Earthquake crisis unveils the growth of an incipient continental fault system

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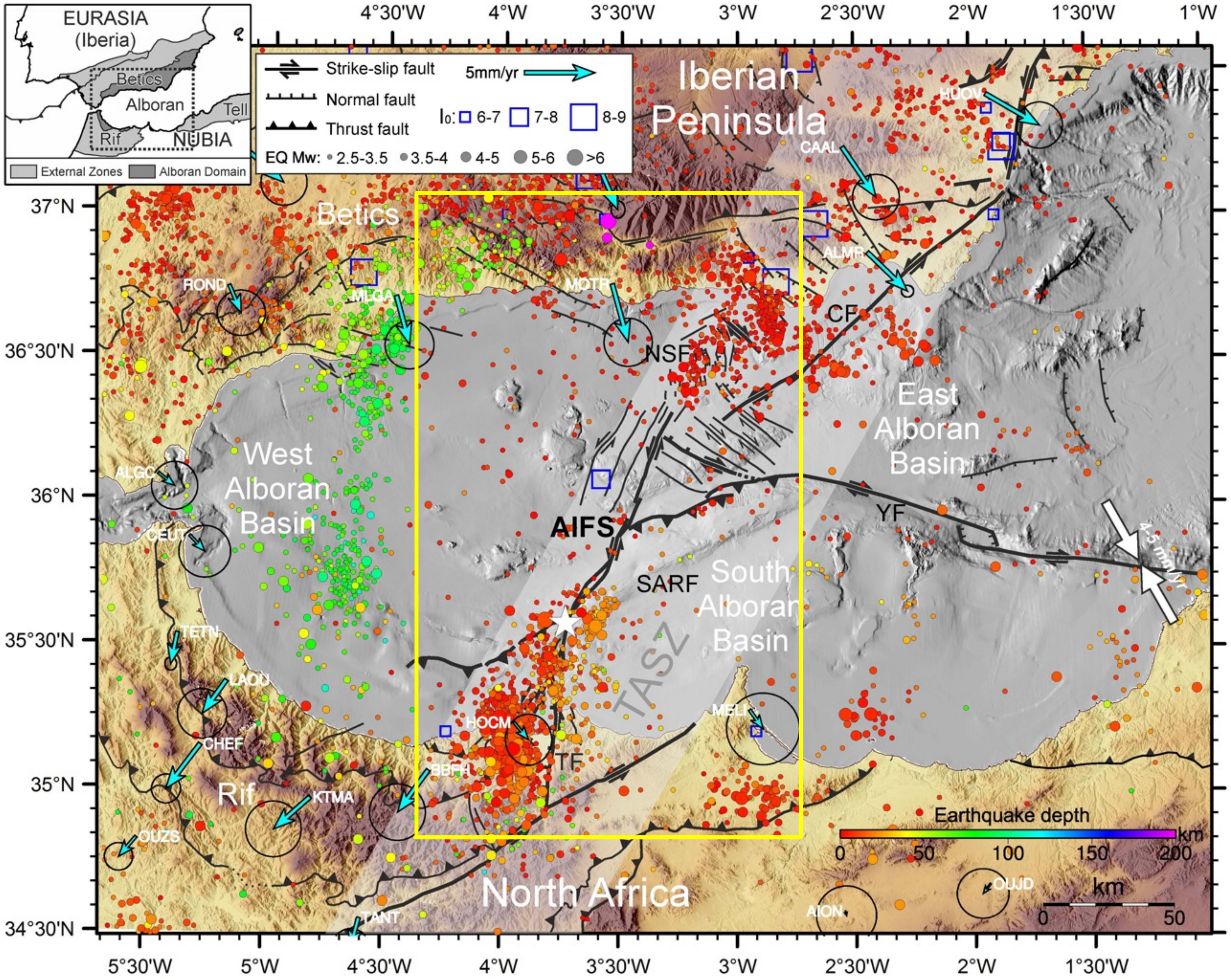
The Alboran Basin: Tectonic setting, seismicity & GPS

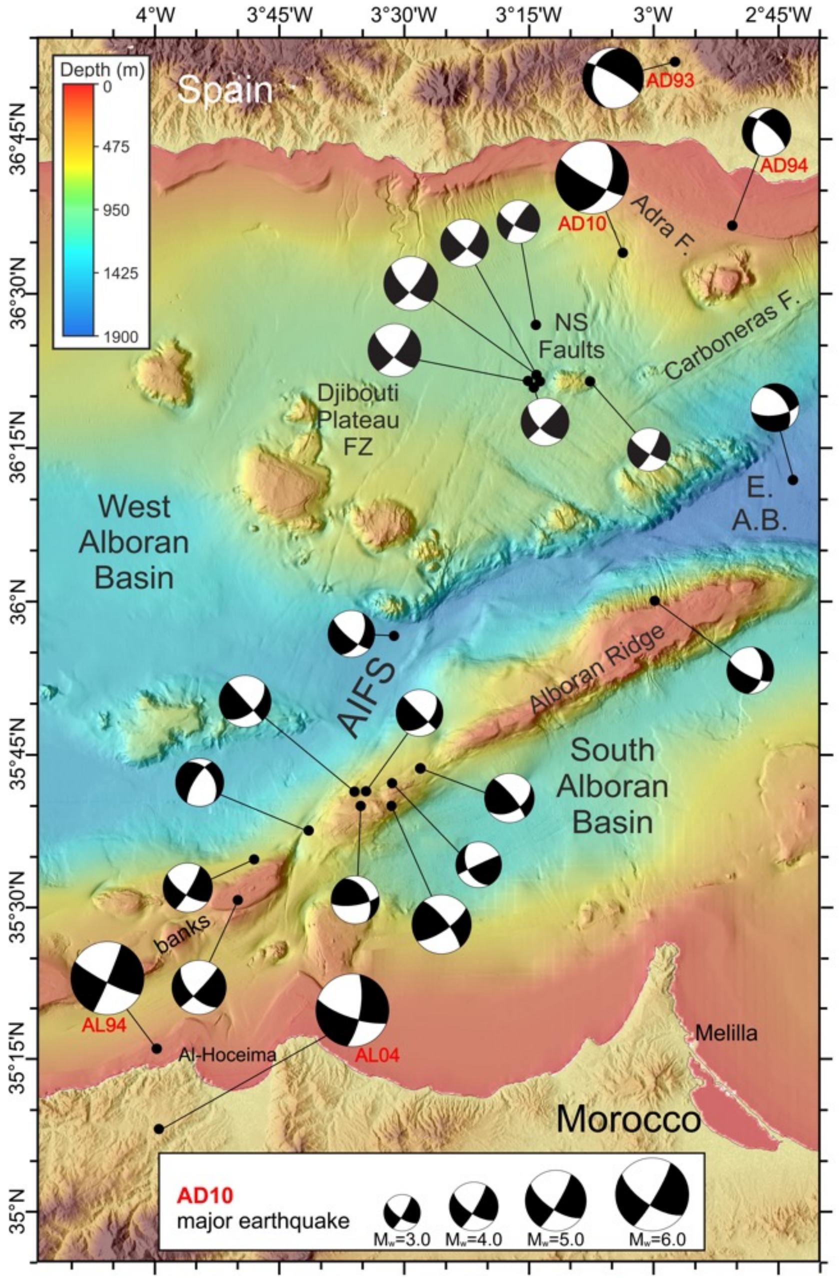
Gràcia et al., *Nature Communiccations* (2019)

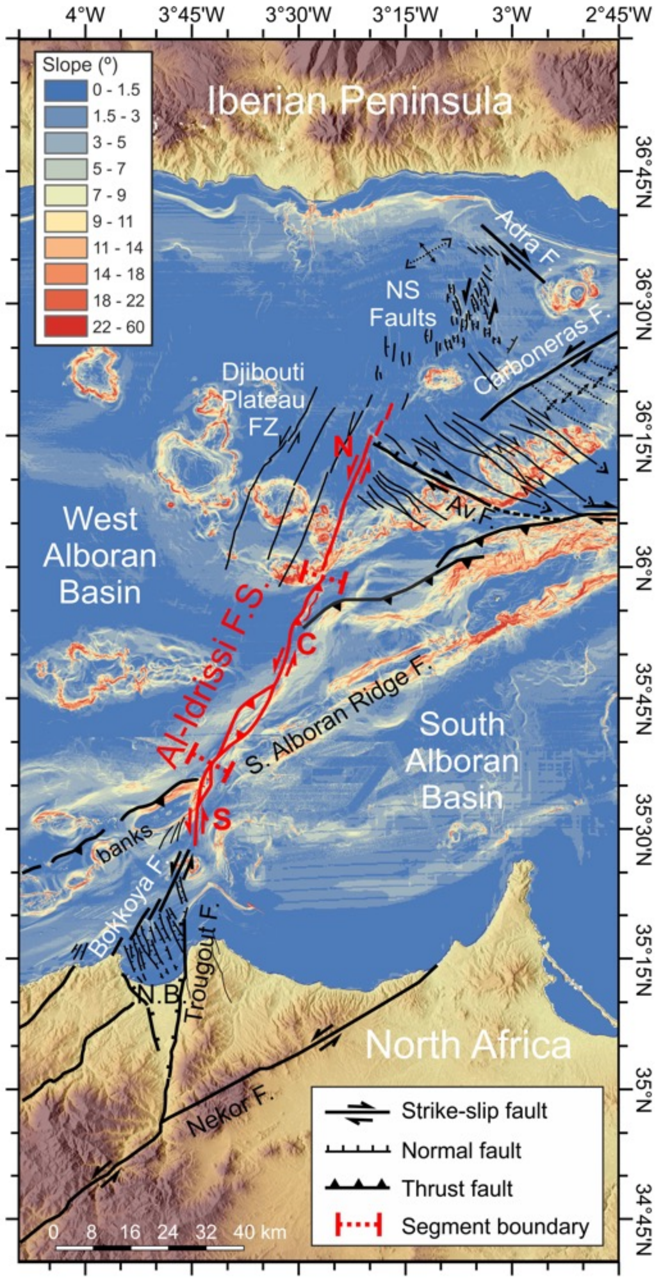


- Topography & bathymetry
- Major active faults
- Historical & instrumental seismicity
- GPS velocity field (respect to AFR)
- NE-SW lineament 200 km TASZ
- Link from the Rif to the Betics

An overlooked continental fault system: Al-Idrissi FS

Gràcia et al., Nature Communications (2019)

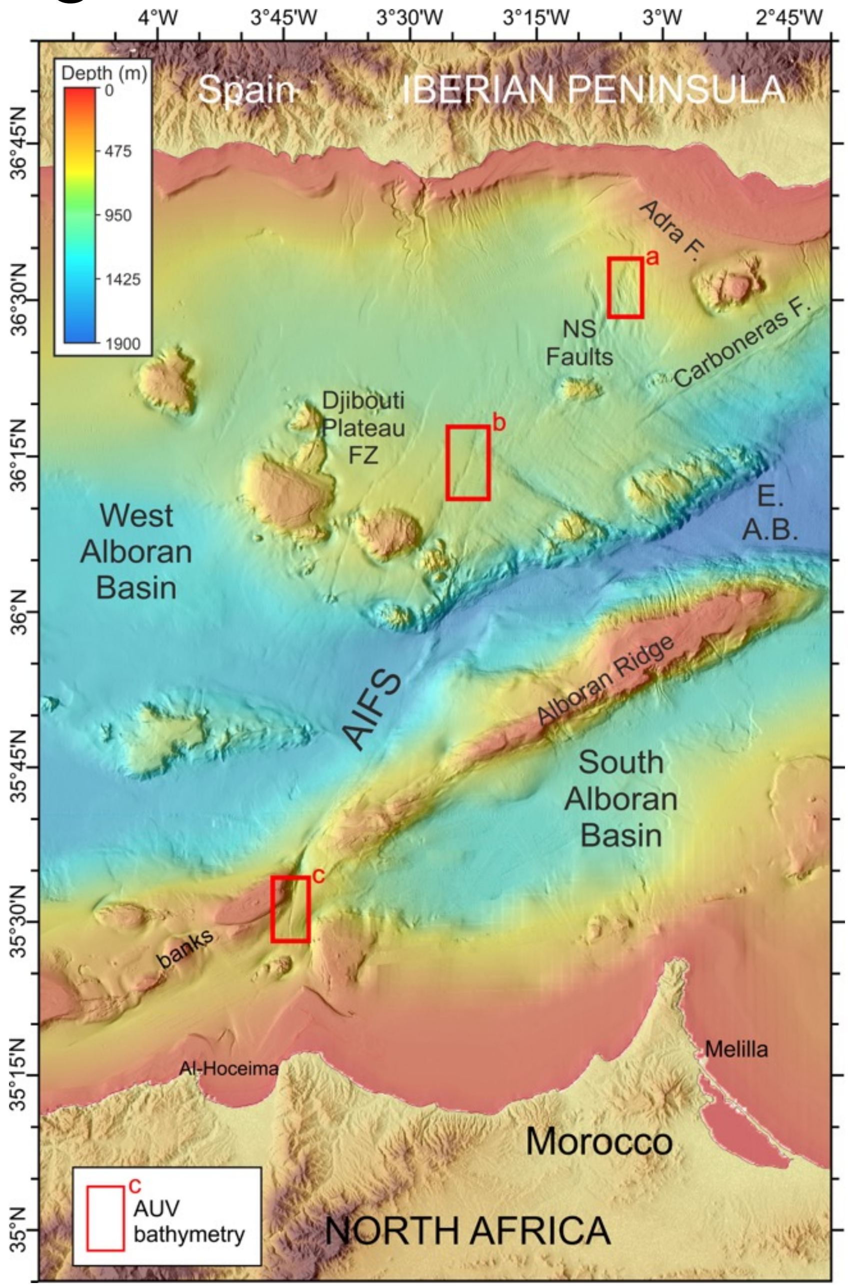




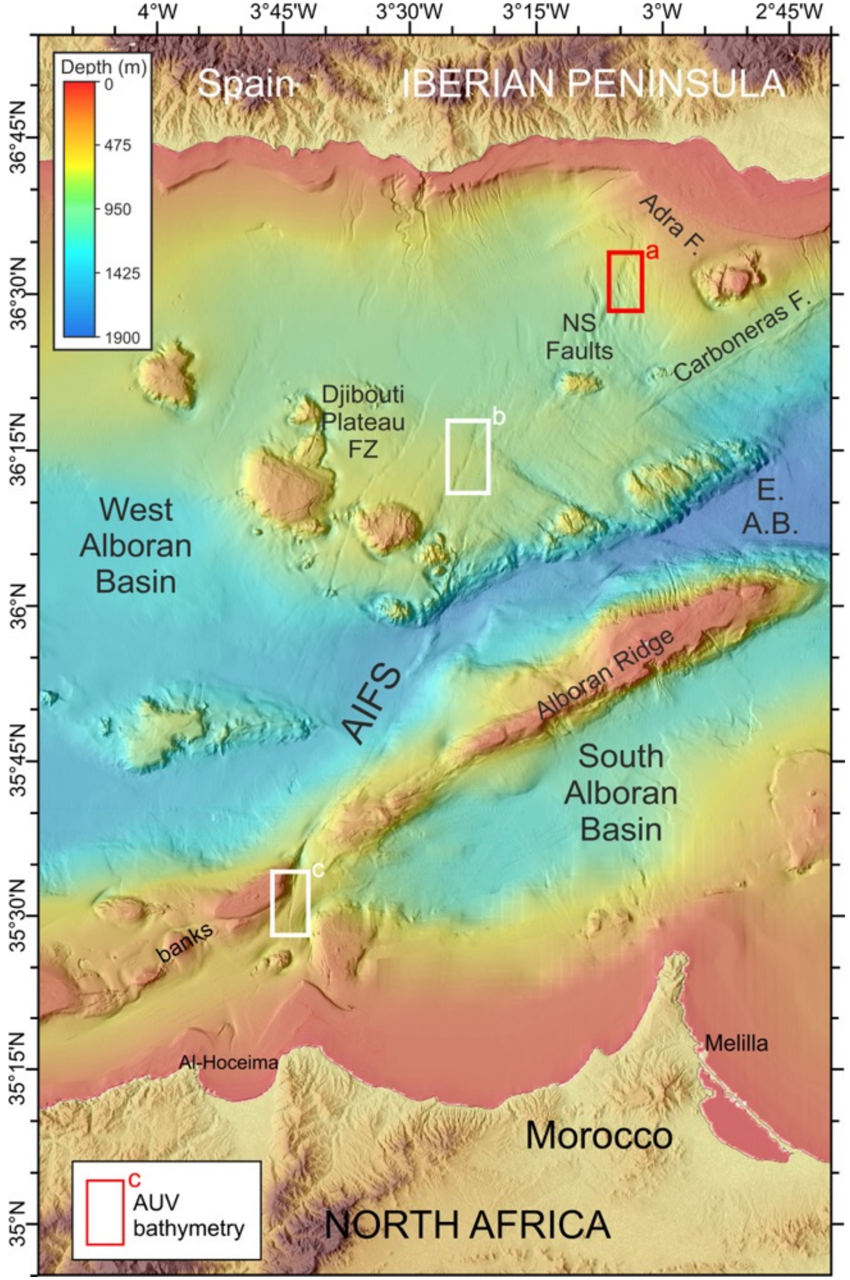
- EQ moment tensor solutions (strike-slip)
- Subdued topography
- Late Pliocene to Quaternary structure, cuts the AR
- AIFS: 1-4.8 km wide, 100 km long, NE-SW left-lateral
- 3 segments:
  - North (N018 / 35 km)
  - Central (N031 / 47 km)
  - South (N007 / 18 km)
- Bokkoya – Trougout faults (South) & NSF (North)

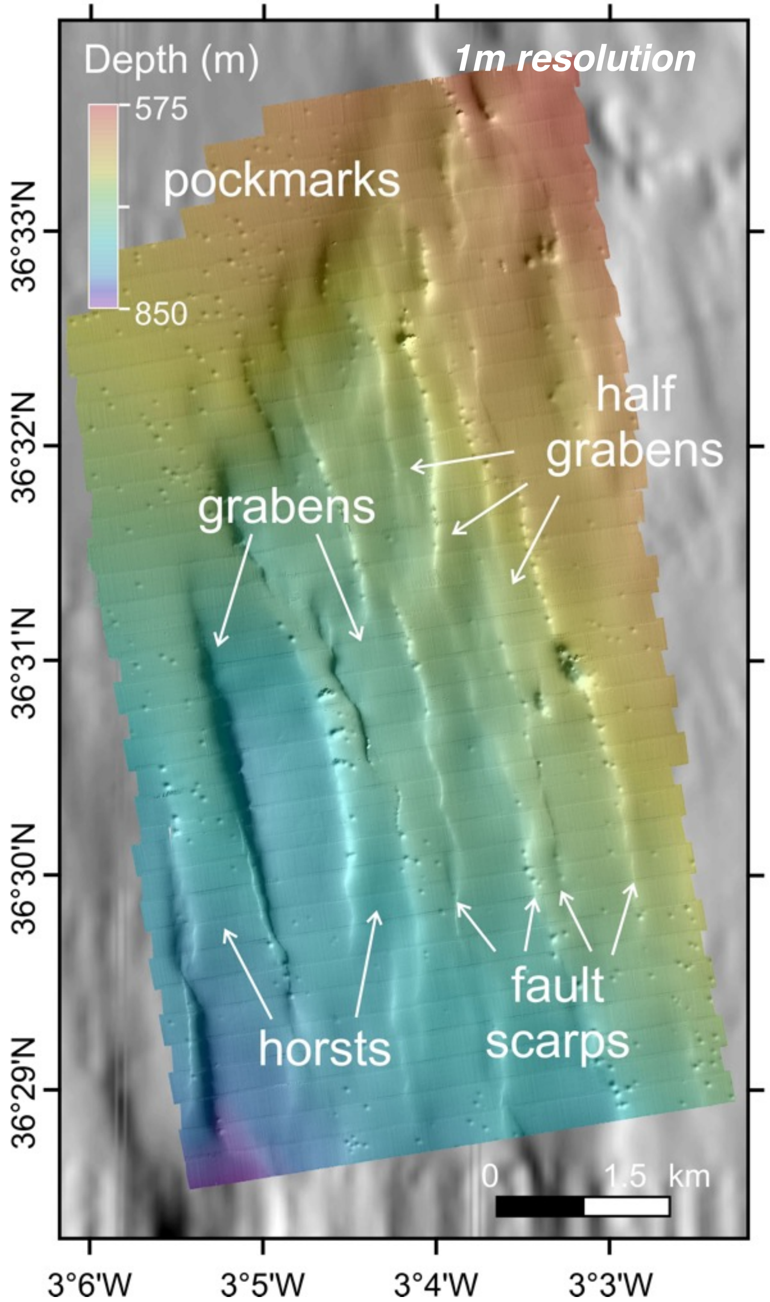
High-resolution near-bottom bathymetry data (AUVs)

Using 2 AUVs, we surveyed 3 areas along the AIFS



Seafloor expression of the Al-Idrissi FS: The NS Faults

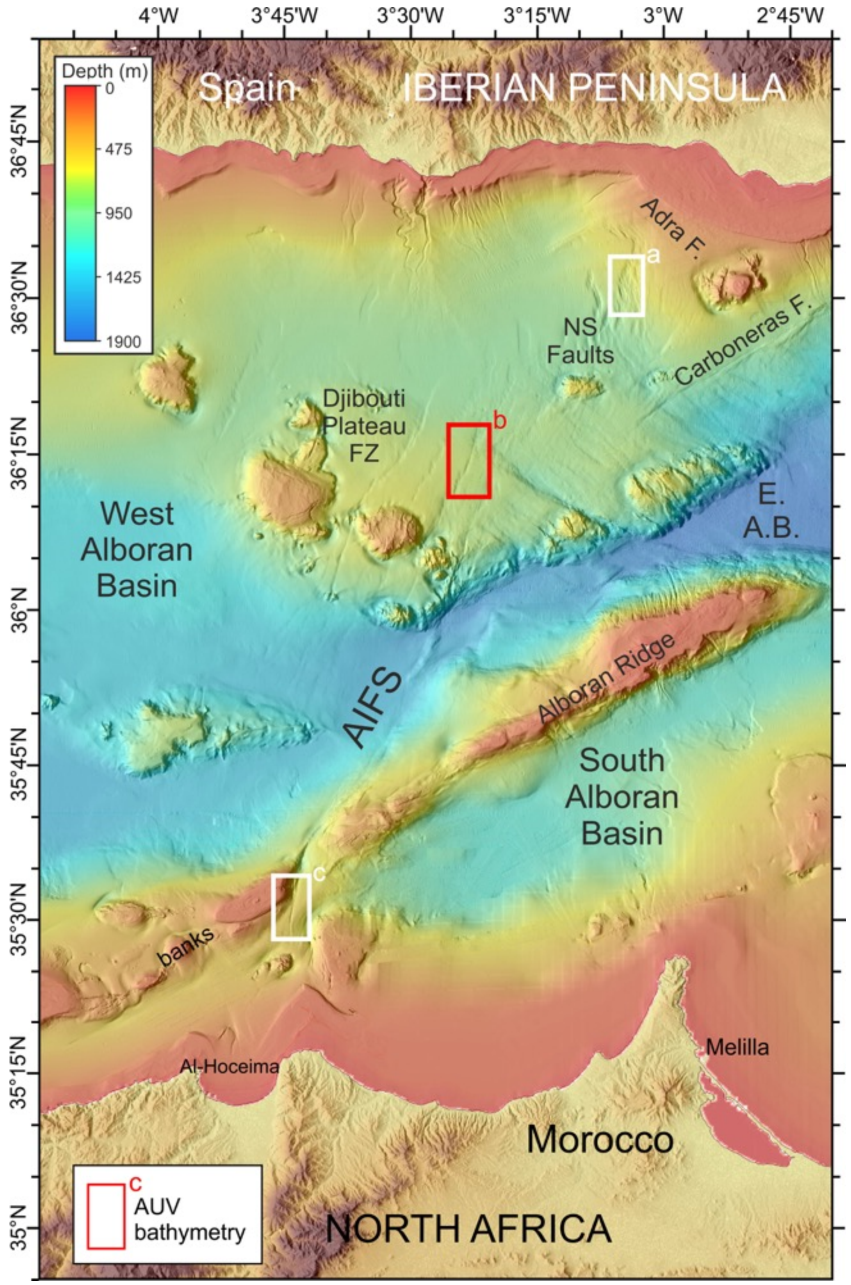


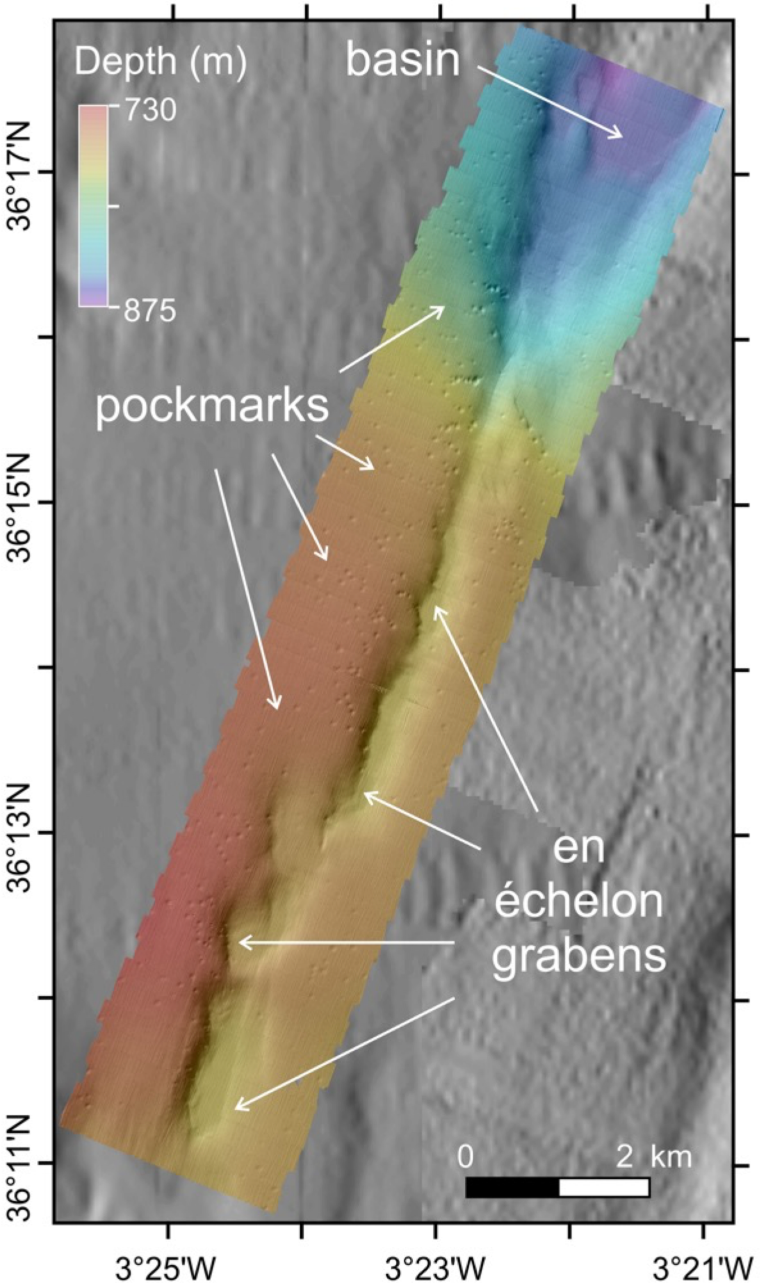


- Almeria Margin
- Left-lateral shear zone
- 20 km long / 5 km wide
- Closely spaced N160 *en echelon* normal faults
- Structured in horsts & grabens
- pockmarks

Seafloor expression of the Al-Idrissi FS: The North AIFS

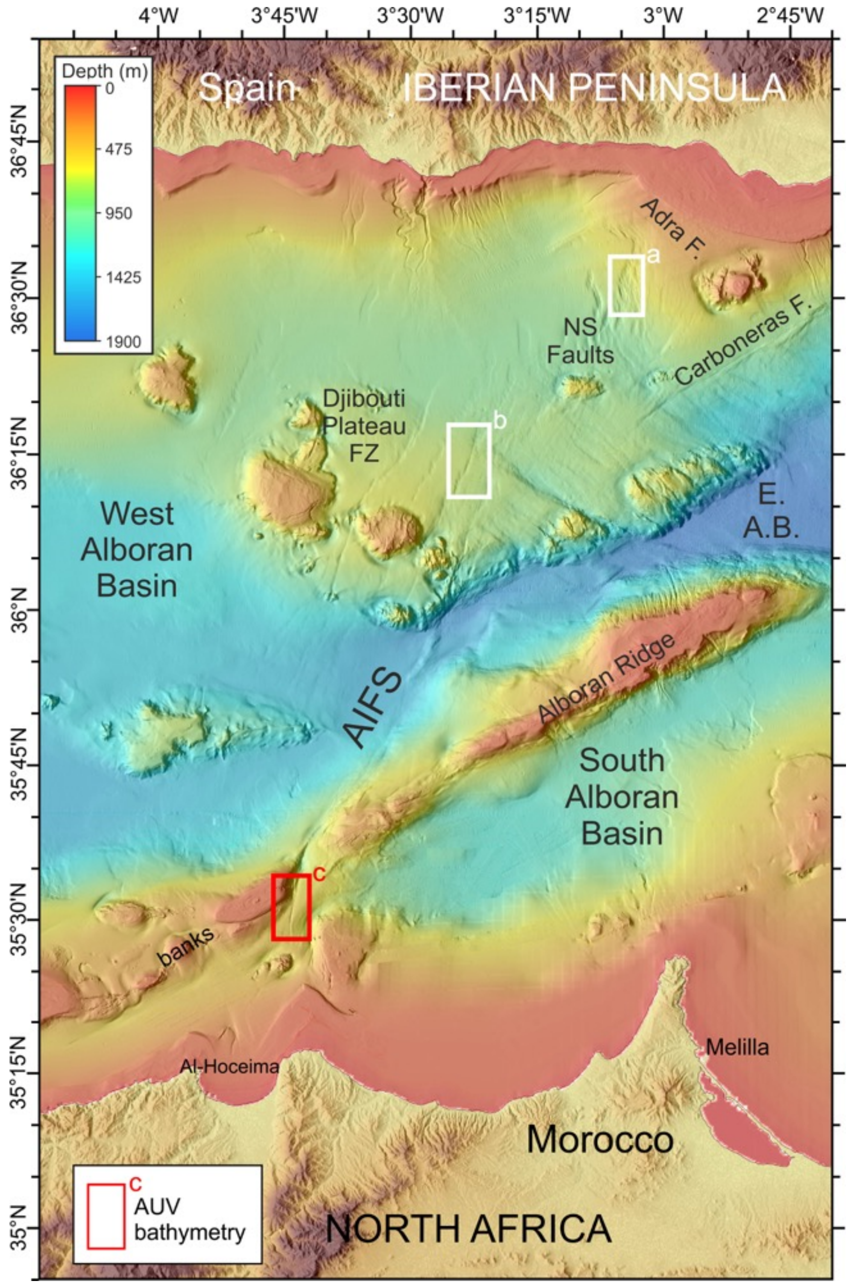
Gràcia et al., Nature Communications (2019)

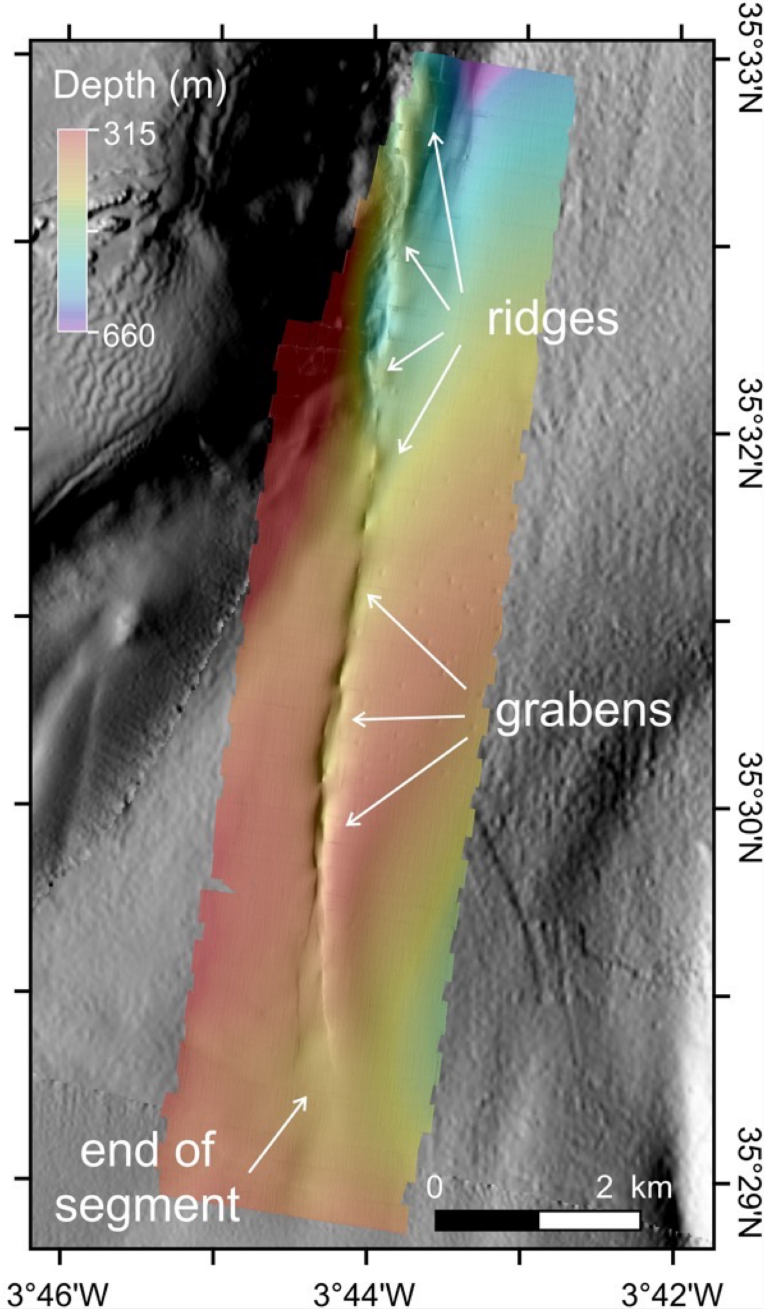




- Djibouti plateau volcanic area
- Cut up by four spaced sets of parallel fault arrays
- Single N10-N20 *en échelon* elongated grabens
- Pockmarks

Seafloor expression of the Al-Idrissi FS: The South AIFS

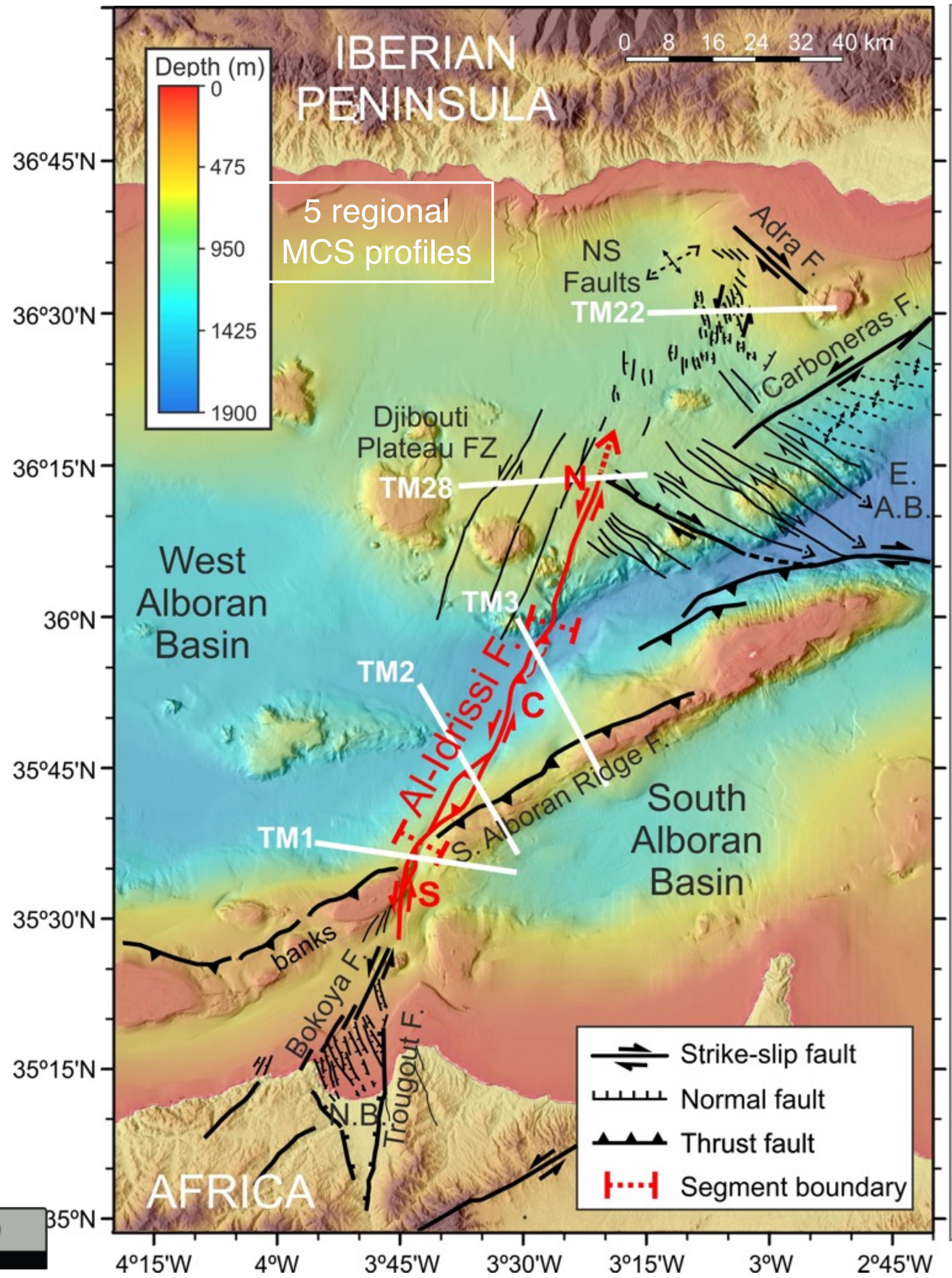




- Moroccan margin
- Elongated sigmoid
- Pressure ridges to *en echelon* elongated narrow grabens (not connected in map-view)
- Pockmarks
- Segment end splits into two branches

Subsurface AIFS multi-channel seismic structure

Gómez de la Peña et al., ESR (2020)



Ia-b: Quaternary (Late)

IIa: Quaternary (Early)

IIb: Late Pliocene

IIc-d: Early Pliocene

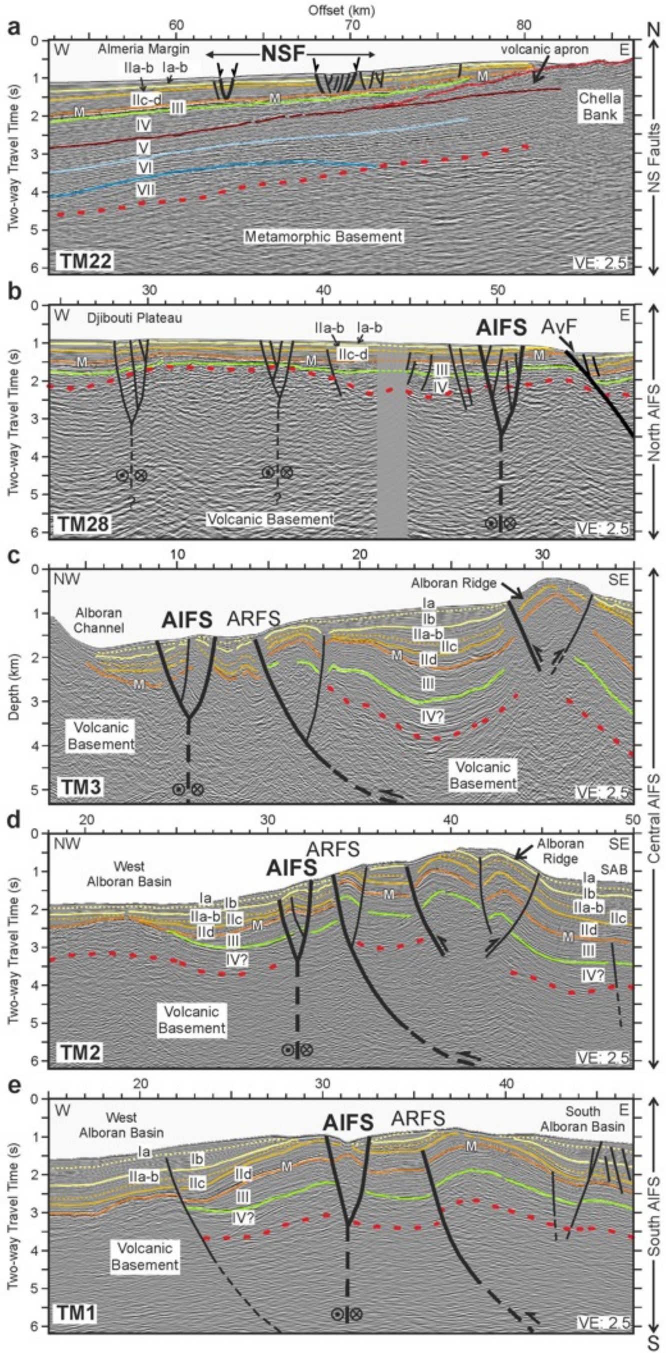
III: Late Miocene (M)

IV: Late Miocene (T)

V: Mid-Late Miocene (S-T)

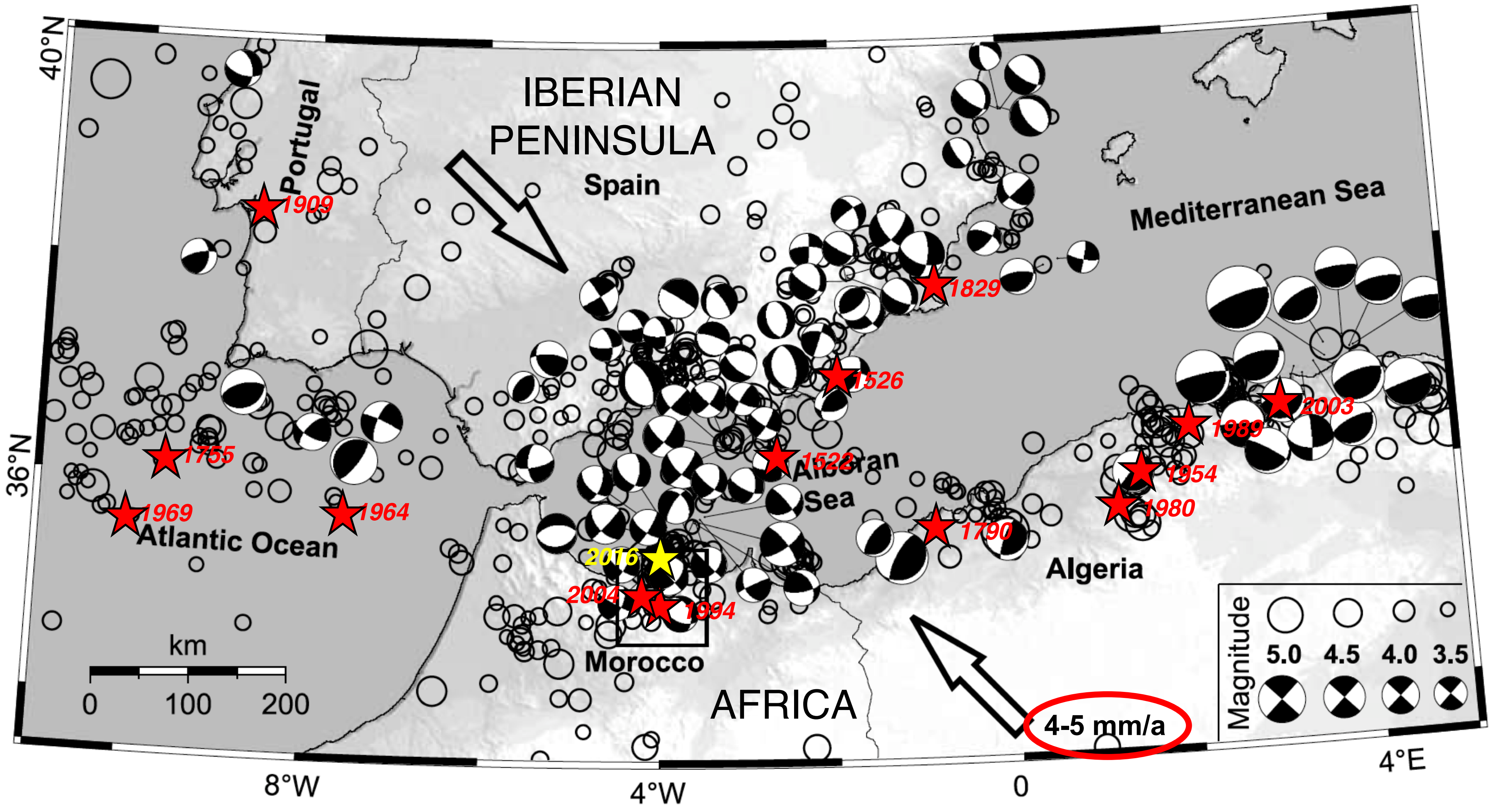
VI: Mid Miocene (L-S)

VII: Early Miocene (B)



- Half-graben to graben
- Transtensional SS fault
- Pressure ridge
- Positive flower structure (restraining bend)
- Negative flower structure (releasing bend)

Seismic activity across the EURASIA – AFRICA plate boundary

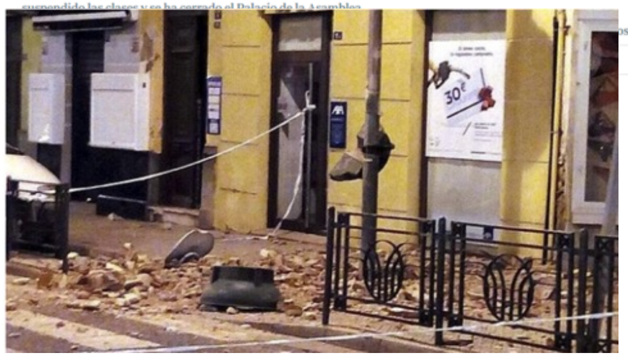


- Moderate seismicity, mainly reverse & strike-slip focal mechanisms
- Large historical (1755) & instrumental EQs occurred (1969, 1994, 2004 & **2016**)

Stich et al. (2006); Meghraoui & Pondrelli (2012)

The 25th January 2016 M_w6.4 earthquake

- Epicentre located 42 km N of Al Hoceima
- Strongly felt on both shores (I=V)
- Damage buildings: S-Spain, N-Morocco & Melilla
- **The largest event ever recorded in this area**

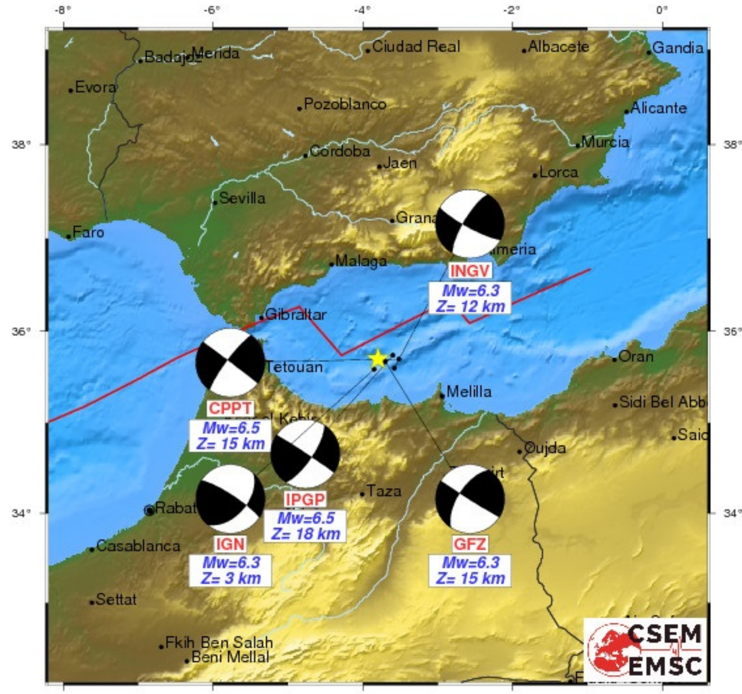


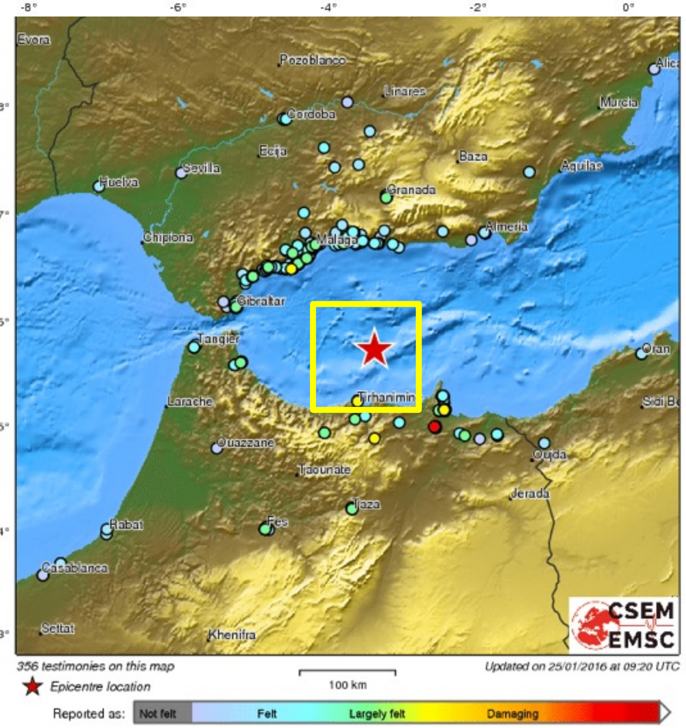
ABC Sociedad

SÍGUENOS EN

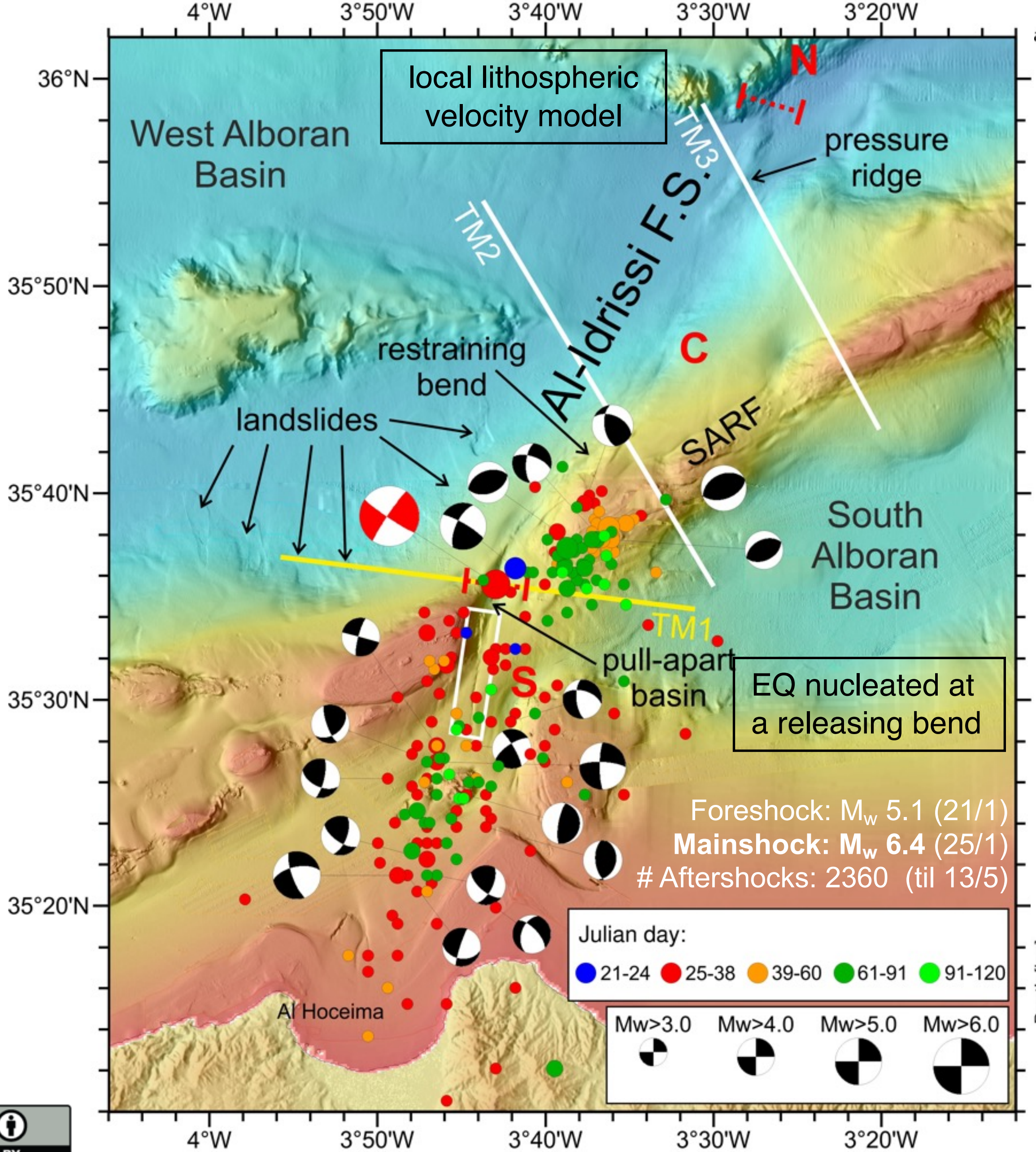
Un terremoto de magnitud 6,3 en el Mar de Alborán sacude Andalucía y Melilla

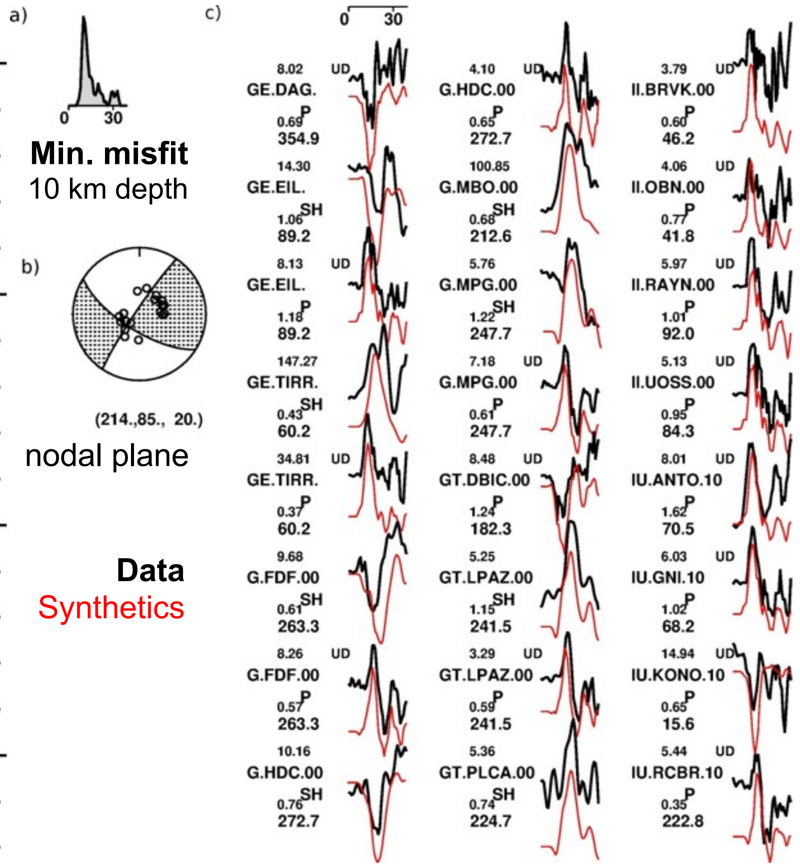
» Un niño ha muerto de un infarto en Marruecos y al menos 26 personas han sido atendidas en Melilla, donde se han suspendido las clases y se ha cerrado el Palacio de la Asamblea

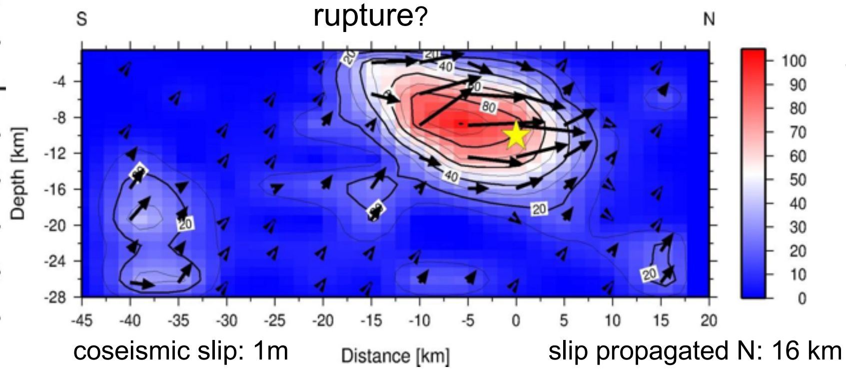




Relocated seismicity & focal mechanism mainshock

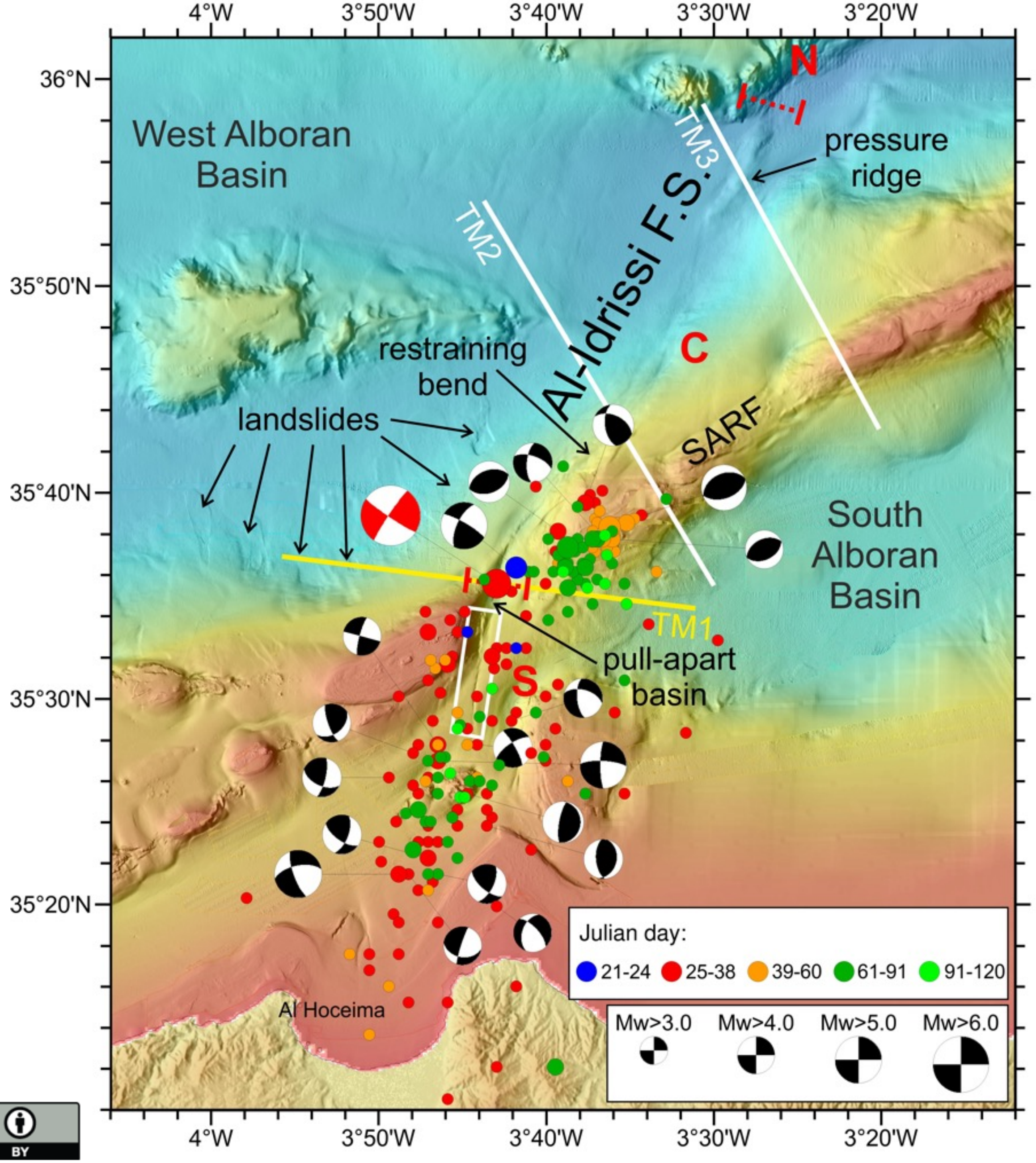


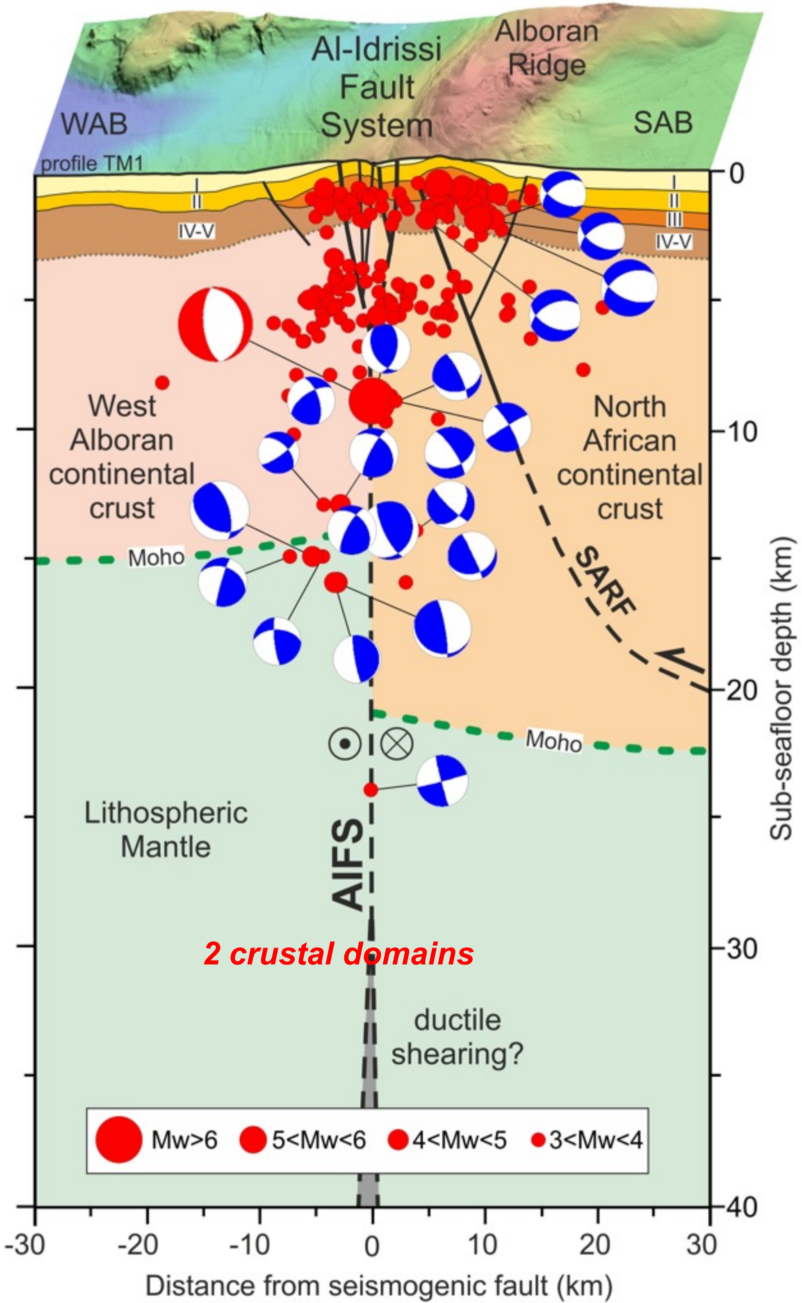




- Moment tensor waveform inversion yields a min. misfit at 10 km depth
- Nodal plane 214º/85º/5º (strike/dip/rake) according with AIFS strike
- Finite source model of co-seismic rupture (1m)

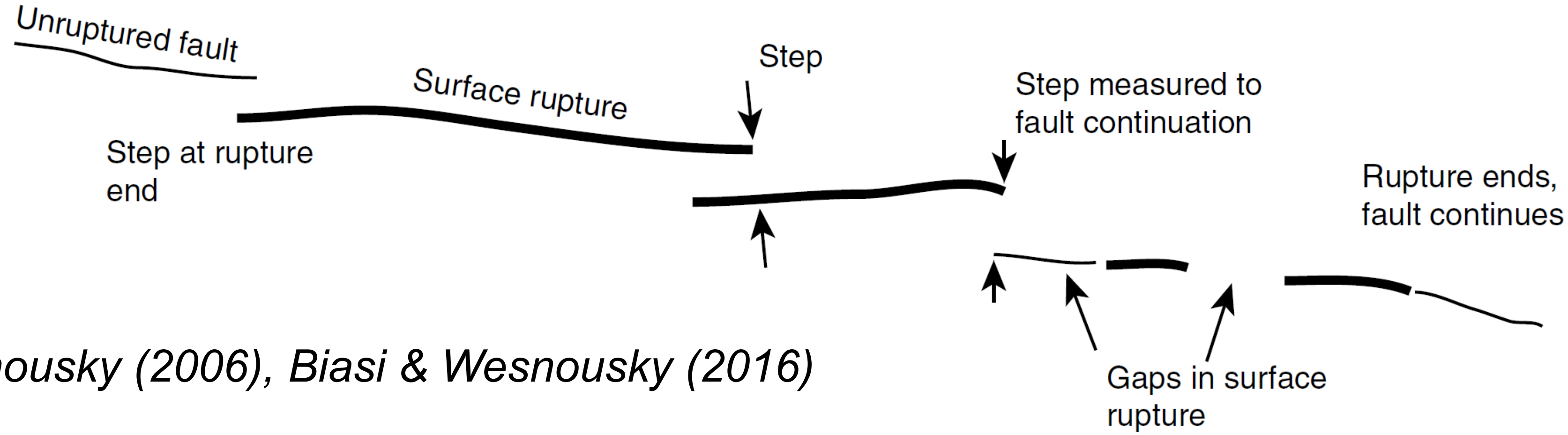
Aftershock analysis & AIFS conceptual cross-section





- LEFT: Aftershock analysis:
  - D21-60 near mainshock;
  - D61-120 S & N end (SARF)
- RIGTH: Cross-section: Thin continental crust together with high HF, restricts depth of seismogenic zone, supporting a rupture of 15 to 20 km depth

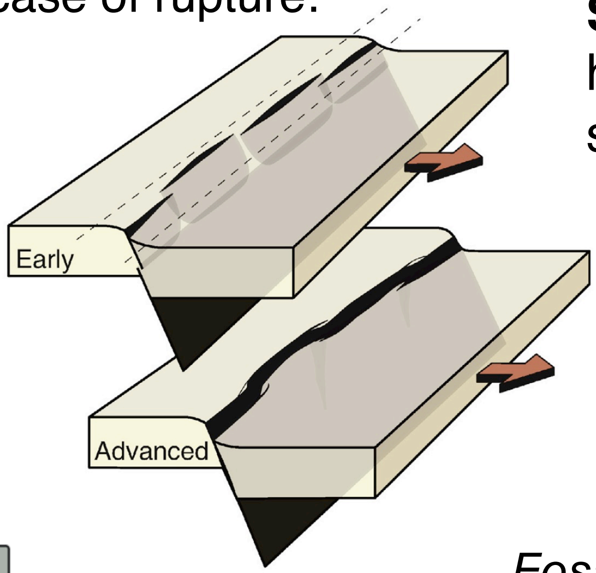
Fault growth, lateral propagation & fault linkage



Wesnousky (2006), Biasi & Wesnousky (2016)

Continental EQs typically rupture active fault traces that are segmented, with segments separated by discontinuities in map-view (e.g. bends, step-overs, gaps & terminations).

In case of rupture:



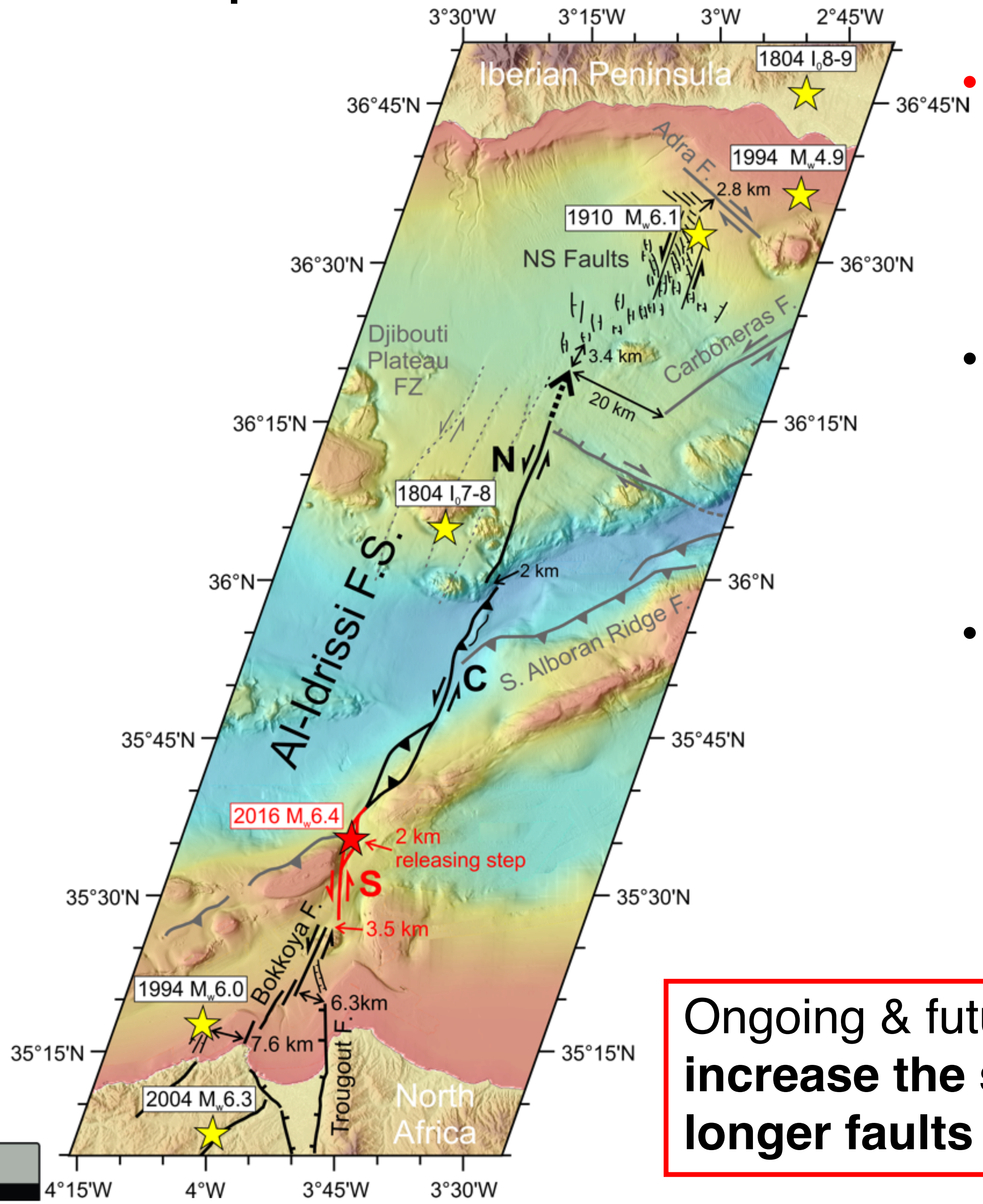
Segmented faults host moderate size EQs

Continuous faults host major EQs, allowing both H & V propagation

Fossen & Rotevatn (2016)

With time, the accumulation of seismic slip **leads to geometrically simpler and longer strike-slip fault zones**.

Earthquake surface trace, fault propagation & linkage of AIFS



- The **South AIFS released elastic strain energy** in 2016 crisis & also in 2004, 1994; **no slip occurred** during recent years in the Central & North AIFS segments.

- The AIFS has the **potential to generate greater events** if EQs propagate across fault step-overs generating multiple segment ruptures *(Cowie & Scholz, 1992).*

- **Fault growth, lateral propagation & fault linkage** between C & N AIFS may be possible, as transfer of slip between the two faults occur over short distance (2 km). Empirical limit of stepovers for SSF (~4 km to ≥ 6 km) *(Wesnousky, 2006; Biasi & Wesnousky, 2016).*

Ongoing & future linkage of C & N AIFS segments at depth may **increase the seismic potential of the system & generate longer faults** ➞ **HAZARD**

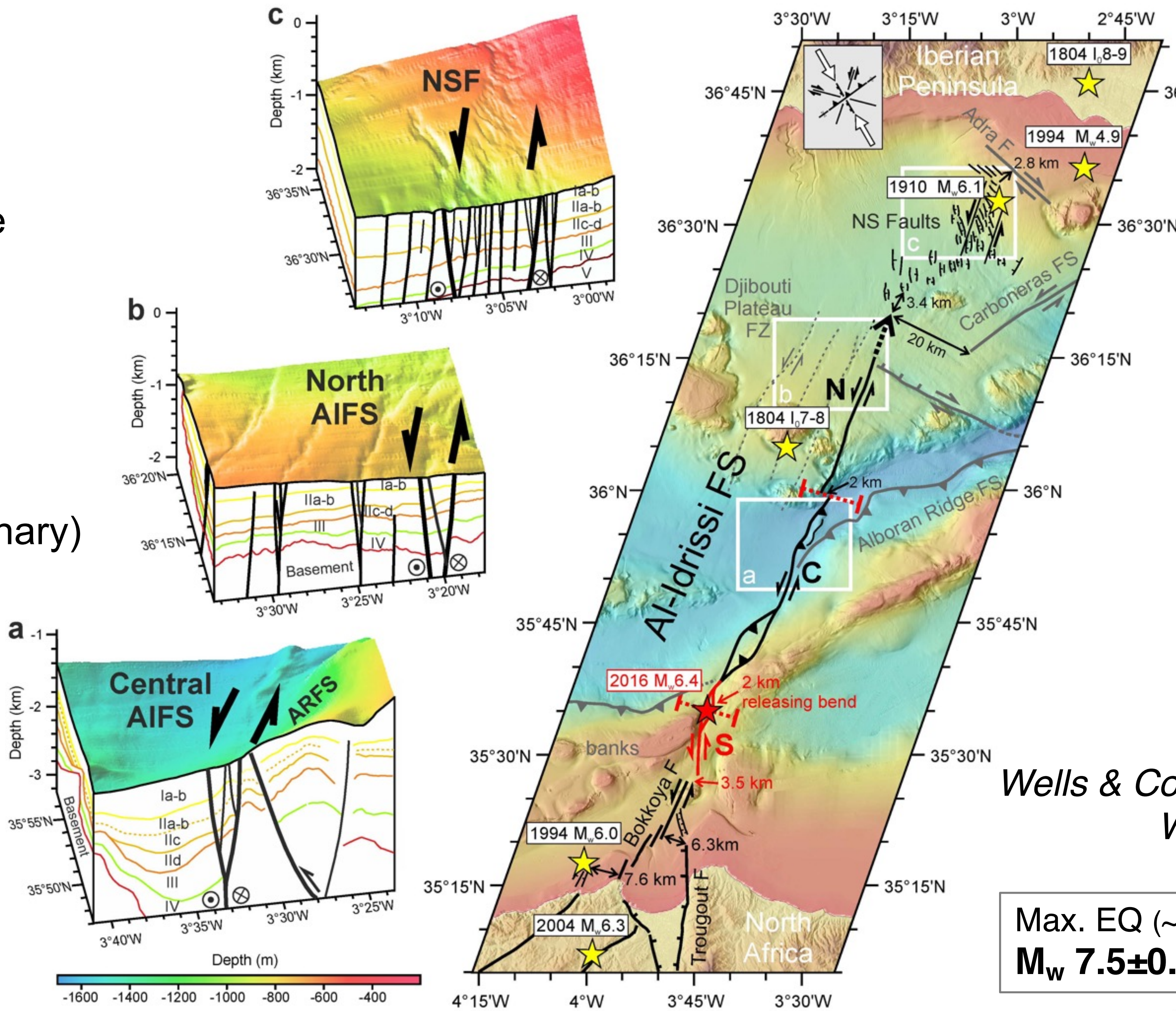
Evolutive stages of the AIFS segments

Martínez-Garcia et al. (2013)

NSF
Array of normal faults developed within a left-lateral shear zone

N AIFS
Discontinuous fault traces. They are in a earlier stage of development (Quaternary)

C AIFS
Well-defined PDZ, mature (Late Pliocene)



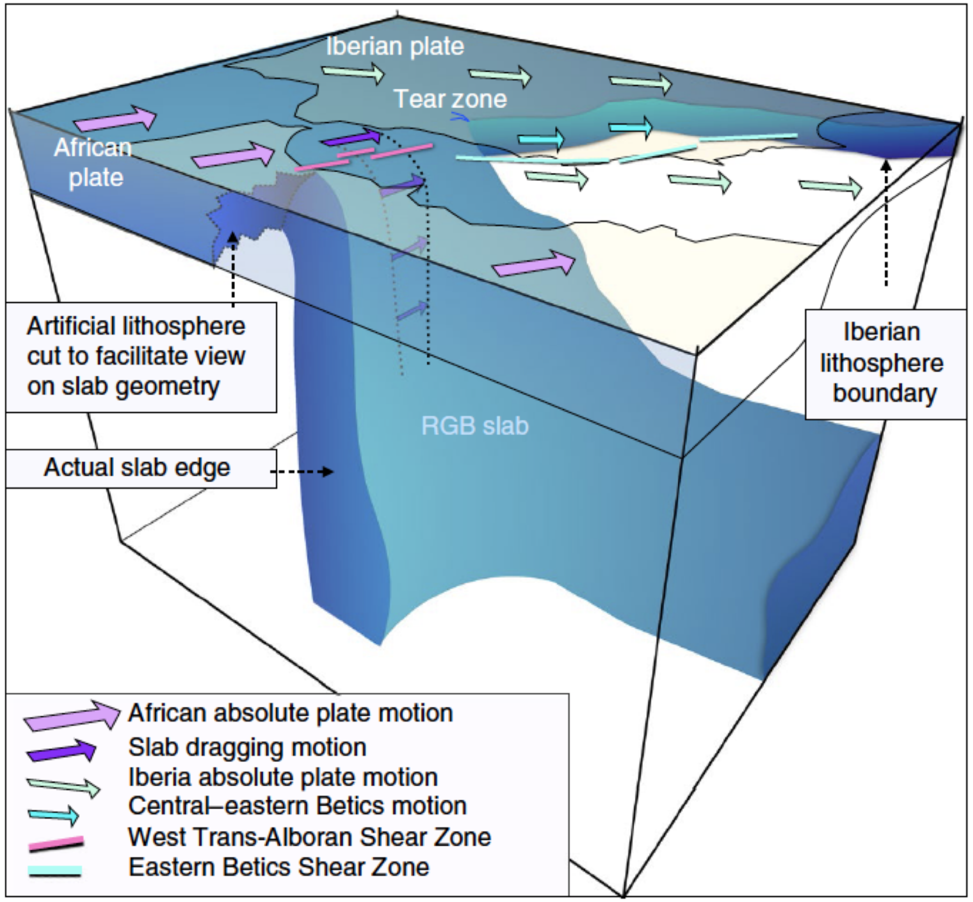
Wells & Coppersmith (1994)
Wesnousky (2008)

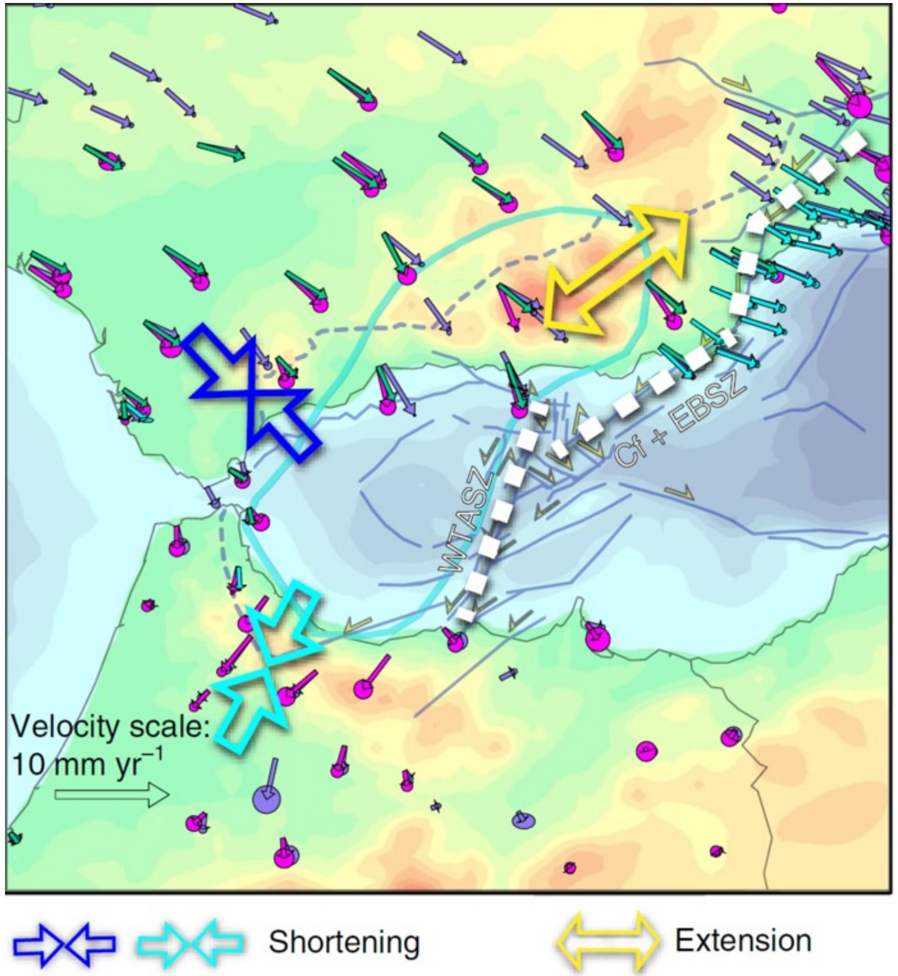
Max. EQ (~160 km long):
M_w 7.5±0.2 / 7.6±0.3

Crustal deformation in AB explained by slab dragging

Spakman et al., NGEO (2018)

Geological, geodetic data & 3D numerical modelling of subduction show that tectonic features, as AIFS, CFS & EBSZ could be consequence of slab dragging

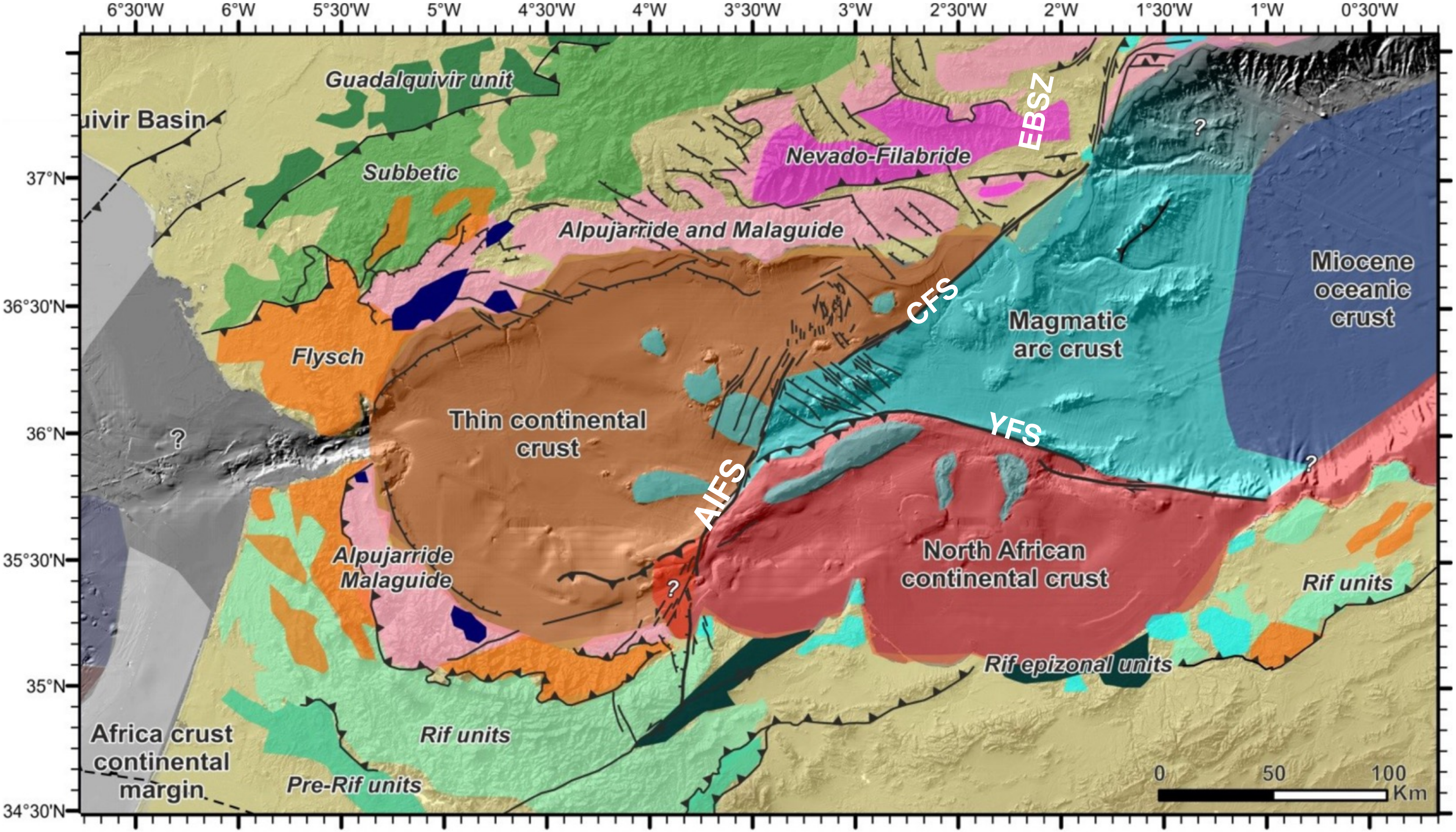




AIFS, CFS, EBSZ & YFS are large fault systems that transfer African to Eurasian plate motion
→ may imply the formation of a nascent plate boundary

Alboran Basin: Crustal domains distribution

Complex & compartmentalized crustal domains → Large strike-slip FS are boundaries



Gómez de la Peña et al. , TECTONICS (2018)

Summary

1) We combine newly acquired **HR bathymetric & seismic reflection** data, together with **seismological** data of the 2016 M_w 6.4 EQ offshore Morocco – the largest event recorded in the area – to unveil the AIFS.

2) We found that, despite of a subdued relief, **the AIFS is a crustal-scale boundary.** We characterize its segments & **demonstrate that the AIFS is the source of the 2016 events.**

3) The occurrence of the M_w 6.4 EQ supports that **the AIFS is currently growing through propagation & linkage of its segments,** & could develop into a **large-scale continental plate-boundary fault.** Segment linkage may **increase the seismic potential** of the FS.

4) The AIFS is an example **of the inception stages of continental fault systems,** with crucial implications for **seismic hazard assessment**.