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Anisotropy beneath an active collision orogen of Taiwan: Results from across islands array observations

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[1] We examined shear wave splitting in SKS phases from a large event recorded by a temporary array across southern Taiwan. The span extends from the western plain to the east coast. We applied particle motion and cross correlation methods to estimate its polarization directions and delay times. Analysis shows clear evidence of splitting except stations on the east coast. The fast split-shear wave along this transect are approximately parallel to the strike of the mountain belt (NE-SW). The delay times show a short-wavelength variation and are well correlated to the surface geology. The largest split time is about 1.6 sec located at Eastern Central Mountain Range and indicates its possible mantle origin. Implications suggest that anisotropy is related to the collision tectonics which built the Taiwan islands, and that this tectonic compression involved the lithosphere and is characterized by a strong coherent deformation of the upper mantle and the crust. **Citation:** Huang, B.-S., W.-G. Huang, W.-T. Liang, R.-J. Rau, and N. Hirata (2006), Anisotropy beneath an active collision orogen of Taiwan: Results from across islands array observations, *Geophys. Res. Lett.*, *33*, L24302, doi:10.1029/2006GL027844.

1. Introduction

[2] Taiwan is a unique product of an oblique convergence between the northeast-trending Eurasian plate in the west and the north-trending Philippine Sea plate in the east (Figure 1). Tectonic processes in Taiwan are characterized by an active collision orogen intervening between two subduction systems [*Wu et al.*, 1997]. Within such a complex tectonic framework, study of the structure and deformation of the Taiwan orogen is critical to understanding the tectonic processes responsible for the uplift of the Taiwan mountain belts. In turn, such study would be valuable in deciphering the geodynamic development of modern orogenies.

[3] Several models have been proposed for the geodynamic evolution of the Taiwan orogenies, and there is still debate on whether the critical deformation of the Taiwan mountain building involved the entire lithosphere [*Suppe*, 1987; *Wu et al.*, 1997]. Recent tomographic studies give some clues about the upper mantle structure and related deformation beneath the collision region of the Taiwan islands [*Kim et al.*, 2005; *Wu et al.*, 1997]. It has been found that the crust of the Central Mountain Range is significant thickening (up to 55 km) and suggests the possible response of upper mantle deformation. The shear wave splitting, thus, an S wave traveling through an anisotropic medium is split into distinct waves with orthogonal and distinct velocities, is a useful indication of such deformation [*Vinnik et al.*, 1992]. Actually, the hypothesis of the coherent upper mantle deformation mechanism is strongly supported by worldwide shear wave splitting observations [*Silver*, 1996]. However, the detail mechanism of its evolution needs more testing. One way to explore hypothesis is to examine spatial variations of splitting parameters in a small active orogen with a well-defined surface geology and history in conjunction with dense closely monitored seismic stations [*Barruol et al.*, 1998].

[4] Taiwan is well suited for such a study and offers an opportunity to investigate short-wavelength variations in seismic anisotropy beneath an active collisional orogen. Here we address this question using seismic measurements of anisotropy at upper mantle depths from a teleseismic event. A dense broadband seismic transect across the mountain belt was designed and deployed in southern Taiwan. The close spacing of transect stations allowed us to monitor variations in splitting parameters among different tectonic environments and surface geology. Here, we present the first results of our shear wave splitting study. A detailed analysis of teleseismic SKS splitting reveals the existence of significant anisotropy beneath the mountain belt of Taiwan Characterization of seismic anisotropy along the transect provides new keys to understanding the geodynamic development of Taiwan orogeny.

2. Data

[5] Our study is part of a multidisciplinary project supported by the National Science Council, with the goal of probing the deep structure of Taiwan to better constrain the geodynamic evolution of the modern orogenies of Taiwan islands. Temporary seismic transects across the Taiwan islands were planned. A data base of events from local, regional and teleseismic distances were constituted for tomographic inversions, surface wave propagation dispersions, receiver functions and shear wave splitting analysis. Data used in this study come from a temporary broadband array across the Taiwan islands which spans from the western coast across western plain, foothills and mountain belt to the eastern coast near Taitung. This array was installed from April 2005 and is still working in the field. This transect is almost perpendicular to the mountain belt of central Taiwan (Figure 2). The transect is 140 km long, and 25 stations were deployed along this transect

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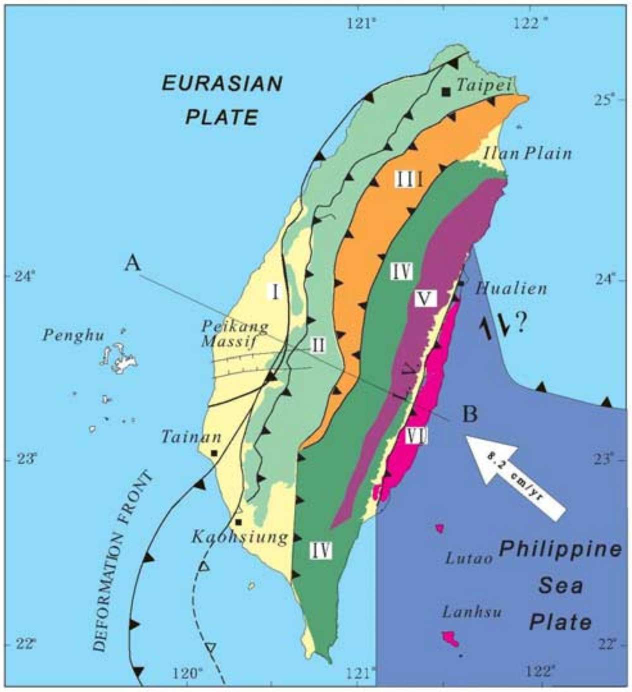

Figure 1. The tectonic framework with a general geological map of Taiwan (modified from *Teng* [1990] and *Lee et al.* [2002]). Rock units I to V belong to the Euroasia plate: (I) the Western plain, (II) Foothills, (III) the Hsuehshang Range, (IV) the Backborn Range, (V) the Tananao metamorphic basement. (VI) The Coastal Range belongs to the Philippine Sea plate.

with average station spacing of about 6 km. The instruments used are digital seismographs (Q330) recording continuously and equipped with three-component broadband (trillium) sensors.

[6] For studies of crustal and upper mantle related anisotropy from teleseismic events, SKS and SKKS phases observed at epicentral distances of 85–120° are the most frequently used phases because the splitting of these phases is caused only by the receiver-side anisotropy [*Silver*, 1996]. Unfortunately, the SKS and SKKS phases recorded in the Taiwan region are usually of poor quality. These are probably limited by global seismicity distribution, lack of large-magnitude events occurring at the specified distance range, and the high level of microseismic noise resulting from the nature of Taiwan as an island [*Rau et al.*, 2000]. Only limited splitting observations from S and ScS waves in Taiwan region were reported and its tectonic discussions were limited by its spatial resolution [*Rau et al.*, 2000]. However, on February 22, 2006, a large earthquake (location = 21.22°S, 33.32°E; depth = 5 km; M_w = 7.5 after USGS) occurred in Mozambique, in southeastern Africa at 22:19 (UTC) with an epicentral distant range near 96° around Taiwan. The epicentral distances of Taiwan stations are suitable to observe SKS phases. Due to a favorable azimuth of shear wave energy radiated, this large earthquake provided unique and high resolution SKS waves and was commonly recoded by broadband stations of Taiwan. Figure 3 shows an example of one seismogram analyzed by this study in which the presence of a SKS on a transverse component is approximately the time derivative of the radial component. This is an important diagnostic tool for detecting the presence of splitting [*Silver*, 1996].

[7] Along this transect, all stations recorded similar SKS and related shear waves. In total, we selected 23 SKS phases from this transect (Figure 2). To remove unwanted noise, all seismograms were band-pass-filtered at 0.02–0.5 Hz for the teleseismic SKS phases. All transect waveforms showed dominant signal periods of 14 s for the SKS phases. We analyzed waves with periods of ~14 s which corresponds, in the uppermost mantle, to a wavelength of ~54 km. Although this event has predominately long period signals, however, it presents us with very simple SKS waveforms in the Taiwan region. Those SKS phases provide us a rare opportunity to examine the upper mantle anisotropy beneath Taiwan.

3. Analysis and Results

[8] We measure the splitting parameters of the teleseismic SKS by applying a particle motion analysis and using the cross-correlation method [*Guilbert et al.*, 1996; *Liang*, 1990] assuming that the splitting is generated by a single anisotropic layer. For the cross-correlation method, the two horizontal seismograms are rotated in the horizontal plane at a 1° increment from −90° to 90°. The seismograms are then cross-correlated in the selected SKS wave time window, with an increment time shift of 0.05 s from 0 to 3 s. When the absolute value of the cross-correlation coefficient reaches its maximum, the rotation direction is chosen for the fast polarization direction (φ) and the time lag (δt) is measured as the delay time of the slow shear wave. The results are accepted only when the absolute value of the maximum cross-correlation coefficient is greater than 0.9. For each observation the error is defined by the area where correlation remains larger than 90% of the maximum

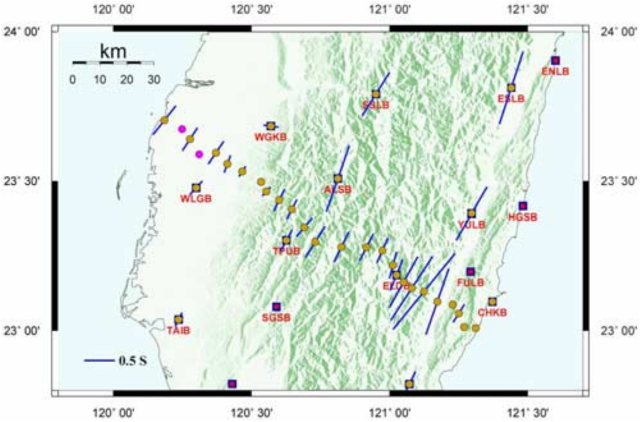

Figure 2. A map of southern Taiwan transect and observed shear wave splitting parameters of SKS phases. Fast polarization directions are given by bar orientation and their lengths are proportional to delay times. The mapped terrain and active faults are also shown. Data from stations 2 and 4 were lost within the February 22, 2006, Mozambique earthquake.

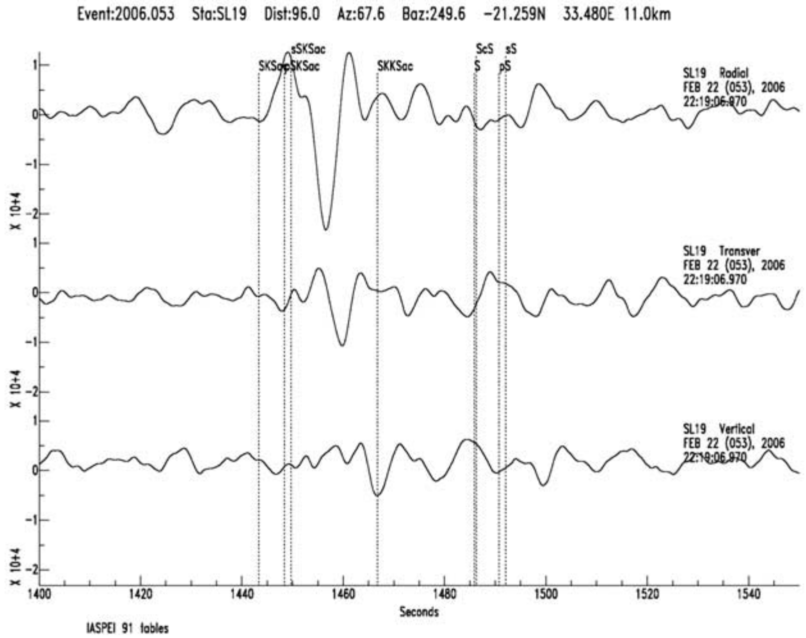

Figure 3. Examples of three component broadband SKS seismograms for transect station SL19 from the February 22, 2006, Mozambique earthquake. Dashed lines show predicted arrival times (from IASP91) of SKS and related shear waves (SKKS, S, ScS) and their surface reflections.

[*Guilbert et al.*, 1996]. An example of our SKS splitting measurement is shown in Figure 4. The maximum of cross-correlation gives the best linear particle motion and also the best correction of the splitting effect. The measurements also demonstrate similar pulse shapes for the two horizontal seismograms and produce linear particle motion along its radial direction after correction for anisotropic effects.

[9] The splitting parameters (φ, δt) from our study are shown in Figures 2 and 5. Figure 2 plots the spatial variation of splitting on the topographic map. Figure 5 plots the individual parameter variations along this transect. Figure 5 shows our measurements with a surface geology profile along this transect. The analysis shows determined splitting with error at all sites. The orientations of anisotropy for the transect stations are generally parallel to the strike of the mountain belt and perpendicular to the direction of relative plate motion between the Eurasian plate and the Philippine Sea plate, although it presents slightly variation from N14°E to N45°E and analyzed results of this study are in agreement with the results of studies in other collision zones [*Vinnik et al.*, 1992; *Barruol et al.*, 1998]. The delay times, on the other hand, vary greatly from 0.05 to 1.6 s and show regional variation. The largest values are from the Eastern Central Mountain Range and are well correlated to the formation of the Tananao Complex and show an abrupt change in the Longitudinal Valley and the Eastern Coastal Range both of which belong to the Philippine Sea plate. Systematic variation of delay times can be correlated to different tectonic environments and are the same as the surface geological distribution (Figure 5). Generally, the observed delay times are much larger than what is estimated for the crust from local events (an average value of 0.16 s reported by *Liu et al.*

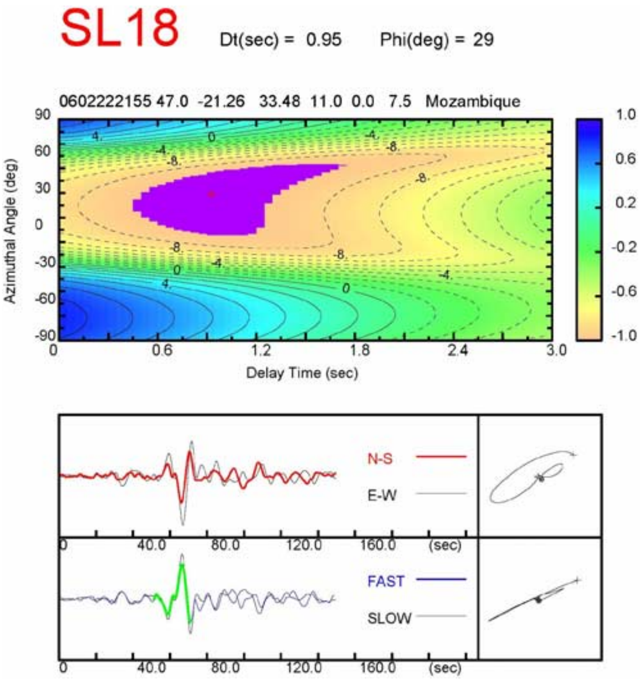

Figure 4. An example of an SKS splitting measurement at station SL18. (top) A diagram representing the distribution of the cross-correlation coefficients in the splitting parameter (φ, δt) space. The red dot indicates the maximum of coefficient and the violet area represents the remaining region larger than 90% of the maximum. (bottom) The top two traces are the superposition of the N-S (red line) and E-W (black line) components. The bottom two traces are the corrected fast (blue line) and slow (black line) components. The marked green trace represents the intervals of seismograms used to make the measurements. Corresponding particle motions are shown to the right.

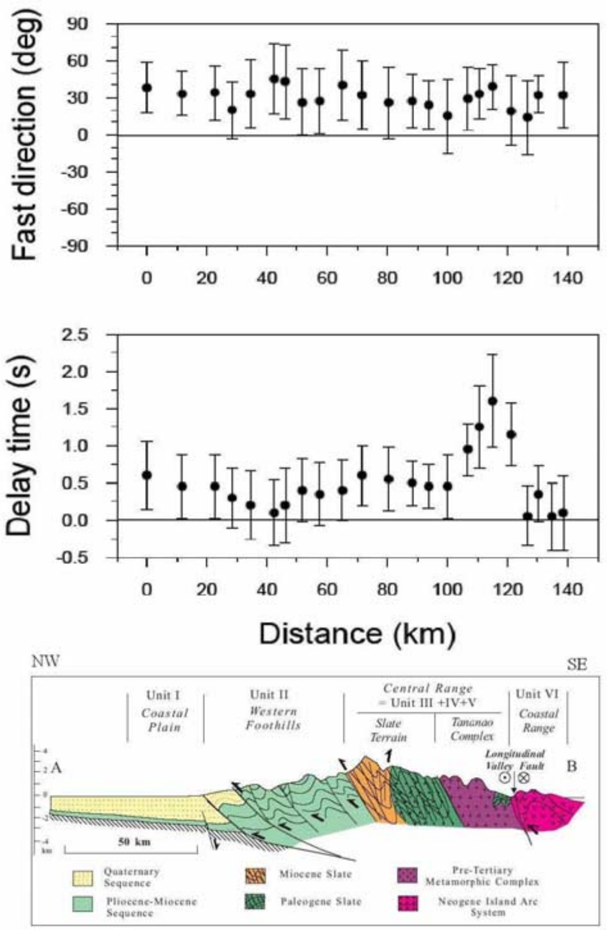

Figure 5. Variations of measured splitting parameters vs. distance along this transect and its corresponding geological profile. (top) Variations of fast directions along this transect. The estimated error for fast direction is marked for each measurement. (middle) Variation of delay time along this transect. Symbols are the same as above. All data are from a single event with similar quality and estimated errors are similar. (bottom) A general geological cross-section of the Taiwan mountain belt along line A-B of Figure 1 [*Teng*, 1990]. The location of transect station SL01 (Figure 2) is considered as the origin and all stations are projected onto this transect.

[2004], beneath the Western Plain) and confirming that the crustal contribution to anisotropy is marginal.

4. Discussion

[10] In general, the splitting parameters derived from the SKS phases are consistent with those from the ScS and S by *Rau et al.* [2000] found in the Taiwan collision mountain belt. However, delay times (δt) in the Western Plain reported by *Rau et al.* [2000] have higher values than measurements of this study. This discrepancy can be explained by the source side effect of *Rau et al.* [2000] using S and ScS phases and/or different frequency bands signals analyzed by each study. Due to small spacing between array stations and dense observations on the mountain belt, in this study, the correlation of splitting parameters and surface geology can be examined in detail. It is found that the orientations of φ are, in general, parallel to the axes of the deformational belts with regional variation across the Taiwan collision zone. The delay times show lateral variations within the Euroasia plate and its peak delay time was found on the oldest rock formation of the Tananao Complex. Across the plate boundary, the delay times abruptly decrease within the Philippine Sea plate. The coherence between splitting parameters and the orientation of mountain belt is consistent with the vertically coherent deformation (VCD) hypothesis [*Silver*, 1996], in which the crust and upper mantle deformation coherently in orogenies. Such internally coherent deformation is commonly observed in active tectonic regions [*Silver*, 1996]. Implications of this study indicate that the mantle deformation in the Taiwan orogen is directly coupled to the overlying crustal shortening and the orogenesis of the Taiwan area may cause a preferential alignment of upper mantle anisotropy minerals parallel to the belt axis. Furthermore, the occurrence of the short-wavelength variations of δt across tectonic boundary suggest that anisotropy beneath the Taiwan orogeny is of shallow, predominantly lithospheric rock. Although the simple asthenospheric flow hypothesis [*Silver*, 1996], in which the seismic anisotropy is dominated by asthenospheric flow, suggests the active mantle flow along the strike direction of collision zone to explain the orientations of φ of this study, however, it is hardly to explain the observed short-wavelength variations of δt.

[11] In this study, all observations were from the same event. Therefore, the relative splitting due to deep mantle anisotropy is negligible, and the split times in the crust of Taiwan are generally near 0.16 s [*Liu et al.*, 2004]. As a result, the upper mantle beneath Taiwan is likely to be the major source of anisotropy. An estimate of the thickness of the anisotropic region may be made from the size of the δt. Assuming an intrinsic shear wave velocity anisotropy of 4%, which corresponds to the average anisotropy of naturally occurring peridotites, 1 s of splitting time corresponds to an anisotropic layer thickness of 115 km [*Mainprice and Silver*, 1993]. Thus, the splitting across Taiwan suggests an anisotropic layer thickness of 5–180 km in the uppermost mantle. In the mountain belt, longer δts (1.0–1.6 s) are observed and suggest a larger thickness (115–180 km) of an anisotropic layer beneath it. Due to their near-vertical incidence, splitting parameters of the SKS phases provide excellent lateral resolution beneath the stations. The oscillation pattern of δt along this transect is an interesting feature (Figure 5) and should be further addressed to relationship of seismic tomography studies.

[12] Our interpretations above are based on the assumption of a single layer anisotropy. However, we cannot ignore the possibility that several layers of anisotropy may be present beneath Taiwan. Based on studies of the effect of several layers of anisotropy on the splitting measurements [*Rümpker and Silver*, 1998], the uppermost layer will control the trend of the measured anisotropy. If several layers of anisotropy did exist beneath Taiwan, the general parallelism of the anisotropy with the Taiwan orogen suggests that the anisotropy is indeed controlled by the uppermost mantle and that the Taiwan orogen is characterized by a strong coherent deformation of the upper mantle

and the crust. Furthermore, because of the observed small scale variability of the δt and the relation of the anisotropy to the surface geology, the main part of the anisotropy probably is also suggested to be located in the uppermost mantle.

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