Crustal flow beneath the eastern margin of the Tibetan plateau*

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Abstract In large continental orogens, an important research topic is the behavior of deep crustal and upper mantle deformation, and the flow styles of ductile material. The morphology of the eastern margin of the Tibetan plateau, adjacent to the Sichuan basin, is characterized by very steep relief with high mountain ranges. The crust beneath this region slows the velocities in the middle and lower crust. We have adopted a relatively dense network to inverse the detailed structure of the crust and upper mantle along the eastern margin of the Tibetan plateau and Sichuan basin, using teleseismic data via receiver function analysis. The results are in-line with the hypothesis that viscous crustal material is flowing beneath the eastern margin of the Tibetan plateau and that this process drives overlying crustal material around the strong and rigid Sichuan basin. When the viscous material hits this obstruction, flows are divided into two or more branches with different directions. The upper part of the upwelling viscous flow produces the pressure to intrude the upper crust, thereby driving uplift of mountain ranges and high peaks. In contrast, the lower part of the downwelling viscous flow produces the pressure to intrude the lower crust and upper mantle to deepen the Moho discontinuity, causing observed crustal thickening.

Key words: eastern margin of the Tibetan plateau; viscous crustal flow; upwelling and downwelling; mountain range uplift; deepened Moho discontinuity

CLC number: P315.2 **Document code:** A

1 Introduction

The behavior of the crust and lithospheric mantle in large continental orogens is an important research subject of continental tectonics. The major questions are the deformation styles and flow processes of the deep crust and lithospheric mantle (Beaumont et al., 2004; Gray and Pysklywec, 2012). The Tibetan plateau is the type example of a large orogenic plateau formed as a result of continent-continent collision. The morphology of the plateau and its margins suggests that the preexisting variations of strength and viscous flow in the deep crust and lithospheric mantle have influenced the growth and shape of the plateau. The morphology

of the region along the eastern margin of the Tibetan plateau, adjacent to the strong rigid crustal basement of the Sichuan basin, is characterized by very steep relief with high mountain ranges and steep peaks (Clark et al., 2004; Burchfiel et al., 1995, 2008; Kirby et al., 2003).

Lower crustal flow has been proposed to occur throughout the Tibetan plateau (Shen et al., 2001; Beaumont et al., 2004; Cook and Royden, 2008; Gray and Pysklywec, 2012). High temperatures, and the presence of even small amounts of fluids or partial-melt, can greatly reduce the strength of continental crust that may have resulted from the generation of high topography. This may enable a lateral flux of material throughout the plateau with minimal deformation of the rigid upper crustal layer (Cook and Royden, 2008). A number of geophysical observation points to the presence of fluids or partial-melt in the middle or lower crust of southern Tibet (Brown et al., 1996; Nelson et al., 1996). Receiver function studies in central Tibet have

* Received 15 October 2012; accepted in revised form 12 November 2012; published 10 December 2012.

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provided evidence of crustal low velocity zones that may have formed as a result of the presence of crustal fluids (Nelson et al., 1996; Clark and Royden, 2000; Clark et al., 2005).

The crust beneath the eastern margin of the Tibetan plateau slows the P- and S-waves in a low velocities zone in the middle crust (Wang et al., 2007; Zhu, 2008; Liu et al., 2009). Teleseismic receiver function analysis indicates the presence of a middle crust low velocity zone extending from the thick crust of the western Sichuan basin through the thinner crust of Yunnan (Xu et al., 2007). In contrast, the Sichuan basin has been interpreted as a region with strong rigid lithosphere and low heat flow (Clark and Royden, 2000; Clark et al., 2004, 2005).

However, the formation of the crustal low velocity zone is still not clear along the eastern margin of the Tibetan plateau, and the distribution pattern and the dynamic process of viscous fluids in the middle and lower crust and upper mantle are unknown. We have adopted a relatively dense network using both temporary and

permanent broadband seismometers that use passive-source data to inverse the fine velocity structure of the crust and upper mantle in the eastern margin of the Tibetan plateau and the Sichuan basin. The results of the fine velocity structure could reveal the distribution pattern of viscous fluids in the crust, and the dynamic behavior of the eastern margin of the Tibetan plateau.

2 Morphology and crustal dynamics of the eastern margin of the Tibetan plateau

The topographic expression along the eastern margin of the Tibetan plateau is irregular and diffuse (Kirby et al., 2003). The eastern margin of the Tibetan plateau adjacent to the strong rigid Sichuan basin is characterized by a series of extremely steep mountain ranges and high peaks. By contrast, the southeastern and the northeastern margins of the plateau are characterized by gentle slopes, and no significant topographic relief (Figure 1).

Figure 1 Morphology of the eastern margin of the Tibetan plateau and the Ordos basin, Qinling, Sichuan basin, and south Yangtze craton. (a) Location of the five profiles along the eastern margin of Tibetan plateau. The famous peaks are denoted by red triangles, and they are Xueboding, Jiudingshan, Xuelongbao, Siguniangshan, Haizishan, Gonggashan, Meilixueshan, and Yulongxueshan, respectively, in order. (b) The elevations along the five profiles.

The Longmenshan, a mountain range in proximity to the Sichuan basin, trends to the northeast along the eastern margin of the Tibetan plateau. Several sub-parallel NNW-trending high mountain ranges also found in the region include Minshan, Qionglaihan, Daxueshan, and Shalulishan. The topography in these mountain ranges is in stark contrast to the very flat central Tibet and has elevations in excess of 5 000 m. However, the topography of the eastern margin of the Tibetan plateau is one of the world's most remarkable continental escarpments (Kirby et al., 2003). Elevations are 400–600 m in the Sichuan basin and 5 500–7 500 m at the peaks. The horizontal distance from the basin to the peaks is about 50–80 km (see the topographic profiles L_2 , L_3 , L_4 in Figures 1a and 1b). The topographic gradients at the steep margins exceed 10%. The elevations of the famous peaks are 5 582 m for Xueboding in the Minshan, 4 984 m for Jiudingshan in Longmenshan, 6 250 m for Siguniangshan in Qionglaihan, 5 820 m for Haizishan, 7 556 m for Gonggashan in Daxueshan.

In northeastern and southeastern Tibet, the plateau has no distinct topographic margin. The elevations decrease gradually from about 4 500–5 000 m to 1 000–1 500 m, over several hundred to thousand kilometers without any sudden variation (see the topographic profiles L_1 to L_5 from Figure 1).

The steep margin adjacent to the Sichuan basin appears to have uplifted in the past 5–12 Ma, with only minor upper crustal shortening (Burchfiel et al., 1995). Pliocene-Quaternary deformation in eastern Tibet is dominated by left-lateral strike-slip faults that cut across both the topographic gradient of the margin and the trend of older structures (Burchfiel et al., 1995). Along the eastern Tibetan orogenic margin, dynamic stresses that have developed in the deep crust as a consequence of flow of weak lower crust may explain anomalously high topography. The elevated topography of the eastern plateau margin has been proposed to be the direct result of crustal thickening by weak, lower crustal material that has recently been evacuated from beneath the central plateau (Royden et al., 1997; Clark et al., 2005).

Quantitative analyses of regional topographic slopes across the eastern plateau margin indicate that the strength of the middle-lower crust beneath the southeastern and northeastern low-gradient margins is very low. By contrast, the middle-lower crust beneath the steep eastern plateau margin which borders the Sichuan basin is strong. The Sichuan basin, which has been proposed to be high-strength heterogeneities that

behave as rigid obstacle to ongoing deformation, often shows concentrated deformation along its margin (Clark et al., 2005).

The regional topographic gradients displayed on a smoothed elevation contour map and 3-D digital topography perspectives show the continental crust ‘flowing’ from the high central plateau around the low-elevation Sichuan basin, reflecting the flow of weak lower crustal material around a strength heterogeneity in the crust along the eastern margin of Tibet (Figure 1a).

3 Passive sources seismic observations in the eastern margin of the Tibetan plateau and Sichuan basin

In order to improve the characterization of crustal heterogeneity and quantitative analyses of the velocities and viscous flow in the deep crust, we have analyzed data from a regional network with about 50 temporary broadband seismometers and 40 permanent seismic stations from the CDSN (Chinese Digital Seismograph Network), which partly belongs to Earthquake Administration of Sichuan Province (Figure 2).

We used data from a network with 90 broadband seismometers. The location of the stations is shown in Figure 2. We analyzed waveforms from seismic events that were selected based on the following criteria: body-wave magnitude $M_b > 5.0$, and epicenter distances between 30° to 100° . A total of 147 events were chosen, mostly from the Circum-Pacific belt and also from the Mediterranean sea and the Indian ocean (Figure 3).

The S-wave velocity profiles are derived by receiver function analysis. The receiver function technique has allowed us to derive a source-equalized teleseismic waveform, in which source, far-field path, and instrument effects are removed by deconvolving the vertical component from the radial/transverse components. The resulting receiver function waveform is an estimate of the ground impulse response.

In this study, the following processing steps are applied to derive the receiver functions: rotation, deconvolution, move-out correction, stacking, and filtering (Xu et al., 2007). First, all teleseismic traces are rotated from an $E-N-Z$ coordinate system to an $R-T-Z$ system. Second, we have deconvolved the vertical components from both the radial and transverse components to remove the effects of the source and the instrument. During this process conducted in the frequency domain,

Figure 2 Location of seismic stations (triangles) from regional network of about 50 temporary broadband seismometers and 40 permanent seismic stations of CDSN, partly belonging to Earthquake Administration of Sichuan Province.

Figure 3 Azimuthal projection centered on the center of study region (black star) showing distribution of events used in this study, recorded over the period from 2005 to 2010.

we apply a water level to stabilize the spectral division.

We invert for S-wave velocity structures consisting of horizontal layers with fixed thicknesses of 2 km. Furthermore, we fix the Poisson's ratios and Moho depths at the values derived from the slant-stacking method. The inversion seeks to minimize the difference between the observed and model-generated receiver function waveforms. The P-wave velocity is derived from these results in conjunction with the v_P/v_S ratio. Approximate densities (ρ) throughout the model are derived using the equation $v_P = 1.73v_S$, $\rho = 0.32v_P + 0.77$.

A least-squares inversion of receiver function waveforms is performed to estimate the crustal velocity structure (Ammon et al., 1990). This technique is more sensitive to velocity contrasts than to the absolute magnitude of the velocities, but it requires a starting velocity model that is close to the actual velocities (Owens et al., 1984; Ammon et al., 1990).

Figure 4 shows the typical v_S profiles selected from Table 1. The most striking contrasts of crustal and upper mantle velocity structures are present between the Sichuan basin and the eastern margin of the Tibetan plateau. In the Sichuan basin higher velocity is shown in the crust and upper mantle and we do not find a low velocity zone. The average thickness of the crust is 4 044 km. The velocity feature may indicate that the basin is a brittle and rigid block.

The prominent features in the S-wave velocity profiles presented here are the crustal low velocity zones in the eastern margin of the Tibetan plateau. The Moho depth variation is 50 to 66 km.

In the uppermost crust almost ubiquitous low velocity layer can be related to the sedimentary basins or meta-sedimentary rocks. The crustal low velocity zone is widely distributed in the eastern margin of the Tibetan plateau, but with significant lateral variation in its depth and strength. In some regions the low velocity zone corresponds to the middle crust, but in other places it marks the lower crust (Xu et al., 2007). The low velocity zone in the middle and lower crust indicates that the rock has ductile properties, and deforms easily.

Figure 5 shows the crustal thickness in the eastern margin of the Tibetan plateau and Sichuan basin. The thickest crust is found in the central part of the eastern margin of Tibetan plateau (~64–66 km), and is also found the thicker low velocity zone in the middle to lower crust. In surface morphology this region shows the highest mountain ranges and peaks (Gonggashan, Siguniangshan), adjacent to the boundary of the Sichuan basin. Along the boundary of eastern

Table 1 Station and receiver function analysis results for the v_S velocity distribution with individual depth d (in unit of km) in the crust and upper mantle

Station	Long. /(°E)	Lat. /(°N)	Elev. /m	Moho depth/km	$v_S/(\text{km}\cdot\text{s}^{-1})$							
					$d=0$	$d=10$	$d=20$	$d=30$	$d=40$	$d=50$	$d=60$	$d=80$
Sichuan basin												
BAJ	103.40	30.98	1 361	44	2.5	3.2	3.5	3.5	4.1	4.6	4.6	4.6
DUJY	103.61	31.03	1 300	44	2.8	3.3	3.3	3.6	4.1	4.6	4.6	4.6
JSC	104.81	30.13	444	42	2.8	3.3	3.7	3.7	3.7	4.3	4.3	4.3
KNS	103.90	31.12	834	44	2.7	3.2	3.6	3.8	3.8	4.3	4.3	4.5
LQY	104.35	30.62	700	42	2.6	2.9	3.7	3.7	4.2	4.5	4.5	4.5
YCG	103.81	31.26	1 175	44	2.9	3.3	3.7	3.7	3.9	4.3	4.3	4.3
ZHZ	106.20	32.18	613	42	2.7	3.1	3.6	3.6	3.8	4.1	4.1	4.5
QZZ	105.23	32.59	805	44	2.7	3.0	3.6	3.6	3.9	4.2	4.2	4.5
SHP	105.28	32.70	817	44	3.0	3.4	3.5	3.5	3.8	4.3	4.3	4.5
AXI	104.43	31.64	587	42	3.0	3.5	3.8	4.3	4.3	4.7	4.7	4.7
BZH	106.74	31.84	442	42	3.0	3.4	4.0	4.0	4.0	4.6	4.6	4.6
CD2	103.75	30.91	692	43	2.4	3.0	3.6	3.6	4.1	4.7	4.7	4.7
HWS	104.74	28.64	860	40	3.3	3.3	3.8	3.8	4.1	4.7	4.7	4.7
HYS	106.84	30.42	555	41	3.1	3.2	3.9	3.9	4.1	4.7	4.7	4.7
JMG	105.56	32.21	801	42	2.8	3.3	3.9	3.8	3.8	4.6	4.8	4.8
JJS	104.55	31.00	908	42	2.7	3.3	3.7	4.1	4.1	4.8	4.8	4.8
JYA	103.93	29.79	570	42	2.6	3.4	4.0	4.1	4.1	4.4	4.4	4.4
JLI	104.52	28.18	480	42	3.1	3.5	3.5	3.7	4.0	4.8	4.8	4.8
MDS	103.04	30.07	1210	42	2.7	3.5	3.9	3.9	3.9	4.4	4.4	4.7
XCO	105.90	31.02	336	40	2.9	3.3	3.8	3.8	4.0	4.6	4.8	4.8
XHA	107.72	31.37	390	42	2.9	3.3	3.6	3.6	3.8	4.3	4.8	4.8
YGD	104.10	30.20	800	42	2.8	3.5	3.8	4.1	4.1	4.8	4.8	4.8
YZP	103.57	30.87	766	44	2.6	3.4	3.8	3.8	3.9	4.8	4.8	4.8
ZJG	104.67	31.79	612	42	3.0	3.5	3.6	4.1	4.1	4.8	4.8	4.8
EMS	103.45	29.58	467	42	2.7	3.5	3.5	3.7	3.7	4.3	4.3	4.6
Northern part of the eastern margin of Tibetan plateau												
MXX	102.45	34.02	3 436	52	3.3	3.6	3.3	3.1	3.1	3.7	3.7	4.0
REG	102.96	33.58	3 470	52	3.2	3.7	3.7	3.4	3.4	3.8	4.5	4.7
BZX	103.36	33.47	3 457	52	3.1	3.9	3.7	3.7	4.1	4.1	4.6	4.6
TKX	102.47	33.41	3 411	52	3.3	4.2	3.0	3.6	3.0	4.0	4.2	4.2
JZG	104.24	33.28	1 440	52	2.8	3.7	3.7	3.4	3.4	3.8	4.2	4.2
GYX	104.33	33.12	1 260	50	2.9	4.1	3.4	3.4	3.4	4.4	4.4	4.6
WEN	104.68	32.95	910	48	3.2	3.5	3.2	3.2	3.2	4.3	4.3	4.3
DGL	102.53	32.81	3 482	52	3.1	3.4	3.1	3.1	3.1	3.9	3.9	3.9
SPA	103.60	32.65	2 905	60	3.2	3.5	3.7	3.7	3.7	3.9	4.3	4.3
LRX	102.44	32.49	3 566	54	3.1	3.5	3.5	3.0	3.0	3.8	3.8	3.8
PWU	104.55	32.42	882	44	3.5	3.7	3.6	3.6	3.6	4.1	4.1	4.3
RTA	100.98	32.27	3 317	60	3.1	3.7	3.7	3.3	3.3	3.8	4.2	4.5
RKX	102.49	32.21	3 539	54	2.8	3.3	3.4	3.0	3.0	3.4	3.4	3.9
HSH	102.99	32.06	2 344	54	3.4	3.6	3.8	3.3	3.3	3.3	4.0	4.3
WGX	103.34	31.98	1 904	54	3.0	3.3	3.0	3.0	3.5	3.5	4.0	4.0
MEK	102.22	31.90	2 765	58	3.0	3.4	3.5	3.9	3.7	3.7	4.5	4.5
BXX	103.54	31.88	1 820	54	2.7	3.1	3.0	3.0	3.5	3.5	3.9	3.9
MXI	103.85	31.69	1 584	46	3.1	3.2	3.2	3.2	3.8	4.5	4.5	4.5
WCH	103.59	31.47	1 315	48	3.6	3.5	3.5	3.5	3.9	3.8	4.3	4.3

Continued on from Table 1

Station	Long. /(°E)	Lat. /(°N)	Elev. /m	Moho depth/km	$v_S/(km \cdot s^{-1})$							
					d=0	d=10	d=20	d=30	d=40	d=50	d=60	d=80
Central part of the eastern margin of Tibetan plateau												
GENDA	103.28	31.10	1 520	52	3.0	3.4	3.2	3.2	3.9	3.9	4.4	4.4
WOL	103.17	31.02	2 019	50	3.2	3.8	3.0	3.0	3.3	4.1	3.3	3.3
RIL	102.77	31.00	3 026	62	3.1	3.3	3.0	3.0	3.6	3.8	3.8	4.2
DAWE	102.63	30.97	2 773	62	3.0	3.4	3.4	3.0	3.6	3.6	3.6	4.3
XJI	102.36	31.00	2 427	66	3.4	4.0	3.5	3.5	3.5	4.0	4.0	4.4
XJZ	102.09	31.00	2 101	66	3.1	3.4	3.6	3.1	3.4	3.6	3.8	4.1
XJW	102.00	30.97	2 004	66	3.4	3.4	4.4	3.4	3.5	3.4	3.5	4.4
DBA	101.75	30.80	2 895	62	2.7	3.3	3.0	2.9	3.7	3.4	4.0	4.3
BMZ	101.53	30.55	3 612	64	3.0	3.3	2.6	2.6	3.5	3.5	3.5	4.1
DFU	101.12	30.91	3 035	64	3.1	3.4	3.4	3.1	3.1	3.7	4.1	4.4
BTA	99.12	30.01	2 639	60	2.8	3.6	3.2	3.2	3.2	3.6	3.9	3.9
XCE	99.79	28.94	3 000	62	2.8	3.5	3.5	3.5	4.1	4.1	4.1	4.7
GZI	100.02	31.61	3 360	60	2.7	3.2	2.8	2.8	3.4	3.9	4.2	4.2
LTA	100.27	30.00	3 951	62	3.1	3.6	3.6	3.4	3.4	4.2	4.2	4.7
YJI	101.01	30.03	2 670	64	3.2	3.7	3.7	3.4	3.4	3.8	3.8	4.2
JLO	101.51	29.00	2 915	60	3.3	3.3	3.7	3.3	3.3	3.3	3.4	3.6
GZA	102.17	30.12	1 410	60	3.3	3.7	3.7	3.4	3.2	3.2	3.7	3.9
SMI	102.35	29.22	860	58	2.9	3.4	3.6	3.3	3.3	3.8	4.0	4.3
Southern part of the eastern margin of Tibetan plateau												
BYD	103.19	27.81	3 160	52	2.9	3.3	3.5	3.5	3.5	3.8	4.1	4.6
HLI	102.25	26.65	1 836	52	3.1	3.4	3.7	3.7	3.7	4.0	4.4	4.6
LBO	103.57	28.27	1 310	50	3.0	3.3	3.4	3.7	4.1	4.1	4.5	4.7
LGH	100.86	27.71	2 669	54	3.2	3.5	3.6	3.6	3.8	3.8	4.6	4.6
MBI	103.53	28.84	640	50	3.1	3.6	3.8	3.8	4.1	4.1	4.6	4.6
MGU	103.13	28.33	2 056	56	3.2	3.8	3.8	3.9	3.9	4.2	4.5	4.7
WMP	103.79	29.05	1 260	46	3.2	3.4	3.7	3.7	3.7	4.5	4.5	4.5
XSB	102.45	27.86	2 800	52	3.2	3.4	3.8	3.8	4.0	4.0	4.2	4.6
YYC	102.26	27.85	1 608	52	3.0	3.3	3.8	3.8	4.1	4.1	4.2	4.5
MNI	102.17	28.33	1 657	50	3.0	3.6	3.6	3.9	3.9	3.9	4.2	4.9
MLI	101.27	27.93	2 437	54	3.3	3.3	4.2	3.3	3.3	3.3	4.1	4.7
PZH	101.74	26.50	1 190	54	3.4	3.7	3.7	3.3	3.3	4.1	4.5	4.7
PGE	102.54	27.38	1 427	52	3.3	3.7	3.2	3.2	3.8	3.8	4.6	4.6
SMK	102.75	26.86	2 360	50	3.0	3.7	3.7	3.3	3.3	4.1	4.7	4.7
YYU	101.68	27.47	2 596	50	3.2	3.8	4.0	3.6	3.6	3.8	4.5	4.5
LUD	102.50	30.00	1 330	57	3.0	3.2	3.1	3.1	3.1	3.4	3.4	4.5
XDQ	101.50	30.10	3 667	61	3.0	3.1	3.1	3.1	3.5	3.5	4.6	4.6
LIJ	100.00	26.80	2 416	55	3.1	3.4	3.1	3.1	3.1	4.3	4.3	4.4
DOC	100.40	29.00	4 448	62	3.1	3.3	3.2	3.7	3.7	3.7	4.4	4.5
YPI	99.60	25.50	2 250	41	2.9	3.8	3.7	3.7	3.7	4.7	4.8	4.8
CXI	101.50	24.90	1 890	50	2.9	3.8	3.8	3.8	3.8	4.7	4.7	4.7
JIC	102.80	24.20	1 806	42	2.8	3.2	3.2	3.2	4.7	4.7	4.7	4.7

Notes: The v_S velocity values of last five stations are from Xu et al. (2007).

margin of the Tibetan plateau and the Sichuan basin the Moho discontinuity has a large displacement gradient from 42 km to 60 km in depth. The crust beneath the Sichuan basin has a thickness of ~40–44 km. In the southern part of the eastern margin of Tibetan plateau

the crustal thickness varies from 54 km to 38 km and gradually thins to the southeast.

Poisson's ratios can help to constrain crustal properties and chemical composition (Zhu and Kanamori, 2000). We interpret the large range of observed Pois-

son's ratio in the eastern margin of the Tibetan plateau and Sichuan basin (see Table 2) to be a result of heterogeneity in crustal composition and, locally, the existence of partial-melt. Most of our study region has

an intermediate to high Poisson's ratio (0.24–0.35). All these suggest the presence of complex heterogeneity in the crust beneath the eastern margin of the Tibetan plateau and the Sichuan basin.

Figure 4 Typical v_s velocity profiles in Sichuan basin (a), northern part (b), central part (c) and southern part (d) of the eastern margin of Tibetan plateau. Data are from Table 1. The red shadow in the profiles indicates the low velocity zone. In the Sichuan basin all v_s profiles indicate the higher velocity and no low velocity zone in the crust and upper mantle. In the eastern margin of the Tibetan plateau most of the v_s profiles indicate the lower velocity in the crust and upper mantle.

Figure 4 Typical v_s velocity profiles in Sichuan basin (a), northern part (b), central part (c) and southern part of the eastern margin of Tibetan plateau. Data are from Table 1. The red shadow in the profiles indicates the low velocity zone. In the Sichuan basin all v_s profiles indicate the higher velocity and no low velocity zone in the crust and upper mantle. In the eastern margin of the Tibetan plateau most of the v_s profiles indicate the lower velocity in the crust and upper mantle.

The most prominent features are the strong and rigid crust and upper mantle beneath the Sichuan basin, indicating the normal value of Poisson's ratios generally decreasing from 0.28 to 0.24.

The ratio is higher in most of the eastern margin of the plateau. The normal-to-high Poisson's ratios (0.24–0.34) were found in the northern part of this region, and very high values (0.30–0.35) in the central part. In the south part of the eastern margin, the Poisson's ratio exhibits more significant variation (0.23–0.34).

The results suggest that the presence of complex heterogeneity in the crust beneath the eastern margin of Tibetan plateau and Sichuan basin. The most prominent feature in this region is that the Sichuan basin exhibits strong and rigid crust and upper mantle. The central part of the eastern margin of Tibetan plateau indicates the presence of partial-melt in the middle and lower crust, whereas the variation of the ratio in the northern and southern parts indicates the higher heterogeneity in the crust and upper mantle in this region.

Table 2 v_P/v_S ratio and Poisson's ratio in the Sichuan basin and the eastern margin of the Tibetan plateau

Station	Long./($^{\circ}$ E)	Lat./($^{\circ}$ N)	v_P/v_S ratio	Poisson's ratio	Moho depth
Sichuan basin					
BAJ	103.40	30.98	1.71	0.24	44
YCG	103.81	31.26	1.80	0.28	44
AXI	104.43	31.64	1.73	0.25	42
BZH	106.74	31.84	1.72	0.24	42
HWS	104.74	28.64	1.79	0.27	40
HYS	106.84	30.42	1.80	0.28	41
JMG	105.56	32.21	1.77	0.27	42
JJS	104.55	31.00	1.82	0.28	42
JLI	104.52	28.18	1.68	0.23	42
MDS	103.04	30.07	1.72	0.24	42
XHA	107.72	31.37	1.76	0.26	42
ZJG	104.67	31.79	1.74	0.25	42
Northern part of the eastern margin of Tibetan plateau					
MXX	102.45	34.02	1.77	0.27	52
REG	102.96	33.58	1.78	0.27	52
DGL	102.53	32.81	1.76	0.26	52
LRX	102.44	32.49	1.75	0.26	54
PWU	104.55	32.42	1.67	0.22	44
RTA	100.98	32.27	1.80	0.28	60
RKX	102.49	32.21	1.80	0.28	54
HSX	102.99	32.06	1.72	0.24	54
WGX	103.34	31.98	1.74	0.25	54
MEK	102.22	31.90	1.71	0.24	58
MXI	103.85	31.69	1.79	0.27	46
WCH	103.59	31.47	2.05	0.34	48
Central part of the eastern margin of Tibetan plateau					
RIL	102.77	31.00	2.10	0.35	62
DAWE	102.63	30.97	2.25	0.38	62
XJI	102.36	31.00	1.82	0.28	66
XJZ	102.09	31.00	1.80	0.28	66
XJW	102.00	30.97	1.88	0.30	66
DBA	101.75	30.80	1.84	0.29	62
BMZ	101.53	30.55	2.10	0.35	64
DFU	101.12	30.91	1.80	0.28	64
GZI	100.02	31.61	1.91	0.31	60
LTA	100.27	30.00	1.93	0.32	62
YJI	101.01	30.03	1.85	0.29	64
GZA	102.17	30.12	1.84	0.29	60
SMI	102.35	29.22	1.88	0.30	58
Southern part of the eastern margin of Tibetan plateau					
BYD	103.19	27.81	1.68	0.23	52
HLI	102.25	26.65	1.68	0.23	52
LBO	103.57	28.27	1.70	0.24	50
LGH	100.86	27.71	1.79	0.27	54
MBI	103.53	28.84	1.74	0.25	50
WMP	103.79	29.05	1.79	0.27	46
SMK	102.75	26.86	1.78	0.27	50
XSB	102.45	27.86	1.90	0.31	52
MNI	102.17	28.33	2.01	0.34	50
PZH	101.74	26.50	1.98	0.33	54
PGE	102.54	27.38	1.94	0.32	52
YYU	101.68	27.47	1.95	0.32	50

Figure 5 Contour map of crustal thickness (in km). The solid line is from this receiver function study. The dashed line is from inversion of Bouguer gravity anomaly data or explosion seismic data.

4 Viscous flows within the middle and lower crust around the Sichuan basin

From 0 to 10 km, v_S is lower in the Sichuan basin because the basin has huge thickness of sediments that are characterized by low velocity. In contrast, the mountain ranges in the eastern margin of the Tibetan plateau show higher velocities. For 10–40 km the Sichuan basin shows higher v_S velocity in the middle and lower crust whereas the eastern margin of the Tibetan plateau shows lower velocity. For 50–60 km the Sichuan basin extends to the upper mantle showing high velocity. Still in this depth range low velocities are found in the lower

crustal portion of the eastern margin of the Tibetan plateau. At 80 km depth, upper mantle is present in both regions, but the velocity distribution indicates the obvious difference. In the eastern margin of the plateau, the low velocity layer is still found in the northern part.

Figure 6 shows the v_S distribution with individual depth in the crust and upper mantle from the receiver function analysis results (Table 1). In the depth range of 0–10 km, v_S is lower in the Sichuan basin because the basin has huge thickness of sediments with low velocity characteristics, whereas the mountain ranges in the eastern margin of Tibetan plateau show higher velocity. In the depth ranging 10–40 km beneath the Sichuan basin, we find higher v_S in the middle and lower crust, while the eastern margin of Tibetan plateau shows lower

Figure 6 v_s distribution at several depths in the crust and upper mantle from the receiver function analysis results (Table 1). The mountain ranges and high peaks of the eastern margin of Tibetan plateau are also shown. The Sichuan basin is delineated by a black dashed line. The short brown arrows show the observed GPS velocity field around the eastern margin of the Tibetan plateau relative to the Sichuan and Yangtze cratons. The thick and fine lines show the main active faults in the region. The green arrows are the inferred crustal flow in individual layers around the strong and rigid Sichuan basin. The mountain range and peak code are the same as in Figure 1.

velocities. In the depth from 50 km to 60 km beneath the Sichuan basin the higher velocities are indicated in the upper mantle. However, in that depth range, the lower crust is still present beneath the eastern margin of Tibetan plateau, with characteristic lower velocities. At the depth 80 km, both regions show the presence of upper mantle, but the velocity distributions are clearly different. In the eastern margin of Tibetan plateau the low velocity layer is still found in the northern part.

According to the distribution and pattern of low velocity zones in each layer, we can infer the presence of viscous crustal flow, which drives the crustal material around the rheologically strong Sichuan basin, shown by green arrows in Figure 6. The direction of crustal viscous flow coincides primarily with the observed GPS velocity field around the Tibetan plateau relative to the Sichuan and Yangtze cratons.

The crustal viscous flow does not show growth in any region, and most of the flow direction is along the main active faults. The effective middle and lower crustal channel thicknesses have been estimated to be 20–40 km, namely, the crustal viscous flow is heterogeneously dispersed over the depth range of 20–60 km. Similar viscous flow in the eastern margin of Tibetan plateau is discussed and presented in several papers (Wang et al., 2007; Zhu, 2008; Xu et al., 2009; Bai et al., 2010).

Recently, several papers have been published that investigate the crustal v_S velocity structure and deformation in eastern Tibet, using ambient noise and surface wave tomography (Yao et al., 2008; Yao and van der Hilst, 2009; Li et al., 2009; Zheng et al., 2010; Yang et al., 2012). Based on 1–2 years of continuous observations of seismic ambient noise data obtained at more than 600 stations in and around Tibet, Rayleigh wave phase velocity maps have been constructed from 10 s to 60 s periods. A 3-D v_S model of the crust and uppermost mantle is derived from these maps. The 3-D model exhibits apparently inter-connected low shear velocity features across most of the Tibetan middle crust at depths between 20 km and 40 km (Yang et al., 2012). Yao et al. (2008) and Yao and van der Hilst (2009) have determined the 3-D shear wave speed variations in the crust and upper mantle in the SE Tibetan plateau, with data from 25 temporary broad-band stations and one permanent station. The results show that, in some regions prominent low velocity layers occur in the middle crust, but in others they may appear in the lower crust. In some cases the lateral transition of shear wave velocity coincides with major fault zones (Yao et al., 2008; Yao

and van der Hilst, 2009).

Throughout the Alpine-Himalaya orogenic belt, continental crust deformation and thickening have resulted in active orogen. These blocks behave as rigid obstacles to ongoing deformation. In the eastern margin of the Tibetan plateau, this obstacle is the strong and rigid Sichuan basin. It has caused crustal thickening and elevated topography along the margin. This has been proposed to be the direct result of weak lower crustal material being evacuated from beneath the central Tibetan plateau (Royden et al., 1997; Clark and Royden, 2000).

The observed GPS velocity field around the eastern margin of Tibetan plateau relative to the Sichuan and Yangtze cratons (Gan et al., 2007; Wang et al., 2008) shows that most of the motion at the surface and uppermost crust is oriented parallel to the boundary of the obstacle. A concave steep region along the eastern margin of Tibetan plateau against the strong Sichuan basin has remained as an undeformed low-lying region.

There is very little convergence across the eastern margin of Tibetan plateau to the boundary adjacent to the strong Sichuan basin. The paths of crustal viscous flow are largely directed parallel to the margin, and coincide with the GPS velocity field. As the eastern margin of Tibetan plateau wraps around the obstruction of Sichuan basin, viscous crustal flow remains parallel to the boundaries of the strong region, particularly in the lower crust. The crustal flow moves around the obstruction, although in some places it has a component of motion toward the plateau margin.

5 The moving pattern of crustal viscous fluid and its dynamics for crustal deformation

As shown in Figure 7, the low velocity layer distribution in the middle and lower crust is irregular, with various thicknesses. Particularly, these low velocity layers act as a viscous fluid, and show different flow directions. In general, flows have moved in the horizontal direction, however, when they hit the strong Sichuan basin, the direction is changed to an up or down direction. We have modeled the middle and lower crust as a viscous fluid bounded within a fixed rigid horizontal boundary overlain by an elastic layer that is free to deform under the influence of the dynamic pressures generated. Flow within the channel is presumed to be driven by horizontal pressure gradients associated

with topographic gradients across the eastern Tibetan plateau boundary adjacent to the Sichuan basin.

The thickness of the low velocity layer varies from 20 to 40 km, even 50 km. The viscosities of the low velocity layer range from 10^{17} to 10^{20} Pa·s. The flow in the crust has been proposed to occur over length scales of tens to hundreds of kilometers and possibly over more than 1 000 km (Clark and Royden, 2000; Cook and Royden, 2008), with flow durations on the order of 10^6 – 10^7 a. Flow within the crust is driven by

horizontal pressure gradients from the central Tibetan plateau, due to topographic gradients and variations in crustal thickness.

The upper part of viscous flow upwelling produces the pressure to intrude the upper crust and to uplift the mountain ranges and high peaks in the eastern margin of Tibetan plateau. In contrast, the downwelling viscous flow produces the pressure to intrude the lower crust and upper mantle to deepen the Moho discontinuity, causing the crust to thicken as shown in Figure 6.

Figure 7 Comparison of the crustal structure and topography along the eastern margin of the Tibet plateau adjacent to the Sichuan basin. Five profiles of v_s velocity of the crust and upper mantle are shown. The black line in these profiles indicates the boundary. Arrows in low velocity layer indicate the flow's dominant direction. The codes for high peaks are same as in Figure 1, and the station codes shown in the profiles. Refer to Figure 1 for mountain peaks marked by red triangles.

6 Conclusions

The eastern margin of Tibetan plateau, adjacent to the strong crustal Sichuan basin, is characterized by a series of extremely steep mountain ranges and high peaks with NE-trend and several subparallel NNW trend. Beneath this region there are low-velocity zones within thick crust, whereas the Sichuan basin is interpreted as a region of strong rigid crust and upper mantle. In order to improve our understanding of crustal low velocity zones, and the dynamic process of viscous fluids in the middle and lower crust, we have adopted the relatively dense network of temporary and permanent broadband seismometers to estimate the fine S-wave velocity structure in the crust and upper mantle in this region.

The crust varies in thickness of 50–66 km in the eastern margin of the Tibetan plateau and 40–44 km in the Sichuan basin. The gradient of the Moho discontinuity is the greatest in the boundary along the eastern margin of the Tibetan plateau toward the Sichuan basin. The same boundary morphology is characterized by a series of extremely steep mountain ranges and high peaks.

According to the distribution of low velocity zones in the middle and lower crust at each point, we can infer that the viscous crustal flow drives the crustal material around the obstacle of the strong rigid Sichuan basin. The crustal flow is not growing anywhere, and most of the flow direction is found to occur along the main active faults. The flow direction coincides with the observed GPS velocity field around the eastern margin of Tibetan plateau relative to the Sichuan basin and Yangtze craton. The effective middle and lower crustal thicknesses have been estimated to be between 20 and 40 km, namely, the crustal viscous flow is distributed dispersedly at the depth of 20 km even extending heterogeneously to 60 km. The viscosities of the flow range from 10^{17} to 10^{20} Pa·s, and occur in the crust over length scales of hundreds of kilometers, and possibly over more than 1 000 km. Flow within the crust is driven by horizontal pressure gradients from the central Tibetan plateau due to topographic gradients and variations in crustal thickness.

When the viscous flows in the middle and lower crusts hit the obstruction of the strong rigid Sichuan basin, these flows are divided into two or more branches with different directions. The upper part of viscous flow upwells to produce enough pressure to intrude the upper crust, thereby uplifting the mountain ranges and

high peaks along the eastern margin of Tibetan plateau. Whereas the lower downwelling part of viscous flow produces the pressure to intrude the lower crust and upper mantle to deepen the Moho discontinuity, causing the crust to thicken.

Acknowledgements We thank Dr. Lili Xu, Prof. Robert D van der Hilst and Prof. Z. Chen for providing us both the field data collected from their south Yunnan array studies and their v_s crustal velocity models. Thanks are also to Dr. Qiang Xu for providing the inversion codes in our velocity structure study. This research was supported by National Natural Science Foundation of China under grant Nos. 40839909, 41074062, and 40674040.

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