Deep Structure of the Northeast Tibetan Collision Zone: INDEPTH IV

The Himalaya-Tibet Collision Zone

The Himalayan Mountain Belt and adjacent Tibetan Plateau (Figure 1) remain the world's foremost natural laboratory for investigation of continental collisional tectonics. The continuing debate over how the Asian continent has responded to the embedding of the Indian subcontinent has variously revolved around concepts such as distributed shortening (e.g. Dewey and Burke, 1973), wholesale continental underthrusting (e.g. Argand, 1924; Powell and Conaghan, 1973; Ni and Barazangi, 1984), indentor tectonics (Tapponnier and Molnar, 1976), orogenic collapse (Tapponnier et al., 1986); delamination (e.g. England and Houseman, 1989); and ductile flow in the lower crust (e.g. Zhao and Morgan, 1985; Clark and Royden, 2000; Beaumont et al., 2001). Intrinsic to most, if not all, of these concepts is the degree of subduction of the Indian plate beneath the southern margin of Asia (see DeCelles et al., 2002, and Chemenda et al., 2000, for recent takes on this issue). Subduction of Asian continental crust beneath the Tibetan Plateau along its northern margin has received less attention, but is a common theme of several recent analyses (Willet and Beaumont, 1994; Tapponnier et al., 2001; Kind et al., 2002). It is this northern margin, and the large-scale geotectonic issues involved, which are the focus of the current proposal.

Project INDEPTH

The Tibetan Plateau has played host to several large, geological/geophysical initiatives designed to probe its deep structure. Perhaps the most notable of these have been the pioneering Sino-French expedition of the late '70s (e.g. Allegre et al., 1984), the 1985 Royal Society (Britain)- Academica Sinica Tibet Geotraverse (Dewey et al., 1988), and INDEPTH.

Project INDEPTH (International Deep Profiling of Tibet and the Himalaya) began in 1992 both as a test of the deep seismic reflection method in the challenging terrain of the Tibetan Himalayas and as the initial segment of a proposed megatransect of the entire Himalayan-Tibet collision zone. (Zhao et al., 1993). Initial success led to two subsequent multi-national, multi-disciplinary field efforts over the past decade (Figure 1) that have made major contributions in our evolving understanding of continent-continent collisions and development of plateaux.

INDEPTH I (1992) identified and traced of the deep geometry of the main decollement (Main Himalayan Thrust) beneath which India underthrusts the Himalaya, detailed the relationship between underthrusting and contemporaneous extensional faulting in the high Himalayas (e.g. South Tibetan Detachment System), and recorded near-vertical echoes from the world's deepest (75 km) Moho (Zhao et al., 1993; Makovsky et al., 1996; Wu et al., 1998).

INDEPTH II results (Fig. 2) helped constraint the overall shortening budget of continent-continent collision (Hauck et al., 1998), revealed the existence of a possible crustal-scale ramp in the MHT system that may control basement complexes in the Tethyan Himalaya (e.g. Kangmar Dome), suggested a possible detachment of the Indus-Zangbo suture (Makovsky et al. 1999), provided new constraints for the onset of extension (Edwards et al., 1997; Edwards and Harrison, 1997) and - perhaps most dramatically - provided compelling evidence of fluids (partial melts?) in the crust of southernmost Tibet (Brown et al., 1996; Makovsky et al, 1996). While the nature and significance of these fluids is still debated (e.g. Makovsky and Klemperer, 1999; D'Andrea et al., 2001), the INDEPTH results have clearly helped fuel the current debate over the role of lower-crustal flow in plateau formation (e.g. Nelson et al., 1996; Clark and Royden, 2000; Beaumont et al., 2001).

INDEPTH II also pioneered the integration of active (controlled source) and passive (natural source) seismic recording in the same field campaign (Brown, 2000), and its results still stands as one the best examples to how near-vertical reflection (Brown et al., 1996), wide-angle reflection/refraction (Makovsky et al, 1996; Makovsky and Klemperer, 1999), teleseismic receiver functions (Kind et al, 1996; Yuan et al., 1997) and MT observations (Chen et al., 1996) can collectively constrain critical physical properties (in this case, fluid content and composition) at substantial depth.

INDEPTH III was primarily designed to a) evaluate the extent of crustal melting (as argued from INDEPTH II and other results) and thus test the viability of the lower-crustal flow as an explanation of plateau uplift as a whole, and b) detail a proposed ”mantle suture” between presumptive subducted Indian lithosphere (beneath the Lhasa Block) and thinned Asian lithosphere or upwelling asthenosphere argued to exist beneath the Qiangtang terrane of northern Tibet (e.g. Ni and Barazangi, 1983; Owens and Zandt, 1997; McNamara, 1997)), the latter argued by some to be the result of lithospheric delamination (e.g. Molnar, 1988.) INDEPTH III was cored by a closely spaced (10km) passive recording array (broadband + short period) that traversed from the northern Lhasa block, across the Mesozoic Nujiang-Bangong suture, and well into the Qiantang Terrane (Figure 1a). Although the INDEPTH III budget did not allow for state-of-the-art reflection or refraction surveys, the “passive” stations were also used to record explosions to obtain basic crustal refraction information (Zhao et al., 2001; Haines et al., 2003). Moreover, the feasibility of future recording of CMP-style reflection data (a la INDEPTH I and II) was tested using a portable (60 channel) engineering-style seismograph (Ross et al., 2003). An extensive suite of MT surveys was also collected as part of INDEPTH III (Figure 3).

Among the principal crustal results from INDEPTH III were new P and S wave velocity models (Figure 3a) for central Tibet from wide-angle recording of both explosions and earthquakes (e.g. Zhao et al., 2001; Haines et al., 2003), major differences in lithospheric velocity structure between southern and northern Tibet (Rapine et al., 2003), MT evidence (Wei et al., 2001) of high conductivities in the lower crust throughout the transect area (Figure 3b), and confirmation that seismicity of central Tibet is limited to the uppermost crust (Langin et al., 2003). The small-scale reflection tests did reveal a highly reflective lower crust, whose thickness has cited as a constraint on the mode of plateau uplift (Haines et al., 2003; Ross et al., 2003). The reflective lower crust corresponds to a distinct jump in seismic velocity (Zhao et al., 2001), which has in turn been interpreted as the first evidence of the alpha-quartz to beta-quartz transition in the crust (Mechie et al., 2003). Although each of these observations is consistent with a weak, perhaps partially molten, lower crust, evidence for fluid bodies such as those observed during INDEPTH II was not obtained during INDEPTH III (e.g. Haines et al., 2003). Keep in mind, however, that there was no meaningful deep reflection profiling as part of INDEPTH III. Receiver functions computed from INDEPTH III results (e.g. Fig. 3c) show clear lateral changes in Moho convertivity and apparent morphology. These latter could be interpreted as Moho faults. At least one intracrustal converter (SC in Fig. 3c) has been interpreted as geological significant, in this case as a marker for the Qiantang anticline (Shi et al, 2003). Field mapping during INDEPTH III provided direct evidence from xenoliths of high temperatures in lower crust of the Qiangtang (Hacker et al., 2000), the first firm constraints on the timing of rifting in the Qiangtang (Blisniuk et al., 1998) and detailed the structural evolution of major thrusts in the central Qiangtang (Dogai Coring).

As mentioned earlier, a major focus of INDEPTH III was the mantle (Figure 3). INDEPTH III recordings provided a more precise identification of Pn velocity contrasts between southern and northern Tibet (Hearn et al., 2000). More dramatic were the teleseismic measurements of a sharp contrast in mantle anisotropy between southern and northern Tibet (Figure, 4a; Huang et al., 2000) and P-wave velocity anomalies which appear to delineate subducted Indian lithosphere beneath the central Plateau (Figure 4b; Tilmann et al., 2003), but no evidence that collisional structures have penetrated to the underlying 410 or 670 km mantle discontinuities (Figure 4c, Kind et al., 2003).

In addition to profiling along the core seismic route during INDEPTH III, the MT team collected a regional traverse across the Qiangtang, Songpan-Ganze-Hoh Xil, Kunlun and into the Qaidam basin (Figure 5). MT Line 100 shows evidence of the low resistivities similar to those observed during INDEPTH II and attributed to partial melt zones in the midcrust (Unsworth et al., 2003). Additional MT profiles across the Zangbo suture in southern Tibet have confirmed that the key features of INDEPTH II continue along strike (Spratt et al., 2003) of this suture zone.

INDEPTH results are significant contributions to our current understanding of the evolution of the southern and central Tibet Plateau. INDEPTH experience has shown the value of carefully selected and closely integrated multidisciplinary field surveys in Tibet. Both aspects have led INDEPTH to identify the northeastern boundary region of the Plateau as the most scientifically compelling target for additional large-scale geophysical study. This region also constitutes the final link in INDEPTH's original vision of traversing the core elements of the Himalaya-Tibet collision zone. However, we are not proposing this next phase simply to achieve geographic closure; rather, we submit that the tectonic issues represented are central not only to understanding the evolution of this particular plateau, but to our general understanding of how continental interiors respond to plate boundary interactions. Such "intra-plate" or "distributed-plate" tectonics remain one of the major frontiers in continental dynamics.

INDEPTH IV: The Northeastern Margin of the Plateau

Geotectonic Setting

The northeastern portion of the Tibet Plateau and adjacent region consists of a series of crustal terranes amalgamated onto the Asia landmass in Paleozoic-Mesozoic time (Figs. 1, 7b). Proceeding from central Tibet toward the northeast (Figure 1,7a), the major components of this tectonic collage (e.g. Dewey et al., 1988; Yin and Harrison, 2000) are the:

Qiangtang terrane: The Qiangtang terrane consists of metamorphic rocks and Late Paleozoic shallow marine strata in the west, and shallow marine carbonates of Triassic-Jurassic age interbedded with terrestrial clastics and volcaniclastics to the east (Yin and Harrison, 2000). It is bounded on the south by the Bangong-Nujiang suture (Figure 1), which spatially corresponds to the boundary between "cold" subcrustal seismological characteristics to the south and "warm" subcrustal characteristics to the north (e.g. Figure 13). Recent mapping has led to recognition of a regional anticlinorium with Jurassic to Upper Cretaceous strata overlying, and in normal fault contact with, a core of blueschist-bearing metamorphic rocks (Yin and Harrison, 2000; Kapp et al., 2000). This core complex has been interpreted to represent a mélange underplated by late Triassic-early Jurassic subduction along the Jinsha suture (e.g. Figure 8a;).

Jinsha suture: The Jinsha suture (Figure 8a) has been variously interpreted as a north dipping or as a south dipping subduction zone along which either a remnant ocean basin (Yin and Nie, 1996) or back arc basin (Gu, 1994) closed. Although presently represented at the surface by a relatively modest topographic feature, the suture appears to correspond with the largest and sharpest contrast in crustal seismic velocities (estimated by teleseismic tomography, with a 6% bulk increase from south to north (Wittlinger et al., 1996).

Songpan-Ganzi-Hoh Xil (SGHX): The Songpan–Ganzi-Hoh Xil terrane in the proposed study area was added to the growing Asian assembly along the Anyimaqen-Kunlun-Muztagh suture in the early Jurassic time (Yin and Harrison, 2000). It is characterized by a thick (several km) sequence of mostly late Triassic deep marine deposits that is referred to as the Bayan Har or Songpan-Ganzi flysch complex. This complex was severely deformed by folding and thrusting in the late Triassic/Early Jurassic as part of the continued convergence between north and south China (Yin and Harrison, 2000). The Songpan-Ganzi flysch may have been deposited in a series of separate basins. The sediments have been interpreted to be deep marine sediments offscraped during subduction along the Jinsha suture (Sengor, 1990) or derived from erosion of the Qinling-Dabie orogenic belt to the east (Nie et al., 1994). The higher seismic velocities and inferred geologic history (Figure 8b) beg the question of whether relict oceanic material (crust and/or upper mantle) may lie buried beneath the voluminous flysch. Straddling the northern

Qiantang and southern Songpan-Ganzi-Hoh Xil terranes is the Fenghuo Shan Thrust belt, which includes the tightly folded, >4km thick Fenghuo Shan Group. The Fenghuo Shan strata are cut by Tertiary thrusts.

The Kunlun: At the northern margin of the Songpan-Ganzi-Hoh Xil terrane is a broad Early Paleozoic arc which has been overprinted by a narrower Late Permian to Triassic arc (Kunlun Batholith, Harris et al., 1988). This arc is juxtaposed against the SGHX along the Triassic Anyimaqen-Kunlun-Muztagh suture. The basement of the Kunlun batholith consists of Middle to Late Proterozoic gneiss, schist and marble, overlain unconformably by latest Proterozoic sedimentary rocks and lower Paleozoic shallow marine carbonates (Yin and Harrison, 2000). Volcanic deposits interbedded with marine deposits became widespread in Ordovician to Early Carboniferous. A rifting event may have split the arc in the Early Permian, followed by northward subduction of the SGHX terrane beneath the Kunlun Batholith (Yin et al., 2000). Structurally the Kunlun (Figure 9a,b) are dominated by a) the Kunlun Fault, a major (1200 km long) east-west trending strike slip system that may have been active over the past 7 Ma (Yin and Harrison., 2000), and b) the North Kunlun Thrust system, which places Proterozoic metamorphics and Paleozoic sedimentary and igneous rocks over Tertiary units of the Qaidam Basin, The Kunlun strike slip fault was the generator of a Ms 8.1 earthquake in November of 2001, which ruptured almost 400 km at the surface and sustained displacements of up to 16 m (Lin et al, 2002). The North Kunlun Thrust system may have accommodated almost 300 km of north-south shortening (Yin and Harrison, 2000).

The Qaidam Basin: The Qaidam Basin (Figure 9a,b) is a low relief intermontane basin that developed beginning in the Late Paleocene-Early Eocene (Song and Wang, 1993). Entrapping of sediments in the basin became significant by the early Eocene, with up to 14 km of post-Oligocene accumulations (Wang and Coward, 1990). Chen et al (1999) have argued from surface geology, subsurface geophysics and earthquake focal mechanisms that the Qaidam basin represents an intermediate step in the uplift of the Tibetan plateau (e.g. Songpan-Ganzi-Hoh Xil terrane) from the lowlands to the northeast of the Qilian Shan. While the North Kunlun Thrust is the major thrust front along the southern edge of the basin, such deformation appears to affect the Qaidam block well north of this major topographic break (e.g. Yousha Shan thrust in the northwestern Qaidam basin (Chen et al., 1999).

The Qilian/Nan Shan: The leading edge of deformation of the Tibet plateau is arguably represented by the thrust belts of the Nan Shan and Qilian Shan (Figure 9b). These terranes consist of deformed early Paleozoic arcs which developed at the southern margin of the North China craton before it was offset by the Altyn Tagh in the Cenozoic (Yin and Harrison, 2000).

The Altyn Tagh fault: Dominating the northwestern margin of both the Qaidam Basin and the Tibetan Plateau proper is the Altyn Tagh fault (Figure 1, 9c). In scale (1200 km long) and geometry (e.g. displacements on the order of 500 km; Peltzer and Tapponnier, 1988), the Altyn Tagh suggests a truly intracontinental equivalent to the great transform faults like the San Andreas. The Altyn Tagh consists of many strands, not all of which are currently active (e.g. Cowgill et al., 2003). Thrust structures of the Qaidam-Qilian terranes show little evidence of being distorted by the Altyn Tagh, suggesting that the former are stronger than the fault zone (Yin and Harrison, 2000). Although some have argued that the Altyn Tagh is essentially a crustal fault, detached from the underlying mantle by a decollement (e.g. Burchfiel et al, 1989b), recent seismic tomography has been used to argue that it penetrates to ca 140 km (Figure 9c; Wittlinger et al., 1998). Quaternary basaltic volcanism near the western Altyn Tagh also suggests a deeply penetrating structure in that region, while the lack of such volcanism adjacent to the Qaidam terrane could be construed as evidence for the lack of deep penetration along its northeastern reaches (e.g. Yin and Harrison, 2000).

Mantle Structure: Although the structures and terranes defined geologically at the surface are critical guides to deciphering the origin of the modern Tibet plateau, no less important are the spatial relationships at deep crustal and sub-crustal depths. A first order issue is the nature and extent of the low velocity, high attenuation region that has previously been associated with northern Tibet (Figure 13). How is the inferred thinning of the lithosphere suggested by these observations to be reconciled with the postulated subduction of (presumably) cold Asian lithosphere? How is the possible lack of a mantle lid to be reconciled with the proposed preservation of faults in the Moho? Is the hot northern Tibetan mantle the result of convective counterflow, delamination, or slab rollback, or a combination of effects (Fig. 13 b,c; Molnar, 1988; England and Houseman, 1989; DeCelles et al., 2003)? Are lateral changes in surface morphology and tectonic related to corresponding changes in mantle dynamics? Is the boundary between terranes a narrow fault zone or distributed in the mantle lithosphere? For these and other reasons it is impossible to consider lithospheric tectonics in Tibet independent from underlying mantle dynamics.

Key issues

"Qaidam basin may still be at a juvenile stage of plateau building. If so, the Qaidam basin provides a modern example of how part of the Tibetan plateau may have uplifted in the past" (Chen et al., 1999).

We propose to complete INDEPTH's original goal of transecting the Tibetan Plateau by implementing a multidisciplinary survey across its northeastern boundary. This boundary represents a current focus of contention among tectonic models that attempt to explain the response of the continental interior to collision at its periphery.

Crustal thickening by thrust stacking: Several workers (Meyer et al., 1998; Chen et al., 1999; Tapponnier et al., 2001) have emphasized the role of large-scale thrust stacks (crustal nappes) in absorbing shortening and generating crustal thickening at the NE Plateau margin (Figure 5c, 8a). This mode of intracontinental failure implies relatively brittle behavior at substantial depth, with strain concentrated in discrete shear zones dipping at moderate angle. Such thrust imbricates may or may not be cross cut by steeping dipping, deeply penetrating strike slip zones that accommodate a substantial fraction of collisional convergence by tectonic escape (e.g. Tapponnier and Molnar, 1976).

Crustal thickening by lower crustal flow: A contrasting view of plateau deformation appeals to ductile flow of relatively weak lower crust to achieve both plateau uplift (Zhao and Morgan, 19785) and marginal expansion (Fig. 12a; Clark and Royden, 2000). Crustal flow has been invoked to explain characteristics of the Himalaya (Fig. 12b; Beaumont et al., 2001) and the eastern plateau boundary (Royden et al., 1997) in particular. The role of lower-crustal flow, if any, in the development of the NE plateau boundary is not clear. However, the low electrical resistivities found beneath the Songpan-Ganze-Hoh Xil terrane near the Kunlun fault suggest that it may be significant (e.g. Fig. 5d), at least along strike. Crustal-scale faults, whether associated with the Kunlun faults or the Jinsha suture offers intrinsic markers to evaluate lower crustal flow. Such faults continue unbroken to the Moho, so flow would presumably be restricted to strike parallel directions. On the other hand, changes in fault geometry with depth (e.g. flattening) could be construed as related to deep material transport by ductile processes.

Subduction of the Asia lithosphere: The shortening attributed to crustal stacking is argued to be matched by detachment and subduction of the underlying mantle (e.g. Tapponnier et al., 1990). Such subduction was predicted by numerical modeling by Willett and Beaumont in 1994. Tentative observational support for such subduction was recently reported by Kind et al. (2002) from receiver functions computed from the relatively sparse US and French passive seismic profiles along the Lhasa-Golmud highway. A prominent south-dipping converter (Figure 10b) indicates a structure extending from the Moho into the mantle beneath northern Tibet. The true vergence and extent of this feature, whether it represents modern subduction or a fossil of previous continental amalgamation, and how it relates to crustal structure, are primary issues to be addressed by the experiment proposed here.

Lithospheric geometry of major strike-slip faults: While thrust faulting has clearly accommodated some of the convergence between India and Asia, strike-slip faults have also played an important role. Such faults are implicit in the rigid-indenter/tectonic-escape model of Asian deformation (e.g. Molnar and Tapponnier, 1975: Tapponnier and Molnar, 1977). Studies of mantle anisotropy (e.g. Hirn et al., 1995; Herquel et al., 1995, 1999; Huang et al., 2000) imply that some major SS faults penetrate the entire lithosphere (e.g. Fig. 5d), a conclusion bolstered by a tomographic study of the central Altyn Tagh (e.g. Wittlinger et al., 1998). Others, however, have argued that other faults, or portions thereof, are limited to the crust (e.g. Fig. 5e), detached from the underlying mantle by low-angle faults (e.g. Burchfiel et al., 1985; Yin et al., 2000). The deformation in the mantle associated with these shear zones could be distributed over a wider region than surface faulting might imply.

Moho Offsets: Of relevance to all the above is the issue of Moho faults. Large Moho offsets were first reported in Tibet from Sino-French seismic wide-angle (fan) surveys (Hirn et al., 1984). They have also been deduced from teleseismic P delay times, tomographic inversions (Wittlinger et al., 1999) and receiver functions (Vergne et al., 2002; Shi et al., 2003) However, the reality of these offsets have been questioned as perhaps the result of mismatching of seismic phases on low-resolution seismic surveys (e.g. Molnar, 1988) or lateral velocity variations instead of true changes in depth. If real, their link, if any, to surface tectonic features is tenuous. Matthews and Hirn (1984) postulate that such faults sole upward into a ductile lower crust. Whatever the reality of the Tibetan Moho offsets, Moho faults are no novelty. They have now been reported from deep reflection profiles at a number of locales, often associated with mantle reflectors that are themselves usually interpreted as fossil subduction zones (e.g. Choukroune et al., 1988; McGeary and Warner (1985), Diasconescu et al., 1998). The important issues with respect to putative offsets of Tibetan Moho are whether they mark Tertiary deformation or simply represent relicts of older accretion events. If the latter, their existence would seem to preclude significant ductile remobilization of at least the lowermost crust/uppermost mantle. In this sense they would place rather firm constraints upon the extent of lower-crustal flow and/or asthenospheric upwelling. Any linkage of such offsets to surface geology would provide a time scale over which relatively brittle behavior has dominated. Conversely, observable structures that link Moho offsets to their surface counterparts would serve as direct markers for testing/quantifying channel flow models at intervening depths.

“Rigid” intracontinental blocks: The Qaidam basin, like its larger counterpart, the Tarim, appear as an island of lesser deformation sandwiched between zones of intensive, crustal-scale faulting (e.g. Figure 1). These contrasts presumably derive from differing rheologies/compositions at depth or perhaps the distribution of pre-existing weakness. Whether these bulk property contrasts are sensible from surface geophysical measurements remains to be demonstrated. However it is reasonable to expect they may be manifest in seismic velocities, seismic reflectivity and/or resistivity structure. In this respect the refraction results in the Tarim basin recently reported (Wang et al., 2003) will be useful. The observed resistivity contrast between the Qaidam basin and the Songpan-Ganzi-Hoh Xil terranes (Fig. 5c) is already quite suggestive, as are the tomographic results across the Jinsha suture (e.g. Fig. 8b). The experiments proposed here, taken en suite, constitute the most thorough attempt to make such measurements for Tibet. Another important aspect of the Qaidam lithospheric block is whether it is currently being thickened, en route to becoming part of the high plateau (e.g. Chen et al., 1999), or whether it its current elevation is as high as it gets. Crustal structure is one part of the equation; thickening of the mantle lithosphere is another. For that reason acquiring a fix on the current lithospheric thickness is also important.

Methodologies

INDEPTH IV builds upon previous INDEPTH experience to integrate controlled source and passive seismic imaging tools together with magnetelluric sounding to define both structure and physical properties at depth and hence identify key elements of the lithosphere-asthenosphere system of northeastern Tibet. The components of this program include:

Controlled source seismics:

Seismic reflection profiling

Seismic reflection profiling remains the highest resolution geophysical tool available for delineating crustal structure (e.g. Klemperer and Mooney, 1998). The moderately dipping, crustal-scale faults and low-angle detachments inferred from surface geology in northeastern Tibet (e.g. Figs 6b,c; 9) have proven to be suitable targets for deep reflection imaging in many tectonic environments (e.g. Smithson et al., 1979, Allmendinger et al., 1983; Green et al., 1988). The inferred subcrustal subduction of Asian crust is also a prime target for deep reflection profiling: reflections from moderately dipping features have been traced well into the upper mantle in a number of areas (McGeary and Warner, 1985; Cook et al, 1998), most of which have been interpreted as fossil normal subduction zones. INDEPTH IV provides an opportunity to test whether these latter may be relicts of intracontinental subduction.

However, deep reflection profiling, as it is conventionally practiced on land, is an expensive option. We here propose to take advantage of new technology to acquire reflection imagery at a much reduced cost. Rather than subcontracting with an oil exploration crew, as was done in INDEPTH I and II, we propose to use the IRIS “Texan” recorders deployed by students and local labor. Cost reduction will be achieved by using more receivers with fewer shots (Figure 15). Experience has shown that fewer, well-placed sources can often recover most of the information that more expensive, conventional surveys with denser shot spacing (higher fold) produce (e.g. Klemperer, 1986; Onishi et al., 2003). Relatively “low fold” surveys have been quite successful in previous deep seismic efforts (e.g. across the Brooks Range in Alaska (Wissinger et al., 1997); in the central Andes (ANCORP working group, 1999)) at a fraction of the cost of using conventional seismic crews. The design of the reflection surveys proposed for INDEPTH IV are also informed by previous attempts by Chinese scientists to collect deep reflection profiles across comparable features (e.g. Gao et al. 2001).

Our default reflection experiment (Figure 15) will consist of 500 recorders spaced 100 m apart, yielding a fixed spread of 50 km aperture. We propose to record explosive sources (100kg) every 1 km along the spread. In order to provide adequate subsurface coverage, we plan to deploy 2 spreads each (100 km) across the Jinsha suture and Altyn Tagh, and 3 spreads (150 km) across the Kunlun. We project that 5 teams can deploy a spread, record the shots, and pick up the spread in approximately 6 days. We estimate that 20 drill rigs (comparable to INDEPTH I and II) will be needed to keep pace with this deployment schedule (See Budget justification for details).

Although deep Moho reflections were recorded with similar size sources during INDEPTH I, the relative lack of deep crustal reflections observed during INDEPTH II raised concerns whether crustal attenuation was so great as to render deep penetration impractical (Alsdorf et al., 2001). However, reflection tests during INDEPTH III were successful in probing to the Moho (Ross et al., in press).

Wide-angle reflection/refraction.

While near-vertical reflection profiling is the best option for detailing crustal (and perhaps some mantle) structure, analysis of controlled source recordings and larger offsets is the mainstay of estimating bulk physical properties at depth. Such properties are important for constraining possible lithologies at depth as well as improving the depth imaging obtained by near vertical profiling. Estimates of Vp and especially Vs have been central to the debate over the nature of the crust within the plateau, especially the issue of widespread partial melting (e.g. Owens and Zandt, 1997, Galve et al., 2002). Good crustal velocity control is essential to establishing the magnitude of faulting at the Moho, even when tomographic imaging of the mantle is available (Wittlinger et al, 1996). Amplitude vs offset variations of P and S waves proved essential to the interpretation of the fluid bright spots encountered during INDEPTH II (Makovsky and Klemperer, 1999)

We propose to acquire wide-angle reflection/refraction data by augmenting the core reflection deployment with less densely populated "wings" that extend recording offsets to well past the expected critical distance for the Moho (Figure 15). These "wings" will be populated by 340 additional Texans from the IRIS pool and 30 short-period instruments to be provided by GFZ Potsdam (Mechie), together with temporary deployments of 60 of the broadband stations of the passive seismic experiment (see below) to achieve an instrument spacing of c. 750 m. To ensure adequate energy to these offsets, we have made provisions for a limited number of very large shots (1-2 tonnes) to be set off during the reflection/wide-angle recording phase. (Figure 15). This strategy worked well during INDEPTH III (Zhao et al., 2001).

It should also be noted that the maximum offset of the "near vertical" reflection spread is actually quite substantial (50 km). This will allow application of wide-angle techniques for estimating physical properties in the upper crust with a high degree of redundancy.

The controlled source component, as usual, represents the costly component of the geophysical program. Most of these costs are concentrated in the Cornell budget to minimize overhead (charged only on a fraction of the total). It is important, however, to note that on a cost per km basis (< $2000 US per km) these profiles are considerably less expensive (by a factor of 4!) than the INDEPTH I and II profiles collected using contract crews and comparable to the cheapest rates to be found even in active oil exploration areas.

Passive seismic techniques:

Receiver function profiling

Although broadband stations have previously been deployed along a portion of the proposed transect (Figure 16), the profiles recovered from them fall far short of the density achieved during INDEPTH III (e.g. Figs 1, 3c). Thus the high-density passive profiles proposed for INDEPTH IV (stations spacing = 5 km vs 10 km for INDEPTH III vs. >30 km for French array) do not duplicate these previous attempts, but address key issues either missed or only hinted at by the earlier studies. We expect a one-year deployment, with a total of 60 stations (30 IRIS BB from US, 30 BB and short period from Germany), will be necessary to acquire adequate data for most purposes of this survey. After that year 30 sets of broadband PASSCAL instruments from the 2D grid (see below) will be redeployed to densify the 2D array in the Kunlun area. Note that the deployments we propose lie outside the no-access corridor associated with the Lop Nor test site (Figure 16; CAGS, personal communication). Teleseismic waveforms with epicentral distances between 35° and 90° will be selected from the data set for calculation of receiver functions. We will apply a depth-domain teleseismic receiver function processing approach with the goal of mapping in detail the Moho beneath the Altyn Tagh fault, the Kunlun Fault, and the Jiansha suture where significant Moho offset is postulated. If the Qaidam block has a steep dip, standard receiver function analysis will fail to image the subducted surface. However, Rondenay et al. (2001) have developed a migration algorithm for 2D structure, using P-wave coda as data, which may be able to image these steeply dipping structures. We will migrate our data using a similar approach to Rondenay et al. for deeper lithosphere conversion surfaces to better understand the geometry of the subducted Qaidam block in our study region.

We will also perform receiver function analysis to determine the depths to the 410 and 660 km discontinuities (e.g., Kind et al., 2002). Absolute depths will be determined using the results of the tomography inversion as a 3D velocity model. The depths of the 410 and 660 km discontinuities depend on temperature (Katsura and Ito, 1989). Thus this analysis will allow us to determine if there is any significant temperature anomaly at depth that may be related to an active upwelling beneath our region or even lateral flow from western Tibet toward eastern Tibet.

Tomographic imaging

The linear geometry and limited aperture of the high density passive profiles, while ideal for probing details of crustal and upper mantle structure, are inadequate for constraining the deep velocity structure of the lithosphere-asthenosphere system. *Uniform* 2D coverage is required to achieve proper tomographic imaging of any potential (likely) large-scale lateral heterogeneity (e.g. hot upper mantle to west, cold upper mantle to east). The proposed transect route lies near the junction of the northern Qiantang, where previous seismic studies have indicated a hot upper mantle (McNamara et al., 1997), and the eastern regions of Tibet, where colder regimes have been implied (e.g. Galve et al., 2002)

Over the projected 24 month interval we will collect a teleseismic P and S wave travel time data set that will be used to determine a 3D model of mantle velocity variation beneath northeastern Tibet and Qaidam. During year one we will deploy an additional 36 PASSCAL equipped stations and 25 UK stations in a 2D grid. The data stream will be set at 40 samples per second with an average station spacing of 80 km. During year 2 we will redeploy 30 PASSCAL stations from the linear array in the Kunlun Shan area; hence during year two we will have a total of about 90 stations deployed in northeastern Tibet. Tilmann et al., (2003) successfully imaged the downwelling Indian lithosphere to depths near 400 km beneath central Tibet (Fig. 4b). With a 2-D deployment, and station spacing comparable to U.S. Array, we expect to have a clear signal from the Qaidam lithosphere if it is indeed being subducted beneath northeastern Tibet (Fig. 10b). We should have abundant earthquake sources from at least three azimuths (the northeast, east, and southwest).

We will measure the travel times of P and S waves, as well as SKS and PKP waves, with a cross correlation technique using stacks of the respective phases as the source wavelet. The data will be inverted using the LSQR algorithm (Nolet, 1993) as is standard today. Given the station spacing and coverage of our 2D array, our tomographic image will produce images of the upper mantle that are far superior to any yet achieved for northern Tibet.

The broad shear-wave velocity structure of the crust and mantle beneath northeastern Tibet and the Qaidam Block can be determined from surface-wave data that will be collected by our proposed experiment. Rayleigh wave phase velocities are sensitive to crustal thickness and shear wave velocity within the crust and mantle. We will measure phase velocities of Rayleigh waves in the period band 20-100 s using the two-plane wave approach of Forsyth et al. (1998). The data will be inverted for shear velocity as a function of depth on a grid with roughly 80 km spacing. Our data will be similar in raypath coverage to the Rocky Mountain Front seismic data used by Li et al. (2001) to image the crust and mantle beneath Colorado. We will use their inversion technique with help from Don Forsyth at Brown University. The results of surface-wave analysis should help constrain whether there is unusually fast mantle beneath the northern edge of the elevated Tibetan plateau that is indicative of subduction of the Qaidam block.

The attempt here is to mesh the high resolution of controlled-source reflection with the deeper penetration power of passive techniques, and to integrate the structural detail from reflection/refraction imagery with the bulk physical properties obtained by wide-angle and tomographic analysis. Likewise the tomography study is better suited to delineating steeply dipping structure then either receiver functions or standard reflection imaging. When combined with the data from ongoing passive source 2D arrays in the region we will be able to effectively resolve the entire upper mantle, including the mantle transition zone, beneath the whole of eastern Tibet.

Seismic anisotropy

Regional shear wave studies in Tibet have been key factors in the interpretation of mantle flow at depth (e.g. Hirn, 1995; Herquel et al., 1997). One of the real surprises from INDEPTH III as the evidence that mantle anisotropy could change so abruptly over such short spatial scales (Huang et al., 2000). Our 2D array offers an important opportunity to test these interpretations over a much larger lateral spatial scale than previously possible. Correlation of mantle anisotropy with surface structural trends and contemporary deformation (e.g. Sandvol and Ni, 1998, Silver and Holt, 2002) will provide a means of assessing the degree of contemporary decoupling within the lithosphere, as well as quantifying the obliquity of Tibet deformation in relation to surface strike. Surface wave phase and Pn velocity studies will also help us achieve some degree of depth resolution in the azimuthal anisotropy beneath the eastern portion of the plateau. This resolution will help determine whether there is evidence for asthenospheric counter flow beneath the northeastern corner of Tibet.

Seismicity

An important element of our proposal is to accurately locate local earthquakes within northeastern Tibet and especially beneath the southern edge of the Qaidam block. Seismicity not only indicates which structures are active, but provides insight into rheology at depth. The lack of deep crustal earthquakes in central Tibet has already been cited as evidence for a weak crustal rheology (e.g. Chen and Molnar, 1983; Zhao and Helmberger, 1991; Langin et al., 2003). A variation in focal depths across the major tectonic boundaries being probed by INDEPTH would be an important clue to rheological contrasts. Moreover, a dedicated search for subcrustal seismicity would be one indication whether the proposed subduction of Asian lithosphere is still active or merely a relict of older tectonics. In order to enhance the locations (particularly depth) of events near the Kunlun, we proposed to redeploy a portion (30 stations) of our 2D array in year 2 to provide denser spatial coverage at the southern margin of the Qaidam basin. We will also determine focal mechanisms for the larger events we record, using the regional moment tensor solution (Dreger et al. 1998). These mechanisms will provide information on the stress state within northeastern Tibet.

The passive seismic experiment will be implemented in year 1 with 66 stations from IRIS PASSCAL (Ni), 30 stations from GFZ Potsdam (Kind) and 25 stations from the UK (Tilmann). In year 2 the PASSCAL instruments used for the high resolution profiles will be redeployed for the densification of the 2D array.

Magnetotelluric profiling:

Project INDEPTH has been benefited particularly from the marriages of deep seismic and MT imaging. The MT data collected during INDEPTH-2 in 1995 showed that the crust in Southern Tibet is characterized by high conductivity at 90° E (Chen et al., 1996; Wei et al., 2001). This anomalously high conductivity is likely due to a combination of partial melt and aqueous fluids. Li et al (2002) showed that when combined with other evidence, it is more likely that partial melt is the dominant cause. In 2001, INDEPTH investigators collected additional MT data in Southern Tibet at 85° E and 92° E. These data showed that the high conductivity extends east-west over a significant distance and is not confined to the Yadong-Gulu rift system (Unsworth et al., 2002; Unsworth et al., 2004). Investigations in the Indian Himalaya in Ladakh have also revealed a high conductivity mid-crust and clearly proved that this feature characterizes the Tibetan-Himalayan orogen for more than 1000 km in an east-west direction (Gokarn et al., 2001).

The geoelectric structure of Central and Northern Tibet was investigated in 1998-99 during INDEPTH-3. Wei et al. (2001) showed that the mid-crust is conductive as far north as the Kunlun Fault, although with more subdued conductivity values than in Southern Tibet. A detailed analysis of the Amdo-Golmud profile has shown that a conductive upper mantle can be imaged, implying that Asian lithosphere does not underthrust northern Tibet at this longitude (Unsworth et al., 2004). A more detailed examination of the structure of the Bangong-Nuijiang suture is presented by Solon et al. (2003).

The only MT data in existence to the north of Golmud are commercial data that were collected for hydrocarbon exploration. Some of these data have been re-processed by Bedrosian et al. (2001) and show that low-angle thrust faults can imaged in the upper 5 km of the Qilian Shan. Some of these profiles cross the Altyn Tagh Fault (e.g. Fig. 9d), but the recorded frequencies are too high for imaging lower-crustal and upper-mantle features that might reveal the true nature of this northern boundary.

Care will be needed in site selection in some areas to avoid the low resistivity salt lakes that are widespread in Northern Tibet. The low resistivity structure can distort the electric fields and severely limit the depth of penetration of the MT signals.

In field analysis will ensure that adequate data are recorded at each station to give good responses to 10,000 seconds. At this period, MT signals are typically sampling the upper mantle in most locations. With new processing, data from long-period MT instruments with fluxgate magnetometers can be used to give data to frequencies of up to 1 Hz. This reduces the need for broadband data collection in some areas.

Time-series processing will be used to derive impedance and magnetic field transfer functions. Inter-station transfer functions will also be computed to give additional constraints on geoelectric structure. The ultimate goal of analysis will be the development of a 3-D geoelectric model for each of the tectonic boundaries studied.

Logistics:

Between August 21 and September 2, 2003 a group of INDEPTH scientists including persons from USA (Brown), Germany (Kind, Mechie) and China (Wu Zhen Han, Shi Danian) examined potential routes for a proposed seismic transect across key features of the northeastern margin of the Tibet-Qinghai plateau. In all, one crossing of the Altyn Tagh, three crossings of the Kunlun and two crossings of the Jinsha suture were undertaken (Figure 14). Of all the routes, the western one from Dunhaung north of the Altyn Tagh, through Golmud to Tuotuohe south of the Jinsha suture (DGT route) is currently felt to be the most favorable. It is the most direct extension of previous INDEPTH work. It crosses both the Altyn Tagh and Kunlun in a region where crustal scale thrust structures are well defined and offers the best logistical route across the Jinsha suture. The distance between the Kunlun thrust and strike slip faults is much smaller than the comparable section along the eastern route, thus requiring a shorter seismic line to span it. Also the DGT option is less likely to duplicate, and more likely to complement, previous Sino-French seismic efforts along the eastern route. Lastly, the eastern route lies near the intersection of the Kunlun system with transverse structures, thus complicating the interpretation of any future deep seismic results. The most serious drawback to the chosen route is its proximity to the busy Lhasa-Golmud highway. However, the passes proved to be sufficiently broad to allow instrument deployments some distance from the highway, and the opportunity in some cases to use natural obstructions to screen ground roll from the traffic. Because field inspection has alleviated our concerns about traffic noise, this route is a clear winner from both logistical and scientific perspectives..

Proposed Science Plan

"The main tenets of this model require testing" (Tapponnier et al., 2001)

Kunlun

In terms of crustal structure, the heart of the proposed geophysical investigations is to test the structural model of thrust stacking and lithospheric subduction at the northeast boundary of the Plateau. The Kunlun are a key region to carry out this test. Does the Kunlun Frontal Thrust penetrate at moderate dip all the way through the crust (as implied in Figs. 6b,c), or does it shallow into a deeper decollement layer, as suggested by Fig. 9a? Is there evidence of lower-crustal flow that might absorb this brittle displacement? Does the Kunlun strike-slip system itself sole into the thrust system , or does it penetrate through to the upper mantle (e.g. Fig. 5d vs 5e)? Are all of these crustal structures decapitated by the postulated underthrusting of Asian lithospheric mantle? Or is the dipping coverter on the receiver function profile (Fig. 10b) simply the root zone of these crustal faults? Is the Kunlun Thrust (and coherence of the Qaidam block) controlled by a measurable contrast in crustal properties with the Songpan-Ganzi-Hoh Xil terrane, or is it the result of pre-existing structure at depth? Is the low resistivity observed beneath the Songpan-Ganzi-Hoh Xil terrane associated with seismic bright spots and hence fluids? All of these basic questions hinge upon the geometry of faults at depth, and the contrasts (if any) in rock properties across them.

Reflection profiling offers by far the best chance to trace the geometry of key faults from surface outcrop to substantial depth. We propose to collect approximately 150 km of reflection profiling across the Kunlun, starting in the Qaidam Basin well outboard of the Kunlun Frontal Thrust and continuing well past the Kunlun Fault that ruptured during the 2001 magnitude 8.1 earthquake. The logistical challenges associated with reflection profiling across the Kunlun near Golmud are 1) traffic noise and b) lack of a simple throughgoing route. However, scouting revealed that the passes through the Kunlun are relatively wide and allow instrument deployment at some distance from the highway (and across a deep river channel in some places). Also, substantial portions of the route lie along secondary roads well away from the main traffic conduit.

Wide-angle recordings across the Kunlun will a) constrain depth conversion of the reflection images, b) identify the Moho continuity and depth across a broader region than the reflection data, c) determine whether there are significant velocity contrasts across the Kunlun that might correspond to rheological contrasts, and d) allow detailed (albeit 2D) tomographic imaging of the fault zones involved.

The high-resolution passive array across the faults should provide confirmation of Moho topography that is associated with the surface faults, detail the relationship, if any, between the crustal faults and proposed subcrustal subduction, and last, but not least, confirm the presence of the dipping converter that may mark such subduction.

The MT data described by Unsworth et al (2003) have already revealed that the Kunlun is a first order feature in terms of geoelectric structure (Figure 5). The lithosphere to the north is relatively normal with resistivity values in excess of 500 ohm-m, while to the south it exhibits a very low resistivity crustal layer, and a low resistivity upper mantle. These data would appear to support the possibility of lower-crusal flow in this region, while at the same time contradict the notion (from the receiver functions) that Asian lithosphere does not significantly underthrust Northern Tibet in this location.

We propose to examine the along-strike variation of this boundary through an array of long-period MT stations. These will be clustered on a set of profiles, but with the goal of addressing 3-D geoelectric structure. The primary focus of the U.S. side will be the collection of high-quality long-period MT data. Broadband MT data will be collected as needed by the Western participants and collaborators from the China University of Geosciences in Beijing.

Of special interest with respect to the Kunlun is seismicity. The recent M=8.1 event (Lin et al., 2002) on the Kunlun fault makes clear that it is a major seismogenic feature. The area to be traversed by INDEPTH IV, although located more than 300 km from the epicenter, still bears evidence of c. 5 m of slip. Delineation of the deep geometry of the Kunlun fault south of Golmud could make a major contribution to assessing the likelihood of a future rupture on this segment.

Jinsha Suture: Moho faults

Every since they were first interpreted from wide-angle fan profiles in southern Tibet (Hirn et al., 1984), Moho faults have been a contentious issue in the tectonics of Tibet (Molnar, 1988)). Do these Moho faults really exist? Or are they artifacts of lateral velocity contrasts or miscorrelated reflection patterns? If Moho offsets exist, do they sole into the lower crust (e.g. Matthews and Hirn, 1984) or do they correlate directly with surface features? The Jinsha suture is a prime opportunity to put this issue to rest (though a similar issue exists with respect to the Kunlun: Zhu and Helmberger, 1998). Although fan recorded data are not available for the Jinsha, tomographic, delay times (Wittlinger et al., 1996) and receiver functions (Vergne et al., 2002) all suggest c. 10 km or more of offset somewhere in the vicinity of the Jinsha suture.

By using all three seismic techniques - reflection, wide-angle reflection/refraction, and receiver functions - we propose to evaluate the nature of the Moho beneath the Jinsha. While both reflection and receiver functions should be capable of detecting an apparent offset, wide-angle recordings are critical to providing velocity control so the true depth dimension of any offset can be measured. Reflection data provides the best means of determining how such an offset is linked to surface geology, while receiver functions ensure that adequate penetration is achieved to see the offset.

Logistically, profiling the Jinsha suture is the easiest of the three target zones. The topographic relief of the Fengguoshan is modest, and the passes are wide with gentle gradients. There is considerable access for working cross country away from highway noise.

Even more so than the Kunlun profiles, the Jinsha surveys will be a test of lower crustal flow. The suture zone itself, should it prove to extend to moderate depth, will provide a marker for deep displacement associated with deep crustal flow. As a partial corollary, the preservation of a Moho offset would seem to preclude significant ductile re-equilibration of at least the lowermost crust and uppermost mantle.

Altyn Tagh: Lithospheric faulting or subcrustal decapitation?

The seismic tomography reported by Wittlinger et al (1998) implies a vertical shear zone through the entire lithosphere (Fig.9c). However, the results are far from definitive. Likewise the only deep seismic reflection survey across the Altyn Tagh (near Qiemo: Gao et al., 2001) does not extend not far enough with sufficient penetration to resolve whether the Altyn Tagh penetrates the crust. Although steeply dipping structures are notoriously difficult to delineate by surface seismic surveys, the combination of active and passive surveys we proposed offers the best chance to identify offsets in crustal and sub-crustal marker horizons that trace the Altyn Tagh to depth. Of particular interest is whether the crust carrying the Altyn Tagh is itself decapitated by a subcrustal decollement, or whether the Altyn Tagh is a true lithospheric boundary. A receiver function profile at the juncture of the western Altyn Tagh and the western Kunlun (Kao et al., 2001) has been interpreted to indicate no subduction of Tarim crust beneath Tibet, but the geological complexity of the locale, and the sparse receiver array used, leave this issue in doubt. The deep geometry will also addressed through the collection of MT at longer periods across the fault.

Mantle tectonics

While the crustal aspects of the above problems are best addressed by the high-resolution geophysical profiles, larger scale issues involving both lithospheric and sub-lithospheric mantle require a different observational strategy. Thus body wave and shear wave tomographic data, together with shear wave splitting observations, from the 2D broadband array will focus on confirming the existence and thickness of subducted Asian lithosphere, evaluate the degree of lithospheric thickening beneath the Qaidam basin and Tibetan plateau, define directions of mantle counterflow on the regional scale, and more accurately define the lateral extent of hot, upwelling mantle beneath the northern plateau. Seismic anisotropy measurements will help differentiate narrow vs broad shear in the mantle associated with the Kunlun and Altyn Tagh faults.

Schedule of Activities

Fig. 1 outlines the proposed location, and Fig. 17 the proposed schedule, of INDEPTH-IV activities. This schedule, however, is highly dependent on the availability of seismic equipment (especially broadband seismometers). Given the current allocation of the IRIS instrument pool, we believe a late summer/early fall 2006 start date for acquisition of the controlled source data and initial deployment of the passive equipment is possible. However, should the equipment not be available then, the acquisition could be deferred until spring of 2007.

In terms of the high-resolution surveys, a legitimate question is, “Why focus on all three at once? Why not seek funding for each on its own merit?” There are two reasons we are proposing to address them together. First, a there is a substantial mobilization effort for both the US recording equipment and the Chinese drilling services. Enormous savings will be achieved by undertaking all of the surveys in one field season, rather than tackling them piecemeal. The second reason is that interpretation of each individual survey is greatly enhanced by comparison of the results from the other surveys. These particular surveys all address certain common issues (e.g. Moho geometry, contrasting crustal/mantle rheologies, role of decollements) in addition to their specific context. Analytical synthesis of these different views is almost certainly to offer a more robust and significant interpretation of the issues involved (e.g. Nelson et al., 1996).

Rationale for Collaboration

As has been the case with previous INDEPTH forays, the scale of the experiment requires collaboration, not only in terms of hardware but in terms of experience. The principal scientists involved are not only leaders in the application of their respective techniques, but individuals who have developed a particularly effective working relationship with our Chinese colleagues and are already familiar with the field challenges of working in Tibet.

The INDEPTH collaboration has already made a significant contribution in stimulating other geological studies in Tibet, particularly by our Chinese collaborators of the CAGS. Thus the INDEPTH umbrella has been found useful as an organizing entity for a range of activities beyond those specifically funded by Continental Dynamics (e.g. Wu, 2003).

This proposal is not intended to cover all possible activities associated with Project INDEPTH. Funding for corollary geological and geophysical projects continues to be sought though other sources. This proposal is carefully focused on the larger scale geophysical component.

Project Management

Project INDEPTH will continue as a international collaboration between scientists of the Chinese Academy of Geological Sciences (CAGS) of the Ministry of Land and Resources and scientists from a diverse group of US, German, Canadian, and Irish institutions (see list below). The core members of this group have worked together extensively in previous INDEPTH field surveys. L. Brown (Cornell) and Zhao Xun (CAGS) will provide overall coordination.

INDEPTH IV Participation and Responsibilities

Seismic Reflection: Larry Brown (Cornell), Simon Klemperer (Stanford) for the US

Wide angle Reflection/Refraction: Simon Klemperer (Stanford), James Mechie (GFZ Germany)

High resolution Passive: Eric Sandvol (Missouri), Shi Danian (CAGS, China), Rainer Kind (GFZ Germany)

2D Broadband Array: James Ni (NMSU), Tom Hearn (NMSU), Shi Danian (CAGS, China), Frederik Tilmann (Cambridge)

MT: Martyn Unsworth (Alberta), Alan Jones (Institute for Advanced Studies, Dublin)

In addition to these senior personnel, the project will rely heavily on graduate student participation. In addition, qualified undergraduates will be sought for involvement in both the field operations and subsequent analysis. For example, note that Dr. Marin Clark, one of the better known proponents of lower crustal flow in Tibet, started as an undergraduate field assistant during INDEPTH II.

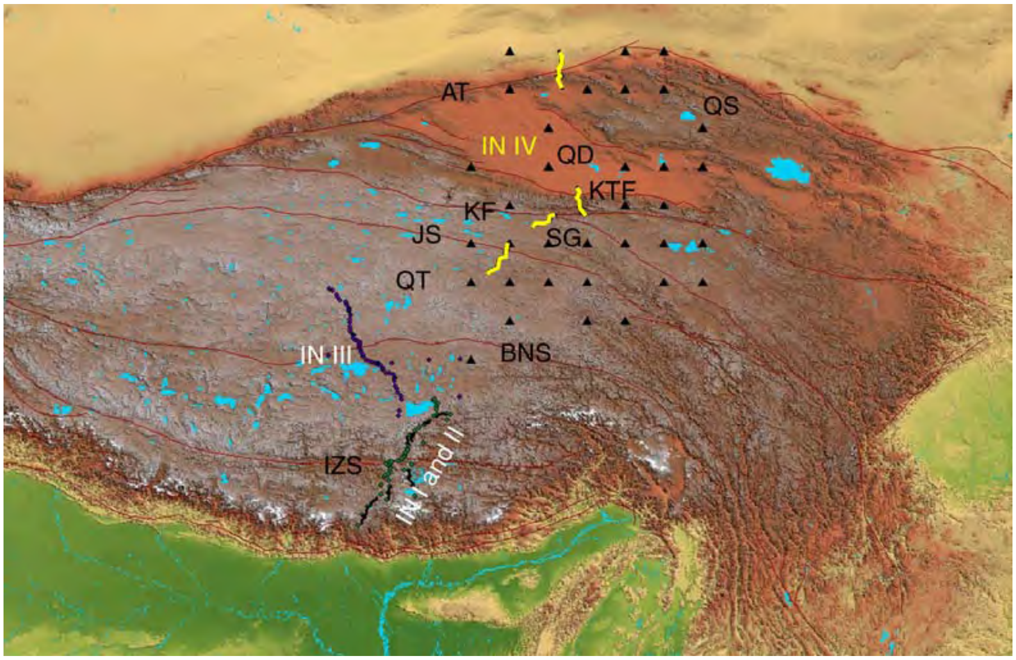

Figure 1: a) Location of proposed INDEPTH IV activities in northeastern Tibet. Yellow lines indicate high-resolution multidisciplinary surveys (controlled-source seismic, passive -seismic and magneto-telluric). Black triangles indicated 2D broadband deployment. Location of previous INDEPTH surveys indicated by blue (IN III) and green and black (IN I and II). Major faults indicate red lines: IZS- Indus-Zangpo Suture, BNS- Banggong-Nujiang Suture, JS- Jinsha Suture, KF- Kunlun fault, KTF- Kunlun Thrust Front, AT- Altyn Tagh. Major terranes: QT- Qiantang, SG- Songpan-Ganzi-Hoh Xil, Q-Qaidam Basin, QL- Qilian Shan.

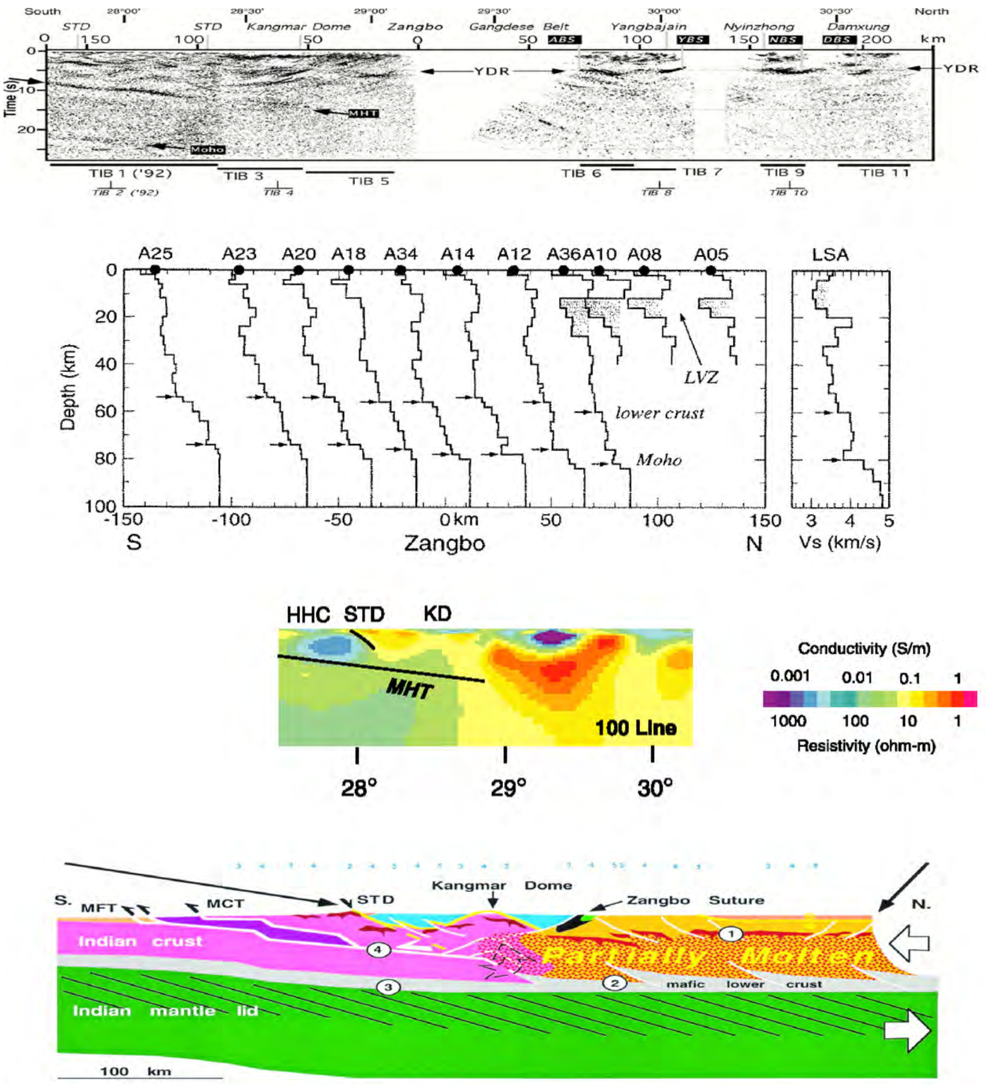

Figure 2.Key results from INDEPTH I and II: a) seismic reflection profile (Brown et al., 1996), b) seismic velocity structure derived from receiver function profile (Yuan et al., 1997) and c) summary interpretation by Nelson et al. (1996).

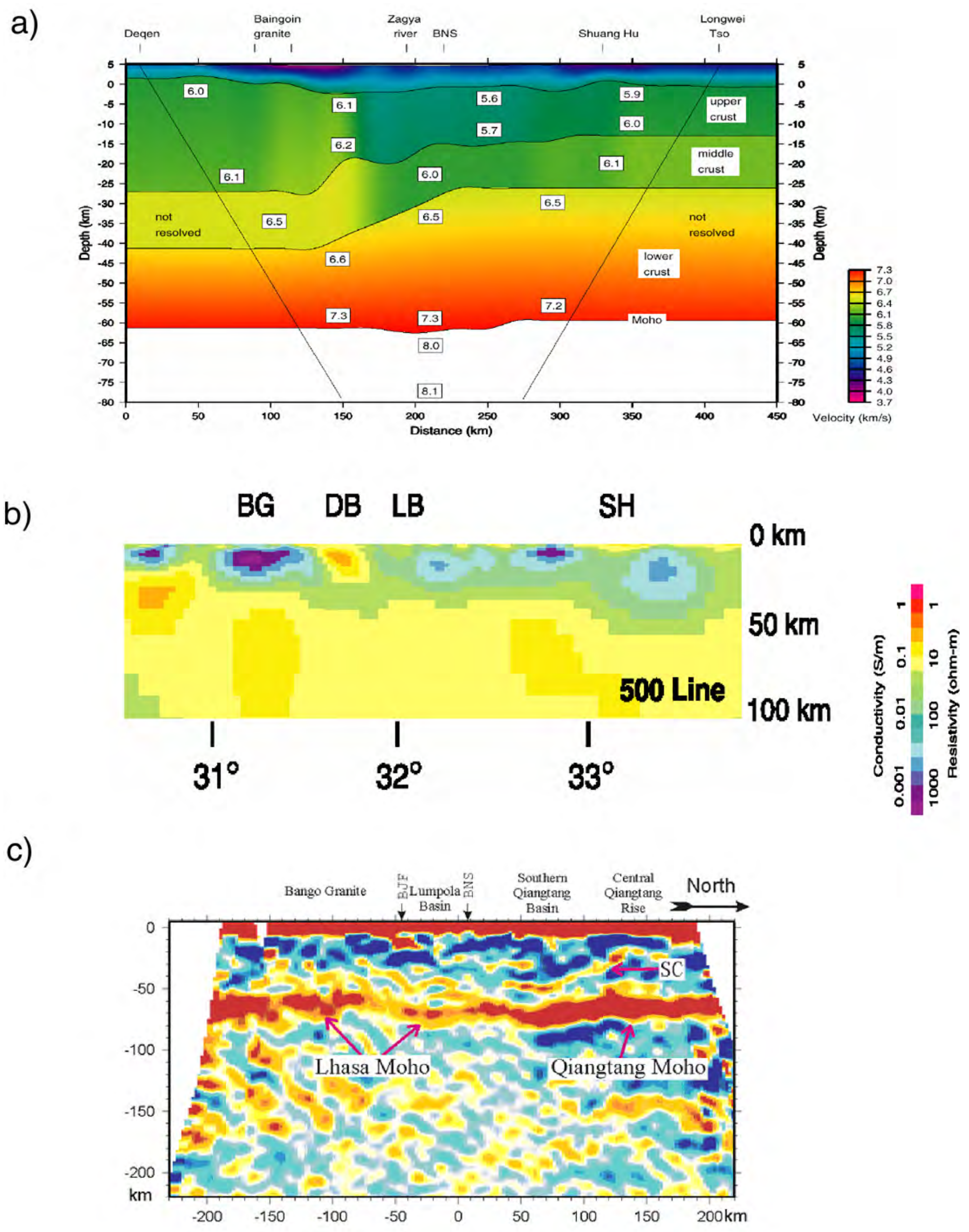

Figure 3. Crustal structure of central Tibet - key results from INDEPTH III: a) P-wave velocity from analysis of wide-angle controlled-source data (after Zhao et al., 2001); b) conductivity from magnetotelluric profiling (after Wei et al., 2001); c) receiver function profile (after Shi et al., 2003).

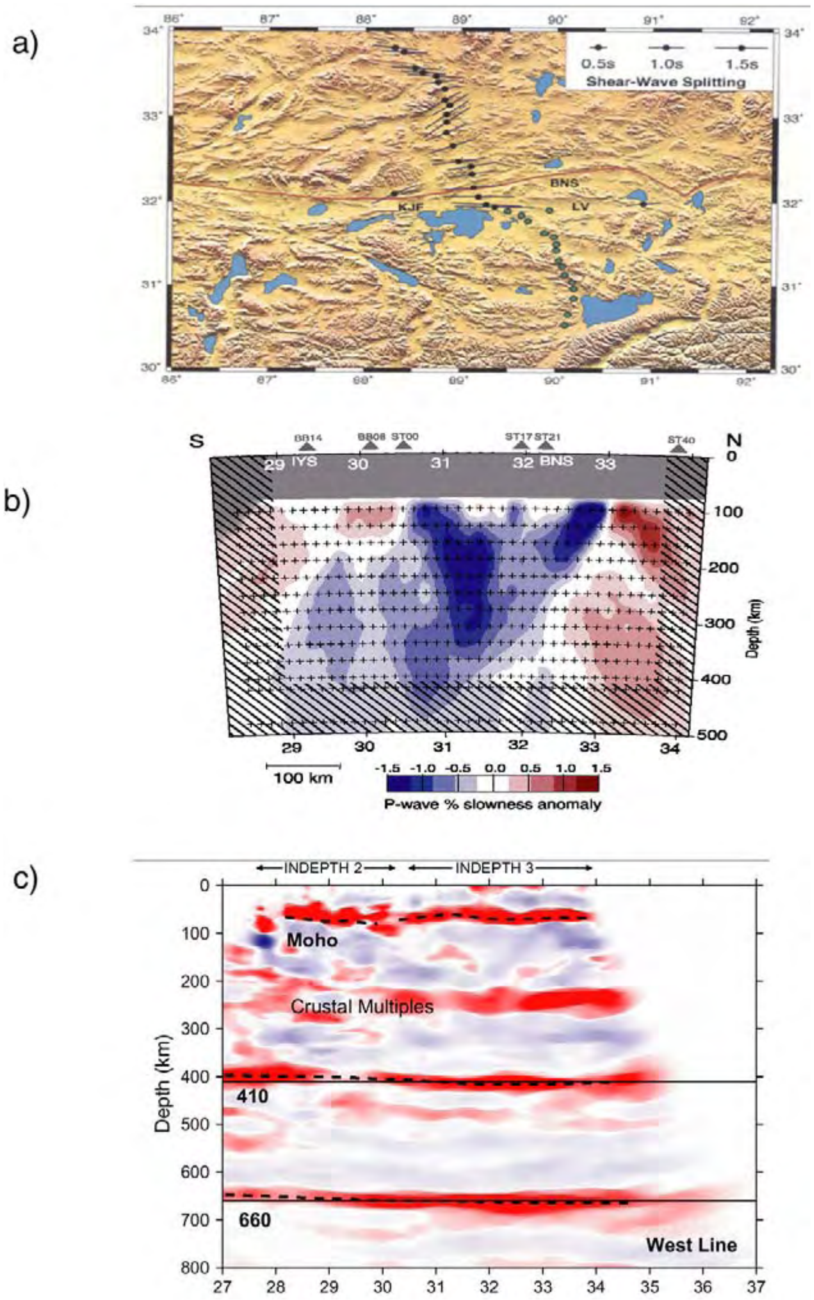

Figure 4. Mantle structure beneath central Tibet- key results from INDEPTH III: a) lateral variation in shear-wave anisotropy as deduced from passive seismic observations (after Huang et al., 2000); b) P-wave velocity anomalies from teleseismic tomography (after Tilmann et al., 2003); c) morphology of the 410 and 670 discontinuities from receiver functions (after Kind et al., 2002).

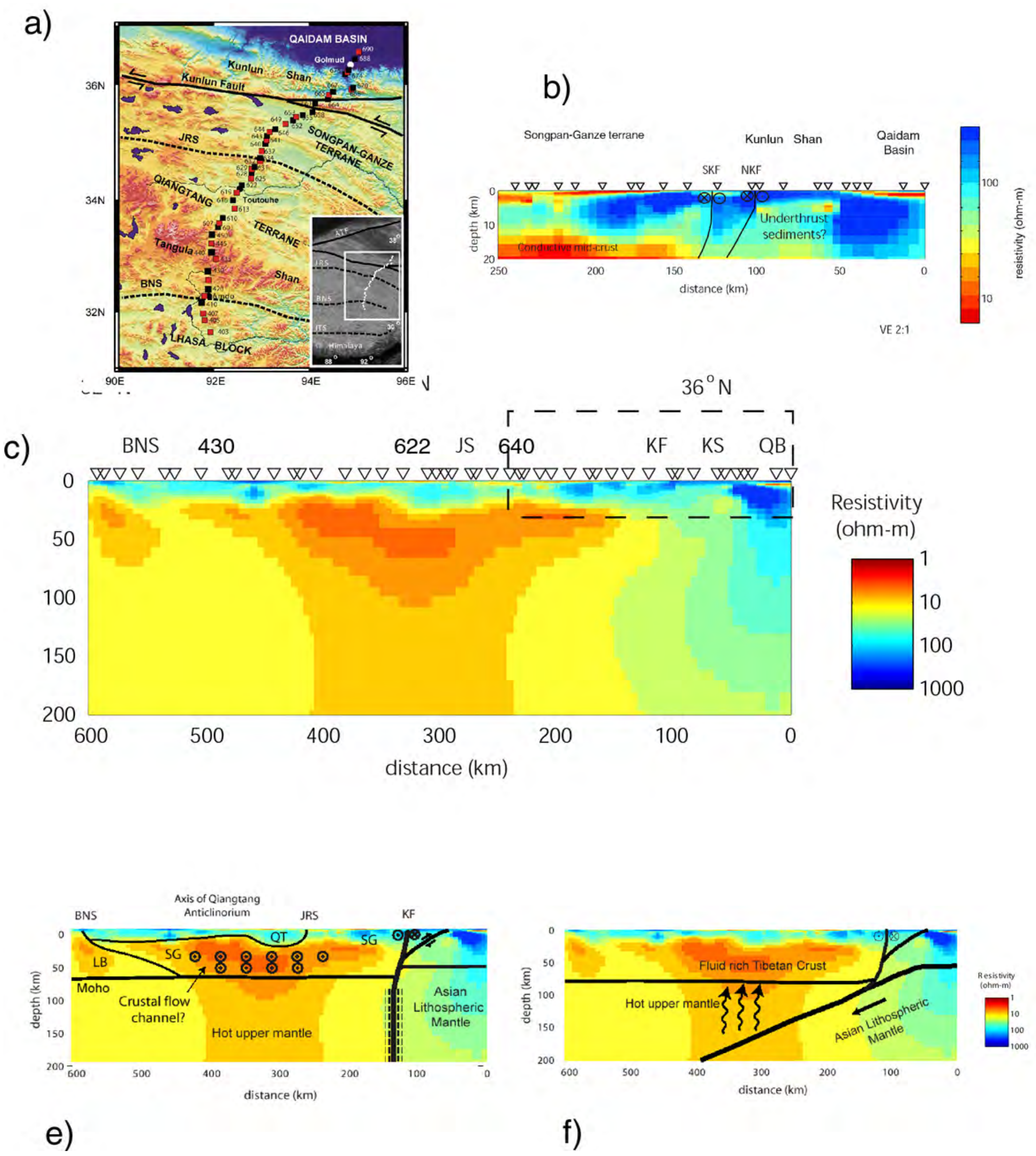

Figure 5. a) Location of MT Line 600 across NE Tibet. b) Detail, with interpretation, of resistivity structure across the Kunlun. c) Larger-scale resistivity structure along INDEPTH MT Line 600. Portion in dotted box corresponds to 5a. e) and f) alternative interpretations of structure as related to resistivity variations. After Unsworth et al. (2003).

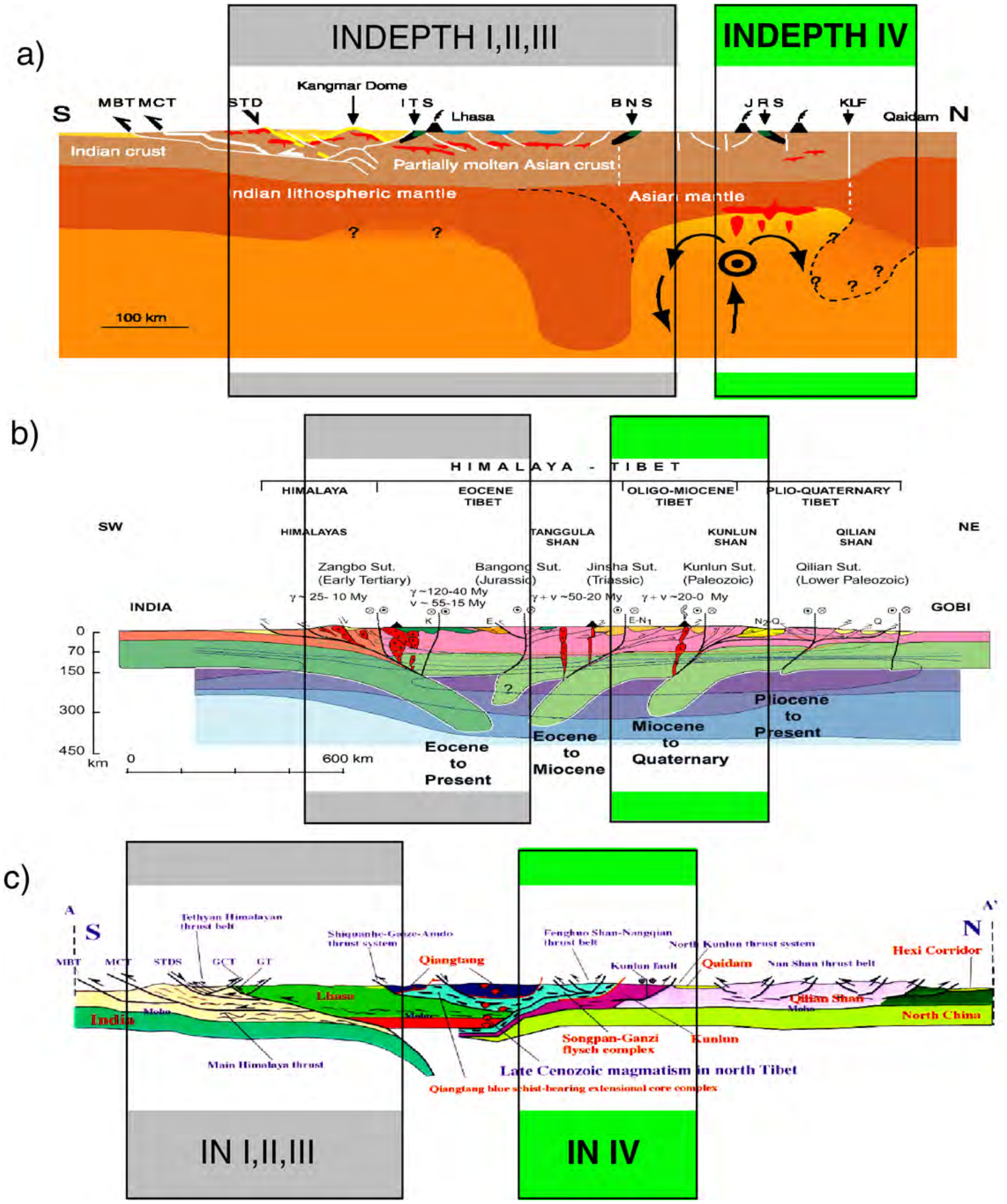

Figure 6. a) Lithospheric model of south and central Tibet as inferred from INDEPTH and other geophysical studies (modified from Tilmann et al., 2003). Recently proposed geotectonic sections across Tibet from b) Tapponnier et al., (2001) and c) Yin and Harrison, (2000)

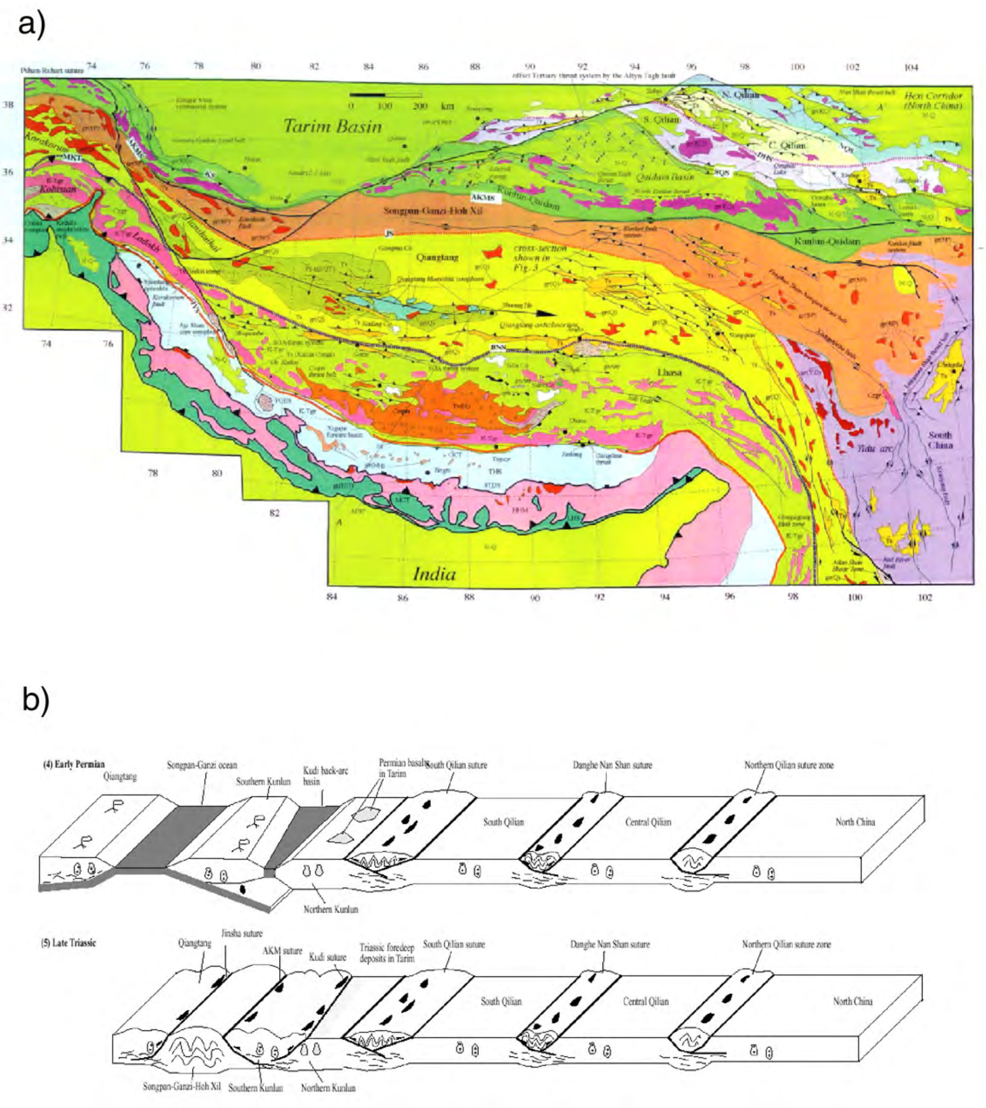

Figure 7. a) Geologic terranes of Tibet (from Tapponnier et al., 2000). Line corresponds to cross-section in Figure 5b. b) Schematic amalgamation of northern Tibetan terranes (from Yin and Harrison, 2000).

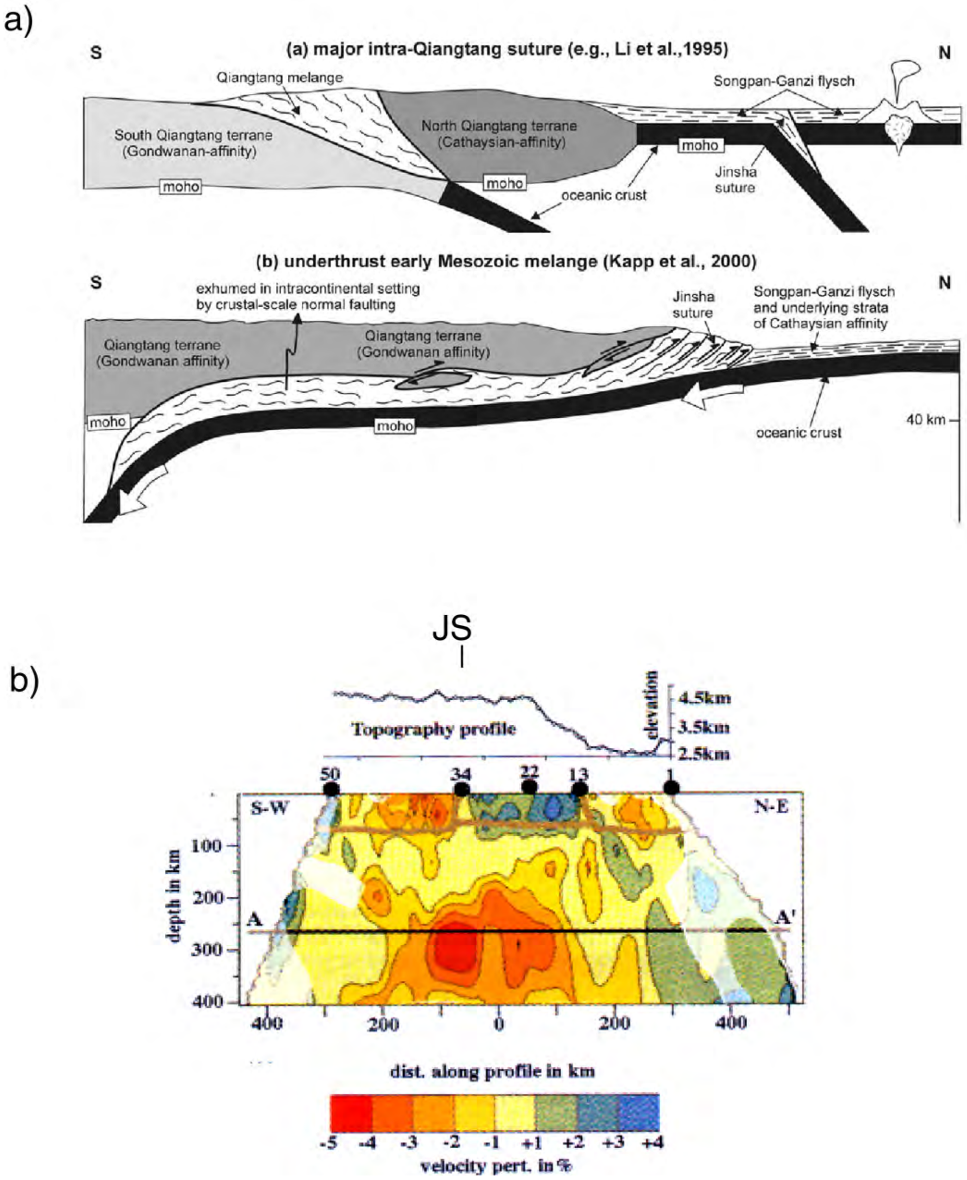

Figure 8. a) Alternative geologic models of the Triassic Jinsha suture (after Kapp et al., 2003). b) Contrast in velocity structure across Jinsha suture from teleseismic tomography (after Wittlinger et al., 1996).

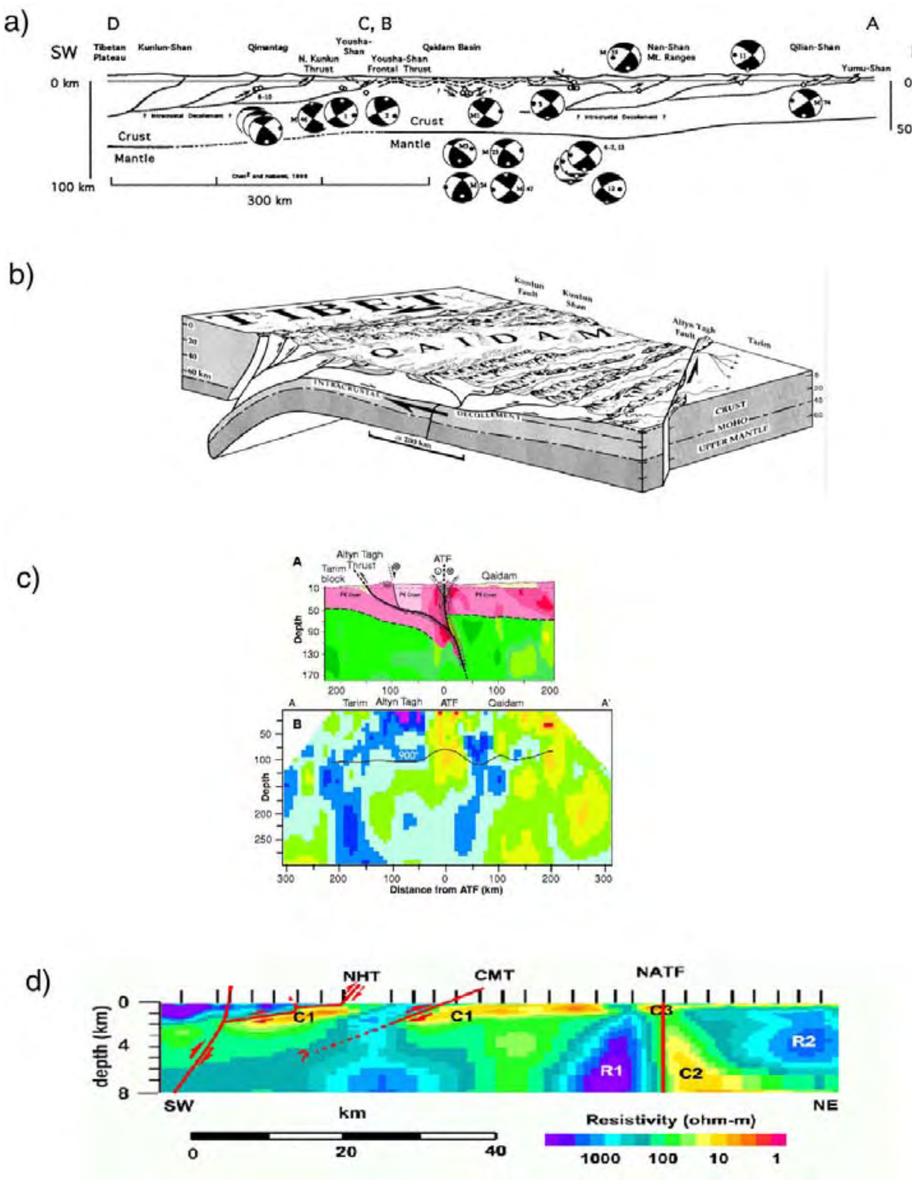

Figure 9. Structure of the Kun Lun-Qaidam-Qilian Shan area proposed by a) Chen et al. (1990) and b) Meyer et al. (1998). c) Penetrative structure of the Altyn Tagh as inferred from tomography by Wittlinger et al. (1998). d) Shallow resistivity structure of the Altyn Tagh inferred from commercial MT data (Bedrosian et al., 2001). NATF- North Altyn Tagh Fault, CMT= Changma Thrust, NHT- North Hills Thrust,

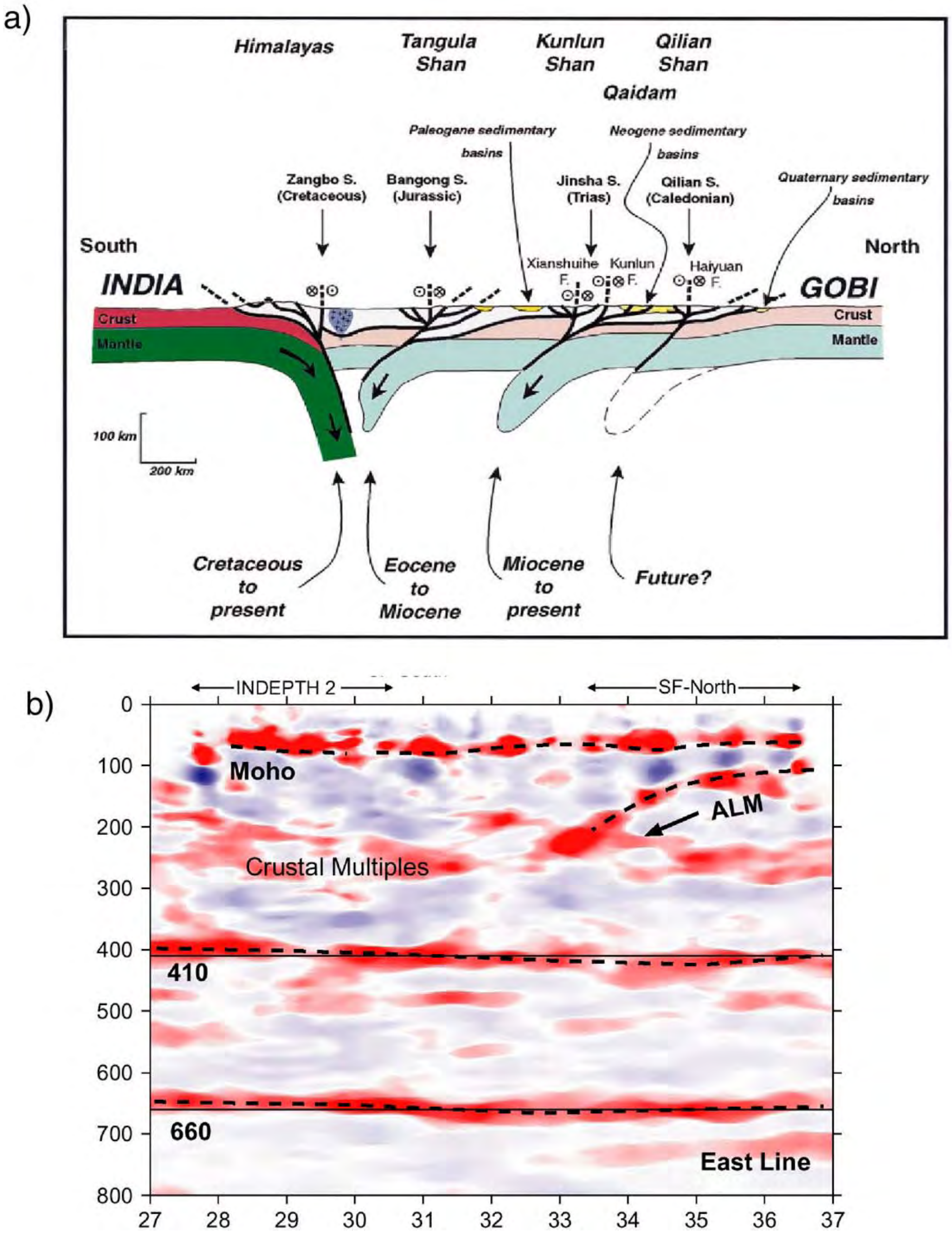

Figure 10: a) Thrust stack model for evolution of NE Tibet plateau (after Meyer et al., 1998). b) Receiver function profile across NE Tibet interpreted to support underthrusting (after Kind et al., 2002).

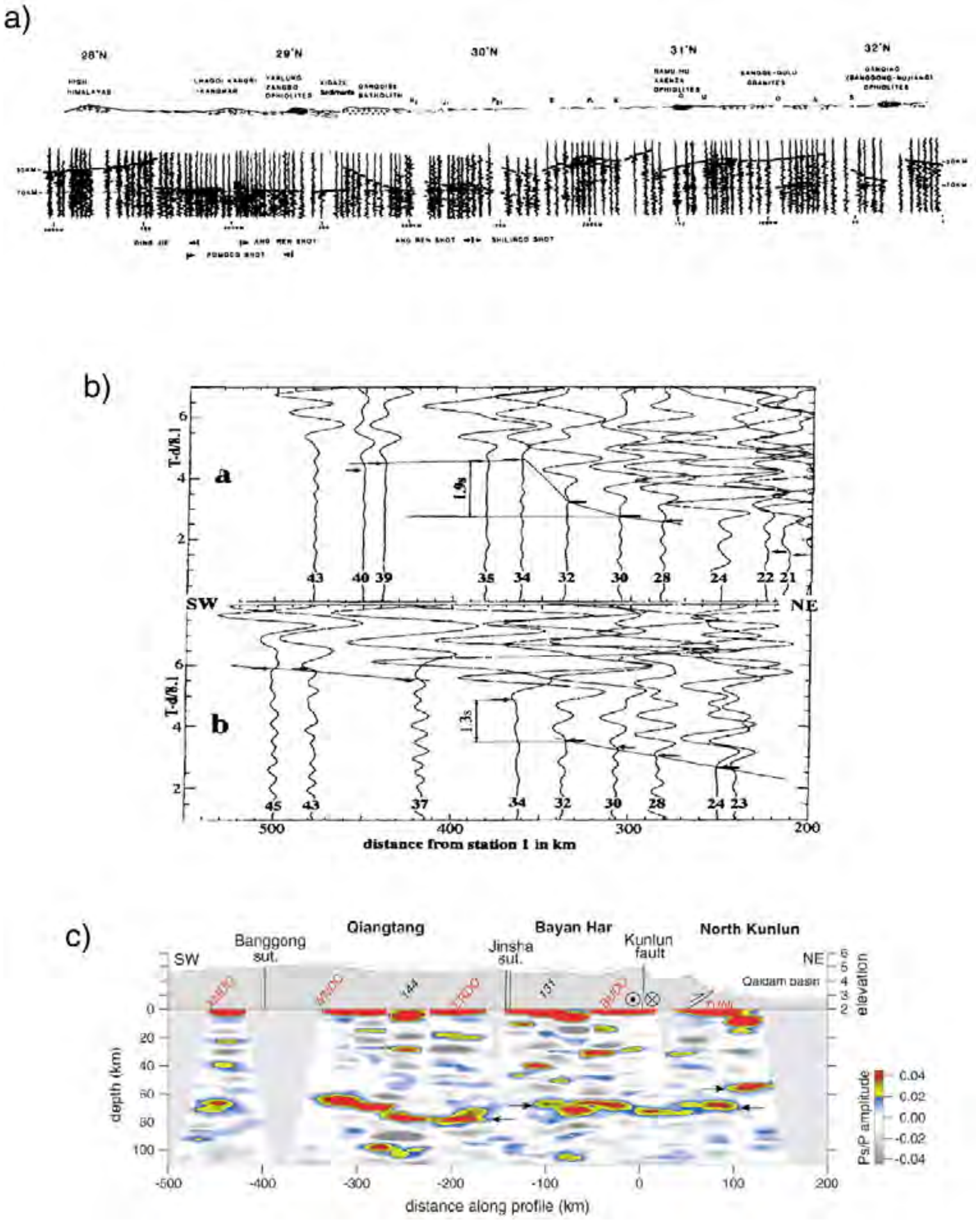

Figure 11: a) Original seismic sections reported to show the existence of major offsets of the Tibetan Moho (Hirn et al., 1984); b) Time delays attributed to a 15 +/- 5 km offset of the Moho beneath the surface trace of the Jinsha Suture (Wittlinger et al., 1996)- top section corresponds to earthquake from southern Tibet; bottom to earthquake from Altyn Tagh; c) Receiver function profile across the Jinsha Suture along the Lhasa-Golmud highway (after Vergne et al., 2002).

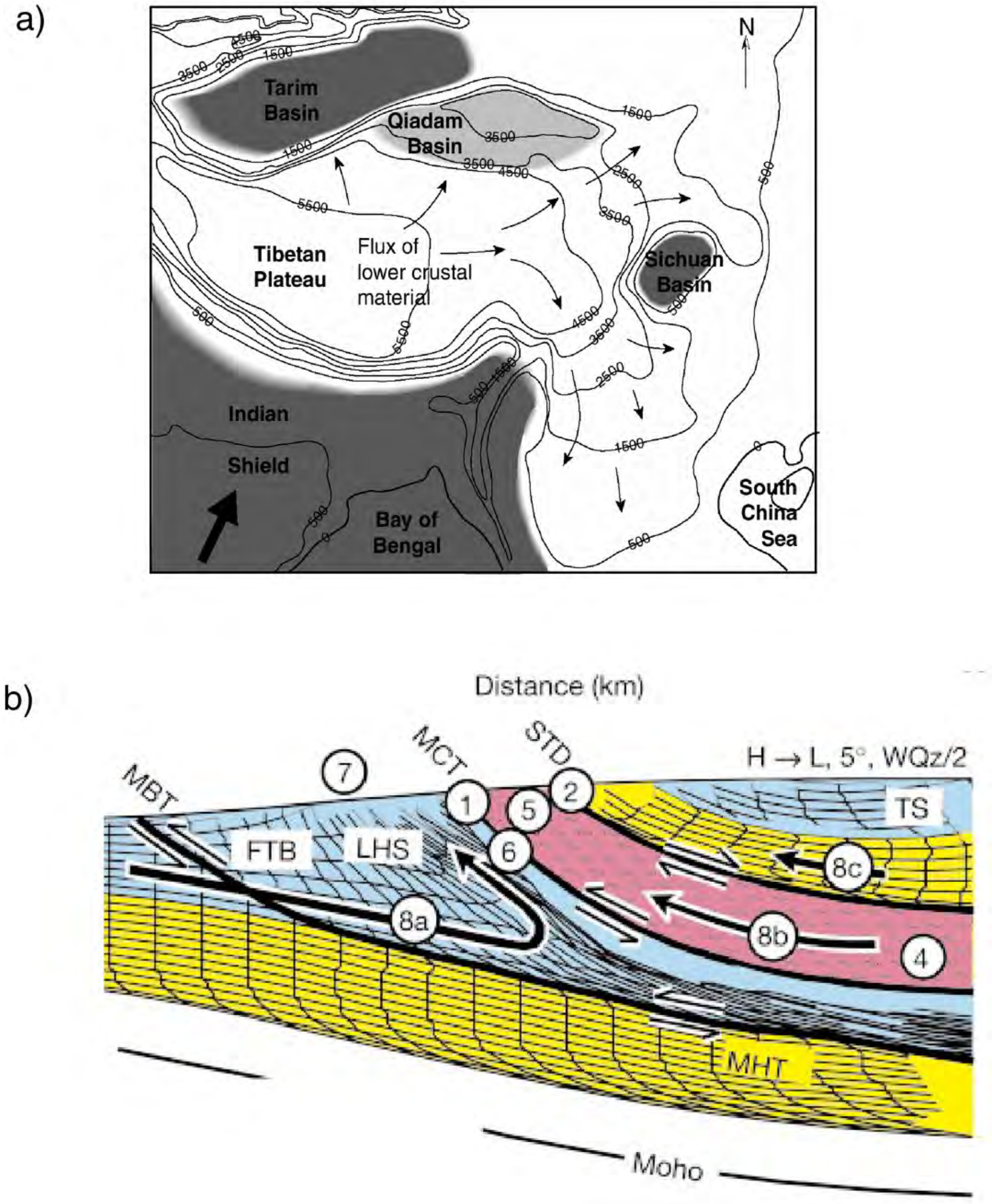

Figure 12. a) Proposed patterns of lower crustal flow beneath the Tibet plateau (Clark and Royden, 2000). b) Channel flow model for Himalayan extrusion (after Beaumont et al., 2001).

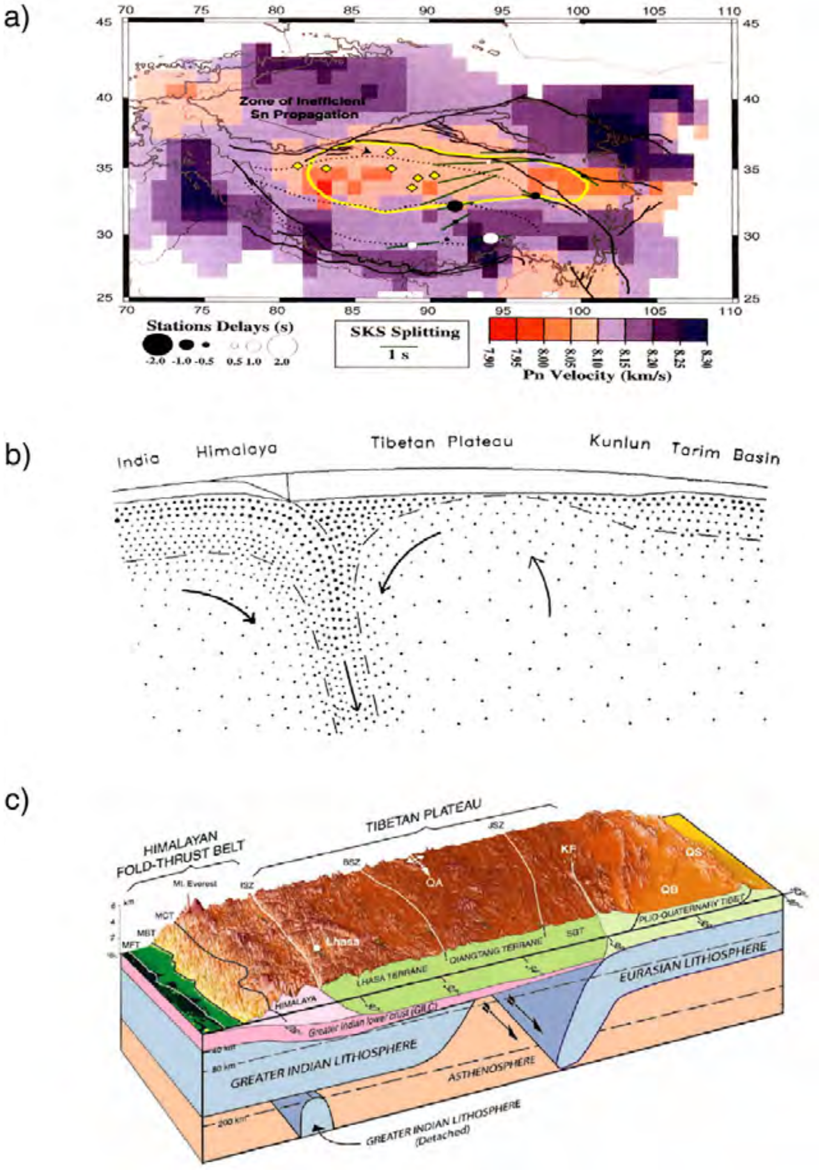

Figure 13. a) Region of low Pn velocity and high Sn attenuation in northern Tibet (after McNamara et al., 1997). Areas of Neogene potassic volcanism indicated by yellow triangles. These observations have been interpreted to indicate thinned mantle lithosphere beneath northern Tibet. Such thinning has been variously attributed to b) mantle counterflow to Indian subduction (e.g. Molnar, 1990) or some c) form of lithospheric delamination/detachment (e.g. DeCelles et al., 2002).

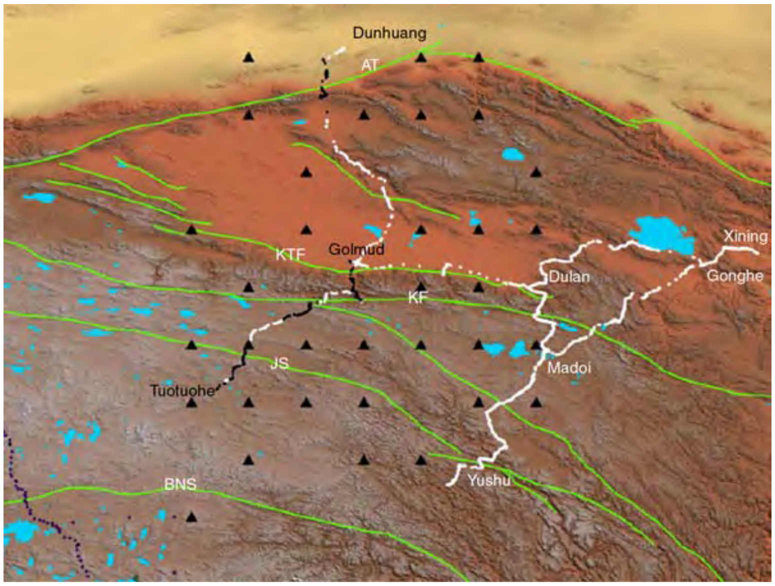

Figure 14. Routes scouted for INDEPTH IV in August-September of 2003. Black triangles represent the proposed 2D broadband array for INDEPTH IV. The black dots indicate the locations for the high resolution geophysical profiles. Blue squares are stations used in INDEPTH III.

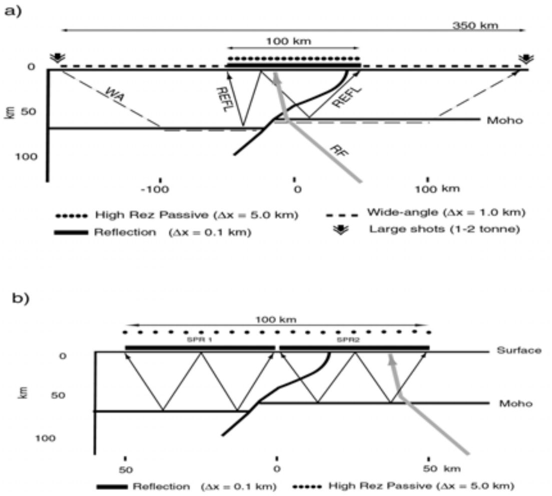

Figure 15. a) Design of high-resolution active-passive profiles. In addition to the shots provided by the reflection component, 2 additional large shots (1-2 tonne kg) will be set off at each end of the refraction/wide-angle profile. b) Details of reflection and high-resolution passive profile. The reflection component will consist of two deployments of 500 instruments (Texans) each. Reflection shots (nominal 100 kg) will be placed every 1 km within each deployment.

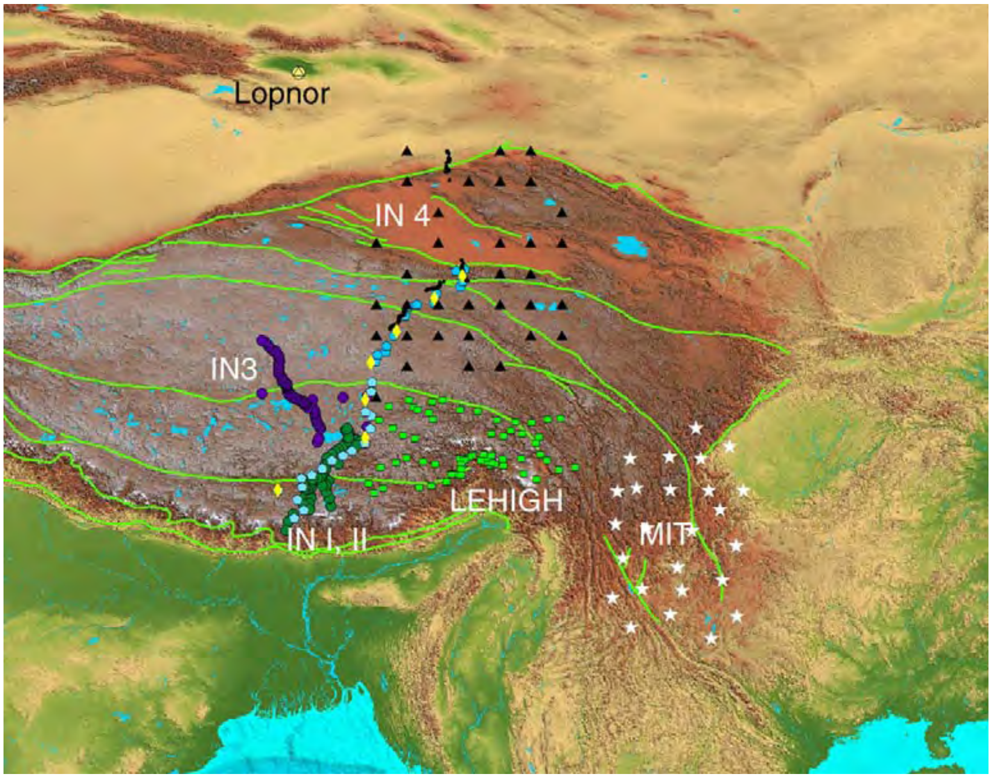

Figure 16. Proposed distribution of broadband stations for 3D mantle tomography (black triangles), in context of previous broadband surveys and arrays. White stars- MIT broadband study of eastern Plateau margin. Green squares- Lehigh broadband study of eastern Tibetan syntaxis. Blue octagons- 1993 Sino-French broadband stations along Lhasa-Golmud Highway (Wittlinger et al., 1996)). Yellow diamonds- 1990 Sino-US broadband stations along Lhasa-Golmud highway (Owens et al., 1993).

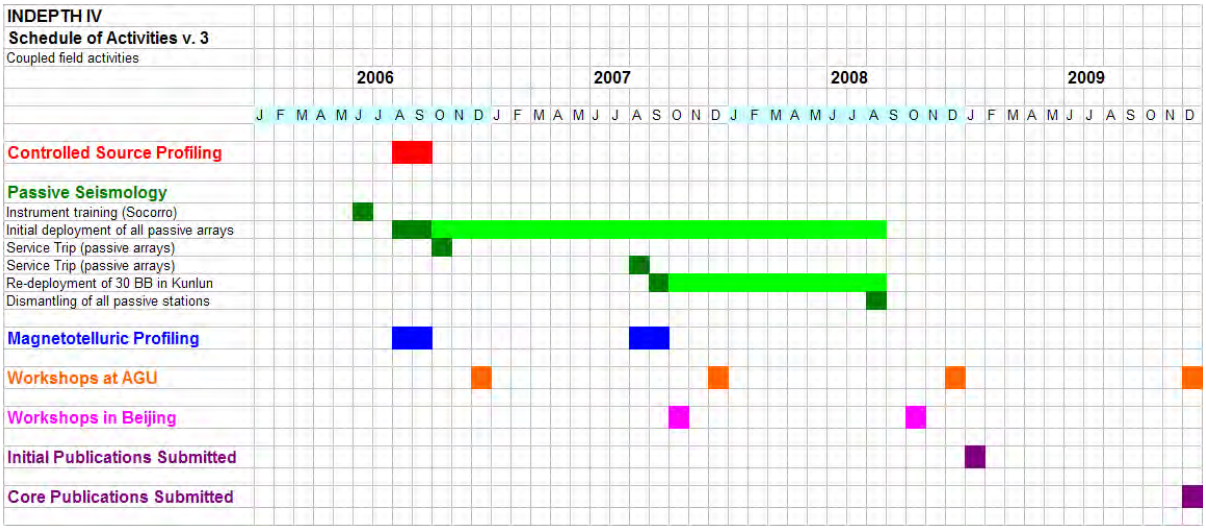

Figure 17. Proposed schedule of INDEPTH IV activities.

References

Allegre, C., et al. (1984). Structure and evolution of the Himalaya-Tibet orogenic belt, *Nature*, **307**, 17-22.

Allmendinger, R.W., J.W. Sharp, D. von Tish, L. Serpa, L. Brown, S. Kaufman, and J. Oliver (1983). Cenozoic and Mesozoic structure of the eastern Basin and Range province, Utah, from COCORP seismic reflection data, *Geology*, **11**, 532-536.

ANCORP Working Group (1999). Seismic reflection image revealing offset of Andean subduction-zone earthquake locations into oceanic mantle, *Nature*, **397**, 341-344.

Argand, E. (1924). La tectonique de l'Asie, *Int. Geol. Cong. Rep. Sess*., **13(1)**, 170-372.

Barazangi, M. and J. Ni (1982). Velocities and propagation characteristics of Pn and Sn beneath the Himalayan Arc and Tibetan Plateau; possible evidence for underthrusting of Indian continental lithosphere beneath Tibet, *Geology* **10,** 179-185.

Baumgardt, D., K. A. Ziegler (1988), Spectral evidence for source multiplicity in explosions; applications to regional discrimination of earthquakes and explosions, B*ull. Seism. Soc. Amer*., **708**, 1773-1795.

Beaumont, C., R. A. Jamieson, M. H. Nguyen, and B. Lee (2001). Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation, *Nature* **414,** 738-742.

Bedrosian, P.A., M.J. Unsworth and F. Wang, Structure of the Altyn Tagh Fault and Daxue Shan from magnetotelluric surveys: implications for faulting associated with the rise of the Tibetan Plateau, *Tectonic*s, **20**, 474-486, 2001.

Blisniuk, P., B. Hacker, L. Glodny, L. Ratschbacher, S. Bi, Z. Wu, M. McWilliams, and A. Calvert (2001). Normal faulting in central Tibet since at least 13.5 Myr ago, *Nature*, **412**, 628 – 632.

Brown, L. D., W. Zhao, K. D. Nelson, M. Hauck, D. Alsdorf, A. Ross, M. Cogan, M. Clark, X. Liu, and J. Che (1996). Bright Spots, Structure and Magmatism in Southern Tibet from INDEPTH Seismic Reflection Profiling, *Science* **274,** 1688-1690.

Brown, L.D. (2000). Case studies in the New Lithospheric Seismology: Projects INDEPTH and URALS, *Comm. Dublin Inst. Advanced Studies, Series D., Bull.* **49**, 6-8.

Burchfiel, B.C., Q. Deng, P. Molnar, L.H. Royden Y. Wang et al (1989). Intracrustal detachment with zones of continental deformation, *Geology*, **17**, 748-752.

Burkhardt, H., R. Vees (1976). Seismic signals from quarry blasts, in C. Prodehl and C. Stein (eds), *Explosion seismology in Central Europe; data and results*, 62-72.

Choukroune, and 30 others (1988). The ECORS deep reflection seismic survey across the Pyrenees, *Nature*, **331**, 508-511.

Chemenda, A.I., J-P. Burg, and M. Mattauer (2000). Evolutionary model of the Himalaya-Tibet system: geopoem based on new modeling, geological and geophysical data, *Earth Planet. Sci. Lttrs*, **174**, 397-409.

Chen, W.-P., and P. Molnar (1983). Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere, *J. Geophys. Res*., **88**, 4183-4214.

Chen L., J. Booker, A. Jones, W. Nong, M. Unsworth, W. Wei, and H. Tan (1996). Electromagnetic Images of Colliding Continents: A Magnetotelluric Survey of the Tsangpo Suture Zone and Surrounding Regions, *Science* **274,** 1694-1696.

Clark, M. and L. Royden (2000). Topographic ooze: Building the eastern margin of Tibet by lower crustal flow, *Geology* **28,** 703-706.

Chen, W.-P., C.-Y. Chen, and J.L. Nabelek (1999). Present-day deformation of the Qaidam basin with implications for intra-continental tectonics, *Tectonophys*., **305**, 165-181.

Cook, F. A., A. J. van der Velden, K. W. Hall, B. J. Roberts, (1998). Tectonic delamination and subcrustal imbrication of the Precambrian lithosphere in northwestern Canada mapped by Lithoprobe, *Geology*, **26**, 839-842.

Cowgill, E. A. Yin, T.M. Harrison, and W. Xiao-Feng (2003). Reconstruction of the Altyn Tagh fault based on U-PB geochronology: role of back thrusts, mantle sutures and heterogeneous crustal strength in forming the Tibetan Plateau, *J. Geophys. Res*., **108**, 2346-1374.

D'Andrea, T.M. Harrison, M. Grove, D. Lin (2001). The thermal evolution of the Nyainqentanglha Shan; evidence for a long-lived, lower crustal magmatic system in southern Tibet, *Jour. Asian Earth Sci*., **19**, 12-13.

DeCelles, P. G., D. M. Robinson, and G. Zandt (2002). Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau, *Tectonics*, **21**, 1062-1087.

Dewey, J.F. and J. M. Bird (1972). Mountain Belts and the New Global Tectonics, *J. Geophys. Res*., **75**, 257-279.

Dewey, J.F. and K.C. Burke (1973). Tibetan, Variscan, and Precambrian basement reactivation: products of continental collision, *J. Geol*., **81**, 683-692.

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

Diaconescu, C., J. Knapp, L. Brown, D. Steer, and M. Stiller (1998). Precambrian Moho offset and tectonic stability of the East European Platform from the URSEIS deep seismic profile, *Geology*, **26**, 211-214.

Edwards, M.A., W.S.F. Kidd, J. Li, Y. Yue, and M. Clark (1966). Multi-stage development of the southern Tibet detachment system near Khula Kangri : new data from Gonto La, *Tectonophys*., **260**, 1-20.

Edwards, M.A., and T.M. Harrison (1997) When did the roof collapse ? Late Miocene N-S extension in the High Himlaya revealed by Th-Pb monazite dating of the Khula Kangri granite, *Geology*, **25**, 543-46.

England, P. and G. Houseman, (1989) Extension during continental convergence, with application to the Tibetan Plateau, *J. Geophys. Res*., **94**, 17561-17569.

Fielding, E., B. Isacks, M. Barazangi, and C. Duncan (1994). How flat is Tibet? *Geology* **22,** 163-167.

Gansser, A. (1964). *The geology of the Himalayas.* Interscience, New York.

Gao, R.., D. Huang, D. Lu, G. Qin. Y. Li, C. Kaugn, Q. Li, P. Li, R. Feng, and Ye Guan (2000), Deep seismic reflection profile cross the junction zone between the Tarim basin and thw

Gao, R., P. Li, Q. Li, Y. Guan, D. Shi, X. Kong, H. Liu (2001). Deep process of the collision and deformation on the northern margin of the Tibetan Plateau: Revelation from investigation of the deep seismic profiles, *Science in China*, **44** (Supp.), 71-78.

Green, A. G., B. Milkereit, A. Davidson, C. Spencer, D.R. Hutchinson, W.F. Cannon, M. Lee, W.F. Agena, J.C. Behrendt, W.J. Hinze, (1988). Crustal structure of the Grenville Front and adjacent terranes, *Geolog*y, **16**, 788-792.

Gu, X.X. (1994). Geochemical characteristics of the Triassic Tethys-turbidites in northwestern Sichuan, China: implications for provenance and interpretation of the tectonic setting, *Geochim. Cosmochim. Acta*, **58**, 4615-1631.

Haines, S., S. L. Klemperer, L. Brown, J. Guo, J. Mechie, R. Meissner, K. D. Nelson, A. Ross, and W. Zhao (2003). Crustal thickening processes in central Tibet: implications of INDEPTH III seismic data, *Tectonics,* **22**, 1-18.

Hacker, B.R., E. Gnos, L. Ratschbacher, M. Grove, M. McWilliams, S.V. Sobolev, J. Wan, Z. Wu, *Science*, **287**, 2463-2466.

Harris, N.B.W., R. Xu, C.L. Lewis, C.J. Hawkesworth, Y. Xhang, (1988). Isotope geochemistry of the 1985 Tibet Geotravese, Lhasa to Golmud, Phil. Trans. *R. Soc. Lond.,* **A327**, 263-285.

Hauck, M. L., K.D. Nelson, L.D. Brown, W.J. Zhao, and A.R. Ross, (1998). Crustal Structure of the Himalayan Orogen from Project INDEPTH Deep Seismic Reflection Profiles at ~90°E, *Tectonics*, *17*, 481-500, 1998.

Hawman, R., M.C. Chapman, C.A. Powell, J.E. Clippard, H.O. Ahmed, 2001, Wide-angle reflection profiling with quarry blasts in the eastern Tennessee seismic zone, *Seismol. Res. Letters*, **72**, 108-122.

Hearn, T., X. Xiano, J. Ni, W. Zhao, (2000), Pn velocity beneath central Tibet, *EOS Transactions, AGU.*

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

Hirn, A., et al., (1995). Seismic anisotropy as an indicator of mantle flow beneath the Himalayas and Tibet, *Nature*, **375**, 571-574.

Herquell, G., G. Wittlinger, and J. Guilbert (1995). Anisotropy and crustal thickness of Northern Tibet- New constraints for tectonic modeling, G*eophys. Res. Lttrs*, **22**, 1925-1928.

Herquel, G, P. Tapponnier, G. Wittlinger, J. Mei, D. Shi, (1999). Teleseismic shear wave splitting and lithospheric anisotropy beneath and across the Altyn Tagh Fault, *Geophysical Research Letter*s, **26**, 3225-3228.

Huang, W., J. Ni, F. Tilmann, K. D. Nelson, J. Guo, W. Zhao, J. Mechie, R. Kind, J.Saul, R. Rapine, and T. Hearn (2000). Seismic polarization anisotropy beneath the central Tibetan Plateau, *J. Geophys. Res.* **105,** 27979-27989.

Kao, H., G. Rui, R.-J. Rau, D. Shi, R.-y. Chen, Ye. Guan, F.T. Wu (2001). Seismic image of the Tarim Basin and its collision with Tibet, *Geology*, **29**, 575-578.

Kapp, P. A. Yin, C. Manning, M. Murphy, T.M. Harrison, M. Spurlin, D. Lin, D. Xi-Guang, and W. Cun-Ming (2000). Blueschist-bearing metamorphic core complexes in the Qiantang block reveal deep crustal structure of northern Tibet, *Geology*, **29**, 19-22.

Ito, E., T. Katsura (1989). A temperature profile of the mantle transition zone, Geophys. Res. Lttrs, **16**, 425-428.

Kind, R., X Yuan, J. Saul, D. Nelson, S.V. Sobolev, J. Mechie, W. Zhao, G. Kosarev, J. Ni, U.Achauer, M. Jiang. 2002, Seismic images of crust and upper mantle beneath Tibet: Evidence for Eurasian plate subduction, *Science,* **298**, 1219-1221.

Klemperer, S.L., T.A. Hauge, E.C. Hauser, J.E Oliver, and C.J. Potter (1986). The Moho in the Northern Basin and Range Province, Nevada, Along the COCORP 40 N Seismic Reflection Transect, *Geol. Soc. Am. Bull.*, **97**, 603-618.

Klemperer, S.L., and W.D. Mooney (1998). Deep Seismic Profiling of the Continents, I and II**,** *Tectonophysics, Special Issues*, **286**.

Langin, W. R., L. D. Brown, E. A. Sandvol, and Project INDEPTH Team, Seismicity of central Tibet from INDEPTH III seismic recordings (2003). *Bull. Seismol. Soc. Amer.,* **93***, 2146-2159.*

Li, S., M.J. Unsworth, J.R. Booker, W. Wei, H. Tan and A.G. Jones, Partial melt or aqueous fluids in the Tibetan crust: constraints from INDETH magnetotelluric data, *Geophys. J. Int.*, **153**, 289-304, 2003.

Lin, A., B. Fu, J. Guo, Q. Zeng, G. Dang, W. He, and Y. Zhao (2003). Co-seismic strike slip and rupture length produced by the 2001 Ms 8.1 Central Kunlun earthquake, *Science*, **296,** 2015-2017.

McNamara, D.E., W.R. Wlater, T.J. Owens, and C.J. Ammons, 1997, *J. Geophys. Res.*, **102**, 493-505.

Makovsky, Y., S. L. Klemperer, L. Huang and D. Lu, (1996), Structural elements of the southern Tethyan Himalaya crust from wide-angle seismic data. *Tectonics*, **15**, 997-1005.

Makovsky, Y., and S. Klemperer (1999). Measuring the Seismic Properties of Tibetan Bright Spots: Evidence for Free Aqueous Fluids in the Tibetan Middle Crust, *J. Geophys. Res.* **104,** 10795-10825.

Makovsky, Y., S.L., Klemperer, L. Ratschbacher, D. Alsdorf, (1999). Midcrustal reflector on INDEPTH wide angle profiles; an ophiolitic slab beneath the India-Asia suture in southern Tibet? *Tectonics, 18*, 793-808.

Mechie, J. S.V. Sobolev, L. Ratschbacher, A. Yu. Babeyko, G. Bock, A.G. Jones, K.D. Nelson, K.D. Solon, L.D. Brown, and W. Zhao (2003). Precise temperature estimation in the Tibetan crust from seismic detection of the a-b quartz transition, submitted to *Geology*.

Meyer, B. P. Tapponnier, L. Bourjot, F. Metivier, Y. Gaudemer, et al. (1998). Crustal thickening in Gansu-Qinghai, lithospheric mantle subduction, and oblique, strike-slip controlled growth of the Tibet Plateau, *Geophys. J. Int.*, **135**, 1-47.

Matthews, D., and A. Hirn (1984). Crustal thickening in Himalayas and Caledonides, *Nature*, **308**, 497-498.

McGeary, S., and M. Warner (1985). Seismic profiling the continental lithosphere, *Nature*, **317**, 795-797.

Molnar, P., (1988). A review of the geophysical constraints on the deep structure of the Tibetan Plateau, the Himalaya and teh Karakoram, and their tectonic implications, *Philos. Trans. R. Soc. London, Ser. A*, **326**, 33 – 88.

Molnar, P., and P. Tapponier (1975). Cenozoic Tectonics of Asia: Effects of a Continental Collision, *Science* **189,** 419-426.

Molnar, P. and P. Tapponnier (1978). Active Tectonics of Tibet, *J. Geophys. Res.* **83,** 5361-5375.

Nelson K. D. and 28 others (1996). Partially molten middle crust beneath southern Tibet; synthesis of Project INDEPTH results, *Science* **274,** 1684-1688.

Ni, J., and M. Barazangi, High-frequency seismic wave propagation beneath the Indian Shield, Himalayan Arc, Tibetan Plateau and surrounding regions: High uppermost mantle velocities and efficient Sn propagation beneath Tibet (1983). *Geophys. Jour. Royal Astro. Soc.*, **72**, 665 – 689.

Ni, J. and M. Baranzangi (1984), Seismotectonics of the Himalayan collision zone: geometry of the undethrusting Indian plate beneath the Himalaya, *J. Geophys. Res,* **89**, 1147-63.

Nie, S., A. Yin, D. Rowley, Y. Jin (1994). Exhumation of the Dabie shan ultra-high pressure rocks and accumulation of the Songpan-Ganzi flysch sequence, central China, *Geology*, **22**, 999-1002.

Onishi, M., T. Kawamura, E. Kurashimo, T. Ikawa, and T. Ito (2003). Deep seismic reflection experiment with a dense array of seismograms and sparse shot-spacing for the deep structure of the Median Tectonic Line (MTL) in east Shikoku, Japan, *Geophys. J. Int.*, submitted.

Owens, T., and G. Zandt (1997). Implications of crustal property variations for models of Tibetan Plateau evolution, *Nature*, **387**, 37 – 43.

Peltzer, G., and P. Tapponnier (1988). Formation and evolution of strike-slip faultsk, rifts, and basins during the India-Asia collision: an experimental approach, *J. Geophys. Res.*, **93**, 15085-15117.

Powell, C.M., and P.G. Conaghan (1973). Plate tectonics and the Himalayas, *Earth Planet. Sci. Lett*. **20**, 1-12.

Quidelleur, X., M. Grove,O. M. Lovera, T. M. Harrison, A. Yin, F. J. Ryerson, F. J. (1997). Thermal evolution and slip history of the Renbu Zedong Thrust, southeastern Tibet, *J. Geophys. Res., 102*, 2659-2679.

Ross, A.R., L.D. Brown, P. Pananont, K.D. Nelson, S. Klemperer, S. Haines, Z. Wenjin, and J. Guo, Deep reflection surveying in central Tibet: Lower crustal layering and crustal flow, *Geophys. Jour Int.*, **in press**.

Sandvol, E. A., J.F. Ni, R. Kind et al. (1997). Seismic anisotropy beneath the southern Himalayas-Tibet collision zone, *J. of Geophys. Res., B*, **102**, 17,813-17,823

Sengor, C., and K. Hsu (1984). The Cimmerides of eastern Asia; history of the eastern end of Paleo-TethysThe Cimmerides of eastern Asia, *Mem. Societe Geologique de France*, **147**, 139-167.

Sengor, A.M.C.(1990). Plate tectonics and orogenic research after 25 years: a Tethyan perspective, *Earth. Sci. Rev.*, **27**, 1-201.

Silver, P.G., and W.E. Holt (2002), The mantle flow beneath western North America, *Science*, **5557**, 1054-1058.

Spratt, J. E., A. G. Jones, K. D. Nelson, M. J. Unsworth, and the INDEPTH team, 2003. Crustal structure of the India-Asia collision zone, southern Tibet, from INDEPTH MT investigations, *Physics of the Earth and Planetary Interiors*, submitted.

Shi, D., W. Zhao, L. Brown, D. Nelson, X. Zhao, R. Kind, J. Ni, J. Xiong, J. Mechie, J. Guo, S. Klemperer, T.Hearn , (2003) Detection of southward intra-continental subduction of Tibetan lithosphere along the Bangong-Nujiang suture by P-to-S converted saves, **Geology**, *in press*.

Smithson, S.B., J.A. Brewer, S Kaufman , J.E. Oliver , and C. Hurich (1979). Structure of the Laramide Wind River Uplift, Wyoming, from COCORP Deep Reflection Data and from Gravity Data, *J. Geophys. Res*., **84**, 5955-5972.

Song, T. and X. Wang (1993). Structural styles and stratigraphic patterns of syndepositional faults in a contractional setting: example from Quaidam basin, northwestern China, *Am. Assoc. Petr. Geol. Bull*.,**77**, 102-117.

Tapponnier, P. and P.J. Molnar (1976). Slip-line field theory and large-scale continental tectonics, *Nature*, **264**, 3190-24.

Tapponnier, P., G. Peltzer, R. Armijo, (1986). On the mechanics of the collision between India and Asia, *Geol. Soc. Lond., Spec. Publ*., **19**, 115-157.

Tapponnier, P., B. Meyer, J.P. Avouac, G. Peltzer, Y. Gaudemer, S. Guo, H. Xiang, K. Yin, Z. Chen, S. Dai, H. Dai (1990). Active thrusting and folding in the Qilian Shan, and decoupling between upper crst and mantle in northeastern Tibet, Earth Planet. Sci., Lett., 97, 382-403.

Tapponnier, P., Z. Xu, F. Roger, B. Meyer, N. Arnaud, G. Wittlinger, and J. Yang (2001). Oblique stepwise rise and growth of the Tibet plateau, *Science* **294,** 1671-1677.

Yin, A., and S. Nie (1996). A Phanerzoic palinspastic reconstruction of China and its neighboring regions, in **The Tectonics of Asia,** A. Yin and T.M. Harrison (eds.), Cambridge Univ. Press, N.Y. 442-485.

Yin, A., and M.T. Harrison (2000) Geologic evolution of the Himalayan-Tibetan crust, Ann. *Rev. Earth Plan. Sci*., **28**, 211 - 280,

Yuan, X., J. Ni, R. Kind, J. Mechie and E. Sandvol (1997). Lithospheric and Upper Mantle Structure of Southern Tibet from a Seismological Passive Source Experiment, *J. Geophys. Res*., **102**, 27491-27500.

Unsworth, M.J., A.G. Jones, W. Wei, J.R. Booker, S. Gokarn, G. Marquis, The Electrical Structure of the Tibetan-Himalayan Orogen, paper S61D-03, F993, *Fall Meeting of AGU*, December 2002.

Unsworth, M., W. Wei, A. G. Jones, S. Li, P. Bedrosian, J. Booker, J. Sheng, D. Ming, and T. Handong, 2003, Crustal and upper mantle structure of Northern Tibet imaged with magnetotelluric data, *J. Geophys. Res*., in press.

Unsworth, M.J., W.Wei, A.G. Jones and INDEPTH-MT team, East-west variations in the geoelectric structure of Southern Tibet and the Himalaya, in preparation for submission to *Geology*, 2004.

Vergne, J., G. Wittlinger, Q. Hui, P. Tapponnier, G. Poupinet, J. Mei, G. Herquel, A. Paul (2002), Seismic evidence for stepwide thickening of the crust across the NE Tibetan Plateau, *Earth Planet. Sci. Letters*, **203**, 25-33.

Wang, Q., and M.P. Coward (1990). The Chaidam basin (NW China): formation and hydrocarbon potential, *J. Petro. Geol*, **13**, 93-112.

Wang, Y., W.D. Mooney, X. Yuan, and R.G. Coleman (2003). The crustal structure from the Altai mountains to the Altyn Tagh fault, northwest China, J. Geophys. Res., 108, 2322.

Wei, W., M. Unsworth, A. Jones, J. Booker, H. Tan, K. D. Nelson, L. Chen, S. Li, K. Solon, P. Bedrosian, S. Jin, M. Deng, J. Ledo, D. Kay, and B. Roberts (2001).

Detection of widespread fluids in the Tibetan crust by magnetotelluric studies, *Science* **292,** 716-718.

Willett, S., D., and C. Beaumont (1994). Subduction of Asian lithospheric mantle beneath Tibet inferred from models of continental collision, *Nature*, 369, 642-45.

Wissinger, A. Levander, N. I. Christensen, 1997, Seismic images of crustal duplexing and continental subduction in the Brooks Range, *J. of Geophys. Res., B*, **102**, 20,847-20,871.

Wittlinger, G., F. Masson, G. Poupinet, P. Tapponnier, J. Mei, G. Herquel, J. Guilbert, U. Achauer, X. Guanqi, S. Danian, Lithoscope Kunlun Team, (1996), Seismic tomography of northern Tibet and Kunlun: Evidence for crustal blocks and mantle velocity contrasts, *Earth. Planet. Sci. Letters*, **139**, 263-279.

Wittlinger, G., P. Tapponnier, G. Poupinet, M. Jian, D. Si, et al, (1998). Tomographic evidence for localized lithospheric shear along the Altyn Tagh fault, *Science*, **282**, 74-76.

Wu, C., K.D. Nelson, G. Wortman, S. Samson, Y. Yue, et al. (1998). Yadong cross structure and South Tibetan detachment in the east central Himalaya (89º-90ºE), *Tectonics*, **17**, 28-45.

Wu, Z. , L. Qisheng, D. Hu, X. Zhao, W. Jiang and Y. Peishen, (2003). Time and emplacement of the Nyainqentanglha Granite in Central Lhasa Block of the Tibetan Plateau, *Tectonics*, **in review**.

Wu, Z.., D. Hu, Y. Peisheng, X. Zhao, Q. Liu, (2003). Thrusting of north Lhasa Block in the Tibetan Plateau, to be submitted to *Acta Geologica Sinica*..

Wu, Z., P. J. Barosh, D. Hu, W. Zhonghai, Z. Xitao, Ye. Peisheng and J. Wan, Geological Hazards Induced by Active Faults in the Vicinity of the Golmud-Lhasa Railway across the Tibetan Plateau, to be submitted to *Engineering Geology*.

Yin, A, M. Harrison, F.J. Ryerson, C. Wenji, W.S.F. Kidd, P. Copeland, (1994). Tertiary structural evolution of the Gangdese thrust system, southwestern Tibet, *J. Geophys. Res*., **99**, 18,175-18,201.

Yin, A. and T. M. Harrison (2000). Geologic evolution of the Himalayan-Tibetan orogen, *Ann. Rev. Earth Plan. Sci.* **28,** 211-280.

Zhao, W., and W. J. Morgan (1987). Injection of Indian crust into Tibetan lower crust: A two-dimensional finite element model study, *Tectonics* **6,** 489-504.

Zhao, L.-S., and D.V. Helmberger (1991), Geophysical implications from relocations of Tibetan earthquakes: hot lithosphere, *Geophys. Res., Lett.*, **18**, 2205-2208.

Zhao, W., K. D. Nelson, J. Che, J. Guo, D. Lu, C. Wu, X. Liu, L. D. Brown, M. L. Hauck, J. T. Kuo, S. Klemperer, and Y. Makovsky (1993). Deep seismic reflection evidence for continental underthrusting beneath southern Tibet, *Nature* **366,** 557-559.

Zhao, W., J. Mechie, L. Brown, J. Guo, S. Haines, T. Hearn, S. Klemperer, Y. Ma, R. Meissner, K. D. Nelson, J. Ni, P. Pananont, R. Rapine, A. Ross, and J. Saul (2001), Crustal structure of central Tibet as derived from project INDEPTH wide-angle seismic data, *Geophys. J. Int.* **145,** 486-498.

Zelt, C.A. (1999). Modelling strategies and model assessment for wide-angle seismic traveltime data, *Geophys. J. Int.*, **139**, 183-204.

From: shidanian [shidanian@cags.cn.net]
Sent: Thursday, November 20, 2003 5:34 AM
To: brown@geology.geo.cornell.edu
Cc: shidanian@cags.cn.net
Subject: Re: INDEPTH IV: Need updated quotes for field expenses

Dear Prof. Brown,

Prof. Zhao has attended a meeting in Yunnan province in southern China. I can't contact with him, because he did not take his mobie phone. I will try to contact him for the question 7.

The following are what I can answer you at this moment.

1. Vehicles (including driver and fuel) (per day)
Landcruisers 150 US$/day (1200 RMB/day)
Truck 150 US$/day (1000-1200 RMB/day or enen a bit more than 1200 RBM for a very long distance in a day)

2. Accommodations for non-Chinese scientists: (per day)
Field 38 US$/person/day (300 RMB: 100-150 RMB for hotel, 100-150 RMB for food)
City 60 US$/person/day (500 RMB: 200-400 RMB for hotel, 100-200 RMB for food)

3. Local labor (per person per day)
20 US$/person/day (160 RMB)

4. Entrance feels (if any) for Qinghai (per person)
None if only within Qinghai province (500 US$ for a person's entrence to Tibet autonomous region)

5. Shipping Beijing to Golmud (per kg)

By rail 1 US$/kg (5.90 RMB/kg from Beijing to Golmud, plus a bit money for stocking etc.)
By Air 2 US$/kg (9.78 RMB/kg from Beijing to Xining by air, then some money from Xining to Golmud by rail and a bit money for stocking etc.)

6. Customs (cost per $USD)

(Except we want to import the instruments, we do not need to pay the import tax.)
We only need to pay for the claiming and mortgage at Customs.

The Customs fee are calculated by times. Usually 3000 RMB for one time is enough,
including claiming fee, stocking, shipment from customs for 20 pices x 100 kg boxes in etc.

800 US$ (3000 RMB x 2 times (in + out))

Sometimes we may need pay another 500 US$ to a company for mortgage, if our official letter does't not work at the customs.

7. Reflection recording (cost per km)*

I personly think it is possible to employ a group rather than a seisic crew to drill and shot for us.
I will also ask both Prof. zhao about the gesture for the trading drilling costs for Texans.

I think the cost for the reflection recording with 500 Texans depends on how many shots and what shot interval we will actually use,
how many labors we need. In addition, we may need to take into account the cost for shipping the drill machines to the plateau from other place.

I will answer this question again if more information available.

8. Drilling (cost per 50 m deep shothole)
1000 US$/well (8000 US$/well is usually enough except too few holes to drill and too long distance to move from place to place)

9. Seismic explosives (cost per kg)
2.5 US$/kg (16000-20000 RMB/Ton including detonator and cables)

Cheers
Danian
---------- Original Message ----------------------------------
From: "Larry Brown" <brown@geology.geo.cornell.edu>
Reply-To: <brown@geology.geo.cornell.edu>
Date: Wed, 19 Nov 2003 13:36:33 -0500

>Dear Zhenhan and Danian:
>
>   I am trying to finish up our INDEPTH proposal (due Dec. 1), and need
>some updated information from you. At the meeting in Syracuse last year you
>gave us some quotes, but they may be out of date. Could you provide an
>update for costs of:
>
>1. Vehicles (including driver and fuel) (per day)
>   Landcruisers
>   Truck
>
>2. Accommodations for non-Chinese scientists: (per day)
>   Field
>   City
>
>3. Local labor (per person per day)
>
>4. Entrance feels (if any) for Qinghai (per person)
>
>5. Shipping Beijing to Golmud (per kg)
>   By rail
>   By Air
>
>6. Customs (cost per $USD)
>
>The next items are need some special consideration. Our plan is to use the
>Texan instruments to record the reflection lines (instead of a contract,
>hardwire seismic crew). Thus the main costs will be drilling and shooting,
>please some labor for instrument deployment and recovery. I am currently
>basing my estimate on the expected shot hole spacing to be used with the
>Texans and the drilling costs, rather than the crew costs originally quoted.

>Is this the correct manner of costing the reflection experiment?
>
>We have also discussed trading drilling costs for Texans to be transferred
>to CAGS. We do not have to deal with that issue in this proposal (since
>whether we pay for drilling in CASH or instruments is doesn't affect our
>budget). However, I did want to check and see what the current CAGS feeling
>is about this.
>
>7. Reflection recording (cost per km)*
>
>8. Drilling (cost per 50 m deep shothole)
>
>9. Seismic explosives (cost per kg)
>
>I greatly appreciate you help on this, and hope you can get back to me very
>quickly. We really need to nail down our budgets by next Monday.
>
>
>Cheers
>Larry
>
>* Note on reflection costs. We are preparing our proposal on the presumption
>that we will be using 500 Texans for recording. We will cover the costs of
>shipping and deploying them (using the Tibetan labor costs cited above)
>
>
>
>Larry D. Brown
>Professor and Director of Graduate Studies
>Institute for the Study of the Continents
>Department of Earth and Atmospheric Sciences
>3124 Snee Hall
>Cornell University
>Ithaca, NY 15853 USA
>brown@geology.cornell.edu
>PHONE: 001-607-255-7357
>FAX: 001-607-254-4780
>
>
>

中国地质科学院

CHINESE ACADEMY OF GEOLOGICAL SCIENCES

Address: Baiwanzhuang Road 26
Beijing 100037
People's Republic of China
Tel: +86-(10)-6831-0893
Fax: +86-(10)-6831-0894
E-Mail: cagsdic@public.bta.net.cn
Http: www.cags.cn.net

November 28, 2003

Prof. Larry D. Brown
Cornell University
Ithaca, NY 15853 USA

Dear Prof. Brown:

This letter is to confirm the joint nature of our plans for geophysical and geological studies of the northeast Tibetan boundary zone as part of Project INDEPTH. We hope to continue our collaboration with INDEPTH scientists for the US, Germany and elsewhere in completing our transect of the Himalaya-Tibet region.

Sincerely,

Zhao Xun