Focal mechanisms for sub-crustal earthquakes in the Gulf of Cadiz from a dense OBS deployment

W. H. Geissler,[1] L. Matias,[2] D. Stich,[3] F. Carrilho,[4] W. Jokat,[1] S. Monna,[5] A. IbenBrahim,[6] F. Mancilla,[3] M.-A. Gutscher,[7] V. Sallarès,[8] and N. Zitellini[9]

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[1] An eleven-month deployment of 25 ocean bottom seismometers provides an unprecedented opportunity to study low-magnitude local earthquakes in the complex transpressive plate boundary setting of the Gulf of Cadiz, known for the 1755 Lisbon earthquake and tsunami. 36 relocated earthquakes (ML 2.2 to 4.8) concentrate at 40–60 km depth, near the base of the seismogenic layer in ~140 Ma old oceanic mantle lithosphere, and roughly align along two perpendicular, NNE-SSW and WNW-ESE striking structures. First motion focal mechanisms indicate compressive stress for the cluster close to the northern Horseshoe fault termination which trends perpendicular to plate convergence. Focal mechanisms for the second cluster near the southern termination of the Horseshoe fault indicate a strike-slip regime, providing evidence for present-day activity of a dextral shear zone proposed to represent the Eurasia-Africa plate contact. We hypothesize that regional tectonics is characterized by slip partitioning. **Citation:** Geissler, W. H., et al. (2010), Focal mechanisms for sub-crustal earthquakes in the Gulf of Cadiz from a dense OBS deployment, *Geophys. Res. Lett.*, *37*, L18309, doi:10.1029/2010GL044289.

1. Introduction

[2] Within the EU-funded NEAREST project (Integrated observations from NEAR shore sourcES of Tsunamis: towards an early warning system), a network of 24 broadband ocean bottom seismometers (OBS) from the German DEPAS pool (Deutscher Geräte-Pool für amphibische Seismologie/German instrument pool for amphibian seismology) and the multi-parameter deep sea observatory GEOSTAR were deployed in the Gulf of Cadiz and offshore Cape St. Vincent (Portugal) for 11 months starting from the end of August 2007 (Figure 1 and Table S1 of the auxiliary material) [*Carrara et al.*, 2008].[1] This area has a well-documented history of strong earthquakes and destructive tsunamis, including the famous Mw ~ 8.6, 1755 Lisbon earthquake, and represents one of the most important tsunamigenic areas in Europe [*Baptista and Miranda*, 2009, and references therein]. So far, it is not well understood along which fault zone(s) such very large earthquakes occur. The NEAREST experiment investigates lithospheric structure and seismotectonics in this complex plate boundary setting and the feasibility of a tsunami early warning system. The OBSs consist of three-component Guralp CMG-40T-OBS seismometers and HighTech HTI-04-PCA/ULF hydrophones. A wide range of signals was recorded, including teleseismic, regional and local earthquakes, and low-frequency (~20 Hz) vocalization of fin whales [e.g., *Rebull et al.*, 2006].

[3] Present day tectonic deformation in the area is conditioned by oblique WNW-ESE convergence of the Nubian and European plates at a rate of 4-5 mm/year [*Serpelloni et al.*, 2007]. According to present knowledge, most of the area is underlain by either oceanic crust or exhumed mantle of Late Jurassic to Early Cretaceous age that has been reactivated in a transpressive deformation style since the Late Cretaceous [*Sartori et al.*, 1994; *Rovere et al.*, 2004; *Zitellini et al.*, 2009], leading to rough bathymetry with alternating abyssal plains and submarine ridges (Figure 1). Seismicity is more intense in the northern part, spanning from the Gorringe Bank to the Guadalquivir Bank Fault at the SW Iberian continental margin (Figure 1). To the south, the most seismically active areas seem to be limited by a set of sub-parallel dextral strike-slip faults that form a narrow band of deformation (SWIM Fault Zone), proposed to represent a nascent plate-boundary developing between Eurasia and Africa [*Zitellini et al.*, 2009]. Available earthquake focal mechanisms show a high degree of heterogeneity with mainly reverse and strike-slip faulting style and average P-axes orientation near NW-SE [*Grimison and Chen*, 1986; *Buforn et al.*, 1988; *Stich et al.*, 2005, 2010; *Serpelloni et al.*, 2007].

[4] In the study area, intermediate deep seismicity is reported in earthquake catalogues, consistent with the expected mechanical coupling between crust and uppermost mantle in old oceanic lithosphere [*McKenzie et al.*, 2005]. However, earthquake locations from distant land stations usually give poorly constrained depths. First conclusive evidence for sub-crustal seismicity down to ~50–55 km depth in the region came from the analysis of primary body wave reflections (depth phases) in teleseismic P-waves [*Grimison and Chen*, 1986; *Engdahl et al.*, 1998; *Stich et al.*, 2007], as well as intermediate period regional waveform modeling [*Stich et al.*, 2005]. These techniques are limited to moderate-to-large earthquakes that generate high quality recordings at distant

[1] Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany.
[2] Centro de Geofisica, Universidade de Lisboa, Lisbon, Portugal.
[3] Instituto Andaluz de Geofisica, Universidad de Granada, Granada, Spain.
[4] Instituto de Meteorologia, Lisbon, Portugal.
[5] Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy.
[6] Centre National pour la Recherche Scientifique et Technique, Rabat, Morocco.
[7] Domaines Oceaniques, UMR 6538, Institut Universitaire Europeen de la Mer, Universite de Brest, CNRS, Plouzane, France.
[8] Unitat de Tecnologia Marina, Centre Mediterrani d'Investigacions Marines I Ambientals, CSIC, Barcelona, Spain.
[9] Istituto di Scienze del Mare, Bologna, Italy.

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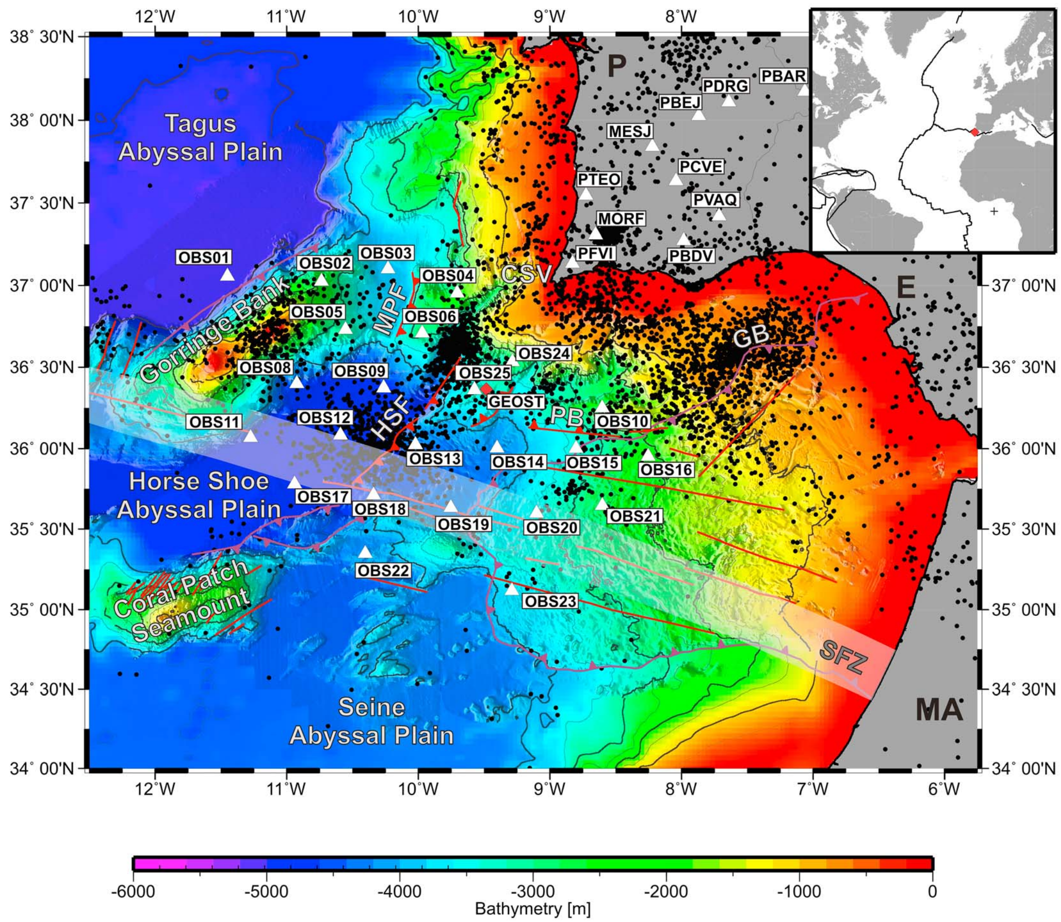

Figure 1. Swath bathymetry (on top of ETOPO2) and faults [after *Zitellini et al.*, 2009], positions of OBS and land stations (white triangles), GEOSTAR deep sea observatory (red diamond), and epicenters listed in the bulletin of the Institute of Meteorology Lisbon (http://www.meteo.pt/en/publicacoes/tecnico-cientif/noIM/boletins/). GB, Guadalquivir Bank; CSV, Cape San Vincent; HSF, Horseshoe Fault; MPF, Marquês de Pombal Fault; PB, Portimão Bank; SFZ, SWIM Fault Zone.

sensors. We use the OBS network to obtain accurately constrained focal depths for small to moderate local earthquakes and invert double-couple focal mechanisms from first motion polarities. We have approximately tripled the focal mechanism inventory for upper mantle earthquakes in the area, which allowed us to identify two different deformation patterns, leading to a consistent interpretation of regional tectonics.

2. Earthquake Relocation and Focal Mechanism Inversion

[5] We selected to relocate and retrieve the focal mechanism of the 36 largest events (Table S2) previously located within the OBS network by IM (Instituto de Meteorologia, Portugal) through routine analysis of land stations [*Carrilho et al.*, 2004]. This selection corresponds to the best quality data set made of recordings with good signal to noise ratio at short epicentral distances and with good azimuthal coverage. For relocation, P and S wave arrivals were picked on the three-component seismometer and hydrophone recordings. The internal clocks of the OBS data loggers were synchronized with GPS time before deployment and again after recovery. A linear time drift correction was applied. We used the SEISAN software package [*Havskov and Ottemöller*, 2005] to analyze waveforms and compute earthquake locations with HYPOCENTER. The velocity model (Table S3) is based on the work by *González et al.* [1996] [see *Carrara et al.*, 2008]. Magnitudes were calculated according to equation (1) following *Carrilho and Vales* [2009].

$$ML = \log A - 1.287 \log \Delta + 0.0061\Delta - 2.147 \qquad (1)$$

When comparing the epicenter locations that include OBS arrival times to the purely land-based locations published by several agencies (Figure 2 and Table S4) a large dispersion is observed and discrepancies exceeding 20 km are not uncommon. This means that a very cautious interpretation of routine hypocenter catalogues for this area is essential. The earthquakes we analyzed concentrate in two distinct clusters close to the northern and southern terminations of the Horseshoe fault (Figure 4), which is thought to be a moderately inclined thrust fault [*Zitellini et al.*, 2004]. The northern cluster shows a general trend close to NNE-SSW, parallel to the Horseshoe fault, while the southern cluster shows roughly a perpendicular, WNW-ESE trend, corresponding to a strong spatial and directional consistency with the dextral shear zone marked by the SWIM lineaments. However, internally the northern and southern clusters show also sub-clusters with WNW-ESE and NNE-SSW orientation, respectively.

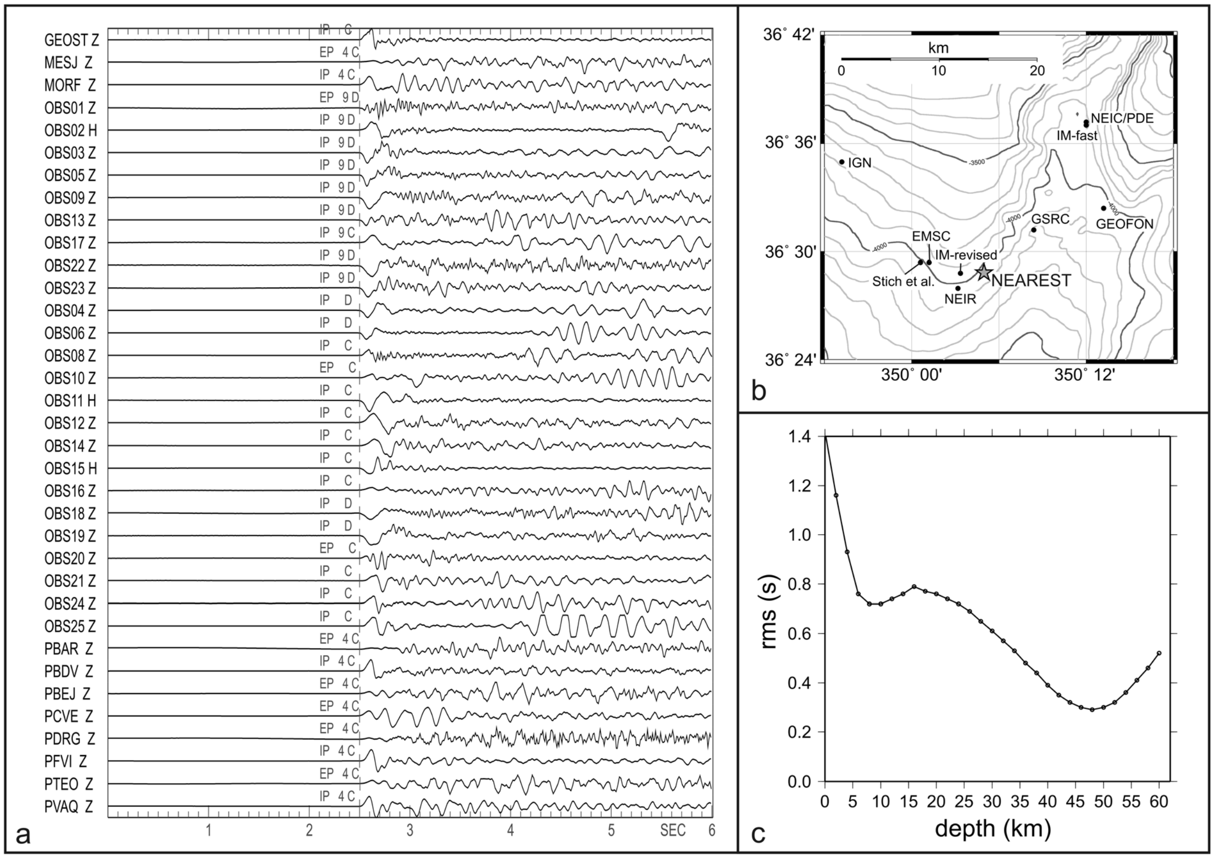

Figure 2. (a) Seismogram of the Jan 11, 2008 00:21 event showing P onsets. Phase quality codes 4 and 9 denote onshore stations not used for event relocation and OBS with clock synchronization problems (only S-P difference time used), respectively. (b) Epicenters from different agencies in comparison to NEAREST solution. (c) Plot of RMS versus depth used to determine focal depths. A focal depth around 48 km is inferred from this plot.

[6] The hypocenter depth was checked for each event by a systematic RMS-versus-depth search with steps of two kilometers (Figure 2c). Relocated events are systematically deeper than reported in the IM catalogue, more than 30 km in several cases. Therefore, previous assumptions on the relationship of earthquakes and active crustal faults [e.g., *Zitellini et al.*, 2001; *Neves and Neves*, 2009] are not supported by the new offshore data. We found that for our selection of earthquakes all except three events occurred in the oceanic upper mantle, most of them close to 50 km depth (Table S2). The variation of ±5% of the velocity model used for earthquake location has minor influence on the absolute depths of the deep events (<4 km), but a large effect on the depth estimates for the three shallow events (~27 km for event #8).

[7] We compute double-couple focal mechanisms using the FOCMEC routine [*Snoke et al.*, 1984] and the maximum likelihood algorithm (MECSEI) of *Brillinger et al.* [1980], based on first motion polarities of the P-wave interpreted on the OBS and Portuguese land stations. Using between 8 and 32 polarity picks, we could obtain reasonably- and well-constrained solutions for 31 events (Figure 3). Faulting orientations appear heterogeneous, but reproduce the known general tendencies of NW-SE oriented P-axes and predominately reverse and strike-slip faulting style observed previously [*Grimison and Chen*, 1986; *Buforn et al.*, 2004; *Stich et al.*, 2010]. For the two largest earthquakes (Jan 11 and May 10, 2008), regional moment tensor solutions are available [*Stich et al.*, 2010]. Moment tensor inversion was based on land stations only because OBS recordings for strong local events show severe distortions due to non-linear instrument behavior, presumably related to seafloor properties and coupling problems of the OBS on soft sediments. Source geometries (Figure 3) agree reasonably well between the two methodologies. We found two cases of nearly pure normal faulting in the upper mantle (including the May 10, 2008 earthquake), corroborating similar mechanisms reported previously [*Stich et al.*, 2005]. Unfortunately, as of yet we have no explanation for this occurrence.

3. Discussion and Conclusion

[8] Relocation of local earthquakes within the OBS network leads to well-constrained depth estimates, showing a pronounced peak at ~50 km. This is close to the 600°C isotherm in Late Jurassic to Early Cretaceous oceanic lithosphere [*McKenzie et al.*, 2005], which is expected to mark the base of brittle deformation and the seismogenic layer. In fact, all except seven earthquakes (Figure 4) concentrate between 40 and 55 km, the depth range of the deepest earthquakes reported in previous studies [*Grimison and Chen*, 1986; *Engdahl et al.*, 1998; *Stich et al.*, 2005, 2007]. Three earthquakes are shallow (≤20 km) and four events fall within 55 and 60 km, pushing the seismicity limit slightly downward

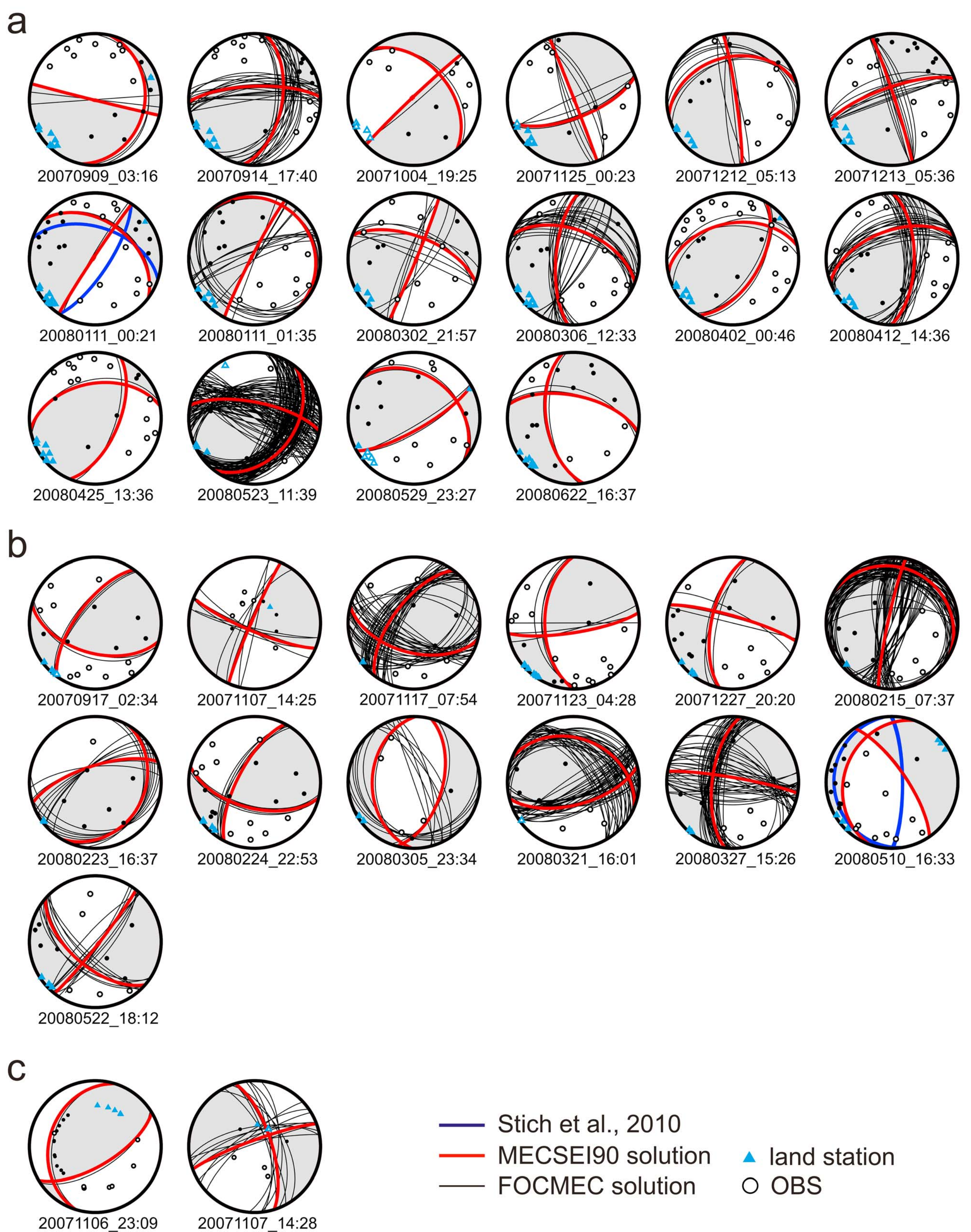

Figure 3. P polarity readings and focal mechanisms for (a) northern and (b) southern clusters. (c) Focal mechanism for two events east of the Horseshoe Fault.

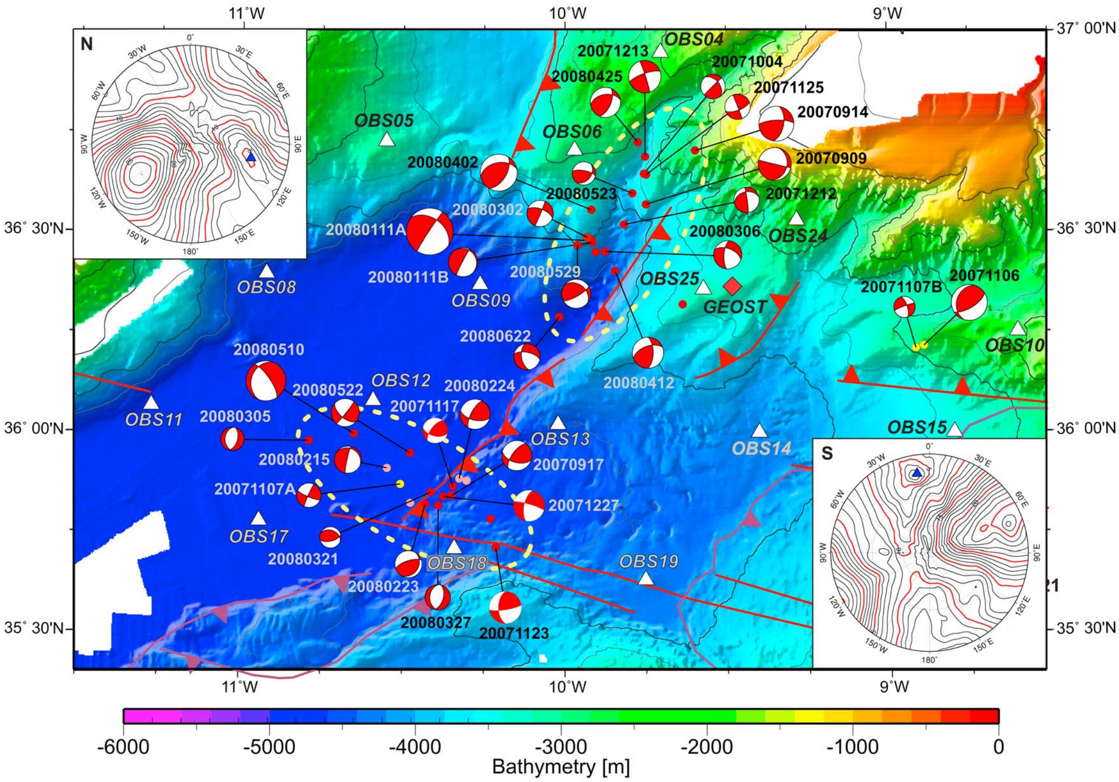

Figure 4. Double-couple focal mechanisms linked with new epicenter locations. Focal depths <20 km (yellow dots), 40 to 55 km (red), and >55 km (pink) are indicated. Ellipses outline the discussed clusters. Bathymetry and faults after *Zitellini et al.* [2009]. Insets: stereographic misfit plots of the grid-search for $\sigma 1$ for the northern (N) and southern (S) clusters; blue triangles mark the best solutions for $\sigma 1$.

compared to previous studies. In our relocations there is a striking absence of seismicity between 20 and 40 km depth, compared to more continuous depth distributions reported previously. We cannot decide yet if the bimodal distribution is observed by chance due to the mere nature of seismicity during the OBS deployment period, or if it is a long-term characteristic that has been blurred before due to depth errors of land based locations. Rheological conditions or bending stresses [*Fukao*, 1973; *Neves and Neves*, 2009] might provide an explanation for the concentration of seismicity at the base of the brittle layer.

[9] The local OBS network allows estimation of focal mechanisms also for small magnitude events down to ML 2.2. They are mostly consistent with previous solutions for moderate to large earthquakes, showing reverse and strike-slip faulting and NW-SE to NNW-SSE shortening. Significant heterogeneity of the mechanisms is possibly a consequence of fault orientation and interaction. There are differences in the focal mechanism populations between the northern and southern seismicity clusters, i.e., a more northerly average P-axes orientation and a less compressive character in the southern population (Figure 4). We quantify differences between the two populations by estimating the average stress tensors most consistent with observed fault slip orientations, using a grid search approach (FMSI code) [*Gephart*, 1990]. The southern cluster is characterized by a strike-slip regime with almost N-S compression ($\sigma 1$ with orientation N351°E/12°, strike/plunge), E-W extension ($\sigma 3$ N81°E/2°) and an axis ratio $R = (\sigma 1 - \sigma 2)/(\sigma 1 - \sigma 3)$ of 0.7. Average rotational misfit for this solution is 2.2°. The northern cluster corresponds to an obliquely oriented compressive regime, with $\sigma 1$ at N103°E/26°, $\sigma 3$ at N221°E/43°, axis ratio R = 0.3, and average misfit of 4.6°.

[10] The different characteristics of the two seismicity clusters indicate different roles of either activity in accommodating regional transpressive strain. Compression acts in the northern cluster, trending perpendicular to present-day plate convergence and placed beneath the SW Iberian continental margin. A strike-slip regime acts in the southern cluster, trending parallel to plate convergence. These differing regimes have two interesting implications for regional tectonics. Firstly, location, trend and stress conditions for the southern cluster provide evidence for present-day activity of a steep dextral shear zone associated with the recently discovered SWIM lineaments [*Zitellini et al.*, 2009], which have been proposed to represent the Eurasia-Africa plate contact. Secondly, our findings suggest that regional tectonics is characterized by slip partitioning. That is, oblique shortening due to African-Eurasian plate convergence is accommodated by an interplay of shortening approximately parallel to the relative plate motion (capable of loading large reverse faults like the Horseshoe fault, and generating large tsunamogenic events like the 1755 earthquakes), and strike slip motion approximately parallel to the plate boundary (loading strike slip faults and generating less tsunamigenic earthquakes). More work is needed in order to assess the validity of our conclusion.

[11] The study shows the necessity to study the seismic activity of lithospheric-scale oceanic fault zones by means of OBS networks, since detailed information can be gained

on hypocenter locations and fault kinematics. We report activity of deep lithospheric structures, providing complementary information to our understanding of shallow faults zones interpreted from swath bathymetry and reflection seismic studies. Different faulting styles associated with slip partitioning, and seismogenic mantle rheology should have consequences on the future risk evaluation and early warning strategies in the Eastern Atlantic.

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F. Carrilho, Instituto de Meteorologia, Rua da Escola Politecnica 58, P-1250-102 Lisboa, Portugal.

W. H. Geissler and W. Jokat, Alfred-Wegener-Institut für Polar- und Meeresforschung, Am Alten Hafen 26, D-27568 Bremerhaven, Germany. (wolfram.geissler@awi.de)

M.-A. Gutscher, Domaines Oceaniques, UMR 6538, Institut Universitaire Europeen de la Mer, Universite de Brest, CNRS, Place Nicolas Copernic, F-29280 Plouzane CEDEX, France.

A. IbenBrahim, Centre National pour la Recherche Scientifique et Technique, Avenue Omar Ibn El Khattab 52, 10102 Rabat, Morocco.

F. Mancilla and D. Stich, Instituto Andaluz de Geofisica, Universidad de Granada, Campus Universitario de Cartuja s/n, E-18071 Granada, Spain.

L. Matias, Centro de Geofisica, Universidade de Lisboa, Campo Grande, Ed. C8, Piso 3, P-1749-016 Lisboa, Portugal.

S. Monna, Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, I-00143 Roma, Italy.

V. Sallarès, Unitat de Tecnologia Marina, Centre Mediterrani d'Investigacions Marines I Ambientals, CSIC, Pg. Maritim de la Barceloneta 37-49, E-08003 Barcelona, Spain.

N. Zitellini, Istituto di Scienze del Mare, Via Gobetti 101, I-40129 Bologna, Italy.