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Near-regional CMT and multiple-point source solution of the September 5, 2012, Nicoya, Costa Rica Mw 7.6 (GCMT) earthquake

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ABSTRACT

We use acceleration data from the Observatorio Vulcanologico y Sismologico, Universidad Nacional de Costa Rica (OVSICORI-UNA) and Laboratorio de Ingenieria Sismica, Universidad de Costa Rica (LIS-UCR) seismic network for the relocation and moment-tensor solution of the September 5, 2012, 14:42:03.35 UTC, Nicoya, Costa Rica earthquake (Mw 7.6 GCMT). Using different relocation methods we found a stable earthquake hypocenter, near the original OVSICORI-UNA location in the Nicoya Peninsula, NW Costa Rica at Lat 9.6943°N, Lon 85.5689°W, depth 15.3 km, associated with the subduction of the Cocos plate under Caribbean plate. Acceleration records at OVSICORI-UNA and LIS-UCR stations (94–171 km), at $0.03 < f < 0.06$ Hz were used in the waveform inversion for a single-point centroid moment tensor (CMT). Using spatial grid search the centroid position was found at the depth of 30 km, situated at Lat 10.0559°N, Lon 85.4778°W, i.e. of about 41 km NNE from the epicenter. The centroid time is 14:42:18.89 UTC, i.e. 15.54 s later relative to the location-based origin time. The nodal plane (strike 318°, dip 27° and rake 115°) is the fault plane that agrees with the geometry of the subducted slab at Nicoya, NNW Costa Rica. Increasing the maximum studied frequency from 0.06 to 0.15 Hz, the multiple point source inversion model leads to two subevents. The first one was located near the centroid and the second subevent was situated 20 km along strike and 10 km down dip from the first subevent and 6 s later. The uncertainty of the source model was carefully examined using complementary inversion methods, *viz* the iterative deconvolution and non-negative least squares.

1. Introduction

The main tectonic feature in northwestern Costa Rica corresponds to the subduction of the Cocos plate at N23°–30°E underneath the Caribbean plate along the Middle America trench (MAT), with a fast convergence rate of 7.7–8.7 cm/yr (McNally and Minster, 1981; DeMets et al., 1990; DeMet et al., 2010). Historic seismicity indicates magnitudes ~7.5 struck Nicoya peninsula in 1853, 1900 and 1950 (Protti et al., 2001).

These facts stimulated seismologists to densely instrument the area in order to document near source rupture characteristics of a future large earthquake. Furthermore, the Peninsula lies above at least 30% of the expected source slip area, offering instrument locations for more precise locations and data resolution.

On September 5, 2012, at 14:42:03.35 UTC, a subduction earthquake of Mw 7.6 (GCMT) was located in northwestern Costa Rica, 50 km from the trench, with a depth of 15 km and Lat 9.6943°N, Lon 85.5689°W (OVSICORI-UNA). Overall, the 2012 Mw 7.6 Nicoya Peninsula earthquake did not cause extensive damage; 12 health care institutions and 98 houses reported moderate and severe damage, respectively; 78 people were injured and 1474 mobilized, due to local hospital evacuations and preventive transfer and no lives were lost (Comision Nacional de Prevencion de Riesgos y Atencion de Emergencias, 2014). However, the Costa Rican engineering report (Laboratorio de Ingenieria Sismica, 2012) and data from OVSICORI-UNA indicates that the peak ground acceleration for this earthquake did exceed 1.8 g for some near stations. Direct application of intensity regression relationships for California (Wald et al., 1999) give a max instrumental intensity of X and a felt area of ~300 km parallel to the trench and ~250 km perpendicular to the trench from the epicenter (Simila et al., 2013).

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Large earthquakes attract attention of seismologists not only because of their societal importance, but also because their large spatio-temporal size enables understanding of their fault complexities more efficiently than possible for small earthquakes. Very important are the subduction megathrust earthquakes whose fault plane is almost completely situated below the land rather than below the ocean. And particularly useful are the events whose focal region had been densely instrumented due to long-term expectation of the earthquake. The Mw 7.6 (GCMT) Nicoya Peninsula earthquake of September 5, 2012 belongs exactly to this rare type of events. Indeed, the earthquake occurred in a seismic gap and it was anticipated due to geodetically proven locking of the plate interface (Protti et al., 2014). The region has been monitored over the decade before the 2012 as the so-called Nicoya Seismic Cycle Observatory (NSCO); see Newman, 2014 (http://nicoya.eas.gatech.edu/). Although the preliminary overall picture is clear and scientifically encouraging – the earthquake released a part of the locked segment of the plate interface – details of the fault process still need a more detailed investigation. For example, the slip distribution published by Protti et al., 2014 was calculated from the static displacements only, and (as documented in Figure S3 of their Supplementary Information) it contained a significant spatial uncertainty. The space-time development of the fault rupture was obtained by Yue et al. (2013), who combined the high-rate GPS (i.e. the static as well as low-frequency transient displacements) with local acceleration and teleseismic data, but their results also contain a significant uncertainty (not explicitly quantified in the cited paper). The uncertainty is due to the fact that their inversion needed tricky weighting between the jointly inverted data sets and because the slip inversion was based on the assumption of a constant rupture speed, weakly constrained by the data. It is therefore clear that a complementary study of the Nicoya earthquake is needed in which possibly some additional data are used, and the assumption of the constant rupture speed is released. To this goal we investigate local and near-regional seismic data recorded in Costa Rica, particularly trying to utilize the low-frequency information contained in the free field acceleration records of a large shallow Mw 7.6 subduction zone earthquake, and we invert the waveforms with two methods (detailed below) both free of assumptions about the rupture nucleation position and rupture speed.

The paper is structured as follows: First we compare the initial OVSICORI-UNA location obtained using real time data with that obtained incorporating non real time data and various methods, including the Source-Scanning Algorithm (SSA). In particular we intend to prove a large difference with respect to the USGS location (Table 1). Then we analyze the resolution power of local and near-regional acceleration data in terms of constructing a single-point source model and multiple-point models, using iterative deconvolution and non-negative least squares methods. Finally, comparing a variety of the source models, we obtain an estimate of the uncertainty of the source model.

Table 1
Summary of Hypocenter and centroid positions for the September 5, 2012, Costa Rica earthquake.

Agency	Origin time	Latitude °N	Longitude °W	Depth (km)	Details
OVSICORI–UNA	14:42:03.35	09.6943	85.5689	15.3	hypocenter
USGS	14:42:08.28	10.0860	85.3050	40.0	hypocenter
USGS	14:42:35.40	09.9720	85.1630	35.0	CMT
GCMT	14:42:23.30	10.000	85.6400	29.7	CMT
Yue et al. (2013)		09.7600	85.5600	13.1	First nucleation point
Yue et al. (2013)		09.8200	85.4700	17.2	Second nucleation point
This work	14:42:18.89	10.0559	85.4778	30.0	CMT

2. Instrumentation, acquisition method and data processing

Three seismograph networks, operated independently by the Universidad Nacional de Costa Rica (OVSICORI-UNA), the Red Sismologica Nacional at Universidad de Costa Rica (RSN-UCR) and the Laboratorio de Ingenieria Sismica of the Universidad de Costa Rica (LIS-UCR) have been recording seismicity in Costa Rica since 1984. The OVSICORI-UNA seismic network started operation in 1984 and the sensors of this network were initially the short period vertical seismometers RANGER SS-1 (1-sec). Starting 2006, the network was complemented with broadband seismometers. In September 5, 2012, the real time network consisted of one CMG-6TD, a Trillium Compact seismometer with Taurus digitizer and ten sites with co-located broadband stations (STS-2 or Trillium 240) and accelerometers (FBA ES-T) with digitizer Quanterra Q330 (DUNO, HZTE, JTS, JACO, COVE, HDC3, CDM, PEZE, RIOS, RIMA). There were also permanent stations not transmitting data in real time at that day and temporary seismic stations administered by OVSICORI-UNA.

Since 2010, EARTHWORM and ANTELOPE software have been used at OVSICORI-UNA center for data acquisition, processing and archiving. For the earthquake locations, the velocity model of Quintero and Kissling (2001) is used.

In this work, data from LIS-UCR at Universidad de Costa Rica are also used. The LIS-UCR instruments are Reftek SMA-130 with flat acceleration response down to zero frequency (uncorrected data). As in most accelerographic networks the data come through routine corrections, including operations like a baseline removal and high-pass filtering (e.g. removing frequencies below 0.1 Hz; http://www.lis.ucr.ac.cr). LIS-UCR provided open-access corrected data from 69 stations at which the frequencies $f < 0.1$ Hz were suppressed during the data processing (Moya, 2006). Such data were used by Yue et al. (2013). We used the corrected LIS-UCR records from 12 near-source stations (GNSR, GNYA, GSTC, GSTR, GLIB, GCNS, GTGA, GJTS, PPUN, PPQR, PCDA, PJAC) in the location procedure by the back-projection method because in the location we need relatively high frequencies (3 and 8 Hz, see below). However, in case of strong events recorded at near stations it is possible and desirable to use also the original uncorrected data, if properly processed. LIS-UCR provided us with 5 uncorrected strong-motion records (GCNS, GLIB, GNSR, GNYA, GSTC) and these were used in this paper for the MT inversion down to the frequency of 0.03 Hz. For details, see the electronic supplement.

3. Location

Considerable discrepancy (~50 km) was detected between location of the earthquake by USGS and OVSICORI-UNA (Table 1 and Fig. 1). The OVSICORI-UNA location was made in real time, using program GENLOC (Pavlis et al., 2004), with the 1D velocity model of Quintero and Kissling (2001). The software GENLOC is implemented inside the seismic software package ANTELOPE. The location was made using 14 stations at distances between 44 and 253 km; in total 14 P- and 4 S-readings were used in the location. Later, when additional 16 temporary stations were included into ANTELOPE, the obtained hypocenter location was within the ellipsoid error, shifted 0.9 km NNE relative to the first location. We also tested the hypocenter location using software outside the ANTELOPE package; using HYPOCENTER code (Lienert and Haskov, 1995) with the 1D velocity model of Quintero and Kissling (2001) and 32 stations in distance range 21–133 km; 32 P- and 16 S-reading. The S-phase picking was made from the transversal