Seismology Across the Northeastern Edge of the Tibetan Plateau

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On 12 May, a great earthquake (*Ms* = 8.0) on the Longmenshan thrust fault rumbled through China's Sichuan province, killing more than 69,000 people and injuring 374,000. The Longmenshan thrust is part of the eastern border of the Tibetan Plateau, but it is not the plateau's only restless margin. An even larger earthquake (*Ms* = 8.1) on the Kunlun fault shook northeastern Tibet in 2001, fortunately in a sparsely populated area. These massive quakes underscore the importance of understanding the tectonic response of Asia to collision by India.

The International Deep Profiling of Tibet and the Himalaya (INDEPTH) program explores the dynamics of the India-Asia collision. Though many past geophysical studies have focused on the Himalayas and the southern Tibetan Plateau, the INDEPTH IV project examines the deep structure of the northeastern margin of the Tibetan Plateau.

Understanding this margin—distinguishing the relative roles of factors that compensate for compression, such as lateral terrane escape along lithospheric strike-slip faults, intracontinental subduction, and ductile crustal flow—is tricky. To learn more, scientists working on INDEPTH IV have used a wide range of geophysical techniques to image the deep structure of this seismically active area.

INDEPTH IV Project: Geologic Setting

Prior to about 57 million years ago, the Indian subcontinent lay far south of the Asian continent, separated from it by major ocean basins and intervening terranes. Continental drift closed these oceans and caused intervening landmasses to be accreted onto Asia as the oceans closed.

To study these collisions, INDEPTH projects I, II, and III have collected seismic, magnetotelluric, and geologic data in phases along a roughly north-south transect from the Himalayas to northern Tibet (Figure 1a) since 1992. Designed to probe the collision zone's deep structure and test uplift models, these surveys discovered crustal fluids in the southern Tibetan Plateau [e.g., *Nelson et al.,* 1996], examined boundaries (known as sutures) where geologically distinct terranes have converged, and measured reflections [see *Zhao et al.,* 1993] from one of the deepest locations of the Mohorovičić discontinuity (Moho; the boundary between the crust and the mantle).

By extending the INDEPTH transect across the northeastern margin of the Tibetan Plateau, INDEPTH IV will test models of relict and current subduction at the two prominent suture zones in the northern Tibetan Plateau: the roughly 190-million-year-old Kunlun suture and the roughly 210-million-year-old Jinsha suture [*Yin and Harrison,* 2000] (see Figure 1b). Previous studies have described pronounced offsets to the Moho under these sutures [e.g., *Wittlinger et al.,* 1996], possibly indicating coupling between upper and lower crustal deformation.

The active left-lateral, strike-slip Kunlun fault, which follows about 1500 kilometers of the eastern portion of the Kunlun suture, has produced five earthquakes with magnitudes greater than 7.0 in the past century, most recently a magnitude 8.1 quake in 2001. The fault splits into two branches in the east (the North Kunlun fault and the South Kunlun fault (SKF); see Figure 1b), and slip at the eastern tip of the SKF may be accommodated by the Longmenshan fault, site of the 12 May Sichuan earthquake. INDEPTH IV's transect crosses both branches and the Songpan-Ganze terrane, which lies between them.

Field studies for INDEPTH IV commenced in summer 2007 through the acquisition of a controlled-source seismic profile, deployment of broadband seismometers, and preliminary geologic mapping. The challenges of fieldwork in this remote area included the near loss of 1000 short-period seismographs in a multiple-fatality truck wreck during shipping, unexpected military restrictions on access to portions of our array, and midsummer snowstorms in the mountains and sandstorms in the desert.

Active Seismic Experiments

The INDEPTH IV active source seismic experiment spanned 270 kilometers from the Qaidam Basin, across the North Kunlun thrusts and the Kunlun Mountains, into northern Tibet (Figure 1b). The recording spread consisted of four elements: (1) a wide-angle deployment of 295 Incorporated Research Institutions for Seismology (IRIS) PASSCAL Texan seismometers at 650-meter spacing, (2) a deployment of 655 Texan seismometers at 100-meter spacing for near-vertical incidence reflection recording, (3) an adjacent deployment of a 1000-channel Sercel cabled spread with 50-meter geophone spacing, and (4) an overlapping three-component (3C) array (48 Geophysical Instrument Pool Potsdam and SEIS-UK short-period and broadband instruments at 5- to 6-kilometer spacing).

Sources included five large shots (KS1 to KS5) roughly evenly spaced along the profile (each containing 1000–2000 kilograms of seismic explosives) augmented by

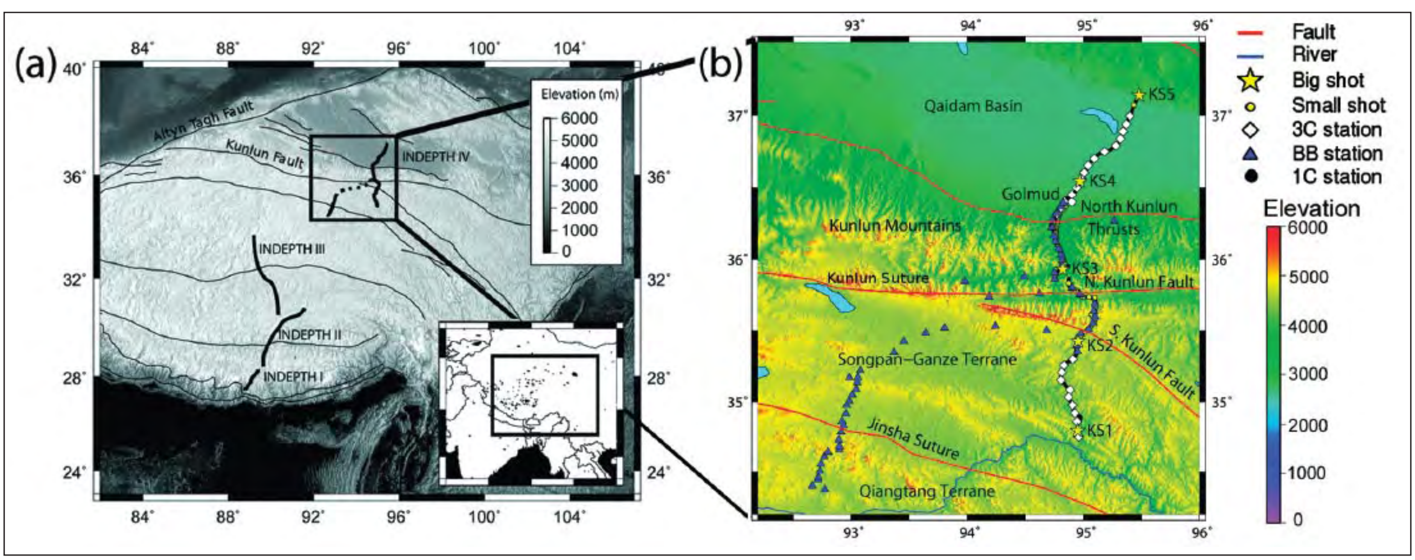

Fig. 1. (a) Locations of International Deep Profiling of Tibet and the Himalaya (INDEPTH) I–IV profiles spanning the Tibetan Plateau. (b) Topographic map of northeastern Tibet showing locations of the different types of INDEPTH IV seismometers and explosive sources. In the legend, 3C are three-component seismometers, BB are broadband seismometers, and 1C are one-component seismometers.

approximately 110 small shots (each containing 60–240 kilograms of explosives) nominally spaced at every kilometer in the central part of the profile.

First arrivals were observed to distances of almost 200 kilometers from some shots (e.g., KS4, Figure 2a). KS5 exhibits clear Moho reflections (see *PmP* in Figure 2b) at approximately 50–55 kilometers beneath Qaidam Basin, calculated from the arrival time and velocity of the wavefront. Other reflectors may mark detachment faults beneath the North Kunlun thrusts. These data are currently being processed by groups in the United States, China, and Germany.

Passive Seismic Experiments

The passive seismic effort was cored by dense, linear broadband seismic arrays (59 stations spaced at about 5 kilometers) deployed across the Jinsha and Kunlun sutures. Receiver function observations from these arrays should allow detailed mapping of the Moho, the base of the lithosphere, and possibly subducted elements of Asia. Data from these passive deployments have just been retrieved this fall.

In a separate effort, a large areal array was simultaneously deployed across northeastern Tibet by the Array Seismology Collaborative Experiments in Northeastern Tibet (ASCENT) consortium, which involves scientists from Beijing University, New Mexico State University, and the University of Missouri.

Field Mapping, Thermochronology, and Magnetotellurics

Field parties from the Chinese Academy of Geological Sciences, State University of New York at Albany, and the University of California at Santa Cruz plan to investigate crustal shortening and strike-slip deformation near the seismic transects in 2008–2009. INDEPTH geologists will also seek to constrain the timing of crustal shortening and exhumation of the Kunlun Mountains with thermochronologic studies, detrital zircon geochronology, and stratigraphic studies. Another goal is to document the total offset on different strands of the Kunlun fault.

Magnetotelluric surveys, from which scientists may calculate the electrical conductivity of crustal rocks, are planned for 2009 by INDEPTH across the Kunlun fault, with additional surveys across the Altyn Tagh fault farther north (Figure 1a) planned by the China University of Geosciences Beijing, the University of Alberta, and the Dublin Institute of Advanced Studies. These new data will augment the INDEPTH III magnetotelluric profile, which showed that the midcrust is conductive as far north as the Kunlun fault, although with more subdued conductivity values than in southern Tibet.

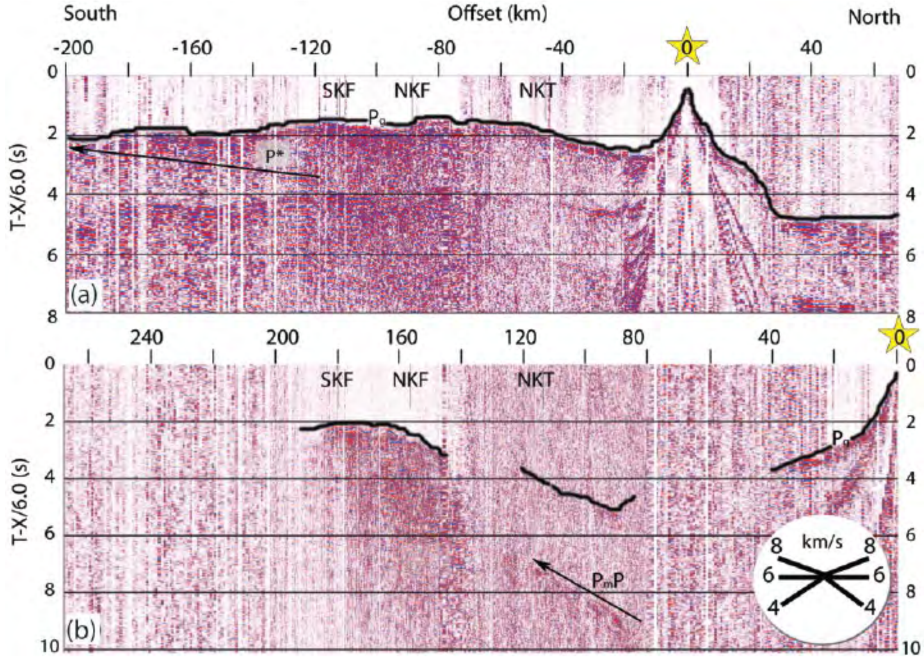

Fig. 2. Example seismic record sections from (a) the 1500-kilogram shot number KS4 and (b) the 2000-kilogram shot number KS5 (see Figure 1b for shot locations). Sections are reduced at 6 kilometers per second and band-pass filtered. Pg *is a crustal diving wave,* PmP *is a reflected phase from the Mohorovičić discontinuity, and* P* *is a lower crustal reflection. The circle in the lower right of Figure 2b shows the angles of wavefronts traveling with the velocities shown (seismic phases traveling at 6 kilometers per second will be horizontal in Figures 2a and 2b).*

Future Work

Over the past 16 years, the INDEPTH program has served as a catalyst to unite several generations of Chinese, North American, and European geoscientists. Collection and analysis of the INDEPTH IV data are just beginning, and the project's future holds great promise of illuminating key questions of large-scale continental dynamics in a continental collision zone.

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