Tectonophysics 578 (2012) 76–86

Contents lists available at SciVerse ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Fault zone Q values derived from Taiwan Chelungpu Fault borehole seismometers (TCDPBHS)

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A R T I C L E I N F O

Article history:
Received 30 November 2010
Received in revised form 13 October 2011
Accepted 19 December 2011
Available online 29 December 2011

Keywords:
Chelungpu Fault
Qp
Qs
Seismic attenuation
Taiwan Chelungpu Fault Drilling Project
Fault-zone attenuation

A B S T R A C T

The attenuation factor, Q, at a fault zone is an important parameter for understanding the physical properties. In this study, we investigated the Q value of the Chelungpu Fault, the main rupture of the Mw 7.6 Chi-Chi earthquake, using the 7-level TCDP borehole seismometer array (TCDPBHS). The TCDPBHS was deployed at depths from 945 to 1270 m throughout the 1999 ruptured slip zone at 1111 m. Three borehole seismometers (BHS1–BHS3) were placed in the hanging wall, and the remaining three (BHS5–BHS7) were placed in the foot wall, with BHS4 near the slip zone. The configuration allowed us to estimate the Q-structure of the recent ruptured fault zone. In this study, we estimated Q values between BHS1 and BHS4, Qs_1 (Qp_1) at the fault zone and between BHS4 to 2 km in depth, Qs_4 (Qp_4) beneath the fault zone. We utilized two independent methods, the spectral ratio and spectral fitting analyses, for calculating the Q value of Qs_1 (Qp_1) in order to provide a reliability check. After analyzing 26 micro-events for Qs and 17 micro-events for Qp, we obtained consistent Q values from the two independent methods. The values of Qs_1 and Qp_1 were 21–22 and 27–35, respectively. The investigation for the value of Qs_4 was close to 45, and Qp_4 was 85. These Qp and Qs values are quiet consistent with observations obtained for the San Andreas Fault at the corresponding depth. A low Qs_1 value for the recent Chelungpu Fault zone suggests that this fault zone has been highly fractured. Qs values within the Chelungpu Fault, similar to those within the San Andreas Fault, suggest that the Q structure within the fault zone is sedimentary rock independent. However, the possible existence of fluids, fractures, and cracks dominates the attenuation feature in the fault zone.

1. Introduction

The 1999 Chi-Chi earthquake (Mw 7.6) activated the Chelungpu Fault in the western foothills of central Taiwan, resulting in a 90 km long surface rupture along the north–south trend and a 15 km length E–W-trending branch at the northern termination (Fig. 1a). Along the strike, horizontal and vertical surface displacements both increased from south to north and reached a value of approximately 12 m in the northern portion of the fault. In the past, the geometry of the fault has been investigated using dense reflection surveys (Wang et al., 2004). Both strong motion (Shin and Teng, 2001) and GPS data (Lin et al., 2001; Yu et al., 2001) indicate that the majority of co-seismic movement within the Chi-Chi earthquake occurred at the hanging wall rather than at the footwall, suggesting that the footwall was nearly fixed during the earthquake (Heermance et al., 2003). The data is also consistent with the fact that the hanging wall underwent harsher damage than the footwall. In order to gain more understanding regarding earthquake processes and the long-term evolution of the fault, the Taiwan Chelungpu Fault Drilling Project (TCDP) drilled two holes (A and B) with one branch (C) at Dakeng, Taichung City (Fig. 1a), where the large surface slip was observed. Hole A was drilled to a depth of 2 km, and the 1999 slip zone, at the depth of 1111 m, was identified. Fault zone features and dynamic processes have been well addressed by numerous studies (e.g. Ma et al., 2006; Sone et al., 2007; Song et al., 2007; Tanaka et al., 2006; Yeh et al., 2007). Low resistivity, density, velocity, and high Vp/Vs and Poisson ratios were also characterized in identified fault zone features (Hung et al., 2009; Wu et al., 2007a).

The quality factor Q, that defines the energy decay of the structural features, was revealed to have a significant contrast across the Chelungpu Fault in images of Taiwan 3-D attenuation tomography (Wang et al., 2010). Corresponding to fault geometry with a 30° dip angle, the hanging wall is located within a zone that has a lower Qp, lower Qs, and higher Qp/Qs in the image surrounding a depth of 10 km. The contrast may suggest the existence of lithologic heterogeneity between the hanging wall and the footwall. Sanders et al. (1995) summarized the relationship among changes in seismic parameters due to changes in rock properties, and considered that an increase in fractural abundance would result in a decrease in Qp and Qs, accompanied by an increase in Qp/Qs. The results suggest that the lower Qp and Qs, and the higher Qp/Qs of the hanging wall of the Chelungpu Fault may be related to highly fractured features that resulted from severe shaking during rupture.

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0040-1951/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2011.12.027

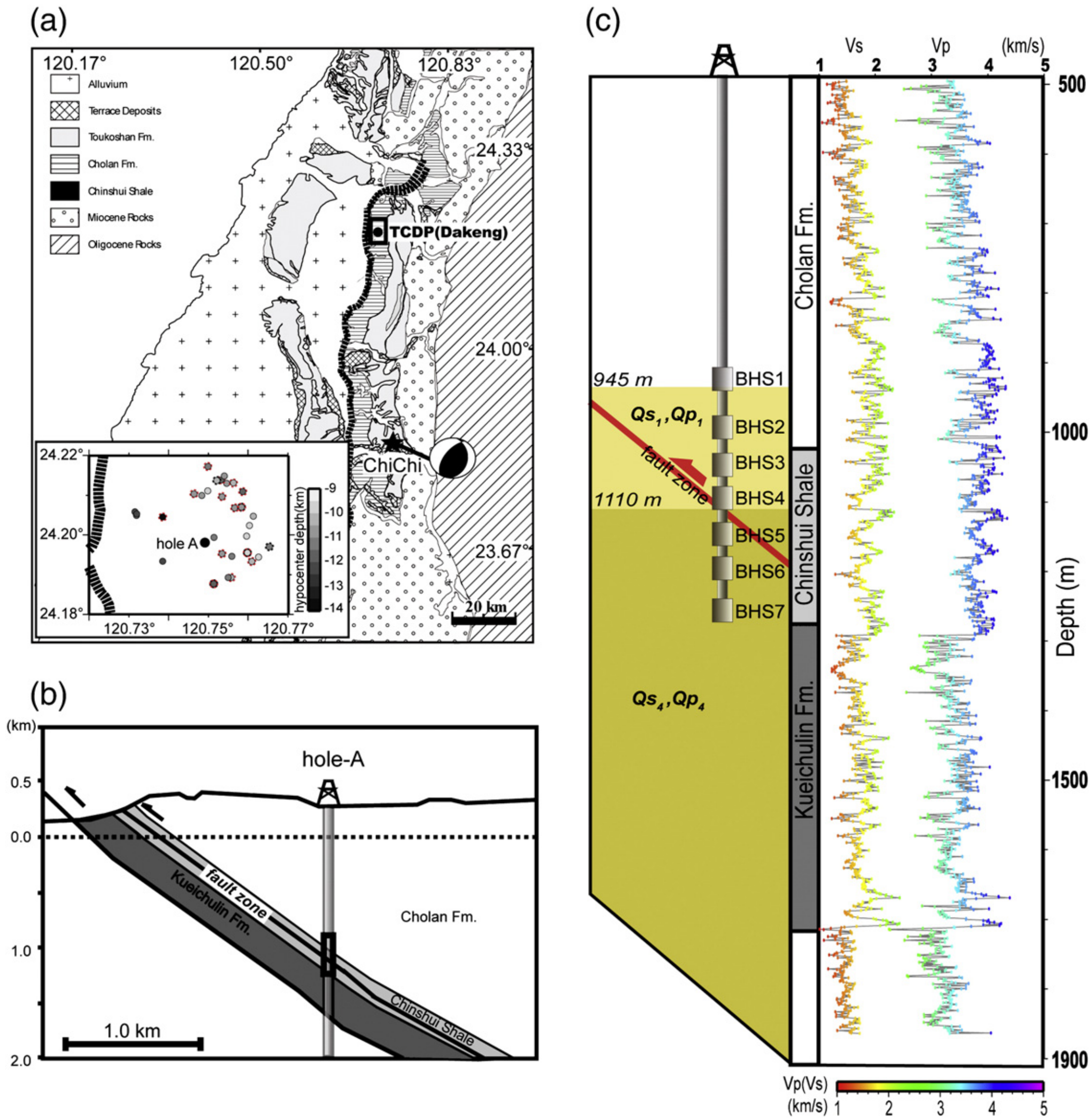

Fig. 1. (a) The geological map of the region near the TCDP drill site (solid dot) (Wu et al., 2007a). The inset shows the distribution of selected micro events in this study. The drill site, Dakeng, is 2.5 km east of the Chelungpu Fault rupture (the wide black dashed line). The location of the Chi-Chi mainshock (asterisk) and its focal mechanism are also shown. The black frame in the lower left inset shows the distribution of the epicenters for thirty-one selected micro events. Events excluded in our data analysis for Qp and Qs with high noise levels are circumscribed in black and red hashed circles, respectively. The color of the circles relative to the events indicates hypocenter depth. (b) A sketch of the geological cross-section near the drill site. Black rectangle marks the location where the TCDPBHS were deployed. (c) The vertical cross-section of hole A showing the depths of 7 deployed TCDPBHS within their corresponding geologic terranes, as displayed in the right-hand bar. The zones in light and dark yellow indicate the extent of depth as defined by Qs_1 (Qp_1) and Qs_4 (Qp_4), respectively. BHS4 is located near the main fault zone (red line).
Referred to Wu et al. (2007a).

However, due to limited resolution in the tomography, the detailed attenuation feature within the fault zone is difficult to determine. Fortunately, after successful TCDP drilling in November 2006, a 7-level vertical borehole seismic array (TCDPBHS) was installed in hole A between the depths of 945 and 1274 m, with intervals of 50–60 m. The array spanned the slip fault zone of the Chelungpu Fault and included the hanging wall and the foot wall (Fig. 1c). Here, using borehole data, we further provide a detailed investigation of Q structure within the fault zone. The primary advantage of using downhole data is avoiding high levels of background noise in order to ensure a higher signal to noise ratio as compared to the surface.

2. A review of the characteristics of the Q value within fault zones

Fault-zone Q is a valuable indicator of the mechanical behavior and the rheology of a fault. In general, the presence of porosity and fluids within a fault zone dramatically reduces Q. Bennington et al. (2008) used three-dimensional tomography in order to characterize the Qp and Qs features of the San Andreas Fault (SAF) in California over 16 km^2. Both Qp and Qs contrasted across the fault were clearly imaged. The high attenuation feature, a Qp and Qs of approximately 50–75 above a 2 km depth on the northeast side of the SAF, was suggested to be attributed to fluid rich rocks. In addition, Blakeslee et al. (1989) analyzed the Qs value of the SAF fault-zone at a depth of 5–6 km using a spectral ratio over the frequency range of 1–40 Hz. By assuming a constant attenuation operator, Blakeslee et al. (1989) estimated a Qs within the fault-zone of 31. Abercrombie (2000) also used the spectral ratio method to calculate the Q in the fault zone, and obtained 50 for Qp and 80 for Qs within 5 km in depth. In addition, Wang et al. (2009a) utilized the quantitative analysis of the correlation coefficients with trapped waves between synthetic and observed waveforms and stated that the shear-wave quality