In any case, the bright spots along the YDR are a strong indication that a fluid, likely magma, is ponding at depths of 15 to 18 km beneath the northern Yadong-Gulu rift. This inference is consistent with the extensional tectonics, abundant geothermal activity, and high heat flow of the region (9), and is supported by other geophysical observations of Project INDEPTH (*10*). The most likely source of magma is partial melting of Tibetan crust induced by crustal thickening (*1*), which would imply that the magma has a granitic composition in contrast to the basaltic intrusions inferred for bright spots in other rift zones worldwide. Non-bright portions of the YDR would presumably represent cooled intrusions. The overall undulatory, discontinuous nature of the YDR suggests either that magmas are intruding along a preexisting structure or that deformation has continued after intrusion of the magmas. If the latter, given the rapid time scale of plutonic cooling, the deformation would have to be very young.

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INDEPTH Wide-Angle Reflection Observation of *P*-Wave-to-*S*-Wave Conversion from Crustal Bright Spots in Tibet

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Three-component wide-angle seismic data acquired in southern Tibet during Project INDEPTH show strong *P*-to-*S* converted reflections from reflectors that are aligned at a depth of ~15 kilometers beneath the northern Yadong-Gulu rift. These converted reflections are locally higher in amplitude than the corresponding *P*-wave reflections. Modeling of reflection mode conversion as a function of incidence angle indicates that this condition obtains for a reflector that is a solid over fluid interface; it is not typical of a solid-solid interface. The likely candidates for a fluid trapped within the crystalline crust of southern Tibet are granitic magma and water (brine).

The wide-angle component of Project INDEPTH acquired three-component seismic data at a range of incidence angles to provide constraints on the composition and structure of the Tibetan crust. We deployed 30 stations equipped with REFTEK digital three-component seismographs for the 5-month duration of the INDEPTH-II CMP experiment [described in (*1*)]. These stations were deployed along, and off the ends of, the CMP profiles in a continuous 400-km-long array [figure 1 in (*2*)] and recorded the INDEPTH explosive sources out to offsets of up to 350 km (*3*). These data provide information on the nature of the crust beneath the region (*4*). Here we report on prominent converted reflections suggestive of intracrustal fluid beneath the northern Yadong-Gulu rift.

INDEPTH CMP profiles show an undulating band of reflections ("YDR" reflections) at a two-way-time (twt) of 5 to 6 s, corresponding to depths of about 15 to 18 km, beneath the northern Yadong-Gulu rift (*1*). The reflection band is extensive for at least 150 km beneath the rift and locally exhibits bright-spot characteristics (extreme amplitude and negative polarity). *P*-wave reflections corresponding to these bright spots are also observed in our vertical-component wide-angle data (P_xP in Fig. 1). However, the highest amplitude reflections recorded in the wide-angle data are not these *P*-wave reflections, but rather, *P*-to-*S*-wave converted reflections from the same reflectors recorded at source-receiver offsets between about 10 and 75 km (most prominent on the horizontal components, P_xS in Fig. 1). Along 5- to 10-km stretches of the reflectors, these P_xS converted reflections have higher amplitudes than the corresponding P_xP reflections. This situation is atypical of crustal reflections and a strong indication of the presence of fluids (5).

Modeling of reflection mode-conversion as a function of incidence angle (6) shows that solid-solid interfaces, which are typical of geologic boundaries in the crust, generally produce *P*-to-*P* reflections that are stronger than associated *P*-to-*S* converted reflections at all incidence angles. In contrast, for a reflector that is a solid-over-fluid interface, *P*-to-*S* reflections are stronger than *P*-to-*P* reflections for incidence angles between about 30° and 60° (5). Fluid in this context refers to a material with zero shear modulus, that is a material that in its bulk properties does not support shear stress on the time scale required for transmission of seismic waves, such as a rock with fluid-filled pores. The minimum fluid-filled porosity needed to reduce the shear modulus of a rock to zero is about 4% (*7*), in the case that the fluid is distributed in thin grain-boundary films or high aspect-ratio cracks. Other pore geometries require a substantially greater minimum fluid fraction (10 to 30%) to drive the effective shear modulus of the material to zero (*7*). This condition implies that the material producing the strong P_xS reflections beneath the Yadong-Gulu rift is either partially molten [that is, contains magma (8)] or has significant water content [for example (9)].

On the premise that the high-amplitude P_xS reflections do result from trapped fluid, we have attempted to map the presence of fluid concentrations between 11- and 25-km depth along the INDEPTH survey by measuring P_xS/P_xP ratios at incidence-angles of 20° to 75° along our profile. Reflections with a high P_xS/P_xP ratio

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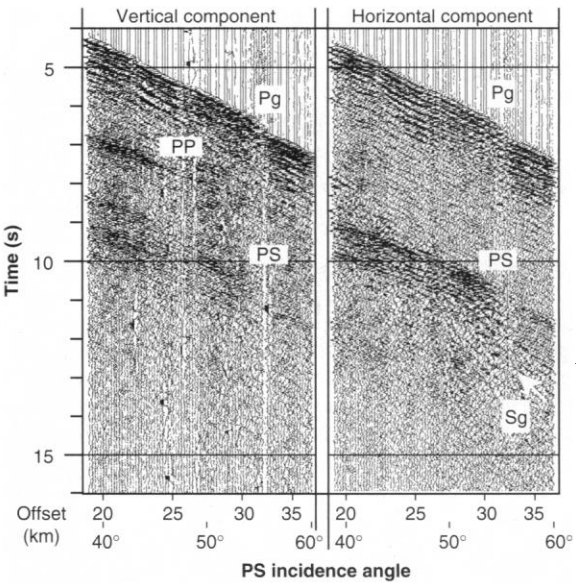

Fig. 1. Vertical- and east-component receiver-gathers of station 7 (located in the northern Yadong-Gulu rift between the CMP profiles TIB-7 and TIB-9 [figure 1 in (2)] recording TIB-9, plotted trace sequentially with true amplitude and no trace-normalization. P_g, direct P wave; S_g, direct S wave. Phases reflected off the bright spots: P_xP, P-to-P reflections [after (8)]; P_xS, P-to-S converted reflections. P_xS amplitude greater than P_xP amplitude suggests the presence of fluids (perhaps melt).

are semi-continuously aligned at 4.5- to 6-s twt (vertical incidence P-to-P reflection time), or between depths of about 13 and 18 km, beneath the northern Yadong-Gulu rift (north of latitude 29°57'N, tops of red areas in Fig. 2). This alignment is in good agreement with the general position of the YDR reflection band imaged on the INDEPTH CMP profiles (*1*), particularly when the asymmetry of the P_xS ray paths is taken into account. South of the Zangbo suture we recognize several additional wide-angle reflection with high P_xS/P_xP ratios corresponding to near-vertical P-wave reflections. These are not as unequivocal as the ones observed beneath the northern Yadong-Gulu rift but may represent a sporadic continuation of fluid in the crust for some distance south of the suture. Specifically, an area with high P_xS/P_xP ratios is observed at latitude 28°50'N (~50 km south of the suture), at 6-s twt (depth of ~17 km), at the same location where a prominent 6-s reflection is observed on the CMP profile (*1*), and where earlier workers measured high heat flow (146 mW/m^2) (*10*). At the scale of the entire traverse, S_g (the direct S-wave) is recorded in our data to >100 km for source-receiver pairs south of the suture, whereas it is not observed beyond 40 km for ray paths to the north. This result implies that Q_s in the upper crust decreases northward in the general vicinity of the suture zone.

Finally, although the shear-wave observations indicate that fluid is accumulating beneath the Yadong-Gulu rift, they do not in and of themselves allow discrimination of the nature of the fluid or its source. If the fluid is meteoric water, then the hydrothermal system, active at the surface (*11*), has to extend to depths of ~15 km over a wide area of the Yadong-Gulu rift, but we know no cause for preferential ponding of meteoric water at a depth of about 15 km. If the water is principally of metamorphic origin, then a large flux from the deep crust would seem to be implied to maintain the fluid reservoirs over the large area that they are observed (*12*). This hypothesis also begs the question of why bright spots and the associated YDR reflection band are not observed beneath the Tethyan Himalaya, where the underthrusting Indian crust must be undergoing prograde metamorphism (and hence presumably dewatering). While necessarily qualitative, these arguments lead us to propose that the fluid responsible for the bright spots is most likely magma or magmatic water (brine) ponding within the crust.

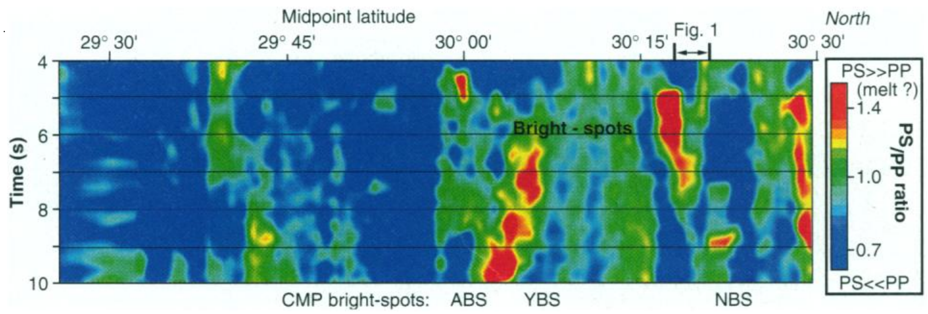

Fig. 2. Amplitude ratio P_xS/P_xP, calculated for data with P-to-S incidence angles of 20° to 75° at 6- to 8-s twt, plotted by the data mid-point latitude (*13*). The tops of high P_xS/P_xP ratio (red) areas map the presence of significant partial fluid concentrations [the continuation of these red areas to later times maps only the coda (amplitude decay) of the P_xS phases and not the continuation of melt to greater depth]. This section shows an alignment of fluid concentrations (melt bodies ?) at about 4.5- to 6-s twt beneath the northern Yadong-Gulu rift and little evidence for the presence of fluids farther to the south.

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13. To obtain this section we used all available data with offsets of 10 to 75 km, thus restricting consideration to data with incidence angles of 20° to 75° at the bright-spot reflector. NMO-velocity measurement and one-dimensional travel-time modeling of the P_xP and P_xS reflections yield an average P-wave velocity of 5.5 ± 0.2 km·s^{-1}, and V_p/V_s ratio of 1.6 ± 0.2, from the surface to the ~15-km depth of the bright spots. On a trace-by-trace basis we calculated the true amplitude envelope of the full wave-field (using the smoothed RMS of the three components) then applied an NMO correction, appropriate either for P_xS or for P_xP, to two copies of each trace using our one-dimensional velocity model. The resulting two traces were ratioed to yield the P_xS/P_xP ratio. The figure is smoothed in time (0.5 s) and space (1.5 km), to compensate for the uncertainty in velocities and in reflection point location, and for the data sparseness.

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