行政院國家科學委員會專題研究計畫 成果報告

海底地震儀之觀測研究--結合有限頻寬走時成像與海底地震儀資料建構臺灣上地慢構造

研究成果報告(精簡版)

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報 告 附 件 ：出席國際會議研究心得報告及發表論文

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中 華 民 國 97 年 07 月 01 日

附件一

行政院國家科學委員會補助專題研究計畫 **x 成果報告**
□期中進度報告

海底地震儀之觀測研究--結合有限頻寬走時成像與海底地震儀資料建構臺灣上地幔構造

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共同主持人：
計畫參與人員：

成果報告類型(依經費核定清單規定繳交)：x□精簡報告　□完整報告

本成果報告包括以下應繳交之附件：
□赴國外出差或研習心得報告一份
□赴大陸地區出差或研習心得報告一份
□出席國際學術會議心得報告及發表之論文各一份
□國際合作研究計畫國外研究報告書一份

處理方式：除產學合作研究計畫、提升產業技術及人才培育研究計畫、列管計畫及下列情形者外，得立即公開查詢
□涉及專利或其他智慧財產權，□一年□二年後可公開查詢

執行單位：國立台灣大學地質科學系

中 華 民 國 97 年 06 月 30 日

Abstract

Taiwan and Tibet are two of major active orogenic belts on the Earth planet and both share many similar tectonic evolutions. Understanding the continental collision process in Tibet will help to illuminate the orogeny in Taiwan. As the OBS data in Taiwan are currently unavailable, we employ the recently-developed finite-frequency, multiscale traveltime tomography to study the crust and upper mantle structure beneath Tibet. We report results of three-dimensional (3-D) P-wave velocity (Vp) structure of crust and upper mantle under Tibet determined from tomographic inversion of teleseismic travel-time data recorded by the Hi-CLIMB seismic network. We combine physically realistic 3-D sensitivity kernels with multi-scale parameterization which facilitates spatially-varying, data-adaptive resolutions, and the resulting tomographic model reveals two distinct, localized low Vp anomalies in the lithosphere confined to depths of about 100 km or less in the proximity of the Indus-Yarlong suture (IYS) and the Bangong-Nujiang suture (BNS) beneath the N-S trending linear array of closely-spaced (~3-8 km) stations. Both the anomalous regions are collocated with the weak and diffuse Moho discontinuity or gradual crust-mantle transition as revealed in the receiver function imaging. At greater depths, a broad swath of high P-wave speeds extends under much of Lhasa terrane beyond the BNS, consistent with the notion that the leading edge of the Indian lithosphere has advanced about 200 km north of the BNS. The two low Vp regions near the IYS are evidently disconnected and correlated with anomalously high conductivities from magnetotelluric (MT) studies, indicating the presence of fluid or melt in the crust but contradicting the popular model of pervasive active flow channelized within the lower crust.

1. Introduction

Since the earlier Eocene the progressive collision between the northward-moving Indian plate and the Eurasian plate has entailed the most prominent and active orogenic system on Earth [e.g., Dewey and Burke, 1973]. The convergence of the two lithospheric plates was accommodated by intensive crustal thickening and uplift of the highest Himalayan mountain and the vast Tibetan Plateau. The Himalayan-Tibetan orogen was evolved from assemblages of continental terranes sequentially accreted to the Eurasian lithosphere. The east-west trending sutures, from north to south, the Jinsha suture, the Bangong-Nujiang suture (BNS), and the Indus-Yalu suture (IYS) marked the boundaries of three main Tibetan continental blocks, Songpan-Ganzi, Qiangtang, and Lhasa terranes [e.g., Yin and Harrison, 2000]. Because of the lack of comprehensive observational evidence for subsurface structures, different competing views how the Indian and Eurasian continent interact at greater depths remain controversial, including underthrusting of the Indian lithosphere, uniform shortening or southward subduction of the Euransian lithosphere, southward channel flow in the weak lower crust, convective removal of the Indian lithospheric mantle, and eastward intrusion of the Asian continent indented by the rigid Indian block [e.g., Argand, 1924; England and Houseman, 1988; Tapponnier et al., 2001]. Regarding the Himalayan-Tibetan orogeny as a paradigm to understand the inner-work of the continental collision, numerous investigations have employed seismic tomographic imaging to reveal spatial variations in seismic wave speeds under this key collision zone [e.g., Van der Voo et al, 1999; Sun et al., 2004; Li et al., 2006]. For example, Sun et al. [2004] used direct Pg and refracted Pn arrivals reported in Annual Bulletin of Chinese Earthquakes to determine the P-wave velocity and thickness of the crust under China. The resolved Moho reaches a depth of over 70 km beneath the central Tibet and gradually becomes shallower by 20 km toward the edge of the plateau. Partly due to very sparse station distribution in the interior of the plateau, global tomographic model only yields very broad structures with seismically slower lithospheric mantle and nearly east-west elongated fast velocity anomaly in the southern edge of the Tibet that has been attributed to the under-thrusting of the Indian lithosphere [Li et al., 2006]. Since early 90s, massive data from temporary deployment of dense broadband seismic arrays has provided steady improvement to the resolution of tomographic models. Project Hi-CLIMB is one of the international collaborative and integrative studies that endeavor to investigate the Himalayan-Tibetan continental lithosphere during mountain building.

From September 2002 to August 2005, Hi-CLIMB seismic experiment operated a north-south trending linear array of over 800 km in length which run from the foreland basin, the Himalayan, Lhasa and Qiangtang terranes (Figure 1a). Data from over 200 stations, spaced only 3-8 km apart, allows for investigation of variations of seismic phase arrival times across the array in unprecedented details required for high-resolution travel time tomography. Moreover, a complimentary east-west trending regional array of comparable aperture deployed in southern Tibet provides crucial constraints on potentially lateral variations along the main E-W trending suture zones. Such likely variations are conflicted with the traditional view of pervasive crustal channel flows beneath the Tibetan Plateau and unable to be detected by previous seismic experiments operated only along the N-S transect in the Tibet region.

On the other hand, recent progress in finite-frequency theory or so-called banana-doughnut theory has rendered seismic tomographers to take full advantage of frequency dependent travel times and their three-dimensional (3-D) volumes of sensitivity to heterogeneous earth structures [e.g., Montelli et al., 2004a; Hung et al., 2004]. In classical ray-based tomography, an observed seismic phase arrival which has actual finite frequency bandwidths is interpreted as a hypothetically infinite-frequency ray and only every velocity perturbation along its geometrical ray path gives equal contribution to the observed travel time anomaly. While the finite-frequency tomography takes into consideration the fact that seismic waves of different periods undergo different degrees of wave front healing effects and thus the accrued travel time anomalies are frequency dependent and sensitive to different volumes of 3-D velocity heterogeneity off their ray path [Dahlen et al., 2000; Hung et al., 2000; Zhao et al., 2000]. Therefore the use of 3-D Frechet kernels in seismic tomography corrects the deficiency of ray theory in the interpretation of intrinsic finite-frequency travel times and resolves better the amplitudes and shapes of small scale velocity structures compared to ray-based tomography [e.g., Montelli et al., 2004b; Hung et al., 2004; Hung et al., 2005]. Furthermore, unlike the commonly-used regular or variable-sized grid parameterizations that invoke a priori smoothing regularizations, we adopt the wavelet-based multiresolution parameterization which results in the velocity structure with spatially varying resolutions objectively determined by regional data sampling [Chiao and Kuo, 2001; Chiao and Liang, 2003].

In this study we essentially combine all the important components for seismic tomographic imaging of crust and upper mantle structure beneath the Tibetan-Himalaya collision zone: high-quality broadband data from the Hi-CLIMB seismic array and more appropriate finite-frequency theory and multiscale parameterization to provide the links between measured travel time residuals and pursued P-wave velocity structure. To fully capture broadband information of seismic waves and characterize physically realistic, 3-D travel-time sensitivity, we measure relative P-wave travel time residuals between the stations of the Hi-CLIMB network by cross correlation of the corresponding waveforms in high- and low-frequency bands. We use both ray theory and finite-frequency theory to construct the Frechet kernels of individual phase arrivals with respect to compressional wave speed perturbations and make comparisons of the derived 3-D P velocity models in Tibet. Because off-path scattering, wavefront healing and other finite-frequency diffraction effects are properly taken into account, the tomography based on full 3-D kernels tends to better resolve the shapes and amplitudes of small scale velocity heterogeneities. Comparing the obtained P-wave model with other independent seismic and magnetotelluric survey results, we will discuss its implications for understanding the evolution and process of continental collision in Tibet.

2. Study Region and Data

We compile available broadband seismic data from the Hi-CLIMB experiment recorded between July of 2004 and August of 2005, the period when the stations deployed in the Himalaya, Lhasa and Qiantang terranes were functionally operated. The P and PcP phases from global teleseismic earthquakes with magnitudes > 5.5 and epicentral distances of 30-95^{o} are systematically searched for relative travel time residual estimation using the multi-channel cross correlation method [VeDecar and Crosson, 1991]. The Hi-CLIMB stations are equipped with different types of broadband sensors (STS-2, CMG-3T, CMG-3ESP, CMG-40T, and Trillium) provided by IRIS PASSCAL Instrument Center, Institute of Earth Sciences (IES), Academia

Sinica and Peking University (PKU) of China. Some of the velocity sensors (CMG-3ESP, CMG-40T, and Trillium) encompass limited low-frequency bandwidths with only the flat amplitude response up to 30 s. Whereas different sensors yield considerably different responses for a velocity impulse input, particularly in the pulse tails which may accordingly have influences on estimated travel time residuals by waveform cross correlation, we convert the instrument responses of individual raw seismograms to be same as the response of the CMG-3ESP sensor.

From a ray-theoretical point of view, the travel time of a seismic wave determined by the onset time of its first-arriving energy is frequency independent and influenced only by the velocity structure along its geometrical ray path. This is, however, true only in the infinite-frequency limit of an ideal impulse wave. Instead, the travel time of an actually band-limited seismic wave measured by waveform cross correlation explicitly shows frequency dependent characteristics because the lower frequency energy samples the structure farther off the ray path and thus experiences larger degree of wavefront healing. Finite-frequency theory encapsulates the details of the 3-D sensitivity kernels that link measured travel time anomalies to velocity perturbations and vary with the frequency contents of the waveforms used for cross correlation travel time measurements [e.g., Dahlen et al., 2000; Hung et al., 2000]. It provides a straightforward application to seismic tomography with joint inversion of short-period and long-period travel time data [e.g., Montelli et al., 2004; Hung et al., 2004] since the travel time residuals of the same phase measured at different frequencies no longer yield the same sensitivity confined on the ray path and contribute complementary knowledge to 3-D earth structure. Therefore, we apply a fourth-order, zero-phase Butterworth filter to the response-corrected seismograms with two pass bands: one in the high-frequency range of 0.3-2 Hz and the other in the low-frequency range of 0.03-0.125 Hz. The band-pass filtered waveforms are then used for inter-station cross correlation to determine relative travel time residuals.

A total of 21787 high-frequency and 14875 low-frequency measured residuals are collected to jointly invert for spatial variations of compressional wave speed perturbations in the crust and upper mantle beneath Tibet. Figure 2 shows the distributions of azimuths and epicentral distances of 343 earthquakes whose P and PcP phase arrivals were unambiguously identified by at least four stations for the travel time measurements. Despite that most of the events originate from the western Pacific subduction zones, the availability of the source-receiver paths provides the sufficient azimuthal coverage for 3-D tomographic imaging.

3. Results

Different from previous tomographic studies mostly conducted along a 2-D vertical cross section parallel to the linear seismic array [e.g., Tilmann et al., 2003], we benefit from 3-D broad off-path sensitivity of finite-frequency travel times recorded at two nearly perpendicular

Hi-CLIMB arrays to construct the actual 3-D P-wave velocity structure beneath Tibet. The lateral resolution of the resolved P-wave model has been greatly enhanced by the large amount of high-quality data recorded at the closely-spaced stations, but the data sampling is yet quite inhomogeneous at greater depths below 200 km due to the limited azimuthal coverage of event and station distribution (see Figure 6). Along the nearly N-S trending profile where the seismic stations are most dense, the intensive and uniform sampling of the region above the 250 km depth results in superior resolution of the P-wave velocity structure in the crust and lithospheric mantle under the Tibetan Plateau. The sampling of the deeper upper mantle deteriorates toward the northern end of the array primarily due to lack of the off-line stations. Along the nearly E-W profile that transects the complementary regional array in southern Tibet, the data constraint is generally good down to the 400 km depth. In the following, we only address the 3-D velocity structures resolved in the regions with good data coverage. There are a number of interesting features identified with good confidence, and we will provide further interpretations of their implications on the continental collision process and dynamics.

In Figure 3 we present the spatial variation of our resolved P-wave velocity model on two vertical cross sections and six constant-depth map views, obtained from the tomographic inversion using finite-frequency theory and multiscale parameterization. The plots are 2-D cross sections of our resolved 3-D P-wave velocity model based on the inversion using finite-frequency theory and multiscale parameterization. In the A-A' vertical cross section slicing through the main linear array, two distinct low-velocity anomalies with 1-2% lower than the surrounding lithosphere are located in the proximity of the Indus-Yarlong Suture (IYS) and the BNS. The anomaly in the south near the IYS has the dimension of ~100 km wide and extends down to the uppermost mantle at about 150 km depth, while the other one near the BNS appears to be slightly shallower and smaller in lateral extent. At greater depths, a broad swath of high P-wave speeds extends under much of the Lhasa terrane beyond the BNS, consistent with the notion that the leading edge of the Indian mantle lithosphere ("Greater India"). The abrupt transition from the high to low velocities occurs beyond a horizontal distance of 100 km north of the BNS which coincides with an anomalous zone of null shear-wave birefringence. In the B-B' cross section running subparallel to the IYS, two pronounced, disjointed low velocity regions in the lithosphere emerge on the west and east ends of the cross section. The anomaly on the west, centered around 29.5°N, 86°E just north of the IYS, has a radius of about 100 km and is part of the structure observed in the southern part of the A-A' profile. The other anomaly which straddles the IYS lies farther east and seemingly continues to extend eastward along the IYS.

4. Conclusion

(1) Mutli-scale, finite-frequency tomography employs physically realistic frequency-dependent

travel time data and and 3-D sensitivity kernels to resolve the robust velocity structures in the crust and upper mantle under Tibet.

(2) Two distinct, localized low Vp anomalies in the lithosphere confined to depths of about 100 km or less near the IYS and BNS along the N-S trending array are collocated with the weak and diffuse Moho discontinuity as revealed in receiver function imaging, indicative of gradual crust-mantle transition.

(3) The low Vp region just north of the IYS yields no observed shear wave splitting and its southern boundary marks a strong velocity contrast associated with the southern terminus of the Eurasian lithosphere.

(4) At greater depths, a broad swath of high P-wave speeds extends under much of Lhasa terrane beyond the BNS, consistent with the notion that the leading edge of the Indian lithosphere has advanced about 200 km north of the BNS.

(5) Two disjointed low Vp and Vs regions along the IYS are correlated with anomalously high conductivities from magnetotelluric (MT) studies, indicating the presence of fluid or melt in the crust but contradicting the model of pervasive active flow channeled within the lower crust.

Figures

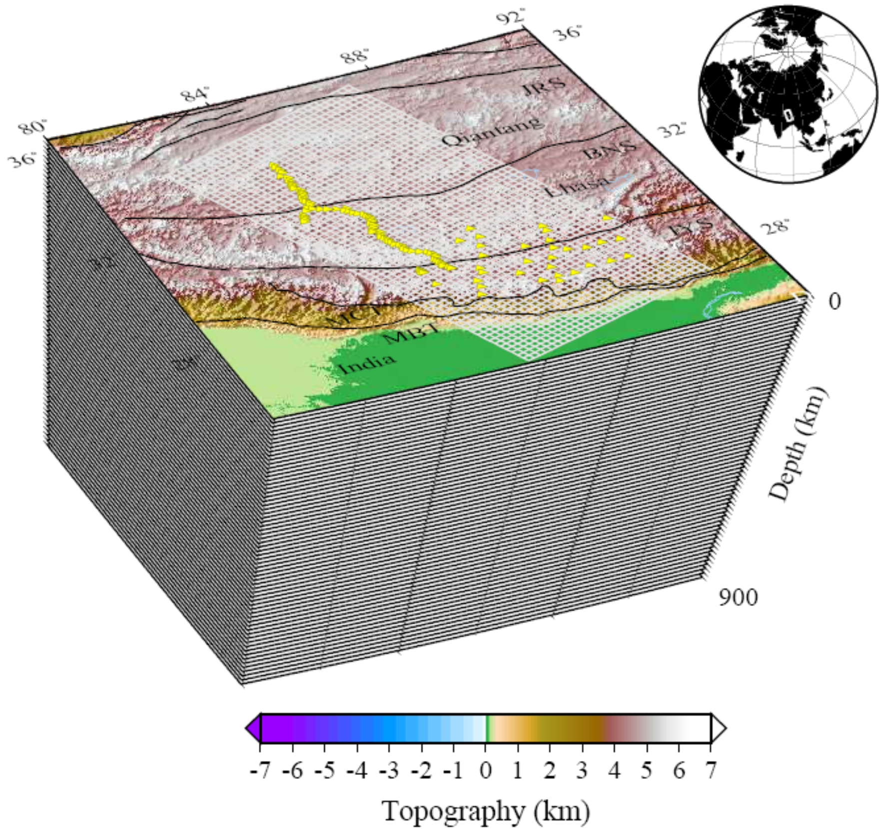

Figure.1. Model configuration for tomographic imaging study under Tibet. Gray-scale topographic map showing 106 Hi-CLIMB broadband stations denoted by triangles that provide P-wave travel time datasets for finite-frequency travel time tomography. The 3-D velocity model delineated by the white box spans ~1000 km along the N19W striking direction, ~500 km along the N71E striking direction, and 900 km in depth and is parameterized into 65×33×65 nodes with approximately equal-spacing of about 15 km. The map also shows the thrusting belts within the Himalaya, Main Central Thrust (MCT), and Main Boundary Thrust (MBT), and the suture zones bounding the Qiangtang and Lhasa terranes of Tibet, from north to south, Jisha River Suture (JRS), Bangong-Nujiang Suture (BNS), and Indus Yalung Suture (IYS).

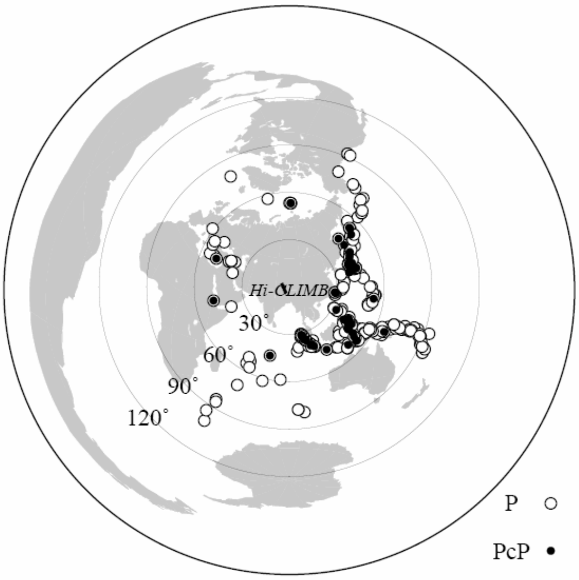

Figure 2. Azimuthal coverage of the earthquakes at epicentral distances of 30-95° that provides useful P (open circles) and PcP (solid circles) phase arrivals for cross correlation travel time measurements.

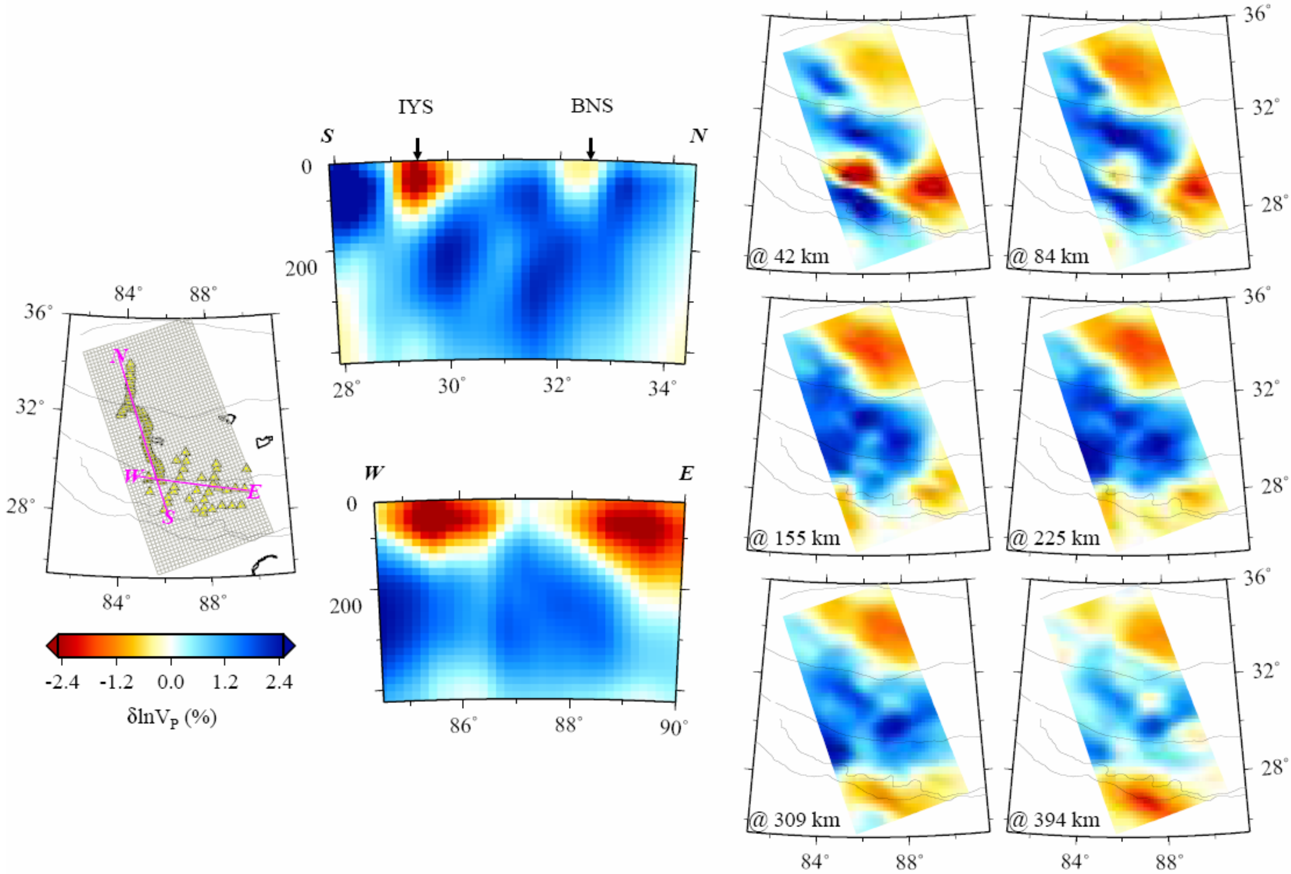

Figure 3. The resolved P-wave velocity model shown on two vertical cross sections slicing through the N-S and E-W trending arrays as denoted on the insert map of Tibet and six maps at different depths as indicated at the lower left corner.

出席國際學術會議心得報告

計畫編號	NSC 95-2116-M-002-007
計畫名稱	海底地震儀之觀測研究--結合有限頻寬走時成像與海底地震儀資料建構臺灣上地幔構造
出國人員姓名 服務機關及職稱	洪淑蕙、國立台灣大學地質科學系、副教授
會議時間地點	自 95 年 12 月 11 日起至 95 年 12 月 15 日止、美國舊金山
會議名稱	地球物理學術會議秋季年會
發表論文題目	Imaging Upper Mantle Structure Beneath the Tibetan Plateau and the Himalaya by Multiscale Finite-Frequency Tomography

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The Tibetan plateau and the Himalaya, created by the Indo-Asian collision started 50 million years ago, are the classic sites for studies of the evolution of continental orogeny. Determining seismic velocity structure of the underlying crust and mantle is essential for understanding how plate tectonics and mantle dynamics shape the towering Himalaya mountains and flat topography of Tibet. Recent development in finite-frequency tomography has been proven useful in imaging 3-D velocity variations on the scale comparable to the characteristic wavelength of the waves. Using available data from the INDEPTH and HIMNT experiments, we conduct finite-frequency traveltime tomography for compressional wavespeed heterogeneity of the upper mantle beneath Tibet. We measure relative delay times of P-wave arrivals between stations using multichannel cross-correlation of bandpass-filtered waveforms in different frequency ranges. The measured traveltime delays of the same phase arrival at different frequencies are actually sensitive to individual unique volume of structural heterogeneity surrounding the ray path. Such frequency-dependent sensitivity is naturally represented by 3-D banana-doughnut shaped Fréchet kernels for tomographic imaging. Moreover, multiscale wavelet-adaptive parameterization is invoked in the inversion and the resulting velocity models have spatially-varying resolutions subject to the quality of data sampling. The preliminary model reveals a region of relatively high P-wave

velocity extending continuously from the uppermost mantle to the depth of 350 km beneath central Tibet (30°N--34°N). At depths above 200 km, there is a strong lateral gradient of 3--4% in P wavespeed from high velocity structure beneath the Himalaya to low velocity beneath the Tibetan plateau.