Raised Shorelines between Plakias und Skinaria Beach

View along the coast looking towards Damnoni Beach (distant left) and Ammoudi Beach (right). An erosional notch about 1m above the waterline as well as raised marine terraces and former rhodolith reefs indicate different stages of tectonic uplift.

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Berlin, December 2024

Contents

Appendix

1 Introduction

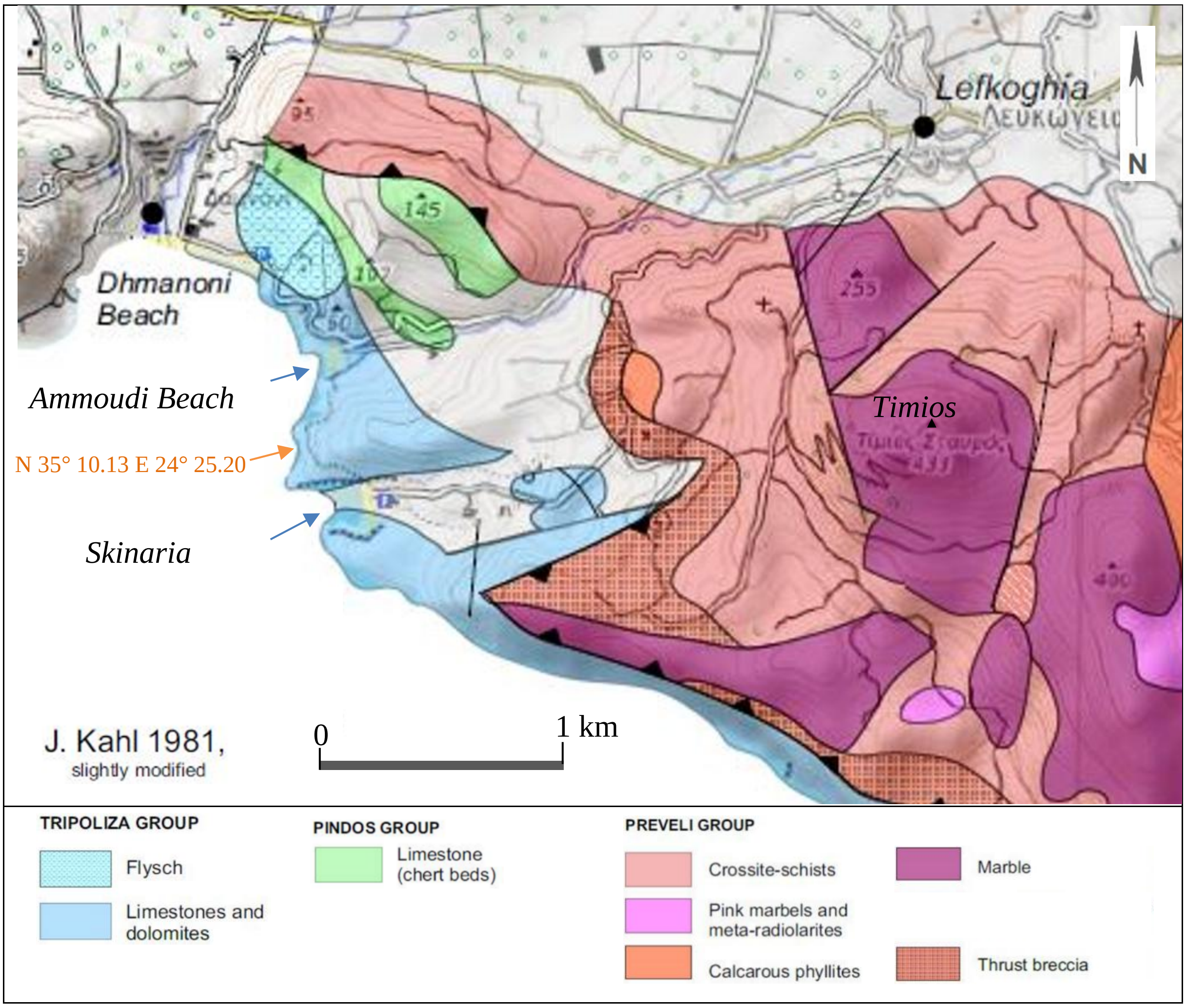
1.1 Quaternary Crustal Movement

In the Mediterranean Sea, the Hellenic subduction has the capability of generating very large earthquakes and tsunamis. This has been indicated for example by the 365 AD Tsunami and the destruction of the ancient harbour at Phalasarna on the west coast of Crete. During the last 5 ma years, western Crete has been uplifted by approx. 1000 m. Uplift is testified by raised shorelines and marine terraces along the southwestern coast. In the Plakias area, several shorelines are recognizable at various elevations; some of them are of Late Pleistocene age and correlate with eustatic peaks (i.e. changes in total ocean water mass, for instance due to ice sheet runoff). Taking both eustatic and tectonic factors into consideration, the shorelines collectively indicate during the late Pleistocene a net average long-term uplift rate for western Crete of 2.5–2.7 mm/y *[Tiberti, 2014]*. Alternatively, Strasser T.F. et. al. describes an uplift rate for the Plakias area of south-western Crete of approx. 1.3 mm/y.

1.2 Recent Crustal Movement

Mourtzas et. al., 2015 have shown based on tidal notches and beachrock combined with archaeological data, that overall submersion in western and southern central Crete during recent times was about 1.60m. This submersion occurred between 4000 years before present (BP) and 396 BP. Around 365 AD, when the sea level was 1.25 m lower than today, the western tectonic block of Crete was divided from its eastern block in a tectonic event. During this event, the western block uplifted by 9.15 m and 7.90 m in its SW and NW extremities, respectively. At the SE side of the western block (south central Crete) uplift is reported to have been about 1.60 m to 2.00 m. The eastern block remained stable. After that, the coast of the entire island submerged by 1.25 m during two subsiding episodes: the first by 0.70 m in the 1604 earthquake and the second by 0.55 m during the last 400 years. *[Mourtzas N. et al., 2015]*

Locations



Geological Map of the Area south of Lefkoghia at the south coast of Central Crete [Kahl J., 1981]

2 Kalypso to Damnoni Beach

2.1 Coralline Rhodoliths and Marine Terraces

Overview of outcrops and locations. I: Recent coralline red algae at the intertidal zone. II: Quaternary coralline red algae carpet reef (light coloured rock) on marine ramp. III: The mountains consist of Tripoliza limestone. IV: Tripolitza limestone containing Nummulities. V: Plakias Graben filled with continental Neogene sediments of the Pandanassa Fm. The location of the fossil reefs indicates an uplift of up to 40m above today's average sea level (asl). [Source of image: Google Maps]

1: Coralline red algae (rhodolith beds). 2: Triopliza limestone. This location now at an elevation of approx. 25m was once at sea level enabling algae and other marine organisms to live submerged near the sea's surface. Coralline red algae can either exist at moderate *temperate ("moderately cool") or at tropical warm water conditions depending on genus and the water depth. Coralline red algae may exist up to depths of 60m [K. F. Kröger, 2004].*

The Tripoliza limestone is grey to dark grey and was formed in shallow marine facies during the Jurassic to Eocene, therefore long before the Quaternary reefs. At this location ("IV" see overview of locations) the rock contains foraminifera (i.e. Nummulities sp.) indicating it to be of Paleogene age. This particular sample displays the eroded surface of the rock, which nicely shows the Nummulities tests.

Former marine ramp at approx. 50m asl displaying a carpet of Rhodoliths and other marine carbonate organisms.

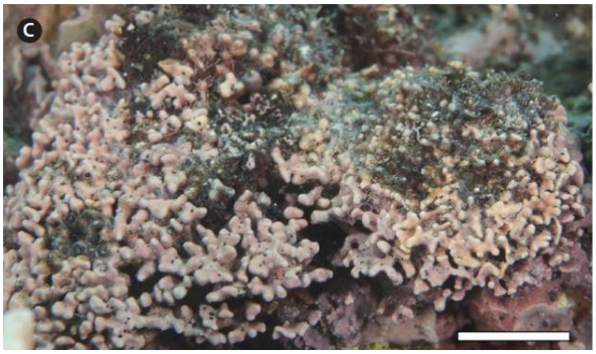
Rhodoliths are calcareous nodules composed of more than 50% of coralline red algal material, which can consist of one to several coralline species growing together. Coralline red algae are organisms that deposit calcium carbonate within their cell walls to form hard structures or nodules that resemble beds of coral. Rhodoliths produce energy solely through photosynthesis and can only grow and survive in the photic zone of the ocean. Rhodoliths are thought to have been present in the world's oceans since at least the Eocene (55 ma ago).

Rhodolith corallines have been divided into two groups, although this division does not constitute a taxonomic grouping:

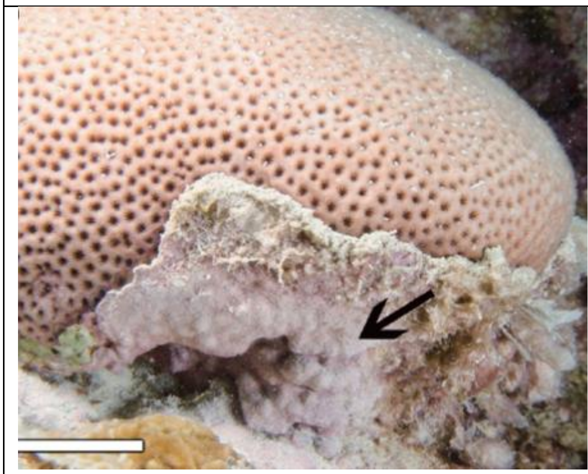
- the geniculate (articulated) corallines;
- the nongeniculate (nonarticulated) corallines.

Lithothamnion, sp. is a genus of thalloid red alga comprising 103 species. Its members are known by a number of common names. [Wikipedia]

Mesophyllum sp. [Wikipedia]



(C) Lithophyllum sp. complex.



(A) Pneophyllum conicum (arrow) overgrowing the stony coral Siderastrea stellata.

(B) Pneophyllum conicum (left side) growing on the stony coral Mussismilia braziliensis (right side)

Common calcareous red algae. A, B and C are found in the Abrolhos shallow reefs of Brazil [G. M. Amado-Filho1 et al., 2018]

Crusts of nongeniculate corallines range from a few micrometres to several centimetres thick. They are often very slow growing, and may occur on rock, coral skeletons, shells, other algae or seagrasses. Crusts may be thin and leafy to thick and strongly adherent. Some are parasitic or partly endophytic on other corallines. Many coralline crusts produce knobby protuberances ranging from a millimetre to several centimetres high. Some are free-living rounded specimens. Some coralline algae develop into thick crusts which provide microhabitat for many invertebrates. Many corallines produce chemicals which promote the settlement of the larvae of certain herbivorous invertebrates, particularly abalone (group of marine gastropods also known as ear shells). Larval settlement is adaptive for the corallines because the herbivores remove epiphytes which might otherwise smother the crusts and pre-empt available light. Nongeniculate corallines are of particular significance in the ecology of coral reefs, where they add calcareous material to the structure of the reef and help cement the reef together. *[Wikipedia]*

Close up of the Rhodolith carpet displaying 1: spherical branching red algae, 2: possibly bryozoans (scale: part of a hammer head)

1: Reef debris

Rhodolith beds

Closeup of above photo 1: Coralline red algae, 2: possibly coral, 3: possibly bryozoans, 4: shell fragments

3 Damnoni Beach to Ammoudi Beach

Location of outcrops, Domani Beach to Ammoudi Beach. I: Flysch, II: Tripoliza limestone with foraminifers (Nummulites), III: Beachrock on flysch, IV: Tripoliza limestone on Tripoliza flysch [Source of image: Google Maps]

3.1 Flysch

Outcrop I: Tripoliza flysch at road cutting behind the beach at Damnoni

Flysch is a marine sedimentary facies that is usually represented by an alternating sequence of mudstones and coarser-grained rocks (typically sandstones). These sediments are often subsequently deformed (folded), sometimes so intensively that they become metamorphic. Flysch series are formed during mountain building and the coarser-grained rocks represent the eroded material of the forming mountain chain. As this material generally enters the depositional area in the form of suspension flows, the term turbidite is often used in geology in connection with flysch.

Flysch normally often consists of sequences that are normally formed by sliding of sediments previously deposited on the continental shelf over the continental slope into the deep sea. This sliding usually takes the form of avalanche-like turbidity or suspension currents. As such landslides are repeated relatively frequently during mountain formation, which lasts millions of years, characteristic sequences are formed in which layers of mudstone alternate with layers of coarser-grained material. The latter often have a very mixed mineral composition. Although, like sandstone, they consist mainly of quartz grains, they usually also contain larger quantities of carbonate or clay. They can also contain a wide variety of minerals, including glauconite, mica and/or feldspar.

In the area of Plakias the flysch is not a sequence of alternating fine- and coarse-grained beds but is made up of mostly of fine-grained material that is thought to have been deposited in a distal environment – therefore sediment coming to rest far away from the source of the marine landslide. The flysch is always deformed and metamorphic and crops out as a dull olive-green phyllite or slate.

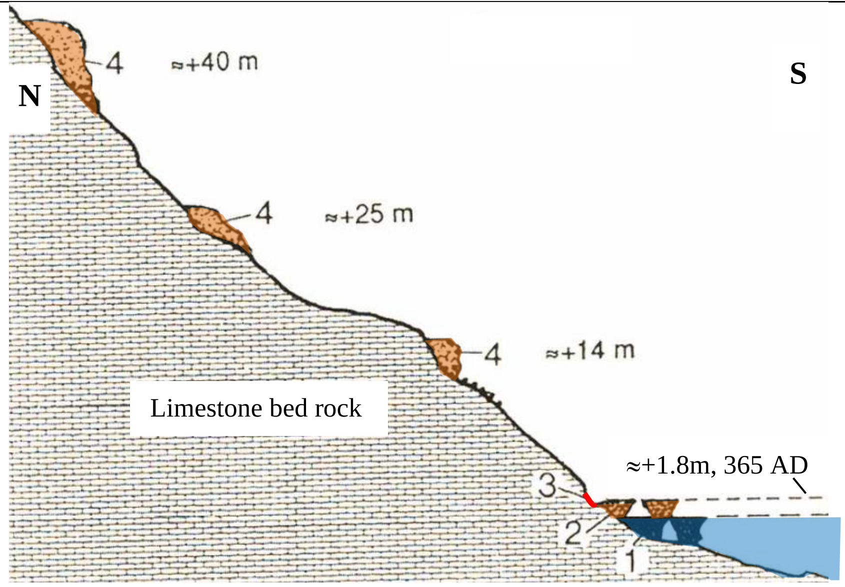
Outcrop I: Closeup of Tripoliza flysch at Damnoni Beach showing dull greenish phyllite. Hammer handle for scale at

3.2 Marine Terraces

The east side of Domani Beach consisting of Tripoliza limestone. 1: Uplifted wave-cut notch (363 AD); 2: Marine terrace.

Marine terraces are commonly formed as a result of sea level fluctuations (eustasy) and/or tectonic uplift. A marine terrace is cut when the rate of uplift of the land matches the rate of rise in sea level. In this case, the surf zone can work for some time to cut the platform. Preservation of the terrace requires that the platform be rapidly uplifted above the surf zone. This typically occurs during earthquakes (i.e. coseismic events), but a rapid fall in eustatic sea level could produce the same result. *[J. M. Rahl et. al.], [See also My GeoGuide No. 1: Pleistocene to Recent Crustal Movement, Outcrops at Phalasarna, Paleochora and Aradhena Gorge]*

Just east of Damnoni there are several paleo indicators for relative sea level change at different elevations. These are marine terraces and fossil coralline red algae deposits that range from 1.8m to around 40m above present-day sea level. The youngest and lowest indication of a raised shoreline is an erosional notch and coralline red algae deposits, which are associated with the earthquake of 365 AD. This involved an uplift of the earth's crust to 1.8 m above sea level (asl) at this location. The next higher tidal marker consisting of mussel boreholes (see Appendix Section: Bioerosion) and fossil coralline red algae remnants lies at approx. 14 m asl. At a dirt road cutting (N 35° 10.39; E 24° 25.19) more sea level markers consisting of an erosional recess and beachrock are visible at approx. 25 m asl. Another fossil marine terrace can be observed at approx. 40 m asl to the left up the slope. At Skinaria Beach, 1.5 km further SE, terraces of similar elevation have been dated to the last cold period of the ice age/ (Strasser et al. 2011).



1: recent coralline red algae (i.e. living and younger than 1600 before present)

2: fossil coralline red algae

3: erosional notch approx. 365AD

4: Pleistocene marine terraces with beach conglomerate

Sketch illustrating fossil coralline red algae and marine terraces at the coast east of Damnoni Beach (nach Kelletat 1996). [Kull]

Outcrop II: fossil rhodolith (red algae reef) about 5m above road cut indicating former sea level. See box on next picture for location.

Outcrop II: Tripolitza limestone containing Nummulites exposed at road cut.

3.3 Foraminifera

Outcrop II: Weathered surface of Tripoliza limestone displaying Nummulites, which belongs to the Macroforaminifera

Foraminifera may be separated into planktonic and benthic types based on their life strategy. However, they are also classified based on their size into three main categories: Microforaminifera (< 0.1 mm), Meioforaminifera (0.1 mm - 1 mm) and Macroforaminifera (>1 mm) .

Today planktonic foraminifera are represented by many species with worldwide occurrence in broad latitudinal and temperature belts, floating in the surface or near-surface waters of the open ocean as part of the marine zooplankton. Benthic foraminifera are as successful as the planktonic foraminifera group. Benthic foraminifera live at all depths of the ocean, or in brackish/freshwater habitats, as either free-floating or attached organisms. Benthic foraminifera include two major types of foraminifera. The small benthic foraminifera, which have simple internal structures, and the larger benthic foraminifera, which have complicated internal structures. Benthic foraminifera occur abundantly in the shelf regions of most tropical and subtropical shallow marine, carbonate-rich environments (Boudagher-Fadel and Price, 2013).

All larger benthic foraminifera are marine and neritic and live in an environment that offers very low levels of nutrients (i.e. oligotrophic). For example, reef and carbonate shoal environments (BouDagher-Fadel, 2008). Living foraminifera occupy low-latitude areas and are most prolific in nutrient-deficient, warm, shallow seas. They are key in the production of carbonate sediment and are most often associated with coralgal reefs (BouDagher-Fadel, 2008).

The fossil record indicates that a similar distribution of foraminifera seen today was prevalent during the Mesozoic and Cenozoic. Sea temperatures over the last 65 million years can be approximated by living foraminifera (McMillan, 2000). As a rule, the presence of larger benthic foraminifera in the fossil record indicates a warm environment and the absence of them indicates a cooler environment. Water depth, as a secondary factor, is another parameter that affects indirectly the distribution of larger benthic foraminifera (BouDagher-Fadel, 2008), as light, temperature and hydrodynamic energy decrease with depth. *[Source: Benthic Foraminifera - SEPMStrata, Kerry McCarney-Castle, summarized from BouDagher-Fadel (2008)]*

Nummulites first appeared in the fossil record during the uppermost Cretaceous and experienced its heyday in the Paleogene, especially in the Tethys Ocean. In the Paleogene, the group was particularly rich in species and formed the so-called nummulite limestones. The genera Assilina and Nummulites are index fossils of the Paleogene. The calcareous shells of Nummulites were sometimes able to accumulate to such an extent that they became a principal rock-forming component. For example, nummulite limestone has been used to build almost 60 % of the pyramids of Giza.

3.4 Marine Terrace Morphology

https://www.wikiwand.com/en/articles/Raised_beach

A marine terrace commonly retains a shoreline angle or inner edge, the slope inflection between the marine abrasion platform and the associated paleo sea-cliff. The shoreline angle represents the maximum shoreline of a transgression and therefore a paleo-sea level.

<table>
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1) low tide cliff/ramp with deposition,
2) modern shore (wave-cut/abrasion-) platform,
3) notch/inner edge, modern shoreline angle,
4) modern sea cliff,
5) old shore (wave-cut/abrasion-) platform,
6) paleo-shoreline angle,
7) paleo-sea cliff,
8) terrace cover deposits/marine deposits, colluvium,
9) alluvial fan,
10) decayed and covered sea cliff and shore platform,
11) paleo-sea level I,
12) paleo-sea level II. – after various authors

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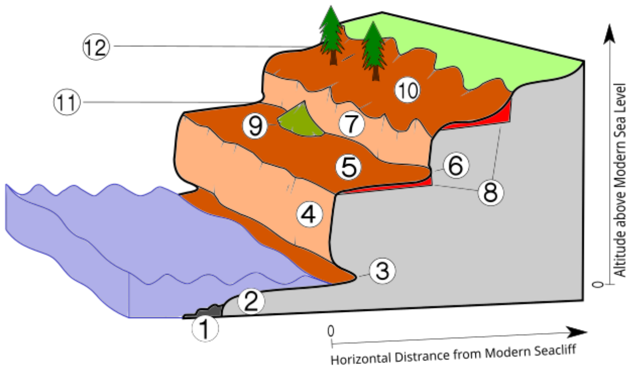

Diagram showing a typical sequence of erosional marine terraces and associated terms. Source: https://www.wikiwand.com/en/articles/Raised_beach

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The platform of a marine terrace usually has a gradient between 1°–5° depending on the former tidal range with, commonly, a linear to concave profile. The width is quite variable, reaching up to 1 km. The cliff faces that delimit the platform can vary in steepness depending on the relative roles of marine and subaerial processes. At the intersection of the former shore (wave-cut/abrasion-) platform and the rising cliff face the platform commonly retains a shoreline angle or inner edge (notch) that indicates the location of the shoreline at the time of maximum sea ingression and therefore a paleo-sea level. Sub-horizontal platforms usually terminate in a low tide cliff, and it is believed that the occurrence of these platforms depends on tidal activity. Marine terraces can extend for several tens of kilometers parallel to the coast.

It is now widely thought that marine terraces are formed during the highstands of interglacial stages, which are correlated to marine isotope stages. While marine terraces in areas of relatively rapid uplift rates (> 1 mm/year) can often be correlated to individual interglacial periods or stages, those in areas of slower uplift rates may have a different polycyclic origin with stages of returning sea levels following periods of exposure to weathering.

Outcrop III near One Rock Beach. 1: Former beachrock or beach conglomerate, which is now slope talus. 2: Tripoliza limestone boulder, 3: Tripoliza flysch

Outcrop III: Former beachrock, which is now slope talus consisting of Quaternary sandstone and conglomerate. 1: sandstone; 2: conglomerate; 3: Tripoliza limestone boulder

Outcrop III: Closeup of previous picture displaying clasts of different composition and roundness/angularity. The clasts that are embedded in a sand matrix are significantly older than the beachrock itself and the marine terrace it was formed on. Some of the casts may be found as singular boulders at the lower marine terrace at Skinaria Beach (see next Section).

Outcrop IV: 1: rhodolith deposits; 2: young conglomerate (beachrock); 3: Tripoliza flysch; 4: limestone boulder adjacent to flysch

Outcrop IV. 3: Tripoliza flysch; 4: Fractured Tripoliza limestone

4 East of Ammoudi

4.1 Indicators of Sea Level Change and Exotic Boulders

Location of outcrops east of Ammoudi Beach and at Skinaria Beach [Source of image: Google Maps]

Outcrop I: uplifted coastline just east of Ammoudi beach displaying elevated red algae reefs (1) and erosional notch at approx. 1m above asl (2).

Outcrop I, closeup. 1: live red algae, 2: contemporary erosional notch, 3: young fossil rhodoliths, 4: old erosional notch (356 AD), 5: old bio-erosive rock pools, 6: Tripoliza limestone, 7: older fossil rhodoliths [N 35° 10.13 E 24° 25,20].

Outcrop II: former marine terrace east of Ammoudi Beach displaying a variety of "exotic" boulders some of which are volcanic (arrows).

Outcrop II: former marine terrace east of Ammoudi Beach displaying a variety of "exotic" boulders some of which are volcanic. 1: large boulder with numerous mussel boreholes (Lithophaga) 2: unkown exotic boulder, 3: Tripoliza limestone with mussel boreholes.

Along the coastline from Ammoudi to Skinaria Beach there are different types of "exotic" boulders lying on Tripoliza limestone or flysch bed rock. At Outcrop II just east of Ammoudi Beach there are greenish porphyritic volcanic rocks as well as metamorphic and sedimentary boulders that do not fit into the surroundings (see also next section on Skinaria Beach). Close examination of the area immediately land inwards shows that there is no such feasible source of volcanic rock such as dykes or lava flows. The geological map previously shown at the beginning of this guide indicates that approx. 1.5 km land inwards there is a possible source area consisting of rocks of the Uppermost nappes. The predominant rocks there are metamorphic HP/LT crossite schists and marbles overlying a thrust breccia. Owing to the nature of thrust breccias the clasts contained therein may have been transported over large distances together with the nappes.

Outcrop II: Dark green volcanic rock probably transported to this location by a former river.

Outcrop II: The volcanic rock is very hard and contains plagioclase phenocrysts

Outcrop II: Closeup of the above photo displaying the porphyritic texture (the rock surface is weathered). The field assessment indicates that it is a porphyritic basalt (or Diasbas). Therefore, a mafic igneous rock having phenocrysts and an aphanitic groundmass. The phenocrysts are probably of calcic plagioclase (light grey in the photo). The finely crystalline groundmass is likely to be a mixture of sodic plagioclase feldspar and pyroxene, which probably has been partly transformed to chlorite – hence the green colour.

5 Skinaria Beach

5.1 Marine Terraces and Exotic Boulders

Four marine terraces have been recognized at Skinaria at elevations of 21, 29, 51 and 82m asl. Characteristic features are often 1 to 3m thick coralline red algae and bryozoa bioherm reefs with interstitial cemented bioclastic and siliciclastic sands. Bivalve and gastropod shells are sometimes preserved in the coralline red algae reef deposits. There is also an underlying approx. 1m thick cemented transgression conglomerate consisting of pebble- to cobble-sized clasts of quartz, limestone and lithoclasts.

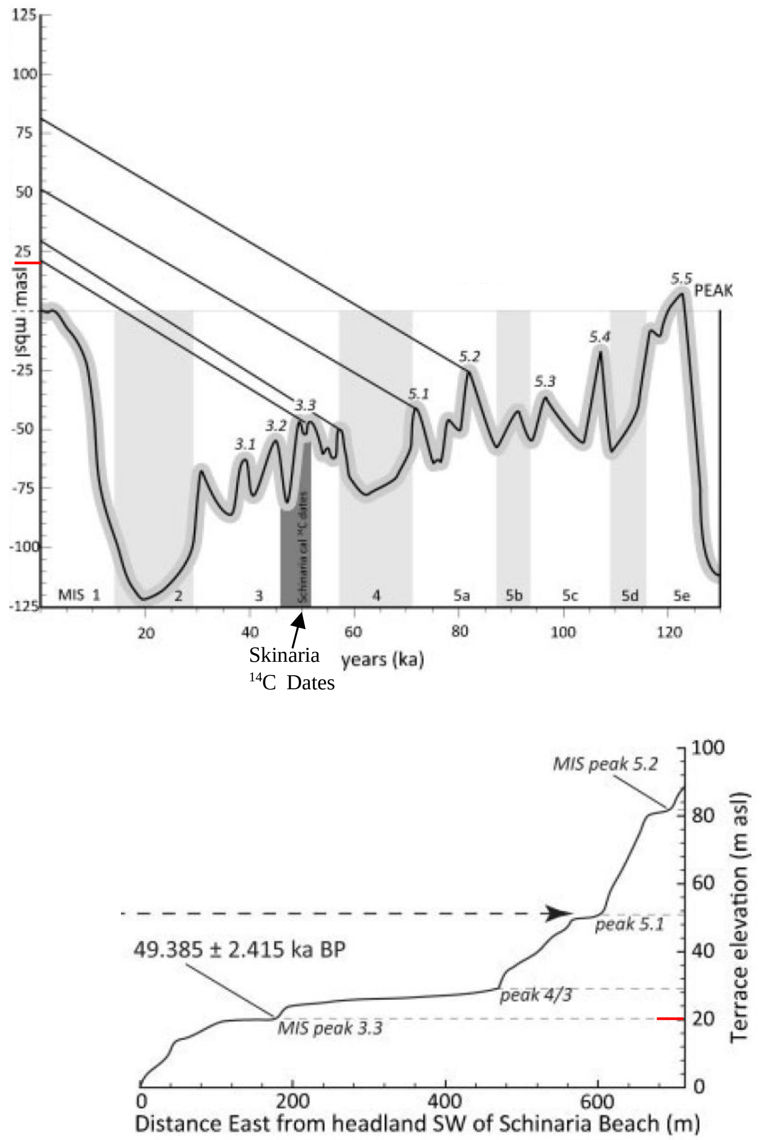
To obtain the absolute age of one of the marine terraces Strasser T.F. et. al. have undertaken radiocarbon analyses on molluscan shells extracted from the 21m elevated marine terrace at Skinaria. Based on ^{14}C-isotope dates (from two samples) the age of the remaining terraces were determined by correlating their elevation with the general Global Sea Level curve (GSL, see Appendix). The use of the Late Pleistocene Global Sea Level (GSL) curve in this way requires the terrasses to have formed during sea-level maxima (therefore to be transgressive) and to have approximately equal uplift rates. *[Strasser T.F. et. al.]*

Terrace elevations, calibrated ^{14}C ages, GSL correlations and uplift [Strasser T.F. et. al.]

Terrace ISA elevation[a]	Assigned MIS[c] (peak)	Assigned age[d] (ka BP)	GSL[d] (m)	Net uplift (m)	Uplift rate[e] (m ka^{-1})
Schinaria (21 m terrace dated age 49.385 ± 2.415 ka BP)					
21 ± 1	3.3	50.5 ± 1.5	−47 ± 12	68	1.3
29 ± 2	4/3	57 ± 1	−50 ± 12	79	1.4
51 ± 2	5.1	72 ± 2	−41 ± 12	92	1.3
82 ± 3	5.2	82 ± 2	−26 ± 12	108	1.3

[a] *Terrace inner shoreline angle (ISA) elevations are in metres above modern sea level, as measured by differential GPS.*
[b] *Reported calibrated ^{14}C ages are 1s values for dated terraces, with the Skinaria age being the sum of two analyses.*
[c] *Terraces are assigned to each peak in the MIS curve following calibrated ^{14}C ages for the lower two terraces. _*
[d] *Assigned age and estimated Global Sea Level (GSL) curve elevations are based on the Huon Peninsula coral record (Lambeck and Chappell, 2001), modified with data from Fairbanks (1989), Lambeck and Purcell (2005) and Kopp et al. (2009), with chronological adjustment to match the middle-to-late Pleistocene MIS boundaries (Lisiecki and Raymo, 2005).*
[e] *Uplift rate errors are consistently _0.08m ka_1.*

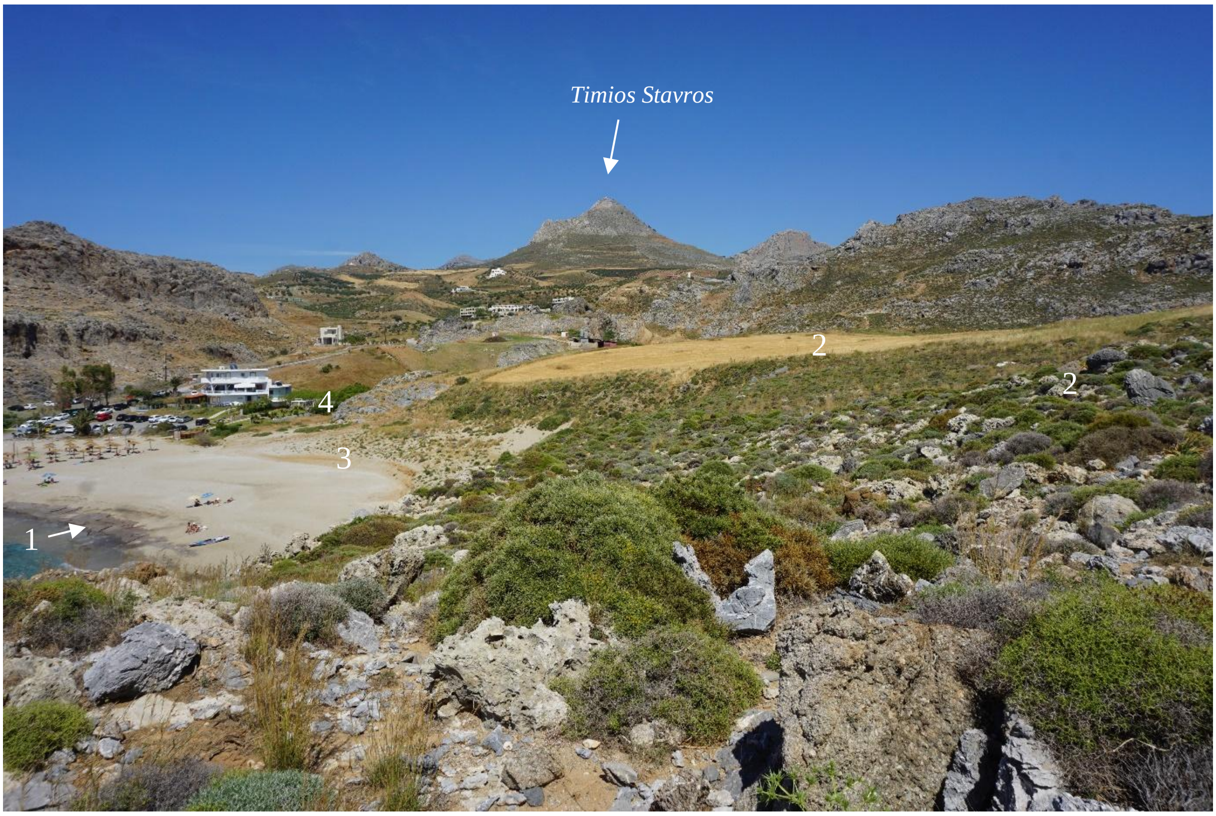
Authors such as Tiberti (2014) and Pirazzoli et al. (1982) have dated similar marine terraces in western Crete using the ^{14}C-method. They have demonstrated that uplift during the Late Pleistocene occurred at rates of approx. 1.5 to 2.5 mm/y. *[J. M. Rahl et. al.]*



Correlation of the Skinaria terrace sequences to the late Quaternary GSL curve of Lambeck and Chappell (2001). The curve is anchored to MIS peaks 3.3 (50.5 ± 1.5k cal a BP) by calibrated radiocarbon ages from the Skinaria terrace sequences (dark vertical band). [Strasser T.F. et. al.]*

** The GSL curve is modified to correlate to the Marine Isotope Stage (MIS) boundaries of Lisiecki and Raymo (2005).*

View of the western side of Skinaria Beach showing the position of former marine terraces. In the foreground and background Tripoliza limestone bedrock.



Overview of the marine terrace at the east side of Skinaria Beach at approx. 21m asl. 1: Recent beachrock, 2: Marine terrace, 3: Estuary sand deposits, 4: Stream

Outcrop III, marine terrace approx. 21m asl. 1: old beachrock, 2: "exotic" sandstone boulder, 3: Tripoliza limestone bedrock

Outcrop III, marine terrace approx. 21m asl. Fossil beachrock

Outcrop III, closeup of previous picture. 1: white partly rounded quartz clast, 2: rounded lithoclasts thought to have originated from the Preveli nappe (Uppermost nappes) further inland.

Outcrop III, marine terrace approx. 21m asl. 1: coralline red algae reef, 2: breccia with lithoclasts (blue hammer handle for scale).

Outcrop III, marine terrace approx. 21m asl. Closeup of previous picture. 1: fossil coralline red algae 2: probably bryozoans.

Outcrop IV, marine terrace approx. 21m asl. Bedrock consisting of flysch lying beneath the Tripoliza limestone.

Outcrop IV, marine terrace approx. 21m asl., "exotic" sandstone boulder encrusted with fossil coralline red algae thought to have originated from the Preveli nappe (Uppermost nappes) further inland.

Outcrop IV, closeup of previous picture. The sandstone is grey, but becomes greenish -brown when weathered.

Outcrop IV, marine terrace approx. 21m asl., hard "exotic" igneous boulder encrusted with fossil coralline red algae.

1

Outcrop IV, Closeup of previous picture. 1: Altered or metamorphic volcanic rock (e.g. meta-andesite). 2: Dark brown rim due to weathering - possibly oxidization of iron (see Appendix). 3: Vesicles are visible on the surface of the rock indicating it to be a lava. Vesicles are small cavities in an aphanitic or glassy igneous rock, formed by expansion of a bubble of gas or steam during solidification.

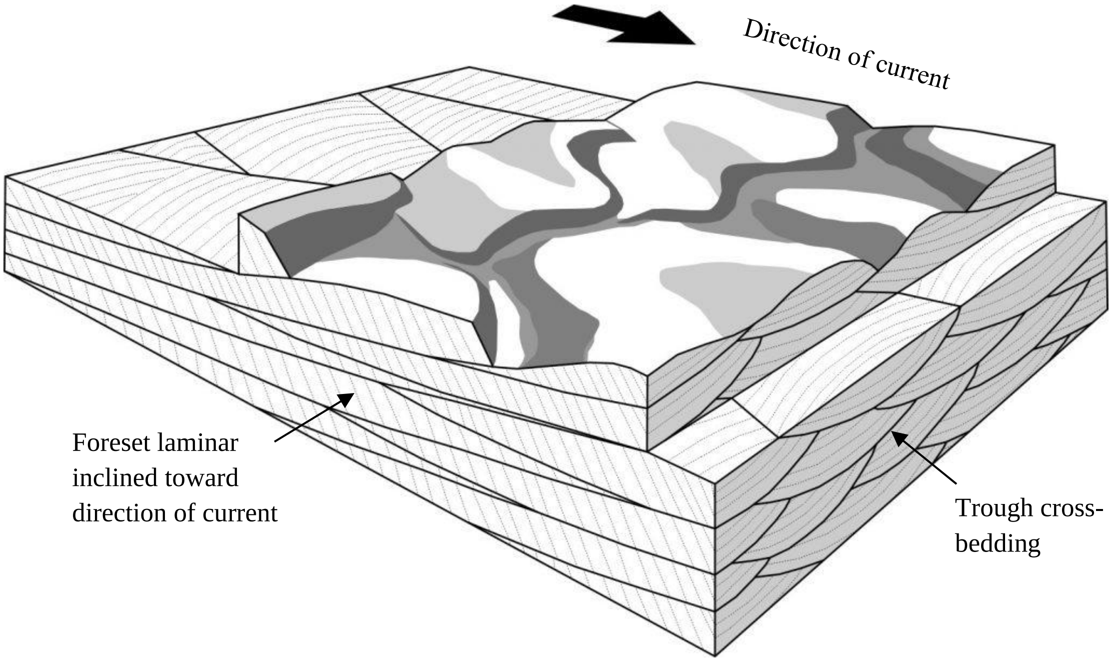
Outcrop IV, marine terrace approx. 21m asl. Very hard greenish-blue metamorphic breccia predominantly with quartz clasts.

Outcrop IV, closeup of previous picture. As the clasts are matrix supported the rock could have once been a debris flow.

5.2 Estuary Sand Deposits

Outcrop V: Quaternary estuary sand deposits at the rear of Skinaria beach. Bedding is generally planar on the mesoscale, but displays some trough cross bedding at macro scale (10cm -50cm)

Outcrop V, close up of the above photo



Formation of trough cross-bedding caused by the migration of ripples with irregular crests. The arrow marks the direction of the current. Modified after Reineck & Singh, 1975. Source: https://geologyistheway.com/sedimentary/bedforms-ripple-marks-and-dunes/

Ripples with curvilinear crests (sinuous, lunate, linguoid etc.) are associated with irregular, curved troughs. The resulting trough cross-bedding is characterized by curved planar erosional surfaces separating different sets of foreset laminae. In sections parallel to the current (see figure above), foreset laminae are inclined toward the direction of the current. On the other hand, in sections perpendicular to the current foreset laminae appear concave and concordant with the basal erosional surface.

Outcrop V: Trough cross-bedding (see figure above). This section of the outcrop is indicated to have been parallel to the current flow. Cross-bedding is an indication of transport within a medium such as water or air. In this case a river that may have been influenced by the tide appears to have existed. Foreset laminae are not visible but the surfaces of the ripples have been preserved by slightly cemented sand grains.

Outcrop V, close up of the above photo. The sand is coarse grained and mainly fairly well sorted. Some horizons, however, are poorly sorted containing additional gravel and pebble sized clasts. This could reflect initial strong currents followed by a gradual waning of flow energy.

5.3 Beachrock

Beachrock is a hard coastal sedimentary formation consisting of various beach sediments, lithified through the precipitation of carbonate cements. The formation, particularly in coastal and beach areas, is triggered by $CaCO_3$ supersaturation. Supersaturation may be caused for example, by strong evaporation (Scoffin, 1970), inflow of carbonate-rich groundwater in the beach area (Hanor, 1978) and microbiological activity (Neumeier, 1999). Under favourable conditions, beachrock only takes a few decades to form.

A low rocky “pavement” of recent beachrock is exposed today at the eastern side of Skinaria Beach. The beachrock is composed of cemented conglomerate and sand, and contains clasts derived from the adjacent bedrock. The beachrock has been partly eroded away by the surf and is also partly submerged.

5.4 Paleo-Sea Cave

Outcrop VI: Palaeo-sea cave preserved in Tripoliza limestone near the access road to the Skinaria Beach. The remains of the sea cave lie at the same elevation as the 51m marine terrace that is associated with the MIS 5.1 transgressive peak on the GSL curve (see Appendix GSL Curve). Deposits of fossil red algae and cemented sediments are preserved within the cave. [Strasser T.F. et al.]

Remnants of older marine terraces are located higher up from the beach on the hillslope. These terraces have been largely eroded away, but at 51m asl next to the access road to Skinaria Beach the presence of a former cave indicates a former shoreline. Sea caves are associated with fresh water streams that drain to sea level (see My GeoGuide No. 1: Pleistocene to Recent Crustal Movement, Outcrops at Phalasarna, Paleochora and Aradhena Gorge. *[J. M. Rahl et. al.]*

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7 Appendix

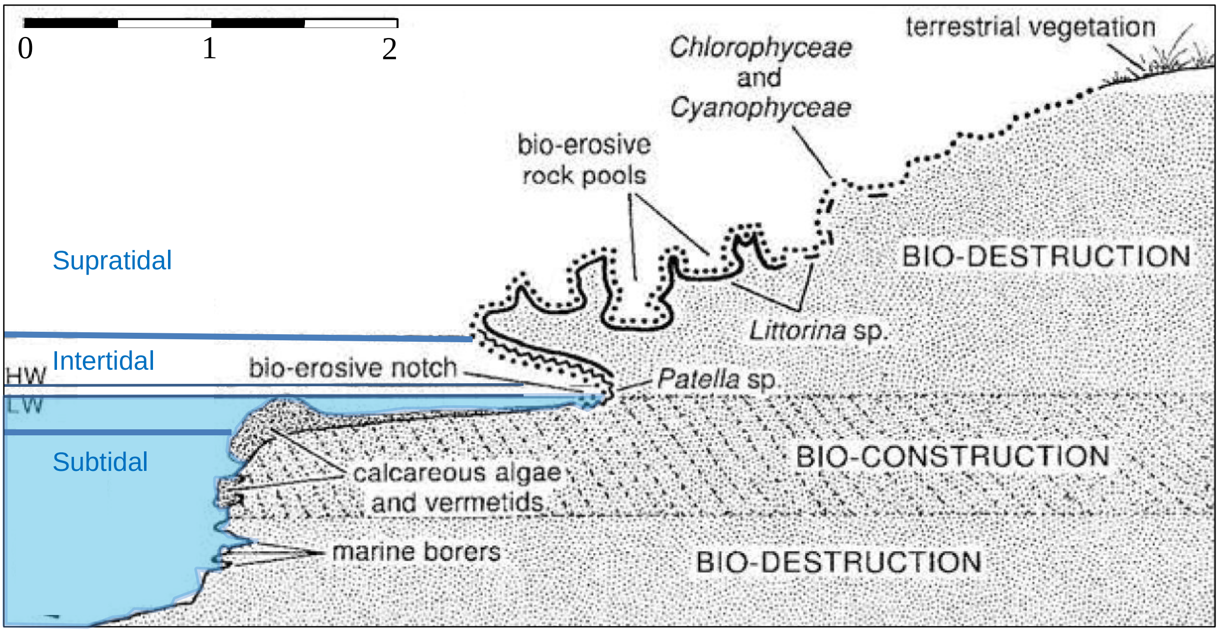
Geological Time Scale of the Cenozoic Era

Eonothem/ Eon	Erathem/ Era	System/ Period	Series/ Epoch	Stage/ Age	mya[1]
Phanerozoic	Cenozoic	Quaternary	Anthropocene[5]		1950 CE
			Holocene		0.0117
			Pleistocene	Upper	0.126
				Middle	0.781
				Calabrian	1.80
				Gelasian	2.58
		Neogene	Pliocene	Piacenzian	3.600
				Zanclean	5.333
			Miocene	Messinian	7.246
				Tortonian	11.63
				Serravallian	13.82
				Langhian	15.97
				Burdigalian	20.44
				Aquitanian	23.03
		Paleogene	Oligocene	Chattian	27.82
				Rupelian	33.9
			Eocene	Priabonian	37.8
				Bartonian	41.2
				Lutetian	47.8
				Ypresian	56.0
			Paleocene	Thanetian	59.2
				Selandian	61.6
				Danian	66.0

[1] Millions of years ago

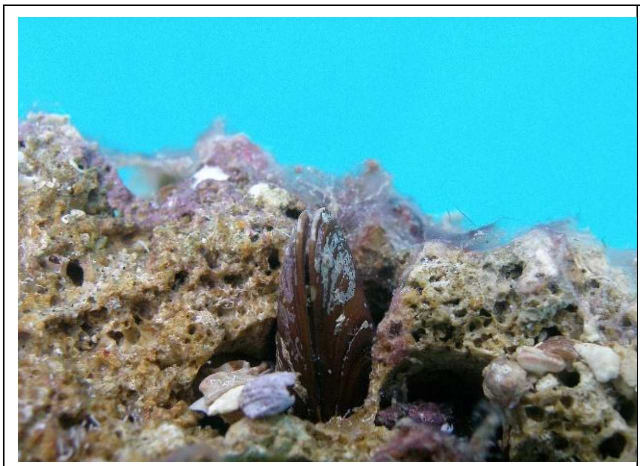
Bioerosion

Subtidal zone



Geomorphological features on the gently inclined sediment-free carbonate coasts of the Mediterranean [D. H. Kelletat, 1997].

The tidal zone can be divided into three zones according to the exposure to sea water: subtidal, intertidal, and supratidal zones. Each zone displays its own characteristic form of bioerosion in limestone rock. Within the subtidal zone that is constantly submerged beneath the water's surface borings of the bivalve *Lithophaga*, the sea urchin *Paracentrotus lividus*, the polychaete *Polydora*, and the sponge *Cliona lampa* are quite frequent. All these organisms penetrate the rock mechanically or by biocorrosion to protect themselves from surf and attack by preditors. The erosional marks they leave within a short period of a few years range from millimetres to several centimetres. They perforate coastal rocks from the lower to the upper subtidal belt.



Lithophaga *is a genus of medium-sized bivalves belonging to the mussel family (Mytilidae). The mussel has bored itself into the limestone and is surrounded by red algae.*

Left and right valve of the ***Lithophaga*** *mussel. The shells can grow up to 80 mm long. The front end is here covered with bryozoans.*

Paracentrotus. lividus *is usually found just below the low water mark at depths down to twenty metres and sometimes also in rock pools. In shallow or exposed waters it can use its mouth and spines to dig into soft rocks to create cavities into which it returns and in which it exactly fits. Where the urchins are numerous, the rock may be honeycombed by these excavations. Smaller individuals particularly use these retreats, which provide some protection from predators.* ***P. lividus*** *is a generalist browser, eating a range of red, green and brown algae in addition to seagrass. The benthic community is much affected by the number of urchins and their food preferences.* ***P.lividus*** *is unable to tolerate low salinity.*

Paracentrotus lividus *has a circular, flattened greenish* test *with a diameter of up to seven centimeters. The test is densely clothed in long and sharply pointed spines that are usually purple but are occasionally other colours including dark brown, light brown and olive green. There are five or six pairs of pores on each ambulacral plate. The tube feet are in groups of 5 or 6, arranged in small arcs.*

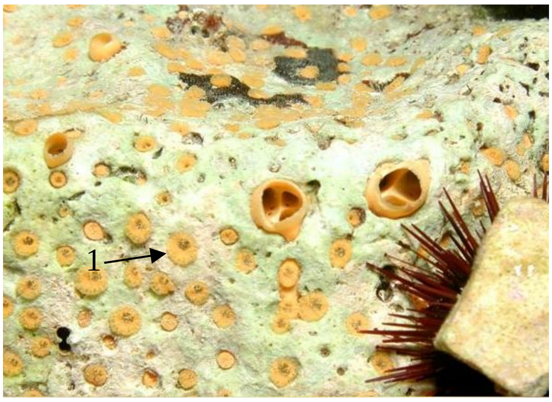
The photo shows an old test that has lost it colour and spines.

*Characteristic double "sunglasses" holes left by **Polydora ciliata** burrowing in rock.*

***Polydora** is a genus of annelid worms. That live in mud, holes bored in rocks, and holes bored in the shells (Photo: Polydora websteri)*

Polydora ciliata (holes)

***Cliona celata** is a yellow to orange excavating (or boring) sponge, occurring in two distinct forms. One is the boring form, recognizable as yellow papillae (1) sticking out of limestone; the other is a massive, wall-shaped sponge covered with characteristic flattened papillae.*



This sponge lives in limestone or in seashells. Outside you can only see the yellow, circular
Oscula (1). The interior of the stone is completely penetrated by the sponge, creating a labyrinth of fine and larger tubes.
***Cliona** is a filter feeder. Water with food particles is sucked in through the pores. Cilia catch these and the remaining water is expelled via the osculum.*

*Shell with uniform holes made by **Cliona.** The sponge is able to produce acids and enzymes that gradually dissolves its way into the shell or rock. In this case the sponge may have been feeding on the bivalve inside.*

*Shell with a maze of bore holes created by **Cliona***

Intertidal to supratidal zone

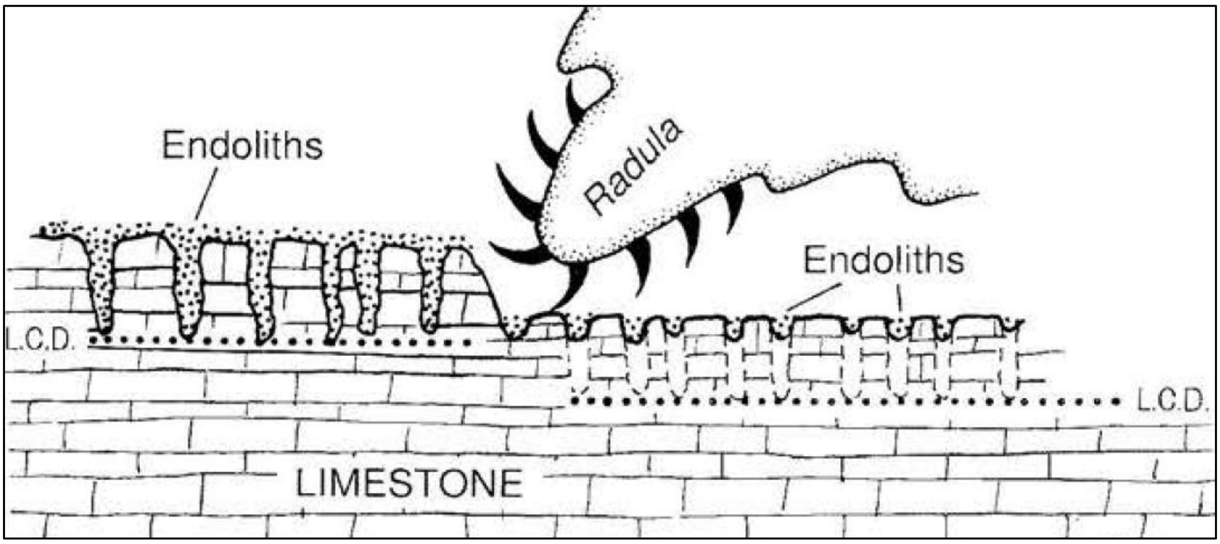


Figure 2 - Grazing by gastropods etc. removes rock and endolilhs. Remaining endolilhs bore to a new "light compensation depth" (LCD) [D. H. Kelletat, 1997].

Grazers, like *chitons* or *Patella sp*. live in the intertidal to lower supratidal belt and *Melarhaphe neritoides* is found in the intertidal to higher supratidal belt. Using a radula, the mollusks file away the rock surface containing endoliths (see next Section), which is their food source. Depending on the species the mollusks' radulae consist of silica or goethite that are harder than the carbonate substratum. The overall effect of this grazing ranges approx. from about 0.1 mm/yr to more than 1 mm/yr. Historical and archaeological evidence gained from vertically uplifted or lowered coastlines indicate that grazing of endolith algae contributes about 70 % to 90 % of Mediterranean coastal bioerosion.

<table>
<tr>
<td>
Patella is a genus of sea snails with gills. They are true limpets belonging to family Patellidae.</td>
<td>
Chitons are marine mollusks that have 8 plates forming a flexible shell. The foot is broad and flat, they have a mouth and a basic endocrine system. Gills are located on each side (6 to 88 pairs). Chitons also have primitive eyes.</td>
</tr>
<tr>
<td>
Melarhaphe neritoides (small periwinkle). The marine gastropod belongs to the family Littorinidae. By adapting to the intertidal to supratidal zone, Littorinidae are able to colonize an unrivalled habitat between land and sea. In the habitat above the mean high tide line, where only waves and splashes provide moisture, other marine snails cannot survive. Similarly, land snails will avoid the zone above the mean high tide line [photo by Theo Fotiadis, Greece].</td>
<td>
Melarhaphe neritoides in dry environment. During the periodic drying of its habitat in the rhythm of the tides, the periwinkle gathers in damp and sun-protected places. When the water runs off and surfaces dry out the snail pulls the shell close to the substrate. The periwinkle is particularly well adapted to prolonged dry periods by closing the shell. The snail can take in oxygen from the air through a tiny gap in the mouth. The intake of atmospheric oxygen can take place due to a special adaptation of the respiratory organs.</td>
</tr>
</table>

Supratidal Zone

Microorganisms, mostly cyanophytes (prokaryote blue algae) and chlorophytes (eukaryotic green algae), contribute to bioerosion in the mid- to the supratidal belts along the coast. Although very small, they can be detected in the field by their black to dark grey, sometimes greenish colour. To protect against desiccation and high temperatures many cyanophytes and chlorophytes, as well as fungi, are able to penetrate and corrode carbonate rock perpendicular to its surface. As blue-green algae require light for photosynthesis they need to reside within the so-called "light-compensation-depth" (LCD), which is a zone that seldom exceeds 0.5 mm below the rock's surface. Algae with the ability to penetrate rock belong to a group of single celled organisms called endoliths that are characterized by their ability to exist under extreme conditions within various types of rock. Under an electron microscope the boring pattern of endoliths within the supratidal zone of limestone rocks can be detected as perforations of up to 800,000 per cm^2. This process is reported to contribute to 10 % - 30 % of bioerosion, according J. Schneider & H. Torunski (1983).

Gray colour due to cyanobacteria (blue-green algae)

Colonization of the rock's surface by blue-green algae.

Source: https://www.biowin.at/meer/oekomedit/felskueste/graue zone.htm

Weathering

https://openpress.usask.ca/physicalgeology/chapter/8-2-chemical-weathering-2/

Weathering occurs when rock is exposed to the "weather" — to the forces and conditions that exist at Earth's surface. Rocks that form deep within Earth experience relatively constant temperature, high pressure, and little or no interaction with moving water. Once overlying layers are eroded away and a rock is exposed to the atmosphere conditions change dramatically. Temperatures vary widely, and pressure is much lower. Reactive gases like oxygen and carbon dioxide are plentiful, and in many climates, water is abundant.

Weathering can be characterized as mechanical (or physical), and chemical. In mechanical weathering, physical processes break rock into smaller pieces. In chemical weathering, chemical reactions change minerals into other more stable forms that are less affected by the condition at the Earth's surface. Mechanical and chemical weathering reinforce each other, because mechanical weathering provides new fresh surfaces for attack by chemical processes, and chemical weathering weakens the rock so that it is more susceptible to mechanical weathering. Together, these processes create the particles and ions that can eventually become either sedimentary rock or soil.

Intrusive igneous rocks form at depths of 100s of metres to 10s of kilometres. Most metamorphic rocks are formed at depths of kilometres to 10s of kilometres. Loose sediments are turned into sedimentary rocks only when they are buried by other sediments to depths in excess of several 100s of metres.

Rate of erosion

Tectonically stable areas erode at only a few meters per million years, regardless of whether they are in a tropical region, a temperate region or in an arid region. In tectonically active areas such as the Himalaya or the Andes, erosion rates are kilometers per million years. One example where erosion rates have been quantitatively compared to known uplift rates is in Italy (Cyr and Granger, 2008; Cyr et al., 2010). Uplift rates have been quantified from well-dated marine terraces that ring the Italian peninsula and islands, and range from 0.2 mm year−1 in the north to 1.6 mm year−1 near the Straits of Messina in the south *[Granger D.E., 2007]* .

University of Saskatchewan

Chemical Weathering

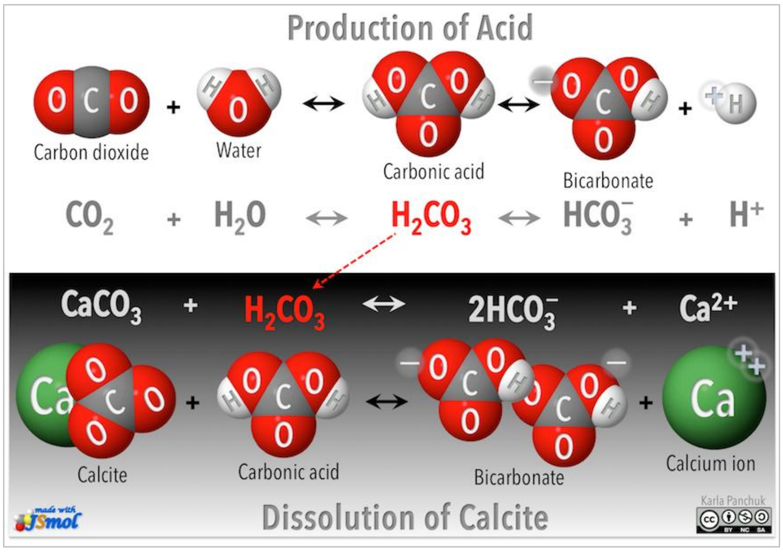
https://openpress.usask.ca/physicalgeology/chapter/8-2-chemical-weathering-2/

Chemical weathering results from chemical changes to minerals that become unstable when they are exposed to surface conditions. The kinds of changes that take place are specific to the mineral and the environmental conditions. Some minerals, like quartz, are virtually unaffected by chemical weathering. Others, like feldspar, are easily altered.

Dissolution

Dissolution reactions produce ions, but no minerals, and are reversible if the solvent is removed. A household example would be dissolving a teaspoon of table salt (the mineral halite) in a glass of water. The halite will separate into Na^+ and Cl^- ions. If the water in the glass is allowed to evaporate, there will not be enough water molecules to hold the Na^+ and Cl^- ions apart, and the ions will come together again to form halite. Gypsum and anhydrite are other minerals that will dissolve in water alone.

Other minerals, such as calcite, will dissolve in acidic water. Acidic water is common in nature, because carbon dioxide (CO_2) in the atmosphere reacts with water vapour in the atmosphere, and with water on land and in the oceans to produce carbonic acid (Figure 8.9).



Calcite weathering by dissolution. Top: Carbon dioxide reacts with water to make acid. Bottom: Acid reacts with calcite and produces ions. Source: Karla Panchuk (2018) CC BY-NC-SA 4.0. Modified after [What-When-How](). Molecules from [JMSE Molecular Editor](), Bienfait and Ertl (2013), with permission for CC BY-NC-SA use.

While rainwater and atmospheric CO_2 can combine to create carbonic acid, the amount of CO_2 in the air is enough to make only very weak carbonic acid. In contrast, biological processes acting in soil can result in a much higher concentration of CO_2 within soil, as well as adding organic acids. Water that percolates through the soil can become significantly more acidic.

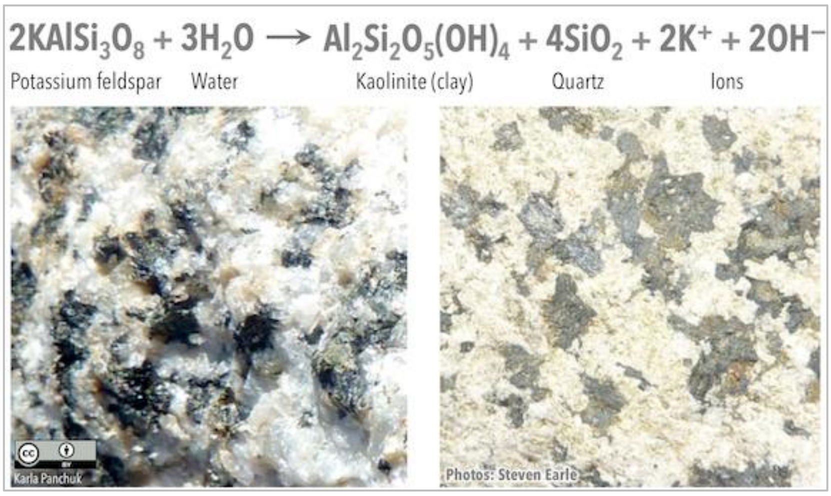
Calcite is a major component of the sedimentary rock called limestone (typically more than 95%). In the presence of acidic groundwater, limestone can dissolve underground. Over time the dissolution can remove enough of the calcite to form caves.

If dissolution of limestone or other materials removes enough rock to undermine support near the surface, the surface may collapse, creating a sinkhole.

Hydrolysis

Silicate minerals other than feldspar can undergo hydrolysis, but with different end results. For example, pyroxene can be converted to the clay minerals chlorite or smectite. Olivine can be converted to the clay mineral serpentine.

The term hydrolysis combines the prefix *hydro*, referring to water, with *lysis*, which is derived from a Greek word meaning to loosen or dissolve. Thus, you can think of hydrolysis as a chemical reaction where water loosens the chemical bonds within a mineral. This might sound the same as dissolution but the difference is that hydrolysis produces a different mineral in addition to ions. An example of hydrolysis is when water reacts with potassium feldspar to produce clay minerals and ions. The results can be seen by comparing weathered and unweathered surfaces of the same sample of granite (see figure below). On the recently broken unweathered surface (left) feldspar is visible as bright white crystals. On a weathered surface (right) the feldspar has been altered to the chalky-looking clay mineral kaolinite.



A piece of granite with unweathered (left) and weathered (right) surfaces. On the unweathered surfaces the feldspars are still fresh and glassy looking. On the weathered surface there are chalky white patches where feldspar has been altered to the clay mineral kaolinite. Source: Karla Panchuk (2018) CC BY 4.0. Photos by Steven Earle (2015) CC-BY 4.0 view source

Hydration

Hydration reactions involve water being added to the chemical structure of a mineral. An example of a hydration reaction is when anhydrite ($CaSO_4$) is transformed into gypsum ($CaSO_4 \cdot 2H_2O$). A consequence of hydration is that the resulting mineral has a greater volume than the original mineral. In the case of the Mosul Dam, hydration of anhydrite has important consequences. The increase in volume applied force to an overlying limestone layer, breaking it into pieces. While unbroken limestone is a strong enough material upon which to build a foundation, broken limestone is too weak to provide a safe foundation.

Oxidation

Oxidation happens when free oxygen (i.e., oxygen not bound up in molecules with other elements) is involved in chemical reactions. Oxidation reactions provide valuable insight into Earth's early surface conditions because there is a clear transition in the rock record from rocks containing no minerals that are products of oxidation reactions, to rocks containing abundant minerals produced by oxidation. This reflects a transition from an oxygen-free atmosphere to an oxygenated one.

In iron-rich minerals such as olivine, the oxidation reaction begins with taking iron out of the mineral and putting it into solution as an ion. Olivine reacts with carbonic acid, leaving dissolved iron, bicarbonate, and silicic acid:

$$Fe_2SiO_4 + 4H_2CO_3 \rightarrow 2Fe_2^{+} + 4HCO_3^{-} + H_4SiO_4$$

Iron and oxygen dissolved in water react in the presence of bicarbonate to produce hematite and carbonic acid:

$$2Fe_2^{+} + \tfrac{1}{2} O_2 + 2H_2O + 4HCO_3^{-} \rightarrow Fe_2O_3 + 4H_2CO_3$$

When the olivine in basalt is oxidized, the basalt takes on a reddish colour that is distinct from the dark grey or black of unweathered basalt.

Basalt pillows in Andalusia, Spain, with reddish weathered surfaces. Where parts of the pillows have broken away, darker unweathered basalt is visible. Source: Ignacio Benvenuty Cabral (2011) CC BY-NC-SA [view source]

The oxidation reaction would be similar for other iron-containing silicate minerals such as pyroxene, amphibole, and biotite. Iron in sulphide minerals such as pyrite (FeS_2) can also be oxidized in this way.

Hematite is not the only mineral that can result from oxidation. In fact, a wide range of iron oxide minerals can form in this way. In granite, for example, biotite and amphibole can be altered to form the iron oxide and iron hydroxyoxide minerals that are referred to in combination as limonite.

Biotite and amphibole in this granite have been altered by oxidation to limonite (orange-yellow coating), which is a mixture of iron oxide and iron hydroxyoxide minerals. Source: Steven Earle (2015) CC-BY 4.0 [view source]

Oxidation Reactions and Acid Rock Drainage

Oxidation reactions can pose an environmental problem in areas where rocks have elevated levels of sulphide minerals such as pyrite. This is because when oxygen and water react with pyrite, sulphuric acid is produced:

$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4$

The runoff from areas where this process is taking place is known as acid rock drainage (ARD), and even a rock with 1% or 2% pyrite can produce significant ARD. Some of the worst examples of ARD are at metal mine sites, especially where pyrite-bearing rock and waste material have been mined from deep underground, and then piled up and left exposed to water and oxygen. In these cases the problem is referred to as acid mine drainage. One example is the Mt. Washington Mine near Courtenay on Vancouver Island (see figure below), but there are many similar sites across Canada and around the world.

Acid mine drainage. Left: Mine waste where exposed rocks undergo oxidation reactions and generate acid at the Washington Mine, BC. Right: An example of acid drainage downstream from the mine site. Source: Steven Earle (2015) CC BY 4.0 view source

At many ARD sites, the pH of the runoff water is less than 4 (very acidic). Under these conditions, metals such as copper, zinc, and lead easily dissolve in water, which can be toxic to aquatic life and other organisms. For many years, the river downstream from the Mt. Washington Mine had so much dissolved copper in it that it was toxic to salmon. Remediation work has since been carried out at the mine and the situation has improved.

UNIVERSITY OF SASKATCHEWAN

Sediments Produced by Weathering and Erosion

https://openpress.usask.ca/physicalgeology/chapter/8-4-weathering-and-erosion-produce-sediments/

The visible products of weathering and erosion are the unconsolidated materials that we find around us on slopes, beneath glaciers, in stream valleys, on beaches, and in deserts. The loose collection of material is referred to as sediment, and the individual pieces that make it up are called clasts. Clasts can be of any size: sand-sized and smaller (in which case they might be referred to as particles or grains), or larger than a house.

Clasts can range widely in size and shape depending on the processes involved in making and transporting them. If and when deposits like these are turned into sedimentary rocks, the mineralogy and textures of these rocks will vary significantly. Importantly, when we describe sedimentary rocks that formed millions of years in the past, we can study the mineralogy and textures to make inferences about the conditions that existed during the deposition of the sediment, and the later burial and formation of sedimentary rock. The properties we look at are composition, grain size, sorting, rounding, and sphericity.

Composition

Composition refers to the mineral or minerals making up the clast. Small clasts might be single mineral grains, but larger ones can have several different mineral grains, or even several different pieces of rock within them. The composition can tell us about what rock the sediments came from, and about the geological setting from which the sediment was derived.

Not all minerals have the same hardness and resistance to weathering, so as weathering and erosion proceed, some minerals become more abundant than others within sediments. Quartz is one example of a mineral that is more abundant. It is highly resistant to weathering by weak acids or reaction with oxygen. This makes it unique among the minerals that are common in igneous rocks. Quartz is also very hard, so it is resistant to mechanical weathering.

In contrast, feldspar and iron- and magnesium-bearing minerals are not as resistant to weathering. As weathering proceeds, they are likely to be broken into small pieces and converted into clay minerals and dissolved ions. Ultimately this means that quartz, clay minerals, iron oxides, aluminum oxides, and dissolved ions are the most common products of weathering.

Grain Size

Whether a grain is large or small tells us about its journey from its source to where it was deposited. Mechanical weathering can break off large pieces from rock. Large pieces carried along by streams will bump into each other, causing smaller pieces to break off. Over time the grains get smaller and smaller still. If we find grains that are very small, we can conclude that they travelled over a long distance.

Geologists have a specific set of definitions to describe the size of grains.

	Clast name	Diameter Range
Coarse-grained	Boulder	Larger than 256 mm
	Cobble	64 mm - 256 mm
	Pebble	2 mm - 64 mm
Medium-grained	Sand	63 µm - 2 mm
	coarse	500 µm - 2 mm
	medium	250 µm - 500 µm
	fine	63 µm - 250 µm
Fine-grained	Silt	2 µm - 63 µm
	Clay	Smaller than 2 µm

Classification of grain sizes. Silt and clay are considered fine-grained particles, sand is medium-grained, and particles larger than sand are considered coarse-grained. Source: Karla Panchuk (2016) CC BY 4.0 Click the image for a text version.

The scale has some of the grain sizes listed in microns (µm). There are 1000 µm in 1 mm. The particles classified as sand are what you would intuitively think of as being sand-sized, so an easy way to remember the scale is that anything smaller than sand is fine-grained, and anything larger is coarse-grained. Fine sand grains are still easily discernible with the naked eye. Silt grains are barely discernible in rocks, and silty rocks feel gritty when rubbed. Clay grains are invisible to the naked eye, and rocks comprised of clay feel smooth when rubbed.

One other thing to notice about this scale is that the finest-grained particle is referred to as clay. While a clay-sized particle could be composed of clay minerals (and often they are), it doesn't have to be. Any particle of that size would be referred to as clay.

Grain Size and Transportation

The grain size of sediments is not just for purposes of description. It's also a valuable clue to the processes that have acted on those sediments, because the size of the clast determines how much energy is required to move it.

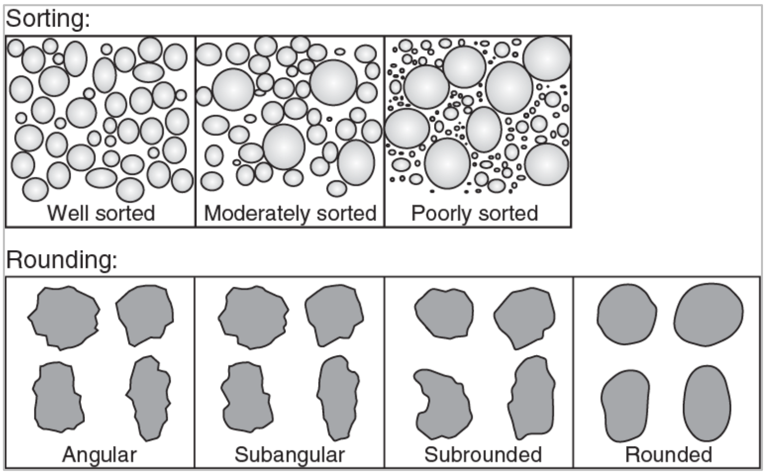
Whether or not a medium such as water or air has the ability to move a clast of a particular size and keep it moving depends on the velocity of the flow. For the most part, the faster the medium flows, the larger the clasts that can be moved. The figure below shows a stream bed that now contains only a trickle of water—barely enough to move particles of sand. But the velocity of water in the stream changes from season to season, as does the volume of water. All of the clasts in the stream bed were transported there by water at some point.

For much of the year the only water in the stream a trickle but in the spring the water can flow rapidly enough to carry boulders. Channel near Golden BC, USA. Source: Karla Panchuk (2009) CC BY 4.0

Very fine-grained particles are the exception to rule that the larger the clasts, the faster the water that is required to transport them. Clay and silt grains stick together, requiring higher water velocities to pick them up and move them than some larger particles. Water that flows fast enough to pick up sand would not be fast enough to pick up clay.

Sorting

Weathering can break off large fragments of rock, and erosion and transport can break these fragments down to smaller and smaller sizes. The extent to which the grains in sediment differ in size is described by sorting.



Top: Sorting of grains, ranging from well sorted where the grains are similar in size, to poorly sorted, where the grains vary greatly in size. Bottom: Rounding refers to how smooth or rough the edges of a clast are. Clasts with sharp edges and corners are angular. Clasts with smooth surfaces are rounded. Clasts that fall in between are sub-angular or sub-rounded. Source: Reagan et al. (2015) CC BY 3.0 view source

If the grains in a sample of sediment are the same size or very nearly so, the sediment is said to be well sorted. If the grains vary substantially in size, the sediment is poorly sorted. Because grains become progressively smaller as they are transported, sorting improves the further the sediments are from their source.

Rounding

Rounding refers to whether clasts have sharp edges and corners or not). If the grains are rough, with lots of edges and corners, then they are referred to as angular. Grains with smooth surfaces are rounded. Grains in between can be sub-angular or sub-rounded. The farther sediments are transported, the rounder they become.

Global Sea Level Curve

Isostatic vs. eustatic sea level changes

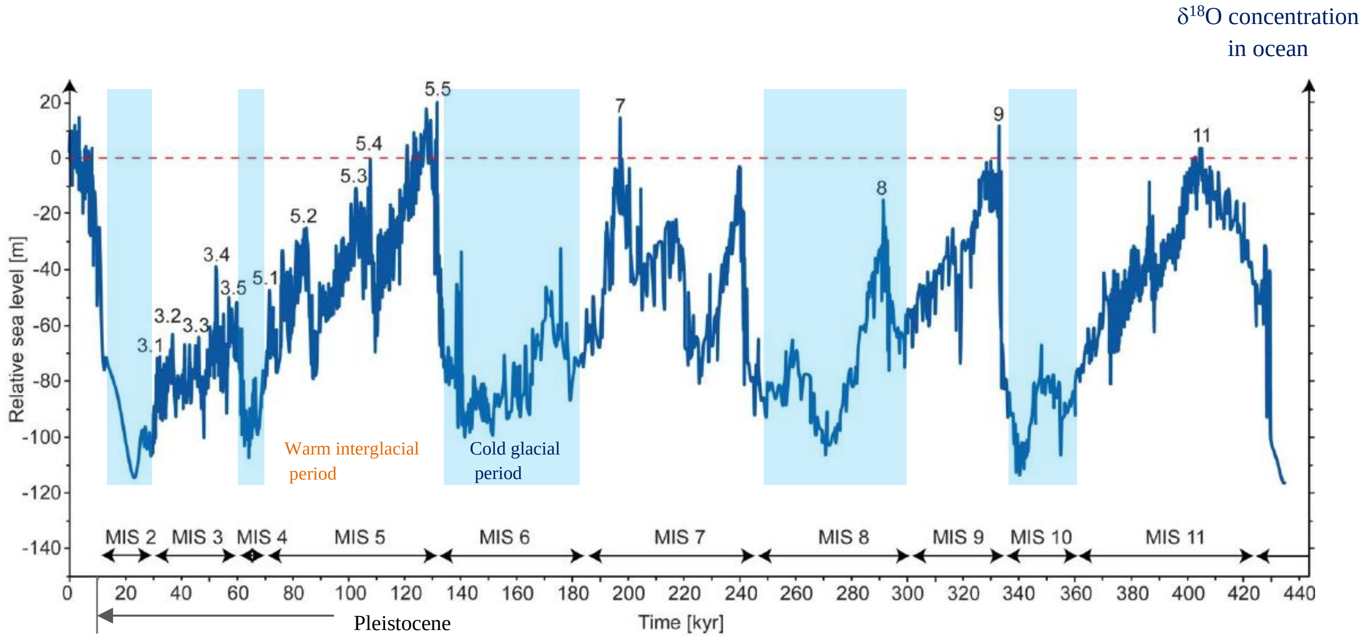
Isostatic sea level changes are local changes caused by subsidence or uplift of the crust related either to changes in the amount of ice on the land, or to growth or erosion of mountains. Eustatic sea level changes are global sea level changes related to changes in the volume of water in the ocean. It is defined by the distance from the center of the earth to the sea surface. An increase of the eustatic sea level can be generated by decreasing glaciation, increasing spreading rates of the mid-ocean ridges or more mid-oceanic ridges. Conversely, increasing glaciation, decreasing spreading rates or fewer mid-ocean ridges lead to a fall of the eustatic sea level.

Owing to the varying eustatic sea level especially during the transition from cool and warm periods of the ice age, the true isostatic uplift of the marine terraces cannot be determined without undertaking some corrections. This can be done by corelating terrace ages with a sea-level curve *[Wikipedia]*.

Marine isotope stages (MIS)

Marine isotope stages (MIS) are alternating warm and cool periods in the Earth's paleoclimate, deduced from oxygen isotope data reflecting changes in temperature. Oxygen isotope ratios have been obtained from deep sea core samples, which has produced an continuous record of temperature change based on pollen and foraminifera (plankton) remains in sediment cores.

Working backwards from the present, which is MIS 1 in the scale, stages with even numbers have high levels of oxygen-18 and represent cold glacial periods, while the odd-numbered stages are lows in the oxygen-18 figures, representing warm interglacial intervals. *[Wikipedia]*



Sea-level curve for the past 440 kyr by Rohling et al. (2014). [S. Rieger, 2015]

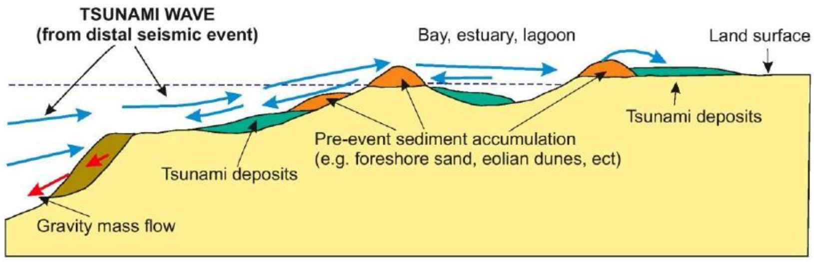
Direct dating of Marine Terraces

There are various methods for the direct dating of marine terraces and their related materials. The most common method is 14C radiocarbon dating, which has been used, for example, on the North Island of New Zealand to date several marine terraces. It utilizes terrestrial biogenic materials in coastal sediments, such as mollusc shells, by analyzing the 14C isotope. In some cases, however, dating based on the 230Th/234U ratio was applied, in case detrital contamination made finding a high resolution dating difficult. In a study in southern Italy paleomagnetism was used to carry out paleomagnetic datings and luminescence dating (OSL) was used in different studies on the San Andreas Fault and on the Quaternary Eupcheon Fault in South Korea. In the last decade, the dating of marine terraces has been enhanced since the arrival of terrestrial cosmogenic nuclides method, and particularly through the use of 10Be and 26Al cosmogenic isotopes produced on site. These isotopes record the duration of surface exposure to cosmic rays. This exposure age reflects the age of abandonment of a marine terrace by the sea.

In order to calculate the eustatic sea level for each dated terrace, it is assumed that the eustatic sea-level position corresponding to at least one marine terrace is known and that the uplift rate has remained essentially constant in each section. *[Wikiwand]*

Tsunami deposits

Tsunami deposits are related to a few high-velocity, long-period waves which catch sediment from the shoreface, beach, and landward erosion environments. The flow depths of a tsunami can be reached higher than 10 m, and sediments transport primarily in suspension, and they distribute the load over a broad region (Morton et al., 2007).



Schematic illustration of a principal pathway of tsunami sediment transport and deposition (after Costa et al., 2015, Einsele et al., 1996) [Thu Anh Vu, 2020]