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Surface displacement of the M_w 7 Machaze earthquake (Mozambique): Complementary use of multiband InSAR and radar amplitude image correlation with elastic modelling

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ABSTRACT

In this paper we investigate the surface displacement related to the 2006 Machaze earthquake using Synthetic Aperture Radar Interferometry (InSAR) and sub-pixel correlation (SPC) of radar amplitude images. We focus on surface displacement measurement during three stages of the seismic cycle. First, we examined the co-seismic stage, using an Advanced SAR (ASAR) sensor onboard the Envisat satellite. Then we investigated the post-seismic stage using the Phase Array L-band SAR sensor (PALSAR) onboard the ALOS satellite. Lastly, we focussed on the inter-seismic stage, prior to the earthquake by analysing the L-band JERS-1 SAR data. The high degree of signal decorrelation in the C-band co-seismic interferogram hinders a correct positioning of the surface rupture and correct phase unwrapping. The post-seismic L-band interferograms reveal a time-constant surface displacement, causing subsidence of the surface at a ~5 cm/yr rate. This phenomenon continued to affect the close rupture field for at least two years following the earthquake and intrinsically reveals a candidate seismogenic fault trace that we use as a proxy for an inversion against an elastic dislocation model. Prior to the earthquake, the JERS interferograms do not indicate any traces of pre-seismic slip on the seismogenic fault. Therefore, slip after the earthquake is post-seismic, and it was triggered by the Machaze earthquake. This feature represents a prominent post-seismic slip event rarely observed in such a geodynamic context.

1. Introduction

On February 22, 2006, a M_w 7.0 earthquake occurred in Machaze, Manica Province, Mozambique (Fig. 1) affecting an area characterised by low-level historical seismicity. This earthquake inflicted little damage on property and individuals, mainly because of the typology and density of housing in the area (i.e. scattered villages with light-weight structures). During the 20th century, three earthquakes with magnitudes larger than 5.0 concerned this area: the first in 1951 and the two others in 1957. They were characterised by shallow slip at depths of less than 20 km (Fenton & Bommer, 2006). The fault system associated with these earthquakes can be related to the southern portion of the East African Rift and belongs to a divergent plate-boundary geodynamic context. The 2006 Machaze earthquake occurred at a depth of 12 km and produced a north-south oriented surface rupture about 30–40 km long with a co-seismic surface slip of up to 2 m (Fenton & Bommer, 2006). The fault ruptured with a normal mechanism with a 70° west dipping fault plane. Fenton and Bommer (2006) stated that the surface rupture, although visible in the field, could not be followed along its entire length due to the danger posed by buried land mines in the area. Moreover, extensive liquefaction phenomena were associated to this event (López-Querol et al., 2007).

In this paper, we called on remote-sensing satellite data to complement data acquired on the ground to help understand the Machaze earthquake. In particular, we used InSAR (e.g. Massonnet & Feigl, 1998) and SPC (e.g. Michel & Avouac, 2002) techniques along with Envisat-ASAR, JERS-1 and ALOS-PALSAR data to measure the ground surface displacement produced by the Machaze earthquake at different stages of the seismic cycle, i.e. before, during and after the earthquake. Then, we used the co-seismic displacement field to constrain the seismogenic fault geometry at depth by inverting the surface displacement field against a simple elastic dislocation model (Briole et al., 1986).

We proceeded as follows. First, we used the ALOS PALSAR data to produce a post-seismic interferogram revealing the position and surface geometry of the seismogenic fault (not observable on the co-seismic interferograms because of high deformation rates). Then we looked at the inter-seismic interferograms to detect possible creep or pre-seismic slip on this previously unmapped fault. Finally, we built a co-seismic interferogram and used the retrieved fault surface

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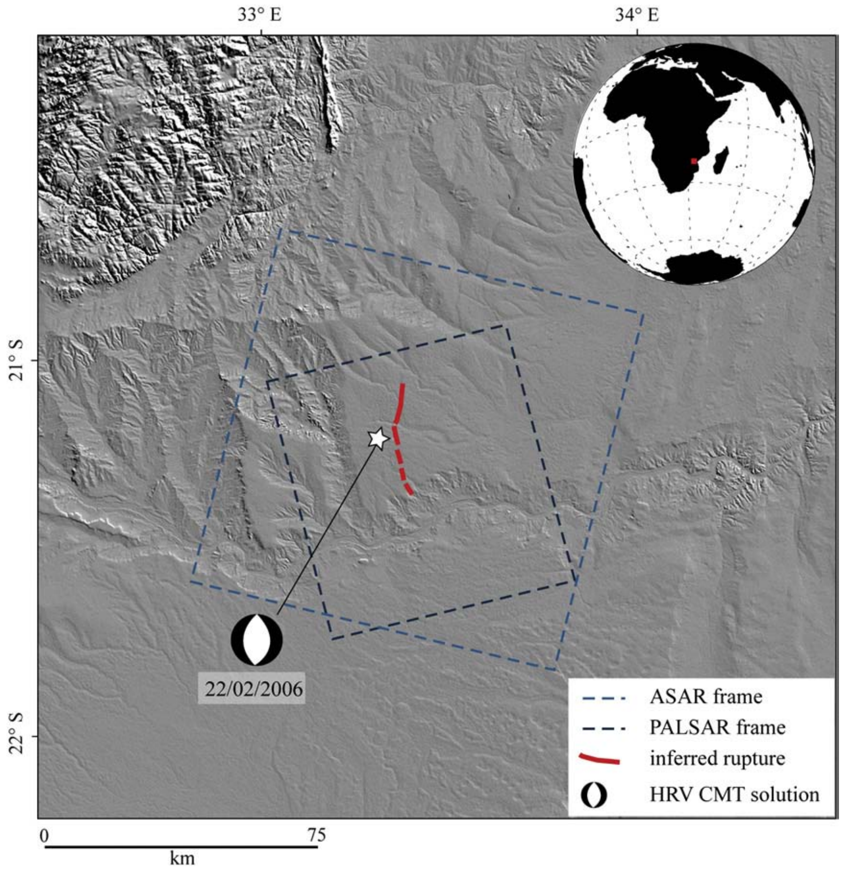

Fig. 1. Location of the Machaze Earthquake.

geometry parameters to constrain the fault's co-seismic slip and geometry at depth by means of an inversion procedure.

2. Data

In this study, we made a complementary use of C and L band radar from different sensors. Due to the dense vegetation covering the terrain in the area of interest and the large size of surface deformation expected (~metre), we decided to use ALOS-PALSAR and JERS-1 L-band radar data. Moreover, the measurements obtained from radar data at longer wavelengths (23 cm as opposed to 5.6 cm for C-band) would be less affected by fringe aliasing as there would be fewer fringes for given deformation values. Therefore, interferometric phases could be unwrapped over larger areas (e.g. Raucoules et al., 2007). Unfortunately, ALOS and JERS-1 data were not available during the co-seismic phase of the Machaze earthquake. We accordingly called on Envisat/ASAR C-band data to retrieve co-seismic surface displacement while using ALOS-PALSAR and JERS-1 to investigate possible post-seismic and pre-seismic surface displacement respectively. In this study we used six PALSAR images (Dec. 2006–Dec. 2008, ascending mode), seven ASAR images (Nov. 2003, Feb. 2007, descending mode) and three JERS-1 images (Apr. 1993–Oct. 1996, ascending mode). Tables 1 to 2 describe the characteristics of the PALSAR, ASAR and JERS-1 interferograms that we built using the GAMMA software (Wegmuller et al., 1998).

3. Data processing

3.1. Post-seismic slip

For each of the three observation periods, we apply different processing strategies.

Hashimoto et al. (2007) detected and provided a preliminary estimate of the post-seismic deformation phenomenon based on a single ALOS/PALSAR pair prior to December 2006 and examined an Envisat/ASAR pair. Our objective here has therefore been to obtain a precise location of the displacement field and to derive the post-seismic displacement rate over a longer period. We further would be interested in ascertaining whether post seismic displacement is decelerating. In this perspective, we built a stack of 15 unwrapped interferograms according to the methodology proposed by Le Mouélic et al. (2005):

$$V = \frac{\langle \Delta\Phi \rangle}{\langle \Delta T \rangle} \frac{\lambda/2}{2\pi} \tag{1}$$

Table 1
Interferograms produced using ALOS PALSAR SAR images. Post-seismic period.

Interferogram	Image1 (date)	Image2 (date)	Perpendicular baseline (m)	Time span (days)
1	20061226	20070210	725	46
2	20061226	20071229	−881	368
3	20061226	20080213	−632	414
4	20061226	20080330	−1191	460
5	20061226	20081231	1512	736
6	20070210	20071229	−1607	322
7	20070210	20080213	−1357	368
8	20070210	20080330	−1916	414
9	20070210	20081231	787	690
10	20071229	20080213	249	46
12	20071229	20081231	2394	368
13	20080213	20080330	−558	46
14	20080213	20081231	2145	322
15	20080330	20081231	2704	276