HIGH-RESOLUTION IMAGING OF SUBMARINE LARGE SEISMOGENIC AND TSUNAMIGENIC STRUCTURES IN THE SW IBERIAN MARGIN: NEW INSIGHTS FROM INSIGHT SURVEY (2018)

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***Abstract**: Large earthquakes, submarine landslides and their occasional tsunami originated are geohazards of great societal concern because of the impact on the world economies and coastal populations. Dramatic examples of such events include the 2004 northern Sumatra and 2011 Tohoku earthquakes and tsunamis. However, earthquakes of magnitude > 7.0 in areas of relatively slow tectonic deformation and with long recurrence intervals, such as the external part of the Gulf of Cadiz, might also have a significant impact as the well-known case of the destructive 1755 Lisbon earthquake, related submarine landslides, and resulting tsunami. Although the Gulf of Cadiz is one of the highest geohazard zones in Europe, we currently lack appropriate understanding of both the rupture areas and stress-state of the faults and sediments in which such catastrophic events originated. The relatively great water depths, poor accuracy on the location of moderate-to-high magnitude earthquakes, lack of understanding of subsurface hydrology and the few constraints on ages of the sedimentary sequences, hinder an appropriate understanding of location and characteristics of earthquake ruptures and associated submarine landslides in the Gulf of Cadiz. Our hypothesis is that such understanding can only be developed by using ultra-high resolution (UHR) tools capable of providing the characterization of faults, submarine landslides, and fluid escape structures while being able to work in deep waters such as those of the external Gulf of Cadiz. INSIGHT project tackles this problem by using state-of-the-art UHR techniques such as microbathymetry, 2D high-resolution seismic data, and sampling using gravity cores. We aim at 1) Map in detail the active faults with largest seismogenic potential, 2) Accurately determine the seismic parameters of these faults, 3) Characterize associated submarine landslides, 4) Assess the likelihood of recent submarine landslides activation, and finally, 5) Evaluate the seismogenic and tsunamigenic potential of the largest tectonic sources.*

***Keywords**: Active faults, submarine landslides, earthquakes, ultra-high resolution technologies.*

Introduction

Geological hazards, such as earthquakes and submarine landslides, are a major societal concern. They are capable of generating a tsunami that threatens coastal communities, infrastructure, and global economies at distances of many thousands of kilometers. This power and its effects were shown by the catastrophic 2004 Sumatra earthquake (Mw 9.3) and 2011 Tohoku earthquake (Mw 9.0) and subsequent tsunamis. Smaller earthquakes and landslides also have the potential to create hazards for coastal communities, as well as for oil and gas production infrastructures in deep water. Examples of such earthquakes and associated slope failures are found in the southern margins of the Iberian Peninsula, such as the 1755 Lisbon earthquake and tsunami, and the 1969 Horseshoe earthquake (Fukao 1973, Buforn et al. 1995, 2004, Baptista et al. 1998, Martínez-Solares and López-Arroyo 2004). The Gulf of Cadiz represents one of the most hazardous areas in Europe (Papadopoulos et al. 2014), despite the long recurrence period for large earthquakes (generated offshore) (and tsunamis Gràcia et al. 2010).

Seismogenic faults may be silent in the instrumental and historical periods and, therefore, their seismic potential may remain inadvertently hidden. In active areas, where deformation rates are high, it has been demonstrated that an on-fault analysis can detect and characterize the fault geometry and the fault seismic potential, slip rate, recurrence period, displacement per event, and elapsed time since the last event (Pantosti and Yeats 1993, Goldfinger et al. 2003). These parameters are commonly used for seismic hazard evaluation. Nevertheless, areas of relatively slow tectonic deformation with faults capable to generate large-magnitude earthquakes (Mw > 6) with long recurrence intervals (10^3 to 10^4 years), such as those in the Gulf of Cadiz, deserve special attention.

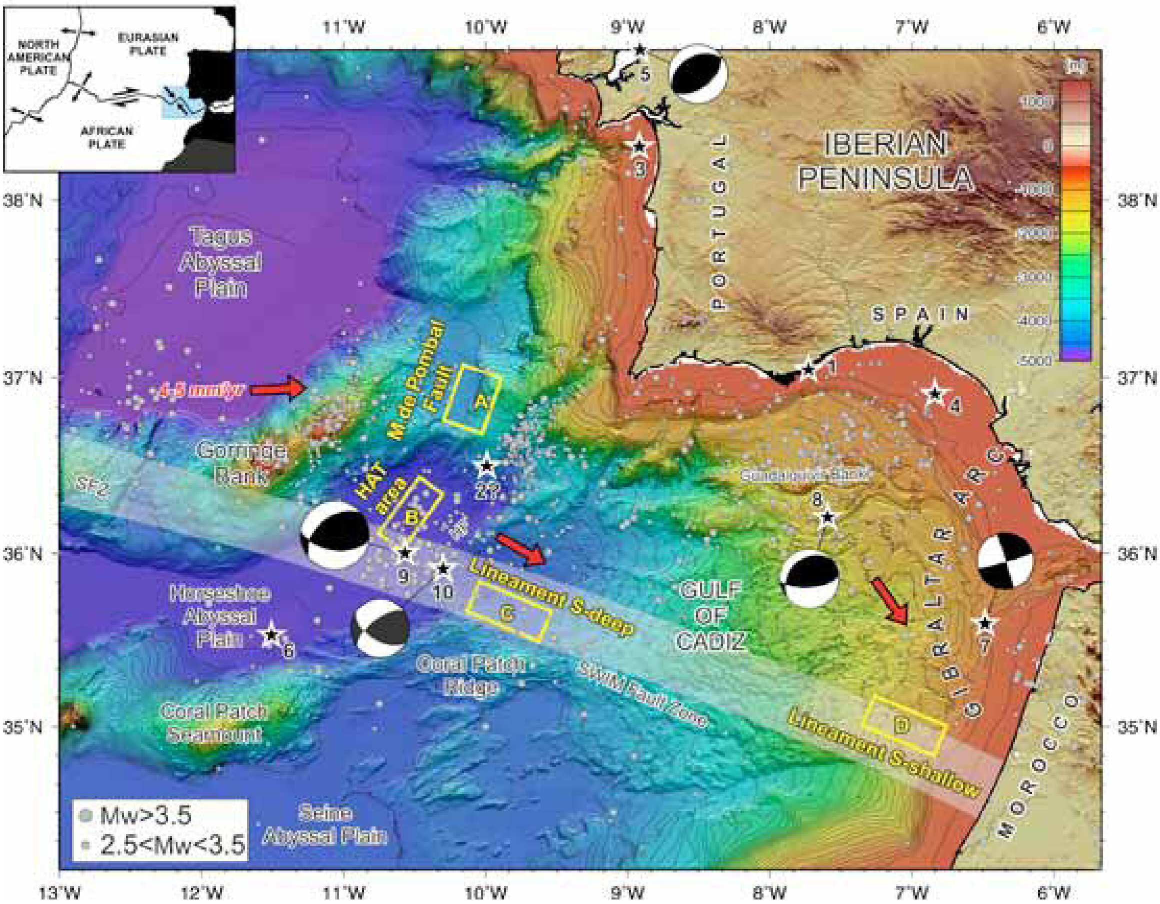

Figure 1: *Compilation of geological and geophysical dataset acquired in the Gulf of Cadiz by the ICM-CSIC (Barcelona-CSI team) during the INSIGHT survey. Black stars are epicenters of earthquakes Mw ≥ 6.0. We highlight 2?: proposed locations for the 1755 Lisbon EQ, ~Mw 8.5 [Buforn et al., 2004]; 9: 1969 Horseshoe EQ, Mw 7.8 10: 2007 Horseshoe Fault EQ, Mw 6.0 [Stich et al., 2007]. Yellow boxes outline INSIGHT study areas of micro-bathymetry acquired using an AUV.*

Moreover, submarine landslides can be several orders of magnitude larger than their biggest terrestrial counterparts are (Urgeles and Camerlenghi 2013).

Both earthquakes and submarine landslides are characterized by releasing stress in the form of strain over a range of temporal and spatial scales. Fluids are essential to both processes and determine the style, timing and amount of energy released in both processes. Faults are often major fluid flow pathways (Silver et al. 2000, Hensen et al. 2015), but fluids may become trapped in the subsurface and form gas hydrates (Berndt 2005) that may dissolve and/or dissociate at a later time originating submarine landslides. The occurrence of mud volcanoes and pockmarks at the seafloor is a manifestation of subsurface fluid flow and an indicator of the sediment stress-state. However, several questions still need to be addressed in order to resolve the significance of fluid flow in controlling the occurrence of both earthquakes and submarine landslides, including the determination of quantitative relationships between seismic activity, shallow faulting, landsliding and hydrologic processes.

The reason why INSIGHT survey concentrates around the Horseshoe Plain area is that in this area occurred the AD 1755 and AD 1969 earthquakes (Mw >8.0). A detailed study of the surface expression of these structures may constrain the determination of the 1755 Lisbon earthquake source.

Geological setting

In the SW Iberian Margin, seismicity is characterized by shallow to deep earthquakes of low to moderate magnitude (Mw < 5.5) (Buforn et al. 1995, 2004, Stich et al. 2005, 2007, 2010). However, this region is also the source of the largest and destructive earthquakes that have affected Western Europe (AD 1531, 1722, 1755 and 1969) (Fukao 1973) (Fig. 1). The 1755 Lisbon Earthquake (estimated Mw > 8.5) destroyed Lisbon (intensity X-XI MSK). The event was accompanied by one tsunami that devastated the SW Iberian and NW African coasts (Baptista et al. 1998, Baptista and Miranda 2009). None of the tsunami models satisfactorily accounts for the estimated magnitude of the earthquake and tsunami arrival times at the different localities onshore. The data obtained from 24 OBS (Ocean Bottom Seismographs) deployed during a year at the external part of the Gulf of Cadiz, showed that earthquakes in the Horseshoe Abyssal Plain are generated in the upper mantle at depths between 40 and 60 km (Stich et al. 2010, Geissler et al. 2010). Along the same line the Horseshoe Abyssal Thrust (HAT), has been identified on wide-angle seismic modeling as the source of deep earthquakes (Martínez-Loriente et al. 2014).

Dataset

Despite a well-documented history of large earthquakes, landslides and destructive tsunamis that makes this region one of the principal tsunamigenic areas in Europe, and despite significant research done in the area during the last years, the structures that are capable of generating such large events still remain largely unknown. The reasons behind this lack of knowledge are manifold: 1) the relatively poor accuracy on the location of moderate-magnitude earthquakes that continuously occur in the area complicates the task to assign the seismicity to individual faults; 2) the relatively great water depths (i.e. most of the structures of interest are located > 4000 m depth), which requires using sophisticated vehicles, (such as Autonomous Underwater Vehicles and Remote Operated Vehicles AUVs and ROVs) to image possible earthquake ruptures. 3) The few constraints on ages of the sedimentary sequences in faults and submarine landslides.

Fault investigations have focused in the past on the active structures located at the external part of the Gulf of Cadiz, which correspond to active NE-SW trending west-verging folds and thrusts of the Marques de Pombal Fault, Horseshoe Fault and Coral Patch Ridge Fault (Gràcia et al. 2003, Zitellini et al. 2004, Terrinha et al. 2009). In addition, long WNW-ESE dextral strike-slip faults referred as SWIM Lineation's have recently been identified (Zitellini et al. 2009, Terrinha et al. 2009, Bartolome et al. 2012) (Fig. 1).

Figure 2: *AUV "Abyss" micro-bathymetry system was used to map fault escarpments at unprecedented resolution.*

Therefore, the data presented in this abstract is focused on specific structures (Fig. 1). To the north, the Marques de Pombal Fault (MPF), a 50 km long west verging monocline thrust cutting through the Plio-Quaternary. This fault and associated landslide have been suggested as a potential source of the 1755 Lisbon earthquake. In the center, the Horseshoe Abyssal Thrust (HAT) is a 30º dipping thrust separating exhumed mantle which may sink below the oceanic crust (subduction initiation?) (Martínez-Loriente et al. 2014), and being this morphological feature the most plausible source of the 1755 Lisbon EQ. To the south, the deep segment of the Lineament South is a seismogenic, WNW-ESE trending 3 to 6 km wide dextral strike-slip fault (Bartolome et al. 2012). This segment has been further explored and deep (>4 km) mud volcanoes have been found, evidencing the rise of deep fluids and formation of gas hydrates along the fault (Hensen et al. 2015).

Methods

Surveys on submarine active faults and landslides integrate the most advanced technologies in marine geosciences covering different scales of resolution, which is the key to study active processes. It includes a) acoustic mapping techniques and seismic imaging methods, which allow the geomorphic evidence of the structures and stratigraphic evidence of past seismic activity; and b) sediment sampling and analyses, which allow characterizing and dating specific horizons and earthquake-triggered mass transport deposits to obtain the recurrence interval of large magnitude events. However, up to now, seafloor processes remain poorly understood because of the lack of high-resolution imaging at great depths (>3000 m). Even the most advanced hull-mounted or deep-towed marine, geophysical instrumentation do not provide the same degree of observation detail and accuracy as the current techniques used onland. The acquisition of high-resolution data using state-of-the-art underwater vehicles, such as Autonomous Underwater Vehicles (AUV) operated/employed in the INSIGHT project (Fig. 2), is a way around this limitation.

Dataset used in this work includes:

A. Ship-based techniques on board the RV Sarmiento de Gamboa to characterize the seafloor:

1) Swath-bathymetry and acoustic backscatter allowing geomorphological studies to depict recent and active geological processes. It provides information on fault extension or areal coverage of mass transport deposits, and recent seafloor deformation, with an accuracy of 50 cm or 0.2% the water depth. Multibeam bathymetry-derived backscatter is important to understand lateral variability in sediment composition and provides additional clues on sedimentary processes.

2) Sub-bottom profiler (Atlas Parasound P35), allows identifying the shallow structure and sedimentary units in the first tens of meters below the seafloor with a resolution of a few decimeters. Recent and past sedimentary processes are inferred from acoustic facies. Parametric sub-bottom data is useful to quantify fault offsets, to characterize the tridimensional geometry of mass-failure deposits and to determine the presence of fluids.

3) Sediment coring (Gravity), providing a ground truth of the data imaged by acoustic methods, in this case, penetration is often limited to 3-5 m maximum. Sediment core analyses include grain size measurements, physical properties (magnetic susceptibility, GRAPE density, P-wave velocity, Lightness) and geochemical composition by using the non-destructive X-Ray Fluorescence (XRF).

B. Nonship-based techniques:

1) The AUV "Abyss": is an autonomous underwater vehicle of the REMUS 6000 type owned by the German research facility IFM-GEOMAR and one of the barter equipment offered by Germany in the OFEG (Ocean Facilities Exchange Group). It is designed to work up to 6000 m depth, using a multibeam echosounder with 200/400 kHz (microbathymetry and water column imaging) at an

average working speed of 2.5-4 knots.

2) The 2D multi-channel High-Resolution seismic reflection method image geological features and sedimentary basin infill by using an airgun array of 930 c.i. at 3.5 m depth, able to work down to 4000 m depth, providing 2 m resolution in 2 s TWTT profile section.

Results and Discussion

Seismic and tsunami hazards have been characterized up to now in the short period of instrumental and historical earthquake catalogs. During the last decade, an effort has been made to adapt the paleoseismological approach to slow active faults offshore, such as the ones from the Gulf of Cadiz and Alboran Sea (Gràcia et al. 2003). Data recently acquired in the framework of INSIGHT survey and project should be processed and analyze during the next months, particularly seismic profiles. Despite that, and based on the preliminary images that we have collected, we have recorded the crucial data for obtaining parameters to assess the seismic and tsunami hazard in the future

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