Bioerosional features in coastal notches

Reconstructing sea level fluctuations during MIS 5e by using biological indicators (Sur, Sultanate of Oman)

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Statutory Declaration

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Index of abbreviations

asl: above mean sea level
BI: Bioerosion Index
BIL: Bioerosion Index Level
DGPS: Differential GPS (Global Positioning System)
ITCZ: Intertropical Convergence Zone
OSL: Optically Stimulated Luminescence
MIS: Marine Isotope Stage
MSL: Mean Sea Level
HLDM: Handheld Laser Distance Meter
RSL: Relative Sea Level
Abstract

Bioerosion notches are one of the most precise sea level indicators. They are primarily carved into carbonate rocks during stable sea levels at mean sea level (MSL). It is assumed that the main erosion is caused by bioeroding organisms. They live in vertical belts associated with MSL and generate a typical zonation. This zonation is widely used as an indicator for sea level position and is generally coinciding with bioerosion notches. A shifted zonation of organisms may be caused by post notch formation sea level changes. Under these conditions, notch and bioerosional features indicate multiple sea levels and cannot be used to reconstruct one precise sea level. This study shows that the combination of a bioerosion notch and biological indicators can be used to determine sea level development during MIS 5e. Broadened and conflicting zonations provide evidence for a more complex sea level history than simply one stable highstand. A distinct sea level rise of several decimeters after the notch formation and most likely a subsequently dropping sea level was proven. The results show that biological indicators like Lithophaga, oysters and others adapt to changing sea levels with their distribution. Sea level research often focusses on sea level indicators emerging during stable conditions or on indicators roughly representing distinct climate periods. The combination of stable and quickly corresponding sea level indicators, notches and biological indicators, improve the information of sea level changes before or after the stable sea level. These methods support the investigation of highly interesting periods like MIS 5e.
1 Introduction

1.1 Aim

Coasts and sea level are in constant transition. With rising sea levels in recent times, the investigation of past sea levels is of increasing importance. A large portion of human populations, settled down near coastal areas. These people in particular are affected by sea level rise and associated coastal hazards.

Different tools and indicators are used to examine former sea levels (see Rovere et al. 2016). One of these important sea level indicators are coastal notches. They are widely used as potential indicators of former sea levels and relative sea level changes (Abad et al. 2013, Evelpidou et al. 2012a, Kázmér et al. 2015). In particular, notches formed during MIS 5e are of great interest and can provide important information about possible future changes and developments (Rovere et al. 2016).

The only way to reconstruct paleo sea levels in a direct way is to measure geomorphological and biological indicators (Rovere et al. 2016). In this thesis different trace fossils associated with a bioerosion notch were surveyed. The notch was presumably formed during MIS 5e. The gathered data supports the attempt to reconstruct not only the MSL (mean sea level) associated with the bioerosion notch but also to investigate short term sea level fluctuations within this sea level highstand. Hence, this study is the first approach to reconstruct short timed and small scale sea level fluctuations with organism zonations present in a bioerosion notch. Moreover, notches that formed as a consequence of mechanical erosion are also present in the study area and are examined regarding their ability to reconstruct former sea levels.

The summarized main aims of this thesis are:

- mapping the outcrops of the bioerosion notch and abrasion notch
- measuring the bioerosion notch and the zonation of the occurring organisms
- documenting bioerosional features
- tracking the development of sea level by separating different phases of notch development
- and, to a lesser extent, investigating the second notch type, classified as an abrasion notch, with respect to origin and sea level reconstruction

The investigation of notches is the simplest at tectonically stable coasts (Baker et al. 2001, Sisma-Ventura et al. 2017). Such a probably tectonically stable coast is studied in this master thesis. The study area is located at the south-easternmost part of the Arabian Peninsula, in the Sultanate of Oman. At a lagoon near the city of Sur two types of notches were explored. The principally examined notch is hypothesized to be generated at MIS 5e (Last Interglacial). This was a time in the earth’s history with comparable conditions to today’s temperature. Hence, the investigation of these geomorphological structures is important, especially in respect to rising temperatures in near the future (Rovere et al. 2016). The second type of notch examined was originated presumably through mechanical erosion and is classified as an abrasion notch. This notch type has a subordinated value as
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a tool for sea level reconstruction. Nevertheless, abrasion notches were investigated in relation to their genesis and their validity to reconstruct former sea levels.

1.2 Supporting projects

This master thesis is part of two projects related to coastal geology. The first project is supported and performed by the IGCP (International Geoscience Program) and called “Sea level changes from minutes to millennia” (IGCP Project 639). The goal of this project is a better understanding of long-term changes influencing coastlines and their development. This is strongly connected to climate change naturally accompanied by coastal hazards. In particular, the anthropogenic influence on sea level change and generated coastal hazards is the main focus of this project. In combining different short-term and long-term records of different fields like archaeology and geology, the attempted is to provide a “hazard toolkit” particularly for those people in endangered coastal areas.

The second project is called “Quantification of relative sea level change along the coastline of Oman (Arabian Sea)” and is supported by the German Science Foundation (DFG). The general topic of this project is coast geomorphological analyses. The study area is located at the northeastern coast of Oman. Here, marine terraces of quaternary age are shaping the landscape. They formed due to a combination of uplift and eustatic sea level change. But the concrete mechanisms of uplift still need to be investigated. Therefore, the aim of this project is to reify the different mechanisms leading to the formation of these stair-cased terraces and to calculate the general uplift rate. Moreover, deposits of extreme wave events like tsunami deposits and storm surges are examined.
2 Geography

2.1 Geographic location and landscapes

The Sultanate of Oman is located on the Arabian Peninsula at the south-easternmost part and shares borders with Yemen, Saudi Arabia and the United Arab Emirates (Figure 2.1a) (Al-Charaabi & Al-Yahyai 2013, Hoffmann et al. 2013b, Kwarteng et al. 2009). The country covers an area of approximately 309,500 km$^2$ and has a coastline of about 1700 km length (Al-Charaabi & Al-Yahyai 2013, McLachlan et al. 1998, Kwarteng et al. 2009). It adjoins to the Arabian Sea (Indian Ocean) and the more sheltered Gulf of Oman (Figure 2.1a) (Hoffmann et al. 2013b). The sultanate is characterized by two mountain chains: the Al Hajar Mountains with a height of maximal 3000 m and a length of 700 km located in the north of Oman and the Dhofar Mountains with a height between 1000 m and 2000 m in the south of the country adjacent to Yemen (Hoffmann et al. 2016, Hoffmann et al. 2013b, Kwarteng et al. 2009). A large number of wadis, which originated in the west to east oriented Al Hajar Mountains, form large alluvial fans to the north and south (Hoffmann et al. 2016, Hoffmann et al. 2013b).

The countryside of Oman is strongly characterized by desert environments like Wahiba Sands, Sharqiyyah Sands or the gravel desert Qarat Kibrit (Hoffmann et al. 2016). These areas are arid to locally hyper-arid and are further very sparse in any kind of vegetation (Hoffmann et al. 2016). Desert environments are covering 82 % of the countryside (Kwarteng et al. 2009). In contrary to these arid zones with minor vegetation, the coastal plains of Oman are fertile and thus used for agriculture (Kwarteng et al. 2009).

Figure 2.1: a) Map of the Arabian Peninsula and surrounding countries. Oman is colored purple. The study area is marked with a red rectangle.
Especially the last years and decades were marked by the rapidly increasing infrastructure, which is strongly emphasized by growth rates of villages and cities, as well as ongoing road construction (Hoffmann et al. 2013b). This is in particular noticeable for coastline in the northwestern part of the Oman (Al-Charaabi & Al-Yahyai 2013).

2.2 Climate

2.2.1 Recent climate

The climate of the entire Arabian Peninsula is mainly characterized as arid (Rohling et al. 2013). The conditions in Oman reach from semi-arid to hyper-arid depending on the location (Al-Charaabi & Al-Yahyai 2013, Hoffmann et al. 2013b, Hoffmann et al. 2015, Kwarteng et al. 2009). Rainfall in these regions is very variable in time, duration and quantity (Choudri et al. 2013, Kwarteng et al. 2009). Therefore, water is of great value, especially in agriculture (Al-Charaabi & Al-Yahyai 2013). A great amount of groundwater recharge is controlled by wadi flow (Choudri et al. 2013). These flows occur after heavy rainfall and last a few hours to a few days depending on different factors like hydrological setting and intensity of rainfall (Choudri et al. 2013). It is difficult to achieve equilibrium between groundwater recharge and agriculture usage because agriculture is indentured to irrigation (Al-Charaabi & Al-Yahyai 2013). Moreover, it needs most water out of all sections (94 %) (Kwarteng et al. 2009). The consumption of water in the northern part of the country exceeds the annual groundwater recharge about 25 % (Al-Charaabi & Al-Yahyai 2013). The excessive removal of water out of the aquifer led to saltwater intrusion into aquifers and increasing water scarcity (Al-Charaabi & Al-Yahyai 2013). To prevent or mitigate this increasing water scarcity desalination of sea water is used to provide more water (Al-Charaabi & Al-Yahyai 2013) in particular for domestic use (Kwarteng et al. 2009).

The Arabian Peninsula is mostly influenced by two air masses, the Polar Continental in winter and the Tropical Continental in summer (Al-Charaabi & Al-Yahyai 2013, Kwarteng et al. 2009). The Polar Continental causes cold temperatures and the Tropical Continental brings hot and dry air (Al-Charaabi & Al-Yahyai 2013). Depending on these air masses, the topography and other conditions rainfall occurs (Kwarteng et al. 2009). In general a positive correlation of height and average annual precipitation is observable (Kwarteng et al. 2009). The annual precipitation in the Sultanate Oman reaches from less than 50 mm up to 400 mm at the Hajar Mountains (Hoffmann et al. 2013b, Al-Charaabi & Al-Yahyai 2013). Kwarteng et al. (2009) investigated that the average annual precipitation in Oman between 1977 and 2003 is about 117 mm (Kwarteng et al. 2009). It is important to mention that the average annual rainfall is highly variable (Kwarteng et al. 2009). In the central and northern part of Oman the strongest precipitation occurs in the Hajar Mountains (Figure 2.2) (Al-Charaabi & Al-Yahyai 2013, Hoffmann et al. 2013b). The rainiest months are February and March with one third of the annual precipitation (Figure 2.3) (Kwarteng et al. 2009). The Dhofar region in the most southern part of Oman as well as Yemen are strongly influenced by heavy precipitation during the summer, called Khareef (Al-Charaabi & Al-Yahyai 2013, Hoffmann et al. 2016, 2015 and 2013c, Kwarteng et al. 2009). During this period almost two third of the annual rainfall of this region occurs (Kwarteng et al. 2009). The reason for those rain events is the shift of the Intertropical Convergence
Zone (ITCZ) to the north causing the southwesterly monsoon (Hoffmann et al. 2016, 2015 and 2013c, Kwarteng et al. 2009).

Due to the strongly varying topography the temperatures differentiate depending on the location (Kwarteng et al. 2009). For example the coastal areas in the northeast of the country show the highest annual average temperature up to 30 °C, while the lowest average annual temperatures occur at the peaks of the Hajar Mountains (Figure 2.2) (Al-Charaabi & Al-Yahyai 2013). The hottest month in Oman is June while the coldest is January (Al-Charaabi & Al-Yahyai 2013). Nevertheless, plant communities and their flowering is more dependent on rainfall than on varying temperatures (Kwarteng et al. 2009).

In the last few years devastating tropical cyclones like Gonu (2007) and Phet (2010) reached the coastal areas of Oman. They caused damages of billions of dollars and several casualties (Al-Charaabi & Al-Yahyai 2013). It is likely that with increasing temperatures the severity of such meteorological events will intensify (Al-Charaabi & Al-Yahyai 2013).

Figure 2.2: Average annual temperatures (left) and average annual rainfall (right) in Oman (Redrawn after Al-Charaabi & Al-Yahyai 2013).

Figure 2.3: Average monthly rainfall in Oman. Red outlined bars mark rainiest month of the year (Redrawn after Kwarteng et al. 2009).
2.2.2 MIS 5e

MIS 5 (abbreviation for Marine Isotope Stage 5) is located around 80,000 a BP till 130,000 a BP. This stage can be subdivided into five substages from MIS 5a to MIS 5e (Shackleton et al. 2003). The main focus of this thesis is on MIS 5e because it is the probable period the investigated bioerosion notch was formed. This is indicated by a sea level probably 4 m higher than it is today and the dating of a near associated beach rock to 80,000 +/- 3,000 a BP (Mauz et al. 2015).

Marine Isotope Stages are based on benthic oxygen records collected almost all over the oceans (Shackleton et al. 2003). To create these records mostly foraminiferal shells of deep sea sediment cores were used (Yokoyama & Esat 2016). The different stages describe a cycle of climatic and sea level changes of 100,000 a (Yokoyama & Esat 2016). This cyclicity is named after Milankovitch who first recognized this pattern. Only 10 % of each cycle shows warmer temperatures and a high sea level (Yokoyama & Esat 2016). These warm periods are the MIS with uneven numbers like MIS 5.

MIS 5e is located in the Last Interglacial called the Eemian. The duration of this substage, which shows the highest sea levels of the entire MIS 5, is not fully elucidated. Abad et al. (2013) sets the start of MIS 5e around 133,000 a BP and the end to 116,000 a BP. In contrast Murray-Wallace and Woodroffe (2014) define a shorter timespan from 128,000 a BP till 116,000 a BP. These various durations can be explained by different responses to glacio-hydro-isostatic processes based on spatially differences (Murray-Wallace & Woodroffe 2014).

The temperatures were just 1,5 °C above the contemporary mean temperatures (Figure 2.4) (Abad et al. 2013, Lorscheid et al. 2017b, Rohling et al. 2007, Rovere et al. 2016, Shackleton et al. 2003). The polar temperatures on both hemispheres were 3-5 °C higher than today (Rovere et al. 2016). Therefore, it is assumed that the polar ice sheets were smaller and hence the sea level several meters higher (Ferranti et al. 2006, Lorscheid et al. 2017b, Rohling et al. 2007, Rovere et al. 2016, Shackleton et al. 2003). On an average the sea level was 6m (+/-3 m) higher (Sisma-Ventura et al. 2017) and presumably in some parts of the world in short term fluctuations about 10 m higher (Abad et al. 2013, Rohling et al. 2007). The number of highstands during MIS 5e is still investigated and unclear (Abad et al. 2013) but it is assumed that the highest sea levels of MIS 5e were reached near the end of this highstand (Murray-Wallace & Woodroffe 2014, Rovere et al. 2016). Hearty et al. (2007) assumes a broader and lower peak at the beginning of MIS 5e and a sharp and high peak at the end of MIS 5e with single and relatively short sea level stagnations. They portray these periods as likely to generate notches (Hearty et al. 2007).

Presumably caused by the Industrial Revolution the temperature increased since 1880 by ~0,85 °C (Rovere et al. 2016). There are assumptions that the global mean temperature will rise another 1 °C till the end of the century (Rovere et al. 2016). This would cause the polar temperatures to increase probably by another 3-5 °C (Rovere et al. 2016). This would arouse the ice sheets to loose volume and hence the sea level to rise. With rising global mean temperatures initiated by anthropogenic greenhouse-gas emissions the climatic conditions of the future probably fit to the conditions during MIS 5e (Abad et al. 2013, Rohling et al. 2007). In contrast to the situation today the rising temperatures in MIS 5e were likely caused by orbital forcing on insolation instead of greenhouse-gas
emissions (Hearty & Tormey 2017, Rohling et al. 2007, Rovere et al. 2016). Therefore the CO$_2$ concentrations during MIS 5e were as high as before the start of Industrial Revolution (Lorscheid et al. 2017b). Nevertheless, the investigation could provide important information about future changes of sea level. Geomorphological features like marine terraces, coastal notches, beach rocks and more provide a great amount of information about this distinct sea level highstand (Murray-Wallace & Woodroffe 2014, Rovere et al. 2016).

The climate in Oman during the Quaternary was very variable respectively to precipitation and temperature (Hoffmann et al. 2016). The climate was more humid during interglacial periods and more arid during glacial periods (Hoffmann et al. 2016 and 2015).

Figure 2.4: a) Relative sea level changes of the last 140,000 a BP (Burbank & Anderson 2012). The red dashed lines roughly mark the substage MIS 5e/Eemian. b) Possible sea level fluctuations during MIS 5e. Blue stars mark the timespans when notches were likely generated (Redrawn after Hearty et al. 2007).
2.3 Tides

The tidal range is not a steady value but varies depending on the lunar cycle and the position of the sun (Grotzinger et al. 2007). The moon has twice the influence on oceanic and lake waters than the sun (Reading 1996). The fluctuation of water in near-shore areas is triggered by a bulge of water which forms in the open ocean (Grotzinger et al. 2007). This body of water, less than 1 m in height, rises and falls while earth rotates (Reading 1996). On earth, this typically leads to two high tides and two low tides a day, called semi-diurnal tides (Reading 1996). However, depending on the shoreline geomorphology and other variables some coasts only experience one high and one low tide per day (Reading 1996).

A high tide occurs roughly every 12 h and 26 min (Reading 1996). This exact time frame of 12 h and 26 min can be explained with the difference between the lunar and the solar day (i.e. the lunar day is longer) (Grotzinger et al. 2007). The moon needs in general longer to orbit earth than the sun. This relationship between earth, moon and sun is the reason why the tidal configuration of high and low tide shifts every day and that the high tide gets gradually 50 min later (Reading 1996).

The spring tide occurs when the moon and the sun are lined up which happens only at new or full moon (Grotzinger et al. 2007, Reading 1996). During this time the tidal range reaches its maximum and is about 20% higher than normal (Reading 1996). On the contrary, the lowest tide occurs when moon and sun are in a 90°-angle to the Earth (Reading 1996). This phenomenon is called neap tide and leads to a tide 20% lower than normal (Grotzinger et al. 2007, Reading 1996). The height of the tide is not only influenced by the lunar cycle but also depends on the geomorphology of the area (Grotzinger et al. 2007). Narrow passageways between the open ocean and the shore can, for example, force the water to rise higher than the average amplitude of high tide and thus increase the variance between high and low tide (Grotzinger et al. 2007).

The maximum range of the spring tide at the northeastern coast of Oman is about 3 m (Figure 2.5b) (Hoffmann et al. 2013b). This tidal range classifies the northeastern section of the coast of Oman as mesotidal (Hoffmann et al. 2013b). In contrast to microtidal seas, which have a very small tidal range, mesotidal seas by definition must have a tidal range between 2 m and 4 m. At the northeastern coast of Oman semi-diurnal tides occur, with two highs and lows per day (Figure 2.5a). The tidal range inside of the lagoon next to Sur is significantly smaller than in the open sea and has been found to be in the microtidal range with tides on average of 1.2 m (Donato et al. 2009). During low tide the lagoon is mostly water-free so that sandy deposits are exposed (Donato et al. 2009). With great probability the current tidal range and the Eemian tidal range were not identical (see chapter 7.1.3). Mean tidal ranges are not stagnant and often change over longer time periods due to changes of the geomorphology (Pirazzoli et al. 1986, Woodroffe & Barlow 2015).
Figure 2.5: Tidal datum’s measured at the sea level station in Sur. a) Tidal range surveyed at the 15th of August. Example for the mesotidal conditions at the coastline of Oman. b) Tidal range with its change over the course of one month. Alternation of neap and spring tides (Redrawn after Sea Level Monitoring Facility 12.09.2017).
Regional geology of northeastern Oman

In the following chapter the stratigraphic units and their depositional history are elucidated. It is focused on the northeastern part of Oman, in particular the Hajar Mountains. In general the stratigraphic units of the Oman Mountains can be divided into two superordinate groups: autochthonous units and allochthonous units (Glennie 2005, Hoffmann et al. 2016). The geological development is described between the Proterozoic and the Quaternary (see Figure 3.2).

3.1 Stratigraphic units

*Crystalline basement*

The crystalline basement provides the oldest rocks of Oman with an age of approximately 800 Ma (Neoproterozoic) (Glennie 2005, Hoffmann et al. 2016). The basement encompasses metamorphic rocks like gneisses or micaschists. Moreover, igneous rocks, mostly granites, granodiorites, diorites and dolerites, are intruding into the metamorphic rocks (Gass et al. 1990, Glennie 2005, Hoffmann et al. 2016, Mercolli et al. 2006). The rocks of the crystalline basement for example are exposed in the Hajar Mountains at Jabal Qahwan, at Qalhat and near Sur (Gass et al. 1990, Glennie 2005, Mercolli et al. 2006). This unit was formed during the Late Proterozoic by continental accretion, which means that several island arcs and microcontinents accreted to form this basement (Gass et al. 1990, Glennie 2005). It is part of the Pan African domain and therefore younger than the basement identified in Saudi Arabia (Gass et al. 1990).

*Sedimentary Basement (Autochthonous Unit A)*

During this period Oman was part of the supercontinent Gondwana (Allen 2007, Hoffmann et al. 2016). The rocks of this unit - which are exposed around Huqf and in the related salt basin - represent the best known sequence of Precambrian rocks and can primarily be associated with the two supergroups Huqf (Late Proterozoic and Early Paleozoic) and Haima (Late Paleozoic) (Glennie 2005). They were deposited from the Late Proterozoic to the Early Silurian (Glennie 2005, Hoffmann et al. 2016). The rocks of the Early Permian are part of the Haushi Group (Glennie 2005).

The Abu Mahara Group is part of the Huqf Supergroup and consists of diamicritites linked to global glaciation periods (Allen 2007, Glennie 2005). This group was simultaneously accumulated with the Mistal Formation and the Hatat Formation and is covering the crystalline basement (Allen 2007, Glennie 2005, Hoffmann et al. 2016). All deposits are predominantly clastic sediments accumulated in extensional fault basins (Bowring et al. 2007). The following Nafun Group (Huqf Supergroup) is made up of mostly carbonate and clastic sediments and generally referred to as platform carbonates (Allen 2007, Bowring et al. 2007, Hoffmann et al. 2016). It can be subdivided into four formations representing more of a regional subsidence with a widespread deposition in contrast to the Abu Mahara Group (Allen 2007, Bowring et al. 2007). The transition of the Nafun Group to the overlying Ara Group is marked by tectonic activity separating a larger basin into several smaller fault controlled basins, called the South Oman Salt Basin, the Ghaba Salt Basin and the Fahud Salt Basin (Bowring et al. 2007, Droste 1997, Schröder et al. 2003). Simultaneously, the climate got more arid
leading to the deposition of evaporates in this graben system (Bowring et al. 2007, Droste 1997). In deep areas of the basins salt was accumulated whereas in higher parts (uplifted blocks) carbonate was deposited (Allen 2007, Bowring et al. 2007, Schröder et al. 2003). These Ara Group deposits are very good source rocks for hydrocarbon (Bowring et al 2007, Glennie 2005, Schröder et al. 2003).

Rocks of Cambrian, Ordovician and Silurian age are not present in the Hajar Mountains and only in parts in Huqf and Sayh Hatat. These rocks are part of the Haima Group (second supergroup) and the Amdeh Formation (Glennie 2005, Hoffmann et al. 2016). The depositional environment of the Haima supergroup is mostly continental but changing into shallow marine and deltaic for the upper part (Droste 1997, Glennie 2005). These sedimentary rocks lay unconformable on the Ara Formation and fill up the previously mentioned basins (Allen 2007, Droste 1997). They are important source rocks of oil and gas (Glennie 2005). In Late Silurian and Carboniferous times the basin infills got tilted towards the west and the active salt movements led to increasing erosion in these regions (Droste 1997). During the Devonian and the Carboniferous the depositional environment was probably continental (Glennie 2005, Hoffmann et al. 2016). No deposits were preserved in continental basins leading to the assumption that a time of crustal stability was prevalent (Glennie 2005).

The Haushi Group represents deposition in Late Carboniferous and Early Permian times (Glennie 2005). The Gharif Formation, part of the Haushi Group, indicates uplift concurrently to Early Permian deposition (Blendinger et al. 1990).

**Arabian Platform (Autochthonous B) and Hawasina nappes (Allochthonous Unit)**

The climate changed from a glacial period in the Early Permian to tropical conditions in the Middle Permian (Angiolini et al. 2003). The breakup of Gondwana and the emergence of the Neotethys Ocean basin led to the development of the passive continental margin of the Arabian Plate (Angiolini et al. 2013, Warburton et al. 1990). The precise timing is still under debate (Angiolini et al. 2003). Concurrently with the opening of the Neotethys Ocean a regional and great subsidence of the Arabian Platform started and a major transgressive event led to the deposition of the Khuff Formation in Mid-Permian times and represents the carbonate shelf sedimentation (Figure 3.1) (Angiolini et al. 2003, Hoffmann et al. 2016). Mostly limestones and marls were deposited. They have a high content of fossils and among others contain bivalves, brachiopods, trilobites (Angiolini et al. 2003). The color of the limestone ranges between white and grey. The carbonates were deformed during the Eo-Alpine Orogenesis and locally metamorphosed (De Weaver et al. 1990). This led to the end of carbonate deposition caused by uplift (Hoffmann et al. 2016).

During the Late Permian a great intracontinental basin at the passive margin of the Southern Tethys developed (Béchennec et al. 1990, DeWever et al. 1990). The basin was formed due to rifting and extension along the northern part of Gondwana and limited by the Arabian Platform (Béchennec et al. 1990, Searle 2007). The basin is called Hawasina Basin and can be divided into the proximal Hamrat Duru Basin and the distal Umar Basin (Figure 3.1) (Béchennec et al. 1990, Bernoulli et al. 1990). Along the continental slope sediments of the Sumeini Group were deposited.
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(Figure 3.1) (Bernoulli et al. 1990, Glennie 2005). The accumulation of the deeper parts was characterized by pelagic sediments, commonly radiolarites and calcareous turbidites (Béchennec et al. 1990, Bernoulli et al. 1990). The deposition of this unit and the Autochthonous B was concurrent (Béchennec et al. 1990, Glennie 2005). The Arabian Platform was one of the main sources of the Hamrat Duru Basin (Béchennec et al. 1990). It is assumed that a second rifting and extensional phase during Late and Middle Permian times led to magmatic activity, especially in the Umar Basin (Béchennec et al. 1990, Searle 2007).

Initiated by subduction roughly 105 Ma BP the sediments of the Hawasina Basin were transported and faulted as well as folded, leading to the appearance of the Allochthonous Unit at the present day (Glennie 2005). The stratigraphic unit was emplaced on the Arabian Platform (Béchennec et al. 1990, De Weaver et al. 1990, El-Shazly & Coleman 1990, Le Métour et al. 1990). Nowadays, it is positioned between the sediments of the Arabian Platform and the Samail Ophiolite (De Weaver et al. 1990, Hanna 1990). The uppermost part of the Umar Group that is in contact with the ophiolite is metamorphosed (Glennie 2005).

Samail Nappes (Allochthonous Unit)

The Samail Ophiolite originated during the Early Cretaceous and obducted onto the Arabian Platform from NE to SW in Late Cretaceous times (DeWever et al. 1990, Hanna 1990, Searle 2007). Concurrently the Tethys Ocean closed (El-Shazly & Coleman 1990). The Samail Nappe is the largest and best exposed ophiolite worldwide. The oceanic crustal sequence is covering an area of roughly 20,000 km² (see Figure 3.2) (Warren et al. 2005). Starting at the base, the sequence consists of harzburgites and dunites followed by gabbros and sheeted dykes and eventually pillow lavas and pelagic sediments at the top (Figure 3.2) (Warren et al. 2005). Underneath the ophiolite a thin metamorphic sole is present (Figure 3.1) (El-Shazly & Coleman 1990, Warren 2005). This sole consists of amphibolite and greeenschists (El-Shazly & Coleman 1990). It is assumed that the ophiolite was formed in a supra-subduction zone setting (Warren et al. 2005). The precise procedure of the emplacement of the Hawasina Nappes as well as the Samail Nappes remains controversial (see Glennie 2005, Searle 2007, Warren et al. 2005). The questions if one or two subduction zones led to these structures and the direction they are dipping in, as well as whether the Hawasina Supergroup and Samail Ophiolite were obducted on a passive Arabian platform are still unclear (see Fournier et al. 2006, Searle 2007, Warren et al. 2005). Further research is needed to determine the formation of the stacked sequences.
Figure 3.1: Formations of the Arabian Platform and the Hawasina Basin with a NE dipping subduction zone (Redrawn after Searle 2007).

**Sedimentary Cover (Autochthonous Unit) and uplift of mountain chain**

Simultaneous to the emplacement of the ophiolite the formations Muti and Juwaizah were accumulated (Fournier et al. 2006). The Fiqa Formation was deposited into the foreland basin that developed in front of the Nappes concurrent and subsequent to the emplacement of the ophiolite (Fournier et al. 2006, Nolan et al. 1990). All three formations are part of the Aruma Group (Searle 2007). They consist of conglomerates, deep water shales, siltstone and eroded debris of the Samail Nappes (Searle 2007). The end of tectonic movements is roughly dated to 70 Ma BP (Searle 2007).

The area of what is nowadays called the Hajar Mountains was subaerially exposed due to eustatic sea level fall during the Late Cretaceous and hence deferred to erosion and weathering (Nolan et al. 1990, Searle 2007). Subsidence in areas N and NW of the mountain chain led to the accumulation of the Qahlah, Al Kwahd and Simsima Formations (Nolan et al. 1990). Some researchers are allocating them to the Aruma Group (see Fournier et al. 2006), but others separate the three formations from the Aruma Group (see Searle 2007). The Qahlah Formation mainly consists of fluvial or shallow marine terrigenous deposits (Nolan et al. 1990). The Al Kwahd Formation is consisting of conglomerate, sandstone, shale and limestone (Nolan et al. 1990). Both formations, especially Al Kwahd, lay at many localities unconformably above the Samail Nappe (Searle 2007). The Simsima Formation consists of shallow marine carbonate and is conformably overlying the Qahlah Formation (Nolan et al. 1990). These shallow marine sediments were primarily accumulated above the Samail Nappe during the Late Cretaceous until Oligocene (Fournier et al. 2006, Glennie 2005, Searle 2007). During the Late Cretaceous minor deformation and a slight uplift of the mountains took place visible at the unconformities underneath and above Simsima Formation (Searle 2007). However, the Simsima Formation indicates stable shelf conditions and definitely marks the end of nappe emplacement (Searle 2007). The accumulated sediments are often referred to as neo-autochthonous.
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(Fournier et al. 2006, Glennie 2005). With the start of the Paleocene (Danian) shallow marine deposition finally dominates in northeastern Oman. Three cycles of regression and transgression made for the deposition of the Hadhramaut Group (Fournier et al. 2006). After the formation of the Murka platform the carbonate platform of the Jafnayn Formation was accumulated (Fournier et al. 2006). Above the Jafnayn Formation marine deposits of the Rusayl Formation are following. The last cycle is characterized by the Seeb Formation which is made up of shelf carbonate deposits (Fournier et al. 2006).

The main uplift of the mountains and domal structures like Jabal Akhdar and Sayh Hatat are by most authors assigned to the Tertiary (Late Oligocene) (see Fournier et al. 2006, Glennie 2005, Le Métour et al. 1990, Searle 2007). The majority state that compressional tectonic led to the uplift (Glennie 2005, Le Métour et al. 1990, Searle 2007, Warburton et al. 1990) but the exact processes leading to the compression and uplift are still under debate (see Hanna 1990). However, the uplift was at least about 2000 m strong (Searle 2000). The compression primarily caused large scale open folds as well as box folds (Searle 2007).

One theory is that extension in the Gulf of Aden started the process which resulted in the collision of the Arabian Plate and the Eurasian Plate in the Zagros region in Iran. This was followed by compression in the Oman Mountains (Fournier et al. 2006, Searle 2007, Warburton et al. 1990). This led to a rapid uplift of Jabal Akhdar roughly 25 Ma BP (Fournier et al. 2006). The rifting in the Gulf of Aden is still active in recent times (Fournier et al. 2006).

Quaternary evolution

The Quaternary was a very characterizing period for the landscape of Oman. Climate changes as well as tectonic activity shaped the appearance of the relief. The alternation of glacial and interglacial periods and the associated climate changes originated distinct geomorphological features and deposits. In recent times only the southernmost part of Oman and primarily Yemen are influenced by the Indian Monsoon due to the position of the Intertropical Convection Zone (ITCZ) (Blechschmidt et al. 2009). Nonetheless, samples of lake deposits and speleothems indicate that in former times greater parts of the Arabian Peninsula and therefore northern Oman were affected by monsoon climate (Blechschmidt et al. 2009, Fleitmann et al. 2003). These phases roughly correspond with interglacial periods and are characterized by a significantly higher humidity and a rising sea level. The wetter climate was caused by a northward shift of the ITCZ and hence of the monsoon belt (Blechschmidt et al. 2009, Fleitmann et al. 2003, Preusser et al. 2005). Due to a higher humidity in interglacial periods the mountain chain was more prone to erosion. This resulted presumably in the transportation of debris by reactivated rivers into coastal areas which led to the formation of alluvial fans and fan deltas (Blechschmidt et al. 2009, Hoffmann et al. 2016, Preusser et al. 2005). Another occurrence of a wetter climate was karstification with the ensuing development of large cave systems (Fleitmann et al. 2003).

The recognition of glacial periods with decreased humidity, increased aridity and lower sea level is more difficult (Preusser et al. 2005). However, higher values of dust input in marine sediment records
are indicating a southward shift of the ITCZ in glacial periods (Preusser et al. 2005). Moreover, the formation of great sand bodies like the desert Wahiba Sands are connected to a low sea level indicated by a high content of shells and other bioclastic fragments in the sediment (Preusser et al. 2005). This can be explained by the exposure of the continental shelf.

![Geological map of northeastern Oman](image)

Figure 3.2: Geological map of northeastern Oman. Conspicuous is the large extent of the Samail Ophiolite (Hoffmann et al. 2016).

### 3.2 Tectonic setting

The Arabian Plate has an extent of 2600 km north to south and 3000 km east to west (Stern & Johnson 2010). In the southeast and east the plate borders the Owen Fracture Zone (Figure 3.3) (Stern & Johnson 2010). The Makran Subduction Zone separates the Arabian and Eurasian plate (Hoffmann et al. 2013a) and is located in the east of the plate but with an east-west orientation. Since the Eocene the Makran Subduction Zone, located in the Gulf of Oman, is active and has a dextral strike-slip motion (Fournier et al. 2006). The Arabian Plate dips with an angle of 5° northward beneath the Makran accretionary wedge and is being subducted (Fournier et al. 2006, Hoffmann et al. 2013a). The Makran Subduction Zone is assumed to be the reason for the earthquake and following tsunami in the Arabian Sea in 1945 (see Hoffmann et al. 2013a). The north of the plate is mainly limited by the Zagros collision zone (Figure 3.3) (Stern & Johnson 2010). The Zagros collision zone is a main part of the orogeny of the Hajar Mountains as described in the previous chapter. The
western part of the Arabian plate is confined by the Dead Sea transform fault zone and the Red Sea spreading axis (Figure 3.3) (Stern & Johnson 2010). The Red Sea is currently spreading with roughly 16 mm/a (Stern & Johnson 2010). The south of the Arabian Plate is defined by the Gulf of Aden spreading axis with a yearly spreading value of 20 mm (Stern & Johnson 2010).

Figure 3.3: Map of the tectonic setting of the Arabian Plate and adjoining areas (Redrawn and simplified after Stern & Johnson 2010).

3.3 Study area

3.3.1 Location

The study area is located at the northeastern coast of Oman at the city of Sur (Figure 3.4b). The studied notches are situated along a lagoon about 4 m and 2 m above recent MSL. This lagoon covers an area of approximately 12 km$^2$ (Donato et al. 2009). The sea water exchange between the lagoon and the Gulf of Oman is limited by a single connection between them.

Notches are typically preserved in areas with a relief and without settlements. Therefore, both types of paleo notches (bioerosion and abrasion notches) do mostly occur in the southern part of the study area and are less common near the harbor, as well as other developed parts of the city of Sur in the north (Figure 3.4a).

Three independent master theses have been conducted on the coastal notches around Sur. While two theses mostly investigated the bioerosion features of the bioerosion notch and only to a lesser extent the abrasion notch, the third thesis focused on the entire lagoon of Sur investigating a possible tectonic impact on the notch height (Bagci 2017). In order to allow a detailed field study, the lagoon area has been subdivided into two working areas, of which the eastern side will be the focus of this study, while the western side has been surveyed by Cahnbley (2017). The study of the
bioerosion notch included the reconstruction of the sea level fluctuations after the formation of the notch.

Figure 3.4: a) The lagoon of Sur with marked outcrops and notch types. The red dashed line marks the boundary of the two study areas. Notch outcrops at the eastern side are further described in the results (see chapter 6). b) Geographic location of the study area (red rectangle) at the northeastern coast of the Oman.
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3.3.2 Geology

The stratigraphic units around Sur are all part of the sedimentary cover deposited after the emplacement of the Samail Nappe on the Arabian Platform (Fournier et al. 2006). Hence, the sediments were accumulated during the Late Cretaceous and Tertiary (Fournier et al. 2006). The bioerosion notch (approximately 3.7 m asl) is present in Miocene limestone which is located in the eastern and southern areas around the lagoon and is a little less widespread at the western margins of the lagoon. This beige to slightly yellow colored limestone is part of the Sur formation (Fars Group) (Fournier et al. 2006). Depending on the location, the composition of the limestone varies with respect to its fossil and clay content.

The second characteristic lithology of the study area is the quaternary fluviatile deposits. This lithology consists primarily of polymictic conglomerate. The clasts are dominantly pebble-sized with lesser amounts of granules and cobbles. They consist of limestone, sandstone, quartzite and less common chert. The matrix of this polymictic conglomerate is made of middle to coarse grained sand. The sediment was accumulated about 230,000 a BP (Hoffmann 2017, unpublished data). Both peninsulas, located inside of the lagoon, are almost completely constituted of fluviatile deposits and are controlling the relief of the lagoon. The peninsulas are characterized by a bioerosional horizon appearing at a height of approximately 4 m asl. Below this horizon, at a height of approximately 2 m asl, the abrasion notch is carved into the sediment. At the margins of both peninsulas beach rock is backed against the fluviatile deposits.

The coastal deposits, which are significantly narrowing the entrance to the lagoon, are dated to 80,000 a BP +/- 3,000 a (Mauz et al. 2015). These beach rocks were accumulated in different facies and show a strongly variable composition (see Chapter 6.5) (see Falkenroth 2017). The fossil content, as well as the clast and grain size is very divergent. This beach rocks are located mostly at the coastline facing the Gulf of Oman, but can also occur at the margins of the lagoon.

The lagoon itself is filled with very fine grained Holocene deposits. The surface sediment of the lagoon is largely fine to very fine grained sand (Donato et al. 2009, Pilarczyk et al. 2011). Primarily muddy sediments have been found in-between the mangroves, as well as behind (Donato et al. 2009). Towards the wadi mouth the sediment gets coarser and more gravelly. Near Wadi Salmiyah a typical delta systematic can be found (Donato et al. 2009, Pilarczyk et al. 2011). The deposition inside the lagoon is mainly characterized by tidal currents, wind driven waves, wadi inflow and storm events (Donato et al. 2009). The mean tidal range is about 1,2 m. During low tide most of the lagoon is exposed (Donato et al. 2009).
3.3.3 Qalhat fault and marine terraces

The studied area is located southward of the Qalhat fault and is assumed to be not affected by tectonic movements (see Bagci 2017). During the Paleogene the Qalhat fault was active as a normal fault (Fournier et al. 2006). In late Cenozoic times the Qalhat fault was reactivated as a reverse normal fault. The inversion corresponds with the tertiary compression leading to the uplift of the Hajar Mountains (see chapter 3.1) (Fournier et al. 2006). The fault is located near the village of Qalhat with a striking of the fault close to the NS direction. After an earthquake approximately 500 a ago the village remained unpopulated with only some ruins preserved, which could indicate recent tectonic activity (Musson 2009).

Over the course of the Quaternary the area northwestward of the Qalhat fault is influenced by an uplift-movement. The fault separates two areas, allowing them to move independently from each other. While the northwestern block was lifted, the southeastern block remained more-or-less stable. The exact processes leading to the uplift are still under investigation by Dr. Gösta Hoffmann and his research staff.

On the northwestern block marine terraces have been found. These were formed during interglacial periods with subsequent uplift (Ermertz 2017, Hoffmann et al. 2016, Hoffmann et al. 2013b). The marine terraces were sampled by Dr. Gösta Hoffmann and students to create an age model (see Monschau 2016). By dating the terraces it was possible to ascertain that the third terrace built up during MIS 5e simultaneously to the bioerosion notch at the lagoon of Sur (Ermertz 2017, 

Figure 3.5: Geological map of the area around Sur. The dotted areas highlight uncertain lithologic classifications (Redrawn and modified after Peters et al. 2001).
Notch types and their formation

Hoffmann et al. 2016). Hence, the notch in Sur and the second terrace approximately 100 km northwestern were presumably originated coincidentally (Hoffmann & Mechernich 12.06.2017, personal communication). Thus, a difference in height of about 50 m is recognizable between the northwestern and southeastern areas (Hoffmann et al. 2013b).

4 Notch types and their formation

Coastal notches are undercut cliffs or steep slopes with an incision of a few centimeters to decimeters or even meters (Figure 4.1a) (Rovere et al. 2016, Schneiderwind et al. 2016b, Trenhaile 2015). To retain this geomorphological structure the rocks have to be resilient enough to carry the surcharge of the overhanging parts and to hold the structure (Trenhaile 2015). Notches are mostly u- or v-shaped (Sisma-Ventura et al. 2017) or have a rounded shape and emerge through mechanical wave action and abrasion, bioerosion and, with lesser significance, chemical weathering (Figure 4.1) (Evelpidou et al. 2012a and b, Evelpidou & Pirazzoli 2016, Pirazzoli 1986, Rovere et al. 2016, Trenhaile 2015). The effects are intertwined and the erosional impact of the single processes is difficult to estimate (Sisma-Ventura et al. 2017). Hence, the term notch describes a relatively wide and diverse geomorphological feature (Rust & Kershaw 2000). One of the first detailed researches on coastal notches and their origin was performed by P. A. Pirazzoli (see Pirazzoli 1986). He separated the processes which have an effect on the formation of notches and tried to examine their significance. Furthermore, he investigated different influences on the shape of the notch like sea level change or the angle of the cliff (Pirazzoli 1986).

Notches formed due to bioerosion often originate within or shortly above the intertidal zone (Pirazzoli 1986). In contrast, abrasion notches form in areas that are current and wave dominated (Pirazzoli 1986). A stable sea level over a sufficient period of time is required to form a notch (Abad et al. 2013, Pirazzoli 1986, Rovere et al. 2016, Sisma-Ventura et al. 2017). Assuming quite small erosion rates of around 1mm/a, a stable sea level over tens to hundreds of years or a balance between eustasy, isostacy and tectonic movements is needed to form a bioerosion notch (Schneiderwind et al. 2016b). Abrasion notches are more difficult to evaluate in terms of their formation. Therefore, bioerosion notches in particular represent relicts of paleo sea levels and can be used to reconstruct former sea levels (Evelpidou & Pirazzoli 2016, Pirazzoli 1986, Rust & Kershaw 2000) and the offset of tectonic movements in a certain area (Evelpidou et al. 2012b, Kázmér et al. 2015, Rust & Kershaw 2000). Bioerosion notches represent former sea levels with an accuracy within a few decimeters. The height of a notch refers usually to the tidal range (Schneiderwind et al. 2016b, Pirazzoli 1986) or to the range in which wave action or currents occur (Pirazzoli 1986).

Different types of notches are generally distinguished by their formation (Sisma-Ventura et al. 2017) or their place of origin. The two main types are abrasion notches and bioerosion notches, sometimes called tidal notches (Figure 4.1b and c). Another type are structural notches. They emerge due to the erosion of a weaker lithology or through the heterogeneity of a cliff caused by chasms (Kershaw & Guo 2001, Pirazzoli 1986). The latter mentioned type is impractical to reconstruct sea level. Thus, only the first two types are discussed in the following. Furthermore, bioerosion and abrasion notches
are the only types present in the observed area. Both show similar measurable features. The top of
the notch is called the roof, the lowest point is called the floor. The apex is located in between these
two points. At this point the strongest erosion occurs and therefore the deepest incision into the rock
(Figure 4.1a). A detailed explanation is in chapters 4.1.2 and 4.2.2. In this study the terms notch and
coastal notch are used synonymously.

Figure 4.1: Notch morphology. a) General structure of a notch. b) Example for an abrasion notch in beach rock
and fluviatile sediment without bioerosion. c) Example for a bioerosion notch in limestone filled with beach
rock (Picture height approximately 1,80 m).

4.1 Bioerosion notch

In this study the term bioerosion notch is comparable to the term tidal notch which is used in
literature to describe notches emerging in the intertidal zone close to MSL (Antonioli et al. 2015,
Pirazzoli 1986, Schneiderwind et al. 2016a, Schneiderwind et al. 2016b). They form preferably in
microtidal seas (Schneiderwind et al. 2016b). Bioerosion is, most likely, the main factor causing this
notch type (Evelpidou et al. 2012a, Furlani et al. 2011, Schneiderwind et al. 2016a, Schneiderwind et
al. 2016b). Tidal notches formed by bioerosion exist primarily in carbonat rocks (Kershaw & Guo
2001, Rovere et al. 2016, Schneiderwind et al. 2016a, Schneiderwind et al. 2016b). This rock type is
preferred by most of the bioerosional organisms. A layer of bioeroding cyanobacteria and algae leads
to grazing by other organisms and therefore to progressing bioerosion (Benac et al. 2004, Kázmér et
organisms live in distinct, almost horizontal, belts near MSL (Laborel & Laborel-Deguen 1994,
Rovere et al. 2015, Schneiderwind et al. 2016a).

Bioerosion notches are created by a variety of eroding organisms. The most important are
Lithophaga, limpets, chitons, sponges (Cliona) and sea urchins (Kázmér et al. 2015, Laborel &
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Laborel-Deguen 1994). Furthermore, bioconstructing organisms like barnacles, oysters and tube building worms have an impact (Kázmér et al. 2015). They characterize the shape and look of the notch and can give further information about climate and sea level stands during the time of their formation.

As mentioned in the beginning, bioerosion notches emerge within the intertidal zone around MSL. Hence, they are often used to reconstruct former sea levels or tectonic movements (Furlani et al. 2011, Laborel & Laborel-Deguen 1994, Pirazzoli 1986, Rovere et al. 2016, Trenhaile 2015). Their relatively small vertical error is also a big advantage (Sisma-Ventura et al. 2017). The direct dating of a notch by using rock samples is not possible. Remnants of organisms are required to date the geomorphological feature. But, due to external circumstances like uncertainties and limitations of dating methods, dating is often challenging or not feasible (Rovere et al. 2016).

4.1.1 Organisms

Studying bioeroding and bioconstructing organisms is the most important part in investigating bioerosion notches and reconstructing former sea levels. By determining which bioeroders and – constructers are involved in forming the notch it is possible to reconstruct the arrangement of organisms in belts (Rovere et al. 2015, Schneiderwind et al. 2016a). Because of the extreme adaption of organisms to specific conditions of temperature, light intensity and so on these belts are formed (Laborel & Laborel-Deguen 1996). Therefore, organism positions can furnish bathymetric information (Bromley & Asgaard 1993). With the help of the zonations the exact sea level stand at the time of the formation of the notch can be determined. The combination of fossil traces and geomorphological features like tidal notches minimizes the uncertainty in sea level reconstruction using organisms with a wide living range like Lithophaga (Laborel & Laborel-Deguen 1994, Laborel & Laborel-Deguen 1996). Hence, the investigation of organisms and the notch provide useful information about the former position of MSL. If the organisms represent different sea levels, the compilation of organisms is not transferable to one particular sea level and not usable in defining MSL. Such broadened and contradictory zonations form when the sea level fluctuates after notch formation, for example due to warming or cooling temperatures. Less adaptable organisms will be replaced by more tolerant organisms (Laborel & Laborel-Deguen 1996). The living range is shifted. Dead organisms leave remnants like shells or fossil traces behind. Such remnants are often called biological indicators (see Rovere et al. 2015). They are defined as organisms or traces of organisms living in almost horizontal belts parallel to the water surface on hard substrate (Laborel & Laborel-Deguen 1994, Rovere et al. 2015, Schneiderwind et al. 2016a). If a sufficient amount of organic matter is left for radiocarbon dating biological indicators are most useful (Laborel & Laborel-Deguen 1994, Laborel & Laborel-Deguen 1996, Rovere et al. 2015). The feasibility of dating is depending on the age of the sample.

In this case these biological indicators are used to reconstruct the development of short-term sea level fluctuations during MIS 5e. To preserve trace fossils in paleo notches the penetration into the rock has to be relatively deep (Bromley & Asgaard 1993). Shallower traces will be obliterated by ongoing bioerosion or by abrasion (Bromley & Asgaard 1993, Miller 2007). At limestone cliffs with
constant cover of sea water deep bioerosion traces can be expected. Under those conditions shallow trace fossils are not preserved for a long time.

In the following only organisms which appear in the paleo bioerosion notch are described.

**Lithophaga**

Lithophaga is a genus of boring mussels living in the subtidal and intertidal zone. Their upper limit is roughly at MSL (Laborel & Laborel-Deguen 1994, Rovere et al. 2015). They are sessile organisms of the family *Mytilidae* (Abad et al. 2013). They bore into hard substrates, mostly carbonate, to avoid predators (Kázmér et al. 2015). *Lithophaga* primarily use a weak acid (Kázmér et al. 2015, Westheide & Rieger 2007), produced by their glands (Antonioli et al. 2015), to dissolve the carbonate. They bore into rock by slightly opening both shells and spinning around their long axis (Pirazzoli 1986, Westheide & Rieger 2007). They are abundant on outer surfaces but also in crevices or caves (Laborel & Laborel-Deguen 1994). The openings of their borings are dumbbell-shaped due to their exhaling and inhaling siphons (Figure 4.2a) (Kázmér et al. 2015). When they grow the borehole is broadened and the diameter of the boring increases from a few millimeters to a few centimeters (Kázmér et al. 2015). The maximum size of a shell is reached in up to 80 a (Laborel & Laborel-Deguen 1994). After their deaths the boreholes start to get eroded. During this process the upper part of the borehole is demolished and the previously dumbbell-shaped opening is now round and circular (Figure 4.2b) (Kázmér et al. 2015). Very small *Lithophaga* borings are more likely to sustain the dumbbell-shape, especially, if they are rapidly buried (Figure 4.2a). In general the shells of *Lithophaga* are destroyed shortly after their death. In some cases the shells are preserved by the filling of the borehole by fine grained sediment (Laborel & Laborel-Deguen 1994).

Their living range is quite great and ranges from the subtidal to the lower part of the intertidal zone (Laborel & Laborel-Deguen 1994, Kázmér et al. 2015). However, they typically concentrate in the upper few meters of this range and their limit at MSL is very distinct (Rovere et al. 2015, Laborel & Laborel-Deguen 1994). As such they are fairly useful in determining sea level. *Lithophaga* generate very deep boreholes around 5 cm to 7 cm. Therefore, they correspond to the trace fossil *Gastrochaenolites* and, more precise, *Gastrochaenolites torpedo* (Abad et al. 2013, Miller 2007) which creates boreholes deeper than 5 cm and thus is very good preservable (Bromley & Asgaard 1993). More generally, this type of trace fossil can be allocated to the group *Fugichnia*. This group describes traces formed while the organism tried to escape a predator (McCann & Valdivia Manchego 2015). This is just one of several groups separated by the behavior of organisms (McCann & Valdivia Manchego 2015).

Single boreholes are not useful for the exact reconstruction of the sea level. But large surfaces penetrated by *Lithophaga* and a distinct upper line of boreholes are rather good sea level indicators (Laborel & Laborel-Deguen 1994). Combined with bioerosion notches *Lithophaga* boreholes are very accurate indicators (Laborel & Laborel-Deguen 1994).
Notch types and their formation

Figure 4.2: a) Small *Lithophaga* boreholes with typical dumbbell-shape. b) On the left large and eroded *Lithophaga* borehole and on the right mediocre sized *Lithophaga* borings.

**Sponges**

Sponges are sessile organisms and filter feeders (Miller 2007, Westheide & Rieger 2007, Taylor & Lewis 2005). Due to filtering they perform gas exchange and absorb carbon and nourishment (Westheide & Rieger 2007). They are subdivided into three different taxa, depending on their skeleton elements (Westheide & Rieger 2007, Taylor & Lewis 2005). Many boring sponges, like the generic group *Cliona*, are part of the taxon *Demospongiae* (Westheide & Rieger 2007). *Cliona* is part of the family *Clionidae* and uses a weak acid to dissolve calcite (Figure 4.3) (Westheide & Rieger 2007). They create small openings on the rock surface, called papillae, to lead away water and small, detached calcite particles (Figure 4.3) (Hoeksema 1983, Nava & Carballo 2008, Westheide & Rieger 2007). The inhaling and exhaling papillae have a diameter in the range of a few millimeters. The sponge creates internally connected borings which build up a wide network of borings (Kázmér et al. 2015, Nava & Carballo 2008). Through erosion of the first layer of the rock the connections between the single openings are visible (Kázmér et al. 2015, Miller 2007). They also penetrate living organisms like oysters and other bivalves (Hoeksema 1983).

Figure 4.3: Bioerosion performed by *Cliona*. A) Corrosive sponge cell on carbonate rock. B) The cell develops an appendix on each site and dissolves calcite. C) Increasing dissolution of calcite. D) Calcite particle is detached and lead away by papillae (Redrawn after Westheide & Rieger 2007).
Notch types and their formation

Many sponges are restricted to the subtidal zone because of their intolerance to dryness (Kázmér et al. 2015). But, depending on the species, it is possible that they occur above the upper subtidal boundary inside of the intertidal zone (Abad et al. 2013). *Cliona* is a generic group that occurs up to MSL (Abad et al. 2013, Laborel & Laborel-Deguen 1994). The sponge creates borings that are presumably part of the trace fossil *Entobia* (see Bromley & Asgaard 1993). It is characterized by borings about 2 cm deep (Bromley & Asgaard 1993). They primarily live in shallow waters on rocky shores with low sedimentation (Abad et al. 2013).

While the sponge is alive its borings are covered by the tissue of the sponge (Kázmér et al. 2015, Kázŵér & Taďoroši ϮϬϭϮaͿ). The main part of the sponge is inside the borings. After the death of the sponge and the disappearance of the tissue the borings become visible (Figure 4.4) (Kázmér et al. 2015).

**Figure 4.4**: Network of sponge voids in-between eroded *Lithophaga* boreholes.

**Oysters**

Oysters are part of the family *Ostreidae* (Laborel & Laborel-Deguen 1994). They use a secretion to cement their left shell to a hard substrate (Figure 4.5b) (Kázmér et al. 2015, Westheide & Rieger 2007). From this point on they are immovable (Westheide & Rieger 2007). Oysters live preferably in warm and temperate waters (Westheide & Rieger 2007). They do not need to be covered by water continuously; the tides provide them enough nourishment. This enables them to have a great living range, starting at the water surface and down to about 30 m (Laborel & Laborel-Deguen 1994).

They frequently concentrate at a specific area of their living range and build up ledges or small rims (Laborel & Laborel-Deguen 1994, Kázmér et al. 2015). The position of such ledges varies depending
Notch types and their formation

on the working area. Their natural enemies are starfishs, crabs and gastropods (Westheide & Rieger 2007, Kázmér et al. 2015). External circumstances like the distribution of natural enemies can limit their living range (Kázmér et al. 2015). They are very adaptable to different salinities. Hence, they can survive in a marine milieu as well as in brackish water (Laborel & Laborel-Deguen 1994, Laborel & Laborel-Deguen 1996).

All in all, they are powerful bioconstructors (Kázmér et al. 2012) and their shells are very well preservable (Figure 4.5a and b) (Laborel & Laborel-Deguen 1994, Laborel & Laborel-Deguen 1996).

Worms

The term worm is very broad (Taylor & Lewis 2005). It is rather a description of shared appearance that it is of genetic relationship. Hence, worms live in all environments. Many of them are not well preservable and so are just a small part of the fossil record (Taylor & Lewis 2005). Some of the marine genera are drilling as well as tube building. Because of their greater significance to sea level reconstruction and their appearance in the study area only tube building worms are described in this chapter.

At one location, *Pomatoleios krausii*, the distinct species of the tube building worms could be identified. The exact determination of this species was possible by the decisive geometry of the tube. The side, which is not attached to the surface, shows a slightly curved flat with a wavy pattern (Figure 4.6b).

*Pomatoleios krausii* is able to live in the subtidal to intertidal area. It is one genus of the class of *Polychaeta* and furthermore part of the family *Serpulidae* (Belal & Ghobashy 2012, Westheide & Rieger 2007). Nowadays they are most common in the Indo-West-Pacific Ocean (Belal & Ghobashy 2012, Crisp 1976). They are sessile worms and build up their tubes out of calcareous material and cement themselves on hard substrates or other tubes (Figure 4.6a and b) (Belal & Ghobashy 2012, Miura & Kajihara 1984, Westheide & Rieger 2007, Shalla & Holt 1999, Taylor & Lewis 2005). The tubes can form dense encrustations and aggregations on hard substrates, typically located in the intertidal area (Figure 4.6a) (Belal & Ghobashy 2012, Shalla & Holt 1999, Shishikura et al. 2006). Shishikura et al. (2006) even say that this species can only survive in a very
Notch types and their formation

narrow vertical range in the mid-tidal area around MSL. Straughan (1969) determined that they form a narrow band just shortly above MSL in sheltered areas but can reach down to the subtidal zone. Because of their sensibility to air exposure they do not occur in the supratidal zone (Straughan 1969). Because of their narrow distribution they were used to estimate displacement caused by earthquakes (Shishikura et al. 2006).

It is hypothesized that, with rising temperatures, the reproduction and growth of these worms will increase as seen presently in the Suez Canal (Belal & Ghobashy 2012). As mentioned before, they prefer weak currents and sheltered areas as well as a low sediment intake (Belal & Ghobashy 2012, Straughan 1969). In these areas they can even reach higher elevations than MSL (Straughan 1969).

Figure 4.6: a) A small ledge, build up by Pomataleios krausii and barnacles, covers eroded Lithophaga boreholes. b) Single, fossil worm tubes attached to limestone.

Barnacles

Barnacles are part of the subphylum Crustacea and of the subclass Cirripedia (Westheide & Rieger 2007). In their adult form they are exclusively sessile and part of the group of filter feeders but can also be parasitic (Westheide & Rieger 2007). To use barnacles as a sea level indicator it is necessary to classify them, at least to the families Balanidae or Chthalamidae. Otherwise a meaningful determination of the paleo sea level is not possible, because the vertical range of barnacles reaches up to the supratidal zone and down to the subtidal zone (Rovere et al. 2015). The barnacles occurring in the paleo bioerosion notch are classified to the family of Balanidae (Figure 4.7a). Barnacles which are appearing in a recent notch are not yet classified (Figure 4.7b).

Most genera of the family Balanidae live near MSL in shallow waters and can be therefore used relatively well as a sea level marker (Laborel & Laborel-Deguen 1994 and 1996, Rovere et al. 2015). The lower boundary of their living range is located in the lower midlittoral or middle-to-lower intertidal (Rovere et al. 2015). Balanidae either live in single layers or can build up small ledges (Laborel & Laborel-Deguen 1994, Rovere et al. 2015). It is difficult to assign them to an individual species and thus they are often just assigned to the family (Laborel & Laborel-Deguen 1994, Laborel & Laborel-Deguen 1996). Like oysters, they are able to survive in brackish environments (Laborel & Laborel-Deguen 1994, Laborel & Laborel-Deguen 1996). They are well preserved when they are
Notch types and their formation

uplifted into the supratidal zone as opposed to being submerged (Laborel & Laborel-Deguen 1994, Pirazzoli et al. 1984).

Figure 4.7: a) Fossil barnacles with missing cover plates, in-between worm tubes. b) Recent barnacles at the roof of a recent notch.

4.1.2 Shape

A notch is typically v- or u-shaped with the greatest incision in the middle of the structure, the called apex (Evelpidou & Pirazzoli 2016, Rovere et al. 2016, Kázmér et al. 2015, Schneiderwind et al. 2016a). The shape of bioerosion notches refers approximately to the height of the tide (Evelpidou et al. 2012a, Pirazzoli 1986, Schneiderwind et al. 2016a, Schneiderwind et al. 2016b, Trenhaile 2015). The roof is roughly located at the height of high tide, the floor at low tide and the apex nearly at MSL (Evelpidou et al. 2012a, Pirazzoli 1986, Rovere et al. 2016, Schneiderwind et al. 2016a). Hence, the apex represents a former MSL (Laborel & Laborel-Deguen 1994, Schneiderwind et al. 2016b, Trenhaile 2015). With a constant erosion and a periodical tide the main erosion takes place at MSL and decreases rapidly at and near the boundaries of the intertidal zone (Figure 4.8) (Murray-Wallace & Woodroffe 2014, Schneiderwind et al. 2016a, Schneiderwind et al. 2016b).

If a notch is originated with a symmetric or asymmetric shape is depending on the tilt of the cliff and the surrounding conditions, for example exposure to the open sea (Schneiderwind et al. 2016b). With constant biological and climatic conditions and a sheltered vertical cliff a symmetrical notch would form most likely (Schneiderwind et al. 2016b). But existing notches can be redesigned by a slowly changing sea level or, for example, by a change in the isostatic component either through uplifting or subsiding (Pirazzoli 1986, Schneiderwind et al. 2016b). Another possibility of redesigning is the impact of mechanical erosion during or after the formation of the notch.
4.2 Abrasion notch

Abrasion notches develop through mechanical erosion. Waves carrying sediment load, called tools, erode the rock and create this geomorphological structure (Kershaw & Guo 2001, Kline et al. 2014, Pirazzoli 1986, Rust & Kershaw 2000, Schneiderwind et al. 2016b, Trenhaile 2015). Because of the bad conditions for bioeroding organisms bioerosion is, under these conditions, barely existing or not present (Schneiderwind et al. 2016a, Schneiderwind et al. 2016b, Trenhaile 2015). Abrasion notches are often associated with beaches (beach rock) backing onto the rocky cliff. Material of this beach is then used to erode the cliff (Kershaw & Guo 2001). Therefore, sediment has to be available to create this geomorphological structure (Rovere et al. 2016). This type of notch is more present in exposed and wave-dominated areas than in sheltered (Trenhaile 2015).

Another factor promoting the genesis of notches is the removal of clasts or bigger parts of the rock by trapped air in joints and other disconformities (Kline et al. 2014, Schneiderwind et al. 2016a, Trenhaile 2015). Waves trap air inside of disconformities. After the wave retreats, the former compressed air expands and the joints get broader (Kline et al. 2014). The compression by waves then removes the weakened parts (Trenhaile 2015). This process is most present in mid-latitude regions or weak strata (Trenhaile 2015). Notches formed by this process often show irregular shapes and are called wave quarries (Trenhaile 2015). The appearance of this geomorphological feature is characterized by vertical columns inside of the incision.

If no organisms or trace fossils are present, abrasion notches are unprecise sea level indicators (Rovere et al. 2016). The main reason is that they are not bound to one distinct sea level (Pirazzoli 1986, Trenhaile 2015, Sisma-Ventura et al. 2017). Additionally, the dating of this structure is even more difficult to accomplish in comparison to bioerosion notches (Sisma-Ventura et al. 2017).

4.2.1 Lithology

In contrast to bioerosion notches, abrasion notches usually do not form in any distinct lithology. They can appear in every lithology (Rovere et al. 2016). Abrasion notches occur in non-carbonaceous as well as carbonaceous rocks (Sisma-Ventura et al. 2017). Nevertheless, they are often present in igneous rocks and sediments, as described in this study. In limestones bioerosion is additionally present in many cases, unless there is too much debris or the wave regime is too strong. Under these conditions, as mentioned before, organisms like bivalves or sponges cannot survive (Schneiderwind et al. 2016a, Schneiderwind et al. 2016b).
Notch types and their formation

4.2.2 Shape

The shape of abrasion notches is typically u- or v-shaped but is often rounder than bioerosion (tidal) notches (Pirazzoli 1986, Schneiderwind et al. 2016a, Trenhaile 2015). Due to the place of origin and the prevailing conditions they are either symmetric or asymmetric (Sisma-Ventura et al. 2017). Deep as well as asymmetric shapes develop more likely through breaking waves in open areas than due to already broken waves in sheltered areas (Carobene 2015, Sisma-Ventura et al. 2017). Due to abrasion they show a smoother surface than their bioerosional equivalent (Pirazzoli 1986, Schneiderwind et al. 2016a, Schneiderwind et al. 2016b, Sisma-Ventura et al. 2017). Moreover, the height of a notch is lower than their depth in less resilient rocks. In resilient rocks it is the opposite (Sisma-Ventura et al. 2017). The resistance of rocks against wave action depends not only on the lithology of the rock but on structural discontinuities like joints, cracks and more (Schneiderwind et al. 2016a). Neither the apex, nor floor or roof of this notch type is generally an indicator of a specific sea level.

Abrasion notches are associated with wave or current action and in general of a greater height than bioerosion notches (Rovere et al. 2016). They can potentially emerge near the breaking point of waves and up to the storm swash wave height which is the maximum elevation that is reached by waves during extreme storms (Pirazzoli 1986, Rovere et al. 2016). Some authors limit abrasion notches exclusively to the intertidal zone (Kline et al. 2014).

All in all, the height of a notch is often correlated to the range of wave action with the upper limit at the storm swash wave height (Trenhaile 2015). A positive correlation between notch height and wave height is often noticed (Trenhaile 2015). The greatest erosion occurs where the greatest energy stresses the stone. Rovere et al. (2016) state that this is commonly the storm wave swash height. This has the greatest effect on exposed areas (Trenhaile 2015). Kershaw and Guo (2001) are convinced that abrasion notches can originate up to 2 m above MSL if unsheltered conditions are dominating (see also Rust & Kershaw 2000). In contrast, Trenhaile (2015) believes that abrasion notches are most common in the intertidal zone, especially at the foot of cliffs where sediment is likely to accumulate and then be moved around by waves. Because of this great spectrum of possibilities it is difficult to reconstruct a distinct sea level where the erosional feature originated (Pirazzoli 1986). The spectrum in which abrasion notches can form reaches from the point currents occur up to the point waves can reach the rock surface (Pirazzoli 1986).
5 Methodology

5.1 Mapping

A main goal of this thesis was to map the study area with relation to bioerosion and abrasion notches. The bioerosion notch with a height of roughly 3.7 m asl was categorized as exceedingly interesting. Following the general methods of geological mapping we prospected the area around the lagoon to find as many preserved notches as possible. The main focus was on investigating bioerosional features associated with the bioerosion notch. Outcrops with an existing notch shape were preferably searched. The area was mapped for around five days to receive a good overview before starting detailed investigation on certain locations and profiles with well-preserved notches.

Three notch types were distinguished: a paleo bioerosion notch, which is the main focus of this study, an abrasion notch and a notch that is still forming, which is also classified as bioerosion notch but not included in this study. The notches all developed in different heights (see also Cahnbley 2017).

5.2 Measuring and investigating

After dividing the lagoon into two working areas (see chapter 3.3) we started measuring the notch and examined all occurring organisms. Measuring tape was used to survey the distribution of the organisms and their position inside of the notch. The lowest and highest points of bioerosional features on the rock surface as well as the distribution of every organism were surveyed (Figure 5.1a). To reconstruct the amplitude of sea level fluctuations it is necessary to examine where and in what range a specific biological indicator appears.

The shape of the notch was surveyed by measuring the roof and the floor of the notch (Figure 5.1a). Due to its shape the notch itself provides data referring to MSL. The lowest to uppermost part of the notch (roof to floor) represent probably the mean tidal range during the formation of the notch. This range, and therefore the height of the notch, should be more-or-less stable. The allocation of organisms to specific areas of the notch is essential for a later comparison of the profiles.

The notch floor of the most investigated outcrop is not visible (see chapter 6.1). Hence, the height of this feature was calculated by using an imaginary, vertical axis starting at the roof of the notch and reaching down to the rock surface. The intersection of rock surface and imaginary axis was defined as the floor (Figure 5.1a). The distance between these two points is defined as notch height. The uncertainty generated by this measurement technique is estimated to be a few centimeters. However, the overall consistent values indicate that they are convincing (see chapter 6). A profile represents a horizontal area with a width of a few decimeters to guarantee a representative depiction of the organism zonation. At the abrasion notch just the floor and the roof were measured (Figure 5.1b).

Beside the zonation of the organisms the appearance and preservation of the organisms was recorded. Moreover, the amount and the way of occurrence of organisms was estimated. Changes in
Methodology

appearance can possibly indicate changes of the sea level or different organism generations. The information were later used to compile the model of sea level fluctuations.

Single profiles were measured with a Handheld Laser Distance Meter (HLDM) (see Kázmér & Taboroši 2012b). The model Leica Disto D8 was used to measure the elevation and horizontal distance of the notch. The imprecision to the measurement device is around +/- 1 mm with a measurable maximal distance of 200 m (Kázmér & Taboroši 2012b). With these measurements the position of the apex was calculated afterwards (see chapter 7.1.2).

![Diagram](image)

Figure 5.1: a) An example for the measurements on the bioerosion notch. Two organism zonations are shown exemplarily. Generally measured points are marked. b) Measurements performed on an abrasion notch with denoted measured features.

To achieve not only the relative heights of the features but also absolute heights (height above recent MSL) further measurements were necessary. For this approach Bagci (2017) used a DGPS to survey the highest Lithophaga boreholes of the notch. On that account a base station was positioned on a nearby mountain. The measurements express the difference in height between the base station and a transmitter located at the highest Lithophaga borehole of the notch. To calculate the absolute height, the sea level at different tidal datums was measured first and normed to MSL. Then the difference in height between MSL and the Lithophaga boreholes were examined (Bagci 2017). The uncertainty of the measurements is, in general, about a few centimeters and is possibly even smaller.
if the distance between the surveyed outcrop and the base station is not greater than a few kilometers (Lorscheid et al. 2017b).

The measured profiles of this study and the survey points of the DGPS do not always match. Hence, the nearest measurement, or in some cases the mean value of two surveys, was calculated and used as absolute height of the profile. For, more information, on the DGPS surveys see Bagci (2017).

5.3 Bioerosion index and distribution of organisms

It is feasible to classify how stressed the rock surface is by bioerosion. For that reason the often used bioturbation index (McCann & Valdivia Manchego 2015) was adjusted to hard substrates and in the following called bioerosion index (BI) (Table 1). Seven levels and associated percentages were prepared referring to the levels of the bioturbation index. Each level describes to what extent the rock surface was stressed by bioerosion, in this case borings created by *Lithophaga* and sponges (*Cliona*) (Table 1). Every zone of the profiles will be valued with this classification, called bioerosion index level (BIL). It is important to mention that not only the amount of surface affected by bioerosion but also the depth of penetration was taken into account. Hence, deeper boreholes were associated with stronger bioerosion and valued stronger than shallow boreholes created by sponges.

<table>
<thead>
<tr>
<th>Level</th>
<th>Percent</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>No signs of bioerosion.</td>
</tr>
<tr>
<td>1</td>
<td>1-5</td>
<td>Rare or very shallow occurrence of bioerosion. A few borings with a depth of a few centimeters are penetrating the rock surface or a bigger amount of shallow borings are present.</td>
</tr>
<tr>
<td>2</td>
<td>6-30</td>
<td>Minor amount of bioerosion. Only a small part of the rock surface is penetrated by rather deep boreholes or the borings are just slightly penetrating the rock surface.</td>
</tr>
<tr>
<td>3</td>
<td>31-60</td>
<td>Moderate amount of bioerosion. Between one third and two thirds of the rock surface is penetrated by deep borings or a greater surface is covered by borings just slightly penetrating the rock surface.</td>
</tr>
<tr>
<td>4</td>
<td>61-90</td>
<td>Great amount of bioerosion. The rock surface is heavily penetrated by borings. Almost the whole surface is covered by relatively deep borings penetrating the rock several centimeters.</td>
</tr>
<tr>
<td>5</td>
<td>91-99</td>
<td>Huge amount of bioerosion. Almost no surface without borings is left. All borings are deeply penetrating the rock.</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>Completely bioeroded rock surface. Walls of the borings are touching. No surface left without borings. All borings are at least several centimeters deep.</td>
</tr>
</tbody>
</table>

Depending on the height and the shape of the notch the profiles are, at most, divided into five zones (Figure 5.2). The first zone is located above the notch, the second is represented by the upper part of the notch (roof and apex) and the third zone is the lower part of the notch reaching down to the floor of the notch. The remaining zones are describing the area below the notch and divided depending on the height of this area. If this part of the profile exceeds 1 m, it is separated into two zones. Otherwise only one zone is used to describe it. The abundance of organisms is illustrated with
pie charts. These values are just an approximation based on estimations. Hence, the shown charts represent quantitative propositions and are not measured in a way that could provide quantitative information. These values are only given where a notch shape is present. Bioerosion and distribution of organisms are not mentioned at locations without this feature. It is not possible to introduce a new division where zonation not depends on the shape of the notch but on the organisms and their distribution. The occurrence of organisms is too irregular. *Lithophaga* is the only organism present at every outcrop. A division into zones based on just one biological indicator is not feasible.

Figure 5.2: Exemplary division of a profile into different zones (Main Notch).
6 Results

Almost everywhere in the area near the lagoon at least one of the two notch types are present. While the bioerosion notch is more commonly encountered in the south, the abrasion notch is more prevalent in the north. The complete shape of the bioerosion notch is only preserved in one spot on the eastern side whereas the shape of the abrasion notch is typically recognizable.

In the following chapter the surveyed outcrops and respective profiles are introduced. For this purpose, the study area was divided into six locations and fourteen profiles were surveyed. Every profile is described regarding its position and height, as well as the zonation of organisms and a classification into different levels of bioerosion as well as the abundance of organisms if the notch shape is visible. At outcrops without preserved notch shape the abundance of organisms and bioerosion level are not estimated. The abrasion notches were measured and a short description of their lithology is given. This notch type was investigated only by lesser means and embodies just a small part of this thesis. The sedimentology of the limestone, as well as conglomerate and beach rock, are not the main interest of the conducted study and therefore at the utmost mentioned and not interpreted.

Five different groups of organisms can be recognized. A species-level identification was only possible for one organism; in all of the other cases the names of stem, family or generic group are used.

The *Lithophaga* boreholes are divided into three subgroups for a more detailed view. The main criteria are diameter and developmental stage. The first group is called *Lithophaga I*. They represent an early juvenile stage and show a very small diameter. Most distinct is their dumbbell shape. The second group is *Lithophaga II*. They are advanced in age compared to *Lithophaga I* and their boreholes have a round shape with a diameter primarily between 1 cm and 1,5 cm. The depth of these borings is ranging between a few millimeters to several centimeters. The last group is named *Lithophaga III*. They show a very large diameter (>2 cm) but their shape is variable. In many of the profiles they have a straight and deep borehole with a round shape. The outline of the borehole is clearly identifiable. In some cases however, the *Lithophaga III* borholes are penetrated by *Lithophaga II* which leads to a more bowl-like shape and a reduced depth as consequence of the erosion.
6.1 Main Notch

The Main Notch is the key outcrop of this study and thereby represents the best investigated outcrop with the most detailed profiles. It is exposed in the southern part of the lagoon and comprises a bioerosion notch with a fully pronounced morphology (Figure 6.1). An intact and wholly developed notch shape is important for the general investigation of organisms and provides a fixed marker for a better comparison between different profiles. Six profiles are placed here (Figure 6.2a).

The notch is located southward of the city of Sur, near the lagoon (Figure 6.1). The outcrop is easily accessible from the main road and is situated next to the mouth of Wadi Salmiyah (Hoffmann et al. 2016). It is about 50 m long with a total height of about 5 m. This height indication involves the entire rock surface that is being stressed by bioerosion and additionally the areas in which bioconstructing organisms like oysters occur. For more information about the measurements see chapter 5.2.

In contrast to a typically symmetric u- or v-shaped notch, this notch shows a relatively steep slope transitioning into a small u-shaped notch which is on average 76 cm in size (Figure 6.2 b). The roof of the notch is more-or-less horizontal aligned and well recognizable (Figure 6.2b). The floor of the notch is missing, which creates a ramp-like appearance. In most parts of the notch the organisms described in chapter 4.1.1 were recognized. Furthermore, remnants of beach rock are found near the apex of the notch.

Figure 6.2: a) Extent of the key outcrop with completely preserved notch-shape. Profile locations are numbered. Horizontal aligned notch roof is marked with a red dashed line. b) Detailed view of the notch with the roof marked in orange and the floor marked with a blue dashed line. Remnants of beach rock are visible inside of the notch (outlined in white).
6.1.1 Profile 1 (GPS 117: UTM 40Q 759913 2495752) 

The first profile is situated at the westernmost part of the Main Notch. Nearby a little bay with beach rock is exposed. Due to vegetation and debris just a small part of the notch is visible at this profile location but well preserved organisms are occurring. The height of the profile is only about 29 cm. The total height of the notch was not measurable due to the debris. The zone bars in the profiles mark all areas of organism presence without considering the notch shape.

The profile is roughly separated into two zones. The position of these zones is described in chapter 5.3. These two zones differ in their organism composition and distribution (Figure 6.3). The uppermost zone is situated above the roof of the notch and is just slightly affected by bioerosion. *Lithophaga* boreholes are the greatest part of organisms occurring in this zone (Figure 6.3), still their total amount is low. They are most common in a crack adjoining the profile. The BIL is between 1 and 2. The second zone is represented by the rest of the profile, the upper part of the notch. For the most part *Lithophaga* boreholes are the dominating feature. Oysters, worm tubes and especially barnacles are less common. Beach rock is covering a great part of the surface. Without taking the beach rock into account the BIL is classified as 4. In the upper part of the notch the beach rock is eroded and only present inside of the *Lithophaga* borings (Figure 6.4c). The beach rock consists of middle to coarse grained sand, shell fragments and a small quantity of foraminifera. The components are hold together by cement. The clasts contained in the sediment have a diameter ranging from 1 cm to 2 cm. No sedimentary structures are visible in the beach rock remnants.

*Lithophaga* boreholes are present in the entire profile (Figure 6.4a). They reach up to 4,32 m asl which is 10 cm above the roof of the notch. There are probably even more *Lithophaga* boreholes further above the roof but a clear determination is not feasible. Moreover, in some parts of the notch the bivalve *Lithophaga* bored into probably older boreholes (Figure 6.4d). In this profile neither *Lithophaga I* nor *Lithophaga III* boreholes are present.

Oysters occur in a large part of the profile. They cover eroded *Lithophaga* boreholes. The oyster shells are very well preserved, especially in the lower part of this profile (Figure 6.4b). They form no ledge or band and only single organisms are present in the profile. The shells have a wavy and layered exterior with a row of ribs (Figure 6.4b). The interior of the shell is not visible. The largest amount of oysters appears above the notch in an adjoining crack. Their distribution ranges vertically from 4,07 m to 4,26 m asl.

About 40 cm eastward of the profile worm tubes (Figure 6.4c) and barnacles are present in the upper part of the notch. They appear only in a small amount. Barnacles are even rarer than worm tubes and only occur between 4,12 m and 4,15 m asl. Most of them are located inside of *Lithophaga* boreholes and are missing their cover plates (Operculum). They are about 1 cm in diameter. Comparable to barnacles, worm tubes most of the time occur inside of eroded *Lithophaga* boreholes, where they were more-or-less sheltered against mechanical erosion. The tubes are a few centimeters long and show a flat top side, which is not attached to the rock surface, with a wavy pattern. The diameter is around 2 mm. All this indicates the classification as *Pomatoleios krausii* (see chapter 4.1.1). They range from 4,11 m up to 4,16 m asl.
Results

Sponge borings occur in between the eroded *Lithophaga* boreholes (Figure 6.4c). Presumably, these borings are eroded too. This is indicated by the low penetration into the rock of only a few millimeters. The openings of the borings are very small (1 mm to 2 mm in diameter) and almost round (Figure 6.4c). They occur in very small amounts and range between 4.09 m and 4.15 m asl.

![Figure 6.3: Zonation of the organisms and BIL at profile 1 of the Main Notch. Zonation bars with a wavy pattern show the distribution and presence of organisms 0.4 m eastwards. The lower black line marks the beginning of the profile and of the bioerosional features. Colors of zonation bars and pie charts are matching. The brown layer covering the limestone represents the beach rock. Elevation above mean sea level (asl).](image)

![Figure 6.4: a) Presence of *Lithophaga* boreholes above the notch roof. b) Very well-preserved oyster shells in the middle of the notch (base of the profile). c) With beach rock filled, eroded *Lithophaga* boreholes (Black arrow: Worm tube. Blue arrow: Sponge borings. Red arrow: Partly preserved oyster shell). d) Younger *Lithophaga* borings penetrates older borehole (green arrow).](image)
6.1.2 Profile 2 (GPS 118: UTM 40Q 759912 2495754)

The second profile of this location is situated about 4 m eastwards. In contrast to profile 1, a greater part of the notch is visible and measurable. The height of the complete profile is 1,25 m and reaches up to 4,39 m asl. The height of the notch is 63 cm.

This profile is divided into four zones because of the greater height and the better accessibility in comparison to profile 1. Every zone of the profile is primarily characterized by *Lithophaga* boreholes. The first zone is just slightly affected by *Lithophaga* boreholes and oysters appear only in small amounts too (Figure 6.6). The BIL is categorized as 1. The impact of *Lithophaga* is highest inside the notch (Zones 2 and 3; Figure 6.6). Hence, the level of bioerosion is ranked the highest there. In particular, the upper part of the notch (Zone 2) is heavily bioeroded and classified as BIL 5. The first zone sponge borings appear is zone 3. The amount of *Lithophaga* slightly drops here. The third zone classifies as BIL 4. The notch is further characterized by worm tubes and barnacles which occur to a rather small degree. The section is less bioeroded. In general the zone can be classified as BIL 3. Only sponge borings and *Lithophaga* boreholes are present in this area. The lower part of the profile also shows a smooth and sleek surface, almost like it is covered with a thin layer (Figure 6.7b). Presumably, the surface was polished by mechanical erosion.

In the entire profile *Lithophaga* boreholes are present (Figure 6.7a). The most boreholes are in close vicinity and directly within the apex of the notch. In some cases the borings are located so close to each other that the remaining, seperating wall is extremely thin or sometimes completely gone. This exacerbates the preservation of the boreholes. The diameter of the boreholes in this profile ranges from 0,5 cm to 2,5 cm. The biggest borings are presumably widened through mechanical erosion. The most common diameter is between 1 cm and 1,5 cm. This is also the most common diameter of the borings near the apex of the notch. The depth varies between 0,9 cm and 5 cm. Therefore, it appears that most of the boreholes are eroded to some extent (Figure 6.7a). In very rare cases the shell of *Lithophaga* is preserved inside of the borehole (Figure 6.7a). The borings are mostly aligned parallel to the surface or with a small tilt. Comparable to profile 1, *Lithophaga* borings sometimes penetrate older *Lithophaga* boreholes. The highest boreholes of *Lithophaga* reach up to 4,32 m asl.

To investigate *Lithophaga* boreholes in more detail, depth and diameter of twenty *Lithophaga* boreholes were measured. In both surveys a trend is recognizable: the majority of Lithophaga boreholes show a decrease in depth with increasing distance to the roof of the notch (Figure 6.5a). Concurrently the diameter of some *Lithophaga* boreholes increases (Figure 6.5b). That does not apply to every borehole and several discordant values are present. Nevertheless, an overall trend can be conveyed to the measurements but should not be weighed with great importance because of the deviants.
Results

Figure 6.5: a) Depiction of the coherence between the distance of *Lithophaga* boreholes to the notch roof and the depth of the boreholes. b) Depiction of the coherence between the distance of *Lithophaga* boreholes to the roof and the diameter of the boreholes.

Sponge borings are not as common in the profile as *Lithophaga* boreholes. They reach up to a height of 3.97 m asl. Hence, they appear below and inside of the notch. In the lower part of the profile (Zone 4) they are most abundant and form uninterrupted networks over small sections of the notch surface (Figure 6.7b). In the upper areas on the other hand sponge borings only appear in between *Lithophaga* boreholes (Zone 3) or are not visible at all (Zone 2; Figure 6.6).

Bioconstructors like barnacles or worms appear only within the notch. Worm tubes are primarily preserved inside of eroded *Lithophaga* boreholes (Figure 6.7a) and are thereby younger than the mentioned *Lithophaga*. The worms are classified as the specimen *Pomatoleios kraussii* which is present between 4.12 m and 4.27 m asl. Their vertical distribution in this profile is quite small. However, they are far more common than in profile 1. Barnacles appear in a wider range starting at 3.71 m and stretching up to 4.02 m asl. They are occurring in an even smaller amount than worm tubes. The shape and the size of barnacles and worms are comparable to profile 1.

The oysters appear at the roof of the notch and slightly above (4.24 m to 4.39 m asl). In comparison to the first profile the shells are not as well preserved and their overall amount is low. They almost merge with the rock surface and show a nacreous luster (Figure 6.7c). The original shape of the shell is no longer visible.
Results

Figure 6.6: Zonation of organisms at profile 2 of the Main Notch. Depiction of presence and distribution of the organisms and the level of bioerosion they caused in different zones of the profile.

Figure 6.7: a) Eroded *Lithophaga* boreholes in parts filled with worm tubes situated in the middle and upper part of the notch. Green arrow marks *Lithophaga* shell. b) Sponge borings in the lower part of the profile beneath the notch. c) Oyster shells slightly above the roof of the notch. d) Single barnacles in the middle and lower part of the notch.
Lithophaga boreholes can be subdivided into three subgroups. Each subgroup represents a different stage of development of the organism. In the first 20 cm of the profile very big and probably secondary eroded Lithophaga III boreholes are present (Figure 6.8). They show a diameter of up to 3.5 cm and are about 4 cm to 5 cm deep. Lithophaga I boreholes with a length between 1 mm and 2 mm overlap with this layer. They range from 3.12 m up to 3.52 m asl and show a typical dumbbell-shape. Because of their very small size the extent of penetration is unknown. In some parts they appear concentrated. In almost the entire profile Lithophaga II boreholes are present. They start at a height of 3.17 m and reach up to 4.32 m asl. This is the most common group which is especially widespread inside of the notch. The openings of the boreholes of this subgroup are round due to erosion. The diameter is smaller in comparison to Lithophaga III. From base to top of the profile their abundance decreases. In the first 15 cm of the profile the identification of Lithophaga borings is hampered by erosion (Figure 6.8).

Figure 6.8: Zonation and distribution of Lithophaga subgroups of the second profile. The green lines mark the area Lithophaga III boreholes with a diameter greater than ~2 cm appear. The yellow lines highlight the area where Lithophaga I boreholes with a typical dumbbell shape are present. The blue lines mark the area where Lithophaga II boreholes with a round opening and a diameter mostly ranging between 1 cm and 1.5 cm are present.
6.1.3 Profile 3 (GPS 119: UTM 40Q 759916 2495762)

This profile exhibits a vertical range of 2.88 m and is therefore higher than the previous profiles. It is located about 6 m eastwards of the second profile. The notch, with its well-developed notch shape, takes up 83 cm of the total profile length, which reaches up to 4.46 m asl.

The profile is divided into five zones. These zones depict the changing distribution of organisms in the vertical profile. Lithophaga boreholes are the main characterizing feature of the entire profile (Figure 6.9). In particular the second and third zone (notch) is dominated by them and therefore heavily eroded (Figure 6.9). The BIL of the second zone is set to 5 and the BIL of the third zone is classified as 4. The lower zones 4 and 5 are dominated primarily by sponge borings. They characterize the fourth zone beneath the notch in terms of quantity (Figure 6.9). Zone 4 is characterized by a lower intensity of bioerosion caused by a shallower penetration depth and hence, the BIL is classified as 3 (Figure 6.9). The bioerosion index of the last zone (Zone 5) is set to 2, because weathering has caused parts of the zone’s surface to break off.

Oysters are mostly present in the upper part of the profile and dominate the zone above the notch (Zone 1) (Figure 6.9). Only a small number of Lithophaga boreholes are present too (Figure 6.9). Hence, the level of bioerosion is comparatively small in this section and the BIL is classified as 1 (Figure 6.9). Next to this profile the apex of the notch is partly filled with a beach rock layer of up to 6 cm thickness. Parts of this beach rock fills up single Lithophaga borings (Figure 6.10a). The beach rock consists of middle to coarse grained. Fragments of bivalves or other fossils are not as common as in profile 1.

Lithophaga boreholes occur in the entire profile with the greatest quantity in the upper part of the notch, especially near the apex and shortly above. The borings of Lithophaga are present up to a height of 4.32 m asl. Sponge borings (Figure 6.10b) are quite as widespread as Lithophaga boreholes. Especially at the base of the profile they cover a large surface, despite the fact that they are not recognizable in the first 20 cm of the profile. Sponge borings occur up to the center of the notch and shortly above. Inside of the notch only small spots of borings are preserved. Despite their minor occurrence inside of the notch they are very widespread in the lower parts of the profile and far more common than Lithophaga boreholes. All in all they cover a vertical area of 239 cm and reach up to 3.97 m asl (Figure 6.9).

Worm tubes and especially barnacles are not very common in the third profile. They are only present near the apex of the notch (Figure 6.9). Worm tubes are more widespread than barnacles and fill up some of the eroded Lithophaga boreholes (Figure 6.10a). They occur in a narrow band between 3.84 m and 4.14 m asl. Barnacles appear only separately inside the Lithophaga boreholes within the small range of 3.93 m to 3.99 m asl. Their shape and size is comparable to profile 1. Both barnacles and worm tubes mainly appear associated with beach rock remnants (Figure 6.10a).

Oysters are very common at the notch roof and cover up eroded Lithophaga boreholes (Figure 6.10c). Their presence starts at 4.12 m and stretches up to 4.46 m asl. They are pretty well-preserved and the shell structures are still visible.
Results

Figure 6.9: Zonation of organisms at profile 3 of the Main Notch. Depiction of presence and distribution of organisms and the level of bioerosion they caused in different zones of the profile.

Figure 6.10: a) Eroded *Lithophaga II* boreholes filled with worm tubes and beach rock. b) Sponge borings in the area below the notch, as well as heavily eroded *Lithophaga* boreholes. c) Oyster shells on eroded *Lithophaga* boreholes at the notch roof. d) Greater remnant of beach rock within the apex of the notch and next to the profile.
All three *Lithophaga* subgroups appear in this profile. *Lithophaga III* borings are not only common in the lower part of the profile but reach up to 3,62 m asl and are therefore located inside of the notch. A large section of *Lithophaga III* boreholes is overprinted by *Lithophaga II* boreholes. Hence, the upper part of these boreholes is widened (Figure 6.11). Compared to the previous profiles *Lithophaga I* borings are not as widespread. They appear between 2,84 m and 3,04 m asl. *Lithophaga II* boreholes are more common at the base than before and appear in great quantity in the notch itself, especially in the upper part. They reach up to 4,32 m asl.

**Figure 6.11:** Zonation and distribution of *Lithophaga* subgroups within the third profile of the Main Notch. The green lines mark the area *Lithophaga III* boreholes with a diameter greater than ~2,5 cm appear. The yellow lines highlight the area where *Lithophaga I* boreholes with a typical dumbbell shape are present. The blue lines mark the region *Lithophaga II* boreholes with a round opening, and a diameter mostly ranging between 1 cm and 1,5 cm, occur.
Results

6.1.4 Profile 4 (GPS 121: UTM 40Q 759922 2495768)

This profile is located several meters eastwards of profile 3 and roughly marks the middle of this outcrop. With a height of 291 cm it is just slightly smaller than the previous profile and reaches up to 4,89 m asl. The notch itself covers a vertical range of 90 cm.

The profile is divided into five zones and is even more penetrated by Lithophaga than the previously described profiles. In particular, the area around the apex is heavily bioeroded (Zone 2) (Figure 6.12). The Lithophaga boreholes lie close to each other with contacting walls, which are broken off in some parts. Zone 2 is the area with the greatest bioerosion of the profile and has the highest BIL of the outcrop with a value of 6. No other organisms besides Lithophaga are visible. The third zone is not quite as heavily penetrated by Lithophaga. Hence, it is classified as BIL 5. Between the Lithophaga boreholes occasionally sponge borings are present. The transition into the fourth zone is marked by an increasing amount of sponge borings and a decreasing amount of Lithophaga boreholes (Figure 6.12). The BIL is set to 4. The lowermost zone of the profile is characterized by a slight decrease of Lithophaga borings in comparison to zone 4 and a steady amount of sponge borings. The BIL is classified as 3. The first and uppermost zone is defined by a low-to-moderate number of Lithophaga boreholes in the first centimeters of this zone and oyster shells reaching up to 40 cm above the roof of the notch. The oysters occur more frequently in comparison to Lithophaga boreholes. In 1 m distance to the profile, remnants of beach rock fill the apex of the notch and cover up Lithophaga boreholes (Figure 6.13).

Lithophaga boreholes cover a great part of the profile and reach up to 4,39 m asl. In most cases the depth of the borings near the base of the profile does not exceed 2 cm. At the apex and roof Lithophaga boreholes occur in a huge amount. The walls of the borings are touching or broke off. Most of the time they are oriented horizontal to the rock surface. Inside of the notch the borings are for the most part tilting slightly upwards. Only at the base of the profile they are in parts slightly tilting downwards.

Sponge borings are still present in great amounts and cover up big areas. In particular, beneath the notch in the two lowermost zones they cover the space between Lithophaga boreholes (Figure 6.13b). They appear between 1,43 m and 3,91 m asl.

Barnacles and worm tubes are not present in this profile. Hence, they are not included in the profile zonation.

Oyster shells primarily occur at the roof at the notch and in smaller amounts up to 40 cm above the notch (4,29 m up to 4,89 m asl). The area above the notch seems to be more sheltered than most sections of this outcrop. This is related to the shape of the rock. The shells are well-preserved and weathering did not affect their appearance in any way (Figure 6.13c).
Figure 6.12: Zonation of organisms at profile 4 of the Main Notch. Depiction of presence and distribution of organisms and the level of bioerosion they caused in different zones of the profile.

Figure 6.13: a) *Lithophaga II* boreholes, as well as bowl-shaped *Lithophaga III* boreholes, penetrated by smaller and younger *Lithophaga* borings. b) Sponge borings in-between eroded *Lithophaga* boreholes. c) Very well-preserved oyster above the notch in a sheltered part of the profile. d) Beach rock filling of the apex approximately 1 m westwards of the fourth profile covering up the *Lithophaga* boreholes.
Results

*Lithophaga* I boreholes do not appear in this profile. *Lithophaga* III boreholes are present from the base of the profile up to the lower part of the notch (1,43 m to 3,15 m asl). In contrast to the previous profiles, mainly broad and bowl-shaped *Lithophaga* III boreholes appear. These boreholes are heavily penetrated by *Lithophaga* II boreholes that are of a lower depth than the larger boreholes (Figure 6.14). They are rather flat and do not exceed a depth of 2 cm. The other *Lithophaga* III boreholes match the description in profile 2 and 3. They show a clearer shape, great depth and are not penetrated by other *Lithophaga*. *Lithophaga* II boreholes occur throughout the entire profile in a great amount (1,43 m up to 4,39 m asl) (Figure 6.14). Their number at the base of the profile increased marginally in comparison to the third profile.

Figure 6.14: Zonation and distribution of *Lithophaga* subgroups at profile 4 of the Main Notch. The green lines mark the area *Lithophaga* III boreholes with a diameter greater than ~2 cm appear. The blue dotted lines frame the area *Lithophaga* II boreholes are present. They have a round opening and a diameter that mostly ranges between 1 cm and 1,5 cm.

6.1.5 Profile 5 (GPS 122: UTM 40Q 759928 2495771)

The profile covers a vertical range of 2,77 m whereof 74 cm over covered by the notch itself. The highest point of bioerosion is located at 4,45 m asl while the highest oyster shell is placed at 4,62 m asl. The lower part of the profile is rather weathered.

The profile is divided into five sections. The first zone is more heavily penetrated by *Lithophaga* than in previous profiles. Thereby, the BIL is set as 2. Both, *Lithophaga* and oysters, are present in this part of the profile. The second zone is characterized by a large number of *Lithophaga* borings. The roof is heavily penetrated and classified as BIL 5 (Figure 6.15). In this zone, oysters are not as common as in
profile 3 but slightly more common than in profile 4. In the following zone, classified as the lower part of the notch, sponge borings appear and the strength of bioerosion decreases to level 4 (Figure 6.15). The rest of the profile is divided into two zones which both are classified as BIL 3.

*Lithophaga* boreholes are most prevalent in the profile (Figure 6.15). They appear up to great heights and reach at maximum up to 4.45 m asl. They are not evenly spread above the roof but appear cumulated in certain areas. Moreover, they occasionally penetrate oyster shells (Figure 6.16d). Near the base of the profile they are rather eroded (Figure 6.15). Inside the notch, near the apex, the boreholes are deeper but the walls are in parts broken off due to the proximity of single boreholes (Figure 6.16a). They contact each other and are more prone to erosion. Most of the boreholes are slightly tilting downwards.

Sponge borings occur in a great range from 2.03 m up to 3.89 m asl. They cover large areas, especially underneath the notch (Figure 6.16b). In these parts, the rock surface appears very smooth and influenced by abrasion (Figure 6.16b). Inside the notch, sponge borings are not as common and just appear in the lower part in-between *Lithophaga* boreholes. In the upper part of the notch, sponge borings are no longer visible. They are as well missing in the first 18 cm of the profile although sponge boring are common in the fifth zone (Figure 6.15).

Neither barnacles nor worm tubes are present. Therefore, they are not included in the zonation. Oysters occur at the roof of the notch (Figure 6.16c) as well as above. At some points, they reach up to a maximum of 40 cm above the notch (4.62 m asl). Conspicuous is the appearance of oyster shells. While they cover up eroded *Lithophaga* boreholes at the notch roof, this behaves reversely above the notch where oyster shells are penetrated by *Lithophaga* borings (Figure 6.16d).

Figure 6.15: Zonation of organisms at profile 5 of the Main Notch. Depiction of presence and distribution of organisms and the level of bioerosion they caused in different zones of the profile.
Results

Figure 6.16: a) *Lithophaga* boreholes at the apex of the notch. Boreholes are in close vicinity and heavily eroded. Younger borings are partly penetrating boreholes advanced in age. b) Sponge borings and *Lithophaga* boreholes below the notch. The surface looks smooth. c) Oyster shells and *Lithophaga* boreholes at the roof of the notch. d) Oyster shells in parts penetrated by *Lithophaga* borings above the notch.

Comparable to the previous profile, the small, dumbbell-shaped *Lithophaga* I boreholes do not appear. *Lithophaga* III boreholes are rather widespread and reach up to 3,37 m asl. They are not as common as in profile 4 (Figure 6.17). Similarly to the fourth profile, mainly broad and bowl-shaped boreholes are present. These boreholes are rather flat with not exceeding a depth of 2 cm, and are heavily penetrated by *Lithophaga* II boreholes (Figure 6.17). Only in few exceptional cases, *Lithophaga* III boreholes are not penetrated by other *Lithophaga* and show a more clear shape and a greater depth. *Lithophaga* II boreholes are common throughout the entire profile in great amounts (Figure 6.17). The greatest height they reach is 4,45 m asl.
6.1.6 Profile 6 (GPS 123: UTM 40Q 759936 2495777)

This profile is the last one of this outcrop and covers a vertical area of 243 cm. The notch starts at a height of 3.54 m and reaches up to 4.29 m asl (notch height 75 cm) (Figure 6.18). The weathering increases from the first profile to the last profile of this outcrop, therefore from profile 1 to profile 6.

The sixth profile is separated into five zones. The first zone (above the notch) is just slightly penetrated by *Lithophaga* boreholes and classified as BIL 1. In the following zone (Zone 2), the bioerosion is very strong and characterized as BIL 5. Only *Lithophaga* boreholes occur. The part below, representing zone 3, is not as deeply bioeroded. Instead of *Lithophaga* boreholes covering the entire surface, sponge borings are present in-between *Lithophaga* boreholes. They penetrate the surface only about 2 mm deep. Therefore, the zone is classified as BIL 4. The fourth zone is more intensely influenced by sponge borings while *Lithophaga* boreholes are less common. The BIL is downgraded to 3 because of the decreasing penetration depth. The following and last zone is similar to the fourth zone. Sponge borings are just slightly more common and parts of the rock surface are missing as a result of weathering. Therefore, the BIL is classified as 2. The lower parts of the profile are very smooth looking (Figure 6.19b) and the rock surface seems like a thin layer and not as porous as the upper parts of the profile. The part underneath the bioerosional features is heavily weathered and fractured (Figure 6.19d).
Results

*Lithophaga* boreholes are present in the entire profile. They appear at maximum 18 cm above the notch (4.47 m asl) and are very prevalent in the upper part of the notch (Figure 6.19a). In the lower part of the profile, mostly the last zone, the boreholes are strongly eroded and are only 0.2 cm to 2 cm deep. Near the apex, the boreholes are up to 4 cm deep. They are positioned very close to each other and parts of the borehole walls are eroded (Figure 6.19a).

Sponge borings appear in great numbers below the notch (Figure 6.19b) and in smaller amounts in the lower part of the notch itself. In total they reach from 2.04 m up to 3.86 m asl. They mostly cover up the areas between *Lithophaga* boreholes. They penetrate the rock just slightly and have depths about 3 mm to 4 mm.

Oyster shells, worm tubes and barnacles do not occur in this profile.

![Profile sketch](image)

Figure 6.18: Zonation of organisms at profile 6 of the Main Notch. Depiction of presence and distribution of organisms and the level of bioerosion they caused in different zones of the profile.
Figure 6.19: a) *Lithophaga* boreholes near the apex of the notch. b) Sponge borings and eroded *Lithophaga* boreholes below the notch. Surface of the rock seems smooth. c) *Lithophaga* III borehole and *Lithophaga* II boreholes below the notch. Remnants of sponge borings around and especially below the *Lithophaga* III boring. d) Entire profile with heavily fractured part below the bioeroded surface.

The last profile is characterized by all three *Lithophaga* subgroups. As almost described for each profile, the *Lithophaga* II boreholes appear throughout the entire profile (2,04 m to 4,47 m asl) (Figure 6.20). The *Lithophaga* I boreholes only occur in a very narrow belt near the center of the profile from 3,05 m up to 3,17 m asl (Figure 6.20). *Lithophaga* III boreholes appear in a greater area ranging from 2,04 m to 3,25 m asl (Figure 6.20). The boreholes are often bowl-shaped but also a great amount of deeper boreholes is present.
Figure 6.20: Zonation and distribution of Lithophaga subgroups at profile 6 of the Main Notch. The yellow lines highlight the area where Lithophaga I boreholes with a typical dumbbell shape are present. The green lines mark the area Lithophaga III boreholes with a diameter greater than ~2 cm appear. The blue dotted lines frame the area Lithophaga II boreholes are present. They have a round opening and a diameter mostly ranging between 1 cm and 1.5 cm.

6.2 Southern Notch
This outcrop adjoins the Main Notch to the south (Figure 6.21). It is ranged along the mouth of Wadi Salmiyah for about 500 m. In contrast to the Main Notch, no obvious notch shape is present. The occurring bioerosion appears in a bioerosional horizon building up a distinct top line. It is uncertain if the roof height at the Main Notch and the height of this upper Lithophaga line are more-or-less the same height. No height measurements of DGPS are available. Therefore, it is not possible to validate these assumptions. In many parts of the outcrop a very distinct and dense oyster band occurs about 0.5 m above the distinct Lithophaga line. Unlike at the Main Notch, the superposition of oyster shells and Lithophaga boreholes as well as their significant interference is not as pronounced at this location.

The lowest and highest bioerosion tracks and the different organism belts were measured and described as exemplified by the following profile.
6.2.1 Profile 1 (GPS 136: UTM 40Q 760059 2495519)

The profile is situated about 290 m south of the Main Notch. The surveyed profile stretches over 155 cm. After one third of the profile a distinctive line of *Lithophaga* boreholes is visible. A decreasing number of *Lithophaga* boreholes and a significant oyster band are located at the top of the profile. A division of the profile according to the profile shape is not possible owing to the non-existent notch shape.

The lower third of the profile is massively penetrated by *Lithophaga* boreholes. The borings are all part of the subgroup of *Lithophaga II*. *Lithophaga III* as well as *Lithophaga I* do not occur. As a result, the diameter only ranges between 0,5 cm and 2 cm. The depth ranges between 1 cm and 4,5 cm. The distinct line of *Lithophaga* boreholes is located at a height of 0,45 m while the highest *Lithophaga* boreholes reach up to 1,18 m (Figure 6.22).

The presence of oysters ranges between 0,93 m and 1,55 m with the greatest amounts in the upper part. They are more-or-less preserved. The shells do not show the original architecture but a nacreous luster is clearly visible. They appear to pass into the rock surface.

![Figure 6.22: Zonation of organisms at the Southern Notch. The red dotted line marks the distinctive *Lithophaga* line which divides a heavily penetrated part from a less bioeroded part of the profile.](image-url)
Results

6.3 Eastern Notch

This outcrop location is situated next to the main street in the southeast of the lagoon. The notch is only visible in a few single spots and only one profile is compiled (Figure 6.23). A large amount of debris fills up and covers the notch. Thereby, most of the time just the upper few centimeters to decimeters of the notch are visible. No measurements with DGPS were implemented, so that no absolute heights can be used to correlate this profile with the profiles of the Main Notch. In some cases brecciated limestone covers the notch (Figure 6.25d).

6.3.1 Profile 1 (GPS 220: UTM 40Q 760990 2496380)

This profile is surveyed at one of the rare spots with a completely visible notch shape. The height of the profile is about 1,42 m. The notch itself is 72 cm high. All zones are primarily characterized by Lithophaga boreholes (Figure 6.24). In the area above the notch neither oysters nor Lithophaga boreholes are present. Therefore, the BIL is classified as 0. The upper part of the notch is not as deeply penetrated by Lithophaga as at the Main Notch and classified as BIL 3 to 4. The part beneath is slightly deeper penetrated and set as BIL 4 (Figure 6.24). The lowermost zone is more heavily penetrated than it is at the Main Notch. In comparison to the Main Notch, Lithophaga boreholes do not appear in a greater number but numerous boreholes exhibit a greater depth. The BIL is classified as 4.

Lithophaga boreholes are common in each zone, with zone 1 above the notch as an exception. They are the most widespread organism throughout the whole profile (Figure 6.24). The depth of the boreholes ranges between 0,5 cm and 4 cm (Figure 6.25a). In the lowermost zone, the diameter of the boreholes increases with a maximum of about 2,5 cm. However, Lithophaga III boreholes are not as common as at the Main Notch and their size and shape is not as distinct. The Lithophaga borehole diameter overall averages 1 cm.

Oysters are most common inside the notch. Here, they form a band ranging between 0,73 m and 1,20 m. This is best visible 1 m left of the surveyed profile (Figure 6.25b). The oysters are more-or-less well preserved but the original shape is not easily distinguishable anymore. The spacing between individual organisms amounts several centimeters. Hence, the amount of oysters is rather small to mediocre (Figure 6.24).

In comparison, barnacles are the least in this profile (Figure 6.24). They occur in the third zone and are mostly present inside of eroded Lithophaga boreholes (Figure 6.25c). They appear in a very small quantity with well preservation and range from 0,78 m up to 1,00 m.
Figure 6.24: Zonation of organisms at the Eastern Notch. Depiction of presence and distribution of organisms and the level of bioerosion they caused in different zones of the profile.

Figure 6.25: a) *Lithophaga* boreholes in the lower part of the profile (Zone 4). b) Oyster band 1 m left of the profile. The shape of the shells is more-or-less recognizable. c) Single barnacles within eroded *Lithophaga* boreholes. Blue arrows are directed to the best preserved barnacles.
6.4 Western Outcrops
This location includes a variety of small outcrops, all positioned westward of the Main Notch near the boundary between the two study areas (Figure 6.26). In most cases, the outcrops are heavily weathered and the notch shape is not visible. Zones cannot be defined. This prevents statements about bioerosion and organism distribution. The quantity of worm tubes in this area is significantly higher in comparison to the other sites.

6.4.1 Profile 1 (GPS 124: UTM 40Q 0759656 2495583)
This profile was surveyed about 310 m westwards of the Main Notch. It is 0,95 m high reaching up to 4,42 m asl and a clear notch shape is not distinguishable (Figure 6.27). The rock surface is fractured and in some parts heavily weathered.

*Lithophaga* boreholes exist between 3,47 m and 4,30 m asl (Figure 6.27). Only *Lithophaga II* borings appear. They have a diameter between 0,5 cm and 2 cm. Their depth is very variable and ranges between 0,5 cm and 4 cm. The greatest number of boreholes appears up to 4,08 m asl, which is about 20 cm lower than the roof at the Main Notch.

Sponge borings range between 3,47 m and 3,99 m asl. They are rather eroded and penetrate the rock surface just marginally. They are not appearing in a great amount. Worm tubes reach a little bit higher up to 4,08 m asl. They are more common than at the Main Notch and fill up not only eroded *Lithophaga* boreholes but occur in the on the rock surface too (Figure 6.27 and Figure 6.28b). Apart from their quantity, they are comparable to their counterparts at the Main Notch.

Oysters occur with the greatest quantity in the upper part of the profile just above the *Lithophaga* boreholes (Figure 6.28a). Here, they form a faint marked band. Beneath that area, they appear fragmentary and mostly inside of *Lithophaga* boreholes. The height of the oysters at this location and at the Main Notch correlates well. They range from 4,08 m to 4,42 m asl. Oysters are not that well preserved; only remnants are fixed to the rock surface.
Results

Figure 6.27: Zonation of organisms at profile 1 of the Western Outcrops. A clear notch shape is not visible. A relatively great number of worm tubes is present inside of Lithophaga boreholes as well as on the limestone.

Figure 6.28: a) Oyster shells forming a band. b) Worm tubes on the rock surface near the base of the profile.

6.4.2 Profile 2 (GPS 198: UTM 40Q 759591 2495455)

The second profile is situated about 140 m northwards of profile 1 of this site. The height of the profile is 1.10 m. DGPS measurements are not available for this location. Therefore, the mentioned height cannot be compared to other profiles. Despite the intensive weathering of the limestone, the notch shape is partly recognizable. While the roof is more-or-less preserved, base and especially the central part of the profile are partially broken off. In these parts, the zonation was completed by transferring lateral information. The lower part of this profile does not seem to embody the original notch shape. For that reason these parts were not used to evaluate the BIL or organism distribution. Only zone 2 and 3 are described.
Results

The profile is dominated by *Lithophaga* boreholes. They are most common in the second and third zone and do not appear above the roof. The bioerosion in the second zone is classified as 3 to 4. The zone beneath is slightly more bioeroded and classified as BIL 4. Comparable to the Main Notch, remnants of beach rock are present in the middle of the profile at a height of about 60 cm.

As mentioned before, *Lithophaga* boreholes are widespread, they occur in the entire profile, starting at 0 m and stretching up to 1,09 m. Notably, the area near the roof of the notch is heavily penetrated (Figure 6.30a). The diameter of the boreholes ranges between 0,5 cm and 2 cm and their depth ranges between 0,5 cm and 4,5 cm. Neither *Lithophaga III* nor *Lithophaga I* appear. This may be contributed to the poor preservation of the lower part of the profile.

Sponge boreholes occur in the lower part of the profile starting at 0 cm and reaching up to 87 cm. Especially near the base, they appear widespread and form a distinct net-like pattern (Figure 6.30c). The depth of the borings is difficult to estimate but probably ranges around 0,5 cm to 1 cm.

Worm tubes appear at more-or-less the same height as sponge borings. They exceed the sponge borings about 10 cm, stretching up to 97 cm. They occur inside of eroded *Lithophaga* boreholes as well as on the rock surface (Figure 6.30d). The preservation of the worm tubes is comparable to profile 1 but the number is significantly smaller. Barnacles are not present at this location.

The oyster shells seem mostly flaky and cover up eroded *Lithophaga* boreholes at the roof (Figure 6.30b). The general shape is recognizable although they are not as well preserved as at the Main Notch. The greatest quantity of oysters is present at the roof of the notch and decreases in direction towards the base. Nevertheless, they are present in the entire profile (0 m to 1,10 m).

Figure 6.29: Zonation of organisms at profile 2 of the Western Outcrops. Depiction of presence and distribution of organisms and the level of bioerosion they caused in different zones of the profile.
Results

6.4.3 Profile 3 (GPS 126: UTM 40Q 0759553 2495652)

The profile is located at the most western part of the investigated area. At this site, the greatest numbers of worm tubes and barnacles arise. Both organisms form a thick ledge (Figure 6.31). The profile is only 26 cm high and stretches up to 4,28 m asl. Parts below and above are highly weathered and, as mentioned before, no notch shape is visible. The height of this outcrop coincides with the height of the roof at the Main Notch (see chapter 6.1).

Barnacles and in particular worm tubes form an approximately 7 cm thick ledge which is covering eroded Lithophaga boreholes (Figure 6.31). The aggregation exhibits a sharp boundary at the top. The boundary at the ledge base is not as distinct. Worm tubes and barnacles occur in a range roughly between 4,02 m and 4,20 m asl. The worms are part of the species Pomatoleios kraussii. The dense encrustation of the worms hinders the recognition of details each individual might show. The tubes appear to be quite small with a length of up to 3 cm and a diameter between 2 mm to 3 mm (Figure 6.32a). Barnacles are present in a variety of sizes (Figure 6.32b). In contrast to the other outcrops, the diameter ranges between 0,4 cm and 1,5 cm. Due to their appearance it is assumed that they are part of the family Balanidae. Barnacles and worm tubes are well preserved. However, all barnacles are missing their cover plates (Operculum) (Figure 6.32b).
The covered *Lithophaga* boreholes are all part of the subgroup of *Lithophaga II*. Their diameter ranges between 0.8 cm and 2 cm and their depth between 1 cm and 3 cm. Neither *Lithophaga III* boreholes nor *Lithophaga I* boreholes were discovered at this location.

Figure 6.31: Zonation of organisms at profile 3 of the Western Outcrops. Pictured is a thick ledge consisting of worm tubes and barnacles on miocene limestone.

Figure 6.32: a) Encrustation of worm tubes. b) Large amounts of barnacles of different sizes on a worm tube ledge.
6.5 Northern Peninsula

The elongated peninsula is located in the northern part of the lagoon and reaches towards the southwest (Figure 6.33). Hence, the peninsula is well accessible from both sides. Abrasion notches, as well as a bioerosional horizon, occur on the peninsula. The two sides of this peninsula differ in many ways. The appearance and composition of beach rock is completely divergent and only the eastern side exhibits a bioerosional horizon in the conglomerate. Therefore, this survey area is further divided into two parts.

Western side

The investigated abrasion notch was formed in beach rock. The sediment composition varies lateral as well as vertical. The height of the notch changes from a few decimeters to above 3 m. The smallest heights are located near mainland and increase towards the lagoon. The sediment is rich in coral fragments and bivalve shells. Almost the entire sediment consists of fossils. Moreover, the sediment gets generally coarser towards the base of the profile. At this side of the peninsula no bioerosional horizons are present. Due to measurements of the notch floor about 75 m north of the profile, the absolute height of this profile was calculated (Bagci 2017, unpublished data).

6.5.1 Profile 1 (GPS 150: UTM 40Q 758822 2497588)

The complete profile is composed of beach rock. The lowermost layer of the profile is 198 cm thick and consists of coarse to very coarse sand in a sparitic matrix. A great amount of bivalve shells, in parts oyster shells, and coral fragments occur in the entire layer. The good sorting decreases from the top towards the base. Moreover, clasts are present in the complete layer. Granules and medium pebbles are present at the base and a layer of small cobbles at the top. The clasts are primarily angular to subangular. Some of the clasts are penetrated by sponges and a small number of barnacles, as well as worm tubes, are attached to them. The notch was carved into this part of the beach rock. The feature shows a broad u-shape and ranges from 1,10 m up to 3,08 m asl (Figure 6.34). No sediment structures are visible but weathering features are present in the upper third. They have a net-like appearance because of rounded parts missing in the sediment (Figure 6.34).

The second layer is just 17 cm thick and located above the band of small cobbles. It reaches from 3,08 m up to 3,25 m asl (Figure 6.34). Grain and clast size, as well as their distribution, is very similar to the first layer. However, in contrast to the first layer, no cobbles are present. The layer is characterized by very distinct cross stratification. Due to partial weathering the structure is very prominent (Figure 6.34).

The last layer at the profile top consists as well of coarse to very coarse sand. The clast size varies and is maximal classified as small cobbles. Comparable to layer 1, bioeroded clasts and worm tubes as well as barnacles are present (Figure 6.34). In some cases worm tubes also appear in the matrix.
Results

(Figure 6.34). Very similar to the first two layers, a great number of fossils like coral fragments, gastropods and different bivalves are present. The layer starts at 3,25 m asl and is about 20 cm to 25 cm thick (Figure 6.34). Due to erosion, no accurate measurements are possible.

![Profile sketch](image)

**Figure 6.34: Profile of the abrasion notch on the western side of the Northern Peninsula. Left: Roughly sketched profile with layer boundaries and notch shape. Middle: Photography of the notch with layer boundaries and marked areas of detail photographs. Right: a) Detailed view of the third layer. Matrix consists of coarse to very coarse sand with gravel. Worm tubes can be found in the matrix and on clasts, as well as *Lithophaga* boreholes, sponge borings and barnacles. b) Relatively large-scale cross stratification and a band of gravel and small cobbles. c) Net-like weathering of the upper part of the first layer. On the left side of the picture the weathered parts are highlighted, on the right side the natural conditions are visible.**

**Eastern side**

Over the course of the eastern side of the peninsula several spots with remnants of bioerosional horizons are visible. A great part of the fluviatile sediments and therefore of the bioerosional horizon is affected by erosion and weathering. Hence, the remnants of the bioerosional horizon are rather small. An abrasion notch is present underneath this horizon. The vertical size of the notch varies between 1,50 m and 2 m. In some cases, the bioerosional horizon is situated directly above the abrasion notch and in other cases the bioerosional horizon is located several meters towards the center of the peninsula.

The abrasion notch is visible over the most parts of the peninsula. But due to erosion some parts are broken off and other parts of the abrasion notch are covered by debris.

Furthermore, the beach rock on this side of the peninsula is only partly preserved. Examples for preserved beach rock can be found in larger areas near the mainland. The beach rock consists mostly
of coarse sand and small clasts. The sediment often shows cross stratification. The fossil content is rather low, shell fragments appear only in a few spots.

The abrasion notch formed within fluviatile sediments and beach rock, as far as the latter one is present. The beach rock was possibly accumulated at the same time as the beach rock at the Main Notch. On the roof of the abrasion notch, small *Lithophaga* I boreholes, sponge borings (*Cliona*) and more rarely oysters occur.

### 6.5.2 Profile 1 (GPS 165: UTM 40Q 758752 2497122)

The bioerosional horizon is visible in a poorly sorted, polymictic and sandy conglomerate. The clasts are primarily in the size of small cobbles but in smaller quantity also large cobbles appear. The only visible bioerosional traces were created by *Lithophaga* (Figure 6.35). The *BIL* is mediocre and classified as 3. The boreholes have an average diameter of 0.5 cm to 1 cm and are therefore part of the subtype *Lithophaga* II. They show a depth between 1 cm and 4 cm. *Lithophaga* boreholes occur in a narrow band located between 4.15 m and 4.39 m asl but are more concentrated in the lower half. *Lithophaga* bored into limestone clasts as well as into the matrix. The elevation of the *Lithophaga* boreholes corresponds with the bioerosion notch in the south. Oyster shells are present in an even narrower band between 4.31 m and 4.36 m asl (Figure 6.35). They cover some of the *Lithophaga* boreholes and are not as well preserved as at the bioerosion notch in the south. In some cases *Lithophaga* bored through oyster shells.

The horizon is situated several meters towards the center of the peninsula and does not parallel the abrasion notch below. At this location the abrasion notch is broken off. Hence, the height was measured about 3 m northward. The abrasion notch shows a broad u-shape, starting at a height of 0.57 m and reaching to 2.43 m asl. Aside from the bioerosional horizon, bioerosion occurs above the roof of the abrasion notch. *Lithophaga* I boreholes cover limestone clasts. They appear in a height of roughly 2.70 m asl. The exact distribution is not measurable.
Figure 6.35: Profile of the abrasion notch and the bioerosional horizon at the eastern side of the Northern Peninsula. Fading parts of the zonation represent unclear distribution.

6.6 Northeastern Notch

At this outcrop an abrasion notch, as well as a recent bioerosion notch, is present. They are located near the lighthouse of Sur at the coastline and face the open sea (Figure 6.36). The height of the abrasion notch is not constant but changes over the course of the outcrop. The profile location was chosen to cover the largest magnitude. The absolute height of the abrasion notch was calculated by using DGPS surveys of the abrasional platform in front of the notch. The recently forming bioerosion notch is situated below the abrasion notch and shows a distinct oyster ledge. The absolute height of this ledge was measured as well. At this location, no paleo bioerosion notch or bioerosional horizon is present.
6.6.1 Profile abrasion notch (GPS 187: UTM 40Q 761145 2498062)

The abrasion notch covers a vertical range of about 1.71 m and shows a very broad and u-like shape. The lower angle of the u-shape is steeper than the upper one near the roof. This creates a slightly asymmetrical appearance (Figure 6.37). The notch floor is located roughly 1 m asl (Bagci 2017, unpublished data). The roof reaches up to about 2.74 m asl.

The sediment matrix consists of coarse to very coarse sand. The clasts are primarily in the range of granules to small cobbles and in most cases subangular to subrounded or even rounded. A few large cobbles occur as well. The clasts consist of grey limestone, red or orange sandstone and quartzite. It should be noticed that most clasts are on the same level as the sandy matrix. No shells or other fossils are present in the sediment. This polymictic and matrix supported conglomerate is probably of fluvial origin. Wadis are cut into the relief of the mountains and carry material to the coast and adjoining areas in wetter periods. The sediment was accumulated around 230,000 BP (Hoffmann 2017, unpublished data). The dating was performed with cosmogenic nuclei on a sample of fluviatile sediment collected in the south of the lagoon. To the west the notch gets smaller and smaller and covers at the end of this outcrop only a vertical range of 1.15 m.

Figure 6.37: The abrasion notch of the northeastern Notch with a vertical size of about 1.71 m (roof to floor). The u-shape is not completely symmetrical. The floor of the notch is very flat leading to a steeper angle at the floor.
Results

6.6.2 Recent notch – Oyster ledge (Near GPS 187: UTM 40Q 761145 2498076)

A recent notch is forming below the abrasion notch. The rock surface is covered with a film of algae and cyanobacteria and therefore colored black (black terrace) (Figure 6.38). Moreover, grazers (e.g. limpets) and bioconstructers (e.g. barnacles) are present on the rock surface. The most distinct feature of this outcrop is the oyster ledge occurring in the upper and middle part of the notch (Figure 6.38). The ledge has sharp boundaries and is several centimeters thick. Young oysters settle down on old and already dead shells and generate an oyster band, affecting the shape and relief of the notch. This ledge covers a vertical area of roughly 20 cm to 30 cm. Oysters are bioconstructing organisms and protect the rock surface. The ledge height was measured to examine the exact position of oysters relative to the MSL in this region. The DGPS measurement resulted in an absolute average height of 0.24 m ± 0.2 m asl. This is also suggested by measurements at the Northern Peninsula. The position of the ledge ranges between 4 cm and 62 cm asl and never falls below MSL.

Figure 6.38: Thick ledge of oysters (orange dashed line) located in the upper and middle part of a recently forming notch at the Northeastern Notch. The ledge has a diameter of 20 cm to 30 cm. The black coating of the rock is consisting of algae and cyanobacteria.
7 Interpretation

The compiled profiles described in the previous chapter 6 are used in the following to create a model of sea level fluctuations. The overall information provided by the profiles is of greater importance than the interpretation of single profiles. Hence, single profiles are not included in detail into the construction of the model.

7.1 Bioerosion notch and its polyphase development

As seen previously on the profiles, especially the Main Notch, the bioerosion notch and the preserved fossil remains do not always characterize the same relative sea level (RSL) or point in time. This indicates a changing sea level. An instant dating of bioerosion notches is difficult and often not achievable. Due to the limited time frame of a master thesis, the dating of fossil remains was not feasible. However, the dating of a nearby beach rock to 80.000 a BP +/- 3.000 a (Mauz et al. 2015) indicates that the notch was formed during Eemian (Last Interglacial). The position of the bioerosion notch 3.7 m above recent MSL (Hoffmann et al. 2016) further supports this theory because the position of the notch corresponds to the sea level during that time (see Shackleton et al. 2003). But sea level depends on three variables. Tectonics, isostatic movements and eustatic changes all affect the position of relative sea level ($RSL = \text{eustatic} + \text{isostatic} + \text{tectonics}$).

Therefore, the position of the notch could be influenced not only by a higher sea level than today but also by uplift or subsidence after or during the formation of the notch. The working hypothesis is that the investigated area was not affected by tectonic events since the emergence of the notch (see chapter 3.3.3) (see Bagci 2017). This is implied by DGPS measurements inside of the study area as well as on the marine terraces in the north (Bagci 2017). That means that the Qalhat fault, located northwestward of Sur, has no influence on this area. Only the northwestern block is uplifting, while the southeastern block remains stable. To reconstruct former sea levels by using geomorphological features not only tectonic but also isostatic movements, like glacioisostatic rebounds, have to be considered. During glacial periods the ice masses never reached the Arabian Peninsula and just led to a dropping sea level. Hence, no glacioisostatic movements have to be taken into account (see Lorscheid et al. 2017b). Another process leading to isostatic movements is karstification. In some parts of the Hajar Mountains large caves were formed due to this process. Parts of the carbonate rocks were soluted and the water saturated with $\text{CaCO}_3$ drained away into the sea and generated in imbalance and a loss in weight. The impact of this process in this area is unclear but is assumed rather small. Hence, the influence of karstification is considered negligibly.

As a main conclusion, no tectonic action is and was occurring in this area and no isostatic movements have to be taken into account by reconstructing sea level. As a result the position of the bioerosion notch only depends on the eustatic component. Hence, the difference between the RSL today and the RSL during the Last Interglacial, represented by the bioerosion notch, is just driven by sea level change. In summary, it can be stated that the notch is a fixed marker and represents the position of a former sea level.
7.1.1 Organisms

The results show some trends and fixed features that are visible in almost every outcrop. These fixed features, for example organism distributions, are combined with the actual living range gathered from literature or recent organisms in the study area to compile a schema of notch development. This is used to reconstruct and illustrate sea level fluctuations. Therefore, all trends and perceptions of the investigated organisms are summed up and generally interpreted in the following. It must be kept in mind that the zonation of organisms was not identical at every profile location. This is due to the fact that the belts the organisms are living in are never totally horizontal (Laborel & Laborel-Deguen 1994). They are warped, even over just short distances (Laborel & Laborel-Deguen 1994 and 1996). Moreover, the living range varies with differences in tidal range, salinity, exposure and more. Hence, on a regional scale the living range of the same organism can be significantly different (Woodroffe & Barlow 2015). As a result, the following summary of living ranges and other features refers only to the area around Sur and the lagoon with its specific conditions.

Bromley and Asgaard (1993) introduced two new ichnofacies arose from the Trypanites Ichnofacies (see Knaust et al. 2012). The Entobia Ichnofacies or Ichnocoenoses fits the situation of an older notch with only deep bioerosional traces left. The ichnofacies is characterized by deep penetrating into the rock surface over a longer period of time (Bromley & Asgaard 1993, Miller 2007). Therefore, no shallower traces are preserved. This characterization matches the bioerosional notch investigated in this study. The second ichnofacies is named Gnathochinus (Bromley & Asgaard 1993, Knaust et al. 2012). For a general description of the organisms, their living range and mode of life see chapter 4.1.1.

**Lithophaga**

The borings of Lithophaga are subdivided into three groups due to their appearance. These subgroups represent different developmental stages. They are mostly limited to specific areas of the outcrops. The youngest developmental stage of Lithophaga is just about 2 mm in diameter, dumbbell-shaped and mostly occurs in the lower part of the profiles (Figure 7.1). The next developmental stage is represented by the Lithophaga II boreholes. They are about 0.5 cm to 1.5 cm in diameter and occur in the entire profile. They not only appear inside of the profile but often above the roof of the notch (Figure 7.1). They are very important for the following interpretation of sea level fluctuations. The last stage is named Lithophaga III. In comparison with the other two subgroups they are probably the oldest developmental stage because of their large diameter of 2 cm and larger. During their lifetime Lithophaga constantly broaden their boreholes. As a consequence, it can be assumed that broader Lithophaga boreholes generally represent a greater life span. They occur mainly in the lower part of the profiles and to, or slightly above, the floor of the notch (Figure 7.1).

Inside of the notch Lithophaga II boreholes, especially with a diameter between 1 cm to 1.5 cm, are most widespread. Moreover, the greatest density and the greatest depth of borings occur inside of the notch. Boreholes at the base of the profile are generally more heavily eroded with respect to depth and diameter than boreholes in the upper part of the notch. This is supported by the diagrams
of the second profile at the Main Notch. The trend shows that in general the depth of boreholes decreases towards the base of the profile and the diameter increases. Due to many outliers the validity of these diagrams should be handled with care. Nonetheless, it can be assumed that the \textit{Lithophaga III} boreholes not only represent a greater life span but are older in comparison to \textit{Lithophaga II}. This correlates with the increasing erosion rate towards MSL and the clustering of \textit{Lithophaga} near their upper limit range. Additional indication could be that in some profiles at the Main Notch \textit{Lithophaga III} boreholes are heavily penetrated by \textit{Lithophaga II} boreholes. The uppermost \textit{Lithophaga} boreholes state the highest position of MSL characterized by this organism. The position of MSL indicated by the bioerosion notch and the MSL indicated by \textit{Lithophaga} boreholes are not coincident. This is explained by the erasure of previous highs (MSL’s) marked by \textit{Lithophaga} boreholes due to an increasing sea level.

All in all, the most convincing indicator of sea level change after the formation of the notch are \textit{Lithophaga} boreholes above the roof of the notch. They show a sea level clearly higher than the apex of the notch. To simplify the zonation used to create the phases it is assumed that the upper limit of \textit{Lithophaga} coincides with MSL and therefore with the apex of the notch in the second phase (see chapter 7.1.2).

\textbf{Sponges}

Sponge borings occur in many of the described profiles. They mostly appear beneath the notch in the lower parts of the profiles but can reach up to the middle of the notch near the apex (Figure 7.1). There are a few indicators that they might be present in the upper part of the notch as well but that cannot be proved. Very distinct is the net-like pattern they create on the rock surface. The traces were generated by \textit{Cliona}, a boring sponge which is part of the family \textit{Clionidae} (Westheide & Rieger 2007). This sponge and its traces is typically part of the subichnotaxa \textit{Entobia} (Bromley & Asgaard 1993).

There is some indication that the sponge borings in the lower areas of the profiles are younger than the large \textit{Lithophaga} boreholes in these areas. This is mostly based on the depth of the erosional traces. In comparison \textit{Lithophaga} bore about three times deeper than \textit{Cliona}. According to Hoeksema (1983) \textit{Cliona} can penetrate 3 cm deep into the rock, depending on the substrate. Nevertheless, the sponge borings are still visible in-between the heavily eroded \textit{Lithophaga} boreholes. This indicates that the sponge bored into the rock after the \textit{Lithophaga} boreholes were already eroded to some extent.

Together with \textit{Lithophaga} they probably mark the MSL (Laborel & Laborel-Deguen 1994). Therefore, they are classified as a relatively good sea level indicator. The connection of MSL and the uppermost position of Cliona is of course a simplification and facilitate the compilation of a model.

\textbf{Worms}

The worms discovered in the study area are classified as \textit{Pomatoleios krausii}. Their tubes are found usually inside of the bioerosion notch (Figure 7.1). Only the second profile at the Western Outcrops indicates that they appear underneath the notch, too. Most of the time, they occur in rather small
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amounts. They are either present inside of *Lithophaga* boreholes or are located on the rock surface. Their presence inside of *Lithophaga* boreholes implies that they appeared after the *Lithophaga* settled down and died. In particular, at the third profile of the Western Outcrops they cover up *Lithophaga* boreholes with an approximately 7 cm thick ledge. Therefore, they are definitely younger compared to the *Lithophaga* boreholes inside of the notch. *Pomatoleios krausii* is thought to be limited to the area around MSL and therefore considered as a good sea level indicator (Shishikura et al. 2006). Anyhow, they do not necessarily indicate the exact MSL but a position close to it. For the compilation of sea level fluctuations the appearance of worm tubes is used to indicate the position of MSL. An appearance near other tidal datums is excluded to ensure the preparation of a model.

**Barnacles**

It is assumed that the appearing barnacles belong to the family *Balanidae*. This is clearly recognizable at the third profile of the Western Outcrops. Beside their appearance their position indicates the affiliation to *Balanidae*. They commonly occurred in the same areas as *Pomatoleios krausii* (Figure 7.1). *Pomatoleios krausii* exists especially near MSL, similar to *Balanidae*. As a result, their positioning indicates the proximity to MSL. The occurrence of *Balanidae* was therefore used to reconstruct MSL. They can build up small ledges (Laborel & Laborel-Deguen 1994, Rovere et al. 2015) visible at the previously mentioned profile location. At this location they occur in a ledge together with *Pomatoleios krausii*. That implies a similar age for barnacles and worms. Hence, they are younger than *Lithophaga* as well as oysters. At the other outcrops they only appear in rather small amounts and do not build up ledges. Their diameter is mostly about 1 cm. The profiles show that barnacles occur only inside of the notch. Beside the discovered ledge of worm tubes and barnacles no clear band or upper line of barnacles is visible.

**Oysters**

Oyster shells are very common in most of the profiles. They are always situated in the upper parts of the profile, normally near the roof of the notch or above. The exception is the profile surveyed at the Eastern Notch. At this location oyster shells form a band in the middle of the notch. Nevertheless, they are in general appear between the middle of the notch and several centimeters above the roof (Figure 7.1). The preservation of the oyster shells is very variable, depending on their location and protection against weathering and mechanical erosion. Nevertheless, the different levels of preservation could also indicate various generations and various ages. To what extent they are part of one phase and formed during one specific sea level is unclear.

Oysters have generally a very wide living range (see chapter 4.1.1) (Laborel & Laborel-Deguen 1994). As described in chapter 6.6 the measurements of recent oysters show that they are most common in the upper part of the intertidal zone in this region. They form typically a distinct ledge with a width of 20 cm to 30 cm about 0,24 m +/- 0,2 m asl. The most common position of the oyster ledge is about 30 cm asl. Despite the fact that oysters can occur also in the subtidal zone these measurements could be a hint that their typical living range in this area is situated in the upper part of the intertidal zone. Presumably, this range can be transferred to the living environment of oysters during MIS 5e if we assume comparable conditions to nowadays. The clustering of individuals in ledges and bands is also
visible in our fossil outcrops but not as distinct. They cover a width of maximal 55 cm. Moreover, the
distribution seems more widespread than today. At least they always mark an area beneath the
supratidal zone and therefore the extent of the intertidal zone.

Figure 7.1: General distribution of all investigated organisms within the notch. Primarily data of the Main Notch
outcrop was used to compile this sketch.

7.1.2 Different phases

In many diagrams, based on coral reefs as sea level indicator, MIS 5e is shown as one plateau with a
more-or-less constant sea level and no peaks (Cutler et al. 2003, Laborel et al. 1999). The profiles
taken in Sur (Oman) showed that the notch experienced different phases of sea level fluctuations
indicated by several organisms and their fossil traces. The fluctuations are probably short term
events and limited to a range smaller than 1 m.

As mentioned before, the notch and the preserved fossil traces represent different periods in time
and thus different sea levels. In the following chapter the development of the notch and therefore of
RSL is divided into different phases represented by the investigated organisms. The apex of the notch
was not measured in the field but roughly calculated by using other measurements, photos and
HLDM. The position of the apex is set as 3,75 m (asl) (see Kázmér 2017, unpublished data).

An important point in reconstructing sea level development is to distinguish which organisms are
older, younger or lived concurrent. In particular clustering different organisms that might have lived
concurrently into groups is very difficult. Thus, the following described phases are just a suggestion
and there is clearly room for more investigation. Moreover, the zonation of the organisms to one
distinct living range contains an uncertainty. In particular, if the organism is just classified to the
genus and not the species, it could increase the uncertainty and in some cases mistakenly indicate
sea level fluctuations. If just the term Lithophaga is used it is in general referred to Lithophaga II.

The phases described in this chapter are mainly based on surveyed data from the Main Notch
(Chapter 6.1). At this location the shape of the notch, as well as the organisms, were both
examinable. Hence, it was the best site for measurements in the study area. The phases are based on
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basic assumptions and are therefore should not be considered as fixed. General uncertainties are not integrated into the compilation of this model.

**Phase 1: Oldest Bioerosion**

Even before the notch was formed bioerosion took place. The remnants of this bioerosion are *Lithophaga III* boreholes visible at the base of the profiles and at the lower part of the notch. It is unknown how much older than the notch they are. Certainly, other organisms were present during this period as well, but the traces are not recognizable anymore because of extensive erosion. They are not suitable to determine a specific sea level and are therefore just mentioned here. Their maximal height is located just a few decimeters below the apex of the bioerosion notch and suggests a MSL a little bit lower than during notch formation. *Lithophaga I* appear in this part of the notch, too. They are probably much younger but cannot be allocated to one phase and are therefore not used to reconstruct the sea level either.

**Phase 2: Formation of the notch and first Lithophaga**

The formation of the notch was the next and more distinct step of sea level development. To form this geomorphological feature it requires a more-or-less stable sea level over quite a long time (Pirazzoli 1986, Trenhaile 2015). The greatest effect on forming the notch presumably was *Lithophaga*. They seem to be the most common and powerful bioeroder. Pirazzoli (1986) states that in sheltered areas with carbonate rocks the bioerosion rate of *Lithophaga* is about 1 cm/a. Simply with this depletion of carbonate rock by *Lithophaga* the development of the notch would take a few hundred years. But it can be assumed that many more organisms were grazing and boring during this time, for example sponges. The absence of most of the organisms or their fossil traces excepting sponges, is described by Bromley and Asgaard (1993). They mentioned that ongoing bioerosion tends to get deeper and deeper into the surface and obliterate shallower grazing traces. The sponge borings are possibly related to the phase of notch formation but to what extent remains unclear. The borings discovered are most common in the lower part of the profiles underneath the notch. This is possibly explicable with fight for habitat. Hence, the clear boundary between areas with generally sponge borings and areas with generally *Lithophaga* boreholes is caused by competition for space.

It is also possible that sponges occurred in a latter phase. They may have formed during this phase, while the notch was generated, and were then penetrated by following *Lithophaga* generations. They may have appeared afterwards in the entire notch during, for example, the third phase and were penetrated by *Lithophaga* settling down on the roof of the notch. Either way, they are presumably older than the youngest *Lithophaga* traces because no sponge borings are visible on the rock in the upper parts of the notch, probably due to the boring of the youngest *Lithophaga*. Another possibility is that sponges never reached this height. Sponge borings appear at least up to the lower half of the notch but this is does not indicate any kind of sea level change. The boring sponge *Cliona* appears like the bivalve *Lithophaga*, in the subtidal area and reaches up to MSL (Abad et al 2013, Laborel & Laborel-Deguen 1994). Therefore, the visible distribution of *Cliona* borings not necessarily indicates a rising or falling sea level.
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At this point *Lithophaga* boreholes very likely only reached the apex of the notch or were slightly beneath (Figure 7.2a). They would not have reached the roof of the notch. Usually MSL is stated as their upper limit (Laborel & Laborel-Deguen 1994, Rovere et al. 2015). All in all, this phase represents the initial sea level represented by the notch. There is a high probability that the apex marked the MSL of this time, located at 3.75 m asl.

**Phase 3: Second generation of Lithophaga**

The next phase is characterized by *Lithophaga* reaching the roof of the notch or getting even higher (Figure 7.2b). The roof of the notch at the Main Notch outcrop is on average located at 4.27 m +/- 0.04 m (asl). During this phase, or shortly after, *Lithophaga* settled down in the upper part of the notch and maybe above, indicating a rising sea level. The notch is strongly penetrated near the roof with a BIL about 5. The boreholes tend to be quite deep but some of them are heavily eroded and only the end of the borehole is preserved. The difference in depth of the boreholes as well as the great extent of bioerosion could be a hint for a quite long period of *Lithophaga* boring or it could be just the result of the dense boring activity of *Lithophaga*. The shape of the roof and other parts of the notch were probably modified during this period. But up to what extent, or what the original notch shape was like, is unknown.

**Phase 4: Oysters and Lithophaga**

After *Lithophaga* penetrated the upper part of the notch oysters arrived and settled down on the eroded *Lithophaga* boreholes at the roof (Figure 7.2c). The elapsed time between *Lithophaga* boring into the rock and oysters’ settling down on the eroded boreholes is unknown. The oysters mainly occur in the upper part of the notch, at the roof and above. They are very adaptable organisms and have a wide living range (Laborel & Laborel-Deguen 1994). Measurements of recent oyster ledges in this region indicate that they are most common several decimeters asl. The fossil oysters not only appear on the roof of the notch. They are also present several decimeters, maximal 55 cm, above the roof. The uppermost oyster shells in the outcrops represent the minimal shift of the intertidal zone into higher areas. This is presumably caused by a rising sea level. It seems likely that oysters settled down during an increasing sea level and the wide distribution mirrors a gradually rising sea level. If we assume that the position of oysters relative to MSL did not change massively since MIS 5e, the comparison with recent counterparts signal a location above MSL. Despite the fact that the exact position of MSL cannot be reconstructed, they clearly indicate a rising sea level. This increasing sea level is also indicated by *Lithophaga* located above the roof of the notch. *Lithophaga* reach up to maximal 20 cm above the roof. On average they are situated 10.5 cm +/- 6.8 cm above it. In some cases they bored into oyster shells. The oyster shells are completely pierced. This could be a sign that the oysters were probably already dead. This could indicate an age gap between *Lithophaga* and oysters or could be explained by competition for space or just single dead oysters.

*Lithophaga* boreholes represent the highest directly indicated position of MSL during the described phases (Figure 7.2c). They appear only in a relatively small quantity and the BIL in this area ranges between 1 and 2. This could suggest that this phase did not last long enough to create more widespread bioerosion tracks and a clear upper limit. Either way, the sea level had to be significantly
higher than at the time of notch genesis to enable *Lithophaga* to reach this position. A concurrent existence of Lithophaga and oysters appears the most likely.

**Phase 5: Worms and barnacles**

Worm tubes and barnacles primarily occur inside of eroded *Lithophaga* boreholes or on rock surfaces inside of the notch. This clearly shows that they are younger than the *Lithophaga* boreholes they use for protection. At the Western Outcrop in the third profile worms and barnacles built up a 7 cm thick ledge in a height of 4.20 m asl. The average height of worm tubes is 4.17 m asl and of barnacles 4.08 m asl. If we take the assumptions of Shishikura et al. (2006) that *Pomatoleios kraussii* only settles down near MSL to be correct, the worms inside of the notch (zone 2 and zone 3) indicate a slightly decreasing sea level after the high represented by the uppermost *Lithophaga* boreholes (Figure 7.2d). It is assumed that they are younger than all *Lithophaga* present in the profiles. If they were younger than the *Lithophaga* boreholes inside of the notch but older than the *Lithophaga* appearing above the notch, it would be considered that the younger *Lithophaga* would have penetrated the aggregation of worm tubes and barnacles. Moreover, the barnacles, which are probably part of the family *Balanidae*, are most common near MSL and a few decimeters below (Rovere et al. 2015). Their position inside of the notch supports the theory of a dropping sea level (Figure 7.2d).

**Phase 6: Beach rock filling**

The filling of the bioerosion notch by beach rock is defined as the end of this sequence. The beach rock probably preserved both worm tubes and barnacles against erosion. This is indicated by the appearance of worms and barnacles in the vicinity of the beach rock. Therefore, the time gap between these two stages of notch development was rather small. Presumably the beach rock filled up the entire notch in former times. This beach rock was dated with OSL (Optically Stimulated Luminescence) to about 80,000 a BP +/- 3,000 a (Mauz et al. 2015). That indicates an origin during a lower sea level than during notch formation. The accumulation of beach rock at 80,000 a BP +/- 3000 a would imply that the MSL during the deposition of beach rock was at least 40 m lower than during notch formation. This height difference would prevent the beach rock from filling up the bioerosion notch. During the period of beach rock accumulation MSL was more-or-less the same height as the apex of the notch. The height of MSL is indicated by the classification of beach rock to the upper and lower foreshore facies which is accumulated in the intertidal zone (Falkenroth 2017). This implies a rapid filling of the notch with beach rock after worms and barnacles settled down. Moreover, it explains the good preservation of both organisms. The deposition of coarse clastic sediments like sandstone and in some cases conglomerate implies a more energetic deposition environment than nowadays. The accumulation today is characterized by clayey and muddy sediments indicating a very low energy milieu.

OSL dating is heavily dependent on different factors and unknown quantities. Depending on how the variables are set, the age of the sample can vary in a wide range. Therefore, it is not advisable to fully rely on the dates delivered by this dating method. It is just an approximation and most useful when no other dating methods fit. In this particular case the accumulation of beach rock in a height of
Interpretation

3.7 m above recent MSL is not possible at this significant decreased sea level around 80,000 a BP. Moreover, after the Last Interglacial the sea level dropped more-or-less continuously. Not until approximately 20,000 a BP the sea level started to rise again until reaching recent conditions. Hence, the formation of this beach has presumably to be roughly 35,000 a to 40,000 a earlier than the dating suggests.

Figure 7.2: This sketch is just a schematic approach. MSL does not embody fixed heights but only shows one possible development of sea level. Phase 1 is not represented. a) Formation of the notch (Phase 2). MSL is stable for a long time. Lithophaga are the most prominent bioeroders and reach up to the middle of the notch (apex). b) The sea level rises and Lithophaga start to penetrate the notch roof (Phase 3). c) Oysters cover the eroded Lithophaga boreholes at the notch roof and occur above indicating a rising sea level. Lithophaga boreholes appear above the notch roof as well and support the theory of an increasing sea level (Phase 4). In some cases Lithophaga bore through oyster shells. d) The MSL drops a few decimeters. Barnacles and worm tubes occur inside of the notch and are present inside of Lithophaga boreholes as well as on the rock surface (Phase 5).
7.1.3 Shape and height of the bioerosion notch

All outcrops with fully preserved notch shape were compared in respect to notch height. The average height is 0.76 m +/- 0.09 cm. The apex is positioned at about 3.75 m asl. The notch height at the western side of the lagoon is 0.66 m +/- 0.17 m (Cahnbley 2017). The apex of the notch is located at 3.80 m (Cahnbley 2017). Both values are close to the ones from the eastern side of the lagoon. That is a further affirmation of our values.

In comparison, Donato et al. (2009) set the mean tidal range inside of the lagoon to 1.2 m. The average notch height should roughly mirror this mean tidal range (Antonioli et al. 2015, Trenhaile 2015). The quite great variance of several decimeters between the two values could give information about the conditions during the formation of the notch and maybe indicate a change in tidal range (see Lorscheid et al. 2017a). Empirical data shows that in general the notch height is even greater than the mean tidal range. The height of the notch results from the mean tidal range and the highest tidal values (spring tide) (Antonioli et al. 2015, Lorscheid et al. 2017a). That is also given in sheltered areas (Antonioli et al. 2015). This fact would indicate an even bigger variance between the height of the bioerosion notch and the recent tidal range of the lagoon. The significantly smaller tidal range during the formation of the bioerosion notch could be generated by a highly different lagoon setting compared to recent times. With a more open lagoon the tidal range would be considerably smaller. That is due to the effect of small passageways. The narrow opening forces the water to rise higher during tides (Grotzinger et al. 2007). Hence, a case can be made that the morphology of the lagoon is responsible for the change in tidal range. The currently existing small opening of the lagoon was possibly broader in Eemian times. This could be accomplished if the coastal deposits narrowing the lagoon today were not yet deposited during this period. The significantly more open shape of the lagoon would cause the tidal range to become smaller. That would explain the great variance of about 0.64 m between current tidal range and the height of the bioerosion notch. Moreover, the distinctly higher sea level could have also led to broader openings to the sea (see Bagci 2017). Another reason for a change in the tidal range could be provided by tectonic action affecting the shape and the depth of the lagoon (Hill 2016). But due to the assumption that the area is not affected by tectonic movements this hypothesis is considered as doubtful. The first two hypotheses or a combination of both, seems the likeliest.

The Main Notch is termed as the key outcrop of this thesis mainly because the notch shape is preserved. The notch shape is atypical in comparison to the usual u- or v-shape with a recognizable roof and floor. The area beneath the notch transitions into the notch without a geomorphological boundary. This creates a ramp-like appearance. The lacking floor cannot be explained by the tilt of the outcrop or the tilt of rock layers. Such circumstances only influence the symmetry of the notch itself and not the presence of a floor. Moreover, a rise of sea level is also not responsible for this type of shape. An increasing sea level would rather create a w-shape (two overlapping u-shapes) or a broad u-shape with an additional smaller incision in the center of the notch (Schneiderwind et al. 2016a).
There are two possibilities that could have led to this anomaly of the shape. The first possibility is that mechanical erosion modified the notch after organisms originally formed the geomorphological feature. The typically higher sediment supply in more humid periods like MIS 5e (Hoffmann et al. 2013b) suggests that the intensity of erosion could have been pretty high during that time. Next to the Main Notch the mouth of Wadi Salmiyah is located. Thereby, it can be assumed that during rainfall great amounts of sediment were transported into the lagoon. To create the actual shape a relatively high erosion rate would have been necessary, especially at the lower part of the notch and several decimeters beneath. This would erase existing bioerosional traces and lead to the question of why boreholes of *Lithophaga* in these specific areas are of quite great depth and fit the mould with the rest of the notch. Vice versa, boreholes which originated after the erosion of the floor would be assumed to be of greater depth than they are. Moreover, it is likely that sand was the primarily tool for erosion because only strong currents can mobilize greater grain sizes. A great amount of sand-sized sediment in the water contradicts the conditions the subichnotaxa *Entobia* typically forms in. Furthermore, the outcrop is located inside of a more-or-less sheltered lagoon. Even with a higher sea level and additional inflow of the Arabian Sea during MIS 5e (see Bagci 2017) weaker currents compared to the open sea are expected. Nevertheless, mechanical erosion definitely occurred and wave action was probably stronger than nowadays. That is visible via the eroded *Lithophaga* and sponge borings as well as the polished looking rock surface in the lower parts of the profiles (see Palyvos et al. 2008). To what extent mechanical erosion occurred is unexplainable with the available data.

The second possible genesis of this notch shape is due to extreme penetration by boring organisms. Pirazzoli (1986) says that in sheltered areas intensive boring activity can cause an irregular appearance or the absence of the floor. As described and seen in chapter 6 the notch and the parts below are at most outcrops extremely penetrated by boreholes created by *Lithophaga* and by lesser extent sponges. In this case Pirazzoli (1986) recommends basing the investigation on measurements of the top of the notch. The main bioeroder at all outcrops is *Lithophaga*. With its deep borings it could have led to the disappearance of the floor. But comparable to the theory before, it is not possible to prove this assumption. But it seems likely that in more-or-less sheltered areas the boring activity is higher than normal. And due to the fact that the strongest bioeroders live subtidally and up to the middle of the intertidal zone it seems like a coherent theory that extremely high penetration could have caused this shape.

In the other study area only a few hundred meters away a second outcrop with complete notch shape exists (Cahnbley 2017). Nonetheless, the shape of this bioerosion notch is significantly different to the shape at the Main Notch. The ramp-like appearance is missing and a clear defined floor is visible. The different shape can only be explained by deviant conditions during the formation (Trenhaile 2015). Possible divergent conditions are multifarious. Differences in the strength of currents, sediment supply, and salinity are all factors that can influence the characteristics of a notch and the zonation of organisms. Which do apply is undetectable.
The other outcrops rarely show a notch shape and are often heavier weathered. This is possibly due to the position of the outcrops. Many surveyed sites are located inside or near a wadi mouth. Maybe the higher accumulation rate of sediments in these areas prevented the formation of a distinct notch shape.

7.2 Abrasion notch and its formation

7.2.1 Location and lithology

Abrasion notches appear at several locations around the lagoon (see chapter 6). Both bioerosion and abrasion notch cannot be recognized at every outcrop. Abrasion notches are missing in the south of the lagoon. They are more common in the north, for example on the Northern Peninsula. The overall appearance of this notch type is very similar at the different outcrops. The shape is typically round or u-shaped and rarely v-shaped. The surface often appears smooth. Conglomerate formed notches, especially, show a smooth surface, whereas sandstone formed notches are in some cases not as smooth or symmetric. The conglomerate is of terrigenous origin and was deposited by wadis. The conglomerate was formed around 230,000 a BP (unpublished data, Hoffmann 2017). The beach rock, which in large parts consists of sand-sized grains, was dated to 80,000 a BP +/- 3,000 a (Mauz et al. 2015) but is probably several thousand years older (see chapter 7.1.2). The sample was taken off of an outcrop in the south of the lagoon near the Main Notch. The beach rock near and inside the Main Notch was accumulated in the foreshore facies (intertidal zone) (see Falkenroth 2017). This facies is characterized by ripple features, cross bedding and parallel lamination (see Falkenroth 2017). In contrast, the depositional environment of the beach rock at the Northern Peninsula was with high probability the shoreface facies (Falkenroth 2017) which is bound to the subtidal zone. This accumulation space is indicated by the grain size and sedimentary structures (Falkenroth 2017). The assumption was made that both beach rocks were concurrently deposited and are the same age. The discovered beach rock is significantly younger than the conglomerate, even considering the uncertainty of both dating methods.

7.2.2 Formation

On the eastern side of the peninsula a bioerosional horizon is situated above the abrasion notch. On the western side no horizon is visible but bioeroded clasts appear in the beach rock and could indicate the former existence of a bioerosional horizon in this area. The clasts, mainly grey and blueish limestone, are very similar to the ones appearing in the wadi conglomerate. Presumably the bioerosional horizon on this side was completely eroded and bioeroded clasts were worked into the beach rock. The bioerosion on the eastern side of the peninsula primarily occurs in the calcareous parts of the conglomerate. The height of 4,39 m asl of this horizon (Bagci 2017, unpublished data) and the height of the bioerosion notch in the south of the lagoon suggest a concurrent development. The history of sedimentation on both peninsulas is presumably as follows. First the fluviatile conglomerates transported by wadis were deposited. Afterwards the bioerosional horizon was formed in the conglomerate in a height of roughly 4 m followed by the accumulation of beach rock which was backed against the conglomerate. The deposition of the beach rock had to be subtidal as indicated by sedimentary structures (Falkenroth 2017). Concurrently, beach rock was deposited
inside the notch in the south of the lagoon. After the accumulation of beach rock the abrasion notch was formed. The sea level during the formation of the abrasion notch is unknown but estimated in the following. Abrasion notches originate from the subtidal zone up to the supratidal zone depending on currents, wave action and sediment load. Kershaw and Guo (2001) think that abrasion notches can form up to 2 m asl but referred to unsheltered areas. Pirazzoli (1986) states that as wave energy lessens in shallow water, abrasion notches are found in the upper part of the intertidal zone. The position of abrasion notches is relatively consistent around the lagoon. The floor is located between 0.5 m and 1.1 m asl at all measured sites (unpublished data, Bagci 2017). The difference in height is negligible. Abrasion notches are often irregular in height and shape and change their profile over the course of just a few meters (Pirazzoli 1986). The sea level during the genesis of the abrasion notch was presumably slightly above recent MSL due to the more-or-less sheltered position. The position of the floor implies a sea level of approximately 1 m or 2 m above recent MSL. Considering these assumptions the formation of the bioerosion notch, the accumulation of beach rock and following genesis of the abrasion notch took place in a narrow timeframe.

The great height of the abrasion notch at some sides inside of the lagoon is striking. On average abrasion notches on the outer parts of the Northern Peninsula are 1.93 m +/- 0.13 m in size. One would not expect an abrasion notch of this height inside of a lagoon because it is contradictive to the sheltered position. This type of notch is generally more common in exposed areas (Trenhaile 2015). This could be a broad hint that the conditions in present times and during the emergence of the abrasion notch are not comparable. Maybe a second opening to the sea led to stronger currents and wave conditions. As described in chapter 7.1.3 the coastal deposits might not have been deposited yet. The highest abrasion notches are present at the outermost parts of the peninsula facing the middle of the lagoon. The smallest occur near the mainland. Abrasion notches are generally of greater height than tidal (bioerosion) notches and not limited to the tidal range. Stronger wave action could have shaped the abrasion notch. Trenhaile (2015) suggests a positive correlation of wave height and notch height. Moreover, the height of the notches could possibly indicate storm events entering the lagoon. It is questionable whether principally different weather conditions or maybe single storm events generated this notch type. The erosion rate leading to such deep incisions is unclear. Hence, it is not clear whether single events could be strong enough to originate these structures. However, both possibilities would probably imply a MSL at the same level as the floor of the abrasion notch. This height appears very likely.

Nonetheless, the exact sea level remains unknown as long as the conditions leading to the origin of the abrasion notch and the geomorphology of the lagoon are not clarified. The difficulty of abrasion notches is that they can hardly be used to reconstruct a defined sea level. In contrast to bioerosion notches the MSL is not located at the point of the greatest erosion. Abrasion notches can be located above (Kershaw & Guo 2001) as well as below MSL (Pirazzoli 1986, Trenhaile 2015).

The lithologies on both sides of the peninsula are very diverse. The western side is characterized by highly fossiliferous beach rock. On the eastern side only small remnants of beach rock are present. Conglomerates deposited by wadis characterize most of the area there. The reason beach rock is
almost completely lacking on this side of the peninsula could be connected to a differing wave and current regime during the accumulation of beach rock. Fossils like bivalves and coral fragments were transported to the western side of the lagoon and accumulated there. The center of the lagoon and the associated eastern side of the peninsula were no depositional regime. Furthermore, a greater erosion taking place in this area could have led to this appearance, too. A combination of both aspects is considered most likely. Another interesting fact is that the abrasion notch is only present in clastic sediments and not shaped into the limestone in the south of the lagoon. This could be related to the lithology because limestone is in most cases affected by bioeroding organisms or it could be related to the decreasing wave and current energy before reaching the most internal areas of the lagoon. The last hypothesis is preferred because abrasion notches are not necessarily limited to non-carbonate rocks (Sisma-Ventura et al. 2017). But this also depends on the resistance of the lithology (Sisma-Ventura et al. 2017).
8 Discussion

The main goal of this study was the investigation of a bioerosion notch and an associated biological assemblage representing sea level changes. The bioerosion notch is located along the northeastern coast of Oman and clearly mirrors a sea level approximately 3,7 m higher than nowadays. This height is associated with the Last Interglacial (MIS 5e), a period with a sea level several meters higher than at present day (Hearty et al. 2007, Rovere et al. 2016). This time period is topic of many investigations around the world and a summary, focusing on different sea level indicators that can be used to analyze this highstand, is given by Rovere et al. (2016).

Inside the bioerosion notch, several biological indicators were discovered during field work. These indicators were investigated and their zonation measured to reconstruct the development of sea level in greater detail than provided by the notch itself. The bioerosion notch was used as a fixed marker of the zonation measurements. Further research on sea level was performed by Falkenroth (2017). She investigated beach rocks in the vicinity to the lagoon of Sur as well as in the Hajar Mountains on the marine terraces. Petrographic as well as sedimentary approaches were used to allocate the beach rock to a depositional environment and thus reconstruct the sea level indicated by the sediment.

The biological indicators clearly indicate sea level changes subsequent to the notch formation. In the following the sea level fluctuations are divided into different phases. It should be considered that this model is based on different assumptions relating to the discovered organisms. These assumptions contain an uncertainty due to missing data, the method of measuring and general simplifications of the relationship between biological indicator and sea level. In this thesis, the likeliest conditions and assumptions were chosen to compile the model. However, if presumptions are changed, the entire model will change too.

Six phases were recognized within the bioerosion notch, which was carved into the Sur Formation. The first phase roughly indicates a sea level several decimeters to one meter below the notch forming during the second phase. No clear indication regarding a specific sea level is given and the phase is valued with low importance. In contrast, the second phase implies a sea level 3,75 m asl, which is marked by the apex position, the deepest incision of the notch (see chapter 7.1.2; Table 2). The subsequent phase is characterized by a gradually sea level rise of several decimeters indicated by the presence of Lithophaga boreholes at the notch roof. Lithophaga occur in a great amount and form a distinctive band. This distinctive band is considered as a precise sea level indicator (Evelpidou et al. 2012c, Laborel & Laborel-Deguen 1994). A subsequent rise of sea level is represented by the presence of oysters and Lithophaga occurring above the roof. The appearance of localized Lithophaga boreholes in certain spots rather than extensively is noticeable. Their appearance is not valued as an exact sea level indicator because no distinct upper line is visible. However, their position above the roof clearly implies a sea level located several decimeters higher than the notch roof. Oysters as well as Lithophaga are filter feeders and rely on water availability. The exact height of the sea level is, however, difficult to determine. For that reason, the presence of Lithophaga boreholes at the roof of the notch are categorized as indicators of a minimum rise of the
sea level, whereas the highest *Lithophaga*, located above the roof, represent a possible maximum rise of the sea level (Table 2). A subsequent fall of the sea level is implied by the presence of barnacles and worm tubes and finally by the accumulation of beach rock inside the bioerosion notch (see chapter 7.1.2; Table 2).

In particular, investigations related to the biological indicators as well as their recent counterparts are of great interest. The estimated sea level fluctuation phases are almost completely based on these organisms. Changes in classification or associated living ranges could therefore possibly highly influence the compiled model.

Table 2: Summarized sea level fluctuations with associated sea level indicators and interpretation of the sea level fluctuation phases. The starting point (0 cm) of the fluctuations is equated with the apex of the notch (3,75 m asl). The table is related to the phase model described in chapter 7.1.2 and is only a schematic approach.

<table>
<thead>
<tr>
<th>RSL-fluctuations</th>
<th>sea level indicator</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beach rock (Phase 7) approx. 120,000 a BP</td>
<td>- development of the notch ends with the accumulation of beach rock - MSL near the apex of the notch is assumed</td>
<td></td>
</tr>
<tr>
<td>Worms and barnacles (Phase 6)</td>
<td>- with a dropping sea level worms and barnacles settle down inside of the notch - both organisms indicate a position near MSL</td>
<td></td>
</tr>
<tr>
<td>Oysters and Lithophaga II (Phase 4 and 5)</td>
<td>- sea level rises indicated by highest oyster shells and Lithophaga settling down above the roof - MSL (related to Lithophaga) is situated in average 10 cm above the roof (red dotted line: maximal rise, blue dotted line: minimal rise) - oysters younger than Lithophaga inside the notch (covering eroded boreholes)</td>
<td></td>
</tr>
<tr>
<td>Lithophaga II (Phase 3)</td>
<td>- a rising sea level leads to propagation of Lithophaga up to the roof of the notch - during this period MSL is located near the prior formed roof of the notch</td>
<td></td>
</tr>
<tr>
<td>notch formation (Phase 2)</td>
<td>- stable sea level for presumably several hundred years - strong bioerosion in a height of roughly 3,75 m (location of MSL)</td>
<td></td>
</tr>
<tr>
<td>Lithophaga III (Phase 1)</td>
<td>- Lithophaga III settle down and indicate a MSL several decimeters below the not yet formed notch - boreholes are secondary widened</td>
<td></td>
</tr>
</tbody>
</table>
8.1 Biological indicators and their zonation

The identification of sea level fluctuations and a possible maximum sea level is of significant importance for the investigation of the MIS 5e highstand along the northeastern coast of Oman. A number of biological indicators is used to estimate possible phases of sea level development. For these estimations, the living range of the potential biological indicator is essential. These organisms are associated with a bioerosion notch, which represents a former, stable sea level at 3.75 m asl. Bioerosion notches, which form over the course of tens to hundreds of years, are very precise indicators of former sea levels and have an uncertainty in the range of a few decimeters (Rovere et al. 2016).

The bioerosion notch of this study area is characterized by zonations, which overlap and were broadened due to a shifting sea level. It is unfeasible to define living ranges of organisms based on field measurements because the fossil traces and remnants in one locality do not represent the same sea level. However, with considering zonations compiled by other authors it is possible to determine the small-scale development of the sea level and value the extent of overlapping zones.

It is clear that there are a number of problems related to reconstructing sea level fluctuations. These problems are discussed in the following and are divided into three main topics:

1) The organism classification-level and its influence on the zonation accuracy
2) The precise relationship between organism and sea level
3) The large vertical distribution of biological indicators
4) The amount of elapsed time between rock submergence and colonization by organisms

Organism zonations defined in different publications often vary in their classification-level. In general, a large part of organisms is only classified to the family-level and not to the species- or genus-level (Rovere et al. 2015). The reason why different classification-levels are used is not definitely specified by the authors. In some cases, the used biological indicator is classified to the species-level but obviously a zonation only based on the genus is used (Evelpidou et al. 2012c). If the living ranges of different species, being part of the same genus, are similar is possibly not investigated. Or potentially, missing data about species zonations are the reason for using the zonation on genus-level.

Therefore, it appears generally unnecessary to classify biological indicators to species-level. One exception is possibly the worm *Pomatoleios kraussii*. In this case, the distinct species is used to reconstruct a position near sea level (Miura & Kajihara 1984, Shishikura et al. 2006). If other species of this genus are occupying the same vertical distribution and could be used to estimate sea level in the same way is unknown, or if even the entire genus could be used to classify this specific living range, is not clear as well.

Moreover, an accurate classification on species-level can be complicated by the lithology of the substrate the organisms dwell on. Bioeroding indicators are primarily classified by using their grazing traces or boreholes. Different substrates can possibly lead to divergent appearances of these fossil
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traces. Hoeksema (1983) notes that the depth of Cliona borings is possibly limited by a rapid decrease in oxygen with increasing depth. Therefore, more porous substrates potentially have brighter conditions for a deeper penetration of the rock whereas compacted limestones are probably not as deeply penetrated by sponges. These differences of the appearance of fossil traces could exacerbate the classification of the species. However, as long as a classification to family- or genus-level can be realized, and does not lead to divergent living ranges in comparison to the species, it has no influence on the sea level reconstruction.

In the following, organism zonations prepared by different researchers are introduced (Figure 8.1), as well as advantages and possible restrictions of the indicators. The zonations, which were used to compile the model, will be highlighted.

The boreholes of Lithophaga are the most useful indicators of sea level fluctuations in this study area but not used to define one precise sea level. The position of Lithophaga boreholes in comparison to the distinct shape of the notch, and additional information due to their living range, rendered the sea level rise visible. The MSL represented by the notch was considered as a fixed point of the observations. Hence, the comparison of the notch shape and the position of Lithophaga boreholes is the most important tool of this study. Laborel and Laborel-Deguen (1994) as well as Rovere et al. (2015) state that the upper limit of Lithophaga is close to MSL (Figure 8.1) (see also Glynn 2015, Spencer & Viles 2002). Laborel and Laborel-Deguen (1994) even say that the upper line of Lithophaga boreholes is useful to determine the biological sea level which is mostly coincident with MSL (Figure 8.1). Rovere et al. (2015) set the limit of Lithophaga a little lower than Laborel and Laborel-Deguen (1994) but state that the upper limit of the living range of Lithophaga can possibly match with MSL. Kázmér et al. (2015) do not mention exact limits but set the general living environment to the
intertidal and subtidal zone. In particular, the information from Laborel and Laborel-Deguen (1994) were used to compile the sea level phases.

The distribution of the bivalve *Lithophaga* is very wide and is therefore often considered as an imprecise sea level indicator unless a distinctive upper line is present (Evelpidou et al. 2012c, Laborel & Laborel-Deguen 1994, Palyvos et al. 2008). Furthermore, younger *Lithophaga* frequently overprint *Lithophaga* boreholes of advanced age and create an irregular appearance of the rock. Due to the overprint of multiple generations it is difficult to allocate the *Lithophaga* boreholes to one specific sea level (Evelpidou et al. 2012c). In contrast, *Lithophaga* colonies with a distinctive upper limit and a great abundance are valued as a precise sea level marker (Evelpidou et al. 2012c, Palyvos et al. 2008, Vacchi et al. 2012). In particular, the combination of a geomorphological feature like a bioerosion notch and *Lithophaga* is assessed as a very precise indication of a former sea level (Laborel & Laborel-Deguen 1994, Palyvos et al. 2008). In this study the position of *Lithophaga* is used as an estimation of sea level fluctuations and in single cases for the location of a former MSL.

*Lithophaga* are occurring very abundant at the roof and the upper limit is clearly visible despite single boreholes appearing above the roof. This upper limit can probably be used to deduce a former, more-or-less stable sea level, whereas the *Lithophaga* boreholes above the roof just indicate an approximate, minimum position of MSL. Since the goal of this study is to investigate possible sea level fluctuations, a more precise location of MSL is not necessary. The accuracy of such a *Lithophaga* line for sea level reconstruction is estimated to +/- 10 cm (Evelpidou et al. 2012c).

However, the *Lithophaga* boreholes, which appear above the roof of the notch, indicate an ongoing rise of the sea level. Their spot-like appearance and low abundance is probably due to a short-term peak in sea level (Evelpidou et al. 2012c). The short duration of this higher sea level presumably prevented further propagation of the organisms and the formation of a distinct upper limit (Evelpidou et al. 2012c). It is unlikely that the presence of *Lithophaga* at the notch roof and the *Lithophaga* above are part of the same phase and that the upper *Lithophaga* boreholes simply represent a higher part of the intertidal zone. The bivalve is limited to the lower part of the intertidal zone near the MSL and relies on a water cover during most of the time of the tide. Hence, it seems most likely that the uppermost *Lithophaga* boreholes are representing an independent phase indicating an increasing sea level.

The elapsed time between both phases and the duration of the highstand is unknown. A precise estimation is difficult to make but the higher sea level lasted for at least various years. Evelpidou et al. (2012c) state that it takes several years before *Lithophaga* can colonize limestone (see also Laborel & Laborel-Deguen 1994). During this time the sea level was either stable or possibly further rising. Additionally, the discovered boreholes were part of the second subtype (*Lithophaga II*) and at least a few years old. It can last up to 80 a until the bivalve *Lithophaga* reaches its maximum size (Evelpidou et al. 2012c, Laborel & Laborel-Deguen 1994). How long it takes to fully colonize a rock surface by *Lithophaga* to create a continuous band is not investigated yet. Hence, a precise duration of this higher sea level cannot be given but it was most likely in the range of various years to a few decades. However, the small quantity of *Lithophaga* boreholes supports the assumption of a
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transgressive peak of the sea level. Overall, the great living range of Lithophaga surely adds uncertainty to the estimation of a distinct sea level or the amplitude of sea level fluctuations. But at the same time, it appears that sea level fluctuations indicated by this organism are rather underestimated than overestimated. This is due to the simplification of identifying Lithophaga with MSL, whereas they mostly appear shortly below (Rovere et al. 2015, Vacchi et al. 2012).

Cliona is named together with Lithophaga as an indicator of MSL if the highest perforations are used (Laborel & Laborel-Deguen 1994). The same is stated by Abad et al. (2013) for the clinoid sponge but only in combination with other indicators. This is performed in this study by the comparison of sponge distribution and the shape of the bioerosion notch. In contrast Kázmér et al. (2015) say that sponges like Cliona are very sensitive to sun exposure and desiccation and that they are limited to the subtidal zone (Figure 8.1). The zonation of Laborel & Laborel-Deguen 1994 was used to create the sea level fluctuation phases. If the zonation of Kázmér et al. (2015) was used it would have changed the structure of the phases. Sponge borings would indicate a rising sea level. Hence, the organism would not be part of the second phase (stagnating sea level) but the third or higher phase with a rising sea level. Comparable to Lithophaga clinoid sponges have a wide distribution with the lower limit inside the subtidal zone (Figure 8.1). This is a main reason why Cliona borings are primarily only used for approximate estimations of the former water depth or in comparison with other indicators (Abad et al. 2013, Morhange & Pirazzoli 2005). In contrast to Lithophaga, which build up a distinctive top line, clinoid sponges do not create significant markers. Hence, it is difficult to evaluate the water depth the borings were created. The elapsed time between the submergence of the rock and the colonization of this organism is not known.

The most difficult part of using barnacles as sea level indicators is their classification. In this thesis the documented barnacles are allocated to the family Balanidae. That enables statements about the sea level during their lifetime. Balanidae itself are categorized as good sea level indicators because their upper limit coincides with MSL (Figure 8.1) (Laborel & Laborel-Deguen 1994, Rovere et al. 2015). Laborel and Laborel-Deguen (1994) describe a little higher upper limit than Rovere et al. (2015). However, both classifications were used to compile the phases of sea level fluctuations and it was generally assumed that the uppermost band coincides with MSL. Contradicting classifications to specific living environments do not exist.

The tube building worm Pomatoleios kraussii creates a different problem. The zonation is very variable depending on the researcher. They are most common in the intertidal zone (Belal & Ghobashy 2012). Miura and Kajihara (1984) even claim that these serpulid worms only appear in a very narrow band in the middle of the intertidal zone (Figure 8.1) (see Shishikura et al. 2006). It is presumed that they construct ledges coincident with MSL (Shishikura et al. 2006). Straughan (1969) noted that Pomatoleios kraussii can survive in subtidal environments but prefers to dwell in the intertidal area around the MSL (Figure 8.1). However, despite the fact that Pomatoleios kraussii can survive in the subtidal zone, almost every source states that they are most common in the intertidal area and form a narrow band approximately around the MSL (Belal & Ghobashy 2012, Miura & Kajihara 1984, Shishikura et al. 2006, Straughan 1969). To compile the phases of notch development
the zonation of *Pomatoleios kraussii* was simplified and it was assumed that their appearance roughly marks MSL using the classification of Miura and Kajihara (1984) and Shishikura et al. (2006). In particular, the distinct ledge in the Western Outcrops indicates the position of the worms in the intertidal and not subtidal zone. Nevertheless, these in some parts contradicting zonations show clearly the uncertainty that is involved in compiling this phase. This is especially due to the small amplitude the sea level fluctuations show. Moreover, it is guessed that warmer temperatures during MIS 5e potentially led to the great amounts of *Pomatoleios kraussii* occurring at some sites (see Belal & Ghobashy 2012).

Tube building worms like *Pomatoleios kraussii* as well as barnacles are bioconstructing organisms. They do not bore into the rock or create grazing marks and after their death only calcareous parts remain. Therefore, they are prone to mechanical erosion and not well preservable. A rapid sedimentation of sand and smaller clasts probably preserved the worm tubes as well as the barnacles within the notch. Higher elevations remained free of beach rock and were stronger affected by ongoing mechanical erosion. Worm tubes or barnacles possibly attached to the rock surface in these heights were eroded in all likelihood. This possibility challenges the model and the presented phases. A falling sea level appears hard to verify if the living range of the indicator is that widespread. However, the two main arguments for a falling sea level are first of all the aforementioned aggregation of worm tubes at the Western Outcrops and second of all the beach rock itself. Irrespective of the researcher, ledges indicate a position near MSL and the allocation of the beach rock to the intertidal area supports this assumption (Belal & Ghobashy 2012, Miura & Kajihara 1984, Shishikura et al. 2006, Straughan 1969). Moreover, *Pomatoleios kraussii* almost instantly settle down in new living spaces and a great gap between submergence of the rock and settling down of the worm is not to be expected (Straughan 1969). This species even wanders depending on seasonal changes (Straughan 1969).

Oysters are in general more-or-less widespread. They are common in the subtidal as well as in the intertidal zone, and depending on the region, they build up ledges in different heights and related to different tidal datums (Figure 8.1) (Laborel & Laborel-Deguen 1996). Therefore, they are most suitable to use if recent oysters and their living range can be surveyed. This was realized in this study. The result was a roughly 20 cm to 30 cm wide ledge situated approximately 24 cm asl. This matches the statement of Kázmér et al. (2015) that oysters in some cases form a thick band in the middle of the intertidal zone (Figure 8.1). This regional variability of their appearance as well as their formation in accretions prevents more-or-less the use of general zonations. It seems like oysters do not necessarily appear in the upper part of their possible living range. The only clear indication of oysters is the limitation to the intertidal and subtidal zone and in this area the dense occurrence in the upper intertidal area. In general, oysters are not a common sea level indicator and rarely used in studies (Laborel & Laborel-Deguen 1994).

It must be taken into account that the zonation can not only differ due to changing conditions or changes in sea level but also based on seasonal changes. Organisms such as *Lithophaga, Cliona* or barnacles modify their living range depending on seasons and fluctuating temperatures. This adds
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another uncertainty of several centimeters to our measurements of the zonations and the compiled phases.

Biological indicators have a great potential to be used as sea level indicators, in particular in combination with geomorphological features like bioerosion notches (Palyvos et al. 2008). Especially Lithophaga are often used as an accurate indicator of sea level in many field studies (e.g. Evelpidou et al. 2012c, Palyvos et al. 2008, Vacchi et al. 2012). The investigation of recent Lithophaga and their distribution relative to MSL could provide more accurate data for sea level reconstruction based on fossil Lithophaga. This is in particular useful, if realizable, in the same region (see Vacchi et al. 2012). Especially during the last years the research of recent counterparts of fossil organisms gained in importance to estimate the indicative meaning of these biological indicators and therefore to quantify sea level changes (Shennan 2015, Rovere et al. 2015, Lorscheid et al. 2017a). More information about the precise position of organisms relative to a tidal datum and their controlling parameters such as temperature, salinity, wave action and tidal range would facilitate statements about regional differences or trans-regional accordances. This is important because of possibly great regional and even local varieties of these indicators (Laborel et al. 1994). Furthermore, the research of recent organisms could allow conclusions regarding their adaption to changing sea level or climatic changes (e.g. rising temperature). The insights could be applied on biological indicators of periods with special interest, like MIS 5e.

A main argument for investigating biological indicators is that they not only furnish bathymetric data but provide information about the associated environment, like energy of currents, salinity or sediment input. Moreover, this study shows that the combination of a geomorphological feature and biological indicators decrease the possibility of measuring uncertainties and enables to recognize broadened distributions of organisms originated by sea level fluctuations.

The compiled model (chapter 7.1.2), based on biological indicators, can be used to verify sea level change after the formation of the bioerosion notch at this particular study site. Using single biological indicators with a broadened zonation is not feasible for reconstructing distinct sea levels because of its limited accuracy. Furthermore, this approach was only viable due to the comparison with an associated bioerosion notch. Hence, a clear geomorphological feature with a related tidal datum is needed to investigate sea level fluctuations as implemented in this study.

8.2 Regional tectonic setting

The bioerosion notch not only provides information about the sea level and possible fluctuations during MIS 5e, but is a main indicator for a more-or-less stable area without tectonic activity. The bioerosion notch was generated during the Last Interglacial (MIS 5e) with a sea level several meters higher than nowadays. The geomorphological feature appears at several locations around the lagoon (see also Cahnblye 2017, Bagci 2017). Measurements of the highest Lithophaga boreholes, which presumably mark the highest sea level of this period, are more-or-less at the same height (see Bagci 2017). The deviations between different measurements are within the range of a few decimeters and, therefore, negligible. Hence, tectonic movements influencing the area itself can be
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excluded. In contrast, the area which is approximately 30 km northwest of Sur is influenced by lithospheric uplift (Kusky et al. 2005). This uplift occurred during the Quaternary and led to the formation of staircased marine terraces (Kusky et al. 2005, Hoffmann et al. 2013b). Each terrace represents one interglacial period. Sampling and dating of the terraces by Dr. Gösta Hoffmann and several students (Monschau 2016) allocated the third terrace to MIS 5e, which is the same period the bioerosion notch was formed in (Hoffmann & Mechernich 21.06.2017, personal communication). The elevation difference between the notch and the third terrace totals approximately 50 m (Hoffmann et al. 2013b). This leads to the assumption that during the last ca. 120,000 a BP this northwestern area was raised by at least 50 m. The stable conditions near Sur can be explained by the separation of these two areas by the Qalhat fault. This reactivated reverse normal fault is situated near the village of Qalhat and is assumed to enable these two blocks to move independently. In summary, the comparison of the bioerosion notch and northwestern areas is a good indicator for the estimation of tectonic activity along the northeastern coastline of Oman. Furthermore, the indication of a tectonically stable area around Sur enables the compilation of a model illustrating solely eustatic sea level fluctuations.

The exact processes leading to the uplift of the northwestern block are still under investigation and further research on this topic is going to be published by Dr. Gösta Hoffmann (see also Ermertz 2017).

8.3 Sea level fluctuations and RSL curves

RSL curves either represent long periods and several glacial cycles (Grant et al. 2014) or concentrate on specific periods like MIS 5e and related sequences (Cutler et al. 2003, Hearty et al. 2007). A few of these curves try to illustrate a global view on MIS 5e with its sea level changes (Hearty et al. 2007). However, many studies approaching MIS 5e and related sequences have a regional approach (Cutler et al. 2003, Rohling et al. 2007, Shackleton et al. 2003). Although these MIS 5e curves allow a more detailed look on this period the shape of the MIS 5e curves heavily depends on the used sea level indicators. Researched coral reefs often suggest a plateau-like appearance of the curve (Chen et al. 1991, Cutler et al. 2003, Gallup et al. 2002) and cannot be recommended to reconstruct sea level changes because they lack the possibility of fast response to sea level changes (Hearty et al. 2007).

Grant et al. (2014) compiled a sea level curve over the last five glacial cycles by using samples gathered in the Red Sea. This provides information about glacial as well as interglacial periods and their maxima and shows a general overview of climate and sea level change. This entails that the focus of the curve is on changes in the range of several meters while small-scale changes are difficult to attain because of the great uncertainties going hand in hand with this kind of approach. In contrast, this thesis focuses on very small changes in the range of decimeters. These fluctuations are not clearly assessable due to their small amplitude, the kind of indicator we use and a relatively high measuring uncertainty. They occur in a vertical range of on average 0,63 m with a mean standard deviation of +/- 0,05 m. The maximal values are about 0,1 m greater than the average value. These
values were calculated by using only the uppermost *Lithophaga* boreholes. Oyster shells are difficult to relate to MSL and therefore not used to quantify the fluctuations.

Missing information about the precise age of the notch prevents an accurate placement of the observed sea level fluctuations into a MIS 5e sea level curve. Hence, combining both fluctuations of the sea level during MIS 5e and a more general sea level curve is not possible. Another reason hindering the comparison with the sea level curve of Grant et al. (2014) is that the duration of the observed fluctuations is unknown. No absolute age of the appearing organisms is available.

However, Grant et al. (2014) provide a very precise sea level curve over the last 500.000 a (Figure 8.2). This is especially important for the research of our study area and investigations in the entire region of the Red Sea, but a more regional RSL curve representing the northeastern coast of Oman would be even better. The curve of Grant et al. (2014) was compiled by using a speleothem $\delta^{18}O$ record and synchronized with Red sea dust-flux data and monsoon events. The sample interval for the RSL curve was about one sample every 200 a (Grant et al. 2014).

In contrast to Grant et al. (2004), Hearty et al. (2007) provides a very detailed RSL curve of the Last Interglacial. In this approach MIS 5e is not illustrated as one single highstand or as a plateau but shows two phases of sea level development (Hearty et al. 2007). The first phase is characterized by a rising sea level and a long-term, stable sea level at about 2,5 m (asl) (Figure 8.3). This phase ends with a rapid sea level drop until reaching recent conditions. The second phase of this curve is defined by a renewed sea level rise. The sea level rises briskly until it reaches the height of the first phase. After this point the rise decelerates for a few thousand years, followed by a very rapidly increasing sea level (Figure 8.3). After reaching the maximum height at about 9 m the sea level dropped very fast and steadily (Figure 8.3) (Hearty et al. 2007). The end of MIS 5e was mainly defined by changing climate conditions with rising storminess (Hearty et al. 2007). It must be taken in mind that this curve is a global approach and do not has to correlate exactly with regional sea level changes.

The curve was compiled with data from numerous sites with tectonic stability or just minimal tectonic movements. Mainly geomorphological features like tidal notches or benches were used as sea level indicators (Hearty et al. 2007). The entire curve features an uncertainty of +/- 1 m.

As described at the beginning of this chapter the integration of the data of this study into RSL curves, such as the curve of Hearty et al. (2007), is not possible because of non-existent dating of the organisms. Taking the uncertainty of the RSL curve into consideration, the bioerosion notch of this study could have developed during different periods. In general, formation during the early stage as
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well as during the late stage of MIS 5e seems generally possible. If we include the abrasion notch with its lower sea level into consideration a development around 130 ka or 120 ka to 118 ka seems most likely (Figure 8.3). The changing climate conditions during the late stage of MIS 5e could explain the enormous height of the abrasion notches inside of the lagoon. However, Hearty et al. (2007) rule out the possibility of a notch formation during the early stage of MIS 5e. They explain it on the one hand with a probable destruction of the bioerosion notch due to the retreat of the sea level and on the other hand with a possible covering with dune sands.

Nevertheless, the deviation in height of the RSL curve and measurements in Sur could imply the formation of the bioerosion notch during an earlier stage of MIS 5e (approximately 130 ka) or a significantly lower sea level along the coast of Oman of around 120,000 a BP. A regional RSL curve could help to calculate the maximal rise of the sea level during MIS 5e at the northeastern coast of Oman and, therefore, to estimate the period the investigated sea level fluctuations occurred.

A final decision for one of the hypotheses is not possible due to the lack of evidence and data. As mentioned previously, this RSL curve is a global one and does not reflect the regional conditions of northeastern Oman. Therefore, the pathway of the RSL curve and the sea level during MIS 5e in the study area do not necessarily have to correlate because the impact of sea level rise differs depending on the locations.

The dating of the organisms present could further improve the mentioned curve of Hearty et al. (2007), and other MIS 5e sea level curves, and enlarge the information on the exact processes of sea level fluctuations during the Last Interglacial. Moreover, it could give indications about other periods with short-term sea level stability during MIS 5e and associated notch formations, beside the already known (Figure 8.3).

Figure 8.3: RSL curve of MIS 5e with a very distinctive pathway. Blue stars are highlighting points of possible notch formation (Redrawn after Hearty et al. 2007).
8.4 Abrasion notch and its related sea level

As mentioned in chapter 7.2.2 the abrasion notch does not provide accurate information about the sea level. This is primarily caused by the fact that abrasion notches can develop very differently with regards to shape and the position relative to sea level. Because abrasion notches provide only imprecise information, they are not as explored as bioerosion (tidal) notches. They are often generally described with reference to their shape and their distribution (see Guo & Kershaw 2001, Pirazzoli et al. 1986, Rovere et al. 2016, Trenhaile 2015). However, only a few case studies are known to use abrasion notches to reconstruct sea level. One of them reconstructs the sea level during MIS 5e utilizing abrasion notches at the coast of Israel (see Sisma-Ventura et al. 2017). Beside the problem of correlating the shape of the abrasion notch with a tidal datum like MSL, the dating of abrasion notches is the main problem in using them for reconstructing sea levels (Sisma-Ventura et al. 2017). In contrast to bioerosion notches, normally no fossil remains are present to date the notch.

Sisma-Ventura et al. (2017) uses the floor of the abrasion notch as the index point for MSL during MIS 5e. This assumption is based on data gathered in the western Mediterranean with comparable conditions to the study site in Israel (Sisma-Ventura et al. 2017). The tidal range of this region is very small, about 0.4 m. Abrasion platforms are assumed to have protected the notches during MIS 5e. This means that only already broken waves reached the cliff. The height of the paleo abrasion notches at the coast of Israel is twice as great as the height of their recent counterparts (Sisma-Ventura et al. 2017). The overall conditions are comparable to the survey site described in this study. If we assume that the lagoon was more open than nowadays, the tidal range was essentially smaller, maybe in the range of about 0.7 m (see chapter 7.1.3). Hence, the tidal range inside of the lagoon can be depicted as micro-tidal. Despite the fact that the lagoon was presumably significantly more open during MIS 5e, it seems likely that the area inside of the lagoon was sheltered to some extent. This increases the probability that primarily already broken waves entered the lagoon, in contrast to waves breaking inside of the lagoon. This is supported by the great height of the abrasion notches in comparison to the not so highly developed depth. Sisma-Ventura et al. (2017) explain the large height of the abrasion notches in the study area with a prolonged exposure to waves that broke previous to reaching the cliff or overall stormier conditions of the sea but with a more-or-less sheltered position of the cliff. The same approach was mentioned to explain the abnormal height of the abrasion notches studied in this survey (see chapter 7.2). Broken waves entering the lagoon combined with stormier conditions would explain the atypical shape of the notch. The resistance of the rock can also influence the height of the abrasion notch. More resistant lithologies tend to get higher while less resistant lithologies tend to get deeper (Antonioli et al. 2015, Sisma-Ventura et al. 2017). In particular, the very resistant conglomerate indicates a stable sea level over a vast period or extremely erosive conditions.

The statements of Sisma-Ventura et al. (2017) conveyed to this study would imply a MSL just slightly higher than nowadays, ranging between 0.5 m and 1.1 m asl (height of notch floor). Stormier conditions and a more open lagoon infer the great height of the abrasion notches. This means that primarily mechanical erosion performed by waves is the main agent of notch formation.
Most studies, which focus on abrasion notches, state that the geomorphological feature forms above MSL. This implies that they primarily form due to wave action (see Bini et al. 2014, Carobene 2015, Trenhaile 1998). A direct reliance between notch and tidal range is difficult to affirm but a positive correlation of high tide and notch height often exists (see Bini et al. 2014, Carobene 2015, Trenhaile 1998). Although a connection between high tide and notch position as well as notch height is visible the exact mechanisms appear to be principally depending on tidal range and wave action. It appears that in mesotidal and macrotidal regions notches, which primarily formed due to wave action, are positioned near or shortly below high tide (Trenhaile 1998). Furthermore, Carobene (2014) found out that in microtidal regimes the height of the notch has a wider vertical range than the tidal range. This is matching with insights of Sisma-Ventura et al. (2017) as well as the data of this study. Therefore, the roof of the notch is always located above high tide. The position of the apex and the elevation of high tide correlate more-or-less in all mentioned studies.

Abrasion notches are not limited to a tidal regime or a lithology and are present at every degree of latitude (Bini et al. 2014, Carobene 2015, Sisma-Ventura et al. 2017, Trenhaile 1998). Considering this, basic requirements for a widespread use as sea level indicator are fulfilled. However, research and investigation are in an early stage and uncertainties are still high. Moreover, this type of notch is not limited to the origin due to waves. Hence, it would be prematurely to assume this relation for every abrasion notch.

Research on recent forming abrasion notches and related parameters like the interaction of tidal range, exposure of the study site and position of the apex as well as notch height would improve the comprehension of formation mechanisms. These insights are especially important for reconstructing former sea levels on coasts without other indicators or only indicators with a high uncertainty (Bini et al. 2014).

9 Conclusion and prospects of future research

Bioerosion notches are a distinct geomorphological feature and therefore of great importance for sea level reconstruction (see Evelpidou et al. 2012a, Lorscheid et al. 2017b, Pirazzoli et al. 1986, Rovere et al. 2016, Trenhaile 2015). In particular, the combination of notch shape and organism zonation can further improve the calculation of a former sea level position (Laboré & Laboré-Deguen 1994). Hence, organism zonations are of great value for sea level research. This thesis focused on the investigation of a bioerosion notch formed during MIS 5e and located at the northeastern coast of Oman. The aim was to investigate the occurring sea level indicators and to ascertain their meaning regarding to sea level and sea level fluctuations. General zonations describing the distribution of the discovered organisms are crucial for this study.

The apex of the bioerosion notch is located at approximately 3.7 m asl and marks the MSL of this period. Some organisms reach several decimeters higher but the deviation always stays below 1 m. Investigations regarding the distribution of the organisms indicated changing sea levels subsequent to the formation of the notch. After the notch formation, during a stable sea level, a transgressive phase commenced and the water level rose for several decimeters. The most reliable indicator is the
deviation between height of the apex and height of the upper *Lithophaga* boreholes and upper oyster shells. The exact sea level is not determinable. After reaching the maximal elevation the sea level probably dropped, which is indicated by worm tubes and barnacles covering eroded *Lithophaga* boreholes within the notch. This phase is the most uncertain and difficult to estimate. The thick ledge that was found at one outcrop is the best evidence of this assumption. The model is the best current approach but clearly needs further and more detailed research.

As mentioned previously in this thesis, abrasion notches are in general considered as uncertain sea level indicators by many researchers. It can be hypothesized that their apex coincides with the high tide elevation but their use is only recommended if other sea level indicators are not available. Nevertheless, abrasion notches, if investigated precisely, can give a first estimation of sea level. To use this information in a sensible way the assignment to a specific age is necessary. This is even more difficult and exacerbates the usage of abrasion notches to reconstruct sea level. Detailed research and case studies in this topic are rare but needed for an advancement of this study field (Bini et al. 2014). In this thesis abrasion notches are useful to investigate the development and former appearance of the lagoon. Their presence indicates a different environmental setting than today but the exact period in time remains unclear. With the help of RSL curves an approximate estimation of the sea level during their formation can be made. It appears likely that somewhat between 118 ka and 130 ka the lagoon was far more open than nowadays and led to the formation of great abrasion notches. This is indicated by the notch height. The sea level during the formation of the abrasion notch is assumed to be in the range of 1 m above recent MSL.

The potential for further research on this topic, especially in this area, are vast. Many issues have been discussed only in a small part or even just mentioned. More information on the recent zonation of organisms in this area is badly needed. This could improve the classification of the phases associated with the bioerosion notch and therefore the understanding of sea level development during MIS 5e. Furthermore, it would eliminate the necessity of relying on general zonations compiled by other researchers. A comparison of organisms indicating MSL like *Lithophaga* in recent coastal notches and measurements of the actual position of MSL would decrease uncertainties. Moreover, by comparing recent and fossil organism distributions the *indicative meaning* between recent and fossil counterparts could be calculated (see Shennan 2015). This is a direct approach to calculate sea level change. The *indicative meaning* not only provides a standardized procedure in sea level research but also supplies a measurement method with a realistic uncertainty analysis (Shennan 2015). Using this approach sea level fluctuations of small amplitude cannot be compiled, but the sea level change between the Eemian and recent times could be calculated.

The reconstruction of sea level development and therefore the compilation of the presented model fully rely on the investigation of a few organisms. To ensure the accuracy of the zonation it would be a huge improvement if the organisms could be classified to the specimen. A more exact delineation of the living range would enhance the precision of the phases, especially relating to organisms with no recent counterparts for investigations.
Conclusion and prospects of future research

Furthermore, the investigation of the shape of the bioerosion notch itself would be advisable. In this thesis the location of the apex was calculated by using a HDLM and photos. With further investigation of the shape and especially the position of the apex, it would be possible to study the genesis of the notch in more detail. The development of sea level is often mirrored by the shape of the notch (see Schneiderwind et al. 2016a). Moreover, the distance between floor and apex as well as apex and roof can be used to calculate values depicting symmetry and shape (Carobene 2015, Schneiderwind et al. 2017). This would ensure a better comparison between different outcrops and is feasible for the bioerosion notch as well as the abrasion notch.

In general, a way to gather more data, and therefore information, regarding the bioerosion notch would be to map the area in more detail. In particular, the area west of the lagoon could be the source of more helpful outcrops (see Bagci 2017). Moreover, additional information and an accurate investigation of the bioerosional horizon and the abrasion notches would facilitate a broader view on the development of the lagoon with its depositional history.

The bioerosion notch is assigned to MIS 5e. This was implemented based on the dating of a beach rock sample nearby the Main Notch. To consolidate this association it would be recommended to date the remnants of the fossils located inside of the notch. Especially suitable for this task would be parts of the worm tube ledge or well preserved oyster shells. A combination of a RSL curve and the investigated fluctuations could be possible through a precise temporal classification of the bioerosion notch (see chapter 8.2). For this approach a RSL curve representing the region of northeastern Oman would be the most valuable. Moreover, the dating of the beach rocks at the peninsulas could verify the assumption that all beach rocks in the area of the lagoon were accumulated more-or-less simultaneously. This would provide data about the development of the lagoon.

For a more detailed investigation of the abrasion notches, the shape of the feature and the resistance of the lithology should be examined. Both could provide important information about its way of formation and dominating climate conditions during this period.
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- Model of sea level fluctuation phases
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