Bioerosional and bioconstructional textures in the lagoon of Sur (Oman) and their relevance for sea level research

Master’s thesis
at the Steinmann-Institute of Geology, Mineralogy and Paleontology of the Rheinische Friedrich-Wilhelms-University of Bonn

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Bonn, 15. November 2017
So eine Arbeit wird eigentlich nie fertig, man muss sie für fertig erklären, wenn man nach Zeit und Umständen das Mögliche getan hat.

(Johann Wolfgang von Goethe 1749-1832)
ABSTRACT

Being able to reconstruct the paleo sea level is a valuable tool to make assumptions about the future sea level. This can be done with so called sea level indicators such as coastal notches, beachrocks, marine terraces, archeological remains of human settlements or biological indicators. The latter are called FBI’s (Fixed Biological Indicators) and can generally be divided into bioerosional and bioconstructional organisms. They include e.g. bivalves (*Lithophaga*, oysters), gastropods, barnacles and serpulid worms, which have been successfully used as sea level indicators in various locations around the world (Japan, Australia, Jamaica, Thailand, Colombia, Turkey, Greece, Syria and Malaysia). However, the distribution of biological indicators and their potential use for the reconstruction of the paleo sea level have not been investigated in the Sultanate of Oman before.

In this thesis, the location of coastal notches from the Eemian period as well as recent coastal notches with biological indicators around the lagoon of Sur, Oman, are noted. Furthermore, the vertical distribution of the comprising bioerosional and bioconstructional organisms is described. The research shows that from the investigated FBI’s oysters, *Lithophaga* and sponges can be used to identify certain tidal zones in the study area. Moreover, the presence of impossible distributions, such as oysters in the supratidal zone, where they cannot survive, or the appearance of certain organisms located on top of each other reveal regression/transgression phases in a decimeter to meter range since the Eemian period. As the area around Sur lagoon is tectonically stable, the sea level changes are attributed to eustatic and not isostatic changes.

As this was the first research of its kind in the Sultanate of Oman, continuing work and more data is necessary to provide further evidence for the conclusions described herein.
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<tr>
<td>BMSL</td>
<td>Biological Mean Sea Level</td>
</tr>
<tr>
<td>DGPS</td>
<td>Differential Global Positioning System</td>
</tr>
<tr>
<td>FBI</td>
<td>Fixed Biological Indicators</td>
</tr>
<tr>
<td>GLOSS</td>
<td>Global Sea Level Observing System</td>
</tr>
<tr>
<td>HLDM</td>
<td>Handheld Laser Distance Meter</td>
</tr>
<tr>
<td>IGCP</td>
<td>International Geoscience Program</td>
</tr>
<tr>
<td>ITCZ</td>
<td>Intertropical Convergence Zone</td>
</tr>
<tr>
<td>IUGS</td>
<td>International Union of Geological Science</td>
</tr>
<tr>
<td>LECZ</td>
<td>Low Elevation Coastal Zone</td>
</tr>
<tr>
<td>MIS</td>
<td>Marine Isotopic Stage</td>
</tr>
<tr>
<td>MSL</td>
<td>Mean Sea Level</td>
</tr>
<tr>
<td>OSL</td>
<td>Optically Stimulated Luminescence</td>
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Coastal areas are a dynamic and fast changing environment. Furthermore, they are and have been an attractive place for human settlements since historical times. The reason for people to settle near the coast have not changed much in the past millennia: the coast provides access to water and thus transportation as well as fertile soil. The process of urbanization led to the formation of large cities from former small settlements. Therefore, the Low Elevation Coastal Zone (LECZ), which is defined as the coastal area that is less than 10 m above the Mean Sea Level (MSL) and covers only 2 percent of the world’s land area, is home to 10 percent of the global population and 13 percent of the world’s urban population (McGranahan et al., 2007).

Recent extreme events, like Hurricane Katrina in 2005, the Indian Ocean Tsunami in 2004 or the Tohoku-Oki Tsunami in 2011 have once more shown the vulnerability of coastal areas. Hurricane Katrina for instance caused the death of 1836 people and cost 108 Billion US$ (Zimmermann, 2015). Hallegatte et al. (2013) point out that the average global flood losses for major coastal cities are estimated to increase from 6 billion US$ per year in 2005 to 52 billion US$ in 2050. This increase in cost is due to an increase in flood exposure, which again is caused by the growing population in those cities as well as climate change and subsidence that lead to a rise of the relative sea level. A worst-case scenario with a global temperature increase of 4 °C would likely cause a sea level rise of 0,5 to 1 m (Schellnhuber et al., 2012).

Sir Charles Lyell accurately stated that ‘the past is the key to the present’ (Spalding, 2002). Therefore, to be able to understand the consequences of a sea level rise in the present and future, it is necessary to study the past and learn from it. For this cause, the Last Interglacial (Eemian Period) is often used as a reference for today’s sea level rise as during that period the sea level was about 4 to 6 m higher than it is nowadays (Gavin Schmidt, 2007).

For the recreation of past sea levels, it is necessary to have so called sea level indicators. According to Evelpidou and Pirazzoli (2015), these include erosional geomorphological indicators (e.g. coastal notches), depositional indicators (e.g. beachrocks, marine terraces or speleothems), sedimentological indicators (e.g. samples from coastal marshes or wetlands), archeological indicators (remains of human presence along the coastline) and biological indicators. This thesis focuses on the last indicator.

In the literature, biological indicators are often referred to as Fixed Biological Indicators (FBI’s), as they are organisms that are fixed to a hard substrate (Laborel and Laborel-Deguen, 2005). They are either bioerosional organisms that damage the rock surface or bioconstructional organisms that produce sedimentary structures. Their living range is
4. Introduction

located at or near sea level, which makes them a valuable sea level indicator. Their use was first initiated about 55 years ago (Donner, 1959, Van Andel and Laborel, 1964) and since then, FBI’ s have, for example, successfully been used for the study of past coseismic events (e.g. Laborel and Laborel-Deguen (1994), Shishikura et al. (2007)). Organisms that are typically used as FBI’s include gastropods, sponges, barnacles, bivalves (e.g. boring mussels, oysters), worms, coralline algae and corals (Rovere et al., 2015, Kázmér and Taboroši, 2012a).

FBI’ s can be studied very well in coastal notches, where multiple organisms appear with an individual living range and thus create several zonations. These features have been studied well in the past at both recent- and paleo coastal notches all over the world (e.g. Malaysia (Kázmér et al., 2015), Thailand (Kázmér and Taboroši, 2012a, Kázmér, in prep.), Greece (Laborel and Laborel-Deguen, 1996, Laborel and Laborel-Deguen, 1994, Evelpidou and Pirazzoli, 2016), Australia (Baker et al., 2001), Jamaica (Perry, 1998), Colombia (López-Victoria and Zea, 2005) or Turkey and Syria (Laborel and Laborel-Deguen, 1994). However, they have not been investigated in the Sultanate of Oman before. Therefore, this thesis has the aim to research the distribution of bioerosional and bioconstructional organisms in coastal notches in Oman and evaluate their use as a sea level indicator. The study area in question is thereby located around a lagoon at the coast in the northwestern part of Oman, in the city of Sur.

For this goal, following working hypotheses were formulated:

1) bioerosional and bioconstructional features in coastal notches can be used as a sea level indicator in the area of Sur lagoon.

2) the bioerosional and bioconstructional features found in the same notch were all produced during a single regression/transgression phase.

This thesis was financed by the Research Council Oman and is included in the IGCP Project 639: ‘Sea Level Changes from Minutes to Millennia’, which is sponsored by the UNESCO, the IUGS (International Union of Geological Science) and the IGCP (International Geoscience Program). It is furthermore groundwork for the DFG Project HO 2550/11-1 ‘Quantification of relative sea level change along the coastline of Oman (Arabian Sea)’. 
5. GEOGRAPHICAL AND GEOLOGICAL OVERVIEW OF OMAN

5.1 GEOGRAPHY AND PRESENT CLIMATE

The Sultanate of Oman is located in the southeast of the Arabian Peninsula (see Figure 1a). It borders the United Arab Emirates to the northwest, Saudi Arabia to the west and Yemen to the southwest (Figure 1b). Oman’s long coastline is formed by the Gulf of Oman in the northeast as well as the Arabian Sea in the east and south. Furthermore, the national border of Oman includes the island Masira in the east of the Sultanate as well as the peninsula of Musandam, which is located in the north and encircled by the United Arab Emirates (Figure 1b).

The Sultanate of Oman’s main ecological regions are dominated by two prominent mountain features, the Hajar mountains in the north and the Dhofar mountains in the south, as well as wide deserts in between, for example the Jiddat al Harasis and the Wahiba Sands (Hoffmann et al., 2016). Oman’s major cities are located along the mountain chains: the capital Muscat, Sohar and Sur in the north and Salalah in the south (see Figure 1b).

Figure 1: Geographical overview of Oman with its position on the Arabian Peninsula (a). A close-up (b) shows the national borders of Oman as well as its main ecological regions and cities and the capital Muscat. Both maps are based on Google Earth (2017) © and were created using CorelDraw X8.
5. Geographical and geological overview of Oman

As part of the Arabian Peninsula, Oman is dominated by desert environments with a climate that is arid to semi-arid and average temperatures that show a seasonal variation ranging from 32°C to 48°C in the summer to 26°C to 36°C in the winter (Hoffmann et al., 2016). In average Oman receives a yearly precipitation of 117.4 mm, however, its quantity and duration are irregular: In the northern part of Oman the main rainfall occurs between December and April, whereas in the southern part (Dhofar region, see Figure 1b) this takes place between July and August. This is associated with the northwards movement of the ITCZ (Intertropical convergence zone) towards the southern part of the Arabian Peninsula (Hoffmann et al., 2015, Kwarteng et al., 2009).

5.2 Quaternary Climate

In contrast to the mostly arid to semi-arid climate that Oman experiences nowadays, climate during the Quaternary (2.6 Ma to present (Menning, 2012)) showed considerable variations: It was characterized by changes in precipitation, where the interglacial periods in higher latitudes co-occur with humid periods in Oman and glacial periods were rather arid (Hoffmann et al., 2016, Fleitmann et al., 2003). Furthermore, precipitation during the wetter periods was up to five times higher than nowadays, as shown by Woods and Imes (1995). The variability in precipitation during the Quaternary is presumably controlled by changes in location of the ITCZ and the associated rainfall belt of the Indian Ocean Monsoon (IOM): the shift of the ITCZ northwards during increased summer season insolation draws the IOM onto the continent, which results in a rainy season that affects the whole country. Such wet periods are recorded for the Early and the Middle Holocene as well as for the Pleistocene. However, the latter also shows some periods with arid to hyper-arid conditions (Radies et al., 2004, Hoffmann et al., 2016).

Of all the variation during the Quaternary period, the Last Interglacial (Eemian Interglacial), that took place from roughly 128 to 116 ka before present (Rovere et al., 2016), is the most important one for this thesis: It is known that the coastal notches were formed during the Marine Isotopic Stage (MIS) 5e (Hoffmann et al., 2016), which is usually correlated with the Eemian Interglacial (Anklin et al., 1993). The formation of notches during MIS 5e has been observed by several authors (e.g. Lorscheid et al. (in press), Rovere et al. (2016) Antonioli et al. (2006)). The Last Interglacial correlates with a well-known wet period (e.g. Burns et al. (2001)), during which a global sea level high is recorded (Lambeck and Chappell, 2001).
5.3 GEOLOGY

Oman is located on the eastern rim of the Arabian plate and therefore bordering active plate boundaries. To the east the country is neighboring the Owen Fracture Zone, which is a strike-slip fault zone and represents the boundary of Arabia and the Indian subcontinent. It connects with the Gulf of Aden and the Red Sea spreading ridges in the south, which separate the Arabian plate from the African plate. Furthermore, the Arabian plate is bounded by the Dead Sea transform fault to the northwest, which came into existence about 5 million years ago (Early Pliocene), when the Arabian plate was separated from the African plate (Hempton, 1987, Hoffmann et al., 2016). Currently, Oman and the rest of Arabia are pushed northwards at a speed of 2 cm/year while the Red Sea expands. At the northern end of the Gulf of Oman lies the very active Makran Subduction Zone. The zone has been active since the Miocene, where the oceanic crust of the Gulf of Oman (former Neotethys) is being subducted below the continental crust of Makran at a rate of about 4 cm per year (Hoffmann et al., 2016, Glennie et al., 1990, Copley et al., 2010).

Figure 2: Simplified geological map of the eastern part of northern Oman (a) displaying six of the seven major tectono-stratigraphic units (b), including the Samail Ophiolite, the crystalline basement, the sedimentary basement, the Arabian platform, the Hawasina nappes and the sedimentary cover (modified after Hoffmann et al. (2016) and Le Métour et al. (1993)). Both maps were created using CorelDraw X8.
As can be seen in Figure 1b, Oman has two prominent mountain features: the northern Hajar Mountains and the southern Dhofar Mountains, bordering the country of Yemen. As the study area of this thesis is located in the northern part of Oman (see Figure 3a), only the Hajar Mountain chain is described in more detail:

The Hajar Mountains contain the best exposed oceanic plate material in the world (Samail Ophiolite, see Figure 2) that is sequenced in the typical way described by Frisch et al. (2010): pillow basalt (not displayed in Figure 2), sheeted dikes, layered gabbro, ultramafic cumulates and peridotites. The oceanic lithosphere was formed during the Middle to Late Cretaceous as a result of the spreading of the seafloor in the center of the Neotethys Ocean. Another ophiolite covers most of Oman’s largest island, Masirah, which is located approximately 24 kilometers of the east coast (see Figure 1b) and was emplaced after the Samail Ophiolite (around 65 Million years ago).

The massifs of the Hajar Mountains are mostly composed of limestone units (e.g. the Jebel Akhdar massif and Saih Hatat). Those limestone have many large caves that mainly formed due to the process of karstification: In fact, the Paleogene limestone that crops out on the eastern end of the Hajar Mountains includes a number of the largest caves in the world e.g. Majilis Al Jin cave (Hoffmann et al., 2016).

The described Samail Ophiolite is the fifth out of seven of Oman’s major tectono-stratigraphic units, alongside the crystalline basement, the sedimentary basement, the Arabian platform, the Hawasina nappes, the sedimentary cover and the surficial deposits. Except for the last one, all units are shown in Figure 2 (Hoffmann et al., 2016):

The crystalline basement (first unit) formed due to the accretion of continental material during the Late Proterozoic, with the formation and cooling of the rocks dated from 830 to 730 million years ago (Gass et al., 1990). It consists of metamorphic rocks (e.g. gneiss) with various types of igneous rocks intruding (e.g. dolerites and granites).

The rocks of the sedimentary basin (second unit) have an age range from the latest Proterozoic to the Early Permian, during which Oman was part of the supercontinent Gondwana. Thus, sedimentation was mostly restricted to the intercontinental basin as well as the shelf of the continent. The sedimentary basin is only fragmentarily exposed in the northern part of Oman, with the exception of the Amdeh formation, which is composed of rocks from the Lower Paleozoic, mainly Ordovician (Hoffmann et al., 2016).

The rocks from the Arabian platform present the third unit and formed during the Late Permian to Late Cretaceous. It is a carbonate platform, which was established on the Arabian plate as a consequence of the break-up of Gondwana and the resulting formation of the Neotethys ocean basin. During most of the Mesozoic, the platform was characterized by the sedimentation of mostly shallow-water carbonates like limestone and dolostone. The
sedimentation lasted until the Cretaceous, when the carbonate platform was uplifted (Hoffmann et al., 2016).

The Hawasina nappes (fourth unit) can be found in the north of the Hajar Mountains. During the initial rifting of Gondwana in the Permian, an ocean basin (Hawasina basin) was established in which deep sea and continental slope deposits from the open sea as well as turbidite sediments formed. This happened simultaneously to the sedimentation of shallow-water carbonates onto the Arabian Plate (Arabian platform unit). The basin has a characteristic seafloor topography (continental slope, seamounts and mid-ocean ridge) with the formation of different rock types accordingly. These include for instance radiolarian chert, shallow marine reef limestone and volcanic rocks (Hoffmann et al., 2016).

The sixth unit represents the sedimentary cover/post nappe unit, which lasted from the Late Cretaceous to the Neogene. During this period, northeastern Oman was once more exposed to marine conditions, except for some regions where terrestrial sediments were accumulated: for example, the Al-Khod conglomerate from the Maastrichtian, where bones from ornithopod and sauropod dinosaurs were found (Schulp et al., 2008). At the very end of the Late Cretaceous a marine transgression allowed the shallow marine sedimentation to resume in northeastern Oman. It lasted until the end of the Oligocene and is dominated by marl deposits. During the Cenozoic, northern Oman experienced a complex history of tectonics, before compression lead to the uplift of the Oman Mountains beginning as early as the Late Oligocene (Hoffmann et al., 2016, Fournier et al., 2006).

The seventh unit is the surficial deposits/post-nappe unit which comprises the influence of climate and tectonics during the Quaternary. As mentioned in section 5.2, the climate of the Arabian Peninsula was different and characterized by changes in precipitation. Wet phases on one hand were responsible for intense weathering and led to karstification with the formation of large cave systems, like the mentioned Majilis Al Jin cave. Cold phases on the other hand led to a drop in sea level and thus to the exposure of the continental shelf. Furthermore, large alluvial fans formed and the uplift of the mountains led to the erosion of the sub-aerially exposed rocks, like the ophiolite. The wind was able to transport sediment and form the sand deserts that dominate the area south of the Hajar Mountains (Hoffmann et al., 2016).
6. Study area

6 STUDY AREA

6.1 INTRODUCTION

Legend

- recent notch
- abrasion notch
- bioerosion notch
- separation between the two working areas
6. Study area

As displayed in Figure 3, the studied area for this research is located around the coastal lagoon of Sur, which has a size of approximately 3.5 by 2.5 km (Hoffmann et al., 2016). Considering the size of the study area and the short time frame under which the fieldwork took place (about two weeks, see section 7), it was decided to separate the research area into a western and an eastern part, indicated by a red dotted line in Figure 3c. This thesis focuses on the western part, with exception of the recent notches indicated by yellow circles in Figure 3 (b and c), whereas the thesis by Adolphs (2017) is focusing on the eastern part.

The study area is located in the city of Sur, which belongs to the Ash Sharqiyah Region and is set at the northeastern part of the country on the coast of Gulf of Oman, about 150 km southeast of Muscat, the capital of Oman (Figure 3a).

A prominent feature in the landscape of Sur is a horseshoe-shaped lagoon, which is connected to the Gulf of Oman via a single, approximately 103-209 m wide entrance (Pilarczyk et al., 2011). A total of four Wadis flow into the lagoon, of which the largest is Wadi Shamah (Figure 3b), located in the south and ending in an approximately 1 km wide delta. The lagoon itself is made up of mudflats and intertidal sands (see section 6.2), which are exposed and submerged several times a day due to tidal cycles. Sur lagoon is a microtidal region with a mean tidal amplitude of approximately 1.2 m. The exposure of the sediments ranges from 90% at low tide to 10% at high tide (Pilarczyk et al., 2011, Donato et al., 2009). A fact that is well known by the locals: at low tide, the interior of the lagoon is used for instance for soccer practice, as the sediments make for an excellent sports ground.

The elevation of the lagoon surface itself varies between approximately ± 2 m MSL, with the mouth of the lagoon being located on the eastern edge of a low-lying sand spit that has an elevation of 2-3 m above MSL. Mangroves flourish in the southern, western and northern part of the lagoon (see Figure 4). They belong to the species *Avicennia marina* (Black Mangroves) and serve an important function, providing shelter for birds and marine life (Pickering and Patzelt, 2008).
6. Study area

Figure 4: Part of the coastal lagoon of Sur, displaying mangroves of the species *Avicennia marina* (Pickering and Patzelt, 2008) at falling tide. The sediments (consisting of mudflats and intertidal sands) are exposed during daily tidal cycles, with an exposure rate of 90 % at low and 10 % at high tide (Pilarczyk et al., 2011).

6.2 GEOLOGY

Sur lagoon is a very typical environment for the coastline of the Gulf of Oman, as it is dominated by lagoons. During the late Holocene, they formed in the mouth of wadis with the constitution of barrier bars and spits (Donato et al., 2009). As can be seen in Figure 5, Sur lagoon is surrounded by Paleocene to Eocene highlands (limestone/dolomite), Early to Middle Miocene aged marl/limestone as well as Quaternary fluvial and coastal deposits. The highlands are carved by several large wadis that enter the lagoon from the south of which the largest is Wadi Shamah as previously mentioned in section 6.1. The lagoon surface sediment (sandflat) is dominantly fine- to very fine sand, whereas the elevated lagoon margins in and behind the mangroves are mud-rich (mudflats). Including those two, there are a total of 12 sub-environments within the lagoon, which were first described by Pilarczyk et al. (2011) and are based on field observations, a digital elevation model and satellite imagery: Wadi, mangrove area, lagoon shoreface, lagoon creek (intertidal), flood delta, shelly firm ground, lagoon channel (subtidal), wadi delta, entrance channel and marine shoreface. The Wadi systems provide the poorly sorted sediment (mud-gravels) to the lagoon, whereas the prevailing fine to medium sands come from the Gulf of Oman.

The entrance channel of the lagoon is restricted by a low-lying sand spit that was built out of erosion products from exposed bedrock to the west through a combination of wave and wind action. This sand spit is characteristic for the spit-lagoon system defined by Alsharhan and El-Sammak (2004). It is composed of sub-parallel spits and lagoons in which the spits act as...
a barrier and enclose the lagoon. The town of Sur is built on such a barrier spit (Donato et al., 2009).

As indicated by the dating of beachrocks around Sur lagoon (see section 6.3.3), the study area is stable in contrast to other regions of the coastline of Oman, which show stair-cased coastal terraces as an geomorphological evidence of crustal uplift (see e.g. Ermertz (2017) or Hoffmann et al. (2016)).
6. Study area

Coastal notches (also called marine notches) are undercuttings left by sea erosion in coastal rocks (a few centimeters to meters deep). To develop the typical shape of a notch (see Figure 6), the coastal rock needs to be made of a material strong enough to support the weight of the roof (Pirazzoli, 1986, Trenhaile, 2015).

The term coastal notches includes structural notches, abrasion notches as well as notches referred to the tidal level (Pirazzoli, 1986). Around the lagoon of Sur only tidal and abrasion notches are of importance.

6.3 MORPHOLOGY

In general, coastal notches can be described using different zonations as well as significant parameters (Pirazzoli, 1986, Trenhaile, 2015), which are displayed in Figure 6. Three main zones are defined in a coastal notch that all refer to the tidal level:

- the subtidal zone is always submerged.
- the intertidal zone is characterized by intermittent immersion by tide or waves and thus comprises the area from low- to high tide.
- the supratidal zone covers the highest level of marine influence from wave splash and sea spray.

Besides the defined zonation, the most significant parameters that can be used to describe the morphology of a notch are height and depth. For a notch cut into a vertical cliff (this is the case in the investigated notches for this thesis) the height (H) is the difference in elevation between the roof (or in this thesis referred to as ‘top’ (T)) at the front of the notch and the floor (F) of the notch immediately below. Notch depth (D) is the horizontal distance from the notch vertex (the deepest part of the notch) to the vertical plane along which the height is measured (Trenhaile, 2015). However, if the roof of the notch is collapsed, it is difficult to determine the depth of the notch accurately.

According to Pirazzoli and Evelpidou (2013) tidal notches typically take on a U- or V-shaped profile if the sea level remains rather stable, with the roof/top located near the highest tide level, the floor near the lowest tide level and the vertex located near the MSL (see Figure 6).
According to Evelpidou and Pirazzoli (2015), the vertex is also the area, where the bioerosion rate is the highest, gradually decreasing towards the upper and lower limits of the intertidal range. This corresponds to the Biological Mean Sea Level (BMSL), which is marked by a sudden increase in specimen diversity. BMSL coincides with the MSL with an approximation of ±10 cm (Laborel and Laborel-Deguen, 1994). The profile of a notch is thus an excellent seal level indicator as it provides information about the former MSL.

![Figure 6](image)  
*Figure 6*: (a) The nomenclature of coastal notches (Pirazzoli, 1986) with the three zonations (subtidal, intertidal and supratidal) as well as the parameters height (H) and depth (D). (b) Shows the application of those parameters on a coastal notch around Sur lagoon.

### 6.3.2 Formation

There are numerous ways how a coastal notch can be formed. Besides bioerosion, which is described in more detail in section 6.5, there are other various processes as described by Trenhaile (2015). Those include:

- mechanical wave erosion, which can be further subdivided in wave quarrying (removal of joint blocks by wave impact) and wave abrasion (abrasive action of sand, gravel and other material being swept back and forth, mostly in the intertidal zone).
- weathering, which can be further subdivided into weathering by salt, by wetting and drying and by chemical means.

Mechanical wave erosion is responsible for the formation of abrasion notches, that, unlike bioeroded tidal notches with a rough surface, lead to a round, smooth surface (Pirazzoli, 1986).

Although those notch forming mechanisms can be listed separately, it is usually a combination of those processes that form a notch, e.g. in Japan the formation of a notch in tuff was due to a combination of wetting and drying, hydration, chemical dissolution and the effect of organic acid from decaying vegetation (Emery and Foster, 1956, Trenhaile, 2015).
6. Study area

Hand in hand with the formation goes the morphology of a notch. It also depends on a high variety of factors that are related to wave conditions, tidal range and geology (Trenhaile, 2015).

The height of a notch for instance coincides with the area over which marine erosion (whether by waves or other means of marine erosion) is effective. Tidal range has a similar influence as it controls the height over which the mentioned erosional processes are effective. Thus, notch height increases with the tidal range (Trenhaile, 2014). As the roof or top of the notch is located at the highest point of effective marine erosion, it decreases when the resistance of the rock to those erosional processes (geological factors) increases.

6.3.3 Rock facies

Coastal notches can be found in a wide variety of environments and also in a wide range of rock types (Trenhaile, 2015). Around the lagoon of Sur, they can be found in five different rock facies: limestone, beachrock, conglomerate, calcarenite and boundstone (produced by coralline red algae). Different lithological patterns were used for each rock facies in the resulting profiles in section 8, which are displayed in Figure 7.

Examples of coastal notches formed in limestone (Figure 7a) are Profiles 1 to 8, with the notches in Profile 1 to 6 being exclusively formed in limestone. The limestone is dolomitized, of Miocene age (Hoffmann et al., 2016) and shows biological zonations. As mentioned in section 5.2, the notch was formed during the Eemian Period (MIS 5e, according to Hoffmann et al. (2016)).

Two different type of beachrock facies are found along the lagoon of Sur. The first one is comprised purely of coarse sand (Figure 7b) and is displayed in Profile 2, 4 and 5. It is situated within the notch, but the notch is not comprised of it. The sandy beachrock was dated with Optically Stimulated Luminescence (OSL), a suitable method to analyze beachrocks (Mauz et al., 2015), to the MIS 5e (Hoffmann et al., 2016).

The second beachrock type (Figure 7c) is a matrix supported (sand, sometimes with foraminifera) conglomerate with sub-rounded clasts that have a diameter of 0.1 to 7 cm and embedded oysters, gastropods (both allochthonous) as well as burrows from crabs (for further information on the lithology of beachrocks around Sur, see Falkenroth (2017)). The conglomerate beachrock is displayed in Profile 7 and 8 and in contrast to the sandy beachrock, the whole notch is comprised of it. No biological zonations were found in both types of beachrocks.

The conglomerate facies (Figure 7d) consists of a fluvial conglomerate, made up of sediment from the wadis entering the lagoon (see section 6.1). Unlike the second type of beachrock, the fluvial conglomerate has a lighter colored matrix with more clasts and is therefore clast-supported. It is polymictic, with sub-rounded to sub-angular clasts composed of chert, lime-
and sandstone. They vary in size from 0.4 to 18 cm. The fluvial conglomerate is displayed in Profile 7 and 8. In both cases, biological horizons are present. The fluvial conglomerate was dated using cosmogenic nuclides (Beryllium) to an age of 120 to 230 ka before present (according to Hoffmann (2017), unpublished work).

The rock facies calcarenite (Figure 7e) and boundstone produced by coralline red algae (Figure 7f) make up the two recent notches displayed in Profile 9 and 10 respectively. Both show biological zonations.

![Figure 7: Lithological facies (with patterns) found in coastal notches around Sur lagoon and used for the profiles in section 8: (a) limestone, (b) coarse sand beachrock, (c) conglomerate beachrock with embedded oysters, gastropods and burrows, (d) fluvial conglomerate, (e) calcarenite and (f) boundstone (produced by coralline red algae).](image)

According to Pirazzoli (1986), coastal notches, in which bioerosion/bioconstruction is present, can be classified as tidal notches and are further called ‘bioerosion notches’ in this thesis. Where no bioerosion or bioconstruction is present, the notch must have formed by the means of other erosion e.g. mechanical erosion due to wave action. These are referred to as abrasion notches.
6. Study area

6.4 Tides

As mentioned in section 6.3, the tidal level defines the three main zones used in notch morphology (see Figure 6) and thus plays an important role in determining the occurrence of grazing and boring bioerosional and bioconstructional organisms.

The tidal level has a semi-diurnal range that varies in a two-week cycle. At the time of full and new moon (when sun, moon and earth form a line and are thus increasing the tidal force), the tidal range is at its maximum, which is called spring tide. The opposite is the case when the moon is at its first or third quarter (half-moon) and sun and moon are separated by a 90° angle (when viewed from the earth) and the solar tidal force is partially canceled by that of the moon. During that time the tidal range is at its minimum, which is called neap tide (Grotzinger and Jordan, 2011).

Sur lagoon is a microtidal region with a mean tidal amplitude of approximately 1.2 m (Donato et al., 2009). This amplitude and the influence of a neap tide on the tidal range can be seen in Figure 8, where the sea level at Sur from March 28th to April 4th 2017 is displayed. The data was taken from the Sea Level Station Monitoring Facility (Sur Station), which is part of the GLOSS (Global Sea Level Observing System) program.

![Sea level at Sur station](image)

**Figure 8:** Sea level at Sur station, Oman from March 28th to April 4th 2017. The semi-diurnal tidal range of the microtidal region (mean amplitude of 1.2 m (Donato et al., 2009)) is visible as well as a neap tide caused by the half moon on April 3rd 2017. Redrawn after data from the Sea Level Station Monitoring Facility (2017).
6.5 BIOEROSION AND BIOCONSTRUCTION

Organisms and their traces found in coastal notches around Sur can be divided into two features: bioerosional and bioconstructional.

Bioerosional textures are traces directly made by living organisms that damage rock surfaces by either mechanical (teeth, shell, spines etc.) or chemical means, e.g. production of metabolic acids (Taboroši and Kázmér, 2013). They can be found on different scales, which range from micro- (for example Glaub et al. (2007)) to macro scales (coastal landforms, for example Spencer and Viles (2002)). Coastal notches surrounding the lagoon of Sur show bioerosion on a meso-scale and can therefore be observed very easily with normal eyesight. A very good guide to bioerosion on a meso-scale is given by Kázmér and Taboroši (2012). Bioerosional organisms that can be found in coastal notches around the lagoon of Sur include the bivalve *Lithophaga*, sponges, the gastropods *Littorina* and Limpets as well as chitons.

In contrast to bioerosional textures, where the rock surface is being damaged, bioconstructional features include living organisms that attach themselves to a substrate (e.g. rock surface) and can be defined as producers of sedimentary structures as well as accumulator by organic means (Naylor et al., 2002). To do so, these organisms are capable of building free-standing calcium carbonate structures. They typically live in a colony or aggregates with sessile lifestyles (Taboroši and Kázmér, 2013). Bioconstructional organisms present in coastal notches around the lagoon of Sur include oysters, barnacles and worms.

This section will provide an overview of all organisms found in the area of Sur lagoon with descriptions of their main characteristics, starting with the bioerosional, followed by the bioconstructional organisms.

6.5.1 LITHOPHAGA

*Lithophaga* (date or boring mussels) is a rock-boring genus of bivalve, which belongs to the family of Mytilidae (Ziegler, 2011) and is the most abundant bioerosional organism found around Sur lagoon. They are filter feeders and produce acid mucus from their mantle edges to dissolve and weaken the limestone subtract (chemical mean). *Lithophaga* also use vertical and rotational movements (physical means) to bore into a rock in order to escape from predators (Kázmér and Taboroši, 2012a, Ziegler, 2011). By doing so, the organism creates deep cavities that penetrate vertically into the substrate and accommodate the shell. The cavity increases in diameter according to the growth of the organism. The respective boreholes are very unique and therefore easy to recognize in the field. It is even possible to distinguish different generations of *Lithophaga* (Figure 9, Kázmér and Taborosi, 2012).
6. Study area

In the initial phase, the boreholes show an opening, which is shaped like a dumbbell or keyhole, according to the animal’s double siphon morphology with an inhalant and exhalant siphon (Figure 9a, first generation). However, after the first few layers of the rock surface have been eroded, the original dumbbell-shape is lost and replaced by a more circular shape (Figure 9b, second generation). In the end, with further erosion, only the deepest part of the cavity remains and is visible as a conical pit (Figure 9c, third generation). In some cases, a light-colored, calcareous lining can be observed surrounding the borehole walls (Figure 9d).

![Figure 9](image.png)

**Figure 9:** Boreholes of the bivalve genus *Lithophaga* showing different generations: first generation (a) displays a typical dumbbell or keyhole shape, which takes on a more circular shape with further erosion (b, second generation, with individuals situated inside the boreholes). Finally, only the deepest part of the borehole remains and is visible as a conical pit (c, third generation). In some cases, the borehole walls are surrounded by a light-colored, calcareous lining (d). The first three pictures were taken in coastal notches around Sur lagoon, the fourth near Wadi Tiwi, Oman.

The depth of the cavities created by *Lithophaga* depends on the specimen and according to Glynn and Manzello (2015) varies between one and ten centimeters. The borings observed in the field have a diameter that ranged typically from 0.1 cm (first generation, dumbbell shaped), to 2 cm (second generation). Occasionally, even larger holes up to 6 cm were found. The depth of the cavities has a similar range, varying from 0.2 cm up to 4 cm in holes that have been eroded deeply and are open sideways, resembling a ‘Swiss-cheese’ structure.
(Figure 9c). However, in some cases the holes are filled up with sediment, so it is possible that their true depth is greater than the measured one.

6.5.2 Sponges

After Lithophaga, sponges are the second most abundant bioerosional organism found in the coastal notches around Sur. They most likely belong to Cliona spp. (family Clionaidae), which according to Glynn and Manzello (2015) are nowadays among the most common and destructive endolithic borers on coral reefs worldwide. They are known for penetrating calcareous substrate such as rock or shells and produce an interconnected network that, if cracked open, looks like a honeycomb-structure and resembles the sponges own anatomy (Kázmér and Taboroši, 2012a, Ekdale et al., 1984). The boring itself is accomplished by amoebocytes (moving cells), which etch minute fragments from calcareous substrate. Sponges appear as numerous small spherical shaped holes in the rock surface that have a diameter of approximately 0.1 to 0.3 cm (Figure 10a). Because of their size and numerous appearances, they are sometimes hard to distinguish from small Lithophaga borings. The key hereby is to look for the dumbbell shape of borings from a first generation Lithophaga as well as for the quantity of borings. Luckily, they can occasionally be found right next to each other (Figure 10b). However, if they have been already eroded, the distinction becomes quite difficult (see Profile 6).

![Figure 10](image-link)

**Figure 10:** Borings produced by sponges, most likely Cliona spp. They produce numerous small, spherical holes in the rock surface of about 0.1 to 0.3 cm (a) and are sometimes hard to distinguish from borings of a first generation Lithophaga (b). Both pictures were taken from coastal notches around Sur lagoon.

6.5.3 Chitons

Chitons visually belong to some of the most prominent bioeroders in the intertidal zone (Kázmér and Taboroši, 2012a), but were only observed in recent notches in Oman (see
6. Study area

Profile 9) and not in any of the paleo notches. Chitons are marine mollusks that belong to the class of Polyplacophora (Ziegler, 2011). They have eight articulating aragonite valves on their back surrounded by a margin of soft tissue that gives them a distinctive appearance and makes it easy to recognize them in the field (Figure 11a). Several species of chitons, e.g. *Acanthopleura* erode the rock substrate in a mechanical way by feeding on biofilms. In order to do so, they use their radula, a tooth-bearing strap of chitinous material that inhabits hard teeth enriched with magnetite or other minerals. It can thus easily remove uppermost layers of rock made out of calcium carbonate, aragonite or other substrates as they graze upon them (Taboroši and Kázmér, 2013, Lowenstam and Weiner, 1989).

Chitons can leave behind two kinds of bioerosional features. The first one are grazing marks which are usually shaped as meandering or straight sets of parallel grooves (Wisshak, 2006). The second are homing scars, prominent holes that accommodate an individual chiton. They venture away from the scar to graze on the surrounding rocks but return to the exact same spot, which therefore represents a long-term residence (Kázmér and Taboroši, 2012a). In Figure 11a two living chitons can be seen sitting inside their homing scar. Presumably some grazing marks were also found in one locality of a recent notch (Profile 9) and are displayed in Figure 11b.

![Figure 11](image)

*Figure 11:* Chitons, marine mollusks, are very prominent bioeroders that can be found in recent notches around Sur lagoon. Their bioerosional features are on the one hand homing scars (a) and on the other hand grazing marks (red circle, b) that are produced with their magnetite enhanced teeth upon grazing. Picture (a) taking by S. Adolphs.

6.5.4 **SEA URCINS**

Sea urchins (Figure 12a), also called echinoids, belong to the class of Echinoidea and the phylum of Echinodermata (Ziegler, 2011). Like chitons, they erode the rock substrate in a mechanical way through rasping as they graze on the surface to feed on algae. For this purpose they have a highly specialized chewing organ, known as the Aristotle’s lantern, that
consists out of five united jaws in which each tip bears a fast growing calcite tooth (Taboroši and Kázmér, 2013).

Their bioerosional features consist of grazing marks that have a typical star-shaped pattern and of hiding places, which they expand during their lifetime. When those hiding places are deepened and widened by the merging of multiple holes, the echinoids eventually create meter-scale tide pools (Figure 12b), which become major intertidal features and a unique habitat for other organisms, for instance sea stars (Schoppe and Werding, 1996, Taboroši and Kázmér, 2013).

The observed sea urchins presumably belong to the genera *Echinometra*, an especially effective bioeroder (Kázmér and Taboroši, 2012a).

Sea urchins were not directly found in notches around Sur lagoon but in a dead coral reef in front of one recent notch (No. 51) in the northwest of Sur (see Figure 3b in section 6.1).

![Figure 12](image1.png)

*Figure 12*: (a) Sea urchins (echinoids) are effective bioeroders of the intertidal zone. They use a chewing organ, consisting of five united jaws with calcite teeth to graze on the surface of rock substrate and eroding it at the same time (Taboroši and Kázmér, 2013). An additional erosional feature is their hiding places that, when expand and merged, form meter-scale tide pools (b). Both pictures were taken (picture (a) by S. Adolphs) in the reef in front of a recent notch (No. 51) in the northwest of Sur lagoon (see Figure 3b).

6.5.5 **LIMPETS**

Limpets are gastropods that have a conical shape and cling tightly to a rock substrate (Figure 13). Like sea urchins and chitons they possess a radula with enhanced teeth (silica and goethite (Sone et al., 2005)) in order to scrape off algae from the rock substrate (Kázmér and Taboroši, 2012a). Limpets activities also cause two kinds of bioerosional features: rasping marks that are produced due to grazing and homing scars that often correspond to the conical shape of each individual (see Figure 13). Around Sur lagoon, limpets were found in one recent notch (No. 51, Profile 10). However, neither the organisms themselves or their homing scars were found in any of the paleo notches.
6. Study area

6.5.6 Littorinidae

Beside limpets there are also other gastropods that are effective bioeroders, for instance littorinid gastropods, commonly known as winkles (Taboroši and Kázmér, 2013). They feed on biofilms (e.g. cyanobacteria) as well, but unlike limpets and sea urchins, littorinid gastropods do not have a mineralized radula and therefore do not leave any visible rasping marks (Spencer, 1988). However, they are able to remove carbonate grains that have been loosened by other organisms and can destroy rocks that have been weakened before by microborings of cyanobacteria (De Waele and Furlani, 2013, Taboroši and Kázmér, 2013). Around the lagoon of Sur littorinid gastropods (Figure 14) can be found numerously in recent notches (mainly no. 56, see Figure 3c and Profile 9 in section 8), but as they do not leave behind any visible traces, they could not be observed in any of the paleo notches.

Figure 13: Limpets that sit inside their homing scars that perfectly fit their conical shape. Next to the homing scars limpets leave rasping marks as a bioerosional feature. The picture was taken in a recent notch (51) northwest of Sur lagoon (see Figure 3b) by S. Adolphs.

Figure 14: Littorinid gastropods are bioerosional organisms that appear numerously in recent notch no. 56 in the north of Sur lagoon (see Figure 3c). Only the organism itself could be observed, as they do not leave behind visible scraping marks like chitons and limpets (Spencer, 1988).

6.5.7 Oysters

Oysters are the first of three bioconstructional organisms present in coastal notches around Sur. Oysters, like Lithophaga, are bivalves and therefore belong to the phylum of Mollusca. They have a split shell, consisting of a left and right valve (Ziegler, 2011). As mentioned in
the beginning of this chapter, in contrast to bioerosion, bioconstruction means the attachment of living organisms in order to produce sedimentary structures (Naylor et al., 2002). Herefore, oysters attach one of their valves permanently to the substrate and thereby match the surface topography of the substrate they are attached to. Upon death, the unattached valve may break off but the attached one remains permanently on the substrate, so that a new generation of oyster can settle on it. This can lead to up to one meter large ledge shaped accumulations in the intertidal zone (Kázmér et al., 2015, Taboroši and Kázmér, 2013). Around the lagoon of Sur, oysters can be found preserved as fossils in coastal notches, forming zonations of 10 to 35 cm thickness (Figure 15a) and as scattered individuals (Figure 15b). Living oysters are present in all recent notches (for locations see Figure 3b and c) and can form impressive buildups: In Figure 15d such an accumulation with a thickness of approximately 40 cm is shown.

Whenever oysters occur in coastal notches, whether as a scattered individual or zonation, they are attached on top of the boreholes of Lithophaga and sponges (Figure 15a and b). On rare occasions, Lithophaga borings can be found inside oysters that again are situated on top of older generations of Lithophaga cavities (Figure 15c).

![Figure 15](image.png)

**Figure 15:** Oysters, bioconstructional organisms, can be found fossilized either in a zonation (a) or as scattered individuals (b) inside coastal notches around Sur lagoon. They are always situated on top of borings of Lithophaga or sponges. On rare occasions oysters are also prey for Lithophaga as can be seen in (c). Living organisms are also present in recent notches, forming impressive buildups (d).
6. Study area

6.5.8 BARNACLES

The second typical bioconstructional organisms are barnacles (Cirripedia), a type of arthropod that belongs to the subphylum of crustaceans. In their nektonic larval stage they settle on some marine substrate (rock, shell etc.), where they begin their sessile, adult life inside a self-produced calcareous shell (Newman and Abbott, 1980). Barnacles are almost exclusively marine organisms that can live in all kinds of temperature zones: in the tidal area, shallow water and in the deep sea (Ziegler, 2011). In the intertidal zone, they cover large patches of coastal rock substrate and therefore act as a bioprotector. The tendency of barnacle larvae to settle in areas, where adult specimen are already present lead to the formation of a dense community and therefore to a concealment of extensive stretches of exposed bedrock, which minimizes the exposure to bioeroding organisms (Taboroši and Kázmér, 2013, Newman and Abbott, 1980).

Around the lagoon of Sur, fossil barnacles in coastal notches as well as living ones in recent notches were observed (Figure 16). The species is unknown, although the recent barnacles might belong to the family of Chthamalidae as they have been described before along the coast of Oman (Shahdadi and Sari, 2011). The fossil barnacles are not as common as borings from *Lithophaga* or sponges. If they appear, they are often eroded and therefore hard to recognize and reach a size of 0,1 to 0,5 cm. In two localities, bigger patches of them were found (Figure 16a). In contrast, living barnacles appear numerous in recent notches (Figure 16b), reaching an individual size of up to 2,5 cm. Important to note is also, that if barnacles appear in coastal notches they are, like oysters, exclusively covering/situated in the borings of *Lithophaga* and sponges.

**Figure 16:** Barnacles: marine bioconstructional organisms that can live from the tidal zones to the deep sea. Around the lagoon of Sur, they can occasionally be found in coastal notches as fossils (a) and numerous as living organisms in recent notches (b).
6.5.9 WORMS

Although worms are omnipresent in intertidal environments (Kázmér and Taboroši, 2012a), they belong to the rarer organisms in coastal notches around Sur and were found in four localities (see Profile 2, 3, 4 and 5).

The observed worms presumably are of the species *Pomatoleios kraussii* (personal communication, Prof. Dr. M. Kázmér, 2017), which belongs to the family of Serpulidae in the class Polychaeta, also known as bristle worms (Straughan, 1967). Serpulidae are sessile, tube-building filter-feeders, which construct white colored, calcareous tubes that are attached to the rock and can easily be identified in the field (Figure 17a). They therefore belong to the bioconstructional organisms. The worms use the tube as a means of protection and unlike most Serpulidae cannot leave it (Ziegler, 2011).

The worm tubes found in four localities around the lagoon of Sur range in length from 0.5 to 2.5 cm. When present, they are covering the bioerosional features produced by sponges and *Lithophaga* (Figure 17b).

![Figure 17: a) White colored, calcareous tubes, presumably produced by the Polychaeta worm *Pomatoleios kraussii* with a length of 0.5 to 2.5 cm. They belong to the rarer bioconstructional organisms around Sur lagoon and cover the borings of *Lithophaga* and sponges (b).](image-url)
Field work for this thesis took place from the 20th of March until the 3rd of April 2017 and was conducted first in a three-man team and later alone. Methods used include a mapping of the study area as well as a detailed recording of several coastal notch profiles.

7.1 Mapping of Study Area

The first week of the field work had the goal to map the approximately 15 km² large study area and locate coastal notches. This was necessary as only one location of coastal notches in Oman had been described before (Hoffmann et al., 2016). For this task, a three-person team, consisting of two other master students (S. Adolphs and H. Bagci) and myself, used the knowledge of the position of the previously described and dated coastal notch to find additional localities. As the area around Sur lagoon is assumed to be tectonically stable (see section 6.2), new notches needed to be positioned at about the same height above mean sea level as the previously described notch to ensure the same age and hence make it possible to compare them.

Every discovered notch was written down with its characteristics and marked using an eTrex® 10 GPS Device. Due to the size of some notches multiple GPS points were taken to indicate e.g. changes in the biological horizons. The resulting overview map is displayed in chapter 6.1 (Figure 3) with detailed maps of certain notches following in chapter 8. A table with all taken GPS Points can be found in the appendix.

7.2 Recording of Notch Profiles

As mentioned in chapter 6.1 and as can be seen in Figure 3, the study area was divided into an eastern and western part. This decision was made after the first week of field work, because of the numerous notches that needed to be mapped in detail. The separation line was chosen, so that both students were able to investigate the two different types of coastal notches that were discovered: abrasion- (red rectangles) and bioerosion notch (green rectangles). Recent notches (yellow circles) are utilized as a comparison and therefore used in both studies.

As mentioned in section 6.1, this thesis focuses on the western part of the area around Sur lagoon, whereas the eastern part is described by Adolphs (2017).

Ten profiles of coastal notches were recorded in total, of which two are from recent coastal notches, six from the bioerosion and two from the abrasion type (beachrock and fluvial conglomerate, see section 6.3.3). The profiles were chosen in areas, where the highest
diversity of bioerosional/bioconstructional organisms, described in chapter 6.5, could be found. The profiles were recorded using a measuring tape. As the goal of this thesis is to describe the bioerosional and bioconstructional textures in coastal notches and evaluate their potential as a sea level indicator, the focus of the measurements was on those horizons. The classical suggestion of Pirazzoli (1986) on how to record notch shapes, which is described in section 6.3, was therefore modified slightly as to not include the depth of the notch (D) as well as the vertex. The following parameters were taken:

1. the total height of the profile, indicated by start ($B_0$) and end of bioerosion/bioconstruction ($B_1$).
2. the height (H) between floor (F) and top (T) of the notch (if preserved), which indicates the height difference between high and low tide.
3. the start and end of each bioerosion/bioconstruction horizon produced by different organisms.

Figure 18 shows these different parameters taken for each profile on an example of a bioerosional (Figure 18a) and an abrasion notch (Figure 18b). Not displayed is the third parameter as this is done extensively in chapter 8 with a detailed description of each of the ten profiles. As abrasion notches hardly show bioerosion, only the second of the described parameters was taken. However, if they show bioerosion (e.g. Profile 7), wherever possible, all three parameters were recorded. In case of a recent notch, an extra apostrophe is added to the bioerosion indicator ($B_0'$, $B_1'$).

Figure 18: Parameters that were measured for detailed notch profiles for (a) bioerosion notches and (b) abrasion notches include the total height of the profile, indicated by start ($B_0$) and end of bioerosion ($B_1$) as well as the height between floor (F) and top (T) of the notch itself (if preserved). As hardly any bioerosion is found in abrasion notches, only the latter parameter was recorded most of the times (except for Profile 7 and 8).
7. Methods

7.3 Notch Profile Recording Using a Handheld Laser Distance Meter

Out of the ten recorded profiles in the way described in section 7.2, two were additionally recorded by M. Kázmér using a Leica Disto D8 Handheld Laser Distance Meter (HLDM), which is described in detail in Kázmér and Taboroši (2012b). It allows for an easy and fast plotting as well as the profiling of notches that are inaccessible or dangerous to reach. This was not the case in Oman, so here the HLDM was used for gaining additional and more precise data, as the typical accuracy is about +1,0 mm: a precision that is hard to reach with the naked eye. It is therefore a method that provides an exact, reproducible measurement of coastal notches.

7.4 Differential Global Positioning System (DGPS)

To put an absolute scale on the measurements taken for each profile, additional data was collected by the third member of the Sur lagoon investigation group, H. Bagci. He measured the height of different notches all around Sur lagoon with a Differential Global Positioning System (DGPS) and is using those data to reconstruct the highest sea level during the Eemian interglacial along the NE coast of Oman (Bagci, 2017). With this additive data, it is possible to display the scale in the figures of the following results section in meters above MSL.

7.5 Sources of Errors

As the measurement of the coastal notches and the distribution of the organisms were done with a measuring tape, an error in a range of centimeters to decimeters must be considered. Especially as the measurement of several meters high profiles proved to be quiet a challenge for a 1,70 m tall person. Furthermore, the typical notch form (see Figure 6) was not always as well preserved as in Figure 18, thus making the identification of the top and floor of the notch quite difficult.

Moreover, because of the lack of time the notches were only measured at the points where profiles were taken. Depending on where the measurements were taken, the result of the parameters might differ as well.

Regarding the measurements of single organisms (see section 6.5), an error in the range of millimeters must be considered.
As mentioned in section 7, the methods and therefore also the results of this thesis consist of two parts: mapping and detailed recording of notch profiles.

The first part led to a detailed map of all coastal notches that were located around the lagoon of Sur, which is displayed in section 6 (Figure 3c).

For the second part, a total of ten profiles were recorded during fieldwork. As a result, they are described and displayed in figures created with CorelDraw X8. Each figure shows, from left to right, the different bioerosion/bioconstruction horizons, a HLDM profile (if applied, see section 7.3) or a hand-drawn profile of the corresponding notch as well as a photo (see for example Figure 20).

For the description, a few general remarks need to be noted first:

As mentioned in section 7.4, the scale provided in all figures is, when applicable, displayed in meters above MSL, according to the measurements taken by Bagci (2017). However, for one notch (Profile 6), those data were not recorded so that a display of the scale in meters above MSL is not possible. In that case, the scale has no absolute value and the beginning of bioerosion/bioconstruction is the point of origin.

Although the different horizons of organisms, displayed in the middle of all profiles, include bioerosional (*Lithophaga*, sponges, chitons and Littorinidae) as well as bioconstructional organisms (oysters, barnacles and worms) they are only referred to as bioerosion horizons in the following text. As mentioned in section 6.3.3, the same goes for the term ‘bioerosion notch’ which also includes both types of biological indicators.

Furthermore, the upcoming profiles are grouped according to the different notches that were investigated. For easier reference, a detailed map of the corresponding area representing the squared regions in Figure 3 is provided in front of each group.

Additionally, a name was given to each notch to be able to distinguish them. However, these are no scientific names but rather trivial names that were developed during fieldwork. For instance, Profiles 1 to 5 are all located in a notch that was also home to some dogs. The notch was thus named ‘Dog Notch’ and the corresponding section 8.1 includes all profiles taken in that area.
8. Results

Finally, in all following profile-figures certain symbols as well as colors are used to display the different bioerosional/bioconstructional organisms. For better orientation, they are listed below:

**Table 1:** Symbols and colors used for displaying different organisms in the following coastal notch profiles.

<table>
<thead>
<tr>
<th>Organism</th>
<th>Symbol</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithophaga</td>
<td><img src="image" alt="Symbol" /></td>
<td><img src="image" alt="Color" /></td>
</tr>
<tr>
<td>Sponges</td>
<td><img src="image" alt="Symbol" /></td>
<td><img src="image" alt="Color" /></td>
</tr>
<tr>
<td>Chitons</td>
<td><img src="image" alt="Symbol" /></td>
<td><img src="image" alt="Color" /></td>
</tr>
<tr>
<td>Limpets</td>
<td><img src="image" alt="Symbol" /></td>
<td><img src="image" alt="Color" /></td>
</tr>
<tr>
<td>Littorinidae</td>
<td><img src="image" alt="Symbol" /></td>
<td><img src="image" alt="Color" /></td>
</tr>
<tr>
<td>Oysters</td>
<td><img src="image" alt="Symbol" /></td>
<td><img src="image" alt="Color" /></td>
</tr>
<tr>
<td>Barnacles</td>
<td><img src="image" alt="Symbol" /></td>
<td><img src="image" alt="Color" /></td>
</tr>
<tr>
<td>Worms</td>
<td><img src="image" alt="Symbol" /></td>
<td><img src="image" alt="Color" /></td>
</tr>
</tbody>
</table>
8.1 ‘Dog Notch’

The ‘Dog Notch’ is a bioerosion notch, located in the south-west of the lagoon of Sur in the village of Nismah (see Figure 3b and c). It is the most prominent and longest bioerosion-notch in the western part of the study area, making it the key outcrop of this thesis. Therefore, five of the ten recorded profiles were taken here. Figure 19a shows the position of those profiles as well as the GPS points 1 to 22 from the overview map in section 6.1. The notch covers approximately 400 m in length. It was named ‘Dog Notch’ as there were always dogs playing around it. Another prominent feature is the large number of beachrocks situated within the notch (Figure 19b).

Figure 19: (a) Detailed map of the bioerosional ‘Dog Notch’ located in the south-west of Sur lagoon, in the village of Nismah (see Figure 3 in section 6.1). Urban areas are indicated in grey and vegetation in green. The map shows the position of five recorded profiles as well as the GPS points 1 to 22. With a length of approximately 400 m the ‘Dog Notch’ is the key outcrop of this thesis. Another prominent feature is the large number of beachrocks (red arrows, b) situated within the notch itself (map based on Google Earth (2017) © and created using CorelDRAW X8).
8. Results

8.1.1 Profile 1

**Figure 20**: First profile of the bioerosional ‘Dog Notch’. From left to right it shows the different bioerosion horizons of *Lithophaga*, sponges, oysters and barnacles, a profile, created with a Leica Disto D 8 handheld laser distance meter (data from M. Kázmér, unpublished) and a corresponding photo.

Profile 1 is displayed in Figure 20. In total, the profile reaches to a height of 4,38 m with a bioerosion horizon of 1,87 m thickness beginning at a height of 2,51 m (B₀) and ending at 4,38 m (B₁). The notch itself has a height of 0,76 m. Four bioerosional zones could be identified.

The *Lithophaga* zone spreads over the entire bioerosion horizon with a thickness of 1,87 m, starting at 2,51 m and ending at 4,38 m. Multiple generations of *Lithophaga* are recognizable, with holes varying in diameter from 0,3 to 6 cm. However, the typical dumbbell shape of a very young generation of *Lithophaga*, which has not been affected by erosion yet (see section 6.4.1), is not present in this particular profile. The depth of the *Lithophaga* borings varies between 0,3 and 1 cm in spherical shaped and up to 3 cm in conical shaped individuals. Some of the boreholes exhibit a complete, secondary, infilling with sediment.

Sponge borings are easily recognizable in the lower part of the profile, and start at the same height as *Lithophaga* does, at 2,51 m. They are, however, only clearly visible until the beginning of the notch at 3,34 m (F), which gives the zone a thickness of 0,83 m. They might extend further in the upper part of the notch (from 3,34 until 3,95 m) but this is hard to tell as that part is entirely covered by strongly eroded *Lithophaga*, that appear more often in the upper part of the profile than in the lower and resemble a ‘Swiss-cheese’ structure (see section 6.5.1, Figure 9c).
Oysters appear at the top of the notch and mostly above the notch itself. The zone varies in thickness along the profile (between approximately 10 and 35 cm). Using the value for the highest thickness of 35 cm, the oyster zone reaches from a height of 4,03 m to the end of the profile at 4,38 m. Scattered oysters can also be found in the lower part of the notch but they do not form a zone like in the upper part. It should be noted that the oysters are situated on top of the holes produced by *Lithophaga*.

The Barnacle zone is almost exclusively restricted to the notch itself, reaching from 3,17 m to 3,95 m and therefore has a thickness of 0,78 m. The Barnacles itself are rather small with a diameter of about 0,3 to 0,5 cm and are situated on top of the *Lithophaga* borings.

Besides the distribution of the individual organisms, Profile 1 provides additional information: it is the only profile that was completely scanned with a HLDM and thus makes a reconstruction of the vertex possible, which was not measured in the field (as mentioned in section 7.2). As the vertex forms near the MSL (see section 6.3.1 (Pirazzoli and Evelpidou, 2013)), the past MSL can be set at a height of 3,80 m above the present MSL.

### 8.1.2 Profile 2

Profile 2 is displayed in Figure 21 and is situated near Profile 1 (see Figure 19a) and therefore has a similar distribution of the different bioerosion horizons. However, Profile 2 shows an additional bioconstructional organism (worms) as well as a beach rock that is situated in the notch itself.

Like the previous profile, Profile 2 extends to a total height of 4,38 m, with the bioerosion horizon reaching from 2,28 (B₂) to 4,38 m (B₁), giving it a thickness of 2,10 m. The notch itself takes up 0,85 m, starting at 3,35 m (F) and ending at 4,20 m (T). This includes the mentioned beachrock, which has a height of 40 cm, reaching from 3,35 m until 3,75 m. As the beachrock covers part of the profile, the bioerosion behind it was interpolated, e.g. if *Lithophaga* appeared below and above the beachrock it was assumed that it appears behind the beachrock as well. In total, five bioerosion zones could be identified.

Like in Profile 1, the *Lithophaga* zone spreads over the entire profile, from 2,28 m to 4,38 m, which gives it a thickness of 2,10 m. Different generations of *Lithophaga* were identified, which display a similar size range as mentioned in the description of Profile 1.

Sponges are easily recognizable in the lower part of the profile, from 2,28 m up until the start of the beachrock at 3,35 m, which gives the zone an assured thickness of 1,07 m. The notch itself has a numerous display of highly eroded *Lithophaga* borings, which makes it difficult to tell if sponges are present in the notch or not (indicated by question marks in Figure 21, from 1,07 m to 1,81 m).
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Oysters appear in a zone only at the top and above the notch, with a dimension of 0.18 m (from 4.20 m until 4.38 m). Isolated oysters can also be found in the lower part of the notch, but they do not form a zone and are therefore not displayed in Figure 21. However, in both cases, the oysters are situated on top of the *Lithophaga* borings.

Barnacles are most abundant around the beachrock in the lower part of the notch, but can also be found occasionally in the upper part. The barnacle zone is therefore once more restricted to the notch itself and reaches from 3.35 m until 4.09 m, which gives it a total height of 0.74 m. The barnacles themselves are situated on top or inside of eroded *Lithophaga* borings.

In contrast to Profile 1, Profile 2 shows an additional organism: worms. Their tubes are small with a length of approximately 0.5 cm and few individuals appear exclusively in a narrow zone right next to or occasionally even on top of the beachrock sediment. As mentioned in section 6.5.9, the worms are covering or are situated inside the borings of *Lithophaga*.

**Figure 21**: Second profile of the bioerosional ‘Dog Notch’ that includes a beachrock (40 cm high). From left to right it displays the different bioerosion horizons of *Lithophaga*, sponges, oysters, barnacles and worms, as well as a hand drawn outline of the profile and a corresponding photo.

### 8.1.3 Profile 3

Profile 3 is displayed in Figure 22 and is situated approximately 140 meters east of Profile 2 (see Figure 19a). In this region of the ‘Dog Notch’ the lower part of the profile is covered by debris so that only the notch itself is visible. Therefore bioerosion (B₀) and the notch-floor (F) both start at 3.50 m. In total, three bioerosional zones were identified.
Like in the previous profiles, the *Lithophaga* zone spreads over the entire bioerosion horizon from 3,50 m ($B_0$) until 4,44 m ($B_1$) and therefore has a thickness of 94 cm. Different generations of *Lithophaga* were identified that also display a similar size range as described in Profile 1.

The bioconstructional organisms barnacles and worms are both present from the start of the bioerosion at 3,50 m until 4,15 which gives both zones a thickness of 0,65 m. Like in the previous profiles, barnacles as well as worms are situated inside or on top of *Lithophaga* borings.

**Figure 22:** Third profile of the bioerosional ‘Dog Notch’, showing a partly covered profile, so that only the notch itself is visible. From left to right, the different bioerosion horizons of *Lithophaga*, barnacles and worms, a hand drawn outline of the profile from the side as well as a corresponding photo showing the notch from the front are displayed.

### 8.1.4 PROFILE 4

Profile 4 is displayed in Figure 23 and is located approximately 90 m east of Profile 3 (see Figure 19a). No direct measurements for the scale in meters above MSL were taken at the location of Profile 4 by Bagci (2017), but because of its closeness to Profile 3 the same data was applied here as well.

The fourth profile has a total height of 1,56 m, starting from 2,88 m ($B_0$) to 4,44 m ($B_1$). The notch itself is not very well pronounced and reaches from 3,84 m (F) to the end of the profile at 4,44 m (T), giving it a thickness of 0,60 m. Like in Profile 2, a beachrock of 0,32 m thickness and 5,30 m length is situated in the middle of the profile. In total five bioerosional horizons could be identified.

The *Lithophaga* zone spreads over the entire profile from the start of bioerosion at 2,88 m to 4,44 m and has therefore a thickness of 1,56 m. Different generations are present, with *Lithophaga* borings that still have the typical dumbbell-shape and reach a diameter of 0,3 cm
8. Results

to holes that are 2 cm wide. The depth of the borings varies as well, it ranges from holes completely filled by sediment to ones reaching 0,3 to 4 cm into the rock.

Borings of sponges are present from the initiation of bioerosion at 2,88 m until the upper part of the notch at 4,28 m, which gives the zone a total height of 1,40 m. In the lower part of the zone, sponges appear numerously, whereas in the upper part only a few borings could be identified.

Oysters appear in a zone of 0,16 m thickness at the upper part of the profile, reaching from 4,28 m to 4,44 m, which coincides with the end of the profile as well as with the borings of Lithophaga. Some scattered individuals are also present above the Lithophaga borings. However, they do not appear in a zone and are therefore not listed in Profile 4. All oysters found along this profile cover the borings of Lithophaga and sponges.

The preservation and quantity of worms as well as barnacles from the fourth profile is the highest and best of all recorded paleo notches in the western part of Sur lagoon. Some worm tubes have a diameter of up to 2,50 cm. Both zones reach from above the beachrock at 3,54 m to the upper part of the notch at 4,28 m, giving them a thickness of 0,80 m. Like oysters, worms and barnacles are either situated on top or inside the borings of Lithophaga and sponges.

Profile 4

![Image of Profile 4]

**Figure 23:** Fourth profile of the bioerosional 'Dog Notch', including a beachrock (32 cm high) and a hardly visible notch. From left to right the figure shows the different bioerosion horizons (including Lithophaga, sponges, oysters, barnacles and worms), a hand drawn outline of the profile from the side as well as a corresponding photo showing the notch from the front.
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8.1.5 Profile 5

The fifth profile of the ‘Dog Notch’ is displayed in Figure 24 and located in a small valley south of the other four profiles (see Figure 19a). Like in Profile 4, no direct measurements were taken by Bagci (2017) for this position. The scale in meter above MSL was interpolated from the other data taken at the ‘Dog Notch’ by taking the mean value, as observation in the field showed that the notch from Profile 5 and Profile 1-4 were all at approximately the same height. The profile has a total height of 1.57 m, of which the first 0.75 m (from 2.92 until 3.67 m) are occupied by a large beachrock. The notch itself has a total height of 0.50 m, reaching from 3.83 m (F) to 4.33 m (T). The floor of the notch in this profile also indicates the start of bioerosion (B₀). In total, five bioerosion horizons could be identified.

The Lithophaga zone spreads from the start of the notch at 3.83 m (F) to 4.49 m, reaching 0.16 m above the end of the notch at 4.33 m (T). It therefore has a thickness of 0.66 m. The zone is made up of multiple generations of Lithophaga ranging from juvenile borings that still show the typical dumbbell shaped form to borings that have a circular shape and a diameter up to 2 cm. The depth of the cavities also varies from 0.2 cm to 3 cm. Unique to this profile is that oysters most likely became prey for the Lithophaga as some borings can be found inside the oyster shells (see Figure 15c in section 6.5.7). Sponges are present in the whole notch (from 3.83 m (F) to 4.33 m (T)), which gives the zone a thickness of 0.50 m.

Figure 24: Fifth profile of the bioerosional ‘Dog Notch’, including a beachrock (75 cm high). From left to right, the different bioerosion horizons (including Lithophaga, sponges, oysters, barnacles and worms), a hand-drawn profile outline from the side as well as a corresponding photo showing the notch from the front are displayed.
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Oysters appear at the top of the profile with a 0.16 m thick zone that reaches from 4.33 m to 4.49 m. They are situated on top of the *Lithophaga* borings with the one exception mentioned above.

Barnacles and worms are present in the upper half of the notch, from 4.03 m to 4.33 m, giving the two zones a thickness of 0.30 m. The barnacles are rather small in this profile, showing a diameter of approximately 1 cm. Like oysters, both organisms are situated on top or inside the borings of sponges and *Lithophaga*.

8.2 ‘Cliff Notch’

The ‘Cliff Notch’ is also a bioerosion notch and the extension of the ‘Dog Notch’ to the west along the southwestern line of the lagoon. Figure 25a shows a detailed map of the notch with the position of the taken GPS points as well as the profile. In contrast to the ‘Dog Notch’, the ‘Cliff Notch’ hardly shows any notch-preservation, making it difficult to take the measurements described in section 7.2. Thus, only one profile was recorded over the entire range of approximately 565 m. The notch is called ‘Cliff Notch’ as it is located on a cliff right at the lagoon with a mangrove forest surrounding it (see Figure 25b).

![Figure 25](image_url)

**Figure 25**: (a) Detailed map of the bioerosional Cliff Notch, which extends the ‘Dog Notch’ to the west (note GPS point 22, that marks the transition between both notches) and is located in the southern part of Sur lagoon. Vegetation is indicated in green. The map shows the position of the recorded profile as well as the taken GPS points. The notch is located right on a cliff (hence the name) surrounding part of the lagoon, with a mangrove forest growing in front of it (b). The map is based on Google Earth (2017) © and was created using CorelDRAW X8. Figure 25b was taken by S. Adolphs.
8. Results

8.2.1 PROFILE 6

The profile is displayed in Figure 26 and has a total height of 1,56 m. However, it was not clearly visible in the field if the whole notch or just part of it was preserved. No DGPS data was taken by Bagci (2017) from the ‘Cliff Notch’, so the scale does not have an absolute value and is displayed in meters with the start of bioerosion (B₀) being the point of origin. The notch itself has a height of 0,60 m (from 0,96 (F) to 1,56 (T)). In total three bioerosion horizons could be identified.

The Lithophaga zone spreads over the entire profile, starting at 0,00 m (B₀) and ending at 1,56 m (B₁), giving it a thickness equal to that of the profile itself. Different generations of Lithophaga are present showing the same size range as described in the previous profile (e.g. Profile 1 in section 8.1.1). The lower 23 cm of the notch shows less Lithophaga borings than the rest of the profile (indicated by a lighter blue in Figure 26).

As mentioned in section 6.5.2, it is very hard to distinguish borings of sponges from those of small Lithophaga in this profile. The distribution of the zonation from 0,00 m to 0,40 m is therefore regarded with suspicion and marked in the profile accordingly.

Some oysters appear in the small area of 23 cm that show less Lithophaga borings than the rest of the profile. They appear individually and not in a zone like in the other profiles. However, they once more cover the borings of Lithophaga.

Figure 26: The first and only profile of the bioerosional ‘Cliff Notch’. From left to right, the different bioerosion horizons of Lithophaga, sponges and oysters, a hand-drawn outline of the profile as well as a corresponding picture are displayed.
8. Results

8.3 ‘Small Notch’

The ‘Small Notch’ (Figure 27b) is located in the south-west of the study area and includes the GPS points 37 to 39 (see Figure 3c in section 6.1). The notch consists of a fluvial conglomerate instead of limestone (see section 6.3.3, Figure 7d). Some bioerosion (borings of *Lithophaga* and oysters) is visible in the pebbles that are presumably limestones, however not in the matrix itself, which is why the ‘Small Notch’ is considered an abrasion- and not a bioerosion notch. As this study is focused on bioerosional notches, no profile was recorded. However, measurements by Bagci (2017) show that the height of the borings of *Lithophaga* and oysters are in average at 4.62 meters above MSL, a value that is similar to B1 of the other profiles. The height of the notch itself varies from 0.30 m to 0.80 m. Figure 27a shows a detailed map of the ‘Small Notch’ including the taken GPS points.

![Figure 27](image)

*Figure 27:* (a) Detailed map of the ‘Small Notch’, a notch made of fluvial conglomerate (b). It is located in the southwest of the study area and includes GPS points 37 to 39 (also see overview map in Figure 3c). Some bioerosion was identified in presumably limestone pebbles, but none in the matrix. The map is based on Google Earth (2017) © and was created using CorelDRAW X8.

8.4 ‘Miklos Notch’

‘Miklos Notch’ (named after my second supervisor Miklos Kázmér, who called our attention to this outcrop) is a very unique notch in the study area as part of it comprises a triple notch containing a recent, a bioerosion as well as an abrasion notch. Furthermore, a conglomerate type beachrock is part of the notch (see description of notch and beachrock types in section 6.3.3). ‘Miklos Notch’ is located in the west of the study area with an approximate size of 0.2 km² and comprises the GPS points 40 to 50 (see also overview map in section 6.1) as well as Profile 7 and Profile 8, which are both located on a peninsula (Figure 28b). Figure 28a shows a detailed map of the position of each GPS point and of the profiles.
8. Results

Figure 28: (a) Detailed map of the largest abrasion notch of the working area, covering approximately 0.2 km² (‘Miklos Notch’). It is located in the west and includes the GPS points 40-50 (see Figure 3c in section 6.1) as well as Profile 7 and Profile 8. The profiles are located on the peninsula of which the north side is shown in (b) and include horizons of bioerosion. The map is based on Google Earth (2017) © and was created using CorelDRAW X8.

8.4.1 PROFILE 7

The seventh profile is displayed in Figure 29. It has a total height of 3.80 m and is located at the northern side of the peninsula. The profile itself consist of three different notches, which for easier references are named one to three, starting at the bottom.

The first notch is an early stage recent notch made up of limestone, which has a total height of 20 cm and reaches from 0.73 m (F₁) to 0.93 m (T₁). Three bioerosional horizons were identified:
8. Results

Oysters are present in a 10 cm thick zone in the lower part of the notch, reaching from 0.73 to 0.83 m. Littorinid gastropods can be found over the entire range of the notch and are attached to oysters when these are present. The third bioerosional horizon is made up of barnacles, which only appear infrequently and are situated on top of the oysters like the littorinid gastropods.

The second notch is an abrasion notch, containing two different rock facies: a fluvial conglomerate that reaches from 1.42 m to 2.13 m and therefore has a thickness of 71 cm and a beachrock (see sedimentological description in section 6.3.3) with a height of 1.74 m (2.13 m to 3.87 m). The notch thus reaches from 1.42 m ($F_2$) until 2.76 m ($T_2$), giving it a total thickness of 1.34 m. No bioerosional horizons could be identified.

Unlike all previously described profiles, the third bioerosional notch is found in a fluvial conglomerate instead of a limestone. This conglomerate is similar to the underlying conglomerate notch. It has a total height of 66 cm, reaching from 3.87 m ($F_3$) to 4.53 m ($T_3$). Two bioerosional horizons are present.

The *Lithophaga* zone spreads over the entire bioerosional notch, giving it a thickness of 66 cm. Like in the previous profiles (e.g. Profile 1), different generation of *Lithophaga* borings are present, varying in size from 0.4 to 2 cm and in depth from 1 to 4 cm. The cavities can be found in the matrix of the conglomerate as well as in single pebbles.

Oysters are present in a zone at the upper part of the notch with a height of approximately 20 cm (from 4.33 m to 4.53 m). The zone continues beyond the taken profile with a total horizontal length of 1.30 m. Most of the oysters cover the borings of *Lithophaga*. However, in some cases borings of *Lithophaga* can also be found inside oyster shells.

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Figure 29: Profile 7 (first profile of ‘Miklos Notch’) shows a triple notch, containing an early stage recent notch, an abrasion notch and a bioerosional notch situated within a fluvial conglomerate. On the left side, the different bioerosion horizons of the recent as well as the bioerosional notch (including *Lithophaga*, oysters, Littorinidae and barnacles) are displayed. This is followed by a combination of a hand drawn outline and a profile created with a Leica Disto D 8 handheld laser distance meter (data from M. Kázmér, unpublished data) as well as a corresponding photo on the right side of the figure showing the notch from the front. The lithological pattern for the beachrock was modified after Falkenroth (2017).
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8.4.2 Profile 8

Profile 8 is the second and last profile of ‘Miklos Notch’ and lays opposite to Profile 7 on the peninsula’s southern side. It is displayed in Figure 30. Out of the ten profiles, this is the largest one with a total height of 4.06 m, from 0.37 m to 4.43 m. Profile 8 also consists of three notches, which are, like in the previous profile, named one to three with the first one starting at the bottom:

The first notch is an early stage recent notch with a limestone facies and a total height of 20 cm, starting at 0.63 m (F₁) and ending at 0.83 m (T₁). It is covered by one bioerosion horizon (oysters) that extends through the entire range of the notch (from B₀' to B₁').

The second notch is, like in Profile 7, an abrasion notch shaped like a V. It reaches from 1.78 m (F₂) to 3.13 m (T₂) and therefore has a thickness of 1.35 m. The notch is composed of the same two rock facies as in the previous profile: a fluvial conglomerate, that starts below the notch at 1.62 m and ends at 2.50 (total height of 0.88 m) and a beachrock, which begins at a height of 2.50 m and extends above the notch until 3.81 m (thickness of 1.31 m). No bioerosional horizons were identified.

The third and thus last notch is a bioerosional one which is composed of the same fluvial conglomerate that also makes up part of the second notch. It extends from a height of 4.03 m (F₃) to 4.43 m (T₃), giving it a thickness of 40 cm. In total three bioerosion horizons are present:

The Lithophaga horizon spreads over the entire range of the notch and therefore has the same thickness of 40 cm. Different generations of borings are present with size ranging from 0.1 to 1.7 cm and depth from 0.5 to 4 cm.

Borings of sponges appear together with those of Lithophaga, giving the sponge horizon a thickness of 40 cm as well.

Oysters are present in an up to 20 cm thick horizon that spreads in the middle of the notch, from 4.13 m to 4.33 m and covers the cavities of Lithophaga and sponges.

Figure 30: Profile 8 (second profile of ‘Miklos Notch’) consists of a triple notch, containing an early stage recent notch, an abrasion notch with a beachrock and fluvial conglomerate part as well as a bioerosional notch situated within a fluvial conglomerate. On the left side, the different bioerosion horizons of the recent as well as the bioerosional notch (including Lithophaga, oysters, Littorinidae and barnacles) are shown. This is followed by a hand drawn profile outline as well as a corresponding photo showing the notch from the front. The lithological pattern for the beachrock was modified after Falkenroth (2017).
8. Results

8.5 Recent Notches

To better understand the zonation of bioerosion horizons in the geological past, two examples of recent notches are presented here for comparison. The location of both is displayed in Figure 3 in section 6.1, with No. 56 located in the northern peninsula of Sur lagoon (Figure 3c) and No. 51 in the area of Ar Rusagħ in the northwest of the town of Sur (Figure 3b).

8.5.1 No. 56: Profile 9

![Profile 9](image)

Figure 31: Recent notch No. 56 (see overview map in section 6.1) displaying from left to right the different bioerosion horizons (including *Lithophaga*, barnacles, oysters, Littorinidae and chitons), a profile outline as well as a respective photo.

The first profile of a recent notch is Profile 9, which is displayed in Figure 31. The notch has a total height of 0.73 m, reaching from -0.44 m (F) to 0.29 m (T). However, due to the V-shaped nature of the notch, it decreases in height inward. The notch is made up of a calcarenite (Vinx, 2011), in which a total of five bioerosion horizons were identified. *Lithophaga* are present in the inner part of the notch from -0.44 until 0.16 m, giving it a thickness of 60 cm. Littorinid gastropods have the exact same range, but are most abundant on the floor of the inner part of the notch.

Oysters appear at the top of the notch, where they hang down with a thickness of up to 29 cm (from 0.00 m to 0.29 m).

This profile is the only one that shows possible grazing marks of chitons (see section 6.4.3), which are present at the roof of the notch.
The barnacle zone starts above all other organisms at the top of the notch (0.29 m) and reaches until 0.42 m, which also marks the end of bioerosion ($B_1^1$). The zone therefore has a total thickness of 13 cm.

8.5.2 No. 51: PROFILE 10

The second recent notch profile is displayed in Figure 32. It is situated within a dead coral reef which stretches along the coast northwest of Sur lagoon and is inhabited by for instance sea urchins, chitons and sea stars (see section 6.5.4). The notch itself has a total height of 1 m, reaching from -0.10 m (F) to 0.90 m. It is embedded in a bioconstructional feature of coralline red algae, which belong to the most widespread encrusters along karst coastlines. While growing and fusing together they follow the substrate’s relief and produce multiple layers (Taboroši and Kázmér, 2013, Giaconne et al., 2009). According to the modified classical carbonate classification (Dunham, 1962) by Wright (1992) the bioconstructional feature can be described as a boundstone. In total, three bioerosion horizons were identified. Barnacles are present across the whole notch, thus starting at -0.10 m ($B_0^1$) and ending at 0.90 m ($B_1^1$). However, they appear mostly on top of oysters, which occur in the upper part of the notch in a 27 cm thick zone (from 0.57 m to 0.84 m).

The third bioerosion horizon is made up of limpets, which can be found in the upper region of the notch as well. However, they only appear as scattered individuals.

Figure 32: The second recent notch (No. 51, see Figure 3b in section 6.1) is embedded in a boundstone produced by coralline red algae. From left to right the different bioerosion horizons of barnacles, oysters and limpets, a profile outline from the side as well as a respective photo from the front of the notch are displayed.
9. Discussion

To make an interpretation and discussion of the results displayed in the previous section more convenient, they are summarized in Figure 33 and 34. Figure 33 shows all recorded distributions of the bioerosional/bioconstructional features of paleo coastal notches, whereas the recent ones are represented in Figure 34.

To make a discussion of the organisms’ distribution and a comparison with literature possible it is necessary to define the area of subtidal, intertidal and supratidal zone. Herefore, the definition by Pirazzoli (1986) was used (see section 6.3.1) and displayed exemplarily in Figure 33 for Profile 1:
the subtidal zone is always submerged and therefore stretches from the floor (F) of the notch, which in tidal notches marks the low tide, downwards. The intertidal zone is characterized by the tides and thus reaches from low tide (the floor of the notch) to the top (T), which marks high tide. The supratidal zone covers the highest marine influence (e.g. spray water) and thus reaches from the top of the notch upwards.
In the following, each bioerosional/bioconstructional feature of the profiles is interpreted in detail and their potential use as a sea level indicator in the area of Sur is discussed. Hereby, the focus lies on the paleo notches, as one of the hypotheses of this thesis (see section 4) is to see if bioerosional/bioconstructional features can be used as an indicator for the past sea level. Therefore, only the organisms present in paleo notches (Lithophaga, sponges, oysters, barnacles and worms) are interpreted and discussed in detail. The data collected from recent notches is hereby used for comparison.
Those organisms, commonly known as FBI’s, have been used as sea level indicators multiple times before (see for example Laborel and Laborel-Deguen (2005), Rovere et al. (2015) and Baker and Haworth (1999)).

Figure 33: Summary of bioerosional horizons in all paleo coastal notches around Sur lagoon that are described in section 8 and are provided with an absolute scale in meters above MSL according to the data by Bagci (2017). For Profile 6 from the ‘Cliff Notch’ (see section 8.2) no such data was provided, and it is thus not included. Furthermore, the definition of the tidal zones is exemplary displayed for Profile 1.
9. Discussion

Figure 34: Summary of bioerosional horizons in all recent notches around Sur lagoon that are described in section 8. The scale is given in meters above MSL, according to the data provided by Bagci (2017).

9.1 LITHOPHAGA

*Lithophaga* borings are the most abundant type of bioerosional features in the coastal notches around Sur, appearing in all recorded profiles of paleo notches and always covering not just the notch but the entire profile (see Figure 33). The borings thus appear in the subtidal, intertidal as well as the supratidal zone. The observations made in recent notches differ slightly, as the borings found in Profile 9 cover most of the intertidal zone (see Figure 34). However, as the notch in Profile 9 starts with the ground, no statement about subtidal *Lithophaga* could be made.

The zonation in paleo coastal notches is in contrast to what is known from the literature as according to Glynn and Manzello (2015), Lowenstam (1974), Laborel and Laborel-Deguen (2005), Rovere et al. (2015), Kázmér et al. (2015) as well as Kázmér (in prep.) *Lithophaga* borings are present in the subtidal zone, extending into the intertidal zone to a small degree. It is further noted by Laborel and Laborel-Deguen (1994) that the upper limit of the *Lithophaga* zone may concur closely with sea level.

In all localities *Lithophaga* borings appear in different generations, which differ in the state of erosion (as described in section 6.5.1). Adolphs (2017), who investigated coastal notches in the eastern part of Sur lagoon, described the different generations of *Lithophaga* in more detail: the first generation of borings (dumbbell shape, up to 0.5 cm in diameter) are only...
present below the notch in the subtidal area, the second generation (0.5 cm to 2 cm) is present over the entire range of the profile and the third generation (> 2cm) is present in the subtidal region with a small degree ranging into the intertidal zone. The appearance of different generations in one locality has been observed before, e.g. by Akpan (1991), who described up to five different, closely spaced generations of Lithophaga in stromatolitic structures in SE Nigeria.

As mentioned in section 6.5.7, Lithophaga borings can also be found inside oyster shells (e.g. Profile 5). Although this situation was only observed occasionally it is not unusual as the vertical living range of Lithophaga and oysters overlap as can be seen in Figure 33 and 34. Adolphs (2017) described the same phenomenon in the eastern part of Sur lagoon and Mauna et al. (2005) noted this on oysters along the Argentinian Atlantic coast from the late Miocene Puerto Madryn Formation.

Lithophaga are filter feeders (see section 6.5.1) and are thus dependent on being submerged in water on a regular basis (Ziegler, 2011). The fact that Lithophaga borings were found in the supratidal area in coastal notches around Sur lagoon (Profile 1, 2, 3, 5 and 7) is therefore not possible. This distribution can only be explained if the mean sea level and thus the zonation of subtidal, intertidal and supratidal was different either before or after the initial development of the notch during the Eemian period. As the boreholes of Lithophaga above the top of the notch are not eroded to a stronger degree than the ones in the notch itself, I would postulate that they were produced after the initial formation of the notch. The appearance of Lithophaga borings in the supratidal area is thus an indication for another regression/transgression phase that brought the sea level to at least such a height that the supratidal zone of the Eemian period became an intertidal zone.

Considering this assumption, the zonation of Lithophaga in paleo notches needs to be viewed with caution, but can still be used as a sea level indicator when compared with recent notches in the same area. Profile 9 from Figure 34 shows an assured distribution in the intertidal zone, which is partly consistent with the literature. Borings of Lithophaga can thus be used as a sea level indicator for the intertidal zone and possibly for the subtidal zone around Sur lagoon.

9.2 Sponges

Borings of sponges are, after Lithophaga, the second most abundant bioerosional feature around the coastal notches of Sur. They were only identified in the paleo notches and not in any of the recent notches (compare Figure 33 and 34). The borings were most likely produced by Cliona spp. (see section 6.5.2). When they appear, the borings cover a great deal of the profile, however, they never reach above the top (T) of the notches, thus
9. Discussion

extending into the supratidal zone. The expansion of sponge borings into the intertidal zone in Profile 1 and 2 needs to be treated with caution as for reasons explained in section 8.1.1, it was difficult to see if the borings extended further or not. Nevertheless, Profile 4, 5 and 8 show the unequivocal appearance of sponge borings in the intertidal zone.

In contrast to the distribution of Lithophaga in paleo notches, the literature shows a better agreement regarding the zonation of sponge borings: Glynn and Manzello (2015) and Lowenstam (1974) state that clionaid sponges, like Lithophaga, appear most abundant in the subtidal zone and reach into the intertidal zone to a small degree. Kázmér et al. (2015) also postulate that sponges live in the subtidal zone as the organisms cannot tolerate any dehydration. Furthermore, studies by Perry (1998) and López-Victoria and Zea (2005) show that sponges are dominant at fore-reef sites, which can be compared to the subtidal zone as it is also always submerged.

To sum up, the literature agrees that Cliona spp. is most abundant in the subtidal zone, whereas around the paleo notches of Sur, they appear in the subtidal as well as the intertidal zone. However, if, like the supratidal appearance of Lithophaga borings indicate, another regression/transgression phase is assumed the appearance of sponges in the intertidal zone, which the organisms cannot tolerate (Kázmér et al., 2015), could be explained. In contrast to Lithophaga, sponges were not identified in any of the recent notches which can thus not be used as a comparison to verify this assumption.

Although a comparison is not possible, in my opinion sponges can still be used as a sea level indicator for the subtidal zone around Sur lagoon. The appearance in the intertidal zone can be explained with sea level changes that cause the strain of the distribution, leaving a distribution of sponges in the subtidal zone, which is coincident with the literature.

9.3 OYSTERS

In paleo notches as well as recent notches around Sur lagoon, oysters are mostly present at the top of the notch (upper intertidal zone) and often even reach above the notch into the supratidal zone (Profile 1, 2, 5 and 7 in Figure 33 and Profile 9 and 10 in Figure 34). Profile 8 from the paleo notches as well as the early stage recent notches from Profile 7 and 8 are an exception with oysters located in the entire intertidal or lower intertidal zone.

This is mostly opposing to the literature as for instance Rovere et al. (2015) state that oysters live in shallow water (subtidal zone) with certain members of the genera Saccostrea and Crassostrea reaching into the intertidal zone. Kázmér (in prep.) investigated the zonation of biomarkers in Thailand, where oysters live in the middle of the intertidal zone. The same goes for Kázmér et al. (2015), who postulate that oysters are dominant in the middle part of the intertidal zone.
Like *Lithophaga*, oysters are filter feeders and thus cannot survive in the supratidal zone. They also need to be wetted on a regular basis to avoid dehydration (Kázmér, in prep.). The distribution of oysters in the supratidal zone in coastal notches around Sur lagoon is therefore a supplementary argument for additional regression/transgression phases after the initial formation of the notch during the Eemian period.

In contrast to the borings of sponges, oysters are present in all recorded recent notches (see Figure 34), which allows for a comparison. There, oysters are always present in the intertidal zone, in Profile 9 and 10 in the upper intertidal zone. If supratidal oysters are not considered for the described reasons, the organisms appear in the upper intertidal zone in paleo notches as well and are therefore only restricted to a single tidal zone. Oysters can thus be used as a sea level indicator for the intertidal zone around Sur lagoon.

On a further note, Laborel and Laborel-Deguen (1994) state that the vertical accuracy of oysters in indicating sea level depends highly on the species. Thus, if the species could be determined, an even more precise conclusion about the sea level can be made. In addition to the zonation, oyster’s hard shell, which is very resistant to erosion, can also be dated and thus used as a sea level indicator (e.g. Davis et al. (2000)).

### 9.4 Barnacles

As can be seen in Figure 33, barnacles appear in paleo notches in Profile 1 to 5, which all belong to the ‘Dog Notch’. In Profile 2, 3 and 5 they cover most of the intertidal zone except for the upper intertidal zone in Profile 2 and 3 and the lower intertidal zone in Profile 5. In Profile 1 barnacles extend into the supratidal- and in Profile 4 into the subtidal zone. Profile 7, 9 and 10 of the recent notches (see Figure 34) show a similar distribution with barnacles covering the entire intertidal zone in Profile 10, the lower half in Profile 7 and the supratidal zone in Profile 9.

The comparison with the literature is a bit more difficult as the distribution of barnacles depends strongly on the family and as mentioned in section 6.5.8 the family of the observed barnacles around the lagoon of Sur is only an assumption. For instance, the vertical range of the family Balanidae reaches from the subtidal to the intertidal zone with the upper limit beginning near MSL. Genera like *Balanus* or *Tetraclita* from this family are thus often used as sea level indicators (Rovere et al., 2015). On the contrary, the range of the family of Chthamalidae is limited to the spray zone but varies strongly with surf exposure, tidal amplitude and topography and therefore is a poor sea level marker (Rovere et al., 2015, Laborel and Laborel-Deguen, 1994). Kázmér et al. (2015) state that many barnacles live in the upper intertidal and lower supratidal zone. The latter distribution is consistent with Profile 1 and 5 of the paleo notches as well as Profile 9 and 10 from the recent notches. The
distribution of the barnacles from Profile 9 also agrees well with the distribution known from the Chthamalidae family (Rovere et al., 2015), which strengthens the assumption that the living barnacles found around Sur lagoon belong to that family (see section 6.5.8).

Like the bioconstructional oysters, barnacles are also always situated on top or inside the borings of Lithophaga. As mentioned in section 6.5.8, barnacles can settle on any kind of hard substrate after their nektonic larvae stage. This can be rock, other organisms or even drifting substrate (Ziegler, 2011). It is therefore not surprising to find barnacles situated in or on top of borings of Lithophaga, especially as their vertical ranges overlap (see Figure 33). Nevertheless, this phenomenon could also be explained by another regression/transgression phase that brought the sea level to a similar height and let to the settling of barnacles on the already eroded Lithophaga borings (see Figure 35a). However, as there are two possible explanations for barnacles to be situated inside boreholes of Lithophaga, it is not such a strong indicator for regression/transgression phases after the Eemian period as e.g. the supratidal Lithophaga or oysters (section 9.1 and 9.3) are and must be therefore viewed with caution.

Regarding the question if barnacles can be used as a sea level indicator, possible regression/transgression phases must be considered that strain the typical distribution. However, as done with Lithophaga and oysters the comparison with the distribution in recent notches is not as helpful as it is not consistent, and barnacles appear in the intertidal as well as the supratidal zone (see Figure 34). Without further profiles in recent notches with a clear identification of the family, barnacles cannot be used as a sea level indicator around Sur lagoon.

9.5 Worms

The calcareous tubes of serpulid worms, most likely belonging to the species Pomatoleios kraussii, were identified in four profiles of the paleo notches and in none of the recent notches (compare Figure 33 and 34). In Profile 2 no true horizon was found, only scattered individuals next to the beachrock located in the intertidal zone (see section 8.1.2). However, Profile 3, 4 and 5 show a horizon of worm tubes in the intertidal zone with an extension into the subtidal zone in Profile 4.

This observation agrees with the general knowledge from the literature, although it highly depends on the species: As mentioned by Rovere et al. (2015), the family of Serpulidae consists of various genera with a broad bathymetric range that varies with each individual species. The authors further note that some species, e.g. of the genus Galeolaria, are abundant in the intertidal zone, although isolated tubes can be found in any zone.
9. Discussion

Straughan (1969) e.g. states that *Pomatoleios kraussii* forms a well-defined horizon in the intertidal zone in many areas along its Indo-Pacific distribution and Miura and Kajihara (1984) postulate that the species can only survive in a small range (0.4 m vertically) of the intertidal zone. Nevertheless, the species is also capable of surviving in the subtidal zone according to Straughan (1968).

Like oysters and barnacles, worms are always situated either on top or inside of borings from *Lithophaga* and sponges (see Figure 35b). As with the other two bioconstructional organisms, this phenomenon can be explained by another regression/transgression phase that brought the sea level to the same height as the location of the, until then, eroded *Lithophaga* or sponge borings.

As with the other organisms, regression/transgression phases that strain the worm's zonations must be considered. Unfortunately, no worms were found in any of the recent notches, so a comparison is not possible. However, as stated, the distribution of worms in the intertidal zone in paleo coastal notches around Sur lagoon agrees well with the literature. I would therefore postulate that they might be used as a sea level indicator for the intertidal zone around Sur lagoon, but with caution. Further data, especially of recent worms in that area are necessary.

![Figure 35](image.png)

**Figure 35:** Pictures from coastal notches around Sur that show barnacles (a) and worms (b) situated inside eroded *Lithophaga* borings, which possibly support the hypothesis of regression/transgression phases after the initial formation of the notch (Last Interglacial, Eemian period).

As mentioned in section 6.2, the area around Sur lagoon is assumed to be stable (Ermertz, 2017, Hoffmann et al., 2016). The here postulated changes in sea level indicated by the supratidal appearances of *Lithophaga* and oysters, intertidal sponges and presence of worms and possibly barnacles on top of *Lithophaga* and sponge borings can therefore be explained by eustatic instead of isostatic sea level changes.
9. Discussion

9.6 NOTCH MORPHOLOGY AND ITS IMPLICATIONS

As described in section 6.3.1, the morphology of a notch with its significant parameters height and depth can be used to make assumptions about high-and low tide as well as the height of the MSL in the past. For this, the position of the top (T), the floor of the notch (F), the resulting height as well as the vertex are essential (Pirazzoli and Evelpidou, 2013). Table 2, 3 and 4 summarize this information for all the taken profiles around Sur lagoon in paleo coastal notches (Table 2 and 3) as well as in recent coastal notches (Table 4). Table 2 displays the parameters from bioerosional notches, whereas Table 3 focuses on those without bioerosion (abrasion notches, see section 6.3.3). Only those notches, where absolute heights in meter above the present MSL are available (according to Bagci (2017)), are displayed.

Table 2 shows that the bioerosional notches have an average height of 66±17 cm with the notch starting at 3,68±0,28 m (floor) and ending at 4,34±0,15 m (top). As mentioned in chapter 8.1.1, the vertex and thus the approximate height of the past MSL can be set at 3,80 m. These data fit well with those from Adolphs (2017), whose investigated notches have an average height of 76 ± 9 cm with a past MSL located at 3,75 m. As mentioned in section 5.2 and in 6.3.3, those notches were formed during the Eemian Interglacial (MIS 5e, according to Hoffmann et al. (2016)).

The paleo abrasion notches displayed in Table 3 show higher values with an average height of 1,35 m. The floor of the notch is thereby located at 1,60 m and the top at 2,95 m above the present MSL. The two recent coastal notches in Table 4 have an average height of 87 cm with the notch starting at -0,10 m and ending at 0,77 m above the present MSL. Early stage notches, such as the ones from Profile 7 and 8 were thereby not taken into account.

Considering the data from the bioerosional notches as well as the information by Donato et al. (2009), that Sur lagoon has a mean tidal amplitude of approximately 1,2 m, the tidal ranges during MIS 5e and today differ by 37 to 71 cm. If not the information by Donato et al. (2009) but the average height of the measured recent notches is considered, then the tidal ranges during MIS 5e and today differ by 4 to 38 cm. Those differences can either be explained by changes in the topography of the coastal area under different sea level conditions (Hill, 2016, Lorscheid et al., in press) or by errors during measurement (see section 7.5). The former hypothesis can be supported by the modelling done by Bagci (2017), who displayed the area of Sur lagoon with the present sea level (Figure 36a) and a sea level height of 4,80 m above today’s MSL (Figure 36b). The latter represents the highest Lithophaga borings in coastal notches from the Eemian Interglacial. The model displayed in Figure 36b shows that the water would have been able to flow through multiple instead of a single entrance, which would have influenced the tidal stream and thus the tidal range (Grotzinger and Jordan, 2011). The hypothesis of a more open lagoon can be further
supported by the height of the abrasion notches. As mentioned in section 6.3.1, their morphology depends on mechanical wave erosion (Pirazzoli, 1986). To produce waves that can form an, in average, 1.35 m high notch, the lagoon must have been more open in the past as indicated by Picture 36.

Table 2: Different morphological parameters for bioerosional paleo coastal notches around Sur lagoon.

<table>
<thead>
<tr>
<th>Profile</th>
<th>top (T) [m above MSL]</th>
<th>floor (F) [m above MSL]</th>
<th>height [m]</th>
<th>vertex [m above MSL]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.10</td>
<td>3.34</td>
<td>0.76</td>
<td>3.80</td>
</tr>
<tr>
<td>2</td>
<td>4.20</td>
<td>3.35</td>
<td>0.85</td>
<td>/</td>
</tr>
<tr>
<td>3</td>
<td>4.34</td>
<td>3.50</td>
<td>0.84</td>
<td>/</td>
</tr>
<tr>
<td>4</td>
<td>4.44</td>
<td>3.84</td>
<td>0.6</td>
<td>/</td>
</tr>
<tr>
<td>5</td>
<td>4.33</td>
<td>3.83</td>
<td>0.5</td>
<td>/</td>
</tr>
<tr>
<td>7</td>
<td>4.53</td>
<td>3.87</td>
<td>0.66</td>
<td>/</td>
</tr>
<tr>
<td>8</td>
<td>4.43</td>
<td>4.03</td>
<td>0.40</td>
<td>/</td>
</tr>
<tr>
<td>mean</td>
<td>4.34</td>
<td>3.68</td>
<td>0.66</td>
<td>/</td>
</tr>
<tr>
<td>std dev</td>
<td>0.15</td>
<td>0.28</td>
<td>0.17</td>
<td>/</td>
</tr>
</tbody>
</table>

Table 3: Different morphological parameters for abrasion paleo coastal notches around Sur lagoon.

<table>
<thead>
<tr>
<th>Profile</th>
<th>top (T) [m above MSL]</th>
<th>floor (F) [m above MSL]</th>
<th>height [m]</th>
<th>vertex [m above MSL]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>2.76</td>
<td>1.42</td>
<td>1.34</td>
<td>/</td>
</tr>
<tr>
<td>8</td>
<td>3.13</td>
<td>1.78</td>
<td>1.35</td>
<td>/</td>
</tr>
<tr>
<td>mean</td>
<td>2.95</td>
<td>1.60</td>
<td>1.35</td>
<td>/</td>
</tr>
</tbody>
</table>

Table 4: Different morphological parameters for recent coastal notches around Sur lagoon. Early stage notches (Profile 7 and 8) were not taken into consideration for the calculation.

<table>
<thead>
<tr>
<th>Profile</th>
<th>top (T) [m above MSL]</th>
<th>floor (F) [m above MSL]</th>
<th>height [m]</th>
<th>vertex [m above MSL]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0.29</td>
<td>-0.44</td>
<td>0.73</td>
<td>/</td>
</tr>
<tr>
<td>10</td>
<td>1.25</td>
<td>0.25</td>
<td>1.00</td>
<td>/</td>
</tr>
<tr>
<td>mean</td>
<td>0.77</td>
<td>-0.10</td>
<td>0.87</td>
<td>/</td>
</tr>
</tbody>
</table>
Figure 36: Sur lagoon with the present sea level (a) and Eemian sea level (b). The latter was redrawn according to the model made by Bagci (2017). It shows the area with a sea level height of 4,80 m above present MSL, which represents the highest *Lithophaga* borings from Eemian coastal notches. Urban areas are indicated in grey. Both maps were created using CorelDRAW X8.
As shown in this chapter, the morphology of a notch and especially the measurement of the floor, top and vertex are valuable tools for reconstructing the past sea level (see e.g. Trenhaile (2015) or Pirazzoli and Evelpidou (2013)). However, if the whole notch is not preserved, for example the roof collapsed, it is difficult to tell where the deepest or highest part of the notch is located, and the measurement of the important parameters becomes challenging. The vertical distribution of bioerosional and bioconstructional organisms is not influenced by this and can be used as additional information regarding the position of the past sea level. It is therefore advisable to always consider both indicators.

9.7 DISCUSSION OF POSSIBLE ERRORS

As shown in the discussion, the direct comparison of the distribution of bioerosional/bioconstructional organisms in paleo coastal notches around Sur lagoon with the literature mostly shows strong discrepancy. The most likely reason has also been stated and supported by the appearances of impossible distribution like the supratidal oysters and *Lithophaga*: Further regression/transgression phases after the initial formation of the notch during the Eemian period led to a distortion of the organisms’ distribution and can thus explain the discrepancy with the literature. There are however, further causes that must be considered:

for once, the uncertainty in identifying the species of an organism. It is thus not possible to compare it properly with the literature, as for example it is the case with barnacles.

Furthermore, errors in measurements of the notches (see section 7.5) can lead to a misinterpretation of the definition of the zones defined by Pirazzoli (1986). This is especially most likely if the typical form of the notch was not clearly visible, which made the measurement of the floor and top quite difficult (e.g. Profile 4, 5 and 6) or if the roof collapsed. Hereby, the interpretation of the height of the past MSL in Figure 33 due to the vertex must be also viewed with caution as it is unclear if the roof of the notch was completely preserved or not (see section 6.3.1). In addition, if a beachrock was situated within a coastal notch (e.g. Profile 2 and 4), the zonation of certain organisms had to be interpolated. Moreover, due to the highly eroded stage of some bioerosional features (*Lithophaga* borings) it was not possible to exactly define other zonations (e.g. sponge borings) in some cases (e.g. Profile 1 and 2).
10 Conclusions

During a two-week fieldwork in the area of Sur lagoon, Oman, ten profiles of paleo- as well as recent coastal notches were recorded. In the paleo coastal notches five bioerosional/bioconstructional organisms were identified and their distribution noted in order to evaluate their potential use as a sea level indicator and investigate the hypothesis proposed in the introduction. These organisms include *Lithophaga*, sponges, oysters, barnacles and worms.

From this research it can be concluded that of those five organisms, oysters, *Lithophaga* and sponges can be used as a sea level indicator around Sur lagoon, while worms might be possible to use if additional research is done. The first hypothesis, that bioerosional and bioconstructional features in coastal notches can be used as a sea level indicator in the area of Sur lagoon, can thus, at least partly, be verified. Oysters and *Lithophaga* can thereby be used to identify the intertidal zone, whereas sponges are indicators for the subtidal zone. These conclusions were only possible to make as the distribution of the organisms in the paleo notches was compared to the ones in recent notches. Thereby, the distortion of the zonations due to additional sea level changes was eliminated.

These additional sea level changes after the initial formation of the notches during the Eemian period are proven by the distributions of supratidal oysters and *Lithophaga* borings as well as worms, oysters (and possibly barnacles) that are situated inside or on top of *Lithophaga* borings. All of these factors show that the sea level must have changed in a decimeter to meter range. The second hypothesis, that all bioerosional and bioconstructional features found in the same notch were produced during a single regression/transgression phase is therefore refuted. As the area around Sur lagoon is tectonically stable, the sea level changes cannot be attributed to isostatic but to eustatic changes.

In addition to the two hypotheses regarding the distribution of organisms, this research shows that the morphology of a notch can be further used to make assumptions about past sea level changes: with the identification of the vertex, the height of the MSL can be reconstructed at 3,80 m. Furthermore, comparing the morphology of the investigated recent with the paleo coastal notches reveal changes in the tidal range since the Eemian period in a centimeter to decimeter range. This can be either explained due to an error within the measurements or due to a change in the topography of the coastal area, which most likely was not a lagoon during the Eemian period. This is further proven by the height of the investigated abrasion notches, which have been formed by wave action.
10. Conclusions

10.1 Outlook

This research showed that the Sultanate of Oman is a valuable, and so far, underestimated area when it comes to the study of biological sea level indicators. Further studies from Oman or neighboring countries are necessary to collect more accurate data to either support or refute the conclusions made in this thesis.

Future projects investigating bioerosional and bioconstructional features in coastal notches can hereby be improved by considering following advices.

- It is important that whenever the distribution of organisms in paleo notches is noted, the same must be the case for recent notches. Otherwise a comparison and thus an elimination of a distortion due to e.g. sea level changes is not possible.

- Although the focus lies on the zonation of the organisms, the most significant parameters of a notch described by Pirazzoli (1986) and Trenhaile (2015) need to be recorded as well. This is especially true for the vertex in order to identify the past MSL and to make an identification of the tidal zones easier.

- The position of every location where a profile is taken needs to be recorded with a DGPS. Otherwise, it is not possible to put an absolute scale on the measurements and thus use it as a sea level indicator (as with Profile 6).

- In addition to any measurements taken with a measuring tape, a handheld laser distance meter should be used to record any profiles as proposed by Kázmér and Taboroši (2012b), as a better accuracy can be achieved and the shape of the notch can be recorded more easily.

- If the use of a handheld laser distance meter is not possible, the measurements should at any rate always be taken by at least two people in order to minimize the measurement error with the measuring tape.

- If possible, the investigated organisms should be identified to their family or even species level. Thus, a comparison with zonations described in the literature is easier and more accurate.


KÁZMÉR, M. in prep. Biological indicators of sea level in the tropics.


11. Literature


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12. Acknowledgements

12 ACKNOWLEDGEMENTS

First of all, I would like to thank my supervisors PD Dr. Gösta Hoffmann and Prof. Dr. Miklós Kázmér for providing me with the opportunity to travel to Oman and write this thesis. I would also like to thank them for being always open to any questions and their constructive criticism as well as proofreading the first draft of the thesis.

I would further like to thank all my fellow master students in the ‘Masterraum’ for helpful discussions and working days that were often filled with laughter. In addition, I would like to thank all my fellow students and my brother Michael Cahnbley that made my masters studies in Bonn enjoyable and helped me feel at home. Without you guys, all the lectures would have been only half as good.

Special thanks to Kerstin Ringering and Melina Cahnbley for proofreading the first draft and all their positive criticism that helped to improve this thesis.

I would also like to thank my whole family, especially my parents Karen and Jens Cahnbley as well as my grandmother Anke Töwe. Without their financial help, I wouldn’t have been able to travel to Oman yet alone complete my Masters.

Last but not least, I would like to thank my boyfriend Jelle Heijne for proofreading not only the first but all other versions of this thesis, for his constructive criticism and his continuous support in all aspects of my life.
Table 5: List of all GPS points taken around Sur lagoon with their respective coordinates and a short description. The underlined numbers are part of the western area and were therefore described by Adolphs (2017).

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14 STATUTORY DECLARATION

I herewith declare that I have composed the present thesis myself and without use of any other than the cited sources and aids. Sentences or parts of sentences quoted literally are marked as such; other references with regard to the statement and scope are indicated by full details of the publications concerned. The thesis in the same or similar form has not been submitted to any examination body and has not been published. This thesis was not yet, even in part, used in another examination or as a course performance.

Place, Date: .................................................... Signature: .....................................................................