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should be addressed to
L.-F.C. (lopezcarlos@
uniovi.es)

How much confidence can be conferred on tectonic maps of continental shelves? The Cantabrian-Fault case

Fernández-Viejo Gabriela, López-Fernández Carlos, Domínguez-Cuesta María José & Cadenas Patricia

Department of Geology, University of Oviedo. C/Jesús Arias de Velasco, s/n, 33005 Oviedo (Spain).

The Cantabrian Fault is a long-lived crustal fault, 320 km long on land and extending more than 150 km seawards within the Bay of Biscay, which separates different geodynamic domains. Due to its sub-vertical dip and late strike slip movement is poorly evidenced in the shelf and it has been traditionally mapped following the strike of the deepest submarine canyon in the north Atlantic (~4.600 m drop). Based on multichannel reflection data, seismicity from a thirty year period, a GIS model, and the support of detailed field mapping onshore, the fault has been traced more accurately. Surprisingly, it presents a much more E-W strike than mapped before, and shows a splay fault termination never previously assessed. Moreover, the fault acts as a seismic barrier within the actual stress field of Iberia. Collaterally, a large submarine landslide (2000 km²) associated with its seismicity has been discovered, providing a further argument to support the newly proposed trace of the fault.

The simplicity of tectonic maps of the continental shelves is deceiving; it contrasts with the complexity of their onshore counterparts because of the intrinsic difficulties of geological mapping offshore. Geological mapping seaward within margins has traditionally been a mixture of interpretation and intuition, continuing offshore the onshore measures of strike and dip of tectonic lineations. With the scarcity of constraining data at sea, tectonic features were mapped following bathymetric reliefs, if present, or were inferred in seismic lines. However, seismic profiles rarely start at the coast, but some kilometers offshore, thus leaving the coastal strip in a geological “limbo”. Detailed acoustic surveys are helping with mapping within the shelves with astonishing accuracy¹, and potential field data have also been used to cover the gap between land and offshore geology², demonstrating that mapping of features running deep into the crust relies on multidisciplinary approaches.

The principal aim of this study was to map as accurately as possible the trace of an important crustal feature, the Cantabrian Fault (from now on CF), within the Cantabrian-Pyrenean domain offshore. This structure represents an important transition area within the orogen, coinciding with changes in crustal thickness and differences in stress vectors and type of deformation³⁻⁷. Therefore, the detailed mapping of its submerged section provides valuable information for geodynamic and kinematic studies. The use of different sets of data was necessary for several reasons. First, the fault is an important feature, but its quasi-vertical dip and its later, mainly horizontal, movement, complicates the task of visualizing it in the near vertical seismic profiles. However, the analysis of the seismicity delineates a trace that can be followed and interpreted. Moreover, the integration into a GIS model of up-to-date bathymetry, geological data in the coastal area, and geomorphology, provided a consistent frame for the offshore mapping of fault.

Tectonic framework. The CF was traditionally known on land with the local name of Ventaniella⁸. It is a long-lived rectilinear feature that runs in a NW-SE direction for more than 300 km across northwest Spain. It continues for another ~150 km offshore within the continental platform of the southern margin of the Bay of Biscay as far as the abyssal plain. This structure roughly separates the Cantabrian Mountains (CM) in the west from the Basque-Cantabrian Basin (BCB) and the Pyrenees in the east, the three areas forming a genetically linked 800 km long cordillera (Fig. 1). It is accepted that this outstanding feature developed as a rift border fault active during the Permian and the Triassic extensional processes that culminated with the opening and oceanization of the Bay of Biscay, coetaneous with the North Atlantic rifting. During this period it formed a thick Mesozoic stratigraphic sequence in the east⁵. Later at the Tertiary, the alpine orogeny affected and shortened the previously extended margin along the Europe-Iberia boundary and produced the Cantabrian-Pyrenean orogen on land. The fault moved again, this time as a dextral strike slip fault with a well-structured contractive horsetail splay in its

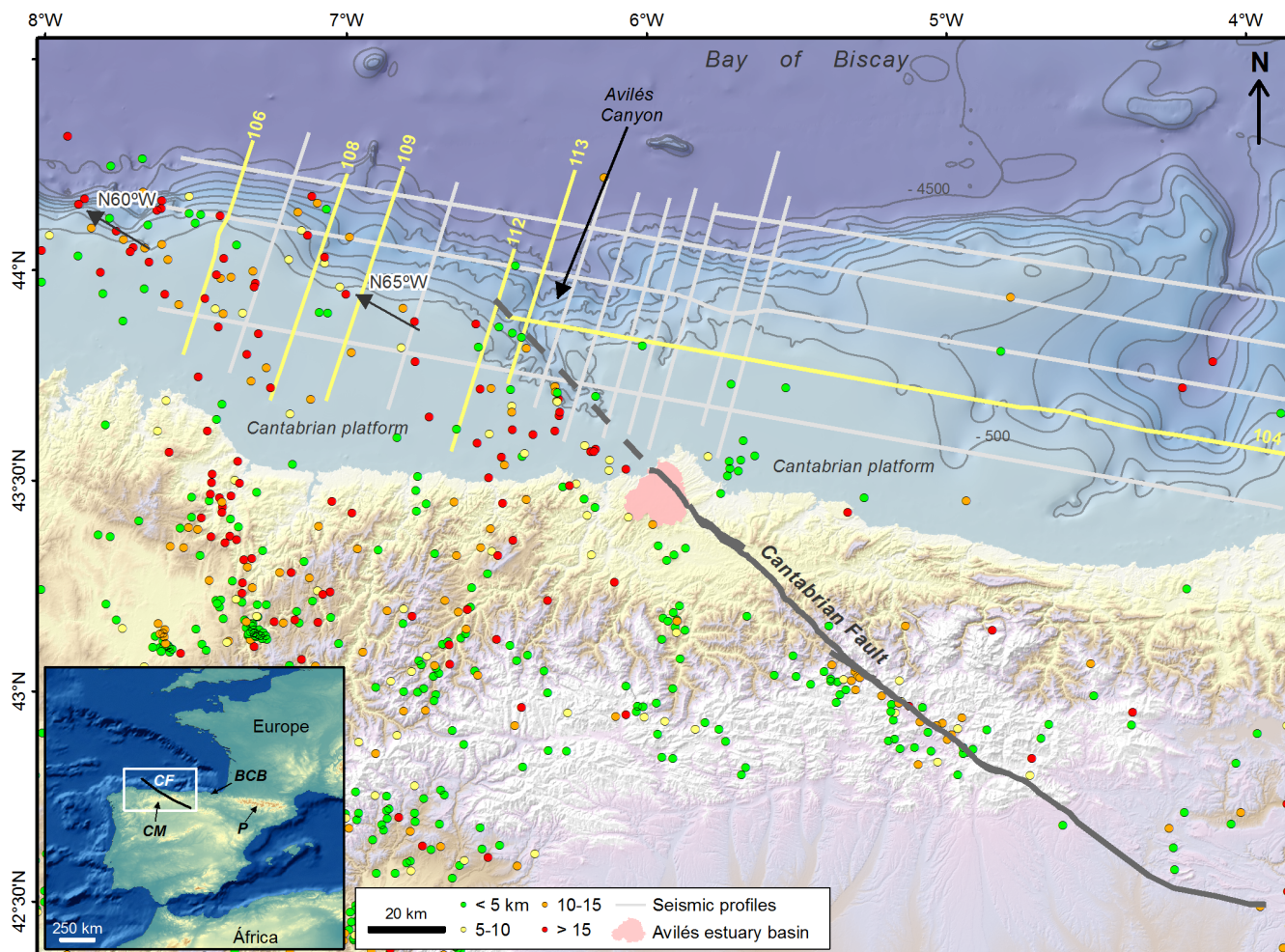


Figure 1 | Study area within NW Iberia. In dots, earthquakes. In grey, seismic reflection profiles across the shelf, those in yellow being referred throughout the article. In black the traditional outline of the CF (dashed at sea, continuous on land). Arrows indicate earthquake clusters directions offshore. Abbreviations as in the text. Figure produced with ArcGIS-ESRI software. Data source for topography and bathymetry: STRM (NASA), TCarta Marine and own data.

southeastern termination. It also has an important reverse component, with SW vergence. Restraining bends along the fault give place to transpressional small basins⁹. It has a relatively low topographic expression, although its NE block is slightly uplifted with respect to its SW one^{7,10}. With the final docking of Iberia into Europe and the migration of the plate limit to southern Iberia during the Cenozoic^{11,12}, the margin began its current passive stage. Apart from being considered a border fault during the Mesozoic, the role of this structure during the opening of the Bay of Biscay is enigmatic, depending on the favoring of either “scissors” type opening models^{13,14}, or those that invoke a considerable strike-slip displacement^{15,16}, or hybrid type models¹⁷. Moreover, the endurance of the structure, its reactivation through the compressional stage, and its modern position within the Cantabrian Mountains uplift, roughly separating thickened crust to the East from a 32 km thick crust towards the West^{4,18}, gives the CF greater importance than previously acknowledged.

Ever since the first bathymetric studies of the Bay of Biscay¹⁹, the CF was continued offshore following its strike on land (N43W), coincident with the axial trace of the Avilés canyon, a deeply incised physiographic feature oblique to the E-W coast trend^{20,21} (Fig. 1). This submarine canyon is located 12 km from the coast, and reaches from 128 m depth at the platform to 4766 m at the base of the slope²². This descent occurs across just the 40 km of the narrow continental platform, making the Avilés canyon one of the deepest in the world in terms of net relief^{23,24}. The timing of its initial inception is uncon-

strained, but there is, undoubtedly, a puzzling disproportion between the size of the canyon and the size of the Avilés estuary (Fig. 1). Its limited entity to produce such a large submarine feature supported the idea of a tectonic link between the canyon and the fault that has remained unquestioned ever since.

Although the North Iberian margin is considered stable, there is persistent, low magnitude seismicity within the surroundings of the CF²⁵.

Methodologies and results

In order to deduce the trace of the fault within the continental shelf, different types of datasets were gathered and analyzed: a modern set of 2D seismic commercial lines acquired across the continental platform and slope in N-S and E-W directions (Fig. 1), a bathymetric database of 90 m resolution that includes points from the seismic profiles, boreholes, and the coastline through satellite, and seismicity from a 30 year period that was relocated and analyzed. Additionally, detailed field mapping at the coast was added, and all of this was implemented in a GIS database with the hydrological networks on land. Joint interpretation of all the information allowed tracing offshore of this important structural lineation for another 120 km.

Seismicity. The seismicity database includes 139 earthquakes catalogued during the period 1980-April 2013 by the National Seismic Network (Fig. 1). In addition, through a temporary network between



1999 and 2002, 36 more earthquakes were registered, diminishing the threshold of recordings²⁵. A maximum magnitude associated with the fault on land was reached in March 1995 with a 4.2 event, and over 20 of them have magnitudes over 3. Within the western shelf, earthquakes cluster around two lineations, one striking N60W, and a second, fainter lineation, striking N65W (Fig. 1). The seismicity is distributed almost exclusively to the southwest, with a drastic drop in activity to the northeast. A similar effect is also observed on land⁶. The relocation study shows that all the events are at remarkable depth (between 8 and 20 km), ruling out the association with mass wasting processes, which are other possible triggers of low magnitude seismicity along a steep continental slope such as this one. Detailed work indicates that most of the Iberian Peninsula is under a NW-SE S_{hmax} in strike-slip regime, and that seismicity nucleates on right lateral strike slip faults²⁶.

Multichannel reflection profiles. A set of fourteen 2D migrated reflection profiles has been analyzed and interpreted, focusing on the expected fault area and its interpretation. The profiles were acquired using a streamer of 6000 m length, 240 channels, and 37.5 m shot spacing, giving 80 fold data. They have a record-length of 15 s TWT, with 4 of them following an E-W direction, and the rest striking perpendicular (Fig. 1). The processing sequence of the data after initial quality check and editing included: demultiple by Radon filter, CDP mix, Wiener-Levinson filter, dip move out correction, Stolt FK migration, NMO and velocity analysis every 1.5 km, demultiple, deconvolution, muting, Stack, inverse Stolt FK migration, Kirchhoff migration, plus time variant filtering and scaling for display.

The fault can be inferred by subtle differences in topography, and by disruptions in seismic sequences at one side or another of the fault (Fig. 2). The fault's quasi-vertical dip and a strike slip movement make it difficult to visualize with near vertical seismic techniques. However, we have identified the fault among 10 of the seismic profiles running N-S along the continental platform and slope, and within 2 of the others that crosscut the latter in an E-W direction. The results show a crustal feature at least 15 km deep, (assuming velocities calculated in regional studies, i.e.²⁷), striking N60W and running coincident with one of the clusters observed in the seismicity study. A splay fault has also been interpreted in some of the seismic lines that could be sub-parallel to the fainter N65W cluster of seismicity. This secondary fault seems to branch out very close to the coastline, although in the seismic lines there is no convincing evidence of their rooting at depth (Fig. 2). Based on the seismicity study and the interpretation of the reflection profiles, the fault was mapped following a direction N60W, with an apparently similar but unconvincing relationship to the strike of the Avilés canyon.

Integration into GIS database: morphology, bathymetry, hydrographic basins. In order to complement and support the proposed trace of the fault based on active and passive seismology, a GIS based geomorphological and bathymetrical project was implemented in ArcGIS (v. 9.3). Images were obtained from the GIS database, through slope gradient algorithms and artificial hillshade maps, 90 m pixel value. This attribute map (Fig. 3) shows a homogeneous slope of around 15° along the whole of the coast, except for the west area of the canyon, where rapid changes in slope gradient are observed. This disrupted slope has an area of around 2000 km², and it is situated to the Northeast of the postulated fault trace. The bathymetric profiles along seismic lines passing through a normal bathymetric slope (CS01-106), and those of the modified slope (CS01-109), can be compared (Fig. 3). We interpret this area of disrupted slope as a great submarine landslide. Profile 109 clearly illustrates the concavity of the head scar and slide, and beneath, the convex shape resulting from the deposition of the displaced mass. Looking at the map, it also seems that the canyon direction has been modified by this massive slide, making a close to 90° turn in the

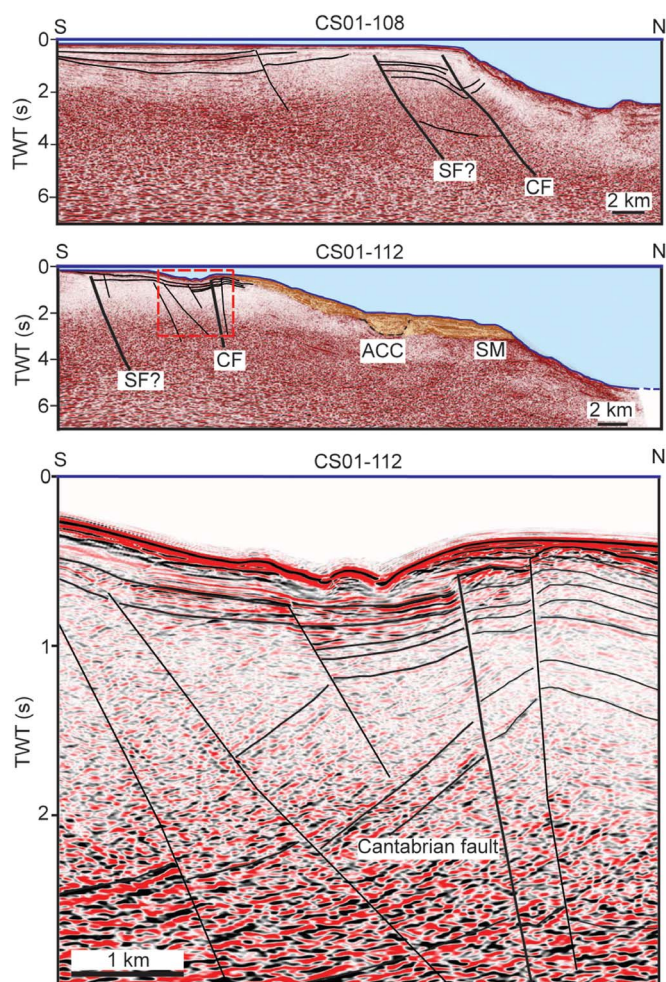


Figure 2 | Detail of the interpreted CF in two of the seismic lines; also showing the splay fault to the south. Top, line CS-108. Middle, line CS-112 showing an inferred former Avilés canyon channel covered by slid mass. Bottom, detail of the CF in line CS-112. SF: splay fault; AAC: ancient Avilés Canyon; SM: slide mass. Figure produced with Kingdom software.

confluence of profiles CS01-104 and CS01-113 (Fig. 1). In profile CS01-112 an interpreted former Avilés Canyon axial incision could be inferred beneath the displaced mass, at 3 s TWT, almost 1 km below the sea-bottom reflection. This ancient channel is filled with the slide sediments (Fig. 2).

A geomorphological analysis of the hydrographic networks around the area confirms that the Avilés estuary is insignificant in terms of the production of such a submarine feature. Therefore, the origin of the canyon could be related to tectonic causes or to a former trajectory of the Nalón River, the largest and main river of the Spanish Cantabrian watershed. This river could have been captured later and bound to disembogue in its current estuary, sited at the West.

Slope stability. Following the recognition of the landslide, numerical modeling of the slope stability has been performed using FEM Phase2 software in order to analyze the causes of this disruption. Considering the break criteria of Hoek-Brown, the stresses related to the materials and the water column, and with the topography unconstrained, the modelization resulted in a Shear Reduction Factor (SRF) of over 2, which indicates an intrinsically stable continental slope for the North Iberian margin. To produce such a deeply rooted submarine landslide, the models show that we need a

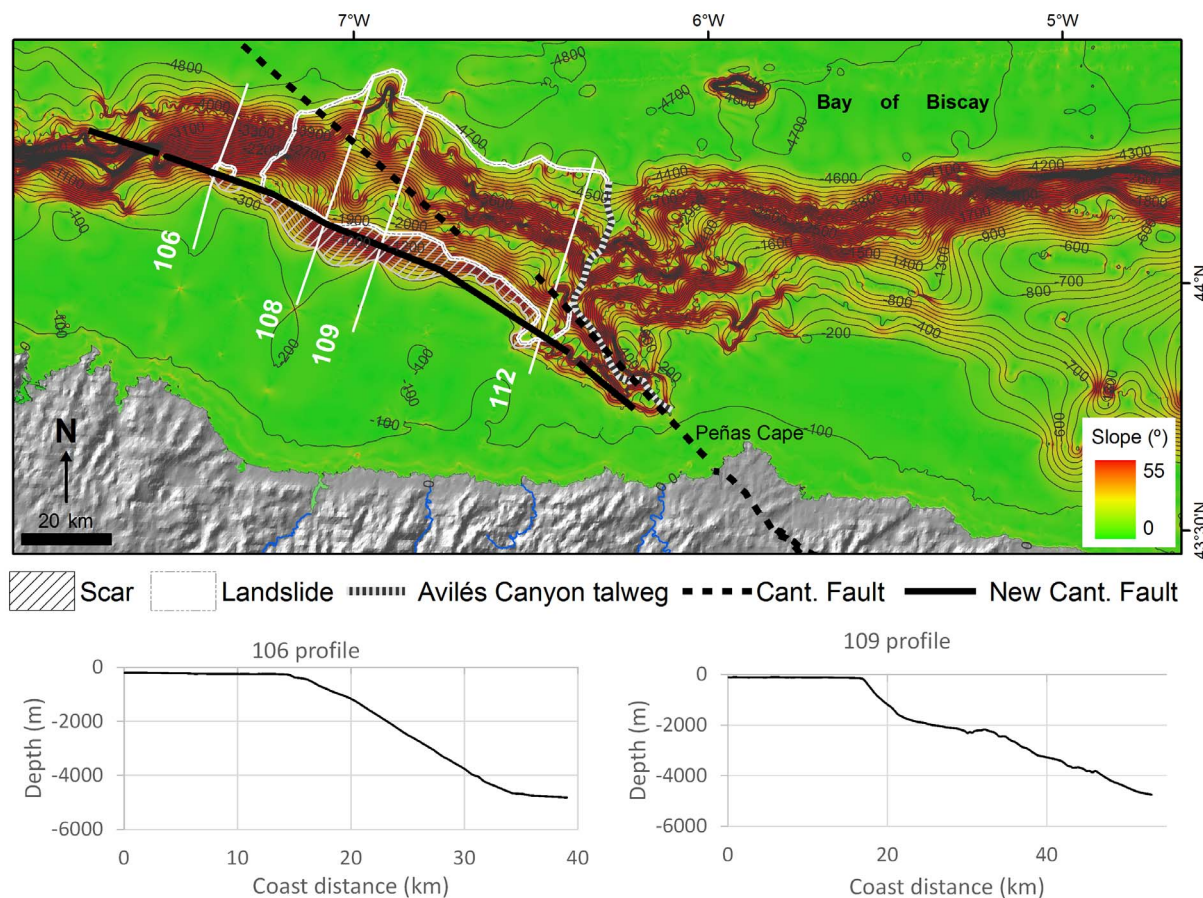


Figure 3 | Attribute map of slope gradient of the study area and representative profiles of the bathymetric disruption produced by the landslide. Figure produced with ArcGIS-ESRI software. Data source for topography and bathymetry: STRM (NASA), TCarta Marine and own data.

seismic acceleration corresponding to an earthquake of a magnitude of at least 7. From the instrumental seismicity records, the maximum magnitude expected here is 5, but evidence of Quaternary powerful earthquakes has been found on land²⁵. The presence of a submarine canyon decreases the possibilities of a slide in the adjacent slopes²⁸, so the cause of this mass movement may be related to lingering seismicity in the fault, probably in combination with stress changes produced during the sea-level variations.

The cantabrian fault offshore

Figure 4 illustrates the newly proposed trace of the CF along the western part of the Bay of Biscay, superimposed on a digital elevation model of the continent and continental platform based on the approaches described above approaches.

Dip and strike. According to the results from the integration of different datasets, the CF strikes in a N60W direction for at least 150 km before dying out in the abyssal plain of the Bay of Biscay, which in this area is composed of oceanic crust topped with Tertiary sediments²⁹. On land, the main orientation fluctuates between N38W and N50W except in its southeast termination, where it follows a strike N60W similar to the one observed now offshore, having, overall, a sigmoidal shape (Figs. 1, 4). The fault follows offshore a significantly more east-west path than previously thought (Fig. 3). Moreover, our interpretation hints at the presence of at least one other fault associated to the southwest striking N65W. These two features could be related in a splay manner, although convincing evidence of this has not been found in the geophysical data. Both of them show a slightly subvertical dip to the north. The new trace does not seem to validate a clear association between the Avilés

canyon and the CF offshore. However, studying the hydrographic basins on land, the canyon may have been formed in relation to a former Nalón river trajectory, subparallel to the fault on land. Continuous uplift of the Cantabrian Mountains since the Eocene merely increased the size of the canyon, but its tectonic origin may be less important than has traditionally been estimated. Although the presence of a fault through the initial strike of the canyon cannot be completely ruled out, there are no evidences of its presence in the data. The integrated analysis shows that the main and active branch of the CF offshore strikes now in a rather more westerly position than pictured in previous studies.

The Cantabrian Fault as a regional seismic barrier. The seismological study of the fault offshore reveals that it coincides with a limit to earthquake propagation and also provides nucleation sites along its trace. The orientation of the plate motion vector relative to the master strike slip fault is subparallel to the NUVEL1 plate motion vector of West Iberia³⁰, reflecting the transition from the obliquely convergent margin in the west to the continental collision to the east. Detailed papers indicate that most of the Peninsula is under a NW-SE S_h max, a strike slip regime that has stayed practically constant since the Upper Miocene⁹. The CF is a concentrator of the stresses and acts as an intraplate focus of deformation³, separating two geodynamic domains within the Cantabrian-Pyrenean realm. Lingering seismicity is the expression of this geodynamic characteristic of the fault. Moreover, the offshore trace of the fault seems to indicate that the CF links in a smooth manner, given the orientation proposed here, to the northern thrust of the Biscay front, acting as a transfer structure of the oblique deformation across the Tertiary plate limit of

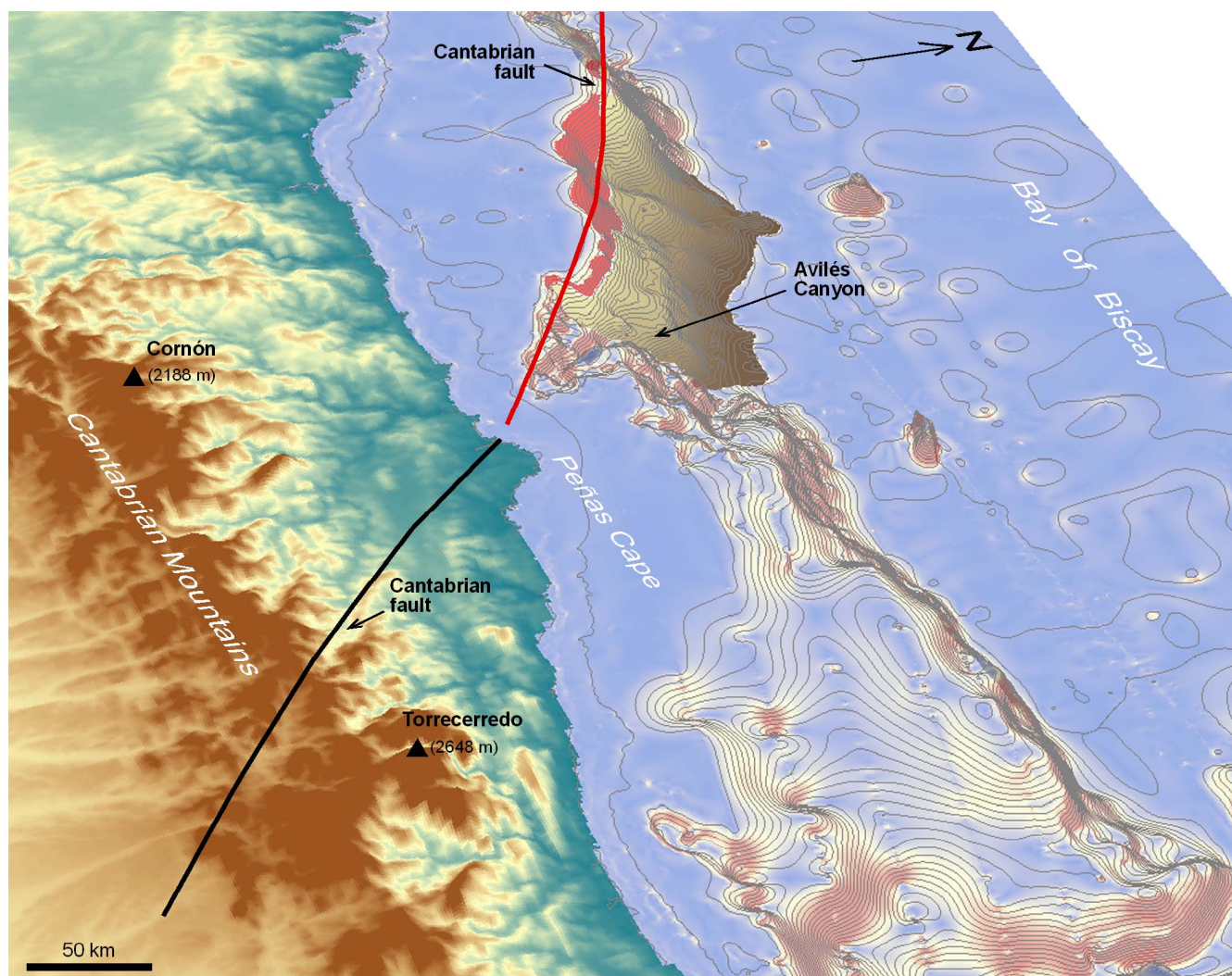


Figure 4 | Final three-dimensional representation of the proposed new trace of the CF and associated submarine landslide within the Cantabrian-Pyrenean context (vertical exaggeration 5 : 1). Figure produced with ArcGIS-ESRI software. Data source for topography and bathymetry: STRM (NASA), TCarta Marine and own data.

the oceanic domain (the Biscay thrust front)²⁷ and the southern front of the Cantabrian thick-skinned uplift¹⁰.

The submarine landslide: a collateral discovery. The submarine landslide interpreted and mapped in the seismic lines has a short run-out distance, and occurs at midslope depth, around 1200 m. An initial estimation of the surface of this submarine slide yields a figure of more than 2100 km² (Fig. 3), making it comparable to other big slides reported in the Atlantic.

Some authors³¹ associate the shape and volume of failure surfaces to their trigger mechanisms, seismicity being capable of generating deeper, larger slope failures. Along the rest of the margin, similar slopes only present minor slumps and mass wasting processes associated with the shallowest sediments. Taking this into account, together with the stability results obtained from the numerical modeling simulations, it would seem fair to say that this large disruption has been caused by the old seismicity associated with the fault.

Some implications of the new map. The proposed offshore trend of the CF helps to explain the NW seismicity associated with the Iberian plate (otherwise stable in this area) in relation to the actual stress state, as the line that nucleates the offshore relocated earthquakes. The transition between the N-S compression of the

Cantabrian-Pyrenean domain and the NW-SE directions associated with the westernmost part of Iberia, occurs at the longitude of the CF. The obliquity of the new trace agrees with the fact that the indentation produced beneath the Cantabrian Mountains³² must have an abrupt end towards the west, as seen in refraction profiles⁴, and that ductile deformation processes must have been important in the deeper parts of the fault at the moment of formation of the crustal root.

Geological restorations of shortening across the Cantabrian Mountains³³ and a plate kinematics analysis in a six-plate circuit¹², seem to be conflicting, especially within the surroundings of the CF. As these authors¹² point out, if faults running off the Kings Through boundary to the Biscay boundary were accommodating deformation not accounted for, these disparities would be much diminished. The continuation of the CF offshore to then die out within the oceanic E-W compressive front may provide another source of displacements in kinematic models.

Moreover, one striking feature is that the CF represents a large-scale crustal feature even though its measured displacement, either strike-slip or vertical, seems to be disproportionately low³⁴. A question still to be answered is if this fault moved in opposing directions throughout its long-lived history, and only allows us to see the destructive interference of these movements. More geological field data needs to be acquired here, including offshore data, in order to



fully understand the real part played by the CF within the Iberian geodynamics.

A secondary point to keep in mind is the presence of the massive submarine slide associated with the proposed trace. Although the recent seismicity is low and the geomorphic characteristics of the continental margin would be unfavorable to produce damage in a slide associated tsunami occurrence, it may be advisable to study the hazards associated to mass movements in the margin.

Conclusions

Mapping structural features submerged in our continental shelves has an inherent difficulty, and the gap between on land, observational geology, and offshore, geophysical-based mapping, must be bridged by use of multidisciplinary approaches. Through an integration of seismology, active seismic reflection data, geomorphological studies, and classical field mapping, a crustal feature of geodynamical importance within the Bay of Biscay has been mapped. The mapping reveals a remarkably different strike to that which had been previously assumed.

The results of the study can be summarized as follows:

- The CF has a strike of N60W, and can be followed along the shelf for more than 150 km. It has a sub-vertical dip and reaches a depth of at least 15–20 km. It shows the presence of a secondary fault striking N65W for at least 80 km length.
- The seismicity of the north Iberian margin diminishes noticeably east of the CF, coinciding with changes in structural style and Moho depths, together with differences in stress vectors and type of deformation. This structure acts as a seismic regional barrier, similar to other strike slip faults in compressional settings where obliquity is predominant.
- While studying the fault trace, a large submarine slide was observed on the continental platform and slope, with an area of roughly 2000 km². This mass of material produced a bend in the trajectory of the Avilés canyon, which, in our view, shows a less obvious tectonic control than traditionally assumed.

Aside from the regional implications, this study caused us to question our confidence in tectonic maps of the platforms and slopes of our continents. Continents, geologically speaking, do not finish at the coastline, but in the submerged continental platform and slope. However, as the CF study suggests, the coast is still a fundamental limit within the landmasses. It might be wise to test how accurately the continuations of faults within the shelves, were marked in the first place, and what kind of data they were based on, prior to using the direction of these lineaments as constraining data for future studies.

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Author contributions

F.-V.G. wrote the main manuscript text, interpreted seismic reflection lines and integrated all the geophysical and geological information. L.-F.C. elaborated the seismological study, the seismotectonic interpretation, modelled the slope stability and prepared the figure 1. D.-C. and M.J. implemented the GIS database, the geomorphologic study and prepared figures 2 and 4. C.P. collaborated in the seismic interpretation and prepared figure 3. All the authors reviewed the manuscript and collaborated in the interpretation of the seismic, geomorphologic and geological data.

Additional information

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