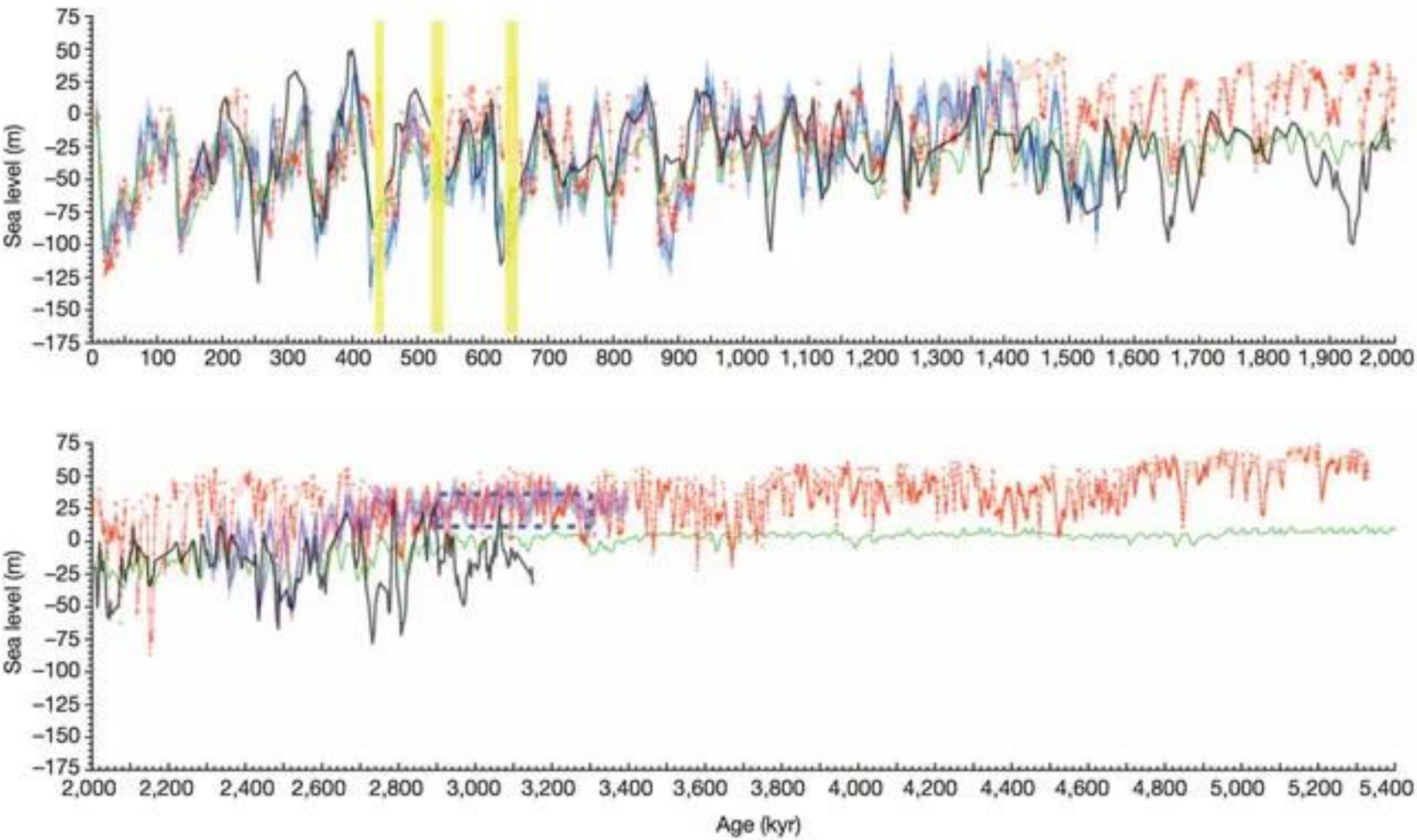
Variazioni del livello del mare:

Modelli,
Tassi,
indicatori

A cura di Stefano FURLANI, a.a. 2021-2022

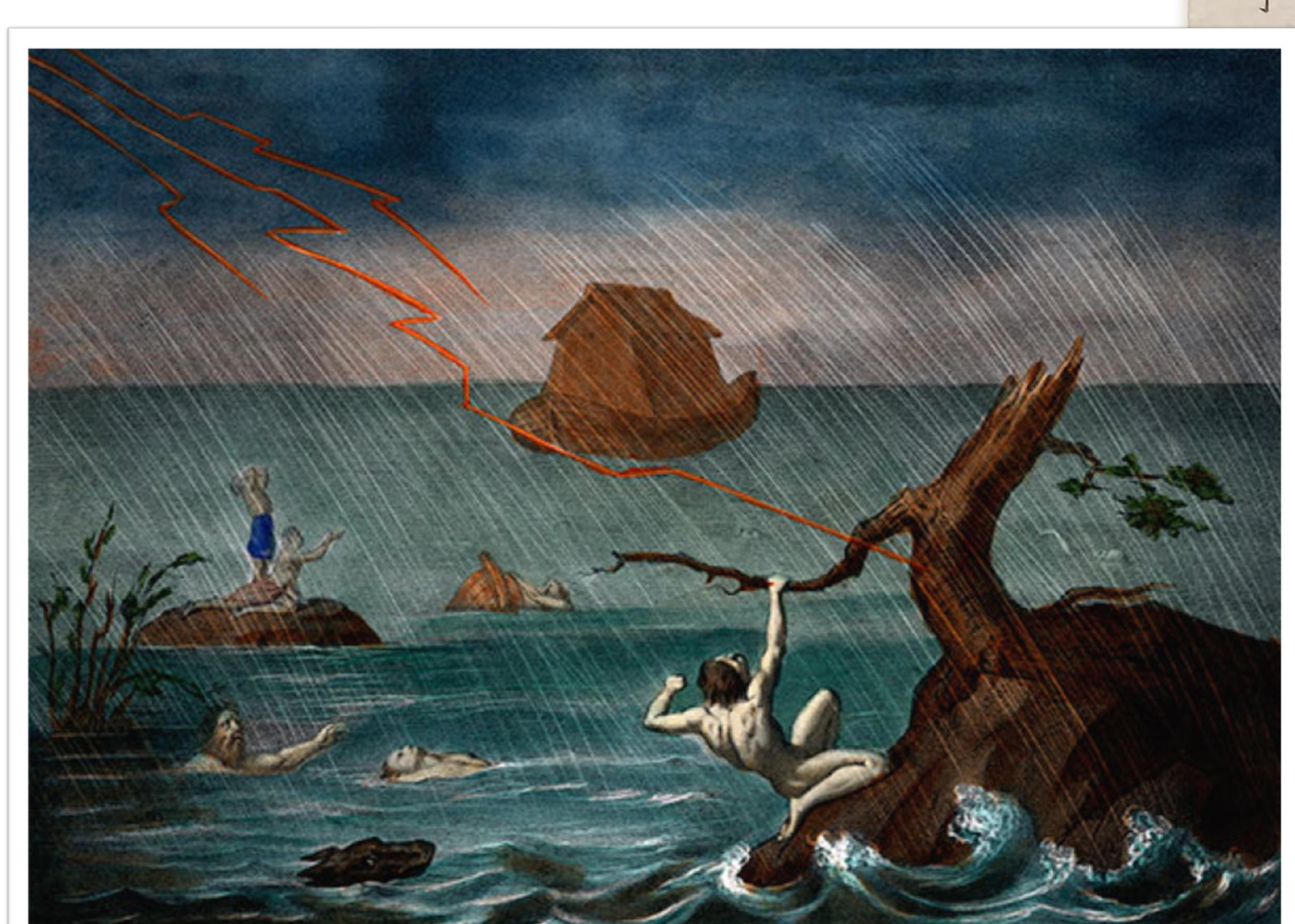
dipartimento di matematica e geoscienze
UNIVERSITÀ DEGLI STUDI DI TRIESTE

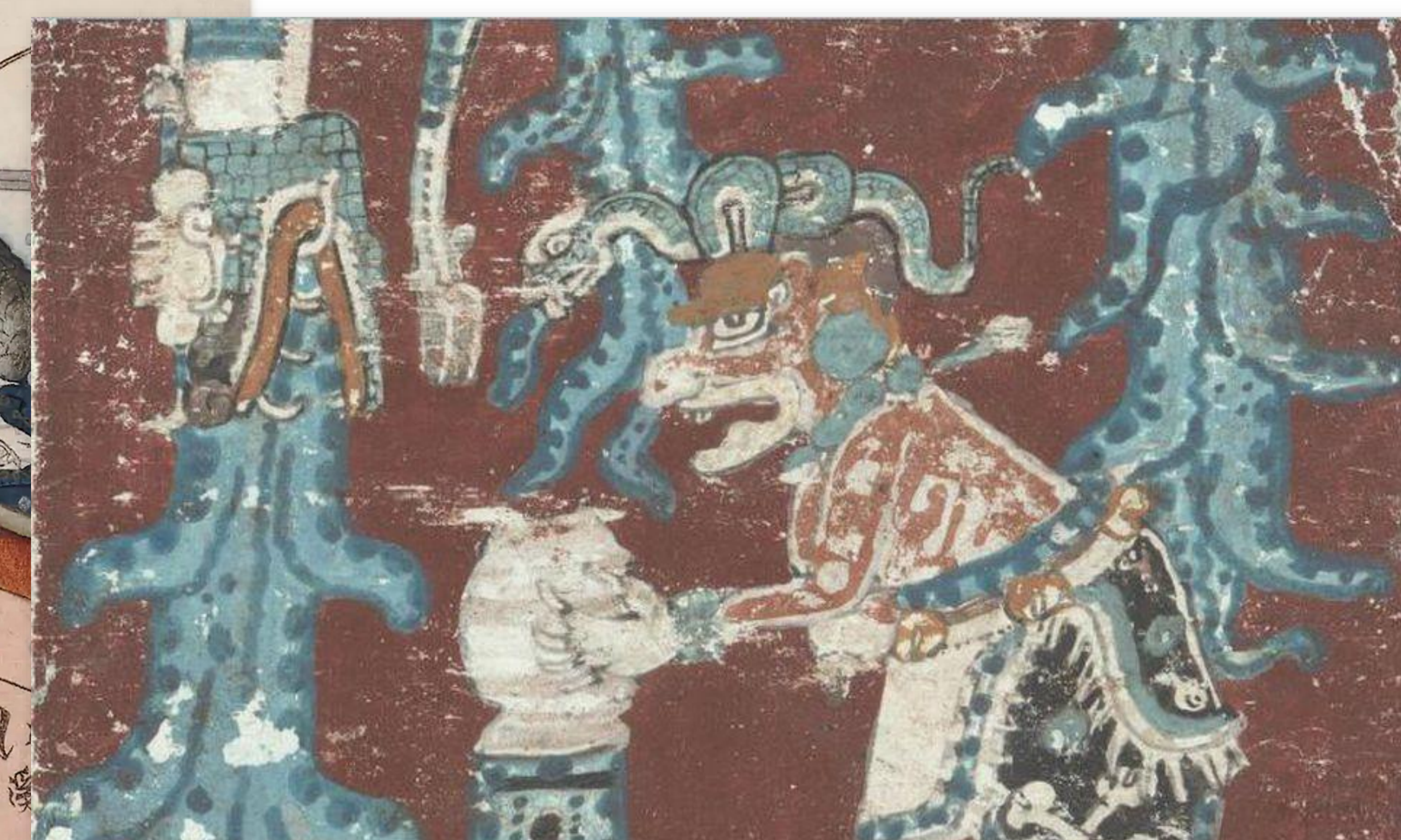
Slc nella storia geologica



Il livello del mare sta cambiando: da quando?

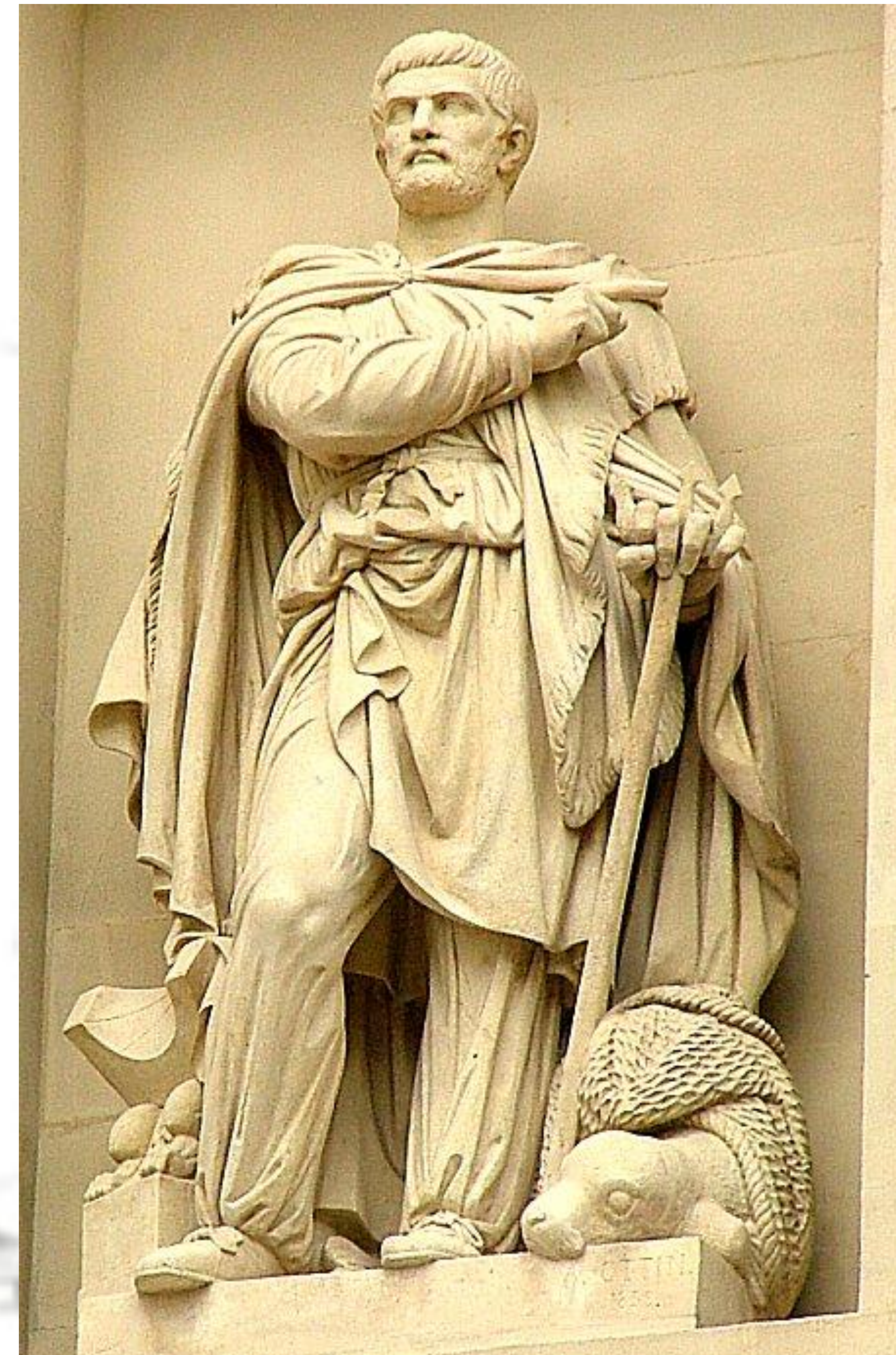
- I cambiamenti del livello del mare sono parte dei grandi miti dell’umanità.
- IL Diluvio Universale è presente in molte culture





Sea level in the past

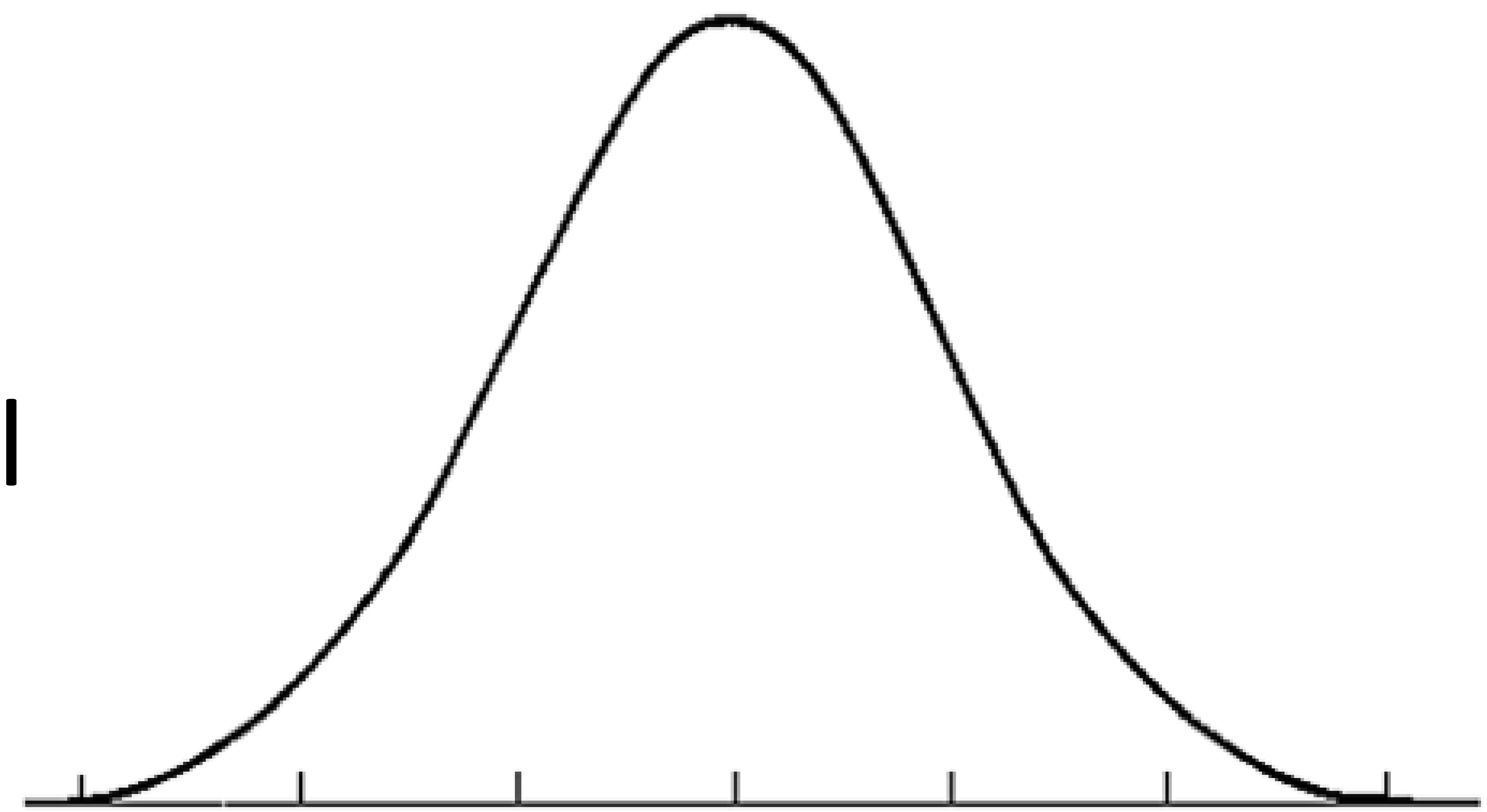
- Pitea di Massalia, III sec AC, osservò che in Gran Bretagna le maree raggiungevano 80 cubiti (Plinio).
- Una risposta molto diffusa a questo valore elevato era data da un'ondata di tempesta.
- Pitea fu il primo ad correlare le maree con le fasi lunari.



Il mare è stabile?

- Il mare era considerato stabile fino al XVIII sec;

- Si pensava che un unico evento abbia cambiato il livello del mare:
- Il Diluvio Universale, ma dopo il mare si pensava fosse tornato al suo posto



And what about fossils?

- Fino al XVII secolo i fossili erano considerati resti del Diluvio;
- Dal XVII sec il dibattito vir sulla base del principio dell'attualismo;
- …ma il livello del mare rimaneva stabile, mentre cambiava solamente la quota dei continenti

- Playfair (1802) osservò che il livello del mare nel passato era stato più alto in località diverse come la Scozia, il Baltico e il Pacifico, ma più basso nel Mediterraneo e nel sud dell'Inghilterra.

- Il concetto di una superficie equipotenziale doveva ancora essere avanzate (Stokes, 1849), e quindi Playfair (1802) sostenne che poiché "*l'oceano ... non può sorgere in un luogo e cadere in un altro*", le differenze devono essere associato ai cambiamenti della quota del suolo.

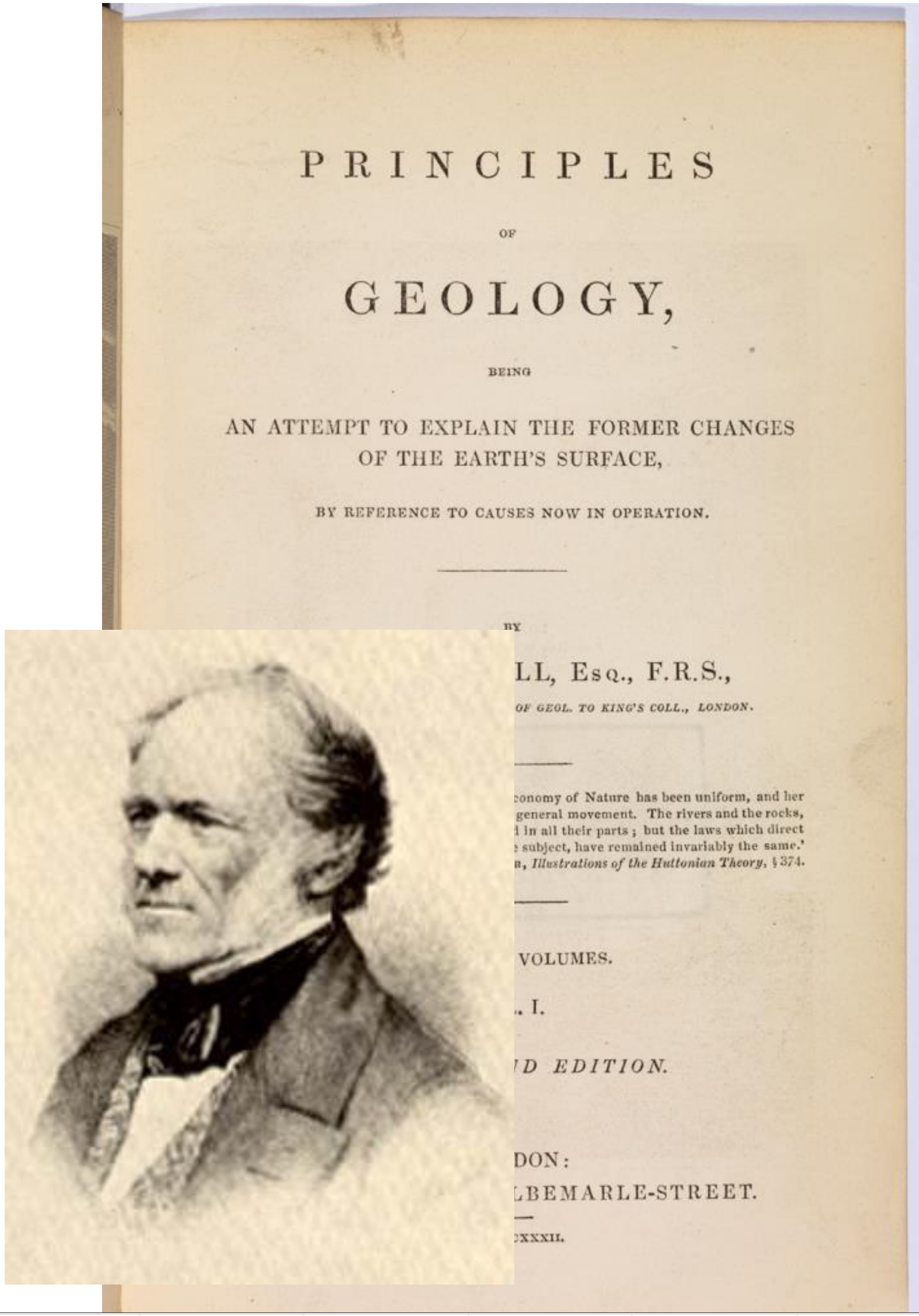
- Senza tecniche per determinare i tempi assoluti del cambiamento del livello del mare relativo in località diverse, l'argomento cadde, ma prove più solide venenro fornite da Lyell (1835), che osservò che in Svezia il cambiamento di livello variava da luogo a luogo (isostasia).

- Lyell (1835) concluse che le sue osservazioni potevano essere spiegate solo da variazioni nel tasso di sollevamento del suolo, poiché presumeva che l'abbassamento del livello del mare avrebbe prodotto un tasso di cambiamento spazialmente uniforme

- Lyell affermò:
- "*Al di sopra di questa è una zona, alta circa nove piedi, dove il marmo è stato perforato da una specie di bivalve marino perforante, Lithodomus*". (Lithodomus è un genere di vongole che si insinuano nei moli e negli ormeggi delle barche).

- Poiché queste vongole non possono vivere al di sopra della linea di bassa marea, Lyell concluse che le colonne un tempo erano state sott'acqua (molti dei fori delle colonne hanno ancora conchiglie di Lithodomus).

- Il tempio originale era stato costruito sopra il livello del mare, ma la presenza dei molluschi sulle colonne significava che le colonne erano state parzialmente sommerse e stavano in piedi nell'oceano. Le colonne erano state poi rialzate al loro livello attuale dall'eruzione vulcanica che produsse il Monte Nuovo appena a nordovest di Pozzuoli.



PRINCIPLES

OF

GEOLOGY,

BEING

AN ATTEMPT TO EXPLAIN THE FORMER CHANGES
OF THE EARTH'S SURFACE,

BY REFERENCE TO CAUSES NOW IN OPERATION.

BY

...LL, Esq., F.R.S.,

...OF GEOL. TO KING'S COLL., LONDON.

...conomy of Nature has been uniform, and her
... general movement. The rivers and the rocks,
... in all their parts; but the laws which direct
... subject, have remained invariably the same.'
...n, *Illustrations of the Huttonian Theory*, § 374.

... VOLUMES.

... I.

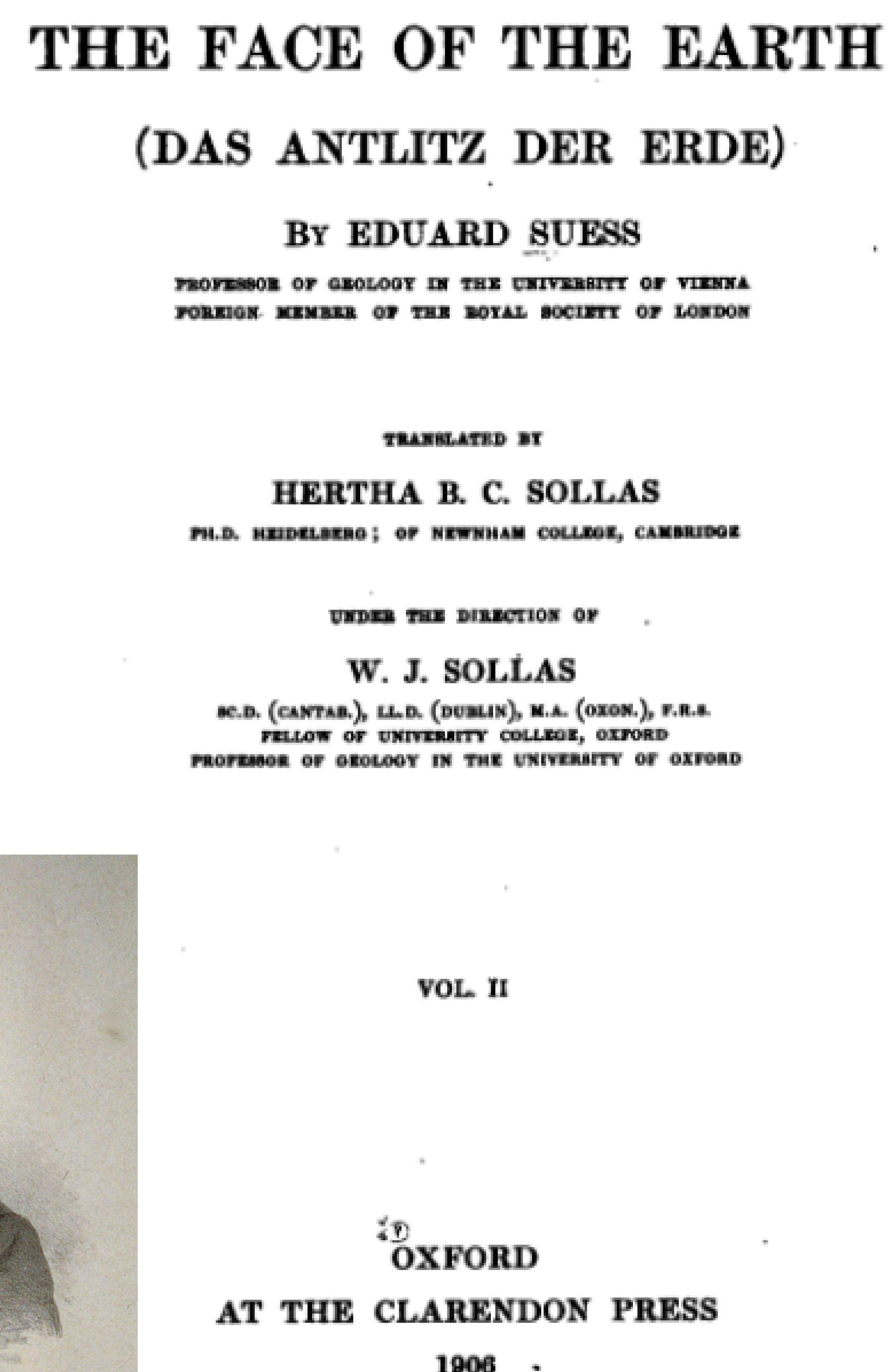
...D EDITION.

...DON:
...LBEMARLE-STREET.

...XXXII.

Eustasy: a global model of sea level change

- Suess (1880) propose il concetto di eustatismo
- è il fenomeno di innalzamento o abbassamento a scala globale del livello medio dei mari, non dipendente cioè da fenomeni locali


THE FACE OF THE EARTH

(DAS ANTLITZ DER ERDE)

BY EDUARD SUESS

PROFESSOR OF GEOLOGY IN THE UNIVERSITY OF VIENNA
FOREIGN MEMBER OF THE ROYAL SOCIETY OF LONDON

TRANSLATED BY

HERTHA B. C. SOLLAS

PH.D. HEIDELBERG; OF NEWNHAM COLLEGE, CAMBRIDGE

UNDER THE DIRECTION OF

W. J. SOLLAS

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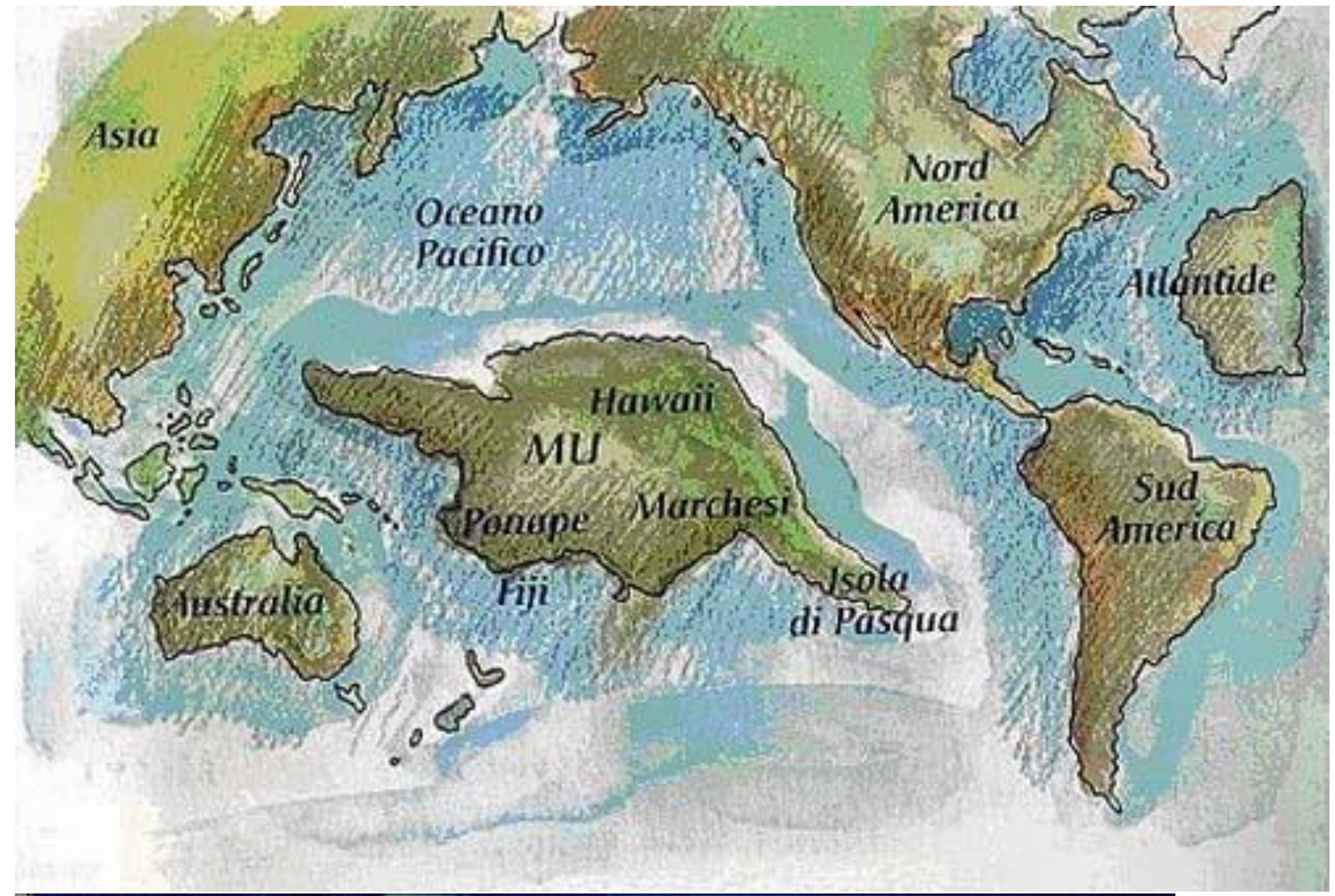
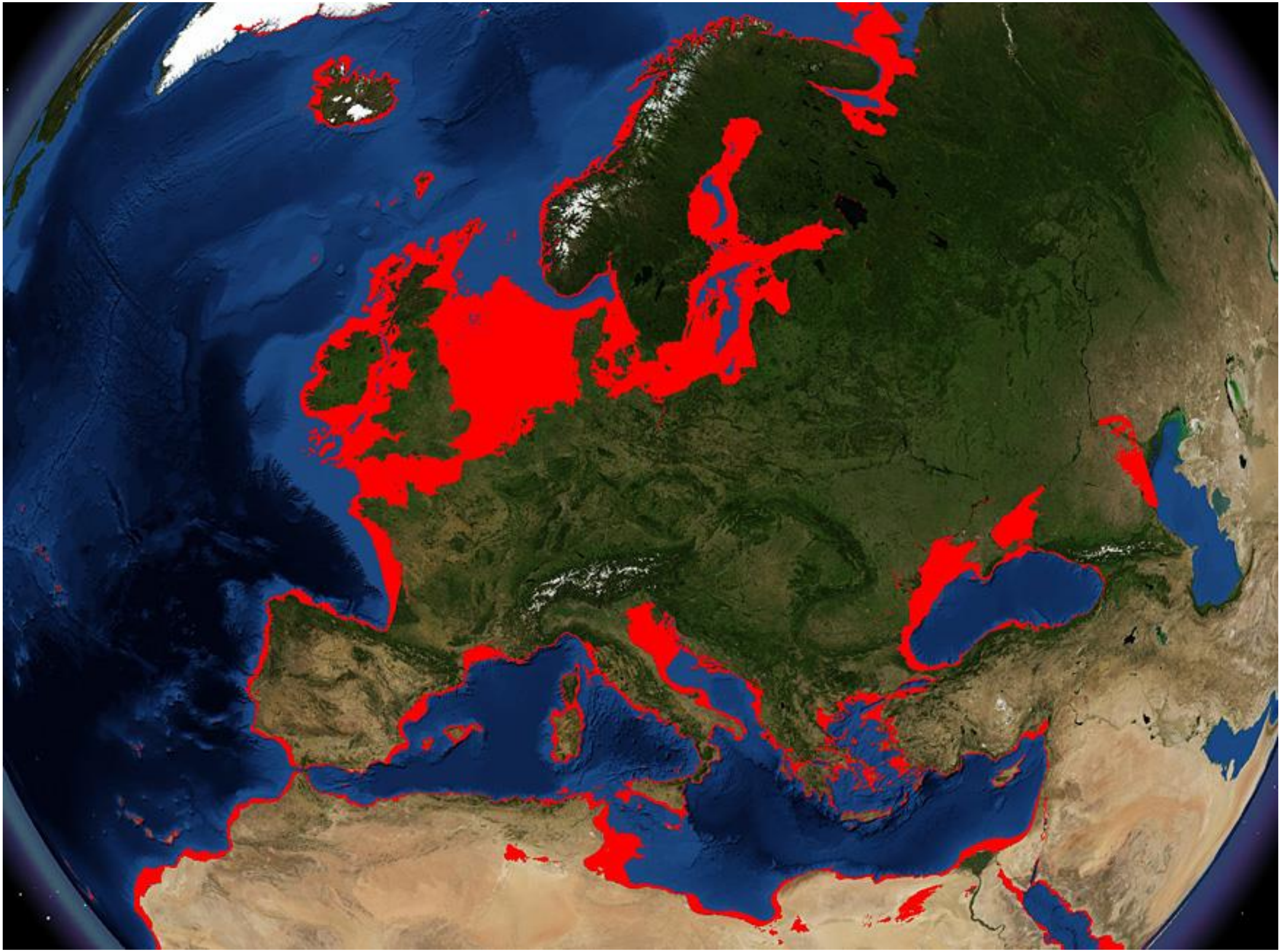
FELLOW OF UNIVERSITY COLLEGE, OXFORD
PROFESSOR OF GEOLOGY IN THE UNIVERSITY OF OXFORD

VOL. II

OXFORD
AT THE CLARENDON PRESS
1906

The mith of Atlantis

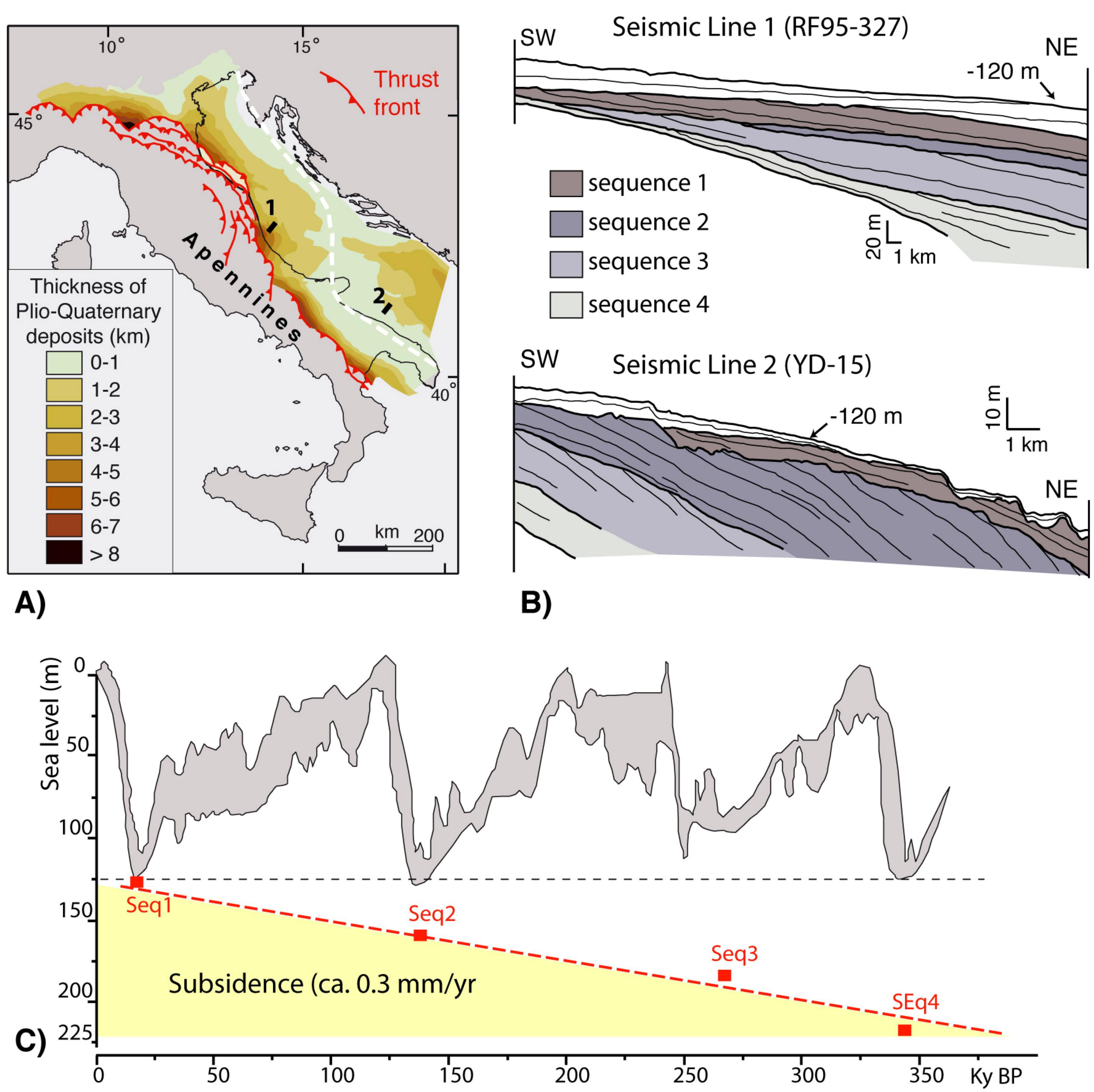




A long history

- 215.000 years ago the sea level was at -18 m;
- 125.000 years ago the sea leval was at +8 m;
- 81.000 years ago the sea level was at -25 m;
- 21.000 years ago the sea level was at -135 m;
- 2500 years ago the sea level was at -1.8 m;
- 2000 years ago the sea level was at -1.3 m;
- 1.000 years ago the sea level was at -0.3 m

Last 350 Kyrs



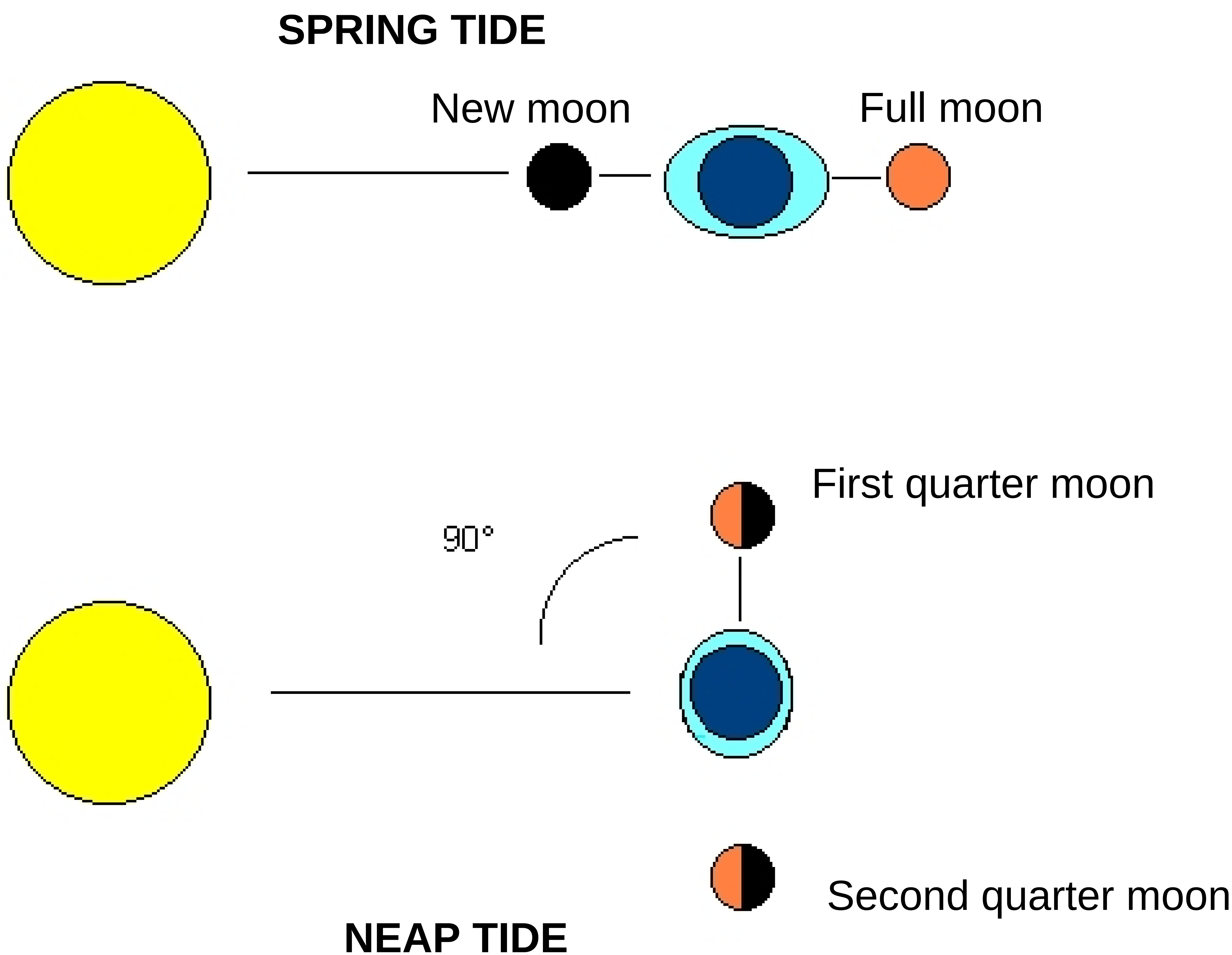
Ridente (2018), Geosciences

Iniziamo dal livello del mare…

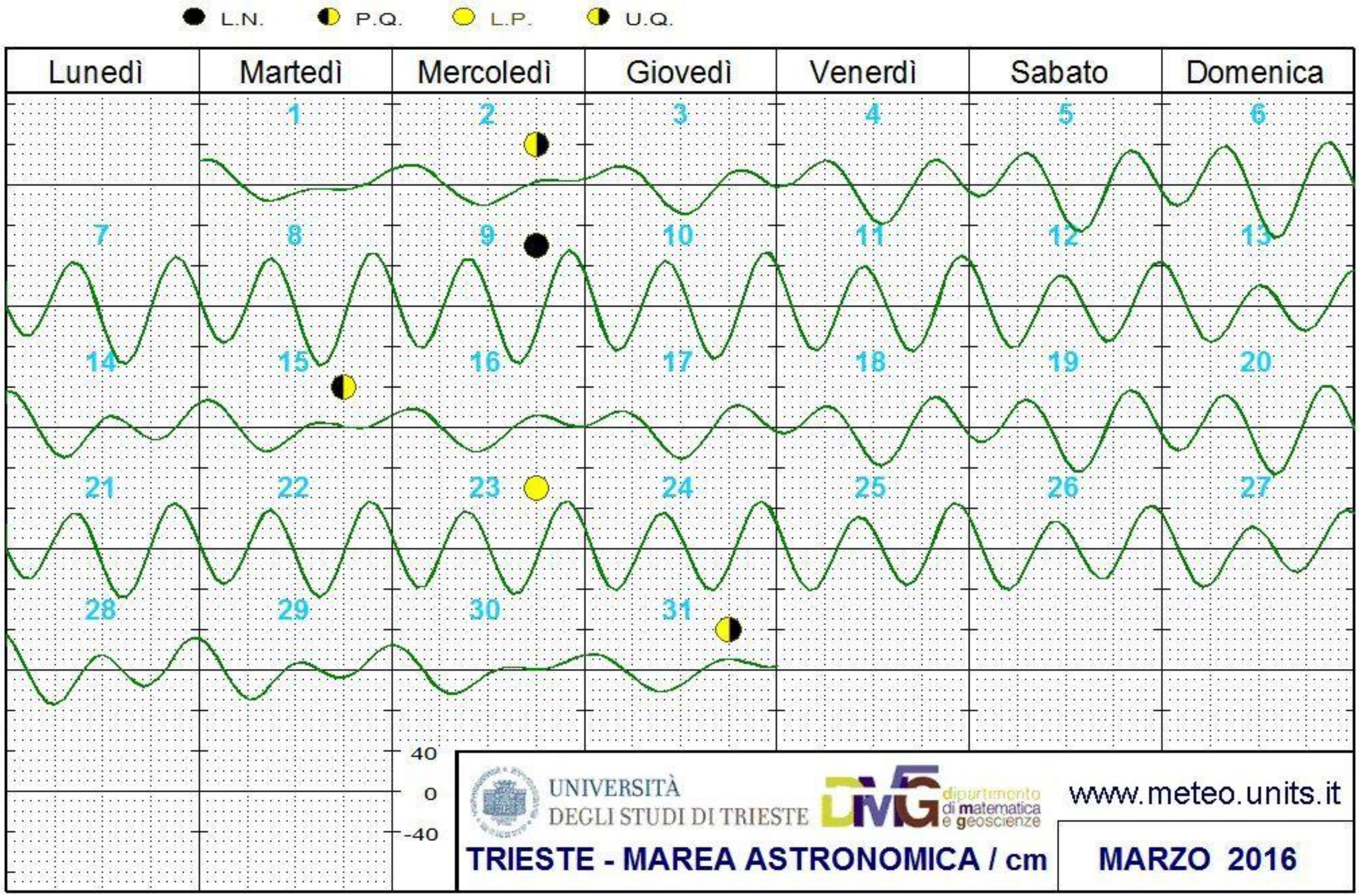
Come si può definire il livello del mare?

- Sea surface can be considered an unstable entity, because of tides, waves, pressure, winds, temperature and salinity variations, …;
- …after filtering all the periodic (eg. Tides) or random movements, the mean sea level can be calculated;
- The altitude above or below the mean sea level of every nation corresponds to a particular reference level, a conventional tide gauge;
- in Italy Genova, in France Marseille, etc.

Tides


SPRING TIDE
New moon
Full moon
First quarter moon
90°
Second quarter moon
NEAP TIDE

Tide tables



L.N.
P.Q.
L.P.
U.Q.
Lunedì
Martedì
Mercoledì
Giovedì
Venerdì
Sabato
Domenica
1
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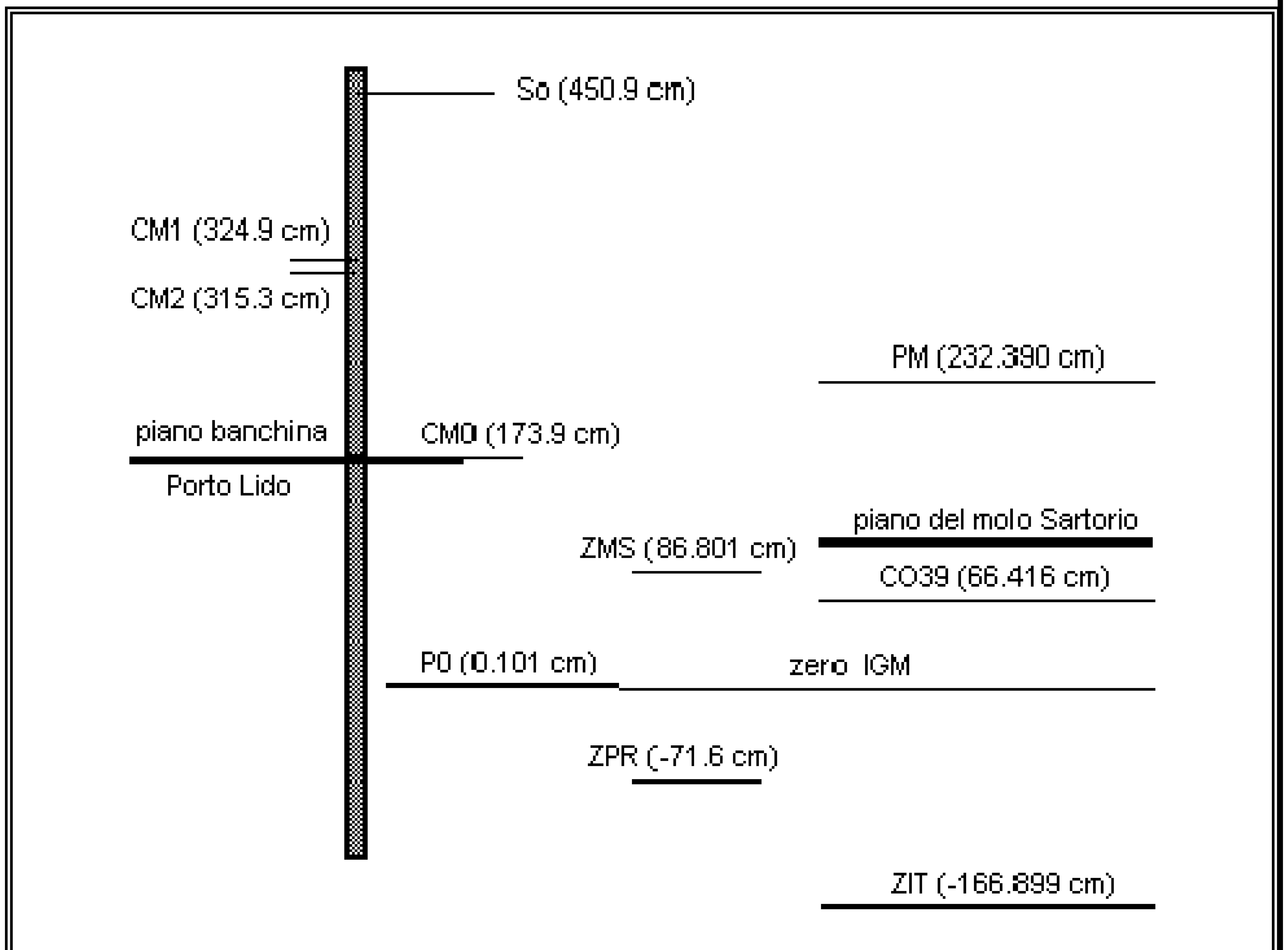
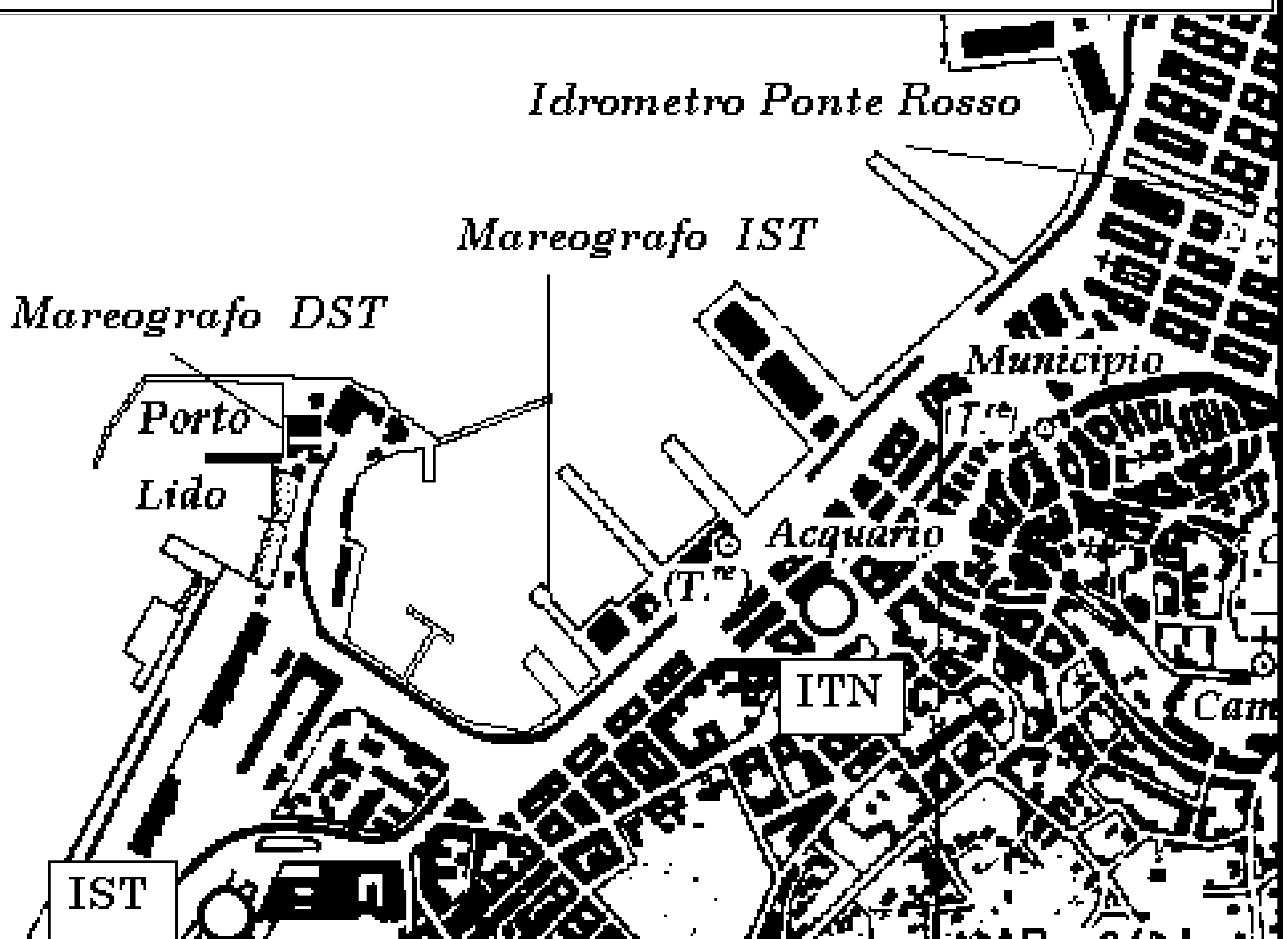
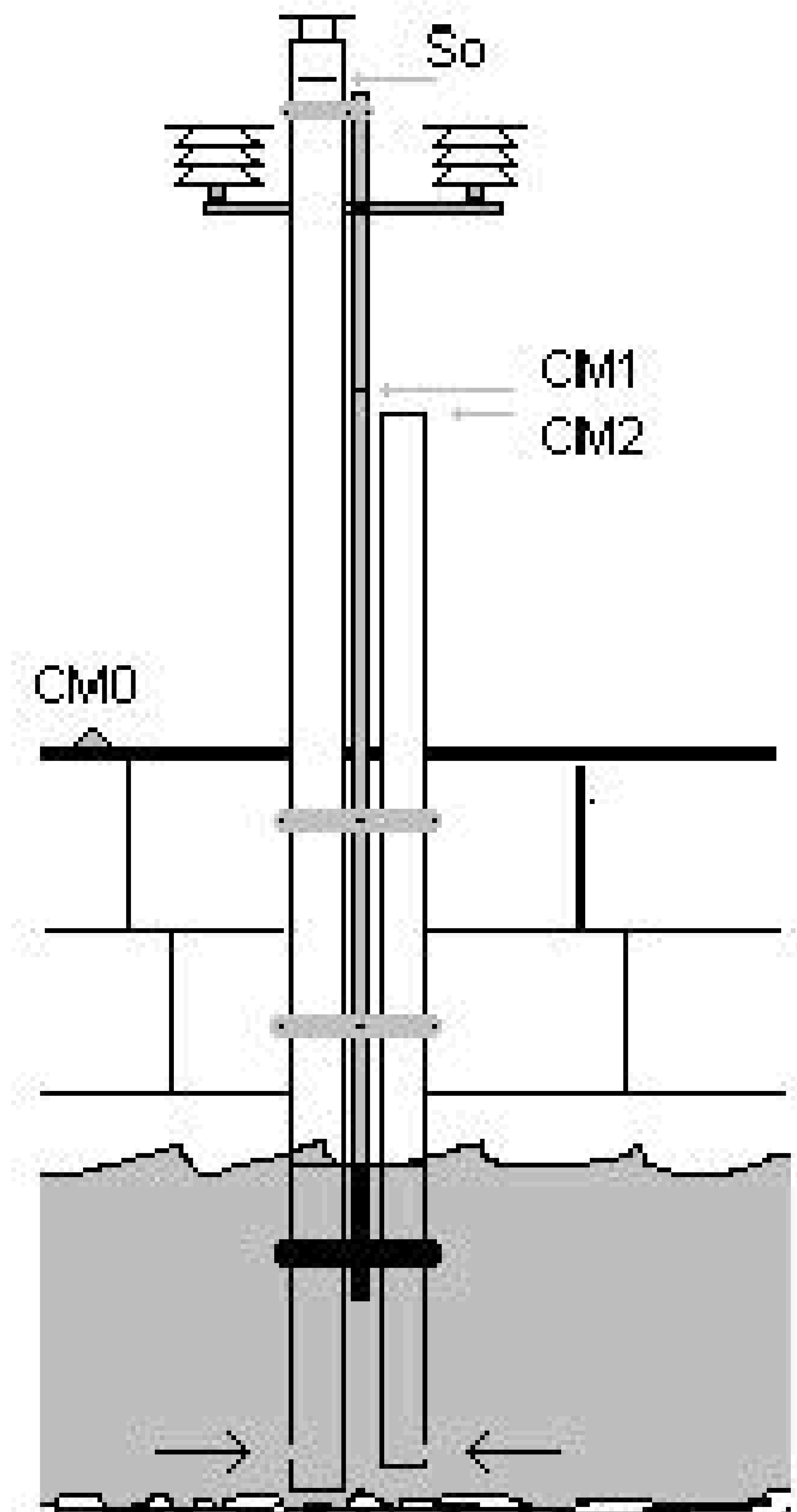
0
-40
UNIVERSITÀ
DEGLI STUDI DI TRIESTE
DMG dipartimento di matematica e geoscienze
www.meteo.units.it
TRIESTE - MAREA ASTRONOMICA / cm
MARZO 2016

Tide gauge, Trieste (NE Italy)

Tide gauge, Marseille (France)

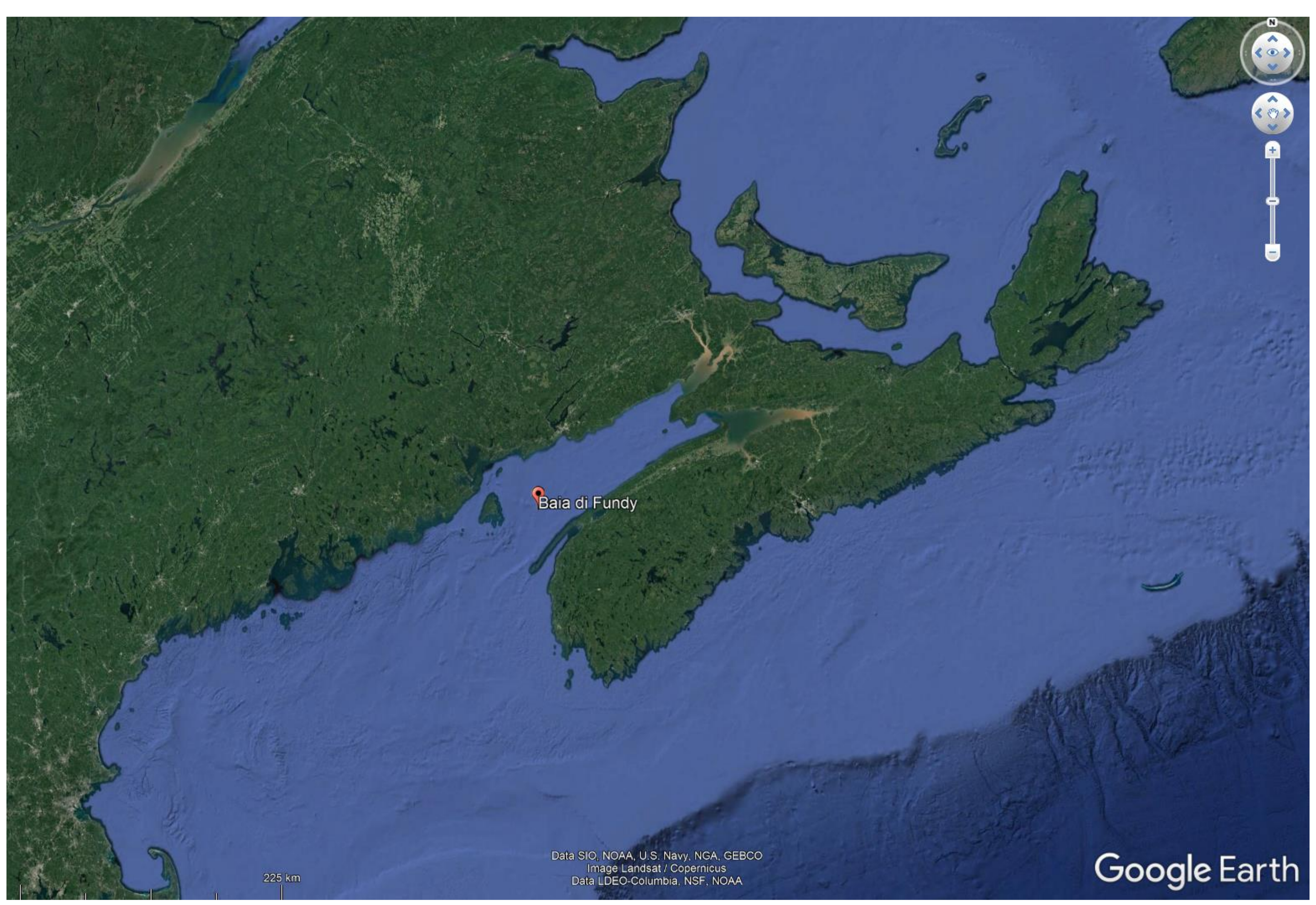

So (450.9 cm)
CM1 (324.9 cm)
CM2 (315.3 cm)
PM (232.390 cm)
piano banchina
Porto Lido
CM0 (173.9 cm)
piano del molo Sartorio
ZMS (86.801 cm)
CO39 (66.416 cm)
P0 (0.101 cm)
zero IGM
ZPR (-71.6 cm)
ZIT (-166.899 cm)


Idrometro Ponte Rosso
Mareografo IST
Mareografo DST
Porto
Lido
Municipio
Acquario
ITN
IST

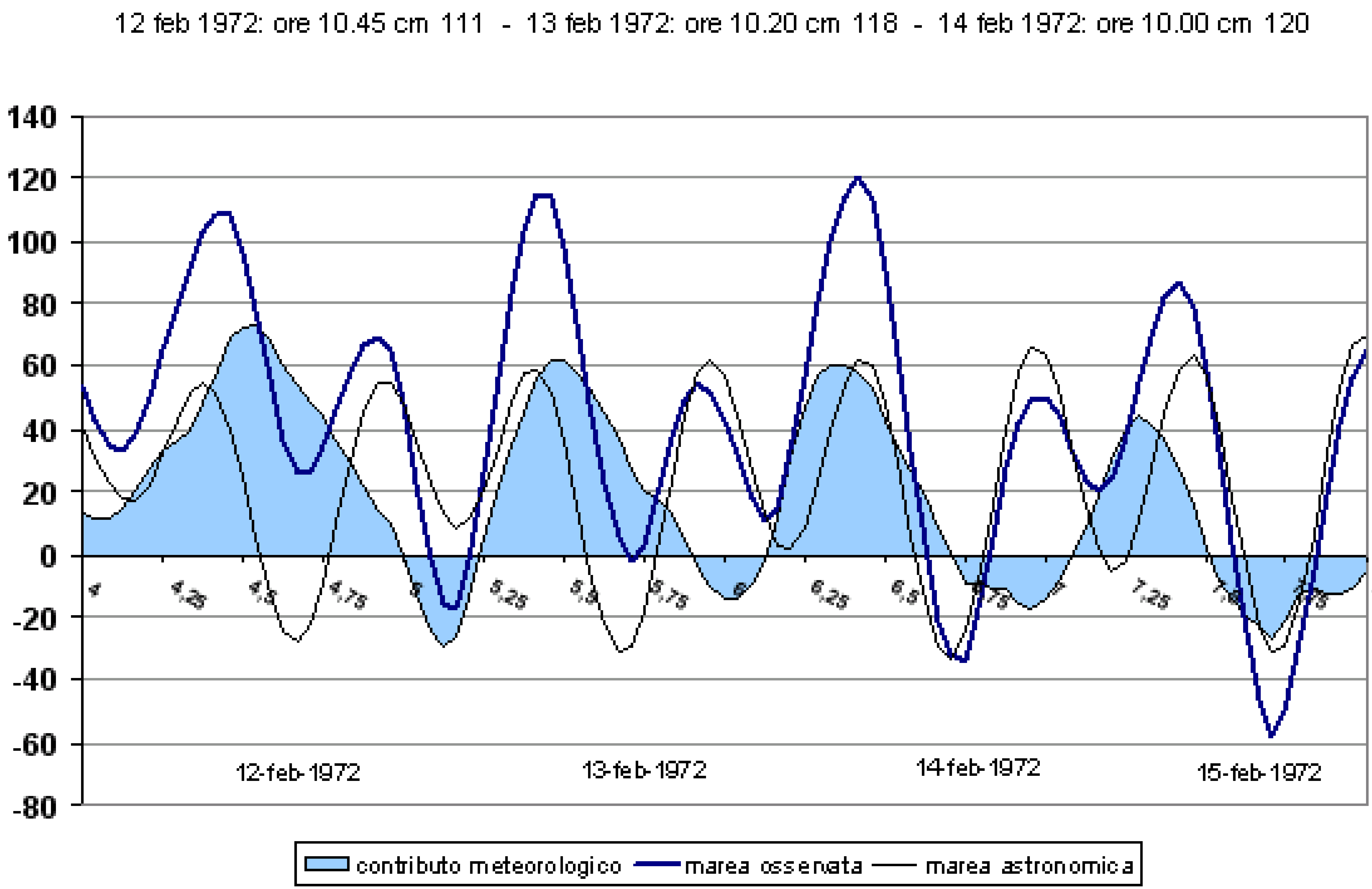

So
CM1
CM2
CM0

Tide amplitude

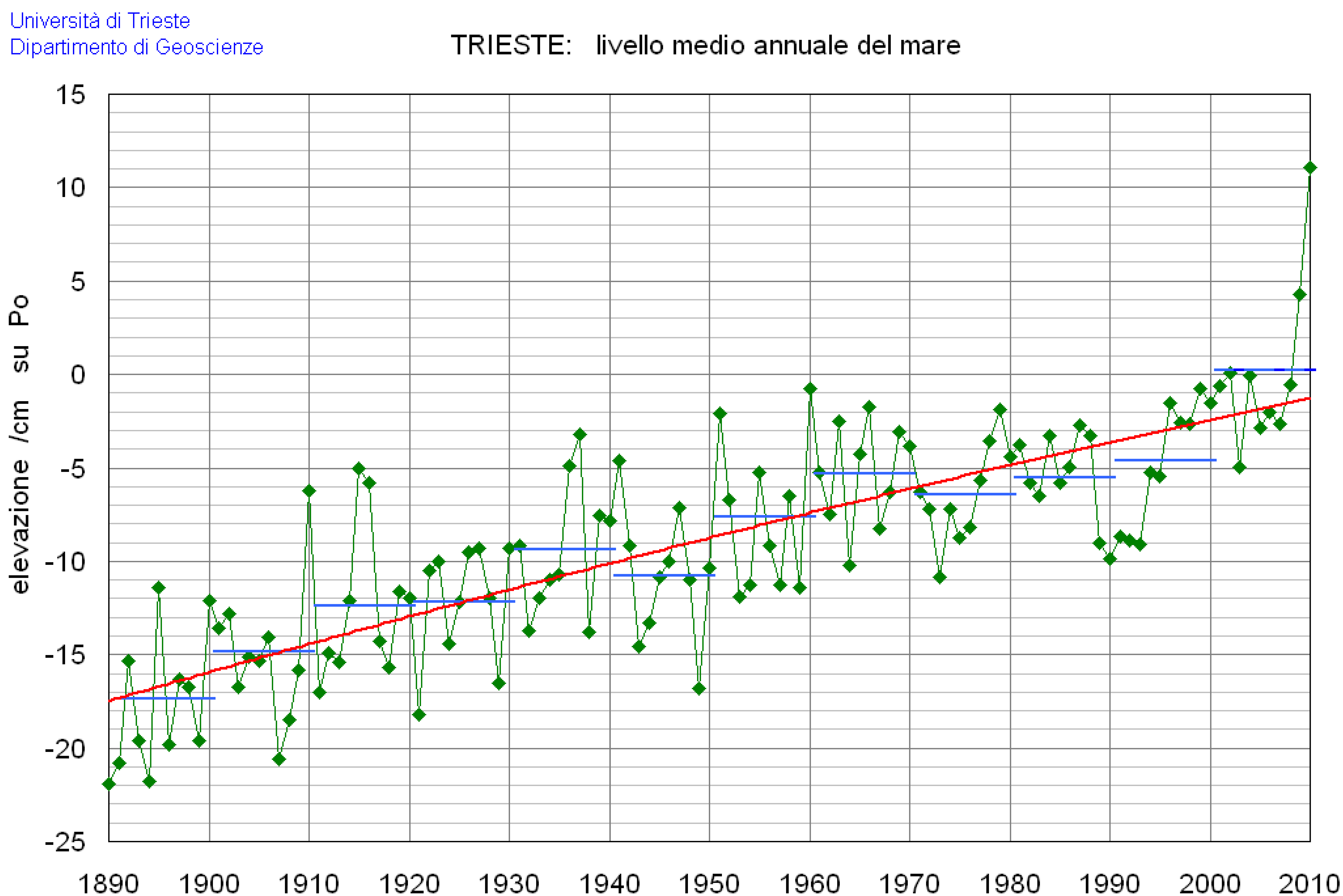
- Tide amplitude is 21 m in the Bay of Fundy (Canada)



Tide variations (modelled, measured)

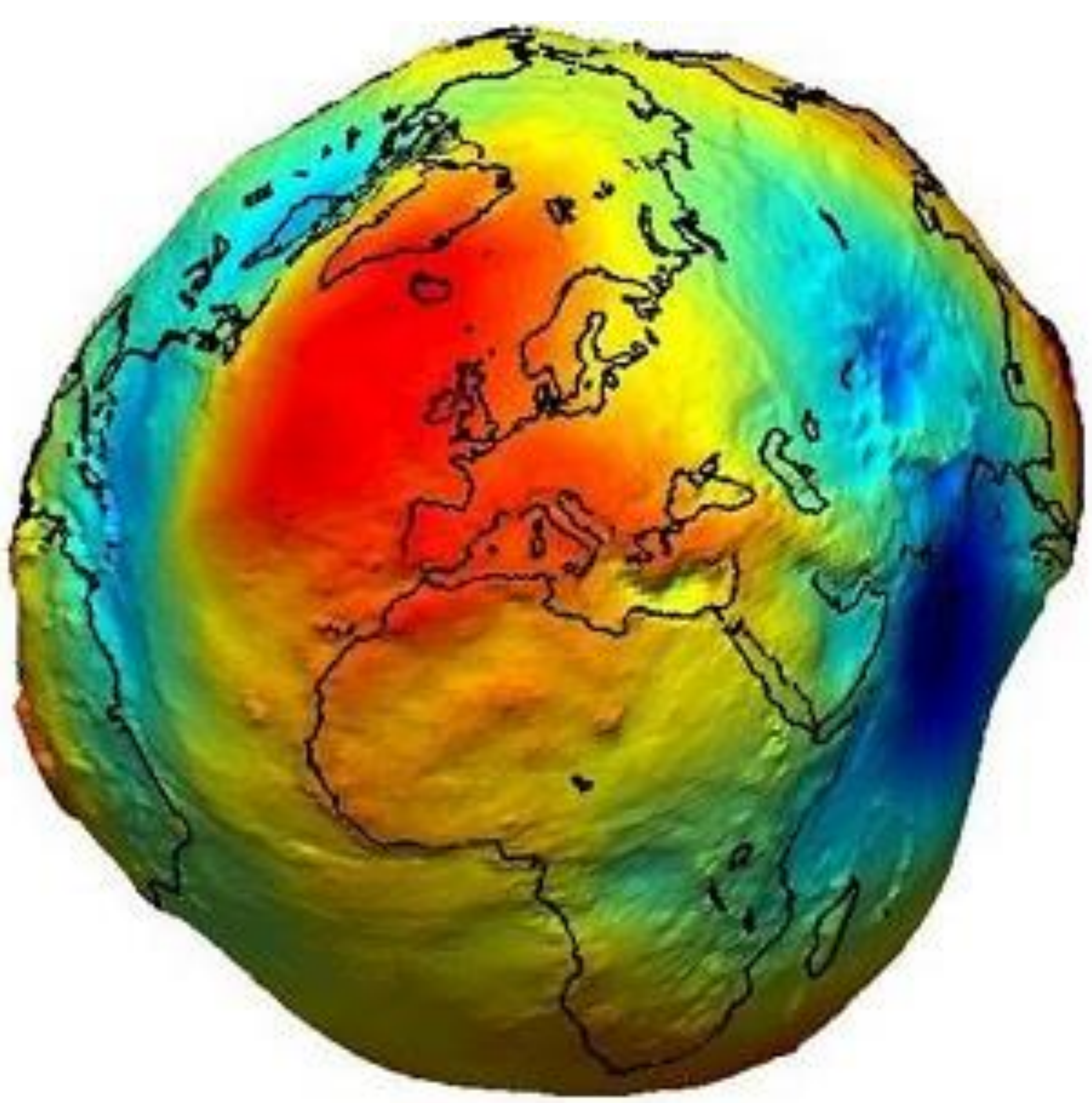


The tide gauge in Trieste



Observations

- Tide gauges
- Satellites



Le basi sulle variazioni del livello marino

COS'È L'AUMENTO DEL LIVELLO DEL MARE?

What is the sea level rise?

The sea level rise represents an increase in global mean sea level due to an increase in the volume of water in the world's oceans

Sea level rise is mainly attributed to changes in global climate by thermal expansion of the oceans and by melting of ice sheets and glaciers on land

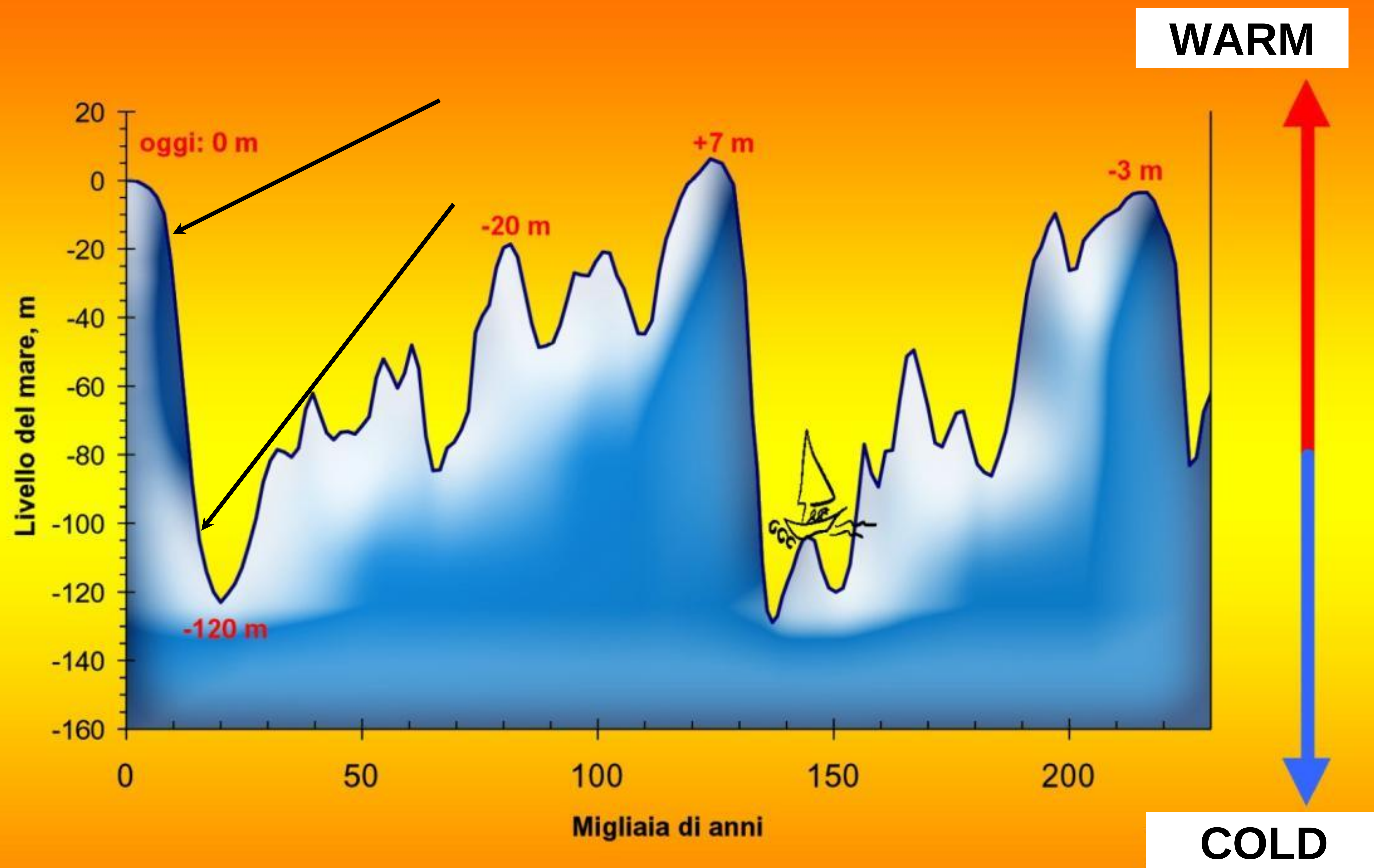
The melting of icebergs at sea would raise sea levels only by about 4 cm

Sea level changes are considered relative variations due to the sum of eustatic, tectonic and isostatic factors

- Sea level changes are considered relative variations due to the sum of eustatic, tectonic and isostatic factors

- The elevation on the mean sea level (msl) of an observed site is related to the sum of:
  - eustatic (global)
  - tectonic (local)
  - isostatic factors (local)

$$\Delta\zeta_{obs} = \Delta\zeta_{e} + (\Delta\zeta_{i} + \Delta\zeta_{w}) + \Delta\zeta_{tect}$$

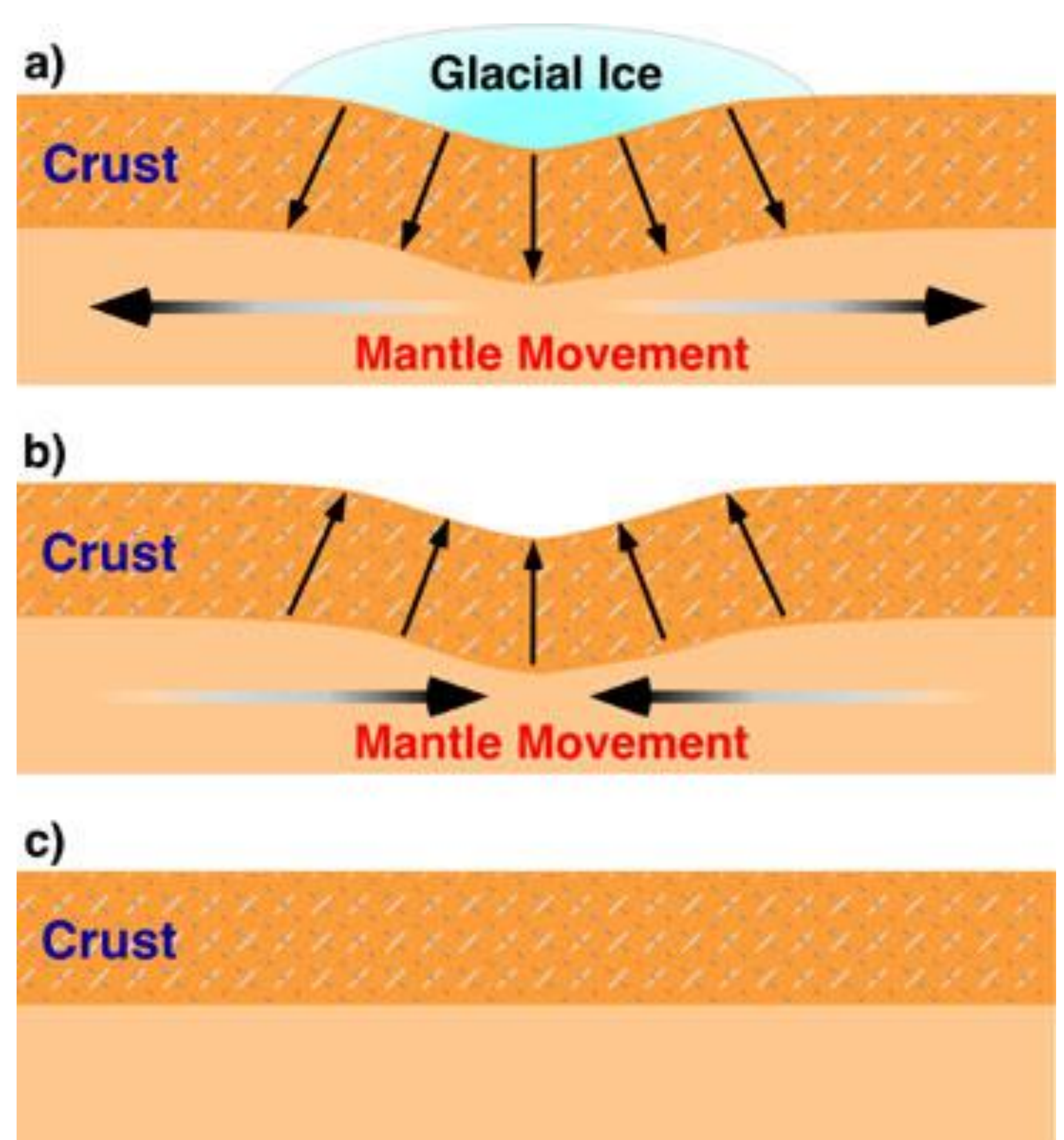


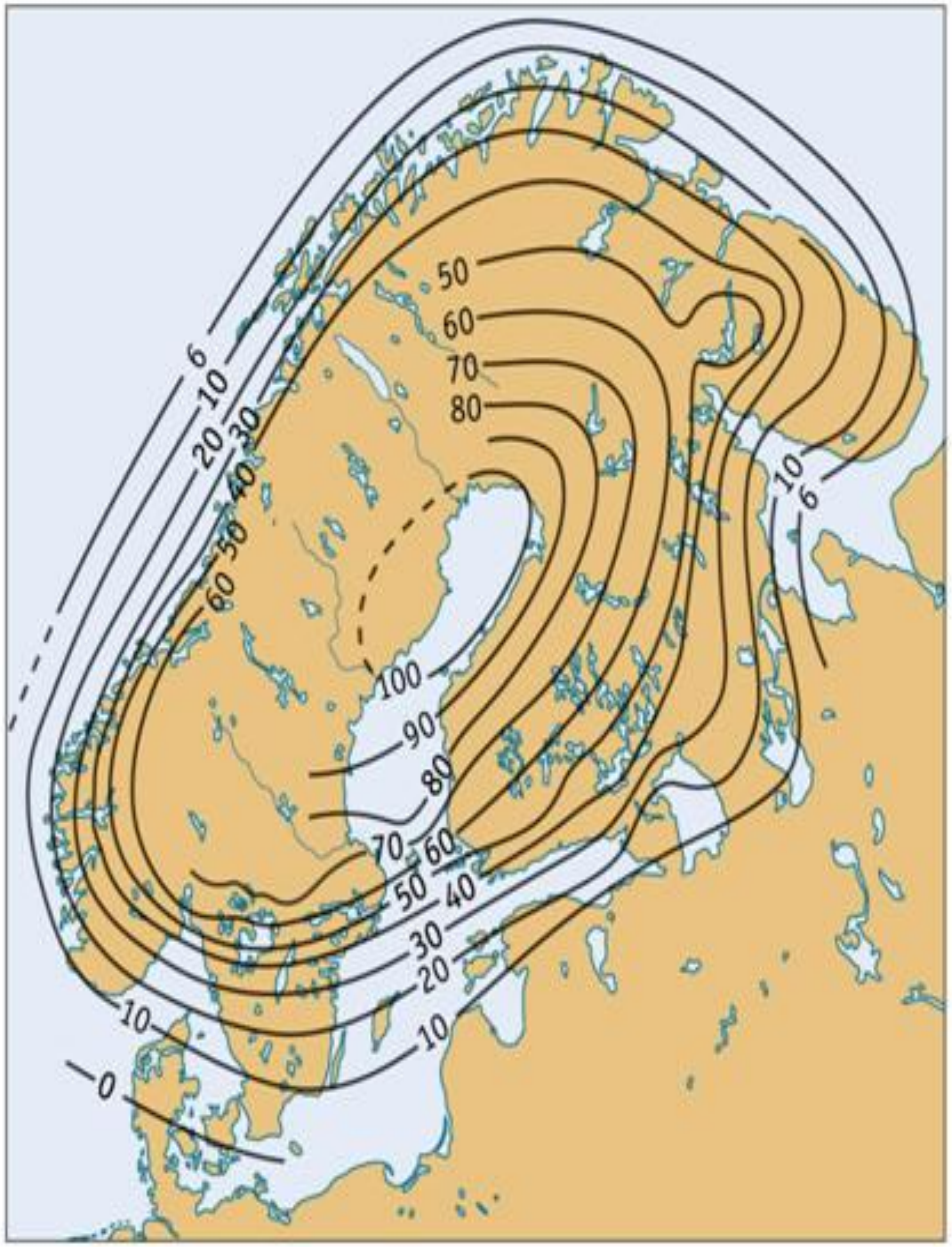
eustatic factor

Glacio-isostasy adjustment (GIA)

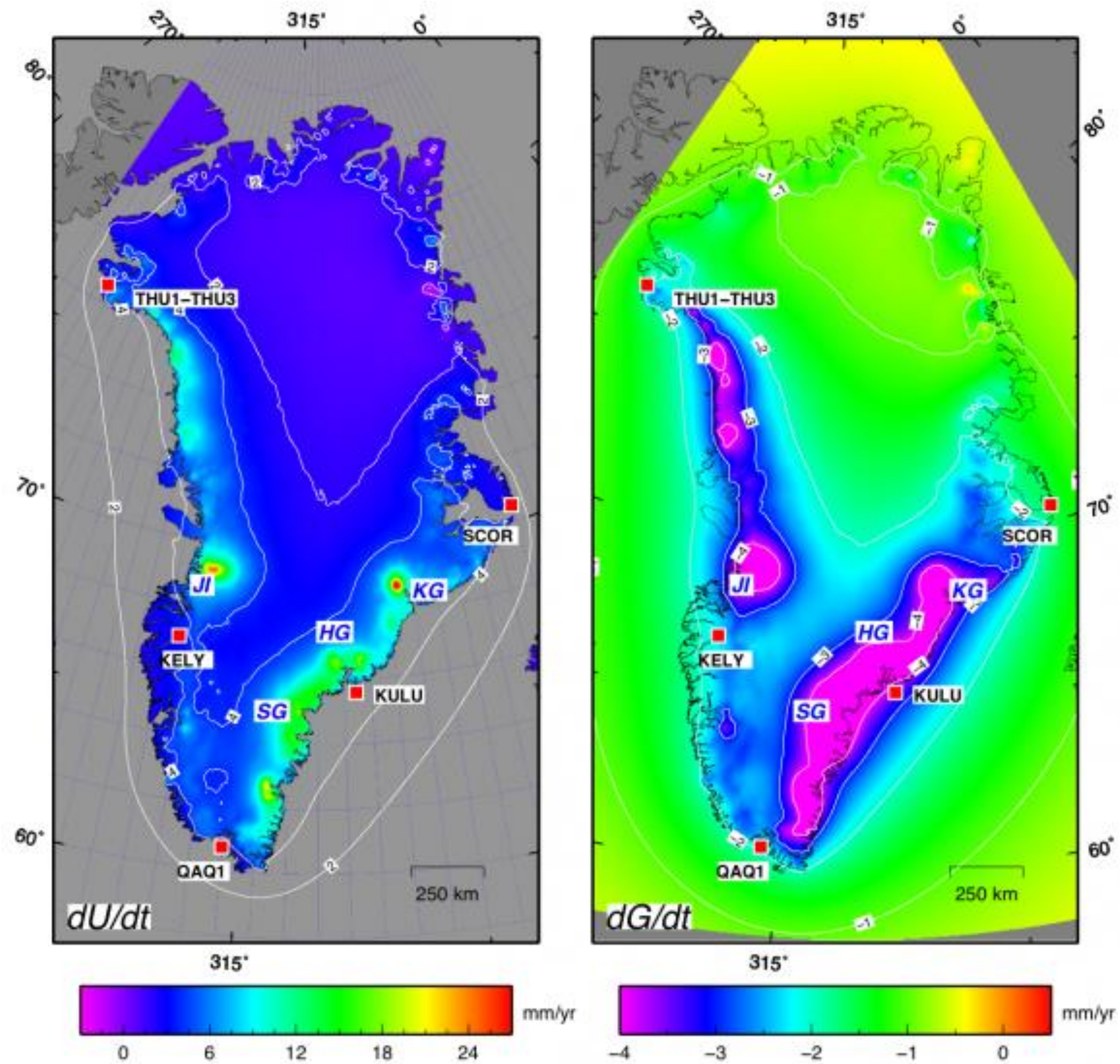
- The increase in ice volume produces a subsidence process under the glacier

- During deglaciation, the crust uplifts up to 50/100 mm/year



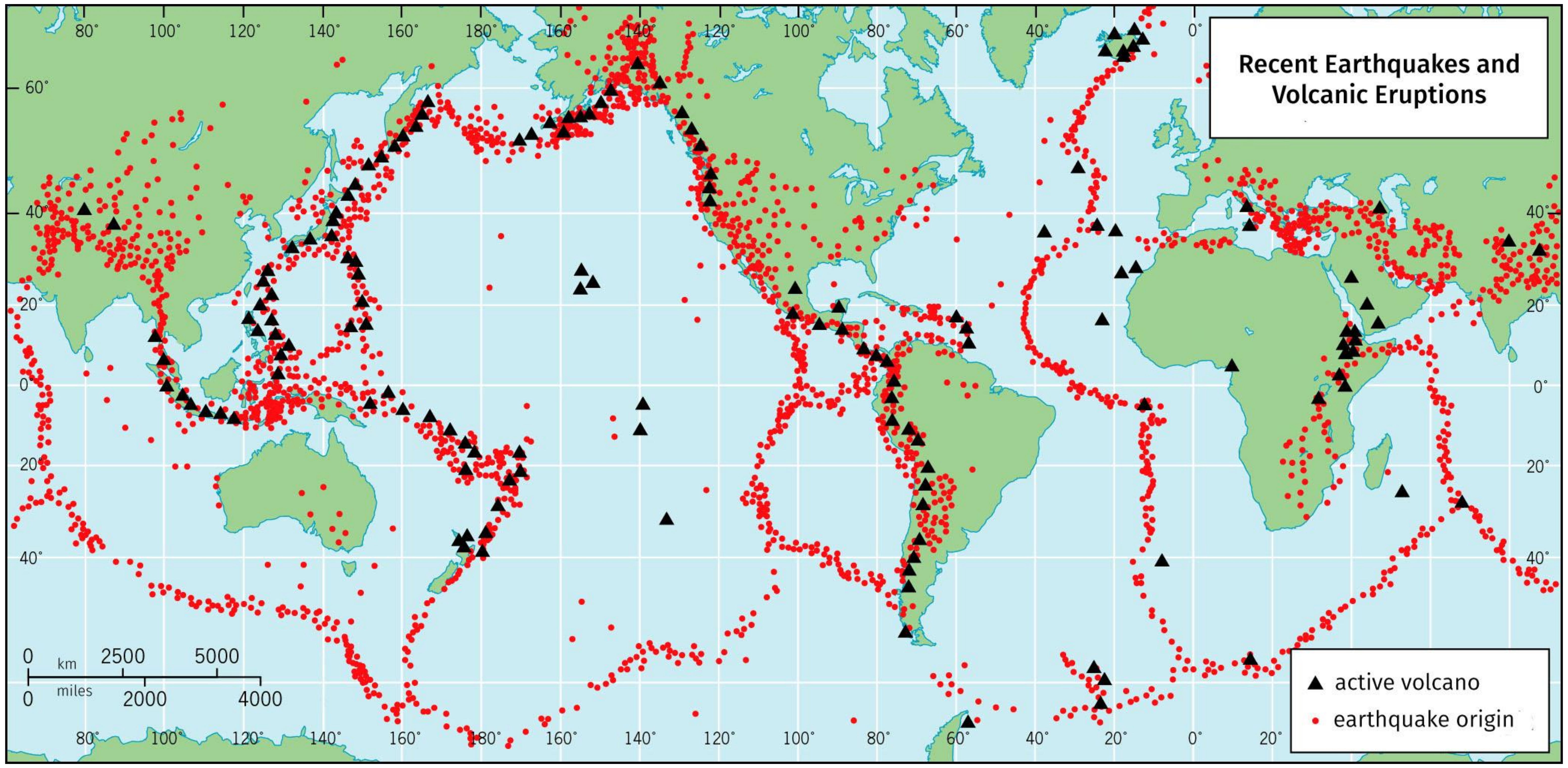


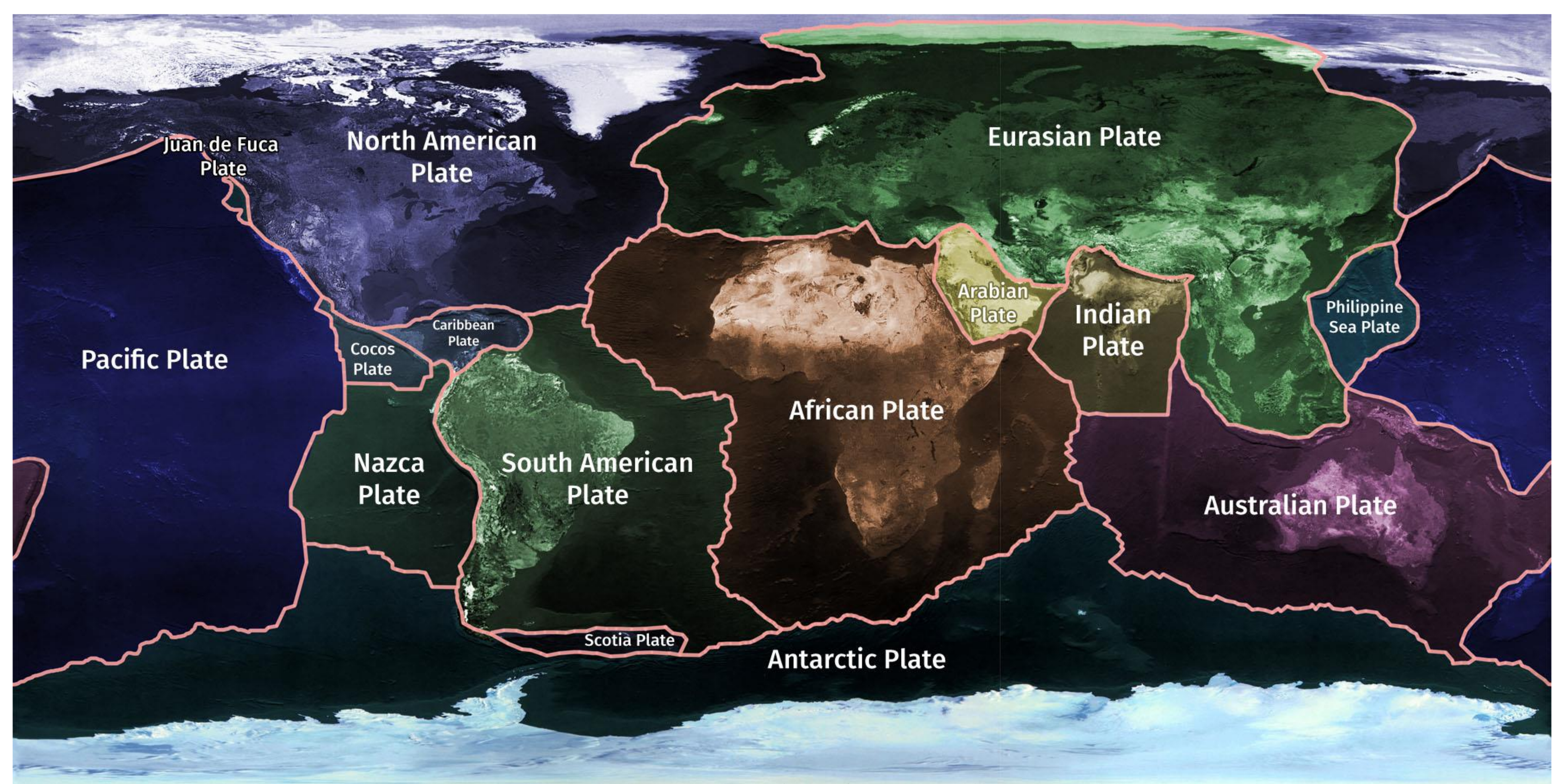
Scandinavian GIA



Greenland GIA

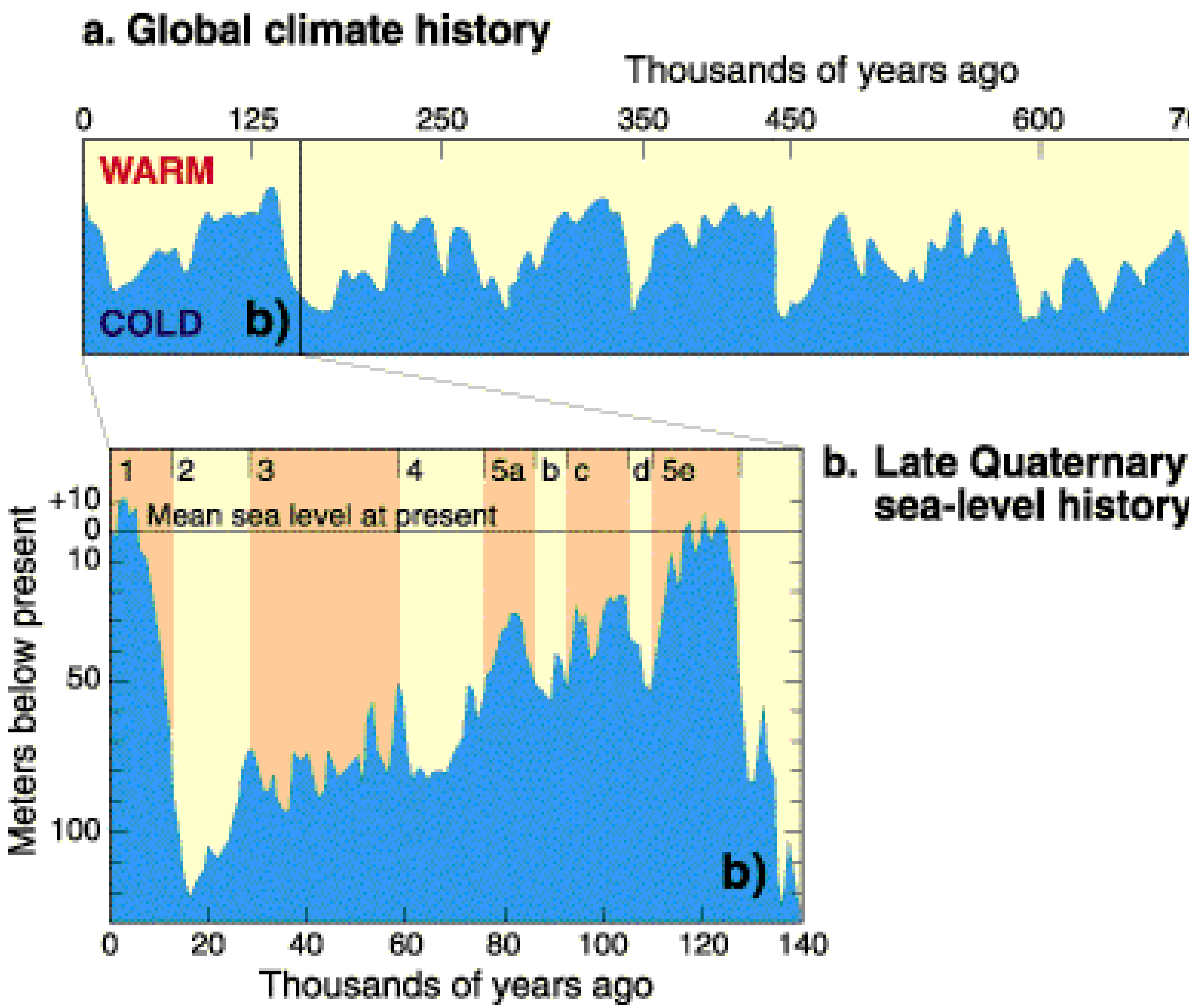
Plate tectonics

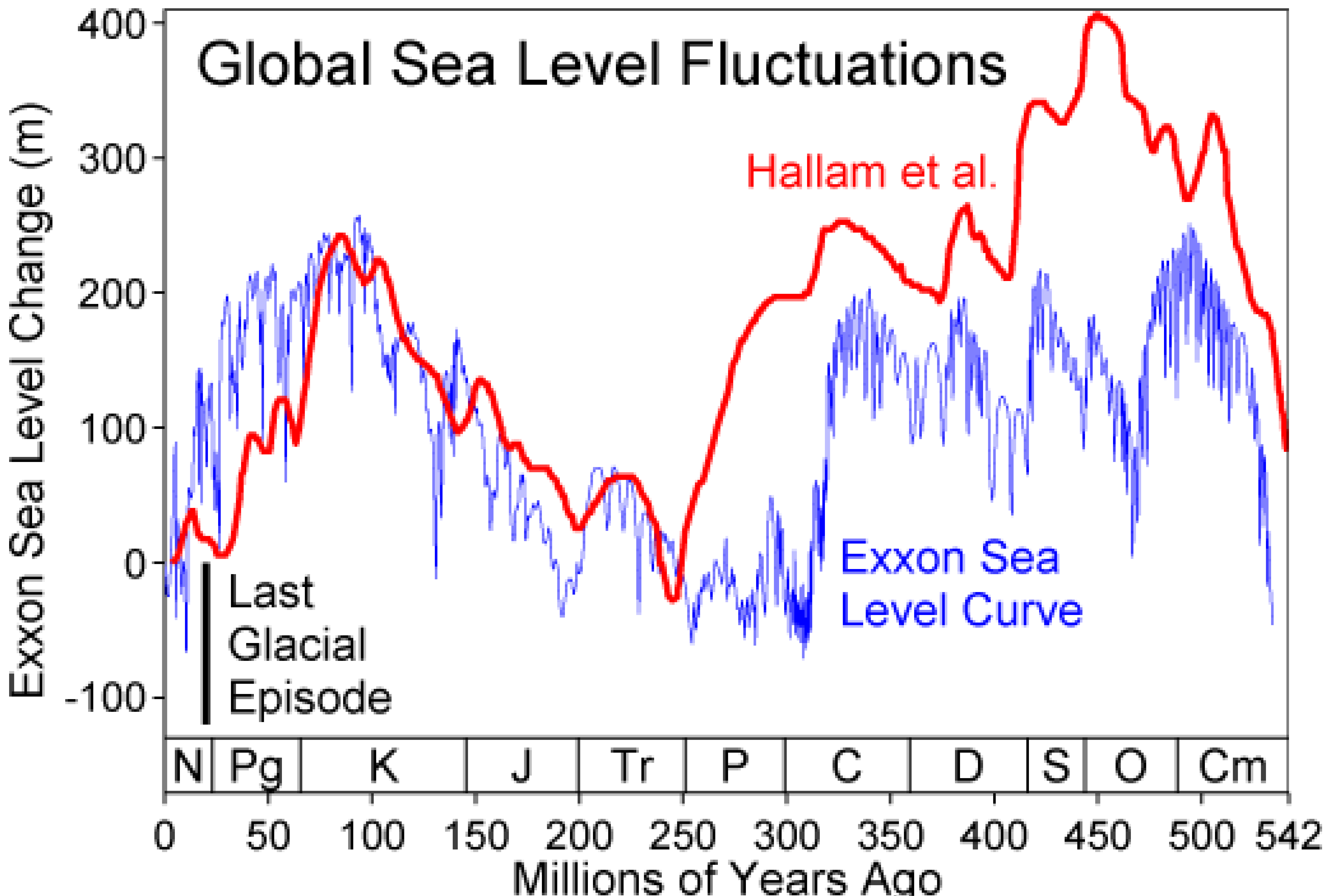




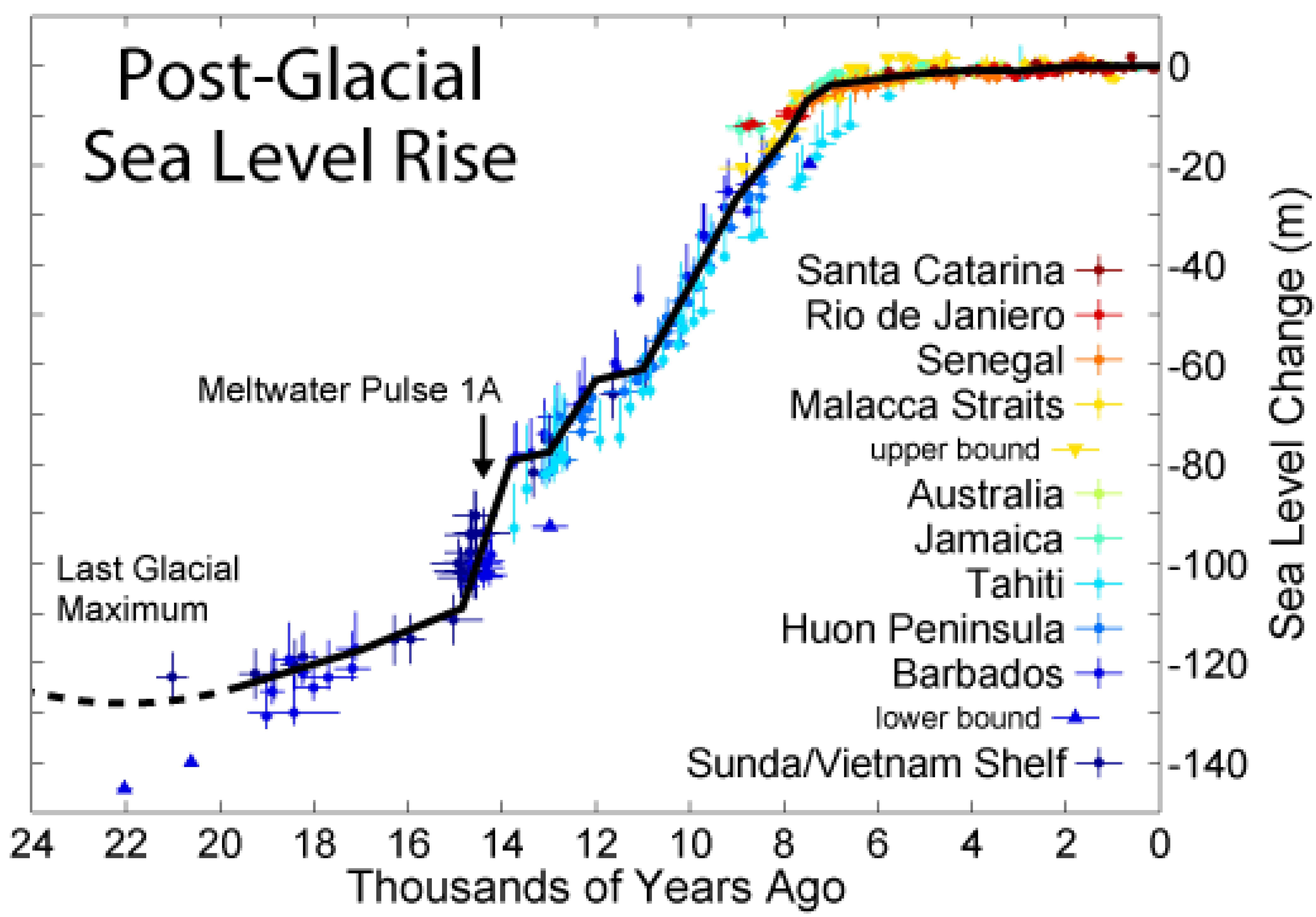
http://the-dialogue.com/en/en66-how-plate-tectonics-is-connected-with-life-on-the-planet/

Slc in the geological history

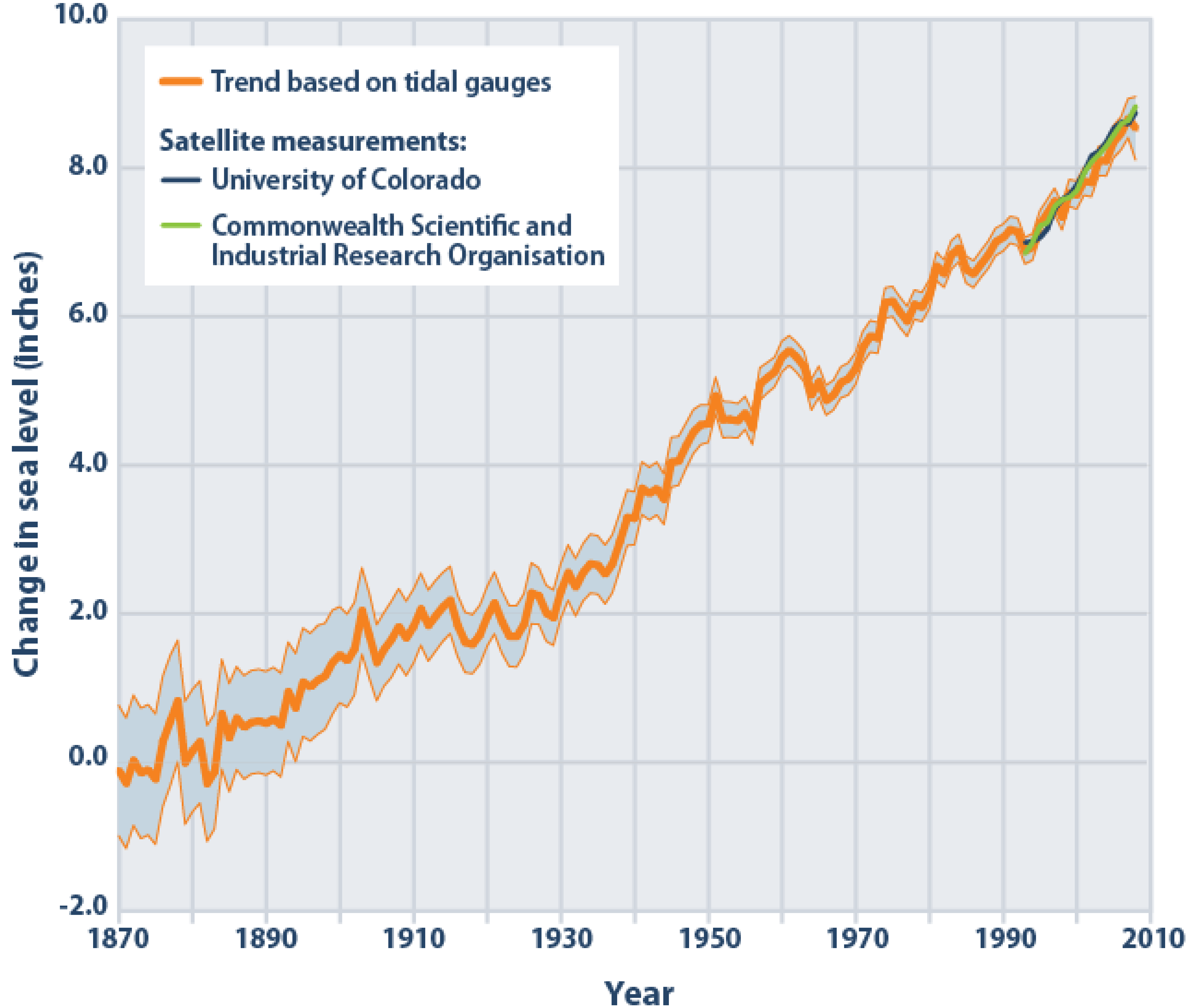



Global Sea Level Fluctuations
Hallam et al.
Exxon Sea Level Curve
Last Glacial Episode
Exxon Sea Level Change (m)
400
300
200
100
0
-100
N
Pg
K
J
Tr
P
C
D
S
O
Cm
0
50
100
150
200
250
300
350
400
450
500
542
Millions of Years Ago

Post-glacial sea level rise

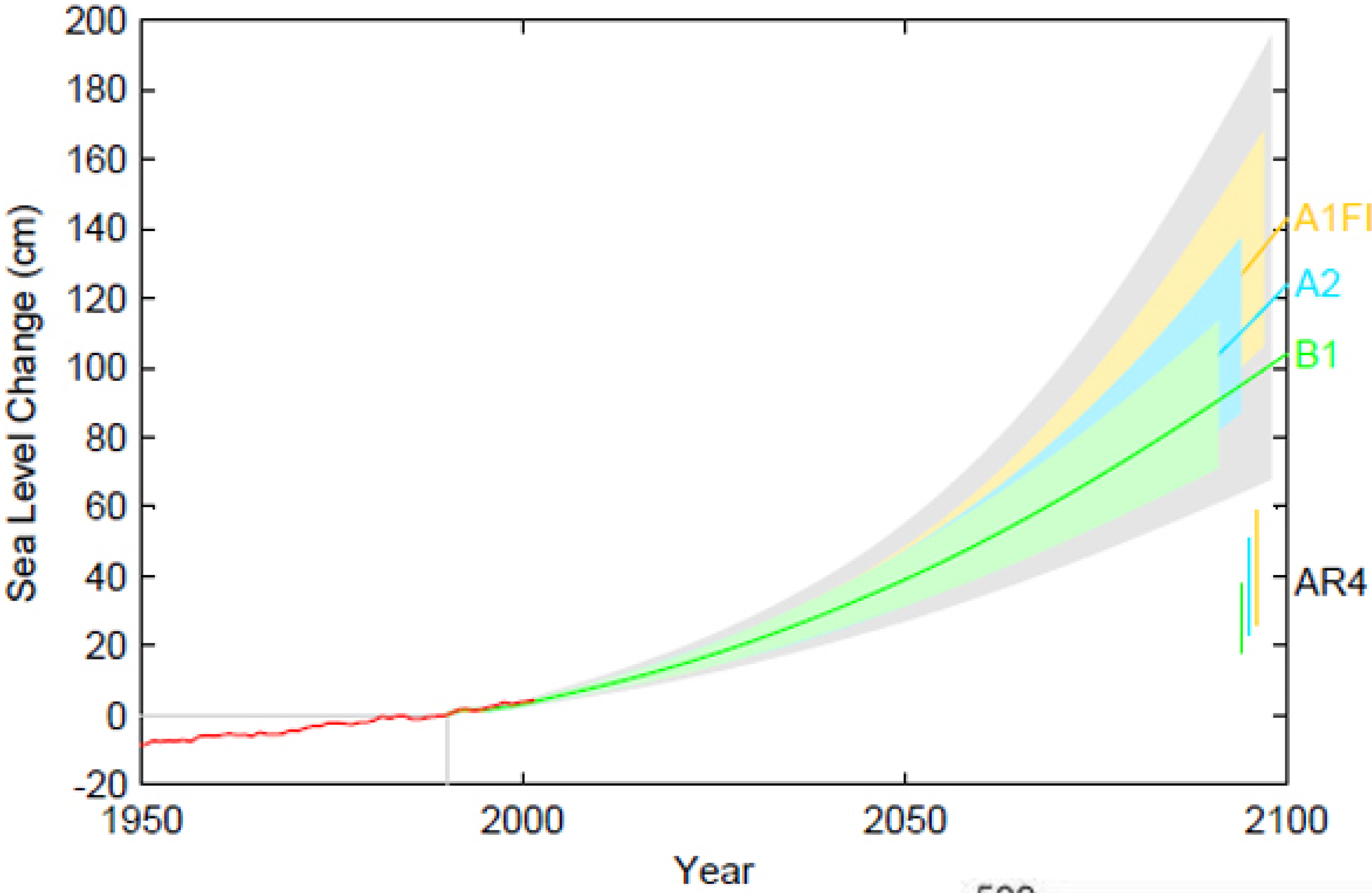


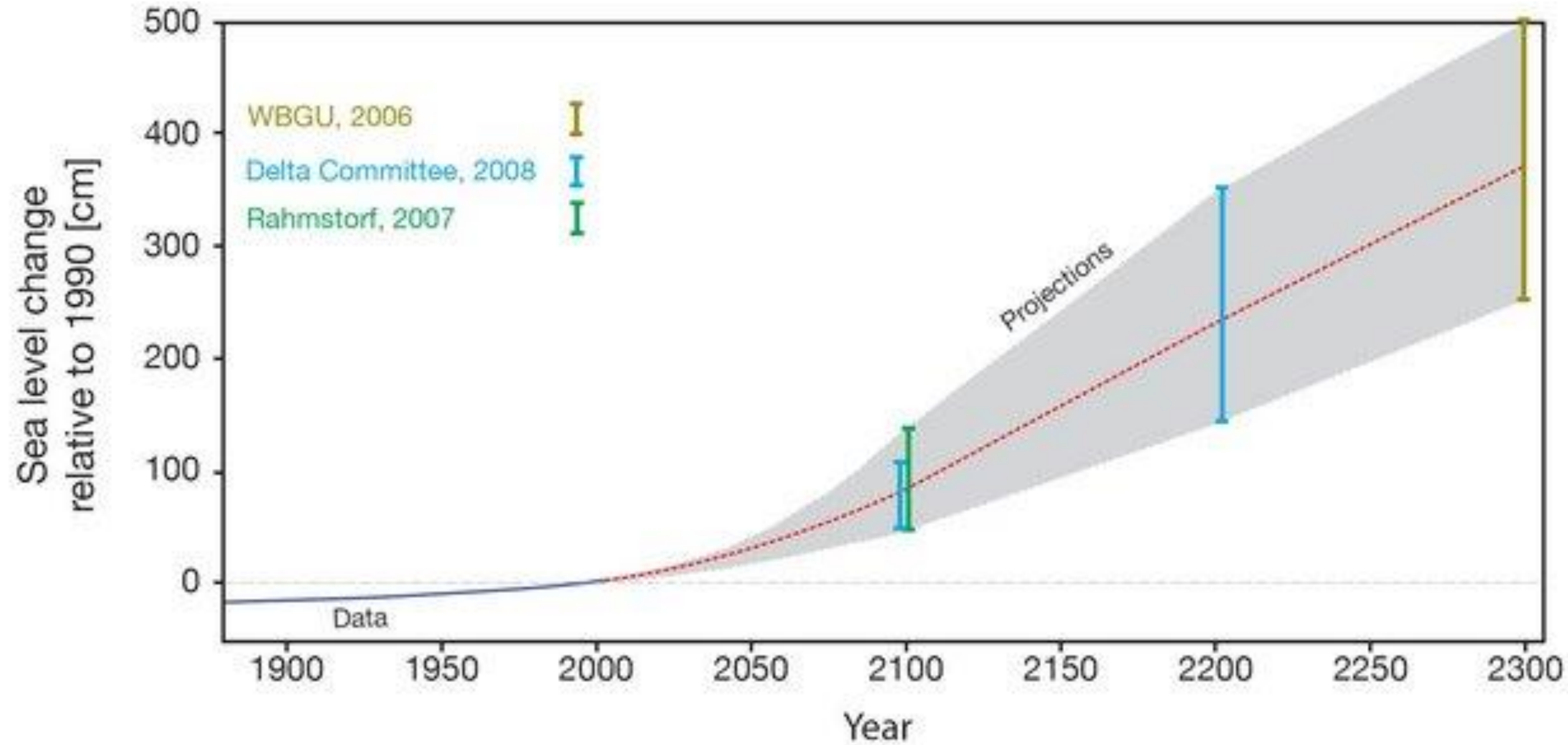
Trends in Global Average Absolute Sea Level, 1870–2008



Data sources:
- CSIRO (Commonwealth Scientific and Industrial Research Organisation). 2009. Sea level rise. Accessed November 2009. http://www.cmar.csiro.au/sealevel.
- University of Colorado at Boulder. 2009. Sea level change: 2009 release #2. http://sealevel.colorado.edu.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climatechange/science/indicators.

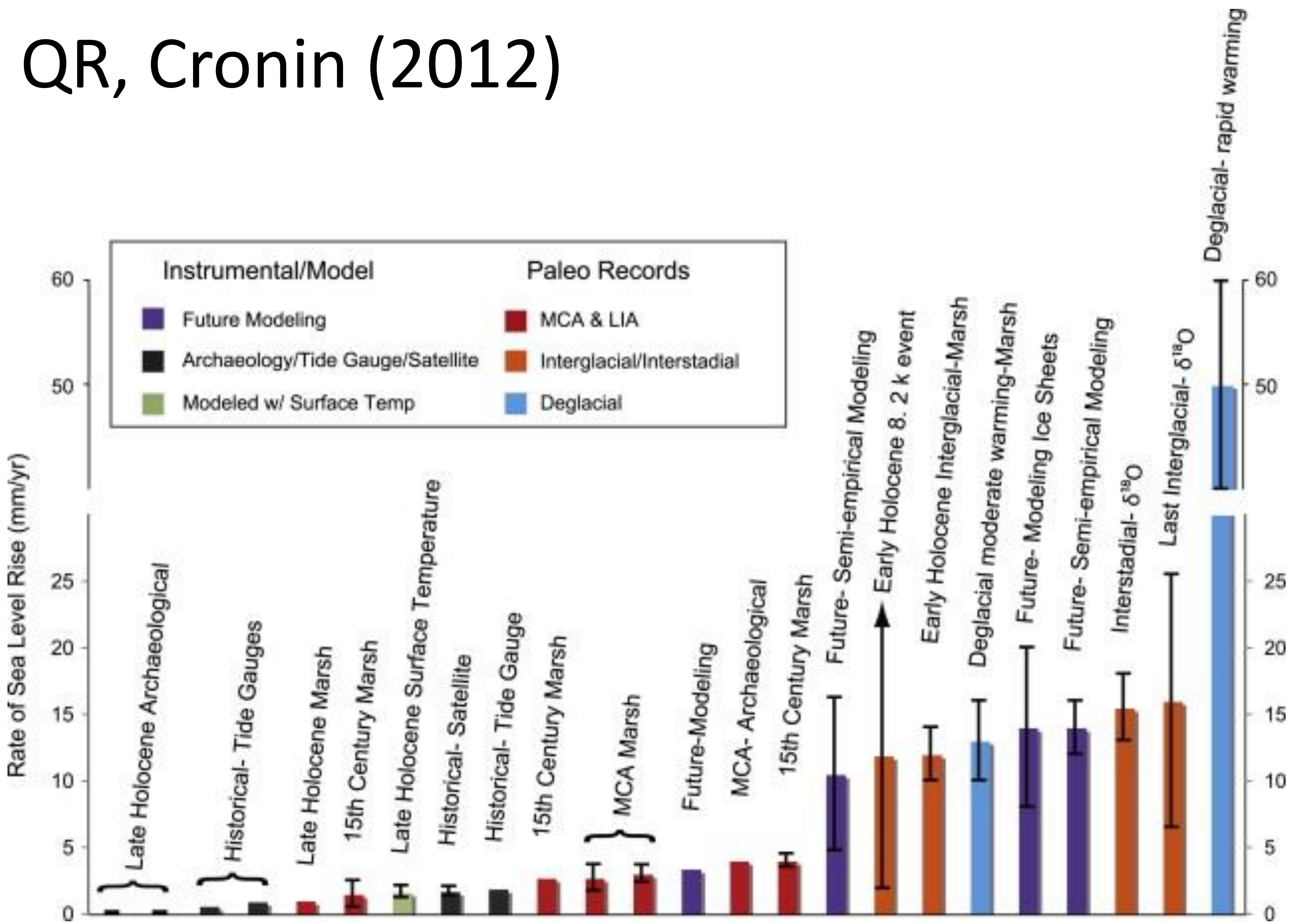




Projections of slr in the future

Contribution to slc

- QR, Cronin (2012)



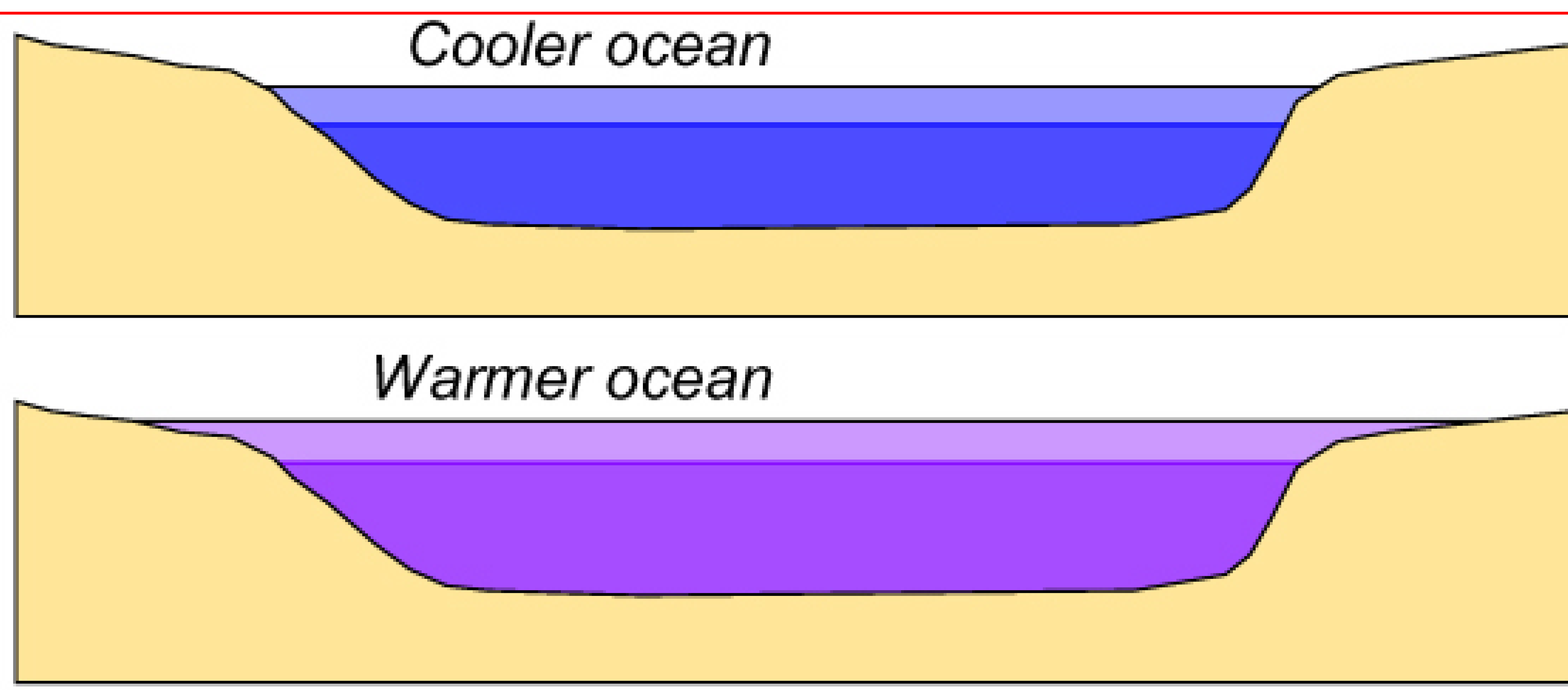
Why the sea level is changing?

FACTORS AND CAUSES OF SLC

Possible causes of sea-level change

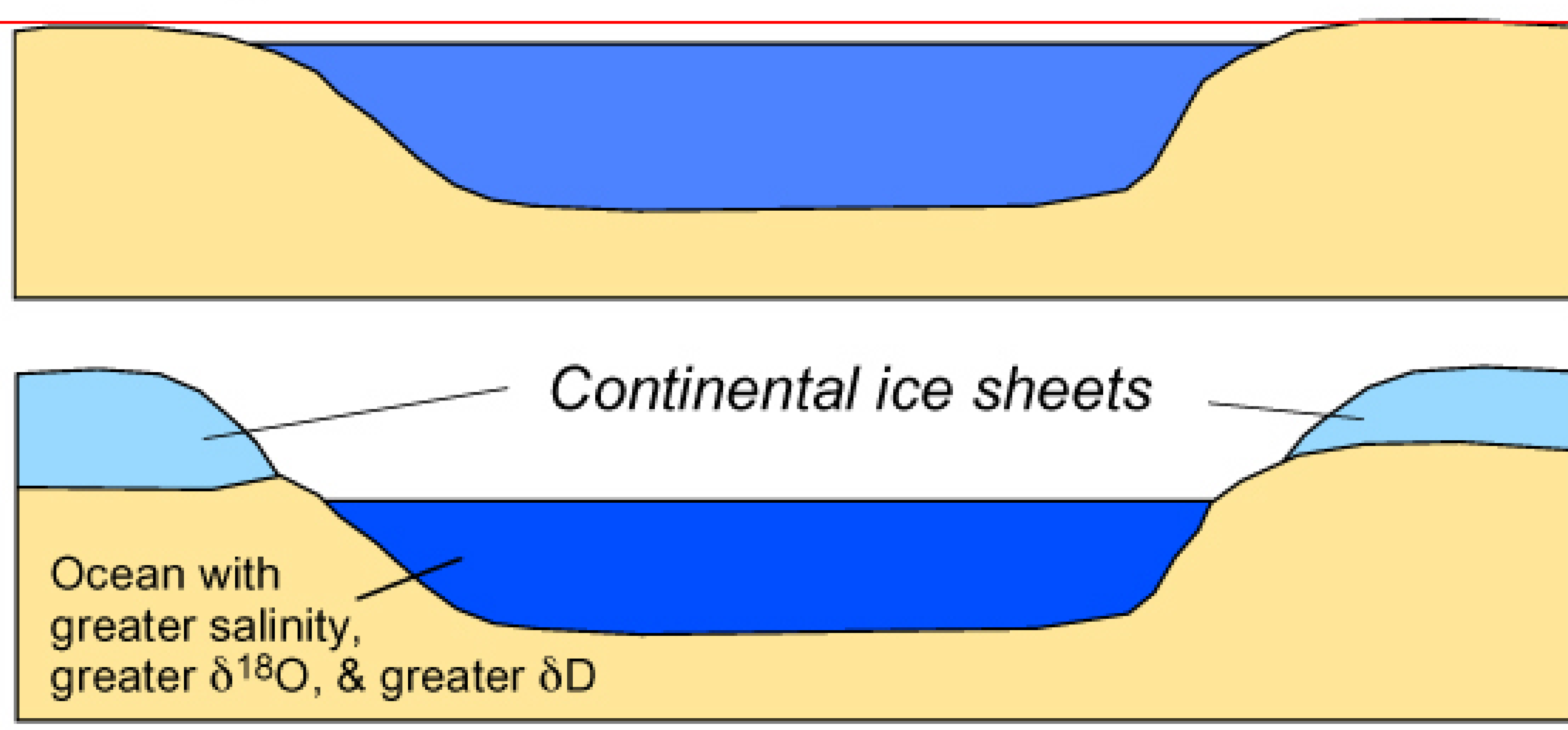
Sea level is known to have changed at geologic time scales. This page uses very schematic cartoons to present four possible causes, with emphasis on their different vertical and temporal scales.

1. **Warming** of ocean's water and thermal expansion



This causes SL change of **centimeters to meters.** Warming of water above the thermocline could be effected in a matter of years by mixing by waves and currents; warming of water below the thermocline requires circulation through the deep oceans and thus takes thousands of years.

2. Storage of ocean's water as ice in **ice sheets**



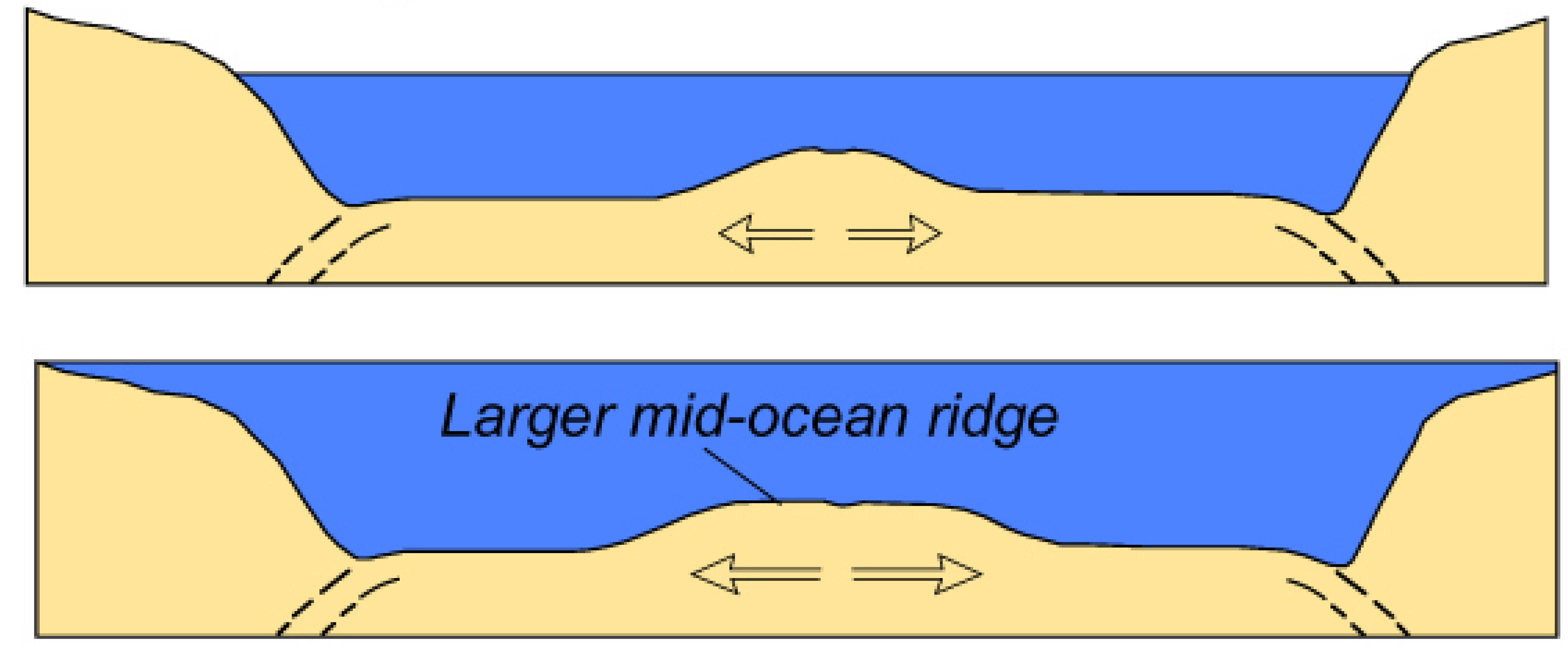
This causes SL change of **tens of meters to 200 meters.** Growth of ice sheets typically takes tens of thousands of years to lower sea level, whereas melt-out and sea-level rise can occur over thousands of years. Note that only this mechanism changes the *amount* of H_2O in the oceans.

Volume of water in the oceans changes

Volume of the ocean basins changes

3. Changes in rate of **sea-floor spreading**

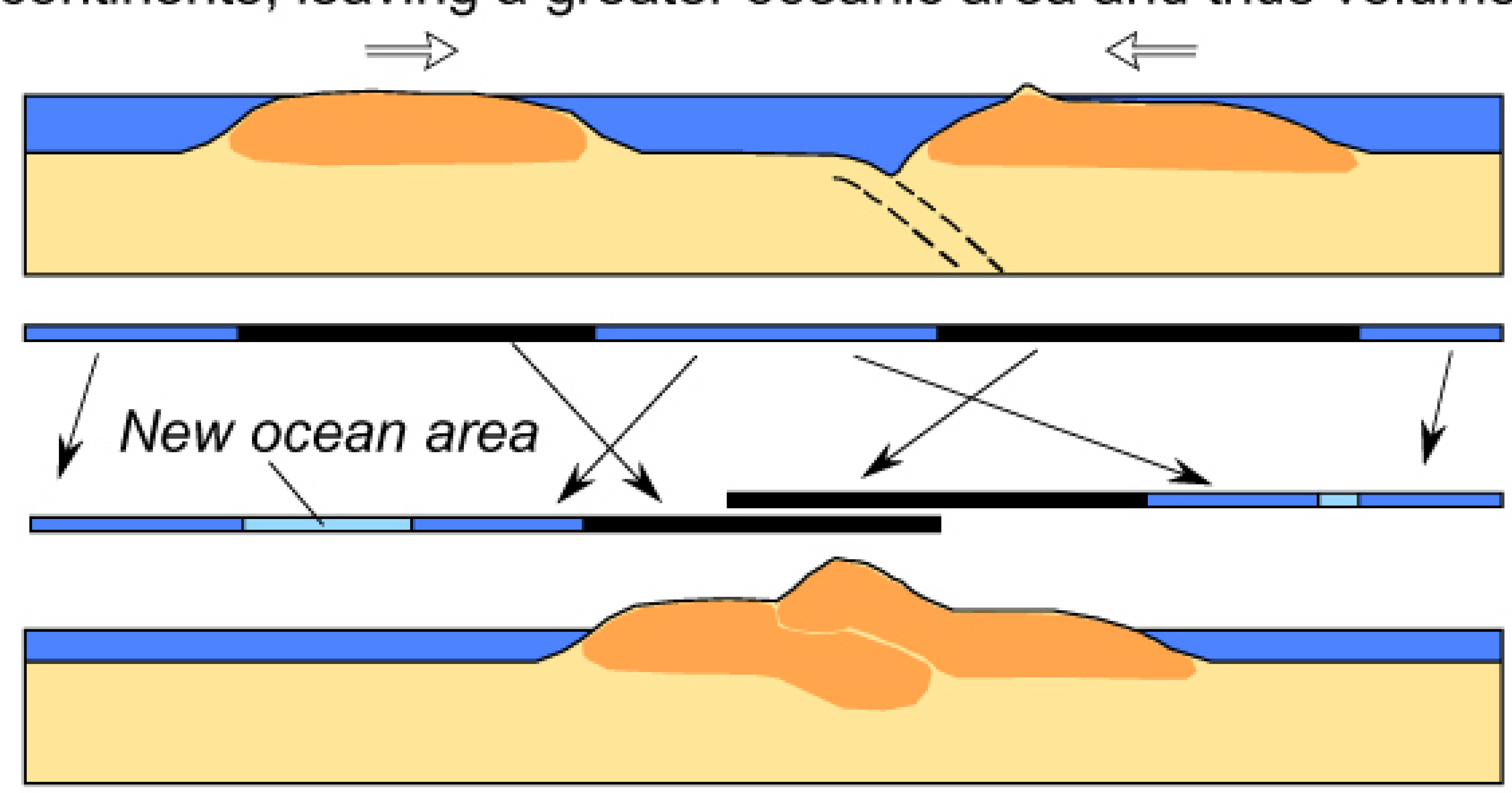
(More young, and thus hot, and thus expanded oceanic crust at MORs occupies more of the volume of the ocean basins)



This causes SL change of **hundreds of meters.** Correlation of lowering of sea level over the past tens of millions of years with slowing of seafloor spreading makes this model attractive.

4. **Continent-continent collision**

(Stacking of continental crust causes reduction of area of continents, leaving a greater oceanic area and thus volume)



This causes SL change of **hundreds of meters.** Correlation of lowering of sea level over the past tens of millions of years with Himalayan collision, and correlation of lower Late Paleozoic sea level with the assembly of Pangaea, make this an attractive model. In addition, it is possible that continent-continent collision could lessen the global rate of sea-floor spreading, so that Causes 3 and 4 could coincide.

Variation of water amount in the oceans

The total amount of water in the oceans

- It depends from the global hydrological balance that is the sum of the following parameters:

  - A+O+L+R+M+B+S+U+I=k

- The letters correspond to parameters, following decribed, that corresond to water amount.

- **K is a constant**

Parameters

- A=atmospheric water (13000 **km3**, 36 mm EWD*)
- **O=Oceans and seas (1370*106, 3.8 km)**
- L=Lakes and reservoirs (125000, 35 cm)
- R=Rivers and channels (1700, 5 mm)
- S=Swamps (3600, 10 mm)
- B=Biological water (700, 2 mm)
- M=Moisture in soils, unsaturated zone (65000, 18 cm)
- **U=Ground water (4-60*106, 11-166 m)**
- **I=Frozen water (32.5*106, 90 m)**

***Equivalent Water Depth**

Climate changes

- The climate change represents the main cause of change in water amount. Following the variations in volume and equivalent depth of the oceans between today and LGM:

Table 2 Volume and equivalent ocean water depth of the main ice-caps, at glacial and present time

	Glacial time			Present time		
Glacier	Ice volume[(a)] (10^6 km^3)	Equivalent water depth[(b)] (m)	%	Ice volume[(a)] (10^6 km^3)	Equivalent water depth[(b)] (m)	%
Antarctica	37.7	104.3	40–56	27.9–29.3	77.2–81.1	90–91
Greenland	2.9–5.6	8.0–15.5	4–6	2.5–3.0	6.9–8.3	8–9
North America	18.0–36.7	49.8–101.6	27–39			
Eurasia	8.2–14.3	22.7–39.6	12–15			
Others				0.2	0.6	1
TOTAL	66.8–94.3	184.8–261.0	100	30.6–32.5	84.7–90.0	100

a) Data from Hughes et al. (1981), Fisher et al. (1985), Berger et al. (1990) and Oerlemans (1993)
b) Without hydro-isostatic sea-floor displacement, using present ocean surface area

Global Glacial Coverage During the LGM

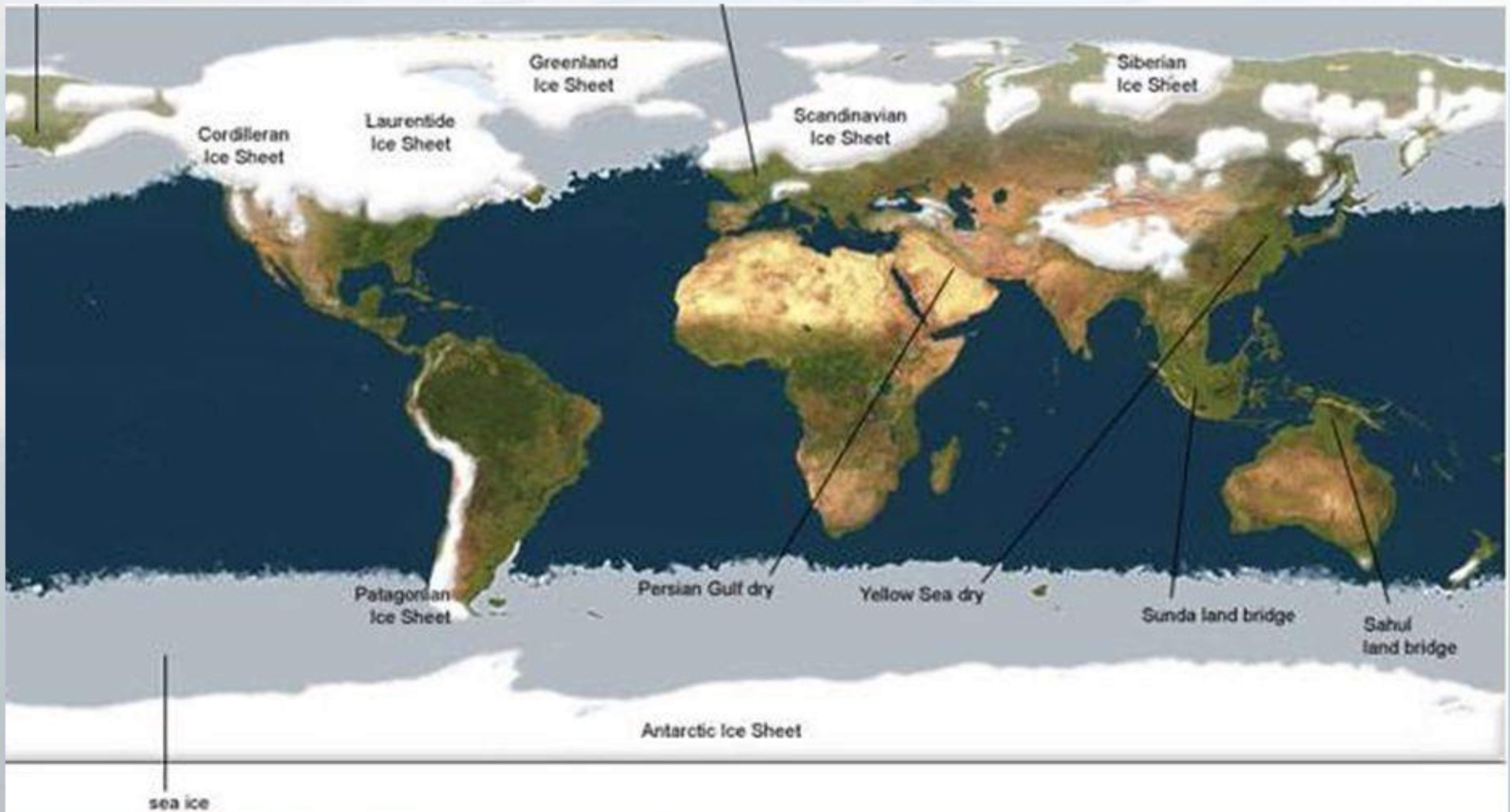
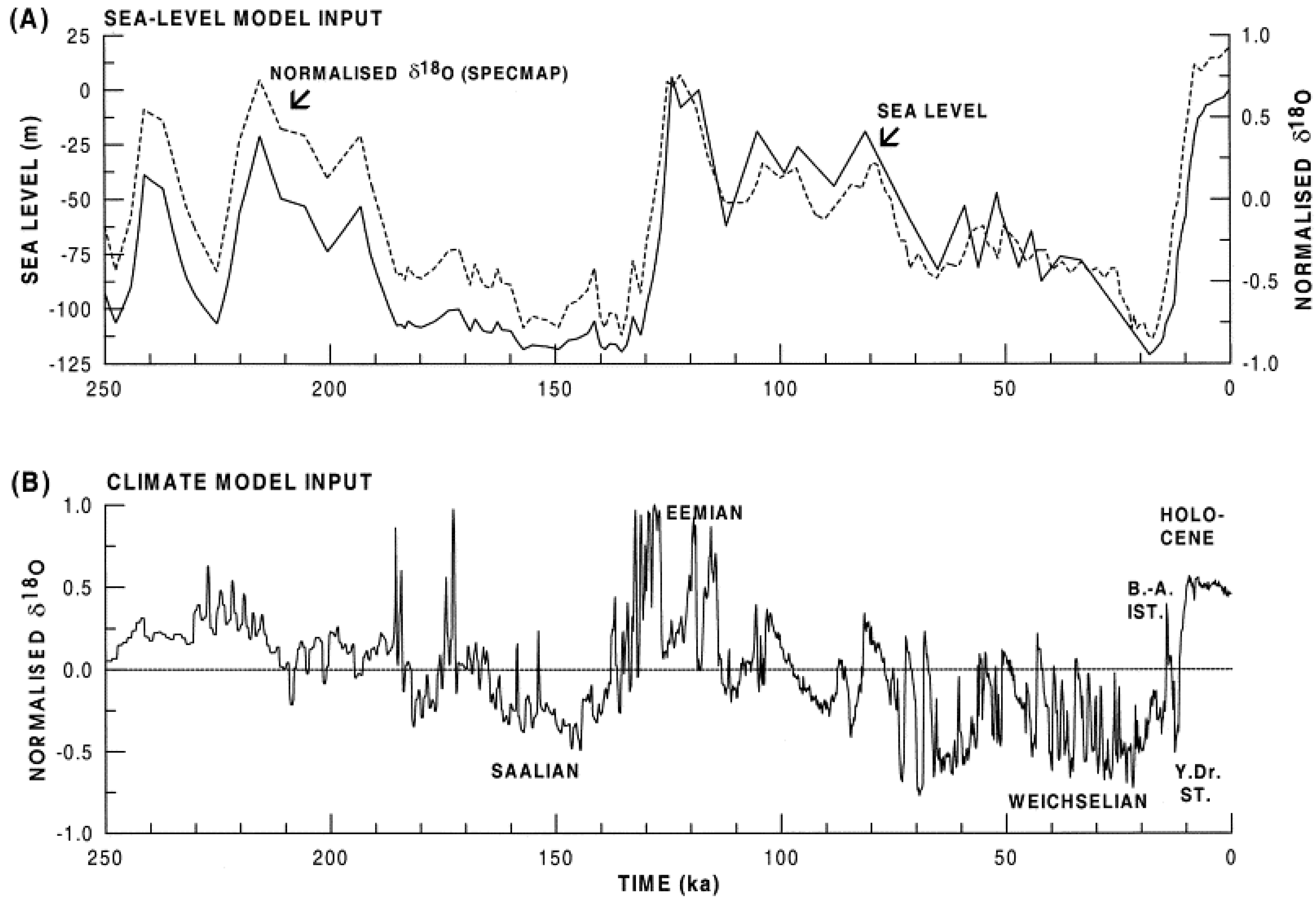


Image Source: http://www.humberriver.ca/globalice.html

Slc during the last 250 Ka

- From Global Planetary Science, Tebbens et al., 2000



Tectonic factors

- Vertical movements of the ground can induce changes in the relative sea level. They can be long-lasting or continous and rapid;
- Continous and slow movements are called aseismic
- Rapid movements related to earthquakes are called co-seismic
- These movements produce several kind of geomorphological, sedimentological and arhcaeological markers of slc at different elevations on the present-day mean sea level.

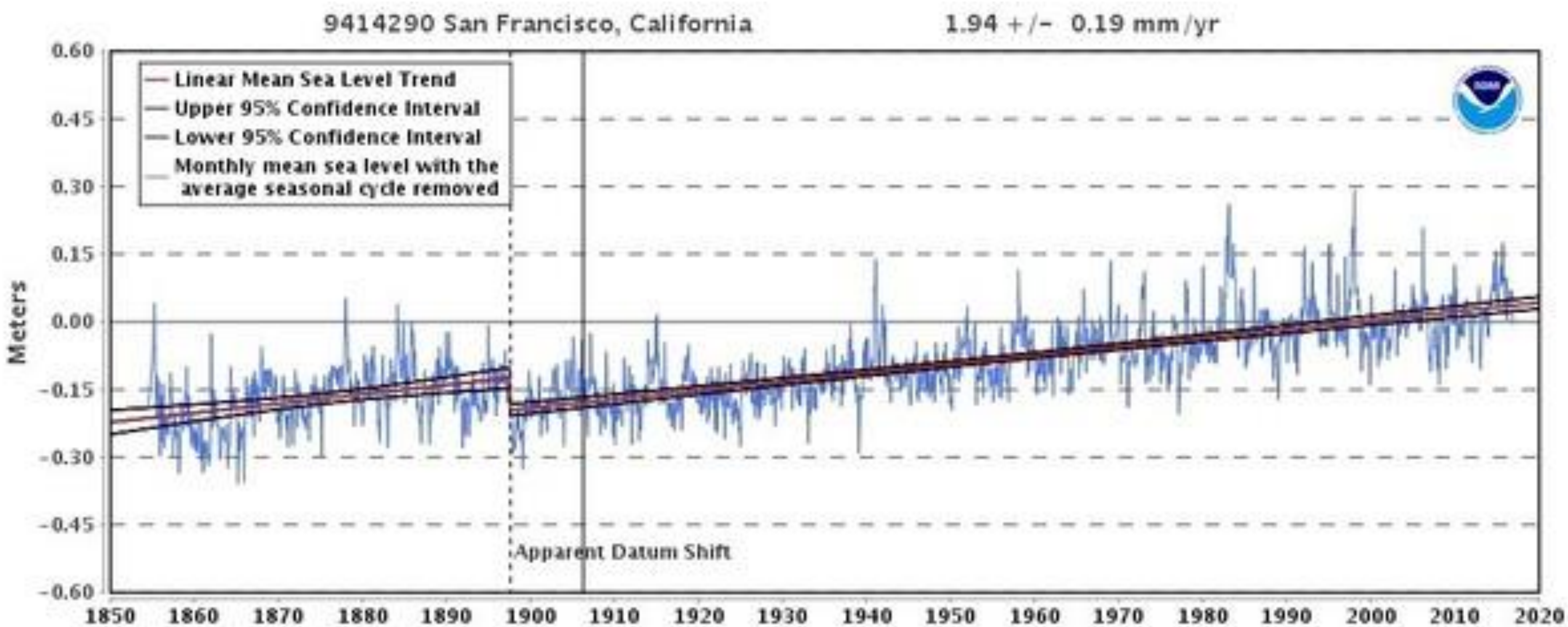

9414290 San Francisco, California
1.94 +/- 0.19 mm/yr
Linear Mean Sea Level Trend
Upper 95% Confidence Interval
Lower 95% Confidence Interval
Monthly mean sea level with the average seasonal cycle removed
Meters
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
Apparent Datum Shift
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020

Fig. 9. Palaeogeographic reconstruction of the ancient harbour of Aigeira at Mavra Litharia cove.

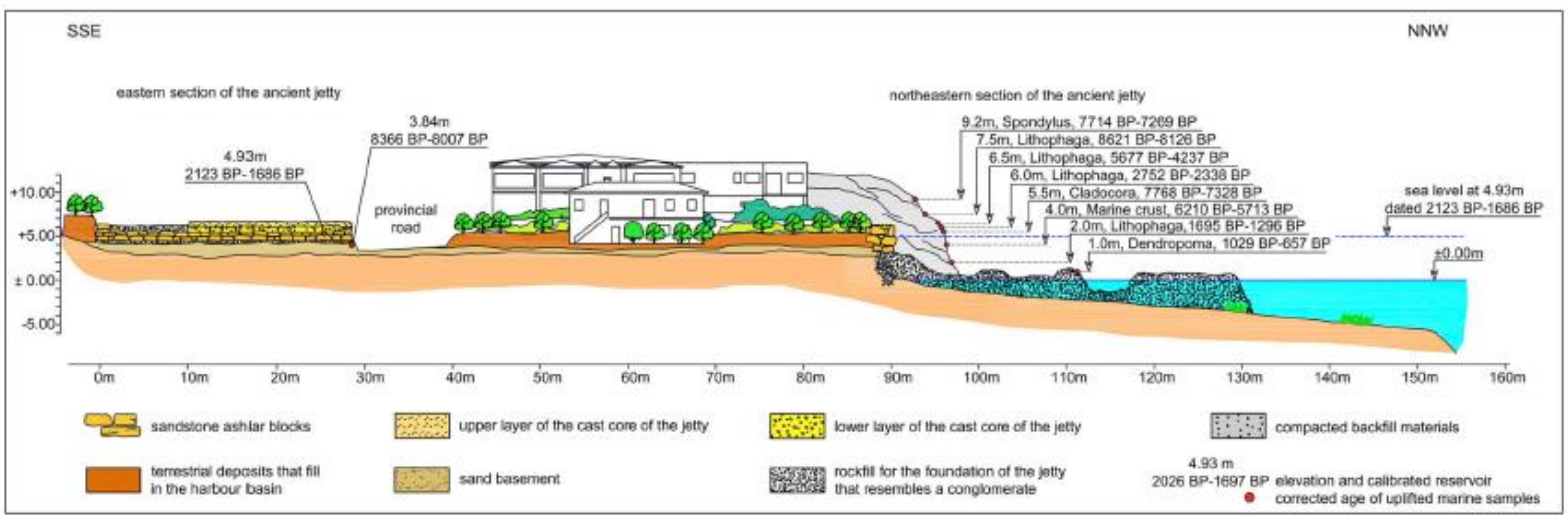
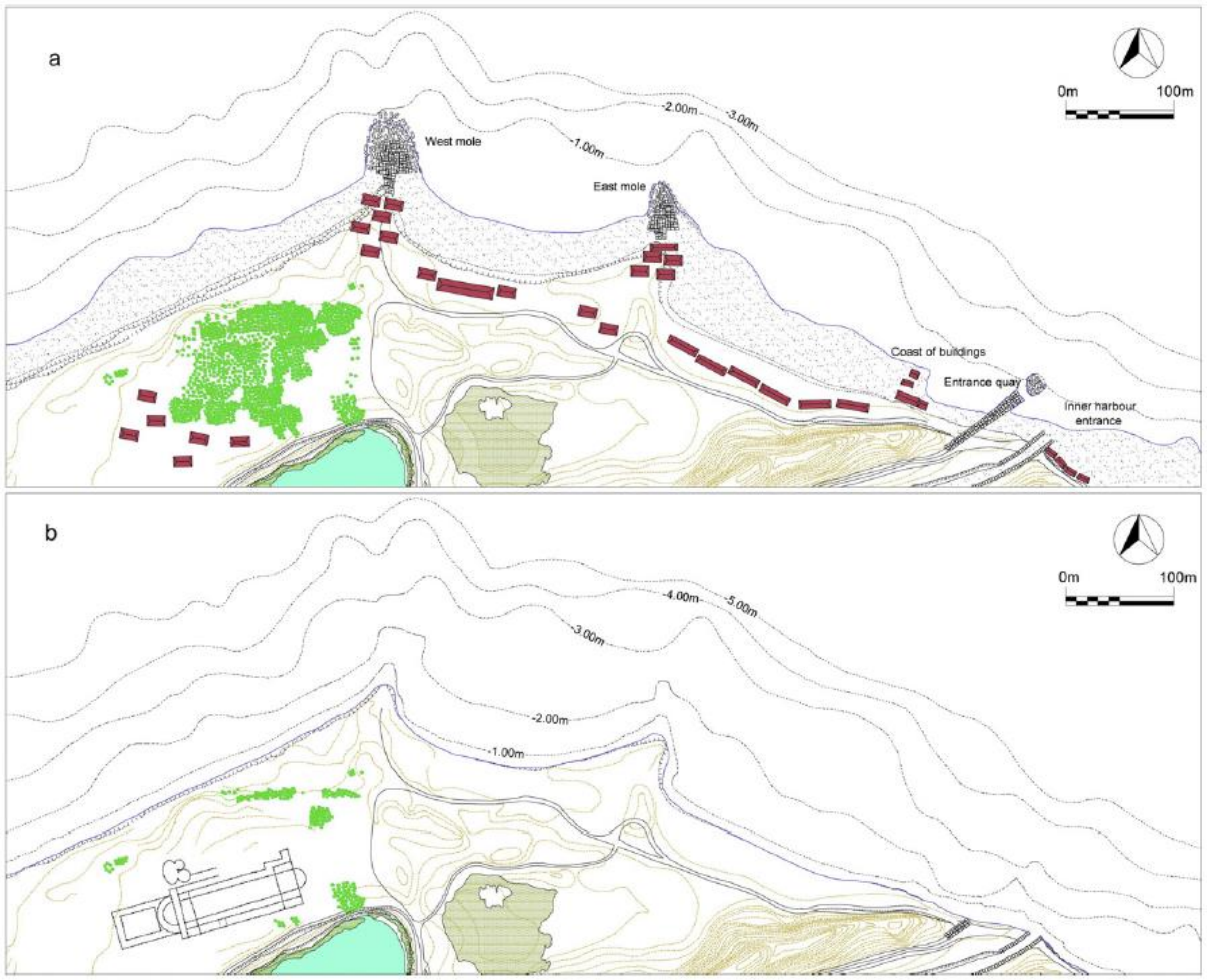
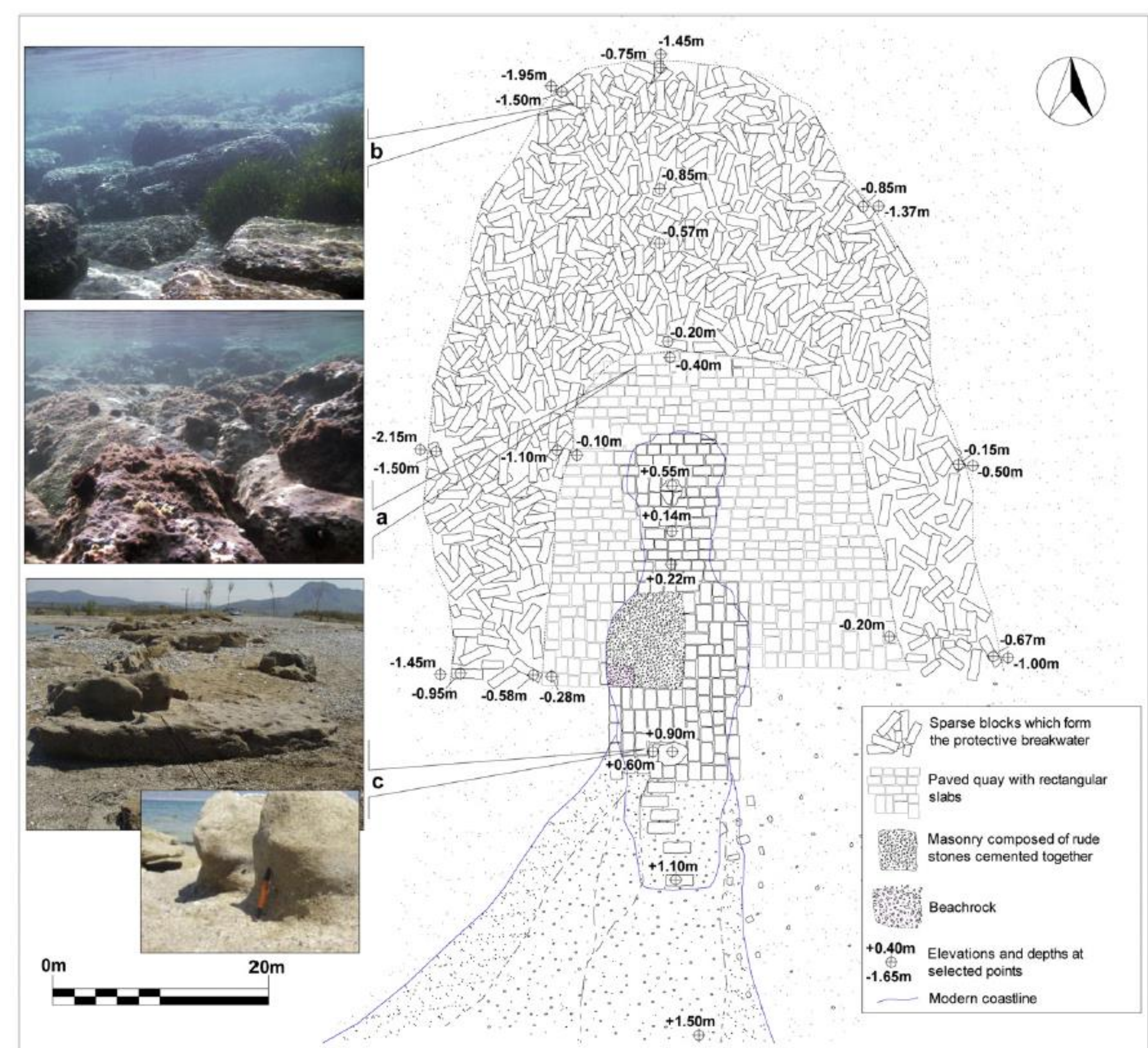


Fig. 6. SSE-NNW cross-section of the study area with the elevations and the calibrated and reservoir corrected ages of the eastern section of the ancient jetty (present study) and of the coral-algal reef, previously dated by Mouyaris et al. (1992), Papageorgiou et al. (1993), Keraudren et al. (1995), Stewart and Vita-Finzi (1996), Stewart (1996) and Pirazzoli et al. (2004).

Kolaiti et al. (2018), Quaternary International

Lechaion (Grecia)



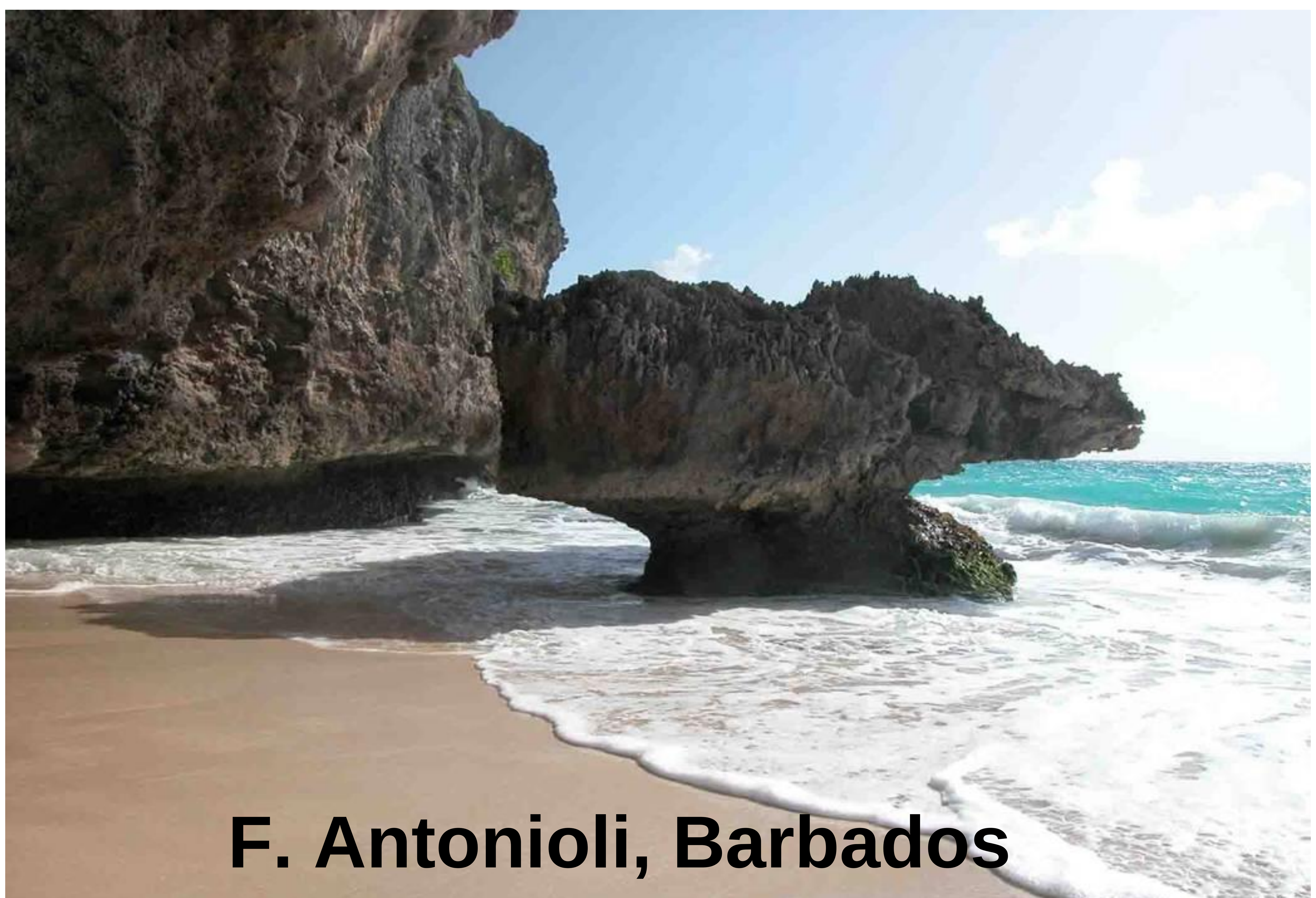


Mourtzas et al. (2013) Quaternary International


MIS 5.5 inner margin 127 m

Tidal notches


Marina di Aurisina (Trieste)


F. Antonioli, Barbados

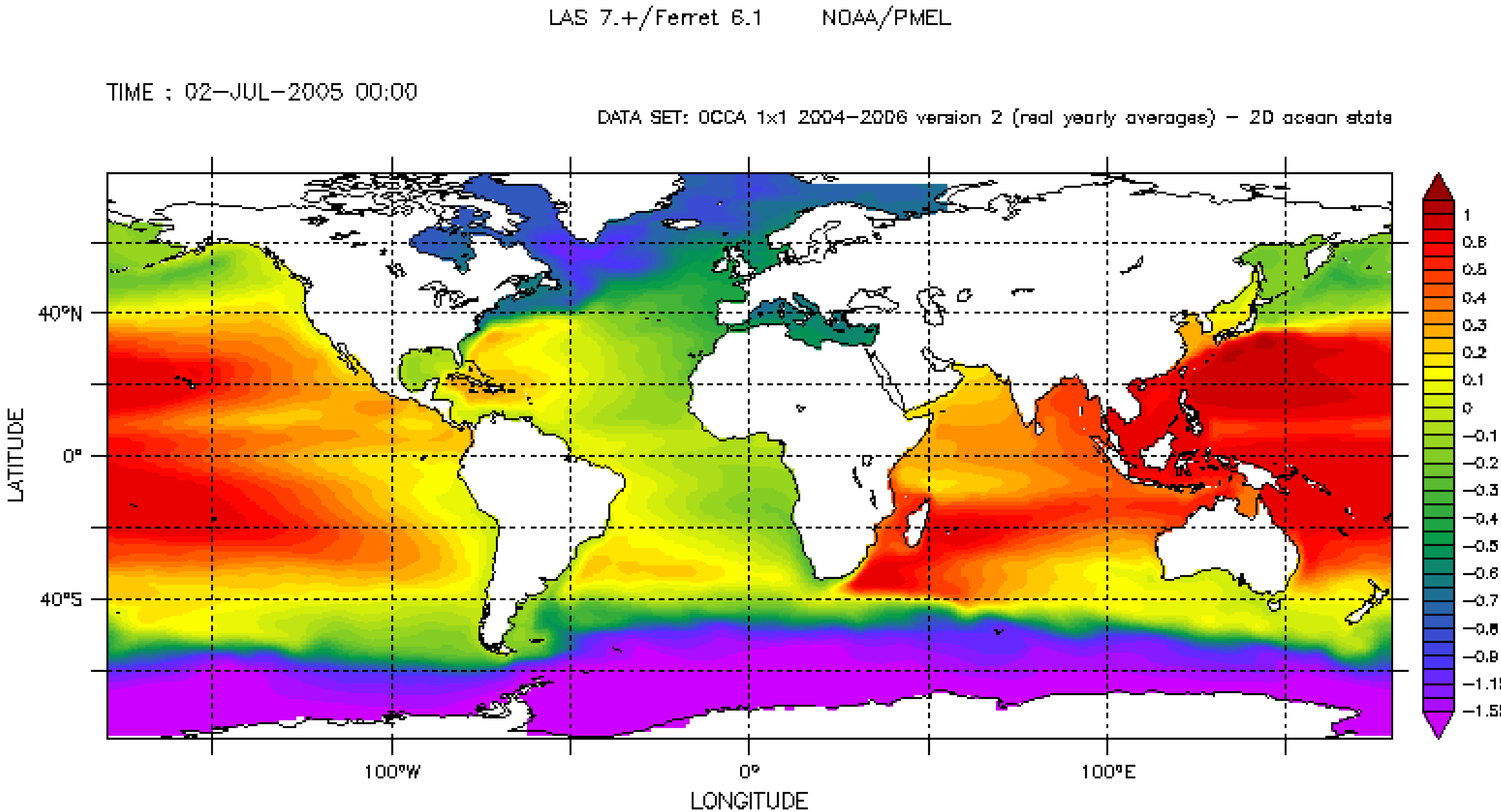

Isole Tremiti (Adriatico)

Steric variations

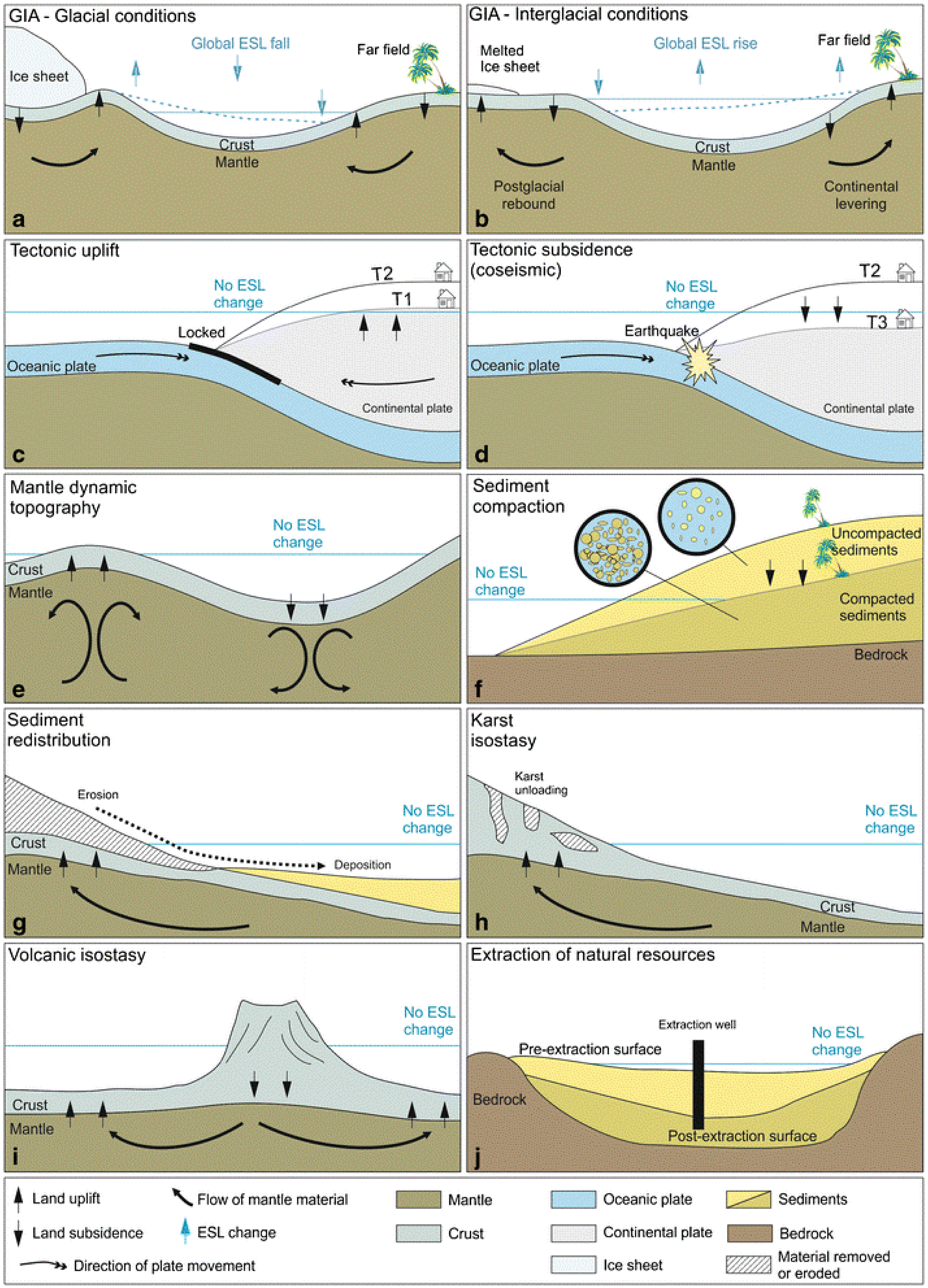
- Sea level can change because of the variations in density related to sea water density that depend from salinity, temperature and pressure.
- Density lower with temperature increasing and increases with incresing in salinity and pressure.
- Dense waters occupy a lower volume and the mean sea level lower, on the contrary, low dense waters cause an increase in sea level.

- An increasing of 1°C (on 4.000 m) produces a sea level rise of 60 cm;
- A variation in salinity of 4 psu produces the same result;
- These effects are higher along the coasts, because of the effects of fluvial input of freshwaters;
- During LGM, the sea was more salty (36 psu instead of 35) and cooler, therefore it was denser than nowadays.

Surface height anomaly



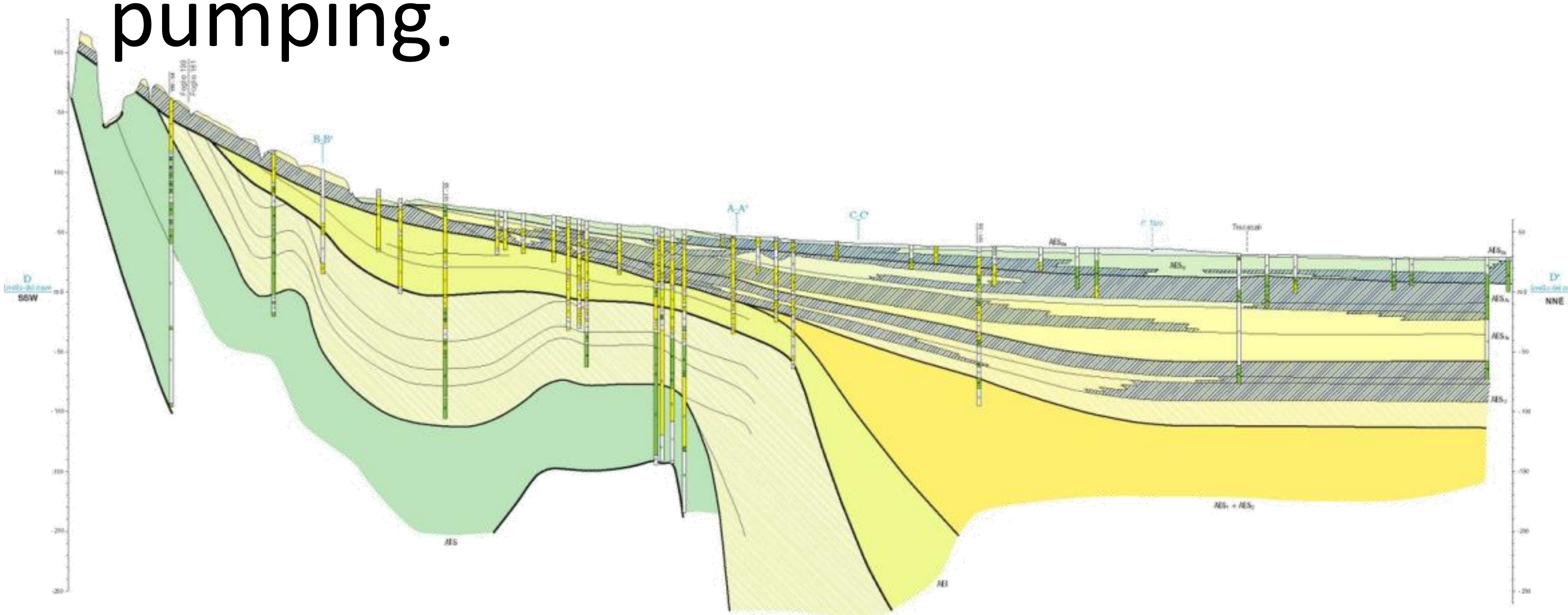
Surface Height Anomaly (m)



Rovere et al. (2016)
Current Climate Change Report

Sediment isostasy (*sediment-isostasy*)

- Along the coasts, deltas can produce subsidence rates up to some millimetres/years;
- They can increase because of water, gas, or oil pumping.

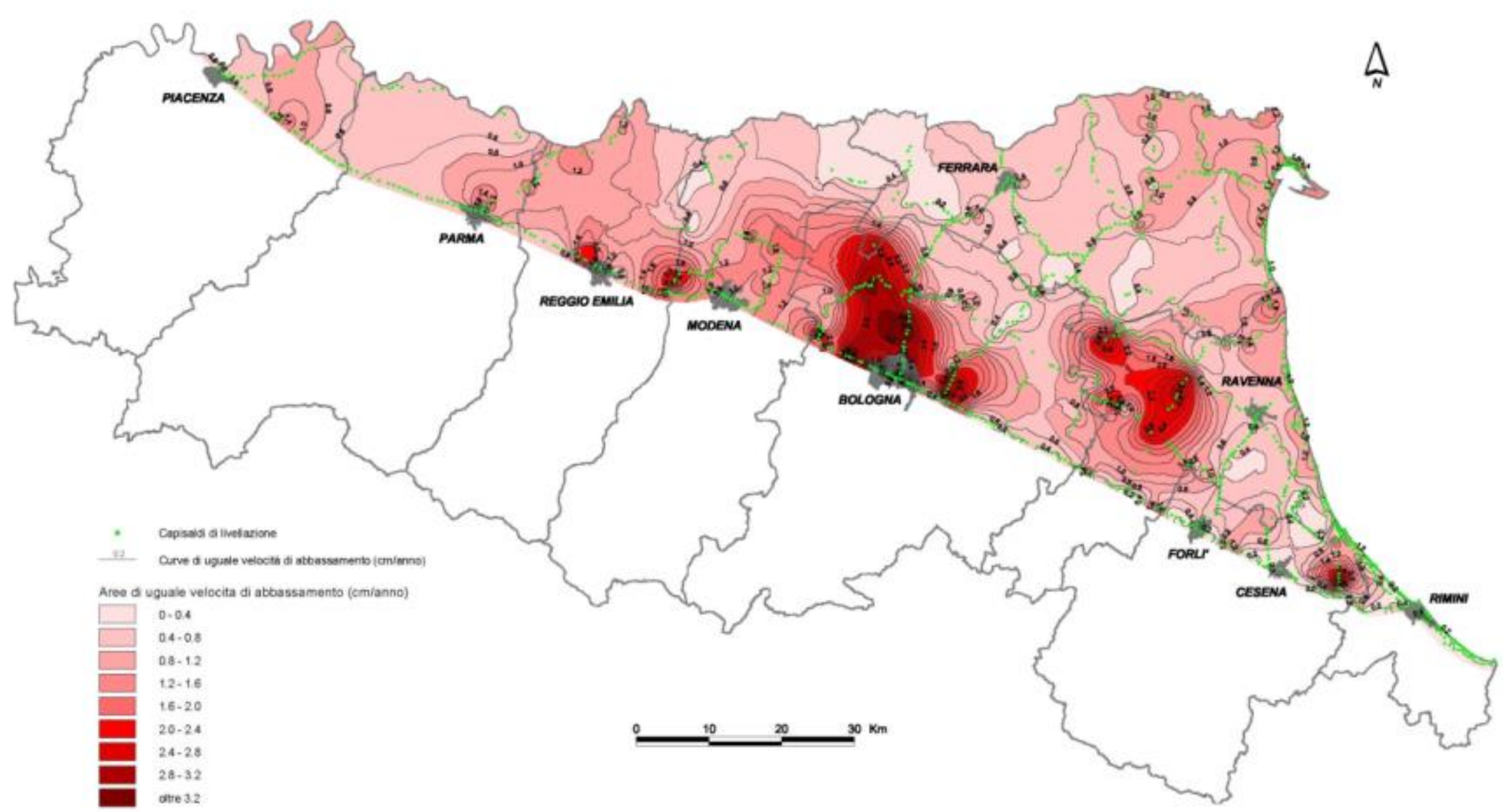


Hydro-isostasy

- During deglaciation, sea water from glaciers produces a load increase on sea-bottoms, so that the sea-bottom can lower
- It depends from the topographical features of the basin and increases off-shore;
- Hydro-isostasy can be very important on small islands in deep basins

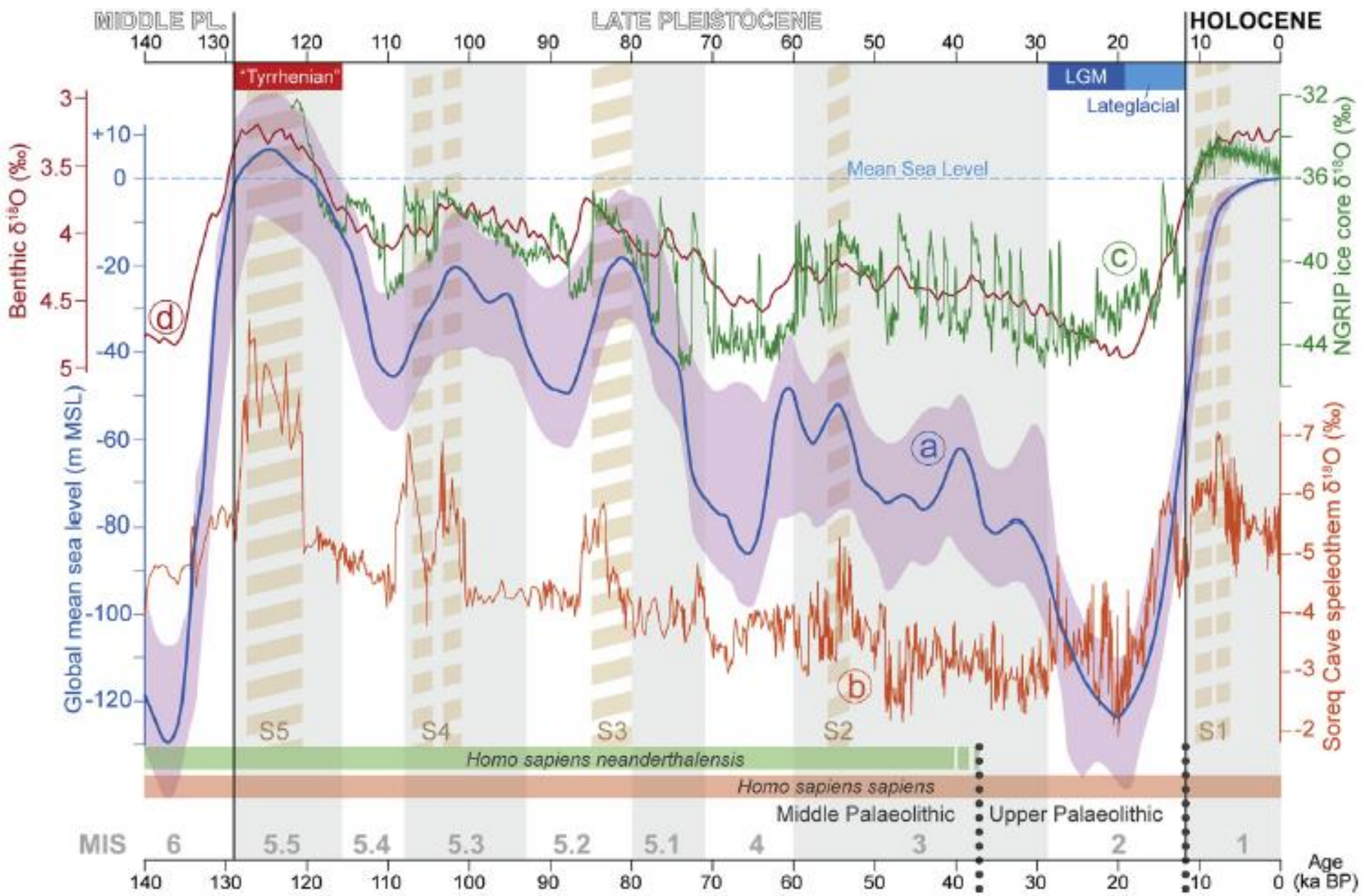
Induced subsidence

- This type of subsidence is induced by human artifacts
- In Tokyo, induced subsidence is up to 4.6 m, at the Po delta 2.7 m, as in Houston (Texas, Mississipi).

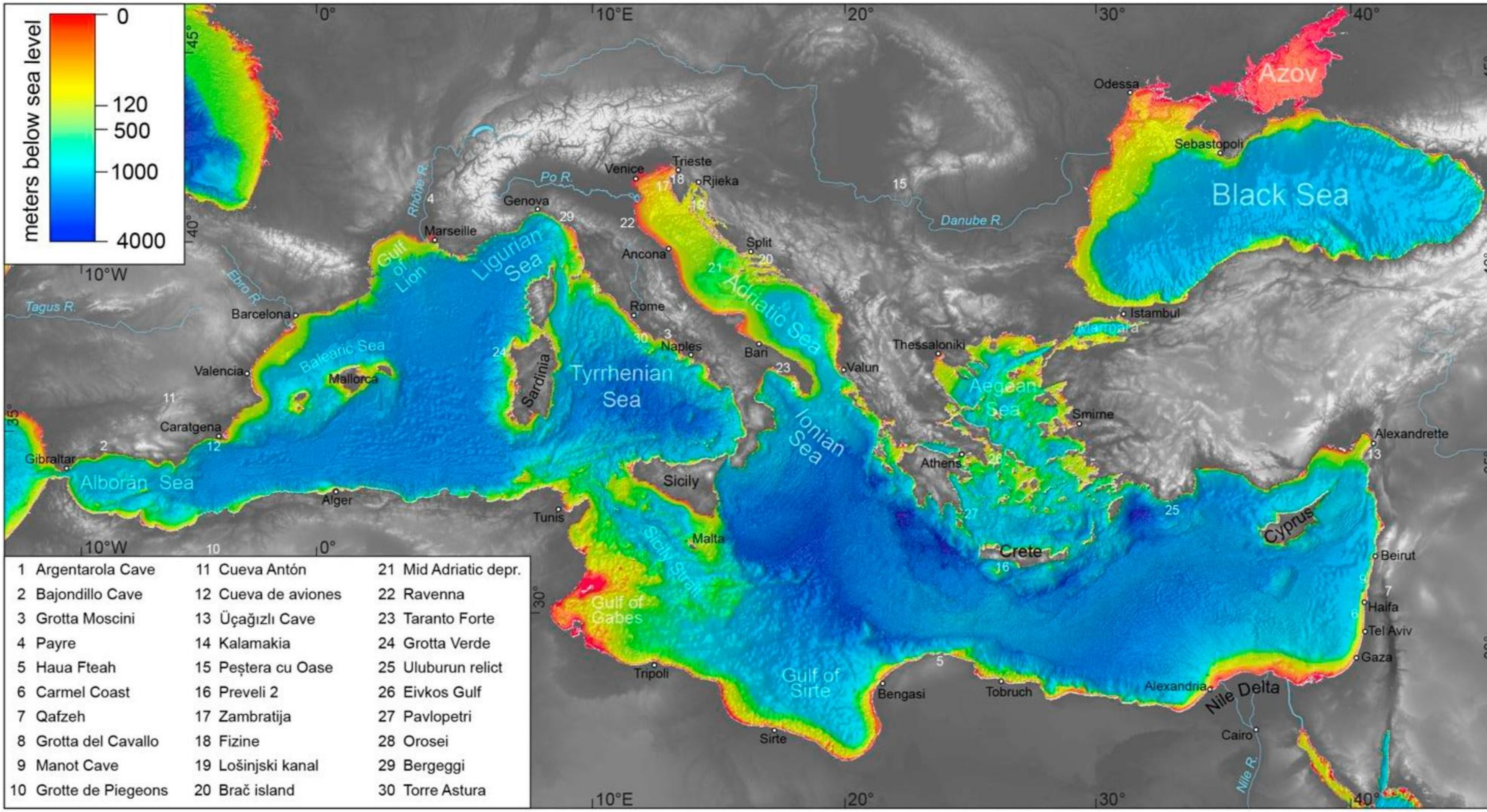


IMPLICAZIONI DELLE VARIAZIONI DEL LIVELLO MARINO

Reconstruction of past sea levels



Benjamin et al. (2017)



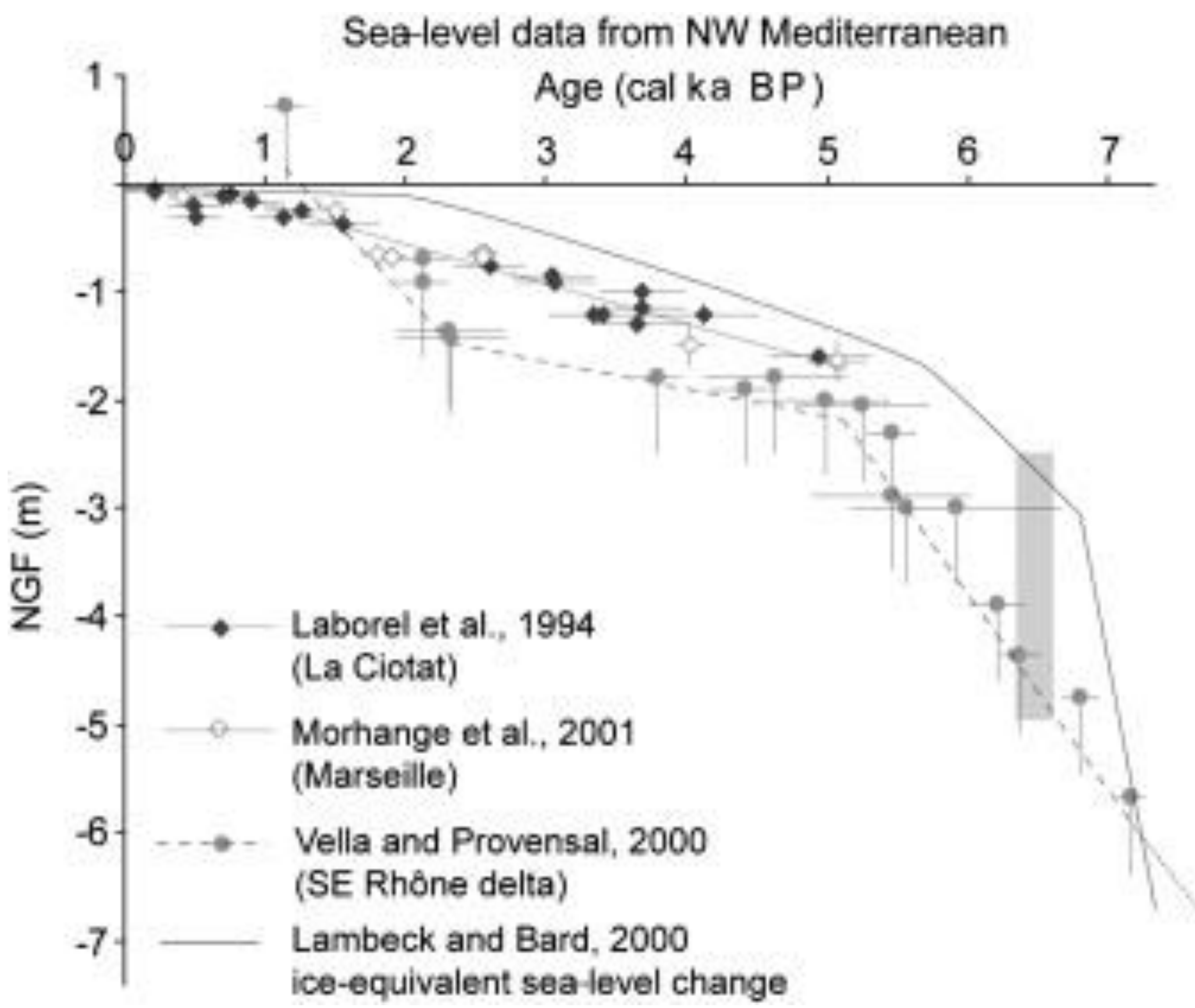
Benjamin et al. (2017)

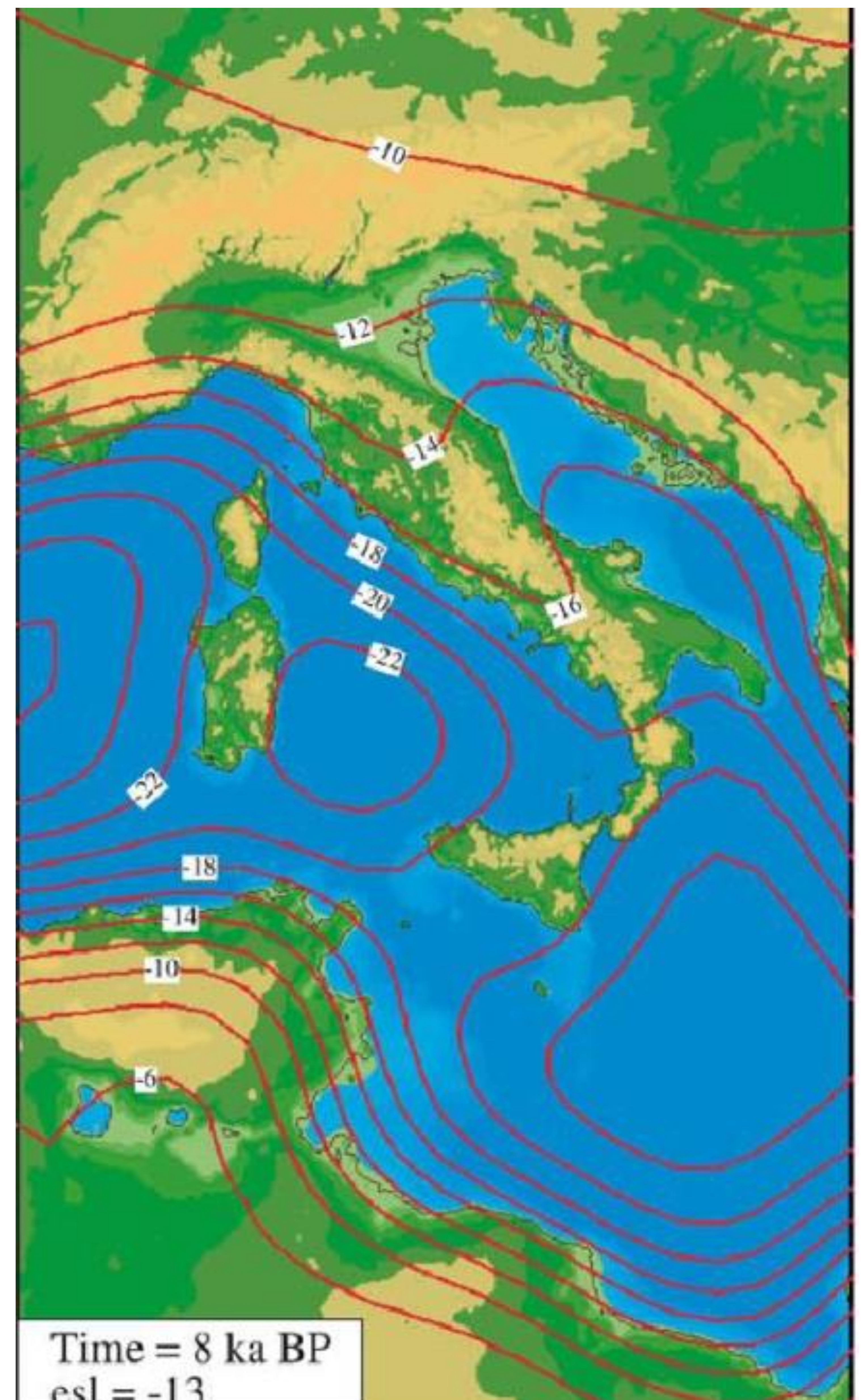
Climex maps Italy, Vai et al., 2004

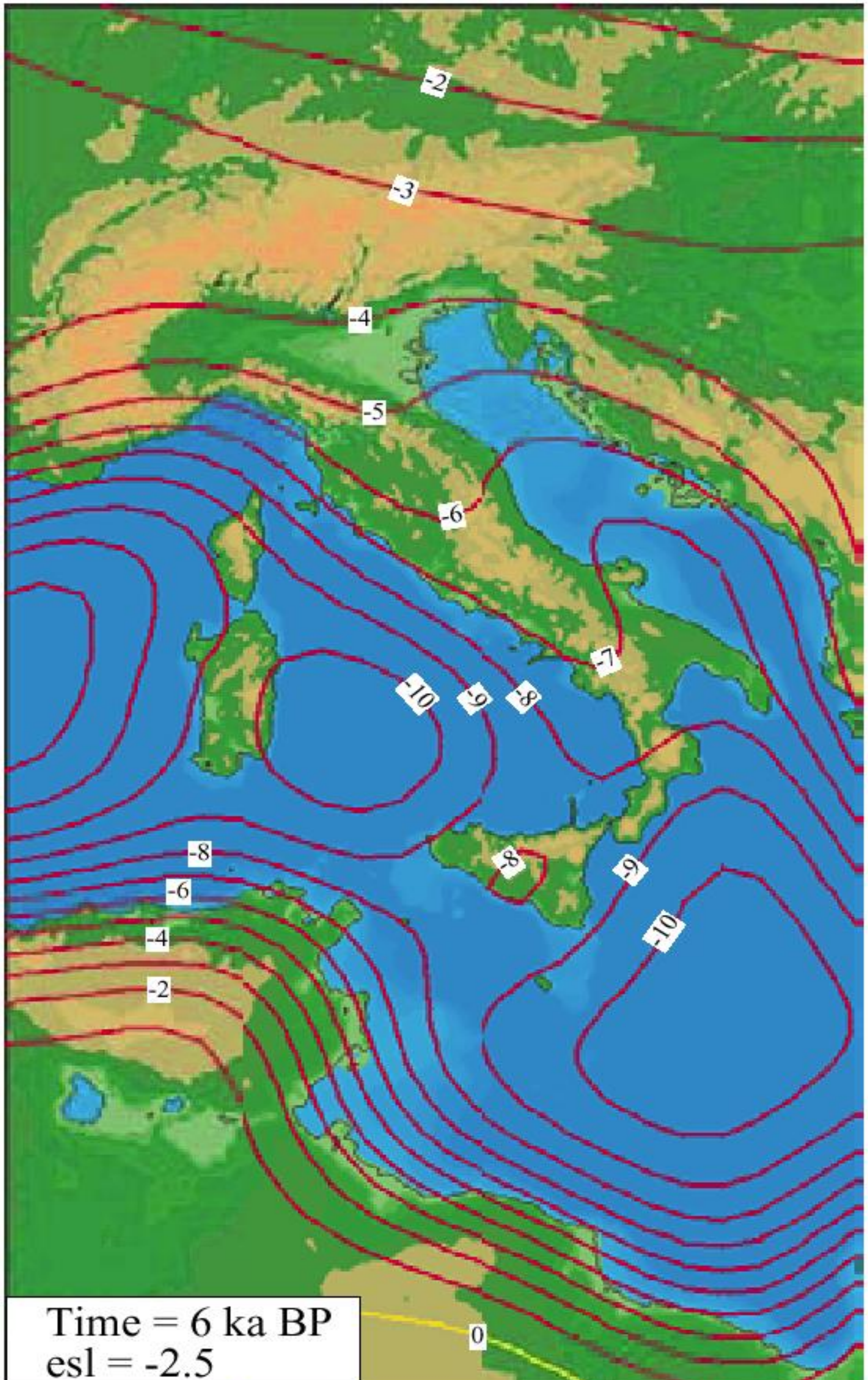
s.l. during LGM -149m

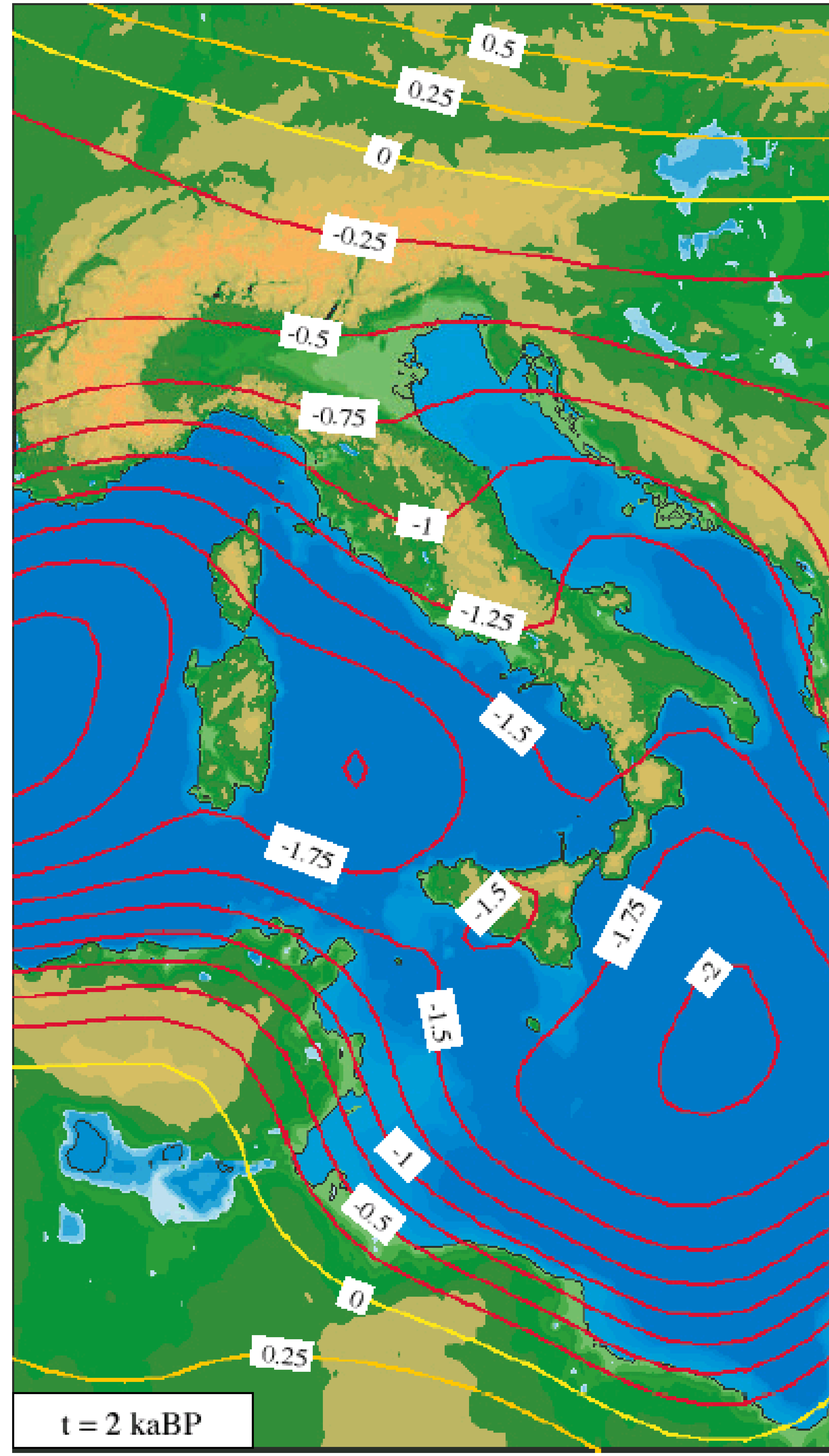
Holocene slc

- Lambeck's model (Lambeck et al., 2004)






-2
-3
-4
-5
-6
-7
-10
-9
-8
-8
-6
-4
-2
-8
-9
-10
0
Time = 6 ka BP
esl = -2.5


0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-1.5
-1.75
-2
-1.5
-1
-0.5
0
0.25
t = 2 kaBP

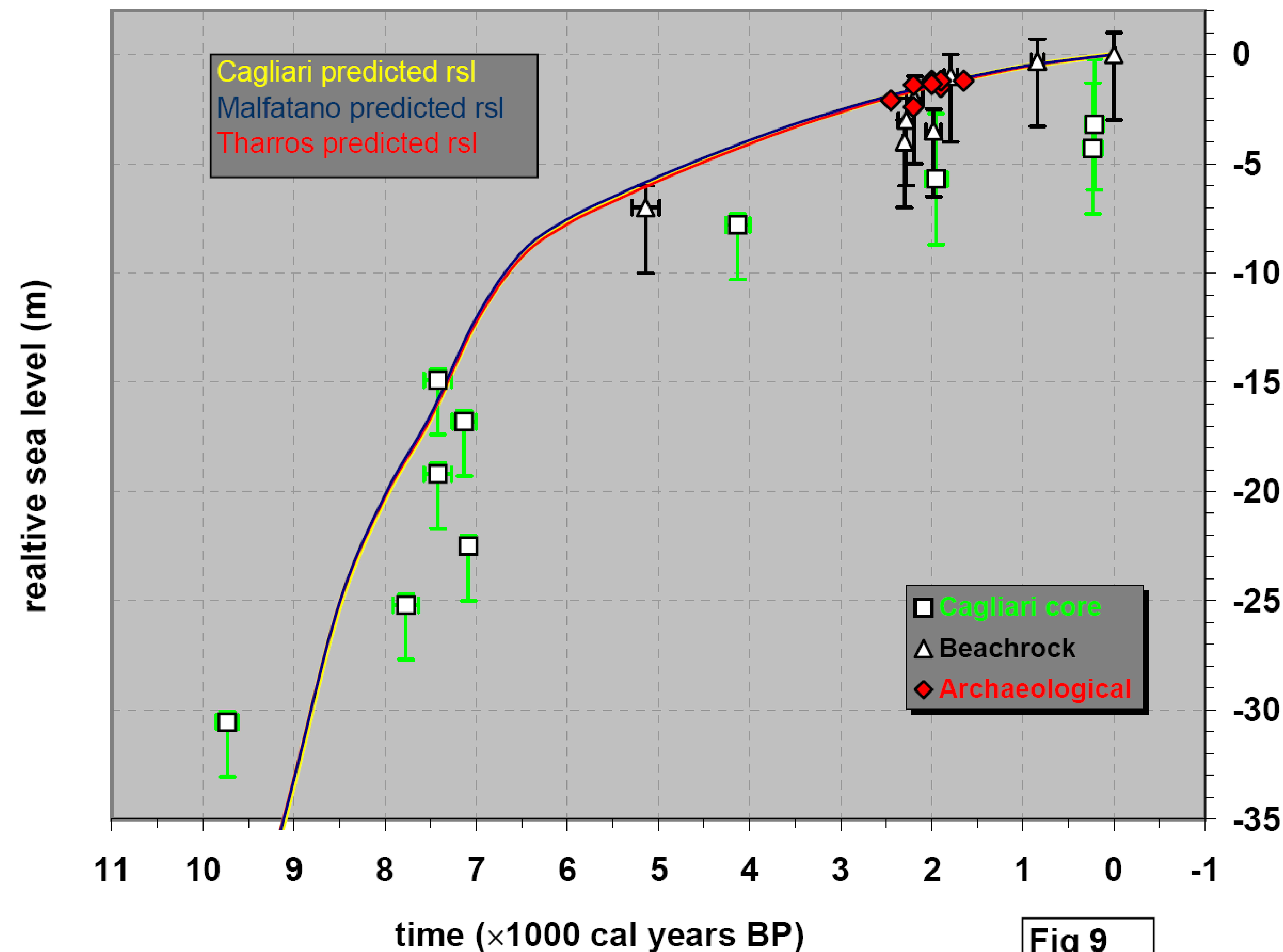
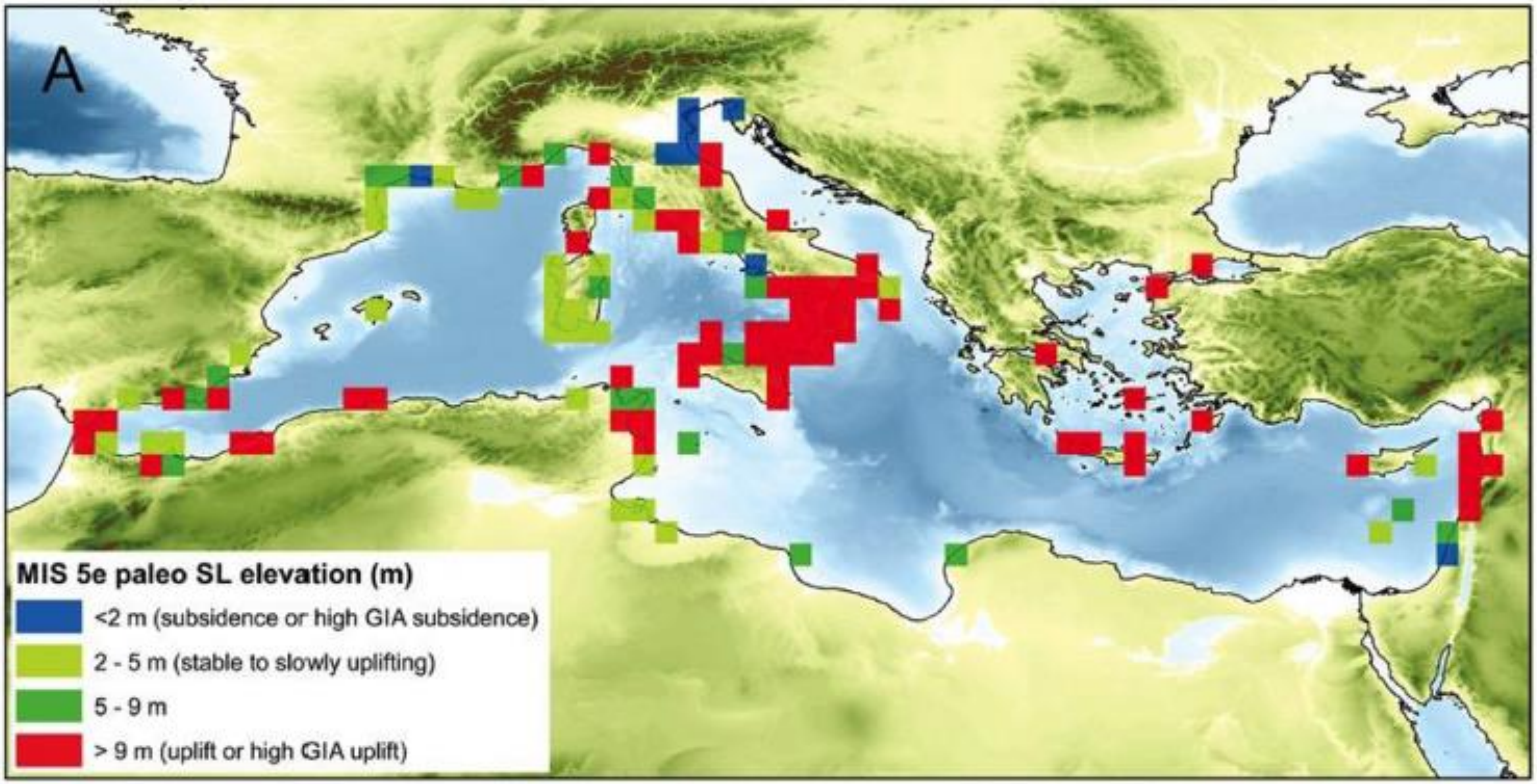

Cagliari predicted rsl
Malfatano predicted rsl
Tharros predicted rsl
Cagliari core
Beachrock
Archaeological
realtive sea level (m)
0
-5
-10
-15
-20
-25
-30
-35
11
10
9
8
7
6
5
4
3
2
1
0
-1
time (×1000 cal years BP)

Fig 9

Average elevation per area of the MIS5.5

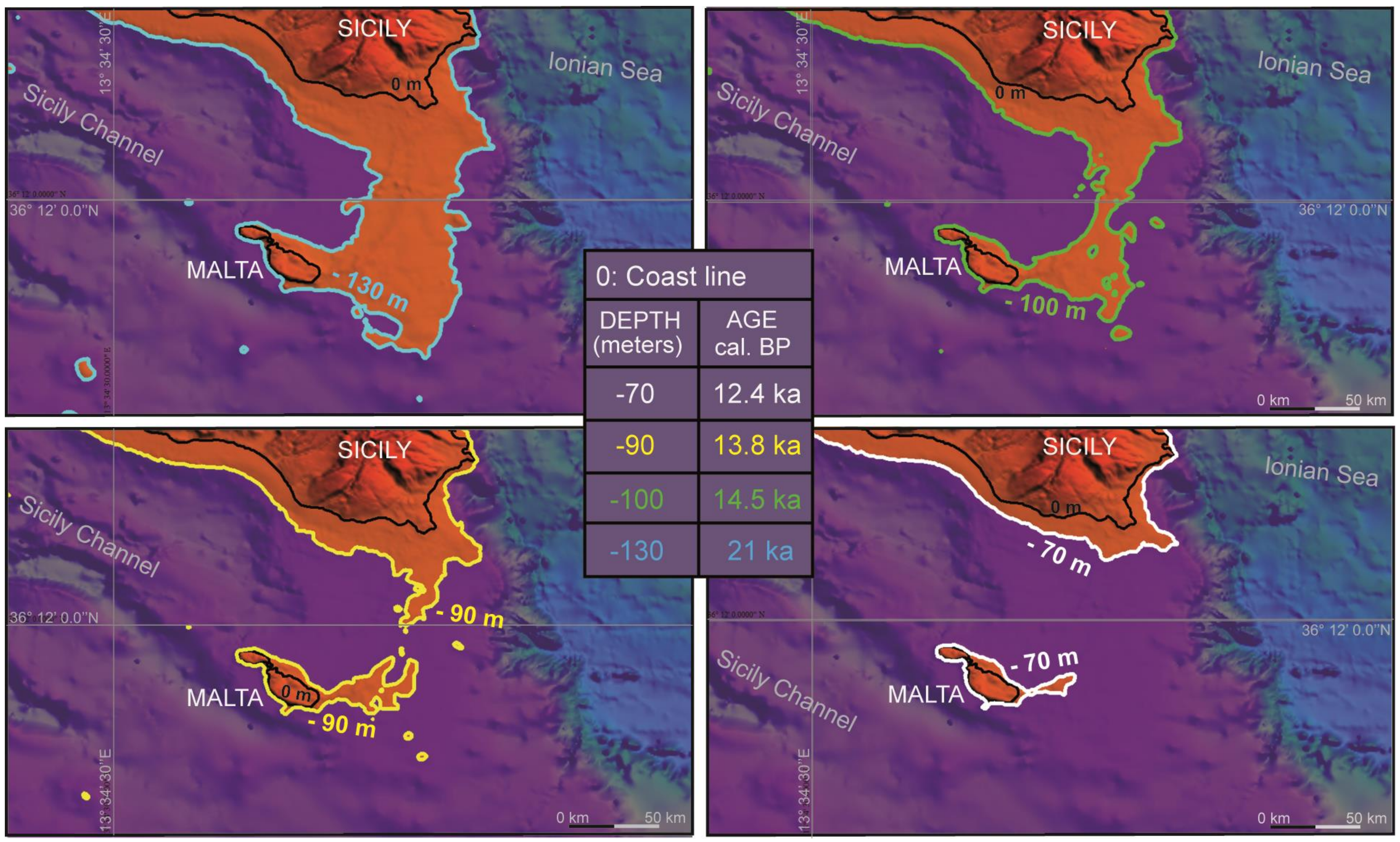


Benjamin et al. (2017)

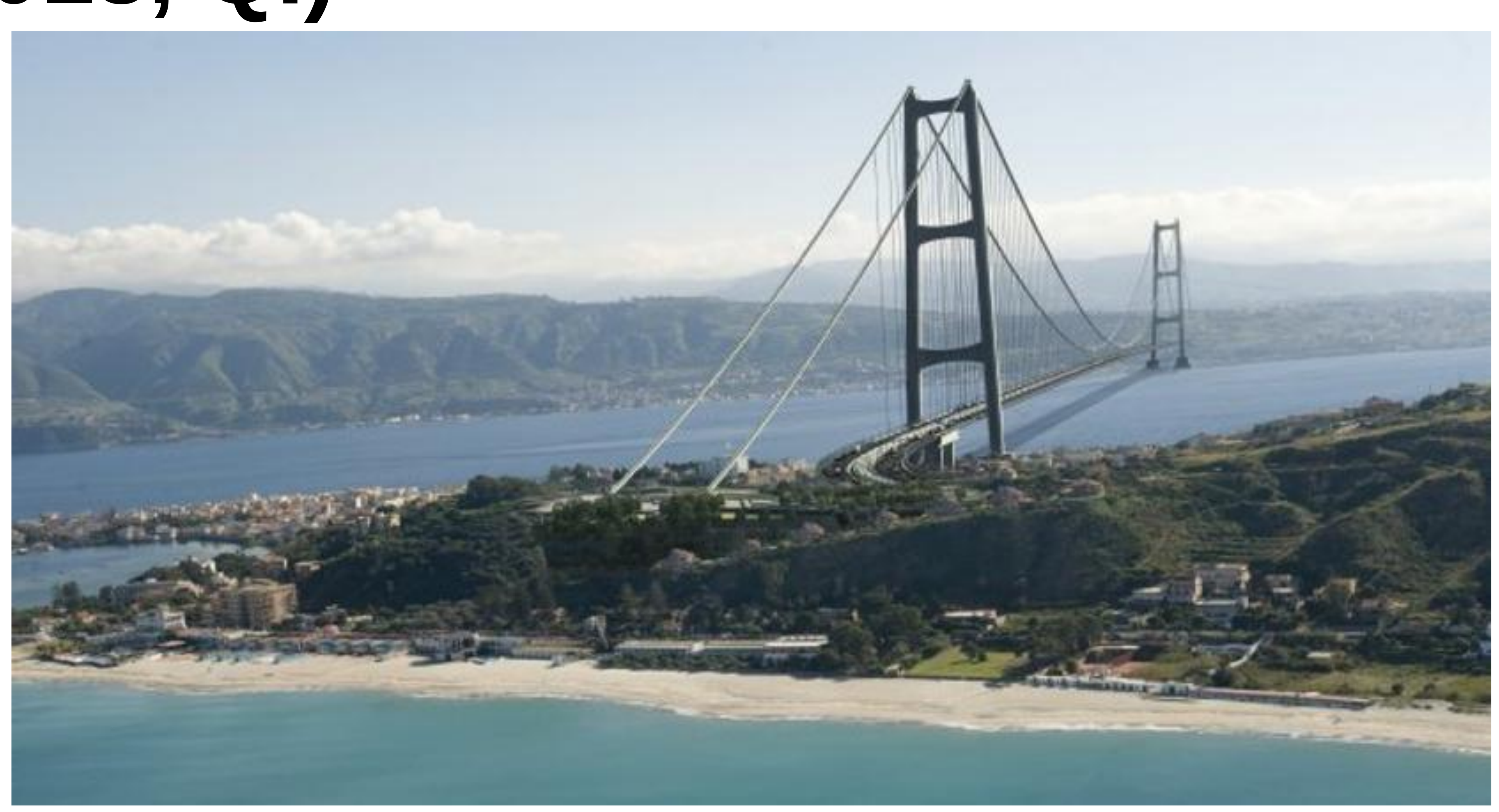
The main impacts of sea level rise are:

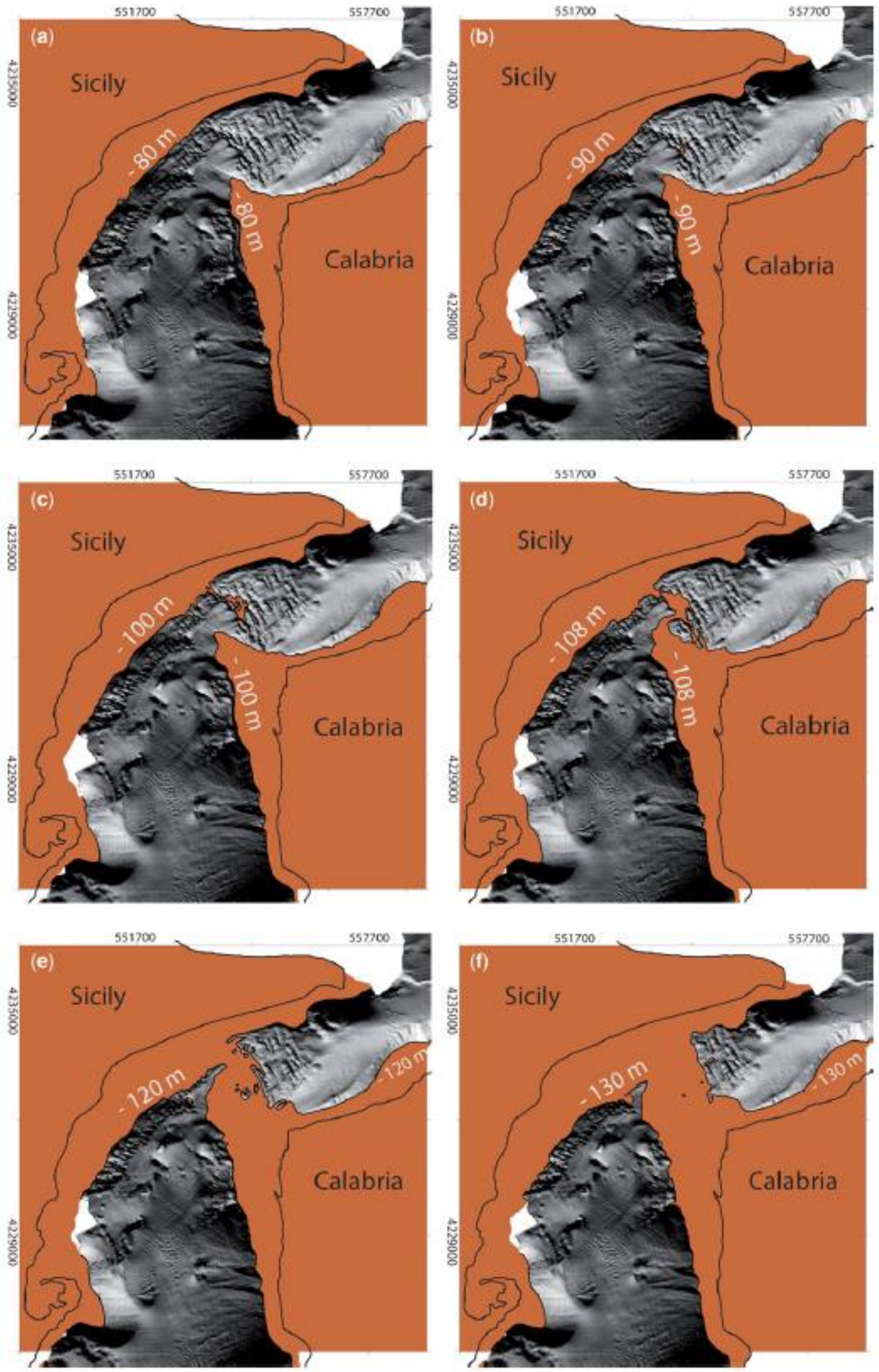
- land loss and increased coastal erosion;
- increased risk of flooding during extreme events;
- increasing groundwater levels up to several kilometers inland;
- salt water intrusion;
- coral reefs and coastal ecosystems, such as mangrove forests, turtle nesting beaches or coastal wetlands in danger.

Slc and continental bridges



Furlani et al. (2013, QI)



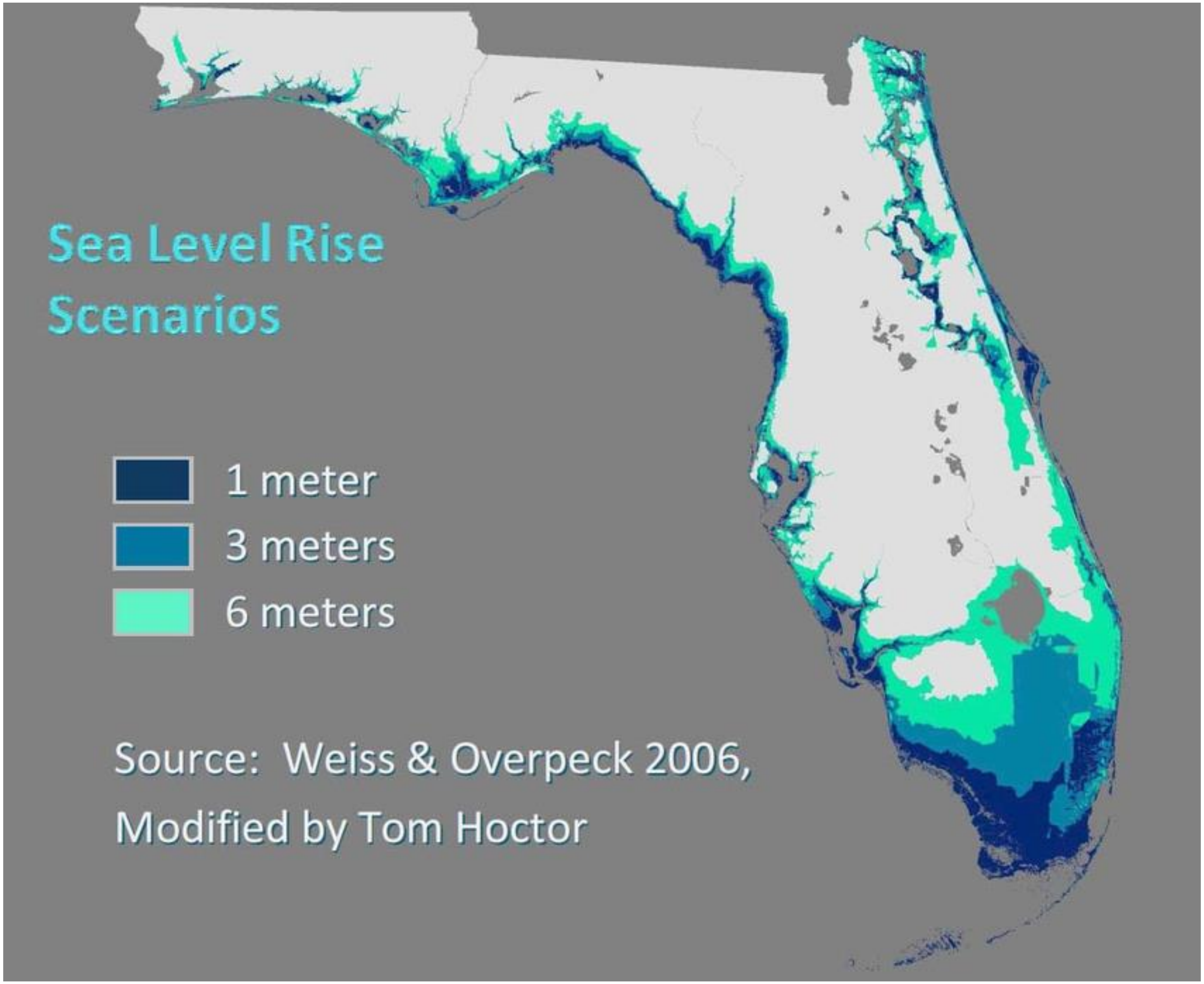


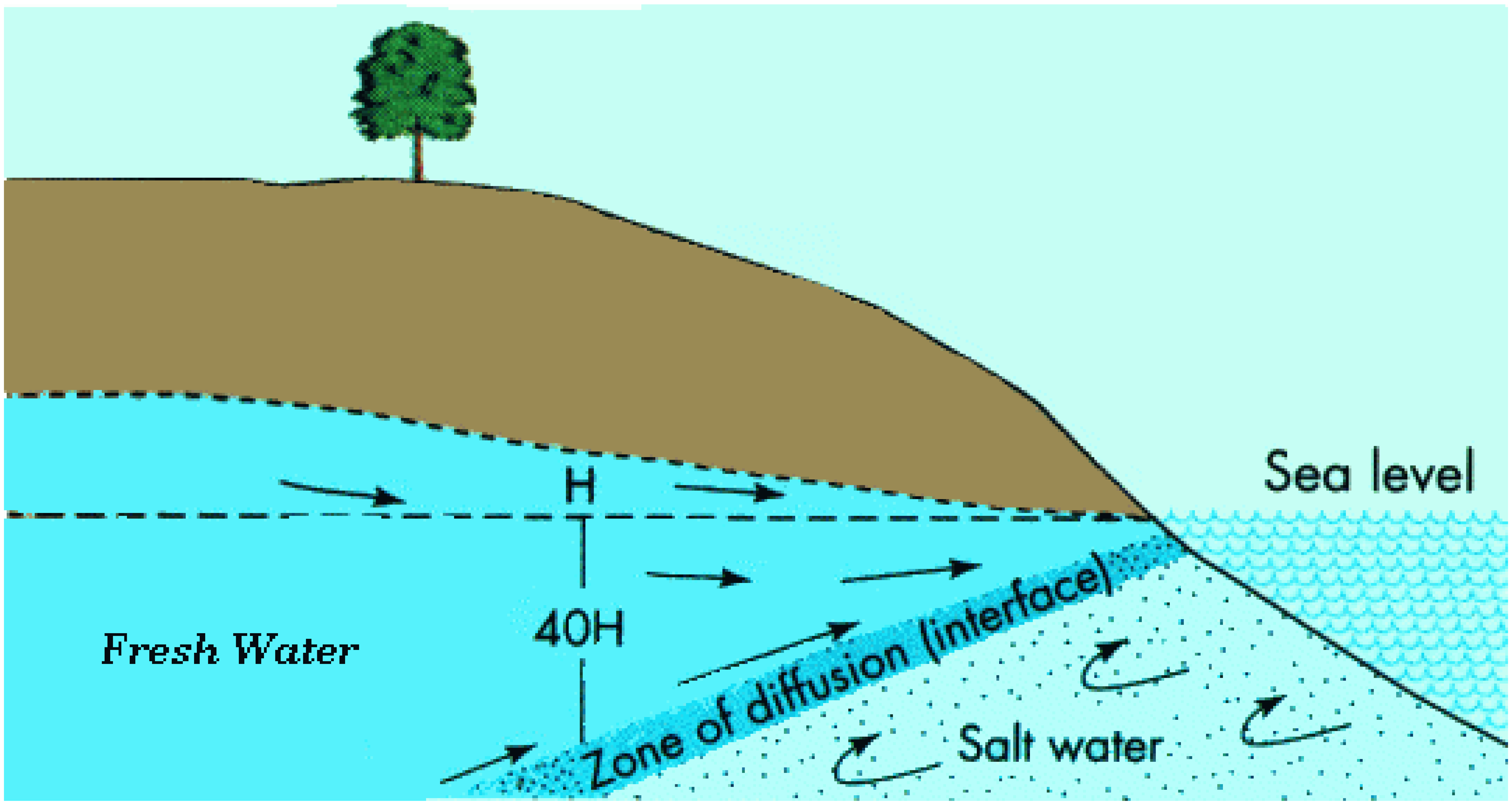
Antonioli et al. (2014, GSL)

Venice in the future

Atolls, coastal erosion

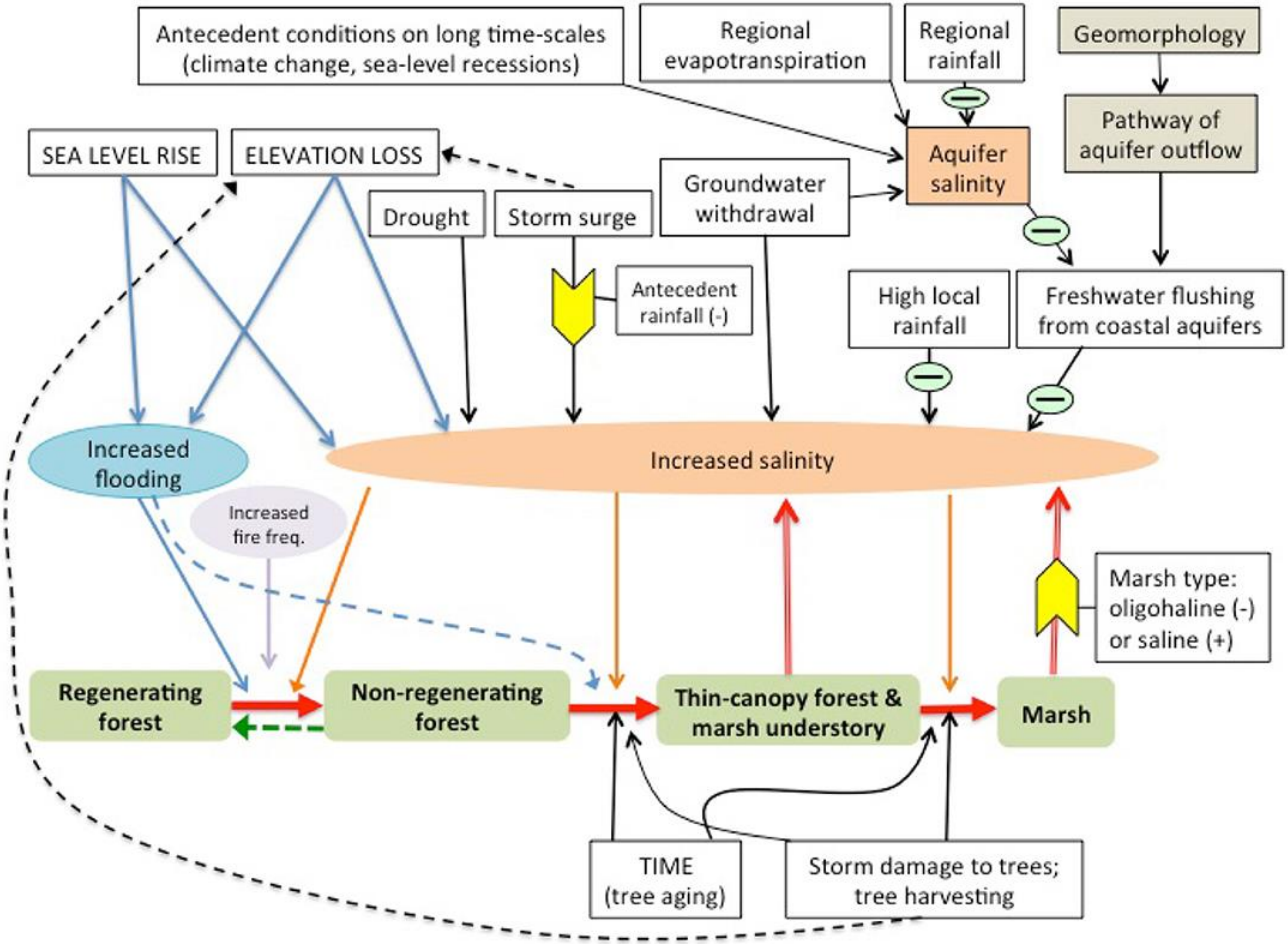
Scenari possibili di sea level rise





Sea level
H
40H
Fresh Water
Zone of diffusion (interface)
Salt water

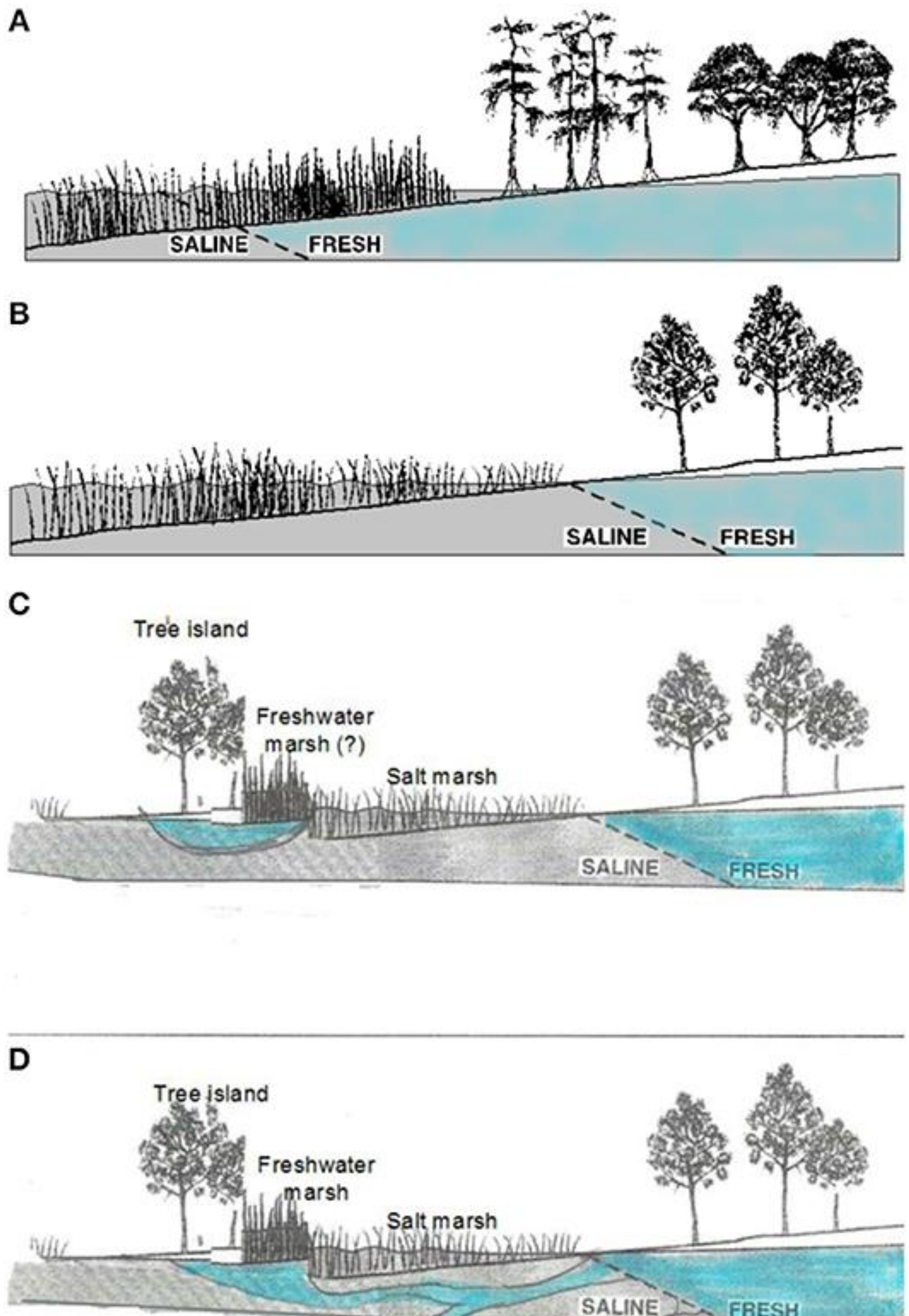
Intrusione salina e migrazione delle foreste



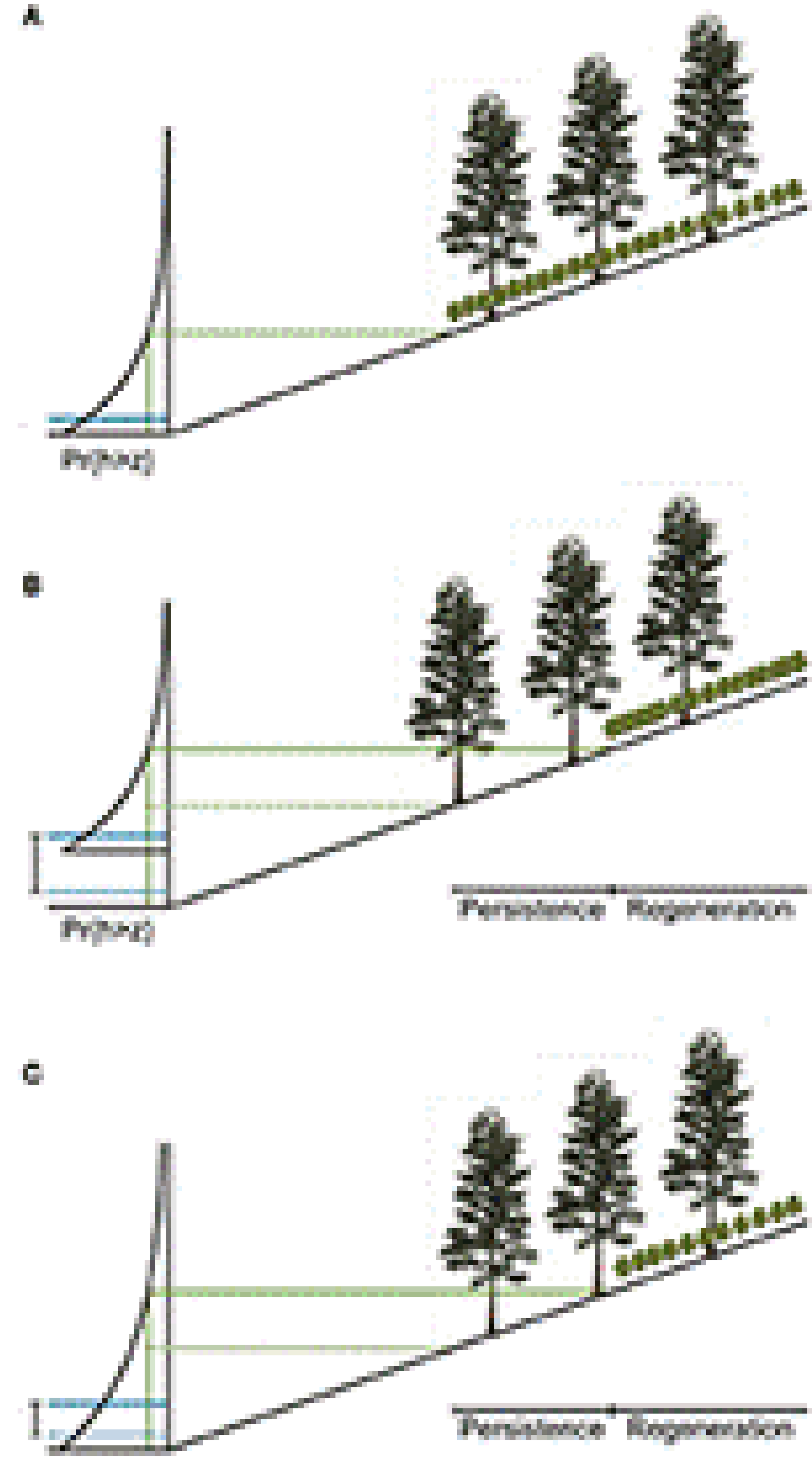
Fagherazzi et al. (2019)
Frontiers in Environment Sciences

Model of marsh expansion into a forest

Migrazione delle foreste



Fagherazzi et al. (2019)
Frontiers in Environment Sciences



Modello concettuale del cricchetto ecologico

GLI INDICATORI DI SLC

Indicatori di slc

Type of RSL marker	Chronology	Typology	Elements improving RSL estimate	References and examples
Tidal notches	Late Quaternary	Geomorphological	Fixed biological indicators	Antonioli et al., 2015, Rovere et al., 2016a, Goodman-Tchernov and Katz, 2016
Abrasion notch and sea caves	Late Quaternary	Geomorphological	Fixed biological indicators (may be difficult to find due to erosion).	Rovere et al., 2016a, Ferranti et al., 2006
Shore/Abrasion platforms	Late Quaternary	Geomorphological	Biological indicators	Rovere et al., 2016a, Ferranti et al., 2006
Marine terraces	Late Quaternary	Geomorphological/sedimentary	Fixed biological indicators or sedimentary features	Rovere et al., 2016a, Ferranti et al., 2006, Lambeck et al., 2004a
Speleothems	Late Quaternary	Geomorphological/sedimentary	Fixed biological indicators	Antonioli et al., 2004, Dutton et al., 2009
Beach deposits	Late Quaternary	Sedimentary	Biofacies, orientation and integrity of shells, sedimentary structures.	Rovere et al., 2016a, Galili et al., 2007, Galili et al., 2015, Goodman et al., 2008
Beachrocks	Late Quaternary	Sedimentary	Sedimentary structures, types of cement	Vousdoukas et al., 2007, Mauz et al., 2015b
Salt-marsh deposits	Holocene	Sedimentary	Faunal assemblages (foraminifera, ostracods, molluscs) and plant remains	Vacchi et al., 2016b, Lambeck et al., 2004a, Nixon et al., 2009
Lagoonal deposits	Holocene	Sedimentary	Faunal assemblages (foraminifera, ostracods, molluscs)	Vacchi et al., 2016a, Vacchi et al., 2016b, Lambeck et al., 2004a
River deltas	Holocene	Sedimentary	Sedimentary structures	Stanley, 1995, Anthony et al., 2014
Fossil fixed bioconstructions	Holocene	Sedimentary	Midlittoral species	Laborel and Laborel-Deguen, 1994, Rovere et al., 2015
Harbour structure (quay, pier, breakwater)	Late Holocene	Archaeological	Fixed biological indicators	Auriemma and Solinas, 2009, Morhange and Marriner, 2015
Fishtanks	Late Holocene	Archaeological	Preservation of all structural parts, presence of fixed biological indicators	Lambeck et al., 2004b, Mourtzas, 2012a
Coastal quarries	Late Holocene	Archaeological	Preservation of the lowest quarry level	Lambeck et al., 2004bAuriemma and Solinas, 2009, Galili and Sharvit, 1998
Slipways	Late Holocene	Archaeological	Fixed biological indicators	Lambeck et al., 2010, Anzidei et al., 2014a, Anzidei et al., 2016b, Morhange and Marriner, 2015
Coastal Water Wells	Holocene	Archaeological	Definition of the ancient water table	Galili and Nir, 1993, Sivan et al., 2004, Rovere et al., 2011

Benjamin et al. (2017)