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The Al Hoceima (Morocco) earthquake of 24 February 2004, analysis and interpretation of data from ENVISAT ASAR and SPOT5 validated by ground-based observations

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ABSTRACT

The magnitude M_w=6.3 earthquake in Al Hoceima, Morocco of 24 February, 2004 occurred in the active plate boundary accommodating the oblique convergence between Africa and Eurasia. Three different sets of estimates of its source parameters have already been published. We try to resolve the discrepancies between them by using additional data including two remote sensing satellite systems (ENVISAT and SPOT5). Using a model with a dislocation in an elastic half-space, we constrain the source parameters. The hypothesis of two subevents on distinct faults as inferred from seismological inversions is confirmed here by adopting a cross-fault mechanism. The rupture began on a left-lateral strike-slip fault striking at N10° azimuth with 90 cm of horizontal slip and then transferred to a right-lateral strike-slip fault striking at N312° azimuth with 85 cm of horizontal slip. The first fault is at 500 m depth from the free surface and the second fault is at 3 km depth. This model is consistent with ground-based observations, including GPS, seismology, and mapped surface fissures. The pair of faults activated in 2004 appears to constitute part of a complex seismogenic structure striking NNE–SSW that separates the Rif tectonic blocks.

1. Introduction

The Al Hoceima region is now recognized as the most seismically active part of Morocco, due to its situation in the complicated boundary zone between the Eurasia and Africa plates. Its high level of seismicity makes it one of the most studied active zones in the western Mediterranean. The tectonic control of the seismicity is still an open question.

Al Hoceima is located between two major left-lateral strike-slip faults, the Jebha fault striking N70° and the Nekor fault striking N50° (Fig. 1), along which the Rif nappes were transported toward the WSW with left-lateral strike-slip through the Miocene (Leblanc & Olivier, 1984; Frizon de Lamotte et al., 1991). The paucity of seismicity and the lack of Quaternary deposits around these two major geological faults (Leblanc & Olivier, 1984; Frizon de Lamotte et al., 1991) make it difficult to investigate the paleoseismicity and the recent morphotectonics within these prominent structural features of the Rif.

The seismic activity in the Al Hoceima region is characterized by predominantly strike-slip and normal faulting trending from NE–SW to NW–SE (Hatzfeld et al., 1993; Calvert et al., 1997). Historically, the Al Hoceima area has experienced many disastrous earthquakes. Notable sequences in 1522, 1624, 1791 and 1800–1802 have been reported by El Mrabet (2005). On May 26, 1994 a M_w=5.9 earthquake occurred there with a left-lateral strike-slip buried fault (Calvert et al., 1997; El Alami et al., 1998; Bezzeghoud & Buforn, 1999; Biggs et al., 2006; Akoglu et al., 2006). Surface cracks trending mostly from NNE–SSW to NE–SW and coeval with the 1994 main shock have been observed in the epicentral area (Hahou, 2005).

The February 24, 2004 (M_w=6.3) earthquake was one of the most catastrophic of the last century in this region. Its devastating effects included: 629 fatalities, 966 injuries, 2539 destroyed and damaged

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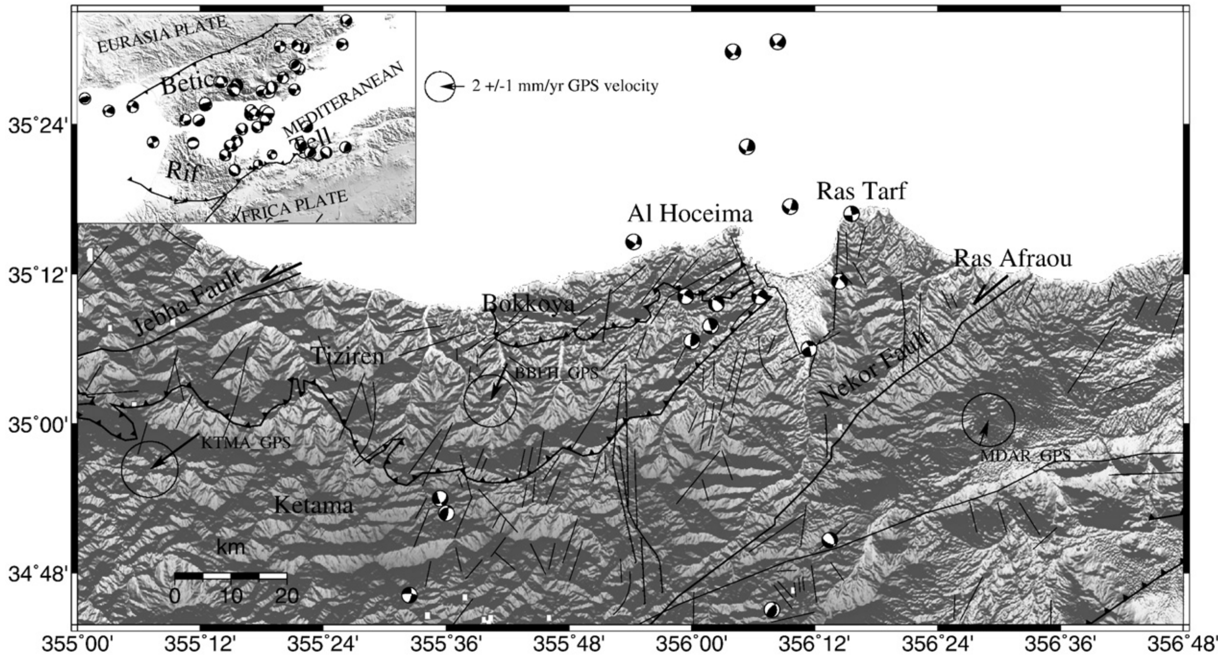

Fig. 1. Tectonic setting of the Al Hoceima (Northern Morocco) region. Focal mechanisms are selected from Stich et al. (2003) and the Harvard (2005) catalog. Tectonic features are from the *Carte des mouvements récents du Rif* (Service Géologique du Maroc, Rabat, 1992). Arrows show velocities of GPS stations for the interval 1999–2005 with respect to Africa plate, with 95% confidence ellipses (Tahayt et al., 2007). The inset shows the regional seismotectonic context of the western Mediterranean Basin. Topography is derived from NASA/SRTM (2005).

houses, and 15,600 homeless. The heavy damage was due in large part to the poor quality of construction combined with site amplification effects. The ground acceleration reached 2.3 m/s/s close to Abdelkarim El Khattabi lake dam located at 20 km SE of Al Hoceima city (CNRST, 2004).

A suite of geophysical studies was undertaken as soon as possible after the Al Hoceima 2004 earthquake using different measurements to determine the source mechanism of the main shock. Jabour et al. (2004) and Aït Brahim et al. (2004) describe the macroseismic effects of the earthquake. Stich et al. (2005) use waveform inversion to estimate the source parameters of the mainshock. They propose a model with two distinct parallel faults striking N11°E. Çakir et al. (2006) estimate the fault geometry and the slip distribution using only descending and ascending synthetic aperture radar (SAR) interferograms to find a curved right-lateral strike-slip fault, striking NW–SE. Biggs et al. (2006) conclude from interferograms and aftershock distribution that the main fault is planar and strikes NW–SE. The differences between these determinations of the source mechanism of the mainshock are due to the complexity of the rupture. Previous solutions for the source parameters are summarized in Table 1.

In this work, we attempt to reconcile these studies by considering most of the available data in a single interpretation. In particular, we analyze data from two satellite systems: ENVISAT and SPOT5. These data constrain an elastic dislocation model to find the source parameters of the earthquake, including the length, width, strike, dip, amount, and rake of the coseismic slip. To validate the interpretation, we compare the model for the earthquake source mechanism to ground-based observations, including seismology, geodesy and geology. Fig. 2 shows the locations of the data sets used in this study.

2. Remotely sensed observations

2.1. InSAR

We use ENVISAT radar images acquired in both descending and ascending tracks before and after the 2004 earthquake to further investigate coseismic deformation (Table 2). Interferometry applied to SAR images (InSAR) yields three coseismic interferograms, two in descending orbital passes and one in an ascending pass. They are

Table 1
Different estimates of source parameters for the 24 February 2004 earthquake in Al Hoceima region using various data sets: (A1) and (A2) are two faults from InSAR, GPS, SPOT5, seismological, and field data (this study); (B) is from InSAR and seismological data (Biggs et al., 2006); (C) is from InSAR data (Çakir et al., 2006); (D1) and (D2) are two faults from seismological data (Stich et al., 2005)

Fault	Longitude (°)	Latitude (°)	Strike (°)	Dip (°)	Rake (°)	Depth* (km)	Length (km)	Width (km)	Slip (m)	Moment (x 10^{18} N m)	$\bar{R}$
A1 (L)	−3.959	35.122	10	88	1.3	0.5	9	11.5	0.92	2.80	0.0688
A2 (R)	−4.028	35.134	312	88	−179	3.0	15	9.0	0.76	3.08	0.0688
B (R)	−3.986	35.137	295	87	−179	2.1	8.8	16	1.4	6.2	0.0522
C (R)	−3.993	35.127	275–310	88	−161	2	21	16.5	2.7	6.8	0.0302
D1 (L)	−4.000	35.140	11	72	−17	1.6	10	10	1	1.9	
D2 (L)	−4.020	35.140	11	72	−17	0.7	8	8	0.6	1.0	
Z											0.0502

(L) for left and (R) for right, indicate the sense of strike slip.
* Depth of the top edge of the fault. $\bar{R}$ is the mean resultant length of the residual difference between the observed phase and the modeled phase, using a near-field area (Fig. 5). *Z* is the null model.