Regional earthquakes in northern Tibetan Plateau: Implications for lithospheric strength in Tibet

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[1] A total of 400 regional earthquakes were located in northern Tibetan Plateau from data recorded by INDEPTH-IV and PKU Eastern Kunlun arrays from May 2007 to June 2009. The distribution of these earthquakes is compatible with a continuously deforming Tibetan lithosphere. Most earthquakes occur at a depth range of 0-15 km, but no event is deeper than 30 km. This observation strongly supports the existence of a hot and weak lower crust beneath the northern Tibet. The crustal seismogenic zone appears slightly thicker beneath the northern Tibet than in the southern plateau, possibly reflecting a difference in the rheological (dry vs. wet) structure of the crust. The absence of lower crustal and uppermost mantle earthquakes in northern Tibet is consistent with a localized asthenospheric upwelling under the Qiangtang and Songpan-Ganze terranes. Finally, the lack of mantle earthquakes should be fully addressed in any models of subduction in northern Tibet. **Citation:** Wei, S., et al. (2010), Regional earthquakes in northern Tibetan Plateau: Implications for lithospheric strength in Tibet, *Geophys. Res. Lett.*, *37*, L19307, doi:10.1029/2010GL044800.

1. Introduction and Tectonics Setting

[2] The spatial and temporal distribution of earthquakes and their depth extent provides crucial information about active tectonics as well as thermal conditions and the mechanical strength as a function of depth. The occurrence of two layers of seismicity in the lithosphere (also known as the "jelly-sandwich model"), one in the upper crust and the other near the uppermost mantle, has been documented in several intra-continental regions [*Chen and Molnar*, 1983]. This correlation indicates that the seismogenic portion of the lithosphere is limited to regions beneath a limiting temperature, above which material is too weak to accumulate seismogenic strain. The limiting temperature is approximately 250-450 °C for crustal earthquakes, and 600-800 °C for mantle earthquakes [*Chen and Molnar*, 1983]. Under similar conditions of temperature and strain rate, the ductile strength of mantle materials is generally greater than that of crustal material. We investigate how such strain models can be applied to the thick crust of Tibet.

[3] Over the last two decades, many field seismic experiments have been carried out over the Tibetan Plateau; until recently however, most seismic experiments have consisted of long linear profiles which are not optimal for earthquake location. Among some crucial results are: 1) the underthrusting of Indian continental lithosphere beneath much of the southern Plateau [*Tilmann et al.*, 2003] and 2) the uniform thickening of the accreted terranes in northern Tibet [*McKenzie and Priestley*, 2008]. In southern Tibet, the mountain building at the collision front is associated with mid-crustal channel flow [*Beaumont et al.*, 2004]. The lithospheric structures beneath the Himalayas and southern Tibet have been successfully imaged by several portable seismic arrays (e.g., Hi-CLIMB [*Nábelek et al.*, 2009], INDEPTH [*Nelson et al.*, 1996], and HIMNT [*de la Torre and Sheehan*, 2005]). The deformation of the crust and upper mantle of the northern Plateau, north of the Bangong-Nujiang suture, is quite different from that of southern Tibet because of structural differences. However, only limited data are available for northern Tibet.

[4] It is also known that the Tibetan Plateau deforms nearly continuously from GPS data [*Zhang et al.*, 2004], however, the faulting makes the deformation appear discontinuous. This may relate to the unique rheological structure of the Tibetan lithosphere. Doubling radiogenic material from a uniformly thickened crust will generate additional heat and steepen the geotherm, thus lowering the strength of the middle and lower crust. Since the depth distribution of earthquakes is a good indicator of the temperature of the crust, we have used the depth distribution of regional earthquakes in northern Tibet to place constraints on the mechanical strength of the crust. In this study we report well-located hypocenters of regional earthquakes from data collected by the INDEPTH-IV seismic array and the PKU Eastern Kunlun array.

2. Data and Methods

[5] Data used in this study were collected from the INDEPTH-IV passive array and the PKU Eastern Kunlun array (Figure 1b). All of these temporary seismic stations are equipped with broadband seismometers and were recorded with a sampling rate of 25 sps. The average spacing between stations is about 100 km, although in some areas the stations were more or less sparsely distributed. The INDEPTH-IV array, consisting of 98 PASSCAL stations, is divided into two sub-arrays. The large sub-array consisting of 57 stations (shown as red diamonds in Figure 1b) was deployed for more

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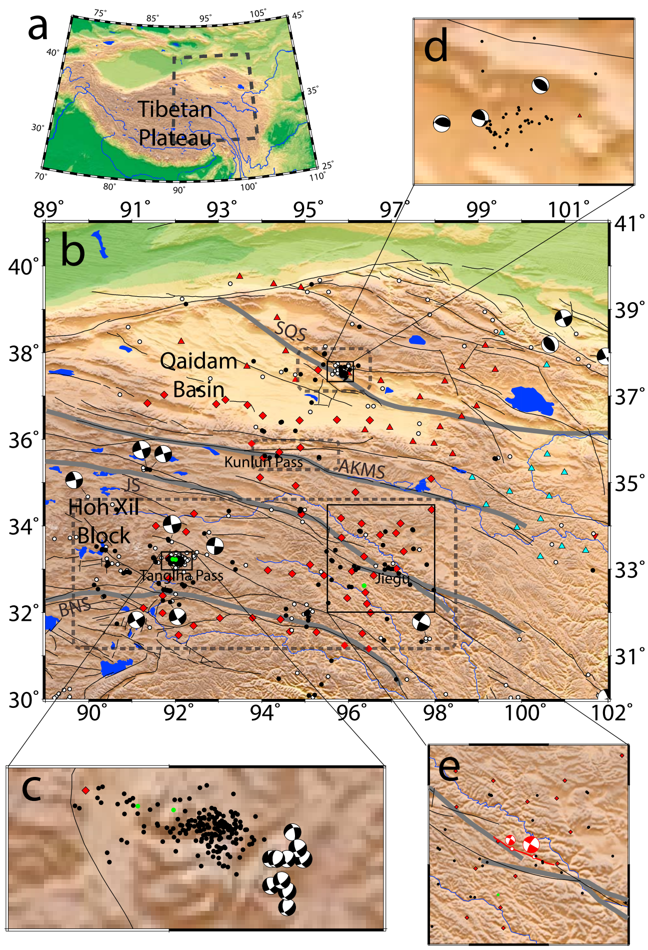

Figure 1. (a) Topography of the Tibetan Plateau and its adjacent areas. The black dashed rectangle outlines the study area. (b) Locations of the portable seismic stations and the earthquakes (black dots shallower than 25 km and green dots deeper than 25 km) compared to the events in PDE catalog (open dots). Red diamonds represent the INDEPTH-IV stations deployed from May 2007 to June 2009. Red inverse triangles represent the INDEPTH-IV stations deployed from May 2007 to August 2008. Red triangles represent the INDEPTH-IV stations deployed from August 2008 to May 2009. Cyan triangles represent the PKU Eastern Kunlun Array which was operated from August 2008 to May 2009. IYS, Indus-Yalutsangpo Suture; BNS, Bangong-Nujiang Suture; JS, Jinsha Suture; AKMS, Ayimaqin-Kunlun-Muztagh Suture; SQS, Southern Qilian Suture. The gray dashed trapezoids outline three seismic active regions. (c) The earthquake cluster in Tanglha Mountain. (d) The cluster in Qaidam Basin. (e) The Ms 7.1 Yushu earthquake (14 April 2010 local time) and its aftershock (open red dots). All focal mechanisms in Figure 1are provided by the Global CMT catalog.

than two years from May 2007 to June 2009 and stations were distributed in the Qiangtang and Songpan-Ganze terranes, as well as in northernmost Lhasa terrane. A smaller sub-array of 18 stations was deployed at the southwestern edge of the Ordos block and along the northeastern edge of the Tibetan Plateau from May 2007 to August 2008 (only one station is shown as a red inverted triangle in Figure 1b). From August 2008 to May 2009 18 stations were redeployed the Qaidam basin and Qilian Mountains along with 5 PKU stations (shown as red triangles in Figure 1b). The PKU Eastern Kunlun Array was operated from August 2008 to May 2009, consisting of 15 broadband seismic stations (shown as cyan triangles in Figure 1b).

[6] In this study, we used a digital trigger with a signal-to-noise ratio (SNR) larger than 3 to automatically detect local events. Then each of these potential events was checked manually and the P and S phases were picked. These selected events have been located using the program of Hypoinverse-2000 [*Klein*, 2002] to obtain an initial catalog. Some of the events, particularly the clusters, have been relocated by HypoDD [*Waldhauser*, 2001] to achieve a better precision.

[7] We divided our study area into three regions and assigned a 1D velocity model for each of these areas. These areas roughly correspond to the Hoh Xil block, the Qiangtang terrane, and surrounding areas. Velocity models were based on preliminary results of ambient-noise-tomography and the receiver function studies (refer to Table S2 of the auxiliary material).[1]

3. Results

[8] A total of 592 regional earthquakes were located by Hypoinverse-2000. The HypoDD procedure is designed for the relative relocation of close events. We were able to apply this to a subset of 275 events. By combining results we obtained a catalog of 400 earthquakes with horizontal errors less than 10 km and vertical errors less than 5 km (Table S1). Comparison with the Preliminary Determination of Epicenters (PDE) catalog has shown that network has significantly reduced the detection threshold compared with the PDE catalog over the same time period.

[9] In general, the distribution of the epicenters correlates well with the surface geology (Figure 1b). Most of the recorded events do not fall on the major faults but occurred within broad zones. While earthquakes were widely distributed throughout the study area three active regions can be identified (shown as the dashed rectangles in Figure 1b): 1) the central Tibet active zone which contains clusters in the Tanglha Mountains and earthquakes in the eastern Qiangtang and Songpan-Ganze terranes, particularly the destructive Ms = 7.1 Yushu earthquake occurring on 14 April 2010; 2) the Kunlun active zone at Kunlun Pass; 3) the southern Qilian active zone near Da Qaidam at the southern foot of the Qilian Mountains, which had a Ms = 6.3 earthquake in November of 2008. These two large earthquakes occurred entirely within major tectonic blocks on previously unmapped faults. For example, the 14 April 2010 Yushu earthquake (Ms = 7.1, April 14, 2010) took place at ~30 km northwest of Jiegu, the capital of Yushu county, caused significant damage to the city of Jiegu. This left-lateral strike-slip event along with another five smaller events occurred at a fault not well studied (Figure 1e).

[10] The depths of regional earthquakes in the northern Tibetan Plateau are quite uniform with focal depths concentrated at 0-15 km beneath the surface (Figure 2b). The deepest earthquake has a depth of about 30 km. In Qaidam

[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL044800.

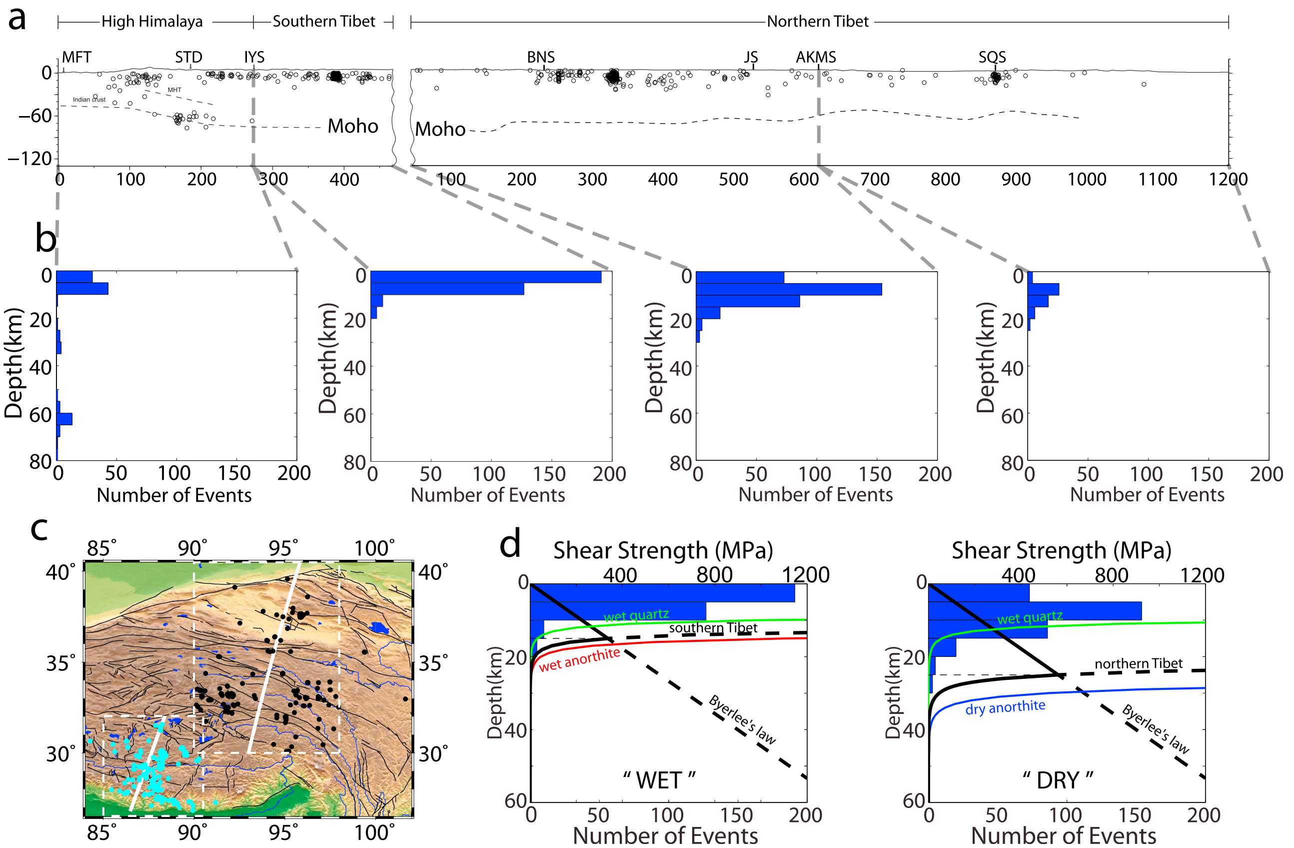

Figure 2. Regional earthquake distributions in this study and those of the Hi-Climb project [*Liang et al.*, 2008]. (a) Cross section of seismicity across (left) the southern Tibet [*Liang et al.*, 2008]) and (right) the northern Tibet. (b) Statistics of the focal depths in the (first panel) Himalayan orogen [*Liang et al.*, 2008], (second panel) the southern Tibet [*Liang et al.*, 2008], and (third and fourth panels) the northern Tibet. (c) Distributions of the events located in this study (black dots) and the events recorded by Hi-CLIMB project (cyan dots). The white lines show the profiles in Figure 2a. The events in the white dashed rectangles are projected to the cross profiles. (d) Statistics of the focal depths and the crustal strength envelope. (left) For southern Tibet, the strength envelope of the wet quartz (the green curve), the wet anorthite (the red curve), the southern Tibetan crust (the black curve), and the Byerlee's Law (the black line) were produced with the thermal gradient of 34 °C/km. (right) For northern Tibet, the strength envelope of the wet quartz (the green curve), the dry anorthite (the blue curve), the northern Tibetan crust (the black curve), and the Byerlee's Law (the black line) were produced with the thermal gradient of 32 °C/km.

basin, the earthquakes are also shallow with most of them residing in the upper 20 km. This is consistent with previous findings [*Chen et al.*, 1999].

[11] We observed clusters of earthquakes in the Tanglha Mountains (Figure 1c) as well as one in Qaidam Basin. During the period of June 2008 to 5 August 2008 seven earthquakes with moment magnitude (Mw) larger than 5.0 occurred very close to each other near the Tanglha Pass along the Tibet highway (Table 1a) with at least 208 aftershocks (included in the 400 events). This includes a Mw = 5.2 event almost two days prior to the June 10, 2008 doublet event of Mw = 5.4. For comparison, the main shock (Mw = 6.3 in Table 1b) of the second cluster at the northeastern margin of the Qaidam Basin was followed by at least 38 aftershocks and no foreshocks (Figure 1d).

4. Discussion

[12] The spatial distribution of the regional earthquakes in northern Tibet is not exclusively concentrated in major fault

Table 1a. Major Earthquakes in Tanglha Mountain From the Global CMT Catalog

Event Name	Date	Initial Time (GMT)	Latitude	Longitude	Mw
200806081756A	08/06/2008	17:56:24.3	33.08°	92.19°	5.2
200806101004A	10/06/2008	10:05:03.8	33.13°	92.25°	5.4
200806101104A	10/06/2008	11:04:18.4	33.04°	92.22°	5.1
200806101415A	10/06/2008	14:15:44.0	33.07°	92.22°	5.3
200806180812A	18/06/2008	08:12:18.2	33.09°	92.21°	5.2
200807162258A	16/07/2008	22:58:24.3	33.15°	92.24°	5.3
200808052159A	05/08/2008	21:59:49.6	33.13°	92.22°	5.0

Table 1b. Major Earthquakes in Qaidam Basin From the Global CMT Catalog

Event Name	Date	Initial Time (GMT)	Latitude	Longitude	Mw
200811100122A	10/2008/11	01:22:10.2	37.51°	95.75°	6.3
200811112156A	11/11/2008	21:56:04.6	37.52°	95.82°	5.1
200811121209A	12/11/2008	12:09:36.3	37.58°	95.93°	4.9

zones but distributed throughout. This seismicity pattern supports the view that deformation of the Tibetan plateau is best explained by continuous deformation as seen in GPS results [*Zhang et al.*, 2004]. All the focal mechanism solutions (from the Global CMT Catalog) show predominant left-lateral strike-slip motion with SE to SEE striking directions and a small amount of normal faulting motion (Figure 1b). Orientation and amount of faulting is consistent with NNE striking normal and orthogonal strike-slip faults mapped in this area [*Wu et al.*, 2005]. These observations imply that the shear strain with a direction of SEE dominates in the eastern part of the Qiangtang terrane.

[13] Intermediate-depth earthquakes beneath the Himalayas and southernmost Tibet have been known since the early 1980s from earthquake source studies [*Chen and Molnar*, 1983]. Based on the waveform modeling a number of intermediate-depth events were confirmed to occur in the mantle-lid beneath the southernmost part of central Tibet [*Zhu and Helmberger*, 1996; *Monsalve et al.*, 2006; *Liang et al.*, 2008]. Seismicity of southernmost Tibet shows two seismogenic zones straddling an aseismic lower crust as an indication of varying mechanical strength of the continental lithosphere (Figure 2). An inverted temperature profile, caused by the under-thrusting of the cold Indian continental lithosphere beneath southern Tibet, may be the main cause of the two-layer seismicity in the lithosphere.

[14] Most of the regional earthquakes recorded by the 2-D Hi-Climb array and by other temporary arrays in southern Tibet occurred in the upper crust, shallower than 25-30 km depth, especially as we move northward [*Langin et al.*, 2003; *Liang et al.*, 2008]. The concentration of shallow earthquakes near the surface in southern Tibet is consistent with the seismic activity associated with east-west extension [*Jin et al.*, 2009]. A mid-crustal low velocity zone in southern Tibet [*Cotte et al.*, 1999; *Rapine et al.*, 2003] prevents the seismicity from extending deeper.

[15] Our results show that the absence of earthquakes in the middle and lower crust effectively extends from southern Tibet to northern Tibet including Qaidam Basin (Figure 2a). This suggests that a hot and weak lower crust also exists beneath northern Tibet and is consistent with observations of inefficient Sn propagation in northern Tibet [*Ni and Barazangi*, 1983].

[16] As shown in Figure 2b the crustal seismogenic zone in northern Tibetan Plateau appears thicker than that in the southern Tibet recorded by the 2-D Hi-CLIMB array [*Langin et al.*, 2003; *Liang et al.*, 2008]. The deepest regional earthquakes could constrain the depth of the brittle/ductile transition. Since the maximum error of the focal depth is 5 km in this study, we estimate the depth of the brittle/ductile transition to be 25 km for northern Tibet and 15 km for southern Tibet, respectively.

[17] We have tested this hypothesis by estimating the shear strength as a function of depth using reasonable geotherms, strain rates, and crustal composition for Tibet [*Bürgmann and Dresen*, 2008]. A strain rate of 1.9×10^{-14} s^{-1} [*Zhang et al.*, 2004] and coefficient of 0.85 for Byerlee's law are used for both southern and northern Tibet. We chose a crustal composition of 67% dry anorthite [*Hacker et al.*, 2000] + 33% wet quartz for northern Tibet and a crustal composition of 67% wet anorthite + 33% wet quartz for southern Tibet to calculate the shear strength envelope. To match the brittle/ductile transition depth of 25 km for northern Tibet and 15 km for southern Tibet, the inverted thermal gradient in northern and southern Tibetan crust are 32 °C/km and 34 °C/km, respectively, which are compatible with previous published results [*Copeland et al.*, 1995; *Mechie et al.*, 2004]. The resulting yield strength envelopes of the crust for northern Tibet and southern Tibet are consistent with the observed focal depth distribution (Figure 2d). We interpret the difference in the depth of the brittle/ductile transition mainly to reflect the different water content in the crust: wet for southern Tibet and dry for central and northern Tibet.

[18] Another significant finding for the depth distribution of seismicity in northern Tibet is that our results did not show any earthquakes in the uppermost mantle. The absence of mantle earthquakes in the Qiangtang and Songpan-Ganze terranes is consistent with the observations of low Pn and Sn velocities, high Sn attenuation [*Ni and Barazangi*, 1983], a low upper mantle velocity anomaly beneath northern Tibet [*Wittlinger et al.*, 1996] and geochemical studies [*McKenna and Walker*, 1990; *Guo et al.*, 2006] which show abundant post-collision Potasic and Ultrapotassic magmatism. The lack of mantle seismicity beneath the Kunlun Mountains suggests that continental subduction is probably not occurring in northern Tibet (East of 90°E).

5. Conclusions

[19] The well-located 400 regional earthquakes in northern Tibetan Plateau were distributed not only at the boundaries of major tectonic provinces but also within these provinces, supporting the hypothesis of continuous deformation within the Tibetan plateau. All well-located earthquakes in northern Tibet occur within the upper crust, mostly at depths of 0-15 km, and there is no event deeper than 30 km. Combining data from previous studies, the depth distribution of regional earthquakes reported in this study strongly supports the existence of a weak and hot lower and middle crust in the northern Tibetan Plateau. Furthermore, the depth of the crustal seismogenic zone in northern Tibetan Plateau is apparently thicker than that in southern Tibet, which reflects the difference in temperature depth profile and rheological structure of the crust between southern and northern Tibet. Finally, there are no mantle earthquakes that would suggest continental subduction along this part of the northern Tibet margin.

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