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Upper mantle seismic velocity anomaly beneath southern Taiwan as revealed by teleseismic relative arrival times

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ABSTRACT

Probing the lateral heterogeneity of the upper mantle seismic velocity structure beneath southern and central Taiwan is critical to understanding the local tectonics and orogeny. A linear broadband array that transects southern Taiwan, together with carefully selected teleseismic sources with the right azimuth provides useful constraints. They are capable of differentiating the lateral heterogeneity along the profile with systematic coverage of ray paths. We implement a scheme based on the genetic algorithm to simultaneously determine the relative delayed times of the teleseismic first arrivals of array data. The resulting patterns of the delayed times systematically vary as a function of the incident angle. Ray tracing attributes the observed variations to a high velocity anomaly dipping east in the mantle beneath the southeast of Taiwan. Combining the ray tracing analysis and a pseudo-spectral method to solve the 2-D wave propagations, we determine the extent of the anomaly that best fits the observations via the forward grid search. The east-dipping fast anomaly in the upper mantle beneath the southeast of Taiwan agrees with the results from several previous studies and indicates that the nature of the local ongoing arc–continent collision is likely characterized by the thin-skinned style.

1. Introduction

Taiwan sits atop the convergent boundary between the Eurasia Plate (EUP) and the Philippine Sea Plate (PSP). The subduction that occurs as a result of the 7–8 cm/yr convergence rates flips the polarity in the vicinity of Taiwan. To the south, the South China Sea portion of the EUP is subducting to the east, underneath the PSP along the Manila Trench. To the north, the predominantly northwest-dipping PSP slab subducts underneath the EUP along the Ryukyu Trench. The pivot of the transition, Taiwan, has been undergoing arc–continent collision since at least 4 m.a. (Ho, 1986), resulting in both rapid uplifting rate and thus modern high mountain ranges and frequent, devastating earthquakes, e.g., the 1999 Mw 7.0 Chi-Chi earthquake. The collision is oblique to the plate boundary and propagates southwesterly. Temporal evolution of the orogenic processes can thus be envisioned by a series of co-latitudinal slices northward from the offshore region of southern Taiwan. They include the east-dipping EUP subduction, in which oceanic lithosphere is consumed off the shore of southern Taiwan, an incipient collision between the EUP continental shelf and the PSP Luzon arc in southern Taiwan, a progressive full-scale collision of the topographic high in central Taiwan, and the post-collision relaxation and flipping of the subduction polarity in northern Taiwan.

Tectonic and geological manifestations of the collisional orogeny have been documented for decades. The nature of the detailed mechanisms of the collision, however, is still under debate. The major argument focuses on the depth scale of the EUP involved in the collision. Whereas the thin-skinned model involves only the crustal part of the EUP (Suppe, 1981), the entire lithosphere of the EUP is proposed to collide with the PSP in the thick-skinned model (Wu et al., 1997). The thin-skinned collision is based on the scenario of subduction and thus implicitly assumes that the east-dipping EUP extends northward all the way to central Taiwan, despite the northern termination of the Manila Trench offshore to the southwestern Taiwan. On the other hand, the thick-skinned collision in central Taiwan bears little connection with an east-dipping EUP to the south. The resolution of the debate thus depends on the verification of the presence or the absence of an east-dipping slab beneath central and southern Taiwan. Being able to clarify the style of the collision also helps distinguish the proposed models for the orogeny. For instance, for the orogenic mechanism of crustal exhumation (Lin, 2002) to be sustained, the style of the collision must be thin-skinned.

Several distinct methods have been used to examine whether or not the east-dipping EUP off the shore of southern Taiwan extends to central Taiwan. For example, the travel-time residuals and amplitude differences of teleseismic P arrivals, as observed by the Broadband Array in Taiwan for Seismology (BATS), have been investigated (Chen et al., 2004). A dense linear array in central Taiwan was deployed across the suture zone between August and October 2003 to study the

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deep crust and mantle structures beneath eastern Taiwan (Lin, 2009). More recently, with a joint inversion of a large number of arrival-time data from local and teleseismic events, a high-resolution 3-D P-wave velocity structure was determined for the crust and upper mantle beneath Taiwan (Wang et al., 2009).

In this study, we use the data collected from a linear broadband array that has been deployed since April 2005. The array transects southern Taiwan in the east–west direction, with 25 stations evenly spaced over a distance of about 140 km (Huang et al., 2006). We carefully picked sizeable teleseismic earthquakes, with epicentral distance ranging from 40° to 80°, in the same azimuth with the linear array (e.g., events from the New Britain Region, the Vanautu Islands and the Fuji Tonga Islands; Fig. 1). In addition, large earthquakes near the antipode from the Nazca subduction zone are also included (Fig. 1). Incident rays of the earthquakes from these subduction zones are on nearly the same cross-sectional plane as the linear array, which provides good teleseismic illumination with a variety of ray angles. In this study, we employed a genetic algorithm to simultaneously align the first P arrivals of the teleseismic events among all stations of the linear array. The resulting patterns of the delayed times systematically vary as a function of the incident angle. Ray tracing attributes the observed variations to a high velocity anomaly dipping east in the mantle SE of Taiwan. Quantitative assessment on the extent and location of the anomaly is further conducted using simulations of the 2-D wave propagations.

2. Methods

2.1. Determining relative arrival times using the genetic algorithm (GA)

Several methods have been proposed for determining the relative delay times of teleseismic body waves within a regional array. One popular method is based on the multi-channel cross correlation (MCCC; VanDecar and Crosson, 1990). MCCC assumes that the errors in the cross-correlation-derived delay times among pairs of many stations are random in nature, and thus, the optimal delay time for each station can be determined by minimizing their overall discrepancies in a least-square sense, a common linear inverse problem (Menke, 1984). However, for noise-contaminated data, the problem is more appropriately posed as non-linear in nature (Rothman, 1985). Both the adaptive stacking method (Rawlinson and Kennett, 2004) and optimization by simulated annealing (Chevrot, 2002) have been proposed to cope with this non-linear inversion. Both methods construct the cost function by measuring the total sum of misfits between the observed traces and the reference trace. The adaptive stacking method derives the reference trace by stacking all of the observed traces with updated time shifts, whereas the simulated annealing solves not only the time shifts of the observed traces but also the amplitude values at each time sample for the reference trace.

Compared with the schemes described above, GA is an even more straightforward method. GA searches for the optimal solution of a non-linear problem by evolving through generations. GA progressively matches the best solution by passing favored characteristics of the current generation of solutions to the next generation. These characteristics are such that they yield the fitness, or the cost function, value toward being optimized (Holland, 1975). One such application is to invoke GA to retrieve the single-crystal constant, C_{ij}, from Brillouin spectroscopy measurements (Chen et al., 2006). In this study, we experiment with GA to simultaneously determine the relative delayed times of teleseismic first arrivals for array data. We first calculate the cross-correlation functions for each pair of traces by the following equation:

$$\phi_{ij}\left(\tau_i,\tau_j\right) = \frac{\sum_{k=1}^{T/\Delta t}(x_i k\Delta t+\tau_i)x_j\left(k\Delta t+\tau_j\right)}{\sqrt{\sum_{k=1}^{T/\Delta t}x_i^2(k\Delta t+\tau_i)}\sqrt{\sum_{k=1}^{T/\Delta t}x_j^2\left(k\Delta t+\tau_j\right)}}, \quad (1)$$

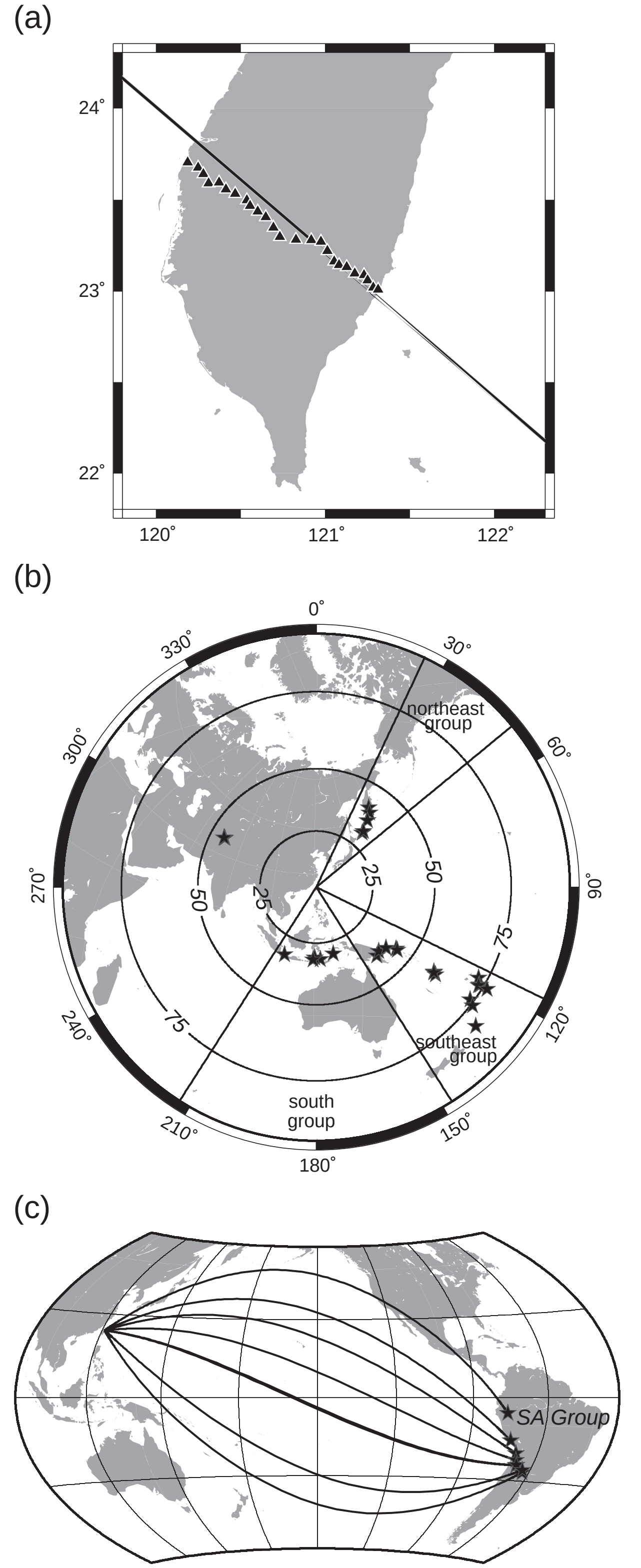

Fig. 1. (a) Distribution of the linear broadband array across southern Taiwan. The line indicates the back azimuth of an earthquake in the southeast group. This line is parallel to the array azimuth. (b) Distribution of earthquakes (stars) with high S/N ratios. According to the back azimuth, they are categorized into groups, and the group names are indicated. (c) Distribution of earthquakes for the SA group and their great circle paths. Note that the epicentral distance is near antipodal.

where T is the length of selected time window, $\Delta t$is the sampling interval, x_i is the ith-trace digital data, and τ_i is the time shift for the ith trace. The same conventions apply to index j for the jth trace. The cost