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Large-magnitude crustal seismic sources in El Salvador and deterministic hazard scenarios

J. Alonso-Henar[a,*], B. Benito[b], A. Staller[b], J.A. Álvarez-Gómez[a], J.J. Martínez-Díaz[a,c], C. Canora[d]

[a] *Universidad Complutense de Madrid, Department of Geodynamics. C/ José Antonio Novais, 12, 28040 Madrid, Spain*
[b] *Universidad Politécnica de Madrid, Department of Topography Engineering and Mapping, Carr. Valencia, Km 7, 28031 Madrid, Spain*
[c] *Instituto de Geociencias IGEO (UCM,CSIC), C/ Dr. Severo Ochoa, 7, 28040 Madrid, Spain*
[d] *Universidad Autónoma de Madrid, Department of Geology and Geochemistry, Calle Francisco Tomás y Valiente, 7, 28049, Madrid, Spain*

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ABSTRACT

During the last years, several crustal seismic sources have been proposed in El Salvador; however, the actual destructive potential of these proposals has not been revealed yet. Here we present several seismic scenarios related with the main crustal faults in the country. We have characterized the corresponding hazard scenarios in a deterministic way, estimating the peak ground accelerations (PGA) including local site effects. In addition, we present a list of 29 sources that can be considered potentially dangerous with their main features when they are available and four seismic scenarios that we consider to be more probable. We have resorted to the February 13th 2001 Mw 6.6 destructive earthquake, the only earthquake occurred in a known crustal source in El Salvador and recorded by the strong motion network, in order to test the methodological approach and the reliability of the PGA results predicted by two available Ground Motion Prediction Equations (GMPEs) including the site effect. The consistence between the values given by the models and the ones recorded during the event provides reliability to our results. This approach allowed us to conclude that faults within the volcanic arc can produce accelerations up to 1 g in the most conservator case (Mw = 7.0), while accelerations up to 0.6 g are usual results related with specific faults within the Salvadoran Volcanic Arc. Besides, the reported damage distribution of the 8th June 1917 earthquakes and its similarity with one of the proposed scenarios allowed us to infer the possible source of this event, the Guaycume Fault.

1. Introduction

The Seismic Hazard analysis in Central America started at the end of the 1980s, as the previous socio-political context affecting this region had impeded the development of such studies until then. In Algermissen et al. (1988) appears the first detailed study of seismic hazard in El Salvador, followed by Alfaro et al. (1990), Singh et al. (1993) and Bommer et al. (1996). The growing methodological development of the PSHA (Probabilistic Seismic Hazard Assessment) led to several studies along the Central American region. At a regional scale, different studies were developed between 1990 and 2000 (Rojas et al., 1993a, 1993b; the Global Seismic Hazard Assessment Program [GSHAP] from Shedlock et al., 2000). Most of these studies were enforced by the International Decade for Natural Disaster Reduction. In this framework, the RESIS I and RESIS II projects were developed and supported by the Norway Cooperation Agency (NORAD) and the *Centro de Coordinación para la Reducción de Desastres en América Central* (CEPREDENAC). RESIS I provided the following main results: a strong motion data base (Taylor et al., 1992), some spectral attenuation models (Climent et al., 1994; Dahle et al., 1995; Schmidt et al., 1997), a seismic catalog (Rojas et al., 1993a, 1993b), empirical relationships for homogenization to moment magnitude M_W (Rojas et al., 1993b), the creation of the Central American Seismological Center (CASC) and microzonation studies in several main cities and seismic hazard assessments of the countries of the region. The RESIS II project resulted in a new generation of hazard maps for the entire region, in terms of PGA and spectral accelerations SA(T) for several return periods (Benito et al., 2010, 2012). Recently, a new zoning model has been proposed, and it is aimed at improving the seismic hazard estimations based on zoned models (Alvarado et al., 2017).

In the PSHA zoned methods, the seismicity is distributed in seismogenic zones considering that each zone has a uniform seismic potential. These methods do not usually take into account the active faults explicitly as independent units, even though these are the real sources

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* Corresponding author.
E-mail addresses: jahenar@geo.ucm.es (J. Alonso-Henar), mariabelen.benito@upm.es (B. Benito), a.staller@upm.es (A. Staller), jaalvare@geo.ucm.es (J.A. Álvarez-Gómez), jmdiaz@geo.ucm.es (J.J. Martínez-Díaz), carolina.canora@uam.es (C. Canora).

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of the earthquakes. However, the zoned methods are useful especially when there are not enough kinematic data of the faults that make it possible to include them as independent and specific sources.

The detailed knowledge of the faults kinematics is fundamental in order to enhance the estimations of the seismic hazard and characterize the shakes related with future seismic events in a more realistic way. The scientific contributions to the faults kinematics in El Salvador during the last decades shed light on the geometric and recurrence parameters of specific sources in El Salvador gathered from paleoseismological, geodetic and kinematic studies which have been developed in the country (e.g. Corti et al., 2005, Canora et al., 2012, Alonso-Henar et al., 2014, Staller et al., 2016, Garibaldi et al., 2016). The results have increased the knowledge of the faults parameters such as their slip-rates, last events, recurrence intervals and elapsed times, thereby allowing to model the faults as sources in the hazard analysis. This fact may suppose an improvement in the knowledge of the expected ground motion for future events and this is the purpose of the present paper.

According to the current knowledge of the fault kinematics and parameters, we present here a proposal of the main crustal sources to be taken into account in future seismic hazard studies regarding the threat that they represent. From the results derived from Canora et al., 2012, Canora et al., 2014, Alonso-Henar et al., 2014, Alonso-Henar et al., 2015 and Staller et al., 2016, we present a list of active faults in El Salvador and their main geometric and kinematic parameters in a related Data in Brief article (Alonso-Henar et al., 2018 in press, and Fig. 2). Based on these data, we propose four deterministic seismic scenarios related with the main faults and different possible ruptures that they may cause. The characterization of the expected ground motions was done using both local Ground Motion Prediction Equations (GMPEs) and local soil classification to assess the local soil effect in each seismic scenario. We also have compared the obtained results with the damage distribution of historical earthquakes. This helped us propose a source for the 8th June 1917 M 6.7 (Larde, 1956; White and Harlow, 1993) destructive earthquake. Although in this article we are focused on onshore crustal earthquakes, it is worthy to note that an important contribution to the overall seismic hazard and risk in this region is due to the offshore subduction processes and the landslides triggered by earthquakes as stated in Bommer et al. (2002, 2006), Bommer and Rodriguez (2002); Crosta et al. (2005).

Finally, we also present a Coulomb Failure Stress analysis of the main active faults using their earthquake history and their slip rates that helped us to constrain which are the most plausible scenarios that may take place in the next decades.

2. Seismotectonic setting

El Salvador is located in the western boundary of the Chortís Block, where the Cocos plate subducts beneath the Caribbean and generates the Central America Volcanic Arc (CAVA). This volcanic arc spans from northern Costa Rica to Guatemala, and is located over three well differentiated crustal tectonic regions; from south to north, there are three main structures within the Central America Volcanic Arc: The Nicaraguan Depression (McBirney and Williams, 1965; van Wyk de Vries, 1993), the El Salvador Fault Zone, (Martínez-Díaz et al., 2004) and the Jalpatagua Fault (Carr, 1976) (Fig. 1). The northern boundary of the Chortís block is the Motagua–Polochic–Swan Island transform fault, a fault zone with pure left lateral strike-slip motion of 20 mm/yr (DeMets et al., 2010; Franco et al., 2012). According to Lyon-Caen et al. (2006) and DeMets et al. (2010), the convergence between Cocos and Caribbean plates has a N40°E trend and a velocity rate of 70–80 mm/year. The Caribbean plate has a velocity rate of 20 mm/year eastward relative to the North-America plate (Fig. 1).

The main seismic sources in El Salvador are related with the El Salvador Fault Zone (ESFZ), a 150 km long and 20 km wide deformation band within the CAVA where shallow seismicity is accumulated (Fig. 2) (Martínez-Díaz et al., 2004). This deformation band is composed of main strike-slip faults trending N90°-100°E, and secondary normal faults trending between N120°E and N170°E. ESFZ has been the source of the 13th February 2001 Mw 6.6 destructive earthquake (Martínez-Díaz et al., 2004; Canora et al., 2010). It may cause earthquakes up to M 7.2 according to Canora et al., 2014 and it has slip-rates up to 11 mm/yr that are accommodated in the faults that it is composed of (Staller et al., 2016), which is consistent with the regional relative motion of the forearc sliver (DeMets, 2001; Alonso-Henar et al., 2017) (Fig. 1).

3. Main seismic sources of El Salvador

The sources that we propose are the main faults that compose the El Salvador Fault Zone, as well as minor faults that may connect with the main ones, increasing the seismogenic potential of the Fault Zone.

In a Data in Brief related article (DiB, Alonso-Henar et al., 2018 in press), we present the information about seismic sources in El Salvador in two maps and a Table (this information is summarized in Fig. 2). The first map of the DiB article contains the fault traces derived from morphotectonic, paleoseismology, field data and teledetection in several studies carried out in El Salvador by Bosse et al., 1978, Martínez-Díaz et al., 2004, Corti et al., 2005, Agostini et al., 2006, Garibaldi et al., 2016, Canora et al., 2010, 2012, 2014, Alonso-Henar et al., 2014, 2015, 2017 (Thinner traces in Fig. 2). A total of 1405 fault traces are included. These traces indicate strictly the places where we found fault scarps or offsets. There is no kind of interpolation between the mapped fault traces and there is not any information about the activity, some of them may not accommodate elastic deformation necessarily (further studies would be necessary to confirm that, see Alonso-Henar et al., 2018 in press). From this map and field studies and the references cited above, we have elaborated a synthesis map where we propose 29 main seismic sources in El Salvador (second map in DiB and table). They are the main structures for defining more probable seismic scenarios and their features are summarized in a Table (thicker traces in Fig. 2, Alonso-Henar et al., 2018 in press). These sources are active faults whose traces are obtained by joining the data available in the first map. We assigned slip rates from geological data if they are available (Canora et al., 2010; Corti et al., 2005; Alonso-Henar et al., 2014) and from geodetic data in most cases, derived from Staller et al. (2016). Details of the sources are provided in Alonso-Henar et al. (2018 in press).

The highest slip rates of the faults within the ESFZ have been attributed to strike-slip faults with strikes close to N90°-100°E and dipping 70°S (Canora et al., 2010). The slip rates of The Guaycume and San Vicente faults are 9 ± 3 mm/yr and 7 ± 1 mm/yr, respectively, both estimated from GPS data (Staller et al., 2016), while the slip rate of San Vicente Fault calculated from a paleoseismological analysis (Canora et al., 2012) is 4 mm/yr (Fig. 3). The slip rate of El Triunfo Fault varies also depending on the method, being of 7.5 ± 3.5 mm/yr from GPS data; 11 mm/yr from a morphologic study by Corti et al. (2005) and 4.8 mm/yr from a morphometric analysis carried out by Alonso-Henar et al. (2014) (Fig. 2). The disagreement between the rates obtained by geological and geodetic data is highlighted. According to Chuang and Johnson (2011), the disagreement between the slip rates inferred from both kind of data could be due to three reasons: a) the long-term slip-rates (geological rates of thousands to millions years) are wrong; b) the short-term slip-rates (geodetic rates of decades) are wrong; or c) both rates are correct but the slip-rates could be varying along time. Viscoelastic models predict a postseismic rapid flow in early stages of the seismic cycle that is decreasing along the cycle (Chuang and Johnson, 2011). This involves a strong dependence of seismic cycle on the resulting slip-rates obtained from GPS data. On the other hand, according to Wesnousky et al. (2012), one of the fundamental keys in order to reconcile geological and geodetic data is to know where and how is recorded geologically the strain measured geodetically. According to these authors, it is important to take into account the blocks rotations. If