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Characteristic repeating earthquakes in an arc-continent collision boundary zone: the Chihshang fault of eastern Taiwan

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Creeping crustal faults often generate a large number of microearthquakes, and less commonly, they may also produce large earthquakes that rupture the brittle crust. The Chihshang fault in eastern Taiwan is characterized by such behavior and has been known to undergo 2-3 cm/yr surface creep, making it one of the most active creeping thrust faults known in the world. It gives an excellent opportunity to study how a creeping fault can generate large earthquakes. However, the understanding of fault behavior at depth in this area has been limited due to sparse sampling from seismic and geodetic stations.

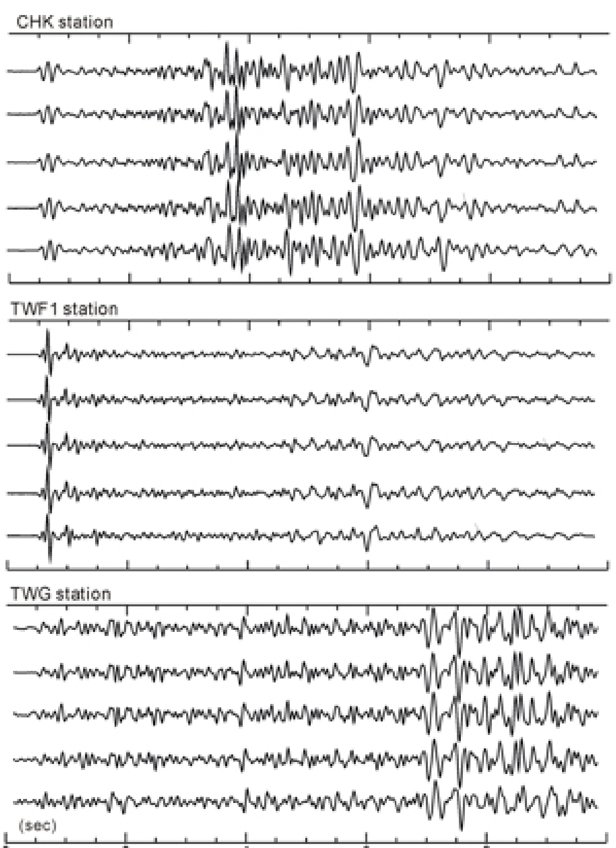

Fig. 1. Filtered 2-18 Hz waveforms recorded at station CHK, TWF1, and TWG from a repeating earthquake sequence. Each trace is normalized by its maximum amplitude.

A new technique for inferring fault slip rate at depth using repeating microearthquakes was recently developed and has been applied in diverse tectonic settings. Repeating earthquakes are defined as groups of events with nearly identical waveforms, locations, and magnitudes and thus represent repeated ruptures on the same fault patch. Fig. 1 shows examples of the waveforms for a repeating sequence. Given an assumption that the frequency of seismic slips on a fault patch is proportional to the tectonic loading rate due to relative plate motion, one can determine the deep fault slip rate at each repeating sequence site using the recurrence intervals and seismic moments of the repeating sequence. A large number of small repeating earthquakes have been found in the creeping sections along the San Andreas fault due to a lower magnitude of completeness in the earthquake catalog with dense station coverage and high resolution data. In the creeping Chihshang area where spatial coverage of stations is sparse and asymmetric around the fault, however, repeating earthquake identification is problematic and challenging.

In this study we determine and evaluate a population of repeating earthquakes to improve the understanding of deep fault deformation. We propose a repeating sequence identification scheme in the region where the station coverage is sparse and one-sided. Using these composite selection criteria, we identified 30 repeating sequences in the

Chihshang area containing 109 repeating events with magnitudes ranging from 1.9 to 3.7. The sequences composed of only two events are excluded from our repeating event data set. The observed repeating events represent about 3% of all the *M* 1.9 to 5.4 earthquakes in the earthquake catalog. Locations of the 30 repeating sequences are shown in Fig. 2. All the repeating sequences occur within the depth range 7 to 23 km, and tend to concentrate on the northern portion of the Chihshang segment (north of 23.1°N).

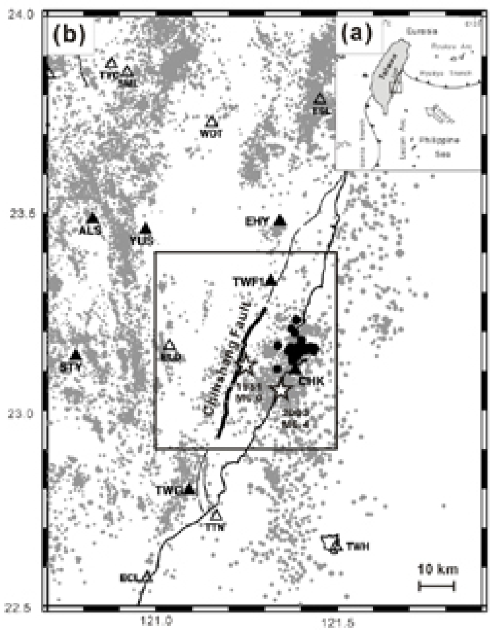

Fig. 2: Mapview of seismicity and repeating sequences in the Chihshang area. (a) Geodynamic framework of Taiwan. Open arrow indicates relative motion between Philippine Sea plate and Eurasian plate in Taiwan Region. (b) The Chihshang fault segment and the Chihshang study area (box). HypoDD relocations of M ≥ 3 seismicity during the study period are shown as gray dots. The 7 seismic stations used in this study are shown as black triangles; others with relatively lower SNR are shown as open triangles. Locations of the 30 repeating sequences that we found are shown as black solid circles. Inset shows the plate-tectonic of Taiwan and the location of the Longitudinal Valley fault. Stars are the M>6 historical earthquakes that occurred on the Chihshang fault.

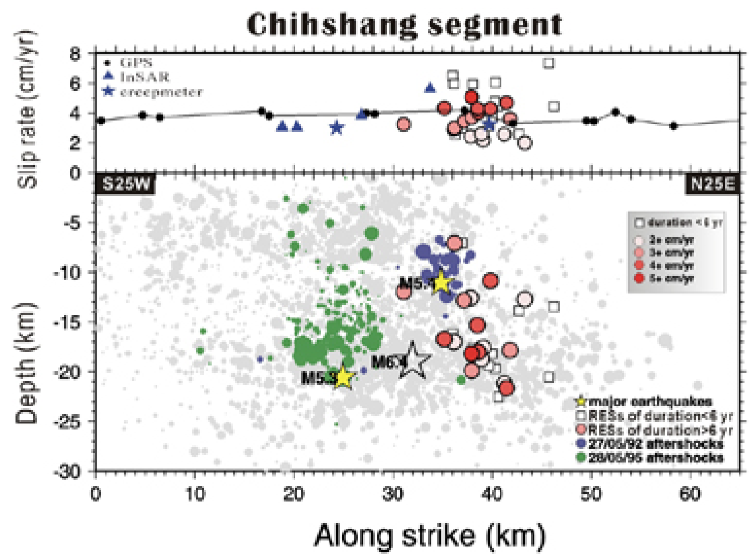

Fig. 3. Spatial distribution of repeating sequence derived slip rates in along-strike cross-section. Upper panel: filled squares show a projection of repeating sequences on the along-strike distance and their corresponding slip rates. Open squares denote the repeating sequences with short duration. Black dot shows a combined surface slip rates from GPS and leveling data measurement. Blue solid triangles and stars are along-dip projection of InSAR data and creepmeter data.

Deep fault creep rates can be inferred using the recurrence intervals and seismic moments of repeating sequence events. The method first relates the seismic moment of a repeated event (M_o) to the surrounding aseismic fault slip (d_i) that loads the event's rupture patch to failure during its preceding recurrence interval. The results of deep creep rates along the strike of the Chihshang fault are shown the filled circles in Fig. 3. The creep rate estimates range from 1.8-4.3 cm/yr with an average of 3 cm/yr. The highest creep rates (above 4 cm/yr) are found on the deep portion of the fault, between 16 and 18 km, and creep rates of less than 2 cm/yr are distributed from 7-21 km depth. The overall creep rates estimates do not reveal a systematic depth-dependent behavior. In the upper panel of Fig. 3, we compare the along-strike variation of deep creep rates with surface observations. Black dots labeled 'GPS' are actually the slip rates estimated from a combination of the average uplift rate from 1985-1994 leveling data and horizontal deformation rate from 1992-1999 GPS data. The InSAR data and creepmeter data are projected into the along-dip direction assuming a fault dip angle of 60° for the shallow portion of the fault. The above surface measurements (particularly creep) are consistent with the deep repeating earthquake creep rates (~3 cm/yr).

In summary, we have found repeating earthquakes on an imbricated reverse fault in the arc-continent collision boundary of eastern Taiwan, the Chihshang fault. The Chihshang fault creeps at the surface with a high rate of 2-3 cm/yr and slips in large earthquakes. To improve seismic hazard assessment, it is important to know how the creep rate observed at the surface is related to the fault slip rate at depth. The recently discovered repeating earthquakes in the Chihshang area offer a new insight into deep fault behavior. We have shown that the repeating events are located in the northern half of the fault, indicating the fault property in this portion is probably different from that in the south. The 30 repeating sequences occurred at 7-23 km depth with 3 cm/yr average deep slip rate consistent with surface creep rate, suggesting that the creeping section probably extends from near surface to the depth of 23 km in the north. We infer a contrasting deep fault slip behavior from north to south on the Chihshang fault. The northern segment is creeping and the southern segment is partially locked with a higher earthquake potential, consistent with the occurrence of the 2003 *M* 6 event.