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The effect of sea level changes on fault reactivation potential in Portugal

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ABSTRACT

The aim of this study is to assess the impact of sea level changes on both the stress field and the potential of fault reactivation in west Iberia. The analysis is applied to a set of five active faults distributed across Portugal, selected for representing predominant fault directions and for being seismically active. The results show that the rise of sea level since the Last Glacial Maximum has produced flexural effects with distinct impacts on different faults. The Coulomb stress changes induced by the sea level rise along the S. Marcos-Quarteira (south Portugal) and the Horseshoe (offshore SW Iberia) faults are found to be extremely small, independently of the elastic plate thickness. These faults are thus unaffected by flexural effects related to ocean loading, and are unlikely to possess any paleoseismic record of this phenomenon. In contrast, the eustatic sea level rise during the late Pleistocene could have raised the Coulomb stress by 0.5–1 MPa along the Manteigas–Vilariça–Bragança (north Portugal) and Lower Tagus Valley (Lisbon area) fault systems. Such stress perturbations are probably sufficient to impact the seismic cycle of the Manteigas–Vilariça–Bragança fault, bringing it closer to failure and possibly triggering the earthquake clusters that have been observed in previous paleoseismologic studies.

1. Introduction

The Portuguese territory (west Iberia) is currently undergoing tectonic deformation due to convergence between Iberia and Nubia, resulting in the reactivation of faults and the generation of infrequent large earthquakes such as the 1755 Lisbon earthquake. Geologic observations onshore indicate fault slip rates in the range of 0.005–0.5 mm/year, which are consistent with a low rate of tectonic activity and long recurrence intervals for maximum (M 6–7) earthquakes (e.g. Cabral, 2012). Paleoseismic studies have demonstrated that some faults have experienced recurrent late Quaternary activity, especially in NE Portugal where there is evidence of paleoearthquake clustering during the Pleistocene (Rockwell et al., 2009). However, most large historical earthquake activity has been located in the central region of Portugal, within or near the Lower Tagus Valley (Lisbon area), while most of the present instrumental seismicity concentrates in the SW offshore region (Fig. 1a).

Based on current observations, there are fundamental questions as to how the long-term strain has been partitioned through time and space in Portugal. Most natural earthquakes result from tectonic processes that act at geologic time scales (>1 Ma). Nonetheless, other processes acting at shorter time scales may induce Coulomb stress changes (as small as 0.1–1 MPa) capable of triggering earthquakes on faults that are already close to failure (King et al., 1994; Stein, 1999). One important class of such processes comprises the impacts of the climatic system on the tectonic system. An increasing body of evidence shows that seismicity rates can be affected by a wide range of meteorological and climate phenomena such as seasonal changes in precipitation (e.g. Bettinelli et al., 2008; Bollinger et al., 2007), snow loads (Heki, 2001), water loading and unloading effects at reservoirs (e.g. Simpson et al., 1988; Gahalaut et al., 2007) and lakes (e.g. Brothers et al., 2011; Kaufmann and Amelung, 2000), as well as isostatic rebound following glacier melting (e.g. Grollimund and Zoback, 2000; Hetzel and Hampel, 2005). Recent studies propose that fast erosion rates linked to high storminess are also a prominent mechanism for inter-seismic loading of active faults (Steer et al., 2014).

In this study, we focus on sea level changes associated with the Milankovitch cycle, which have been proposed to have a significant impact on the seismic cycle of near shore plate boundary fault systems (Luttrell and Sandwell, 2010) and on the occurrence of submarine landslides at passive continental margins (Brothers et al., 2013). These previous works have shown that the loading rates due to time varying surface water loads are generally one to several orders of magnitude lower than the tectonic loading rate. Their ability to affect the seismic

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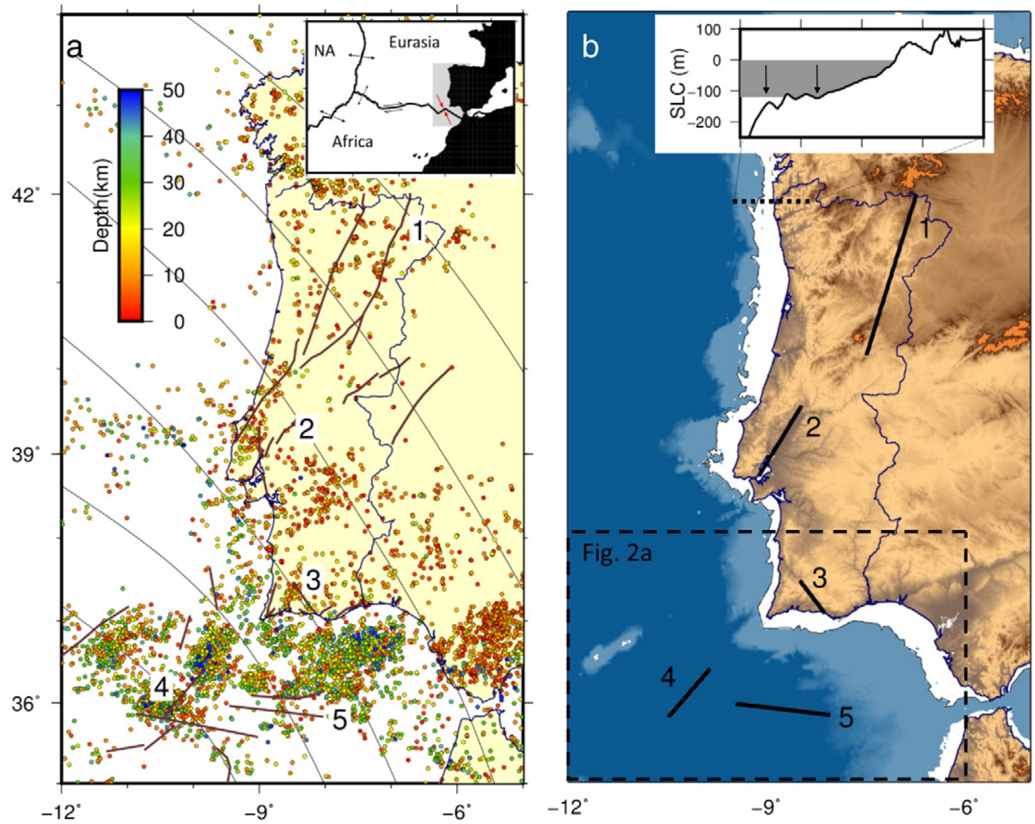

Fig. 1. (a) Map view of the study area with fault traces from the QAFI database (www.igme.es/infoigme/applications/qafi) and maximum horizontal compressive stress trajectories (solid lines) from de Vicente et al. (2008). Numbers indicate the faults analyzed in this study: (1) Vilariça, (2) Lower Tagus Valley, (3) Quarteira, (4) Horseshoe and (5) SWIM (north fault). Dots show the epicentres in the period between 1964 and 2014 taken from the ISC database (www.isc.ac.uk) with hypocentre depth in color scale. (b) White areas show the migration of the shoreline in western Iberia since the Last Glacial Maximum. A topographic profile across the continental margin at 42°N illustrates the extra vertical load (~120 m thick gray layer with black arrows) exerted as a result of sea level change (SLC) during that period. The black dashed rectangle depicts the offshore area presented in Fig. 2a.

cycle is therefore enhanced for regions of particularly low tectonic loading rate, such as west Iberia. As a possible evidence of the causal relationship between increased seismicity and ocean loading, Luttrell and Sandwell (2010) have suggested that the paleo-earthquake cluster found in NE Portugal could be due to rapid sea level rise during the late Pleistocene. Here, we will investigate if this hypothesis is indeed possible.

The Coulomb stress perturbations are calculated for a set of five active faults, geographically apart, that were selected for representing important fault directions and for being among the most seismically active in Portugal. The impact of the ocean loading perturbations, and therefore their probability of detection, depends on the background potential of fault reactivation. Since the fault reactivation potential due to tectonic loading has remained constant at the scale of the eustatic oscillations (10^4–10^5 years) the central question is to know how the stress changes induced by sea level rise compare with the "existing" reactivation potential at each fault.

In order to evaluate the reactivation potential in response to the tectonic loading we rely on a model of the current stress field in west Iberia (Neves et al., 2014) and perform a slip tendency analysis. The main aims of this study are therefore to: (1) estimate the reactivation potential of some of the most important faults in Portugal considering the present tectonic loading, and (2) model the lithospheric bending associated with ~120 m of eustatic sea level rise since the Last Glacial Maximum, and quantify the resulting Coulomb stress perturbations induced on the selected faults. Based on the modeling results we examine the possible relations between paleo-earthquakes and sea level changes and identify preferential targets for future paleo-seismological studies. This offers new insights into the long-term behavior of the faults in Portugal, within the framework of climate and tectonic interactions.

2. Tectonic setting

2.1. Active tectonics

The tectonic setting of mainland Portugal, characterized by a NW–SE trending maximum horizontal compressive stress (SHmax, Fig. 1a), generates significant neotectonic activity, of which the regional seismicity is a current expression (e.g. Borges et al., 2001; Ribeiro et al., 1996). The neotectonic deformations include two major interrelated components that may be distinguished and independently analyzed: vertical movements of the lithosphere, resulting from large scale folding and isostatic adjustments (e.g. Cloetingh et al., 2002) and active faulting. Active faults were largely conditioned by reactivation of pre-existent structures, namely Variscan faults in Paleozoic basement, and faults in Mesozoic extensional basins and in Alpine Cenozoic compressive and strike–slip basins. Fault activity shows a predominance of ~E–W to NE–SW reverse faults and ~N–S to NNE–SSW left-lateral strike–slip faults, reactivated under the present stress field (Cabral, 1995, 2012, and references therein). The present work focuses on some of these active faults, which are briefly described below.

2.1.1. The Vilariça fault

The Manteigas–Vilariça–Bragança fault (hereafter called Vilariça) is a prominent NNE–SSW trending strike–slip fault in West Iberia (Fig. 1, fault 1). Together with the Penacova–Régua–Verin fault, located 60 km to the west, it has been acting as a transfer zone of deformation between the Cantabrian Mountains and the Iberian Central System since the Eocene (de Vicente et al., 2008). With a length of approximately 220 km, the Vilariça fault has undergone polyphase activity since the end of the Variscan Orogeny, producing significant displacements of the