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Focal mechanisms and moment magnitudes of micro-earthquakes in central Brazil by waveform inversion with quality assessment and inference of the local stress field

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ABSTRACT

This paper documents an investigation on the use of full waveform inversion to retrieve focal mechanisms of 11 micro-earthquakes (Mw 0.8 to 1.4). The events represent aftershocks of a 5.0 m_b earthquake that occurred on October 8, 2010 close to the city of Mara Rosa in the state of Goiás, Brazil. The main contribution of the work lies in demonstrating the feasibility of waveform inversion of such weak events. The inversion was made possible thanks to recordings available at 8 temporary seismic stations in epicentral distances of less than 8 km, at which waveforms can be successfully modeled at relatively high frequencies (1.5–2.0 Hz). On average, the fault-plane solutions obtained are in agreement with a composite focal mechanism previously calculated from first-motion polarities. They also agree with the fault geometry inferred from precise relocation of the Mara Rosa aftershock sequence. The focal mechanisms provide an estimate of the local stress field. This paper serves as a pilot study for similar investigations in intraplate regions where the stress-field investigations are difficult due to rare earthquake occurrences, and where weak events must be studied with a detailed quality assessment.

1. Introduction

Knowledge of the crustal stress distribution is fundamental for understanding tectonics and seismicity, particularly in intraplate regions (Zoback, 1992). The vast majority of the stress-field estimates in a global scale were determined by using earthquake focal mechanisms (Heidbach et al., 2004). In Brazil, only few earthquake focal-mechanism studies have been made due to low seismicity and sparseness of the seismographic stations. Therefore, little is known about the state of stress in the Brazilian intraplate. The stress field in Brazil results from a combination of local and regional forces. The former are caused by structural heterogeneities in the lithosphere and thermal anomalies in the asthenosphere (Assumpção et al., 2004). The latter are related to tectonic forces originating mainly at the edges of the lithospheric plates, such as ridge-pushing forces in the Middle-Atlantic Ridge, and resistance forces produced in the contact of Nazca and South-American plates, causing compressive stress within the intraplate region (Assumpção, 1992).

The first studies of focal mechanisms in Brazil were carried out by Mendiguren and Richter (1978), Assumpcao and Suarez (1988), Assumpção (1998a, 1998b) and Ferreira et al. (1998). More recently new results were presented by Barros et al. (2009, 2015), Chimpliganond et al. (2010) and Agurto-Detzel et al. (2014). Almost all previous fault-plane solutions were obtained by P-wave first-motion polarities and/or the amplitude ratios of P, SV and SH phases.

Various computer codes are available to calculate moment tensors at regional and local distances (e.g. TDMT_INV developed by Dreger (2003), ISOLA by Sokos and Zahradnik (2008), FMNEAREG by Delouis et al. (2008) and Maercklin et al. (2011), KIWI by Cesca et al. (2010), the code of Yagi and Nishimura (2011)). Nevertheless, their application to *weak* events is still quite challenging because, as a rule, the micro-earthquakes (Mw < 2) have a good signal-to-noise ratio only at relatively high frequencies (above ~0.5 Hz), and such waveforms can be modeled only at near seismic stations (Fojtíková et al., 2010; Fojtíková and Zahradník, 2014;

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Benetatos et al., 2012). For moment tensor inversions at very local distances and very high frequencies, typical for mining applications, see, for example, Vavryčuk and Kuhn (2012) and Sen et al. (2013). In this paper we use the ISOLA software (Sokos and Zahradnik, 2013) in its version available at http://geo.mff.cuni.cz/~jz/isola_brasilia/.

Various codes are also available for inverting stress field from focal mechanisms (e.g., Angelier, 2002; Gephart and Forsyth, 1984 and Michael, 1987). As shown by Vavryčuk (2014), Michael's method is reasonably accurate when retrieving the principal stress directions even when the selection of fault planes is incorrect. However, the stress-ellipsoid shape ratio (for brevity, hereafter called shape ratio, Vavryčuk, 2011) needs more caution. Therefore, we use the STRESSINVERSE code developed by Vavryčuk (2014) in which Michael's method is modified by inverting jointly for the stress and true fault orientation.

On October 8, 2010, an earthquake of magnitude 5.0 m_b and intensity VI (MM) startled residents in the northern region of the state of Goiás, Brazil, having also been felt in Brasília and Goiania cities, situated as far as 300 km away (Barros et al., 2015). The epicenter was located with a ~5 km accuracy, thus qualifying this event to be one of the first few GT5 (Ground Truth) earthquakes in Brazil (Barros et al., 2015). Due to the proximity of the epicenter to the city of Mara Rosa, hereafter we call it Mara Rosa (or simply MR) earthquake. This event is the largest ever recorded earthquake in the Goiás Tocantins Seismic Zone (GTSZ), so far characterized by low magnitude events (Fig. 1). Due to the low magnitudes and sparseness of seismographic stations in GTSZ, only one focal mechanism has been reported before the MR earthquake, i.e. the Brasilia event (3.7 m_b) of November 20, 2000 (Assumpção et al., 2014).

The MR event was followed by an aftershock sequence recorded by a temporary seismic network. *The aim of this paper* is to investigate focal mechanisms and moment magnitudes of these weak events, mainly by waveform inversion, and to make inferences about the local stress field. In contrast to usual standard procedures, this paper aims to justify the focal mechanism results as much as possible using various quality assessments applied both to input data and output results.

2. Geological and geophysical setting

The study area, shown in Fig. 1, comprises almost the whole Tocantins Province where the Goiás Tocantins Seismic Zone (GTSZ) is located. Seismicity of this zone is characterized by low-magnitude events with parallel distribution, but not coincident, with the large-scale TransBrasilian Lineament (TBL). Only one event of magnitude 5 m_b has ever been observed (October, 2010) and the majority is lower than magnitude 3.5 M_D.

The TBL crosses the study area from SW to NE, starting north of the Parana basin and ending south of Parnaiba basin. It is characterized by high gravity anomalies along the folding track Tocantins Araguaia (Assumpção et al., 1986; Fernandes et al., 1991). The lineament, denominated Brasilia belt, is characterized by folds and thrusts and is a result of the collision and convergence of three continental plates: the Amazon craton (West), São Francisco craton (East) and Paranapanema craton (SouthWest), presently covered by the Parana basin, see Fig. 1 inset. The TransBrasilian Lineament is composed by a set of geological features formed in the Neoproterozoic during the formation of the eastern part of the super continent Gondwana (Fuck et al., 1994, Fuck, 1994). One of the most important questions is whether the Mara Rosa sequence activated some of the known faults of the region, and what is the relation of these faults to the local stress field derived from seismic data.

3. Local network and data

3.1. Seismic network

A local temporary network comprising of 8 stations (Fig. 2) was deployed a few days after the Mara Rosa 5.0 m_b earthquake. The network was implemented with broadband (30 s–100 Hz) and short period seismometers (1 s–100 Hz), both coupled to a 24-bit digitizer. All the data was recorded with 200 Hz sampling.

3.2. Location and green function

The seismic sequence following the MR mainshock was monitored by the local network for 8 months, from October 2010 to June 2011. In this period, more than 600 events were detected. For the events locations, see Barros et al. (2015).

The Green functions were calculated using a local velocity model, derived from the local network, by Barros et al. (2015), which is similar to the upper crustal model from Soares et al. (2006). The density was calculated by a widely used empirical formula (Eq. (3.78) of Červený et al., 1977) and quality factors, Qp and Qs, were only roughly estimated. The model is shown in Table 1 and Fig. 3.

3.3. Selecting events, stations and data quality control

An additional selection was made to find suitable events and stations for the waveform inversion. The selection criteria were adopted as follows: events within the group of 53 processed with HypoDD, magnitudes ranging from 1.2 to 2.0 M_D, recorded by more than 5 local stations (<8 km) and being free from instrumental, cultural or electronic noise at a minimum three stations.

To prevent biasing the focal-mechanism calculations due to problematic data, a thorough visual inspection of raw waveforms was made. We concentrated on several issues, such as, possible data gaps, clipping, electronic noise, excessive microseismic and/or cultural noise and low signal-to-noise ratio (SNR). When detected, the instrumentally disturbed records (see below for more details) were removed from processing. Examples of these problems are shown in Fig. 4a and b. Fig. 4a shows the waveforms of the station MR9, event 10. The signal is from a broadband instrument output, band-pass filtered (1.5–2.0 Hz) and is contaminated by excessive cultural noise. Fig. 4b shows the waveforms of the station MR3, event Ev6. The signal is from a broadband instrument output, band-pass filtered (1.5–2.0 Hz) and is contaminated with an electronic monochromatic noise, probably, from equipment malfunction.

Particular attention was devoted to the instrumental disturbances described by Zahradnik and Plesinger (2005, 2010) and Vackář et al. (2015). They can be easily detected by inspecting the output (raw velocity) without any preliminary band-pass filtering and prior removal of the instrument response, or, if the disturbances are weaker, by inspecting the integrated output (raw displacement). If overlooked, the disturbances can harm the moment-tensor inversion. Such disturbances are demonstrated in Fig. 4c and d. Fig. 4c shows the waveforms from the station MR8, event Ev6. The signal is from a broadband sensor (raw velocity) instrument output, unfiltered and uncorrected. Fig. 4d is similar, showing the station MR11 (short period sensor), event Ev6. All (3) seismograms with similar detected disturbances were removed from processing. Finally we arrived at 11 selected events shown in Fig. 2 and detailed in Table 2. Note that all the events are very shallow (<2 km).