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Rupture behavior of a moderate earthquake (M_W 5.9, April 2006) and its close relation with the 2003 Chengkung earthquake (M_W 6.8) at the southern termination of the plate boundary, southeast Taiwan

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ABSTRACT

The Taiwanese orogen is the result of the active and vigorous collision between the Eurasian and the Philippine Sea plates. In this strong convergence context, a one month-long earthquake sequence composed of two mainshocks of magnitude 6 occurred in April 2006 in the Taitung area. The first mainshock (T1) mobilized a structure just west to the plate boundary, while the second one (T2) is located on the other side. In order to retrieve the exact fault geometry of T2, we inverted waveforms from stations located at local and teleseismic distances. We performed a grid search on strike and dip (each strike-dip couple defining a geometry) considering the source as a point source then as an extended source. In the last case, a simple average over stations misfit failed to isolate a precise geometry. To overcome this problem, we used a more statistical approach on the distribution of misfits to define the best geometry. Comparing the best model to local structures, it appears the generative fault was the plate boundary that rotates from a strike pointing at N20°E north of the event to N0°E in T2 area with an identical eastward dip of 35°. For this model, the fault slip inversion provides a critical slip of 3.5 cm above which slip, rake and rupture time are constrained with uncertainties of 29%, 14° and 0.47 s respectively. The average slip along the rupture was 20 cm with a maximum of 46 ± 13 cm. The movement was inverse with a minor left-lateral component similar to the faulting behavior of the plate boundary. In addition, the slip pattern of T2 is contained within the southern portion of the deepest segment of the plate boundary and at the edge of the rupture area of the 2003 Chengkung earthquake (M_W 6.8), a large event also generated by the plate boundary but 2.5 years earlier. After 1 s of aseismic spreading, the rupture propagated seismically and circularly outward before being stopped by the fault bending.

1. Introduction

Taiwan is an active orogen resulting from the collision between the Eurasian continental plate (EUP) and the Philippine Sea Plate (PSP). The onland plate junction is materialized by a narrow valley, the Longitudinal Valley (LV), filled with Quaternary sediments (Tsai et al., 1974). The valley is early defined as a suture zone between the two plates (Ho, 1986; Tsai, 1986) and lays between two mountain ranges: the Central Range (CER) to the West and the Coastal Range (COR) to the East (Fig. 1). The former belongs to the EUP while the later is part of the PSP. Previous studies on the LV indicate that this valley accommodates up to 25–30% of the total plate convergence (Angelier et al., 2000; Lee et al., 1998), explaining the intense seismicity of this region. More precisely, surface shortening occurs along structures on both sides of the LV and parallel to it: the Longitudinal Valley Fault (LVF) to the east and the Central Range Fault (CRF) to the west (Fig. 1). However, those two structures are not equally active since the LVF is responsible for most of the deformation (geodetic and seismic) due to the collision and is therefore considered as the effective plate boundary (Angelier, 1984; Biq, 1972; Chai, 1972; Ho, 1982). On the other hand, the existence and the nature of the CRF is still a matter of debate because of its low activity and the absence of surface outcrop (Biq, 1965; Crespi, 1996; Lee et al., 2001, 2003; Malavieille et al., 2002). Despite the lack of evidences, Shyu et al. (2006, 2008) speculated that some minor shortening should take place on the CRF regarding the uplifted terraces that distribute along its supposed surface trace.

In April 2006, a one month-long seismic sequence occurred in the southern-end of the Longitudinal Valley, in the Taitung area. Its particularity is to contain two mainshocks of magnitude 6.0–6.1 separated by 14 days and about 20 km; each mainshock was followed by their respective aftershocks sequences. On April

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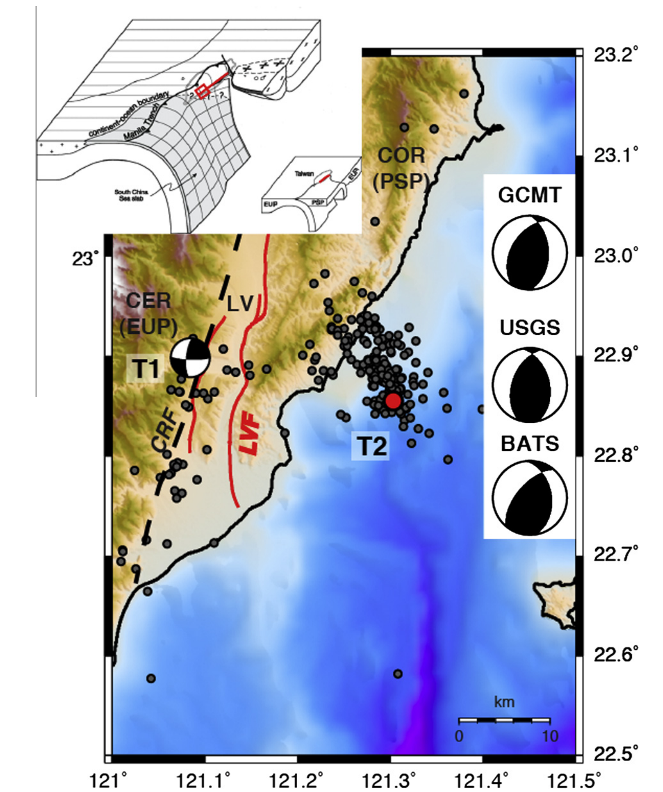

Fig. 1. Location of the two main large earthquakes of the 2006 April earthquakes sequence. Top left: 3D diagram of plate tectonics surrounding Taiwan (modified from Lallemand et al. (2001)). In gray is plotted the oceanic crust of the South China Sea (an oceanic crust that belongs to the Eurasian plate). Red line: Longitudinal Valley Fault. Red rectangle: study area. Main map: study area with the location of both earthquakes. The first event (labeled T1 on the Fig. 1) is plotted by its focal mechanism retrieved from Wu et al. (2006). The location of the second event (labeled T2) is indicated as a red circle. Only the sequence of aftershocks (gray shaded circles) of the second mainshock is plotted. Aftershocks are issued from the CWB and occurred up to 15 days after the mainshock. Events distribute along an alignment oblique to the Longitudinal Valley Fault (LVF). Next to the map, focal mechanisms of T2 are provided according to three different networks (BATS; GCMT; USGS). CER = Central Range. COR = Coastal Range. LV = Longitudinal Valley. LVF = Longitudinal Valley Fault. CRF = Central Range Fault. The LVF is indicated by red lines, while a dashed black line is used for the CRF since its surface trace remains uncertain. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1st 2006, the first mainshock (M_W 6.1) shook the western part of the southern portion of the Longitudinal Valley. Previous studies demonstrated that the CRF generated this event (Chen et al., 2009; Mozziconacci et al., 2013; Wu et al., 2006), bringing this earthquake as the first moderate-large event ever recorded for this structure since the installation of the Central Weather Bureau Seismic Network (CWBSN) in the late 1980s, and putting an end on the

Table 1
Location, magnitude and focal mechanism of T2 from different networks (BATS, CWB, GCMT, USGS). Planes refer to the two nodal planes (strike/dip/rake) of the focal mechanism. Networks are identical as those in Fig. 1.

Networks	Latitude	Longitude	Depth (km)	Magnitude	Planes: strike/dip/rake
CWB	22.856	121.304	17.9	M_L 6.00	
BATS	22.856	121.304	17.9	M_W 5.73	351/43/46 & 221/61/121
GCMT	22.870	121.400	21.7	M_W 5.90	258/48/66 & 212/47/115
USGS	22.802	121.362	08.0	M_W 5.90	246/46/65 & 200/50/114

debate on the existence of the CRF. Fourteen days later, on 15 April 2006, the second mainshock of the crisis (M_L 6.0), occurred off-shores, 10 km east of the Taiwanese coasts (Fig. 1). It is on this late event that we focus our study, and to simplify the reading we call it "T2" by comparison with the first event of the sequence ("T1" in the following text).

In the epicentral area of T2, the main local structure is the Longitudinal Valley Fault (LVF in Fig. 1), the effective plate boundary. It mainly strikes at N0°–20°E and plunges eastward under the Coastal Range. The oblique collision between the EUP and the PSP results in the oblique movement on this structure, with a faulting 2/3 reverse and 1/3 left-lateral (Angelier et al., 1997; Barrier, 1985; Barrier and Angelier, 1986; Yu and Kuo, 2001). From the background seismicity a clear listric geometry was evidenced for the southern portion of the LVF; the dip varying from 60° to 70° in the first 10 km to less than 40° at deeper depth (Chen and Rau, 2002; Kuochen et al., 2004). Interestingly, three seismic networks (BATS, GCMT, USGS) give a consistent focal mechanism, mainly reverse in type with a small strike-slip component, compatible with the interseismic behavior of the LVF (Fig. 1 and Table 1). Concerning nodal planes of those focal mechanisms, all display one set oriented similarly to the LVF with north–south strike and a dip plunging eastward (Fig. 1). However, in map view, aftershocks of T2 align differently from the LVF strike or dip direction, rending the link between this structure and the mainshock difficult to assume. To determine whether the LVF underwent the T2 earthquake, we performed a joint inversion of seismological data (from stations located at teleseismic and local distances) to retrieve the fault geometry and the fault distribution in space and time.

2. Data

We used two sets of seismological data from stations located at teleseismic and local distances from the epicenter. Local records are expected to be rather sensitive on the fault geometry and on the fault slip distribution in space and time. The use of teleseismic data allows a better azimuthal coverage and adds additional constrains on rupture timing.

2.1. Teleseismic data

From the IRIS data center, we selected 12 records of the P wave of stations located between 30° and 90° from the epicenter with a good azimuthal coverage (Fig. 2a). Since the earthquake is moderate (M_W 5.9 to 6.0, depending on the network, see Table 1), most of usable stations are located between 30° and 45°; at further distances, records become too noisy to be exploited. After correction of the baseline, each record was deconvolved from instrument response and integrated in displacement according to the method of Nábělek (1984). A band-pass filter between 0.01 and 0.80 Hz and a time sampling of 0.25 s are used for an optimal time window of 30 s. Time windows are selected by trials and errors to contain direct waves and reflected phases and should be long enough to include any directivity effects.

2.2. Local strong motion data

We used 9 near-field local stations from the CWB network located between 9 and 95 km from the epicenter (Fig. 2b) and restricted within the PSP. The advantage of this restriction lays in a more homogeneous velocity model compared to the case of stations located on the two different plates that are the EUP (continental plate) and the PSP (oceanic plate). Station coverage is satisfying to the west of the epicenter with an epicentral distance lower than 30 km. However, to the east, the station on