Marine bio-erosion cavities in metamorphic limestone, weathering rates, and the post glacial land rise in Salten, North Norway.

by
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ABSTRACT

Marine mollusk activity initiate erosion cavities in marble and dolomite in the Saltsraumen littoral zone. Such cavities are gradually exposed above sea water by the still on-going eustatic rebound since the last Ice age. The diameter of cavities observed above the high tide zone plotted against altitude show a steady increase in size over time due to weathering processes. Weathering rates as a function of land rise are calculated and discussed. The observed growth rates are correlated with chronology of sea level changes in the same period based on alternative data.

INTRODUCTION

A large number of cavities of different sizes have been found within the metasedimentary calcite area of Saltstraumen (Solli 1990). The formation of these cavities is similar to bio-erosion features described from coastal areas of the Mediterranean and Caribbean Oceans (Moe & Johannessen 1980; Kázmér & Taboroši 2012). Bio-erosion initials will expand over time when exposed to weathering in the air as the sea recedes and land rises following the eustatic rebound after the deglaciation in postglacial times (Lambeck et al 1998).

The study of erosion and weathering of rocks, particularly limestone and marble, has been subject to many detailed studies (Colman 1981). In erosion and weathering processes chemical, mechanical, climatic and biotic factors interplay in complex ways, the interpretation of which has caused debate (see Chen et al. 2000, Emmanuel & Levenson et al. 2014). Surface weathering processes in limestone areas are depending on agents like wind, temperature/temperature changes, rain/humidity, frost, and different kinds of radiation (e.g., UV radiation) etc.

Knowledge of weathering rates for different kinds of rocks are important in the maintenance of heritage sites (Meierding 2013, Waragai 2017) and modern construction technology (Grelk et al 2007). Weathering rates have in several studies been shown to not follow a linear function of time. The relation seems more adequately to be described by functions on the form $y = a + b^x$ (Colman 1981).

GEOGRAPHY OF THE SALTEN AREA

The maelstrom Saltstraumen is the only navigable inlet between the Salten and Skjerstad fjords which are separated by a barrier of islands and peninsulas. The bedrock consists of metasediments of assumed Cambro-Silurian age (mainly limestones): calcite marble with layers of gray, banded dolomite and cm-thick layers of calc-silicates and feldspar. In addition to the carbonate rocks, hard and erosion resistant granite and granodiorites occur (Solli 1990, Ramberg et al. 2006). Strong tidal currents pass in and out twice a day through the Saltsraumen inlet. The area is since 2013 defined as a marine nature reserve (Fagerli et al. 2015).

The present-day climate is oceanic, with relatively mild winters and cool summers (Table 1). January and February mean temperatures are just below 0°C, and the July and August mean temperatures are between 12.5 and 13.5 °C (Aune 1993, Met Norway 2021). Precipitation amounts to around 1020 to 1117 mm a year (Førland 1993, MET Norway 2021).

The late glacial history of the Salten area is well documented. The major and final deglaciation of the area is discussed by Andersen (1975 and event B in Andersen et al. 1981). Recent isotope studies indicate rapid deglaciation of the outer islands at about 14.300 ± 400 yrBP (Linge et al. 2007). The major retreat of the ice is dated at around 10.700 BP in the outer coastal area, and most of the studied area was ice-free at 10.500 BP (Andersen et al. 1981). Ice free areas have existed in the eastern parts of Salten at this time (Høeg 1972; Moe 2003), and the Fennoscandian ice sheet was fragmented into valley glaciers about 10.200 BP (Linge at al. 2007).

Well dated sea level changes are documented for several localities north of the Trøndelag area, Central Norway, (Hafsten 1979, Linge et al 2007). Marine deposits are observed within the Salten area up to 105 m (marine limit; Andersen 1975, plate 4; http://geo.ngu.no/kart/losmasse/), and no Holocene transgression is known. The complete Holocene sea level changes in the Nordland County, North Norway, are also partly known (Marthinussen 1962, Møller 1989, Andersen 1975, Vorren & Moe 1986). A sea level curve for the Saltstraumen area constructed according to Møller & Holmeslett (2012), shows a steady and nearly linear decrease of 0.5 m per century through the last 8 .000 years (Fig. 1). The slope of this line will be compared to the distribution of bioerosion cavities observed.

MATERIAL AND METHODS

Erosion cavities are seen several places along Saltstraumen and Godøystraumen. These are initiated by the feeding activities of the commonly occurring mollusks like Steromphala spp. (fig. 2), Littorina spp, Patella spp. and others (Moe & Johannessen 1980).

Three sites, Ripnes (1), Godøy (2) and Ørnneset (3) were selected as study sites (fig. 3). At each locality samples for measurement were taken at random among only intact and undisturbed bioerosion cavities in calcite or dolomite. Sites with uniform bedrock quality both within and between sites was chosen. A transect line was laid out, and freely exposed cavities within 15 cm on either side of the line were measured at intervals along transects in June and July 1981 (DM). Sites with cavities on steep slopes were preferred. The larger diameter for each cavity was recorded and plotted against the vertical distance above the present-day high tide mark for the three localities.

Ripnes, loc. 1 (Knapplund Island, at Saltstraumen, 67°13′41.07″ N lat. 14°37′25.55″ E lon.). The transect was laid out on the gently sloping rocks in the littoral zone and up to 1 m above the high tide mark, exposition SW – SSW, slope 10 – 25° (fig. 4). Cavities were selected at random at 10 intervals along the transect. The area was frequently used by people. Several boathouses (“nausts”) are found close by, and the measurements, therefore, were only taken up to 1.0 m altitude. Above this level several larger cavities were seen, but not measured.

Godøy, loc. 2 (Godøynes at Godøynes, 67°14′33.83 N lat. 14°42′40.71 E lon.). A steep slope facing SW – SSW at 20 – 35° up to a little more than 3.4 meters above high tide was selected for the study, and diameters were measured for randomly selected cavities at 14 intervals along a transect from 0.2 to 3.4 m altitude (fig. 5). This site was little disturbed by man, and the transect line crossed parts with more level ground. Such parts may have been covered by algae or bryophyte vegetation, and organic matter may in periods have accumulated, and were therefore not sampled.

Loc. 3 Ørnneset (Straumøy Island, 67°13′28.77 N lat. 14°36′36.57″ E lon.). This site is situated at the Ørnneset headland on Straumøy close to the northern head of the Sunnan Bridge. The situation here differs from the two others, as the cavities are found on steep cliffs facing south around 30 meters above the present-day sea level. The samples were taken at only two levels, 29.2 and 30.1 masl, since exposed marble cliffs with cavities are not found down to the sea.

At Ripnes and Godøy cavities were distributed more or less continuously upwards from the littoral zone. Samples were taken at altitudes measured as the vertical distance from the brown algal belt, taking the uppermost level of the littoral zone dominated by benthic brown macroalgae as the starting point for the transects. Along the Atlantic coast of Norway *Pelvetia caniculata* and *Fucus spiralis* populate the upper part of this zone along rocky shores (Norwegian Seaweeds 2020, Gitmark 2014, Nervold 2008, Walday et al. 2004). The upper level for *Fucus spiralis* corresponds with the mean highwater neap (MHWN) (Zaneveld 1937) while *Pelvetia caniculata* extends higher up towards the mean high water (MHW) level (White 2008, Rueness 1998). At Saltstaumen MHWN is currently observed at 1.36 m and MHW at 1.50 m above Chart zero (Kartverket.no, 15 December 2020).

At Loc. 3 Ørnneset altitude data was taken from the economic map series, where the zero altitude is currently defined at Mean Sea Level ($MSL_{1996-2014}$) corresponding to 1.01 m above Chart Zero (Kartverket 2009). At this locality cavities were only found at about 30 masl.

Cavities were measured with a 0.1 mm accuracy with the help of a caliper and a hand lens at Ripnes and Godøy. Due to difficult access at Ørnneset a ruler was used for measurement, and fewer observations could be recorded.

RESULTS

Loc. 1 Ripnes. At the lower end of the transect, cavity sizes varied from 1.8 to 10.8 mm diameter, except for five exceptionally small pits at 22 cm measuring from less than 1 mm. These samples were excluded from the statistical analysis as outliers. At the upper end of the transect, cavity size varied between 9.8 and 13.5 mm. The largest cavity measured 15.0 mm (at 0.73 m). Diameter and radius for N=150 cavities were recorded. Details are presented in fig. 6.

Loc. 2 Godøy. At the lower end of the transect (0.23 m), cavity sizes varied from 4.2 to 8.5 mm diameter. At the upper end of the transect, cavity diameters varied between 19.3 and 27.9 mm (radii 9.65 and 14.95 mm). The largest cavity measured 29.2 mm (r=14.6 mm, at 2.7 m asl). Diameter and radius for N=215 cavities were recorded. Details are presented in fig. 7.

Loc. 3 Ørnneset. The sizes of the cavity diameters varied from 61 mm (r=30.05 mm) at 29.2 m to 100 mm (r=50 mm) at 31.2 meters above the present-day sea level. Diameter and radius for N=19 cavities were recorded. The results are presented in figure 8.

STATISTICAL ANALYSIS

As a first assumption, one might expect a linear trend in erosion with time due to weathering on dry land. Given the land rise curve established for the Salten region (Fig. 1), one may furthermore expect a linear relation between land rise and cavity size.

Weathering rates were estimated as a function of altitude by linear regression for each site. Based on the land rise curve for the area approximate erosion rates with time was inferred (mm/ka along the radius; table 2). The regression coefficients of cavity size on altitude at the three localities seem to differ between sites (fig. 8). To answer whether these differences are significant, the statistical package Stata was employed (Bruin 2006). An initial test demonstrated severe deviations from normality in the data, and the variances estimates proved too different (heteroskedastic) to give a reliable test. Log-transforming the cavity data levelled out some of the difference in variance between sites, and pairwise tests for difference between the regression coefficient proved significant. Still high kurtosis values in the Ripnes data was evident, reflecting the high spread in cavity size at the high tide level where mollusks are still active. Five extremely small values (in the range from 0 to 1 mm diameter) were considered outliers and excluded from further analysis. The Stata Heteroskedastic linear regression routine still yielded highly significant tests for the three regression coefficients being different (not shown).

The decreasing regression coefficients with increasing altitude indicates that the weathering rate has slowed down over the centuries, and that the relation of the change in cavity size over time is not linear. A non-linear approximation by the nl routine in

Stata gave a close fit with cavity size as a function of altitude of the form $y = ax^b$ (fig. 9).

Assuming a constant rate of land rise since 8000 BP of 0.5 cm/yr, the relation between cavity size and altitude above sea level may be translated to time scale (Fig. 9). A power function fitted to the data yields an estimated curve given by the expression $Y = ax^b = 0.8557962\ x^{0.5095578}$ ($R^2 = 0.97942$; 95 % confidence interval estimates: $0.7909823 > a > 0.9206101$ and $0.4996494 > b > 0.5194663$).

DISCUSSION AND CONCLUSIONS

In warmer climates it is well known that in a littoral environment, the biological activity of mollusks and other organisms act to erode limestone and form pits and cavities (Kázmér & Taboroši 2012). The phenomenon is also observed in more temperate regions (Andrews & Williams 2000). In Sub-Arctic waters the phenomenon was reported by Moe & Johannessen (1980). They also observed that the postglacial eustatic land rise had resulted in bio-erosion cavities being found high above the present-day sea level (cp. Dons 1996: 121).

The sea level change curve constructed for the Saltstraumen area (Kjemperud 1981:173, Møller & Holmeslett 2012) shows a steady linear relative land rise of 5 mm/yr through the last 8,000 years (fig. 1). Before this, viz. above ca. 40 masl, a more rapid change occurred (Møller 1987, Møller & Holmeslett 2012).

In the present study the size of mollusk-initiated erosion cavities was not found to follow a linear increase with altitude but seemed to fit more closely to a horizontal half parabolic curve (fig. 9). This corresponds closely to the relation between rock weathering and time observed for several situations, and on different scales Colman (1981). The retardation of the weathering rates is interpreted as effected by the accumulation of residuals from the degradative process itself (surface residuals, weathering rinds, corrosive crusts etc.).

Lichenometry might be considered an alternative method (Armstrong 1983, 2016). The method has been used with success with crustaceous lichens growing on acid rocks in arctic and alpine habitats, while on calcareous rocks and in lowland and forested situations, the method is less well suited (Osborn 1975, Benedict 2009). Erosion cavities developed by littoral mollusks may offer an alternative or supplementary dating technique in areas with limestone and calcite rocks (Moe & Johannessen 1980). The technique has the advantage of being rather inexpensive but may however, suffer from lack of precision if not supported by sufficient data. A strict calibration with other dating methods is needed to give an effective tool, and avoid the ambiguity facing lichenometry (McCarthy 2013, Osborn et al. 2015, O'Neal 2016, Osborn et al. 2016).

In and just above the littoral zone the spread in cavity sizes results from the variations in the size of mollusk inhabitants. Cavities produced by *Steromphala* and *Littorina* species are smaller than the ones made by species of *Patella* (Andrews & Williams 2000, Jessica's Nature Blog). Such differences in the initiating stages are generally reflecting the foraging activity and cavity-building of these species, ingesting rock fragments scraped off the surface (Andrews & Williams 2000, Vidal et al. 2013).

Further studies are needed to settle a precise starting point of the size scale. The cavities initially formed by the biological activity of mollusks within the littoral zone necessarily have a dimension larger than 0, and also differ in size according to the species that scrape out the burrows. Some of the species in question also dwell for a part of their life above the high tide level. As a result, it is not settled critically at what point the cavities came out of reach of the mollusks and continuously exposed to weathering processes alone.

Above the marine mollusk activity level in the littoral zone, weathering of carbonate rocks involves chemical dissolution of carbonate, and mechanical erosion on a micro scale. Quantifying the rates of the different processes are challenging, due to the high degree of variability encountered under field conditions in rock quality, microclimate and effect of terrestrial biotic agents. Emmanuel & Levenson (2014) found indications that microscopic grain detachment may be the dominant mode of erosion in fine-grained carbonate rocks in many regions on Earth. Weathering rates due to this process were estimated to be twice the magnitude of chemical dissolution.

The size and time scale must be critically calibrated to take into account the variation in rock quality and the many chemical, climatic and biotic factors that may influence the weathering process. The impact of climate changes over the long timespan involved may have influenced weathering rates significantly (Grelk et al. 2007, Emmanuel & Levenson 2014). In Northern Scandinavia a major climatic warming occurred around 7.000 years ago, that probably had a speeding effect on the rate of chemical weathering.

The general cooling that has occurred the subsequent millennia may have had a significant retarding effect on the weathering rate (Nesje et al. 2005, Eldrevik et al. 2014).

Another important factor is the variations in the calcite rocks of the Saltstraumen area. The variation spans from calc-silicates, via laminated dolomite to a purer calcite marble (Solli 1990). Obvious effects of surface weathering in rocks of different quality are observed in the area, where bands of more resistant calc-silicate layers are protruding as ridges above the more easily weathered dolomite and marble (Fig. 5).

The heterogenic structure in even the purest marble, must lead to variations in the dissolution of carbonates and loss of microscopic grains. A slowing down of the erosion over time is thus expected as the more easily dissolved minerals and grains are lost, and the harder and less solvable fractions remain.

A vegetation cover of lichen and bryophyte species has been shown to affect the weathering of calcareous rocks. The growth of at least some lichen species tend to accelerate the dissolution of carbonates (Chen et al. 2000). On the other hand, in a climate with winter frost, lichens seem to have the opposite effect, reducing the mass loss by up to 50 % compared to a bare rock surface (McIlroy de la Rosa et al. 2014).

Increasing cavity diameters on dry land are related to bedrock quality, and to the local climatic conditions governed by rock surface slope and exposition. In cavities on level surfaces being periodically filled with rainwater, other chemical processes may also take part. Some cavities are seen to form larger hollows due to the fusion of two or more initial cavities caused by weathering processes. To assess the effects of all these factors is not possible on the available data. Still, as a working hypothesis we claim that the increasing cavity sizes may be explained largely by the time available for weathering. On this assumption, the half parabola curve fitted to the observational data is believed to give a realistic description of the relation between cavity size and time available for weathering.

The spread of cavity size at each level may be ascribed to differences in rock quality in addition to the initial variation due to the unequal sizes of foraging mollusks. This would explain the larger size range observed at the highest level, where about 6000 years have lapsed since the cavities were initiated in the littoral zone of that time (cp. Møller & Holmeslett 2012).

To firmly establish the curve describing rock erosion with time and make it suitable for dating sites in the Salten area, more data need to be collected. Observations filling in the interval between 3 and 25 masl would yield critical additions.

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FIGURES

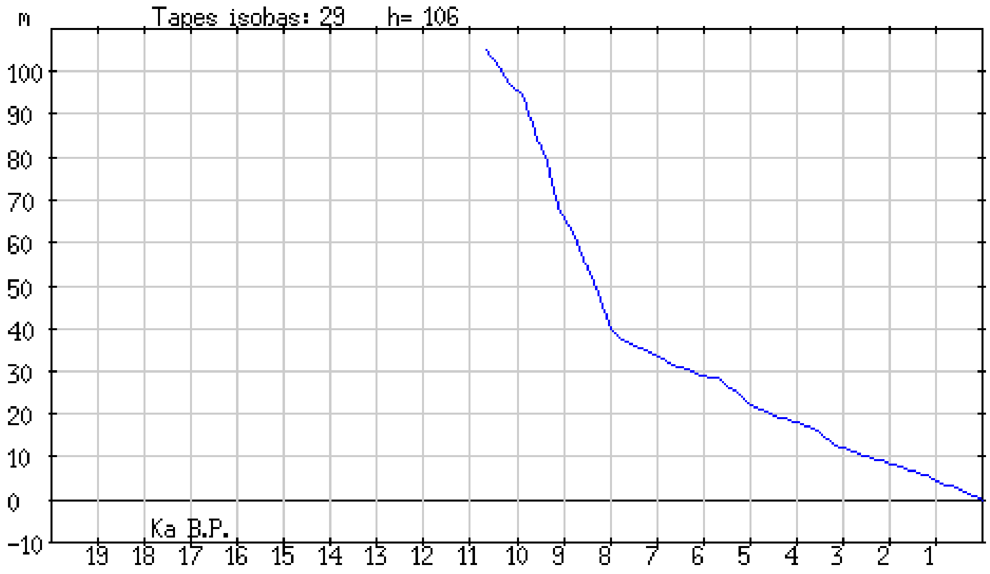

Fig. 1. Estimated curve for the Holocene land rise in the Saltstraumen area (Møller & Holmeslett 2012).

Fig. 2. Cavity inhabited by a group of *Steromphala* (*Gibbula) cineraria* in the intertidal (eulittoral) zone at Ripnes, Saltstraumen. The size of the actual cavity is about 8×4 mm. Microalgae show as an olive-green colour on the rock surface, the exposed whitish rock erosion surfaces inside the cavity results from the activity of the mollusks (Moe & Johannessen 1980, Kronberg 1988 (Photo: DM).

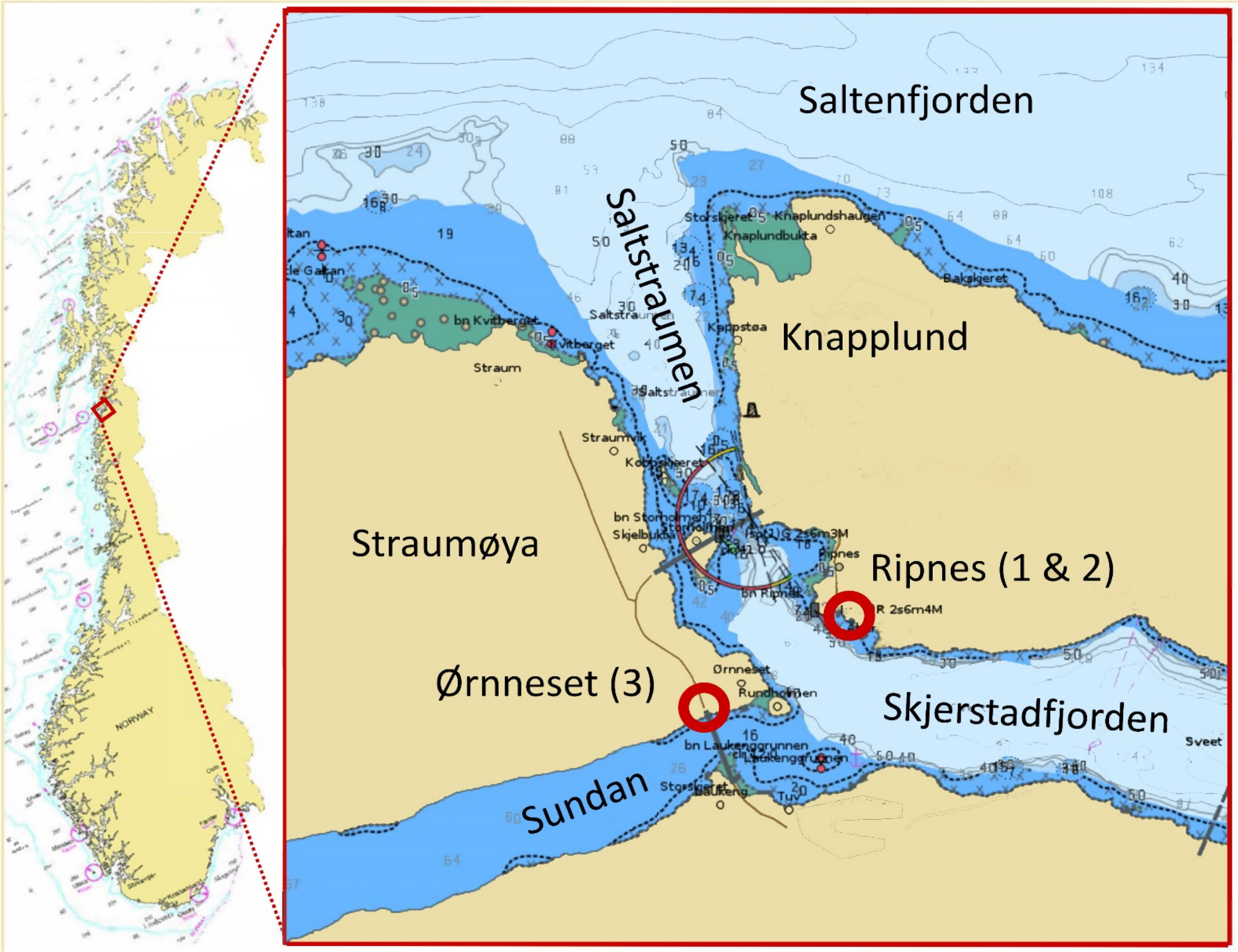

Fig. 3. Saltenfjorden and the saltwater basin Skjerstadfjorden are connected by the main maelstrom Saltstraumen and the shallower inlets Godøystraumen and Sundan. Calcite and dolomite rock cavities were studied at Ripnes (loc. 1) and Ørnneset (loc. 3) on either side of Saltstraumen, and at Godøy (loc. 2) on Godøynes (indicated, base map: Kartverket.no).

Fig. 4 Fieldwork at Saltstraumen (loc. 1 Ripnes; see fig. 2). DM and Kirsten Moe at work in the littoral zone 27 June 1981.

Fig. 5. Cavities on a rocks face from about 0.5 to 2 m above the high tide mark at Godøystraumen, loc. 2 Godøy. The black *Hydropunctaria (Verrucaria*) *maura* dominate in the lower part of the supralittoral zone while conspicuous yellow patches of *Xanthoria* cf. *parietina* characterizes at the higher level. Weathering leads to fusion of expanding cavities in the marble and dolomite layers while the harder calc-silicates protrude as narrow ridges (Photo DM).

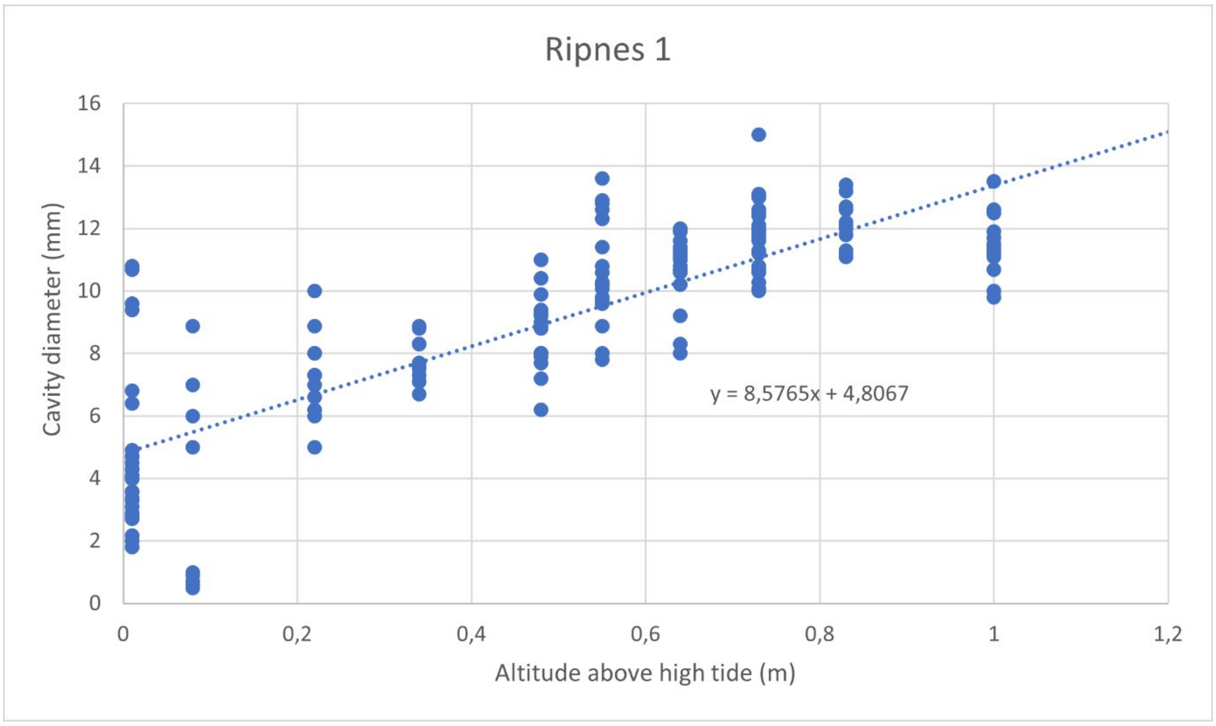

Fig. 6. Diameter of cavities and vertical distance in the supralittoral zone above the *Fucus spiralis* – *Pelvetia caniculata* belt (high tide level) at Saltstraumen, locality Ripnes 1. Linear regression indicated (Excel).

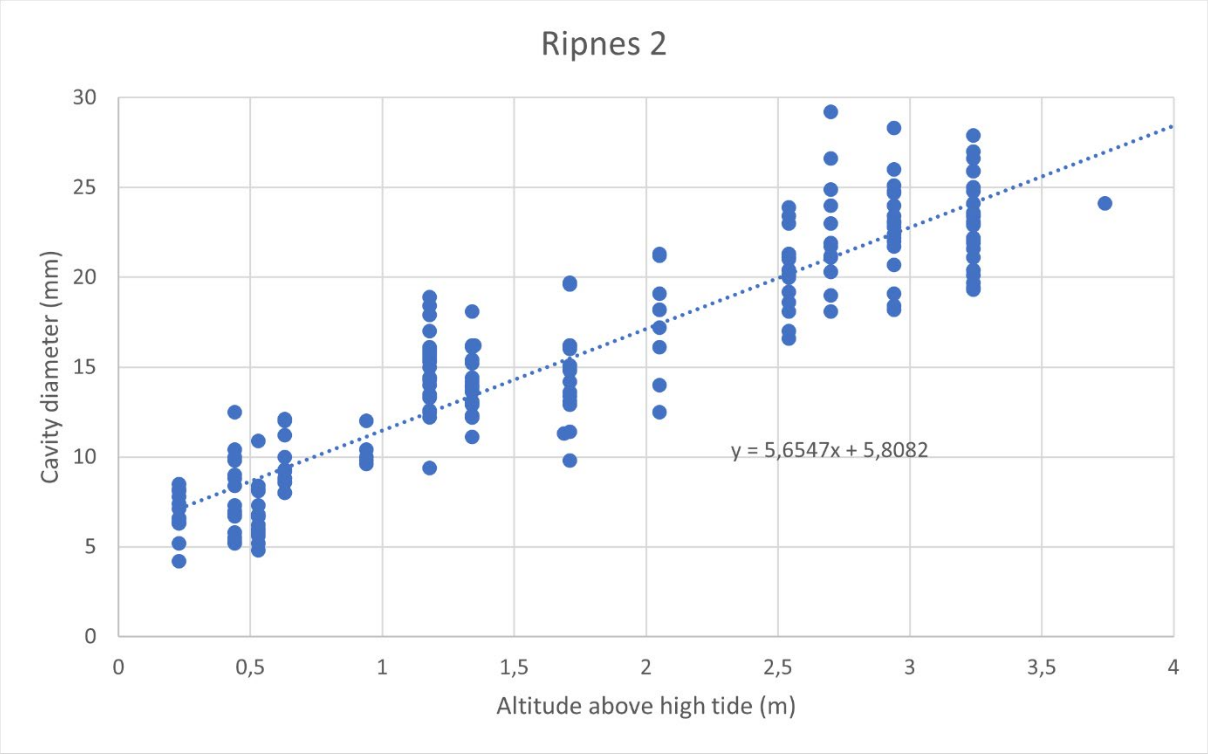

Fig. 7. Diameter of cavities and vertical distance above the high tide level at Godøystraumen, loc. 2 Godøy. Linear regression indicated (Excel).

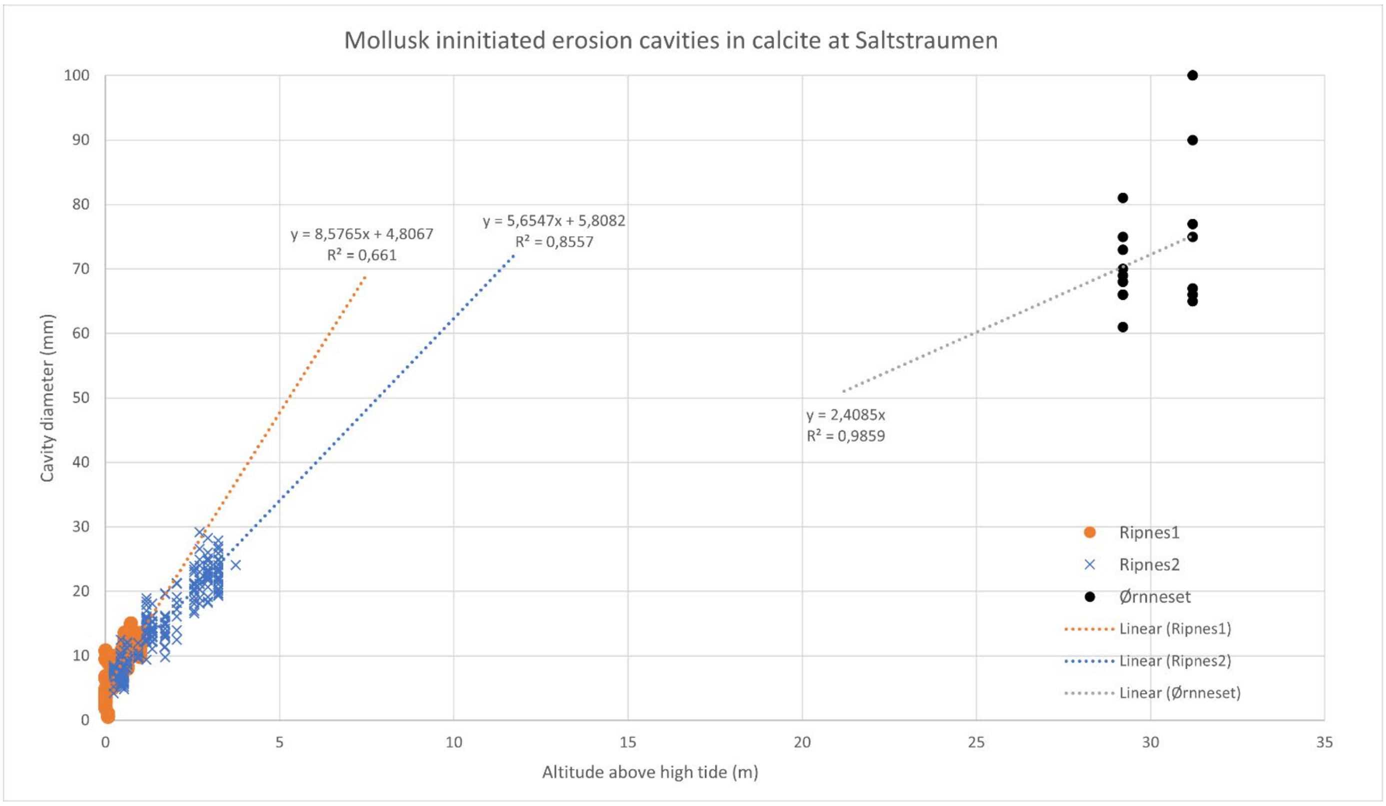

Fig. 8. Summary of linear regression of cavity size on altitude above present day high tide level for the three localities Ripnes, Godøy and Ørnneset. Regression lines for the three sites indicated (Excel).

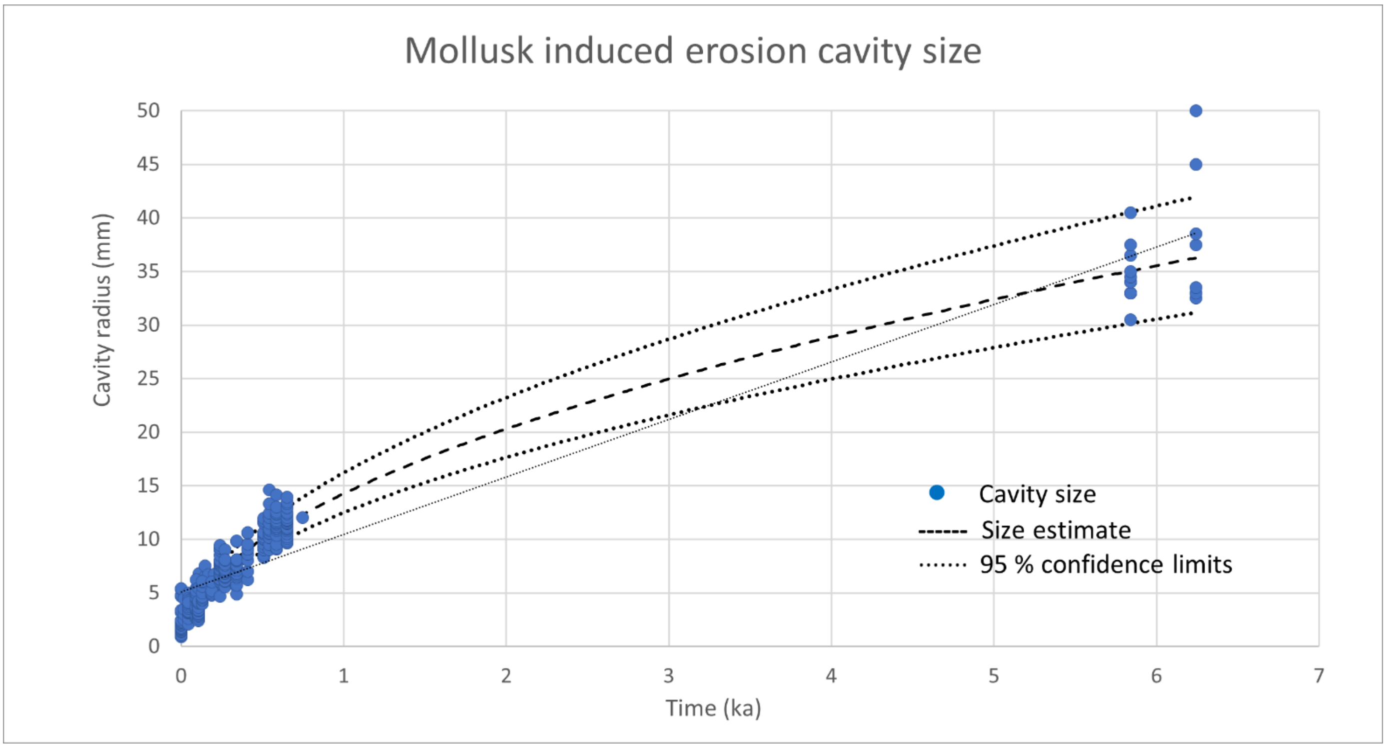

Fig. 9. Cavity size and time. Time scale is estimated on the assumption of a 0.5 cm/yr constant land rise since 8000 BP. Estimated curve and 95 % confidence intervals shown (Stata NL routine estimates; Excel graph).

Table 1. Temperature and precipitation normals recorded at the weather station Bodø VI, the closest available for Saltstraumen.

Temperature normals (°C) SN82290 Bodø VI, 11 masl.

	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Aug	Sept	Okt	Nov	Des	Ann
1961-1990	-2.2	-2.0	-0.6	2.5	7.2	10.4	12.5	12.3	9.0	5.3	1.2	-1.2	4.3
1991-2020	-0,5	-1,0	0,2	3,4	7,4	10,8	13,6	13,2	10,1	5,6	2,6	0,8	5,5

Precipitation normals (mm) SN82290 Bodø VI, 11 masl.

	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Aug	Sept	Okt	Nov	Des	Annual
1961-1990	86	64	68	52	46	54	92	88	123	147	100	100	1020
1991-2020	104	79	81	71	65	65	66	85	129	138	116	119	1117

Temperature normals 1961-1990 from Aune (1993), precipitation normals for 1961-1990 from Førland (1993). Mean tempertures and precipitation sums for 1991-2020 (‘normals’) calculated from data supplied by MET Norway 2021.

Table 2. Weathering rate estimates. Cavity size increase by altitude (mm/m) and time (mm/ka) estimated by linear regression and the power function $y = \alpha \mathbf{x}^{\beta}$.

locality	**altitude** (m)	**age** (ka)	**diam.** (mm/m)	**radius** (mm/m)	**linear** (mm/ka)	**power** (mm/ka)
1 Ripnes	1	0.5	85.8	42.9	21.5	20.7
2 Godøy	4	2	56.6	28.3	14.2	10.7
3 Ørnneset	30	6	24.1	12.0	6.0	7.5
Over all			21.5	10.8	5.4	6.1

Linear estimates for weathering rates: regression coefficient β calculated for $y = \alpha + \beta\mathbf{x}$

Power function estimates for weathering rates: the derivative of the parabola $y = \alpha\mathbf{x}^{\beta}$: $y' = \alpha\beta\, \mathbf{x}^{\beta-1}$