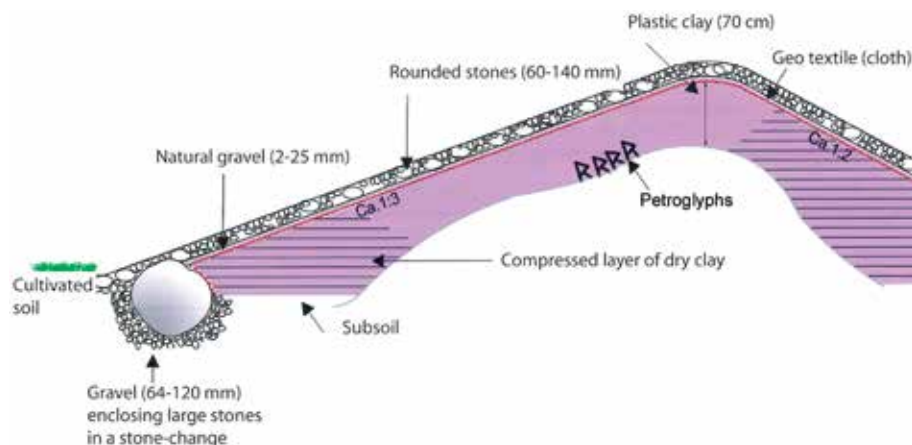
Figure 5. *The principles of the covering. Graphics: Kristin Marie Berg.*

The top layer

It was a requirement that the top layer of the covering construction would entail the least possible annual cost of maintenance. Discussing the possible solutions for a top layer, one alternative was to use a thin layer of fertile soil with turf grass, either maintained by grazing or by annual cutting. An alternative was to create a plant community of heath and dry grassland on sandy, poor soil. The third option was to simulate clearance cairns that were already part of the cultural environment. The cairns would consist of rounded stones on the surface without a vegetation cover. The third alternative was chosen, with the exception of one site where grazing horses made the first option a natural choice.

The interdisciplinary team also discussed the option of adding a middle layer above the geotextile, just beneath the top layer. This should represent an additional protection of the geotextile and the clay, especially considering the unwanted drying-out of the clay layer. A drought would cause a loss of clay plasticity, potentially leading to fissuring and water penetration into the structure. This could alter the chemical and geotechnical quality of the clay further inside. It did not seem possible to avoid influence of such effects within the upper layers of the clay, and it was therefore desirable to avert these changes from extending deeper into the clay. A decision was made to construct a thin mid-layer of natural gravel (2–25 mm fraction). Another possibility was to choose crushed rocks, such as rubble or shingle instead of natural gravel, but the vegetation advisor argued that there would be less corrosion on the natural gravel than on the crushed rocks. It was, however, a requirement that the smallest sand grains were to be sieved out; to make sure this mid layer would not become a healthy cultivation environment for plants. Figure 5 shows a sketch of the construction.

The covering process

Four sites were covered in the autumn of 2005, and one site was covered in the autumn of 2006 (Figs 6, 7, 8, 9 and 10).

At each site the clay distributing operation took an entire day. It was important that the covering of each site could be completed before the end of the week, to prevent that a half finished construction would be exposed to wind and weather during the weekend. A track-driven digger (at one site, two diggers were used) and three to four lorries were used to make the transportation of clay continuous. The agent had a digger situated at the clay supplying site, and was therefore depending on efficient transportation. Most of the time, the work was executed under supervision of an archaeologist, conservator or a landscape architect.

When the clay was first taken out, a geo-technician was present to secure its quality. The archaeologist, conservator and the landscape architect were given instructions on what to look for and how to best secure regularity of the clay quality.

Figure 6. *Adding of marine clay to a rock art site. The depictions at the site consist of several large 'ships', of which one is visible on the photograph, and numerous cupules. Photograph: Ingrid Aune, SA.*

Figure 7. *The marine clay filled all the fissures in the rock, as a result of its plastic character. Photograph: Gro Anita Bårdseth.*

Figure 8. *Dumping of dry clay in front of the marine clay, for the construction of supportive fillings. Photograph: Kristin Marie Berg.*

Observations were done visually and by touching the clay. Especially if the clay changed in colour and consistence, it could indicate lower quality.

When the lorries started to distribute the clay, the work proceeded speedily. The clay turned out to be very plastic, of a grey-blue colouring and with an even texture. It instantly filled all the fissures in the rock completely. We started with what we regarded as the easiest site, a small bedrock outcrop situated in a flat field landscape. We quickly discovered that there was a challenge we had not planned for well enough. The diameter of the site was too large for the shuffle on the digger to reach the centre (where the filling of clay commenced towards the outer rim). The clay was also too soft for the digger to drive over. Further, the clay slowly floated out towards the outer rims when there were no boundaries around the edges. After deliberations with the geo-technician on the spot, a prompt decision was made to change the procedure. It was decided that dry clay was to be used as supportive filling of 15–20-cm-thick layers. The digger would drive over with the tracks and compress the filling. This way a low embankment, 50–70 cm high and of a width approximately that of the tracks on the digger, constructed along the edge of the rock surface. The digger could then drive on to the supportive fillings and reach the centre of the filling with its shuffle. At the same time the supportive filling would also prevent the clay from flowing. The principle of supportive fillings made out of dry clay was used on all the covered sites. After this change of procedure the covering process went smoothly until a 70-cm-thick cover was laid on top of the petroglyphs. When this level was exceeded, the soft clay started to flow over the edges again. This happened despite a slight slanting angle of approximately 1:3. It seemed this was the limitation of what the filled-in masses could bear without expanding the supportive filling surrounding the site.

From what was visible on the site, it seemed as if

Figure 9. *The geotextile (black fibre cloth) covers the layer of marine clay, and the dumping of natural gravel is under progress. Photograph: Gro Anita Bårdseth.*

the clay was somewhat self compressing, being very plastic. The clay instantly flowed into every fissure and hollow, filling them. Further compression was, however, not possible as the clay was too soft. The shuffle on the digger was used to level the clay surface as much as possible. The experience from this project showed that slopes with an angle steeper than 1:3 should not be included. If supportive fillings made of dry clay are used where there are larger differences in height, these can be built with an angle of 1:2 stretching over a 5-metre area.

The construction of a stone chain

The principal plan showed that at some sites there ought to be placed large stones surrounding the clay filling as an additional assurance against agricultural machines. The intention was that these stones should simultaneously act as additional support for the clay in the sloping areas to prevent the clay from flowing. The plan showed that the clay layer should reach to the top of the surrounding stones and that

Figure 10. A covered rock art site. The highway is still under construction, but after completion it passes directly in front of the covered site. Photograph: Gro Anita Bårdseth.

the geotextile should be pulled somewhat further, beneath the stones. In practice, the digger had to drive across this area when placing the clay, making it impossible to lay down the stones before the clay was in its place. Thus, the stones would not be able to function as a support. It was not easy to pull the geotextile beneath the stones, which was cut along the stone chain.

Measurements at the site

It was impossible to walk onto the site after the soft clay filling had been laid. To measure the thickness of the clay layer, the shuffle on the digger containing a person with measuring equipment was used. To investigate the density of the clay compared to the very compressed, low-porous state at the original site, troxler-measurements were carried out on top of the mounds. To get there, pieces of plywood were laid out and moved for each step. A number of measurements were taken from the first two sites to be covered, to extract information on the degree of compression. The density of the clay was the same compared to the measurements obtained before the clay was extracted. Thus, we felt confident that the clay was very dense and would prevent air, water and roots from penetrating.

Reference site and future monitoring

In connection to one of the covered sites an additional area of rock surface without petroglyphs was covered in order to function as a reference site. This area was photo-documented according to surface texture and colour. In addition a freshly cut reference stone of granite was attached to the rock surface. A similar slice is kept indoors at the Museum of Cultural History in Oslo. The reference site and the stone can be used in future investigations to evaluate the effects of the cover.

The covers are planned to be monitored for a nine-year period, until 2014, when a final report will be written and the development of pH levels within the clay, technical stability, maintenance routines and vegetation development are to be evaluated. Sampling will take place to monitor the pH levels and any possible drying of the clay. All sampling is planned to take place at the reference site, in the area without petroglyphs. Until then, all the covers should be inspected annually in relation to stability and vegetation. The County council of Østfold is responsible for carrying out one week of annual maintenance, which includes removing weeds that establish on the surface layer.

Concluding remarks

The interdisciplinary team constituted a true place for discussions, and different aims and demands within the disciplines were thoroughly highlighted and the group formed an effective body for decision-making. The covering of the rock art sites presented in this article could not have been conducted without this broad approach, whose aim was to combine the different essential scientific demands.

This is the first time petroglyph sites have been covered in this manner in Norway. We hope the numerous deliberations and assessments made during this process might be relevant for future discussion and protection.

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