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INDEPTH (International Deep Profiling of Tibet and the Himalaya) multichannel seismic reflection data: Description and availability

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Abstract. Project INDEPTH (International Deep Profiling of Tibet and the Himalaya) has collected over 300 km of multichannel, deep seismic reflection data using explosive sources as part of a multidisciplinary effort to image the structure of the crust and uppermost mantle of the Tibetan plateau. The reflection profiles lie within the Yadong-Gulu rift and were acquired in the summers of 1992 and 1994. Data processing utilized typical industry tools, and a new method was used to migrate the data. Both unmigrated and migrated sections are presented here in large format to facilitate further interpretations.

1. Introduction

The ongoing collision of India with Asia is considered to be the type example of active continent-continent collision [*Dewey et al.*, 1988]. The Himalaya and adjacent Tibetan plateau, which are the product of this collision, encompass the largest expanse of high topography and anomalously thick continental crust on the Earth. How this convergence between India and Asia is accommodated within the crust and upper mantle underlying the region, however, remains a central problem in the tectonics of the region and in the tectonics of mountain belts in general. Project INDEPTH (International Deep Profiling of Tibet and the Himalaya) is an ongoing geoscience project with an overall goal to contribute to an understanding of the crustal and upper mantle structure beneath the Himalaya and Tibetan plateau. Under the direction of a collaborative geoscience team involving scientists from the Chinese Academy of Geological Sciences and several North American and European institutions, INDEPTH has acquired multichannel seismic reflection (common midpoint or CMP data), wide-angle reflection/refraction, broadband earthquake, magnetotelluric, and surface geological data along an approximately 400-km-long corridor, coinciding largely with the Yadong-Gulu rift in southern Tibet (Figure 1). Here, in large format, we present the multichannel CMP seismic reflection profiles augmented by a reflection segment from the wide-angle program.

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2. Data Acquisition

The INDEPTH CMP seismic reflection data were acquired as 11 separate profiles extending from the crest of the Himalaya to approximately the middle of the Lhasa terrane, north of the Yarlung zangbo suture (Figure 1). The profiles were recorded in the graben that comprise the Yadong-Gulu rift, which is one of the largest of the N-S trending extensional systems crossing the Himalaya and southern Tibetan plateau. The rift valleys provided the only logistically feasible route for geophysical work in the otherwise mountainous terrain of southern Tibet. The survey was conducted over two field seasons beginning with INDEPTH I in the summer of 1992, when profiles Tib-1 and Tib-2 were recorded, and again in the summer of 1994 with INDEPTH II, when profiles Tib-3 through Tib-11 were recorded. As detailed in Tables 1 and 2, explosive sources of 50/200 kg sizes were shot every 200/3000 m into a 6-km-long recording spread of 120 channels for Tib-1 and 2 and of 240 channels for Tib-3 through 11. This geometry resulted in a CMP trace spacing of ~25 m for Tib-1 and 2 and ~12.5 m for Tib-3 through 11. All profiles are nominally 15-fold. Since seismic refraction data acquired in the early 1980s have previously shown that the crust beneath the southern Lhasa terrane is 70 to 80 km thick [*Hirn et al.,* 1984], the INDEPTH multichannel data were recorded to 50 s two-way travel time in an effort to ensure images of the entire crust and as much of the uppermost mantle as possible. Difficult drilling conditions (e.g., boulders within the Quaternary graben) or rugged terrain (e.g., the area around the Yarlung river) prevented continuous profiling, resulting in substantial skips in the CMP coverage. The largest gap occurs between the northern end of Tib-5 and the southern end of Tib-6. Portable seismographs were deployed during the shooting of all INDEPTH CMP profiles for the wide-angle recording program. The Yarlung river gap is filled in partly with wide-angle reflection recording (Y. Makovsky, S. L. Klemperer, L. Ratschbacher, and D. Alsdorf, Mid-crustal reflector truncating the India-Asia suture from INDEPTH wide-angle profiling in southern Tibet, submitted to *Tectonics*, 1998, hereinafter referred to as Makovsky et al., submitted manuscript, 1998). Typically, such installations included a three-component geophone and a REFTEK digital

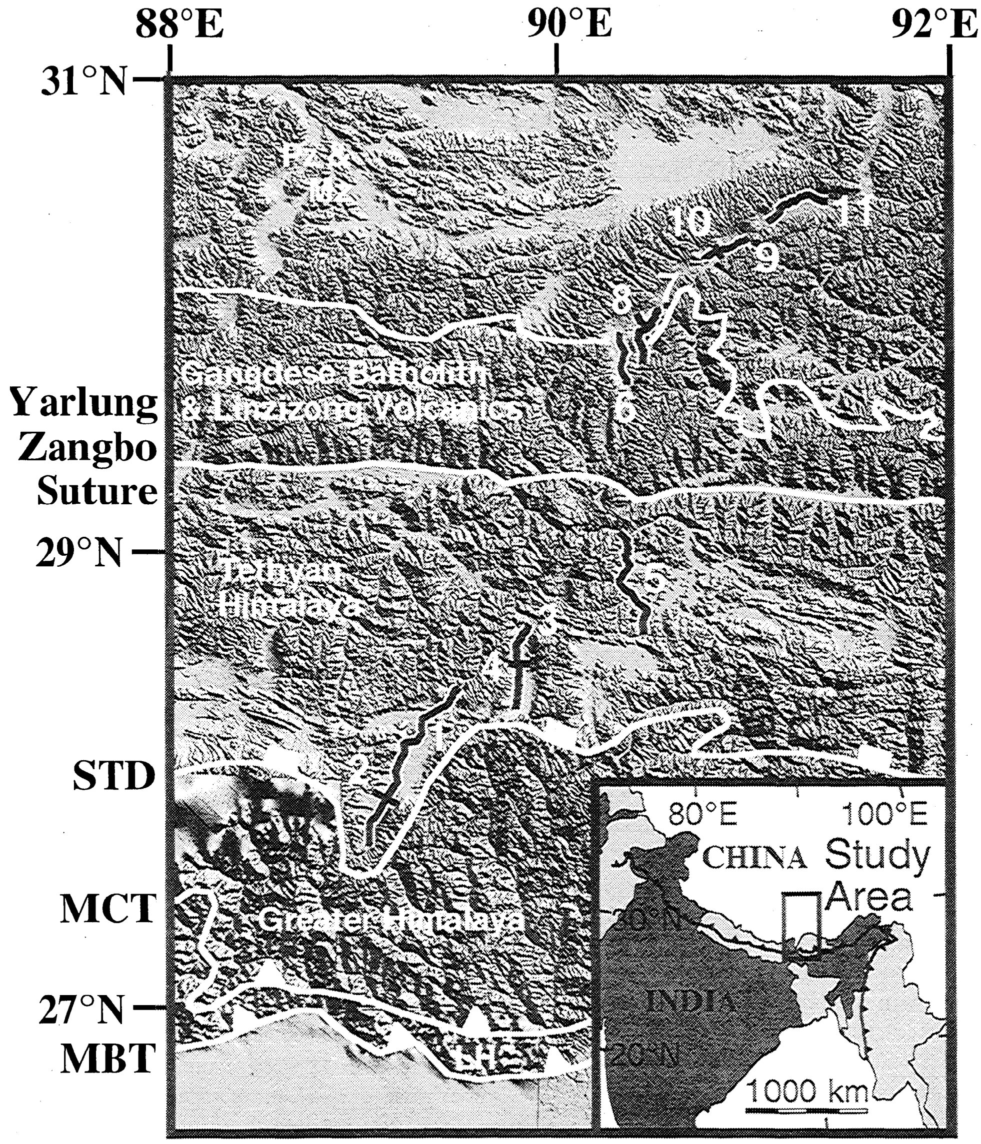

Figure 1. Topographic map showing the location of INDEPTH seismic lines. Major structural boundaries of the India-Tibet collision system include the Main Boundary Thrust (MBT), Main Central Thrust (MCT), South Tibetan Detachment (STD normal fault), and the Yarlung zangbo suture [*Gansser,* 1983; *Burchfiel et al.,* 1992; *Kidd et al.,* 1988]. Generalized geologic units are also noted (LH, Lesser Himalaya; Mz, Mesozoic; Pz, Paleozoic).

Table 1. Acquisition System for Tib-1 Through Tib-11

Recording Parameters	Tib-1 and Tib-2	Tib-3 through Tib-11
Recording system	DFS-V	Wave 3
Number of channels	120	240
Geophones, Hz	10	10
Receiver group spacing, m	50	25
Number of geophones/group	36	27
Receiver array, [a] m	50	25
Record length, s	50	50
Sample interval, ms	4	4
Near offset (normal), m	200	200
Far offset (normal), m	6200	6200
Near offset (large shots), m	3000	3000
Far offset (large shots), m	9000	9000

[a] A uniform, linear receiver array was used.

seismograph with a Global Positioning System (GPS) clock for accurate timing. Within the Yarlung river gap, these portable seismographs recorded the CMP shots only at offsets much greater than normal for the CMP profiles; thus they do not effectively image the upper crust (above ~18 km depth). Nevertheless, they do provide a first-order look at the midcrust and lower crust beneath the Yarlung river. Even where CMP profiling was possible, the choice of routes was limited by available roads and by the presence of rivers and wetlands; hence the lines are crooked and vary in distance from the valley edges.

3. Data Processing

As detailed in Table 3, processing of the CMP seismic data shown here is relatively conventional, including static and normal moveout corrections with signal-to-noise enhancement filtering. Further descriptions of the processing

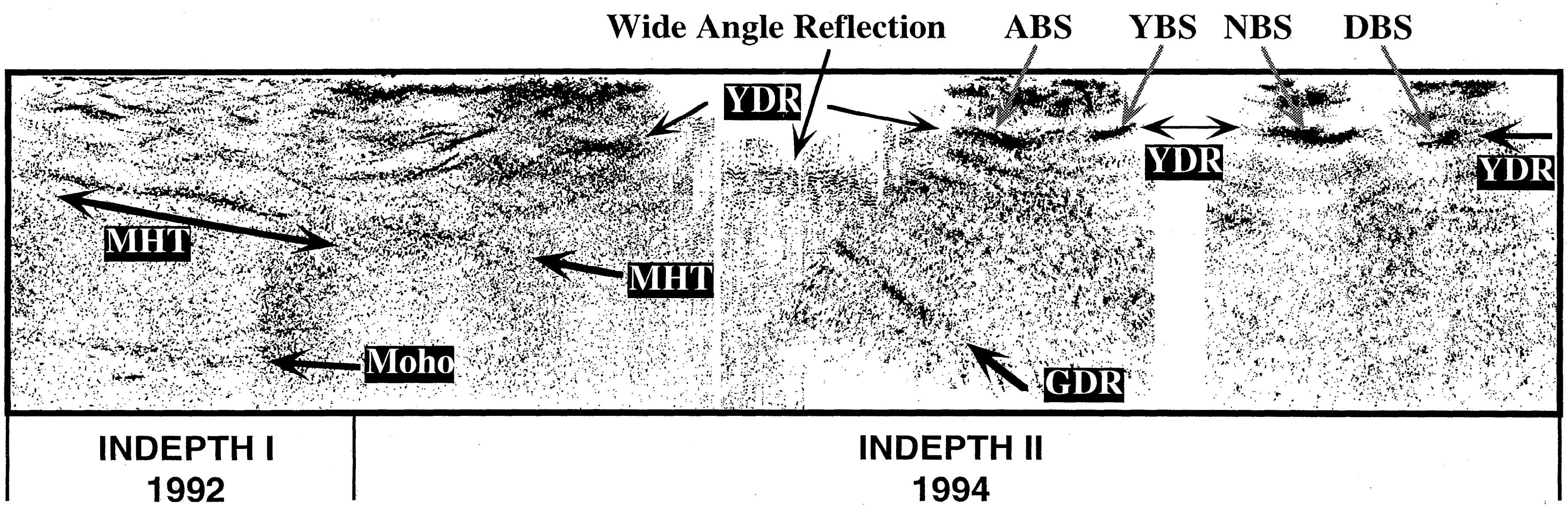

Figure 2. Prominent reflections from the migrated CMP data. Abbreviations are MHT, Main Himalayan Thrust; GDR, Gangdese Deep Reflection; YDR, Yamdrok-Damxung Reflector, ABS, Angang Bright Spot; YBS, Yangbajain Bright Spot; NBS, Nyinzhong Bright Spot; DBS, Damxung Bright Spot.

Table 2. Source Parameters for Tib-1 Through Tib-11

	Tib-1 and Tib-2		Tib-3 through Tib-10	
Explosive Source	Normal	Optional	Normal	Optional
Shot size, kg	50	200	50	200
Shot depth, m	50	50	50	50
Shot spacing, m	200	6000	200	3000
Shot pattern[a]	1 hole	4 holes	1 hole	4 holes

[a]Multiple shallow holes were used when drilling conditions prevented charge placement at target depth of 50 m. Shot depth averaged ~25 m for the survey. Tib-11 used 300 m shot spacing and 100 kg shots in 2 holes throughout the line.

are provided by *Alsdorf et al.* [1996; 1998], *Alsdorf* [1997a; 1997b], and *Hauck et al.* [1998]. After processing each line and creating a CMP stack, the main lines were merged into one profile as described below (Plate 1). Plate 1 also includes a portion of the wide-angle reflection data set to fill the gap between Tib-5 and Tib-6. Processing of the wide-angle data included sorting the data into receiver (station) gathers then applying normal moveout corrections [Makovsky et al., submitted manuscript, 1998].

In general, the India-Asia collision direction is approximately N-S; thus in order to present dip lines, the profiles that have azimuths close to N-S have been projected into a true N-S orientation in Plate 1 (i.e., lines Tib-1, Tib-3, Tib-5, Tib-6, and the southern half of Tib-7). However, the trend of the northern half of Tib-7 (N26°E) and those of Tib-9 and Tib-11 (both N65°E) deviate significantly from N-S, thus they are not projected. The short cross lines include Tib-2, Tib-4, Tib-6, Tib-8, and the northern most section of Tib-11 where it trends approximately E-W. These cross lines are presented by *Alsdorf et al.* [1998], *Hauck et al.* [1998], and *Cogan et al.* [1998].

The narrow aperture (short line length compared to the recording time) and low signal-to-noise encountered at the longer recording times of the INDEPTH data lead to difficulties in migration when using conventional algorithms [e.g., *Warner,* 1987]. Instead, the method developed by *Alsdorf* [1997b], which has proven effective for avoiding the typical migration artifacts (e.g., "smiles," lateral smearing of discontinuous reflections into synforms), was used to produce the migrated section displayed in Plate 2.

Table 3. General Processing Flow

Processing Tool	Parameters
Spike and noise burst edit [a]	
Resample 4 ms to 8 ms	45 Hz antialias filter
Trace DC removal	remove trace mean
Apply top mutes	
Elevation statics	4200 m datum
Maximum power residual statics [b]	
Velocity analysis	constant velocity panels
Normal moveout correction	
Bandpass filter [c]	7-11-45-55
FX deconvolution [d]	
Automatic gain control	4 s window
CDP stack	
FX deconvolution [d]	
Coherency filter [e]	dips of -3 to 3 ms enhanced

ProMAX™ software was used to process the seismic data.

[a] See *Alsdorf et al.* [1996] for examples of processing.

[b] Surface-consistent residual statics of *Ronen and Claerbout* [1985] applied within a 1.0 s window centered on prominent reflections, e.g., the Main Himalayan Thrust (MHT).

[c] Band-pass filter ramps up from 0 to 1 using a Hanning cosine function from 7 to 11 Hz and ramps 1 to 0 from 45 to 55 Hz. Cuts were selected to remove reverberant ground roll which extended to 33 s on some shots.

[d] Frequency-spatial (FX) deconvolution method by *Gulunay* [1986] and *Canales* [1984] applied to shot gathers and stack.

[e] Coherency filtering method of *Kong et al.* [1985].

4. Reflection Naming Convention

Figure 2 incorporates the informal naming convention adopted in the preliminary interpretations reported by *Zhao et al.* [1993], *Brown et al.* [1996], and *Nelson et al.* [1996]. The main Himalayan thrust (MHT) is generally thought to be the active decollement separating the underthrusting Indian lithosphere from the overlying Tethyan Himalaya (e.g., *Zhao et al.* [1993]; note the reflection from the Moho associated with the underthrust Indian crust). The Yamdrok-Damxung reflector (YDR) comprises a series of high-amplitude reflections at 15 to 18 km depth. Local "bright spots" within the YDR have negative reflection polarity and shear wave reflection characteristics that suggest the local accumulation of either a hydrothermal fluid or magma [e.g., *Brown et al.,* 1996; *Makovsky et al.,* 1996]. The Gangdese deep reflection (GDR) is found at similar travel times on two parallel lines, Tib-6 and Tib-7; thus it is not likely related to sideswipe; instead, it may originate from a feature deep beneath the southern Lhasa terrane. About 100 km west of the INDEPTH survey, a steeply dipping reflection at the same depth and lateral position as the GDR was found by the Sino-Franco wide-angle experiments [*Hirn et al.,* 1984]. These wide-angle experiments have previously suggested that the Moho was offset along steeply dipping structures: the GDR may be one such reverse fault. Because the GDR projects to the surface outcrop of the Yarlung zangbo suture, an alternative interpretation is that it marks the suture at depth.

5. Availability

INDEPTH multichannel seismic reflection data are available as raw shot gathers or in the final stack formats shown in Plates 1 and 2 via the internet at http://www.geo.cornell.edu/geology/indepth/data/INDEPTH_data.html or via email to Larry Brown, brown@geology.cornell.edu. The wide-angle reflection data are available via the internet from the IRIS-PASSCAL Data Management Center at http://www.iris.washington.edu/.

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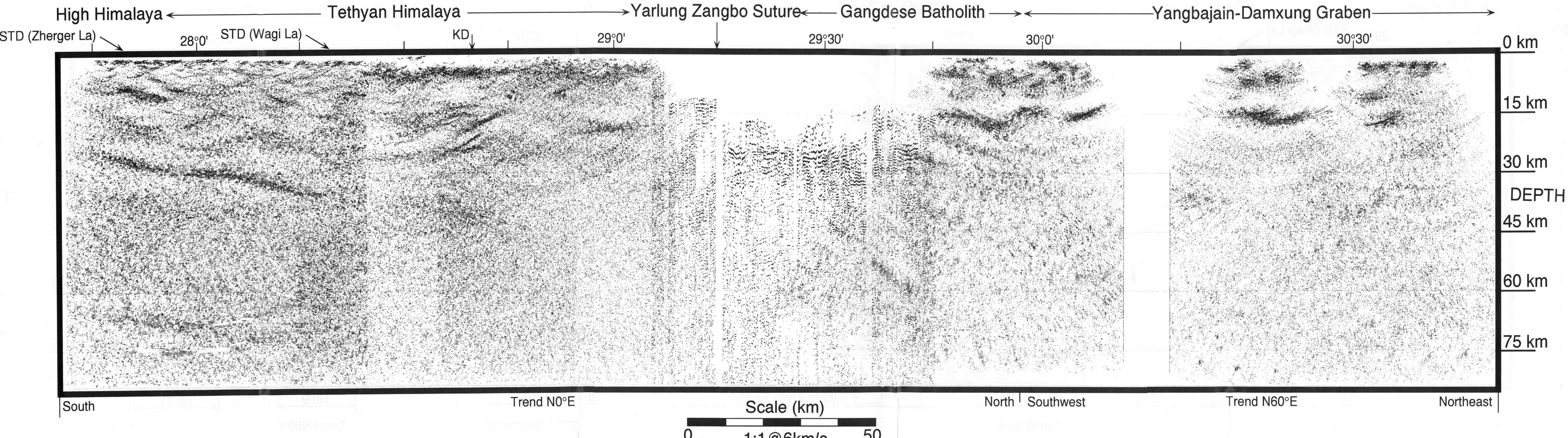

Plate 2. Multichannel CMP reflection profiles migrated by the method of *Alsdorf* [1997b] and depth converted wide-angle suture section. Over 300 km of seismic data detail the crustal section of Tibet from the High Himalaya to the interior of the Lhasa terrane. Nomenclature follows from Figure 2.

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References

Alsdorf, D., L. Brown, D. Nelson, Y. Makovsky, and S. Klemperer, Crustal deformation of the Lhasa terrane, Tibet plateau from Project INDEPTH deep seismic reflection profiles, *Tectonics*, in press, 1998.

Alsdorf, D., Noise reduction in seismic data using Fourier correlation coefficient filtering, *Geophysics, 62,* 1617-1627, 1997a.

Alsdorf, D., A simple method for migrating narrow aperture, noisy seismic reflection data and application to Project INDEPTH (International Deep Profiling of Tibet and the Himalaya) deep seismic profiles, *J. Geophys. Res., 102,* 17807-17811, 1997b.

Alsdorf, D., L. Brown, and D. Nelson, Possible upper mantle reflection fabric on seismic profiles from the Tethyan Himalaya: Identification and tectonic interpretation, *J. Geophys. Res., 101,* 25305-25320, 1996.

Brown, L.D., W. Zhao, K.D. Nelson, M. Hauck, D. Alsdorf, A. Ross, M. Cogan, M. Clark, X. Liu, And J. Che, Bright spots, structure, and magmatism in southern Tibet from INDEPTH seismic reflection profiling, *Science, 274,* 1688-1690, 1996.

Burchfiel, B.C., C. Zhiliang, K.V. Hodges, L. Yuping, L.H. Royden, D. Changrong, and X. Jiene, The south Tibetan detachment system, Himalayan Orogen: Extension contemporaneous with and parallel to shortening in a collisional mountain belt, *Spec. Pap. Geol. Soc. Am., 269,* 41 pp., 1992.

Canales, L.L., Random noise reduction, paper presented at 54th Annual International Meeting, Soc. of Explor. Geophys., Atlanta, Georgia, 1984.

Cogan, M.J., K.D. Nelson, W.S.F. Kidd, C. Wu, and the Project INDEPTH Team, Shallow structure of the Yadong-Gulu rift, southern Tibet, from refraction analysis of INDEPTH common midpoint data, *Tectonics, 17,* 46-61, 1998.

Dewey, J.F., R.M. Shackleton, C. Chengfa, and S. Yiyin, The tectonic evolution of the Tibetan plateau, *Philos. Trans. R. Soc. London Ser. A, 327,* 379-413, 1988.

Gansser, A., Geology of the Bhutan Himalaya, in *Denkschriften der Schweizerischen Naturforschenden Gesellschaft, Mem. Soc. Helv. Sci. Nat., 96,* 1983.

Gulany, N., FXDECON and complex wiener prediction filter, paper presented at 56th Annual International Meeting, Soc. of Explor. Geophys., Houston, Texas, 1986.

Hauck, M.L., K.D. Nelson, L.D. Brown, W. Zhao, and A. Ross, Crustal structure of the Himalayan orogen at ~90° east longitude from Project INDEPTH deep reflection profiles, *Tectonics*, in press, 1998.

Hirn, A., A. Nercessian, M. Sapin, G. Jobert, X.Z. Xin, G.E. Yuan, L.D. Yuan, and T.J. Wen, Lhasa block and bordering sutures - A continuation of a 500-km Moho traverse through Tibet, *Nature, 307,* 25-27, 1984.

Kidd, W.S.F., P. Yusheng, C. Chengfa, M.P. Coward, J.F. Dewey, A. Gansser, P. Molnar, R.M. Shackleton, and S. Yiyin, Geological mapping of the 1985 Chinese-British Tibetan (Xizang-Qinghai) plateau geotraverse route, *Philos. Trans. R. Soc. London Ser. A, 327,* 287-305, 1988.

Kong, S.M., R.A. Phinney, and K. Roy-Chowdhury, A nonlinear signal detector for enhancement of noisy seismic record sections, *Geophysics, 50,* 539-550, 1985.

Makovsky, Y., S.L. Klemperer, L. Ratschbacher, L.D. Brown, M. Li, W. Zhao, and F. Meng, INDEPTH wide-angle reflection observation of *P*-wave-to-*S*-wave conversion from crustal bright spots in Tibet, *Science, 274,* 1690-1691, 1996.

Nelson, K.D., et al., Partially molten middle crust beneath southern Tibet: Synthesis of Project INDEPTH results, *Science, 274,* 1684-1688, 1996.

Ronen, J., and J.F. Claerbout, Surface-consistent residual statics estimation by stack-power maximization, *Geophysics, 50,* 2759-2767, 1985.

Warner, M., Migration - Why doesn't it work for deep continental data?, *Geophys. J. R. Astron. Soc., 89,* 21-26, 1987.

Zhao, W., K.D. Nelson, and the Project INDEPTH Team, Deep seismic reflection evidence for continental underthrusting beneath southern Tibet, *Nature, 366,* 557-559, 1993.

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