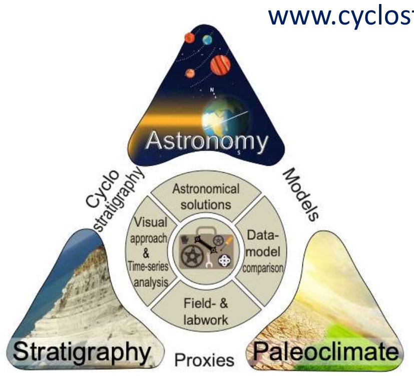
Cyclostratigraphy Intercomparison Project (CIP)
www.cyclostratigraphy.org

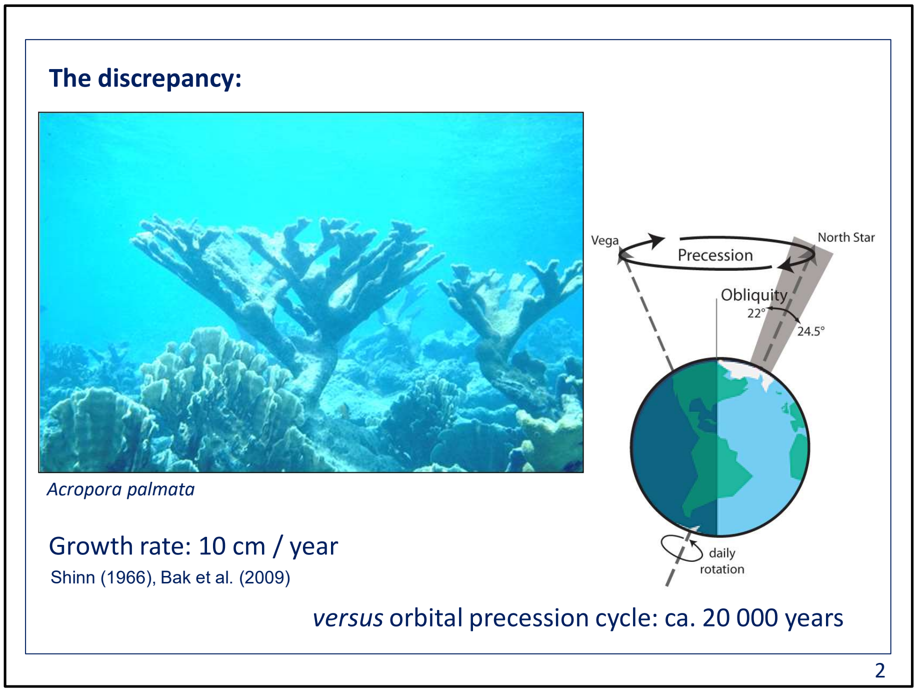


Orbital cycles and time-distribution in shallow-marine carbonate sequences

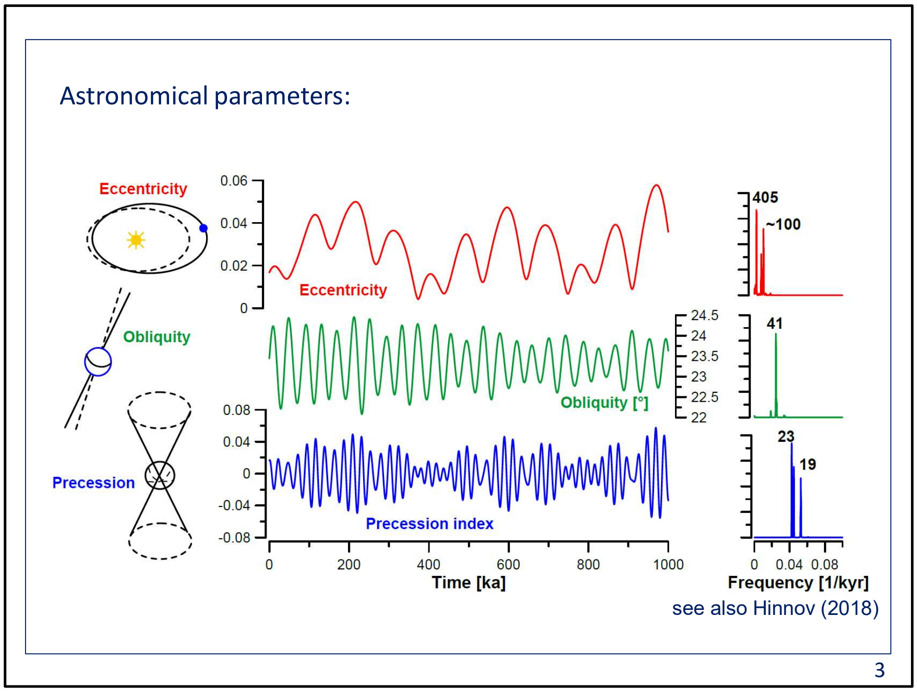
André Strasser
Department of Geosciences, University of Fribourg, Switzerland
2021

andreas.strasser@unifr.ch

Welcome to this lecture, which is part of the Cyclostratigraphy Intercomparison Project. Actually, I'm not an astronomer nor a true cyclostratigrapher but a humble sedimentologist who tries to figure out how carbonate sequences formed in the geological past – and I hope that the link to orbital (Milankovitch) cycles can help in this quest.

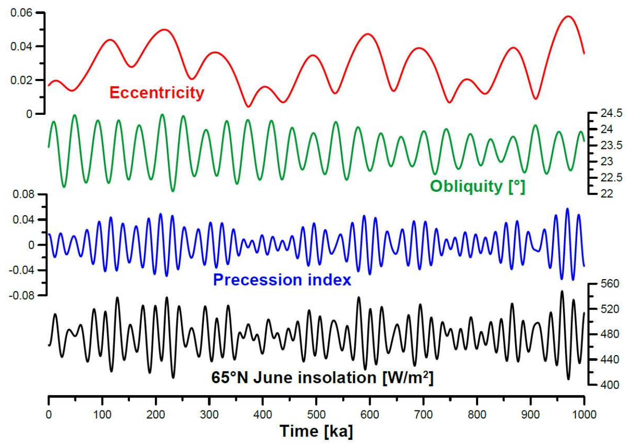


As a sedimentologist, I like coral reefs, which produce carbonate at a high rate. Look at this *Acropora* coral, a branch of which may grow up to 10 cm per year.
However, in the Jurassic and Cretaceous rock record I study with my students, the time-resolution we obtain through cyclostratigraphy is 20 kyr at the best, corresponding to the periodicity of the orbital precession cycle. Thus, there is a discrepancy.



The evolution of the three astronomical parameters (eccentricity, obliquity and precession cycles) is shown here over the last one million years. The precession cycle is the shortest one, with frequency peaks of 19 and 23 kyr. Because these cycles influence the distance between Earth and Sun and also the obliquity of the Earth's axis, they influence the insolation, i.e. the solar energy received at the top of the atmosphere.

From astronomical parameters to insolation:



Insolation changes translate into climate changes, which in turn influence the sedimentary and ecological systems.

4

Based on the astronomical parameters, time series of incoming solar radiation can be calculated (here shown for June 21st at 65°N). The scale is in Watt (i.e. energy) per square meter on top of the atmosphere. Insolation changes then will induce climate changes, which will ultimately influence the sedimentary and ecological systems, and thus the life of our coral.

If we can establish a link between changes in the sedimentary record with cycles controlled by the astronomical parametrs, we have a clock by which to measure time in ancient sedimentary series.

The challenge:

How to reconcile the rates of today's processes of carbonate formation and accumulation with the fossil sedimentary record ?

Rangiroa, South Pacific

?

Berriasian, Salève, France

5

The challenge now is to reconcile the sediment production and accumulation rates as seen today (where we can look at the processes and analyse the products) with the million-years old sedimentary sequences we study in the outcrop or in cores. This will lead to a better understanding of the ecological processes controlling carbonate production, and of the hydrodynamic processes controlling sediment accumulation. On this island in the South Pacific, carbonate skeletons are produced on the reef out there in the ocean. These are then ripped up by storms, reworked by currents, and finally deposited as sand on the beach. Understanding these processes and their timing leads to a better interpretation of the fossil record.

Sediment production and accumulation:

The shallow-marine carbonate factory is mainly run by organisms such as corals, calcareous algae, foraminifera, bivalves, gastropods, echinoderms, serpulids, and microbes.

Sinai, Egypt

Microbially stimulted precipitation of carbonate (cements, ooids, oncoids, whitings) also contributes.

6

In tropical and subtropical shallow-marine environments, carbonate-producing organisms are abundant and have a high potential to produce sediment. Here we see different types of corals forming a patch-reef, but also calcareous algae, foraminifera, bivalves, gastropods, echinoderms, and serpulids contribute. Microbes calcify or stimulate the formation of carbonate to form ooids, oncoids, cements, or whitings.

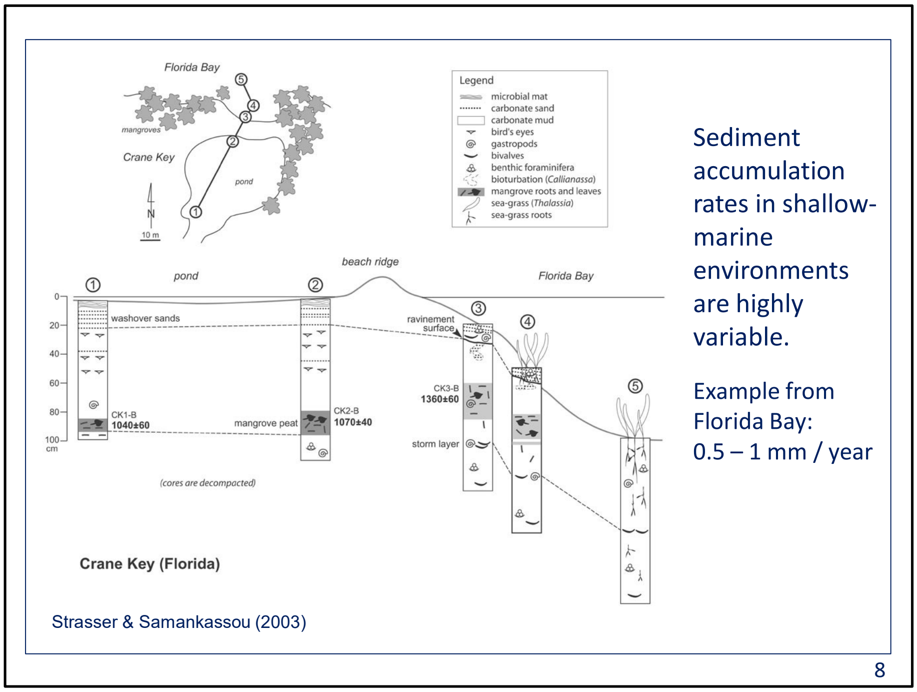
The sediment thus produced can stay in place or is distributed by waves and currents.

Heron Island, Great Barrier Reef, Australia

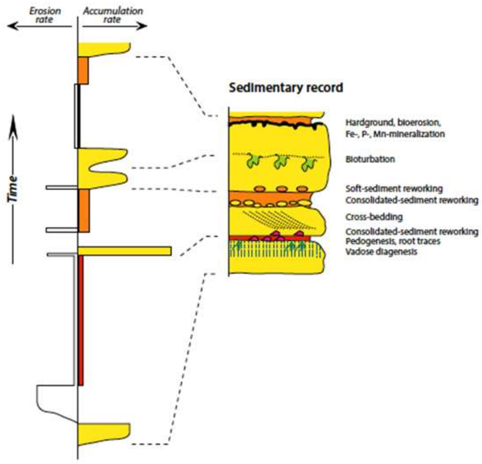
Schooner Cays, Bahamas

7

The sediment thus produced can stay in place such as in a reef, or it can be broken and thrown up onto the beach such as this coral rubble, or it can be rolled around by tidal currents such as here in the Bahamas.



In Florida Bay, we took shallow cores on a small island and dated mangrove peat by C^{14}. Below the quiet pond, about 1 meter of carbonate mud accumulated within about 1000 years. On the bay side, however, storm events created a ravinement surface, meaning that previously deposited sediment was eroded, thus making the accumulation rate lower. Consequently, even over short distances, sediment accumulation rates can be highly variable, like here between 0.5 and 1 mm per year.



Strasser (2015)

Time-distribution in the sedimentary record of shallow-marine carbonate systems is highly irregular. Much time may be taken up in surfaces.

9

When interpreting the sedimentary record in terms of time that is necessary to produce, accumulate, and potentially erode the sediment, it becomes clear that the time-distribution is highly irregular. From bottom to top: formation of a carbonate bed, then erosion, then pedogenesis and reworking. Very rapid deposition of an ooid shoal, followed by cementation and reworking. Again pedogenesis, some reworking, renewed quite rapid accumulation but slowing down to create a bioturbated level. This is followed by the formation of a hardground. Thus, thick sediment bodies may accumulate very rapidly, and much time is taken up in surfaces.

Estimation of time:

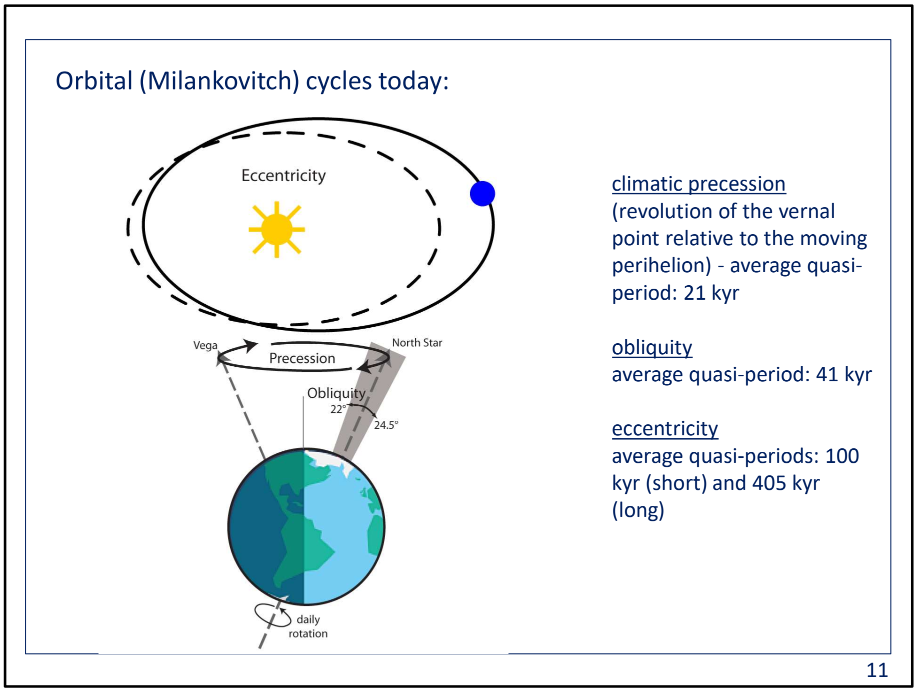
How to measure time in the fossil record, with the highest possible resolution ?

Short time-windows:
- annual to daily cycles (tree rings, warves, speleothems, tidal laminites)

Longer time-windows:
- multi-annual cycles (solar cycles, ENSO, NAO)
- multi-millennial cycles (sub-Milankovitch and Milankovitch cycles)

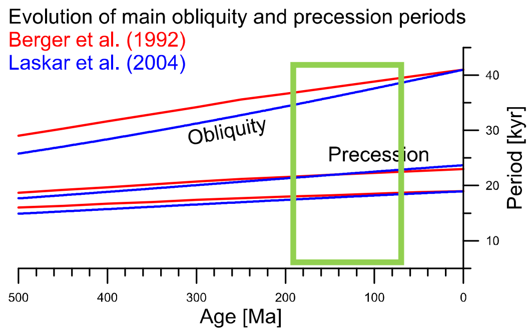
10

In order to reconstruct the evolution of the ecosystems that produce the carbonate and in order to evaluate the sedimentation rates, the notion of time is important. How to measure time in the geologic past with the highest possible resolution ?
Time-windows can be opened, independent of the age of the rocks. Tree rings, warves, or speleothems open short time-windows with a yearly resolution, while tidal laminites even have a twice-daily resolution.
Longer time-windows may be sedimentary records of multi-annual cycles such as caused by solar cycles, El-Niño-Southern-Oscillation, or North-Atlantic-Oscillation. Finally, there are the multi-millennial records of the orbital (Milankovitch) cycles, or the badly defined sub-Milankovitch cycles of enigmatic origin. In this presentation I will focus on the Milankovitch cycles.



Frits Hilgen in his presentation has offered a very detailed explanation of the orbital cycles, and I will only quickly repeat the essentials: the gravitational forces in the solar system cause the Earth's orbit around the sun and the Earth's axis to vary with different periodicities (more precisely quasi-periodicities because of the chaotic behaviour of the solar system), which today have average values of 21, 41, 100, and 405 thousand years.

Precession and obliquity cycles were shorter in the past:



For cyclostratigraphic purposes in the Jurassic and Cretaceous:

Precession: 20 kyr

Obliquity: 40 kyr

Short eccentricity: 100 kyr

Long eccentricity: 400 kyr

12

As the rotation of the Earth slows down over time, the precession and obliquity cycles were shorter in the past. Eccentricity stays stable. For our work in the Jurassic and Cretaceous, we therefore apply the simplified values of 20 kyr for precession, 40 kyr for obliquity, and 100 and 400 kyr for short and long eccentricity, respectively. This also results in a certain hierarchy (5 precession cycles in one short eccentricity cycle, 4 short eccentricity cycles in a long one).

Valanginian, Angles (France)

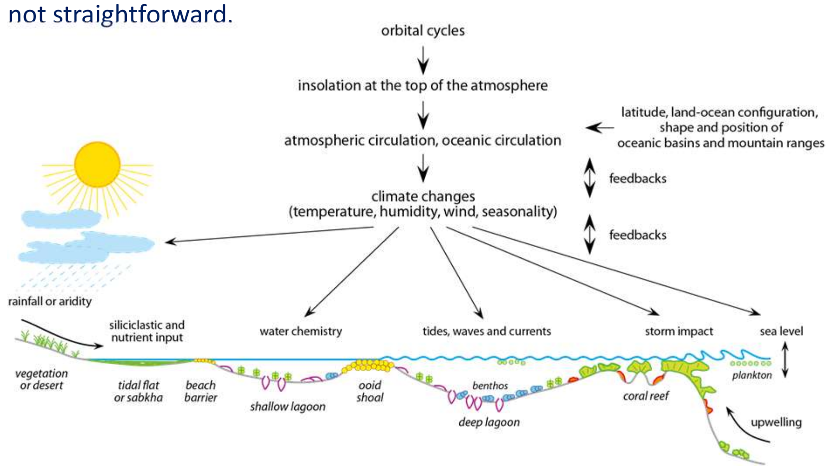
Example:
hemipelagic limestone-marl alternations

13

This is reflected in the hierarchical stacking of beds like in this example of hemipelagic limestone-marl alternations in France (the bundle of 5 beds in the centre of the picture would have formed in tune with the short eccentricity cycle of 100 kyr, and each limestone-marl couplet would correspond to the precession cycle of 20 kyr).

Translation:

On shallow-marine carbonate platforms, the record of orbital cycles is not straightforward.



Modified from Strasser (2018)

14

So, the orbital cycles give the beat, but how exactly does this translate into the sedimentary record? The orbital cycles first of all cause changes in insolation at the top of the atmosphere, dependent on the latitude. These changes then translate into climate changes, themselves dependent on the atmospheric circulation cells, land-ocean distribution, orography, and albedo, including a multitude of feed-back processes. These climate changes then affect the depositional environment, in our case the shallow-marine carbonate platforms.

Rainfall or aridity control vegetation cover and run-off from land to ocean, that is input of siliciclastics and nutrients. Nutrients also come from upwelling and are relevant for the well-being of plankton but should not be too abundant to cause algal growth that smothers the coral reefs. Nutrients, water temperature, water chemistry, and water depth control the carbonate-producing organisms. Tides, waves, currents, and storms that redistribute the sediment depend on wind and oceanic circulation. An important factor is sea level, which controls water depth and accommodation, that is the space available for sediment accumulation. Conclusion: the translation of orbital cycles into the sedimentary record is not straightforward at all.

Sea-level changes:

Eustatic sea-level changes, together with subsidence, control water depth (and thus carbonate-producing ecosystems) and accommodation (and thus sediment accumulation) on the shallow platform.

In greenhouse worlds, insolation changes translated into more or less symmetrical sea-level changes (in contrast to asymmetrical ones when polar ice caps and glaciers built up slowly and melted rapidly).

Metre-scale sea-level changes could be induced by changes in:

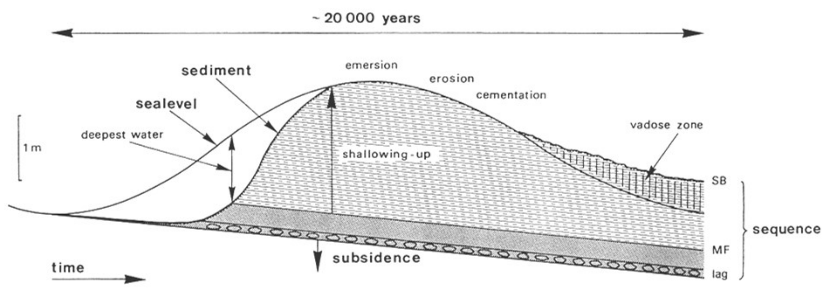
- ice volume of small polar ice caps and Alpine glaciers
- thermally controlled volume of the ocean surface waters
- density-controlled volume of deep ocean waters
- volume of freshwater on the continents

Sames et al. (2016)

Lets look at sea-level changes: orbitally controlled eustatic sea-level changes, together with subsidence, define water depth, which controls the carbonate-producing organisms. Too shallow or subaerial exposure, no or only little carbonate. Too deep, no light for photosynthetic organisms such as green algae or corals. Sea-level changes also define accommodation, i.e. the space into which sediment can potentially be accumulated. Under greenhouse conditions such as the Jurassic and Cretaceous, insolation changes translated more or less directly into sea-level changes, while under icehouse conditions sea-level changes are asymmetrical due to slow build-up and fast melting of polar ice caps and Alpine glaciers.

Small, metre-scale sea-level changes may be induced by changes in ice volume of small polar ice caps and glaciers, by thermally controlled volume changes of the ocean surface waters, by density-controlled volume changes of deep ocean waters, or by retention and release of freshwater on the continents.

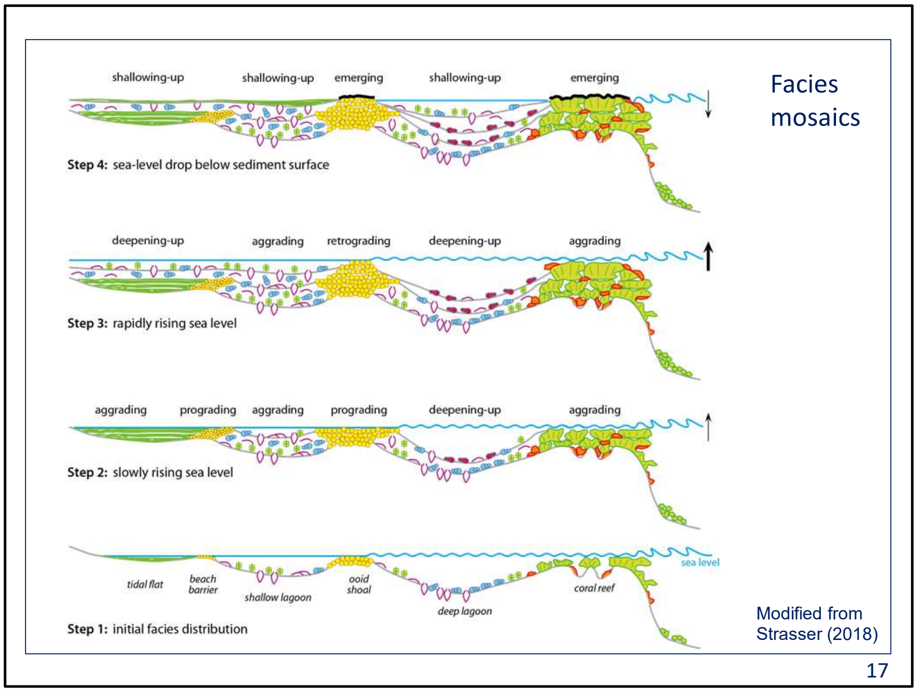
Metre-scale high-frequency sea-level changes have a strong influence on accommodation and facies evolution. Consequently, depositional sequences can be interpreted in terms of sequence stratigraphy.



SB: sequence boundary MF: maximum flooding Strasser (1994)

16

On a shallow platform, metre-scale and high-frequency sea-level changes have a strong influence on facies and accommodation. As we deal now with sea-level changes, we can apply the concepts of sequence stratigraphy to interpret the dynamics of the system.
In this example, after subaerial exposure at low eustatic sea-level, subsidence creates space but only reworked sediment is deposited, creating a lag. Then, the carbonate-producing organisms wake up and colonize the shallow lagoon. When water depth is ideal, carbonate productivity is optimal, and there is space to accommodate the sediment. Deepest water will be indicated by the deepest flora and fauna. Then sea-level rise slows down but sediment is still produced and accumulated, slowly filling up the available space. Emersion, erosion, and early-diagenetic cementation occur while sea-level drops below the sediment surface, creating a vadose zone. Thus, in sequence-stratigraphic terms, a deepening-shallowing sequence is created, defined by sequence boundaries. A maximum-flooding surface or interval indicates deepest water. If the sea-level cycle was controlled by the orbital precession cycle, then this sequence has formed within 20 kyr.



In the previous slide, the evolution through time of only one point on the platform was considered. In the real world, platforms are structured, and facies mosaics are created. With rising and dropping sea level, deepening-up, aggrading, or shallowing-up sequences may be created at the same time, depending on the position of the platform. Lateral correlation of sequences in the fossil record may thus become difficult.

Problem: not only orbitally controlled (allocyclic) sea-level changes are recorded, but also autocyclic processes such as lateral migration of sediment bodies.

Shark Bay, Australia

18

Another problem is that not only orbitally controlled, i.e. allocyclic, sea-level changes influence facies evolution but also autocyclic processes such as lateral migration of sediment bodies. Look at this example from Shark Bay where a spit system pushed by coastal currents is about to close in and isolate a lagoon, which will then develop a facies totally different from the one in the open ocean, and this at constant sea level.

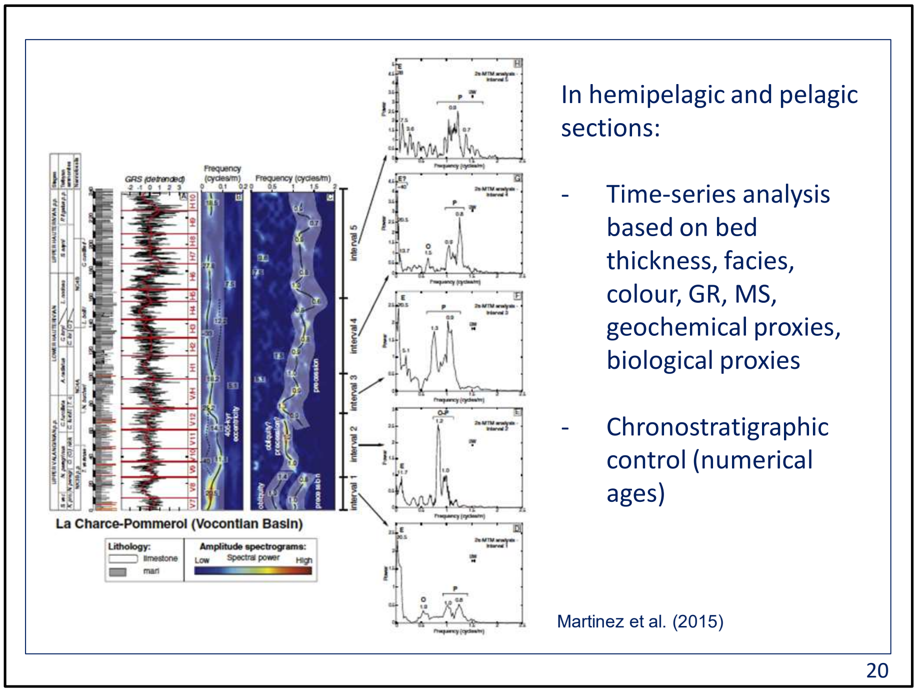
To construct a time-frame:

Climate and sea-level changes have a direct or indirect control on the evolution of shallow carbonate platforms. If they are orbitally controlled, we can construct a time-frame to better interpret this evolution.

Identification of the precession cycle provides a resolution of 20 kyr, which approaches the time-scale of the Holocene where the parameters controlling the ecological and sedimentological processes are much better known.

19

We have seen that climate and sea-level changes have a direct or indirect influence on the evolution of shallow carbonate platforms. If they were orbitally controlled, we can try to construct a time-frame, which allows us to better interpret this evolution.
If we can identify the record of the precession cycle, a time-resolution of 20 kyr becomes available. This approaches the time-scale of the Holocene where the parameters controlling the ecological and sedimentological processes are much better known.



In the hemipelagic and pelagic realms, the sedimentary record often is continuous and displays repetitive patterns such as limestone-marl alternations or colour banding. There, time-series and spectral analyses can be performed. Depending on the type of depositional system, these can be based on bed thicknesses, facies, colour, gamma ray, magnetic susceptibility, stable isotopes, other geochemical proxies, or faunal and floral changes.
Of course, the measured outcrop or core has to be calibrated by numerical ages.
The example here shows an analysis by Martinez et al. from the hemipelagic Vocontian Basin in France, identifying the records of the short eccentricity (E), obliquity (O), and precession (P) cycles. It is interesting to see that the relative importance of these cycles varies through time.

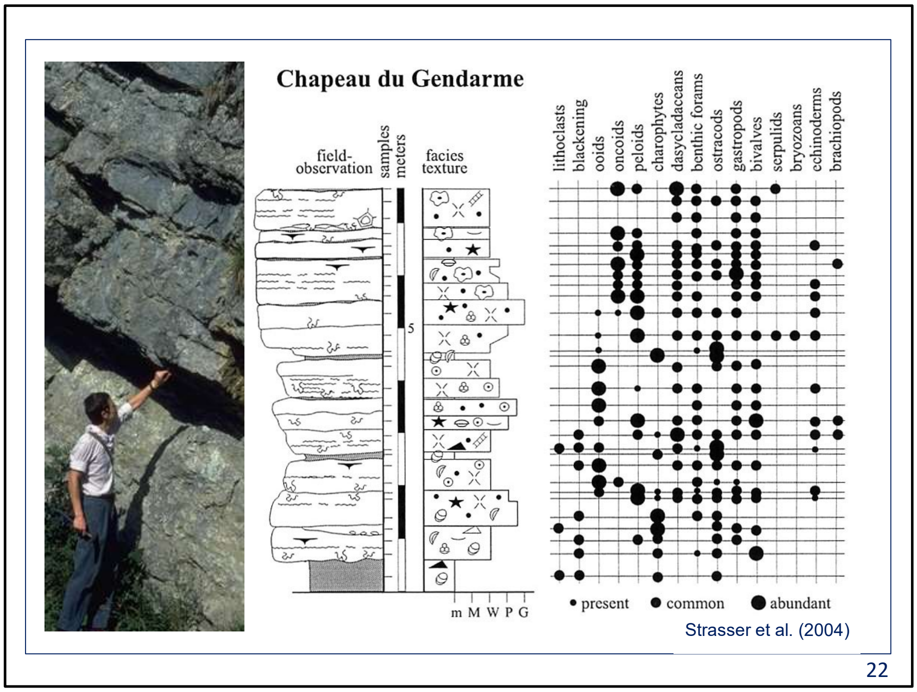
In shallow-marine sections:

- Analysis of stacking pattern
- Analysis of facies trends
- Lateral correlation to distinguish between allocyclic and autocyclic signals
- Chronostratigraphic control

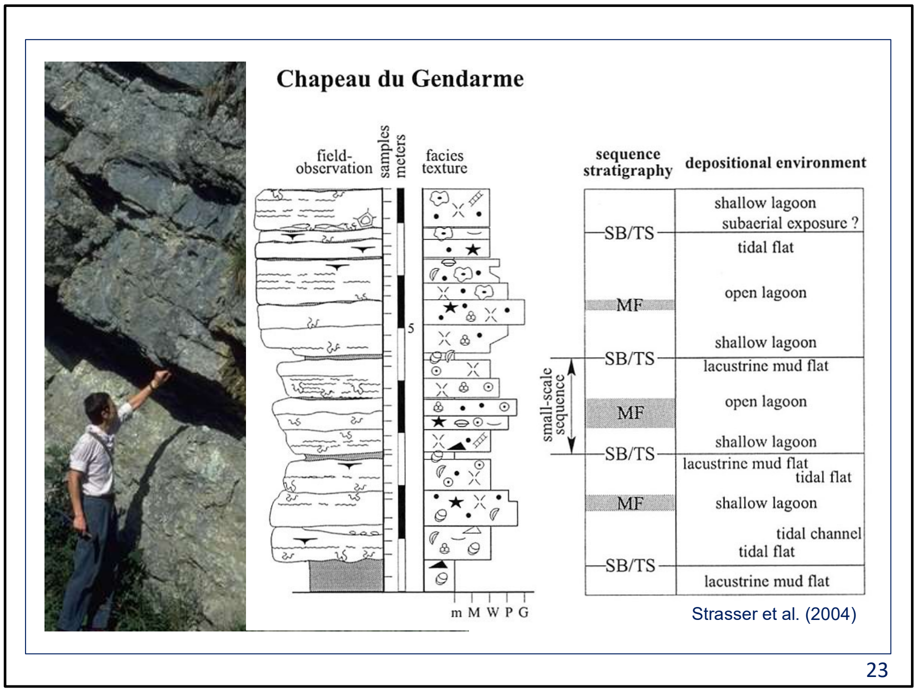
Berriasian, Chapeau du Gendarme, France

21

In shallow-marine sections where facies are complex and erosion and subaerial exposure are common, it is necessary to perform a detailed facies analysis to explain the observed stacking pattern of beds. Also, lateral correlation between sections is necessary to filter out potential autocyclic repetition of beds. Furthermore, like in the deep-water sections, chronostratigraphy is needed to constrain the duration of the studied interval.

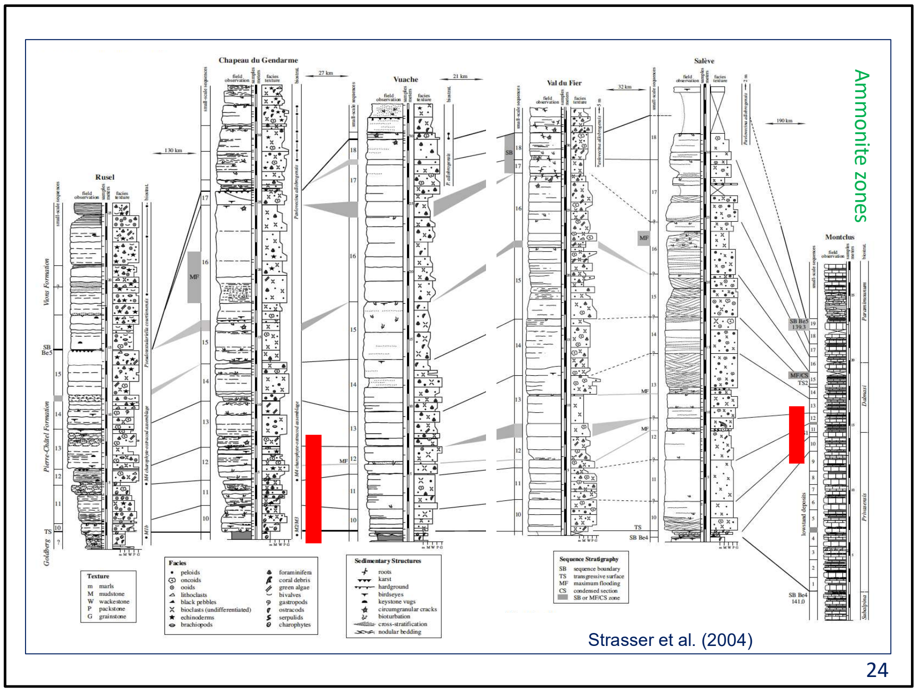


In this example of the Berriasian in the French Jura Mountains, Alex Waehry has looked at closely-spaced thin-sections. In the 7.5 m section shown here, facies evolution goes from charophyte-bearing freshwater marls to marine limestones with echinoderms and back to freshwater marls, defining a first bundle composed of 3 individual beds. This is repeated a second time with a bundle of 5 beds. The third bundle of 5 beds ends with birdseyes indicating intertidal conditions. It is directly followed by reworked pebbles and by circumgranular cracks suggesting subaerial exposure.



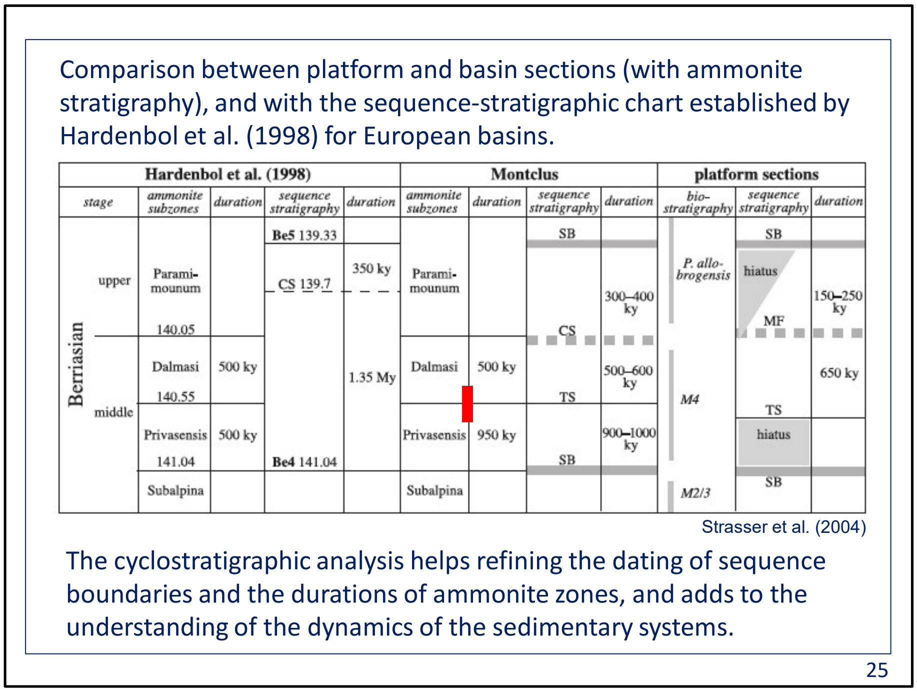
Based on the facies analysis, the depositional environments can be interpreted. They range from lacustrine mudflat to tidal flat to lagoon.

In sequence-stratigraphic terms, the sharp basal surface of each bundle is interpreted as a sequence boundary directly overlain by a transgressive surface (SB/TS), and the relatively deepest water with fully marine fossils represents maximum-flooding conditions (MF). Each bed is interpreted as an elementary sequence (the smallest unit that can be defined), separated from the following one by a thin marly layer. The bundles are called small-scale sequences.



By lateral correlation with other platform sections, it is seen that facies vary but that the stacking pattern is consistent.

By correlation with a hemipelagic section in the Vocontian Basin where ammonite stratigraphy is well established, the studied interval (red bars) can now be placed into a narrow chronostratigraphic framework. This implies that the elementary sequences (in this case the individual beds) formed in tune with the orbital precession cycle of 20 kyr, and that the small-scale sequences correspond to the short eccentricity cycle of 100 kyr.



This figure shows a comparison of the sequence- and cyclostratigraphic analyses of the studied Berriasian platform sections with the time-equivalent basinal section of Montclus. The ammonite zones there are well established and allow correlation with the chart of Hardenbol et al. (1998), which attributes numerical ages to sequence boundaries (Be4 and Be5), condensed sections (CS), and boundaries of ammonite zones. The interval discussed in the previous slides is shown in red. Cyclostratigraphy gives us estimates of the duration between these numerical dates. It is seen that in some cases the correspondence is quite good, while in other cases there are discrepancies. This may be due to the error margins inherent in radiometric dating, to misinterpretation of the cyclical record, and/or to the presence of hiatuses of unknow duration. Nevertheless, the total duration between sequence boundaries Be4 and Be5 is comparable: 1.7 Myr in Hardenbol et al. versus 1.7 – 2 Myr in our study. The fact that the condensed sections respectively the maximum flooding (MF) do not correspond is explained by the different sedimentary systems: different platforms and different basins did not react in the same way to the rapid sea-level rise, and the diagnostic intervals or surfaces did not form at the same time.
Thus, the cyclostratigraphic analysis helps refining the dating of sequence boundaries and the durations of ammonite zones, and adds to the understanding of the dynamics of the sedimentary systems.

Platform to basin correlation: Helps to improve biostratigraphic and chronostratigraphic control, and to understand the processes in the formation of the cyclical deposits in the basin.

Berriasian, Chapeau du Gendarme, France

Berriasian, Montclus, France

26

So, platform-to-basin correlation helps to improve biostratigraphic and chronostratigraphic control, but also to understand the processes in the formation of the cyclical deposits in the basin. While spectral analyses of the cyclical deposits in the basin point to a control by orbital cycles, the processes for the formation of limestone-marl alternations and their relationship to platform sequences are not always clear.

The clays that lead to the marly joints between the limestone beds on the platform as well as to the marly interbeds in the basin stem from the hinterland, and their input is controlled by climate and sea level. Before they reach the basin, they transit across the platform and may be delayed. Thus, marls in the basin are not necessarily isochronous to marls on the platform.

The limestones on the platform commonly form during transgression and sea-level highstand. Carbonate mud is exported from the platform to the basin during sea-level highstands (highstand shedding). The limestone beds in the basin are composed partly of such mud but also of planktonic organisms, which bloom when upwelling or run-off from the hinterland furnish nutrients.

At sea-level lowstands, loose sediment may be washed into the basin through canyons (lowstand flushing).

Conclusion: there is no simple rule, and each case has to be analysed by itself.

See also Martinez (2018)

27

The clays that lead to the marly joints between the limestone beds on the platform as well as to the marly interbeds in the basin stem from the hinterland, and their input is controlled by climate and sea level. Before they reach the basin, they transit across the platform and may be delayed. Thus, marls in the basin are not necessarily isochronous to marls on the platform.

The limestones on the platform commonly form during transgression and sea-level highstand. Carbonate mud is exported from the platform to the basin during sea-level highstands (highstand shedding). The limestone beds in the basin are composed partly of such mud but also of planktonic organisms, which bloom when upwelling or run-off from the hinterland furnish nutrients.

At sea-level lowstands, loose sediment can be washed from the platform into the basin through canyons (which is called lowstand flushing).

Conclusion: there is no simple rule, and each case has to be analysed independently.

The hypothesis:

If it can be shown that the formation of a depositional sequence was controlled mainly by climate and sea-level changes, and if it can be demonstrated that these changes were in tune with orbitally-controlled insolation changes, then a time-frame is available to interpret these sequences with a time-resolution of 20 kyr.

28

After this general introduction to the functioning of a carbonate platform and to the controlling parameters, a hypothesis can be proposed that will allow to go deeper into the details:

If it can be shown that the formation of a depositional sequence was controlled mainly by climate and sea-level changes, and if it can be demonstrated that these changes were in tune with orbitally-controlled insolation changes, then a time-frame is available to interpret these sequences with a time-resolution of 20 kyr.

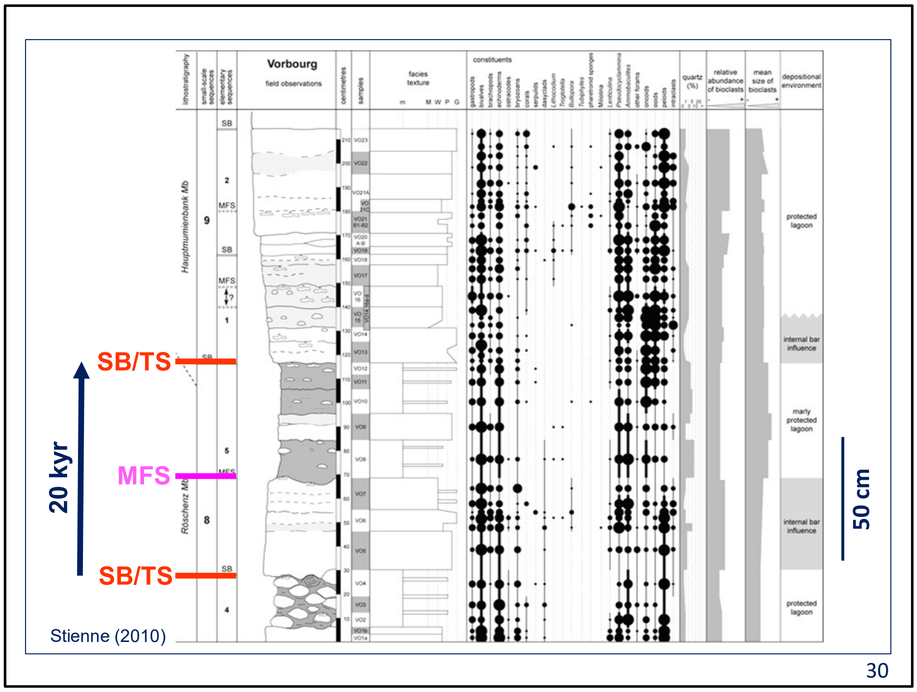
Two case studies will demonstrate this potential.

Case study 1: the Oxfordian of the Swiss Jura

Voyeboeuf section (Jura, Switzerland) hammer for scale

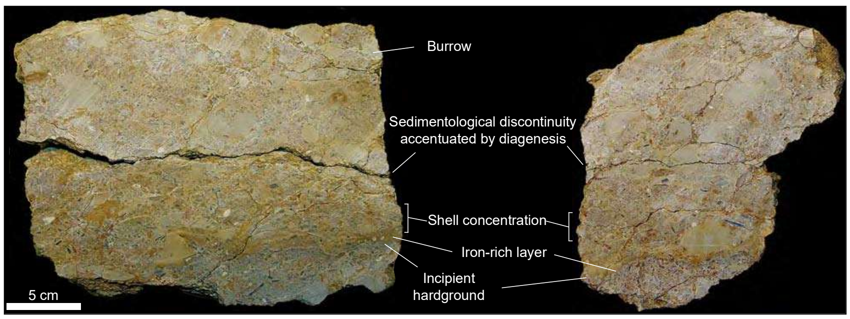
29

The first case study concerns the Oxfordian in the Swiss Jura. In this outcrop, well stratified limestone beds formed in a shallow-marine lagoon. Detailed facies analysis, lateral correlation with other sections, and chronostratigraphy imply that one bed corresponds to the 20-kyr precession cycle. This is one of the results of Noémie Stienne’s PhD thesis.



In this 2.1 m thick section, Noémie has taken 100% samples as polished slabs and thin-sections and analysed the microfacies in great detail. We will focus on an interval between two sequence boundaries (SB), which are directly overlain by transgressive surfaces that installed limestones above marls. The bioturbated top of the first limestone bed is interpreted as the maximum-flooding surface. Lateral correlation and the chronostratigraphic framework tell us that this elementary sequence formed in tune with the 20-kr orbital precession cycle.

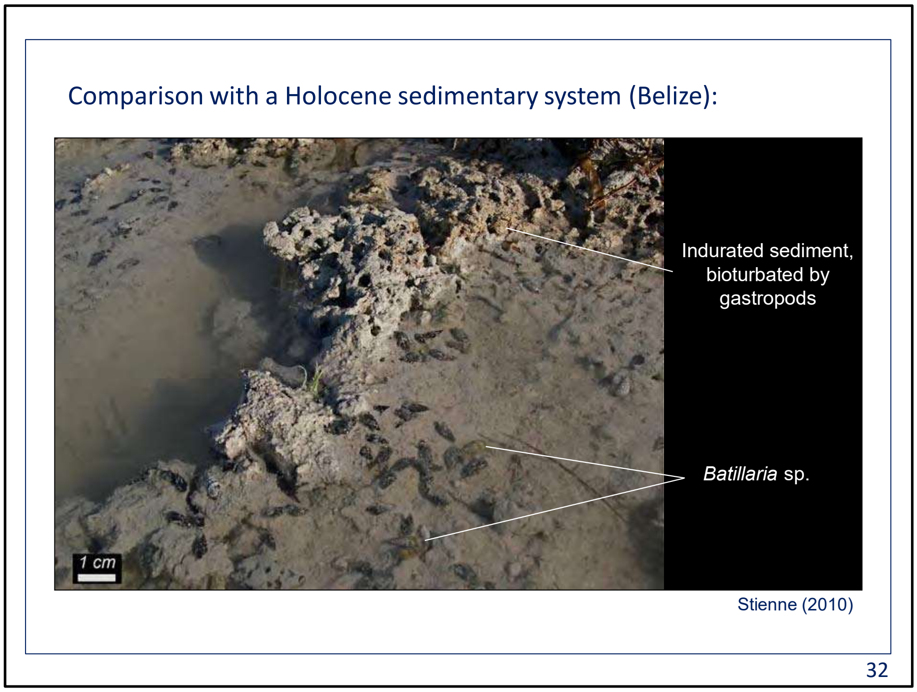
Highly variable sedimentation rates: rapid for shell accumulations, slow for bioturbation, zero for hardground formation.
Also, previously consolidated sediment has been reworked.



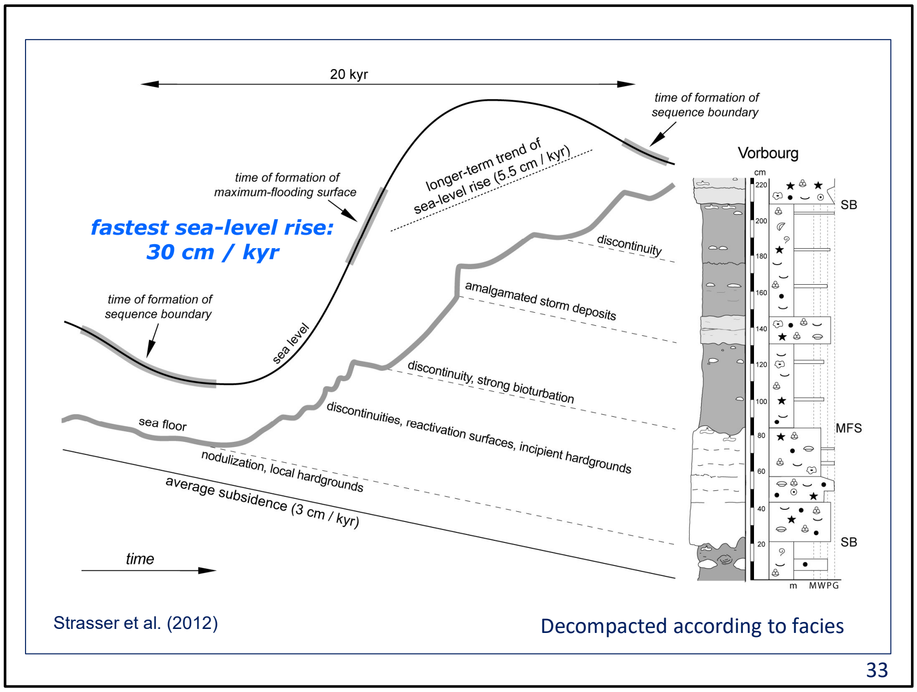
Stienne (2010)

31

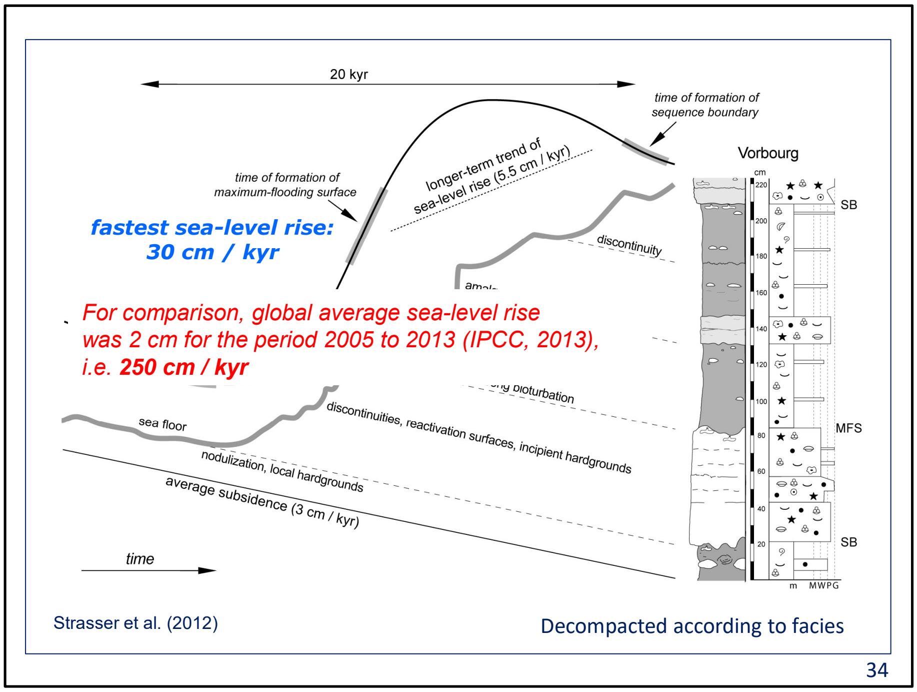
Sedimentation rates were variable: Incipient hardgrounds, here underlined by reddish colour, indicate a break in sedimentation and a beginning of cementation. Intense bioturbation suggests that the same sediment was inhabited by several generations of burrowing organisms. Shell layers point to rapid deposition by storms, or to winnowing by waves and currents. The presence of lithoclasts implies that sediment has been cemented and then was reworked. So, in this 20 cm thick limestone layer, a very complex history has been recorded.



Incipient hardgrounds can be found in the Recent, such as here in Belize: carbonate mud is bioturbated by gastropods, and microbial mats stabilize it for early cementation. Such comparative sedimentology is helpful as it allows to appreciate processes and their timing.



To reconstruct the story of the whole sequence, the rock record first has to be decompacted according to facies (grainstones by a factor of 1.2, packstones 1.5, wackestones 2, and marls by a factor of 3). Subsidence rate is the average of the Jura mountains during the Oxfordian, and sea level is assumed to have been symmetrical, in tune with the 20-kyr precession cycle. In order to accommodate the decompacted sequence, a longer-term trend of sea-level rise of 5.5 cm / kyr must be postulated. The interpretation of the evolution of the seafloor through time is based on the observed features: no or slow accumulation to form the hardgrounds and discontinuities, fast accumulation in the case of a storm deposit. According to the facies, water depth was not more that a few metres. The limestone-dominated lower part of the sequence formed during transgression when terrigenous siliciclastic input was reduced, while the marly upper part corresponds to the highstand when siliciclastics prograded. Furthermore, climate was more humid during sea-level highstands, favouring terrigenous run-off. Even if this interpretation is only tentative, it shows that the fastest sea-level rise (corresponding to the bioturbated surface at the turn-around from transgression to regression) was about 30 cm /kyr.



This looks quite fast on this graph, but it is slow when compared to today's rate of average sea-level rise: 2 cm for the period of 2005 to 2013, i.e. 250 cm / kyr.
This comparison between Oxfordian greenhouse times and Recent interglacial times is interesting and makes us think about the effects of anthropogenically induced global warming and associated sea-level rise.

Case study 2:
The Berriasian of the French Jura

Berriasian, Salève, France

35

The second case study is from the Berriasian of Mount Salève, close to Geneva but situated in France. Shallow-lagoonal and peritidal facies are nicely stacked: elementary sequences (the beds seen here), small-scale sequences (the bundles), and medium-scale sequences (the thinning-up then thickening-up trend). Our cyclostratigraphic analysis suggests that the individual beds formed under the influence of the precession cycle. The small- and medium-scale sequences were controlled by the short and long eccentricity cycles, respectively.
The red arrow points to the outcrop analysed in the next slide.

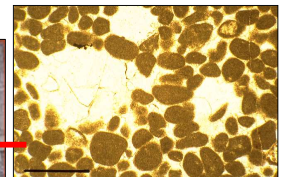
Sequence boundary zone Be 2

Salève section (Jura, France) Bover-Arnal & Strasser (2013)

36

This complex outcrop is interpreted as a large-scale sequence-boundary zone, which has also been recognized in other basins of the Tethys Ocean.

Mudflats, ooid shoals, and beaches:



Keystone vugs

Desiccation polygons

37

Mudstones with birdseyes (formed on a tidal flat) at the bottom of the outcrop are topped by desiccation polygons. After a thin marly interval follow grainstones with ooids and peloids. Birectional sedimentary structures indicate tidal currents. Keystone vugs (air bubbles caught between the grains) indicate a beach.

Beachrock:

Joulters Cays, Bahamas

Beachrock forms in a few 100 to a few 1000 years

(Strasser et al. 1989)

38

The grainstone is broken into slabs, which represent beachrock as it occurs today in the Bahamas. Beachrock forms in the intertidal zone below the beach surface, and cementation is very fast due to tidal pumping and evaporation in a zone of mixed fresh and marine waters. This can occur within a few hundred to a few thousand years. Exposed on the beach, the cemented layer then breaks into slabs.

In the Florida Keys, calcrete grows 0.25 – 0.5 cm in 1000 years
(Robbin & Stipp 1979)

→ 4 cm formed in 8000 to 16’000 years of subaerial exposure

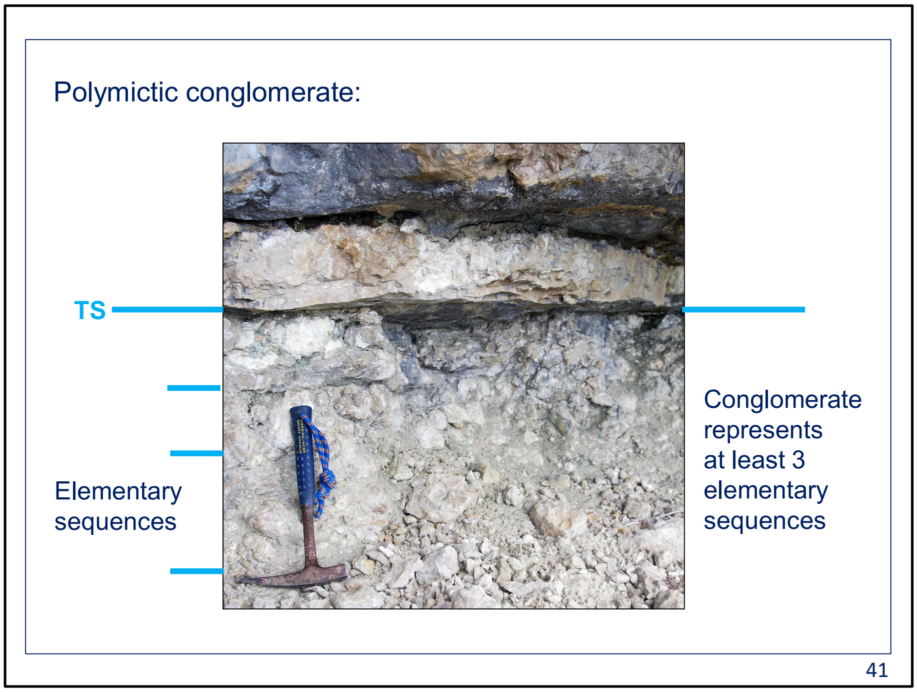
The beachrock is capped by a 4-cm thick calcrete crust, indicating subaerial exposure in a Mediterranean climate. Above then follows a polymictic conglomerate, composed of pebbles of various facies.
In the Florida Keys, calcrete grows 0.25 – 0.5 cm in a thousand years, meaning that the 4 cm seen here imply 8000 to 16’000 years of subaerial exposure.

Sequence boundary zone Be 2

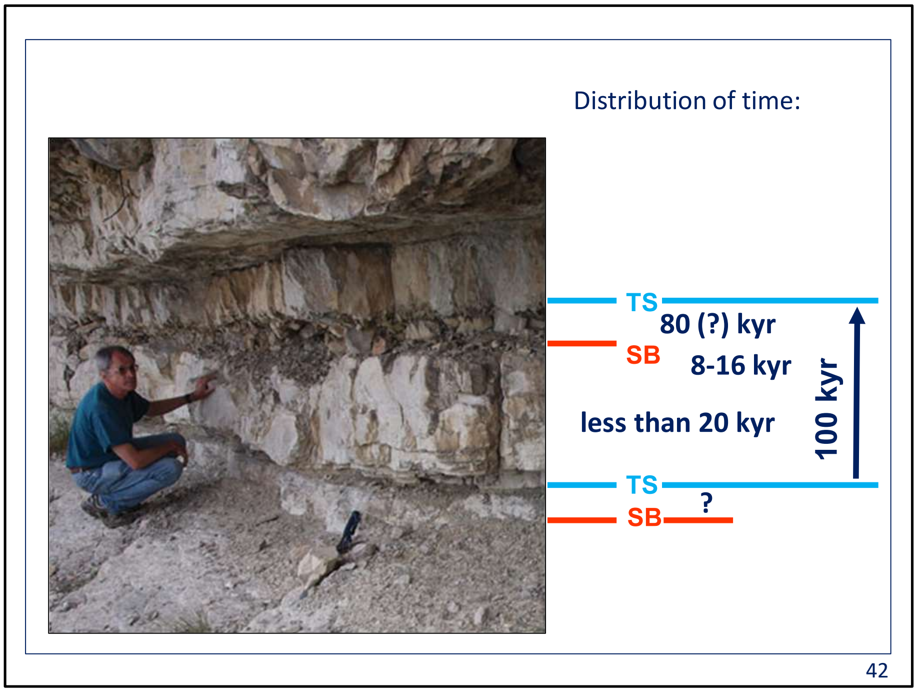
Salève section (Jura, France) Bover-Arnal & Strasser (2013)

40

Coming back to this picture, we interpret the surface with the desiccation polygons as a sequence boundary, and also the calcrete represents a sequence boundary. The base of the oolitic grainstone is a transgressive surface, as is the base of the limestone above the conglomerate.
The cyclostratigraphic analysis suggests that the time interval between the two transgressive surfaces represents 100 kyr.
Apparently, much time has not been recorded, but where is it missing ?



In a similar outcrop, at least three elementary (20 kyr) sequences were dismantled and reworked into a polymictic conglomerate. The history of 60 kyr thus is lost.



The distribution of time in the 100-kyr interval between the two transgressive surfaces can now be interpreted as follows:
Rapid deposition of an ooid shoal but then a few 100 to a few 1000 years for cementation and breaking up into beachrock.
8000 to 16’000 years were needed for the formation of the calcrete crust. The deposition of the beachrock bed and the calcrete crust could easily have formed within one 20-kyr cycle, making it an elementary sequence. The following sea-level cycles then created space to produce and accumulate sediment, but each time this sediment was cemented and reworked into pebbles. Up to 4 elementary sequences, i.e. 4 times 20 kyr, may thus be condensed in the polymictic conglomerate.

First conclusions:

Detailed analysis of facies and sedimentary structures in ancient shallow-marine carbonate sequences allows reconstructing the depositional environments.

If the evolution of these environments was at least partly controlled by sea-level changes, a sequence-stratigraphic interpretation can be made that will underline the dynamics of the system.

If a cyclostratigraphic analysis can be made, a time-resolution of 20 kyr can be obtained.

The processes can then be compared with processes observed and quantified in the Holocene and today, and this at comparable time-scales.

43

After these two case studies, some first conclusions can be drawn:

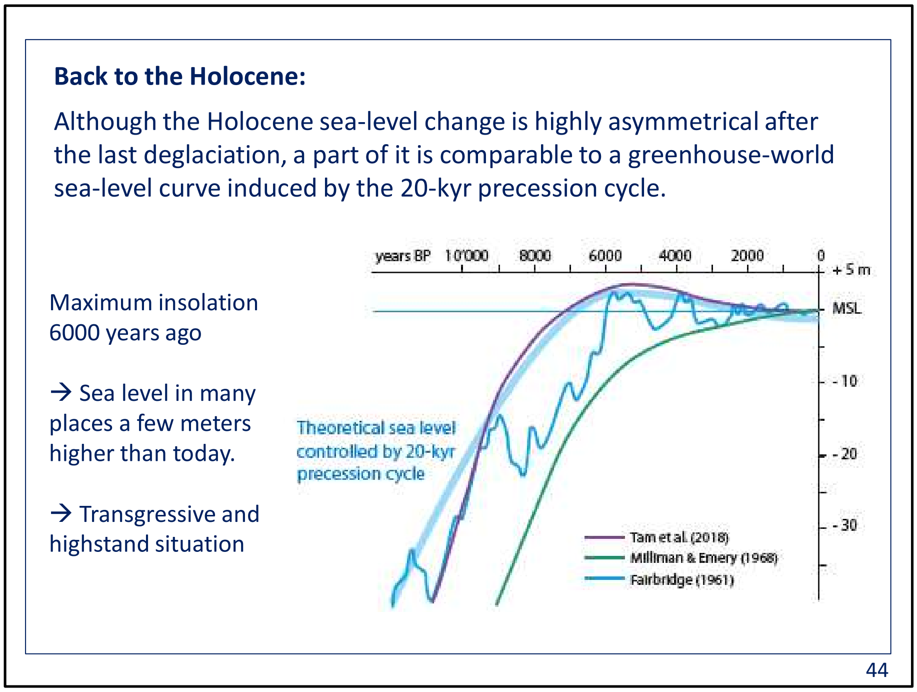
Detailed analysis of facies and sedimentary structures in ancient shallow-marine carbonate sequences allows reconstructing the depositional environments.

If the evolution of these environments was at least partly controlled by sea-level changes, a sequence-stratigraphic interpretation can be made that will underline the dynamics of the system.

If a cyclostratigraphic analysis can be made, a time-resolution of 20 kyr can be obtained.

The processes can then be compared with processes observed and quantified in the Holocene and today, and this at comparable time-scales.

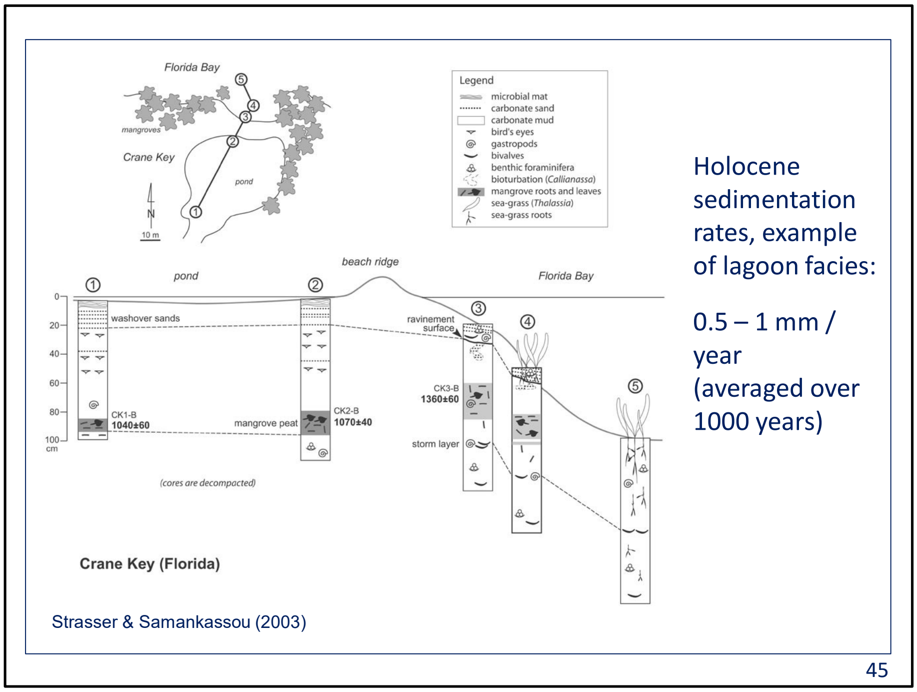
Comparable time-scales: how can we claim this?



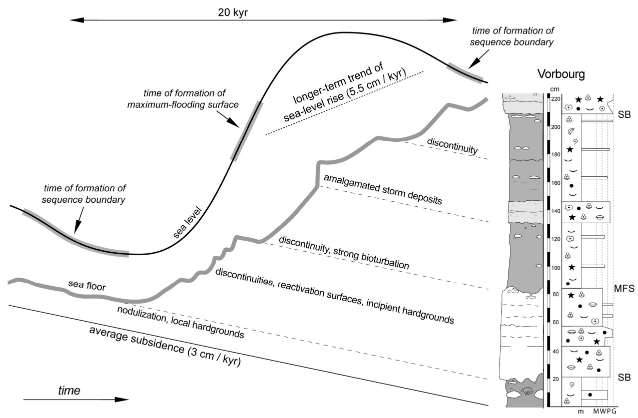
Although the Holocene sea-level change is highly asymmetrical after the last deglaciation, a part of it is comparable to a greenhouse-world sea-level curve induced by the 20-kyr precession cycle.

In most oceans, about 6000 years ago, average sea level was a few metres higher than today. This corresponds to the insolation maximum of the precession cycle.

Looking at the theoretical sea-level curve of the last 8000 years, it is close to the second part of a full 20-kyr sea-level cycle, with a meter-scale amplitude like in a Jurassic or Cretaceous greenhouse world. When the subaerially exposed platforms were flooded after the last deglaciation, the first deposits were mangrove peats and lags of reworked material, followed by transgressive, then highstand deposits. Thus, a direct comparison with ancient sequences becomes possible, at comparable time-scales.



As a reminder, here again the slide from the Holocene of Florida Bay: lateral facies changes and erosion surfaces like in the fossil sequences. Sedimentation rates here are estimated at 0.5 – 1 mm per year, averaged over a time-interval of 1000 years.



Decompacted according to facies

Strasser et al. (2012)

Oxfordian sedimentation rates, example of lagoon facies:
ca. 2 m in 20 kyr → 0.1 mm /year (averaged over 20’000 years)
→ Time is taken up in hiatuses and condensations

46

In the Oxfordian example, 2 m (= 2000 mm) were laid down in 20’000 years, giving us 0.1 mm per year, but here averaged over a much longer time-interval. Hiatuses and condensations in the Oxfordian example can easily explain this apparent discrepancy.

Final conclusion:

Through detailed cyclostratigraphic analysis, time-windows can be opened in the fossil record.

The evolution of the ecosystems of carbonate-producing organisms, processes of sediment distribution and diagenesis, and ancient carbonate sediment accumulation rates can be compared with Holocene ones.

Thus, a dynamic picture of ancient sedimentary systems can be created.

Joulters Cays, Bahamas

47

Here we come to the final conclusion:
Through detailed cyclostratigraphic analysis, time-windows can be opened in the fossil record. The evolution of the ecosystems of carbonate-producing organisms, processes of sediment distribution and diagenesis, and ancient carbonate sediment accumulation rates can be compared with Holocene ones.
We can now much more directly and realistically interpret our ancient sedimentary systems, and envisage dynamic carbonate platforms such as this one in the Bahamas.

Acknowledgements

This work would not have been possible without the help of my MSc and PhD students and post-docs. They did much of the fieldwork and the facies analyses, and contributed to develop the concepts. For this presentation, I specifically thank Alex Waehry, Noémie Stienne, Telm Bover-Arnal, and Elias Samankassou.

The financial support of the Swiss National Science Foundation is gratefully acknowledged.

Finally, I thank www.cyclostratigraphy.org for having invited me to prepare this CIP lecture.

48

Acknowledgements: This work would not have been possible without the help of my MSc and PhD students and post-docs. They did much of the fieldwork and the facies analyses, and contributed to develop the concepts. For this presentation, I specifically thank Alex Waehry, Noémie Stienne, Telm Bover-Arnal, and Elias Samankassou.
The financial support of the Swiss National Science Foundation is gratefully acknowledged.
Finally, I thank the cyclostratigraphy.org project for having invited me to prepare this CIP lecture.

References:

Bak, R.P.M., Nieuwland, G., Meesters, E.H. (2009). Coral growth rates revisited after 31 years : what is causing lower extension rates in *Acropora palmata*? Bull. Marine Science 84, 287-294.

Berger, A., Loutre, M.F., Dehant, V. (1989). Astronomical frequencies for pre-Quaternary palaeoclimate studies. Terra Nova. 1, 474-479.

Berger, A., Loutre, M.F., Laskar, J. (1992). Stability of the astronomical frequencies over the Earth's history for paleoclimate studies. Science 255, 560-566.

Bover-Arnal, T., Strasser, A. (2013). Relative sea-level change, climate, and sequence boundaries: insights from the Kimmeridgian to Berriasian platform carbonates of Mount Salève (E France). Int. J. Earth Sci. 102, 493-515.

Fairbridge, R. (1961). Convergence of evidence on climatic change and ice ages. Ann. New York Acad. Sci. 95, 542-579.

Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., De Graciansky, P.-C., Vail, P.R. (1998). Charts, in de Graciansky, P.-C., Hardenbol, J.,Jacquin, T., and Vail, P.R., eds., Mesozoic and Cenozoic SequenceStratigraphy of European Basins: SEPM, Special Publication 60.

Hinnov, L.A. (2018). Cyclostratigraphy and astrochronology in 2018. In: Montenari, M. (ed.) Stratigraphy and Timescales, Volume 3, Elsevier, 1-80.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B. (2004). A long-term numerical solution for the insolation quantities of the Earth. A.&A. 428, 261-285.

Martinez, M. (2018). Mechanisms of preservation of the eccentricity and longer-term Milankovitch cycles in detrital supply and carbonate production in hemipelagic marl-limestone alternations. In: Montenari, M. (ed.) Stratigraphy and Timescales, Volume 3, Elsevier, 189-218.

Martinez, M., Deconinck, J.-F., Pellenard, P., Riquier, L., Company, M., Reboulet, S., Moiroud, M. (2015). Astrochronology of the Valanginian-Hauterivian stages (early Cretaceous): Chronological relationships between the Parana-Etendeka large igneous province and the Weissert and Faraoni events. Glob. Planet. Change 131, 158-173.

Milliman, J.D., Emery, K.O. (1968). Sea levels during the past 35000 years. Science 162, 1121-1123.

Robbin, D.M., Stipp, J.J. (1979). Depositional rate of laminated soilstone crusts, Florida Keys. J. sed. Petrol. 49, 175-180.

References (cont.):

Sames, B., Wagreich, M., Wendler, J.E., Haq, B.U., Conrad, C.P. , Melinte-Dobrinescu, M.C., Hu, X., Wendler, I., Wolfgring, E., Yilmaz, I.Ö., Zorina, S.O. (2016). Review: Short-term sea-level changes in a greenhouse world – a view from the Cretaceous. Palaeogeo., Palaeclim., Palaeoeco. 441, SI, 393-411.

Shinn, E.A. (1966). Coral growth-rate, an environmental indicator. J. Paleontol. 40, 233-240.

Stienne, N. (2010). Paléoécologie et taphonomie comparative en milieux carbonatés peu profonds (Oxfordien du Jura suisse et Holocène du Belize). GeoFocus 22, 248 pp

Strasser, A. (1994) Milankovitch cyclicity and high-resolution sequence stratigraphy in lagoonal – peritidal carbonates (Upper Tithonian – Lower Berriasian, French Jura Mountains). Spec. Publs. Int. Ass. Sediment. 19, 285 –301.

Strasser, A. (2015). Hiatuses and condensation: an estimation of time lost on a shallow carbonate platform. Depositional Record 1, 91-117.

Strasser, A. (2018). Cyclostratigraphy of shallow-marine carbonates – limitations and opportunities. In: Montenari, M. (ed.) Stratigraphy and Timescales, Volume 3, Elsevier, 151-187.

Strasser, A., Hilgen, F.J., Heckel, P.H. (2006). Cyclostratigraphy – concepts, definitions, and applications. Newsl. Stratigraphy 42, 75-114.

Strasser, A., Hillgärtner, H., Pasquier, J.-B. (2004). Cyclostratigraphic timing of sedimentary processes: an example from the Berriasian of the Swiss and French Jura Mountains. SEPM Spec. Publ. 81, 135-151.

Strasser, A., Davaud, E., Jedoui, Y. (1989). Carbonate cements in Holocene beachrock: example from Bahiret el Biban, southeastern Tunisia. Sed. Geol. 62, 89-100.

Strasser, A., Samankassou, E. (2003). Carbonate sedimentation rates today and in the past: Holocene of Florida Bay, Bahamas, and Bermuda vs. Upper Jurassic and Lower Cretaceous of the Jura Mountains (Switzerland and France). Geologia Croatica 56, 1-18.

Strasser, A., Védrine, S., Stienne, N. (2012). Rate and synchronicity of environmental changes on a shallow carbonate platform (Late Oxfordian, Swiss Jura Mountains). Sedimentology 59, 185-211.

Tam, C.-Y., Zong, Y., bin Hassan, K. et al. (2018). A below-the-present late Holocene relative sea level and the glacial isostatic adjustement during the Holocene in the Malay peninsula. Quat. Sci. Review 201, 206-222.