21. W. Zhao and J. Morgan, *Tectonics* **6**, 489 (1987).
22. T. M. Harrison, P. Copeland, W. S. F. Kidd, O. M. Lovera, *Tectonics* **14**, 658 (1995).
23. B. Wernicke, in *Exposed Cross-Sections of the Continental Crust*, M. H. Salisbury and D. M. Fountain, Eds. (Kluwer, Dordrecht, 1990), pp. 509–544.
24. S. Kruse, M. McNutt, J. Phipps-Morgan, L. Royden, *J. Geophy. Res.* **96**, 4435 (1991).
25. P. England, and A. Thompson, *J. Petrol.* **25**, 894 (1984); ______, in *Collision Tectonics* (*Spec. Publ. 19*), M. P. Coward and A. C. Ries, Eds. (Geological Society, London, 1986), pp. 83–94.
26. C. Pinet and C. Jaupart, *Earth Planet. Sci. Lett.* **84**, 87 (1987).
27. L. H. Royden, *J. Geophys. Res.* **98**, 4487 (1993).
28. Although only loosely constrained, restorable cross sections of the the Himalaya (*29*) suggest that roughly 500 km of shortening has occurred south of the Tsangpo suture since the initiation of collision at ~50 million years ago (Ma), implying a mean underthrust rate relative to the Lhasa block of about 1 cm/yr. Thus, lower plate Indian crust that now lies at depth ~220 km north of the of the thrust front, beneath the Kangmar Dome, has likely been descending and warming, for >20 million years—a time span commensurate with that necessary to reach granite minimum melt temperature (*25*).
29. D. Schelling and K. Arita, *Tectonics* **10**, 851 (1991); L. Ratschbacher, W. Frisch, G. Liu, C. Ghen, *J. Geophys. Res.* **99**, 19917 (1994).
30. L. Hollister, *Geology* **108**, 31 (1993).
31. P. LeFort, *Philos. Trans. R. Soc. London Ser. A* **326**, 281 (1988).
32. ______, *Am. J. Sci. Ser. A.* **275**, 1 (1975).
33. R. R. Parrish and K. V. Hodges, *Geol. Soc. Am. Abstr. Progr.* **25**, A174 (1993).
34. M. S. Hubbard and T. M. Harrison, *Tectonics* **8**, 865 (1989); K. V. Hodges *et al.*, *Science* **258**, 1466 (1992).
35. J. W. Tong and M. Zhang, in *Geological and Ecological Studies of the Qinghai-Xizang Plateau*, Liu Dongsheng Ed. (Gordon & Breach, New York, 1981), pp. 841–846.
36. B. Romanowicz, *J. Geophys. Res.* **87**, 6865 (1982); C. Bandon and B. Romanowicz, *ibid.* **91**, 6547 (1986); K. Y. Chun and T. V. McEvilly, *ibid.*, p. 10405.
37. R. J. Owens, G. E. Randall, F. T. Wu, R. S. Zeng, *Bull. Seismol. Soc. Am.* **6**, 305 (1993).
38. L. Zhu, R. Zeng, F. Wu, T. J. Owens, G. R. Randall, *Acta Seismol. Sinica* **6**, 305 (1993); L. Zhao, M. K. Sen, P. Stoffa, C. Frohlich, *Geophys. J. Int.* **125**, 355 (1996).
39. E. Fielding, B. Isacks, M. Barazangi, C. Duncan, *Geology* **22**, 163 (1994).
40. Y. Jin, M. McNutt, Y. Zhu, *Nature* **371**, 669 (1994).
41. J. P. Burg, P. Davy, J. Martinod, *Tectonics* **13**, 474 (1994).
42. S. Turner *et al.*, *Nature* **364**, 50 (1993).
43. A. Yin *et al.*, *J. Geophys. Res.* **99**, 18,175 (1994); Y. Pan and W. S. F. Kidd, *Geology* **20**, 775 (1992); T. M. Harrison, P. Copeland, W. S. F. Kidd, O. M. Lovera, *Tectonics* **14**, 658 (1995); J. P. Burg, *Carte Geologique du Sud du Tibet*, Institut National d'Astronomie et de Geophysique, C.N.R.S, Paris, France, scale 1:500,000 (1983); W. S. F. Kidd *et al.*, *Philos. Trans. R. Soc. London Ser. A* **327**, 287 (1988); A. Gansser, *Geology of the Bhutan Himalaya* (Birkhauser, Basel, 1983), p. 181; A. Yin *et al.*, *J. Geophys. Res.*, **99** 18175 (1994).
44. Project INDEPTH was supported by the Ministry of Geology and Mineral Resources of China, U.S. National Science Foundation Continental Dynamics Program, National Natural Science Foundation of China, and the Deutsche Forschungsgemeinschaft and GeoForschungsZentrum Potsdam (GFZ), Germany. We thank the personnel of the 4th and 5th Geophysical Exploration companies of the Ministry of Geology and Mineral Resources for their efforts on the behalf of Project INDEPTH. Institute for the Study of the Continents Contribution No. 235. Geological Survey of Canada Contribution No. 1996195.

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Bright Spots, Structure, and Magmatism in Southern Tibet from INDEPTH Seismic Reflection Profiling

L. D. Brown, Wenjin Zhao, K. D. Nelson, M. Hauck, D. Alsdorf, A. Ross, M. Cogan, M. Clark, Xianwen Liu, Jinkai Che

INDEPTH seismic reflection profiling shows that the decollement beneath which Indian lithosphere underthrusts the Himalaya extends at least 225 kilometers north of the Himalayan deformation front to a depth of ~50 kilometers. Prominent reflections appear at depths of 15 to 18 kilometers near where the decollement reflector apparently terminates. These reflections extend north of the Zangbo suture to the Damxung graben of the Tibet Plateau. Some of these reflections have locally anomalous amplitudes (bright spots) and coincident negative polarities implying that they are produced by fluids in the crust. The presence of geothermal activity and high heat flow in the regions of these reflections and the tectonic setting suggest that the bright spots mark granitic magmas derived by partial melting of the tectonically thickened crust.

Multichannel seismic reflection data were acquired by Project INDEPTH in 1992 and 1994 by the Fifth and Fourth Geophysical Prospecting Brigades, respectively, of the Ministry of Geology and Mineral Resources of China (MGMR) under the direction of INDEPTH scientists. Restricted to the Yadong-Gulu rift by logistics [figure 1 of (*1*)], the discontinuous survey consists of seven main profiles and four short cross lines, all recorded to 50 s using explosive sources. Lines TIB 1 and 2 were collected in 1992 with a 120-channel DFS V using a geophone group interval of 50 m and analog cables. Lines TIB 3-11 were collected in 1994 with a 240-channel digital telemetry system (Wave 3) and had a 25-m group interval resulting in a common spread length of 6 km. In both cases the nominal seismic source consisted of 50-kg seismic charges in boreholes ~50 m deep and at intervals of 200 m; additional 200-kg charges were set off every 3000 m.

The most prominent feature of the seismic profiles in the Himalaya is a gently north-dipping band of reflections extending from ~8 to 12 s across TIB 1, continuing as a more subtle feature on TIB 3 to about 15 s (Fig. 1). Termed the Main Himalayan thrust (MHT), it is interpreted (*2*) to be the active decollement along which India is underthrusting southern Tibet because: (i) it can be extrapolated updip to coincide with the plane of thrust-type seismicity beneath the south flank of the Himalaya; (ii) its southern end lies at the same depth as the basal decollement beneath the High Himalaya inferred from surface geology in eastern Nepal (*3*); and (iii) it is discordant with overlying dipping reflections attributed to thrust imbrication in the Tethyan Himalaya. The MHT reflection, which dips northward at an average of about 12°, disappears at a depth of about 50 km beneath the north end of TIB 3 (adjacent to the Kangmar dome), some 225 km north of the Himalayan thrust front (Main Frontal Thrust) but still more than 50 km south of the Zangbo suture.

North of the point where the MHT reflection disappears, the seismic sections are dominated by a subhorizontal band of strong reflections at 5 to 6 s, or at a depth of about 15 to 18 km (Fig. 1). Hereafter referenced as the "Yamdrok-Damxung reflector" (YDR), it extends from beneath Yamdrok Tso on TIB 5 to the Damxung graben on TIB 11, a distance of almost 200 km.

The most striking aspect of the YDR is the local occurrence of unusually large amplitudes, or bright spots (Figs. 1 and 2). Amplitudes for the bright spots range from 13 to 22 db above background (Fig. 2) whereas amplitudes for the rest of the YDR generally average about 6 db higher than background.

Although several bright spots are concave in shape (Fig. 1), neither tuning nor focusing are adequate to explain the high amplitudes. Moreover, each of the bright spots corresponds to a negative reflection polarity (Fig. 3), implying that they represent a decrease in seismic velocity or density, or both, at the reflecting interface. In contrast, parts of the YDR that are not near the bright spots exhibit a positive reflection polarity. The most plausible juxtaposition

L. D. Brown, M. Hauck, D. Alsdorf, A. Ross, M. Clark, Institute for the Study of the Continents, Cornell University, Ithaca, NY 14853, USA.
Wenjin Zhao and Xianwen Liu, Chinese Academy of Geological Sciences, Beijing 100037, China.
K. D. Nelson and M. Cogan, Department of Earth Sciences, Syracuse University, Syracuse, NY 13244, USA.
Jinkai Che, Bejing Computing Center, Ministry of Geology and Mineral Resources, Beijing, 100083, China.
* To whom correspondence should be addressed

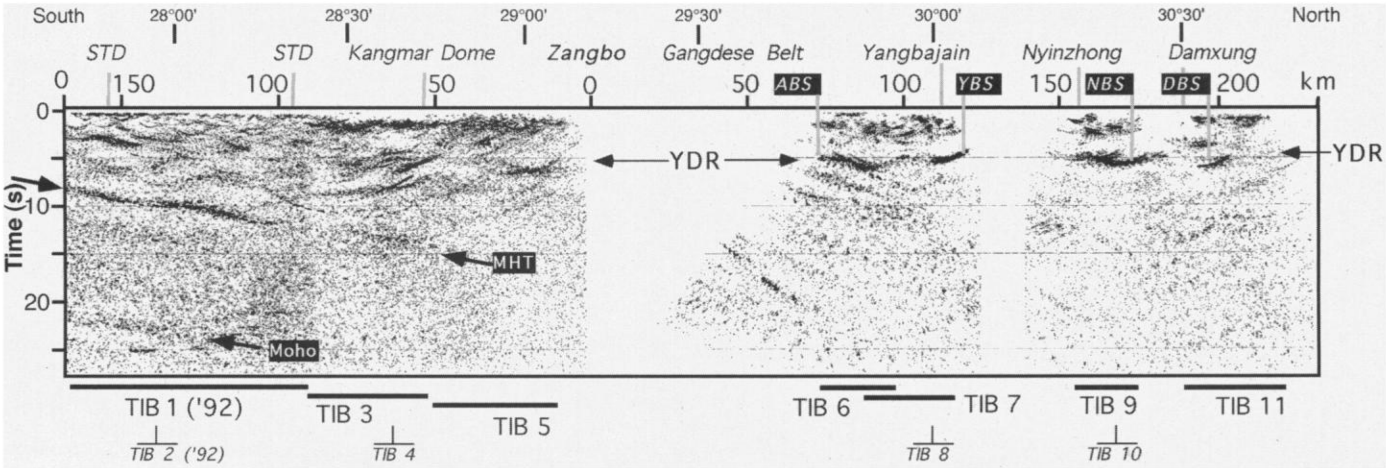

Fig. 1. Composite migrated depth section of reflection profiles collected during INDEPTH I (1992) and II (1994). MHT, Main Himalaya Thrust; STD, South Tibetan Detachment System; YDR, Yamdrok-Damxung Reflection band; ABS, Angang bright spot; YBS, Yangbajain bright spot; NBS, Nyinzhong bright spot; DBS, Damxung bright spot. Note that individual profiles are offset laterally (*1*). Here the profiles were merged after relatively standard common midpoint (CMP) processing, including FX deconvolution and coherency enhancement then migrated at 6 km/s. Sections south of the Zangbo were projected onto a north-south line, the remainder onto a line following the trend of the Nyainqentanglha Mountains.

within metamorphic basement rocks that would generate both a large impedance contrast and a negative reflection coefficient is a boundary between solid and fluid material.

Reflections exhibiting these attributes are relatively rare. Comparable bright spots in sedimentary rocks are frequently associated with hydrocarbon accumulations, particularly gas (*4*). Anomalously strong basement reflections have been observed beneath other active rifts and interpreted as magma. Perhaps the best documented of these is the Soccoro Bright Spot at depths of ~20 km beneath the Rio Grande rift of New Mexico, originally recognized from anomalous shear wave reflections seen on local earthquake seismograms and subsequently mapped by COCORP deep reflection profiles (*5*). Seismic bright spots have been reported in other active rifts (for example, Death Valley, Basin and Range, and the Rhine Graben), as well as certain volcanic areas (the Cascades and Italy). In each case these reflections have been interpreted as an accumulation of fluid, usually magma, at depth (*6*).

High levels of attenuation, as would be expected in association with magma, might explain the relative paucity of deeper reflections on the northernmost INDEPTH profiles. In contrast to the deep Moho reflections recording on TIB 1 (Fig. 1), the only prominent events below the YDR are a series of dipping reflections at the south end of TIB 6 and an isolated, steeply dipping reflector deep beneath the Gangdese batholith. The former could be previously active thrust faults [for example, the Gangdese thrust (*7*)]. Because the latter reflector projects toward the Zangbo suture, it is possible that it represents the suture at depth. If so, it would presumably mark the northernmost incursion of Indian crust beneath the Tibet Plateau. Alternatively it may correspond to one of several lower crustal imbrications inferred from earlier wide-angle seismic experiments (*8*).

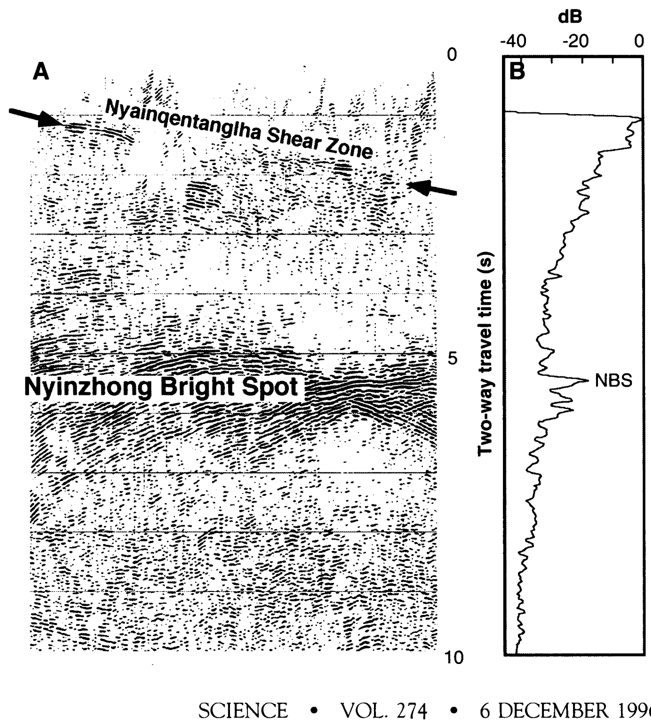

Fig. 2. (**A**) Unmigrated time section with 4-s AGC for TIB 9, showing the Nyinzhong Bright Spot (NBS), one of several bright spots occurring along the YDR horizon. The shallow, north-dipping reflections correspond to the Nyainqentanghla Shear Zone, a low-angle extensional fault exposed in the adjacent Nyainqentanghla Mountains (*11*). (**B**) Amplitude decay curve computed from unprocessed traces showing NBS at 16 dB above background amplitudes.

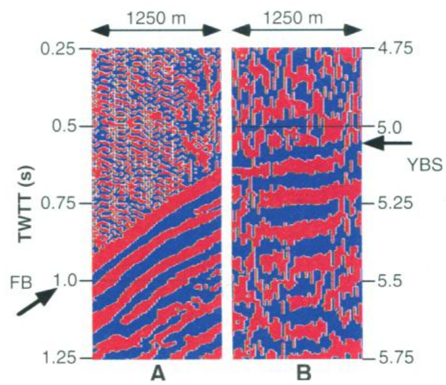

Fig. 3. Sign-bit displays from shot gather 141 on TIB 7. (**A**) Shallow window, showing direct wave (first break, or FB) as red, which for an explosive source should be positive polarity. (**B**) Window across the Yangbajain Bright Spot. Note that the first coherent event is blue, not red, indicating negative polarity. The combination of high amplitude and negative polarity indicates fluids, likely magma at depth. The Yangbajain Bright Spot lies directly beneath the Yangbajain Geothermal Field, which supplies electrical power to the city of Lhasa.

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.

REFERENCES AND NOTES

1. K. D. Nelson *et al.*, *Science* **274**, 1684 (1996).
2. W. Zhao *et al.*, *Nature* **366**, 557, (1993).
3. D. Schelling, and K. Arita, *Tectonics* **10**, 851 (1991).
4. R. E. Sheriff, *Geophys. Prospect.* **23**, 125 (1975).
5. A. R. Sanford *et al.*, *Am. Geophys. Union Monogr. Ser.* **20**, 385 (1977); B. deVoogd, L. D. Serpa, L. D. Brown, *Geol. Soc. Am. Bull.* **100**, 1550 (1988).
6. B. deVoogd, L. D. Serpa, L. D. Brown, *Geol. Soc. Am. Bull.* **100**, 1550 (1988). E. Luschen *et al.*, *J. Geophys.*, **62**, (1987). C. Jarchow, G. A. Thompson, R. D. Catchings, W. D. Mooney, *J. Geophys. Res.* **98**, 22095, (1993). P. T. C. Hammer and R. M. Clowes, *ibid.* **101**, 20119 (1996). F. Batini, G. Bertini, G. Gianelli, E. Pandeli, M. Puxeddu, *Mem. Soc. Geol. Ital.* **5**, 219 (1983).
7. A. Yin *et al.*, *J. Geophys. Res.* **99**, 18175 (1994).
8. A. Hirn *et al.*, *Nature* **307**, 23 (1984).
9. R. P. Armijo *et al.*, *J. Geophys. Res.* **91**, 13803, (1986); M. P. Hochstein and Z. Yang, *Terrestrial Heat Flow and Geothermal Energy in Asia* (Oxford Univ. Press, New Delhi, 1995), p. 331; Francheteau *et al.*, *Nature* **307**, 32 (1984).
10. Y. Makovsky *et al.*, *Science* **274**, 1690 (1996); Chen Leshou *et al.*, *ibid.*, p. 1694; R. Kind *et al.*, *ibid.*, p. 1692.
11. Y. Pan and W. S. F. Kidd, *Geology* **20**, 775 (1992).

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

Yizhaq Makovsky*, Simon L. Klemperer, Lothar Ratschbacher, Larry D. Brown, Ming Li, Wenjin Zhao, Fanle Meng

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

Y. Makovsky, S. L. Klemperer, L. Ratschbacher, Department of Geophysics, Stanford University, CA 94305–2215, USA.
L. D. Brown, Department of Geological Sciences, Cornell University, Ithaca, NY 14853, USA.
Ming Li, Wenjin Zhao, and Fanle Meng, Chinese Academy of Geological Sciences, Baiwanzhuang Road 26, Beijing 100037, China.
*To whom correspondence should be addressed.