Seismic source properties of slow and fast earthquakes in the Guerrero seismic gap, Mexico

メキシコ・ゲレロ地震空白域周辺の地震とスロー地震の震源特性

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1. Introduction

The slow earthquake family incorporates different types of seismic and tectonic events. Based on observations made worldwide, the source and distribution of deep slow earthquakes are well-understood. Compared to regular earthquakes, slow earthquakes have longer durations, emit long-period waves, are less energetic, and have smaller amplitudes. However, this knowledge originates from slow earthquakes occurring in the deep regions of a plate interface. The situation differs for shallow slow earthquakes occurring near the trench. Few shallow slow earthquakes have been observed; therefore, their characteristics and influence on large earthquakes remain unclear. Here, we focused on observations of shallow slow earthquakes to better understand their generation, distribution, characteristics, and role in the seismic cycle. Our target area for observing shallow slow earthquakes was the Guerrero seismic gap in the Mexican subduction zone. The Guerrero seismic gap shows high activity of slow earthquakes in the deep plate interface; however, no shallow slow earthquakes have been observed inside the seismic gap. Because a large earthquake has not occurred in more than 110 years, the Guerrero seismic gap is also considered as an important seismic and tsunami risk, with a large megathrust earthquake expected to occur in this area. Thus, the seismic gap was thoroughly evaluated to assess its true seismic potential. Here, we characterized the source properties of shallow tremors and earthquakes in the Guerrero subduction zone of Mexico to improve the understanding of seismic risk in Guerrero.

2. Radiated seismic energy at the Guerrero subduction zone

We examined radiated seismic energy of earthquakes in the Guerrero subduction zone. We estimated the seismic energy release of three significant earthquakes in Guerrero: the 2012 Ometepec-Pinotepa Nacional (Mw 7.5), 2014 Papanoa (Mw 7.2), and 2018 Pinotepa Nacional (Mw 7.2) earthquakes, as well as of their M ≥ 4.0 aftershocks. Seismic energy estimates of these earthquake sequences enables a detailed examination of energy release to identify mechanisms that may influence the radiation and spatial distribution of seismic energy in the Guerrero seismogenic zone. We estimated energy of 145 earthquakes; estimations were performed by correcting seismic data through attenuation and site effects and obtaining the source spectrums of earthquakes. The source spectrums were then fitted to an ω^{-2} model to estimate their seismic moment. We analyzed scaled energy using the ratio of the radiated seismic energy and seismic moment. The mean value of scaled energy for the entire set of earthquakes (-5.05 ± 0.25) was consistent with global estimates reported for the Mid-American Trench (Converse and Newman, 2011). We observed low values of scaled energy close to the Ometepec-Pinotepa trench over a previous tsunami earthquake rupture zone. Lower energies originate in this area likely because of the interaction of seismic slip over the previous tsunami earthquake rupture patches, repeating its source properties. Therefore, this region is more prone to slow-rupture earthquakes, indicating a larger tsunamigenic potential. We found a heterogeneous distribution of energy release along the trench. These lateral variations may be associated with a complex and variable plate interface associated with asperity patches or physical properties affecting seismic energy release. It is possible that the variations result from the presence of fluids or differences in subducted sediments.

3. Shallow slow earthquakes at the Guerrero seismic gap to decipher large earthquakes

The Guerrero seismic gap is thought to be a major source of seismic and tsunami hazards along the Mexican subduction zone. Because a large earthquake has not occurred in more than 110 years, a megathrust earthquake with a magnitude larger than 8 has been expected to initiate inside the seismic gap. An earthquake of this magnitude would be devastating to densely populated centers, including Mexico City, and may generate a disastrous tsunami. We deployed an array of ocean bottom seismometers (OBSs) in the Guerrero seismic gap to monitor shallow seismic activity close to the trench and continue evaluating the seismic risk in the gap. As the first evidence of shallow slow earthquakes in Mexico, we used our OBS data, and an envelope correlation method based on maximum likelihood to detect and locate shallow tremors (Mizuno and Ide, 2019). We compiled a detailed description of shallow seismicity by including offshore observations of episodic shallow tremors, possible slow slip events, repeaters, residual gravity, and residual bathymetry. We observed a heterogeneous slip behavior along the strike, which helped to describe the mechanical properties at the plate interface. A portion of the shallow plate interface in the Guerrero seismic gap is dominated by stable slip, which may prevent large earthquakes from becoming much larger and rupturing the entire gap. Weak coupling, both offshore and onshore, can also explain the long recurrence period of large earthquakes in the Guerrero seismic gap and indicate that the initiation of a megathrust earthquake in the seismic gap is less likely to occur, as previously expected. However, a sufficiently large earthquake approaching from an adjacent seismic segment can propagate through the gap driven by dynamic effects and the cascading rupture of nearby locked patches. Continuous offshore monitoring of seismic activity in the Guerrero seismic gap, together with physics-based source modeling, may validate our predictions, which are important for further development of approaches for seismic risk mitigation.

4. Source parameters of shallow tremors in the Guerrero seismic gap

Based on the recent development of an offshore seismic network, shallow slow earthquakes have been reported in the Guerrero seismic gap in the Mexican subduction zone. In Guerrero, deep slow earthquakes are well-understood; in contrast, shallow slow earthquakes have not been explored and their characteristics remain unknown. Shallow tremors in the Guerrero seismic gap were observed using data from an array of OBSs. In this chapter, we describe the analysis done to shallow tremors in the Guerrero seismic gap, to estimate their focal mechanisms and radiated seismic energy and characterize their source properties. Focal mechanisms were estimated by correcting the tremor waveforms by shear wave splitting effects and then observing and inverting *S* wave polarization angles (Imanishi et al., 2015; Ohta et al., 2019). The results showed that slip azimuths of shallow tremors tend to follow the subduction plate motion, indicating that shallow tremors tend to rupture at the plate interface. We then used spectral inversion from ordinary earthquakes to estimate an attenuation model for offshore Guerrero and site effects at the OBS stations. Radiated seismic energy was estimated by correcting the shallow tremor spectrum by attenuation and site effects. The radiated seismic energy of the tremors was scaled using a reference seismic moment calculated from the tremor magnitude. A heterogeneous energy release of shallow tremors was observed, which can explain the different mechanical properties inside and outside the Guerrero seismic gap and help characterize the seismogenic zone at the shallow plate interface. New offshore observations such as seismic profiles, tomography, and geodetic observations are valuable for corroborating our observations and improving the understanding of the shallow seismic activity of the Guerreros gap.

5. Final discussion and conclusions

In the final chapter, we discuss the achievements of this study and current state of shallow seismic activity in the Guerrero subduction zone. The limitations of our research and further advances are discussed. We focused on characterizing the source properties of slow and fast earthquakes in the Guerrero subduction zone of Mexico to improve our knowledge of the seismic risk of the region. Overall, we successfully performed a detailed examination of seismicity in Guerrero as never before, by including offshore data and shallow slow earthquakes. Using OBS data, we found the first evidence of shallow tremors and potential slow slip events (SSE) in Mexico. These are important contributions to improving earthquake risk mitigation in Mexico. However, our results for shallow tremors were obtained from only one year of data observation, which is a limited time. Continuous monitoring of shallow plate seismic activity for additional years is required to support our observations and further our understanding of shallow slow earthquakes in Mexico. We used episodic shallow tremor observation as the first evidence of SSE; however, no direct observations of SSE offshore Guerrero have been conducted. Offshore geodetic observations can help confirm the presence of SSE and provide valuable measurements of plate slip deficit near the trench, which will contribute to a completely new perspective of interplate properties to correlate with our observations. The mechanical conditions found in this study may explain the long return period of large earthquakes inside the gap and decrease the possibility of a megathrust earthquake initiating inside the Guerrero seismic gap, as previously expected. Therefore, for an earthquake to rupture the Guerrero seismic gap, it will need to initiate and propagate from an adjacent area and continue rupturing across the gap. Constant monitoring of the shallow plate interface in Guerrero should be performed to develop approaches for seismic and tsunami risk mitigation in Mexico.