Paleo sea level changes: eustasy, tectonics, isostasy

Special thanks to

Dr. Alessio Rovere, MARUM, University of Bremen

SESSION 1

Eustatic sea level changes

The ‘classic’ definition of Eustasy

The term ‘eustasy’ was coined by the Austrian geologist Edward Suess in 1888 and derives from the ancient Greek words eu, ‘well’,and statikos ‘static, fixed’.

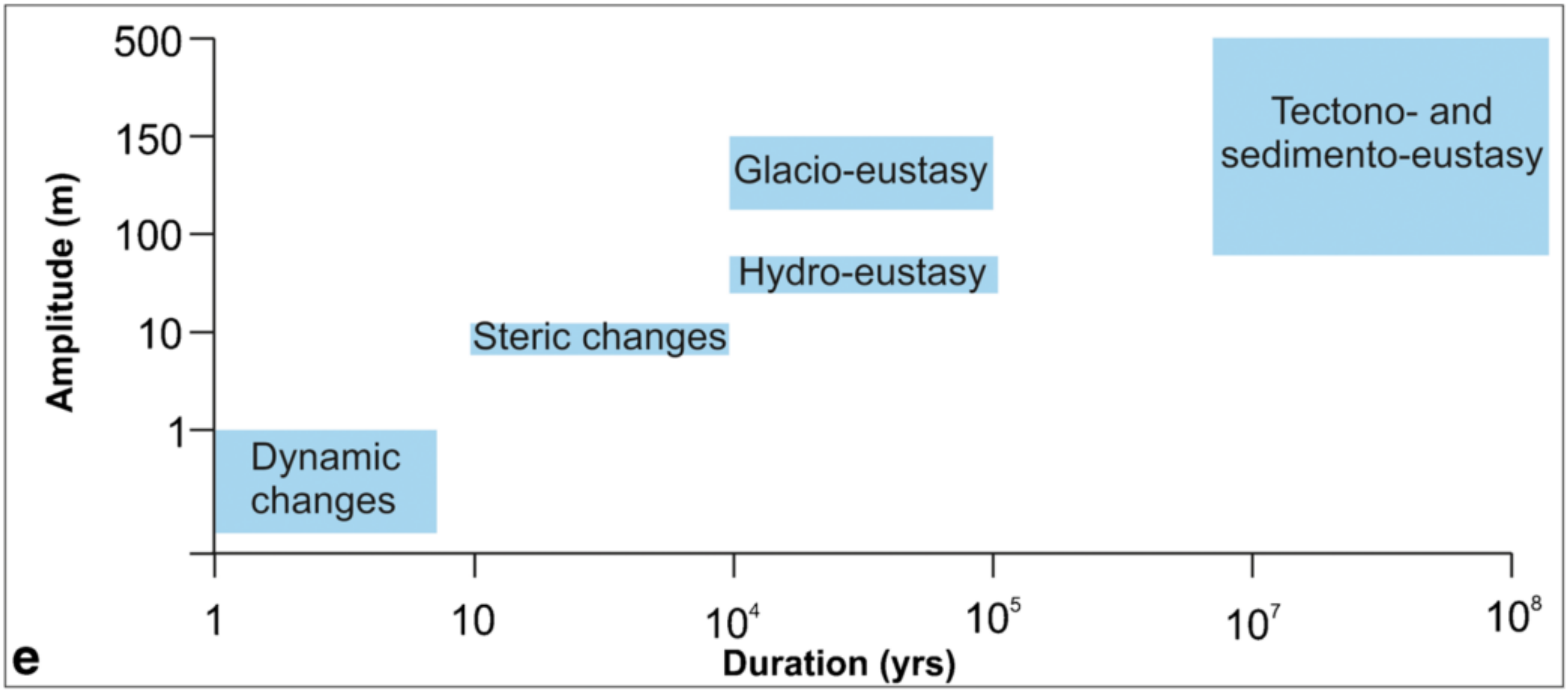
The original definition was introduced by Suess to explain the observation that sea level is characterized by transgression and regression phases that respectively inundate and expose continental shelves.

According to Suess's definition of eustasy, ocean mass variations following ice sheet fluctuations would result in global uniform mean sea level changes. This definition implies that the world's ocean basins are similar to a giant bathtub, with fixed borders represented by continents with sharp and steep boundaries.

Eustatic sea level (ESL) changes are driven by different processes that cause changes in the volume or mass of the world ocean and result in globally uniform mean sea level variations.

Can you think of a few? Discuss with your neighbour (2 min)

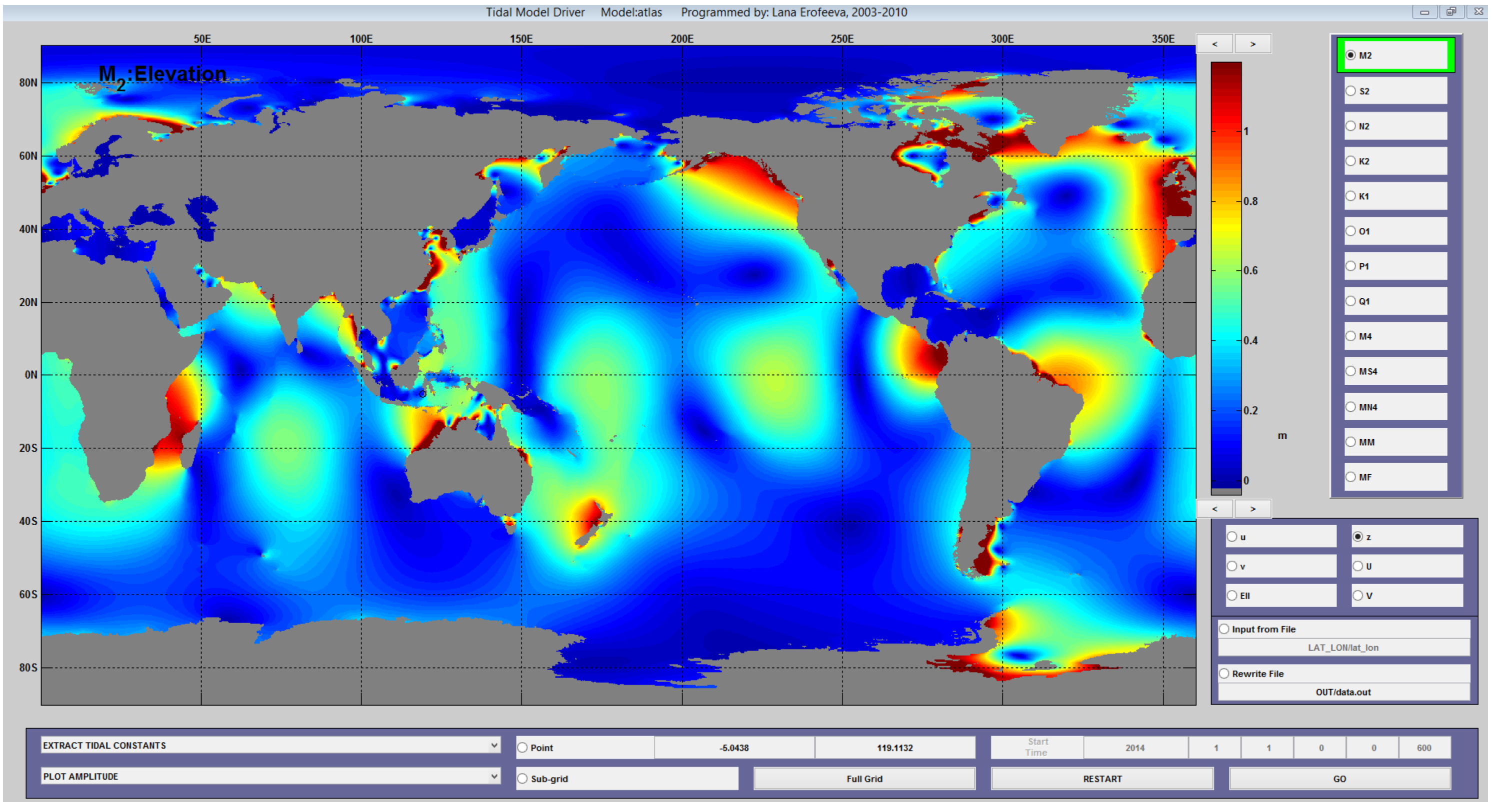
Eustatic sea level changes



Dynamic changes

Diurnal and semidiurnal astronomical tides

Period 12–24 h   Variation 0.2–10+ m



Long period tides

Amplitudes of a few centimeters or less and periods longer than one day, generated by changes in the Earth's orientation relative to the Sun, Moon, and Jupiter

Tidal prediction modelling
http://volkov.oce.orst.edu/tides/

Diurnal and semidiurnal astronomical tides

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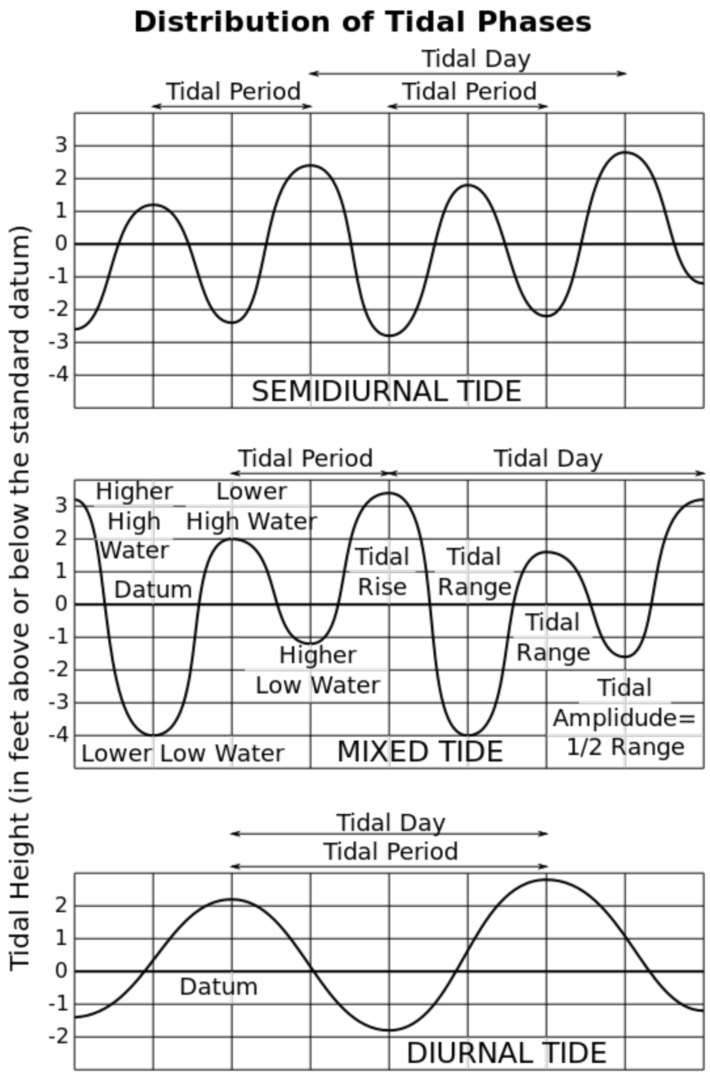
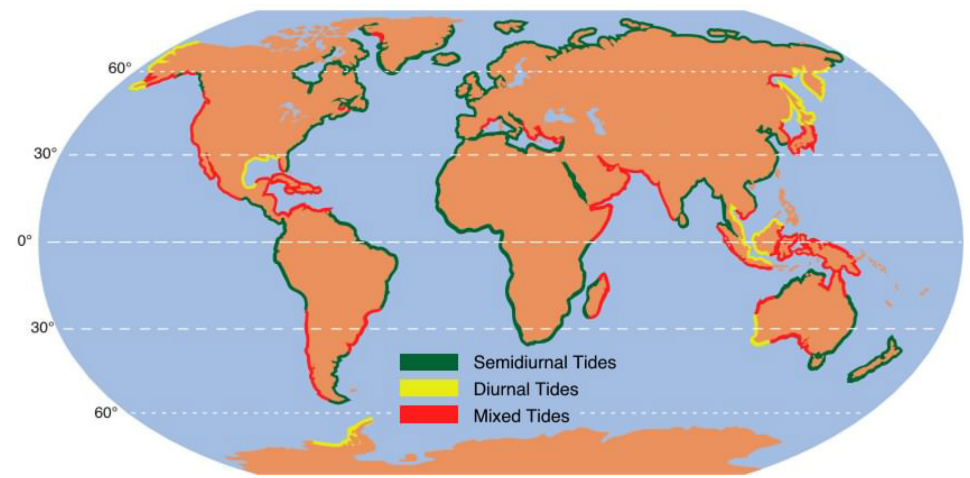
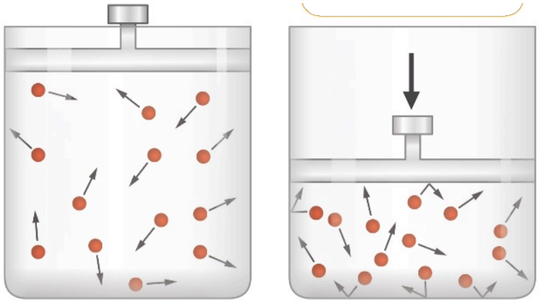




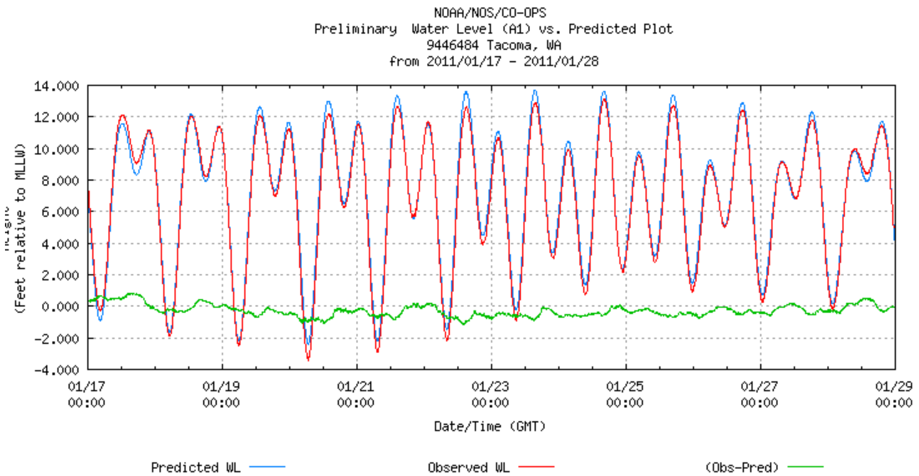
The same tidal forcing has different results depending on many factors, including coast orientation, continental shelf margin, water body dimensions.

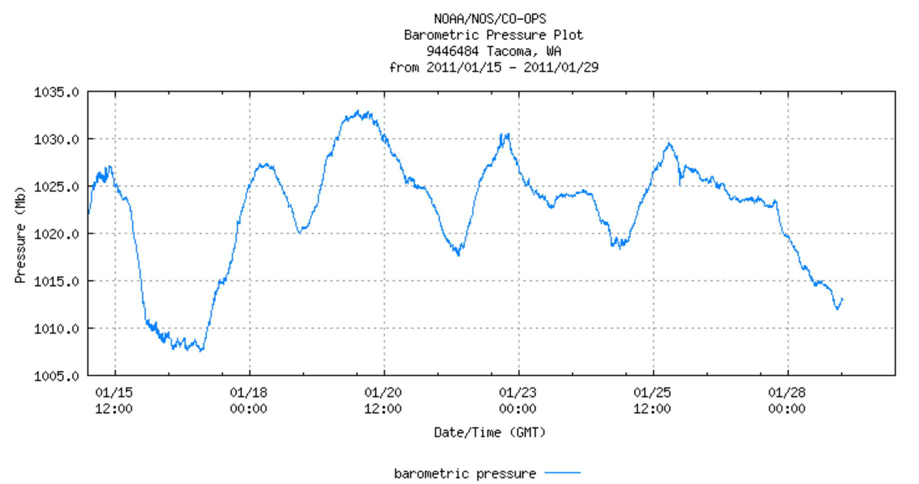
Dynamic changes



Atmospheric pressure

Period: hours to months Variation:−0.7 to

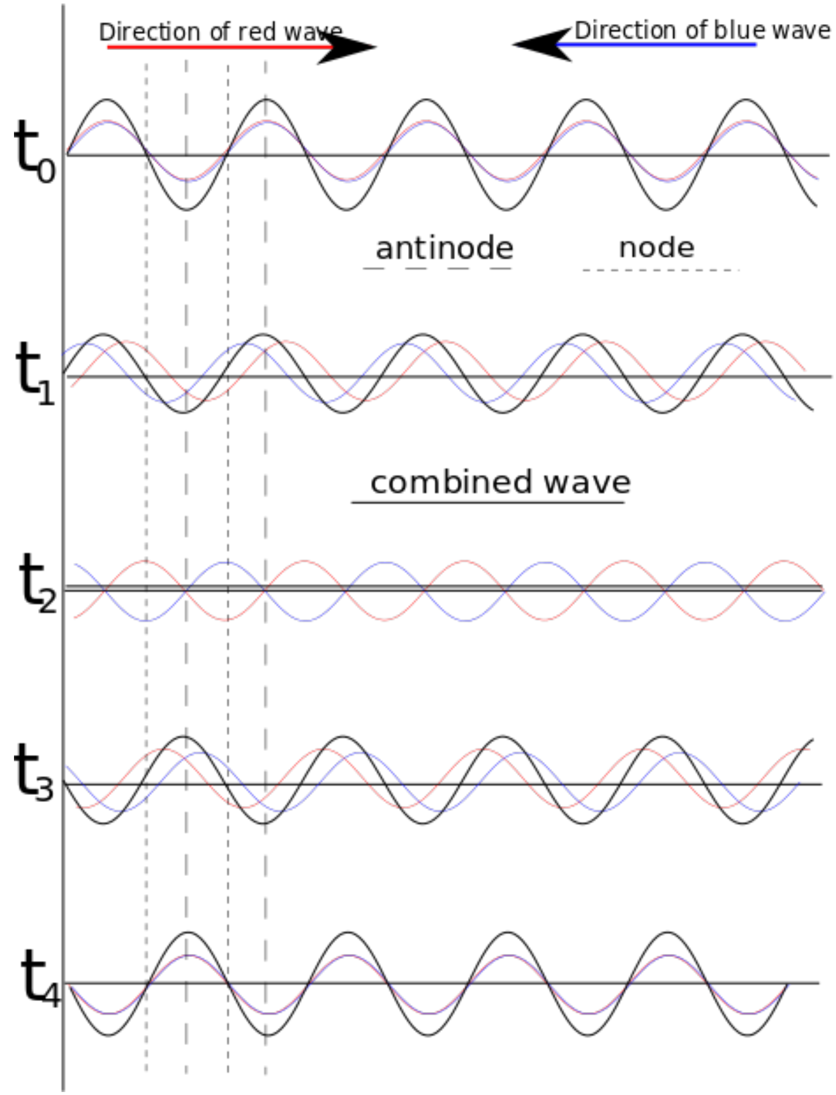




http://cses.washington.edu/

Seiches

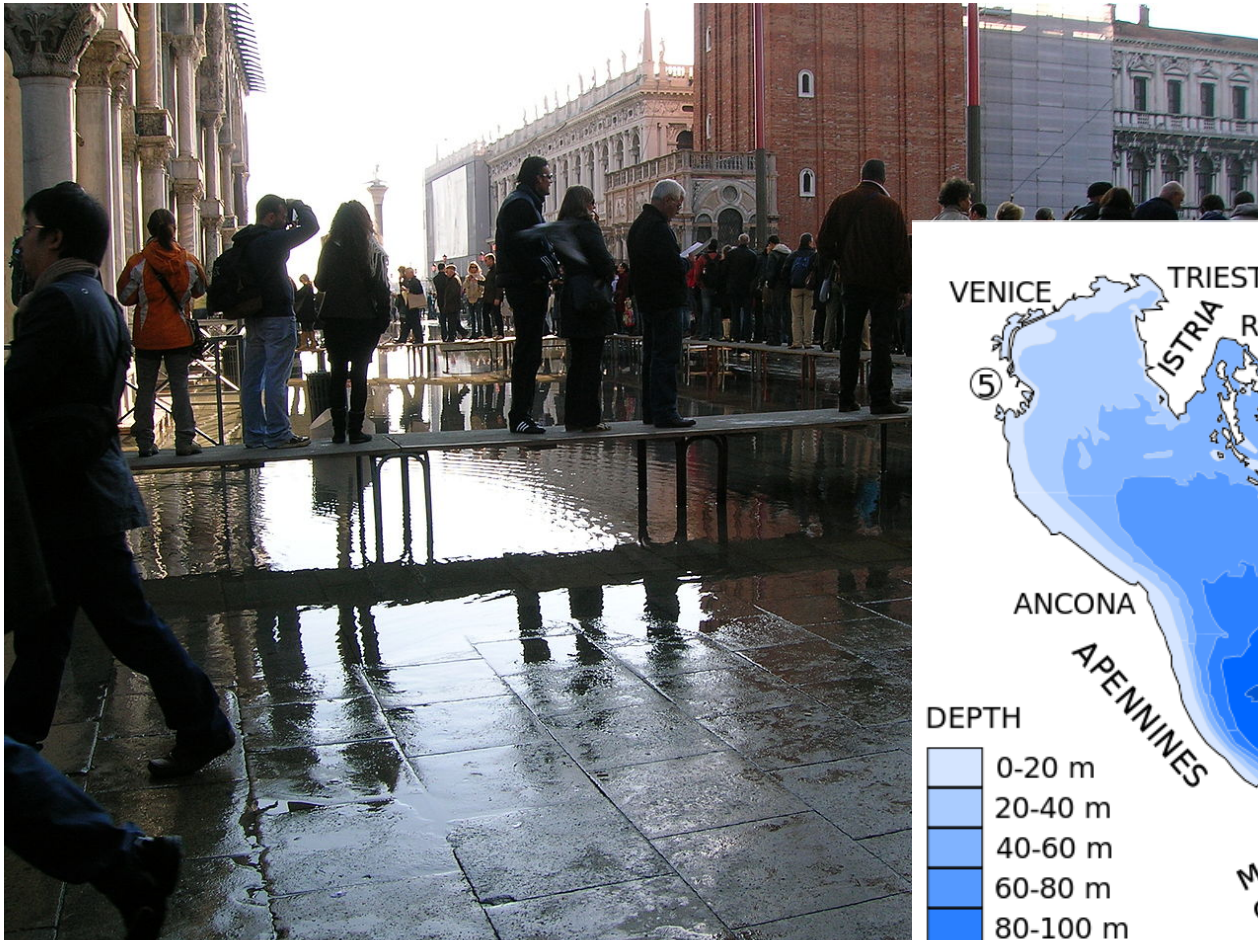
Standing waves up to 2m

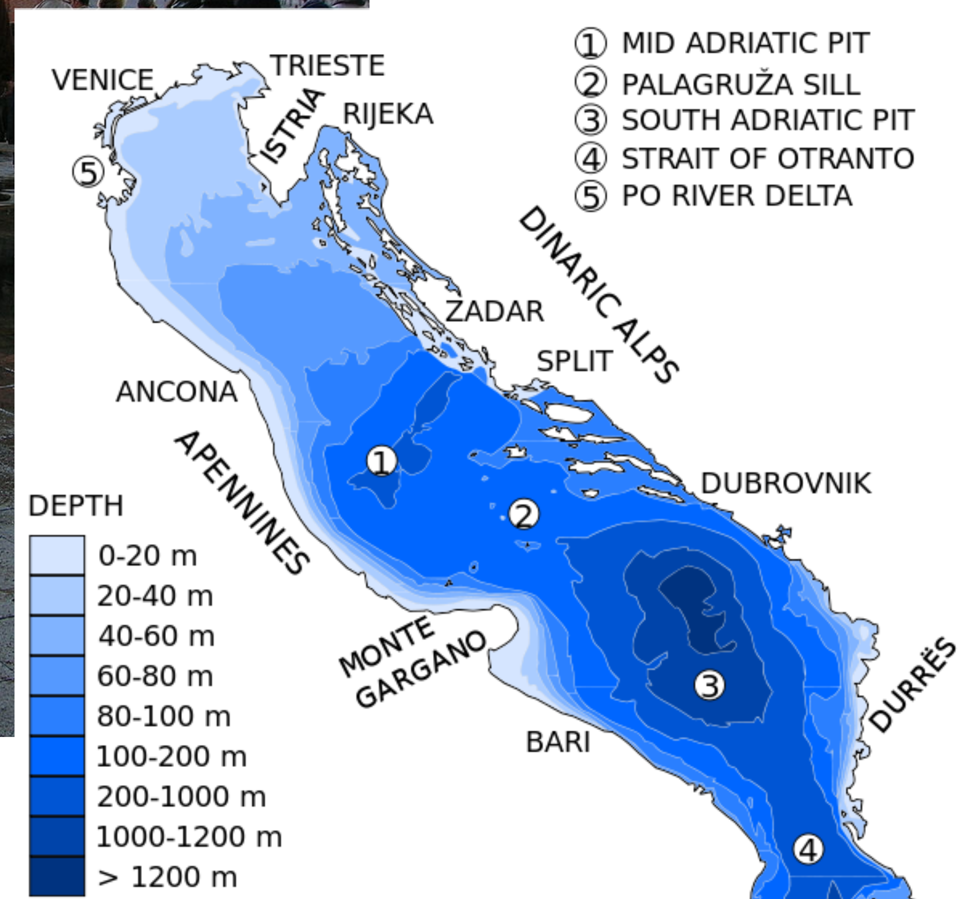


Dynamic changes

Seiches

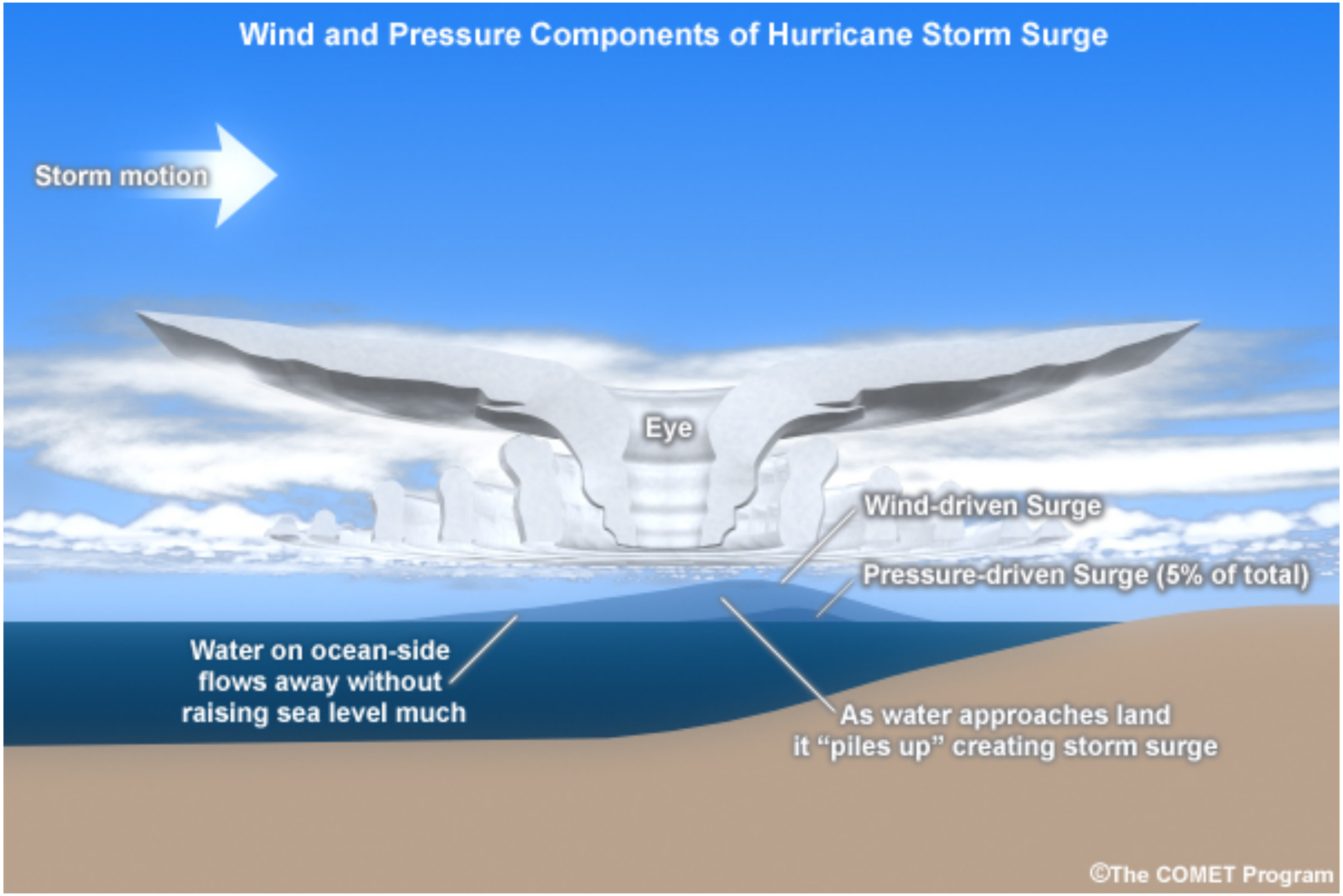
Standing waves up to 2m





Winds (storm surges)

Period 1–5 days   Variation up to 5 m



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Dynamic changes

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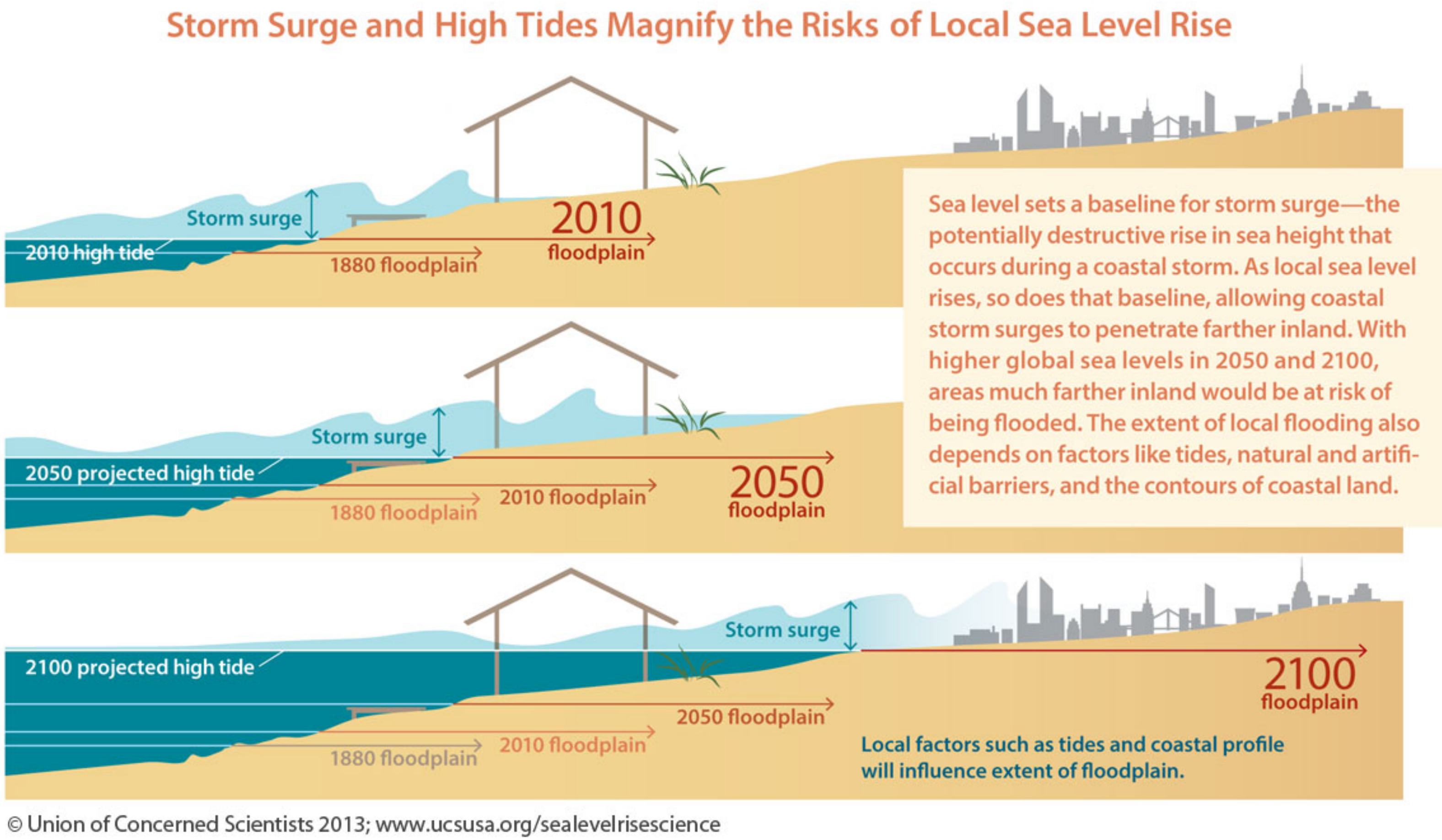


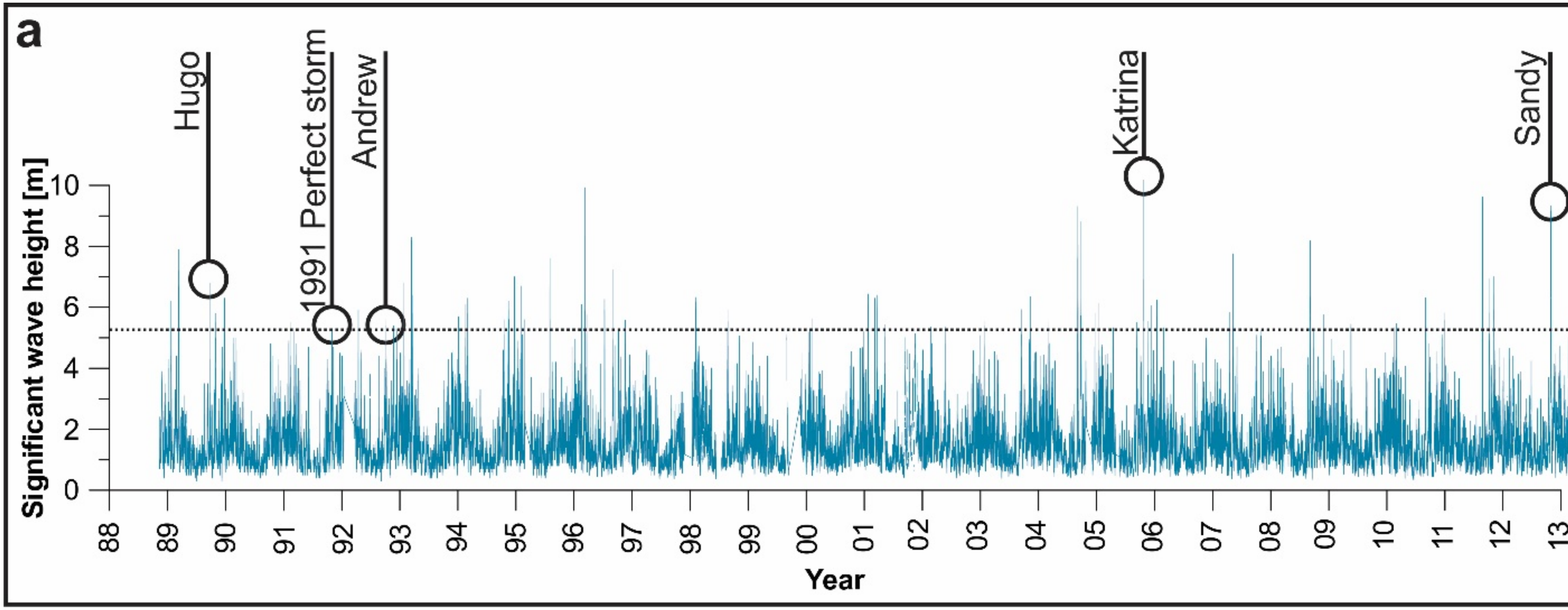
Dynamic changes

Waves

Period: days ***Variation up to…?***

Waves

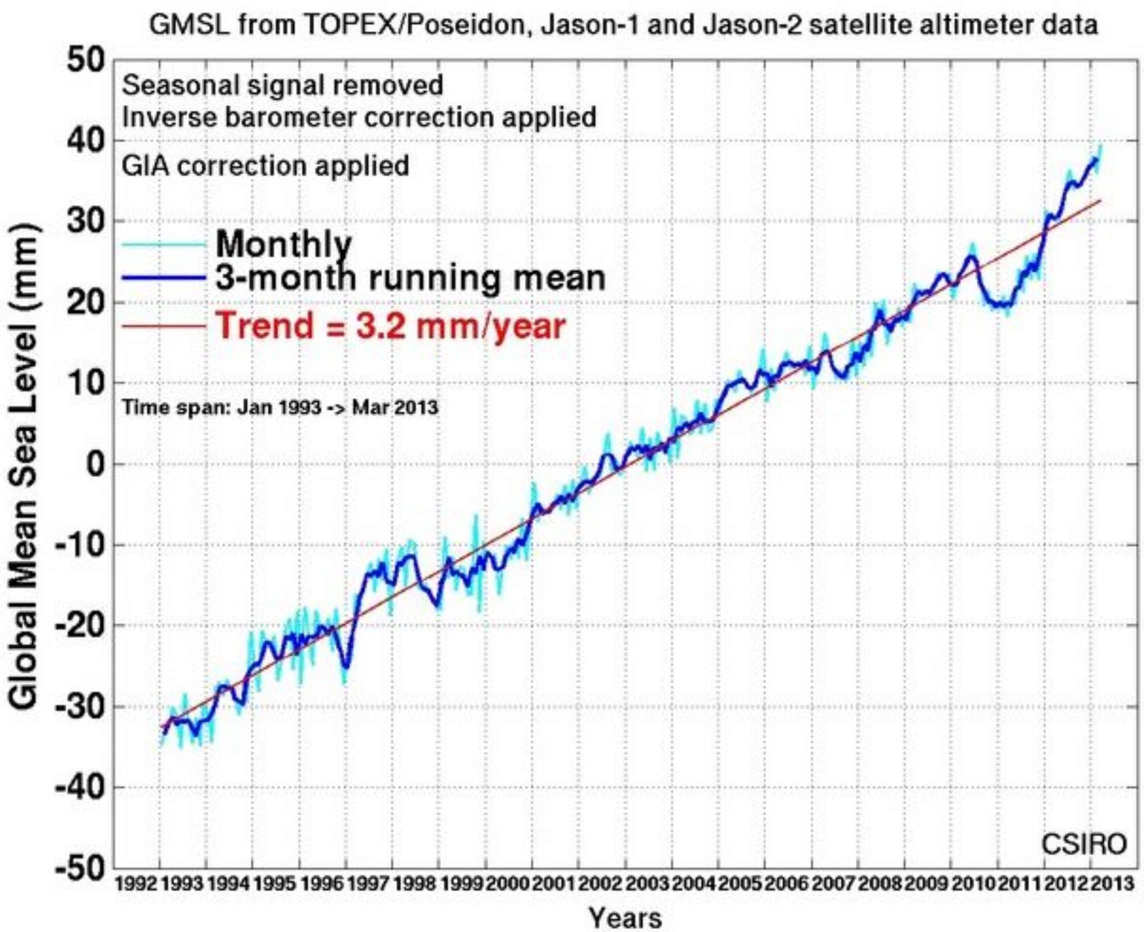
Period: days ***Variation up to…?***



Evaporation and precipitation

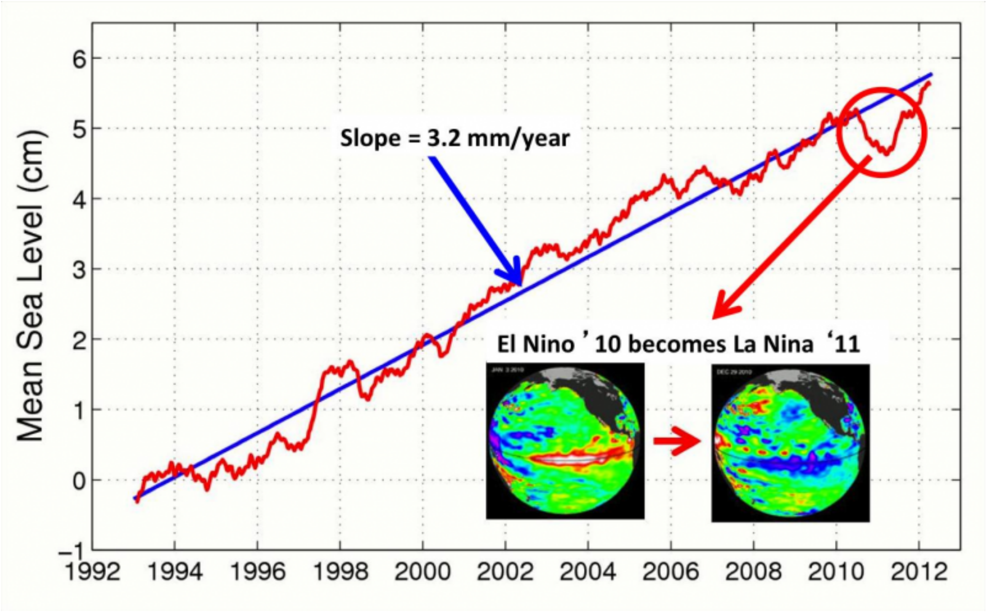
Period: days to weeks

In 2011, a significant drop in global sea level occurred that was unprecedented in the altimeter era.

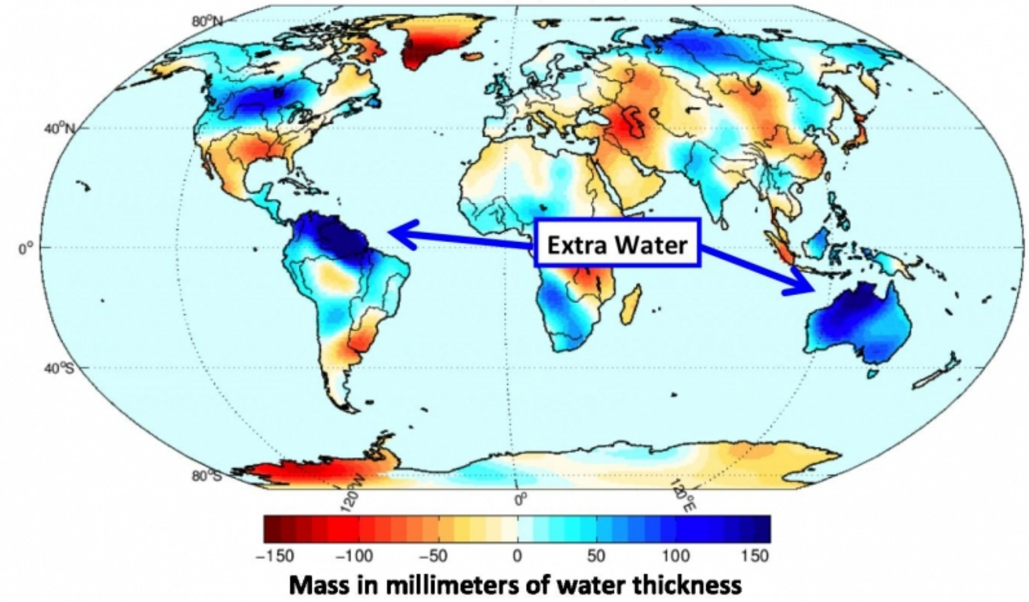


Any ideas what might have caused this?

Dynamic changes



What is ENSO?

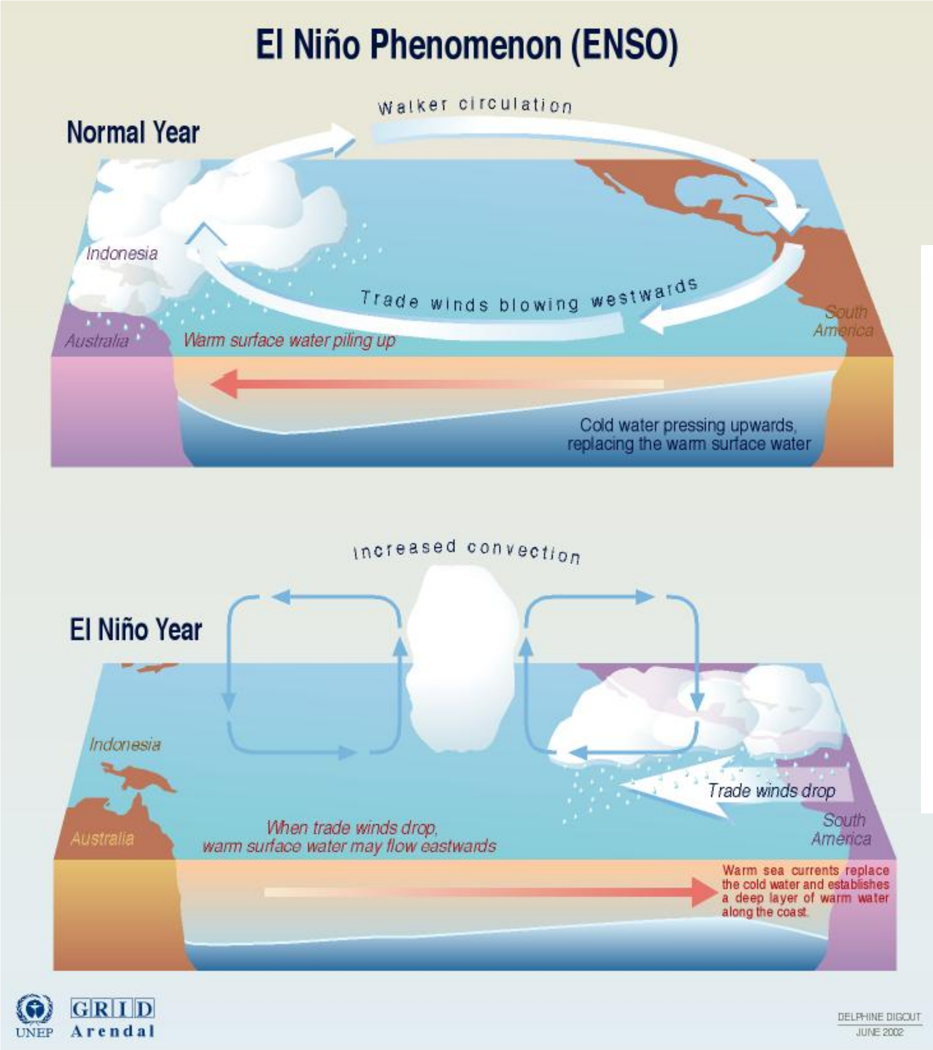


http://podaac.jpl.nasa.gov/

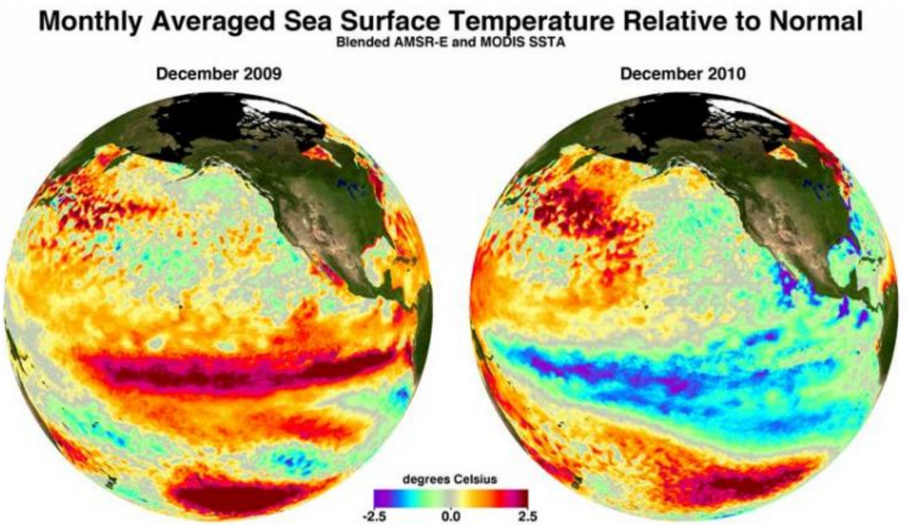
Dynamic changes

ENSO

Period: days to weeks   Variation up to 1m



Sources: Climate Prediction Center-NCEP; NOAA.



http://podaac.jpl.nasa.gov/

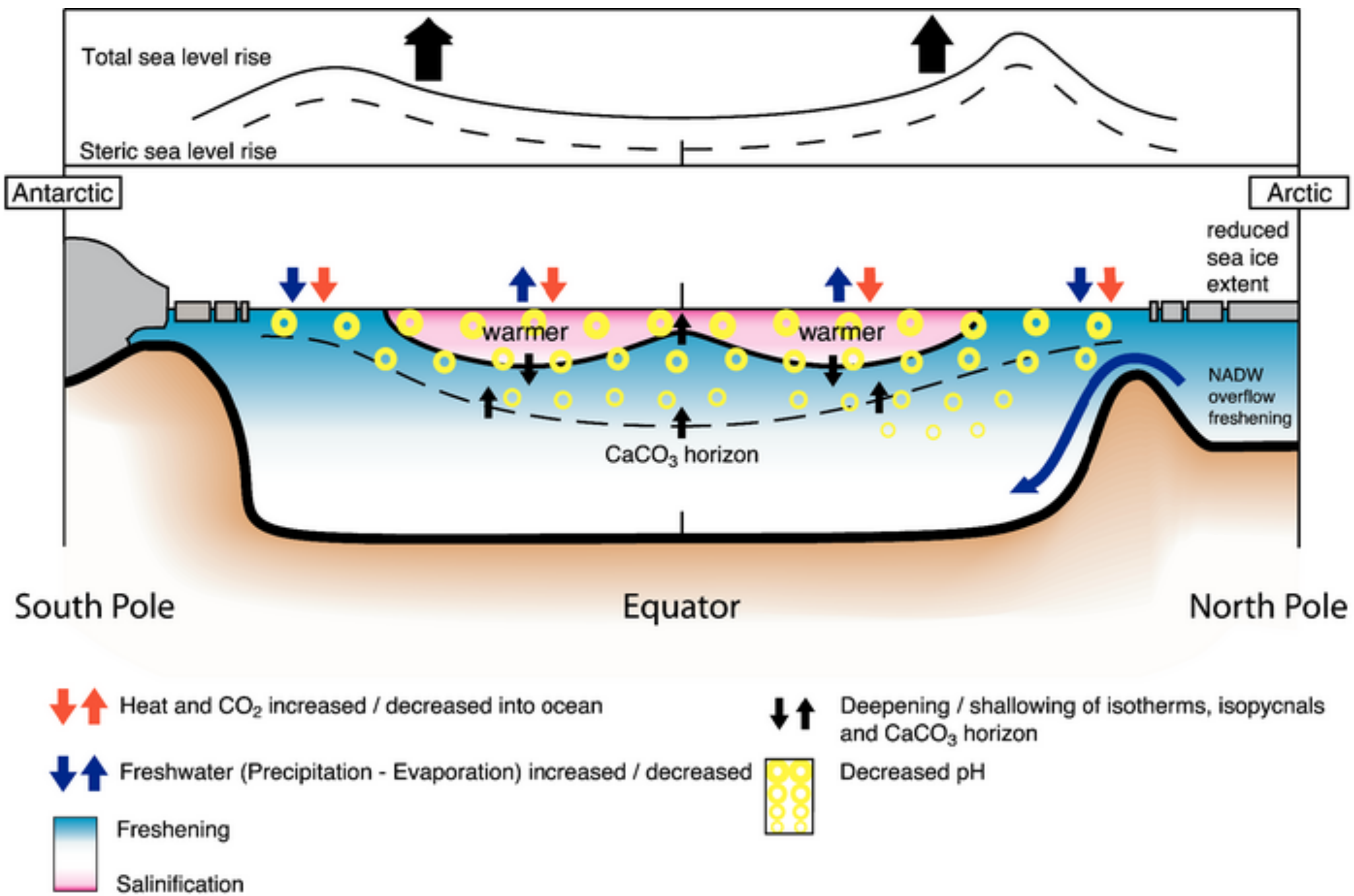
Dynamic changes

River runoff/floods

Period: 2 months   Variation: 1m

Seasonal water density changes

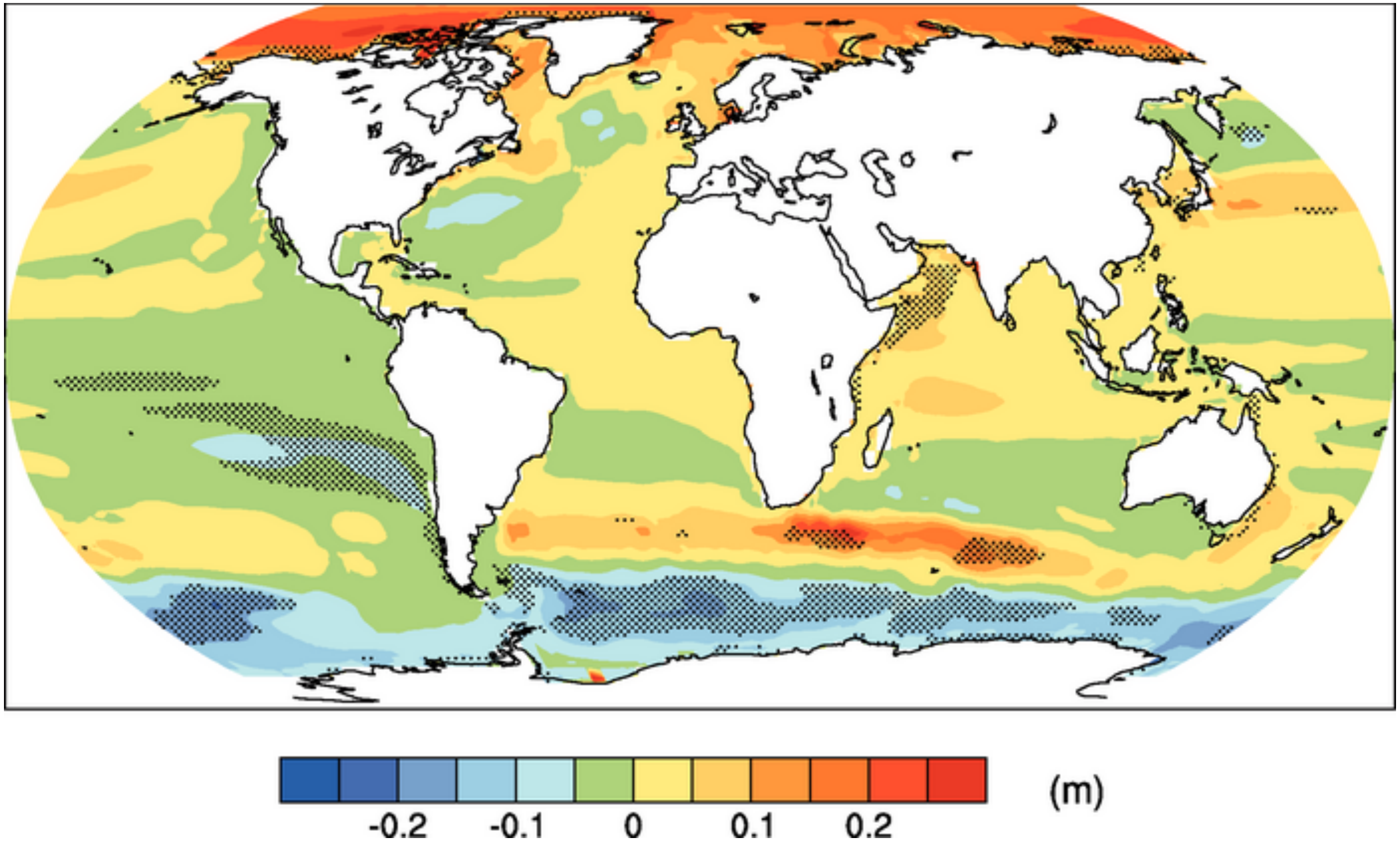
Period: 6 months   Variation: 0.2m



Dynamic changes

Ocean surface topography (changes in water density and currents)

Period: days to weeks   Variation up to 1m



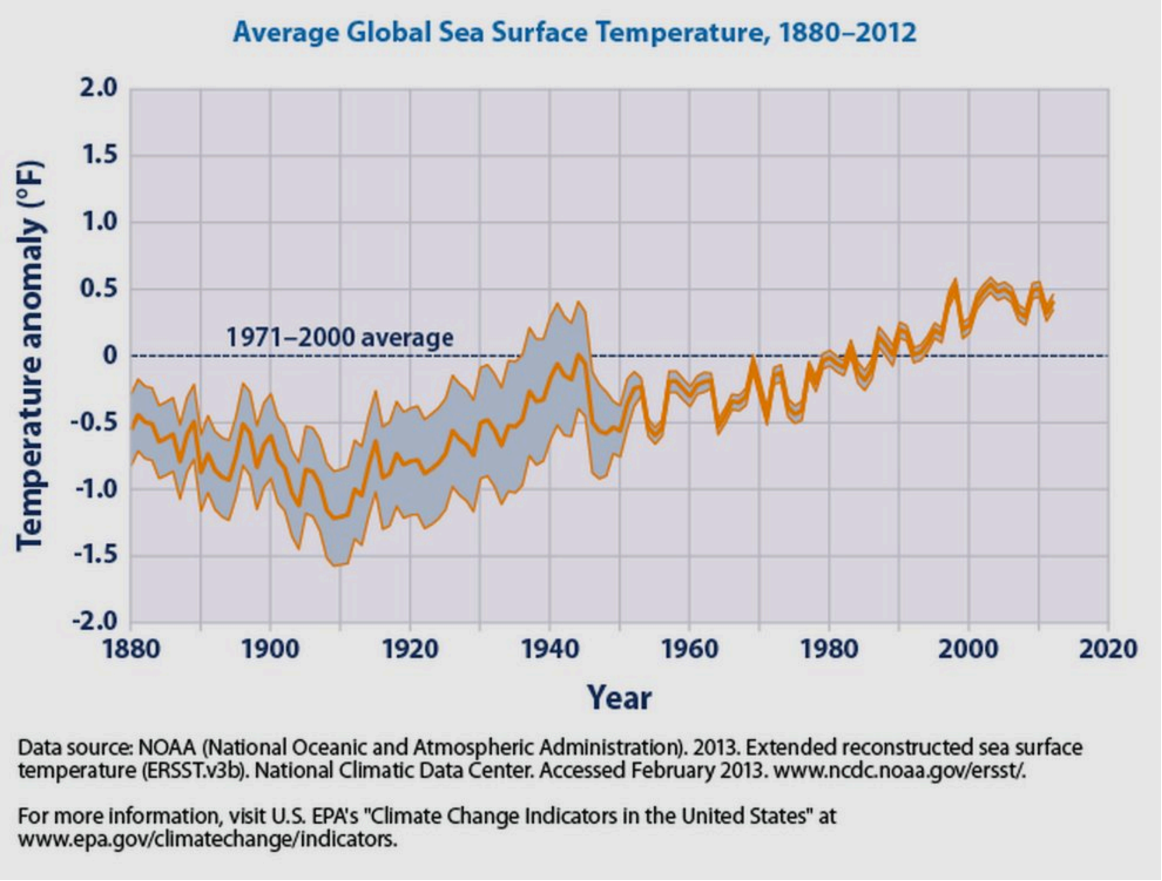
Local sea level change (m) due to ocean density and circulation change relative to the global average

Climate Change 2007: Working Group I: The Physical Science Basis

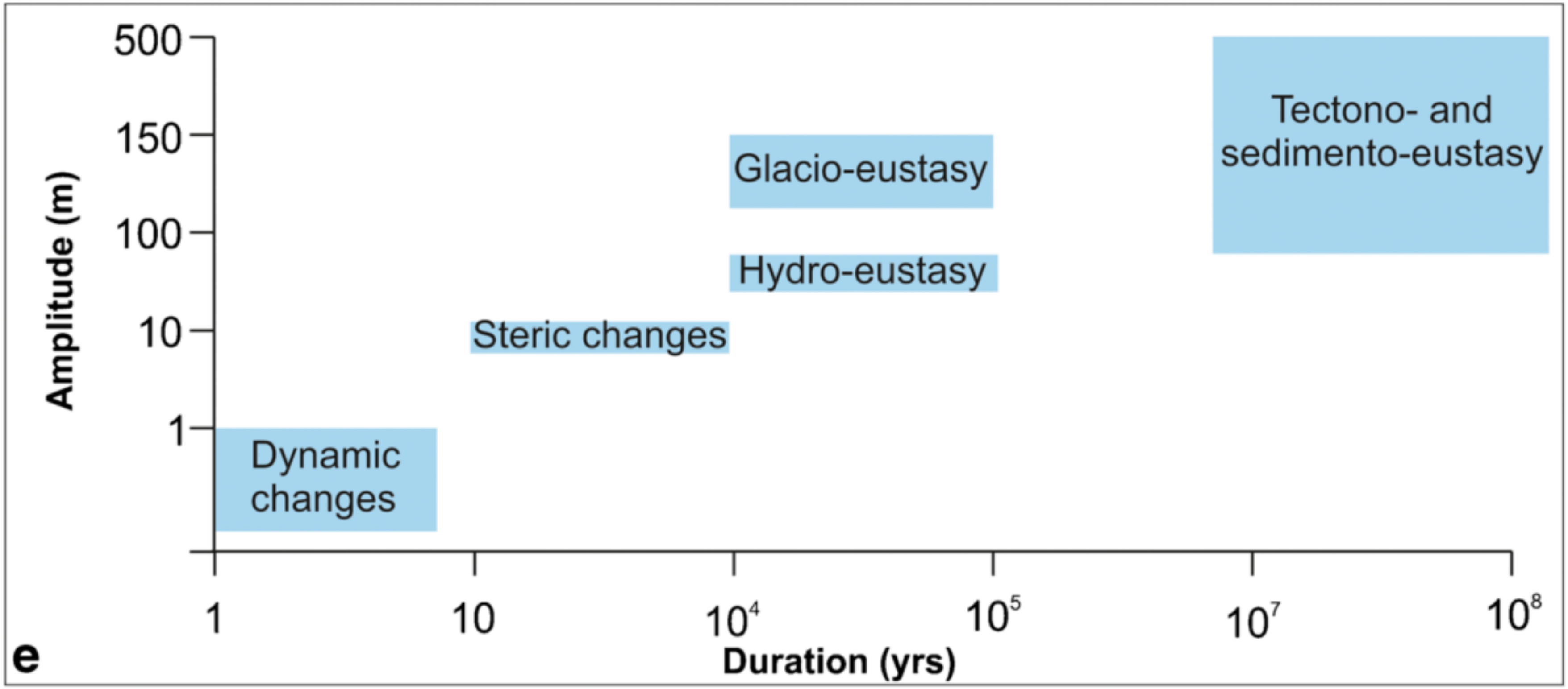
Dynamic changes

Ocean surface topography (changes in water density and currents)

Period: days to weeks   Variation up to 1m

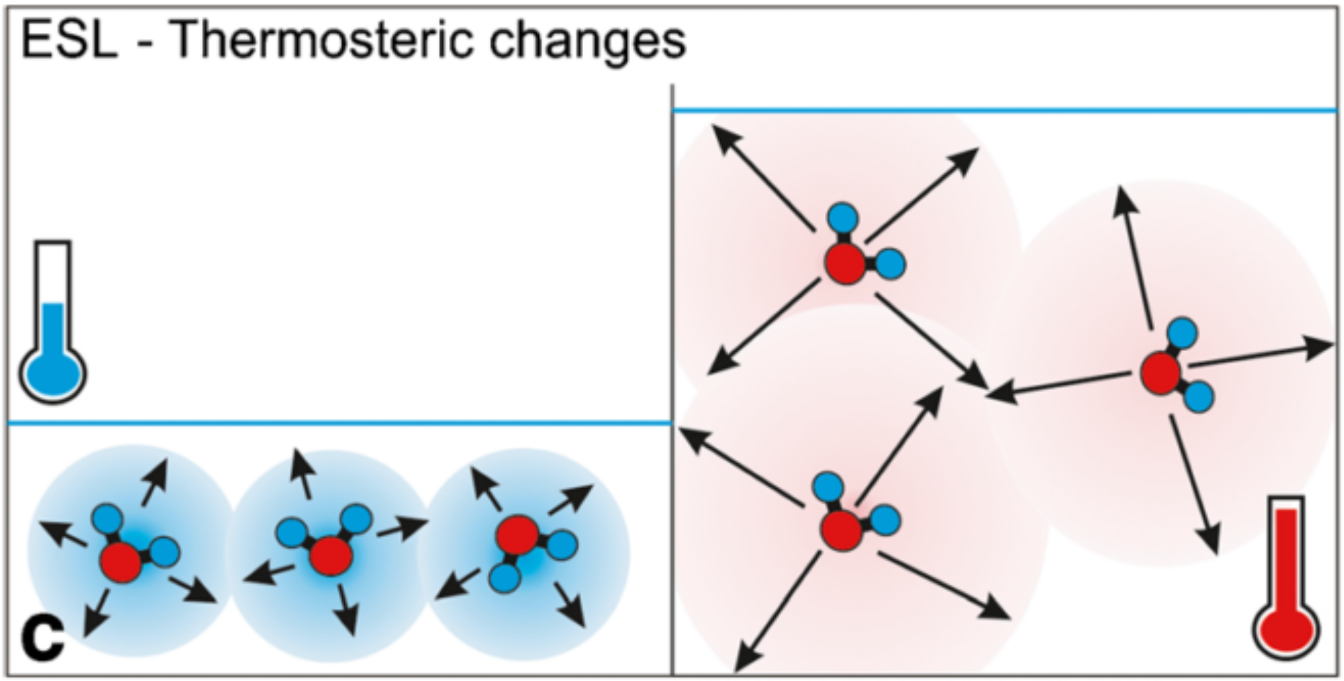


Summary: Eustatic sea level changes



Thermosteric changes

Changes in volume of water masses are caused by variations in ocean water density as a result of cooling or warming of water masses or changes in their salinity (respectively, thermo- and halo-steric changes).

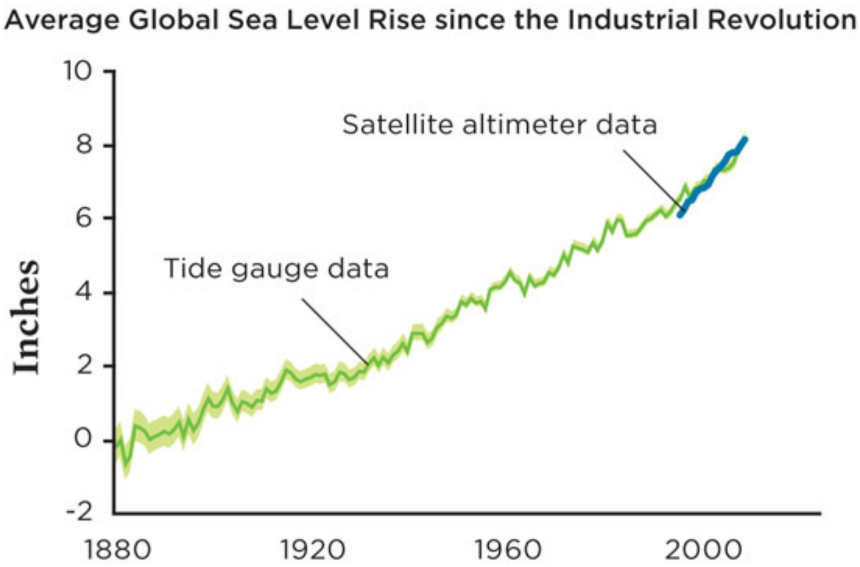


Thermal expansion of water masses (thermosteric changes) at molecular level. Above 4 °C, water expands as it is heated due to greater molecular motions.

Global Sea Level Rise: what is bigger thermal expansion or melting ice?

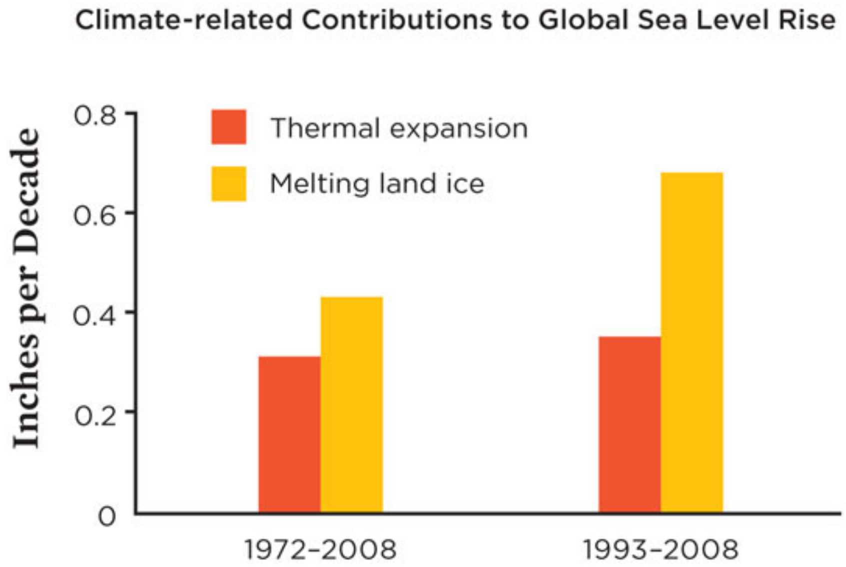
Thermosteric changes

FIGURE 1. Global Sea Level Rise and Recent Causes



Loss of ice on land and thermal expansion of seawater—both primarily caused by global warming—have been the key drivers of an average global sea level rise of about eight inches since 1880. Tide gauges around the world have recorded the long-term rise in sea level since 1870 (green line with shaded error range). Satellite observations since 1993 (blue line) have confirmed the trend.

SOURCES: NRC 2012; CHURCH ET AL. 2011; CAZENAVE AND LLOVEL 2010.

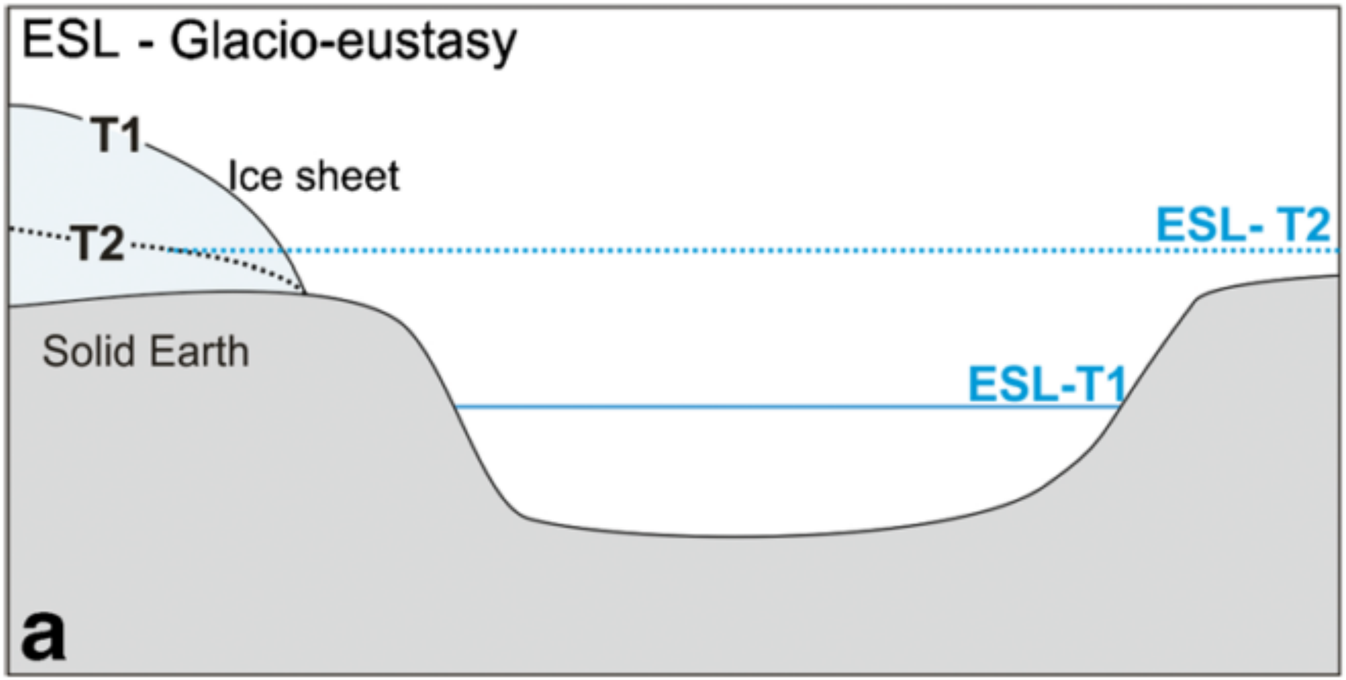


From 1972 to 2008, melting land ice—glaciers, ice caps, and ice sheets—accounted for 52 percent of sea level rise, while warmer oceans contributed 38 percent. Groundwater withdrawal and other factors, both known and unknown, contributed the remaining 10 percent. Ice loss has accelerated since the early 1990s, and has accounted for 75 percent to 80 percent of sea level rise since 2003.

SOURCES: NRC 2012; CHURCH AND WHITE 2011; CAZENAVE AND LLOVEL 2010; NICHOLLS AND CAZENAVE 2010.

Glacio-eustatic changes

How do ice sheets melt?



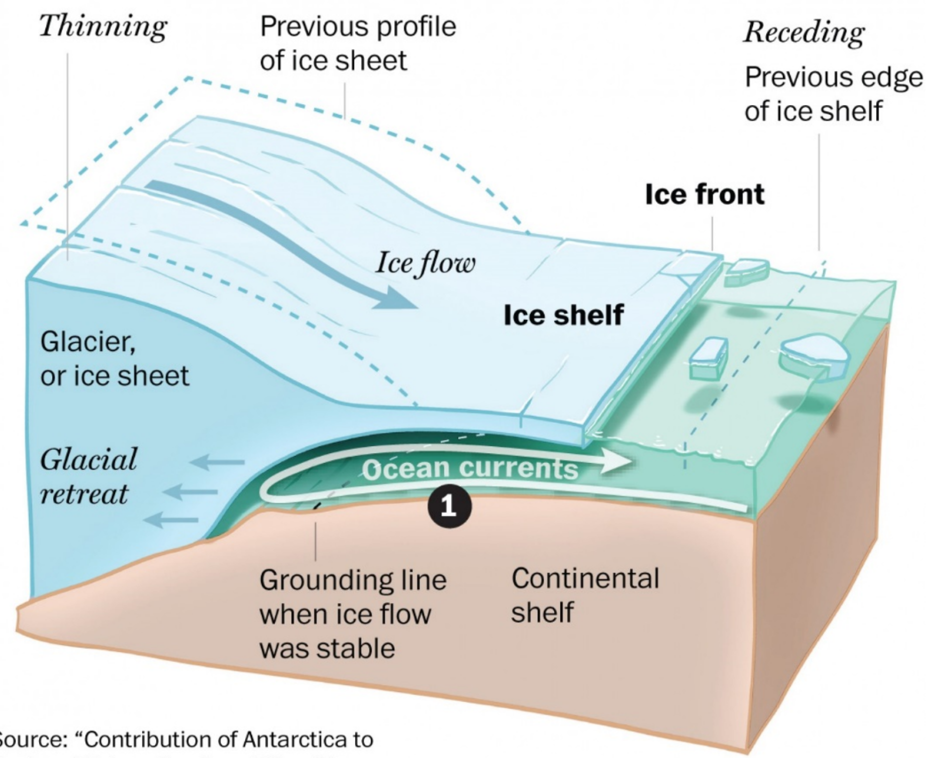
Changes in mass of the world ocean can occur as a consequence of melting or accumulation of continental ice sheets over time (glacio-eustasy)

Glacio-eustatic changes

Melting from below

Scientists have long known that glaciers resting under sea level can be unstable if they rest on a downward sloping sea bed.

1. Warmer ocean currents erode the glacier's base from below. The grounding line retreats downhill, and as it does, even more of the glacier is exposed to warm water. It melts more, and flows faster.



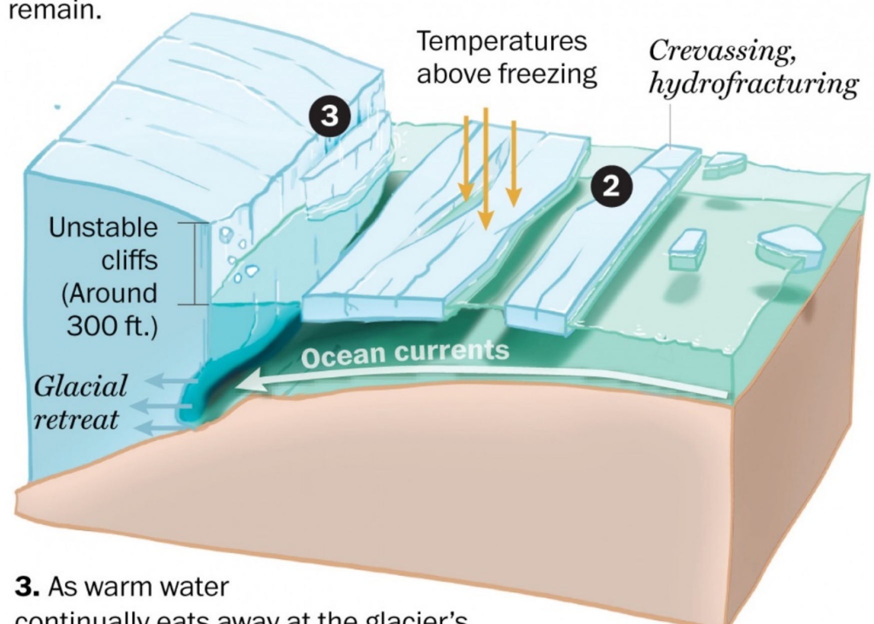
Source: "Contribution of Antarctica to Past and Future Sea-Level Rise," by Robert M. DeConto and David Pollard, in Nature

CHIQUI ESTEBAN, BONNIE BERKOWITZ, PATTERSON CLARK / THE WASHINGTON POST

Shearing from cliffs

Now, researchers have identified two new processes that can make this still worse.

2. Warm air, rain and meltwater cause fissures in the shelf, which breaks away from the glacier in large swaths. Eventually, only vertical ice cliffs remain.

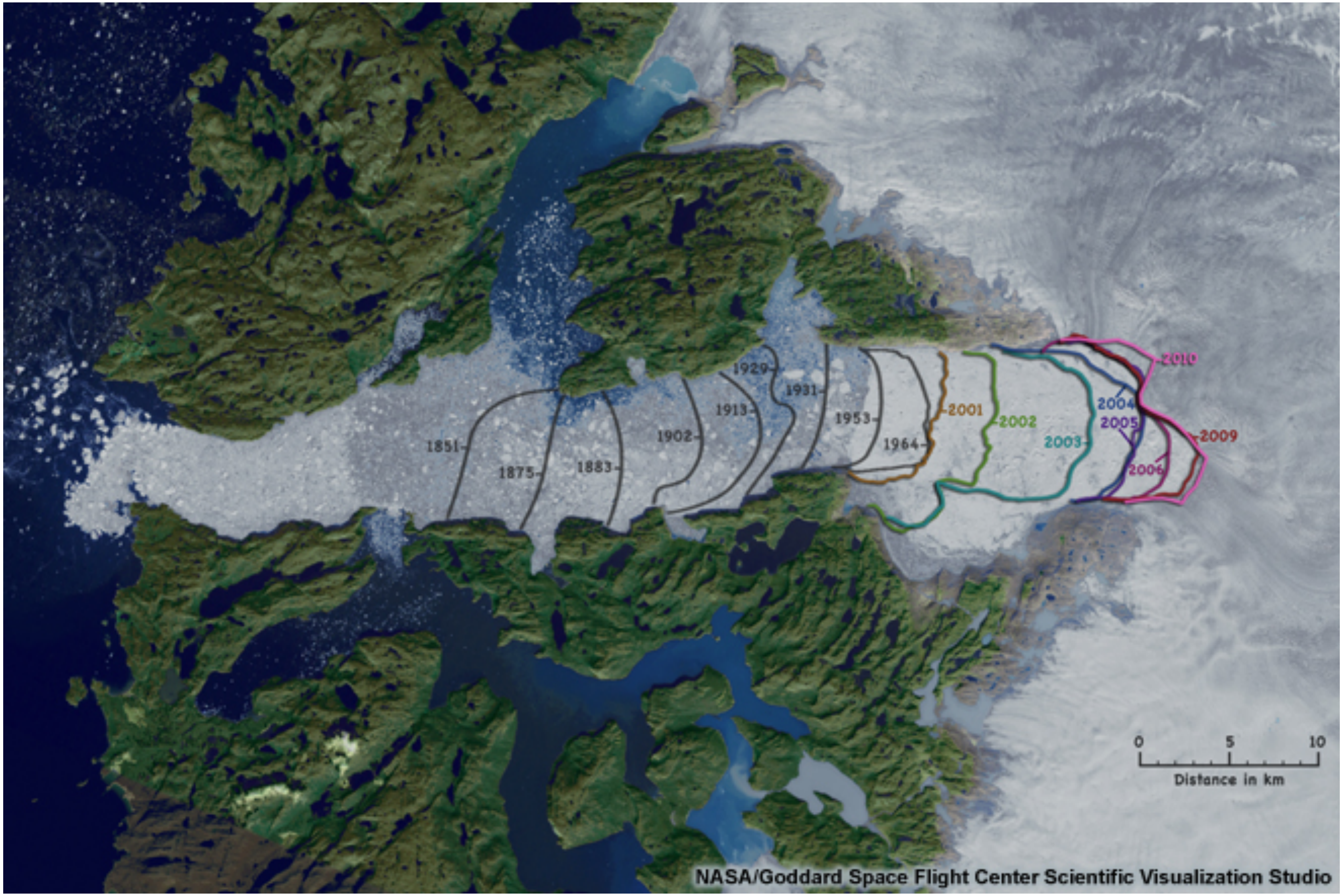


3. As warm water continually eats away at the glacier's base, the unstable cliff faces above the water line shear off under their own massive weight.

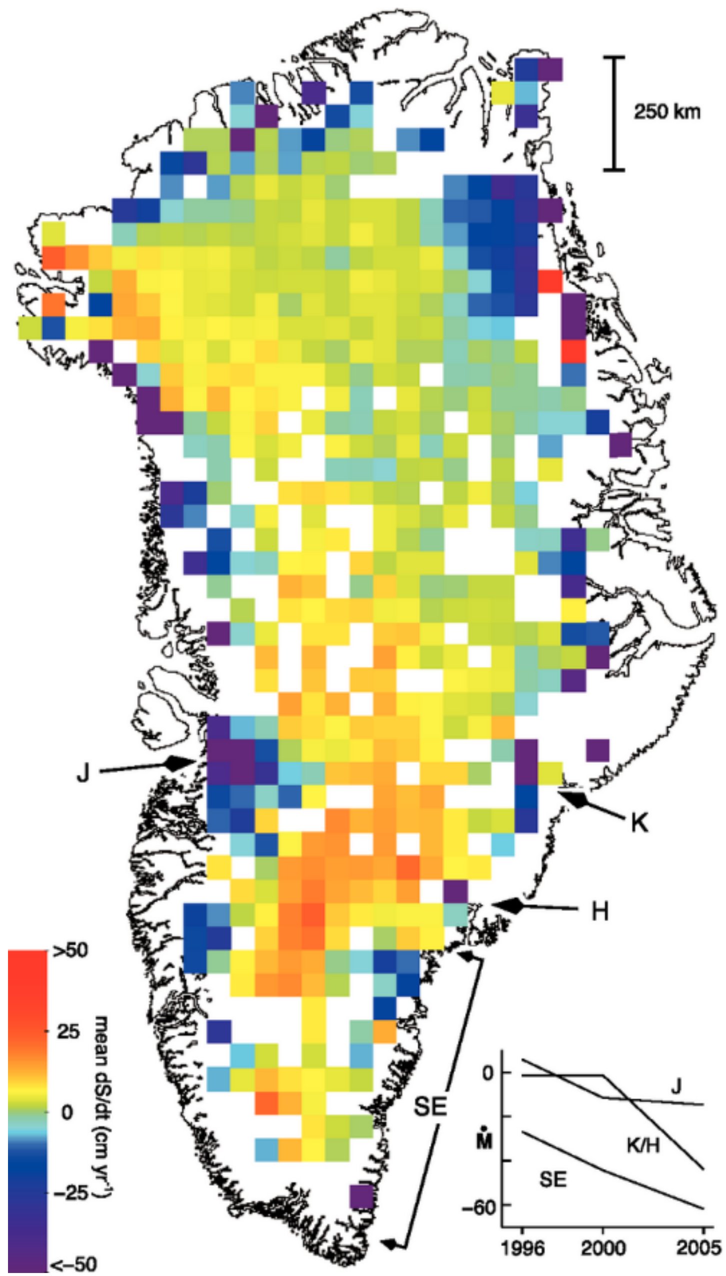
Source: "Contribution of Antarctica to Past and Future Sea-Level Rise," by Robert M. DeConto and David Pollard, in Nature

CHIQUI ESTEBAN, BONNIE BERKOWITZ, PATTERSON CLARK / THE WASHINGTON POST

Glacio-eustatic changes

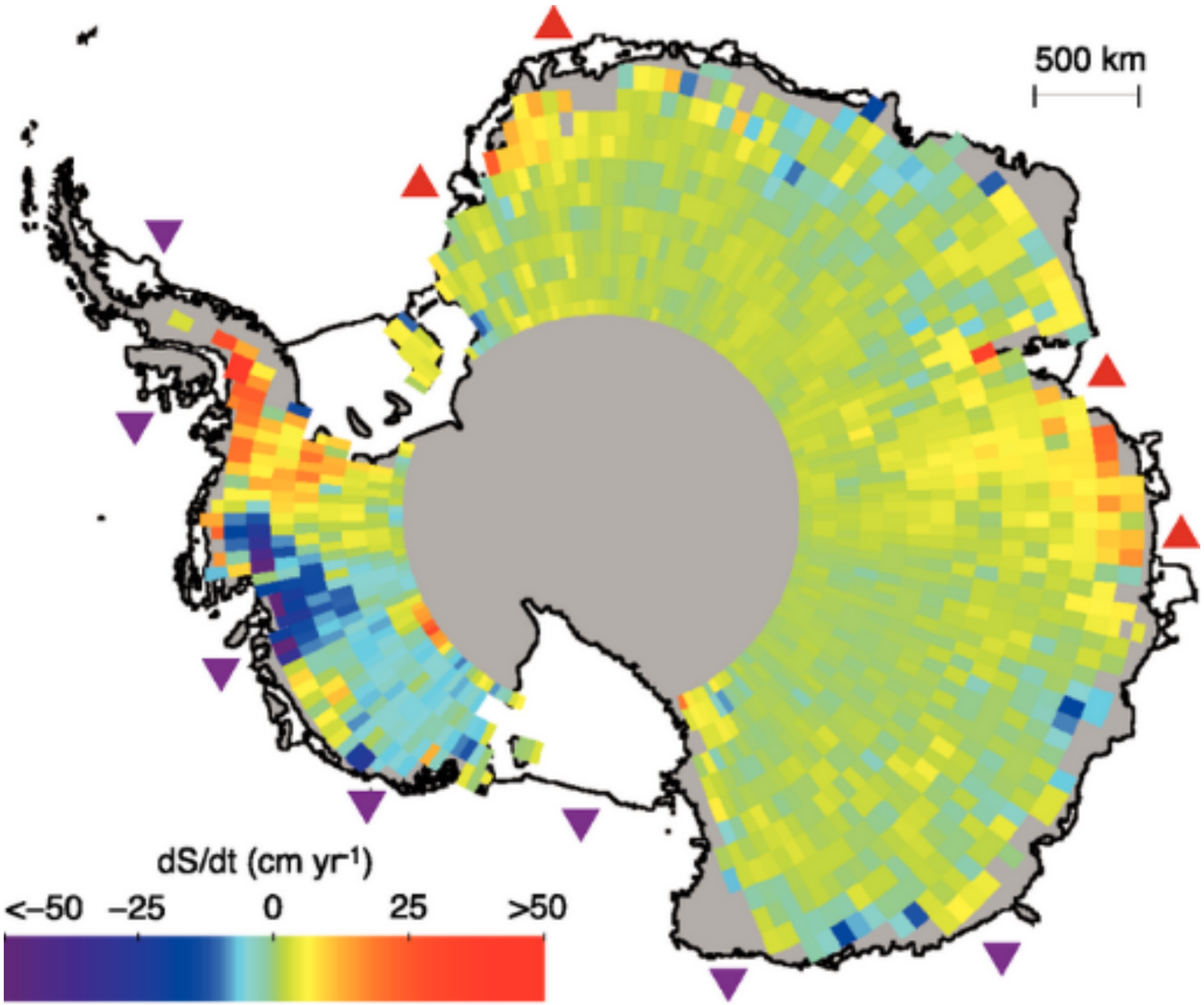


Glacio-eustatic changes



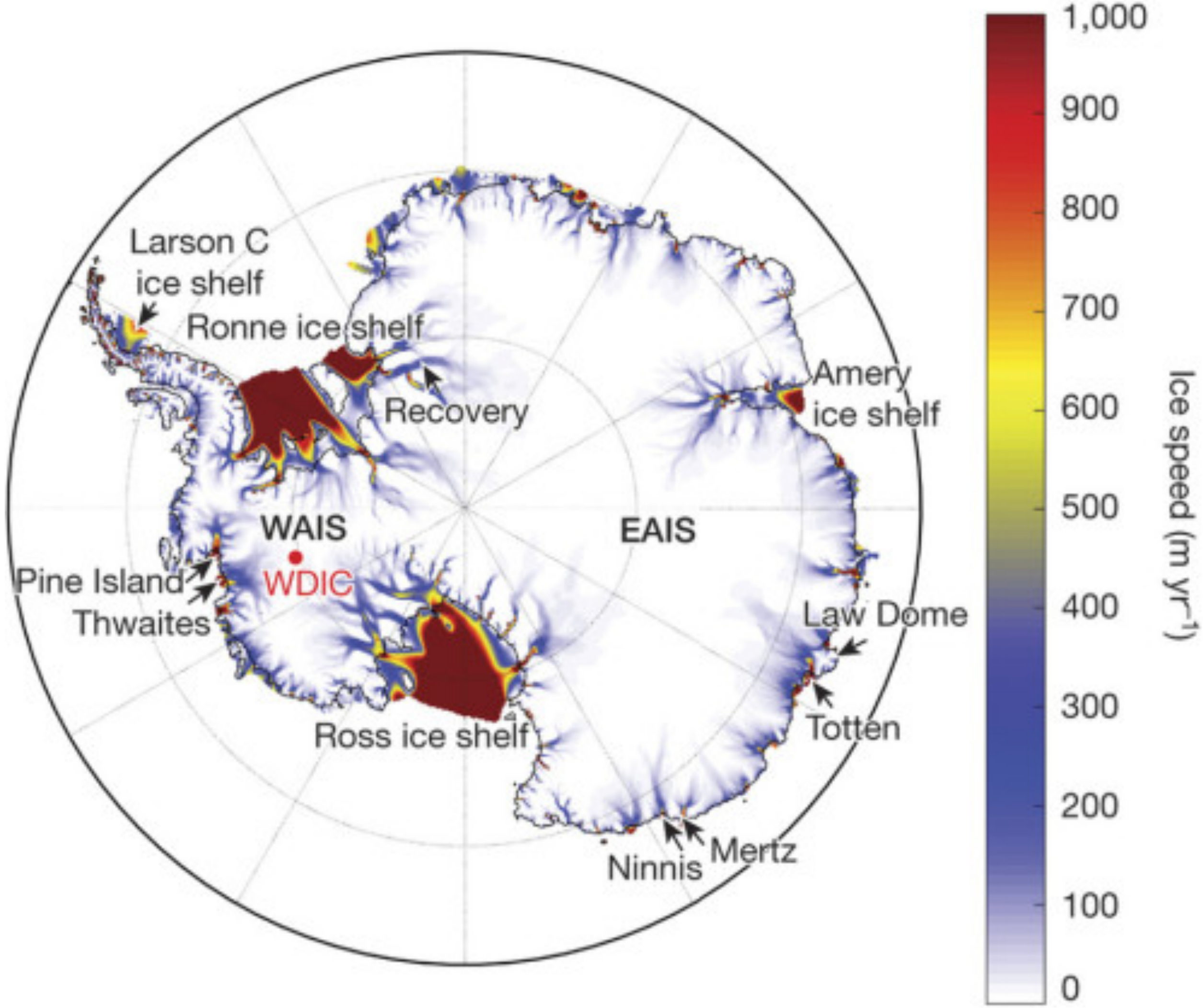
Rates of surface elevation change (dS/dt) derived from laser altimeter measurements at more than 16,000 locations on the Greenland Ice Sheet where ICESat data from 2005 overlay aircraft surveys in 1998/1999 (using methods described by Thomas et al., 2006). Locations of rapidly thinning outlet glaciers at Jakobshavn (J), Kangerdlugssuaq (K), Helheim (H) and along the southeast coast (SE) are shown, together with an inset showing their estimated total mass balance (M· , Gt yr^{-1}) between 1996 and 2005 (Rignot and Kanagaratnam, 2006).

Glacio-eustatic changes



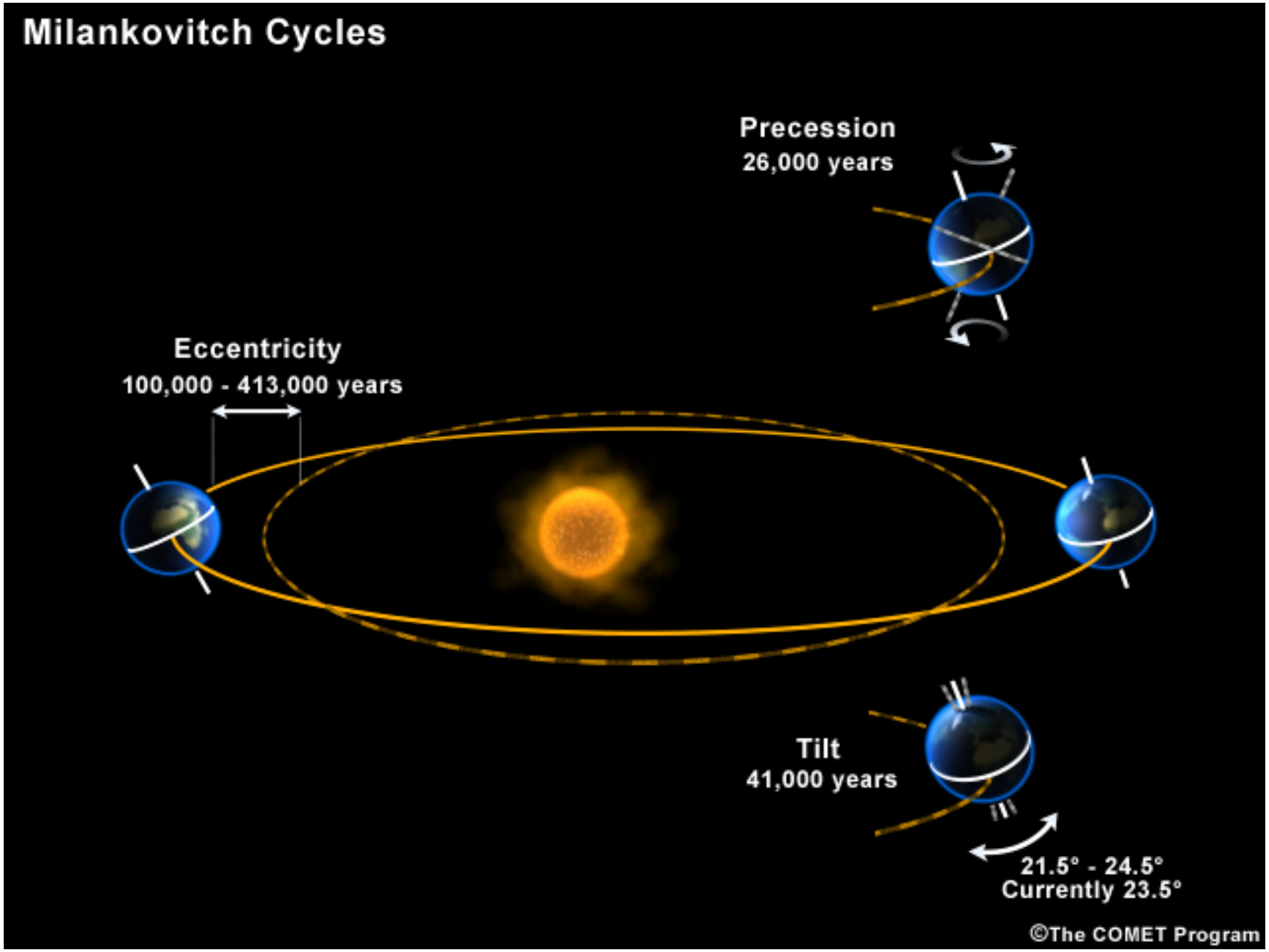
Rates of surface elevation change (dS/dt) derived from ERS radar-altimeter measurements between 1992 and 2003 over the Antarctic Ice Sheet (Davis et al., 2005). Locations of ice shelves estimated to be thickening or thinning by more than 30 cm yr^{-1} (Zwally et al., 2006) are shown by red triangles (thickening) and purple triangles (thinning).

Glacio-eustatic changes



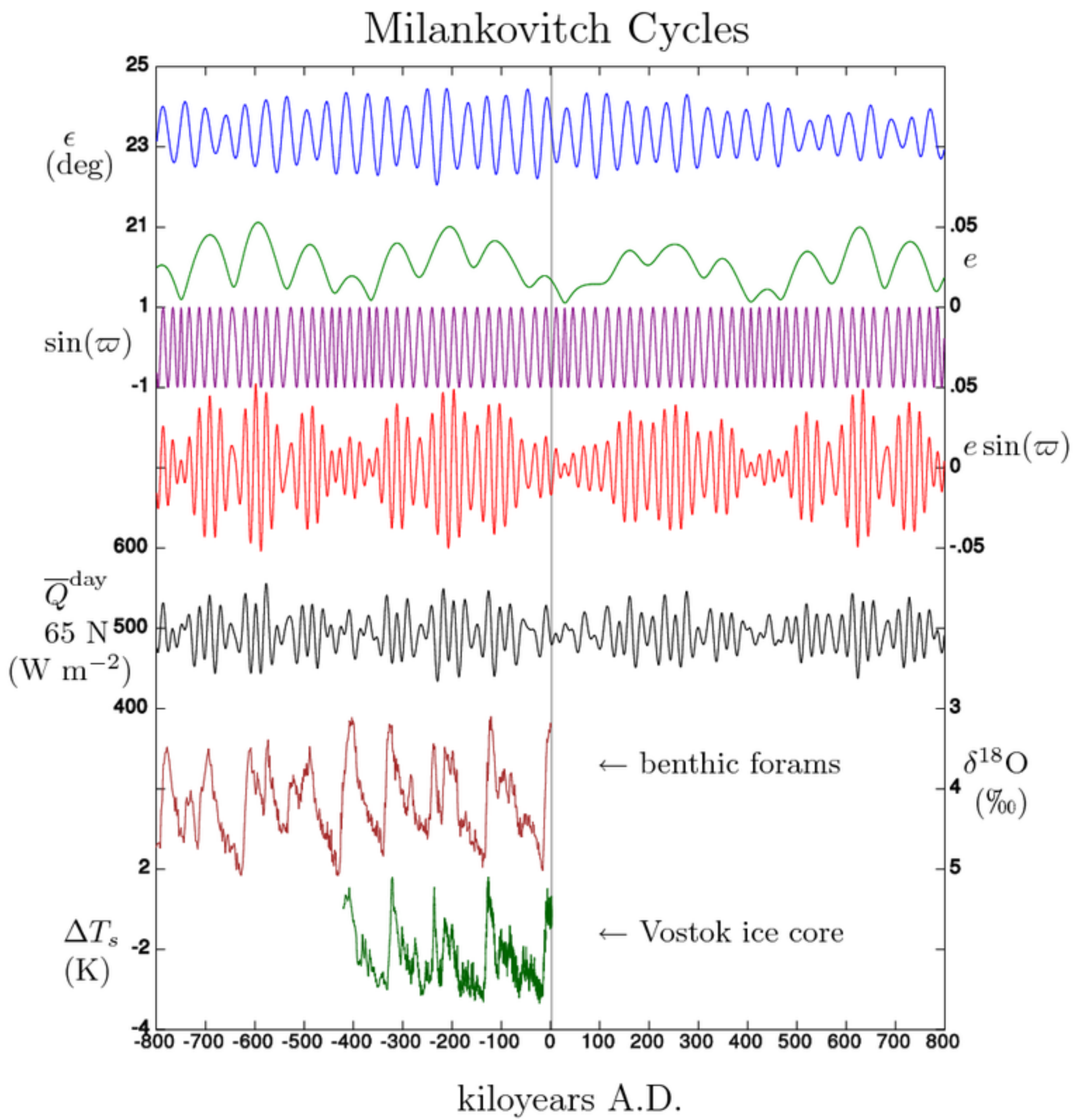
DeConto & Pollard, Nature

Long term eustatic changes

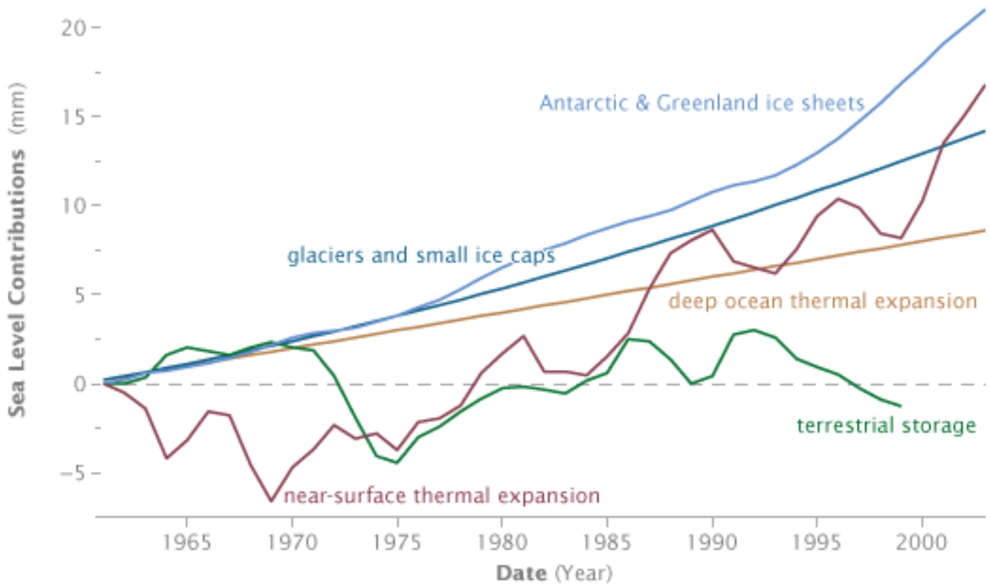


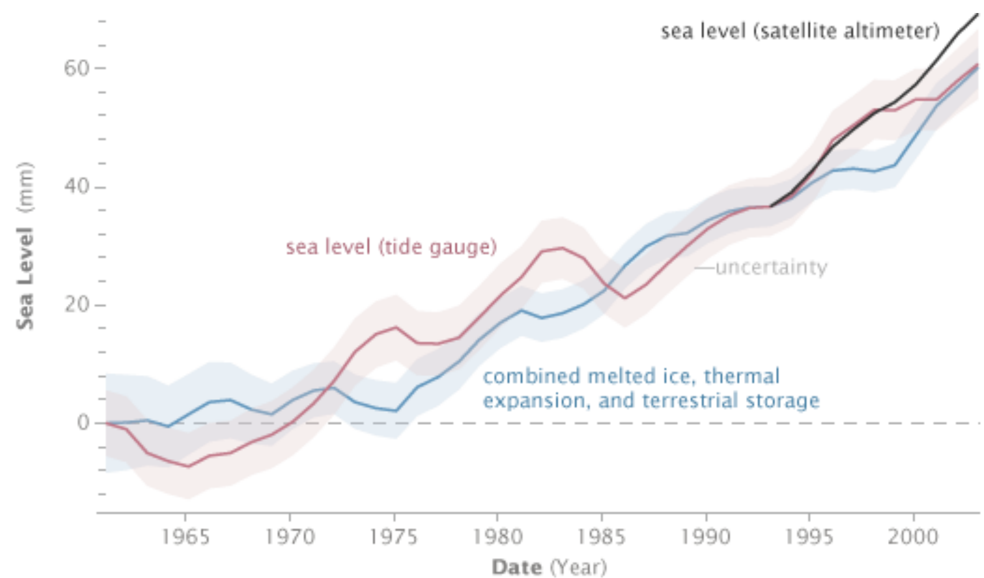
Milutin Milanković (1879 – 1958) was a Serbian mathematician, astronomer, climatologist, geophysicist, civil engineer, doctor of technology, university professor and popularizer of science. Milanković gave two fundamental contributions to global science. The first contribution is the "Canon of the Earth's Insolation", which characterizes the climates of all the planets of the Solar system. The second contribution is the explanation of Earth's long-term climate changes caused by changes in the position of the Earth in comparison to the Sun, now known as Milankovitch cycles.

Long term eustatic changes



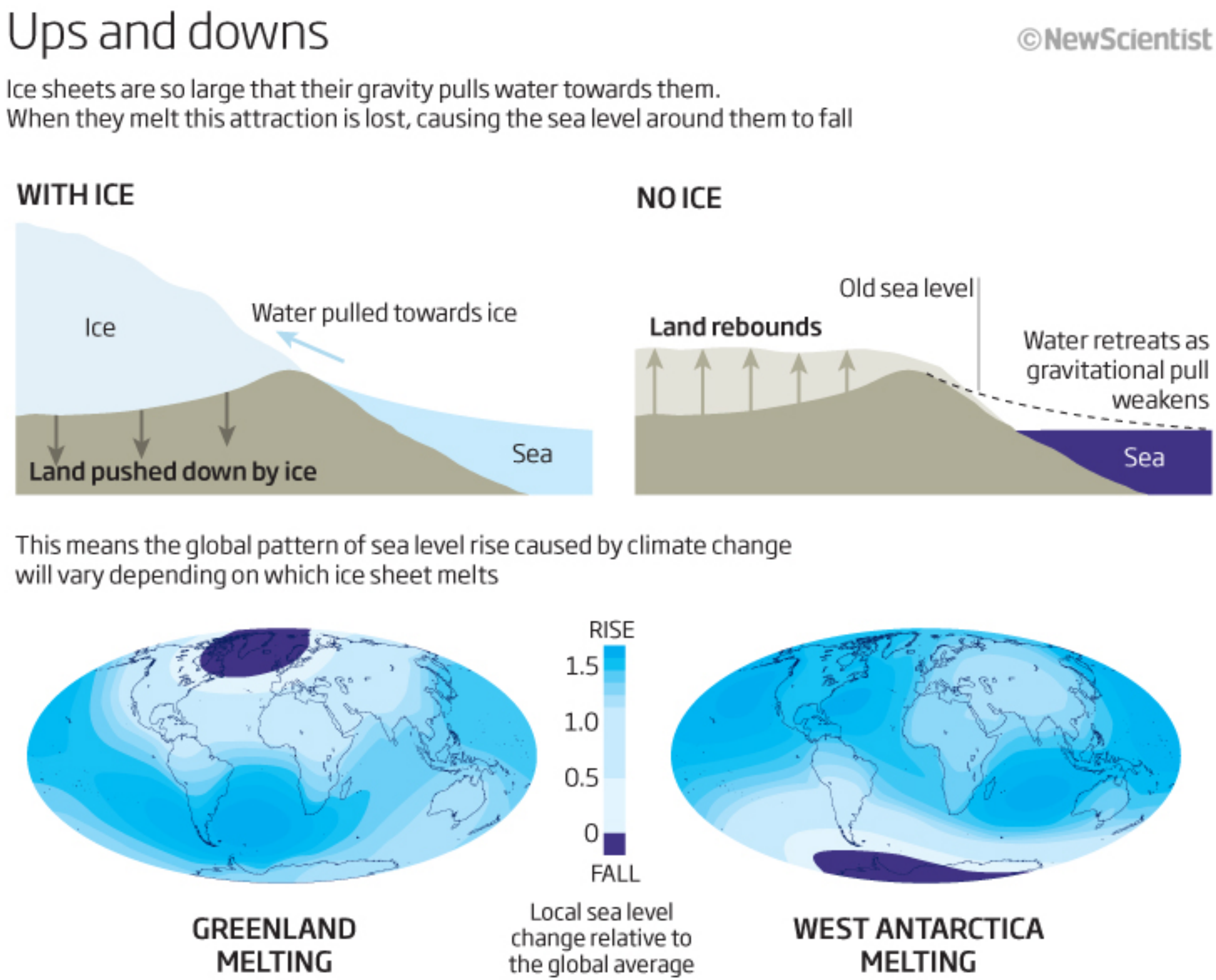
Eustatic sea level changes



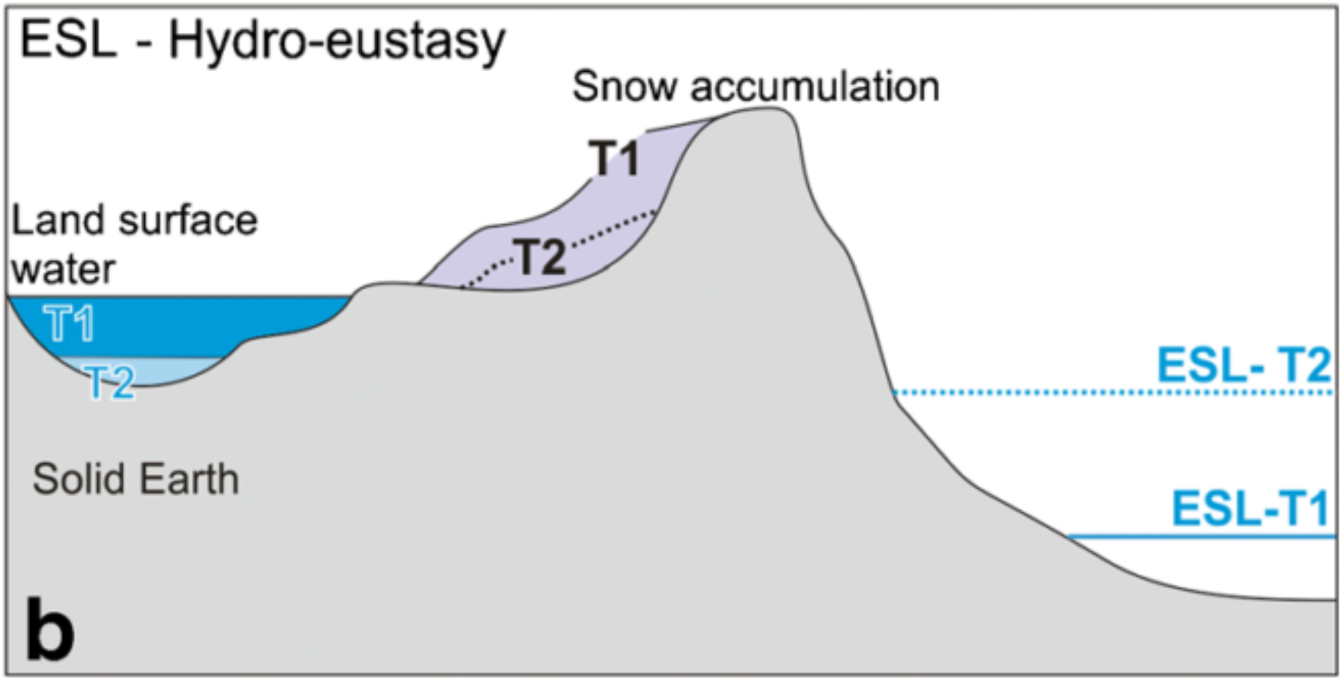


Source: NASA, CSIRO

Gravitational effects

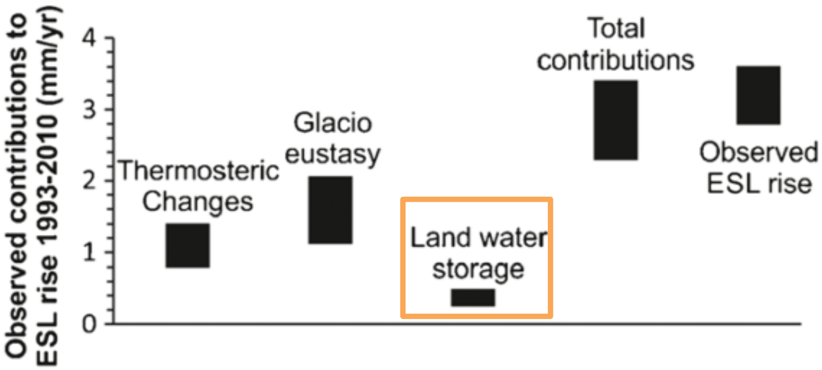


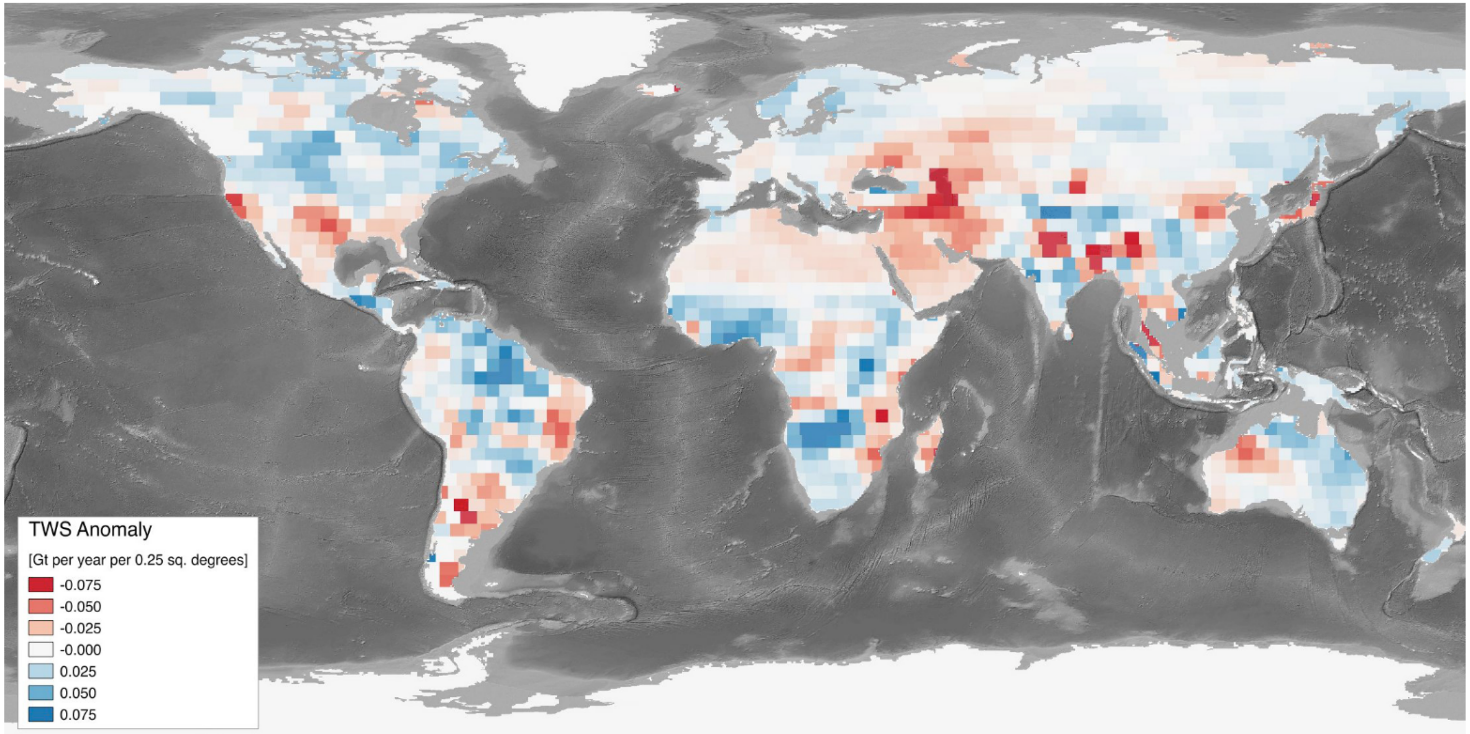
Hydro-eustatic changes



Changes in mass of the world ocean can occur as a consequence of water redistribution between different hydrological reservoirs (snow, surface water, soil moisture, and groundwater storage, excluding glaciers)

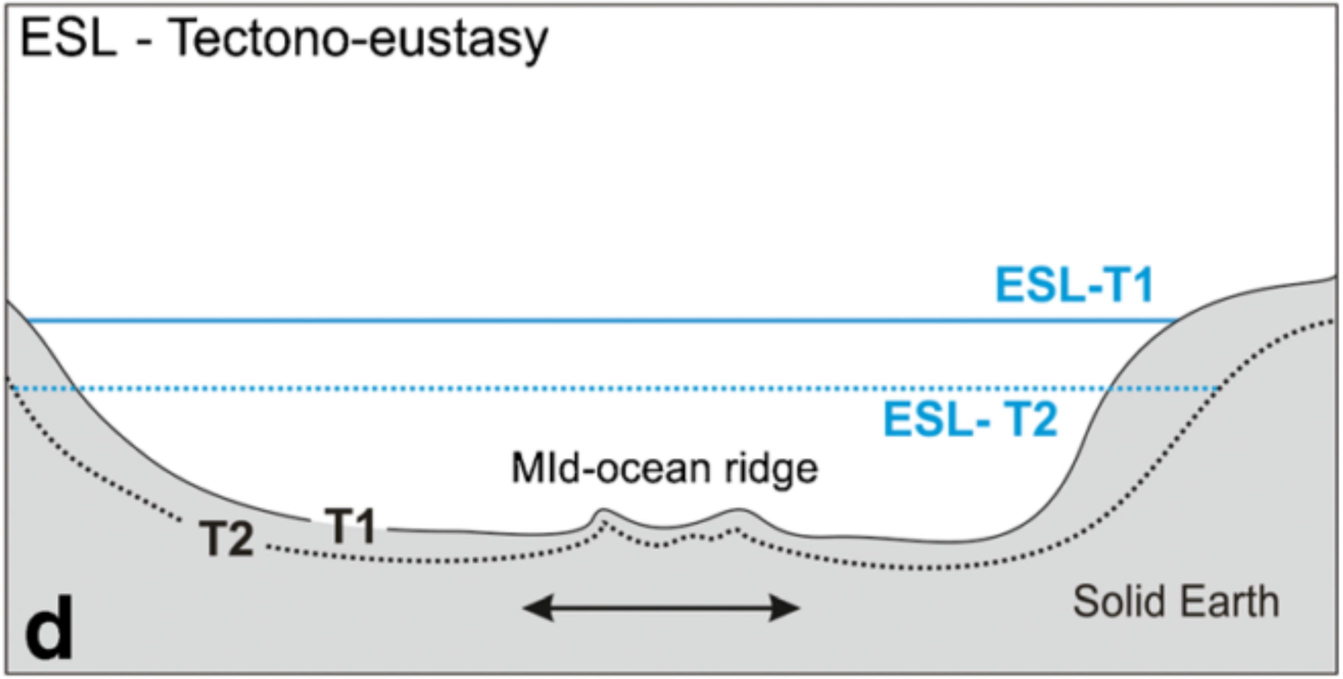
Hydro-eustatic changes





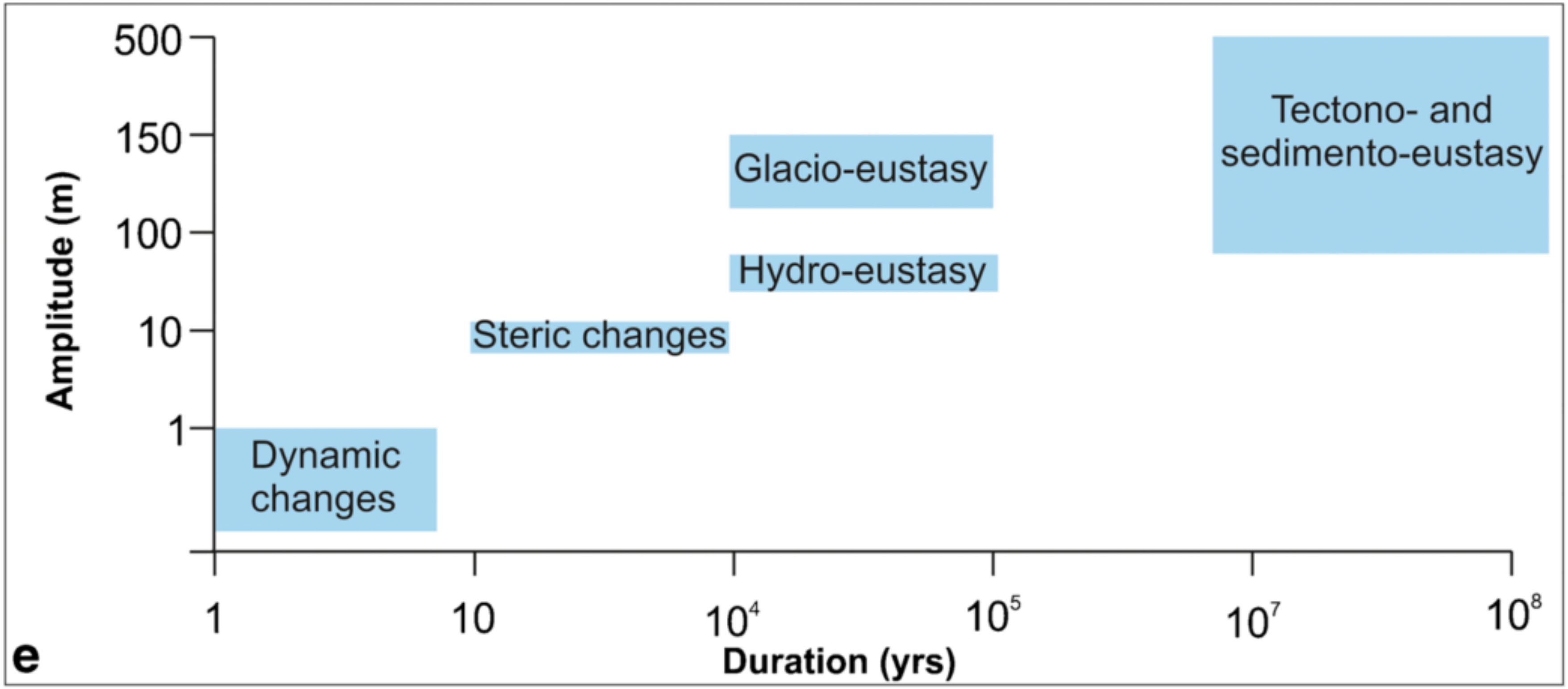
Trend in land water storage between April 2002 and November 2014 across the world. Shading indicates an increase (blue) or decrease (red) in storage. Source: Reager et al. (2016).

Tectono and sedimento-eustatic changes



ESL changes also occur when the volume of the ocean basins changes following tectonic seafloor spreading (tectono-eustasy) or sedimentation (sedimento- eustasy)

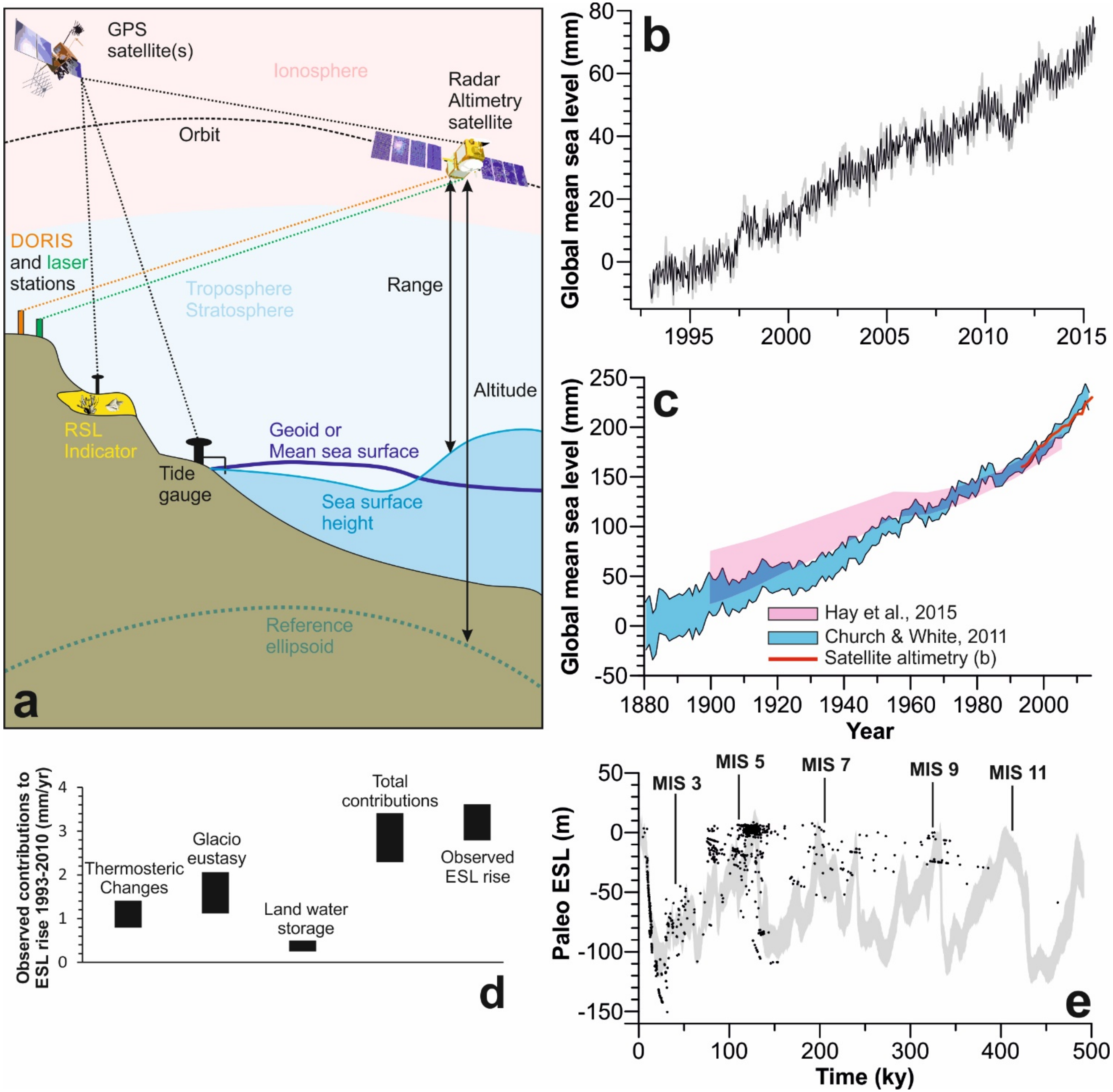
Eustatic sea level changes



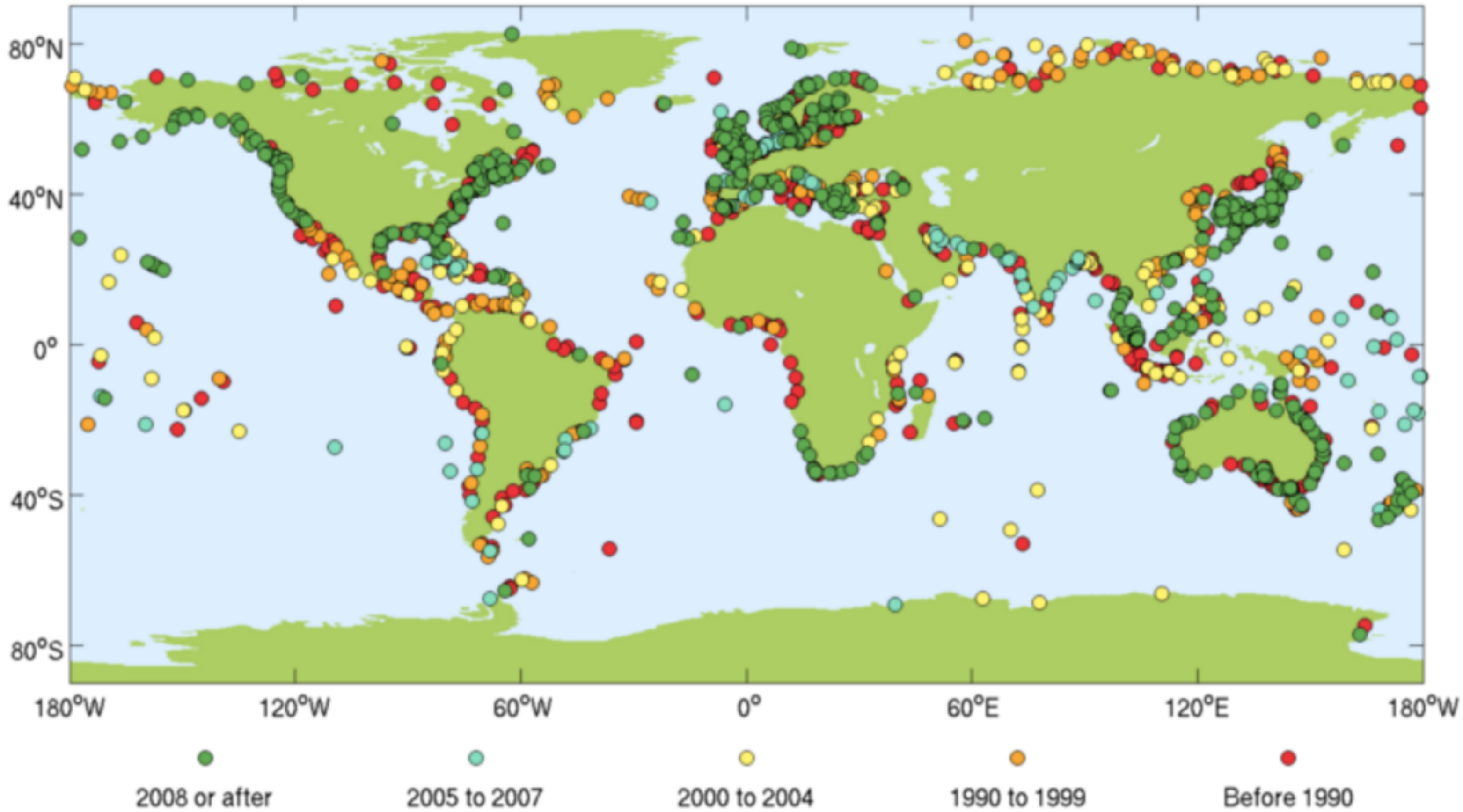
SESSION 2

How do we observe sea level changes?

The very short version

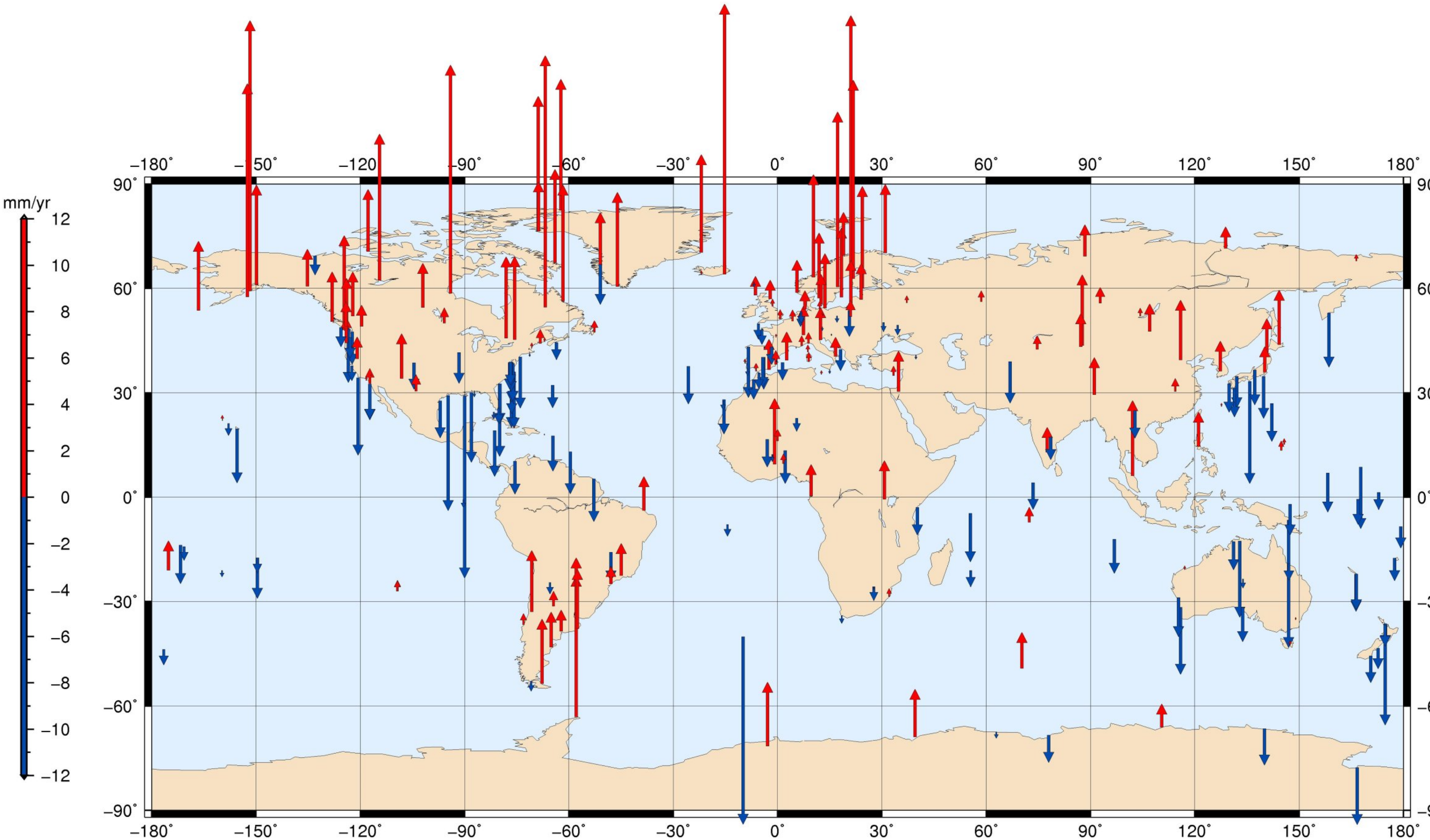


Tide gauges



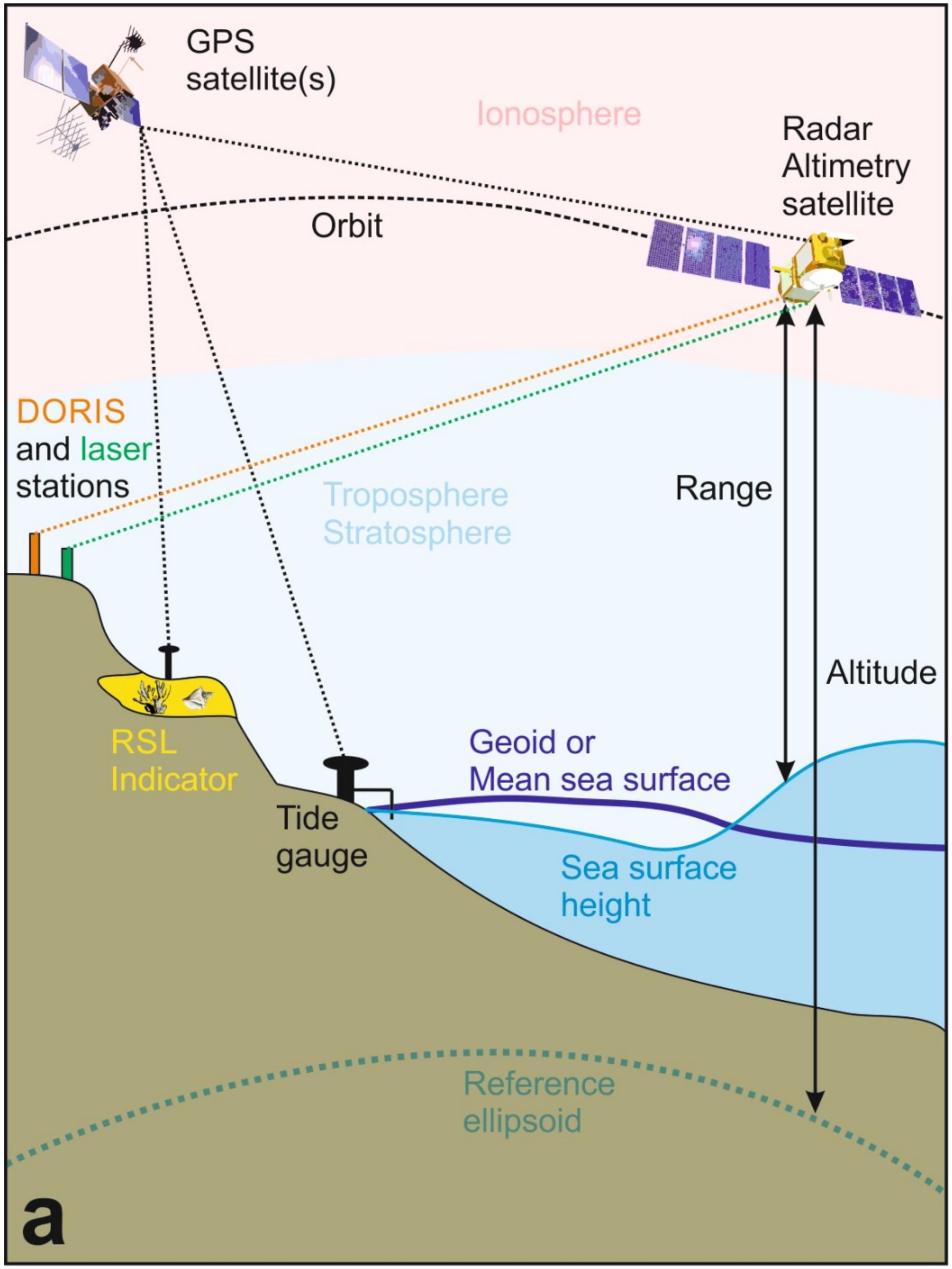
Tide gauge stations contributing mean sea level data to PSMSL (with year of most recent data)

Tide gauges

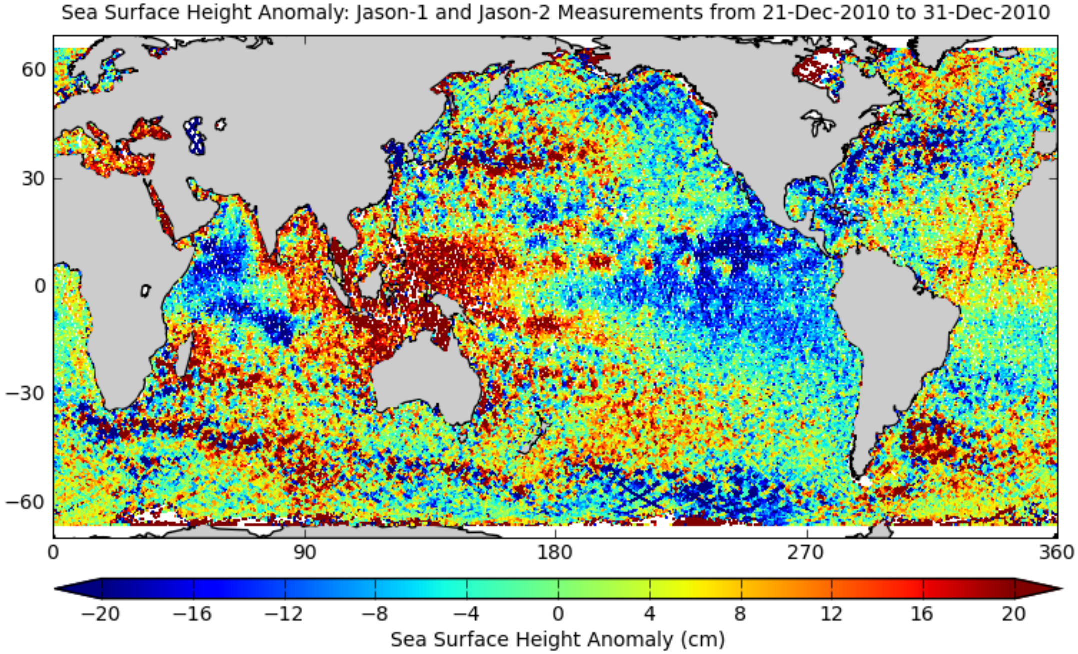


Sonel.org

Satellite altimetry

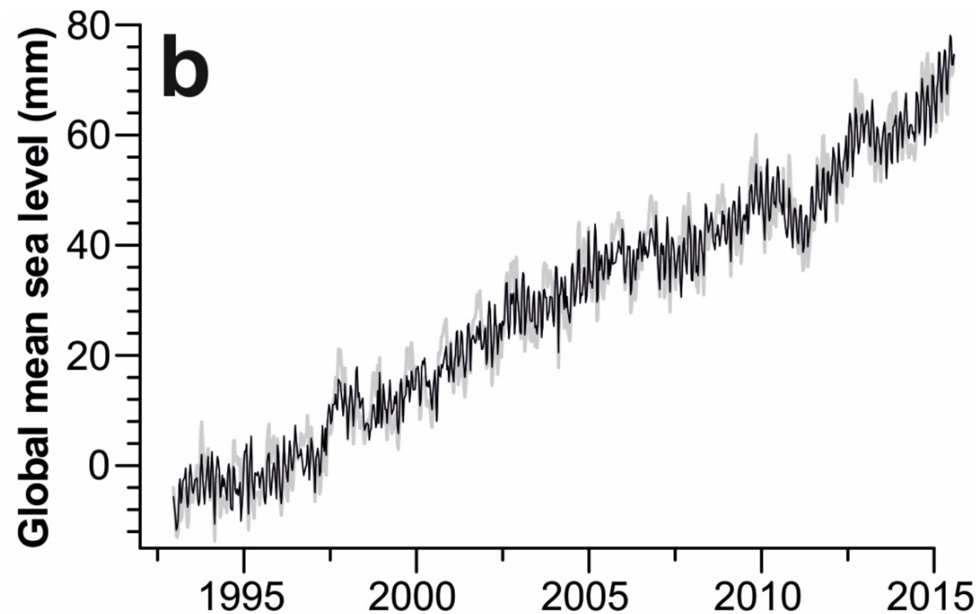


Satellite altimetry



Once corrected for seasonal variations, due for example to ocean currents, and other factors such as glacial isostatic adjustment, the global average of all SSH anomalies can be plotted over time to define the global mean sea level change, which can be considered as the eustatic, globally averaged sea level change

http://sealevel.jpl.nasa.gov/



The paleo record

The common era

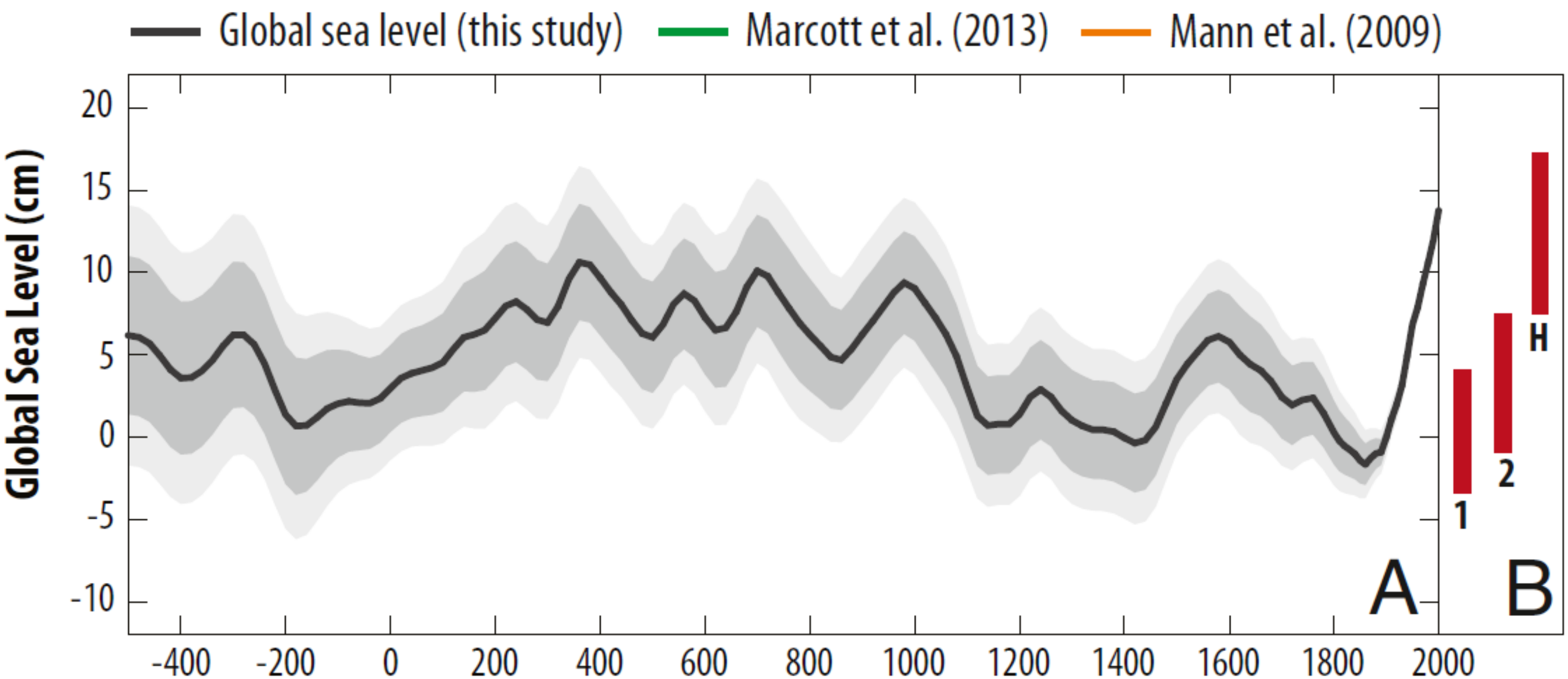
The paleo record

The common era

Temperature-driven global sea-level variability in the Common Era

Robert E. Kopp[a,b,c,1], Andrew C. Kemp[d], Klaus Bittermann[e], Benjamin P. Horton[b,f,g,h], Jeffrey P. Donnelly[i], W. Roland Gehrels[j], Carling C. Hay[a,b,k], Jerry X. Mitrovica[k], Eric D. Morrow[a,b], and Stefan Rahmstorf[e]

[a]Department of Earth & Planetary Sciences, Rutgers University, Piscataway, NJ 08854; [b]Institute of Earth, Ocean & Atmospheric Sciences, Rutgers University, New Brunswick, NJ 08901; [c]Rutgers Energy Institute, Rutgers University, New Brunswick, NJ 08901; [d]Department of Earth & Ocean Sciences, Tufts University, Medford, MA 02115; [e]Earth System Analysis, Potsdam Institute for Climate Impact Research, 14473 Potsdam, Germany; [f]Sea-Level Research, Department of Marine & Coastal Sciences, Rutgers University, New Brunswick, NJ 08901; [g]Earth Observatory of Singapore, Nanyang Technological University, Singapore 639798; [h]Asian School of the Environment, Nanyang Technological University, Singapore 639798; [i]Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543; [j]Environment Department, University of York, York YO10 5NG, United Kingdom; and [k]Department of Earth & Planetary Sciences, Harvard University, Cambridge, MA 02138



The paleo record

The common era

Barack Obama
@BarackObama

Following

We're seeing the fastest rise in sea-levels in nearly 3,000 years: ofa.bo/j9qS #ActOnClimate

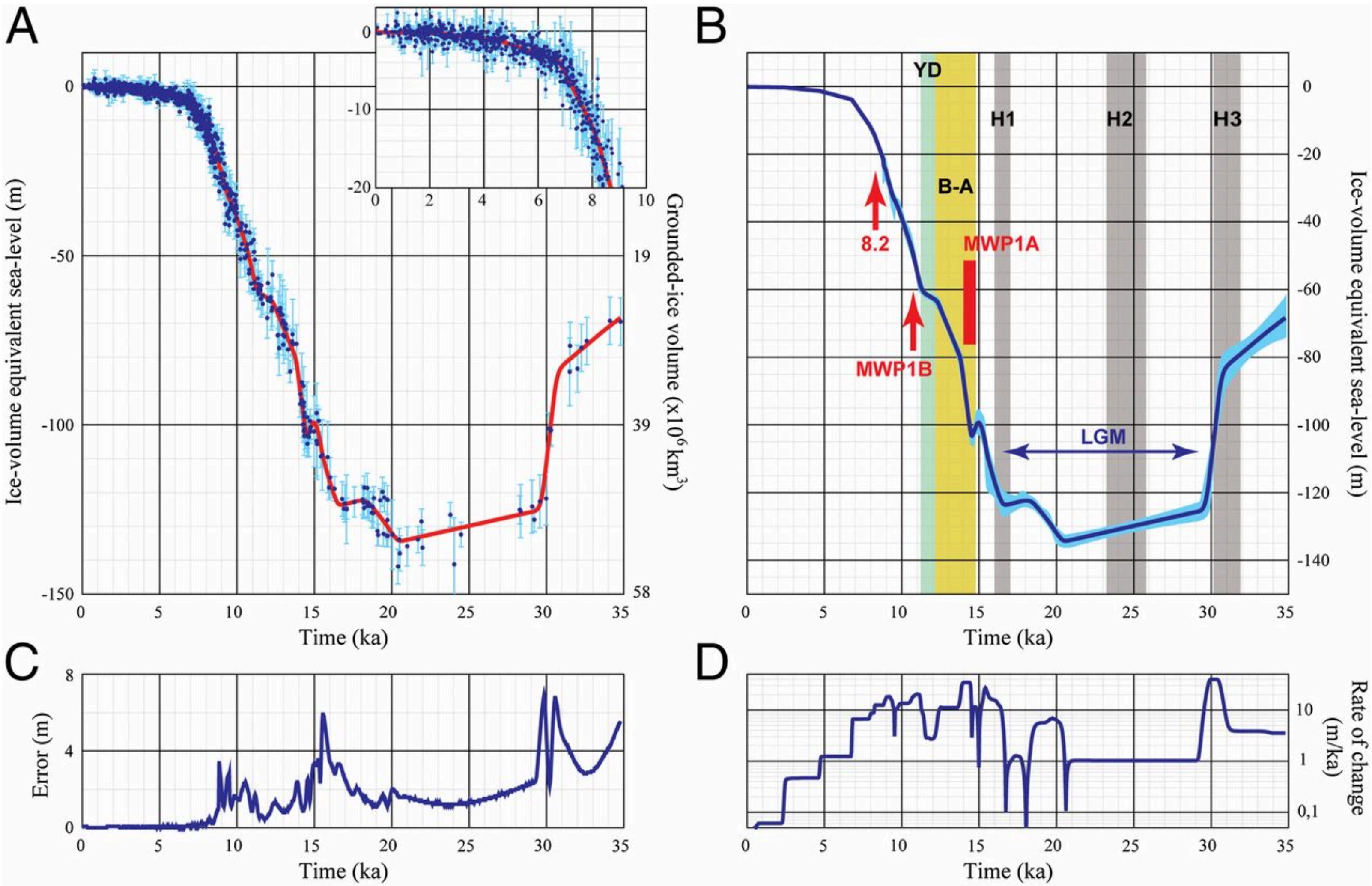
Seas Are Rising at Fastest Rate in Last 28 Centuries

Scientists reported Monday that flooding in coastal communities was largely a result of greenhouse gas emissions, and likely to grow worse.

nytimes.com

The paleo record

The Holocene - deglacial

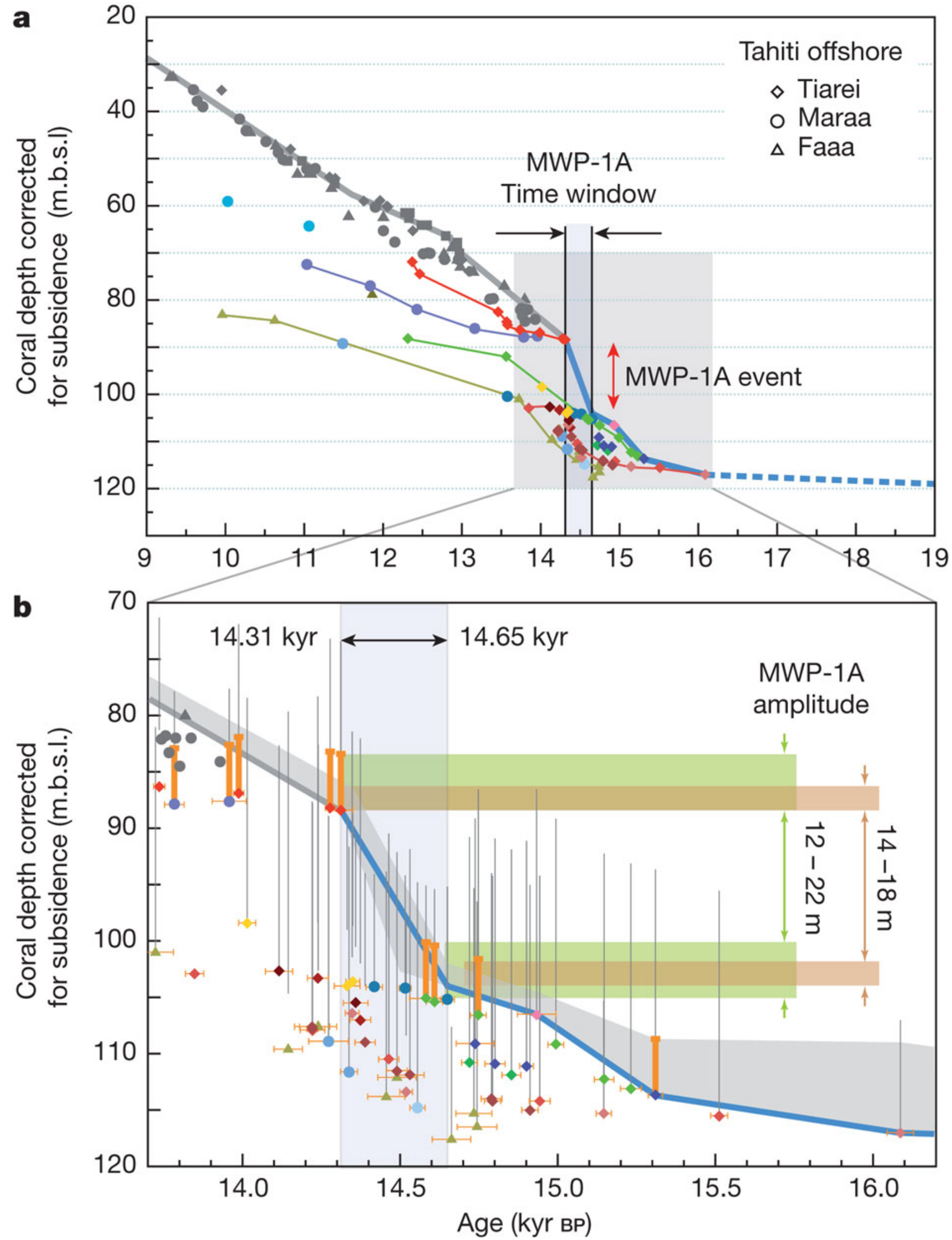


Lambeck et al., 2014, PNAS

The paleo record

The Holocene - deglacial

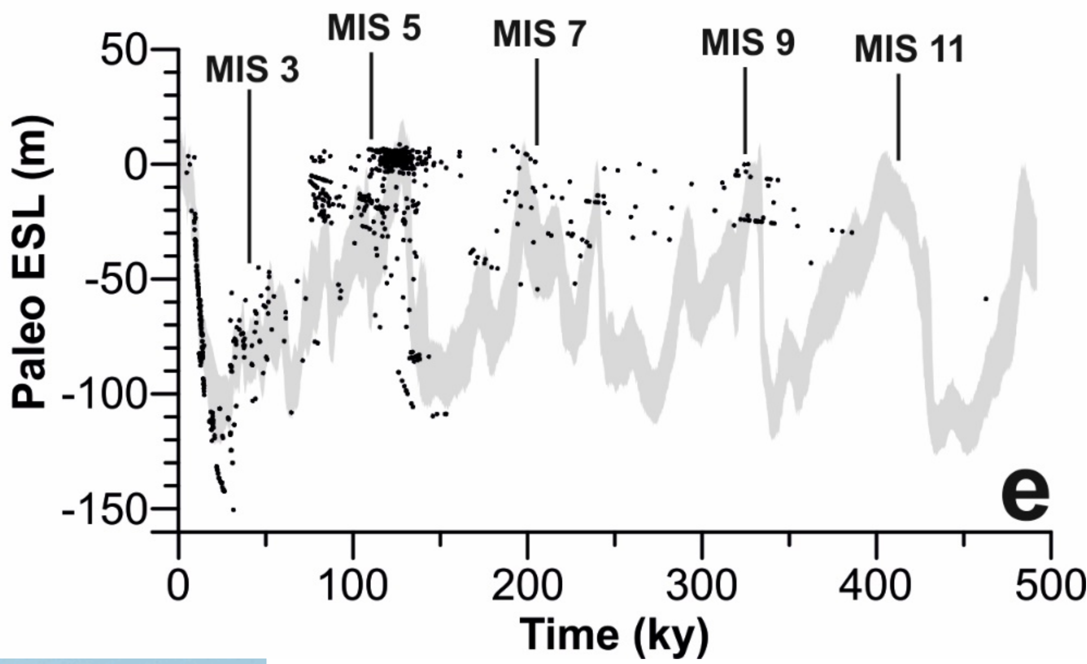
Meltwater pulses

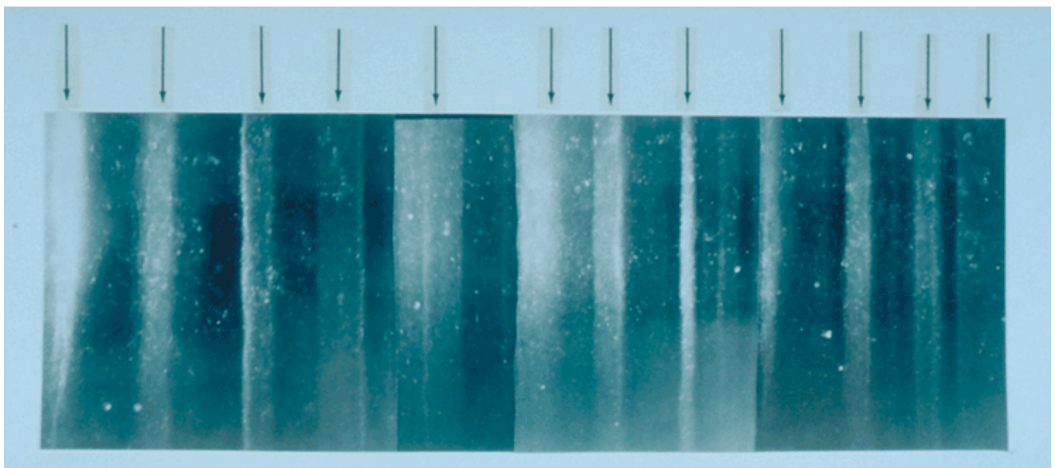


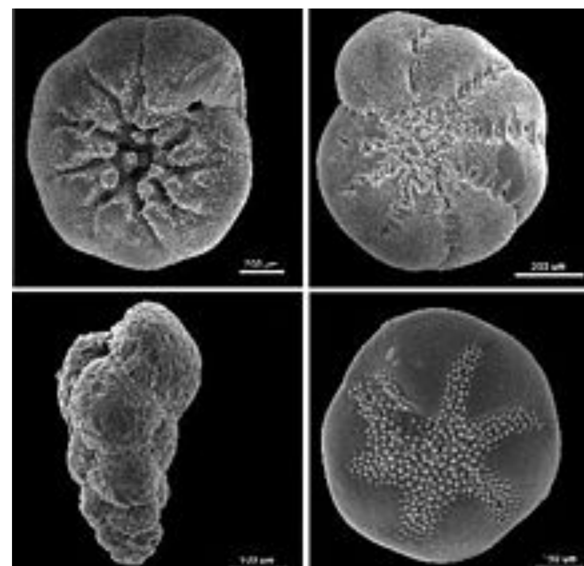
Deschamps et al., 2012, Nature

The paleo record

The Pleistocene

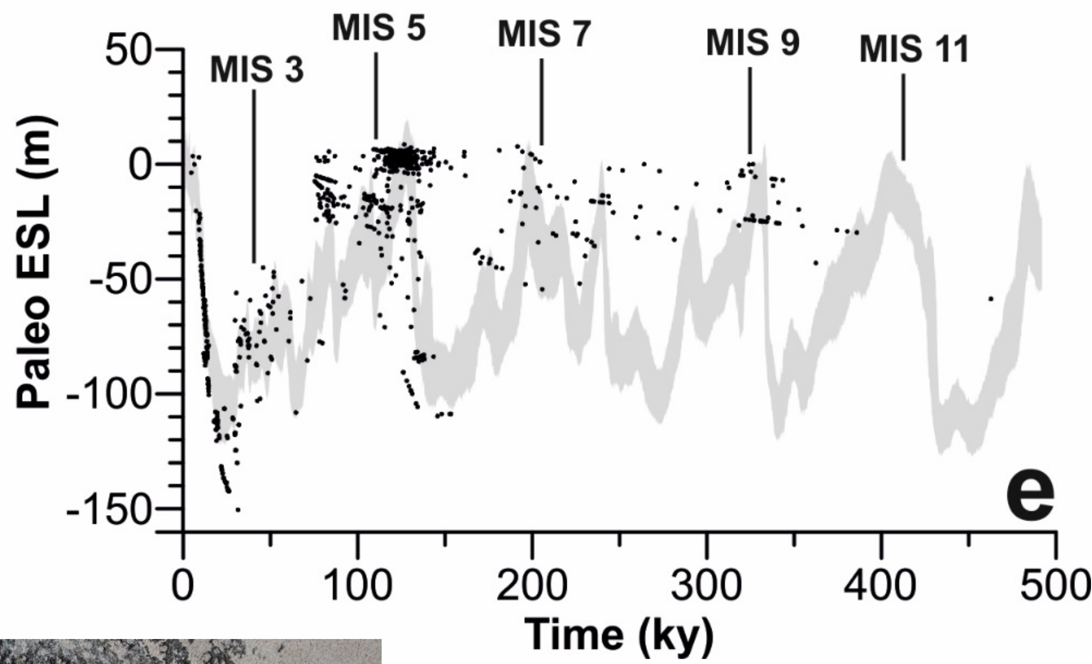


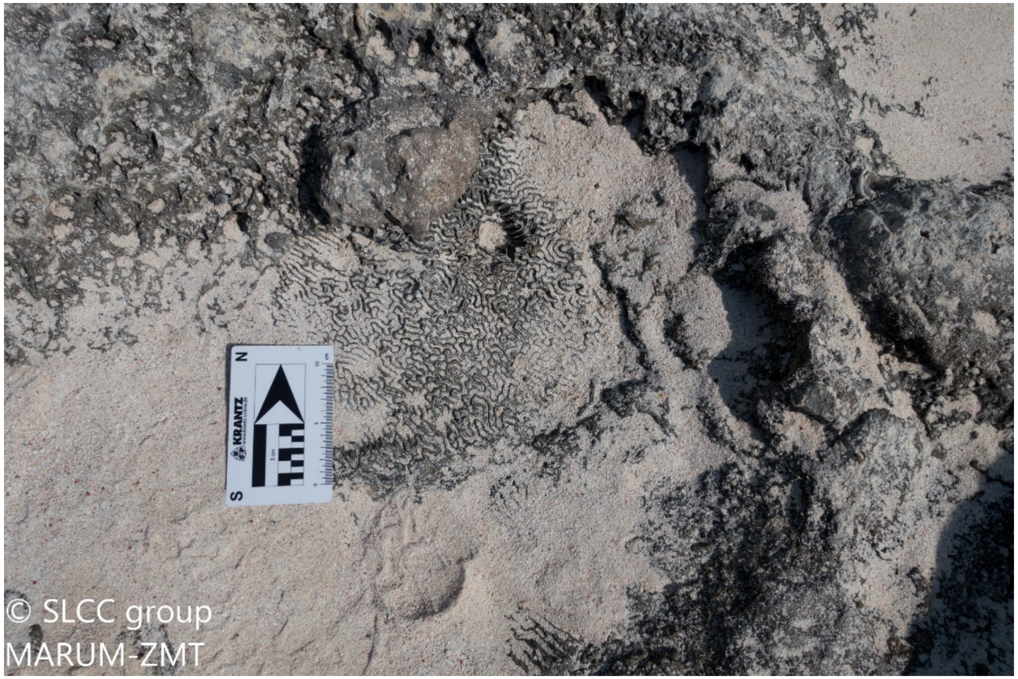




The paleo record

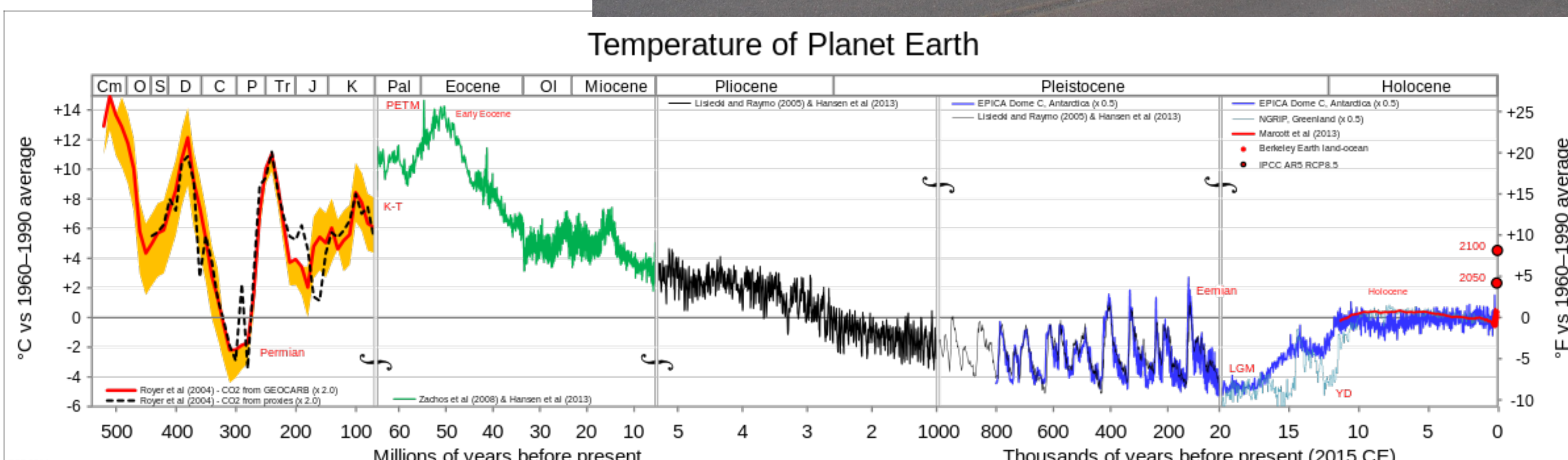
The Pleistocene





The paleo record

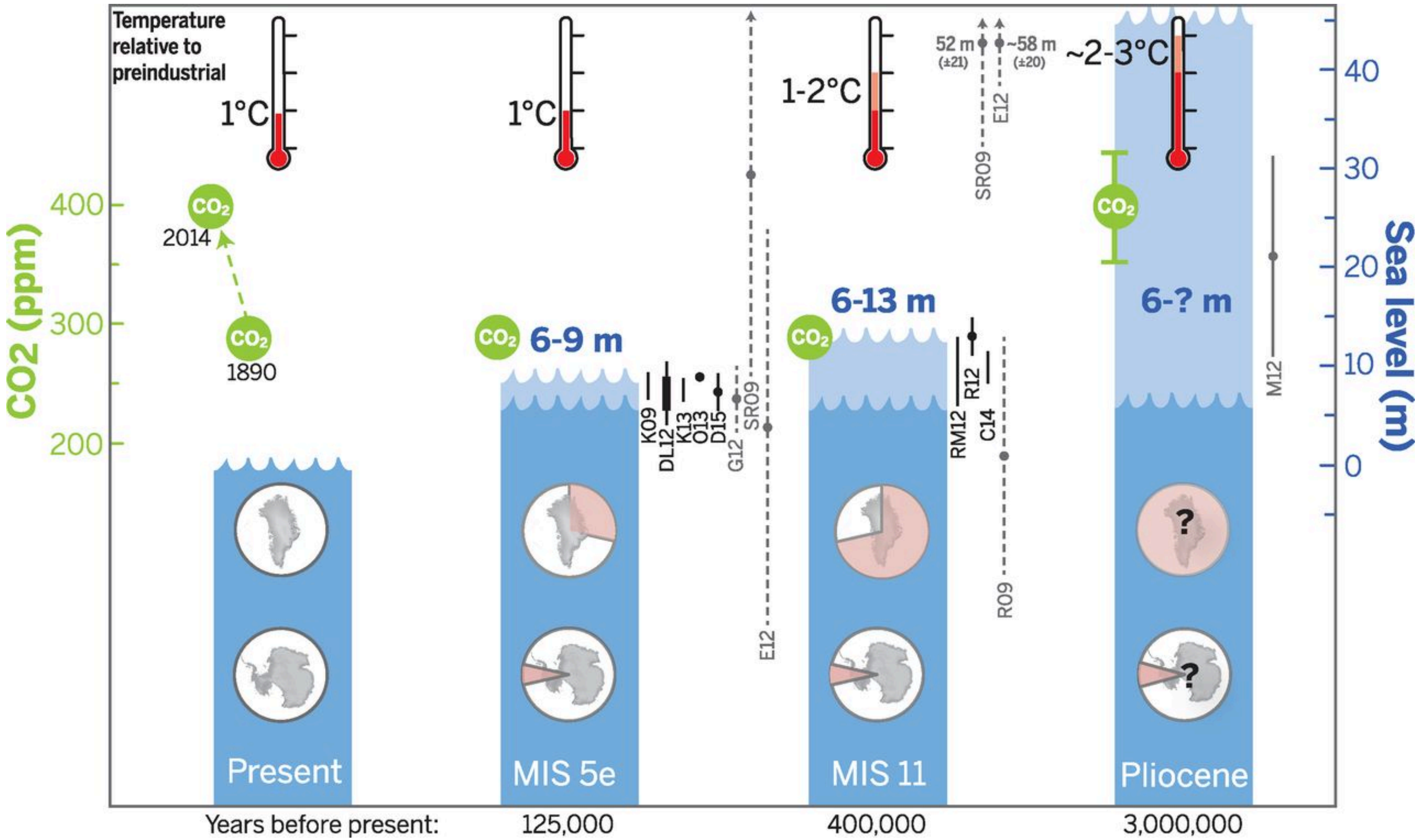
The paleo record



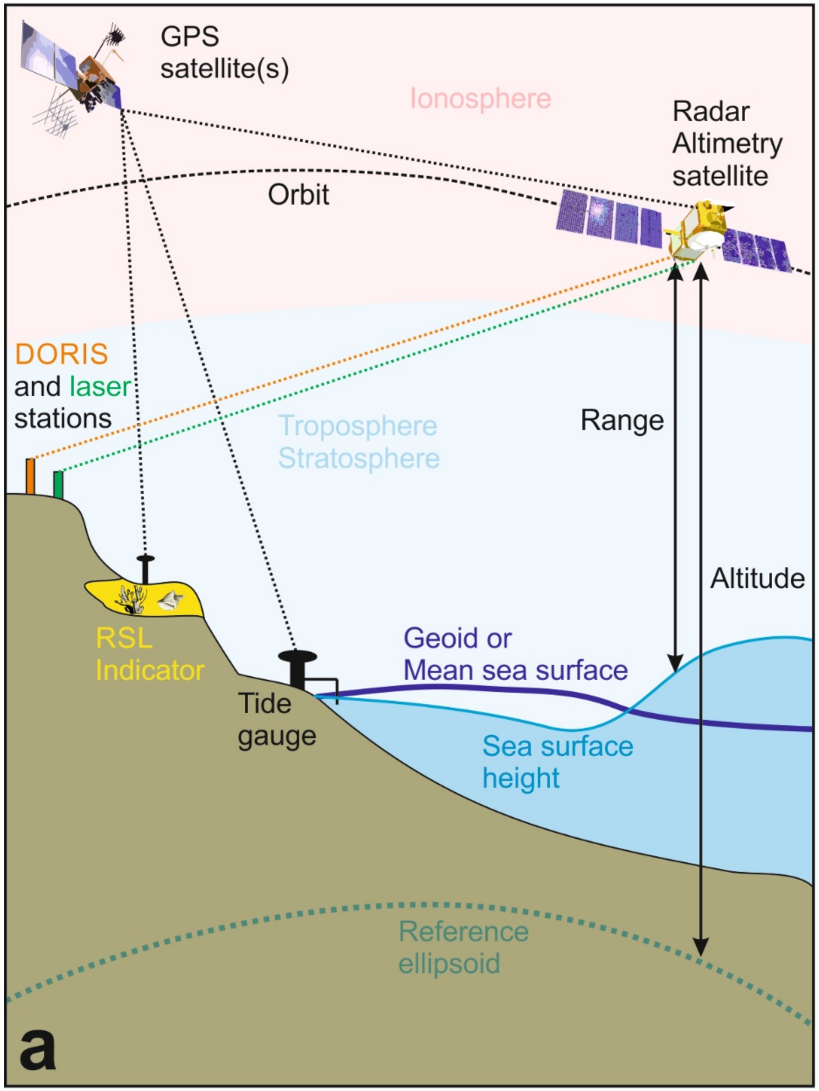
The paleo record

The paleo record

The paleo record

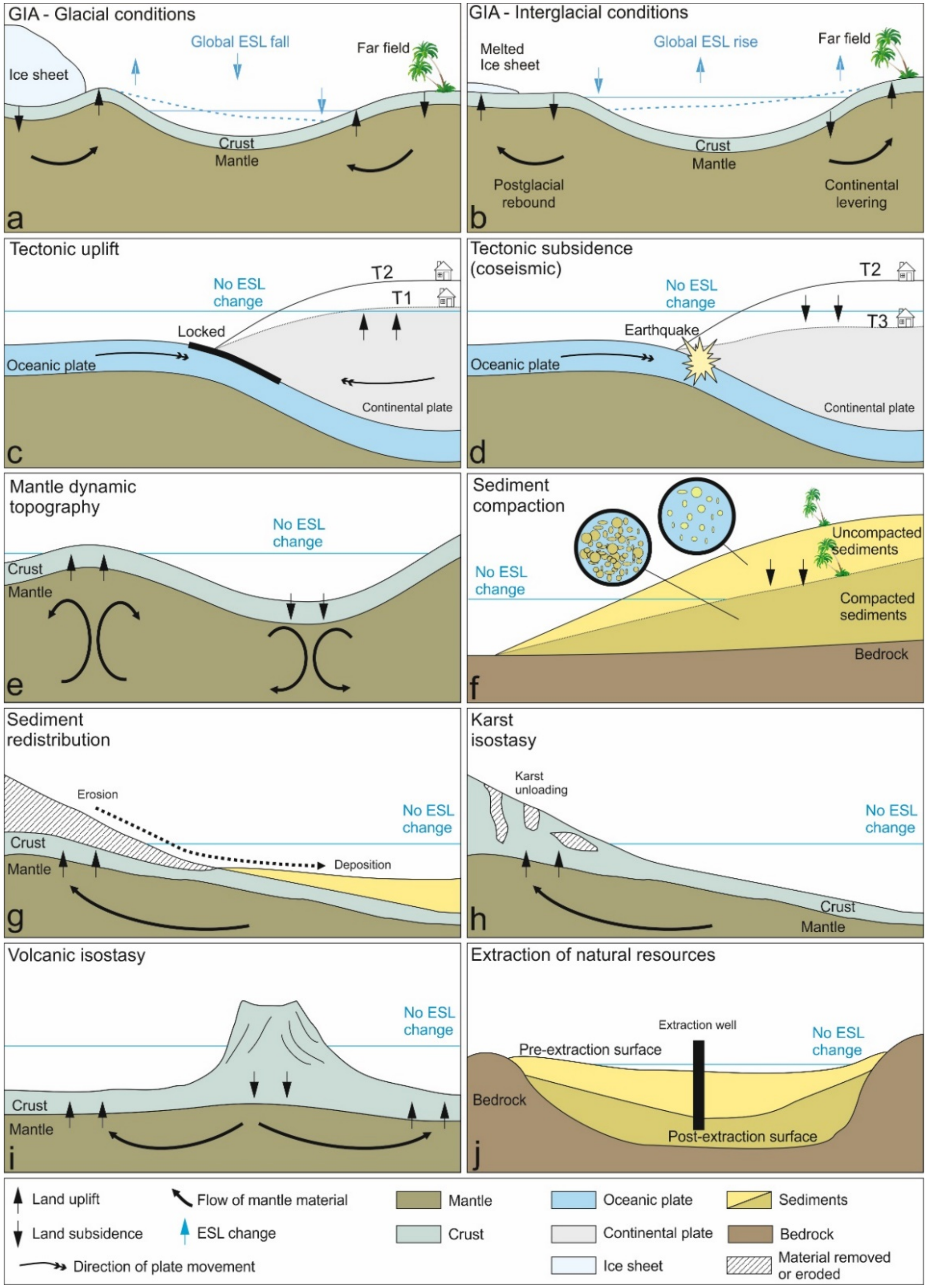


Dutton et al., 2015, Science



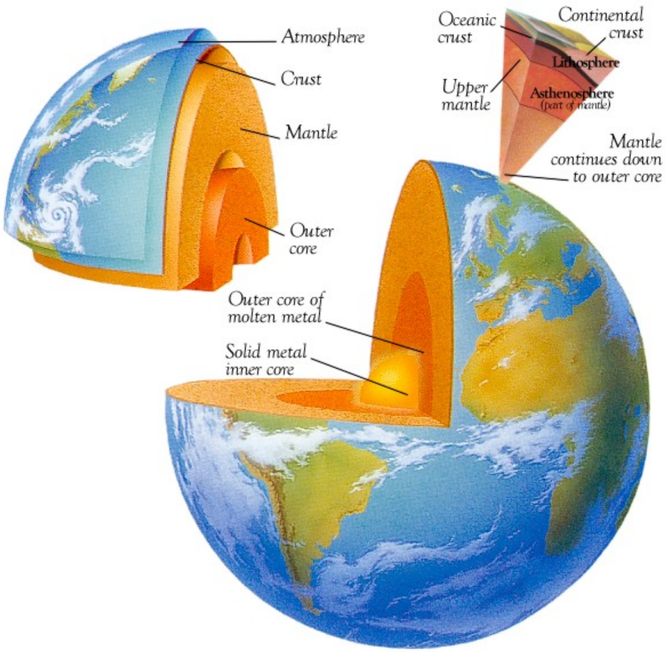
Every sea level measurement is a measurement of Relative sea level change, not Eustatic.

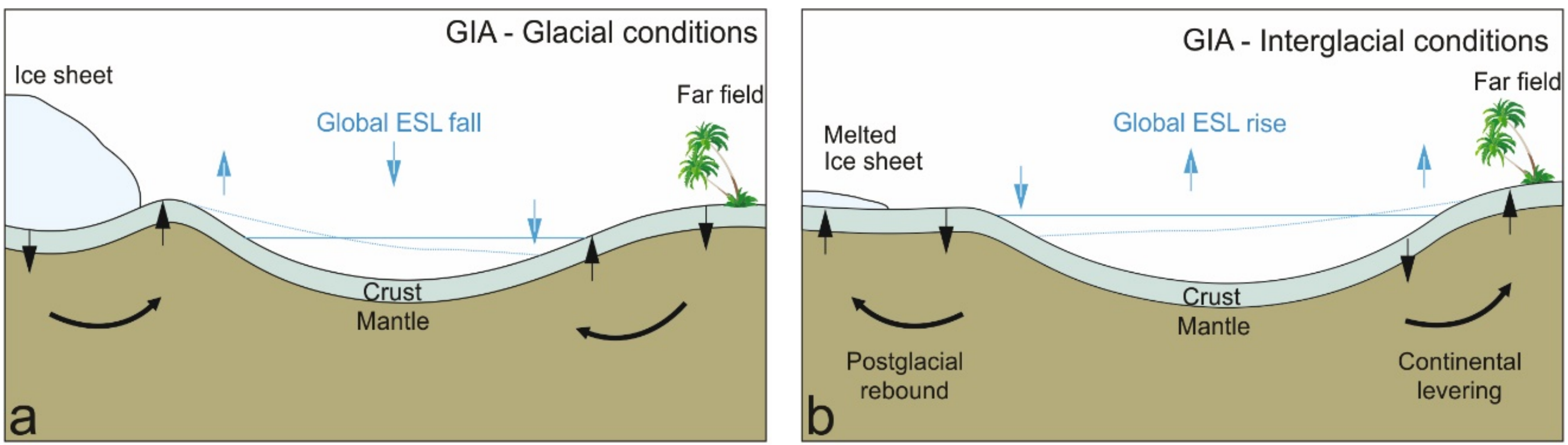
This means that every measure has to be corrected for many factors before being considered representative of eustasy (i.e. ice volume)



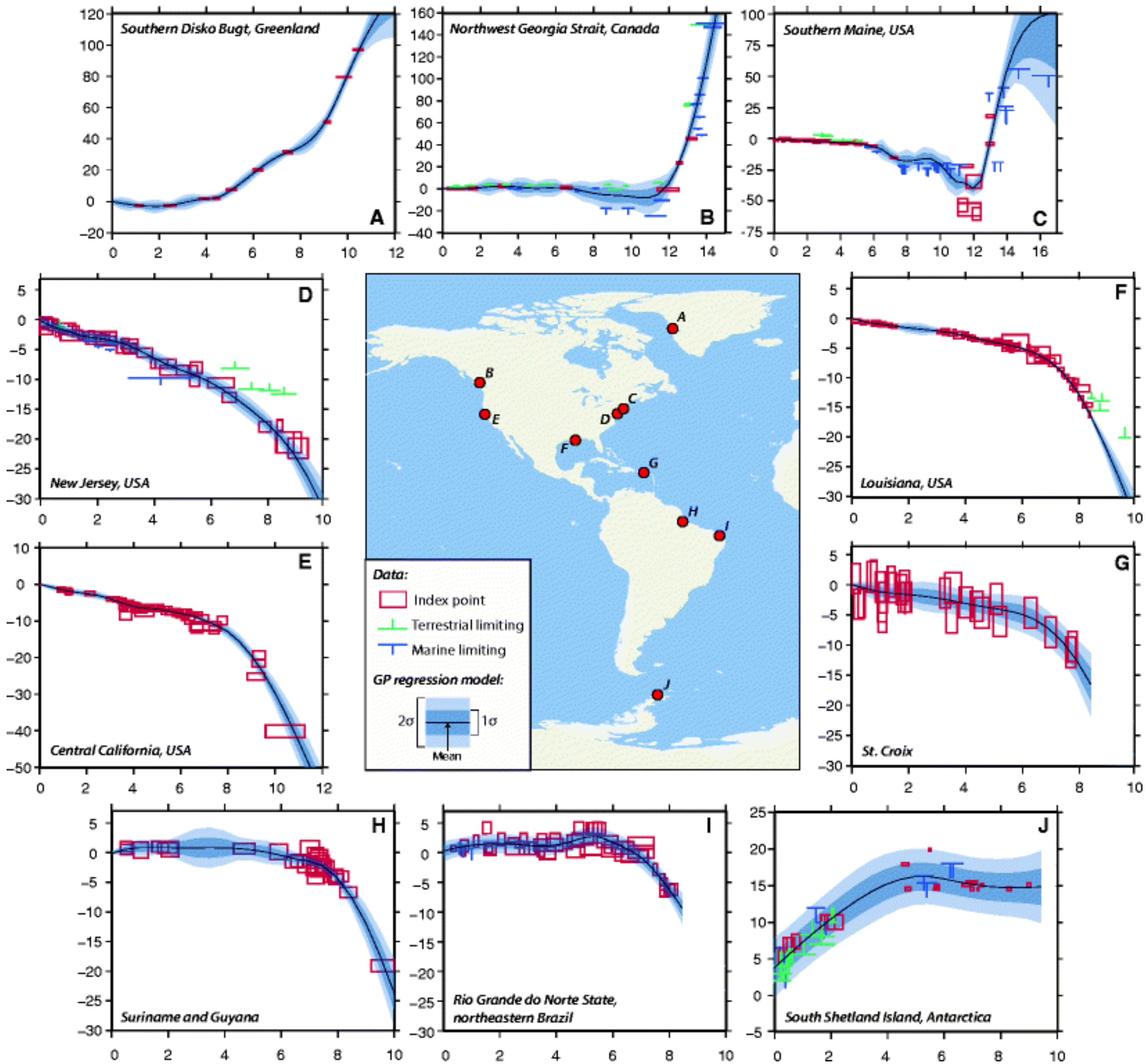
GIA: glacial isostatic adjustment

Isostasy


Atmosphere
Crust
Mantle
Outer core
Outer core of molten metal
Solid metal inner core
Oceanic crust
Continental crust
Lithosphere
Upper mantle
Asthenosphere (part of mantle)
Mantle continues down to outer core

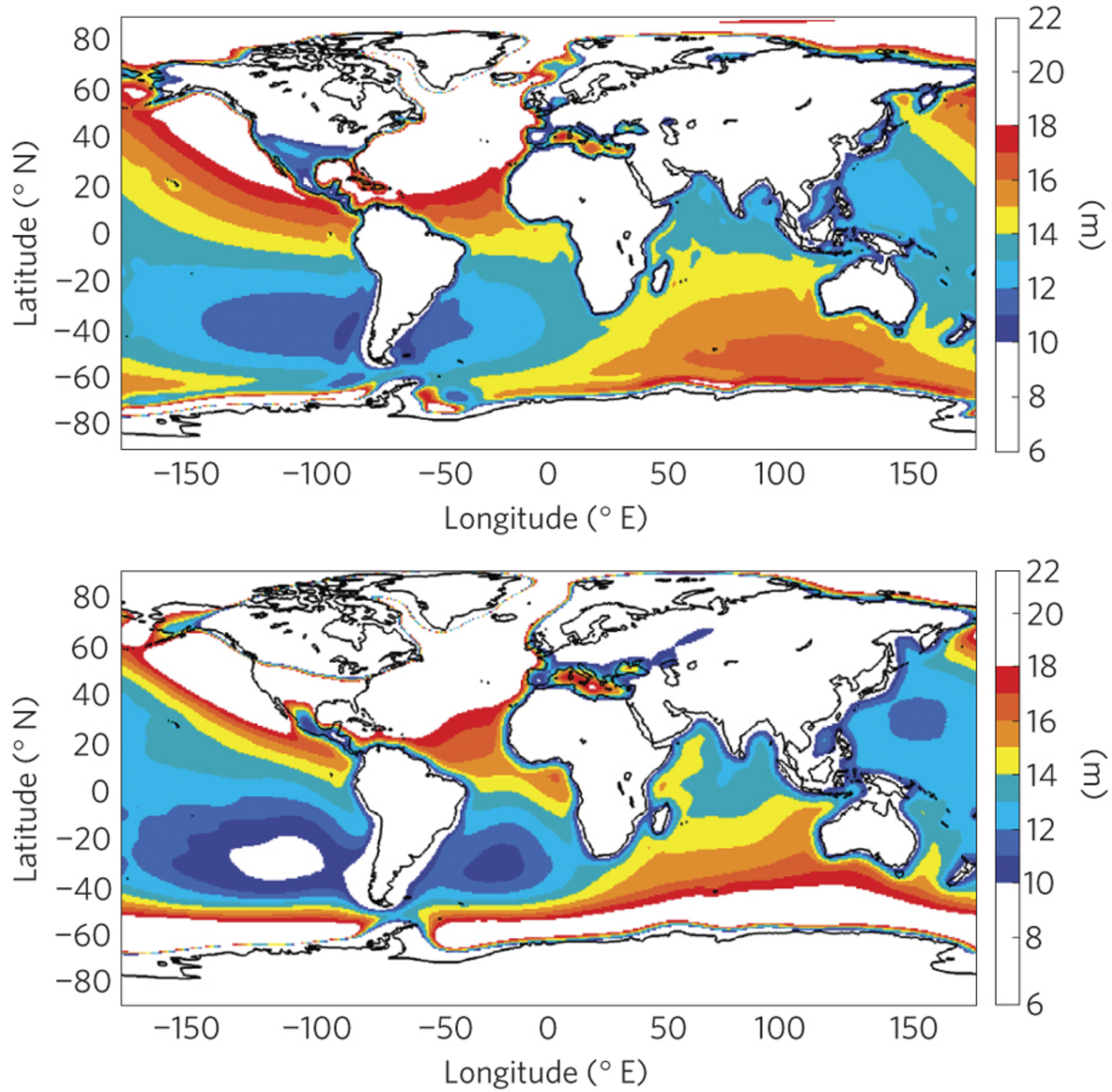

GIA - Glacial conditions
Ice sheet
Global ESL fall
Far field
Crust
Mantle
a
GIA - Interglacial conditions
Melted Ice sheet
Global ESL rise
Far field
Crust
Mantle
Postglacial rebound
Continental levering
b

Isostasy



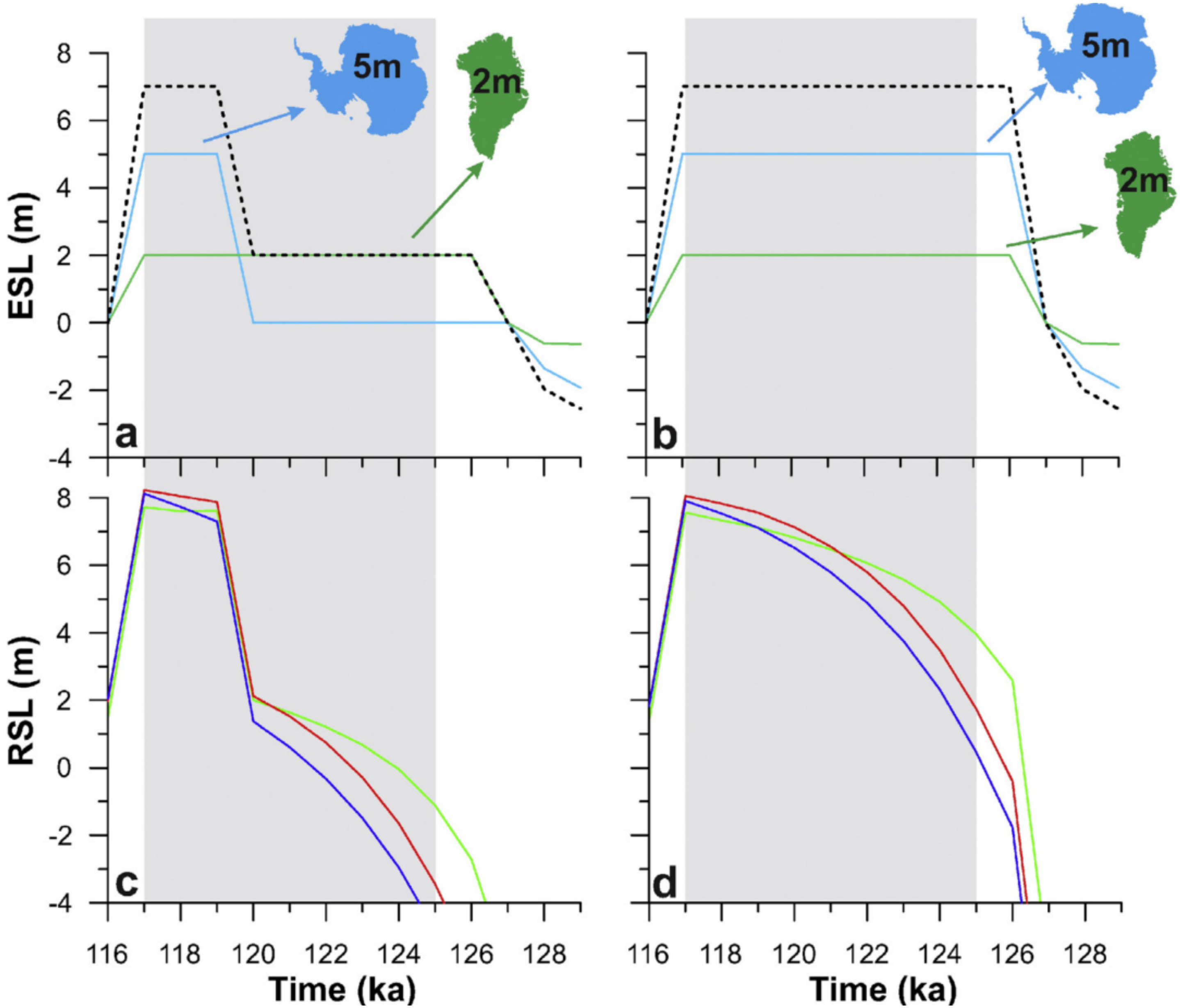
Khan et al., 2015, Current Climate Change Reports

Isostasy



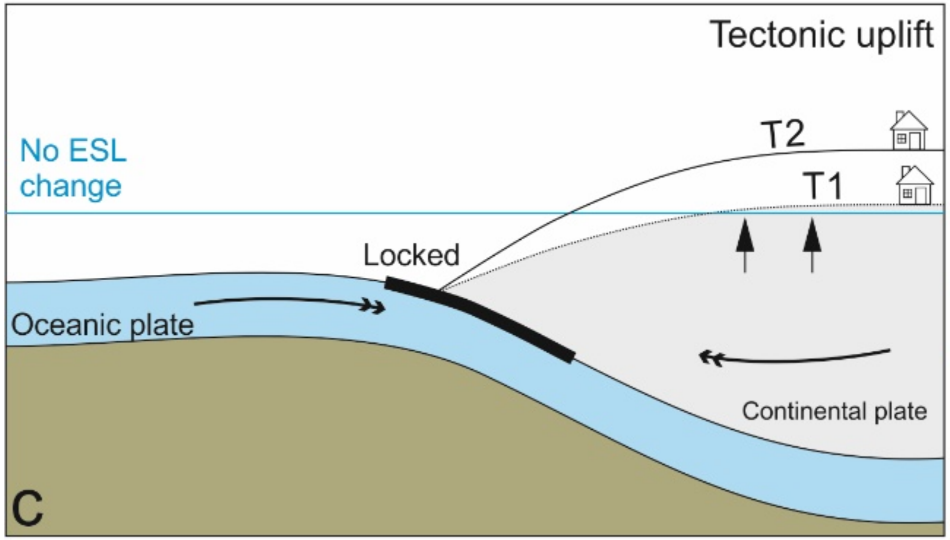
Departures from eustasy in Pliocene sea-level records
Maureen E. Raymo, Jerry X. Mitrovica, Michael J. O'Leary, Robert M. DeConto Paul J. Hearty
Nature Geoscience **4**, 328–332´(2011)

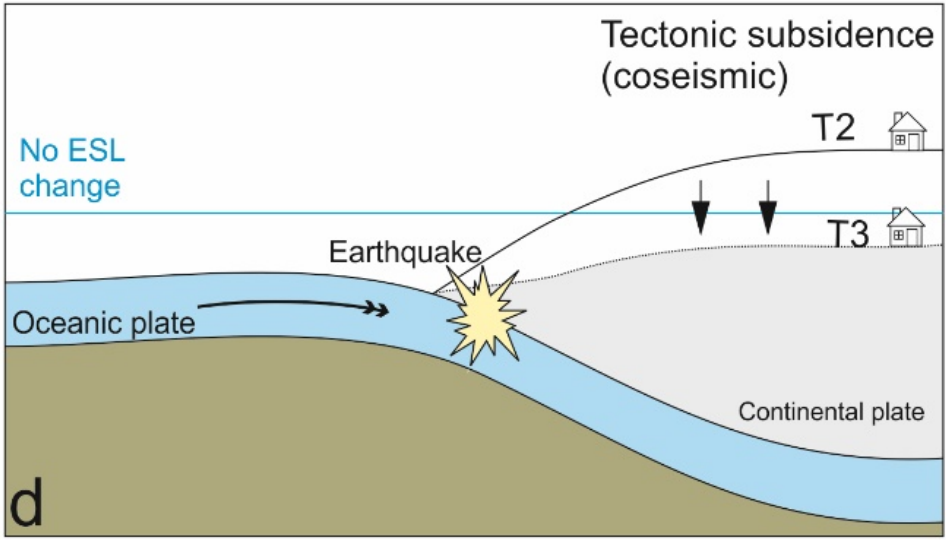
Isostasy

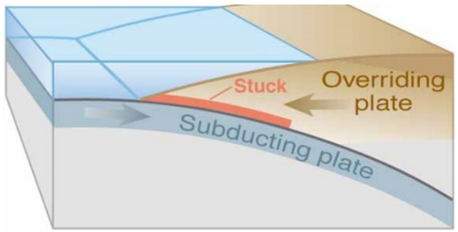


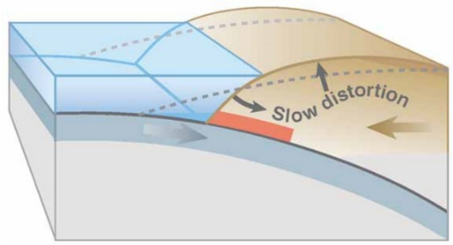
5m
2m
5m
2m
ESL (m)
RSL (m)
a
b
c
d
8
6
4
2
0
-2
-4
116
118
120
122
124
126
128
Time (ka)
Time (ka)

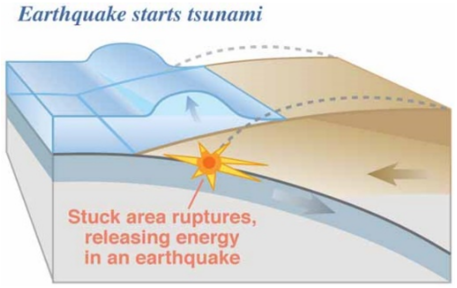
Tectonics











Credits: USGS

Tectonics

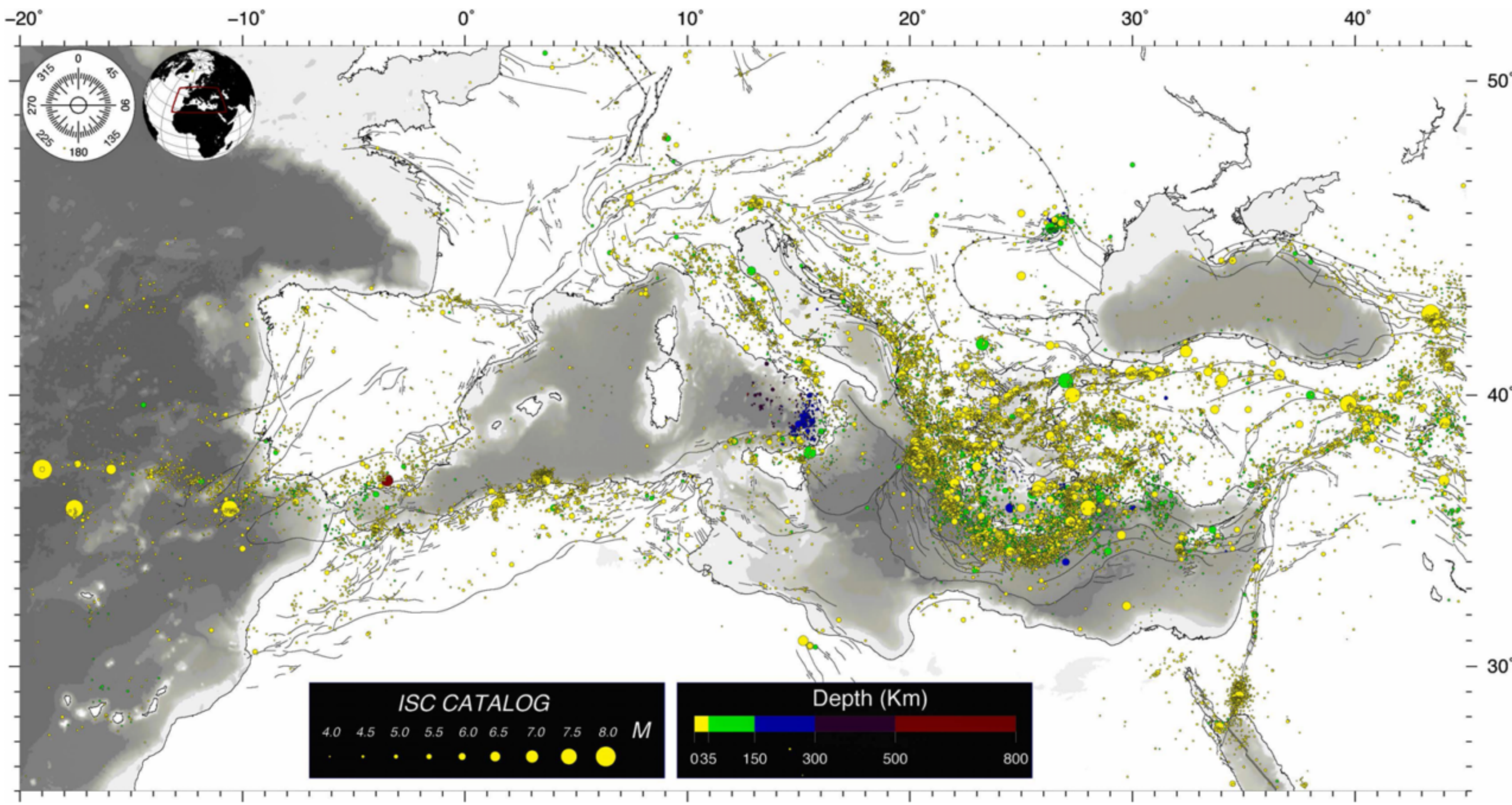
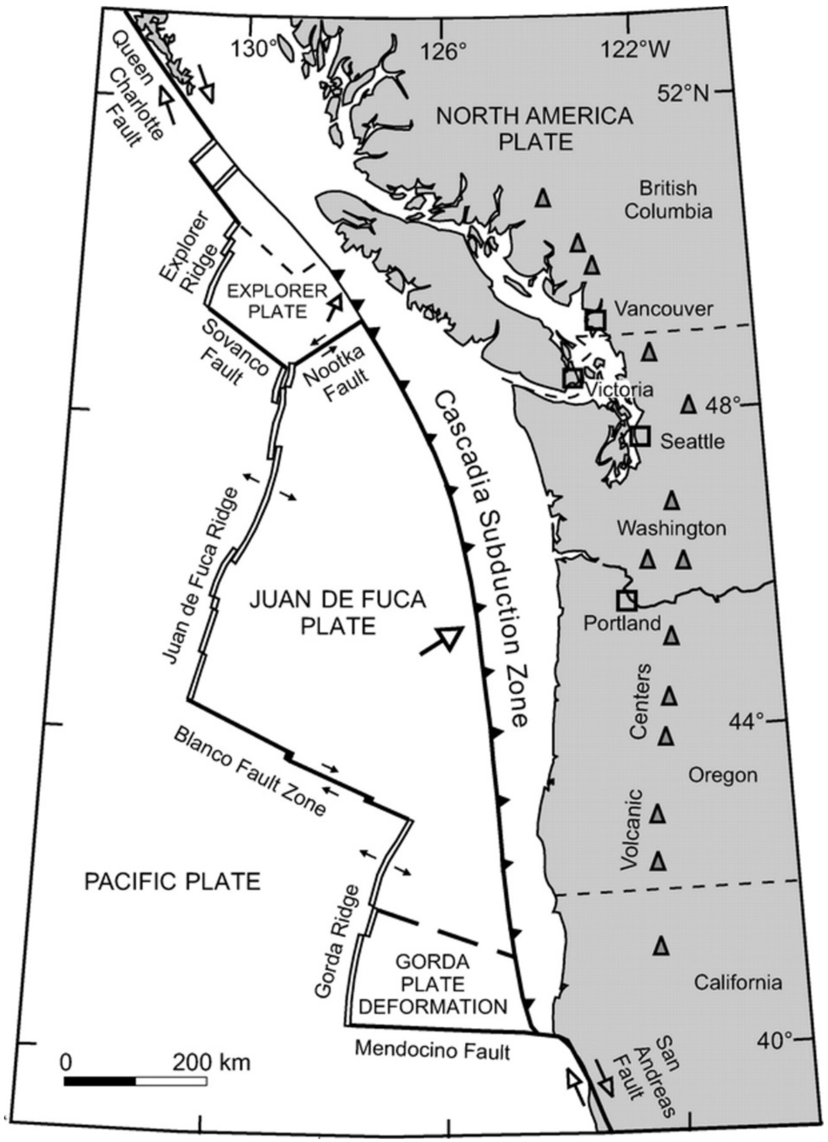


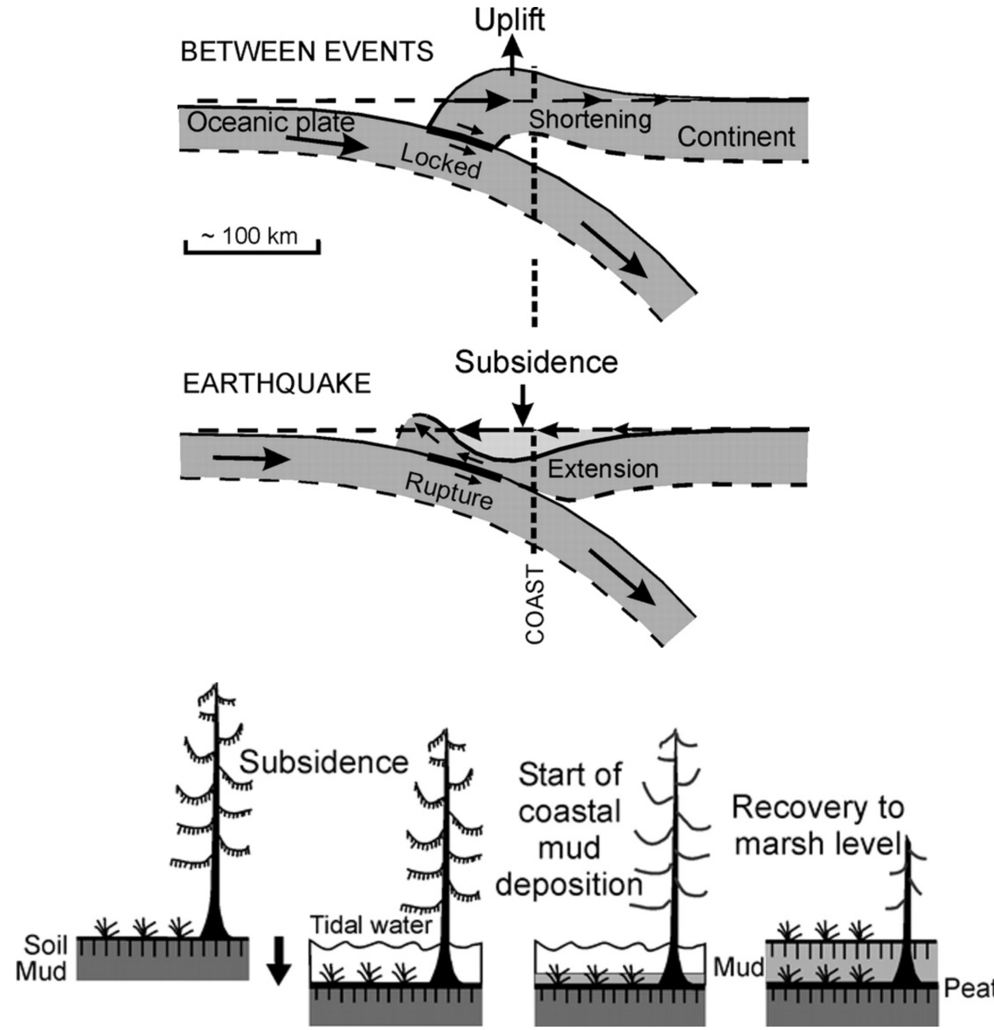
Fig. 5. Seismicity ($M > 4$) of the Mediterranean basin in the time span 1900–2012 from the International Seismological Centre, on-line catalogue (ISC 2001, http://www.isc.ac.uk/).

Tectonics

Mavrolimni port in the northern coast of Perachora peninsula before and after the earthquake of 1981. The sea level change was instantaneous by 0.80m. Courtesy Dr. Nikos Mourtzas

Tectonics

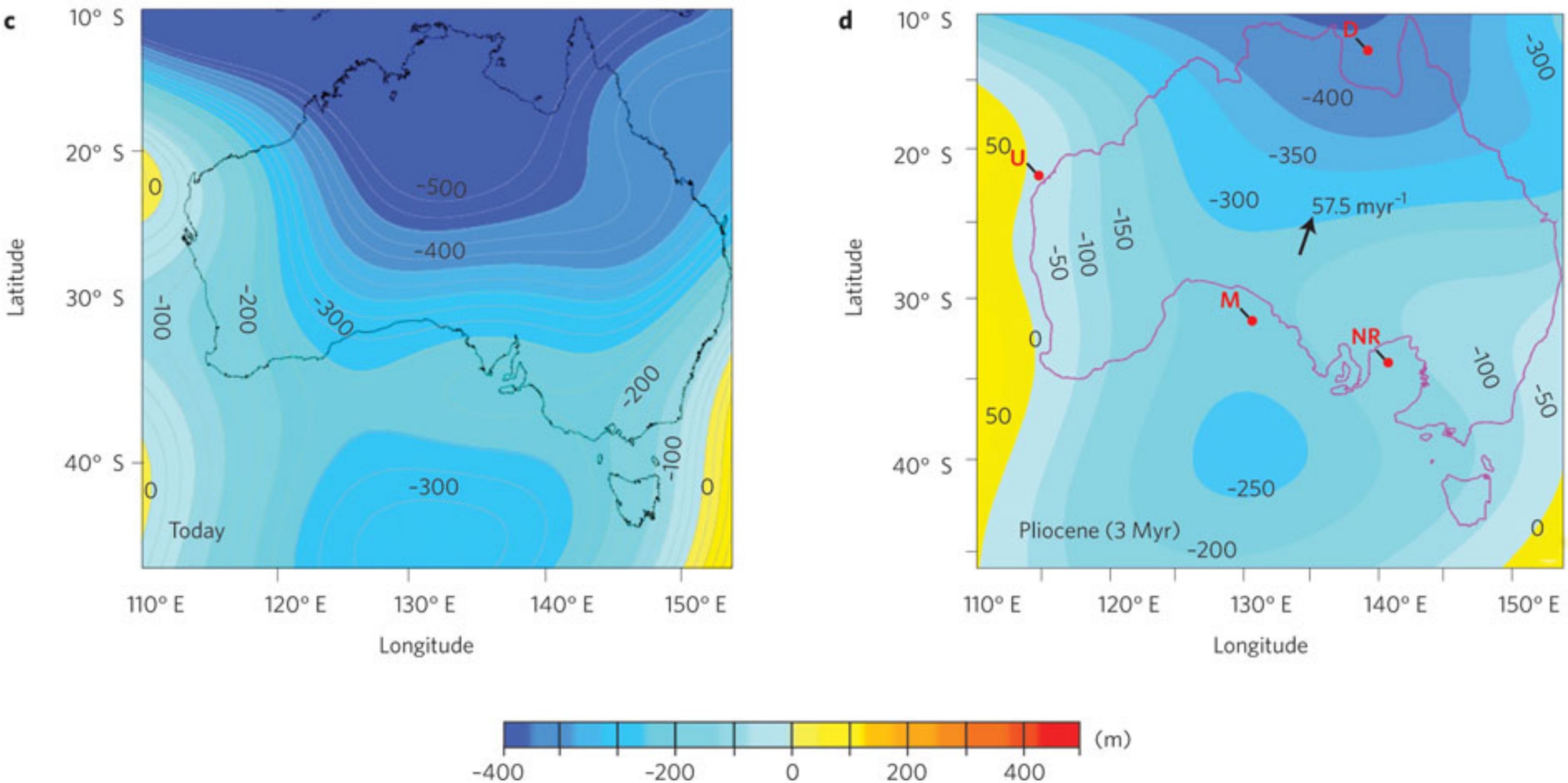




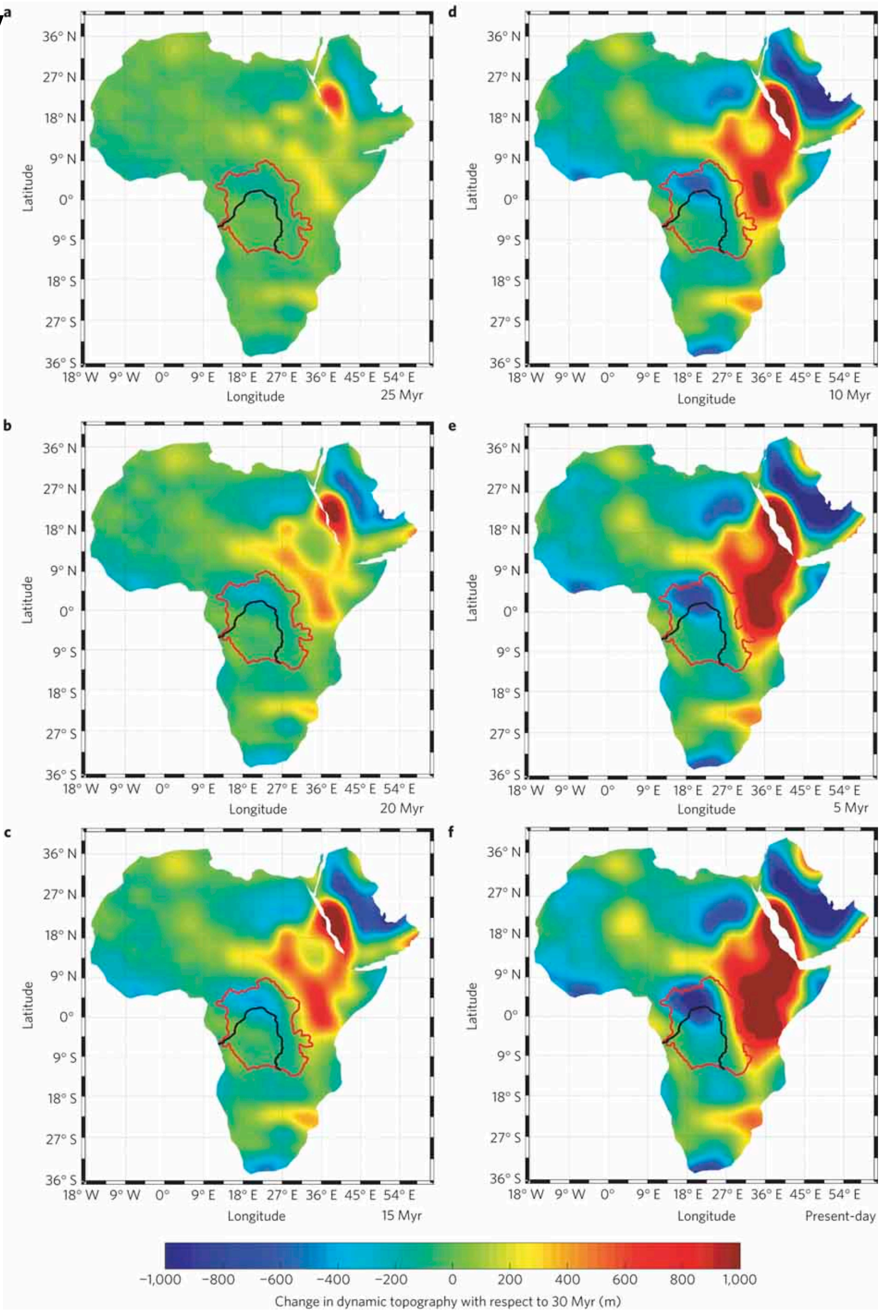
Leonard L J et al. Geological Society of America Bulletin 2004;116:655-670

Dynamic topography

[The many surface expressions of mantle dynamics]
•[Jean Braun]
Nature Geoscience **3**, 825–833 (2010) doi:10.1038/ngeo1020

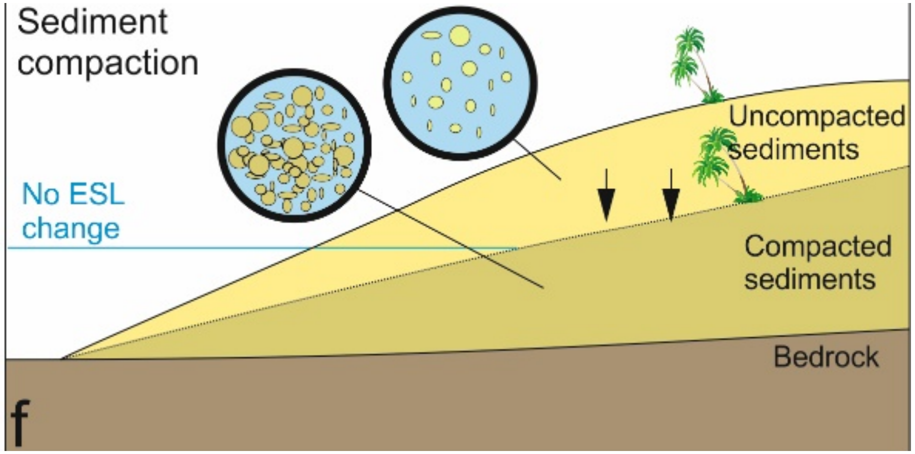


Dynamic topography



[Changes in African topography driven by mantle convection](#)
[Robert Moucha](#) & [Alessandro M. Forte](#)
Nature Geoscience **4**, 707–712 (2011)

Sediment compaction

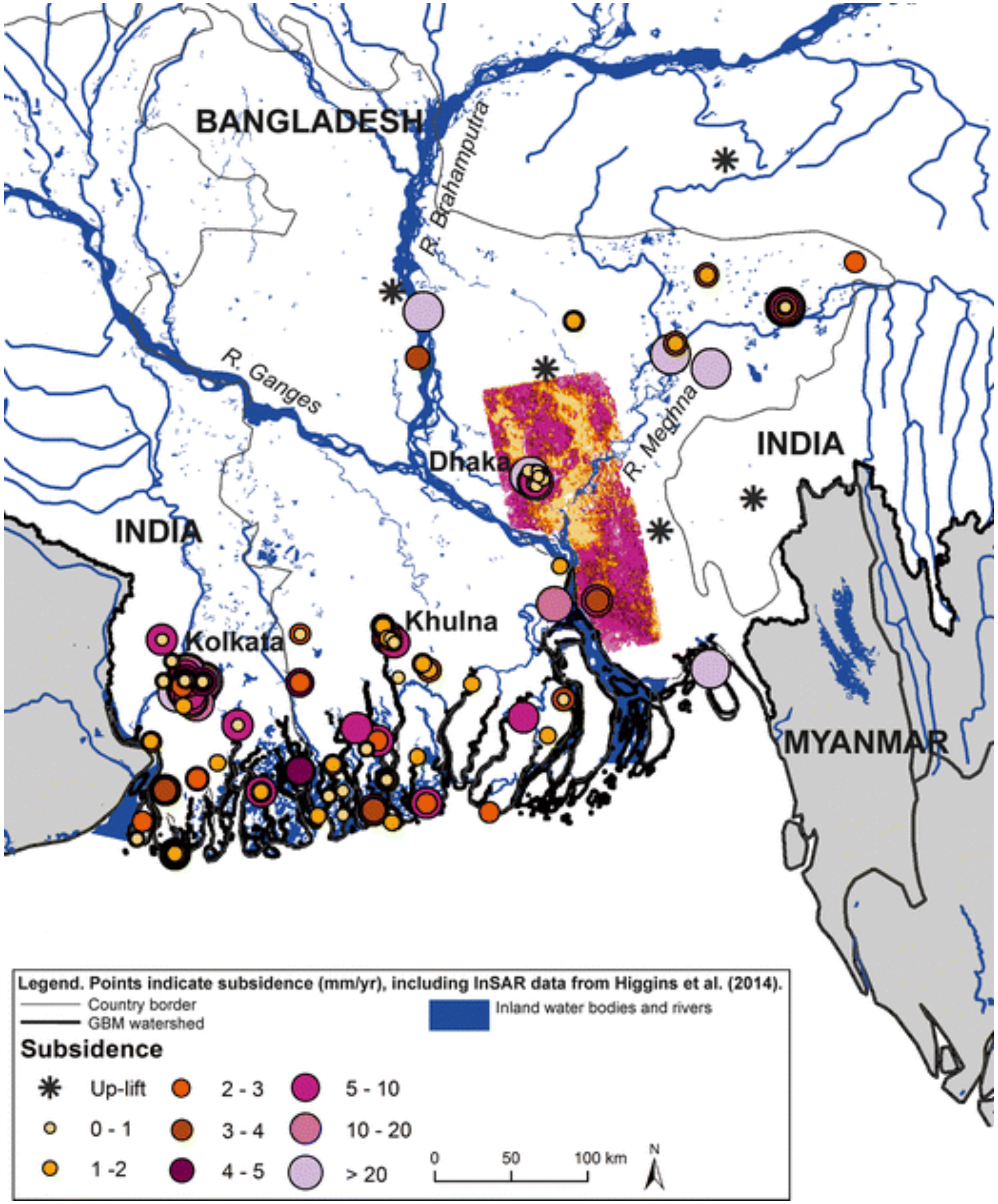


From Brain et al., 2016, Current Climate Change Reports:

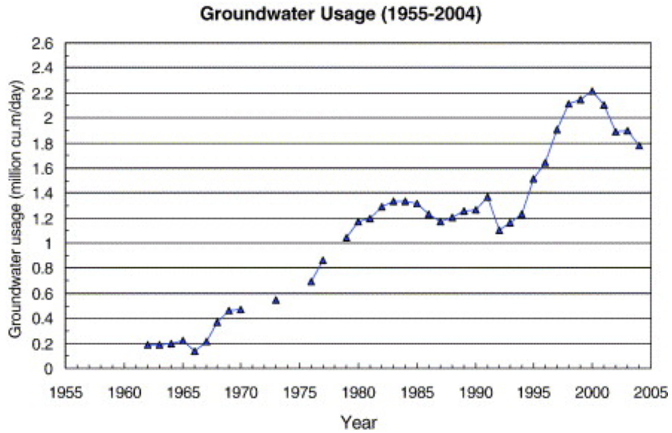
Compaction describes a range of natural syn- and post-depositional processes that reduce the volume of sediments deposited in low-lying coastal areas, causing land-level lowering (i.e. subsidence). This can occur as a result of stress- and time-dependent mechanical compression processes that reduce pore space and increase bulk density. Compression processes include consolidation, which describes the expulsion of pore water from sediment interstices in response to burial by overburden sediments or from self-weight and creep, which describes ongoing viscous rearrangement of sediment particles. Predominantly organic sediments and peat deposits can also undergo florally and faunally mediated biochemical degradation, which can increase mass loss and can change the compressive strength of sediments. Compaction operates at various depths below ground level, and so a distinction is often made between near-surface (depths of ≤10 m or so below ground level) 'shallow subsidence', typically occurring in deposits of Holocene age and deeper sediment compaction in pre-Holocene sediments. Compaction can be accelerated by anthropogenic activity, notably through land drainage and exploitation of aquifers and hydrocarbon reserves.

Sediment compaction

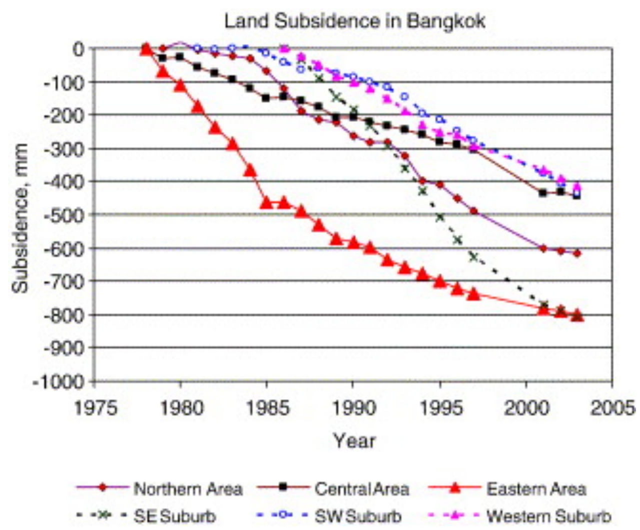
From Brain et al., 2016, Current Climate Change Reports



Sediment compaction



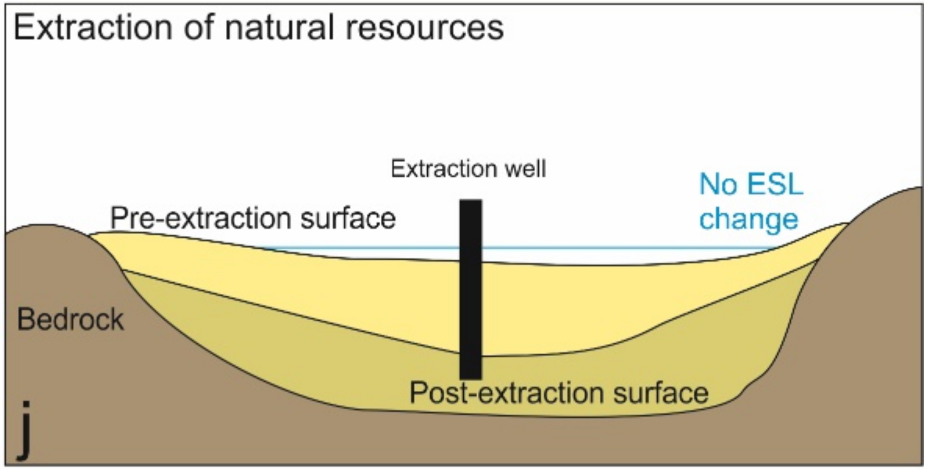
Groundwater pumping rate in the Bangkok Plain versus time.

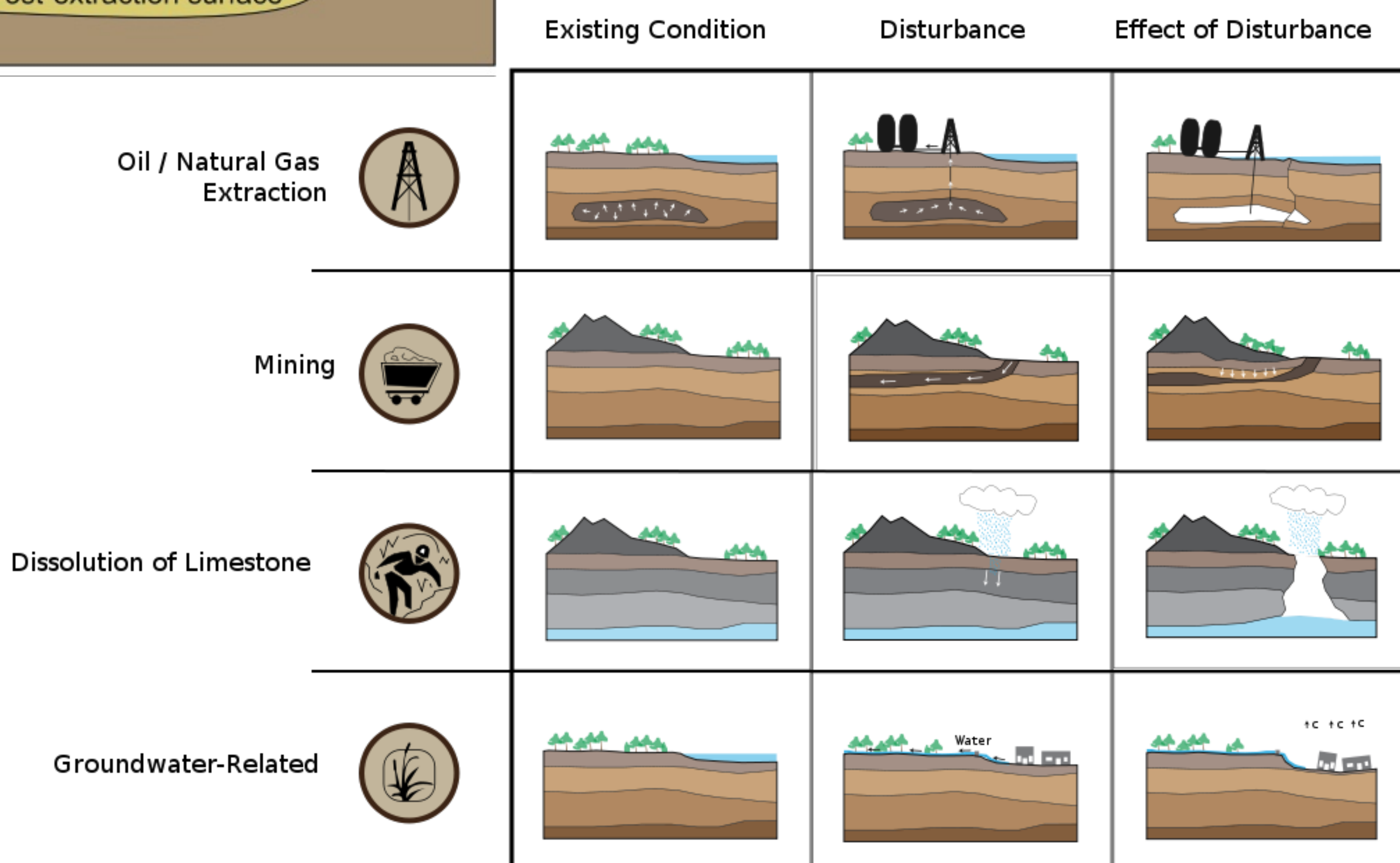


Land subsidence versus time in different areas of Bangkok.

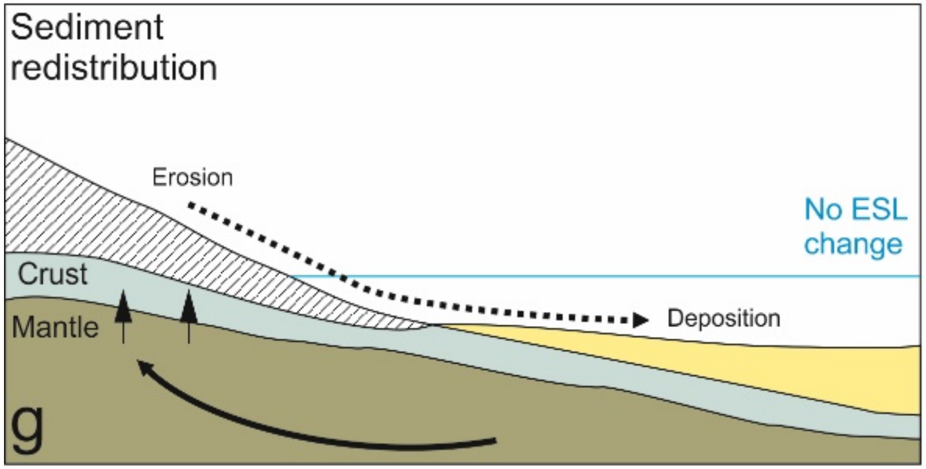
N. Phien-wej , P.H. Giao , P. Nutalaya
Land subsidence in Bangkok, Thailand
Engineering Geology, Volume 82, Issue 4, 2006, 187 - 201

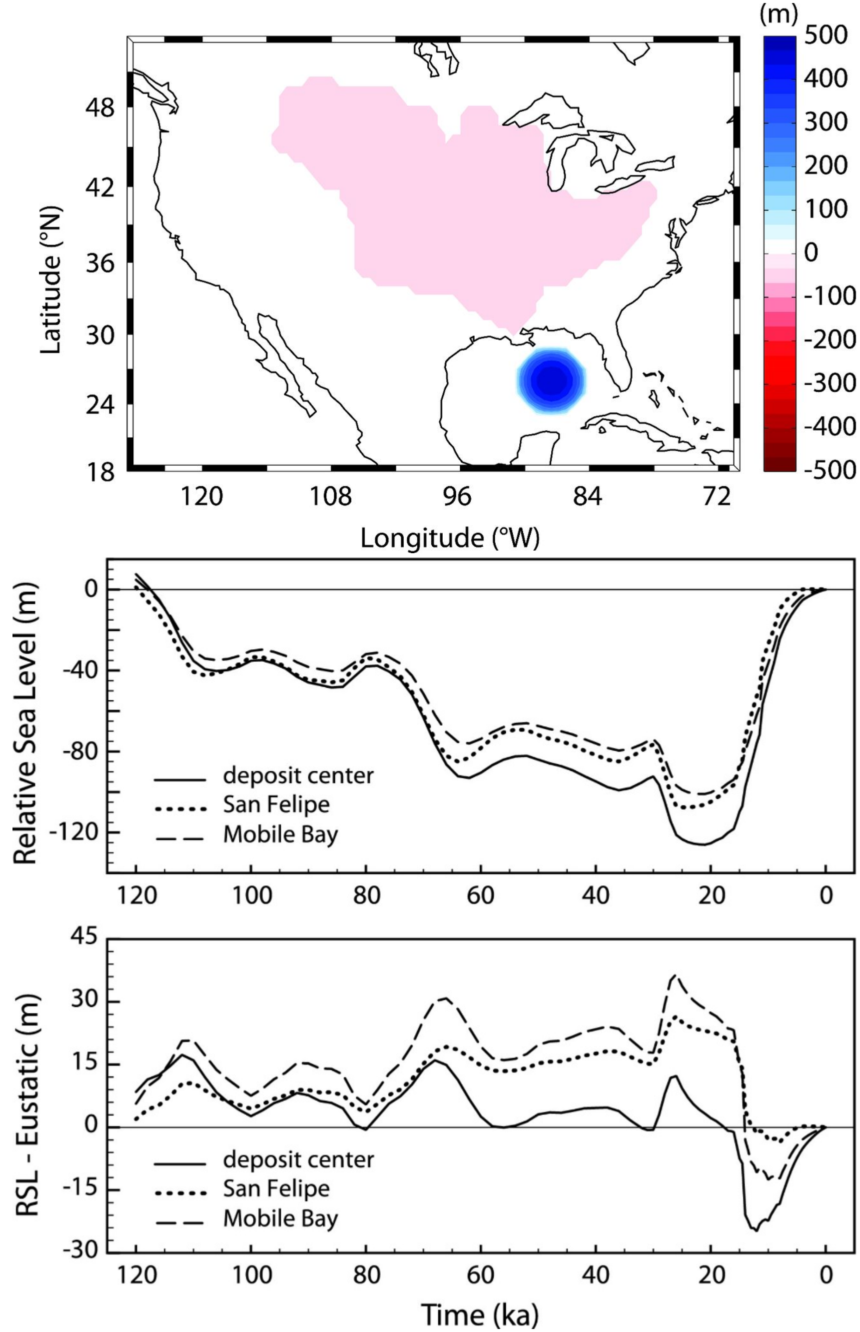
Other subsidence factors





Other isostatic factors





Dalca A V et al. Geophys. J. Int. 2013;194:45-60

Take home message: every sea level record is a record of a relative sea level change, that must then be corrected to estimate eustatic sea level changes

Observed=Eustatic+GIA+PostDep

Relative sea level indicators

Definitions

Any stratigraphic horizon, landform, or paleo-biologic indicator of past sea-level is called an RSL indicator (or sea level index point)

i) Its elevation needs to be referred to a known height datum, and its position (latitude and longitude) needs to be referred to a known geographic system;

ii) Its offset (relative or absolute) from a former sea-level needs to be known;

iii) The age (relative or absolute) of the RSL indicator needs to be established with radiometric methods (such as 230Th/U dating) or through chronostratigraphic correlation with other dated features.

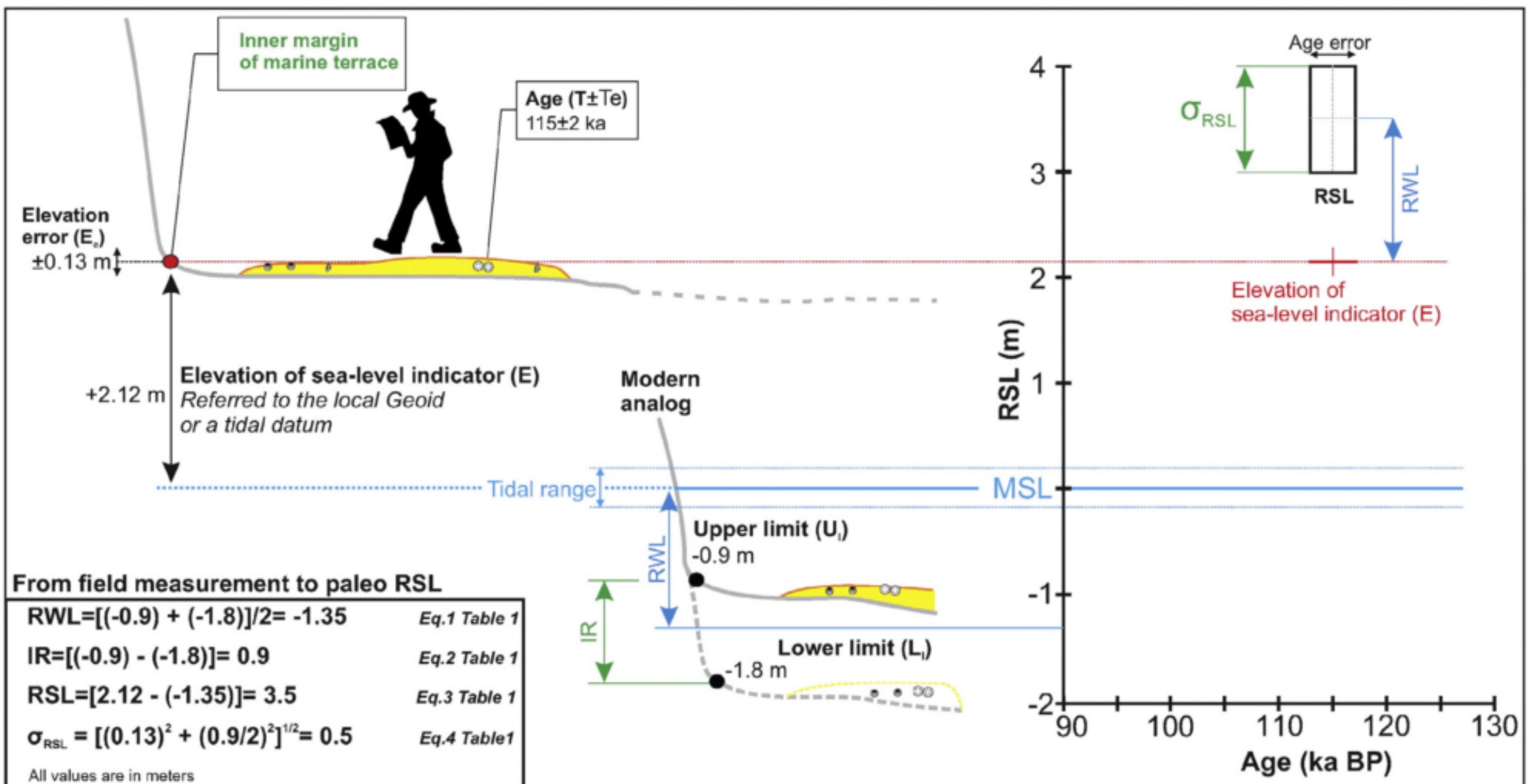


Fig. 1. Example of calculation of RWL, IR, RSL and RSL error from a paleo RSL indicator (marine terrace) and a modern analog.

Definitions

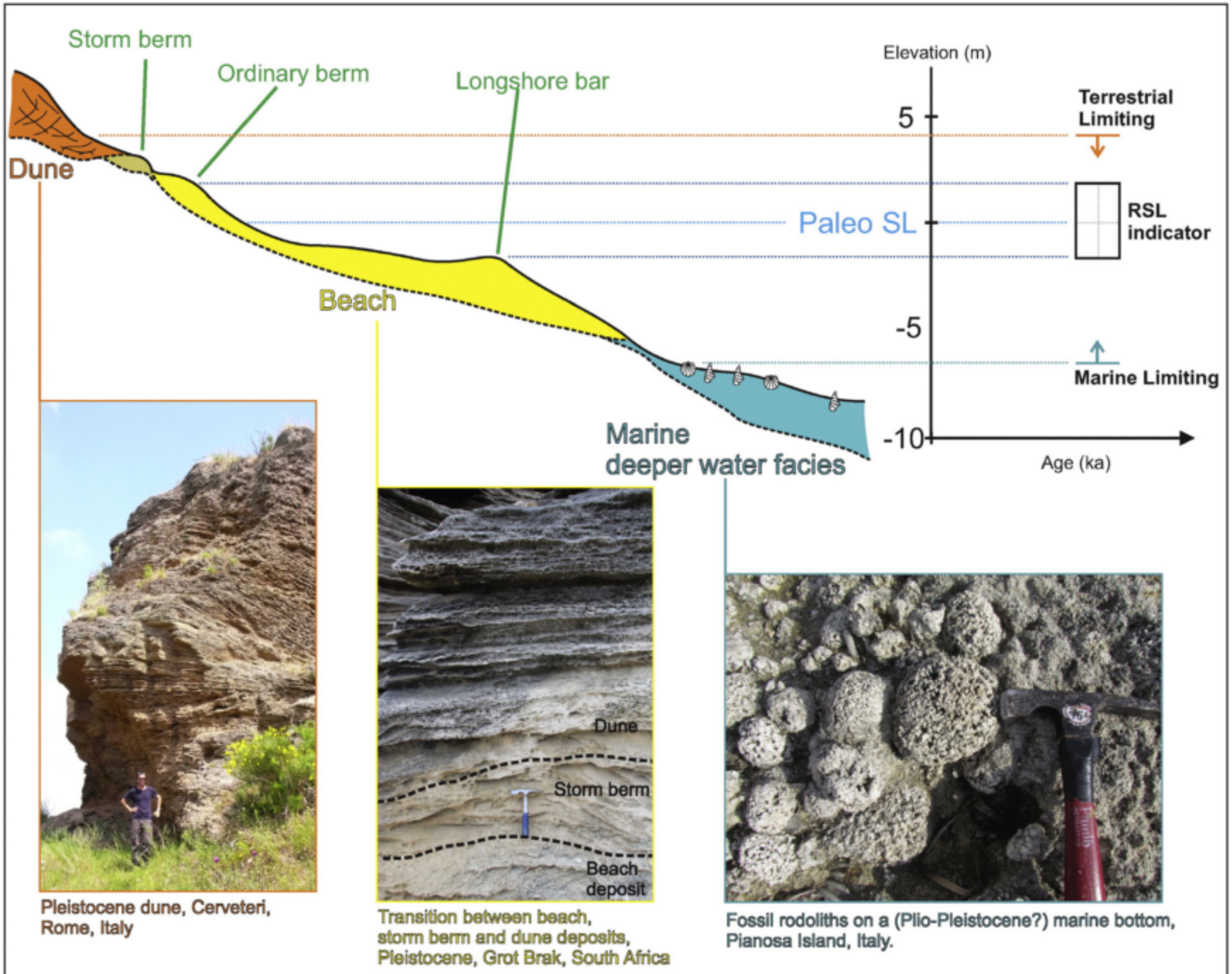
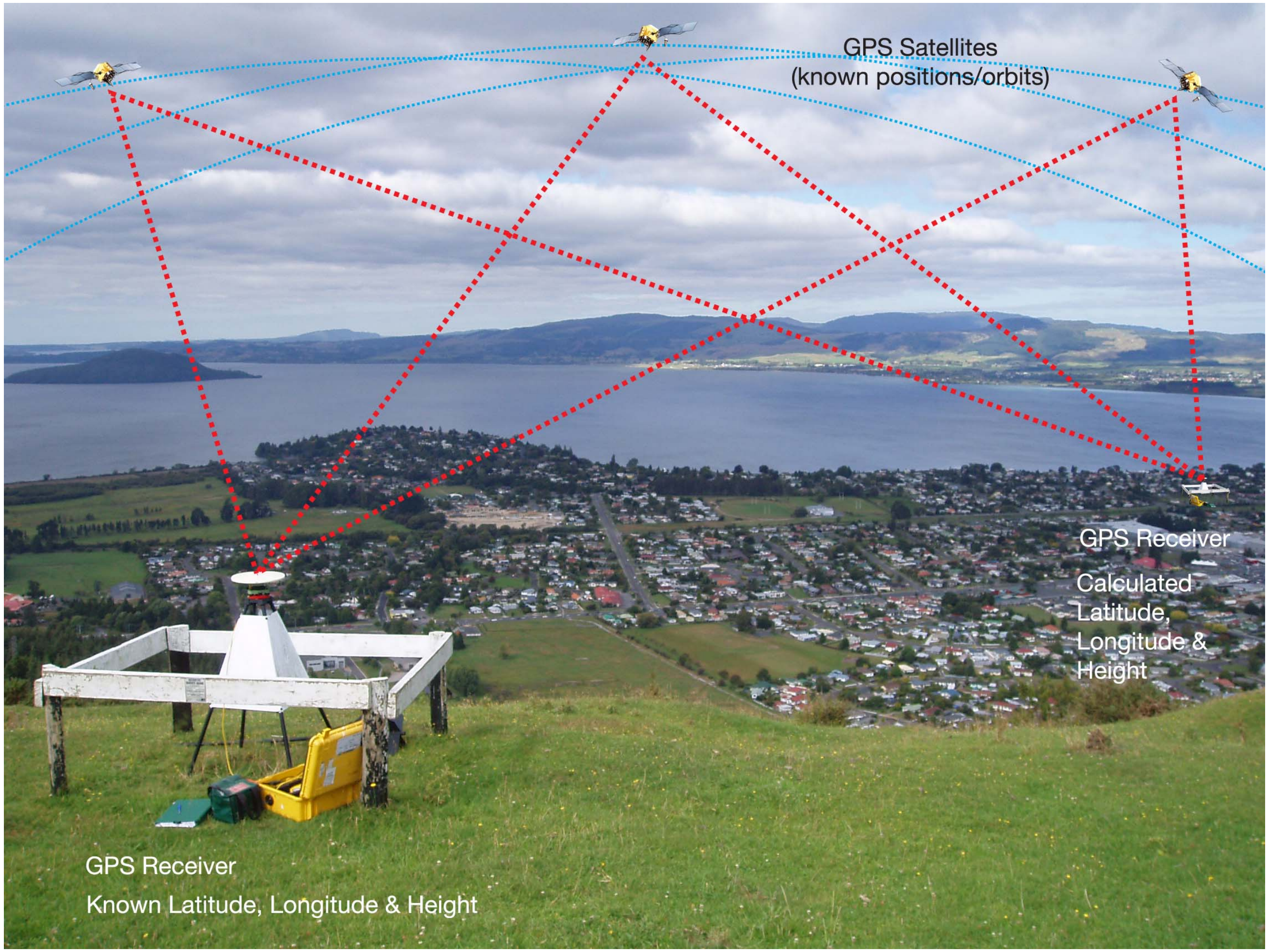


Fig. 2. Difference between RSL, terrestrial and marine limiting points. The Pleistocene dune of Cerveteri is described in Nisi et al. (2003) and references therein. The deposits at Grot Brak are described in Carr et al. (2010). The Plio-Pleistocene marine facies in Pianosa Island are described in Graciotti et al., 2002.

Elevation - GPS

The elevation of an RSL indicator is the vertical distance between the marker and modern mean sea-level, while the elevation error represents the accuracy of the measurement itself. Every measurement needs to be referred to a vertical datum (i.e. a 'zero' reference frame, representing modern MSL). In literature, the survey instruments used to establish elevation, their accuracy, and the vertical datum used are seldom reported.



http://www.icsm.gov.au/

Interpretation

The **Indicative Range** is the elevation range over which an indicator forms. The greater the indicative range, the greater the uncertainty in the final paleo RSL reconstruction.

The **Reference Water Level** is the mid-point of this range

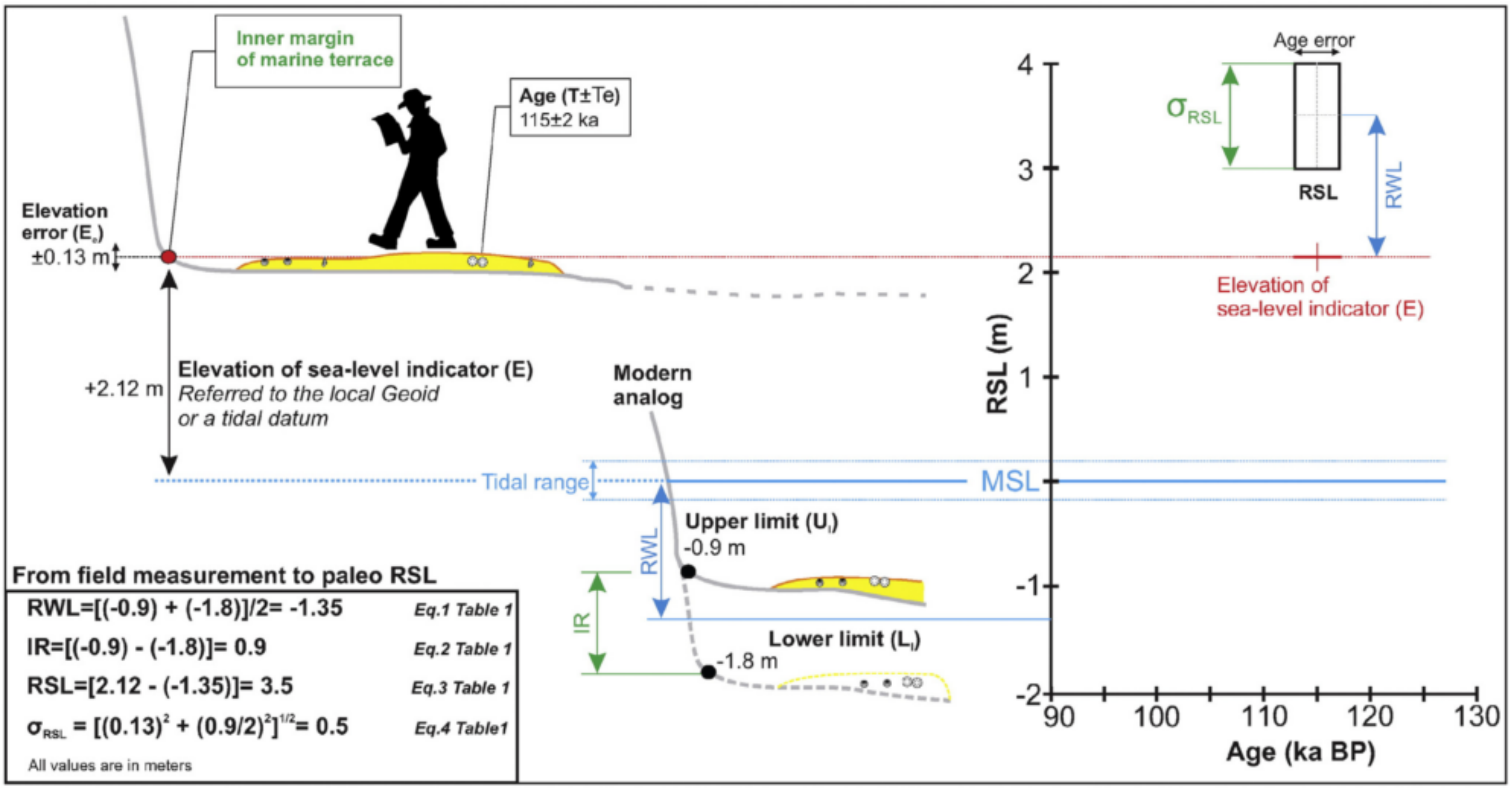


Fig. 1. Example of calculation of RWL, IR, RSL and RSL error from a paleo RSL indicator (marine terrace) and a modern analog.

Definitions

$$RSL = (\text{Marker elevation}) - (\text{Reference water level})$$

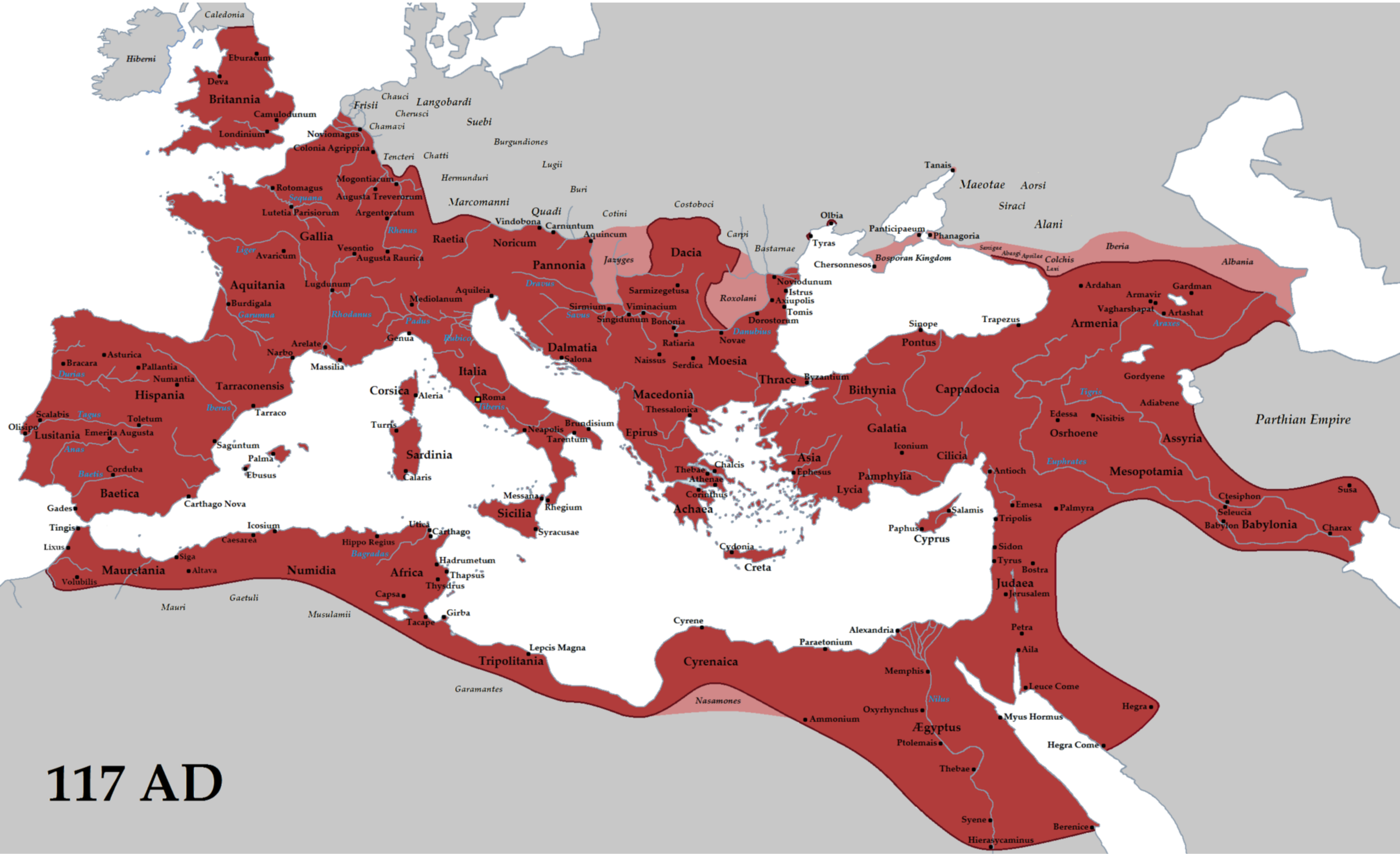
$$RSL\ Error = [(\text{Elevation accuracy})^2 + (\text{Indicative range}/2)^2]^{1/2}$$

The indicative meaning for a given type of feature is determined by measuring its relationship with a specific contemporary tidal level (usually the mean sea-level, MSL) along the modern shorelines (i.e. the **modern analog**).

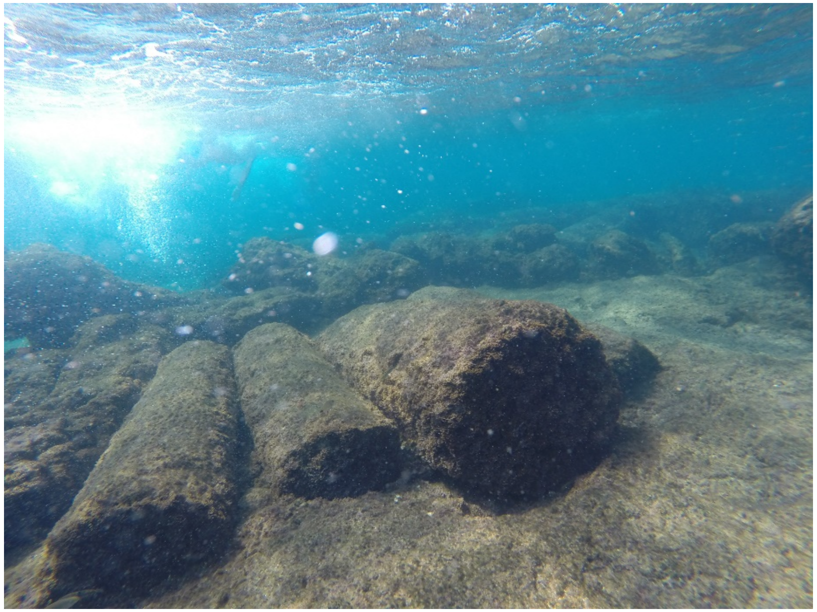
Types of relative sea level markers

- Archeological
- Biological
- Sedimentological
- Geomorphological

Archeological sea level markers



Archeological sea level markers

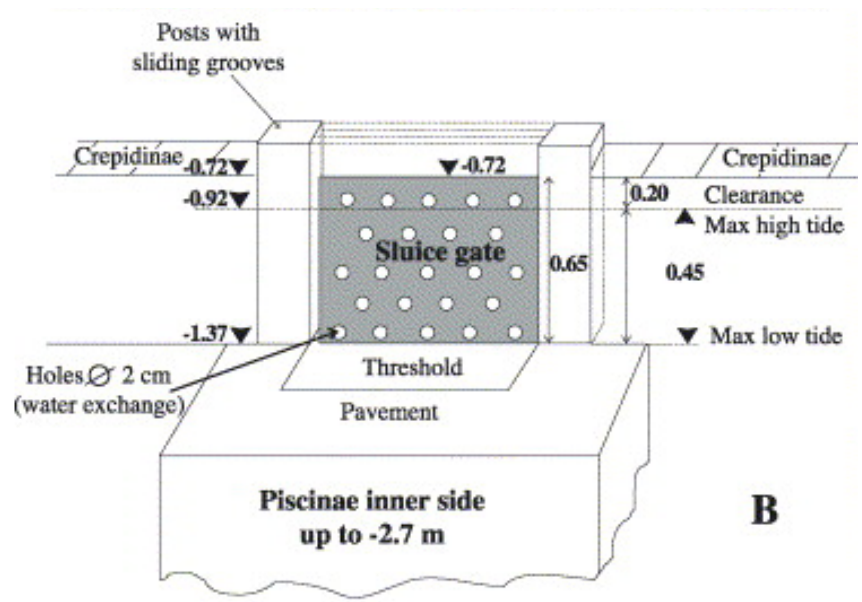


Archeological sea level markers: fishtanks

Rita Auriemma , Emanuela Solinas

Archaeological remains as sea level change markers: A review

Quaternary International, Volume 206, Issues 1–2, 2009, 134 - 146

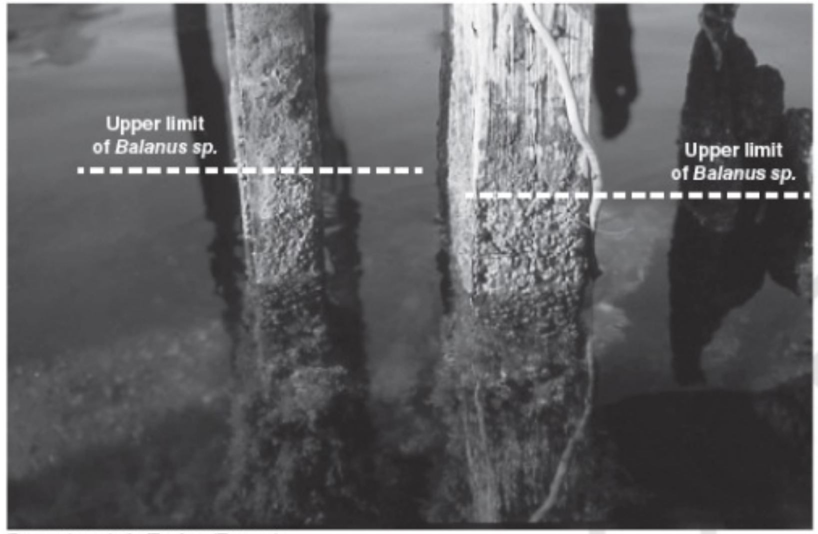


Kurt Lambeck , Marco Anzidei , Fabrizio Antonioli , Alessandra Benini , Alessandra Esposito

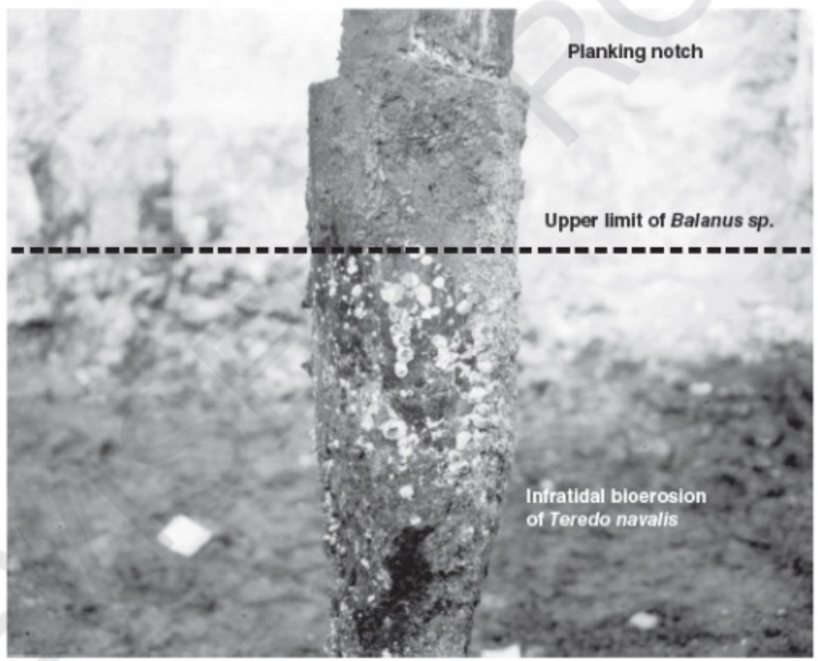
Sea level in Roman time in the Central Mediterranean and implications for recent change

Earth and Planetary Science Letters, Volume 224, Issues 3–4, 2004, 563 - 575

Archeological sea level markers: biological aspects



Present posts in Toulon (France)



Roman post in Marseille (France)

Morhange & Marriner
The new handbook of sea level research

Biological sea level markers

Dendropoma petraeum platform reef

Mushroom-like pillars of *Dendropoma petraeum*

Living balanids (arrow) on intertidal boulders

Fossil and living *Chthamalus stellatus* on an uplifted shore platform

Living balanids (1) and, in the lower part of the boulder, oysters (2) at low tide

Fossil balanids

Living *Mytilus galloprovincialis*

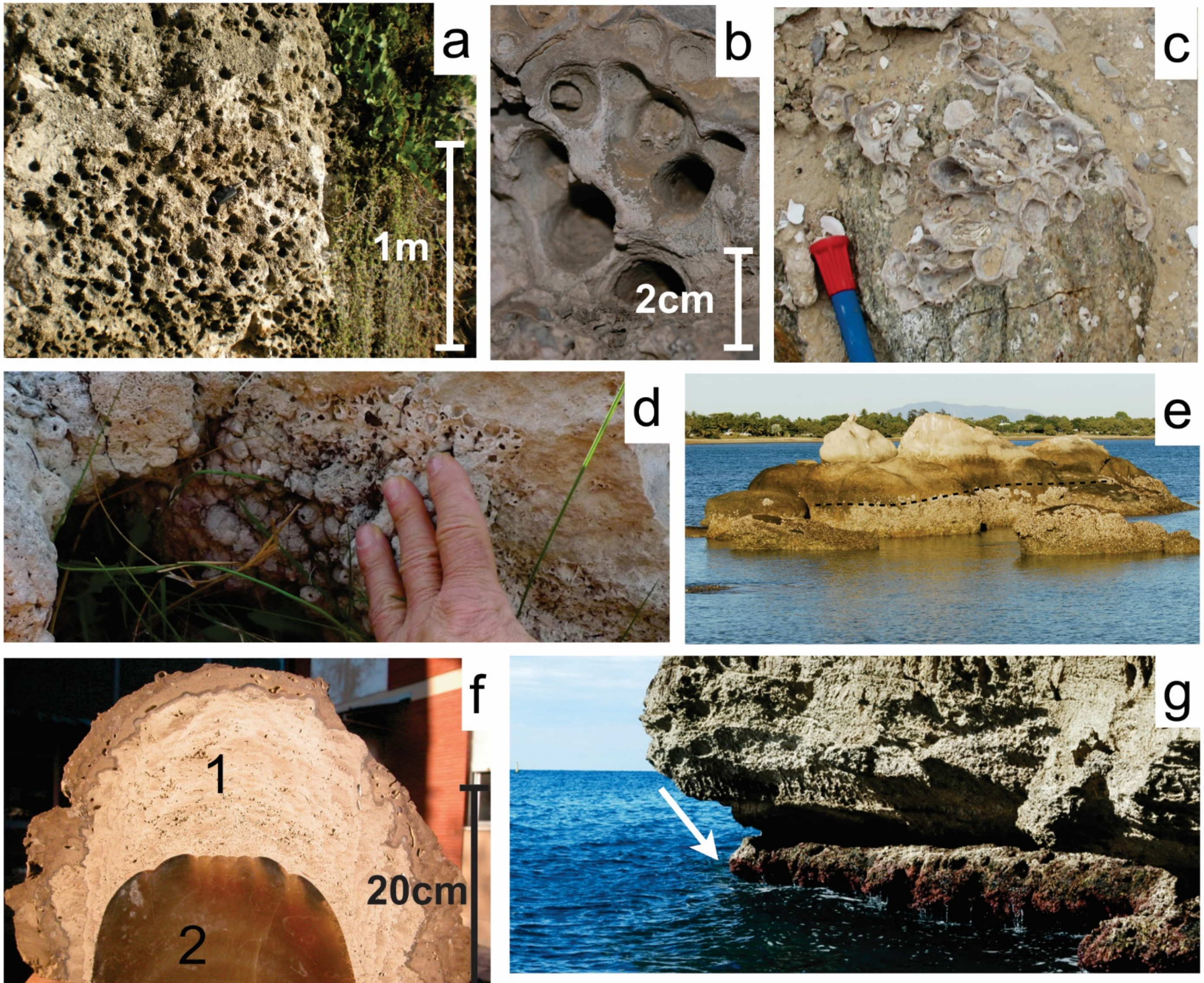
Biological sea level markers

Lihtophaga lithophaga boreholes

Balanids growing upon oysters

Fossil *Perforatus perforatus* on a Archaic-Greek-age harbor boulder

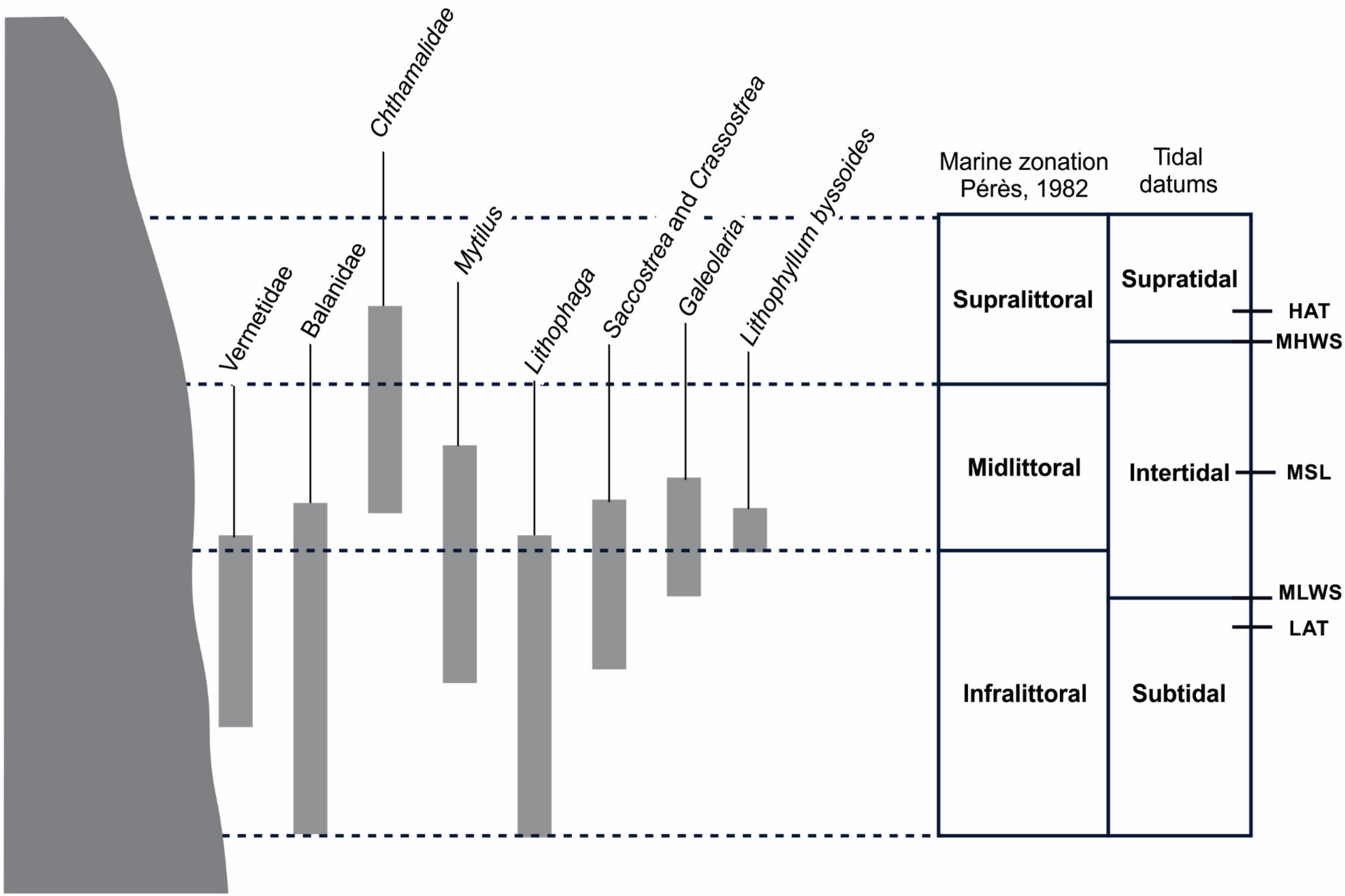
Fossil Holocene *Galeolaria* reef



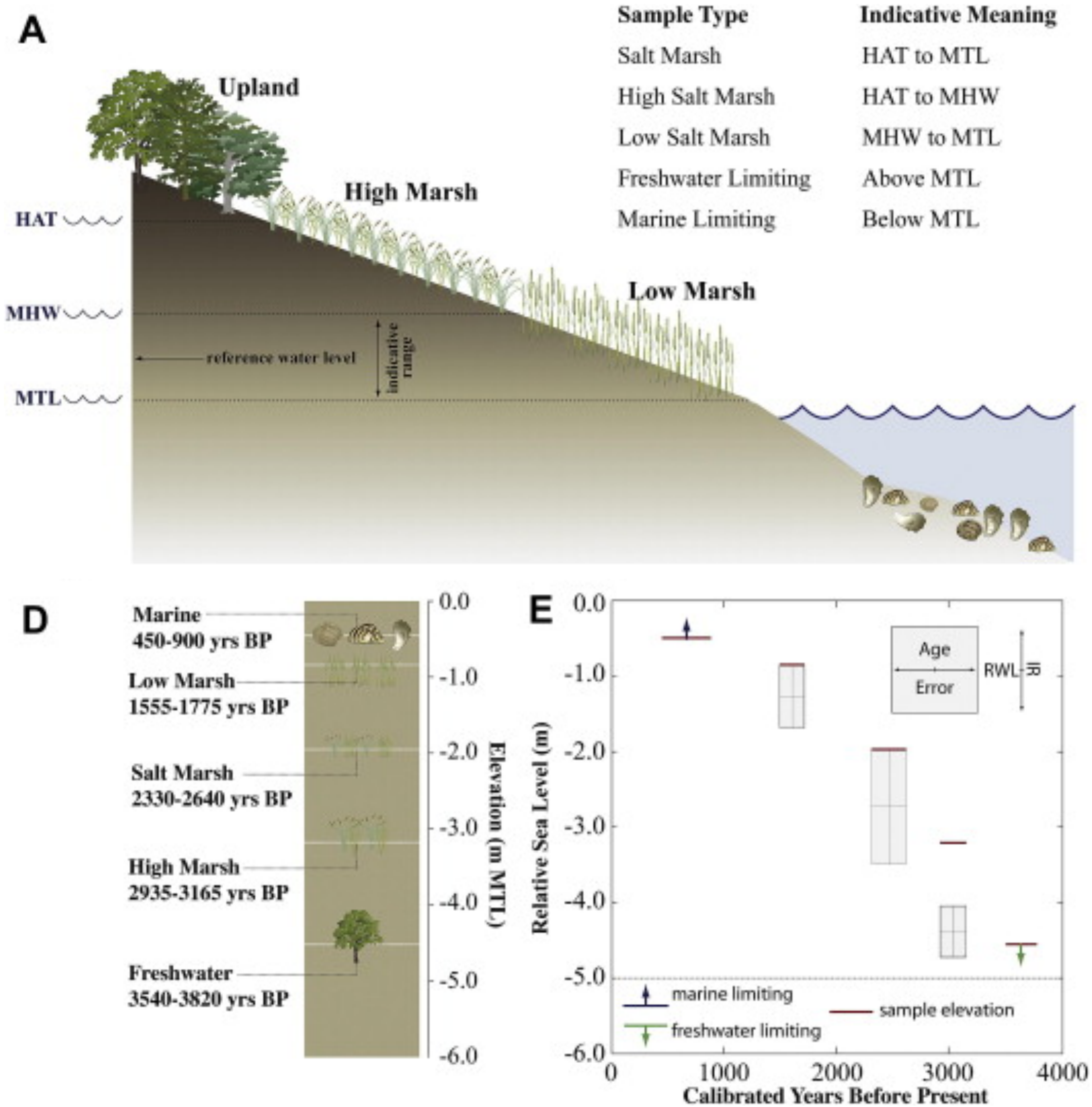
Section of (1) speleothem showing serpulid overgrowth on (2) top of continental deposition

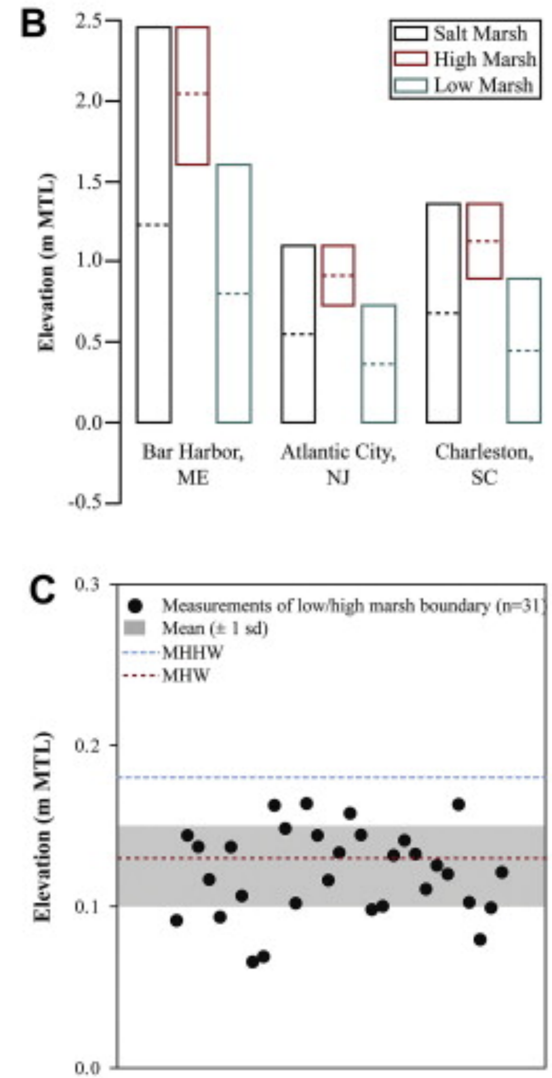
Rim (or “trottoir”) of *Lithophyllum byssoides* (arrow) at low tide

Biological sea level markers



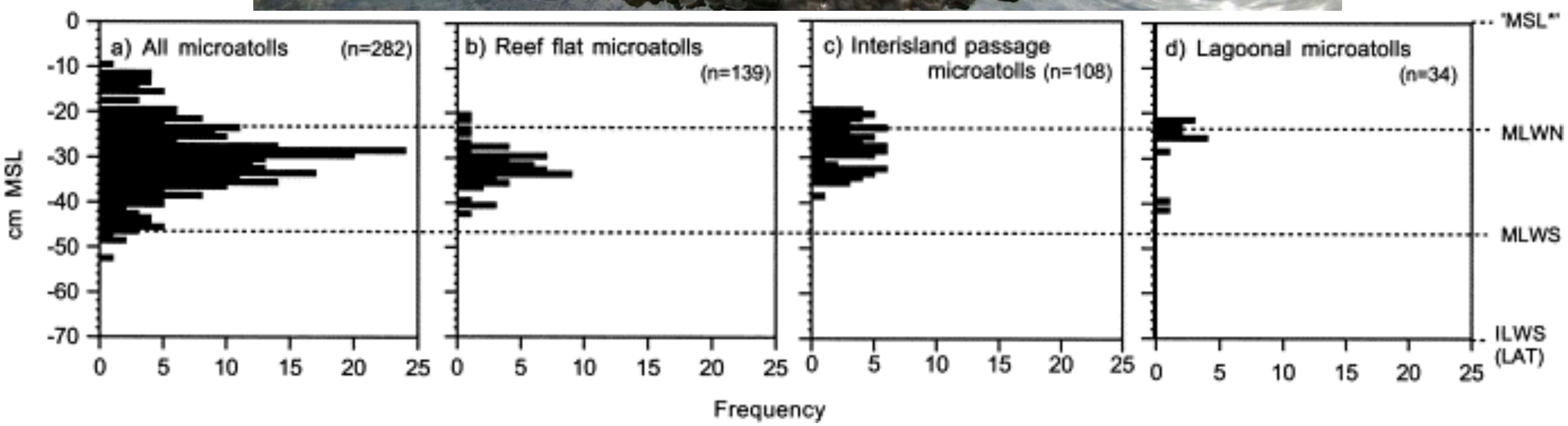
Biological-sedimentological: Salt marshes





Simon E. Engelhart , Benjamin P. Horton
Holocene sea level database for the Atlantic coast of the United States
Quaternary Science Reviews, Volume 54, 2012, 12 - 25

Biological: Microatolls

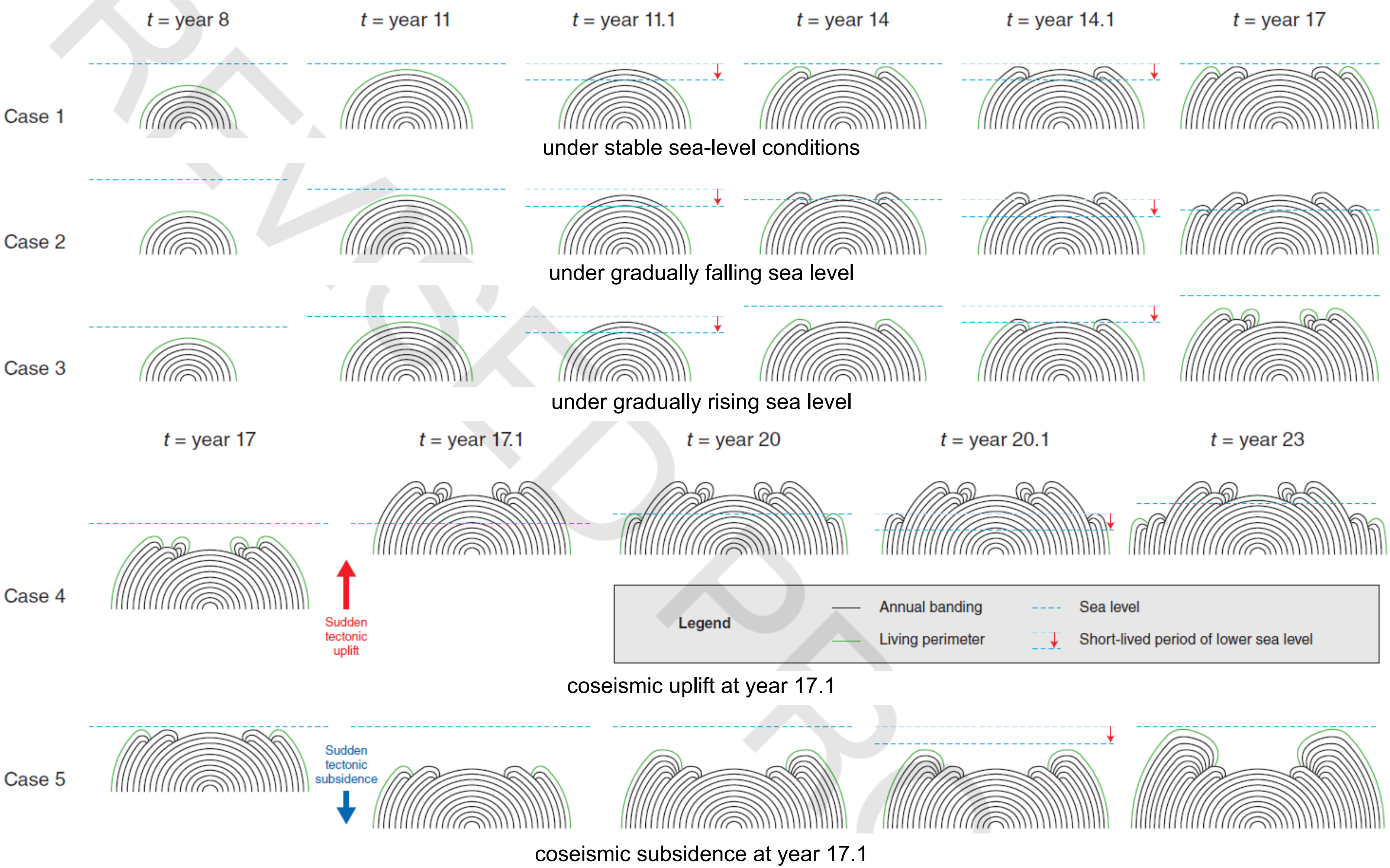


Frequency histograms of microatoll depths relative to MSL datum and predicted mean low water spring and neap tides: (a) entire sample; (b) reef flat microatolls; (c) interisland passage microatolls; and (d) lagoonal microatolls.

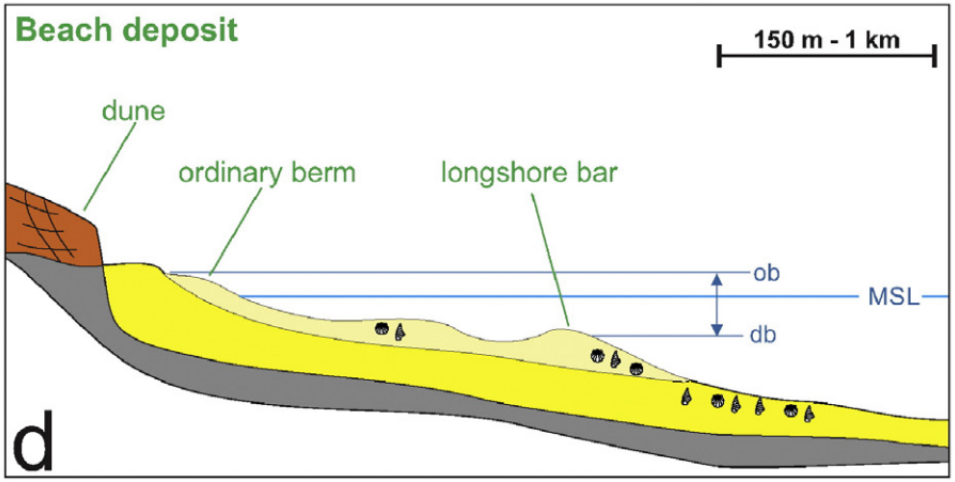
Scott G. Smithers , Colin D. Woodroffe

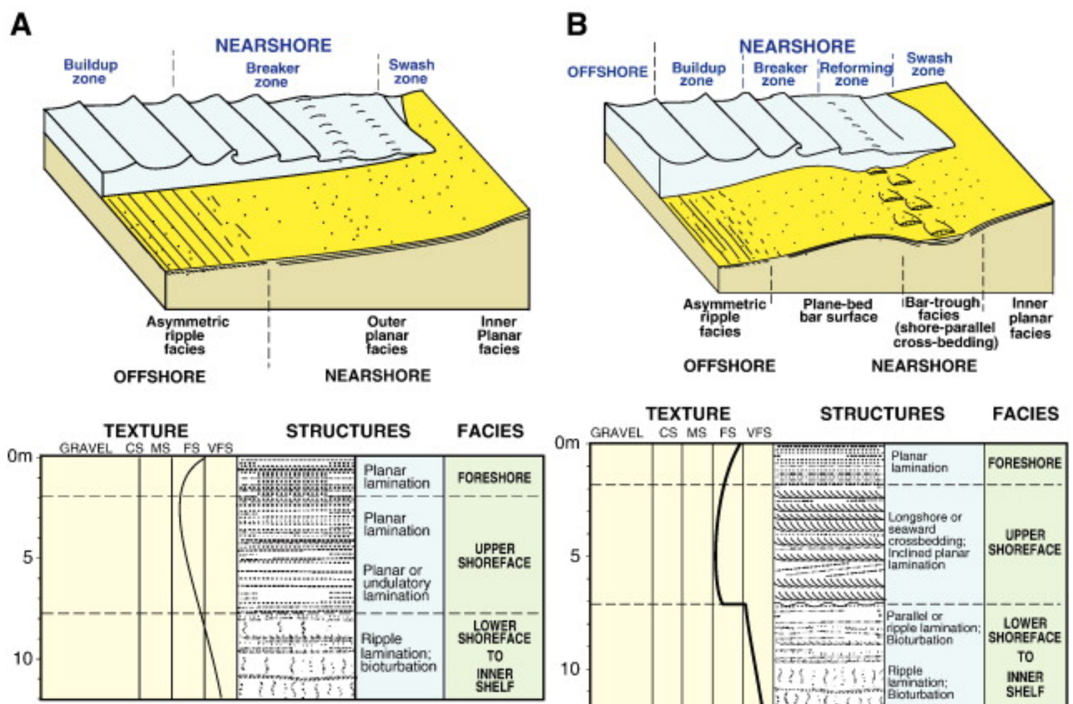
Microatolls as sea-level indicators on a mid-ocean atoll
Marine Geology, Volume 168, Issues 1–4, 2000, 61 - 78

Biological: Microatolls



Sedimentary structures





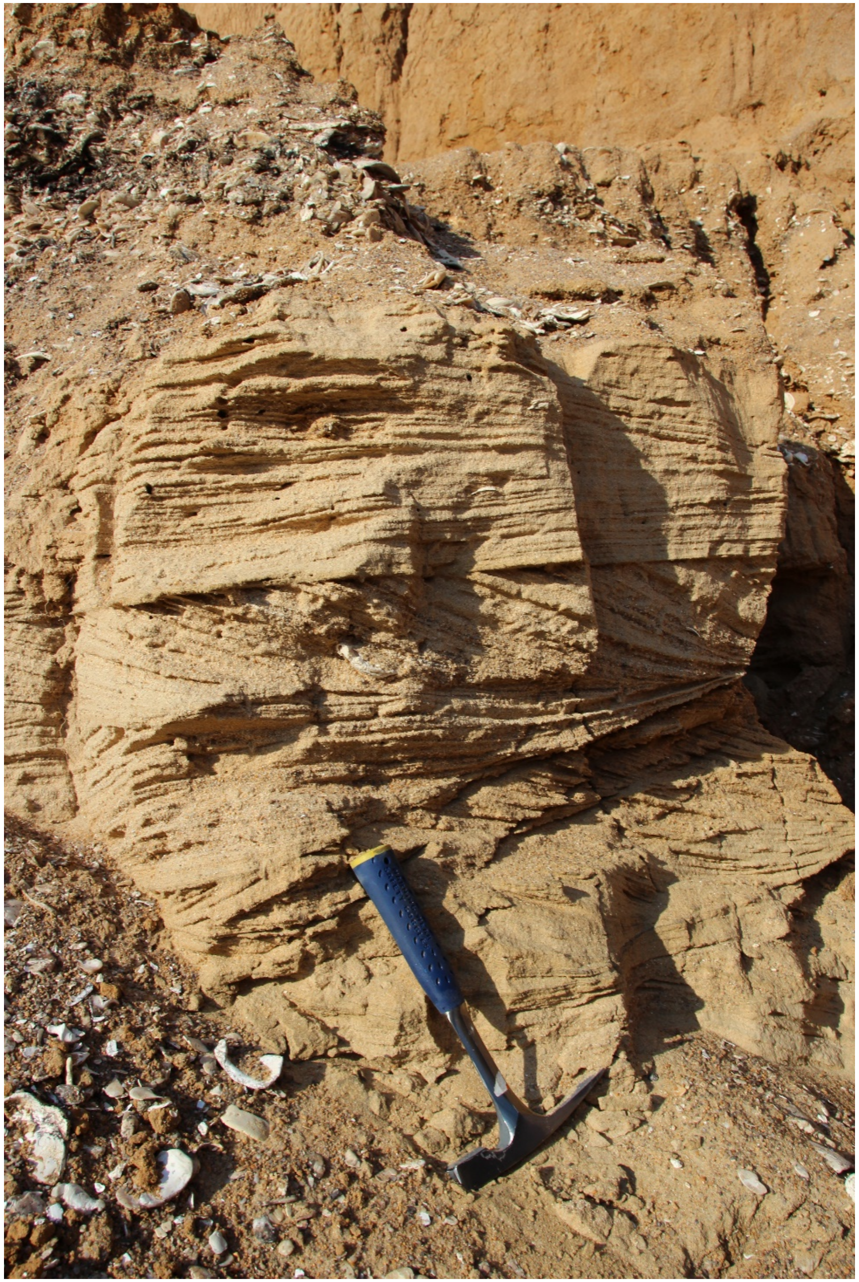
Toru Tamura

Beach ridges and prograded beach deposits as palaeoenvironment records

Earth-Science Reviews, Volume 114, Issues 3–4, 2012, 279 - 297

Sedimentary structures

Subtidal-intertidal transition
South Africa



Morphologies

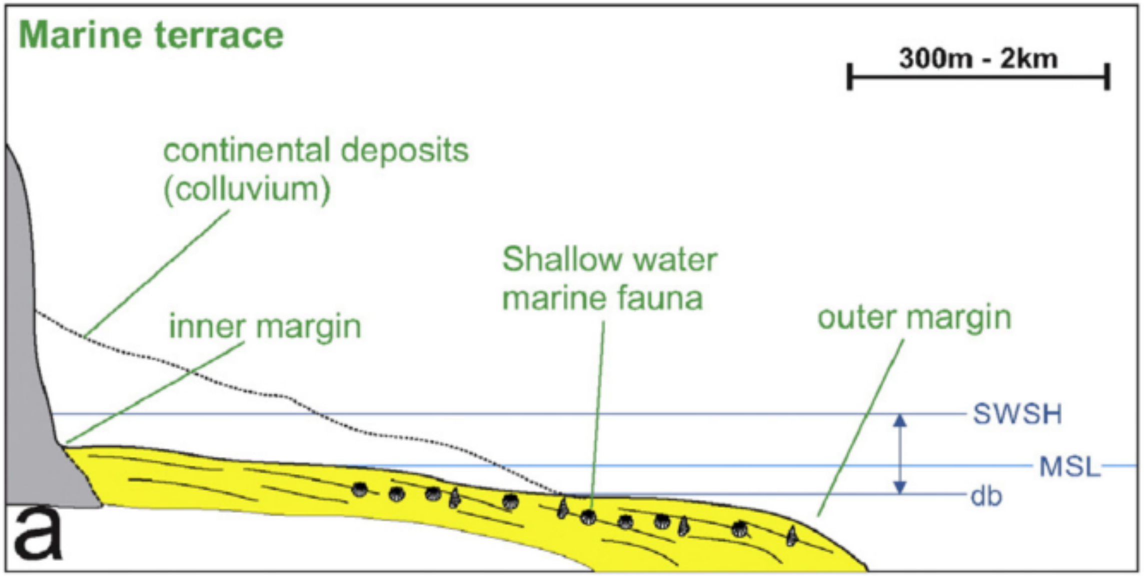
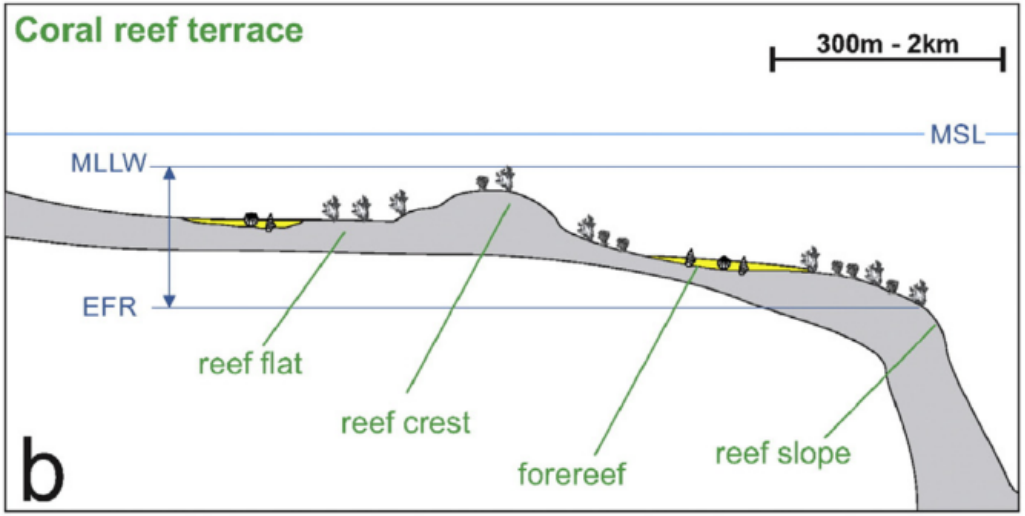


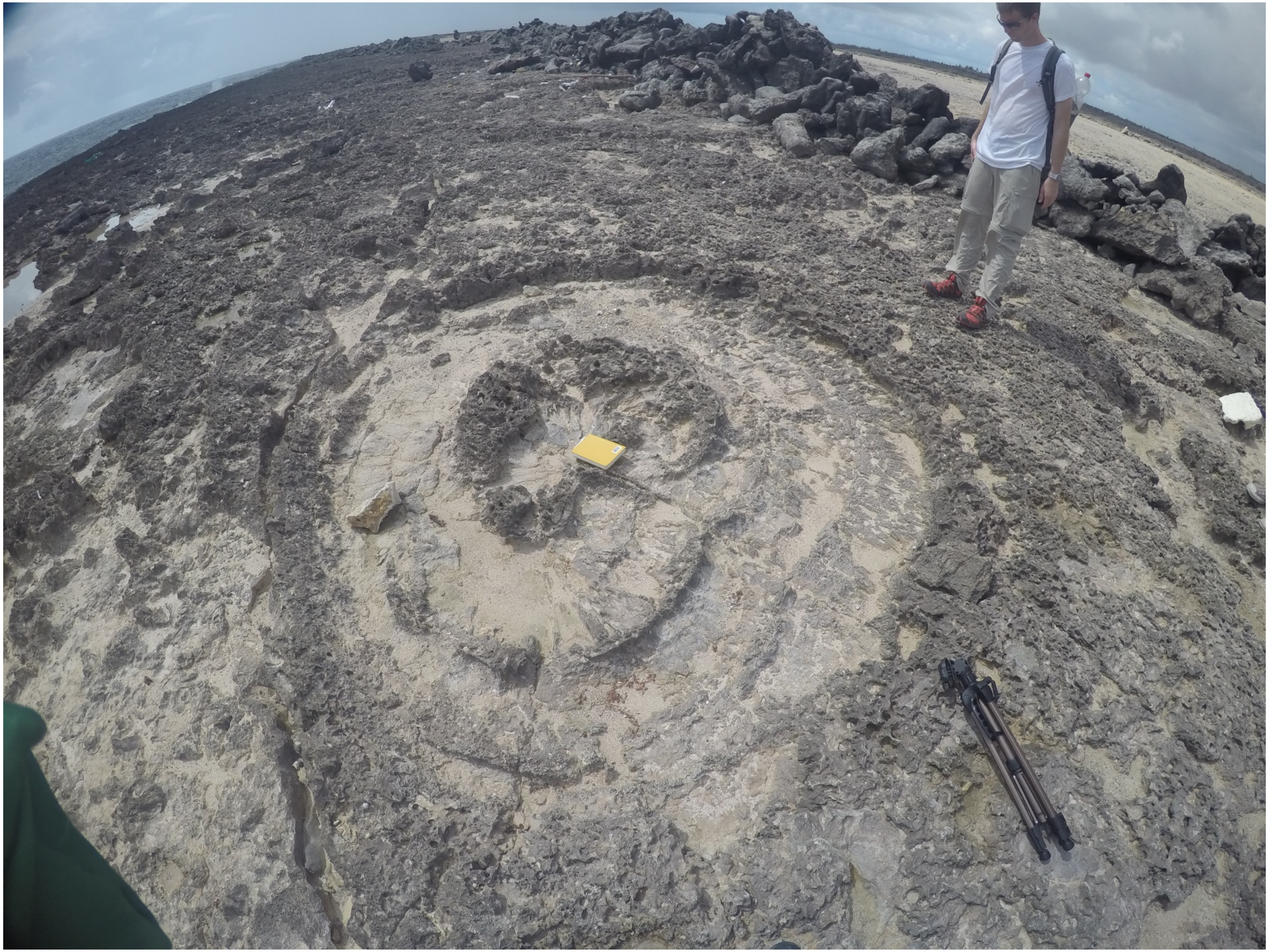
Fig. 5. a) Example of an MIS 5e marine terrace on Santa María Island, Azores (see Avila et al., 2015 for details); b) modern inner margin of marine terrace located in the swash zone, being actively shaped by beach erosion processes (Portugal, Algarve); c) modern inner margin located near the breaking depth of waves at around 4–5 m depth (NW Italy, Capo Noli, Rovere et al., 2011, 2014a). The gray line in each figure represents the location of the inner margin.

Morphologies



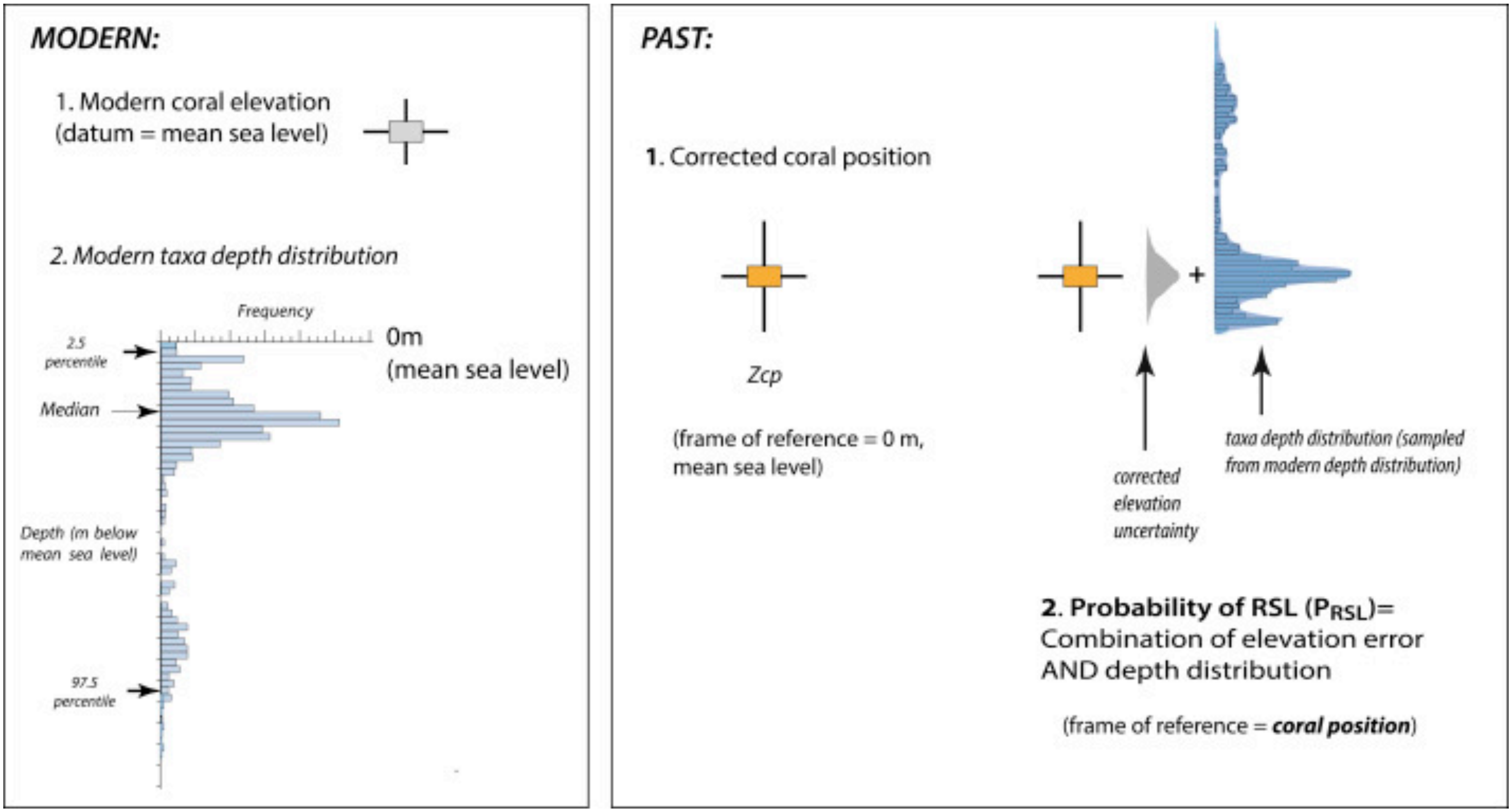
David Hopley
Encyclopedia of Earth Sciences
Series Encyclopedia of Modern
Coral Reefs Structure, Form and
Process

Morphologies



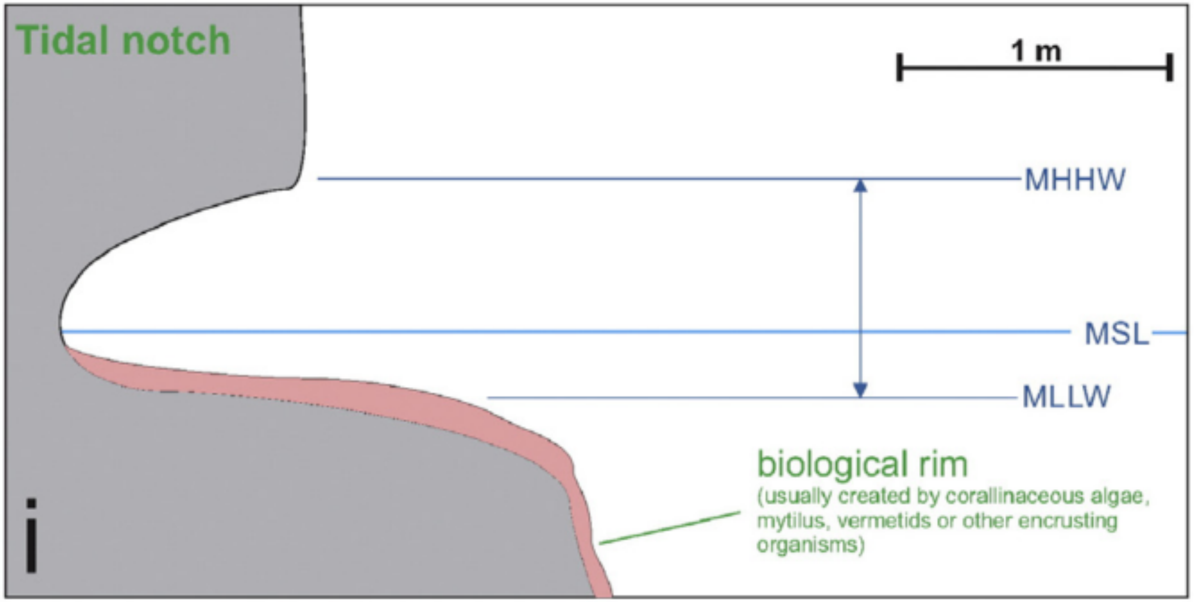
Morphologies

Reef terraces
Using coral paleodepths



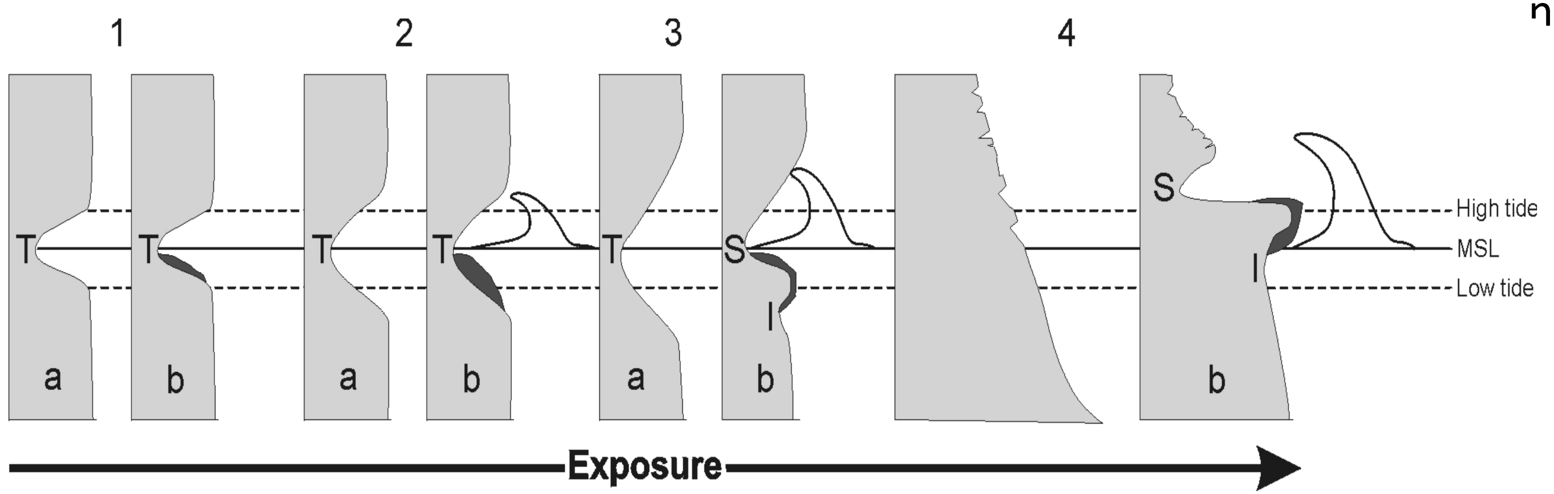
Hibbert et al., 2016, QSR

Morphologies



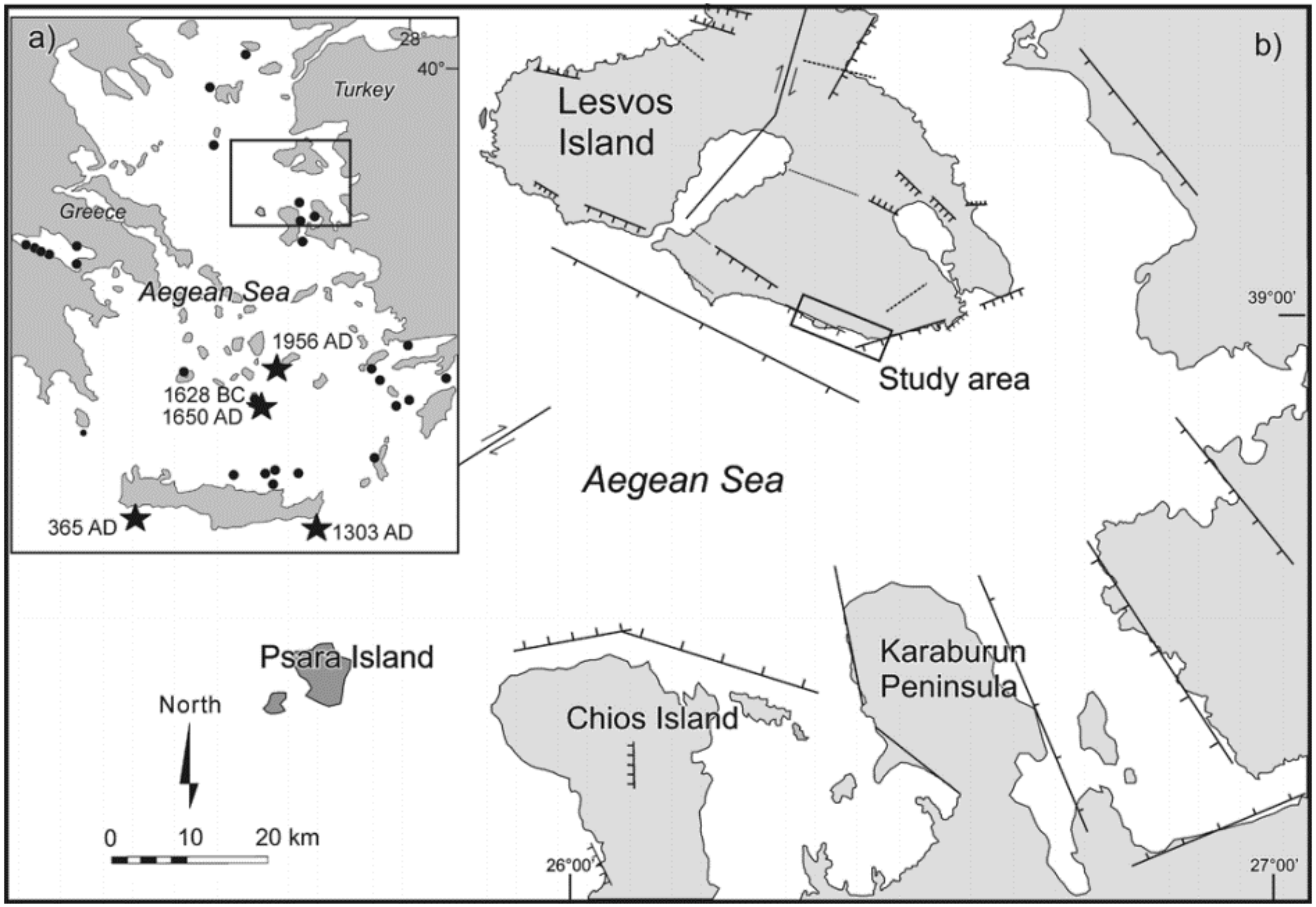
Morphologies

Tidal notches vs abrasion notches

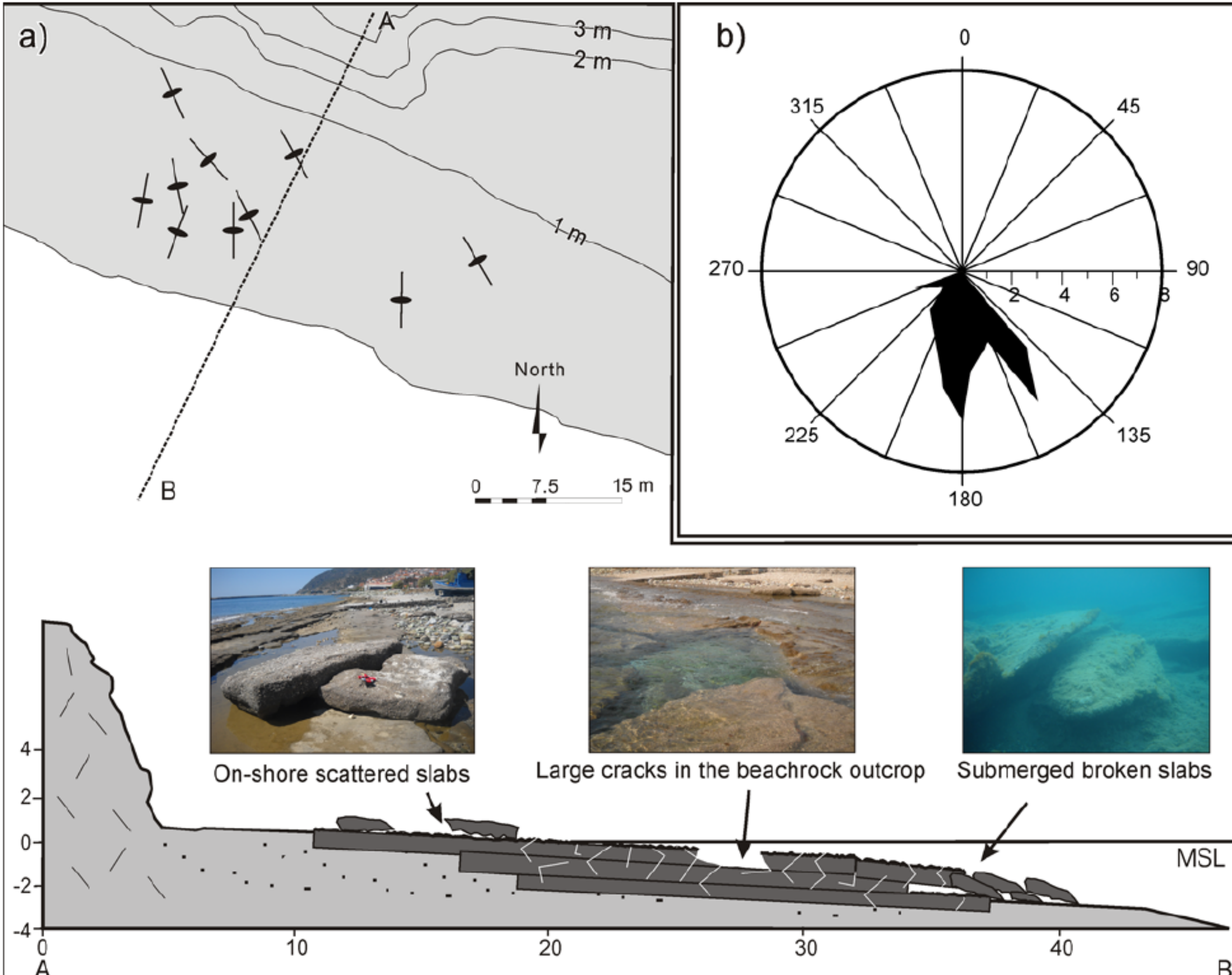


Study of sea level changes: working examples

Rapid sea level changes: evidence for paleo tsunamis



(a) Indicative locations of historical tsunamogenic sources in the broad Aegean area according to Soloviev (1990); Yolsal et al. (2007) and Okal et al. (2009); black stars indicate location and year of the most destructive events. (b) Geographical location and simplified tectonic setting of the study area modified from Mascle and Martin (1990) and Pavlides et al. (2009)


a)
A
3 m
2 m
1 m
North
B
0
7.5
15 m
b)
0
45
90
135
180
225
270
315
2
4
6
8
On-shore scattered slabs
Large cracks in the beachrock outcrop
Submerged broken slabs
MSL
4
2
0
-2
-4
0
10
20
30
40
A
B

Common Era and Holocene sea level changes: the Mediterranean Sea

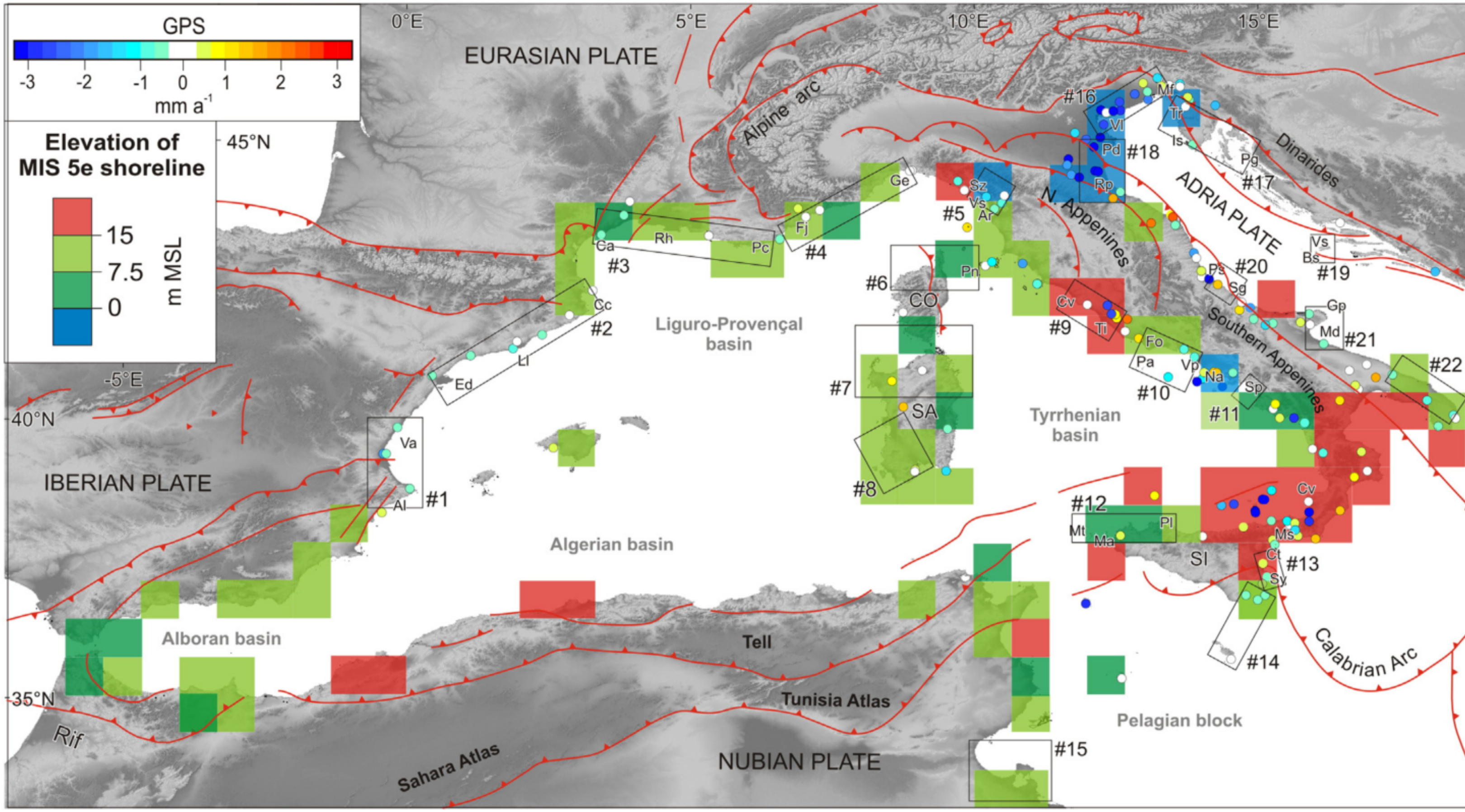
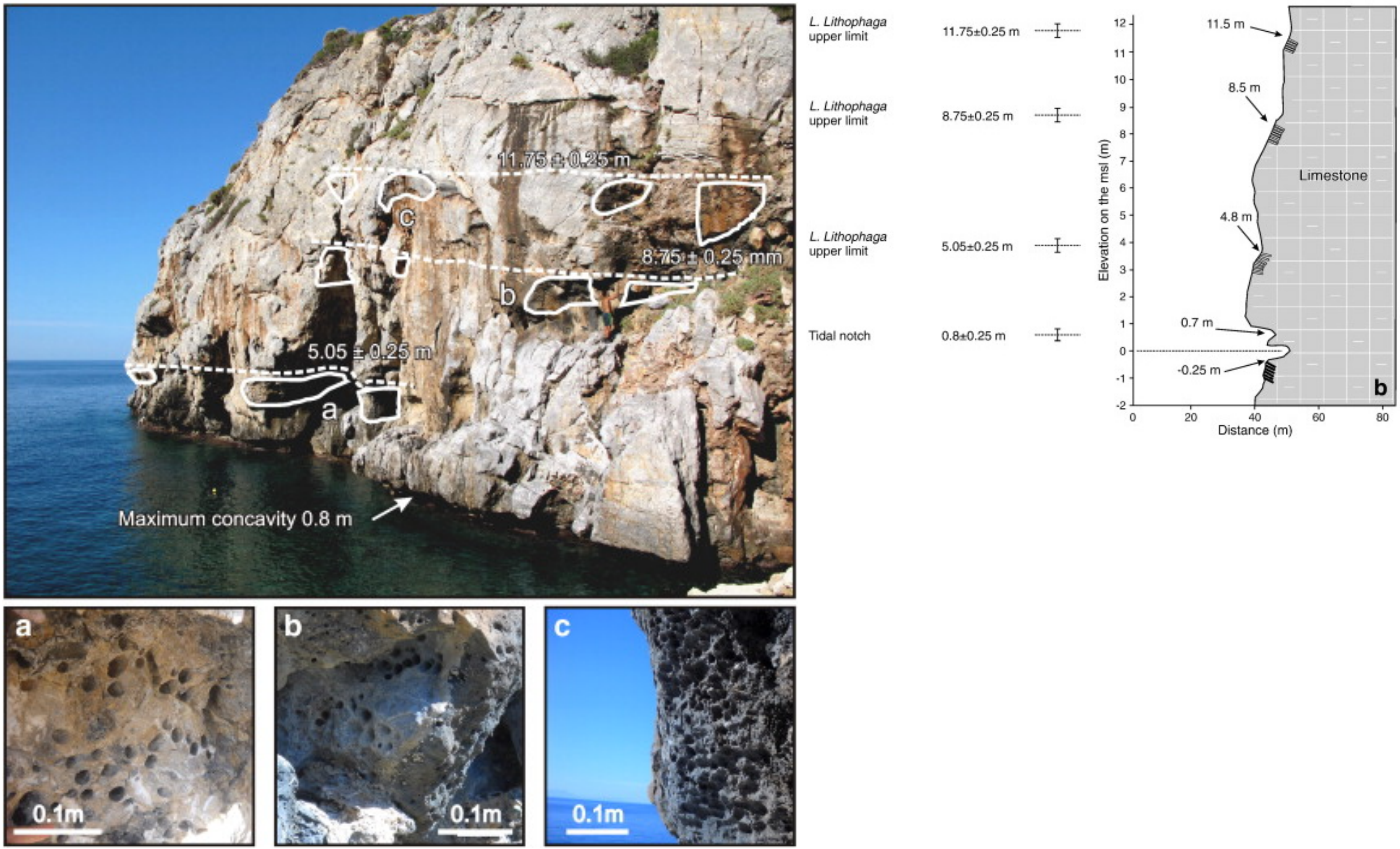
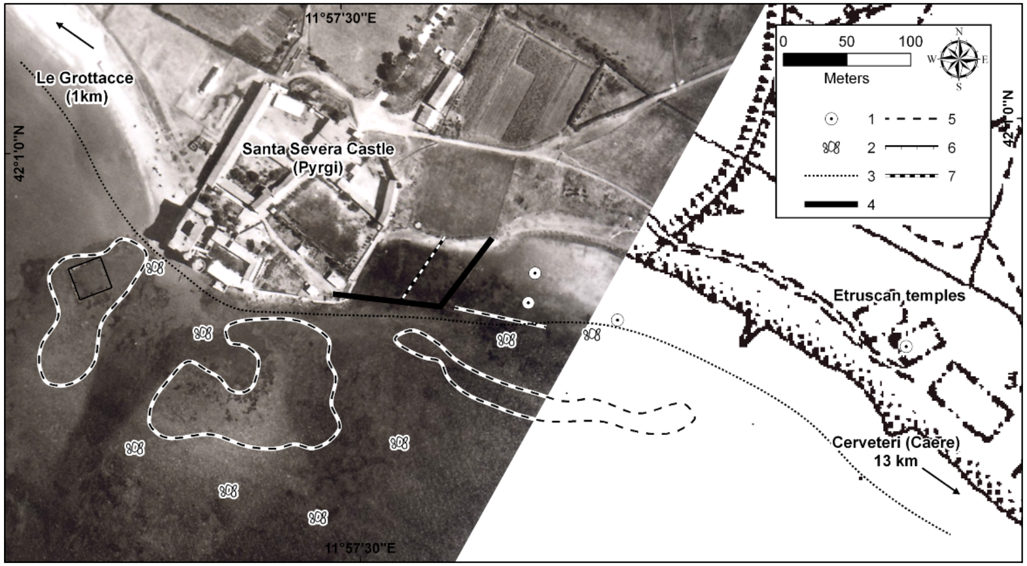
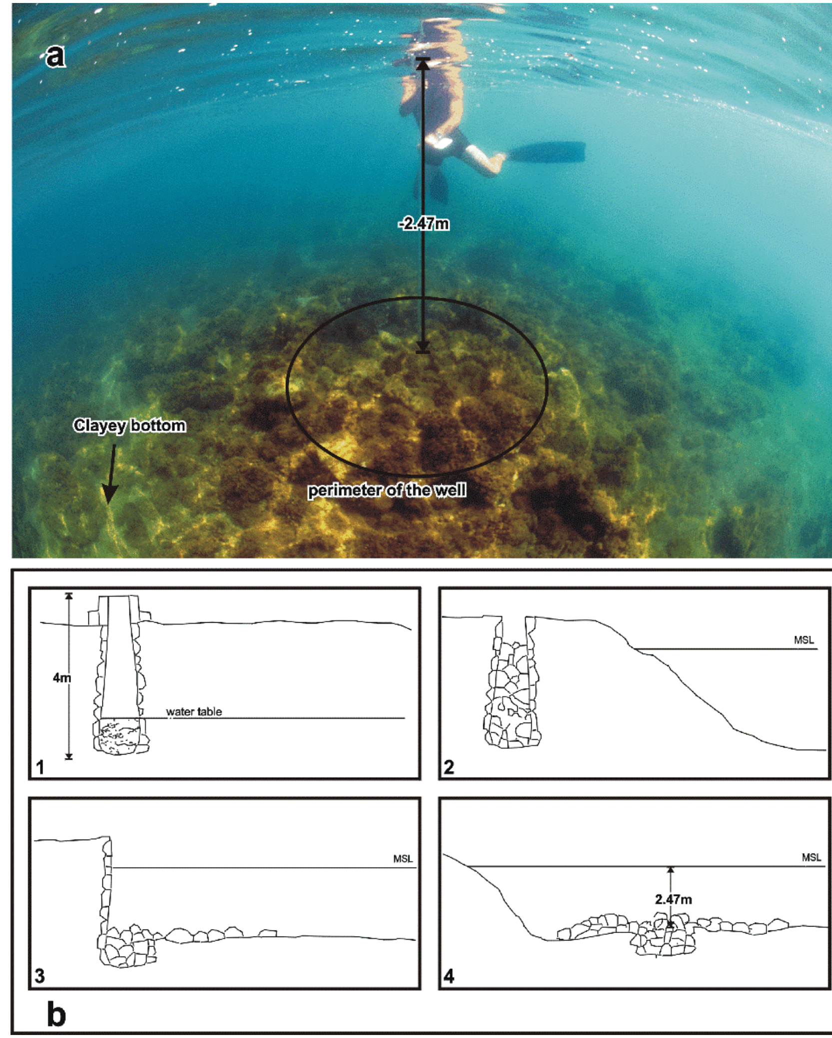


Fig. 2. Tectonic framework of the western Mediterranean. Faults are modified after Faccenna et al. (2014). Squares indicate the average elevation of MIS 5e shorelines (data from Ferranti et al. (2006); Pedoja et al. (2014)). Dots denote the ongoing GPS-derived vertical movements along the Mediterranean coast (data from Serpelloni et al. (2013)). CO, Corsica; SA, Sardinia; SI, Sicily. Al, Alicante; Va, Gulf of Valencia; Ed, Ebro Delta; Ll, Llobregat Delta; Cc, Cap Creus; Ca, Cap d'Agde; Rh, Rhone Delta; Pc, Port Cros; Fj, Frejus; Ge, Genova; Sz, La Spezia; Vs, Versilia plain; Ar, Arno river; Pn, Pianosa Island; Cv, Civitavecchia, CV; Ti, Tiber Delta; Fo, Fondi plain; P, Pontine Archipelago; Vp, Volturno plain; Na, Naples volcanic district; Sp; Sele plain; Cv, Capo Vaticano; Ms, Messina Strait; Mt, Marettimo Island; Pl, Capo Gallo; Ma, Marsala sound; Ct, Catania; Sy, Syracuse; Mf, Monfalcone; Vl, Venice lagoon; Pd, Po Delta; Rp, Romagna coastal plain; Ps, Pescara; Sg, Sangro plain; Gp, Gargano promontory; Md, Gulf of Manfredonia.

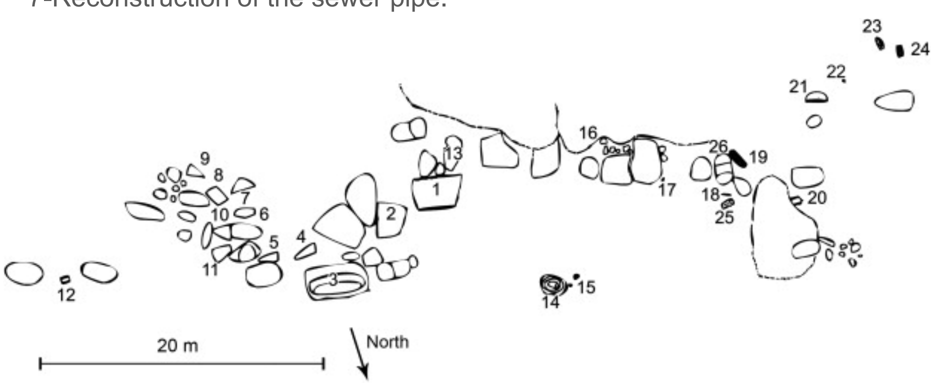

11.75 ± 0.25 m
c
8.75 ± 0.25 mm
b
5.05 ± 0.25 m
a
Maximum concavity 0.8 m
a
0.1m
b
0.1m
c
0.1m
L. Lithophaga upper limit
11.75±0.25 m
L. Lithophaga upper limit
8.75±0.25 m
L. Lithophaga upper limit
5.05±0.25 m
Tidal notch
0.8±0.25 m
11.5 m
8.5 m
4.8 m
0.7 m
-0.25 m
Limestone
b
Elevation on the msl (m)
Distance (m)

Holocene sea level changes – Archeological markers



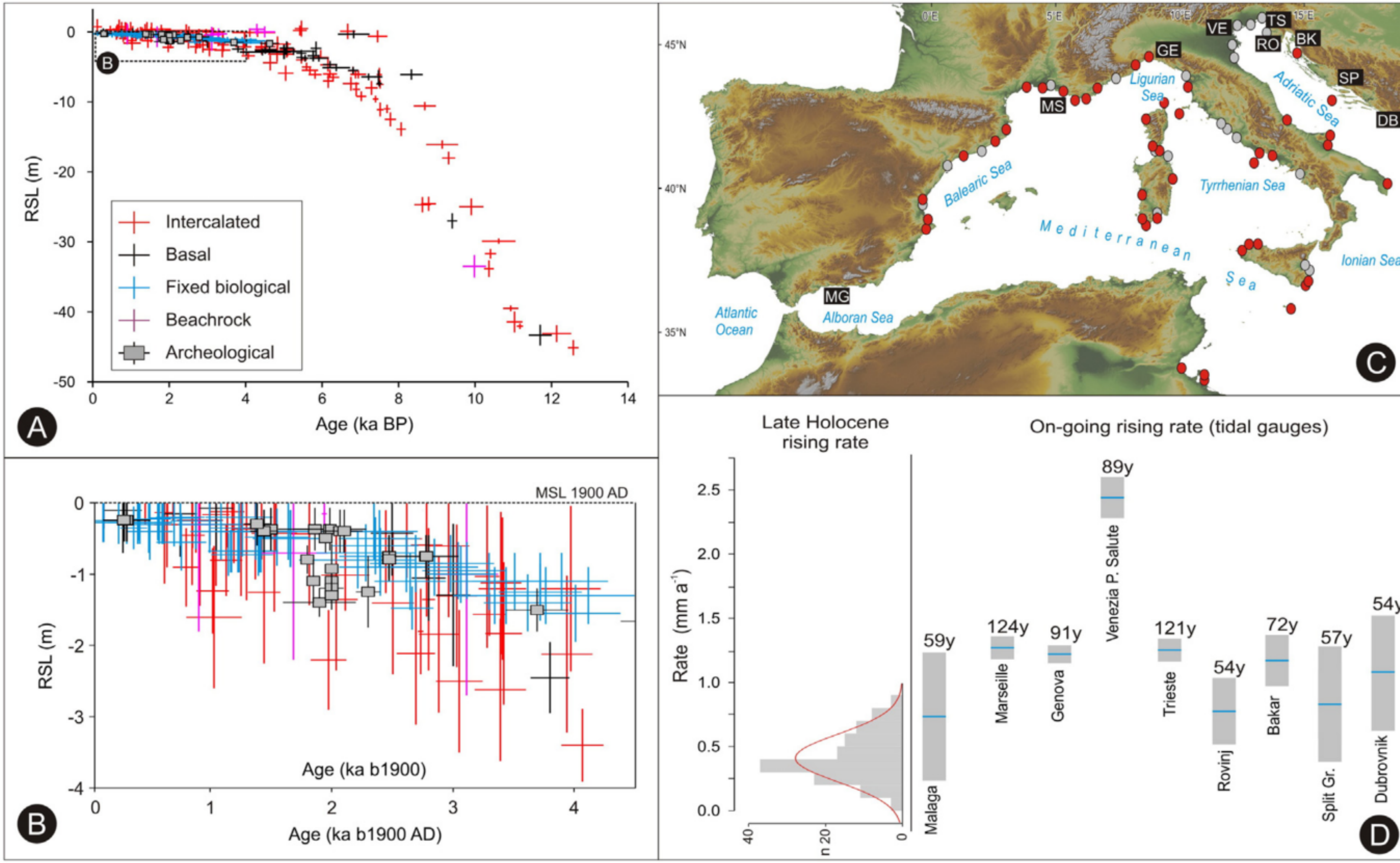


1-Etruscan wells
2-Lithic anchors
3-Reconstructed Etruscan shoreline
4-*Castrum* walls destroyed by wave action
5-Harbor structures
6-*Pyrgi* fishtank
7-Reconstruction of the sewer pipe.

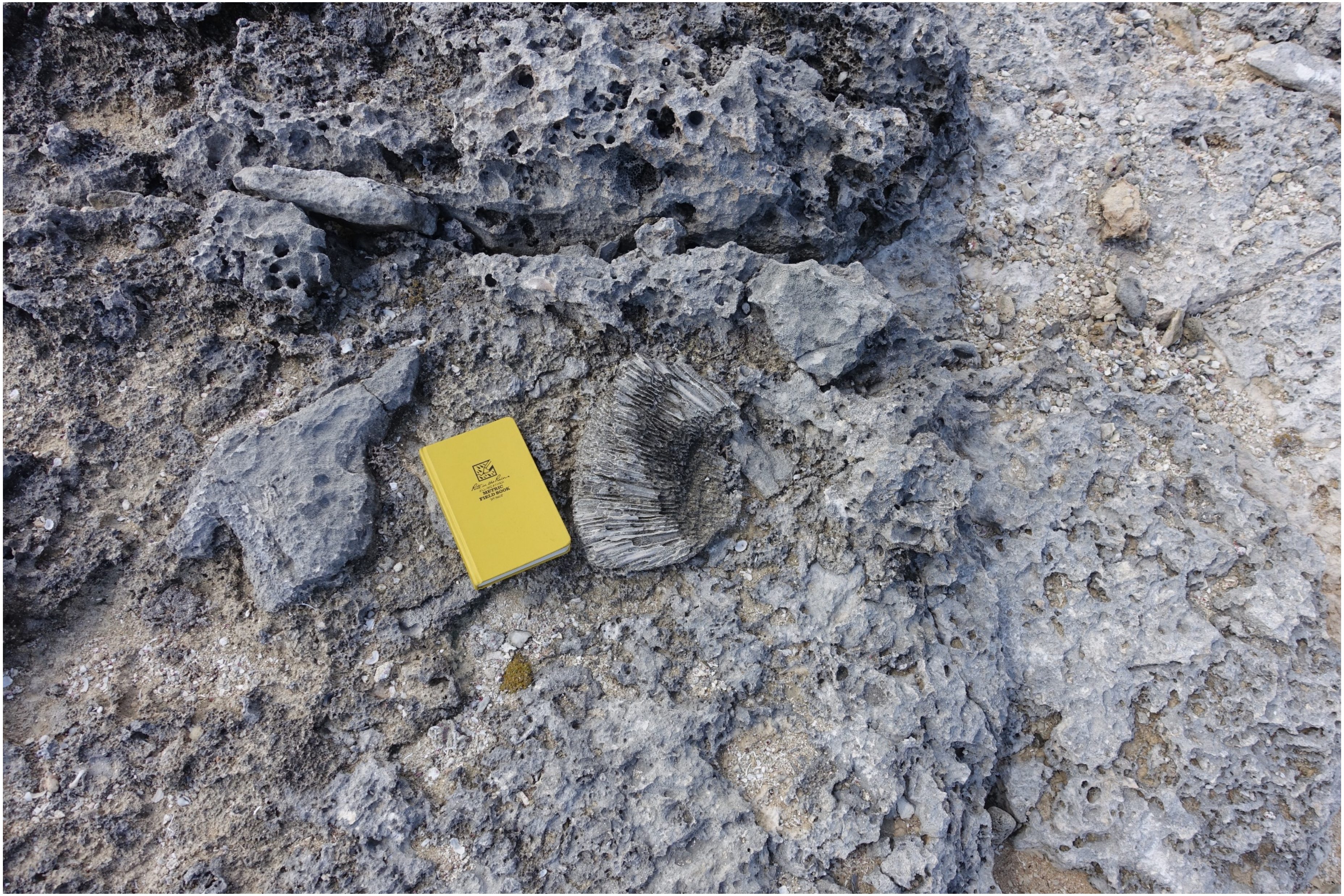


Remnants of harbor structures dislocated by wave action at depths between 1.50 and 2.60 m bsl (redrawn from Enei, 2008). Legend: 1–3) 2.10–2.50 m wall remnants; 4–11) Squared stone blocks coming from the Roman *castrum*: 12, 15–25) Parts of smaller (30–40 cm thick) walls in some case associated to pavements (23,25), limestone *cubilia* (18,22) and roof-ceramics (16,17); 13, 14, 26) Parts of walls with remnants of wooden forms used as foundations.

Holocene sea level changes

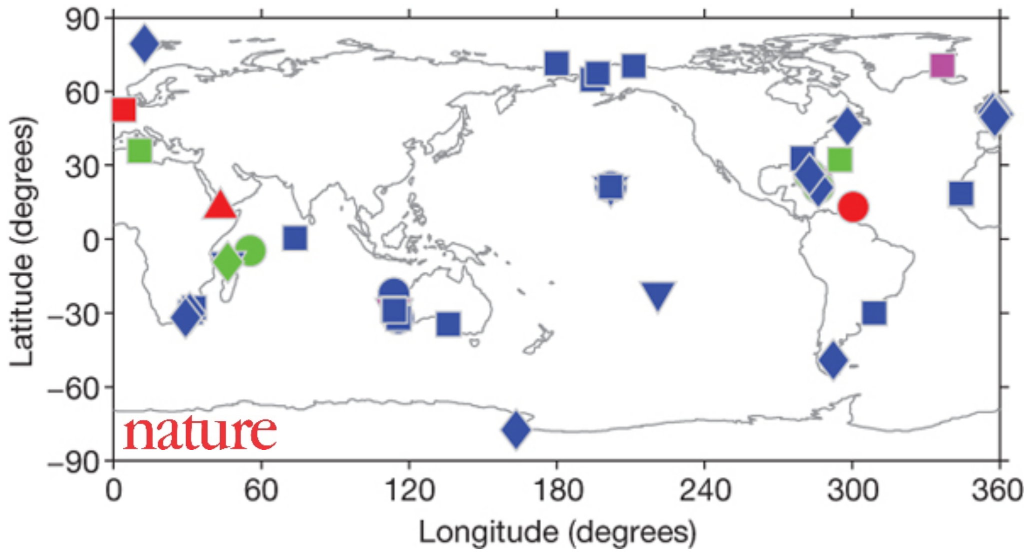


The Last Interglacial

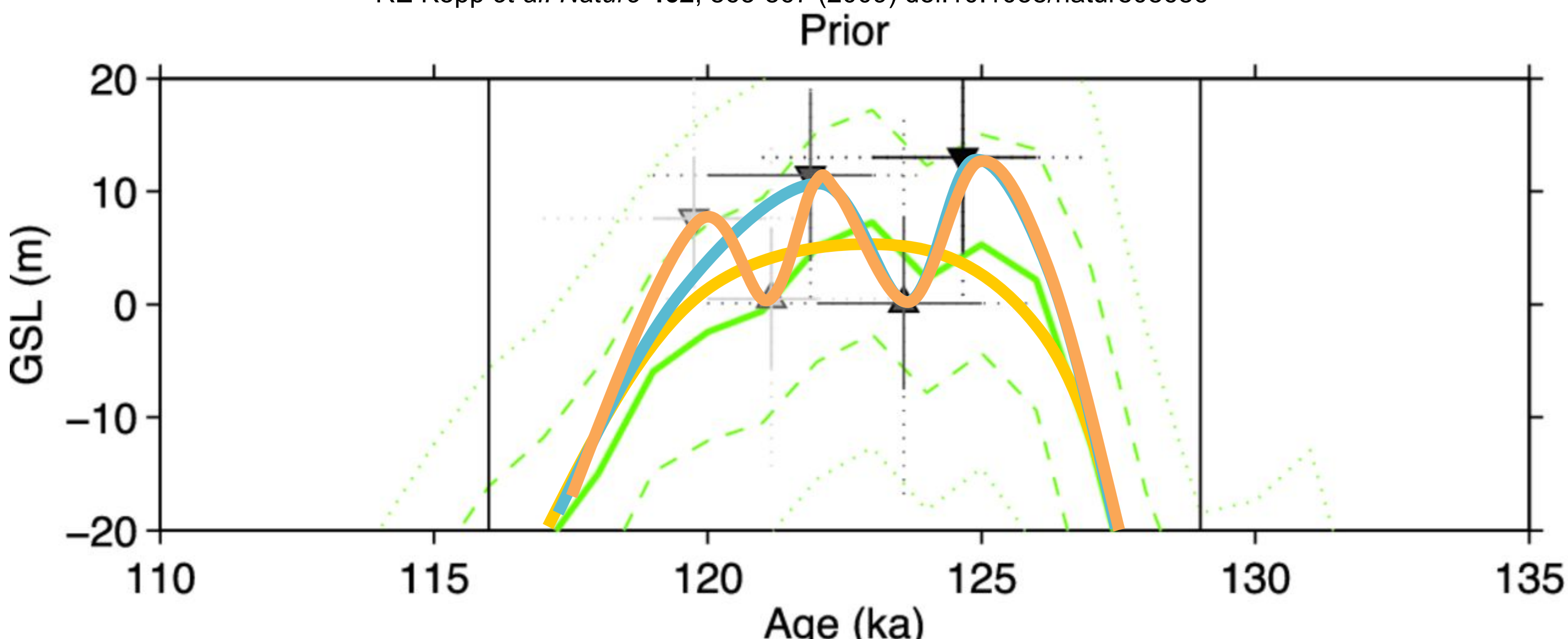


The Last Interglacial

Pleistocene sea level changes – Last interglacial

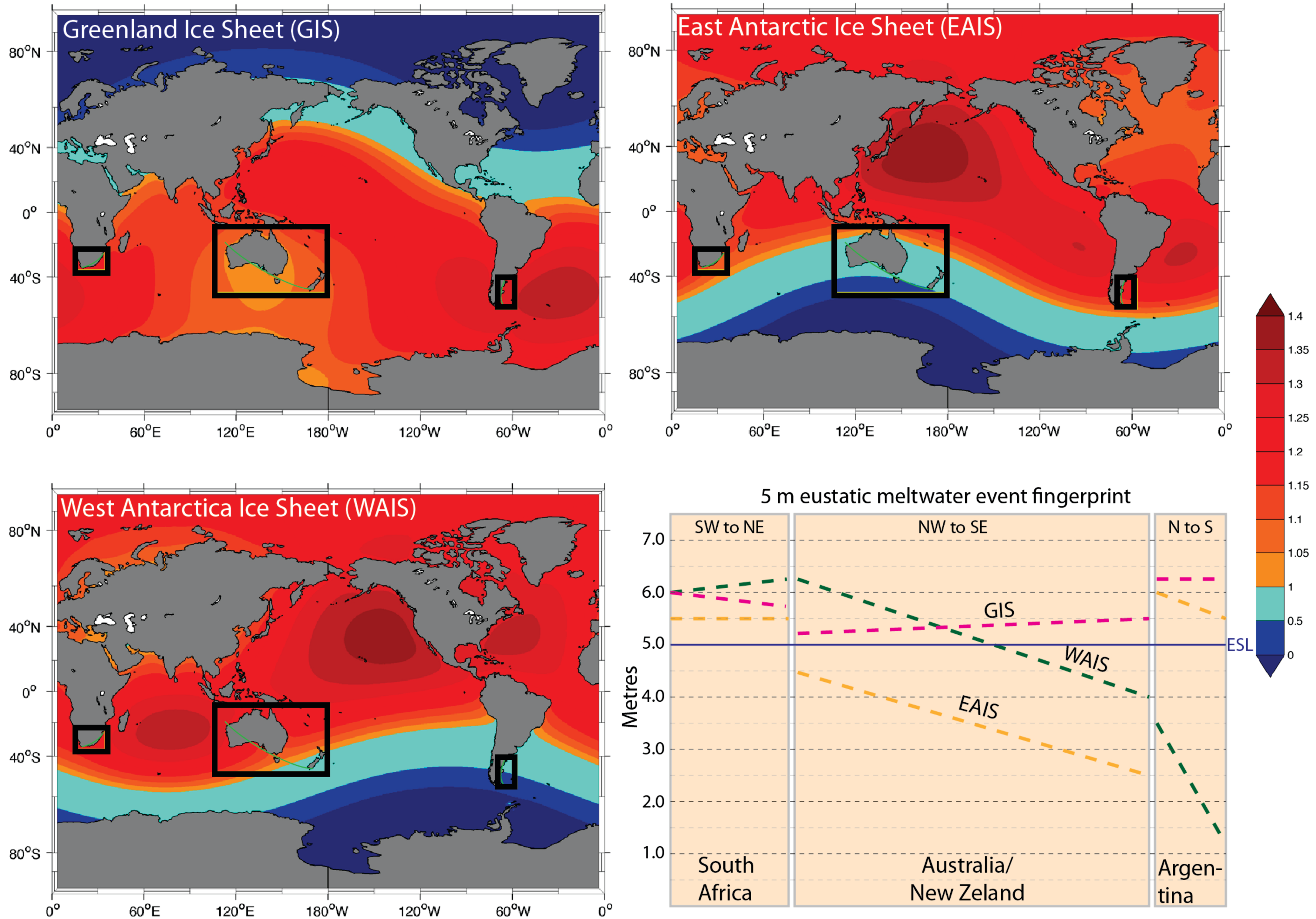


RE Kopp *et al.* *Nature* **462**, 863-867 (2009) doi:10.1038/nature08686



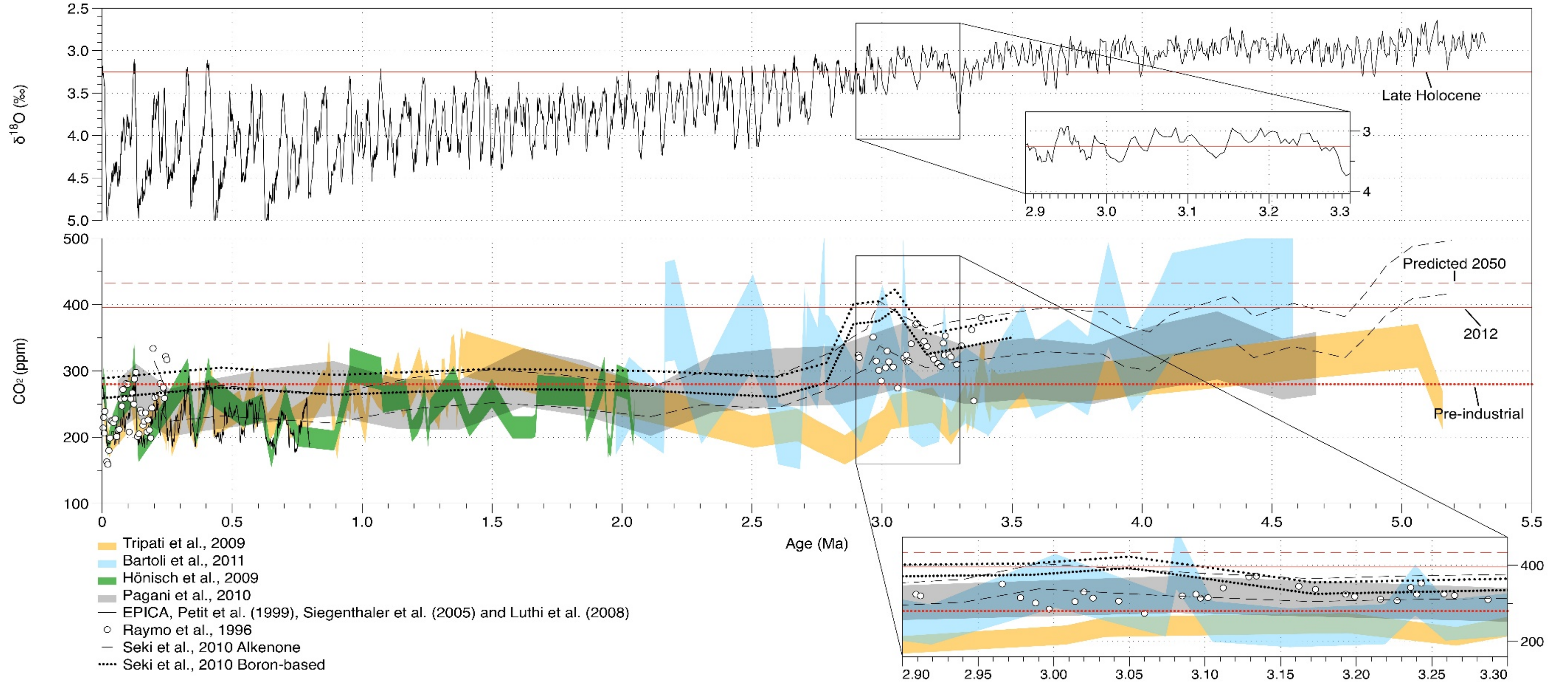
Kopp R E et al. Geophys. J. Int. 2013;193:711-716

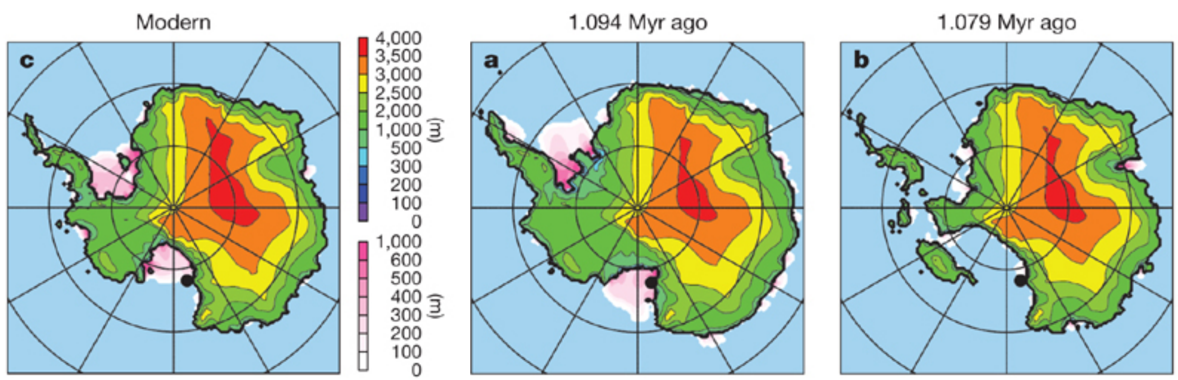
Geophysical Journal International

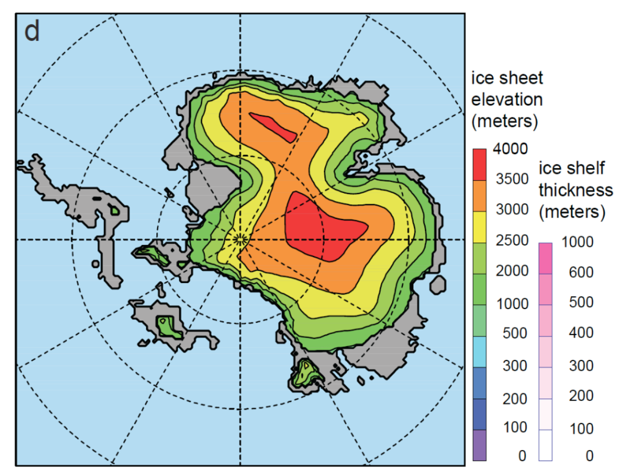


Hay et al., 2014, Interpretation courtesy of M. O'Leary

Pliocene sea level



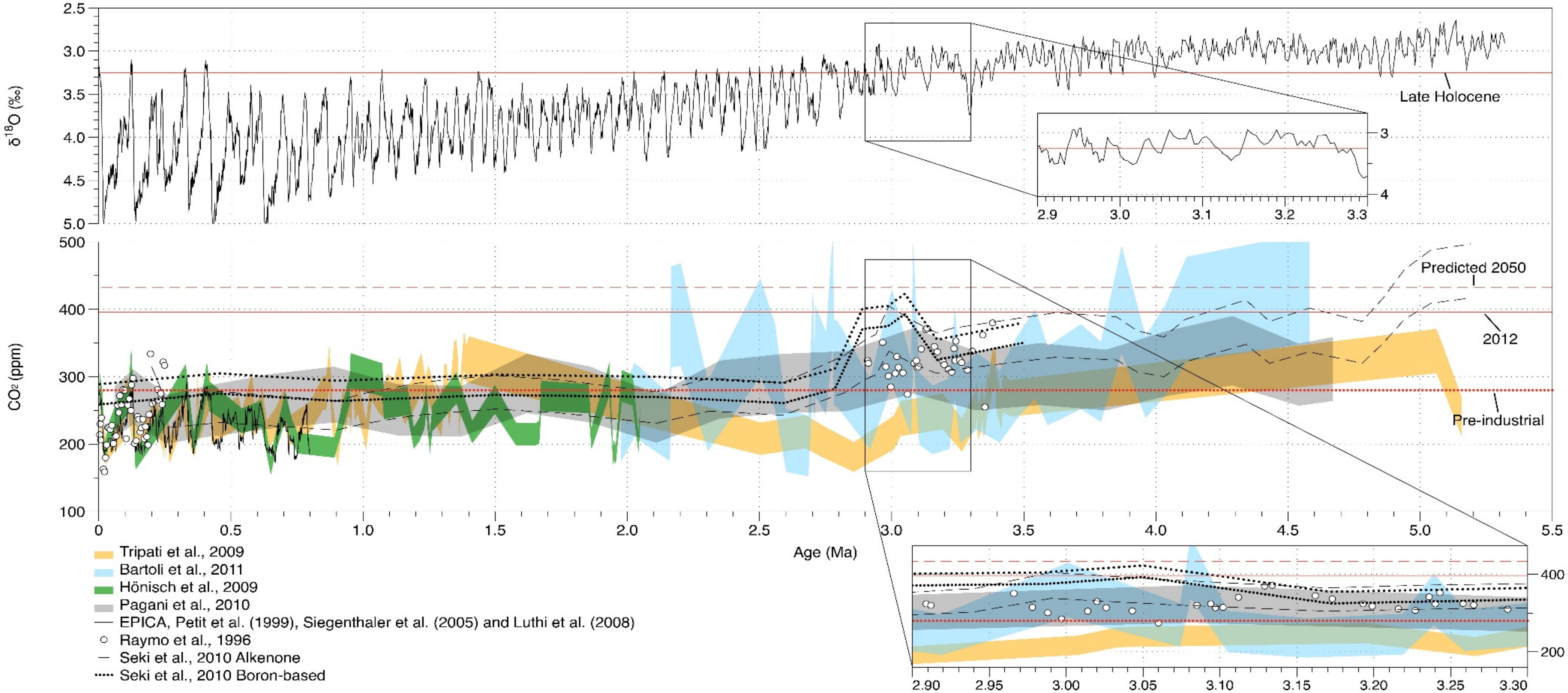




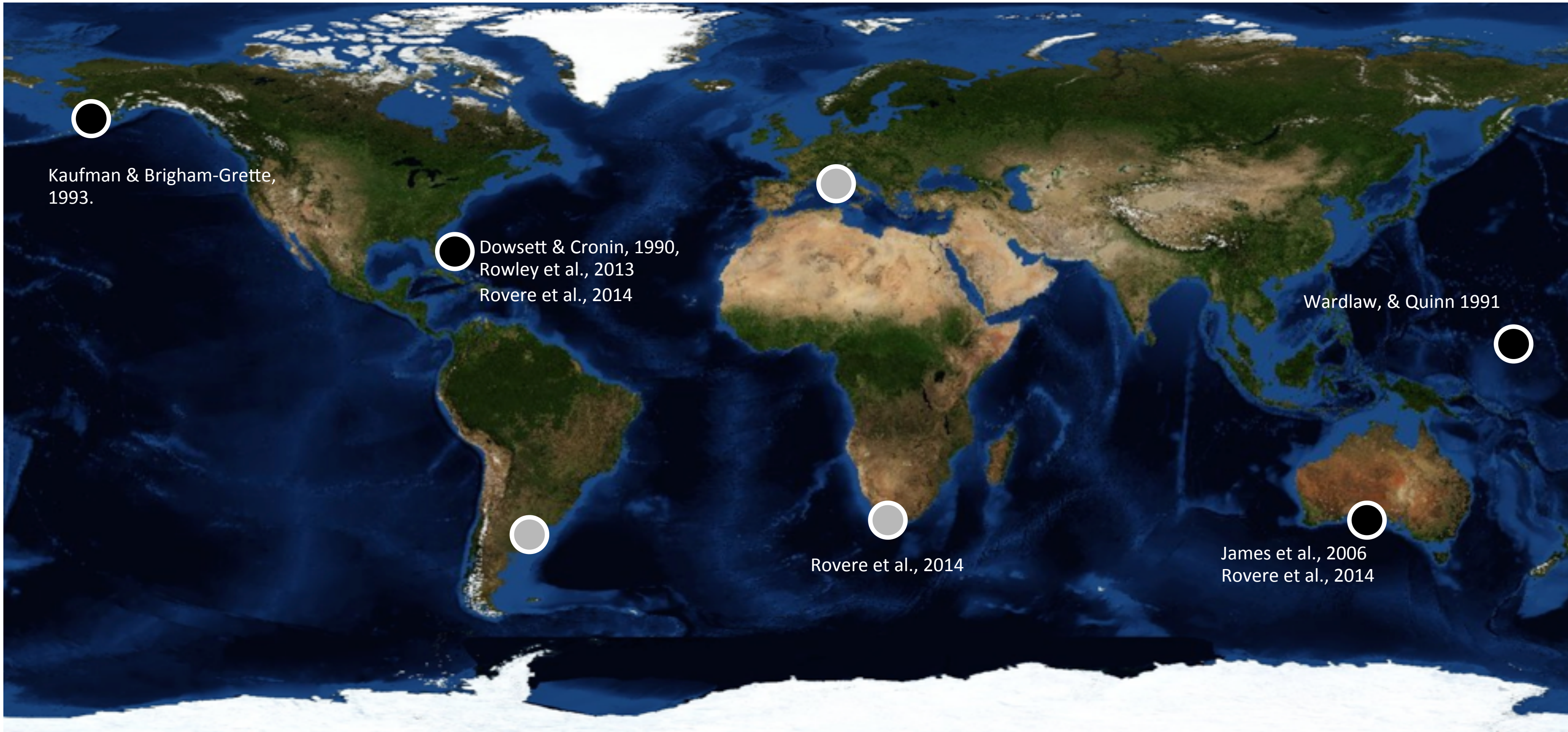
nature

D Pollard & RM DeConto *Nature* **458**, 326-329 (2009) doi:10.1038/nature07809

The Mid-Pliocene



Pliocene sea level



Pliocene sea level