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The intraplate M_W 7 Machaze earthquake in Mozambique: Improved point source model, stress drop, and geodynamic implications

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The February 22nd 2006 $M_W = 7$ Machaze earthquake is one of the largest, if not the largest, earthquakes reported since 1900 within Continental Africa. This large continental intraplate event has important implications to our understanding of tectonics and strong ground motion prediction locally and in the global context. Thus, accurate estimates of source parameters of this earthquake are important. In this study, we inverted the complete azimuthally distributed high frequency (0.05–2 Hz) P waveform dataset available for a best-fitting point source model and obtained stress drop estimates assuming different theoretical rupture models from spectral fitting. Our best-fitting point source model confirms steep normal faulting, has strike = 173° (309°), dip = 73° (23°), rake = −72° (−132°), and shows a 12%–4% improvement in waveform fit compared to previous models, which translates into an error minimization. We attribute this improvement to higher order reverberations near the source region that we took in to account and the excellent azimuthal coverage of the dataset. Preferred stress drop estimates assuming a rupture velocity = 0.9 x shear wave velocity (V_s) are between 11 and 15 MPa though, even higher stress drop estimates are possible for rupture velocities lower than $0.9V_s$. The estimated stress drop is significantly higher than the global stress drop average of intraplate earthquakes, but is consistent with stress drop estimated for some intra-continental earthquakes elsewhere. The detection of a new active structure that appears to terminate in Machaze, its step-like geometry, and lithospheric strength all favors a hypothesis of stress concentration in the source region, which is likely the cause of this event and the higher than average stress drop.

1. Introduction

Large continental intraplate earthquakes are infrequent and the physics governing these events is not fully understood yet (Stein, 2007). Given the significant seismic risk they pose (e.g. M_W 7.7 Bhuj and M_W 7.9 Sichuan events in 2001 and 2008 respectively) and their implications to conventional plate tectonics theory, it is imperative that we gain a greater understanding of these seismic sources. The February 22nd 2006 M_W 7 earthquake in Machaze is probably the largest event ever instrumentally recorded within continental Africa in the past century (Table 1). Due to the large magnitude and the timing of this particular event, 176 globally distributed broadband seismic stations recorded very high quality seismic waveforms from it at teleseismic distances (Fig. 1). Thus, it provides a rare and unique dataset to investigate the physics of a continental intraplate earthquake, which in turn will improve our understanding of slow deformation taking place within the East African Rift System (EARS) and in analog continental intraplate environments and potential of seismic hazard.

Seismic body waveforms can be used to extract spatiotemporal fault slip history and constrain fault-averaged macroscopic parameters describing fault mechanics and dynamics. From forward modeling experiments, Yang and Chen (2008) constrained the focal mechanism of the Machaze event and showed that its P and S_H waveforms are consistent with a west dipping normal fault with a strike 175° whose dip angle is anomalously steep (76°), making it the steepest normal fault reported hitherto. This anomalous dip angle broadly agrees with surface observations (Fenton and Bommer, 2006) and results of body waveform inversion (Craig et al., 2011). A slip distribution map for this particular event has also been constructed from a joint inversion of seismic and geodetic data (Copley et al., 2012), which indicates a peak displacement of

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Table 1
The record of M7 or greater intraplate earthquakes in the African continent from 1900 to present from the ISC catalogue.

Date/Time	Latitude	Longitude	Depth(km)	Mag type	Mag
1910-12-13,11:37:27.33	−6.3513	31.2703	15	MS	7.3
1919-07-08,21:06:14.75	−8.1741	31.5662	15	MS	7.1
1928-01-06,19:31:59.51	0.3404	35.8599	15	MS	7
1935-04-19,15:23:23.78	31.2445	15.315	15	MS	7.1
1990-05-20,02:22:01.18	5.0708	32.1588	14.9	MS	7.2
1990-05-24,20:00:08.22	5.3589	31.866	16	MS	7
1992-09-11,03:57:26.54	−6.0808	26.6392	10.8	MS	7
2001-12-17,04:25:31.52	29.638	30.896	10	Mb	7.7
2005-12-05,12:19:53.73	−6.2415	29.6812	15.8	MS	7
2006-02-22,22:19:09.32	−21.3113	33.5493	16.4	MS	7.4

Accurate estimates of source parameters along with stress drop, particularly of larger events, have important implications in understanding source processes (Kanamori and Allen, 1986; Houston, 1990), to interpretations of tectonics (Liu and Kanamori, 1980; Allmann and Shearer, 2009), and to strong ground motion prediction (Cotton et al., 2013). From the perspective of seismic hazard, improving the precision with which source parameters can be measured is important. In particular, Machaze event is the likely M_{max} event based on historical seismicity of this region and in analog intraplate environments via space-for-time substitution. Because characteristics of the M_{max} event strongly correlates with the predicted hazard level (Ida, 1973; Mueller, 2010; Anderson, 2015), further independent work is required to improve the confidence with which source parameters can be estimated.

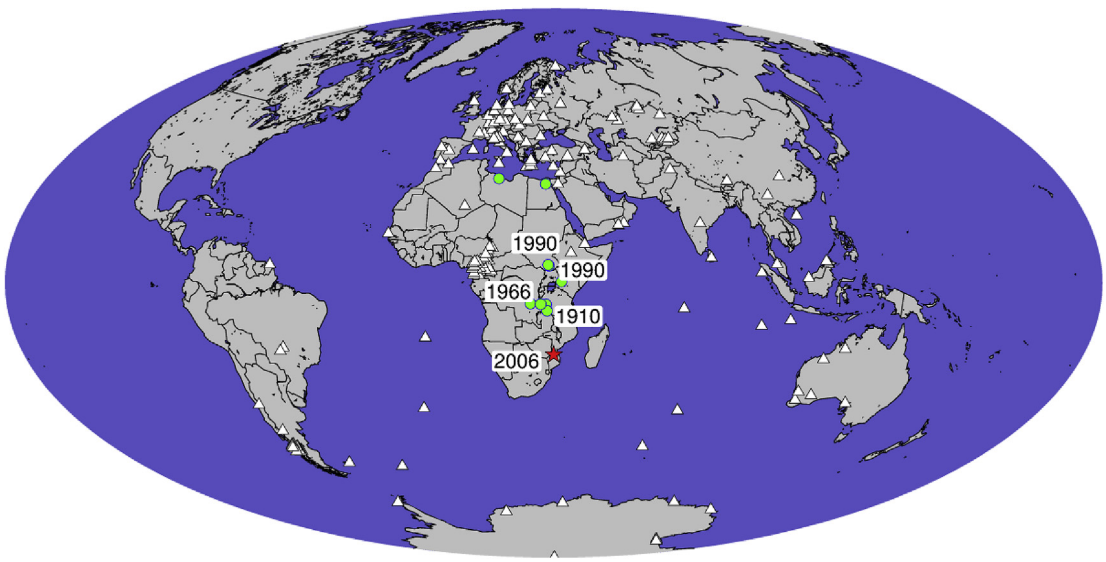

Fig. 1. Earthquake and station distribution. Green solid circles indicate earthquakes having a magnitude M7 or greater in Africa since 1900 given in Table 1. The red star indicates the epicenter of the Machaze event. Triangles represent the 176 stations from which high quality P waveforms were retrieved. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

~4.5 m at depths of 10–15 km and a slip deficit towards the surface from about a 10 km-depth that was partially recovered in post-seismic after-slip. Observation of accelerated post-seismic deformation of about 3.5 cm/yr in the source region is consistent with this slip model (Raucoules et al., 2010). The 16 MPa stress drop estimated by Copley et al. (2012) is significantly greater than the global average of ~6 MPa estimated for intraplate events (Allmann and Shearer, 2009).

On the one hand, some uncertainties still remain about the source parameters of the Machaze event partly because the full seismic dataset has not been exploited in some previous studies. For instance, in constructing the slip distribution map, Copley et al. (2012) used seismic waveforms from only 21 stations in the 30°–80° epicentral distance range. On the other hand, methodological improvements can be made to place stricter constrains on source parameters. For example, the duration of the Source Time Function (STF) in Yang and Chen (7.5s, [2008]) and Copley et al. (~10.5s, [2012]) differs by up to 3s. Also, best-fitting values of the strike of the fault in point source models inverted from body waveforms vary by up to 15° (Yang and Chen, 2008; Craig et al., 2011). In addition, there is some uncertainty in the moment magnitude estimated for the Machaze earthquake. The long period GCMT (Ekström et al., 2012) estimate puts the magnitude at 7.0, whereas results of body waveform inversion suggest a magnitude of 6.9 (Craig et al., 2011).

The purpose of the current paper is two fold. First, we inverted the complete high quality azimuthally distributed teleseismic P waveform dataset in the 30°–90° epicentral distance range for a best fitting point source model to obtain stricter constraints on the focal mechanism solution, focal depth, scalar moment, and the STF. Unlike in previous work, we took in to account the effects of higher order reverberations around the source region whose influence on the amplitude and shape of observed waveforms can be significant (Hong and Fujita, 1981). For the Machaze event, it can be inferred that these effects are important because the seismic structure in the source region, as indicated by past tectonics (Salman and Abdula, 1995), might not be simple. We also explicitly compute cross correlation coefficients to assess waveform misfit between observations and synthetics, which allows for a direct comparison between our best-fitting model and previously published ones. Secondly, we use source spectra with necessary corrections to estimate the stress drop to independently verify if the previously determined estimate of 16 MPa (Copley et al., 2012) using a slip distribution map, which is significantly higher than the global intraplate average, is robust. Note that stress drop and its variability are key parameters in strong ground motion prediction (Cotton et al., 2013). Thus, accurate estimates of these parameters are particularly important for continental earthquakes, where the seismic risk can be extreme both in-situ and in analog environments. In section 2, we describe our data