Earthquake crisis unveils the growth of an incipient continental fault system

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Large continental faults extend for thousands of kilometres to form boundaries between rigid tectonic blocks. These faults are associated with prominent topographic features and can produce large earthquakes. Here we show the first evidence of a major tectonic structure in its initial-stage, the Al-Idrissi Fault System (AIFS), in the Alboran Sea. Combining bathymetric and seismic reflection data, together with seismological analyses of the 2016 Mw 6.4 earthquake offshore Morocco – the largest event ever recorded in the area – we unveil a 3D geometry for the AIFS. We report evidence of left-lateral strike-slip displacement, characterise the fault segmentation and demonstrate that AIFS is the source of the 2016 events. The occurrence of the Mw 6.4 earthquake together with historical and instrumental events supports that the AIFS is currently growing through propagation and linkage of its segments. Thus, the AIFS provides a unique model of the inception and growth of a young plate boundary fault system.
The Alboran Sea is a Neogene basin in the westernmost Mediterranean Sea, located between the Iberia and Nubia plates (Fig. 1). Miocene deformation related to roll-back of the Tethys oceanic lithosphere was followed by a compressional regime, which lasted from the Pliocene until today, and included the development of strike-slip and thrust faults. Present-day crustal deformation is driven by the fault systems within the overall plate tectonic setting of NW-SE to NNW-SSE trending convergence between the Nubian and Eurasian plates (Fig. 1). Seismicity in the study area is characterised by earthquakes of small to moderate magnitude. Large historical and instrumental earthquakes have occurred in the region, such as the 1804 and 1910 Adra earthquakes (MSK Intensity VIII). On 25 January 2016, a Mw 6.4 earthquake (white star in Fig. 2a) hit the area offshore the city of Al-Hoceima on the Moroccan coast. This last event caused 629 fatalities and left 15,600 homeless, making it the most catastrophic earthquake in the region during the last century. On 25 January 2016, a Mw 6.4 earthquake (white star in Fig. 1) hit the area offshore the city of Al-Hoceima on the Moroccan coast. This is the largest event recorded in the Alboran Sea. The earthquake caused one casualty in Al-Hoceima and 30 injured in Melilla. Damages were reported in several coastal cities of northern Morocco and southern Spain, where the event was strongly felt (i.e. Intensity V (EMS-98) in Malaga).

Besides the intermediate (>100-km-depth) seismicity in the West Alboran Basin related to the east-dipping Rif-Gibraltar-Betics slab, an ~80-km-wide NE-SW trending seismic zone extends for ~500-km-long and runs along the so-called Trans-Alboran Shear Zone (TASZ). The TASZ is traditionally interpreted as a complex belt of deformation that crosses the Alboran Sea and its two margins, connecting the Rif (North Africa) to the Eastern Betic Shear Zone (SE Iberian Peninsula). Only a few works have proposed that the TASZ may play the role of a plate boundary across the Alboran Sea, traversing the Nubia-Eurasia plates in the westernmost Mediterranean. Its associated seismicity is characterised by left-lateral strike-slip focal mechanisms with few normal and thrust fault plane solutions (Figs. 1 and 2). A recent work that combines geological, geodetic and 3D numerical modelling demonstrates that crustal deformation in the Alboran Sea, induced by NNE-directed dragging of the RGB slab by the Nubia plate in the past 8 Myr, is still active. The slab dragging is resisted by the mantle and this resistance translates into further crustal deformation at the surface. Such recent deformation has been documented, for example, along the Yusuf Fault System, Carboneras Fault System and especially along the AIFS and associated structures of the Rif and the Eastern Betics Shear Zone (Figs. 1 and 2b), which comprise the main fault systems of the TASZ (Figs. 1 and 2).
Here we present a new and comprehensive geological and geophysical dataset of the entire AIFS. We adopted a multi-scale approach, including detailed morphological analysis of shipboard multibeam bathymetry and near-bottom bathymetry obtained with Autonomous Underwater Vehicles (AUVs), and interpretation of deep penetration multichannel-seismic (MCS) data (Figs. 2a and 3). Combining these data with the analyses of the $M_w$ 6.4 earthquake in 2016 provides us with a unique opportunity to explore the role of seismic deformation in the fault propagation and growth of a continental fault system.

**Results**

**Seafloor expression of the fault system.** Although the AIFS shows a subdued topography, it may still represent the longest active tectonic structure in the region. The AIFS is a Plio-Quaternary structure that offsets the largest bathymetric relief of the basin, separating the prominent thrust of the Alboran Ridge Fault System, of Early Pliocene age, from several banks to the SW (Fig. 2a, b). The AIFS is a left-lateral fault system trending NNE-SSW. The fault system is about ~100-km-long, with a width varying from 1-to-4.8-km-wide. Considering that the AIFS is the major fault structure in a large region, we infer that it accommodates most of the total rate of 3.8 mm/yr $^{34}$ (Figs. 1 and 2b). The AIFS runs from the Djibouti Plateau in the north, where the historical 1804 earthquake occurred (DJ04, MSK Intensity VIII$^9$ (Fig. 2a), to the Nekor Basin (Moroccan margin) in the south (Fig. 2b). Towards the North, the AIFS connects to a parallel structure, a wide shear-zone defined as the NS Faults system (NSF$^5$), located near where the destructive 1910 Adra earthquake (AD10, estimated $M_w$ ~6.1$^{25}$ and the 1993–1994 seismic crises (AD93–94) occurred$^{7,15}$ (Fig. 2a). To the south, the AIFS links to the Trougout and Bokkoya faults (Nekor Basin), the last of which is related to the source of the Al-Hoceima 1994 earthquake$^8$ (Fig. 2a, b).

From 2006 to 2016, a series of shipboard bathymetry campaigns were carried out along the central part of the Alboran Sea$^3$–$5,26$ (gridded at 20 m/pixel) to complete the mapping of the AIFS and related structures (Fig. 2a, b). In 2015, a few months before the 2016 earthquake, we collected high-resolution near-bottom bathymetry data (at 1-metre resolution) of three sections of the AIFS segments (Fig. 3a–c) using multibeam sonars mounted on two AUVs (see Methods). Multi-scale acoustic mapping techniques, such as swath-bathymetry allow identifying the geomorphological expression of active faults, such as seafloor ruptures, fault scarps and fault traces$^{17,28}$. The AUV bathymetric data clearly highlight the surface expression of the AIFS, whose
trace reaches and offsets the seafloor, indicating recent fault activity. There are abundant pockmarks, only visible in the near-bottom bathymetry near the AIFS traces, suggesting past and possibly on-going fluid flow circulation activity (Fig. 3a–c).

According to the fault trend, geometry and timing of activity, the AIFS can be divided into three main segments: north, central and south. Related nearby structures, such as the NSF and the Bokkoya and Trougout faults are also considered part of the AIFS (Fig. 2b). The NSF is a ~20-km-long, 5-km-wide left-lateral shear zone composed of a succession of closely spaced N160 trending en echelon elongated troughs (Figs. 2a and 3a). South of it, the North AIFS segment is 34-km-long, it trends N018 and is of Quaternary age.23 This segment runs across the Djibouti Plateau FZ composed by a magmatic arc crust and magmatic intrusions.30,31 It is cut by four closely spaced sets of parallel fault arrays (Fig. 2b). The North AIFS (easternmost array) consists of a succession of single N10-N20 trending en echelon elongated troughs (Figs. 2a and 3b). Southwards, a 2-km-wide left-stepping offset in the fault trace around 36°N/3°28′W marks the boundary between the North and Central AIFS (Fig. 2b). The Central AIFS segment trends N031, is 50-km-long and of Late Pliocene to Quaternary age.23 It is the longest and most mature segment of the AIFS, and it includes a principal displacement zone (PDZ) that is ~26-km-long, where most horizontal displacement is accounted for. Two NE–SW trending compressional zones can be observed in the slope map (Fig. 2b). A change in strike of the fault trace defines the intersection between the Central and South AIFS, which correspond to a releasing bend (Fig. 2b). The South AIFS segment trends N007, it is 16-km-long, and of Quaternary age.23 The active fault trace defines an elongated sigmoid, which is composed of a succession of en echelon narrow grabens that evolve to the north into a succession of small pressure ridges, which do not appear to be fully connected. Towards its southern end, the AIFS loses its surface expression and splits into two branches (Figs. 2a and 3c). Further south, along the Moroccan Margin, strain is transferred towards the Bokkoya and Trougout faults, which are connected through an intricate network of normal faults accommodating deformation in the Nekor pull-apart basin (Fig. 2b).

**Subsurface structure of the fault system.** To examine the crustal structure of the AIFS segments, we selected five MCS profiles across the TASZ obtained during fall 2011 (Figs. 2a and 4). The seismic profiles are displayed in two-way travel time (first 6s TWTT), except for profile TM3, which is in depth (first 5 km) (see Methods and Supplementary Fig. 1), showing in detail the upper crustal structures. Subsurface images show the tectonic architecture of the AIFS, a sub-vertical, left-lateral strike-slip fault that roots into the basement. Deformation cuts through the most recent sediments up to the seafloor (Fig. 4). In Supplementary Fig. 2 we provide an example of a lithospheric-scale profile across the AIFS (12s TWTT record length) that shows two different crustal domains: The West Alboran continental crust (about ~8s TWTT thick) and the North African continental crust (about ~10.5s TWTT thick).32

The age of deformation is derived from the seismic stratigraphic interpretation combined with scientific and commercial wells available in the Alboran Basin.4,23,31,33 We assume that if a given stratum displays a roughly constant thickness across the fault zone, then that stratum must have been deposited prior to the initiation of a particular fault segment. For example, in profiles TM2 and TM3 (Central AIFS segment), deformation starts in the Early Pliocene (Unit IIc-d), while in profiles TM1 (South AIFS segment) and TM28 (North AIFS segment), deformation starts post unit Ia-b (Early Pleistocene to Holocene in the Quaternary). Our interpretation fits with older data and more recently acquired MCS profiles in the Alboran Basin.4,23,31,33 Hence, this allows proposing a new seismic stratigraphic model (Fig. 4). Above the basement, the following units are identified, Ia-b: Late Pleistocene-Holocene (Quaternary), Iia: Early Pleistocene (Quaternary), IIb: Late Pleistocene, Iic-d: Early Pliocene, III: Messinian (Late Miocene), IV: Late Tortonian (Late Miocene), V: Late Serravalian-Early Tortonian (Middle Miocene-Late Miocene); VI: Langhian-Serravalian (Middle Miocene), and
Fig. 4 Interpreted seismic reflection profiles across the AIFS. From north (top) to south (bottom), multichannel seismic profiles illustrate the geometry and tectonic pattern of the AIFS. The five profiles are located in Fig. 2a. a NSF (profile TM22); b North AIFS segment (profile TM28); c Central AIFS segment - pressure ridge (profile TM3); d Central AIFS segment - restraining bend (profile TM2); and e South AIFS segment - releasing bend (profile TM1). All profiles are plotted in two-way travel time (s) except for TM3, which is in depth (km). Ages of seismo-stratigraphic units are detailed in the text. AIFS: Al-Idrissi Fault System, ARFs: Alboran Ridge Fault System, AvF: Averroes Fault, M: Top Messinian horizon, SAB: South Alboran Basin.
VII: Burdigalian (Early Miocene). The metamorphic basement is of Late Oligocene-Early Miocene age\textsuperscript{31}, and the volcanic basement is of Late Serravalian-Tortonian age\textsuperscript{35,36}.

The seismic profiles displayed in Fig. 4 supports evidence for the inception of fault activity. To the north, the NSF is composed by half-grabens and horst-and-graben structures (Fig. 4a), which are active and consistent with the present-day extensional strain pattern of this area. The North AIFS shows a sub-vertical, left-lateral transtensional strike-slip fault (Fig. 4b). The Central AIFS segment shows local folding and reverse faulting deformation consisting, from north to south, of a 2.5-km-wide and 10-km-long pressure ridge (Fig. 4c), and a 4.8-km-wide and ~18-km-long restraining (compressional) bend with a positive flower structure (Fig. 4d). Narrow folds and sub-vertical faults extending down to at least 5 km depth are observed in the seismic profiles (Fig. 4c). To the south, across a 2-km-wide and 3.7-km-long releasing bend, the seismic image shows wide folding over the AIFS, which converges at depth to form a flower structure. The occurrence of growth-strata in the Late Pliocene to Quaternary units (Iia-b to Ib) west of the AIFS is consistent with the ongoing fault activity (Fig. 4e).

The 2016 $M_w$ 6.4 earthquake and relocated seismicity. The epicentre of the $M_w$ 6.4 earthquake on 25 January 2016 was located in the Alboran Sea\textsuperscript{13–15}, about 42 km north of the city of Al-Hoceima (Morocco; Figs. 1 and 5a). The mainshock was preceded on 21 January by a foreshock of magnitude $M_w$ 5.1 located in the same epicentral area. The mainshock was also followed by an extensive aftershock sequence of $>$2350 events (i.e. from the 25 January until 13 May 2016)\textsuperscript{15}, included 197 events of magnitude $M_w$ $\geq$ 3 (Fig. 5a).

Using a local lithospheric velocity model\textsuperscript{37} we relocated the mainshock as well as the aftershocks (see Methods). For the mainshock, we located the epicentre at 35.59°N and 3.72°W, which corresponds to a transtensional releasing bend between the Central and South AIFS segments (Fig. 5a). The moment-tensor waveform-inversion (see Methods) yields a preferred depth of 10 km, and left-lateral strike-slip focal mechanisms with a preferred nodal plane of 214°/85°/5° (strike/dip/rake). The strike is consistent with the azimuth of the AIFS (Fig. 5a and Supplementary Fig. 3). The slip propagated northward for $<$16 km (Supplementary Fig. 4) with a maximum coseismic slip of about 1 m, which might have ruptured the seafloor south of the epicentral area (Supplementary Figs. 4 and 5). Aftershocks were distributed along the southernmost part of the Central AIFS segment and the whole South AIFS segment. A significant number of aftershocks were also located at the western tip of the Alboran Ridge Fault System (Fig. 5a).

The relocated aftershocks for the first four weeks (days 21–53) roughly outline the mainshock fault trace (Fig. 5a, Supplementary Fig. 6). Their focal mechanisms (i.e., the
and with a rake of 5°. The source fault (light green line) mimics the coseismic slip determined from inversion of teleseismic waveforms (Supplementary Fig. 3), and corresponds to a vertical left-lateral strike-slip fault (rake 5°) that bends in the epicentral area. The South AIFS rupture strikes 007°N and extends for 45 km, while the rupture area and further east (Fig. 5a, Supplementary Fig. 6), appeared near the southern and northern terminations of the System thrust. Consequently, strain partitioning between these two types of tectonic structures (i.e., the strike-slip dominates in the south, and the thrust in the west, the West Alboran Basin is characterised by a thin continental crust3,34, and to the west, the West Alboran Basin is characterised by a thick continental crust3,34). The presence of a relatively thin continental crust (~15–23 km) on both sides of the AIFS, together with high heat-flow57, restricts the depth of the seismogenic zone (Fig. 5b), supporting a rupture at <15–20 km depth.

To illustrate how moderate to large earthquakes might exert control on the distribution of the aftershocks and could possibly trigger large earthquakes along the AIFS and nearby faults, we modelled the change in Coulomb failure stress41,42 (ΔCFS; see methods). The source fault (green line in Fig. 6a, b) mimics the coseismic slip determined from the inversion of teleseismic waveforms (Supplementary Fig. 4), with similar geometry to those described for the South and Central AIFS segments. Strike-slip waveforms (Supplementary Fig. 4), with similar geometry to those described for the South and Central AIFS segments. Strike-slip

Fig. 6 Coulomb stress transfer modelling. a Calculated Coulomb failure stress change41,42 (ΔCFS) at 10 km depth on receiver faults striking 210°, dipping 90° and with a rake of 5°. b Calculated Coulomb failure stress change (ΔCFS) at 10 km depth on receiver faults striking 070°, dipping 45° and with a rake of 85°. The source fault (light green line) mimics the coseismic slip determined from inversion of teleseismic waveforms (Supplementary Fig. 3), and corresponds to a vertical left-lateral strike-slip fault (rake 5°) that bends in the epicentral area. The South AIFS rupture strikes 007°N and extends for 45 km, while the Central AIFS rupture strikes 031°N and extends for 20 km. The boundary between the South and Central AIFS segments is depicted by a dashed red line.
slip and thrust receiver faults are defined, respectively, by strike/dip/rake of 210°/90°/5° and 070°/45°/85° (Fig. 6). The comparison between the distribution of the increase stress lobes and the location of the aftershocks shows a good spatial correlation (Fig. 6). However, it is also noticeable that the increase in stress at the southern tip of the Central AIFS segment is not associated with the occurrence of aftershocks. This may suggest that the 2016 earthquake increased the level of stress along the southern part of the Central segment, which was not released by an aftershock, bringing the Central AIFS segment closer to failure (Fig. 6a).

**Discussion**

Continental earthquakes usually rupture active fault sections\(^4^3\),\(^3^4\) that are bounded by discontinuities such as bends, step-overs, gaps or branches\(^4^5\),\(^4^6\). These discontinuities have been recognised as favourable for initiating and stopping earthquakes\(^4^7\), such as the 2016 \(M_w\) 6.4 event, which started in a 2-km-wide releasing bend (Fig. 5a). The en echelon structural pattern of the South AIFS segment probably controlled the 2016 \(M_w\) 6.4 event rupture: short segmented faults generate small displacements and are thus often associated with small magnitude earthquakes\(^4^8\), as indicated by low magnitude aftershocks located along the South AIFS. Over time, however, accumulation of seismic slip might lead to simpler fault geometry, and eventually longer strike-slip fault zones\(^4^5\) with the potential for larger magnitude earthquakes. This might already be the case for the longest segment of the AIFS, the Central segment, which shows a well-defined PDZ (Figs. 2b and 7a). In contrast, the Northern and Southern AIFS segments, which are younger\(^4^2\),\(^2^3\),\(^3^4\), show more discontinuous fault traces and appear to be in an earlier stage of fault development\(^4^8\) (Fig. 7b, c).

Fault growth, subsequent lateral propagation and fault linkage\(^4^8\),\(^4^9\) between the Central AIFS and North AIFS segments may be possible, as the transfer of slip between the two fault steps would occur over a short distance (2 km; Fig. 7), which is smaller than the established empirical limit for step-over jumps for strike-slip faults (i.e. generally ~4 km\(^5^5\) to ~6 km\(^4^6\)). The North AIFS shows shallow en echelon grabens, which may eventually link by
lateral growth and merge at depth (Fig. 7b). Thus, on-going and future linkage of the North and Central AIFS segments through the entire brittle crust, may generate longer faults and increase the seismic potential of the overall fault system\(^6\). The Southern AIFS, and associated structures further south along the Moroccan Margin (i.e. Bokkoya and Trougout faults), released elastic strain energy during the 2016 seismic crisis and previously in 1994 and 2004. Along the northern margin of the Alboran Sea, a series of earthquakes occurred during the last 200 years, including in two historical events in year 1804 (I\(_0\) ≈ 9 and I\(_0\) ≈ 8–9) and the instrumental 1990 and 1994 events (Fig. 7c). However, no significant earthquake has been reported during the historical and instrumental periods\(^15\) along the entire Central AIFS segment (Fig. 7a) and most of the North AIFS segment (Fig. 7b), with the exception of the 1994 (I\(_0\) ≈ 7–8)\(^31\) earthquake located on a parallel trace (Fig. 7). This observation may indicate that these segments are either locked or possibly creeping\(^3\). Hence, the AIFS may have the potential to generate larger events if earthquakes manage to propagate across fault step-overs and generate multiple-segment ruptures\(^4\), as it has been proposed for other fault systems, such as the San Andreas Fault System (SAFS) in California\(^52\) or the Dead Sea Fault System (DSFS)\(^33\) in the eastern Mediterranean Basin, for example. The AIFS is a unique example of a young continental fault system that is currently in an incipient stage. It is growing and, in the course of time, could develop into a large-scale continental plate-boundary fault along the Trans-Alboran Shear Zone (Fig. 7), similar to the North Anatolian Fault System (NAFS)\(^54\),\(^55\) or the SAFS\(^56\). Although the AIFS is accommodating a slip-rate of ∼3.8 mm/yr\(^2\), an order of magnitude lower that the SAFS or NAFS, and comparable to the DSFS\(^53\) slip-rate, all these systems form major lithosphere cutting faults between tectonic plates, extending for more than 1000 km, and generating large magnitude earthquakes. Earthquake hazard assessment models are based on the potential length of seismic ruptures and whether rupture might stop or not at fault-segment boundaries, to determine the difference between a moderate and a potentially devastating earthquake.\(^45\)\(^,\)\(^57\). Regarding the seismic potential of the AIFS, using classical scaling laws that relate magnitude to rupture length\(^57\), we can envision several scenarios depending on the potential length of fault activated. In a worst-case scenario, considering a rupture that would include the segment ruptured in 2016, the South AIFS segment, together with the North and Central AIFS segments, and the faults located at short distances from the endpoints of the AIFS segments (i.e. such as the 25-km-long Bokkoya fault, located 3.8 km to the SW of the South AIFS segment, and the 35-km-long left-lateral NSF located ∼3.4 km to the NE of the North AIFS segment), eventually, it may result in a maximum rupture of 160 km. This may yield an earthquake of maximum magnitude \(M_w\) 7.5 ± 0.2 to 7.6 ± 0.3 across the entire TASZ from the Moroccan to the Spanish margins (Fig. 7). A sequence of historical (AD1804 and AD1910)\(^8\) and instrumental (1994, 2004 and 2016)\(^9\)–\(^11\) earthquakes with estimated magnitudes ranging from \(M_w\) 5.9–6.4, has hit the Alboran Sea region in northern Morocco and southern Spain in the last 200 years (Fig. 7). Given the low awareness and preparedness for seismic and tsunami hazards\(^58\),\(^59\) in the region, a major earthquake may eventually cause severe damage along the highly populated coastal zones of the Alboran Sea. Therefore, large events should be considered in future seismic and tsunami hazard assessments and mitigation plans. The recent deformation that we now observe along the AIFS, from North Morocco to the Eastern Betic Shear Zone that we refer to as the TASZ\(^15\) (Figs. 1 and 7), may represent a plate boundary that will eventually develop into a large, large-scale continental plate-boundary fault zone\(^57\). Methods Multibeam bathymetry. Multibeam shipboard bathymetry was acquired during the 2006 IEO and IMPULS, 2010 EVENT-DEEP, 2011 TOPOMED-GASSIS, 2012 SARAS and MARLBORO-2, 2015 SHAKE, and 2016 IDRISI cruises. Hull-mounted multibeam data along the AIFS were acquired with a 1\(^\times\)1\(^\times\)16 beam width Atlas Hydroseep DS multibeam echosounder (R/V Sarmiento de Gamboa) and were processed with the CARIS HiPS\&SIPS 9.0 software and gridded at 20 m resolution. For the whole Alboran Sea we used the IEO 25 m multibeam compila-

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determine the slip distribution of the mainshock. In this method, the fault model is parameterised to have a rupture front that spreads over a grid of point-sources discretized in 12 × 8 subsets of 5 km by 3.5 km. The moment rate function for each subfault was expressed by 5 triangle functions of 1.5 s duration and overlapping in time. The model assumes that the rupture consists of a propagating rupture front with slip accumulated in the wake of the rupture front passage. For the rupture speed Vr we tested a range of values between 1.5 and 4.5 km/s and finally found that a slow rupture velocity of 2 km/s showed a minimum variance. We tested a number of different source parameterisations (including size of the rupture area) and found that the slip pattern remained robust. This suggests a shallow slip (<15 km) with a slip maximum near the epicentral area and the largest slip of ~100 cm at 10 km depth, where the point source inversion located the centroid. The inversion shows similar features to the ones obtained by Burofn et al.13. To the south, the inversion suggested that the slip propagated very close to the seabed, perhaps nurturing surface rupture (Supplementary Fig. 3). Further, the slip inversion indicated that slip occurred towards the north. This feature is supported by regional waveform data from Spain, showing that the azimuthal distribution of apparent source times favours the shortest rupture for stations to the north of the rupture zone, and hence corroborates a northward rupture propagation as indicated by the slip inversion (Supplementary Fig. 4).

Regional centroid moment tensors. The determination of focal mechanisms by inversion of waveforms followed the grid-search procedure of Herrmann et al.86. Waveforms were obtained from the Instituto Geográﬁco Nacional (IGN)15, converted to velocity and rotated to radial, transverse and vertical components. Next, the data were bandpass filtered between 0.02 and 0.06 Hz to ensure the best possible signal-to-noise ratio. We used 5 waveforms that showed retrograde motion for the fundamental model Rayleigh wave, good signal to noise ratio, and finite signal duration. The grid search technique takes samples over strike, dip and rake angles in 5 degree increments, and source depth in 1 km increments, in order to determine the shear-dislocation (double couple) that best fits the observed data. A feature of the implementation of the grid search is an efficient method for adjusting the predicted waveforms for time shifts that arise due to uncertainties in the assumed origin time and epicentral coordinates, the sampling of Green’s functions with distance, and differences between the actual wave propagation and that of the 1-D model used. We tried several existing models, and the one that produced the best data fit was the WUS (Western US) model84 (Fig. 5, and Supplementary Table 1). In the Supplementary Fig. 8 we include, for every moment-tensor solution, detailed results and data fit.

Re-location procedure of the seismic sequence. Catalogue data available on the Instituto Geográﬁco Nacional (IGN, Spain) website (https://www.ign.es/igns/layout/sismo.do) were used to determine epicentral locations and focal depth for over 225 local earthquakes with M > 3. The non-linear oct-tree search algorithm NonLinLoc90 was used to calculate the focal parameters91. Travel times in the model were calculated using the finite-difference solution to the eikonal equation with a grid spacing of 2 km. The oct-tree algorithm provides more reliable information on the location of the structural discontinuities by expanding the probability density functions (PDF) of each individual event. The maximum likelihood location is chosen as the preferred location. For each event, NonLinLoc estimates a 3D error ellipsoid (68% confidence) from the PDF scatter samples. Station statics account for localised deviations from the a priori model and are determined from the average residual at a station. For the inversion, the focal depth search was limited to depth >2 km, and thus rare cases of water quakes were avoided. From a previous study using an amphibious network we know that seismicity occurred at crustal levels19. We therefore restricted the focal depths of the crustal levels (<3 km). Travel times were calculated using the 1D local lithospheric velocity model derived from the amphibious network of Greveneyre et al.15 (i.e. ocean bottom seismometers and land stations), covering the Alboran Basin, Rif and Betic. Further, we corrected the 1D local lithospheric velocity model for effects caused by 3D propagation in a heterogeneous setting by introducing station correction terms. We only included stations used in Greveneyre et al.15 in 2010. Fortunately, the data were bandpass filtered between 0.02 and 0.06 Hz to evaluate them after the last 5 years. Therefore, we could use 60–80% of the seismic stations reported in the IGN catalogue (Fig. 5a). The station terms compensate for differences in the velocity structure caused by structural heterogeneity between the onshore and offshore domain, and hence provide an approximation of the 3D velocity structure. The main impact of station corrections is the eastward shift of the original locations reported by the IGN. Thus, relocated earthquakes occur 10–15 km eastward of the IGN located seismicity, providing an excellent spatial correlation between the AIFS imaged by bathymetric and seismic reflection data and the seismicity.

Coulomb failure stress transfer modelling. The Coulomb failure stress change was calculated for dislocations in an elastic half-space18 and on slip planes (receiver faults henceforth) with a given strike, dip and rake19. The Coulomb failure stress change is given by: 
\[
\Delta \sigma = \frac{\mu}{\mu^*} \Delta \sigma, 
\]
where \(\Delta \sigma\) is the change in shear stress (positive in the direction of the fault slip), \(\Delta \sigma\) is the change in normal stress (positive in unclamping of the fault), and \(\mu^*\) is the apparent friction coefficient of the fault. A positive increase in the Coulomb failure stress transfer in an area is interpreted as meaning that a fault plane located in this area has been brought close to failure, whereas if it is negative the interpretation is the opposite (i.e., relaxed). In the models, we have assumed a \(\mu^*\) of 0.4, a typical Poisson ratio of 0.25 and a Young modulus of 8 × 10^{10} bar (last two parameters compute for a shear modulus of 3.2 × 10^{10} bar). Although values of \(\mu^*\) lower than 0.4 might be appropriate on strike-slip faults89, its variation only modestly modifies the stress distribution around a fault170. The modelling was carried out using the Coulomb 3.4 software.

The source fault is the fault plane that is displaced during the earthquake. In the ΔCFS modelling, we considered the source fault to be the one that mimics the coseismic slip determined from inversion of the teleseismic waveforms, and the rupture plane corresponding to a section of the AIFS. This section is bent and extends, from south to north between ~3.61°W/35.75°N and ~3.78°W/35.19°N, and bends at ~3.72°W/35.59°N (location of the epicentre). North of the releasing bend, the source fault extends for 20 km along the Central segment and strikes 031° N. South of it, the South segment extends for 45 km and strikes 007°N. Both sections are vertical and have a rake of 5° (left-lateral strike-slip with a reverse component). To mimic the slip model presented in this work (Supplementary Fig. 3), the source fault was divided into 1408 sub-sources, ~1-km wide and 1.5-km-long, each with its estimated slip. The automatic seismic moment and moment magnitude calculated by the Coulomb software gives a seismic moment (\(M_0\)) of 8.79 × 10^{19} Nm and a moment magnitude (\(M_w\)) of 6.60. These results are slightly larger than those obtained from the seismological data.

The ΔCFS was calculated on two different types of receiver faults. The strike, dip and rake of these faults were established based on information provided by the focal mechanisms of aftershocks recorded in the area. The first type are left-lateral strike-slip faults striking 210°N, dipping 90° and with a rake of 0°, which coincide approximately to the South Al-Idrissi Fault (SAIF) extension parallel to the Alboran Ridge Fault System and to the focal mechanisms solutions for some aftershocks. The second type of receiver faults are reverse faults striking 070°N, dipping 45° and with a rake of 85°, which coincide with the direction of the South Al-Idrissi Fault segment and the moment-tensor solutions of some aftershocks.

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**Author contributions**

E.G. conceived the study, led the EVENT, TOPOMED-GASSIS and SHAKE marine 
experiments, designed the research and wrote the paper with contributions and edits 
from all authors. I.G. relocated the seismicity, calculated the mainshock focal mechanism 
and participated in writing the paper. H.P. modelled the Coulomb failure stress and 
together with R.B., S.M.L., D.S., A.C., S.C. and M.C. participated in the data 
acquisition at sea and completed the data processing and interpretation. A.V. calculated 
the moment-tensor solutions of the aftershocks, and Y.K. contributed in data analysis 
and interpretation. E.d’A. and A.R. acquired and provided new bathymetric data from 
the Moroccan Margin. C.R. led the TOPOMED project, contributed to interpretation and 
participated in writing the paper.

**Additional information**

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