# Partially Molten Middle Crust Beneath Southern Tibet: Synthesis of Project INDEPTH Results

K. D. Nelson,* Wenjin Zhao, L. D. Brown, J. Kuo, Jinkai Che, Xianwen Liu, S. L. Klemperer, Y. Makovsky, R. Meissner, J. Mechie, R. Kind, F. Wenzel, J. Ni, J. Nabelek, Chen Leshou, Handong Tan, Wenbo Wei, A. G. Jones, J. Booker, M. Unsworth, W. S. F. Kidd, M. Hauck, D. Alsdorf, A. Ross, M. Cogan, Changde Wu, E. Sandvol, M. Edwards

INDEPTH geophysical and geological observations imply that a partially molten mid-crustal layer exists beneath southern Tibet. This partially molten layer has been produced by crustal thickening and behaves as a fluid on the time scale of Himalayan deformation. It is confined on the south by the structurally imbricated Indian crust underlying the Tethyan and High Himalaya and is underlain, apparently, by a stiff Indian mantle lid. The results suggest that during Neogene time the underthrusting Indian crust has acted as a plunger, displacing the molten middle crust to the north while at the same time contributing to this layer by melting and ductile flow. Viewed broadly, the Neogene evolution of the Himalaya is essentially a record of the southward extrusion of the partially molten middle crust underlying southern Tibet.

The Himalaya and adjacent Tibetan Plateau play a central role in the study of collisional orogens. It is generally assumed that the tectonic processes at work in this active continent-continent collision zone similarly shaped older collisional orogens and, to a significant degree, the continents as a whole. Despite the attention given to the region in recent years, little consensus has developed with regard to the mechanical evolution of the Plateau lithosphere since the onset of collision about 50 million years ago (*1*). In the hope of advancing knowledge of the geologic structure of this region, Project INDEPTH (*2*) recently undertook geophysical and geological investigations in southern Tibet (Fig. 1). INDEPTH is a collaborative geoscience project between the Chinese Academy of Geological Sciences and investigators from U.S., German, and Canadian geoscience institutions. The project builds on the efforts of previous Sino-French, Sino-British, and Sino-U.S. collaborative efforts in Tibet (*3*). INDEPTH collected a pilot near-vertical incidence common-midpoint (CMP) reflection profile and companion wide-angle reflection data in southern Tibet during the summer of 1992 (*4, 5*). During the summers of 1994 and 1995 a larger program involving the acquisition of CMP reflection, wide-angle reflection, broadband earthquake, magnetotelluric and surface geological data was undertaken (INDEPTH II) [see companion reports in this issue (*6–9*)]. The INDEPTH transect is ~300 km long and extends from the crest of the Himalaya (~27°43′N, 89°09′E) to roughly the center of the Lhasa block (~30°35′N, 91°25′E). Most of the data were acquired in the Yadong-Gulu rift, which is the largest of a set of roughly north-south trending Neogene to Quaternary rifts that extend across the Himalaya and southern Tibetan Plateau. The flat floors of the half-graben and graben valleys that form the rift provided a logistically feasible though discontinuous route for geophysical work in the otherwise mountainous terrain of southern Tibet. The Yadong-Gulu and its sister rifts are accommodating ongoing east-west extension of the Tibet Plateau (*10*).

The thickness of the crust beneath Tibet is roughly twice that of normal continental crust (*4, 8, 11*). Beneath the southern part of the survey this anomalously thick crust is composed largely of the structurally imbricated, pre-Eocene, passive continental margin of northern India; beneath the northern part, at least in the upper crust, it is composed of the Gangdese batholith and Lhasa block, which formed the southern active continental margin of Asia prior to the collision (*12*). The boundary between the two is the Zangbo suture zone, which crops out approximately in the middle of the survey, coincident with the Yarlung-Zangbo River valley. Crustal thickening south of the suture is the result of convergence during the collision between India and Asia (*12*). Recent observations suggest that the Lhasa block crust may have been substantially thickened before the collision while it was part of the southern active margin of Asia (*13*). In the early 1970s, Dewey and Burke hypothesized that a midcrustal zone of intrusion exists beneath the Tibetan Plateau, largely on the basis of analogy with older, more deeply eroded, mountain belts (*14*). Subsequently geophysical investigations undertaken during the early 1980s hinted that such a layer might actually exist beneath at least southern Tibet. These surveys demonstrated that heat flow is locally extreme, consistent with the existence of molten granite at a depth of 10 to 20 km beneath Yamdrok Tso (Fig. 1) (*15*), and identified an electrically conductive layer within the crust north of the Zangbo suture (*16*).

These observations are supported and extended by the INDEPTH results. The new CMP reflection profiles reveal a set of reflections constituting a prominent, undulatory, reflection horizon at depths of 15 to 20 km. These reflections extend from just north of the Tsangpo suture to the north end of the INDEPTH survey ("1" in Fig. 2) (*6*). This reflection band locally exhibits anomalously high amplitude and negative polarity (*6*), and at wide-angle, a strong *P*-to-*S* conversion (*7*)—properties suggesting the local occurrence of fluids along the reflecting horizon. Receiver function analyses of INDEPTH teleseismic data show that a marked low-velocity zone lies within the crust beneath the northern half of the INDEPTH survey, the top of which broadly coincides with the reflection band at depths of 15 to 20 km (Fig. 2, top) (*8*). The low-velocity zone extends southward in the subsurface at least to the outcrop position of the Zangbo suture, south of which it appears to die out. The new MT results indicate that anomalously electrically conductive crust exists at depth beneath the entire northern two-thirds of the INDEPTH survey (north of the Kangmar dome), beginning at a depth of a few tens of kilometers,

K. D. Nelson, M. Cogan, C. Wu, Department of Earth Sciences, Syracuse University, Syracuse, NY 13244, USA.
W. Zhao, J. Che, X. Liu, Chinese Academy of Geological Sciences, Beijing 100037, China.
L. D. Brown, M. Hauck, D. Alsdorf, A. Ross, Institute for the Study of the Continents, Cornell University, Ithaca, NY 14853, USA.
J. Kuo, Lamont Doherty Geological Observatory, Palisades, NY, 10964, USA.
S. L. Klemperer and Y. Makovsky, Department of Geophysics, Stanford University, Stanford, CA 94305, USA.
R. Meissner, Institut für Geophysik, Christian-Albrechts-Universitaet zu Kiel, 24098 Kiel, Germany.
J. Mechie and R. Kind, GeoForschungsZentrum Potsdam (GFZ), 14473 Potsdam, Germany.
F. Wenzel, Geophysikalisches Institut, Universitaet Karlsruhe, 76187 Karlsruhe, Germany.
J. Ni and E. Sandvol, Department of Physics, New Mexico State University, Las Cruces, NM 88003, USA.
J. Nabelek, College of Oceanography, Oregon State University, Corvallis, OR 97331, USA.
L. Chen, H. Tan, W. Wei, China University of Geosciences, Beijing, China.
A. G. Jones, Geological Survey of Canada, 1 Observatory Crescent, Ottawa, Ontario, Canada.
J. Booker and M. Unsworth, Geophysics Program, University of Washington, Seattle, WA 98195, USA.
W. S. F. Kidd and M. Edwards, Department of Geosciences, SUNY-Albany, Albany, NY 12222, USA

* To whom correspondence should be addressed.

and that a highly electrically conductive body coincides with the horizon at depths of 15 to 20 km imaged on the CMP profiles beneath the northern Yadong-Gulu rift (Damxung graben) (*9*). Additionally, the MT data indicate that the highly electrically conductive crust extends outside the northern Yadong-Gulu rift, both to the northwest and southeast. Taken together, these observations imply that the reflection horizon at depths of 15 to 20 km imaged on the CMP profiles marks the top of a midcrustal partial melt layer underlying the northern part of the INDEPTH survey. The local occurrence of bright spots exhibiting negative reflection polarity and strong *P*-to-*S* conversion along this horizon suggests that locally it also marks the top of actual magma accumulations.

Currently it is not possible to trace the top of this inferred partial melt layer unequivocally south of the Zangbo suture, because of a gap in the CMP coverage across the Zangbo River gorge and the sparseness of the broadband coverage. However, several observations suggest that the layer does extend somewhat to the south, roughly to the north limb of the Kangmar Dome (Fig. 1): (i) Heat flow measured south of the suture in Yamdrok Tso (latitude 29°N) is high (average 146 mW/m$^2$) (*15*). (ii) At this location the CMP data exhibit a prominent subhorizontal reflection at a depth of ~18 km, similar in appearance and depth to the bright reflections imaged north of the suture (*6*). (iii) The MT data indicate that highly electrically conductive middle crust, beginning at a depth of a few tens of kilometers, extends without apparent break beneath the suture, as far south as the Kangmar dome (*9*); and (iv) the wide-angle data show that reflections exhibiting strong *P*-to-*S* conversion in the upper crust extend sporadically ~50 km south of the suture (~28°50′N) (*7*). We therefore infer that the partial melt layer extends southward in the subsurface, albeit probably dying away, to roughly the north limb of the Kangmar dome.

The INDEPTH CMP profiles exhibit relatively few reflections from the crust beneath the prominent 15- to 20-km-deep horizon described above, with the notable exception of a steeply north-dipping reflection originating in the deep crust beneath the Gangdese batholith ("2" in Fig. 2) (*6*). In contrast, to the south, where the 15- to 20-km-deep horizon is not observed, the crust is richly reflective down to, at least locally, the Moho at the base of the ~75-km-thick crust underlying the Tethyan Himalaya ("3" in Fig. 2). As there is no obvious change in the near surface conditions or data acquisition parameters coincident with this north-south variation, it likely results from northward-decreasing crustal *Q* associated with the development of the midcrustal partial melt layer. The observation that $S_g$ is a clear arrival in the INDEPTH wide-angle data for travel paths in the southern part of the survey, whereas it is absent beyond about 40 km for travel paths in the northern part of the survey (*7*) is broadly supportive of this interpretation. The reflectivity in the south provides information on the geometry of crustal structures underlying the Tethyan Himalaya.

The most prominent feature visible on the southern part of the CMP traverse is the Main Himalayan thrust (MHT)—the thrust fault along which India is currently underthrusting southern Tibet ("4" in Fig. 2) (*6*). This fault is traceable as a discrete gently north-dipping reflection to ~28°45′N, where it disappears beneath the Kangmar dome. South-dipping reflections observed beneath the south limb of the Kangmar dome indicate that it is the surface expression of a basement-cored antiform in the hanging wall of the MHT. The observed across-strike extent and reflection character of the MHT are strikingly similar to those of basal thrust decollement observed on reflection profiles in fossil collisional orogens such as the southern Appalachians, with the obvious exception that the depth to the decollement at equivalent positions in these older belts is considerably less.

It is unknown whether the disappearance of the MHT reflection beneath the Kangmar dome results from northward steepening of the MHT at this location (a ramp), a northward decrease in reflectivity of the MHT zone (due to widening of the ductile shear zone with depth), or northward decreasing signal penetration. The midcrustal zone of high electrical conductivity observed beneath the northern two-thirds of the INDEPTH survey has a north-dipping tongue that projects upward beneath the north flank of the Kangmar dome (*9*). The observation suggests that partially molten midcrustal material approaches the surface beneath the north limb of the dome. Taken together, the observations suggest that the midcrustal partial melt layer dies out southward in the subsurface between the suture and Kangmar dome.

The Moho is only locally observed on the INDEPTH CMP profiles near the southern end of the transect, where it occurs at a depth of ~75 km (*4, 6*). To the north, its position beneath the survey is constrained by receiver function determinations from the broadband earthquake data (*8*). These indicate that the Moho lies between depths of about 70 and 80 km along the length of the survey, implying that the crust-mantle boundary is essentially flat beneath the region. The spacing of the broadband stations, however, is such that one or more Moho imbrications, of the scale suggested to occur beneath southern Tibet on the basis of earlier fan profiling experiments (~10 to 15 km throw) (*11*), cannot be ruled out. Indeed, some kind of north-dipping structure or structures do appear to be developed in the lower crust or uppermost

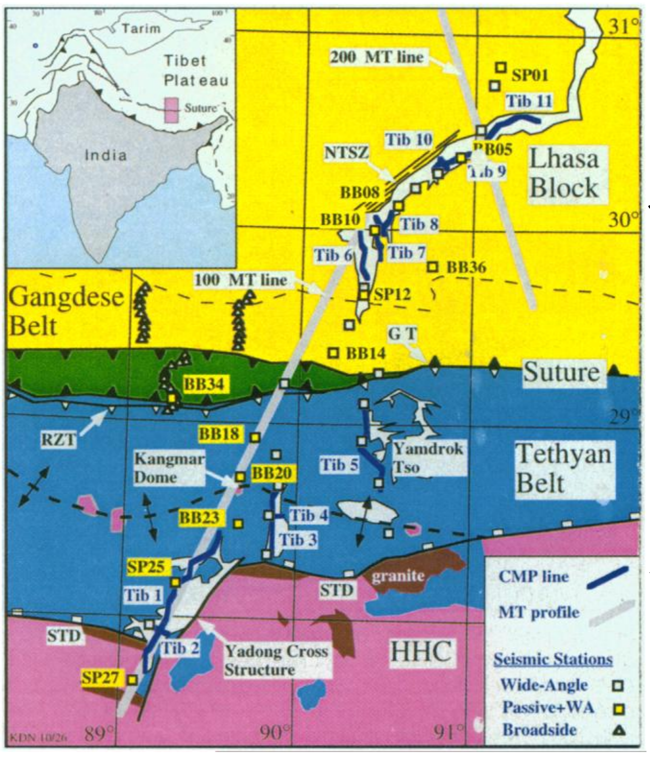


**Fig. 1.** Generalized geologic map of the INDEPTH transect region showing locations of INDEPTH controlled-source seismic, earthquake, and magnetotelluric recording programs. "CMP line," near-vertical incidence common midpoint reflection profile. "MT profile," approximate line of magnetotelluric recording stations; "Seismic stations," temporary seismic stations (REFTEKs) established for wide-angle recording of CMP shots ("Wide-Angle" and "Broadside") and broadband earthquake recording ("Passive"). The geologic base map is generalized from published sources (*20, 43*) and local geological observations made by INDEPTH personnel. HHC, High Himalayan crystallines; STD, South Tibetan detachment system; RZT, Renbu-Zedong thrust; GT, Gangdese thrust; NTSZ, Nyainqentanglha shear zone.

mantle beneath the region. This inference is based on the regionally coincident observations of dipping reflections on fan profiles (*11*), the north-dipping lower crustal reflection observed beneath the Gangdese batholith on the INDEPTH CMP profile ("2" in Fig. 2), and the observation that teleseismic waves emerging from the north beneath the INDEPTH survey exhibit clear mode conversion near the Moho, whereas those emerging from the south do not (*17*). Although the interpretation of these seismologically defined fabrics is problematic, they apparently do not represent a break (or breaks) in the modern Indian lithosphere, as flexural analysis of topographic and gravity data imply that the Indian lithosphere extends as a mechanically continuous unit (supports a bending stress) to a point north of the INDEPTH survey (*18*). This inference is also consistent with seismological results that indicate that relatively fast (cool) upper mantle extends from northern India to roughly the center of the Tibetan Plateau (*19*).

In view of both the crust and mantle observations, it appears that, as the Indian lithosphere underthrusts southern Tibet, its attached crust warms and partially melts, thereby contributing to a partially molten midcrustal layer that underlies the northern part of the INDEPTH survey. The thickness of the partial melt layer is not yet known. The fast upper mantle, and lack of Neogene to recent mafic volcanism in the region imply that the warming results from crustal thickening, not intrusion of mantle-derived melts into the crust. Kinematically, the partially molten middle crust is apparently being added to the trailing (down-dip) end of the High Himalayan Crystalline thrust sheet (HHC), which surface geological observations indicate is being displaced upward and southward relative to the underthrusting Indian plate (*21*). This is essentially the mechanical behavior hypothesized by Zhao and Morgan in 1987 (*20*), with the caveat that the protolith for the partial melt layer may well become Asian (Lhasa block crust) toward the north. From a mechanical perspective, this distinction is probably unimportant. The southern limit of the partial-melt layer, which presumably is a dynamically maintained melt front, apparently intersects the downgoing Indian crust between the Kangmar dome and Zangbo suture, some 220 to 270 km north of the Himalayan thrust front (MFT tip). The top of the layer probably coincides regionally with the wet granite solidus, consistent with the elevated heat flow in the region. In detail this boundary may be a complex, continuously evolving zone of granite intrusions at the top of the layer.

In accord with Zhao and Morgan's hypothesis (*20*), it also appears that the partial melt layer acts as a fluid decoupling layer on the time scale of Himalayan deformation (strain rates of $10^{-15}$ per second). Thermochronologic data (*22*), together with INDEPTH field geological and CMP crossline data, indicate that the footwall of the northern Yadong-Gulu rift (Nyainqentanglha range) has undergone pronounced uplift (~15 km) and rotation during the Late Miocene to Recent opening of the rift, without the development of a correspondingly deep graben. As with the extensional

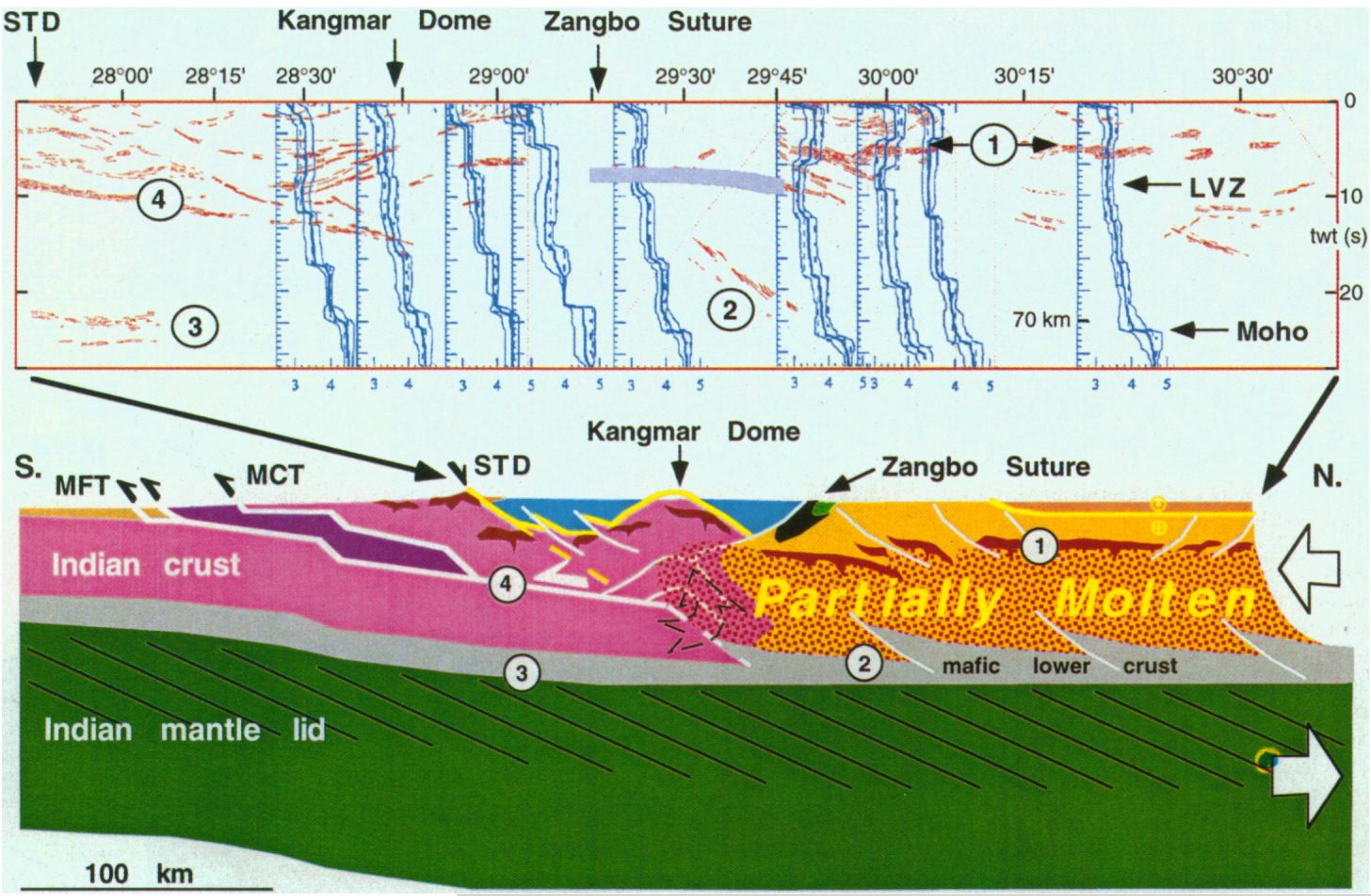


**Fig. 2. (Top)** Composite of selected INDEPTH geophysical observations along the Yadong-Gulu rift in southern Tibet; red, composite north-south CMP profile described in (*6*); blue, one-dimensional shear-wave velocity profiles derived from broadband earthquake data (*7*); blue stipple, wide-angle reflection observed in CMP data gap beneath and just north of the Zangbo suture; LVZ, midcrustal low-velocity zone evident in shear-wave velocity profiles north of the Zangbo suture. **(Bottom)** Interpretive lithosphere-scale cross-section of the Himalayan collision zone (see text). MFT, Main Frontal thrust; MCT, Main Central thrust; STD, South Tibetan detachment system. Numbers refer to features discussed in text.

core complexes of western North America, this geometry essentially requires that the middle crust has flowed laterally to accommodate the opening of the rift [as described in (*23, 24*)]. Presumably, it is also flowing to accommodate the northern impingement of the Indian lithosphere.

The existence of a midcrustal partial melt layer beneath southern Tibet, while not demonstrable a priori by thermal modeling, is plausible in light of such modeling. Doubling the thickness of a generic granitoid continental crust, having global average continental heat production, overlying mantle with global average mantle heat flux, will result in the interior of the thickened crust warming to a temperature sufficient to produce partial melting in the presence of water (~600°C) after a few tens of millions of years (*25*). If the crust has higher than normal concentration of heat producing radioactive elements, such as has been found in the exposed HHC (*26*), then higher temperatures can be obtained. Denudation resulting from erosion or normal faulting, both of which have occurred during the Neogene to Recent evolution of the Himalaya, similarly act to raise temperatures within the crust further (*27*). Thus in southern Tibet, where collision has been in progress for 40 to 50 million years (*12*) and where the middle and lower crust of the Gangdese magmatic arc was presumably molten at the onset of collision, the existence of a midcrustal partial melt zone is likely (*28*).

This picture has a number of implications for the structural evolution of the Himalaya. Geometrically, the HHC can be viewed as an ongoing extrusion of the fluid middle crust. In this view the exposed crystalline rocks of the High Himalaya and North Himalayan domes represent progressively younger, frozen, snapshots of the partially molten midcrustal layer lying at depth to the north. The HHC, which is up to several tens of kilometers thick and contains widespread poly-deformed migmatitic gneisses that exhibit evidence for large-magnitude strain in the presence of melt (*30*) and high-level cross-cutting plutons (*31*), is likely a frozen facsimile of the partially molten middle crust currently existing at depth north of the Kangmar dome. This interpretation accords with the now widely held view of LeFort (*31, 32*) that generation of the Late Oligocene–Early Miocene High Himalayan granites was genetically linked to movement on the MCT. However, in contrast, the geometric evolution described above suggests that initial detachment of the HHC from the underthrusting Indian plate (initiation of MCT) was probably caused by melting in the downgoing Indian crust, rather than being the consequence of it. Geochronological data indicating that the High Himalayan granites intruded at ~20 to 22 Ma (*33*), contemporaneous with ductile movement on the MCT (*34*), would then suggest that melting within the HHC, and its consequent detachment from the underthrusting Indian plate, initiated somewhat before ~20 Ma. Essentially synchronous initiation of the South Tibetan detachment system, resulting from ramping of the HHC (development of a topographic front) combined with weakening of its top due to granite intrusion, follows from this scenario.

While the geologic evolution outlined above implies that a midcrustal partial melt zone is regionally developed beneath southern Tibet, INDEPTH data only constrain such a layer to exist in the vicinity of the northern Yadong-Gulu rift. Determining the regional extent of the layer is of considerable interest. Existing data are permissive of and arguably imply that partial melt is widely developed within the Tibetan Plateau crust. As noted above, the INDEPTH MT results suggest that the partial melt zone extends at least a few tens of kilometers in the subsurface outside the northern Yadong-Gulu rift. Hot springs, suggestive of elevated heat flow, are a ubiquitous feature of the southern Tibetan Plateau (*35*). It has been recognized for some time that seismic wave propagation velocities are generally low within the Plateau crust compared to continental crust worldwide (*36–38*). Receiver function analysis of broadband earthquake data acquired in a transect across the Plateau, indicate that the middle and in some places upper crust exhibits low shear wave velocity (<3.5 km/s) across the Plateau, and that the mean crustal velocity in general is low (*38*). In some areas midcrustal low velocity zones are apparent from modeling these data (stations AMDO, BUDO, TUNL), whereas in others they are not. Notably, where low-velocity zones have been recognized, they are manifest not by an obvious decrease in midcrustal velocity relative to Plateau stations that do not exhibit a low-velocity zone, but rather by the local occurrence of somewhat higher velocity upper crustal material above. Stations SANG and LSA, which are in the general vicinity of the INDEPTH survey but outside the Yadong-Gulu rift, are examples. These stations do not exhibit distinct low-velocity zones but do show that the crust from the near surface to depths of 40 and 50 km has a markedly low shear velocity (3.2 and 3.2 to 3.5 km/s, respectively, for the two stations)—in both cases with no discernible positive velocity gradient (*38*). A reasonable interpretation of these observations is that partial melt is widely developed within the middle crust of the Tibetan Plateau and that where distinct low-velocity zones occur the proportion of partial melt is locally high or the upper crustal rocks locally have somewhat higher velocity than in adjacent regions.

A regionally developed, weak, midcrustal partial melt layer would also provide a simple explanation for the essential flatness of the Tibetan Plateau (*39*), spatial relationship between gravity and topography on the Plateau (*40*), and results of analog buckling studies (*41*), all of which imply that the upper crust of the Tibetan Plateau is regionally decoupled from the lower crust and mantle lithosphere below. Given that the crust underlying the entire Plateau is anomalously thick, such a layer conceivably could have developed through crustal thickening alone (as outlined above). Within the northern Plateau, where Neogene alkalic volcanic rocks are widespread (*42*) and seismological evidence implies that the upper mantle is hot (*19*), advection of heat into the crust by intrusion of mantle-derived magmas is likely to have contributed to the formation and maintenance of such a layer.

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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