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Imaging active faulting in a region of distributed deformation from the joint clustering of focal mechanisms and hypocentres: Application to the Azores–western Mediterranean region

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ABSTRACT

The matching between linear trends of hypocentres and fault planes indicated by focal mechanisms (FMs) is frequently used to infer the location and geometry of active faults. This practice works well in regions of fast lithospheric deformation, where earthquake patterns are clear and major structures accommodate the bulk of deformation, but typically fails in regions of slow and distributed deformation. We present a new joint FM and hypocentre cluster algorithm that is able to detect systematically the consistency between hypocentre lineations and FMs, even in regions of distributed deformation. We apply the method to the Azores–western Mediterranean region, with particular emphasis on western Iberia. The analysis relies on a compilation of hypocentres and FMs taken from regional and global earthquake catalogues, academic theses and technical reports, complemented by new FMs for western Iberia. The joint clustering algorithm images both well-known and new seismo-tectonic features. The Azores triple junction is characterised by FMs with vertical pressure (P) axes, in good agreement with the divergent setting, and the Iberian domain is characterised by NW–SE oriented P axes, indicating a response of the lithosphere to the ongoing oblique convergence between Nubia and Eurasia. Several earthquakes remain unclustered in the western Mediterranean domain, which may indicate a response to local stresses. The major regions of consistent faulting that we identify are the mid-Atlantic ridge, the Terceira rift, the Trans-Alboran shear zone and the north coast of Algeria. In addition, other smaller earthquake clusters present a good match between epicentre lineations and FM fault planes. These clusters may signal single active faults or wide zones of distributed but consistent faulting. Mainland Portugal is dominated by strike–slip earthquakes with fault planes coincident with the predominant NNE–SSW and WNW–ESE oriented earthquake lineations. Clusters offshore SW Iberia are predominantly strike–slip or reverse, confirming previous suggestions of slip partitioning.

1. Introduction

Our understanding of lithospheric deformation and seismogenesis in regions of slow deformation is currently very limited. While the stresses associated with plate boundary processes are dominant in fast deforming regions, in slowly deforming environments these stresses may become comparable to or even smaller than other stresses at work, for example those related to isostatic adjustment, flexure, mantle dynamics, fluctuations of environmental parameters or local anthropogenic activity (e.g.: Cloetingh et al., 2002; Serpelloni et al., 2013; Hainzl et al., 2013; Neves et al., 2014; Faccenna et al., 2014; Cornet, 2015). We may hypothesise that the lithosphere itself may behave differently when subjected to stresses that are applied at low rates. Our limited understanding of the governing processes in regions of slow lithospheric deformation ultimately has implications for earthquake monitoring, as well as for earthquake hazard and risk assessment (Stein, 2007). The seismicity of slowly deforming regions is usually described as being fundamentally different from that of fast deforming regions, namely as displaying a more distributed in space and clustered in time character (e.g.: Stein, 2007; Stein and Liu, 2009). A fundamental limitation in the study of slowly deforming regions is the lack of high-quality observations. In these regions, earthquake catalogues generally show diffuse seismicity patterns, the geomorphological signature of tectonic processes is easily obliterated by erosion, sedimentation and human activity, and surface deformation is too slow to be accurately characterised by

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geodetic data. The location, geometry and activity rate of faults – all basic parameters to understand fault dynamics – are usually poorly known.

Western Iberia and its adjacent offshore (W Iberia), located on the southwestern tip of the European continent, is a privileged natural laboratory to study lithospheric deformation and earthquake generation in a slowly deforming environment. W Iberia marks the transition between a purely strike–slip domain to the west, where the long Gloria fault accommodates dextral motion between the Eurasian and Nubian plates, and the generally compressive Mediterranean domain to the east (e.g. Grimison and Chen, 1986; Buforn et al., 1988a; Sartori et al., 1994; Serpelloni et al., 2007; Bezzeghoud et al., 2014) (Fig. 1). Locally, the two plates converge obliquely. The convergence is oriented NW–SE to WNW–ESE and occurs at a low rate of 3–5 mm/yr (Fernandes et al., 2003; Serpelloni et al., 2007; Nocquet, 2012). Present-day Global Navigation Satellite System (GNSS) data indicates that Iberia currently undergoes negligible horizontal deformation, moving essentially as one single block attached to Eurasia and without significant internal deformation, with the exception of the Betics (Fernandes et al., 2007; Serpelloni et al., 2007; Garate et al., 2014). Recently, Palano et al. (2015) analysed a dense set of GNSS data and suggested that Iberia rotates slowly with respect to stable Eurasia and that quasi-continuous straining of the lithosphere occurs in parts of south and west Iberia. High-resolution analysis of vertical GNSS data reveals that Iberia is generally subsiding at low rates of less than 1 mm/yr, with localised uplift in the Central System (Serpelloni et al., 2013). This observation is at odds with analysis of Pleistocene marine terraces, which indicates that long-term regional uplift in southwest Iberia took place in the recent geological past at an average rate of 0.1–0.2 mm/yr (Figueiredo et al., 2014).

In spite of the low deformation rates currently observed in western Iberia, the region has generated some of the highest magnitude earthquakes in the European historical record. Offshore, these include the 1755 great Lisbon earthquake (M8.5–8.7) and the 1969 M7.9 earthquake. In the intraplate domain, high magnitude earthquakes include the 1531 M6.5–7.1 earthquake in the Lower Tagus Valley, the 1858 M6.8–7.2 Setúbal earthquake and the 1909 M6 Benavente earthquake. The magnitudes proposed for these earthquakes can be found in the works of Fukao (1973), Johnston (1996), Martins and Mendes Víctor (2001), Martínez Solares and López Arroyo (2004), Stich et al. (2005a), Vilanova and Fonseca (2007), Peláez et al. (2007), Stucchi et al. (2013), and Baptista et al. (2014). Earthquake parameters for historical earthquakes can be easily visualised and compared at the AHEAD web portal: http://www.emidius.eu/ahead/main/ (Locati et al., 2014).

High-magnitude earthquakes in the region have typically been explained as occurring on inherited fractures (e.g. Zitellini et al., 2004; Vilanova and Fonseca, 2004; Terrinha et al., 2009; Cabral, 2012; Carvalho et al., 2014). The basement of mainland Portugal was assembled at the core of the Variscan orogen, a major mountain system that resulted from the Palaeozoic closure of Pangea (Ribeiro et al., 1979; Matte, 1986; Matte, 1991). This basement is fractured, containing important belts of structural weakness. Subsequently, during the Mesozoic, Pangea broke apart and Iberia was separated from North Africa and North America (Srivastava et al., 1990; Roest and Srivastava, 1991; Maldonado et al., 1999). The rifting process is thought to have both reactivated pre-existing fractures and created new ones. Some of the fractures associated with Mesozoic rifting have been imaged to extend down through the basement (e.g.: Rovere et al., 2004; Afilhado et al., 2008). Rifting created ocean basins at the southern and western edges of mainland Portugal (Wilson, 1975; Rasmussen et al., 1998; González-Fernández et al., 2001; Terrinha et al., 2002). Later, in the Cenozoic, Iberia underwent episodes of compression associated with the convergence between Nubia and Eurasia and closure of the Tethys Sea (Roest and Srivastava, 1991; Sartori et al., 1994; Maldonado et al., 1999; González-Fernández et al., 2001). These compressive episodes are thought to have reactivated pre-existing fractures (Sartori et al., 1994; Rasmussen et al., 1998). The region offshore south Portugal

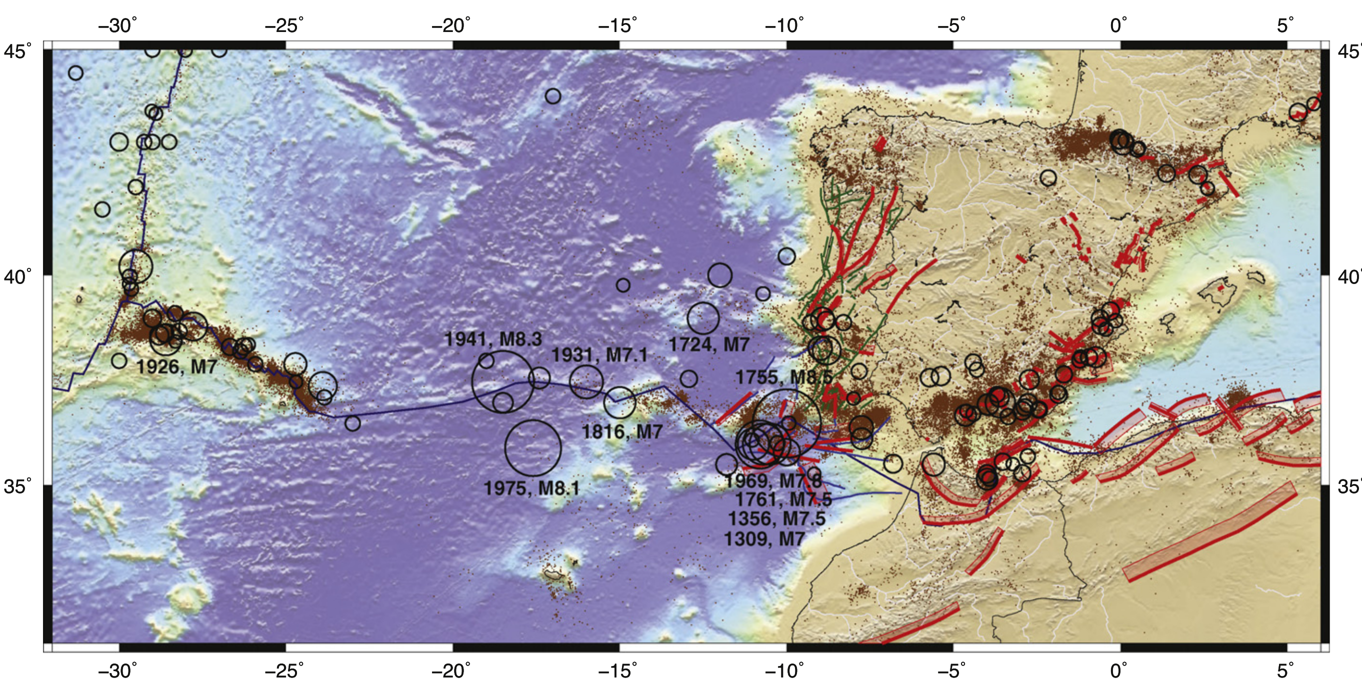

Fig. 1. Seismicity of the Azores–Iberia region. Earthquakes recorded instrumentally since 1996 are shown by small brown dots. Historical earthquakes reported by the SHARE European Earthquake Catalogue – SHEEC – with magnitudes larger than 5.5 are shown by circles whose radiuses correlate to the magnitude of the earthquakes (Stucchi et al., 2013). The earthquakes with magnitudes equal to or larger than 7.0 are labelled with year of occurrence and magnitude. The plate boundaries of the global plate tectonics NNR-MORVEL56 model are shown by dark blue lines (DeMets et al., 2010; Argus et al., 2011). The surface projection of potentially active faults compiled on the SHARE database are shown by red rectangles, the surface trace of the faults is marked by a thick red line (Basili et al., 2013; Vilanova et al., 2014). The SHARE faults in western Iberia are underlain by the original fault traces proposed by Cabral (2012) (green) and Duarte et al. (2013) (blue). The topography in background is taken from the global SRTM30+ model, obtained from satellite altimetry and ship depth soundings (Smith and Sandwell, 1997; Becker et al., 2009).