CRUST AND UPPER MANTLE TOMOGRAPHY IN TIBET USING SURFACE WAVES

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Abstract: We have obtained maps of lateral variations of structure in the crust and lithosphere in Tibet and surrounding regions by inversion of single station measurements of fundamental mode Rayleigh wave phase velocities in the period range 25 - 100 sec, for earthquakes located in central Asia and observed at teleseismic digital stations in Eurasia. Phase velocity maps are obtained using a tomographic method without a priori constraints on region boundaries. The lateral variations of S velocity reveal a symmetric pattern on each side of crustal low velocity zone centered on the Chang Tang region (north central Tibet). This zone is bounded by rather steep velocity gradients to the south and east, about 250 and 400 km north and west of the frontal thrusts of the Himalayas and Lungmen Shan, respectively. The northern boundary of the zone crosses the northern limit of the Tibet plateau (Altyn Tagh and Kunlun) extending into the southwest Tarim and Qaidam basins. The low crustal velocities are consistent with a thick, hot crust in the central part of Tibet, consistent with Quaternary volcanism in Chang Tang. The steep gradients towards higher velocities in the south and in the north are compatible with the documented continental subduction in the south, and suggest that a similar situation might exist in the north.

Introduction

With an average elevation of 5500 m over 700 000 km^2, the Tibet Plateau is one of the most outstanding tectonic features on the earth's surface. Its average crustal thickness of 65-70 km, double that generally found under continents, was inferred early on from group velocity measurements of surface waves propagating across Tibet [Gupta and Narain, 1967] and was later confirmed by more detailed surface wave studies [e.g.: Patton, 1980; Chen and Molnar, 1981; Romanowicz, 1982; Jobert et al., 1985] and seismic refraction experiments [Hirn et al., 1984]. The difficulty of access to Tibet has made its geophysical sounding difficult. Hence, although the existence of thick crust beneath the plateau is beyond doubt, the structure of this crust, and how this structure has evolved, remain problematic. Uplift by underthrusting of the Indian lithosphere beneath Eurasia, resulting in a double crustal thickness [e.g.: Argand, 1922] or homogeneous lithospheric thickening by N-S shortening in front of India [e.g.: Dewey and Burke, 1973] have long been extreme conflicting models. That crustal shortening driven by continental subduction at the northern or eastern edges of Tibet could be equally important to understand its formation has been advocated more recently [e.g.: Mattauer,1985; Tapponnier et al.,1991; Meyer,1991].

While there have been numerous measurements of average crust and upper mantle properties in Tibet, mostly from analysis of individual paths, little work, so far, has addressed specifically the question of lateral heterogeneity in the deep structure beneath Tibet. In recent years, several studies have indicated that such heterogeneity might exist and persist to great depth. In a study of multiple S waves bouncing under Tibet, Lyon Caen [1986] found upper mantle velocities (<100 km) in northern and central Tibet slower by about 4% than in the Indian Shield. In a study of individual surface waves, paths across Tibet, Brandon and Romanowicz [1986] found evidence for a "tear" in the lithospheric lid under the Chang Tang province, consistent with the observation of Barazangi and Ni [1982] of poor Sn propagation across north central Tibet. With the deployment of digital seismological networks around the world, enough data have been accumulated in recent years to allow us to undertake a three dimensional tomographic study of the crust and upper mantle beneath Tibet based on the measurements of surface wave phase velocities on paths crossing the Plateau in different azimuths. In what follows, we present the first results of this work.

Data set and inversion method

We have analyzed 142 measurements of fundamental mode Rayleigh wave phase velocities in the period range 25 - 100 sec obtained from vertical component records of events located in Asia and observed at teleseismic digital stations in Eurasia (Global Digital Seismic Network, GEOSCOPE and Chinese Digital Seismic Network). The measurements were obtained using the single station method, as described for example in Romanowicz [1982], for earthquakes located in and around Tibet with well constrained source mechanisms. Such an approach is necessary due to the lack of stations within Tibet.

In order to assemble a high quality data set, several selection criteria were applied. Earthquakes of magnitudes mb<5 were not considered. Only those records were retained that corresponded to a lobe in the radiation pattern of the source and were thus minimally affected by an uncertainty in the source mechanism. The source parameters were obtained from different studies: Centroid Moment Tensor (CMT) solutions [Dziewonski et al.,1981], body wave and moment tensor solutions from the National Earthquake Information Center (NEIC) bulletins, as well as mechanisms by Ekström [1987] and Molnar and Lyon Caen [1989]. The data were filtered using the variable filtering method of Cara [1973] to isolate the fundamental mode Rayleigh wave. The phase velocity curves were inspected for anomalous jumps accompanied by holes in the amplitude spectrum. And whenever possible results obtained on paths close to each other were compared for consistency. Given the estimated error on source mechanism, depth and origin time, phase velocities were determined to within ±0.03 km/s. Out of the 142 initial paths, only 55% were finally retained. The geometry of the paths considered is shown in Figure 1. Optimal resolution of local structure is expected in the area between 26-44°N and 70-109°E, where the density of paths crossing in different directions is greatest, allowing a lateral resolution on the order of 300 km within the Tibet Plateau.

The phase velocities measured on individual paths were then inverted jointly to obtain maps of local phase velocities at each period considered. The inversion method is that introduced by Montagner [1985] for the study of the upper mantle in the Indian Ocean and includes no a priori assumptions on the distribution of local velocities, such as, for instance, correlation with tectonic features. The inversion relies on the introduction of a correlation length chosen to accomodate the well known trade off between resolution and variance in seismological inverse problems. The initial model used in this inversion is "Model 45" computed for Tibet by

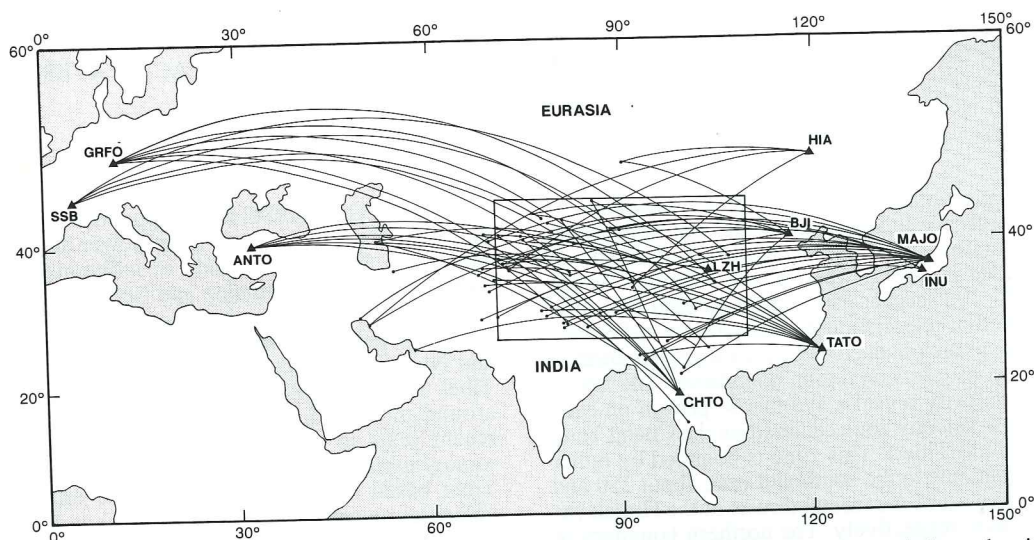* Current address: Seismographic station, U. C. Berkeley, Berkeley, California 94720, USA.

Fig. 1: Geometry of paths considered in this study with events located in Central Asia and recorded at teleseismic digital stations. Box is area where inversion of phase velocities is performed. Note largest density of paths crossing Tibet.
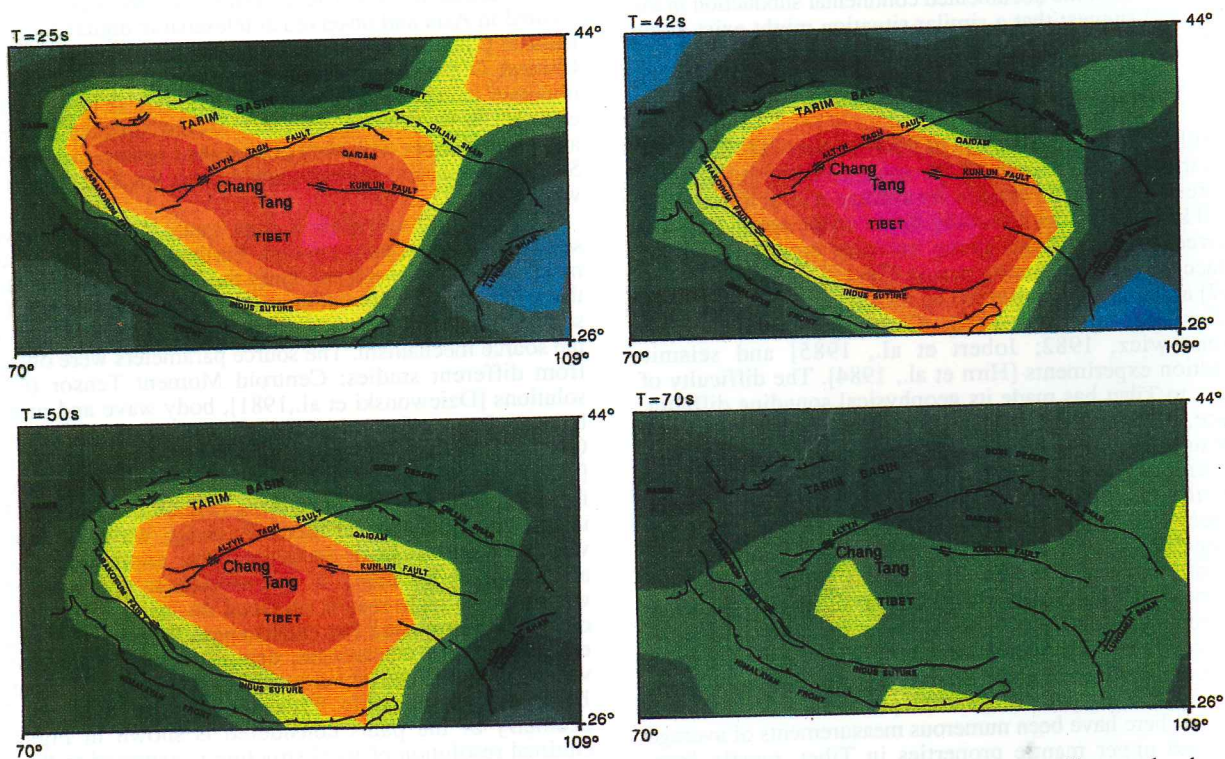
PHASE VELOCITY DISTRIBUTION

Fig. 2: Phase velocity distributions in and around Tibet at periods T = 25, 42, 50 and 70s corresponding to depths of maximum sensitivity of Rayleigh waves of aproximately 30, 50, 65 and 95 km respectively. On each map, color scale is with respect to average phase velocity at each period, with high velocities in blue and low velocities in red. Each color change corresponds to a change of velocity of 0.5%. Maximum variations are on the order of 4%. Thick lines are major cenozoic thrust and strike-slip faults, after Tapponnier and Molnar, 1977, and Armijo et al.,1989.

Romanowicz [1982]. The resulting phase velocity maps can be inverted in a second step to obtain maps of shear velocity as a function of depth.

Phase velocity maps and their interpretation

In Figure 2, we present phase velocity maps of Tibet and surrounding regions at different periods obtained using a correlation length of 350 km. Those periods correspond to a depth of maximum sensitivity of the Rayleigh waves of approximately 30, 50, 65 and 95 km respectively. Several striking features are present on these maps, which represent a sample of the available results.These maps show the result of combined effect of topography, sediments, crustal thickness or crustal variation of structure.

Between 25 and 60 sec, there is a clear zone of low velocities, with minimum velocities in central Tibet (up to - 4% lower than the regional average). The southern and eastern boundaries of this zone, which are clearly marked by steep phase velocity gradients, are roughly parallel to the edges of the plateau (Himalayas and Lungmen Shan frontal thrusts, respectively). They are located inside the plateau, about 250 km north, and 400 km east of these thrusts. The northern boundary of the low velocity zone, on the other hand, crosses the northern edge of the Tibet highlands (>5000m), as well as major tectonic boundaries along it (Kunlun range and Kunlun fault, Altyn Tagh range and Altyn Tagh fault) [e.g.: Tapponnier et Molnar, 1977; Armijo et al., 1989]. In fact, at periods shorter than 35 sec, both the SW Tarim and Qaidam basins form distinct low velocity zones. We interpret such low velocities to result from the combined effect of thick crust (40 km between sedimentary basement and Moho) and thick sedimentary cover (up to 12 km near Hotien and Golmud) in the flexural forelands of the Kunlun [Zhu, 1989]. The amplitude and extent of the zone of low velocities is greatest around 40sec. It is centered in northern Chang Tang. At 50sec and above, the amplitude and size of this zone decrease and its center shifts to NW Chang Tang, between the Kunlun and the Altyn Tagh Faults.

Lateral variations in phase velocity decrease by a factor of two between periods of 42 and 50 sec and, at 70 sec, they do not exceed 1.5%. Resolution is poor above 70 sec or below 100 km depth, which corresponds to the lithospheric thickness in proposed average Tibet models [e.g: Chen and Molnar,1981; Romanowicz, 1982; Lyon Caen, 1986], but there is an indication of continued lower than average velocities in northwestern Tibet.

From these phase velocity maps, average phase velocity curves for the regions of Chang Tang, Tarim and SE China have been computed (Figure 3). In Table 1, we show shear velocity models for the first 100 km of the lithosphere in these regions, obtained by forward modelling and compatible with those phase velocity maps, and the average Tibet model M45 of Romanowicz [1982] for comparison. Crustal thicknesses of 45 km for SE China, 50 km (including sediments in the foreland basins) for the SW Tarim and 65 km for the Chang Tang platform can explain most observed differences in phase velocity. Patton [1980b] found a similar thickness for the region including SE China and the Tarim. In central Chang Tang however, low shear velocities between 35 and 50 km are necessary to explain the very low phase velocities around 35-50sec period, somewhat deeper than suggested previously in a dispersion study by Chun and McEvilly [1986]. It is probable that these exceptionally low velocities are related to particularly hot lower crust [e.g.: Molnar, 1988; Gaudemer et al., 1988] in agreement with the observation of widespread Quaternary volcanism [Ministry of Geology, 1980; Burchfiel et al., 1989; Deng, 1989] and the absence of propagation of Sn waves [Barazangi and Ni, 1982] in this area of Tibet. Shear velocities in the Chang Tang crust are lower by 1.3 to 2.7% compared to average Tibet, with also somewhat lower velocities in the lithospheric lid (Table 1).

Discussion and Conclusions

In the first order analysis presented here, we have made the assumption that surface waves propagate along great circle paths and obey the laws of geometrical optics. The rapid lateral variations found indicate that, in more detailed future studies, it may be necessary to worry about how the steep gradients affect the wavepaths and produce focussing effects on amplitudes. The phase velocity maps obtained in this study indicate lateral heterogeneity in the crust north of the Himalayas with a region of low velocities bounded by steep velocity gradients to the east and south, parallel to, and several hundred km from, the Himalayan and Lungmen Shan
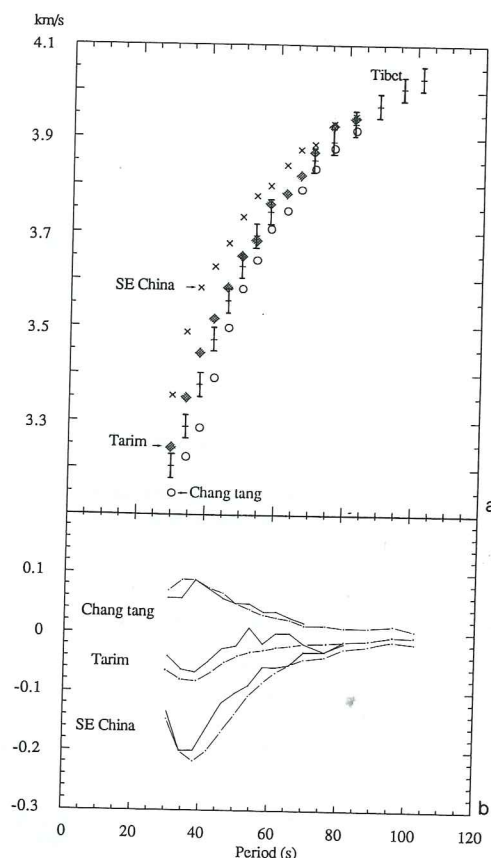

Fig. 3: a: Phase velocity curves for SE China, Tarim basin and Chang Tang platform computed from tomography maps and normalised to a tibetan model, M45 of Romanowicz [1982]. Phase velocities are determined within ±0.03 km/s (errors bars are shown on Tibet curve). b: Variations of velocities with respect to model M45 computed from tomography maps (continuous line) and from best fitting shear velocity models (dashed line).

Table 1: Shear velocity models of the crust and lithosphere in SE China, Tarim and Chang Tang corresponding to the phase velocity curves of figure 3. Model M45 [Romanowicz,1982] is given for comparison.

Tibet		Chang Tang		SE China		Tarim	
Depth (km)	Vs (km/s)	D	Vs	D	Vs	D	Vs
0 - 4	2.55	0 - 4	2.55	0 - 4	2.40	0 - 4	2.40
4 - 20	3.45	4 - 24	3.45	4 - 10	2.60	4 - 10	2.50
20 - 50	3.40	24 - 34	3.40	10 - 20	2.90	10 - 20	3.45
50 - 65	3.75	34 - 50	3.10	20 - 40	3.40	20 - 50	3.40
65 - 100	4.65	50 - 65	3.70	40 - 65	4.60	50 - 100	4.50
100 - 150	4.40	65 - 100	4.60	65 - 100	4.65	100 - 150	4.40
		100 - 150	4.40	100 - 150	4.45		

frontal thrusts. This region is centered on the Chang Tang platform, which exhibits the lowest velocities (-4%), originating (most likely) in the lower crust. This is consistent with the Quaternary volcanism observed in Chang Tang. To the north, the limit of the zone of low velocities does not follow the edge of the Tibetan highlands. We associate upper crustal low velocities in the southwestern Tarim and Qaidam basins with the existence of deep forelands basins (about

12km) on top of thick crust (about 40km) flexed down by continental subduction along the Kunlun. The striking symmetry in the pattern on each side of the central low velocitiy area suggest the possibility of continental subduction not only along the Himalayas but also along the northern edge of the Tibet Plateau.

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