IFM-GEOMAR REPORT

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Leibniz-Institut für Meereswissenschaften
an der Universität Kiel

RV Poseidon POS389 & POS393 & RV Maria S. Merian MSM15/5 TOPO-MED

- Topographic, structural and seismotectonic consequences of plate re-organization in the Gulf of Cadiz and Alboran Sea –

POS389: Valletta, Malta – Malaga, Spain
06.–17.08.2009
POS393: Malaga, Spain – Faro, Portugal
14.–24.01.2010
MSM15/5: Valletta, Malta - Rostock, Germany
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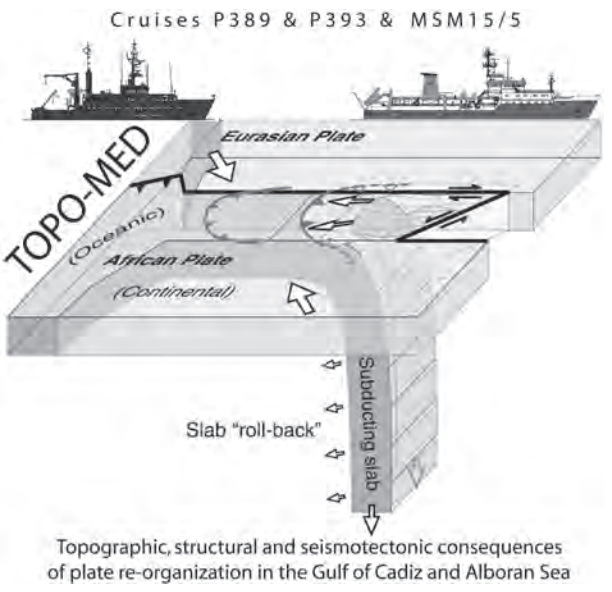

Berichte aus dem Leibniz-Institut
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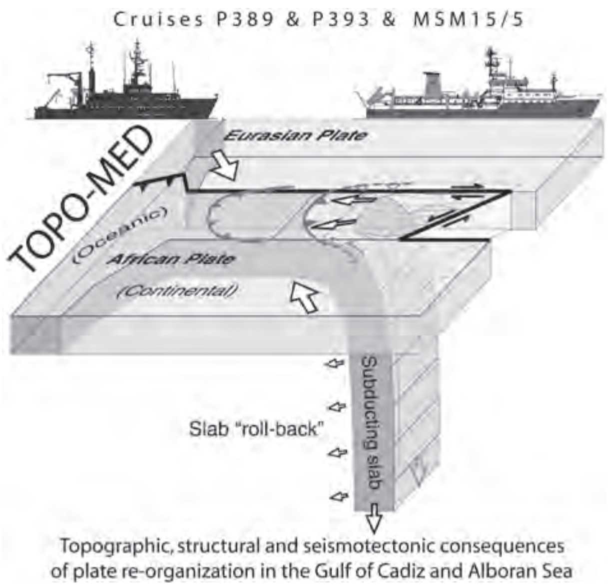

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1.1 Summary / Zusammenfassung

The evolution from the Western Mediterranean Sea is inherently governed by (i) plate convergence between Nubia (Africa) / Eurasia and (ii) subduction related slab-roll back. Both processes are responsible for the surface features / topography of the Gulf of Cadiz / Gibraltar Arc / Alboran Sea / Rif / Betic domain and deep-seated features related to the consumption of African lithosphere. The project is part of the ESF-EUROCORES programme TOPO-EUROPE and is aiming to study the interrelation between convergence and major tectonic fault zones in the Gulf of Cadiz and the Alboran Sea (Trans-Alboran-Shear-Zone – Alboran Ridge) and Miocene subduction / deep-seated seismicity at 40-150 km depth. Monitoring networks with ocean bottom seismometers (OBS) and hydrophones (OBH) were installed first in the Alboran Sea (August 2009 to January 2010) and later in the Gulf of Cadiz (January 2010 to July 2010), providing for the first time local earthquake data collected on ocean bottom stations. First results suggest that the collected data are of every good quality to assess seismotectonics in both domains and yielding travel time data for unique tomographic images of the Gibraltar arc area and Alboran domain, providing seismic constraints on the structure of crust and mantle.

Die Entwicklung des westlichen Mittelmeers ist gesteuert durch (i) die Konvergenz von Afrika und Eurasia und (ii) durch die Bewegung bereits subduzierter Lithosphere im Erdmantel, dem sog. Slab Roll-Back. Bedeide Prozesse prägen sowohl die Oberflächengestallt der Region Golf von Cadiz / Gibraltar Bogen / Alboran See / Rif / Betics als auch die Mantelregion mit der konsumierten (subduzierten) Afrikanischen Lithospäre. Das Projekt ist Teil der ESF-EUROCORES Initiative TOPO-EUROPE und hat das Ziel, den Zusammenhang zwischen der Plattenkonvergenz und großskaligen Störungsstrukturen in dem Golf von Cadiz und in der Alboran See (Trans-Alboran-Scherzone – Alboran Rücken) und Miozäner Subduktion / Tiefe Erdbeben in 40-150 km zu untersuchen. Um dieses Ziel zu erreichen, wurden Beobachtungsnetzwerke mit Ozeanboden-seismometern (OBS) und Hydrophonen (OBH) zur Registrierung der lokalen und regionalen Erdbebenaktivität ausgelegt. Es wurde jeweils für 5-6 Monate die Seismizität in der Alboran Sea und im Golf von Cadiz registriert. Eine erste Analyse der Daten deutet auf einen hervorragenden Datensatz hin, der uns wichtige Erkenntnisse über die Seismotektonik der Region liefern wird. Darüber hinaus liefern die Ozeanbodenseismometer exzellente Laufzeitinformationen für tomographische Untersuchungen der Region, um die Krusten- und Mantelstruktur entlang der Nahtstelle zwischen Europa/Spanien und Afrika/ Marokko abzubilden.

The Logo shown on the front page is based on a cartoon published by Marc-Andre Gutscher in Science honouring the 250 anniversary of the Great Lisbon earthquake of 1755 (Gutscher, 2004).

2. Scientific Prospectus and Aims

2.1. Introduction

The European Science Foundation (ESF) issued within the framework of EUROCORES an initiative to study the "4-D Topography Evolution in Europe: Uplift, Subsidence and Sealevel Change", short TOPO-EUROPE. The western Mediterranean Sea and adjacent continents changed their "face" profoundly over the last 35 Myr. Major changes where mainly driven by the Eurasian/Nubian convergence and subsequent slab roll-back, trench retreat and back-arc extension. A consortium of European research institutions and universities took on the challenge to study the evolution of the western Mediterranean subduction system in a Collaborative Research Project (CRP) called "*TOPO-MED – Plate re-organization in the western Mediterranean: lithospheric causes and topographic consequences*". The proposal is funded by all partner countries. The German contribution is funded through the DFG grant GR1964/12-1.

Rationale of TOPO-MED. The western Mediterranean subduction system, from the northern Apennines to southern Iberia including the tightly-formed Calabrian and Gibraltar Arcs, mostly evolved during Cenozoic time in response to Eurasia-Nubia convergence. The first phase, prior to 30 Ma, was dominated by orogenic wedging. Since 30 Ma, slab roll-back and trench retreat (Fig. 2.1) led to the development of the Alboran, Algerian, Liguro-Provencal and Tyrrhenian back-arc basins, and the almost complete consumption of the African oceanic lithosphere in the region (Fig. 2.2). Through arc-continent collisions (North Africa, Adria) this resulted in the end of subduction, with some important final stage effects ongoing in the Gibraltar (Gulf of Cadiz, Lisbon 1755 earthquake) and Calabrian Arcs. This major slab roll-back process gave the western Mediterranean margins their very peculiar and truly unique character. After subduction had largely ended, Eurasia-Nubia convergence, with associated N-S compression, continued and became the primary process. To accommodate continuing convergence, new plate boundaries (subduction zones) must be initiated. Key questions are: where and how does (did) that happen, and what are the consequences? Geological, geodetic and seismological data indicate compressional inversion ongoing along the coast of northern Sicily, Algeria, and the northern and southern limbs of the Gibraltar Arc. The age of the start of this inversion is uncertain, but likely to be younger than 5 Ma (in some cases < 2 Ma). Similarly, transitional features are observed along the coast of the Liguro-Provencal Basin.

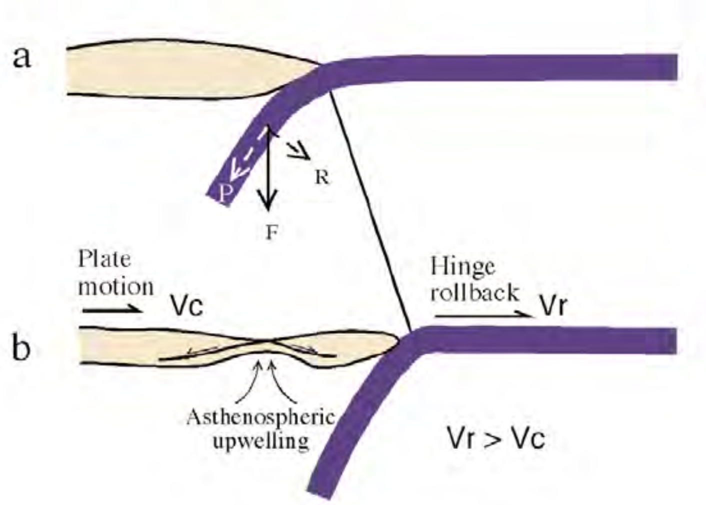


Figure 2.1. Slab roll back is a major mechanism forming the Mediterranean Basin and adjacent continents by causing extension and hence rifting (from Rosenbaum and Lister, 2004).

The western Mediterranean offers a unique opportunity for studying this intriguing process. Results obtained in earlier international projects provide the platform necessary to identify and investigate the transition. Better knowledge of mantle structure (below northern Africa), crustal and lithospheric architecture and recent tectonic/morphological history of the western Mediterranean margins is required to gain understanding of the active geodynamic processes. The latter, in turn, is a prerequisite for mitigation of natural hazards, such as earthquakes and tsunamis, along the densely populated coastal lowlands of the Mediterranean Sea.

Within the framework of the EUROCORES TOPO-EUROPE Programme a Collaborative Research Project (RCP) entitled **TOPO-MED** was scheduled. Main objectives were**:** (1) to determine the recent tectonic and morphological changes (including vertical and horizontal motions) related to the final stages of the slab roll-back phase and the onset of compressional inversion in the coastal regions surrounding the western Mediterranean (i.e. last 5-10 Ma at least), and (2) to unravel links between surface/shallow processes and deep lithospheric/mantle structures and dynamics.

Milestones are (1**)** a map of newly generated onshore/offshore morphological features and faults along the continental margins; (2) a new definition of deep structure of the margins, and (3) a comprehensive model of the present-day tectonic/seismic activity in the western Mediterranean region based on integrating geodynamic contributions of a variety of temporal and spatial scales. TOPO-MED included the following methodologies: surface geology, seismotectonics, multi-channel and refraction/wide-angle seismics, geodesy, geochronology and paleomagnetism, (micro-)structural, petrological, geochemistry (of mantle rocks), 3D gravimetry and geothermics, seismology/tomography, magnetotellurics, and numerical and analogue modelling.

Strategy, and research targets. TOPO-MED combined four main research targets (A to D below). Each integrated complementary studies, methods and approaches from different institutions. Most tectonic domains were probably formed in response to one single, major process in the mantle. The ambition of this project and its partners is to provide a comprehensive, integrated framework for the whole western Mediterranean continental margins.

A. The Gibraltar Arc (Spain, Morocco): Improved understanding requires constraints on deep lithospheric and mantle/slab structures, associated mantle flow, relative motions of tectonic blocks and microplates and their topographic expression, present-day coexistence of extension and compression, and denudation of subcontinental mantle that provides information concerning lithospheric thermomechanical thinning and rollback processes, back-arc extension and associated small-scale convection.
B. Maghrebides and Atlas (Morocco-Algeria-Tunisia): The Maghrebides are of particular importance for the northern boundary of the African plate and its related topographic and seismic hazards. The Atlas (Morocco-Algeria) exhibits complex architecture combining inherited structures from pre-collisional rifting and asthenopheric upwelling attested by quaternary volcanism and recent topographic uplift. Integrated seismic and magnetotelluric imaging, gravity, geodetic measurements and neotectonics analyses inland and offshore will illuminate coupling relationships between deep structures and present-day tectonics suggesting strong compressional inversion. Mantle imaging will provide superior understanding of relationships between mantle upwelling beneath the Atlas and slab roll-back processes further north.
C. Calabrian Arc (Italy): Imagery of the slab beneath the Apennines, the Calabrian arc and Sicily and its induced flow in the surrounding mantle is exemplary and will be used to test numerical and analogue modelling of lateral and vertical strain distribution. Such modelling will elaborate plausible scenarios of evolution and will be of particular importance in tectonic hazards and tsunami genesis characterization.
D. Alpes-Liguro-Provencal boundary (Italy-France): The junction between the Alpine belt and the oceanic Ligurian basin is a complex active boundary resulting from Cenozoic compressional and

extensional events. A pluri-disciplinary approach will characterize the surface, crustal and lithospheric structures that accommodate deformation, space and time relationships between the active extensional and compressional deformation, possible northern Ligurian margin inversion, and its driving mechanism.

Partners. There is one Individual Project (IP) per participating country (7 in total) form the Netherlands, France, Italy, Spain, Ireland, Portugal, and Germany in collaboration with partners from Algeria, and Morocco.

Within the work package of TOPO-MED the German proponets and co-workers from Spain (CSIC Barcelona, Univ. Granada) will focus their efforts on the research targets A and B.

2.2 Evolution of the Gibraltar arc / Alboran sea / Betic-Rif margin

The evolution of the western Mediterranean sea has been amoung the most complex tectonic events in the least 35 Myr. Figs. 2.1 to 2.5 illustrate key features of the evolution and earthquake distribution and mechanisms reflecting a complex tectonic setting.

Extension in the Mediterranean has been intimately related with orogenesis, initiating early, as syn-orogenic extension affecting the shallower levels of the orogenic wedge [*Platt*, 1986], probably detaching in the ductile-brittle transition. Further extension is commonly related with the interaction between the orogenic wedge and underlying subducted or delaminated lithosphere, producing backarc basins in the interior of tight orogenic arcs such as the Calabrian and Gibraltar arcs in the Western Mediterranean [e.g. *Royden*, 1993; *Lonergan and White*, 1997; *Carminati et al.*, 1998; *Faccenna et al.*, 2001; 2004; *Rosembaum and Lister*, 2004]. This later extension is typically accompanied by magmatism and although it is denominated “post-orogenic extension” it is normally coeval to further shortening in more external regions of the orogenic arc [e.g. *García-Dueñas et al.*, 1992; *Martínez-Martínez and Azañón*, 1997; *Platt et al.*, 2003]. Post-orogenic extension is assumed to follow a retreating or delaminating slab, migrating behind the thrusting orogenic belt, such as in the Calabrian or Hellenic arcs [*Royden, 1993; Faccenna et al., 2001; Jolivet, 2001*]. However, the application of such scenario to the Gibraltar arc is a matter of debate for several reasons, among which we can stress the polymetamorphic evolution of its Internal Zones [e.g. *Balanyá et al.*, 1997; *Azañón and Crespo-Blanc*, 2000; *Booth-Rea et al.*, 2005*; Platt et al.*, 2006], the late intracrustal emplacement of the subcontinental Ronda peridotites [e.g. *Balanyá et al.*, 1997; 1998; *Sánchez-Gómez et al.*, 2002] or the age and distribution of crustal extension in the Alboran and Algero-Balearic basins. Here basement highs drilled at Ocean Drilling Program Site 976 in the West Alboran basin register extension starting in the Lower Miocene [*Platt et al.*, 1998; *Comas et al.*, 1999], whilst 200 km to the east, away from the subduction front, oceanic crust and supposedly very thin continental crust in the transition between the East Alboran and the Algero-Balearic basins are onlapped by Upper Miocene sediments [*Comas et al.*, 1995; *Booth-Rea*, 2004], showing an inversion in the age of extension polarity.

Latest Miocene extension in the East Alboran basin and its northern margin, the eastern Betics, is controversial because this region was interpreted to be the site of important Upper Neogene contractive tectonics related with N-S to NW-SE plate convergence between Africa and Eurasia [e.g. *Montenat et al.*, 1987; *Coppier et al.*, 1990; *Griveaud et al.*, 1990; *Montenat and Ott d´Estevou*, 1990; *Stapel et al.*, 1996; *Keller et al.*, 1995; *Huibregtse et al.*, 1998; *Comas et al.*, 1999; *Jonk and Biermann*, 2002]. Widespread volcanism had been genetically related with the occurrence of large-scale transcurrent faults cutting through the eastern Alborán basin and the eastern Betics [*Bellon et al.*, 1983; *Hernandez et al.*, 1987; *de Larouzière et al.*, 1988], although, later work has interpreted this volcanism as mostly extensional [*Comas et al.*, 1999; *Benito et al.*, 1999; *Turner et al.*, 1999]. Recently the tectonic context of these rocks has been reinterpreted, placing them in the context of Neogene arc magmatism at the eastern Alborán basin formed above the subducting Tethys slab coeval to lithospheric mantle delamination under the continental Betic and Maghrebian margins [*Duggen et al.*, 2004; 2005; *Gill et al.*, 2004].

Tomographic studies (Fig. 2.3) have evidenced the existence of an eastern to south-eastern dipping high velocity body in the upper mantle below the Gibraltar arc, interpreted as subducted oceanic lithosphere or delaminating continental lithosphere [*Blanco and Spakman*, 1993; *Calvert et al.*, 2000; *Gutscher et al.*, 2002; *Faccenna* et al., 2004]; or a combination of both, inferring roll-back of oceanic lithosphere under the central areas of the Alborán basin, coupled with continental lithospheric mantle delamination under the Betic-Rif margins [*Duggen et al.*, 2004; 2005; *Martínez-Martínez et al.*, 2006].

A growing body of independent evidence supports this latter hypothesis:

1) Middle to Late Miocene volcanic rocks of tholeiitic through calc-alkaline series typical of arc magmatism outcrop across of the eastern Alborán basin and the Betic-Rif margins. Their chemistry reflects fluids and melted sediments from subducted Tethys oceanic lithosphere [*Gill et al.*, 2004; *Duggen et al.*, 2002; 2004; 2005]. Upper Miocene to Pliocene Si-K-rich magmatism together with coeval to Quaternary Intraplate-type magmatism in the Southeast-Iberian and Maghrebian margins indicate the melting and interaction of two different mantle sources, metasomatized subcontinental lithosphere and sublithospheric plume-contaminated mantle [Duggen et al., 2005]. This magmatic suite and coeval lithospheric uplift has been related with subcontinental-edge delamination associated with upwelling of plume-contaminated sub-lithospheric mantle [Duggen et al., 2004; Gill et al., 2004; *Duggen et al.*, 2005] or slab break-off in the Algerian-Rifean margin [*Maury et al.*, 2000; *Fourcade et al.*, 2001; *Coulon et al.*, 2002].
2) Extensional brittle-ductile westward-directed detachments [*Galindo-Zaldívar et al.*, 1989; *García-Dueñas et al.*, 1992; *Jabaloy et al.*, 1993; *Martínez-Martínez and Azañón*, 1997; *Martínez-Martínez et al.*, 2002; 2004], exhumed the deepest metamorphic complex of the Internal Betics during the Middle to Late Miocene [*Johnson et al.*, 1997]. These low-angle extensional faults and associated E/W-oriented dextral and sinistral transfer faults [*Martínez-Martínez*, 2006] are in principle incompatible with the general NW-SE plate convergence between Africa and Iberia and have been related with deep lithospheric processes occurring below the Betics, such as subcontinental lithospheric delamination [*García-Dueñas et al.*, 1992; *Martínez-Martínez and Azañón*, 1997; *Martínez-Martínez et al.*, 2006] or slab roll-back [*Royden*, 1993; *Lonergan and White*, 1997].
3) Active seismicity in the Gibraltar arc region is produced mostly by structures formed in the context of NW-SE plate convergence [*Grimison and Chen*, 1986; *Buforn et al.*, 1995; *Morel and Meghraoui*, 1996; *Stich et al.*, 2003; 2006], however, both the presence of intermediate and deep earthquakes below the Alborán basin and the Betic margin [e.g. *Buforn et al.*, 2004] and the occurrence of many focal mechanisms with E-W to NE-SW oriented P-axes [*Martínez-Martínez et al.*, 2006] require the presence of a deep slab that disturbs the strain field expected from NW-SE plate convergence.
4) An upper Tortonian subsidence peak related with extension is identified in the Alborán basin [*Rodríguez-Fernández et al.*, 1999; *Hanne et al.*, 2003]; and its margins, such as the eastern Betics [*Fernández and Guerra-Merchán*, 1996; *Rouchy et al.*, 1998; *Soria et al.*, 2001]. The orientation of many Tortonian faults related with this subsidence peak, producing N-S directed extension, is in principle incompatible with NW-SE convergence (e.g. *Lonergan and Schreiber*, 1993; *Booth-Rea and Azañón*, 2003).

Currently two conflicting scenarios have been proposed for Upper Neogene tectonics in the Alborán basin and the eastern Betics: One scenario proposes contractive tectonics producing strike-slip faults and folds with sedimentation occurring in syncline basins and in regions of subsidiary extension in transtensional segments [e.g. *Montenat and Ott d´Estevou*, 1990], and a second scenario proposes that arc magmatism [*Gierman et al.*, 1968; *Galdeano et al.*, 1974; *Gill et al.*, 2004; *Duggen et al.*, 2005] and coeval crustal extension [*Lonergan and Schreiber*, 1993; *Krautworst and Brachert*, 2003; *Booth-Rea et al.*, 2004a] was more important than commonly proposed, but that this phase has been masked by Messinian to present contractive structures [*Booth-Rea et al.*, 2004b; *Martínez-Martínez et al.*, 2006].

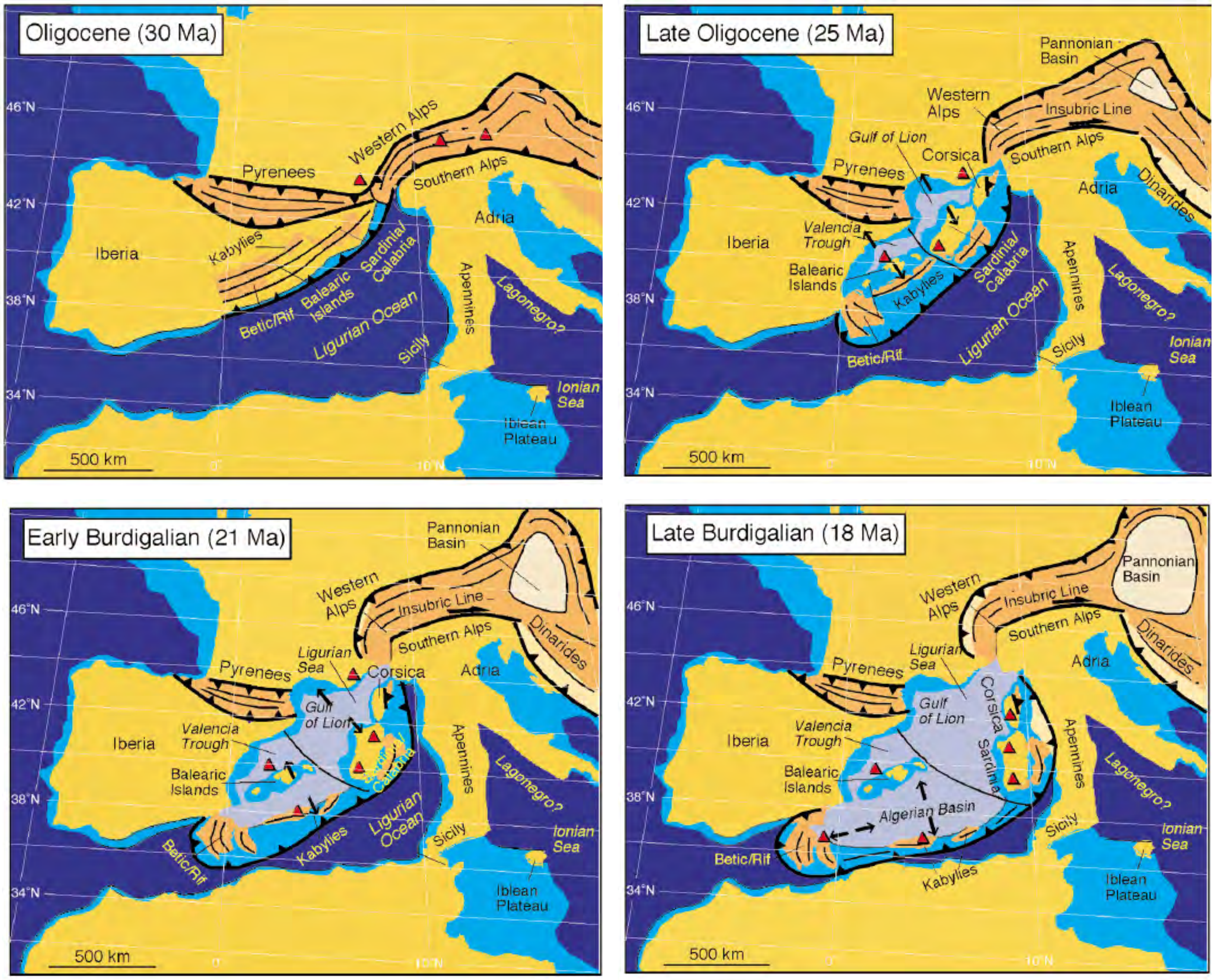


Figure 2.2a. Tectonic reconstruction (Rosenbaum and Lister, 2004)

A major short coming is still that rocks in the Alborán sea are difficult to sample as sediments prevent sampling in most areas, except where faults have exposed volcanic rocks or where Ocean Drilling Program (ODP) drilling sample igneous basement [*Platt et al.*, 1998; *Comas et al.*, 1999; *Duggen et al.*, 2004; 2005]. Though high quality seismic data that penetrate down to mantle depth are limited in the Alborán sea, multichannel seismic reflection (MCS) data obtained during the ESCI-Alboran cruise [*Comas et al.*, 1995] image the transition between the Alboran and the Algero-Balearic basins. Seismic time sections support the idea of a magmatic arc and hence subduction related evolution of the area [*Booth-Rea et al.,* 2007]; data indicate a crustal thickness decrease from west to east from about 5 s Two way Travel Time (TWTT,~15 km thick) to ~2s TWTT typical of oceanic crust (~6 km thick). Three crustal domais could be interpreted in terms of crustal thickness and seismic character. Tilted blocks related to faulting are very scarce and all sampled basement outcrops are volcanic suggesting that the crust was dominantly formed by magmatic processes in the transition between a magmatic arc and a backarc setting, from west to east. The sediments onlapping the igneous basement young from east to west between 12 and approximately 8 Myr in agreement with radiometric dating of volcanic rocks in the region

[*Duggen et al.*, 2004; 2005]. Linking seismic crustal structure with magmatic geochemical evidence suggests that the three crustal domains may represent – from west to east – thin continental crust modified by arc magmatism, magmatic arc crust and oceanic crust fromed at a back arc spreading centre [*Booth-Rea et al.,* 2007]. Recently collected seismic wide-angle and refraction data from research vessel *Meteor* cruise M69/2 support this interpretation. Middle to upper Miocene arc and oceanic crust formation at the Alborán and Algero-Balearic basins, respectively, occurred during westward migration of the Gibraltar arc and shortening in the Betic-Rif foreland basins. Arc magmatism and associated backarc oceanic crust formation was related to early to middle Miocene subduction and roll-back. Subduction of the narrow Gibraltar arc slab beneath the Alborán basin was coeval with the collision of the Alborán domain with the Iberian and Nubia passive margins and subsequent subcontinental-lithosphere edge delamination along the Betic-Rif margins [*Duggen et al.*, 2005].

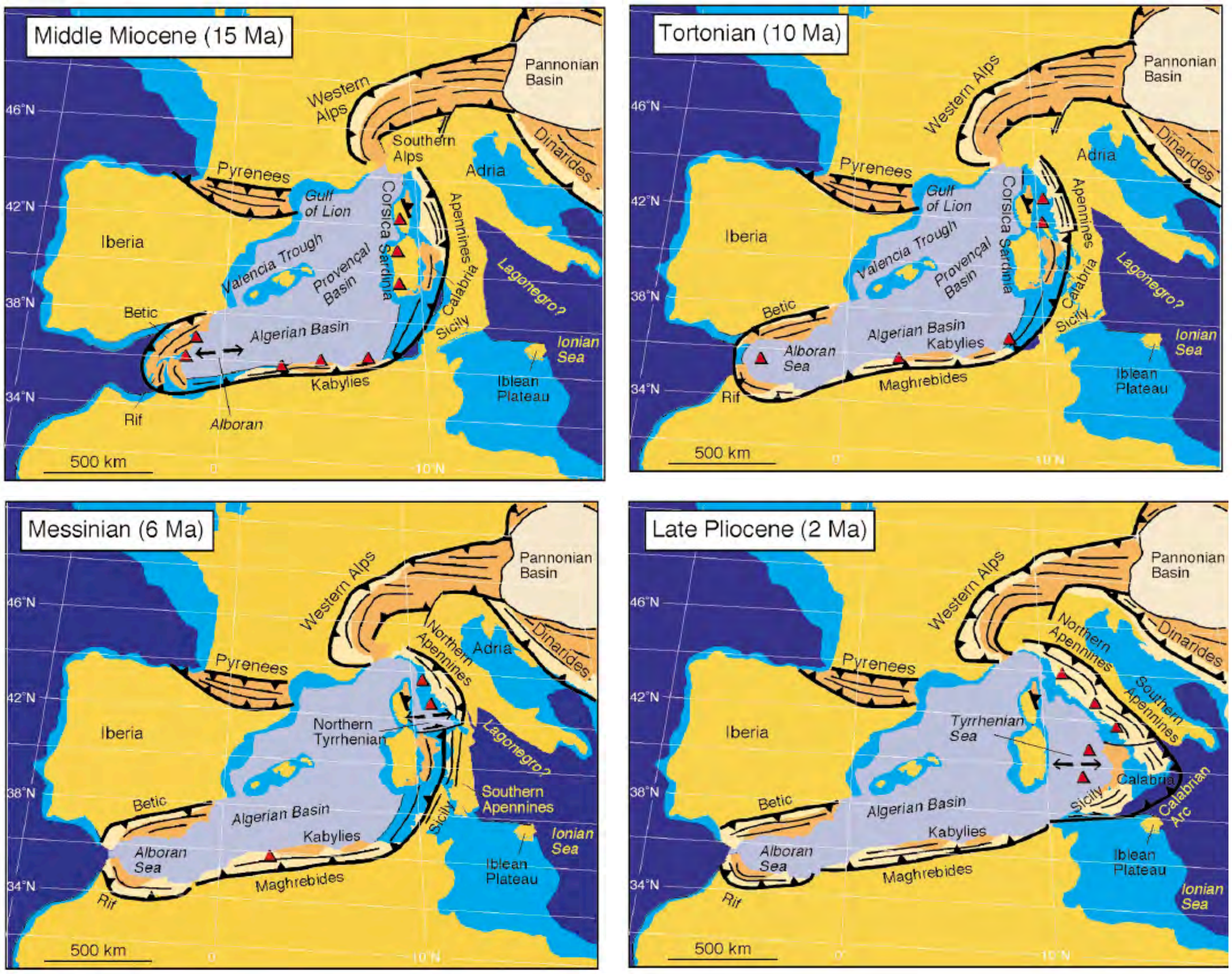


Figure 2.2b. Tectonic reconstruction (Rosenbaum and Lister, 2004)

2.3 Seismotectonics of the Gibraltar arc / Alboran sea

The area along and to the north and south of the Iberia-Nubia plate boundary delimited by the epicenters of shallow earthquakes (< 40 km) represents the surface expression of the plate boundary (Fig. 2.4 and 2.5). Three different areas A to C have been defined by *Buforn et al.* [2004] in terms of distribution of seismicity and fault mechanisms. In areas A and C (Gulf of Cadiz and Algeria regions) the plate boundary corresponds to a narrow band well defined by the seismicity, where large earthquakes (M > 7) occur in association with horizontal compression N-S to NNW-SSE due to the convergence of Eurasia and Africa. In northern Algeria, reverse faulting with SE-NW (~N140°E) oriented P axes dominates (Fig. 2.5) [*Stich et al.*, 2003].The intermediate-depth earthquakes (40-150 km depth) occur primary under the Alborán sea (though a few occur to the southwest of Iberia in area A, but are generally <70 km). No intermediate-depth earthquakes have been observed in the eastern part of the region (area C). In area B the plate boundary is more diffuse and corresponds to a wider area that includes the Betics, the Alboran Sea and the Rif. It is difficult in this case to identify a simple line that corresponds to the plate boundary. Rupture mechanisms are predominantly strike-slip with nearly N-S oriented P axes (~N170°E) and nearly E-W oriented T axes (~N80°E). Most mechanisms include a minor component of normal faulting, consistent with the observed regional extension [*Stich et al.*, 2003]. Moment rate, slip velocity and b values indicate that the strain accumulated in the region is released partly in a continuous seismic activity of moderate magnitude over the whole area [*Buforn et al.,* 2004]. Earthquakes with magnitudes larger than 6 occur at prolonged intervals. From historical seismicity it may be concluded that the 20th century was a period of anomalously low levels of seismic activity in this area.

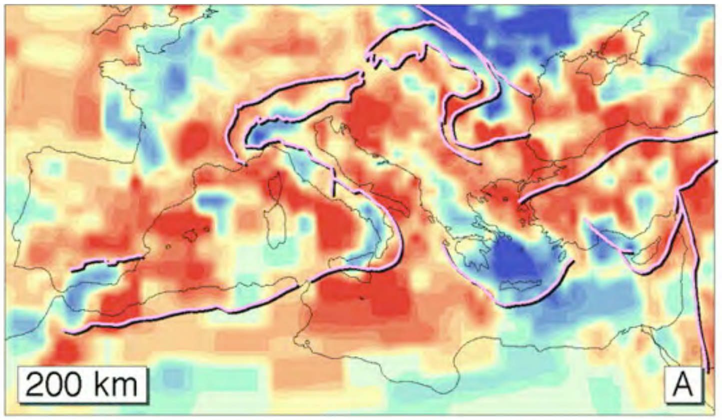


Figure 2.3a. Tomographic image of the mantle at a depth of 200 km in the Mediterranean Sea.

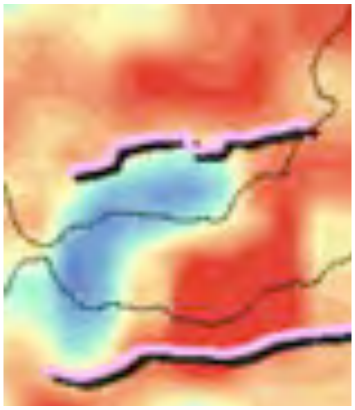


Figure 2.3b. Blow-up shows high velocity material interpreted as subduction slab "hanging" under the Alboran Sea

The existence of important seismic activity at intermediate depth (60 to 150 km) extending in a very narrow vertical band 50-km wide in N-S direction may be explained by the existence of a seismogenic block, of approximate dimensions 200-km long, 150-km deep and 50-km wide, on the eastern side of the Strait of Gibraltar. Inside this block the stress regime, deduced from focal mechanisms of earthquakes, corresponds to nearly vertical tension dipping to the SE [*Buforn et al.,* 2004]. Different tectonic models have been proposed for this region, such as some kind of subduction process, extensional collapse of thickened continental lithosphere, continental lithospheric delamination, backarc extension caused by subduction roll-back (see previous chapter). Some of these models, such as continental lithospheric delamination, are not compatible with the presence of the intermediate-depth earthquakes and their focal mechanisms. The results presented here are consistent with the model of an almost vertical slab of material with strike N-S driven by the extensional E-W forces present on the Alborán Sea, and under NW-SE compressive forces [*Buforn et al.,* 2004]. The slab is being stretched downward, possibly by gravitational instability processes. Models which propose very low angle subduction or delamination [*Calvert et al.*, 2000, and other tomographc models] are not compatible with the results presented in this paper, due to the vertical distribution of hypocenters. Whatever explanation is given for the tectonics of this region, it must satisfy the geometry of the location of hypocenters and their focal mechanisms.

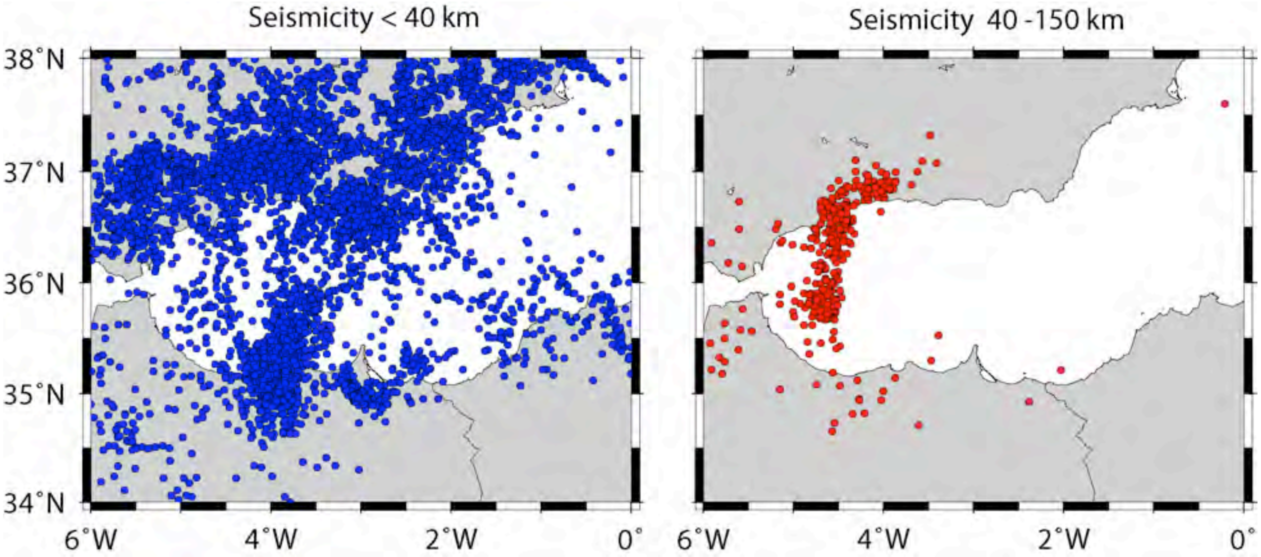


Figure 2.4. Shallow earthquakes (< 40 km; blue) of the Alboran / Rif / Betic domain indicating one of the most tectonically active areas on Earth. Deep seismicity dips nearly vertically and fault mechanisms suggest downward stretching, which is inconsistent with subduction zone models.

2.4 Goals

Roughly 30 Myr ago, slab roll-back and trench retreat led to the development of the Alborán, and Algero-Balearic back-arc basins. Neogene subduction was coeval with continental collision and subsequent delamination processes in the Betics/Rif. Subduction beneath the Alborán and Algero-Balearic basins occurred between the middle and late Miocene, resulting in the formation of the Alborán volcanic arc between middle and late Miocene. Subduction stopped or slowed down greatly after late Miocene, probably because the subducting oceanic lithosphere was consumed and replaced towards the west by continental lithosphere of the Maghrebian and south Iberia passive margins.

After subduction had largely ended, Eurasia-Nubian convergence, with associated N-S compression, continued and became the primary process. To accommodate continuing convergence, new plate boundaries must be initiated. Geological, geodetic and seismological data indicate compressional inversion ongoing along the coast of northern Algeria and thus may represent a newly developing subduction zones. The age of the start of this inversion is uncertain, but likely to be younger than 5 Ma (in some cases < 2 Ma). However, why does plate convergence results into two different modes: simple thrusting along the Algerian margin and complex accommodation in the Alborán sea and Gulf of Cadiz, where oblique over thrusting and/or strikes-slip faults occur? Heat flow in the Alborán sea is with 100-120 mW/m^2 high and mantle is characterised by low density. What is the nature of the mantle? How does high heat flow affects the earthquake distribution along major faults? Thus, down to which depth are faults seismogenic?

In the Gulf of Cadiz, waveform studies based on land-based seismometers (Stich et al., 2005) provided earthquakes at mantle depth. In general earthquakes are crustal events. Thus, is this feature robust or related to bias caused by a lack of offshore seismometers?

Tomographic images of the mantle domain under the Alborán sea suggest an eastward dipping area of fast material, perhaps associated with a subducting slab. However, intermediate depth earthquakes (40-150 km) are nearly distributed vertically and centred at longitude 4°30'W and thus seem to be inconsistent with tomographic images. Is a lack of resolution responsible for inconsistency? We aim to increase the resolution by placing seismological station into the Alborán sea, recording local, regional and teleseismic earthquakes. Offshore stations are supplemented by stations in Spain and Morocco operated by Spanish project partners.

In summary, main aims of the offshore seismological monitoring are:

a) Defining active faults outlined by local earthquakes in the Alboran sea and Gulf of Cadiz. Does seismicity delineates the plate boundary between Europe and Africa?
b) Defining the maximum depth of earthquakes away from the band of intermediate depth earthquakes. Thus, do earthquakes occur in the crust or even at mantle depth?
c) Providing for the first time travel time data recorded at offshore stations from local, regional and teleseismic earthquakes to be used in tomographic inversions.
d) Characterisation of mantle underlying the Gibraltar arc / Alboran domain and earthquake distribution
e) Defining the nature of the tomographically imaged "*subducting lithosphere*"

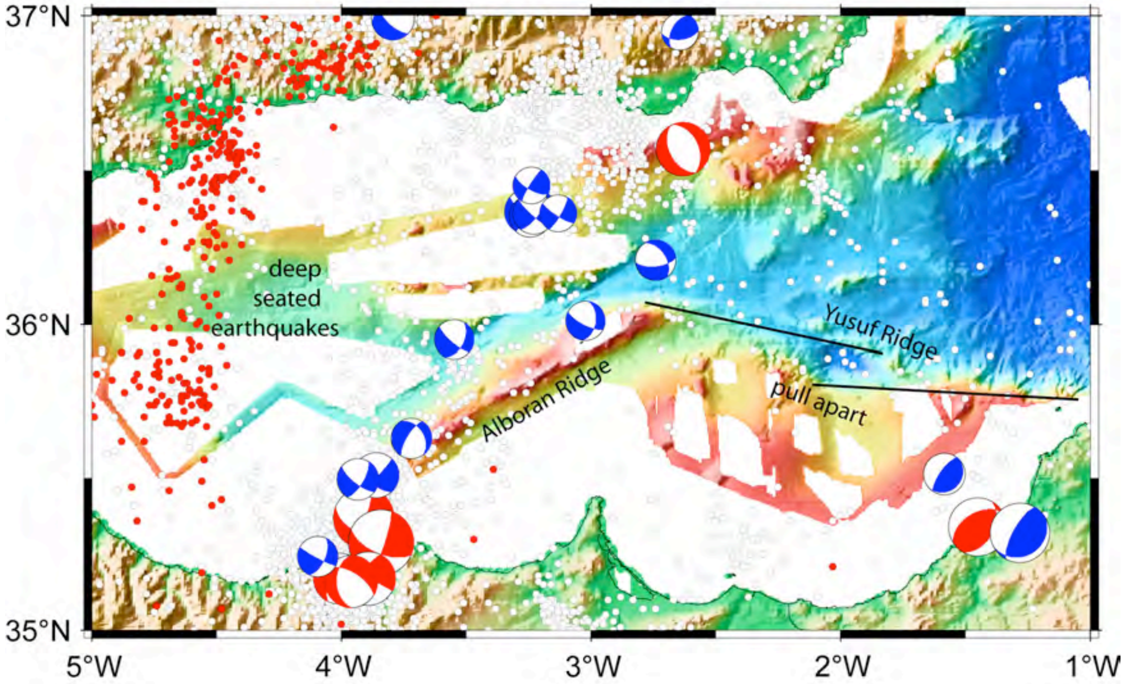


Figure 2.5. Earthquake mechanism in the Alboran domain indicating a complex accommodation of N-S shortening related to the Nubian-Eurasian convergence. Red dots are deep-seated earthquakes (>40-150 km). Mechanisms: blue: Stich et al., 2003; red: gCMT

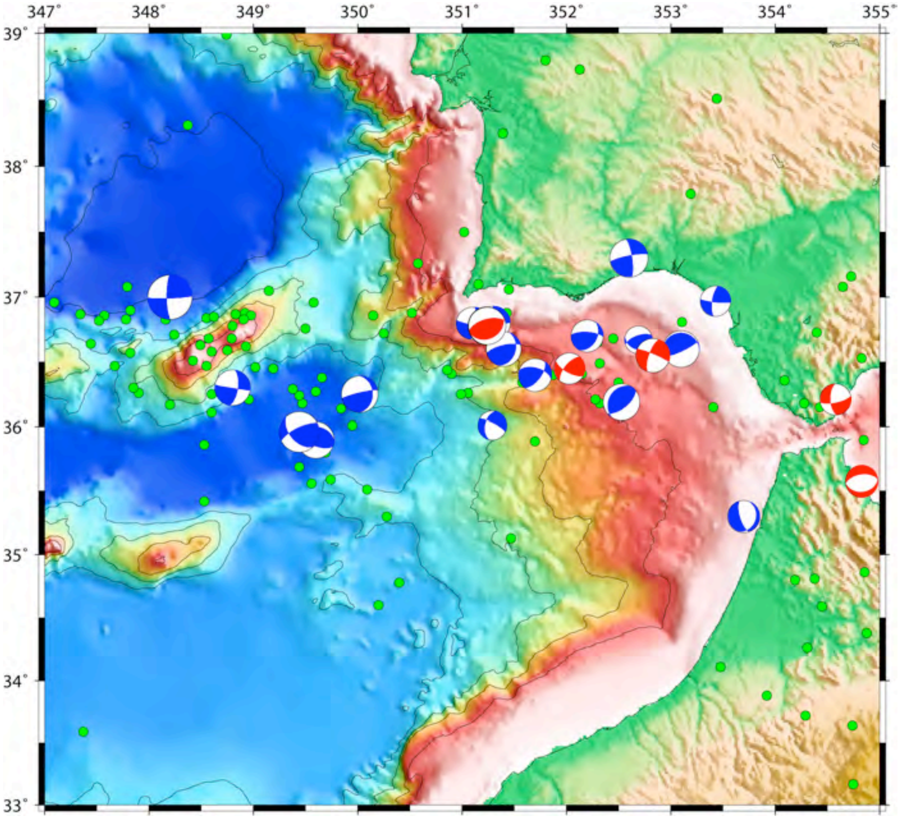


Figure 2.6. Earthquake mechanism to the west of the Gibraltar arc in the Gulf of Cadiz, indicating – like in the Alboran domain – a complex accommodation of N-S shortening related to the Nubian-Eurasian convergence. Mechanisms: blue: Stich et al., 2003; 2005; red: gCMT

3. Sea-going programme

3.1 RV *Poseidon* cruise P389

3.1.1 Narrative of the Cruise P389

On August 6, 2009 research vessel *Poseidon* left the harbour of Valletta, Malta at 18:40 local time and started its transit into the Alboran Sea, Western Mediterranean Sea. Good weather conditions facilitated a cruising speed of more than 9 kn. Poseidon reached the working area in the Alboran Sea after 3 days and 21 hours and the transmitter of the ELAC multibeam echosounding system was deployed, facilitating seafloor mapping. The first ocean bottom seismometer (OBS) was deployed at 16:43 h local time. Deck operation was scheduled for 6 a.m. to 22 p.m. Three OBS could be deployed on Monday August 10, 2009. In the night wind speed picked up and reached magnitude 9-10 on the Beauford scale and the sea state became very rough. *Poseidon* escaped the worst weather condition by sailing into the Bay of Almeria. In the morning hour the wind speed decreased to 6-7. *Poseidon* left the bay and sailed towards the next deployment position. Unfortunately, the sea state was still pretty rough. Average wave height was 3-4 m with maximum wave height of 5-6 m. Thus, deployment of stations was not possible. However, during the day the wind speed decreased to 3-4. At 18:14 local time we started deploying OBS. On average one OBS was deployed per hour. On Wednesday August 12, 2009 wave height decreases to nearly perfect working condition. We could deploy 12 OBS and three ocean bottom magnetometer (OBM). On Thursday 10 OBS and one OBM were deployed. On Friday August 14, 2009 four OBS and two OBM were dropped, leaving an ocean bottom monitoring network with 30 OBS and 6 OBM in operation. After deployment of the network we started mapping efforts in Moroccan waters filling gaps in the existing multibeam bathymetric coverage of the Alboran Sea. On Sunday August 16 at 9:00 we stopped mapping and sailed towards Malaga, meeting the pilot at 16:00 local time.

3.1.2 Cruise participants P389

Name	Discipline	Institution
Grevemeyer, Ingo, chief scientist	OBS	IFM-GEOMAR
Brandt, Thomas, technician	OBMT	IFM-GEOMAR
Schröder, Patrick	OBMT	IFM-GEOMAR
Schwenk, Arne, technician	OBS	KUM
Brunn, Wiebke, scientist	OBS	IFM-GEOMAR
Doktor, Eva, student	OBS	IFM-GEOMAR
Pesquer, David, scientist	OBS	IFM-GEOMAR
Shulgin, Alexej, scientist	OBS	IFM-GEOMAR

IFM-GEOMAR	Leibniz Institut für Meereswissenschaften, Wischhofstraße 1-3, 24148 Kiel, Germany
KUM	KUM Umwelttechnik GmbH, Wischhofstraße 1-3, 24148 Kiel Germany

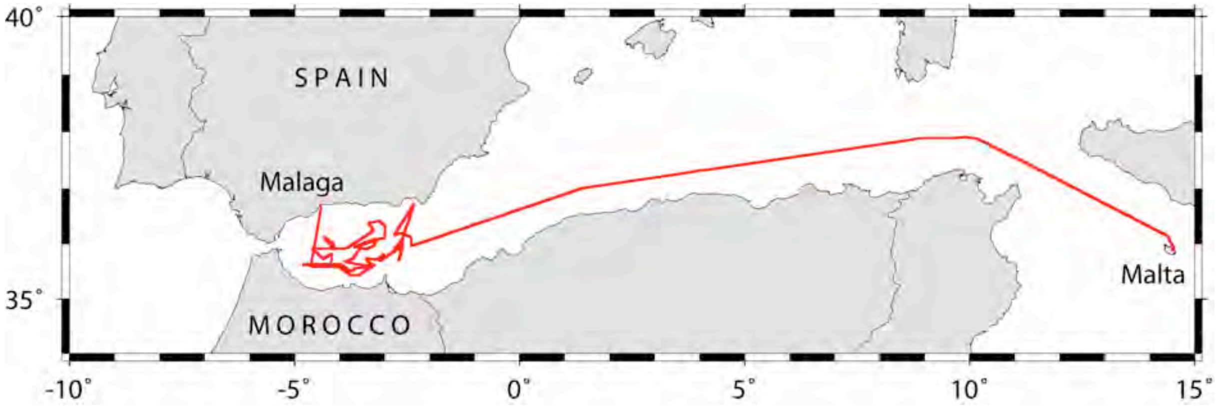


Figure 3.1. Track chart of cruise P389.

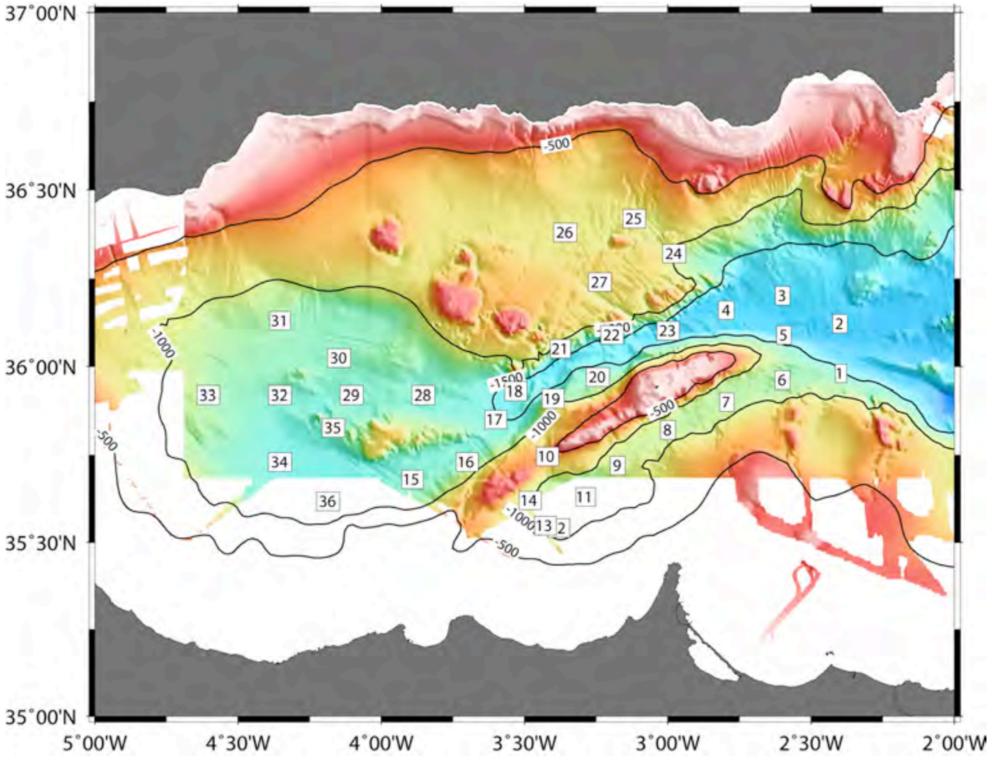


Figure 3.2. Network of ocean bottom seismometers (OBS) operated between August 2009 and January 2010 in the Alboran Sea.

3.2 RV *Poseidon* cruise P393

3.2.1 Narrative of the Cruise P393

Poseidon left the harbour of Malaga, Spain with a delay of one day. Due to strong winds of 9 Bft. waves of up to 7 m height had been predicted for the Alboran sea. On Friday January 15, 2010, the weather has improved and weather conditions were good for at least the next four days. *Poseidon* left Malaga around sunrise at 8:20 local time and sailed straight to the deployment location of OBS16; OBS16 was deployed in August 2009 during RV *Poseidon* cruise P389. The OBS was released on January 15, 2010 at 15:30 local time. At 15:50 h the first instrument was recovered. During the next three days we recovered all 30 OBS deployed during the first Leg of the programme TOPO-MED, *Poseidon* cruise P389. In general, recovery and later deployment was stopped during night time between 22 h and 6 h. The last station was recovered at 16:32 local time on Monday January 18, 2010. Thereafter, we started our transit into the Gulf of Cadiz. In the Morning of Tuesday at 8:20 local time the first OBS, station 31, was deployed. Deployment continued for the next three days. The last station, OBS54, was deployed at 10.50 a.m. on Friday January 22, 2010. *Poseidon* headed towards Faro and reached the port in the morning of January 24, 2010.

Figure 3.3. Track chart of cruise P393.

3.2.2 Cruise participants P393

Name	Discipline	Institution
Grevemeyer, Ingo, chief scientist	OBS	IFM-GEOMAR
Labahn, Erik, technician	OBS	KUM
Brunn, Wiebke, scientist	OBS	IFM-GEOMAR
Dannowski, Anke, scientist	OBS	IFM-GEOMAR
Möller, Stefan, scientist	OBS	IFM-GEOMAR
Shulgin, Alexej, scientist	OBS	IFM-GEOMAR
Breuer, Christian, student	OBS	IFM-GEOMAR

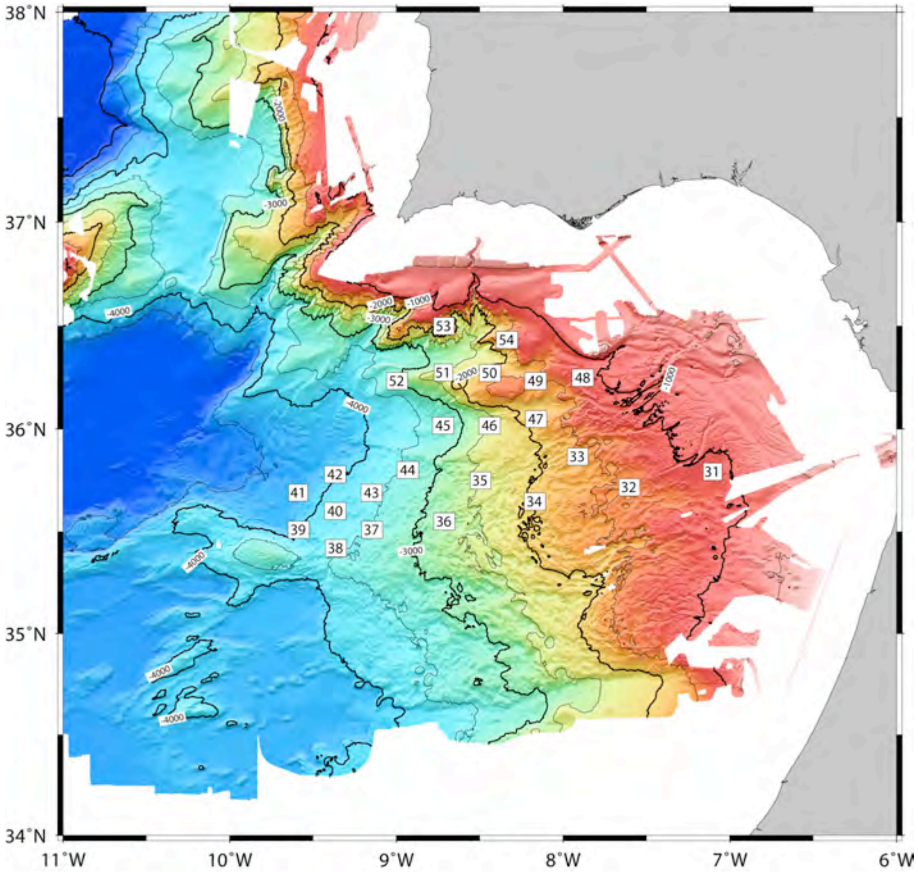


Figure. 3.4. Network of ocean bottom seismometers (OBS) deployed in the Gulf of Cadiz. The network operated between January and July of 2010.

3.3 RV *Maria S. Merian* cruise MSM15/5

3.3.1 Narrative of the Cruise MSM15/5

Maria S. Merian left the harbour of Valletta, Malta, on July 17, 2010 at 10 p.m. Ten hours after leaving Valletta, a multi-net was deployed to the south of Sicily for sampling planktonic foraminifera in the uppermost 700 m of the water column. A second multi-net was taken a day later after entering the territorial waters of Algeria. Due to the tight time constraints of the cruise, sampling of foraminifera during the remaining time of the cruise was conducted just in the surface water using pumps. However, using pumps samples could be take continuously during the transits. On July 21, 2010, at 8 a.m. the *Maria S. Merian* reached the Strait of Gibraltar, entering the Atlantic Ocean before midday. A few hours later, at 17:21 local time the first ocean-bottom-seismometer was released, being recovered at 17:51. Within the next 46 hours all 24 OBS were recovered in record time. The last OBS was on deck at 15:30 local time and we headed north. Within the next days the *Maria S. Merian* sailed past Portugal, through the Bay of Biscay, reaching the English Channel on midday of July 26, 2010. At 9.00 a.m. on July 28 German waters were entered. At 17:30 h the Pilot was met in the German Bight off Cuxhaven. At 20:45 h the *Maria S. Merian* sailed past the “Alte Liebe” and entered at 22:10 h the “Nord-Ostseekanal”. The passage through “Schleswig Holstein” ended in Kiel-Holtenau on July 29, 2010 at 6 a.m. and the *Maria S. Merian* headed toward Rostock. We reached the pilot station offshore of Rostock-Warnemünde on July 29, 2010 at noon and a successful cruise ended.

Figure 3.5. Track chart of cruise MSM15/5

3.2.2 Cruise participants MSM15/5

Name	Discipline	Institution
Grevemeyer, Ingo, chief scientist	Seismics, OBS/OBH	IFM-GEOMAR
Labahn, Erik, technician	OBS	KUM
Brunn, Wiebke, scientist	OBS	IFM-GEOMAR
Kraft, Helene, student	OBS	CAU
Tahayt, Abdelilah, scientist & observer		Morocco
Manzoni, Sonia, scientist & observer		Portugal
Aurahs, Ralf, scientist	Foraminifera	IFGTÜ
Schmidt, Christiane, student	Foraminifera	IFGTÜ
Steinhardt, Juliane, student	Foraminifera	IFGTÜ
Weiner, Agnes, scientist	Foraminifera	IFGTÜ

IFM-GEOMAR	Leibniz Institut für Meereswissenschaften, Wischhofstraße 1-3, 24148 Kiel, Germany
CAU	Institut für Geowissenschaften, Christian-Albrechts Universität Kiel, Otto Hahn Platz, 24108 Kiel, Germany
KUM	KUM Umwelttechnik GmbH, Wischhofstraße 1-3, 24148 Kiel Germany
IFGTÜ	Institut für Geowissenschaften, Eberhard Karls Universität Tübingen Sigwartstraße 10, 72076 Tübingen, Germany

4. Scientific equipment – Ocean Bottom Seismometers

IFM-GEOMAR operates Ocean Bottom Hydrophones (OBH) since January 1992. This type of instrument has proved to have a high reliability; more than 4000 successful deployments were conducted since 1992. A total of 22 IFM-GEOMAR OBS and 8 DEPAS OBS-Pool LOBSTER were available for the Alboran Sea deployment. For the deployment in the Gulf of Cadiz 19 IFM-GEOMAR OBS and 5 DEPAS LOBSTER were available. Thus, during TOPO-MED in total 54 seismometers were operated for long-term earthquake monitoring.

The OBS are a joint IFM-GEOMAR and KUM GmbH design for long-term seismological observations. Syntactic foam is used as floatation body. The release transponder is a model *K/MT562* made by *KUM GmbH*. The recording unit is hosted in a titanium pressure tube. Seismic sleuth are recorded by a hydrophone and a seismometer. The hydrophone is either an *E-2PD* hydrophone from *OAS Inc.* or a *HTI-01-PCA* hydrophone from *HIGH TECH Inc.* The sensitive seismometer is deployed between the anchor and the OBS frame, which allows good coupling with the seafloor. Geophones used for the IFM-GEOMAR OBS (Figure 4.1) had a 4.5 Hz natural frequency. The three component seismometers from KUM GmbH are housed in a titanium tube, modified from a package built by Tim Owen (Cambridge). The signal of the sensors is recorded using *Marine Longtime Seismocorder (MLS)* or *Marine Tsunameter Seismocorder (MTS)*, which are manufactured by SEND GmbH and specially designed for long-time recordings of low frequency bands. In addition, Güralp 3-component broadband seismometers (CMG 40T) were available for the 8 DEPAS-Pool LOBSTERs (Figure 4.2) hosted at Alfred-Wegener Institute in Bremerhaven. DEPAS instruments used *Marine Compact Seismocorder (MCS)* to record seismic signals.

While deployed on the seafloor the entire system rests horizontally on the anchor frame. After releasing its anchor weight the instrument turns 90° into the vertical and ascends to the surface with the floatation on top. This ensures a maximally reduced system height and water current sensibility during deployment. Further, the sensors are well protected against damage during recovery and the transponder is kept under water, allowing permanent ranging, while the instrument floats at the surface.

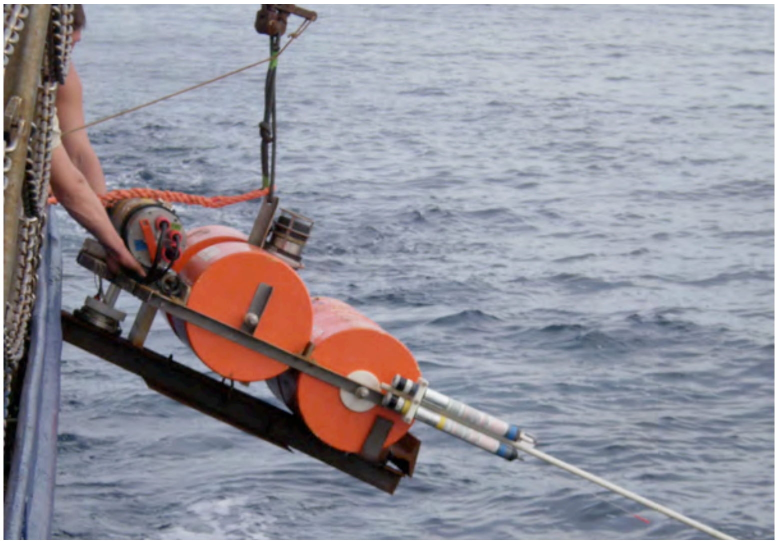


Figure 4.1 IFM-GEOMAR OBS with 4.5 Hz seismometer before deployment during P393

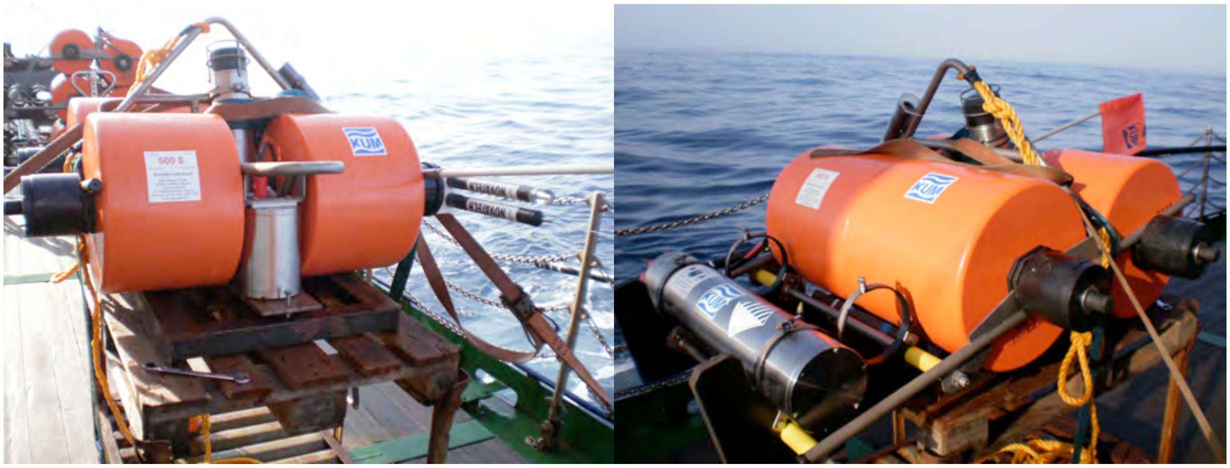


Figure 4.2 DEPAS-Pool OBS with CMG-40T broadband seismometer before deployment during P389.

Recorder type	Internal time base drift [ppm]	No. channels	Sampling rate [Hz]	Resolution	Storage media	Power consumption [mW]	Application
MLS – Marine Longterm Seismocorder	<0.05	4	1-200	50 Hz: 19 bit 200 Hz: 15 bit	PCMCIA Flash disks	250	active seismics, seismology
MTS – Marine Tsunameter Seismocorder	<0.05	5	1-200	50 Hz: 19 bit 200 Hz: 15 bit	PCMCIA Flash disks	250	active seismics, seismology
MCS – Marine Compact Seismocorder	<0.03	4	1-1000	24 bit	20 GByte hard disc	620 + 120 for Güralb CMG40T	seismology

Table 4.1. Performance of seismic recorders.

5. Data quality and first results

5.1 Alboran Sea deployment

5.1.1 Local earthquakes

The seismological network in the Alboran Sea recorded between 13 August 2009 and 15 January 2010 and hence over a period of 5 month. Raw data stored on the recorders were converted to Pseudo-segy or PASSCAL-Segy format of IRIS using *SEND* software. To generate more manageable files sizes and for applying time corrections, the files were cut into 25 hours records with one hour overlap between adjacent records, such that each record generally begins at 0:00:01. For all stations timing errors of the internal clock against GPS time were corrected.

To detect automatically seismic events in the daily records a short-term-average versus a long-term-average (STA/LTA) trigger algorithm was applied. The code used was REFTRIG from the IRIS PASSCAL program library. The trigger parameters include the length of the short term (s) and long term (l) time window, the mean removal window length (m), the trigger (t) and detrigger ratio (d), minimum number of stations (S) and the network trigger time window length (M). The trigger parameters were applied to unfiltered vertical component data of good quality. To test the trigger parameters a continuous 24 hours data stream of all stations is visually checked. Moreover, we tested the parameters for a number of days and transferred the data into the SEISAN package used to analyse and locate the local earthquakes. Applying these trigger parameters we obtain less than ~10% false triggers and lose only those events that were recorded only on a few stations, while all major events are triggered.

After finding event triggers the events were cut from the 25 hours files and stored into subdirectories, one per event. Because we are investigating local earthquakes the appropriate time window length for the events is 3 minutes, starting 30 s prior to trigger time. The SEGY traces in the event directories are converted first into SAC, and then into SEISAN waveform format, which makes it possible to store all traces associated with an event into a single waveform file. After conversion the data are registered into the SEISAN database (*Havskov and Ottemöller*, 2005). *P*-wave and *S*-wave arrival times are picked and events are preliminarily located with the program HYP, which employs an iterative solution to the nonlinear localization problem (*Lienert and Havskov*, 1995). Travel times are calculated using a 1-D velocity model base on the work of *Stich et al.* (2005). The velocity model consists of four layers with a velocity of 4.8 km/s in the uppermost 2 km, 6.0 km/s down to 12 km, 6.5 km/s down to 20 km, and a 7.8 km/s half space below. A test of several velocity models indicate that the epicentres are reasonable robust. However, a more refined model is needed for the post-cruise data analysis.

We detected about 180 local earthquakes with good station coverage. The largest event with M~4 occurred on 30 October 2009 at 90 km. Waveform examples are given in Figure 5.1. However, to obtain a reasonable good coverage we had to include stations from the Spanish TOPO-IBERIA programme, investigating the Iberian Peninsula and Morocco using a dense seismological network. Figure 5.2 gives an overview of the TOPO-IBERIA stations closest to the Alboran Sea.

Most events occurred at a depth of < 20 km and are associated with the Alboran Ridge and its continuation in Morocco. Further, a number of events are associated with a fault system offshore of southern Spain that is clearly visible in the bathymetry (Figure 5.2). A source depth of <20 km suggest that all events are crustal earthquakes. Except about 10 intermediate depth earthquakes at 80-110 km below the western Alboran Basin the western domain remains seismically inactive. The intermediate earthquakes support a near vertical band of earthquakes below the western basin that has been established from land-based observations (e.g., *Buforn et al.*, 2004) believed to be related to subduction (e.g., *Gutscher et al.*, 2002; 2004).

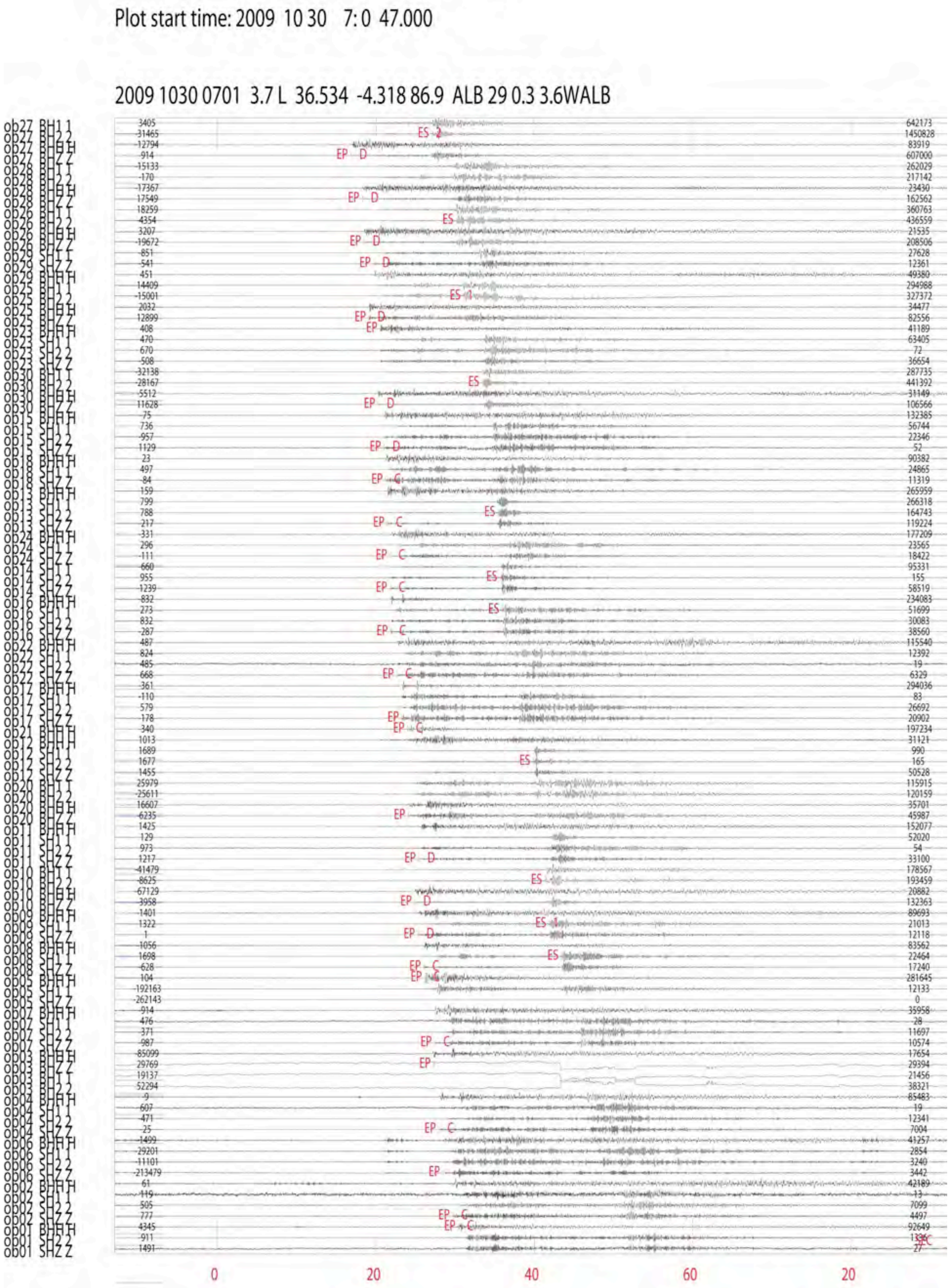


Figure 5.1. Waveform example of a M~4 event recorded on October 30, 2009.

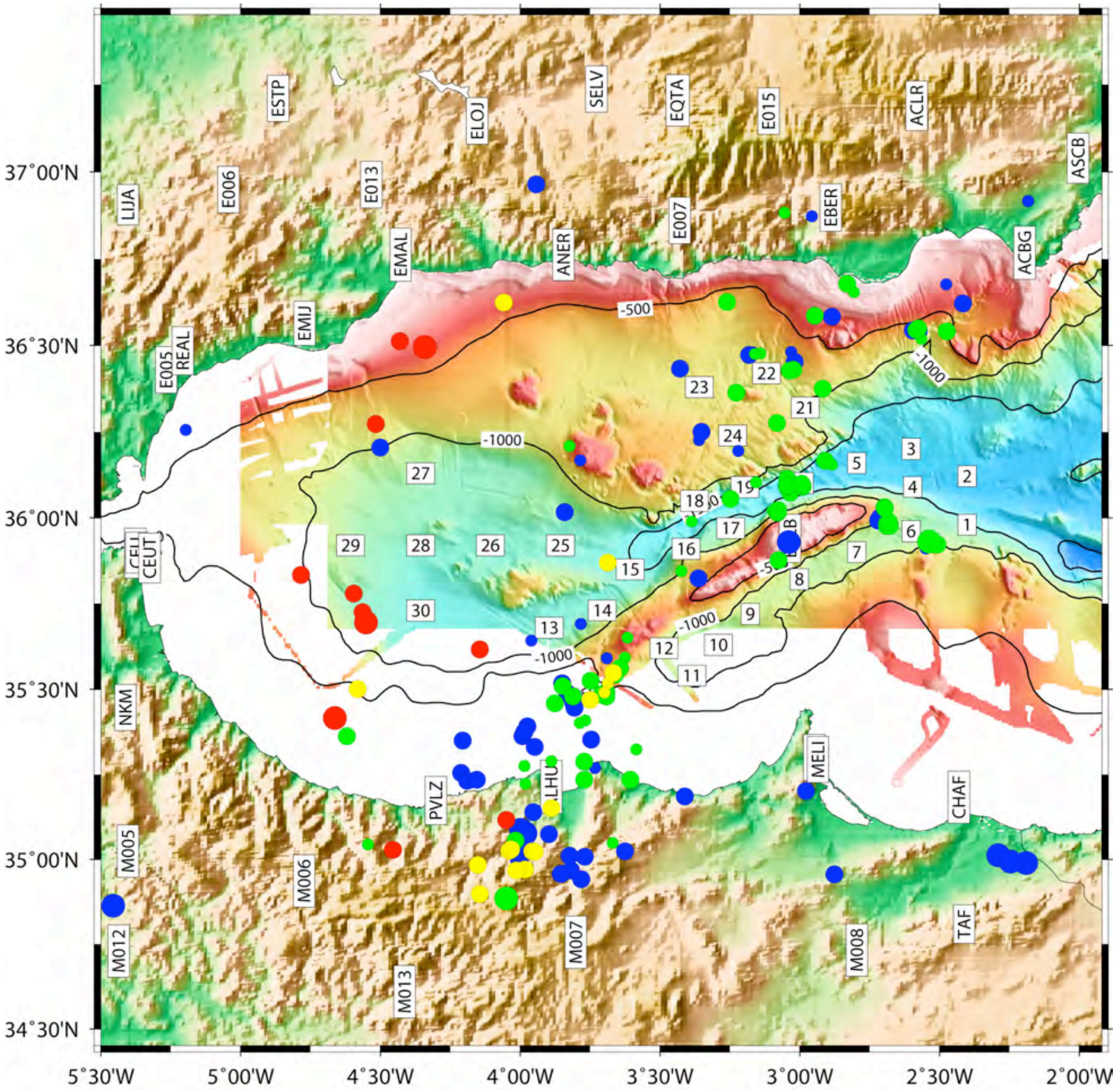


Figure 5.2. Earthquakes recorded with the TOPO-MED offshore network. The dataset has been complemented by data from the TOPO-IBERIA onshore network. Earthquake magnitude scales with the size of the symbols (magnitude ~3.8 to 1.8); depth is coded by colour: blue < 5 km; green 5 km < z < 20 km, yellow 20 km < z < 50 km; red > 50 km.

Further constraints on the structure of the basin will be available from local earthquake tomography. Yet, all tomographic studies are based entirely on recordings on land-based seismometers. Including the 180 local earthquakes recorded during the Alboran deployment on both OBS stations and TOPO-IBERIA seismometers in Morocco and southern Spain will greatly improve the resolution and is expected to yield the resolution needed to resolve the deep structure of the Alboran Sea and the proposed subductiong slab.

5.1.2 Teleseismic arrivals recorded at the Alboran network

The seismological network performed very well and detected arrivals from distant earthquakes at high quality both on the 8 CMG40T broadband sensors and on the hydrophone channels of the OBS. Examples are given for the Mw=7.2 2010 Haiti earthquake in Figure 5.3 (unfiltered) and Figure 5.4 (filtered) and for the Mw=7.9 2009 Sumatra earthquake in Figure 5.5 (unfiltered) and 5.6 (filtered). Figures 5.7 and 5.8 provides delay times with respect to the model IASPEI91 of the onshore/offshore network for seismometer and hydrophone data for a Mw=6.0 occurring on August 20, 2009 south of Svalbard and for the Mw=7.9 Sumatra event of September 30, 2009 shown in Figures 5.5 and 5.6.

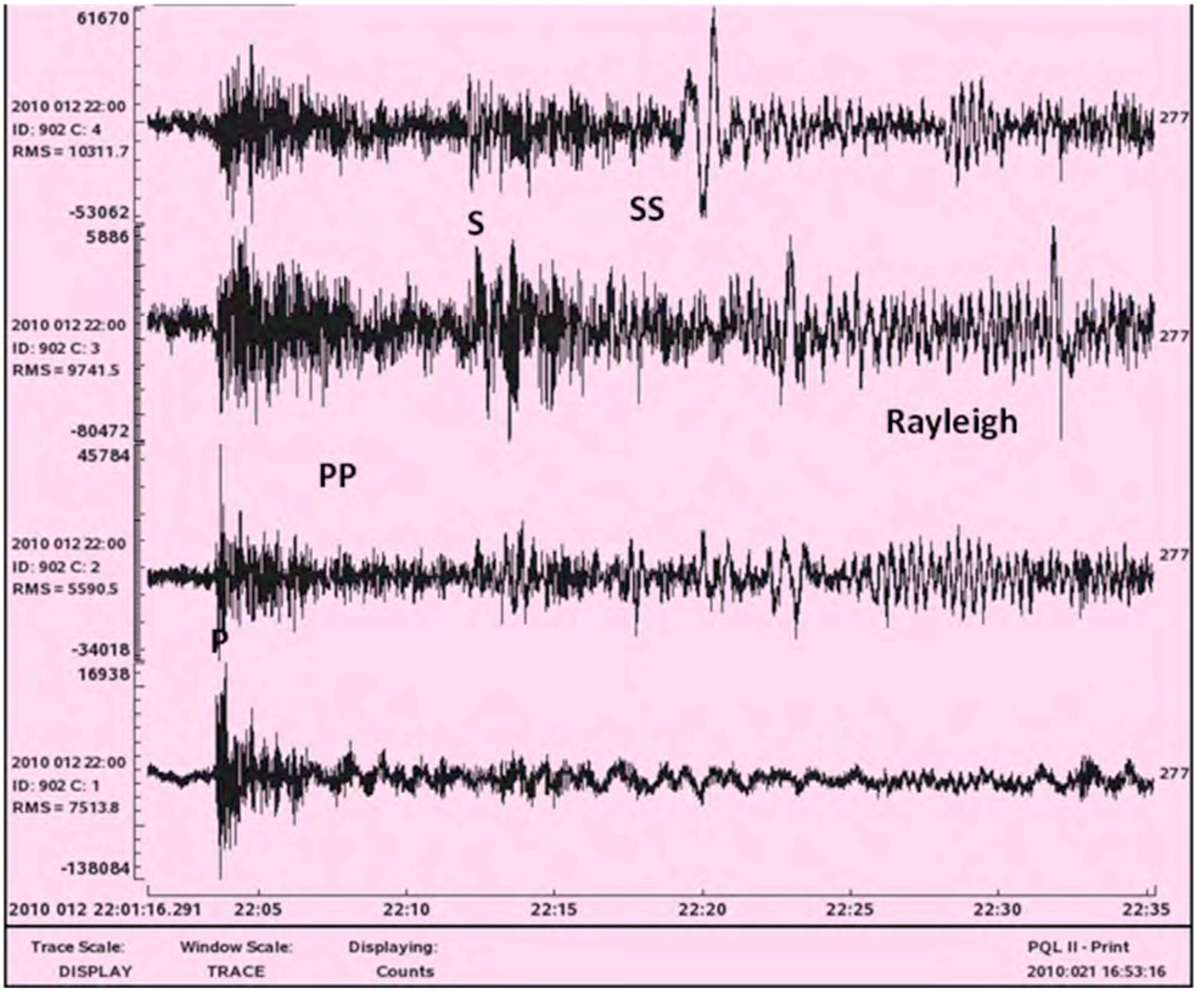
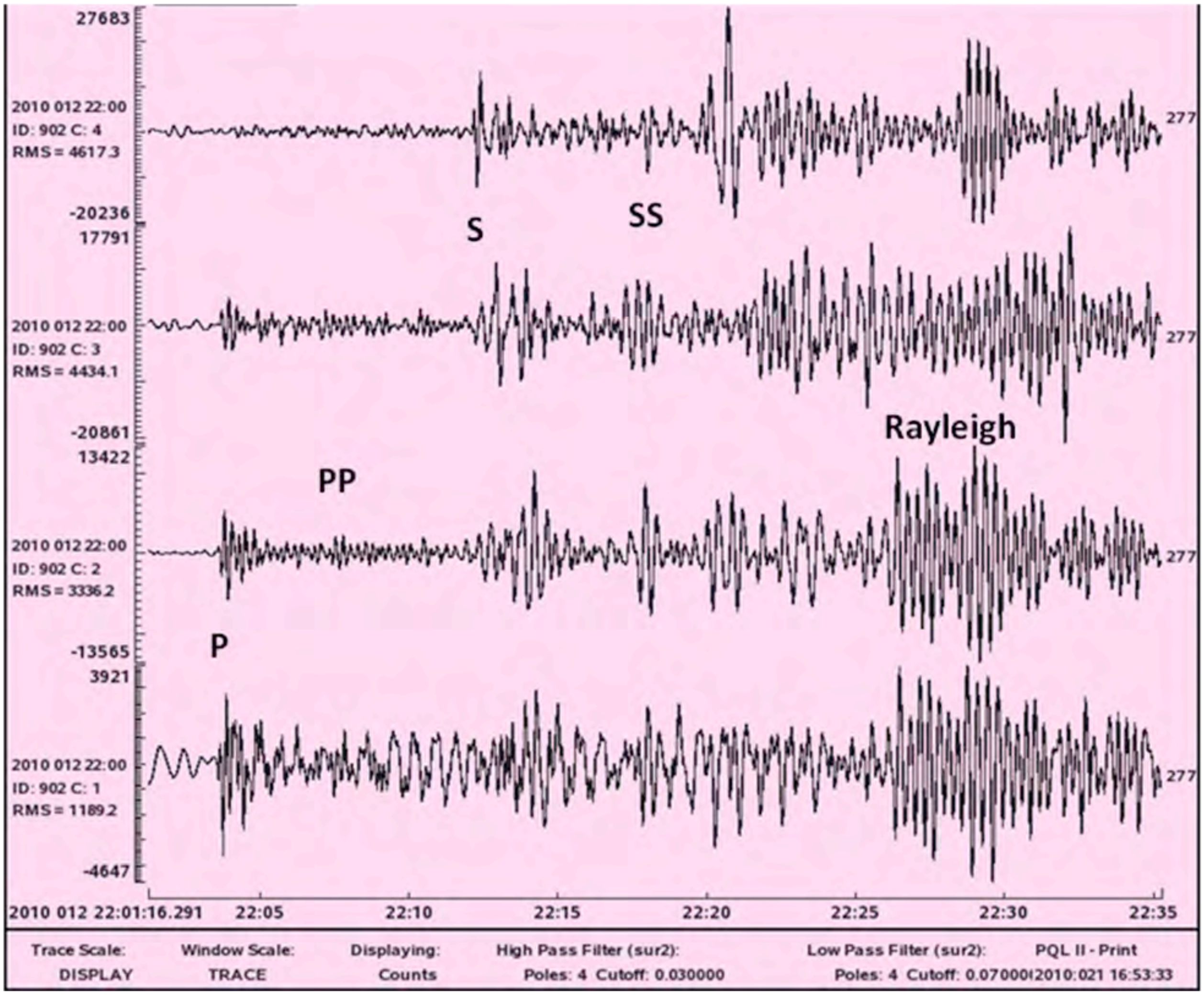


Figure 5.3. Mw=7.2 2010 Haiti earthquake, unfiltered waveforms of OBS10



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Low Pass Filter (sur2): Poles: 4 Cutoff: 0.07000(
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Figure 5.4. Mw=7.2 2010 Haiti earthquake, bandpass filtered waveforms of OBS10

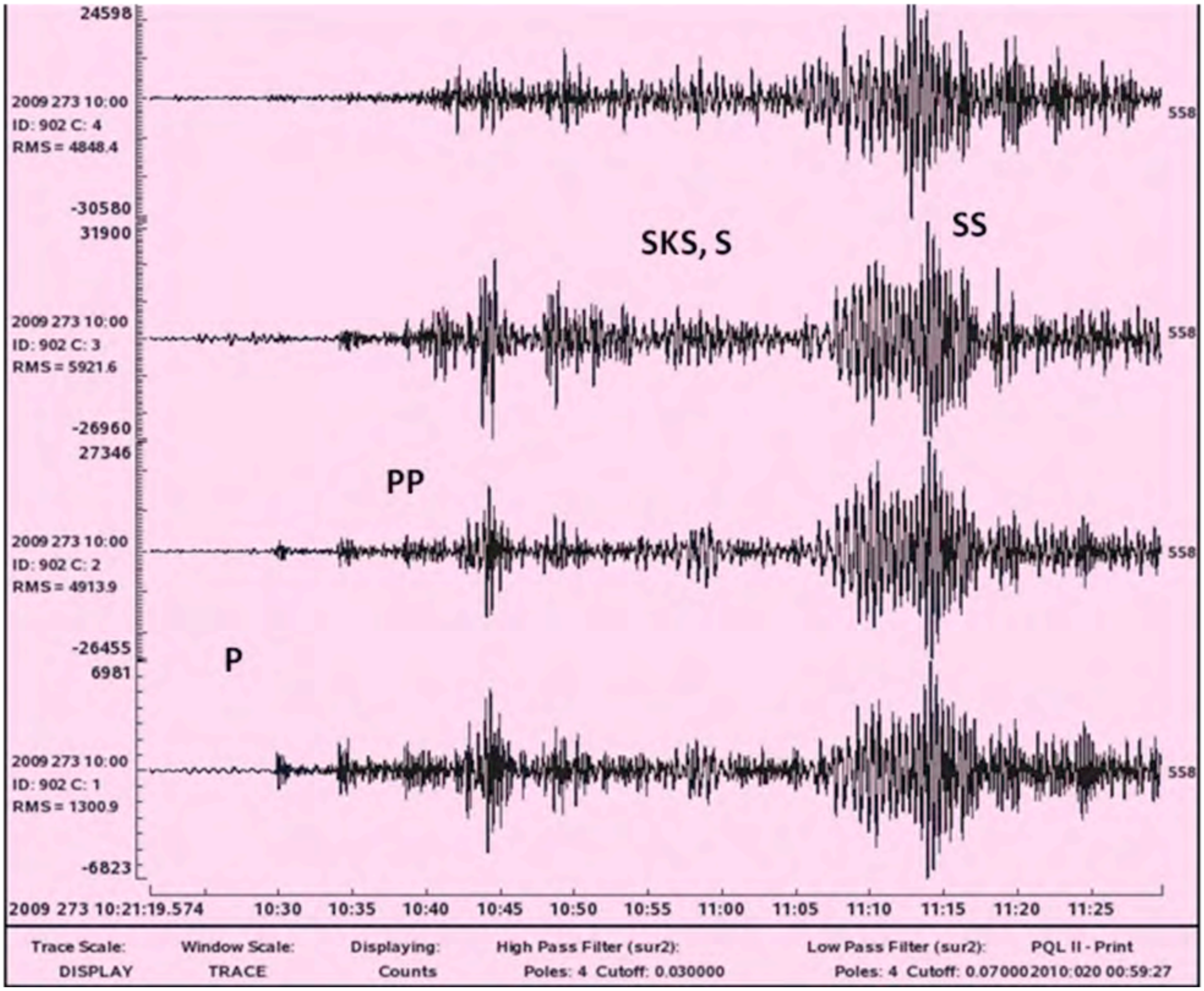

Figure 5.5. Mw=7.9 2009 Sumatra earthquake, unfiltered waveforms of OBS10

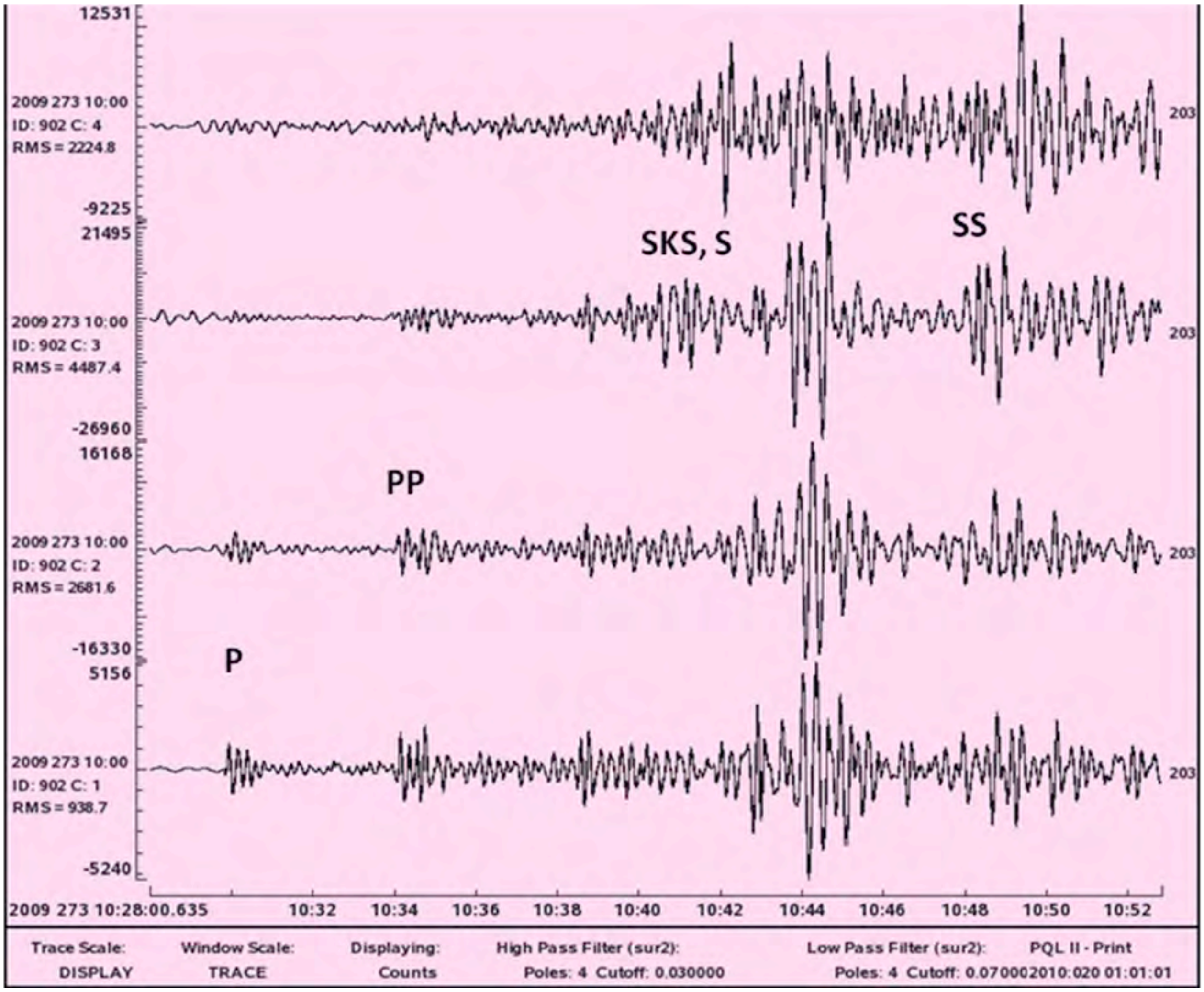

Figure 5.6. Mw=7.9 2009 Sumatra earthquake, bandpass filtered waveforms of OBS10

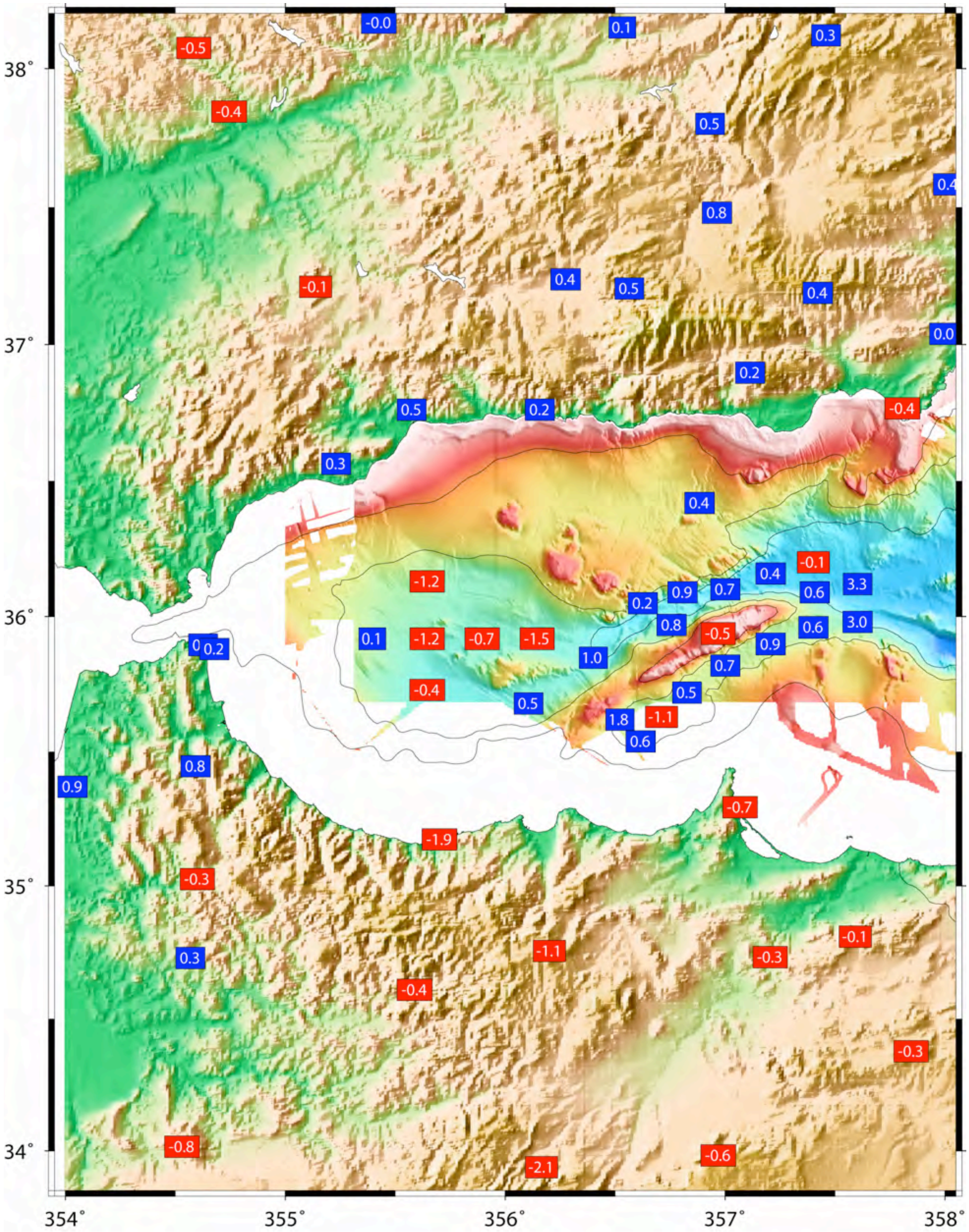

Figure 5.7. First constraints on the deep structure from delay times with respect to IASPEI91 for a Mw=6.0 earthquake occurring south of Svalbard on August 20, 2009.

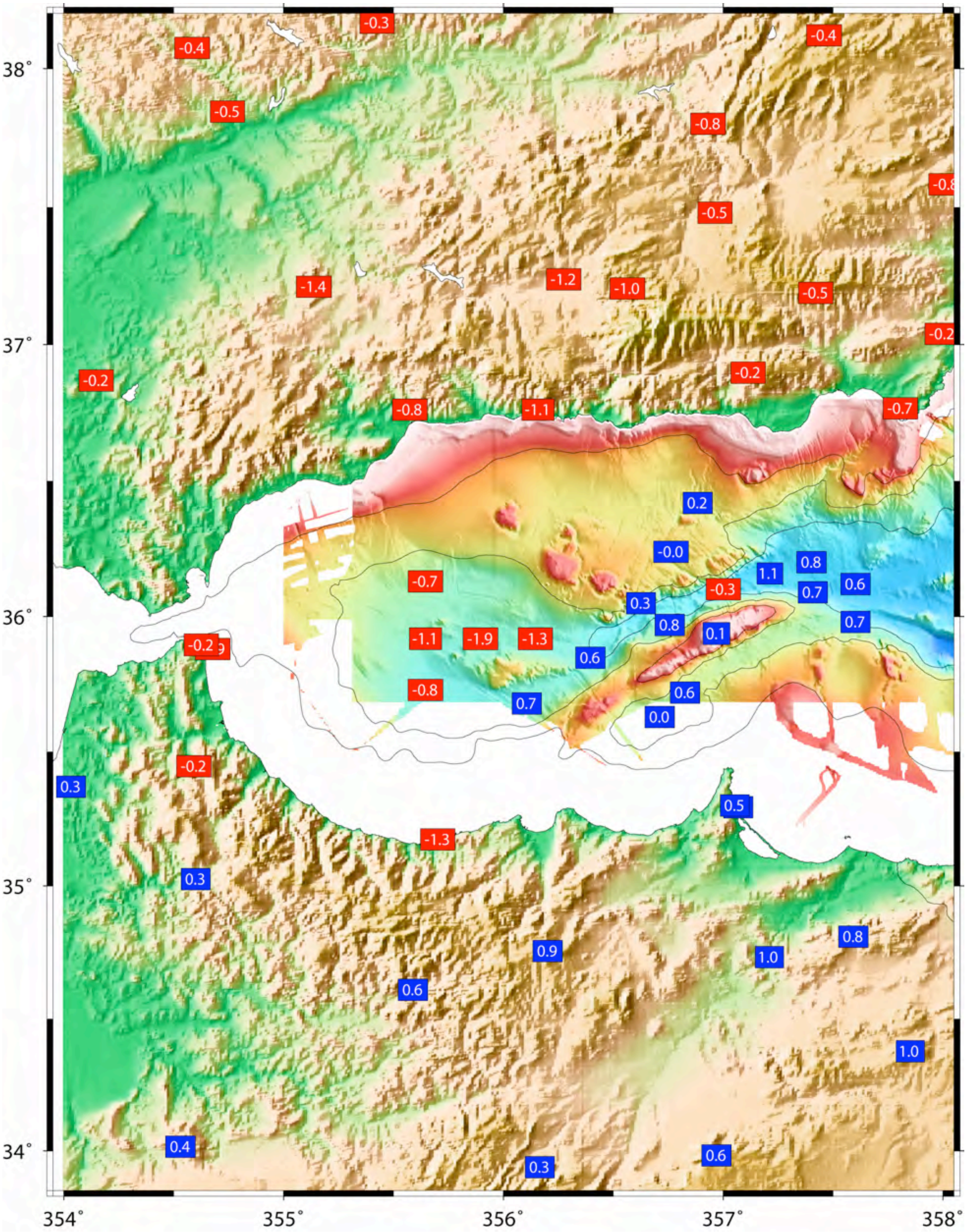

Figure 5.8. First constraints on the deep structure from delay times with respect to IASPEI91 for a Mw=7.9 earthquake occurring offshore Sumatra on September 30, 2009.

5.2 Gulf of Cadiz depolyment

5.2.1 Local earthquakes

The seismological network in the Gulf of Cadiz was operated between 23 January 2010 and 20 July 2010, monitoring an area cut by a number of major fault zones (e.g., Zitellini et al., 2009; Figure 5.9). The data were analyses as described in 5.1.1. Surprisingly, only 66 earthquakes could be detected. Most events occurred between the network and the coast. Therefore a number of land stations from Portugal and Spain like PFVI, PVAQ, and SFS were included, closing a gap in coverage. The largest recorded events had magnitudes of 3.6 to 3.8 and occurred near the Portimao Bank (Figure 5.10 + 5.11), a feature proposed to be bounded by thrust faults at its northern and southern margin (Figure 5.9). For the location procedure we used the velocity-depth model of Geissler et al. (2010). We like to emphasize that most earthquakes occurred at a depth of 30 to 50 km. Recent seismic refraction and wide-angle work in the area suggest that crust under the shelf is in the order of 20 km (Valenti Sallares, pers. communication, 2011). Thus, results support the idea that earthquakes occur in the uppermost mantle as proposed by Stich et al. (2005).

Mapping efforts by Zitellini et al. (2009) suggest that the Gulf of Cadiz is cut by a number of large transcurrent faults that may represent a newly developing plate boundary between Iberia and Africa. However, the deployed network covered partly the so called SWIM-I lineament. Interestingly, the features is seismically quite over the 6 month of monitoring, indicating that either the slip rate is too low to cause any earthquakes in the short period of monitoring or suggesting that the features slips aseimically.

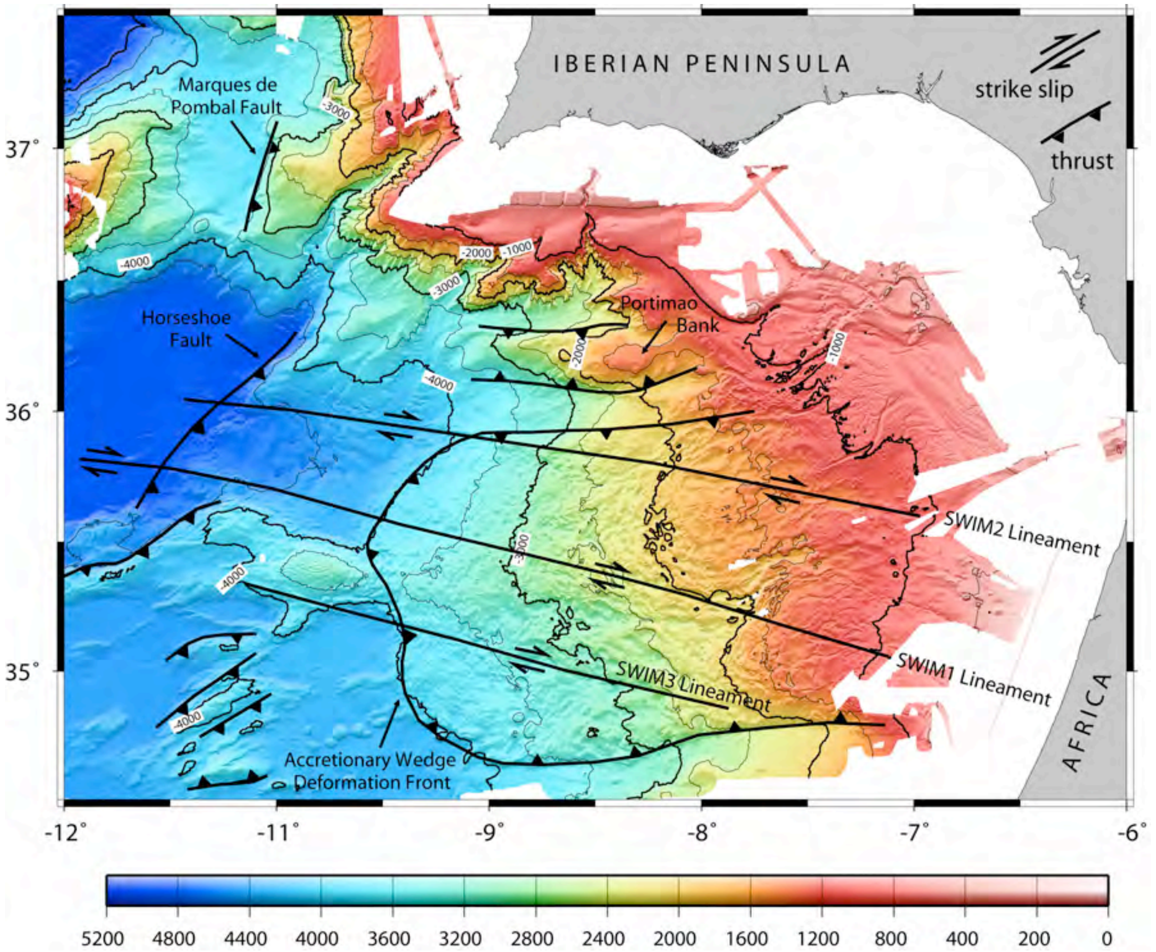

Figure 5.9. Main structural features identified in swath-mapping data in the Gulf of Cadiz (Zitellini et al., 2009).

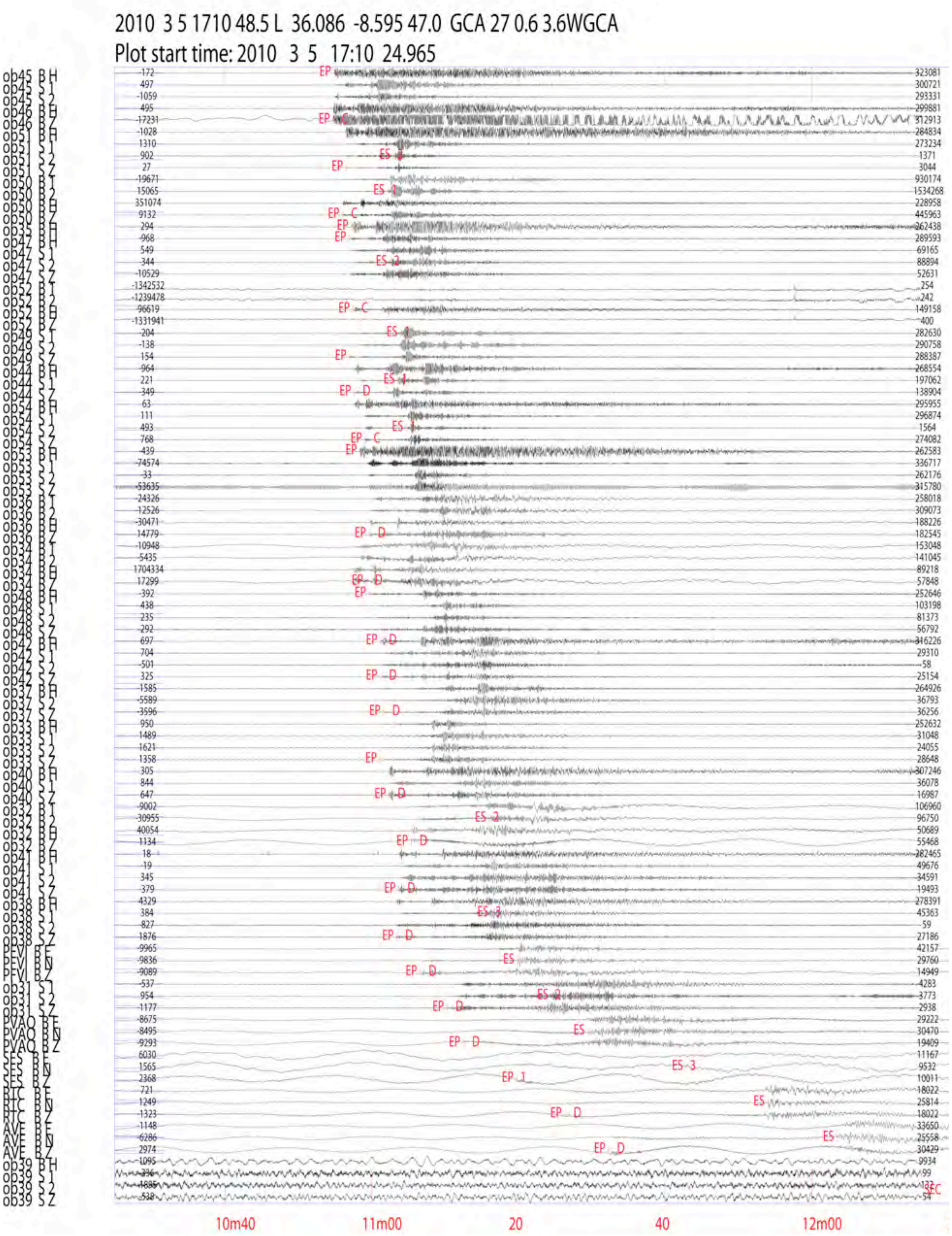

Figure 5.10. Waveform example of an M~3.6 event recorded on March 5, 2010.

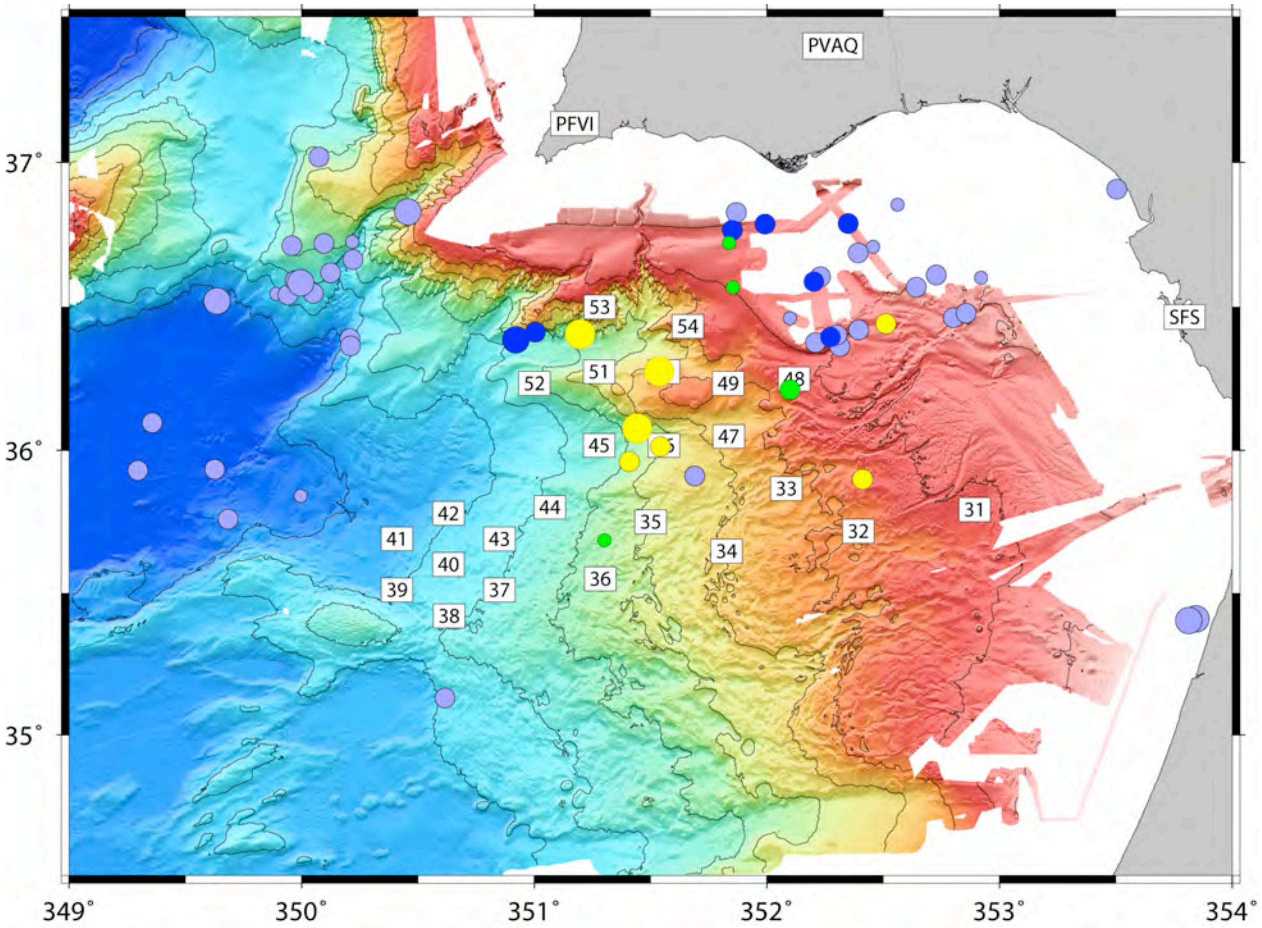

Figure 5.2. Earthquakes recorded with the TOPO-MED offshore network. The dataset has been complemented by data from the onshore stations. Earthquake magnitude scales with the size of the symbols (magnitude ~3.8 to 2.5); depth is coded by colour: blue < 5 km; green 5 km < z < 20 km, yellow 20 km < z < 50 km; red > 50 km. Light blue mark earthquakes were the gap was too large for a precise estimate of both epicentre and depth.

6. Acknowledgements

We greatly appreciate efforts of the European Science Foundation (ESF) initiating the TOPO-EUROPE programme. The German IP of TOPO-MED is founded by the German Science Foundation (DFG) through the grant GR1964/12-1. We acknowledge the excellent and professional sea-going operation of R/V *Poseidon* by Captain Michael Schneider and his crews during cruises P393 and P393. Further, we thank Captain Friedhelm von Staa and his crew of R/V *Maria S. Merian* for the support during the cruise MSM15/5.

7. References

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Appendix

8.1 – Station List Alboran Sea deployment

Station name	Latitude	Longitude
OBS 1	35° 58.812’ N	2° 24.102’ W
OBS 2	36° 07.302’ N	2° 24.102’ W
OBS 3	36° 12.102’ N	2° 36.102’ W
OBS 4	36° 09.612’ N	2° 47.796’ W
OBS 5	36° 05.412’ N	2° 35.796’ W
OBS 6	35° 57.702’ N	2° 36.102’ W
OBS 7	35° 54.012’ N	2° 47.796’ W
OBS 8	35° 49.302’ N	3° 00.102’ W
OBS 9	35° 43.212’ N	3° 10.596’ W
OBM NS3	35° 44.760’ N	3° 25.500’ W
OBS 10	35° 37.812’ N	3° 17.502’ W
OBS 11	35° 32.412’ N	3° 23.196’ W
OBM NS04	35° 32.880’ N	3° 26.040’ W
OBS 12	35° 37.212’ N	3° 29.196’ W
OBS 13	35° 40.812’ N	3° 53.796’ W
OBS 14	35° 43.812’ N	3° 42.396’ W
OBS 15	35° 51.012’ N	3° 36.396’ W
OBM MM06	35° 55.860’ N	3° 32.220’ W
OBS 16	35° 54.612’ N	3° 24.396’ W
OBS 17	35° 58.212’ N	3° 14.796’ W
OBS 18	36° 03.012’ N	3° 22.596’ W
OBS 19	36° 05.412’ N	3° 11.796’ W
OBS 20	36° 06.102’ N	3° 00.102’ W
OBS 21	36° 19.200’ N	2° 58.800’ W
OBS 22	36° 25.200’ N	3° 07.200’ W
OBS 23	36° 22.800’ N	3° 21.600’ W
OBS 24	36° 14.400’ N	3° 14.400’ W
OBS 25	35° 55.212’ N	3° 51.396’ W
OBS 26	35° 55.212’ N	4° 06.396’ W
OBM NS08	36° 01.500’ N	4° 09.000’ W
OBS 27	36° 7.8120’ N	4° 21.396’ W
OBS 28	35° 55.212’ N	4° 21.396’ W
OBS 29	35° 55.212’ N	4° 36.396’ W
OBS 30	35° 43.812’ N	4° 21.396’ W
OBM NS06	35° 49.620’ N	4° 10.200’ W
OBM NS07	35° 37.020’N	4° 11.280’W

Appendix

8.2 – Station List Gulf of Cadiz deployment

Station name	Latitude	Longitude
OBS 31	35° 47.6’N	7° 06.5‘W
OBS 32	35° 43.0’N	7° 36.5’W
OBS 33	35° 52.0’N	7° 55.0’W
OBS 34	35° 38.8’N	8° 10.4’W
OBS 35	35° 45.0’N	8° 30.0’W
OBS 36	35° 33.0’N	8° 43.0’W
OBS 37	35° 30.6’N	9° 09.0’W
OBS 38	35° 25.2’N	9° 22.0’W
OBS 39	35° 30.6’N	9° 35.4’W
OBS 40	35° 36.0’N	9° 22.2’W
OBS 41	35° 41.4’N	9° 35.4’W
OBS 42	35° 46.8’N	9° 22.2’W
OBS 43	35° 41.4’N	9° 09.0’W
OBS 44	35° 48.0’N	8° 56.0’W
OBS 45	36° 01.0’N	8° 43.3’W
OBS 46	36° 01.0’N	8° 26.5’W
OBS 47	36° 02.9’N	8° 09.9’W
OBS 48	36° 15.0’N	7° 53.0’W
OBS 49	36° 14.0’N	8° 10.0’W
OBS 50	36° 16.4’N	8° 26.5’W
OBS 51	36° 16.5’N	8° 43.3’W
OBS 52	36° 14.0’N	9° 00.0’W
OBS 53	36° 30.0’N	8° 43.2’W
OBS 54	36° 25.9’N	8° 20.4’W

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2	RV Sonne Fahrtbericht / Cruise Report SO181 TIPTEQ (from The Incoming Plate to mega Thrust EarthQuakes) 06.12.2004.-26.02.2005. Ed. by Ernst R. Flueh & Ingo Grevemeyer, 2005, 533 pp. In English
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No.	Title
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