CC BY

Modelling the vertical motions of the Alboran Sea since the Messinian Salinity Crisis
Topographic reconstruction and glacial-isostatic sea-level effects

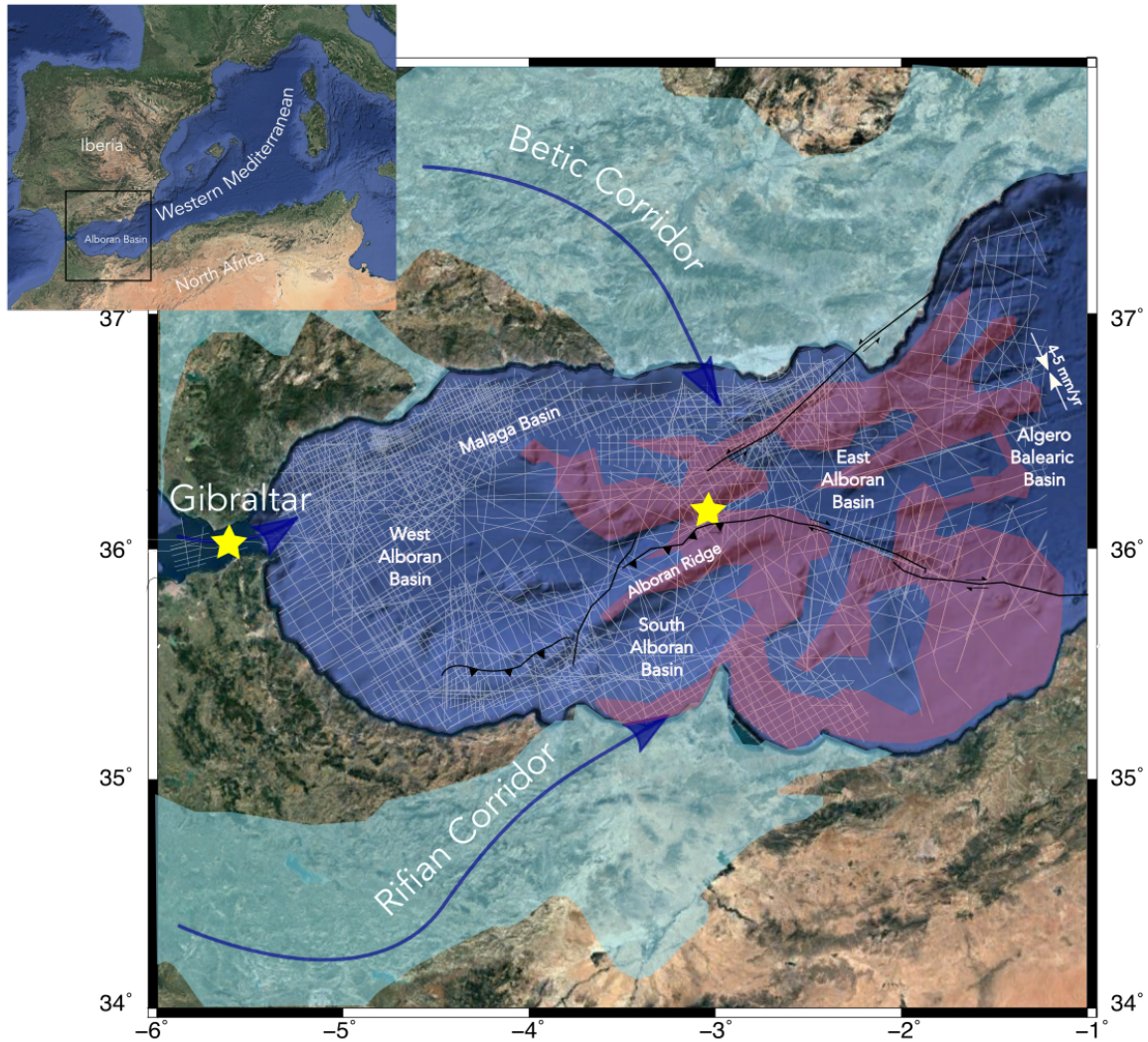
Hanneke Heida[1], Daniel García-Castellanos[1], Ivone Jiménez-Munt[1], Ferran Estrada[2], Gemma Ercilla[2], Sophie Coulson[3], Jerry X. Mitrovica[3], Damien Do Couto[4], Abdellah Ammar[5]

1: Geosciences Barcelona (GEO3BCN) Consejo Superior de Investigaciones Científicas (CSIC), Barcelona, Spain
2: Instituto de Ciencias del Mar, CSIC, Passeig Marítim de la Barceloneta 37-49, 08003 Barcelona, Spain.
3: Department of Earth and Planetary Sciences, Harvard University, Cambridge MA, United States
4:Sorbonne Université, Paris 06, ISTEP, and CNRS, UMR 7193, F-75005, Paris, France
5:U. Mohammed V-Agdal, Rabat, Morocco

SALTGIANT is a European project funded by the European Union's Horizon 2020 Research and Innovation Programme under the Marie Sklodowska-Curie grant agreement no 765256

CC BY

Geological Setting

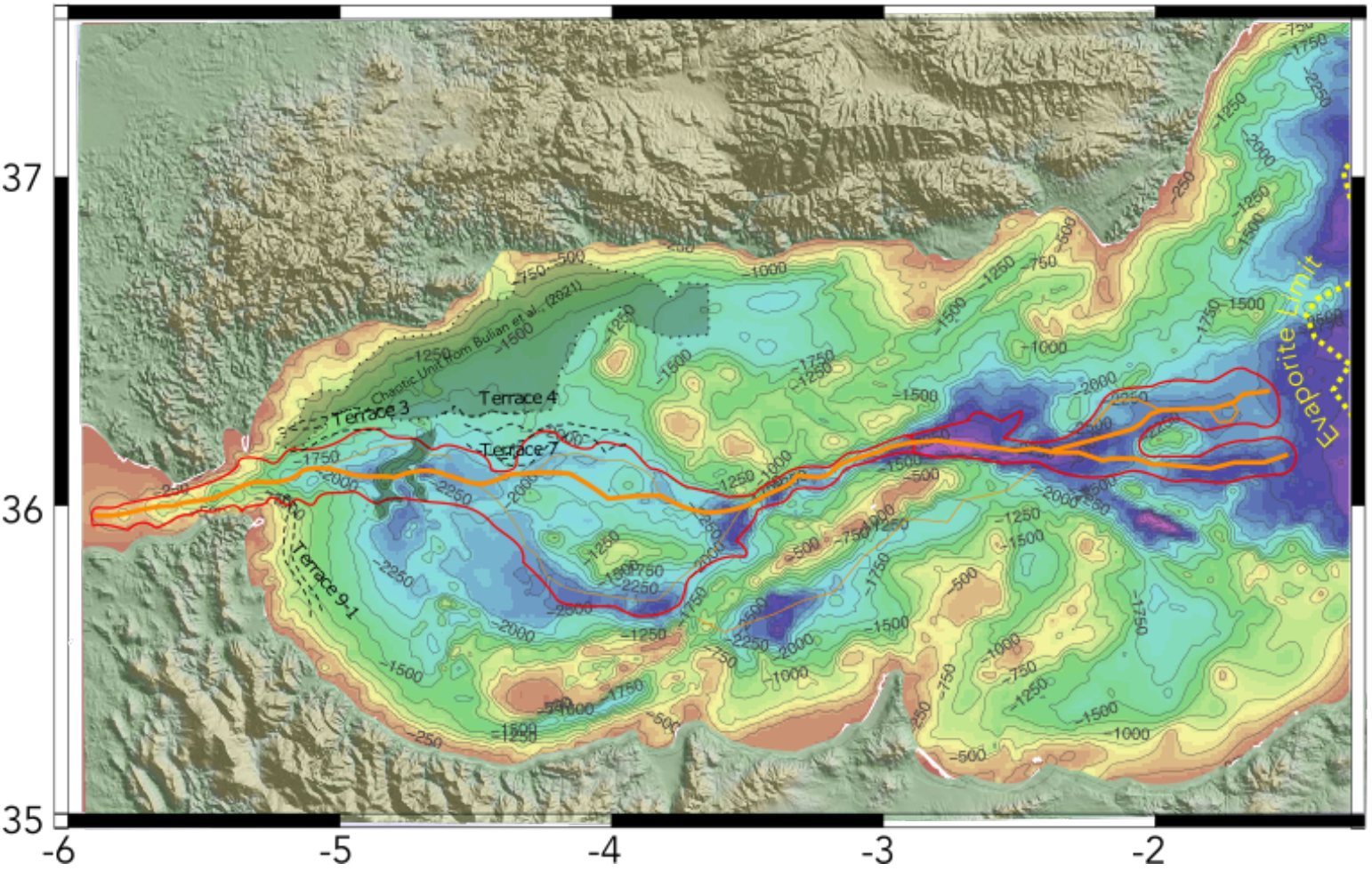


Bathymetric map of study area including the seismic dataset used in this study, the main tectonic features from Goméz de la Peña et al. (2021). Light blue: late Miocene Atlantic-Mediterranean gateways from Krijgsman et al. (2018). Red: East Alboran Miocene Volcanic arc from Booth-Rea et al. (2018) Stars: gateway locations proposed to have ended the MSC.

- Extensional basin formed in overal convergent setting (Af-Ib convergion) due to rollback of subducting slab, ending in late Tortonian
- Basin currently undergoing N-S shortening
- Main tectonic features are Alboran Ridge and Yusuf fault, marking the limit of the indenting African plate and separating the South Alboran Basin (SAB) from the West Alboran Basin (WAB) and East Alboran Basin (EAB)

- Area crucial in the context of the Messinian Salinity Crisis, as it modulates connectivity of the Atlantic with the rest of the Mediterranean!

The Messinian Salinity Crisis in the Alboran Basin



- Erosional channel identified from Gibraltar to Algero-Balearic Basin, linked to Zanclean flood.
- Erosional terraces identified by i.e. Estrada et al., 2011; Juan et al., 2016; Just et al., 2011)
- No halite, but local deposits containing anhydrite clasts (i.e. CU from Do Couto et al., (2018); Bulian et al., 2021)
- Base Pliocene interpreted by some as erosional unconformity, by others as paraconformity.

Depth of Base Pliocene surface in m compiled from extensive seimic dataset. Illustrated are the path of the Zanclean Erosion channel (Estrada et al. 2011, Garcia-Castellanos et al 2020), the extent of a Chaotic Unit as mapped by Bulian et al., 2021, the location of a number of erosional terraces in the MES and the limit of deep-basin halite

CC BY

Objectives

- Messinian Sill proposed to have been located at Gibraltar or at the volcanic arc separating the Eastern and Western Alboran Basins. Was the WAB part of the Mediterranean basins affected by the large MSC sea-level drop? How can we explain the distribution of sediments/evaporites and erosional features?

We attempt to answer this by:

- Restoring bathymetry at at the moment of Zanclean flood event by compensating for isostatic subsidence and compaction of sediments, thermal subsidence and tectonics.

- Constraining the depth at which different erosional features linked to the MSC were formed: do they record a single base level, or were they formed at different water depths?

CC BY

Method: Flexural-isostatic reconstruction

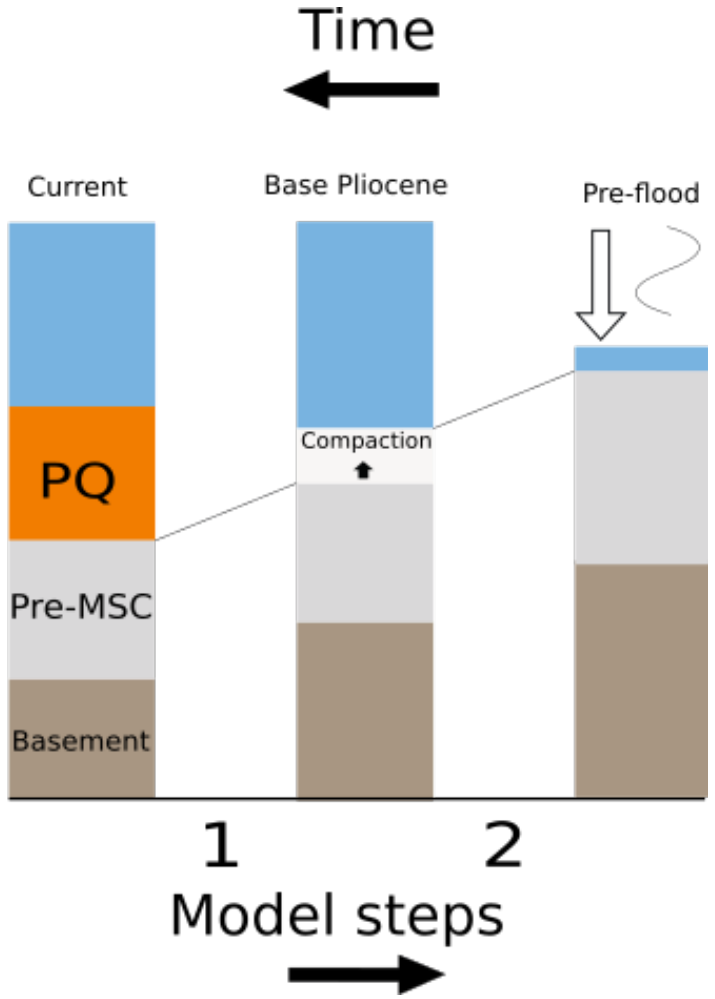
TISC (Tectonics, Isostasy, Surface transport, Climate) code

Numerical finite-element pseudo-3D (planform)

Flexural-isostatic compensation of:

- Post-Messinian sediments (step 1)
- Water load of flooding 1 km water column (step 2)

Decompaction of Miocene sediments



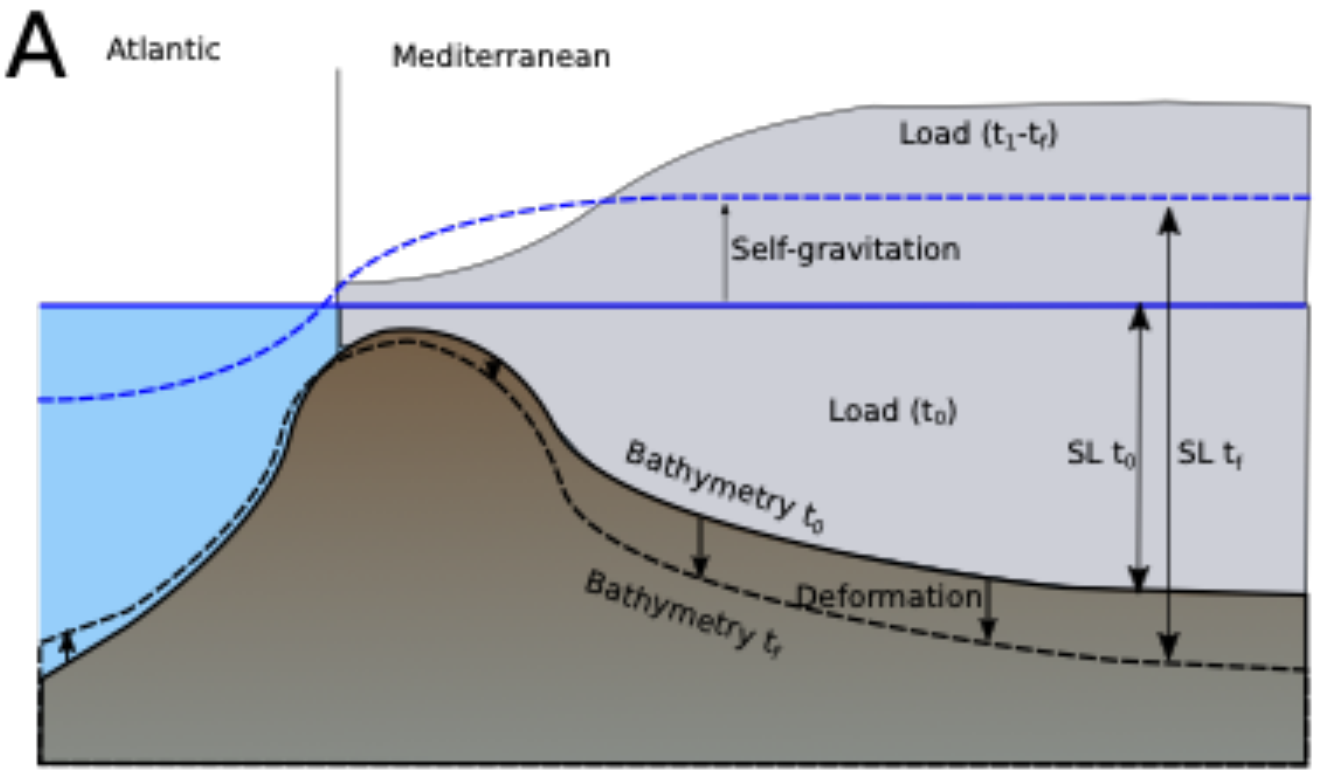
CC BY

Method: Glacial-Isostatic Modelling

Transcient stage (time-dependent component) of flexure constrained using GIA code, to gain insight in the time-dependence of the topographic response to a flooding event.

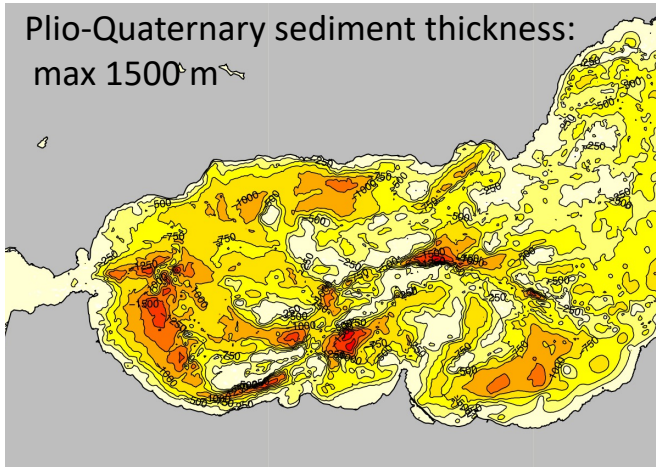
Flooding happens on extremely short timescale relative to other geological processes.

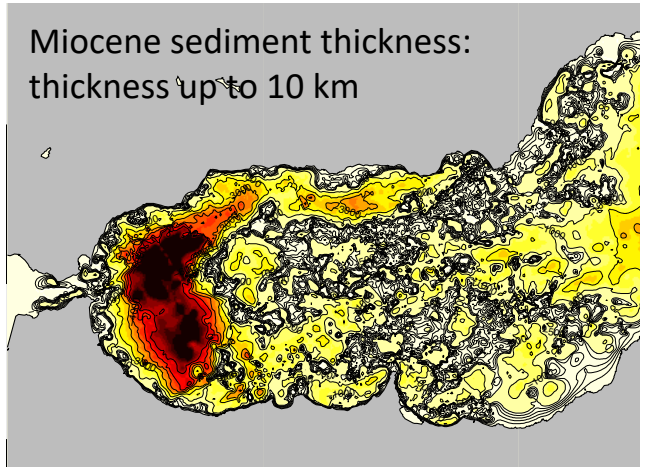
GIA code using pseudo-spectral algorithm to solve the sea-level equation (Kendall et al., 2005) accounting for deformation of the solid earth and equipotential surface due to self-gravitation of seawater.



CC BY

Inputs





Model parameters for flexure:

-Effective Elastic Thickness
(EET, range 5-10 km)

Grid dimensions 450x450 km, 1 km grid spacing

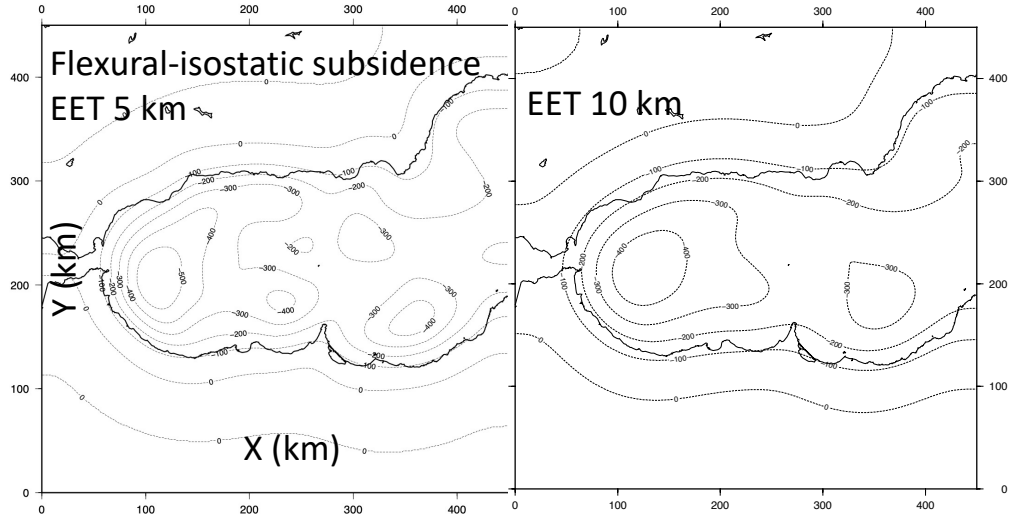
Compaction equation:

$$\phi_z = \phi_0 * e^{-bz}$$

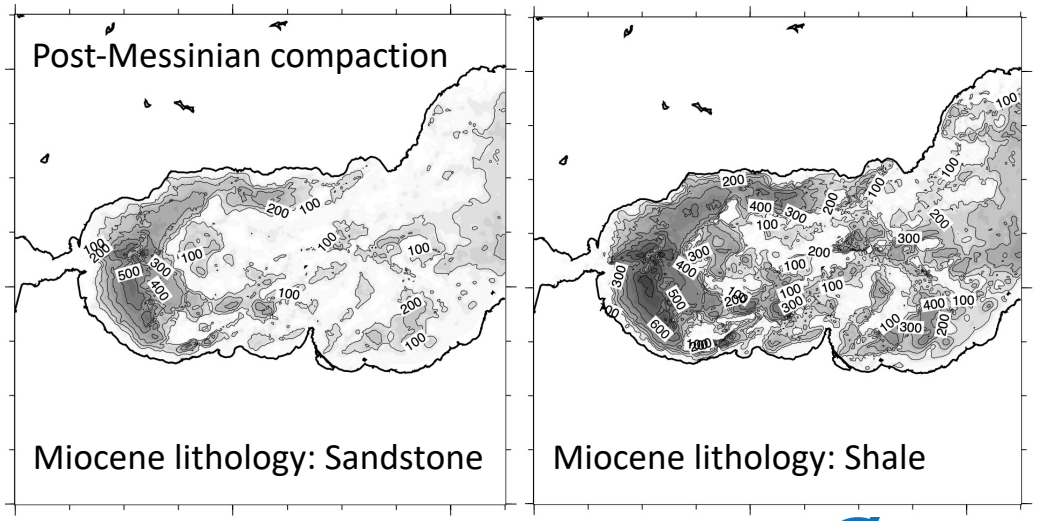
Φ = porosity, z = depth below seafloor (km)
b = compaction coefficient (km^{-1})

for shale $\Phi_0 = 0.67$, b = 0.00051,
for sand $\Phi_0 = 0.49$, b = 0.00027
(Sclater & Christie, 1980)

Outputs

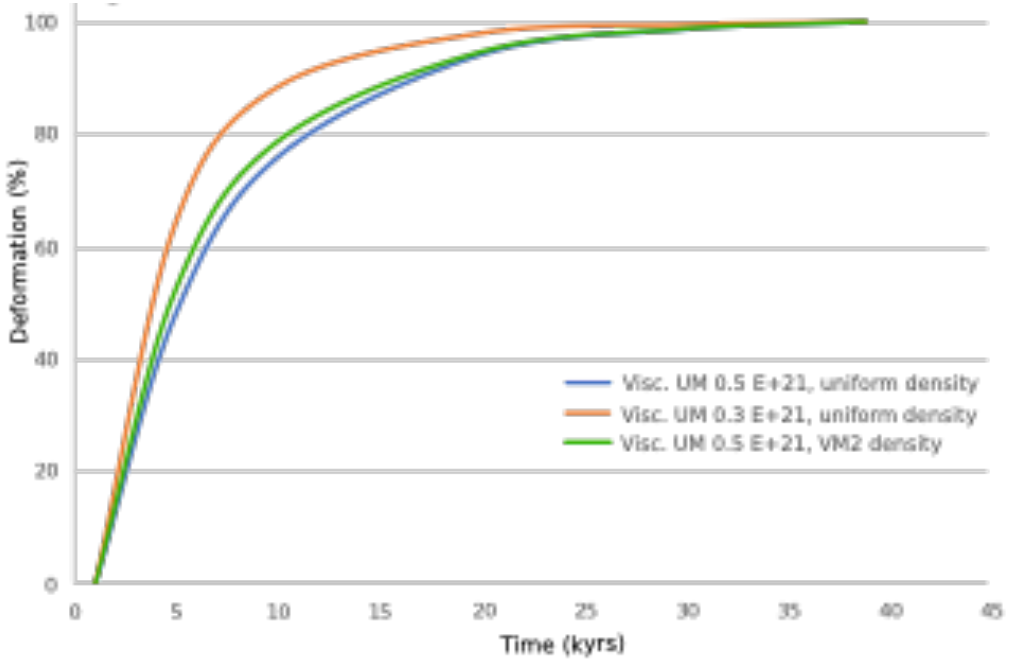


Subsidence induced by Plio-Quaternary sediment (density 2100 kg/m3)
Maximum values around 500 m in WAB, limited sensitivity to EET.
Additionaly up to 300 m subsidence due to flooding with 1 km water column.

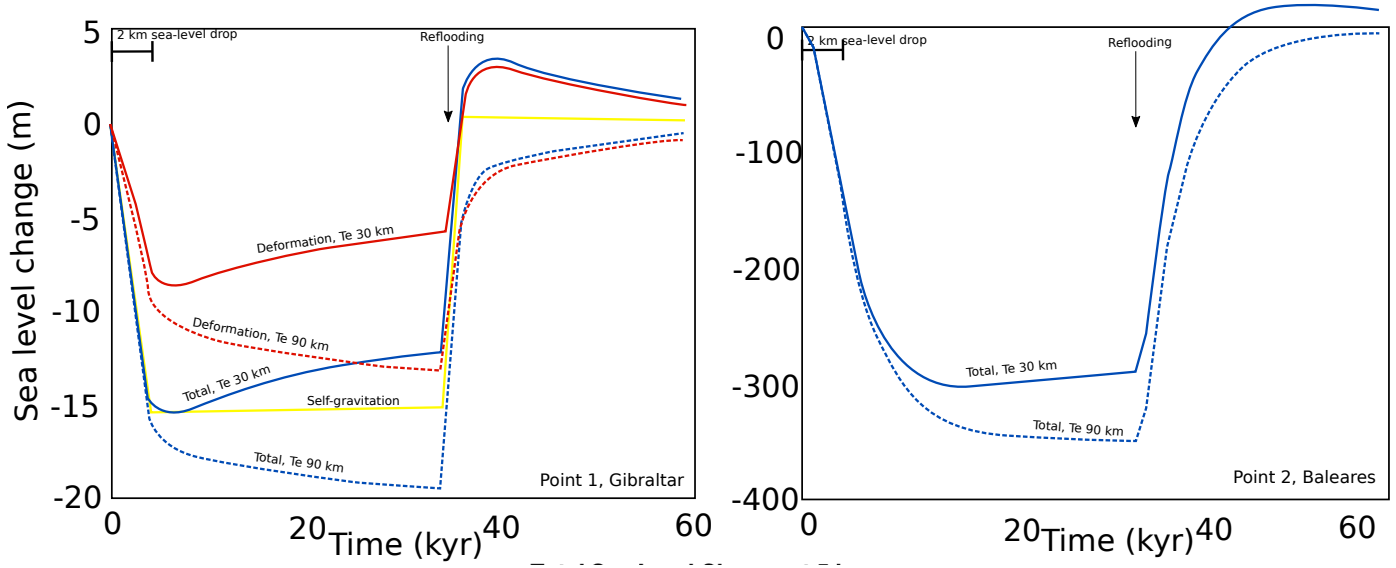


CC BY

Results: Glacial-Isostatic Modelling



Rate at which deformation develops as a response to instantaneous loading for different Earth models (mantle viscosity and density distribution).
Mayority of response develops over first 10 kyr after loading, after 20 kyr development of flexural response is complete.

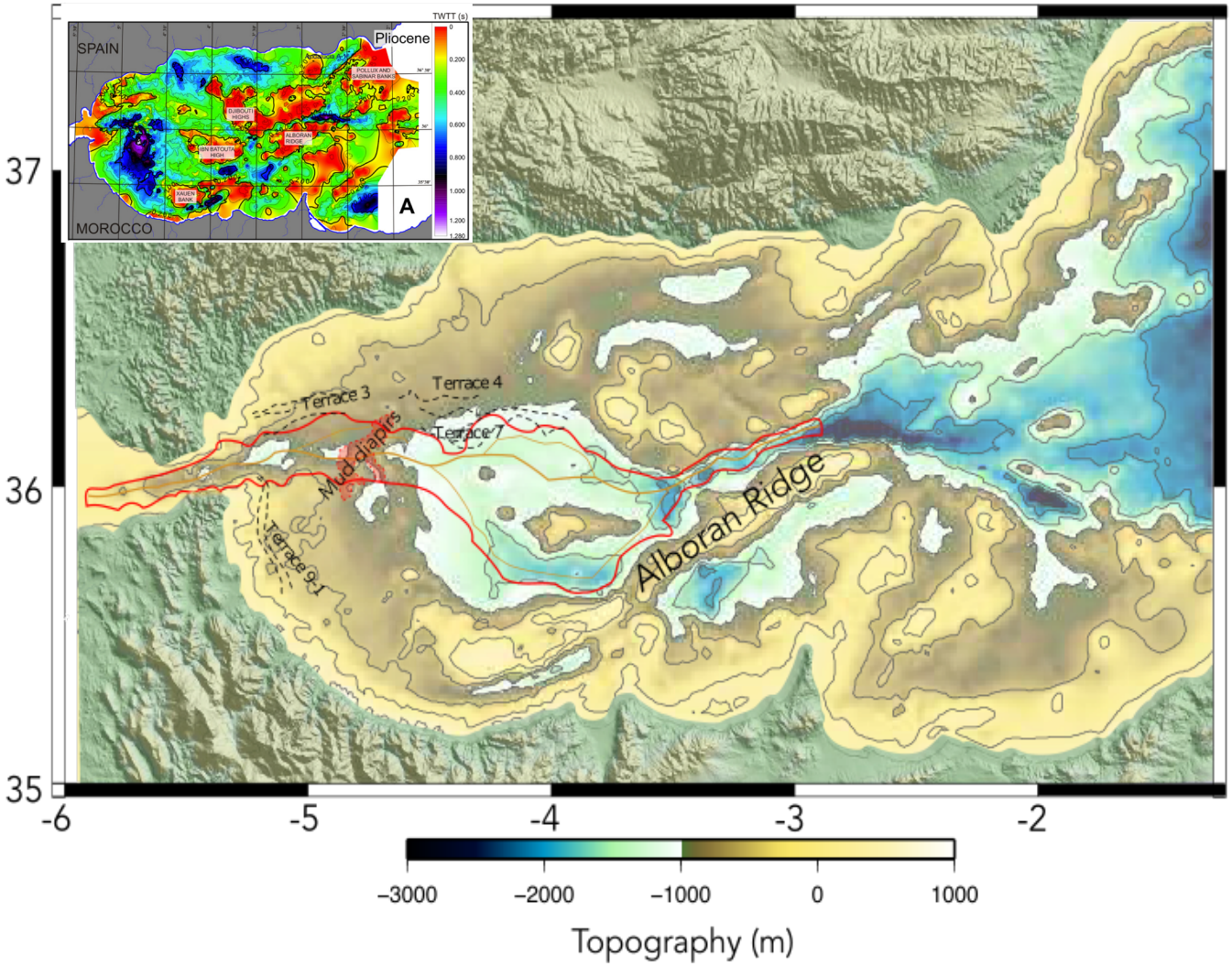


Hypothetical sea-level change due to a large sea-level drop in 4 kyr, and reflooding taking place instantaneously. At Gibraltar, the self-gravitaional effect of seawater and the solid earth resonse act on similar, small scales, while further east the solid earth deformation dominates. The the timescales over which the flexural response develops significantly slower than the proposed duration of the flooding phase, which is a small as a few years (Garcia-Castellanos et al., 2009)

Implication: Topography during and right after the flooding event was still affected by rebound due to the sea-level drop! When reconstructing erosional features formed during the lowstand, the subsidence that occurred due to flooding should be compensated!

Results: Reconstructed topography

(removal PQ sediments, 1 km of water, decompaction sediments)



A: End Messinian paleotopography from TISC reconstruction with terrace locations and Zanclean channel path. Inset: Isochore map of Pliocene sequence from: Juan et al., (2016)

To understand connectivity across the Alboran Ridge/Volcanic arc thermal and tectonic effects should be considered.

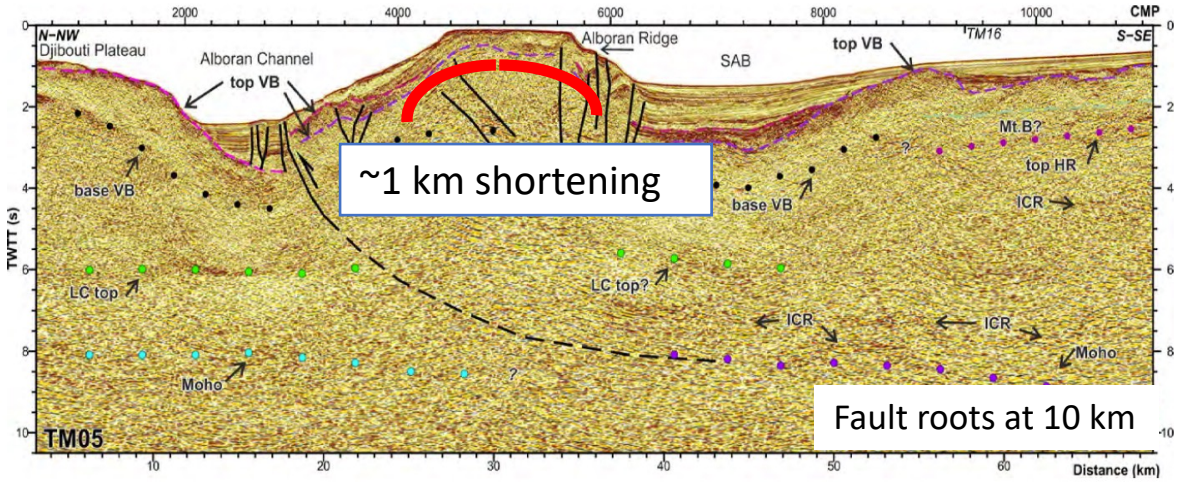
In WAB, the topographic minimum does not correspond to location of largest Pliocene sediment accumulation!

This can be due to:

-overestimation of compaction (mud diapirism indicates undercompaction).
-Sediment distribution controlled by strong bottom currents around topographic highs
-Large sediment supply from tectonically active orogen surrounding WAB, accumulating in the backarc
-Unidentified source of uplift in the Western part of the WAB?

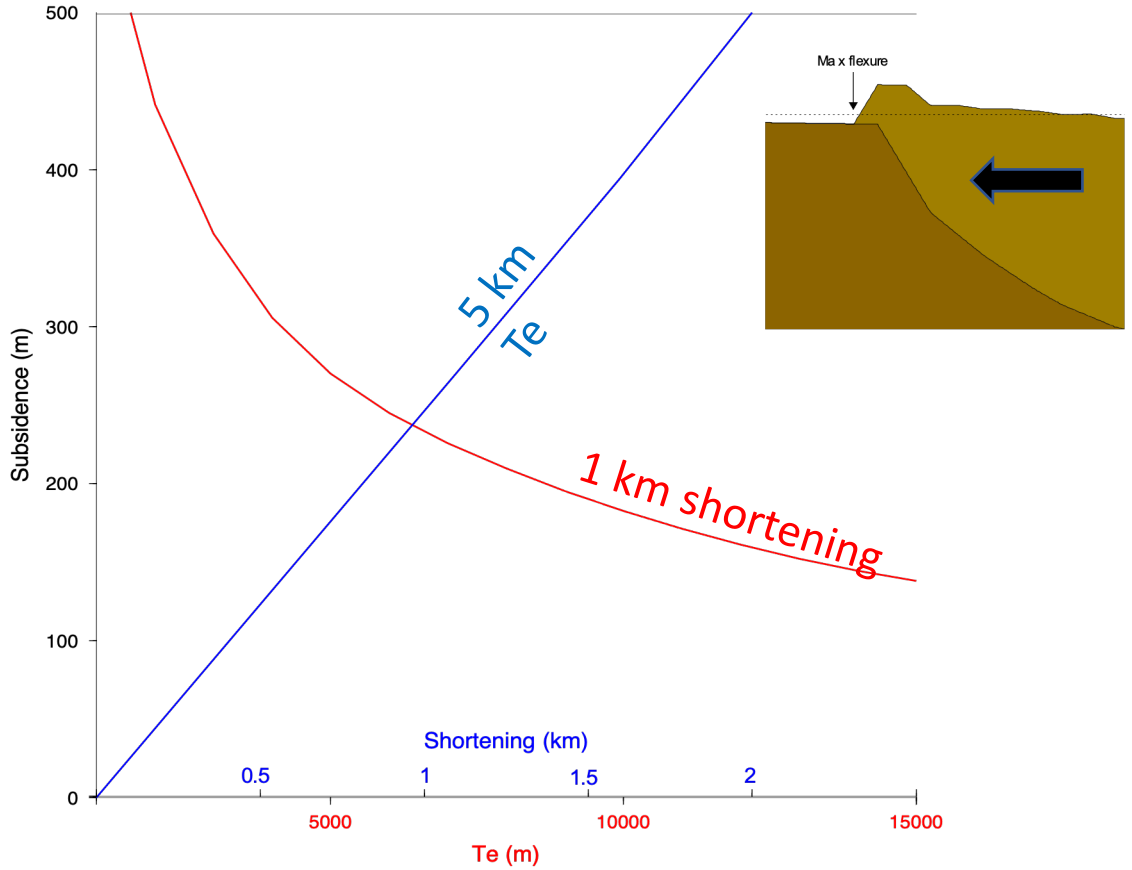
CC BY

Tectonics Alboran Ridge



From: Goméz de la Peña, 2017

Twofold effect of shortening on vertical motions: deformation on fault (creating positive topography) and loading of ridge causing subsidence due to flexure.

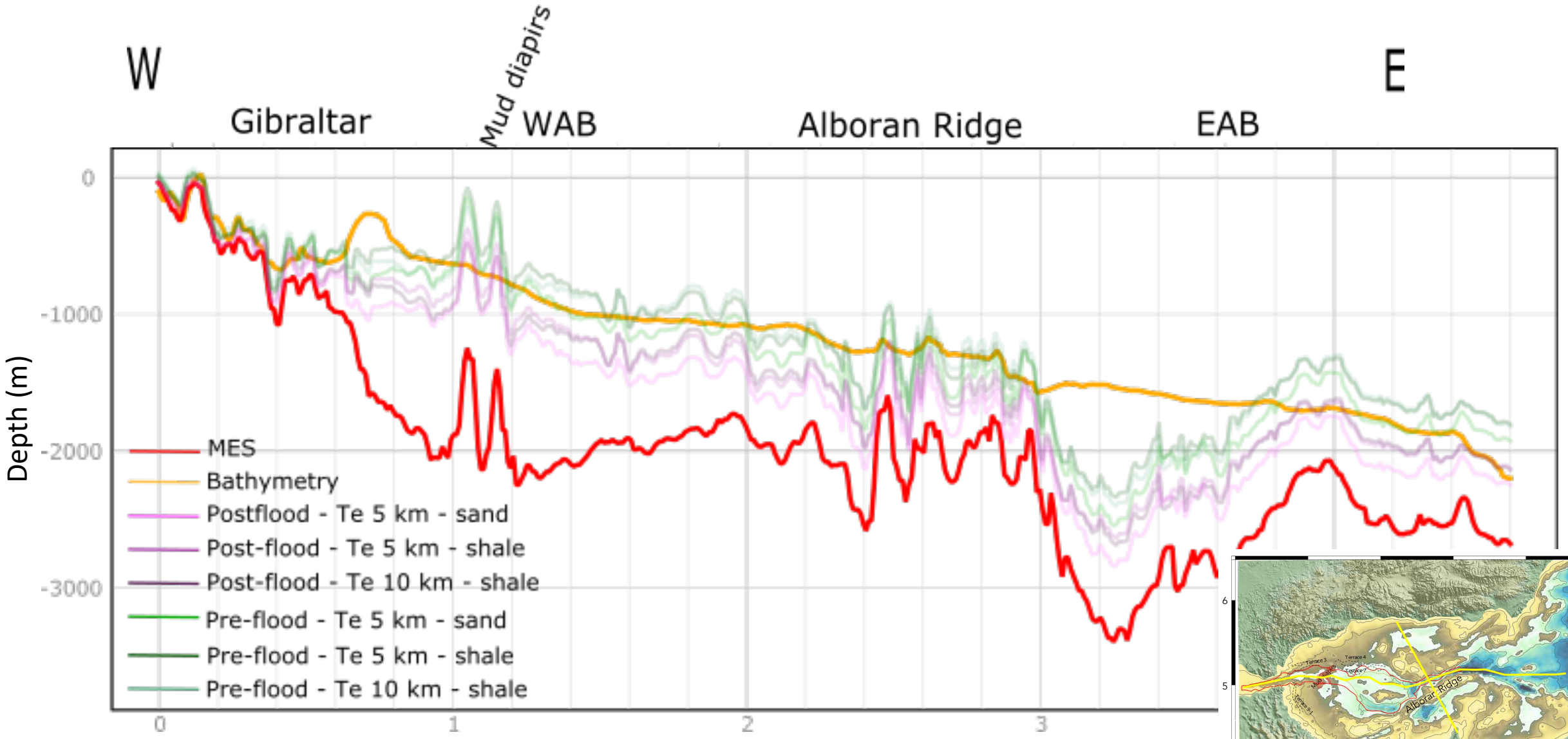


A 2-D flexure model of shortening on the Alboran Ridge shows effect on Zanclean (lower EET yielding more local flexure and higher subsidence values) and total shortening over last 5 Ma (larger shortening rates yielding larger load and subsidence values)
Realistic range of subsidence magnitude on Zanclean Channel 200-300 m.

CC BY

Results: Zanclean channel

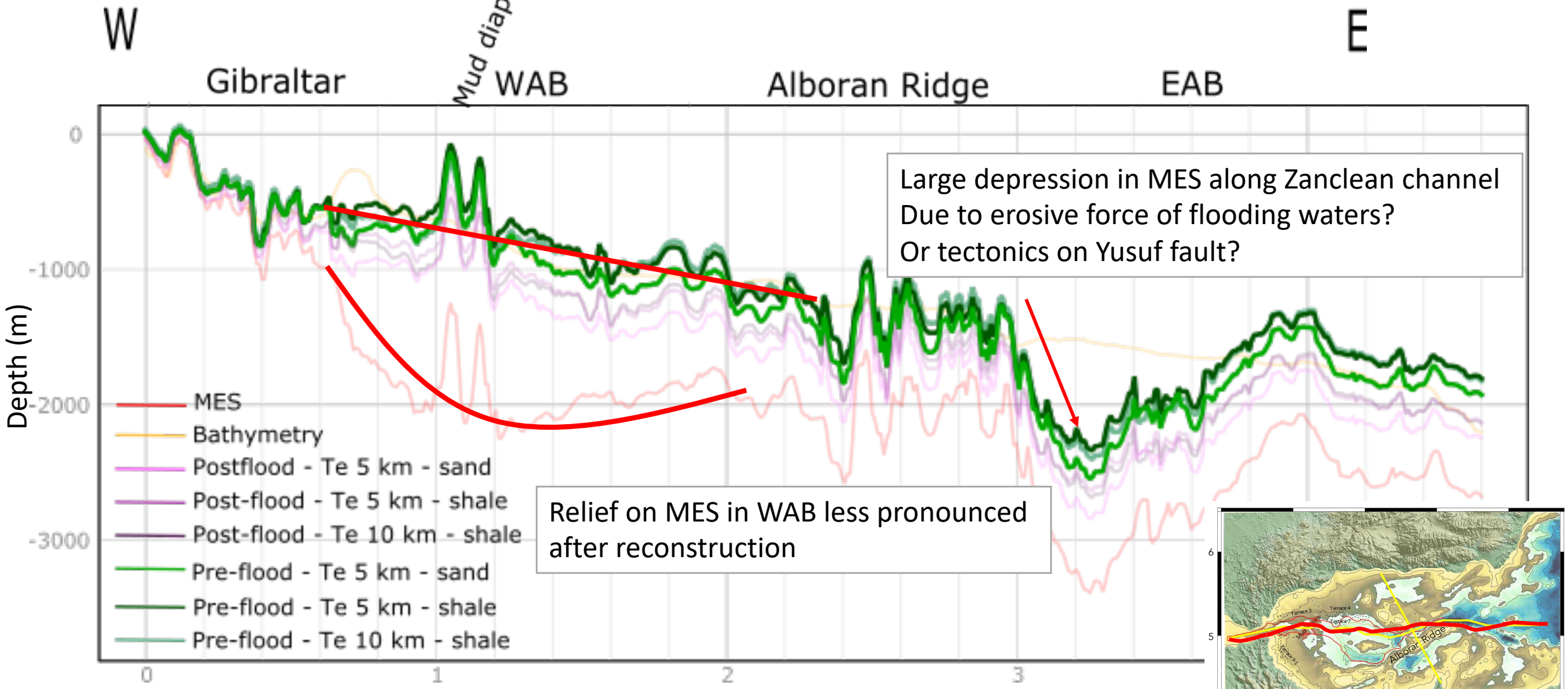
Current bathymetry and depth MES



CC BY

Results: Zanclean channel

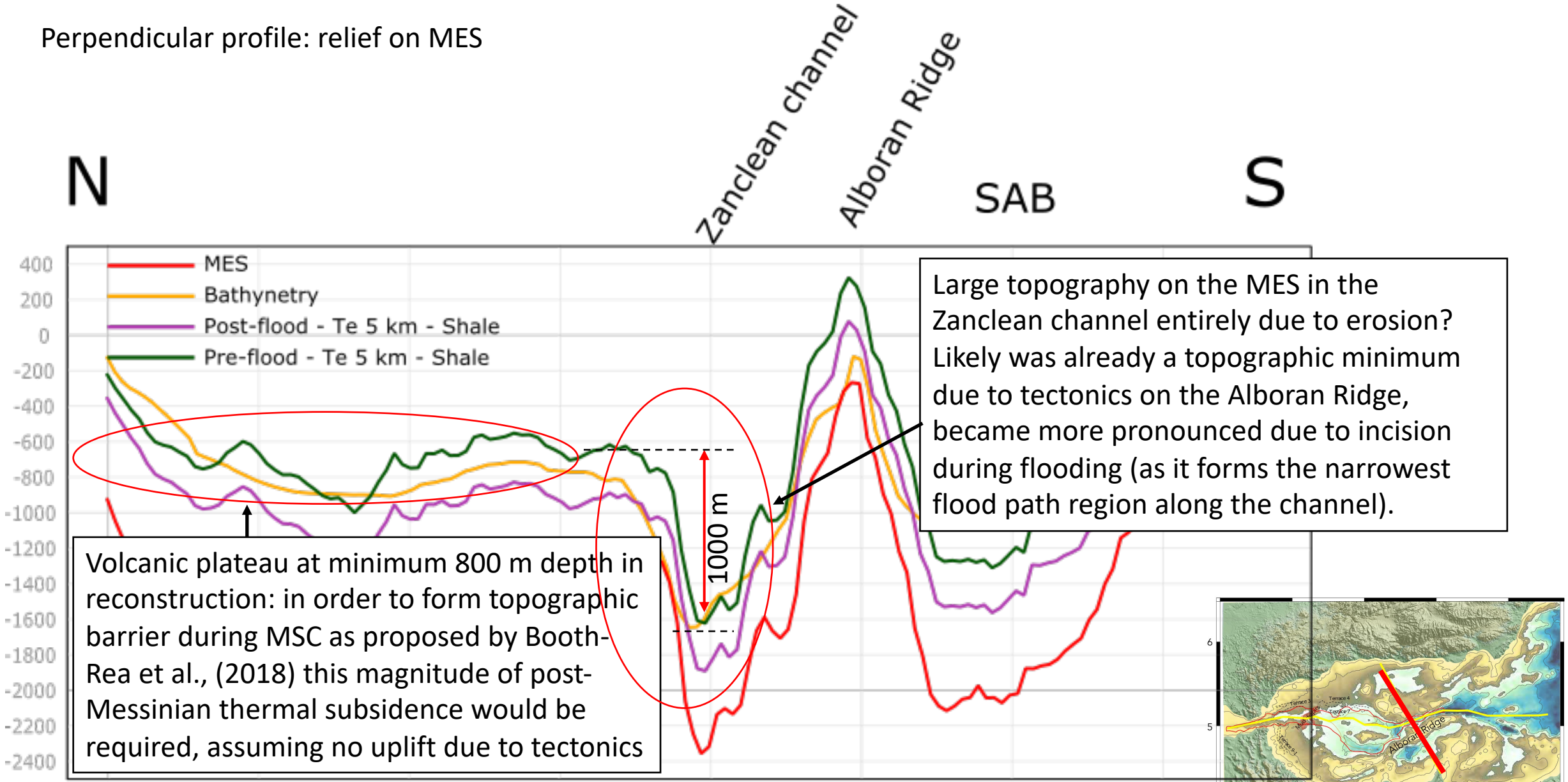
Reconstructed MES after removal PQ sediments and 1 km water column
(Bathymetry around time of Zanclean flood)



CC BY

Results: Zanclean channel

Perpendicular profile: relief on MES



Large topography on the MES in the Zanclean channel entirely due to erosion? Likely was already a topographic minimum due to tectonics on the Alboran Ridge, became more pronounced due to incision during flooding (as it forms the narrowest flood path region along the channel).

Volcanic plateau at minimum 800 m depth in reconstruction: in order to form topographic barrier during MSC as proposed by Booth-Rea et al., (2018) this magnitude of post-Messinian thermal subsidence would be required, assuming no uplift due to tectonics

Thermal subsidence

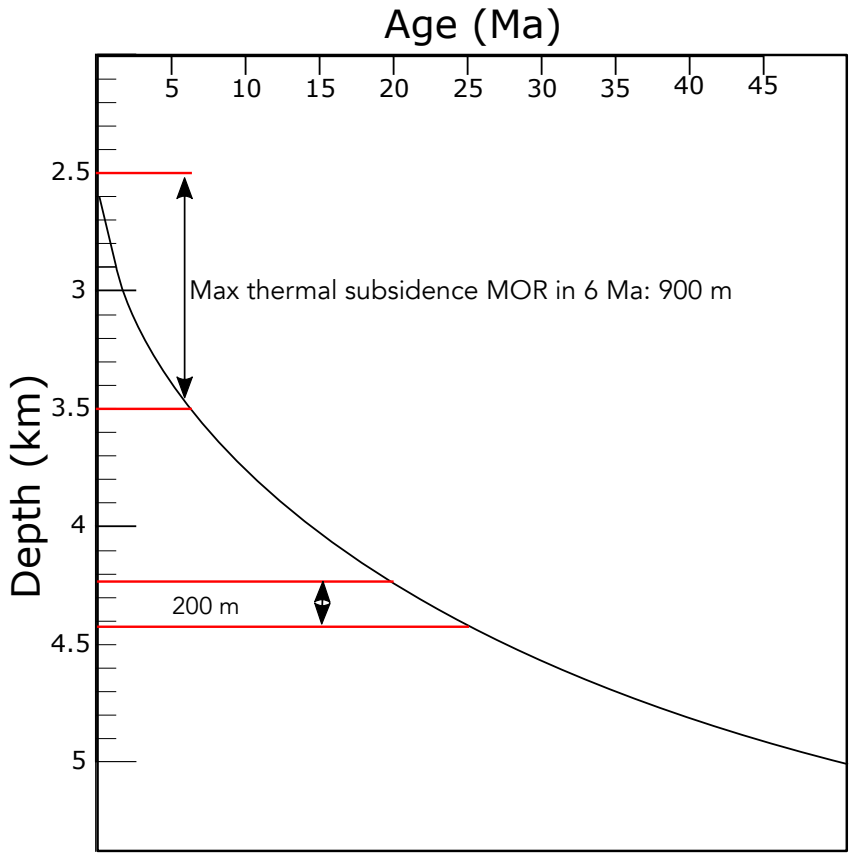


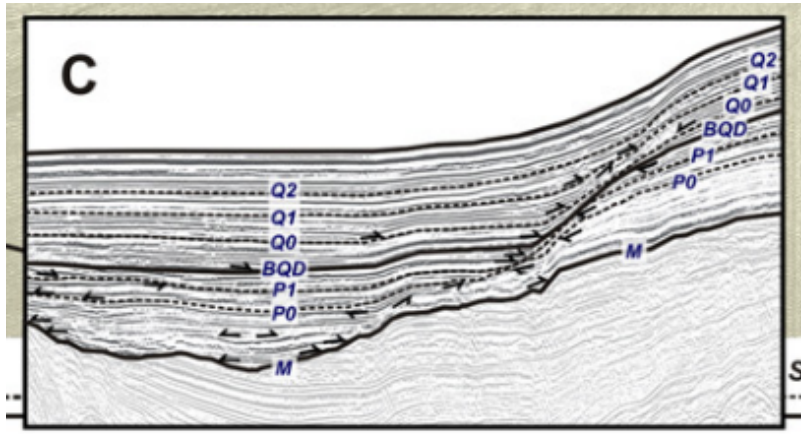
Plate model relating ocean depth to age since rifting, indicating potential post-MSC sinking due to cooling of the ocean floor after *Stein&Stein*, 1992

The maximum thermal subsidence for MOR-equivalent in last 6 Ma is 900 m, the value that would be required to allow for the East Alboran volcanic arc to have been exposed during messinian times and have formed a topographic barrier for Atlantic waters as proposed by Booth-Rea et al. (2018)

But: this assumes onset cooling only at time of MSC (while part of volcanism is older) and that a volcanic arc of 16 km crustal thickness behaves like a MOR, while cooling rates can be expected to be lower. In the context of a narrow basin flanked by continental crust such a magnitude of vertical motion seems unlikely.

If opening age ~20 Ma (Vergés&Fernandez, 2012) : 200 m
Lower limit on estimate of basin subsidence since MSC.

Results: Terraces in MES



Detail from figure 6 from Juan et al. (2016) seismic section identifying Messinian terrace in the WAB

Various features interpreted as erosional terraces identified by i.e. Estrada et al., 2011; Juan et al., 2016; Just et al., 2011) in WAB, on the Alboran Ridge, Bay of Oran and on Mallorcan shelf on Balearic Promontory

Wide range of current depths (from 300 m to 2400 m BSL)
What was their original depth at formation, and by which processes could they have been formed?

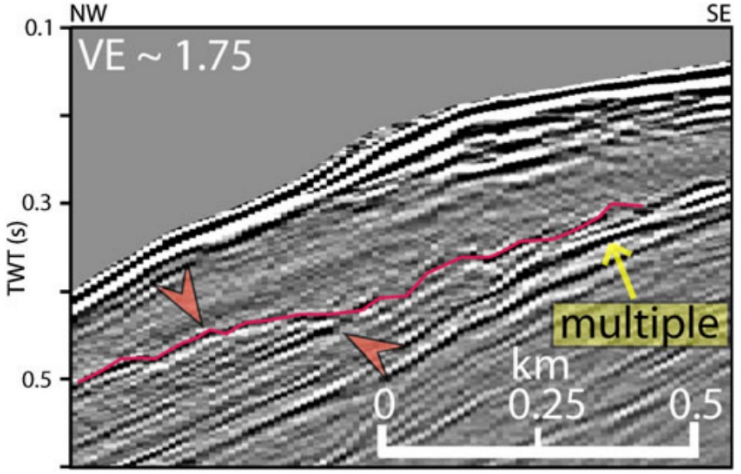


Figure 11 from Just et al. (2011) seismic section identifying Messinian terrace on the Alboran Ridge

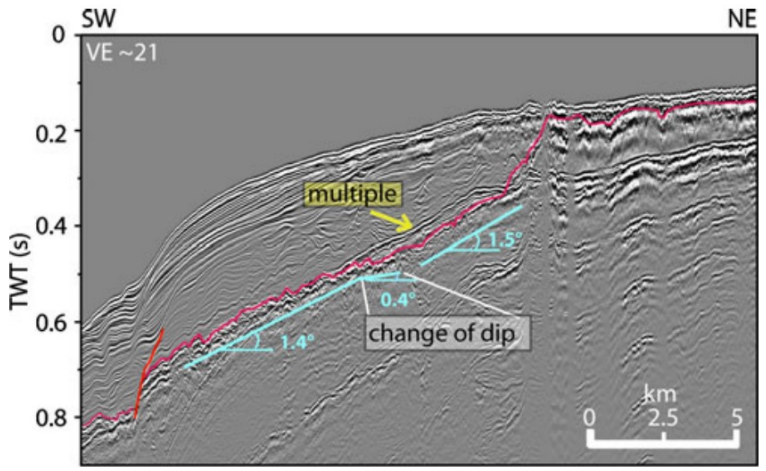


Figure 7 from Just et al. (2011) seismic section identifying Messinian terrace on the SW shelf of Mallorca

Based on only flexural-isostasy and decompaction, terraces from Just et al. (2011) formed at depths of between 100 and 200 m below modern sea-level, but tectonic activity adds large level of uncertainty on Alboran Risge and Bay of Oran.

Distance (deg)

Results: Terraces in MES

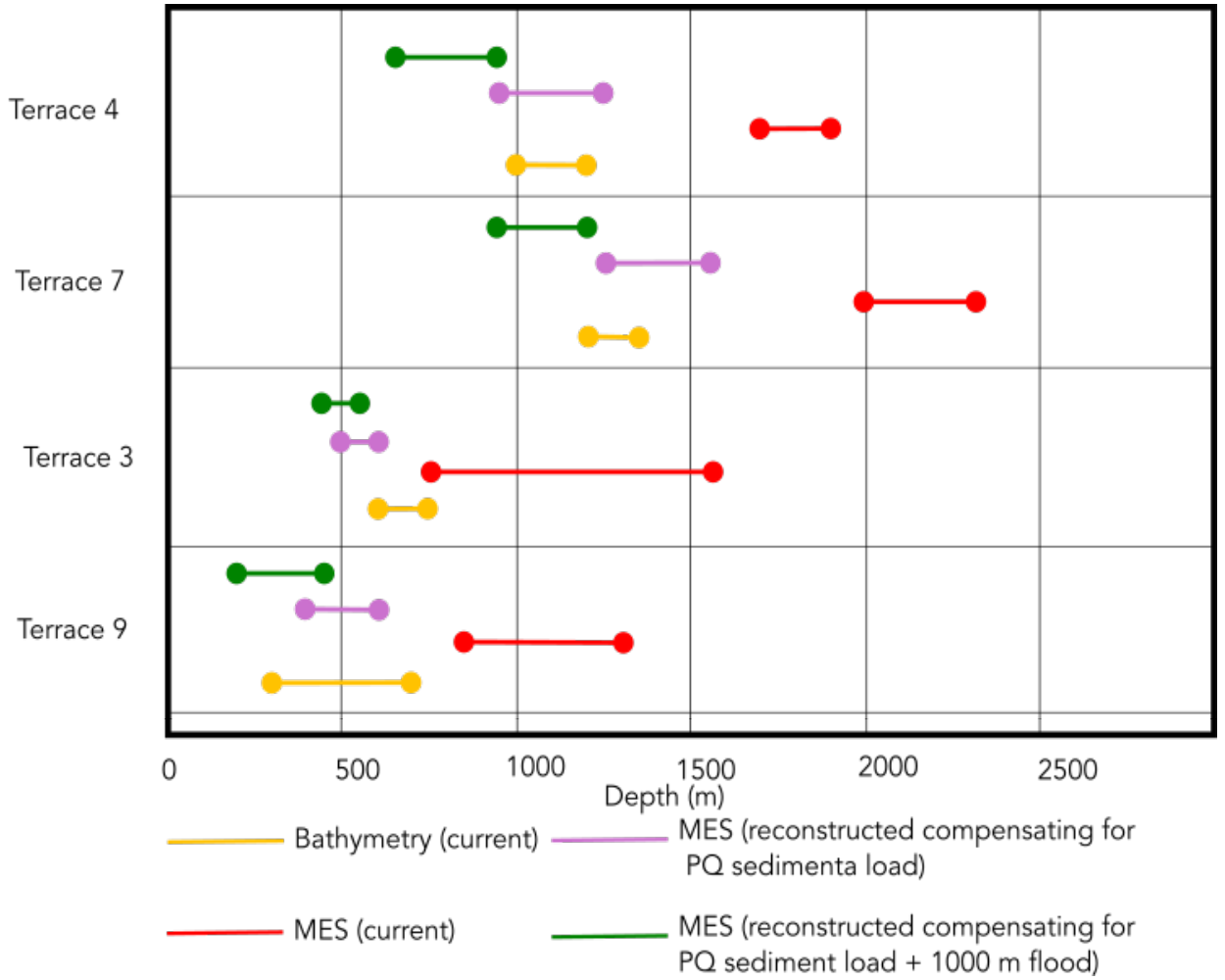
Large depth variations along terrace strike in modern MES are reduced in reconstruction.

Terraces 3 and 9 formed at a shallow level, around 500 m

Terraces 4 and 7 much deeper (1000-1500 m)

If the terraces record a (temporary) stable water level, a Messinian lake must have existed in the WAB and EAB during the lowstand stage. In this case all sediments deposited here were eroded during the flooding event. Alternatively, the deep terrace level was itself excavated during the flooding event.

Shallower terrace level could record a stagnant base level during spillover from western to eastern Mediterranean at the Sicily Sill?



Depth range for bathymetry and MES (modern and reconstructed) for terraces from Estrada et al. (2011)

CC BY

Conclusions

- Shallow reconstructed Messinian bathymetry in the western and central parts of the Alboran Basin (shallower than 1000 m) can explain absence of in-situ evaporites in this region, and imply complete exposure of the basin during the lowstand stage of the MSC.

- Features identified as erosional terraces formed at a wide range of depths, from 100-200 m (Bay of Oran, Alboran Ridge) to >1000 m in the central WAB close to the Zanclean channel.

- Main Pliocene depocentre does not appear to be located in the area with deepest paleorelief, possibly due to current-controlled sedimentation? Or: errors in reconstruction due to overestimation compaction Miocene sediments/unidentified source of post-Messinian uplift in the western WAB (possibly related to mud diapirism)

CC BY

References

Gómez de la Peña, L., R. Ranero, C., Gràcia, E., & Booth-Rea, G. (2021). The evolution of the westernmost Mediterranean basins. *Earth-Science Reviews*, *214*(December 2019). https://doi.org/10.1016/j.earscirev.2020.103445

Juan, C., Ercilla, G., Javier Hernández-Molina, F., Estrada, F., Alonso, B., Casas, D., García, M., Farran, M., Llave, E., Palomino, D., Vázquez, J. T., Medialdea, T., Gorini, C., D'Acremont, E., El Moumni, B., & Ammar, A. (2016). Seismic evidence of current-controlled sedimentation in the Alboran Sea during the Pliocene and Quaternary: Palaeoceanographic implications. *Marine Geology*, *378*, 292–311. https://doi.org/10.1016/j.margeo.2016.01.006

Krijgsman, W., Capella, W., Simon, D., Hilgen, F. J., Kouwenhoven, T. J., Meijer, P. T., Sierro, F. J., Tulbure, M. A., van den Berg, B. C. J., van der Schee, M., & Flecker, R. (2018). The Gibraltar Corridor: Watergate of the Messinian Salinity Crisis. *Marine Geology*, *403*, 238–246. https://doi.org/https://doi.org/10.1016/j.margeo.2018.06.008

Just, J., Hübscher, C., Betzler, C., Lüdmann, T., & Reicherter, K. (2011). Erosion of continental margins in the Western Mediterranean due to sea-level stagnancy during the Messinian Salinity Crisis. *Geo-Marine Letters*, *31*(1), 51–64. https://doi.org/10.1007/s00367-010-0213-z

Bulian, F., Sierro, F. J., Ledesma, S., Jiménez-Espejo, F. J., & Bassetti, M.-A. (2021). Messinian West Alboran Sea record in the proximity of Gibraltar: Early signs of Atlantic-Mediterranean gateway restriction. *Marine Geology*, *434*, 106430. https://doi.org/10.1016/j.margeo.2021.106430

Estrada, F., Ercilla, G., Gorini, C., Alonso, B., Vázquez, J. T., García-Castellanos, D., Juan, C., Maldonado, A., Ammar, A., & Elabbassi, M. (2011). Impact of pulsed Atlantic water inflow into the Alboran Basin at the time of the Zanclean flooding. *Geo-Marine Letters*, *31*(5–6), 361–376. https://doi.org/10.1007/s00367-011-0249-8

Booth-Rea, G., R. Ranero, C., & Grevemeyer, I. (2018). The Alboran volcanic-arc modulated the Messinian faunal exchange and salinity crisis. *Scientific Reports*, *8*(1), 13015. https://doi.org/10.1038/s41598-018-31307-7

Vergés, J., & Fernàndez, M. (2012). Tethys-Atlantic interaction along the Iberia-Africa plate boundary: The Betic-Rif orogenic system. *Tectonophysics*, *579*, 144–172. https://doi.org/10.1016/j.tecto.2012.08.032

Stein, C. A., & Stein, S. (1992). A model for the global variation in oceanic depth and heat flow with lithospheric age. *Nature*, *359*(10), 123–129. https://doi.org/10.1038/359123a0

Gómez, L. (2017). *The origin and tectono-sedimentary structure of the Alboran Basin The origin and tectono-sedimentary structure of the Alboran Basin Memoria de tesis doctoral presentada por*.

Garcia-Castellanos, D., Estrada, F., F., Jiménez-Munt, I., I., Gorini, C., Fernandez, M., Vergés, J., Vicente, D., & R. (2009). Catastrophic flood of the Mediterranean after the Messinian salinity crisis. *Nature*, *462*, 778–782.

Kendall, R. A., Mitrovica, J. X., & Milne, G. A. (2005). On post-glacial sea level - II. Numerical formulation and comparative results on spherically symmetric models. *Geophysical Journal International*, *161*(3), 679–706. https://doi.org/10.1111/j.1365-246X.2005.02553.x

Do Couto, D., Estrada, F., Gorini, C., Ercilla, G., d'Acremont, E., Juan, C., Ammar, A., and Jabour, H. (2018) Chapter 1: Alboran Sea, MSC Clastics & Abraded Surface. In: Lofi, J. (2018). *Seismic Atlas of the Messinian Salinity Crisis markers in the Mediterranean Sea - Volume 2* (Vol. 2). CGMW and Mémoires de la Société Géologie de France. http://commons.wikimedia.org/wiki/Category:Messinian_salinity_crisis.