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Yadong cross structure and South Tibetan Detachment in the east central Himalaya (89°-90°E)

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Abstract. The Yadong cross structure (YCS), occurring at ~89°30' east longitude in the Himalaya, is the largest across-strike discontinuity in the geologic structure and topography of the High Himalaya between the Himalayan syntaxes. It is manifest by a plan view left offset of the topographic crest of the range and a coincident, apparent, left strike offset of the South Tibetan Detachment System (STDS) of about 70 km. New field mapping indicates that the STDS intersects the west side of the YCS at Zherger La and further suggests that the YCS is the surface expression of a large north-northeast striking west facing lateral ramp in the Himalayan thrust system. The Greater Himalayan allochthon is apparently draped across this lateral ramp, resulting in a north-northeast striking monoclinal flexure of the allochthon manifest in the Chomolhari range. Superimposed steep west-northwest directed normal shear appears to have obliterated earlier northerly directed STDS shear fabric along along the YCS segment of the Tethyan belt/Greater Himalayan belt contact. Recent seismicity suggests that the Greater Himalayan allochthon is still moving southward along the lateral ramp. U-Pb monazite dates on leucogranites in the footwall of the STDS on opposite sides of the YCS are suggestive of a south-to-north decrease in the crystallization age of these granites. The age pattern is consistent with southward "extrusion" of the Greater Himalayan allochthon and suggests the possibility of determining an average slip rate for the STDS by dating granites in the immediate footwall of the STDS that are substantially separated in north-south section. An average slip rate of about 7 mm/yr between 23 and 12 Ma is suggested by the data presented here.

1. Introduction

The Himalayan orogen has been a focus of geologic interest for nearly a century [e.g., *Burrard and Hayden,* 1907; *Gansser,* 1964] and, with the advent of plate tectonics, has generally come to be recognized as the "type-example" of an orogenic belt produced by continent-continent collision [e.g., *Dewey and Burke,* 1973; *LeFort,* 1975; *Allegre et al.,* 1984]. Since the enunciation of plate tectonics, the number and kind of geological investigations taking place within the belt have expanded dramatically. Underlying this interest is the premise that gaining an understanding of the evolution of the Himalaya may provide key insights for deciphering the evolution of older orogenic belts and, to a degree, the continental crust as a whole. During the past several years, interest in the belt has been further stimulated by the suggestion that uplift of the Himalaya and adjacent Tibetan Plateau may have substantially influenced Earth' s climate during the Cenozoic era [e.g., *Harrison et al.,* 1992; *Molnar et al.,* 1993].

One of the striking features of the Himalayan chain is the first-order along-strike continuity of the major lithotectonic units and their bounding faults that comprise the orogen. Thus the Main Boundary Thrust (MBT), Lesser Himalayan metasedimentary belt, Main Central Thrust (MCT), Greater Himalayan belt, South Tibetan Detachment System (STDS), Tethyan sedimentary belt, and Yarlung-Zangbo suture zone (Figure 1) are all traceable for >2000 km along the belt between the Himalayan syntaxes [*Gansser,* 1964; *Searle et al.,* 1987; *Burchfiel et al.,* 1992]. Efforts to understand the crustal-scale structure of the orogen have therefore focused on elucidating the structure in dip section. It is now generally recognized that the Himalayan chain grew by progressive southward structural imbrication of the northern passive margin of India, which began to collide with Asia in Eocene time [e.g., *Searle et al.,* 1987; *Dewey et al.,* 1988]. South vergent thrusting took place along the Yarlung-Zangbo suture and migrated southward into the Tethyan belt in Eocene time [*Burg,* 1983; *Burg and Chen,* 1984; *Ratschbacher et al.,* 1994]. The surface expression of thrusting migrated farther southward in early to middle Miocene time to the MCT, which imbricates a large fraction of the Indian continental crust [*LeFort,* 1975; *Hodges et al.,* 1988], and then farther south to the MBT in late Miocene time [*Schelling and Arita,* 1991; *Burbank et al.,* 1996]. The surface expression of thrusting is currently concentrated on the Main Frontal Thrust (MFT), which crops out along the northern edge of the Ganga basin. Surface geological, earthquake, and deep seismic reflection observations imply that the

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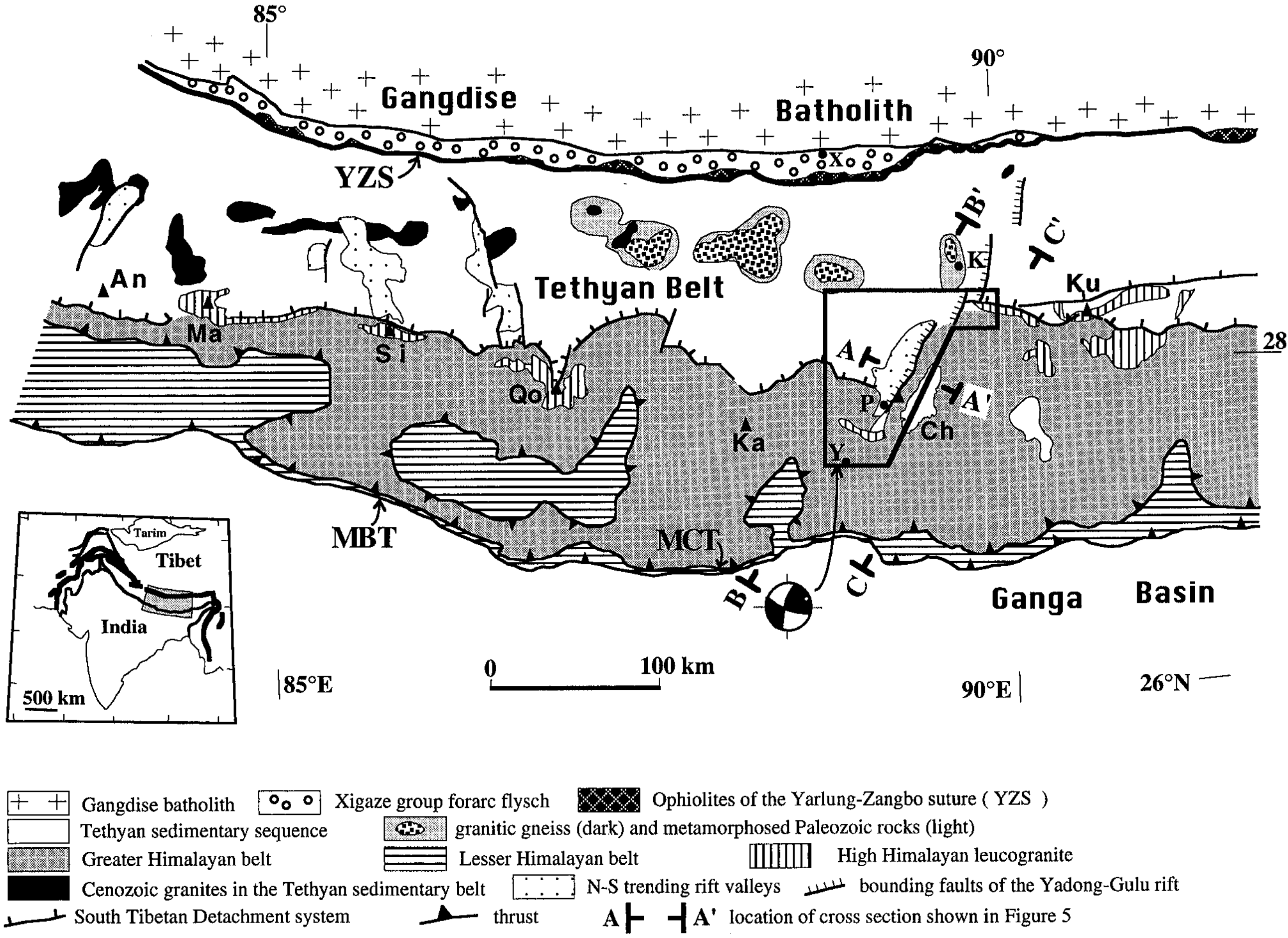

Figure 1. Simplified tectonic map of the central Himalayan orogen [modified from *Burchfiel et al.,* 1992, Figure 1; *Gansser,* 1964]. Polygon shows location of geologic map shown in Plate 1. Beachball indicates focal mechanism of anomalous strike-slip earthquake that occurred on November 19, 1980, in the vicinity of Yadong *(Mb 6* [*Ni and Barazangi,* 1984; *Ekstrom,* 1987]). Major Himalayan peaks are as follows: An, Annapurna; Ch, Chomolhari; Ka, Kangchenjunga; Ku, Khula Kangri; Ma, Manaslu; Qo, Qomolangma (Everest); Si, Sisha Pangma. Towns are as follows: K, Kangmar; P, Pali; X, Xigaze; Y, Yadong.

MFT is the tip of an active basal decollement that dips gently northward beneath the Himalaya and Tethyan belt [*Schelling and Arita,* 1991; *Ni and Barazangi, 1984; Zhao et al.,* 1993]. Zhao et al. [1993] termed this basal decollement the Main Himalayan Thrust (MHT). Recent field geological and thermochronological investigations have additionally shown that there were significant episodes of out-of-sequence thrusting within the evolving Himalayan orogen, notably along the Yarlung-Zangbo suture zone [*Yin et al.,* 1994] and along the MCT [*Macfarlane et al., 1992; Harrison et al.,* 1997]. Last, and of particular relevance to this paper, geological investigations have shown that north-south extension occurred episodically within the evolving Himalayan orogen, while convergence between India and Asia was ongoing.

The principal evidence for north-south extension within the orogen is the South Tibetan Detachment System (STDS) [*Burchfiel et al.,* 1992]. This is a system of Miocene and younger north dipping normal faults that occurs along the north flank of the High Himalaya (Figure 1). Evidence for normal faulting along the Greater Himalayan belt/Tethyan belt contact was first noted by *Burg and Chen* [1984]. Subsequently, *Burchfiel et al.* [1992] described evidence for normal slip along this contact at a number of localities bordering the north flank of the High Himalaya. They noted that east-west trending normal faults cutting earlier formed compressional structures also occur within the Tethyan belt to the north and termed the whole system of Miocene and younger east-west trending normal faults that occur along and immediately north of the High Himalaya the "South Tibetan Detachment System." They showed that the STDS in the Everest area accommodated >30 km of normal displacement during middle Miocene time, and they suggested that it likely extends along the entire length of the Himalayan chain [*Burchfiel et al.,* 1992]. Geological investigations in the far western Himalaya have shown the STDS does, indeed, extend along most, if not all, of the chain [*Searle,* 1986; *Herren,* 1987; *Searle et al.,* 1988]. It is thus a fundamental feature of the orogen. In the period since the STDS was recognized, a number of geochronological investigations have been undertaken with the aim of constraining the timing of normal slip on the detachment system (discussed subsequently), and several additional structural descriptions of portions of the detachment system have been published [e.g., *Edwards et al.,* 1996; *Hodges et al.,* 1996; *Searle et al.,* 1997].

The STDS is of interest because its existence implies that north-south extension has occurred within the upper structural level of the Himalayan orogen contemporaneously with north-south lithospheric convergence across the belt [*Burg and Chen,* 1984; *Burchfiel and Royden,* 1985]. Thermal modeling studies have additionally shown that the STDS probably played a central role in the metamorphic and magmatic evolution of the Himalaya [*Royden,* 1993; *Henry and LePichon,* 1997]. In particular, there is likely to have been a genetic relationship between the generation and emplacement of the High Himalayan leucogranites and slip on the STDS [e.g., *England and Molnar,* 1993]. As the former are arguably the world's type example of collisional granites and the latter is the type example of an extensional fault system within an active collisional orogen, the issue is of general interest. It has been argued that normal slip on the STDS triggered decompression melting within the underlying Himalayan thrust wedge [e.g., *England and Molnar,* 1993] and conversely that weakening of the Himalayan thrust wedge, caused at least in part by internal melting, triggered normal slip on the STDS [e.g., *Nelson et al.,* 1996]. Given the present state of knowledge, both scenarios seem possible.

In this paper, we describe the STDS in the vicinity of 89° east longitude in the Himalaya, together with a related feature in the area called the Yadong cross structure (YCS). The bedrock geology of this area has not previously been described but potentially provides several new insights into the nature and along-strike variability of the STDS, the nature of along-strike discontinuities in the deep structure of the Himalayan orogen, and possibly the temporal relationship between granitic magmatism and slip on the STDS.

2. Yadong Cross Structure

At approximately 89° east longitude, the STDS and topographic crest of the Himalaya are offset in a left-lateral sense by about 70 krn, along a north-northeast trending discontinuity in the range termed the "Yadong cross structure" by *Burchfiel et al.* [1992]. The YCS is the largest along-strike discontinuity in the bedrock geology and topography of the High Himalaya in the ~2500 km length of the range lying between the Himalayan syntaxes. Earthquake data suggest that the YCS coincides with a deep-seated structural discontinuity in the range. On November 19, 1980, a magnitude 6 strike-slip earthquake occurred in the immediate vicinity of the YCS near Yadong (International Seimological Centre location 27.4°N, 88.8°E, first described by *Ni and Barazangi* [1984]). *Ni and Barazangi* [1984] determined a focal depth for this event of 13 ± 3 km. *Ekstrom* [1987] subsequently reanalyzed the event using additional seismograms and both short- and long-period data and reported a focal depth of about 42 km. The focal mechanism for the earthquake is well defined *[Ekstrom* , 1987] and is consistent with left slip at depth along the YCS. This is in marked contrast to the thrust-type focal mechanisms exhibited by the majority of intracrustal earthquakes occurring beneath the south slope of the Himalaya [*Ni and Barazangi,* 1984; *Chen and Kao,* 1996].

The actual bedrock offset defining the YCS occurs across the southern part of the Yadong-Gulu rift, which is one of the more prominent of the northerly trending Neogene/Quaternary graben systems that extend from the Himalaya into the interior of the Tibetan Plateau (Figure 1). These rifts are the geomorphologic expression of ongoing east-west extension of the plateau [*Molnar and Tapponnier,* 1978; *Armijo et al.,* 1986]. *Burchfiel et al.* [1992] recognized the YCS from the map pattern depicted on existing small-scale geologic maps of the central Himalaya [i.e., *Gansser,* 1983; *Liu et al.,* 1988] and suggested that the strike separation across the YCS might be as much as 150 km. They identified and described the STDS in the field a short distance east of the YCS at Wagye La. However, because of border-access restrictions in existence at the time, they were unable to examine the YCS directly in the field, nor were they able to determine directly from field observation where the STDS projects into the YCS from the west. Thus, while noting the regional significance of the YCS, they were unable to determine whether it was a strike-slip fault cutting the STDS, a transfer fault on the STDS, or some other structure or combination of structures. Similarly, the actual strike separation across the YCS could not be determined.

In 1992, 1994, and 1995, the International Deep Profiling of Tibet and the Himalaya (INDEPTH) project undertook geophysical investigations along the Yadong-Gulu rift, aimed principally at characterizing the deep structure of the crust beneath the region [*Zhao et al.,* 1993; *Nelson et al.,* 1996]. As part of this effort, reconnaissance field geological investigation of the bedrock geology adjacent to the southern Yadong-Gulu rift was undertaken in hope of locating and characterizing the STDS in the area and determining the nature of the YCS.

3. Southern Yadong-Gulu Rift

The southern Yadong-Gulu rift is composed of the Pali and Duoqen valleys, which together extend approximately 90 km in a north-northeast direction across the southern Tethyan Himalaya (Plate 1). The width of the valleys varies from a few kilometers to a maximum of about 20 km. Seismic profiling shows that Duoqen valley is an asymmetric half graben that deepens to the east and contains a maximum of about 1.5 km of Plio(?)-Quaternary clastic sediments [*Cogan et al.,* this issue]. The subsurface geometry of the smaller Pali valley to the south is unknown, but the occurrence of bedrock cropping out in the middle of the valley suggests that it is quite shallow. Both valleys are bordered on the east by a rugged, anomalously north-northeast trending segment of the High Himalaya dominated by Mount Chomolhari (7313 m), referred to subsequently as the Chomolhari range. The Chomolhari range is the geomorphologic expression of the YCS. The western foot of the range, bordering Duoqen and Pali valleys, is marked by an en echelon set of active high-angle normal faults which, in aggregate, we refer to as the Chomolhari fault system (CFS) (Figure 2). The CFS is evidenced by conspicuous scarps cutting moraines, hanging glacial valleys, and triangular range-front facets [*Armijo et al.,* 1986]. These features

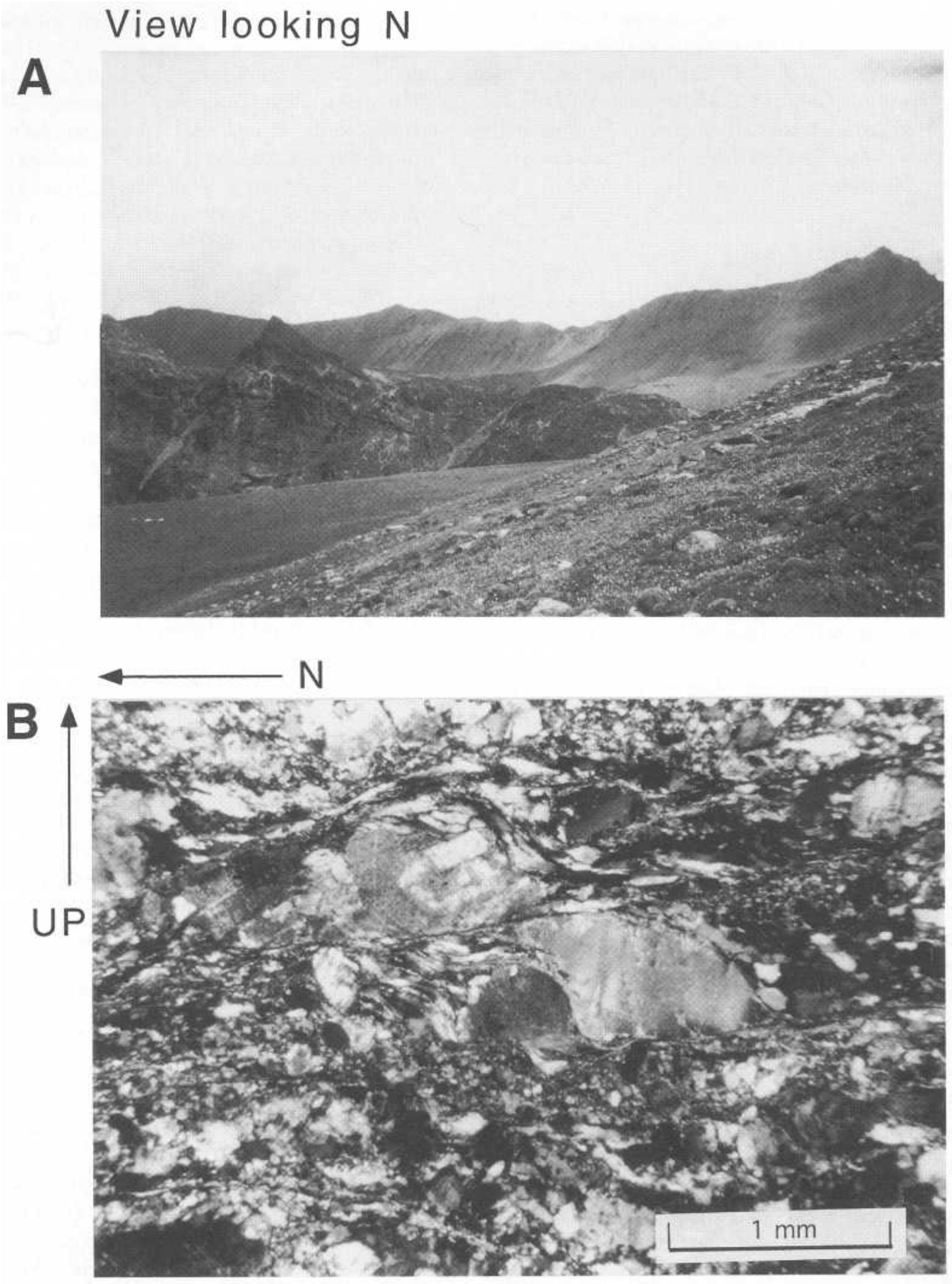

Figure 2. (a) View looking north at the Zherger La detachment, approximately 5 km west northwest of Zherger La. The detachment separates Tethyan sandstones above (light grey making up far ridge) from mylonitic granite gneiss below (dark grey in near ridge). (b) Photomicrograph of mylonitic granite in the immediate footwall of the Zherger La detachment. The section is oriented approximately perpendicular to the mylonitic foliation and parallel to lineation. Large asymmetric grains are mica fish. S-C fabric indicates top-to-the north (left) sense of shear.

are evident both in the field and on thematic mapper images. West of Duoqen valley, generally east-west striking Paleozoic and Mesozoic sedimentary strata of the Tethyan belt are exposed. These strata are succeeded southward by a diverse assemblage of granite, granite gneiss, schist, phyllite, and locally marble, the bulk of which we assign to the Greater Himalayan belt. These strata are readily observed along the west side of Pali valley and along the two principal north-south roads through the region, which converge near the southern edge of the map area at Yadong (SW corner of Plate 1). Immediately east of Pali, fossiliferous Tethyan belt strata [*Lin et al.,* 1989] are exposed in an enclave on the west slope of the Chomolhari range. Our field observations together with the regional mapping by *Gansser* [1983] suggest that the crest of the Chomolhari range is underlain by high-grade metamorphic rocks and granites of the Greater Himalayan belt. To the east in Bhutan, the Himalaya are similarly underlain by greater Himalayan belt strata, with local outliers of Tethyan belt strata preserved above [*Gansser,* 1983].

4. Zherger La Detachment

Our new field observations show that the contact between Tethyan belt sedimentary strata and crystalline rocks of the Greater Himalayan belt trends west-northwest immediately west of Duoqen valley and intersects the southern end of Duoqen valley at Zherger La (Figure 2). Zherger La is a small pass in a northeast trending basement ridge that protrudes into southern Duoqen valley. Mylonitic granitic augen gneiss is exposed immediately south of Zherger La. The rock appears to be a typical "type I" mylonite [*Lister and Snoke,* 1984]. Feldspar augen average 2-5 mm across, and the rock exhibits a well-developed S-C fabric and obvious mineral elongation lineation (Figure 2b). The mylonitic foliation dips moderately north-northeast (representative S surface dips 39° toward 020° and representative C surface dips 48° toward 020°), and the lineation similarly plunges moderately north (representative plunge 34° toward 005°). The shear sense indicated by the S-C fabric is consistently top-to-the-north. Unmetamorphosed gray quartz-biotite sandstone is exposed in the ridge immediately north of Zherger La. These strata strike east-northeast and dip moderately north. They pass northward and stratigraphically upward into gray limestone containing abundant brachiopod fossils. The sandstones immediately above the contact have been assigned a Devonian age by *Liu et al.* [1988] and *Xia et al.* [1993].

At Zherger La, the actual contact between the mylonitic gneiss and sedimentary strata to the north is covered by a few hundred meter wide talus zone. However, it is well exposed approximately 5 km along strike to the west-northwest, in a west-northwest trending glacial valley at the headwaters of the Chobogabo River (Figure 2a). This location is easily reached on foot from the western road running southward from Gala through Keshe and Ding'ga to Yadong (the road follows the Chobogabo River south to Yadong). The contact is exposed in the north wall of the valley and dips to the north. Mylonitic augen gneiss, identical to that cropping out south of Zherger La, comprises the footwall. The mylonitic foliation dips moderately north-northeast (representative S surface dips 20° toward 020° and representative C surface dips 30° toward 015°). Lineation defined by elongated quartz grains and quartz ribbons similarly plunges moderately north-northeast (representative plunge 25° toward 020°). The shear sense indicated by the S-C fabric is top-to-the-north. The mylonitic gneisses are cut by a number of spaced brittle normal faults that dip somewhat more steeply north than the mylonitic foliation, which they offset (representative dip 40° toward 355°). The footwall mylonites are overlain by yellow-weathering limestone, assigned a Devonian age by *Liu et al.* [1988]. These, in turn, pass upward into reddish-weathering siltstone that forms the bulk of the valley wall above the contact. The yellow limestone is brecciated immediately adjacent to the contact with the underlying mylonitic gneiss, and the contact itself is occupied by an apparently undeformed quartz vein roughly 3 m in thickness. Taken together, the field observations indicate that the contact between the Tethyan belt sedimentary strata and Greater Himalayan belt crystalline rocks west of Duoqen valley is a north dipping detachment fault. We locally term this structure the "Zherger La detachment" and argue below that it is the local expression of the STDS.

Granitic gneiss, granite, and injection complex (undifferentiated migmatite, augen gneiss, granite, and schist) are exposed for approximately 15 km southward from Zherger La. Moderately north dipping mylonitic fabric is well developed in the northern 5 km of this belt; southward, the foliation flattens and becomes weaker. A possible erosional outlier of Tethyan strata occurs within this belt immediately southeast of Ding'ga. At this locality, yellow-weathering foliated limestones cap a high ridge. These limestones are generally similar in appearance to known lower Paleozoic Tethyan limestones cropping out a short distance farther east (immediately east of Pali, discussed subsequently). The belt of granitic gneiss, granite, and injection complex is succeeded southward by an approximately 10-km-wide belt of greenschist to low-amphibolite-grade polydeformed metasedimentary phyllites and schists. The age and tectonic affinity of this phyllite/schist belt is uncertain. Unfossiliferous low-grade metasedimentary strata have been found at a number of localities along the crest of the Himalaya near the structural top of the Greater Himalayan belt, the North Col Formation in the Everest region being a relatively well-studied example [*Yin and Kuo,* 1978; *Lombardo et al.,* 1993]. Chinese workers have tended to assign these strata a Sinian-Cambrian age on the assumption that they stratigraphically underlie fossiliferous Tethyan strata and overlie the Greater Himalayan belt "basement". For the purposes of this paper, we include the phyllite/schist unit south of Ding'ga in the Greater Himalayan belt, noting that (1) the rocks comprising this unit are markedly higher grade than known Tethyan strata to the north, (2) they exhibit a polyphase deformation fabric unlike that of the known Tethyan strata to the north (and east), and (3) the boundaries of the unit are not associated with a structural or metamorphic break comparable to that observed at Zherger La. The phyllite/schist belt is succeeded southward by a mixed assemblage of granites, quartzofeldspathic gneiss, and schist extending southward beyond Yadong. A large apparently undeformed leucogranite body which we term the Gaowu granite occurs within this assemblage (Plate 1). The Gaowu granite intrudes Tethyan sedimentary strata cropping out south of Pali.

5. Comparison of Zherger La Detachment With Previously Described STDS Localities

In their study defining the STDS, *Burchfiel et al.* [1992] examined the Tethyan belt/Greater Himalayan belt contact at six localities spaced along an approximately 700-km segment of the north slope of the Himalaya. They concluded that where not intruded by granite, the contact was a north dipping normal fault and stated the following:

> 1. The fault places Paleozoic or Mesozoic rocks onto Cambrian to Precambrian(?) footwall lithologies;

> 2. The hanging-wall lithologies are unmetamorphosed or contain greenschist facies mineralogy, whereas the footwall mineral assemblages are indicative of middle to upper amphibolite facies;
> 3. North-vergent S-C mylonitic fabrics are well developed in the footwall, their intensity becoming greater near the contact between the Greater Himalayan and Tibetan sedimentary sequences; and
> 4. The footwall shows evidence for the progressive development of north-vergent ductile to brittle extensional structures [*Burchfiel et al.*, 1992, p. 36].

The Zherger La detachment lies within the 700-km-long segment of the Greater Himalayan belt/Tethyan belt contact spot examined by *Burchfiel et al.* [1992] and exhibits each of these characteristics. We conclude that it is the local expression of the STDS immediately west of Duoqen valley. The strike separation of the STDS across Duoqen valley and therefore across the YCS is about 70 km.

In their descriptions of the STDS, *Burchfiel et al.* [1992] noted that there appears to be a west-to-east change in the slip direction recorded in the STDS footwall mylonites in the vicinity of the YCS. In the four localities they examined west of the YCS, the prominent STDS lineation trends northeasterly (Gyirong, Nyalam, Everest and Dinggye areas). In contrast, in the two localities they examined to the east it trends north-westerly. As described above, the prominent lineation in the footwall mylonites at Zherger La trends north northeast, consistent with Burchfiel et al.'s western localities. We similarly examined the mylonitic STDS footwall at several localities at the south end of Nieru valley, just east of the YCS (including Wagye La), and confirm their observation that the prominent lineation there plunges to the northwest (representative plunge 14° toward 330°). We are presently unsure whether the northwesterly lineation trend evident in the vicinity of Wagye La reflects an actual along-strike change in the slip direction of the STDS or subsequent local rotation of the basement exposed in the Wagye La area along northeast trending splays of the Chomolhari fault system (suggested by Landsat and digital topography images). In either case, the combined observations at Zherger La and Wagye La constrain the along-strike change in lineation azimuth noted by *Burchfiel et al.* [1992] to occur across the YCS.

Finally, *Burchfiel et al.* [1992] also noted brittle north dipping normal faults cutting earlier STDS mylonites at several of the localities they examined (e.g., Everest and Lhozag-La Kang areas). More recently, *Edwards et al.* [1996] have described a multistage evolution for the STDS in the vicinity of Khula Kangri, which includes the development of an early top-to-the-north ductile shear zone ("Gonto La detachment"), which is cut by a steep north dipping brittle normal fault ("Dzong Chu fault"). INDEPTH reflection profiling across the projection of the Zherger La detachment beneath Duoqen valley similarly suggests that the detachment there is cut or reactivated by a younger (Plio-Pleistocene?) north dipping normal fault, which carries a small half graben in its hanging wall [*Hauck et al.*, 1995; *Hauck*, 1997]. As noted by *Searle* [1986], the abrupt topographic break that occurs at a number of locations along the north flank of the Himalaya suggests that down-to-the-north normal slip has locally occurred along this boundary in Recent time. Taken together, these observations suggest that down-to-the-north normal slip has continued episodically along the north flank of the Himalaya since the inception of the STDS in middle Miocene time. We return to these observations subsequently.

6. Field Observations Along the YCS

As described above, the YCS is defined by the strike separation of the STDS, which occurs along the Chomolhari range. We examined the bedrock outcrop at several localities along the west slope of the Chomolhari range in the hope of characterizing this structure. The macroscale structure underlying the west slope of the range appears to be a north-northeast striking, west dipping monocline. In general, both Tethyan sedimentary strata and Greater Himalayan belt gneisses and schists cropping out along the west slope of the range are strongly deformed, with both lithologic layering and prominent foliation striking parallel to the range and dipping steeply west to northwest (Plate 1 and Figure 3a). This is in marked contrast to the generally east-west regional strike and weakly deformed (outcrop-scale) character of the Tethyan belt strata cropping out west and north of the range.

The west slope of the Chomolhari range east of Pali is underlain largely by Paleozoic limestones. These are locally fossiliferous and thus clearly of Tethyan affinity [*Lin et al.*, 1989]. These strata were examined along several east-west side valleys leading into the range. In the southern part of the outcrop belt (SE of Pali), the limestones are little deformed, and bedding strikes east-northeast and dips gently to moderately north. Toward the north, the limestones become increasingly deformed. In the northern part of the outcrop belt, they exhibit a strongly developed foliation, and in most outcrops primary lithologic layering appears to be transposed parallel to the foliation. The foliation strikes north to northeast and dips moderately steeply to the northwest (strike and dip varies from 355°, 45°W to 050°, 65°NW). Foliation surfaces exhibit a strongly developed downdip lineation, parallel to the hinge lines of intrafolial folds in transposed lithologic layering. The deformation fabric in these strata is clearly suggestive of dip-slip shear (west-northwest azimuth). No evidence for strike-parallel slip (N to NE azimuth) was observed in these rocks.

Along the east-west side valley that leads to Qukalongla La (pass to Bhutan), the limestones can be seen in scattered outcrop to pass structurally downward (east) into pelitic schists and then granitic augen gneiss. The pelitic schists exhibit the same moderately steep northwest dipping foliation and downdip lineation as the overlying limestones. Notably, lineation in the underlying augen gneiss is subhorizontal and northwest-southeast trending (representative plunge 5° toward 125°).

North of the Pali area, the west slope of the Chomolhari range is underlain by Greater Himalayan belt gneisses, schists, and granites. Immediately east of Tang La feldspathic gneisses are exposed in a side valley leading up the southwest slope of Chomolhari. At the entrance of the side valley, gneissic layering strikes north-south and is vertical. The gneisses are riddled by little-deformed, centimeter-to-decimeter-thick quartz veins. Eastward up the gully, the orientation of the gneissic layering changes to northeast striking and steeply northwest dipping (representative strike and dip 050°, 60°NW), and an approximately 50-m-wide, undeformed leu-

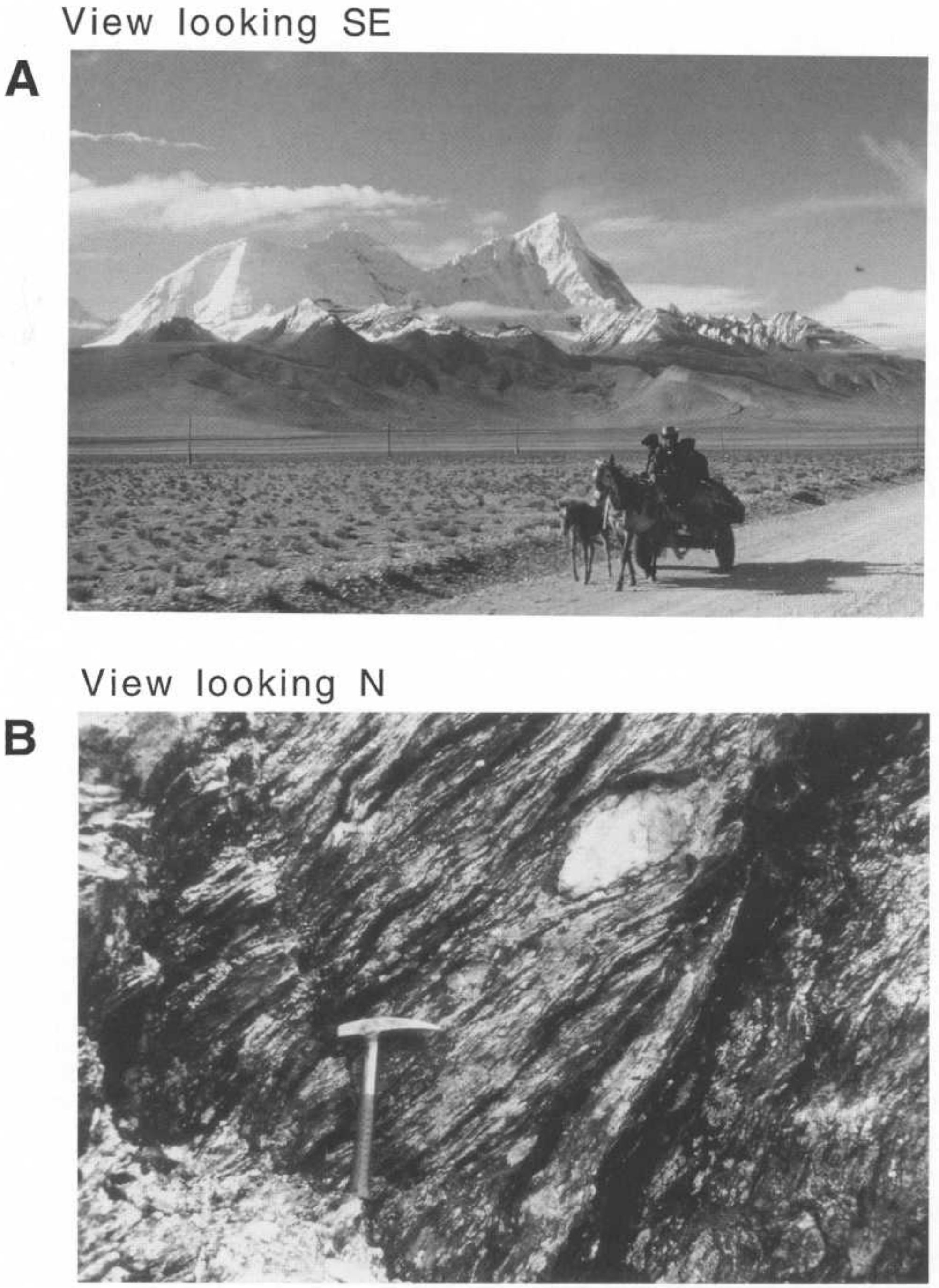

Figure 3. (a) View looking southeast across Duoqen valley at Mount Chomolhari. Knife-edge ridge extending from the west flank of Chomolhari (toward the right side of the photo) is underlain by subvertical, northeast striking Greater Himalayan belt strata. (b) Asymmetric quartz boudin in steep west-northwest dipping, normal-sense shear zone on the western flank of Chomolhari (view looking to the north).

cogranite body can be seen cutting the gneiss. Farther east, where moraine deposits dam the gully, the gneisses are cut by an approximately 200-m-wide shear zone. The gneisses within the shear zone are intensely fractured and overprinted by a strong northeast striking, steep northwest dipping foliation. Lineation associated with the foliation plunges essentially downdip (representative plunge 50° toward 305°), and abundant boudinaged quartz veins and S-C fabric observations indicate normal-sense (NW side down) shear within the zone (Figure 3b).

Immediately north of Chomolhari, the Chomolhari range bends to the east for a short distance and then continues its north-northeast trend. In the area of the bend, pelitic schists and phyllites exposed at the foot of the range locally strike east-west (attitude of foliation). To the north, glacial/alluvial cover extends high on the west flank of the range, and we were unable to examine bedrock directly. Reference to thematic mapper imagery, however, shows that the bedrock cropping out high on the western slope of the range along this segment strikes north-northeast parallel to the range. Examination of the float at the foot of the range indicates that these are Greater Himalayan belt strata.

We summarize the available geologic constraints on the nature of the YCS as follows: (1) Generally east-west striking Tethyan belt strata are exposed west of the Chomolhari range (west of Duoqen valley). In contrast, structurally underlying Greater Himalayan belt strata are exposed within and over a wide area east of the Chomolhari range at the same and higher elevation [*Gansser,* 1983]. *(2)* Tethyan belt and Greater Himalayan belt strata exposed along the western slope of the Chomolhari range are rotated into a regional north-northeast striking, west-northwest dipping monocline. *(3)* Tethyan strata within the monocline have been ductily deformed in dip-slip shear (west-northwest azimuth), and both Tethyan strata and underlying Greater Himalayan belt strata within the monocline have been cut by brittle west-northwest to north-west dipping normal faults (Chomolhari fault system, shear zone observed in gneisses beneath Chomolhari). (4) No evidence for transcurrent slip was observed along the Chomolhari range and *(5)* Our mapping shows that the generally east-west striking Tethyan strata exposed north of the Chomolhari range are not offset across the northern extrapolation of the YCS (Plate 1).

7. Geochronological Constraints on the Age of the STDS

In conjunction with the INDEPTH field studies, we have attempted to date several granites in the immediate footwall of the STDS using Th-Pb and U-Pb techniques. These include the locally mylonitic Khula Kangri granite, lying in the footwall of the STDS approximately 100 km east of the YCS; the locally mylonitic Wagye La granite, lying in the footwall of the STDS immediately east of the YCS; and the undeformed Gaowu granite that intrudes Tethyan sediments at the south end of Pali Valley, just west of the YCS (Figure 1 and Plate 1). The goal of this effort was to provide constraints on the slip history of the STDS in the eastern Himalaya.

To provide a context for interpreting these new dates, we first briefly summarize results of prior geochronological studies of the STDS. During the past decade, substantial progress has been made in constraining the timing of slip on strands of the STDS at scattered localities along the north slope of the Himalaya. This has been accomplished primarily through the application of high-precision U-Pb dating methods to associated leucogranites. In a number of areas, ductily deformed granites in the immediate footwall of STDS strands have been dated, in principle providing a maximum age limit for slip (Zanskar, Shisha Pangma, Nyalam, Annapurna, Everest, and Khula Kangri areas [*Searle,* 1986; *Hodges et al.,* 1996; *Harrison et al.,* 1995; *Searle et al.,* 1997; *Scharer et al.,* 1986; *Hodges and Bowring,* 1997; *Edwards and Harrison,* 1997]). In a few areas, undeformed granites cutting STDS strands have been dated, in principle providing a minimum age limit (Manaslu and Everest areas [*Guillot et al.,* 1994; *Parrish,* 1990; *Hodges et al., 1992; Harrison et al.,* 1995]). Where coincident cooling ages have been obtained on footwall granites through K-Ar or Ar/Ar methods, they generally are within 1 to 2 million years of the crystallization age of the granites interpreted from the U-Pb dates [e.g., *Copeland et al., 1990; Hodges,* 1992; *Searle et al.,* 1997] thus implying that crystallization of the granites, normal slip on the STDS, and exhumation of the STDS footwall in the dated localities occurred in rapid sequence. Summarizing published interpretations, it presently appears that slip on the STDS initiated at about 23 Ma in the far western Himalaya (Zanskar), 22.5 Ma in the Annapurna area, 22 Ma in the Manaslu area, 16.5 Ma in the Everest area, and 12 Ma in the Khula Kangri area (references cited above). With the exception of Khula Kangri, all of the dated localities are substantially west of the YCS.

While these U-Pb dates represent a major advance in knowledge of the Himalaya, their interpretation is not without ambiguity. U-Pb dating of accessory minerals from the Himalayan leucogranites is inherently difficult because of their young age and because of the ubiquitous presence of xenocrystic zircon in these rocks [e.g., *Scharer et al., 1986; Copeland et al.,* 1988]. Most of the ages summarized above are based on monazite determinations, which in these studies have generally been interpreted to be a primary igneous phase. Young monazites typically contain ^{206}Pb* in excess of that produced from radioactive decay of ^{238}U as a result of decay from ^{230}Th, an intermediate daughter of ^{238}U [e.g., *Scharer,* 1984]. Thus analyses of young monazites from Himalayan leucogranites commonly plot above the concordia ("reversely" discordant analyses). For this reason, the ^{235}U/^{207}Pb date of the youngest monazites in a dated array has commonly been taken as the best estimate of the crystallization age of the granite [*Scharer,* 1984]. In essentially all of the examples of reversely discordant monazite analyses, it could be argued that the grains have suffered some degree of lead loss, and thus the actual crystallization age of the granite is older than the age suggested by the ^{235}U/^{207}Pb dates. Conversely, it could be argued that every analyzed grain contained some degree of xenocrystic component, and thus the actual crystallization age of the granite is slightly younger than the age suggested by the ^{235}U/^{207}Pb dates. In principle, analyses of multiple spots on single monazite grains using a high-sensitivity ion probe can minimize the potential problems of monazite lead loss and inheritence, and several High Himalayan granite bodies have been dated by this technique (e.g., Manaslu and Khula Kangri [*Harrison et al.,* 1995; *Edwards and Harrison,* 1997]). Even this technique, however, would yield an erroneous crystallization age for a granite if every monazite grain analyzed were xenocrystic. That this might be the case for at least one Himalayan granite, the Rongbuk granite north of Mount Everest, has recently been argued by Kip Hodges and Sam Bowring (personal communication, 1997). They report that an adjacent foliated granite, which the Rongbuk granite apparently intrudes, yields statistically indistinguishable single-crystal monazite, zircon, and xenotime ages that are substantially younger than previously determined U-Pb and Th-Pb ages for the Rongbuk granite (16.7 Ma versus 19-23 Ma [*Hodges and Bowring,* 1997; *Copeland et al.,* 1988; *Hodges et al.,* 1992; *Harrison et al.,* 1995]).

With these caveats in mind, we discuss the new Th-Pb and U-Pb determinations for STDS footwall granites determined during the INDEPTH study. These are the first such determinations reported from the eastern Himalaya.

Monazites from the Khula Kangri granite were analyzed using the University of California, Los Angeles ion-microprobe mass spectrometer. These data have been reported by *Edwards and Harrison* [1997], who have interpreted a crystallization age of 12.5±0.4 Ma for the Khula Kangri granite based on 26 ^{232}Th-^{208}Pb determinations from 12 monazite grains. The Khula Kangri granite lies in the footwall of the STDS approximately 100 km east of the YCS. The STDS at this locality is locally termed the Gonto La detachment. The granite is mylonitized adjacent to the detachment, and thus the 12.5 Ma age has been interpreted by *Edwards and Harrison* [1997] to be an older limit for the initiation of the STDS at this location. As they point out, the 12.5-Ma age for Khula Kangri granite is substantially younger than reported ages for STDS footwall granites in the central and western Himalaya. The 12.5-Ma age is only slightly older than biotite and muscovite ^{40}Ar/^{39}Ar dates that have been reported for the Khula Kangri granite in accord with the previously stated observation that STDS footwall granites generally appear to have been intruded, deformed, and denuded in a relatively short interval (11.4 to 10.7 Ma [*Maluski et al.,* 1988], 10.7-11.1 Ma muscovite, and 11.6-13.0 Ma biotite [*Guillot et al.,* 1998]).

Zircons and monazites from the Wagye La and Gaowu granites were analyzed at Syracuse University by thermal ionization mass spectroscopic techniques (sample localities shown in Plate 1). The Wagye La granite lies in the immediate foot-wall of the STDS at Wagye La and exhibits a variably developed northwest dipping foliation. Thus a crystallization age for the Wagye La granite should provide an older age limit on the time of slip on the STDS at Wagye La. As is typical of Himalayan leucogranites, analyses of zircons from the Wagye La granite (including single crystals) showed that every zircon fraction contained a xenocrystic component. Further effort was therefore concentrated on dating monazites. Analyses of four multigrain fractions of monazite from the Wagye La granite are reversely discordant but yield ^{235}U/^{207}Pb dates of 11.6 - 12.1 Ma (Table 1 and Figure 4). We take the mean of these four dates, 11.9 Ma, as the current best estimate of the crystallization age of the Wagye La granite. Recognizing the caveats outlined above concerning the possibility of slight degrees of Pb loss or inheritance, the actual crystallization age could be slightly older or slightly younger than this mean age. The coincidence of the Wagye La monazite ^{235}U/^{207}Pb dates with the ^{232}Th $_{208}$Pb ion-probe monazite dates from the along-strike Khula Kangri granite, however, lends geological support for the interpretation that 11.9 Ma closely approximates the crystallization age of the Wagye La granite. We infer that both the Wagye La and Khula Kangri granites crystallized at about 12 Ma and that ductile normal slip occurred along the STDS over a distance of at least 100 km eastward from the YCS at or shortly after this time.

The Gaowu granite is exposed immediately west of the YCS, at the south end of Pali valley. In contrast to the Wagye La and Khula Kangri granites, it is little deformed, and intrudes low-grade Tethyan sedimentary strata lying immediately to the north. U-Pb dates for five multigrain monazite fractions and one single grain were determined for the Gaowu granite (Figure 4 and Table 1). The interpretation of these dates is more complicated than for those of the Wagye La granite because of the obvious presence of xenocrystic monazite components. Two of the multigrain analyses from the Gaowu leucogranite yielded ^{207}Pb/^{206}Pb ages of 102 Ma and 272 Ma (I and J, Figure 4), whereas the other three multigrain analyses yielded ^{235}U/^{207}Pb dates ranging from 24.1 to 25.2 Ma. The single grain yielded a ^{235}U/^{207}Pb date of 22.9 ± 0.17 Ma. As noted above, xenocrystic monazite has been recognized in other Himalayan leucogranites [e.g. *Copeland et al.,* 1988; *Noble and Searle,* 1995; *Harrison et al.,* 1995] and might be an unrecognized problem in a number of these granites. Because all of the monazite analyses from the Gaowu granite lie on a well-defined regression line, it is probable that all of the multigrain fractions contain variable amounts of a xenocrystic component. We therefore consider the 22.9 Ma ^{235}U/^{207}Pb date of the single monazite, which is slightly younger than the youngest of the multigrain fractions, to represent the current best estimate for the crystallization age of the Gaowu granite. Again, we recognize that the actual crystallization age of this granite could be slightly older or slightly younger than this age. The observation that all of the Gaowu monazites that were analyzed yielded ^{235}U/^{207}Pb dates greater than 22 Ma, in contrast to the Wagye La and Khula Kangri granites which yielded abundant approximately 12-Ma monazite grains, however, strongly suggests that the Gaowu granite is substantially older than these two more northerly granites.

8. Geologic Interpretation

On the basis of the geologic observations described above, we conclude that the Zherger La detachment is the principal strand of the STDS west of Duoqen valley. Elsewhere along the Himalaya, the STDS has been shown to consist, locally, of several detachments separated in north-south section (e.g., Annapurna area [*Hodges et al.,* 1996]). We found no compelling field evidence for more southerly strands of the STDS within our map area for as far south as Yadong (southern limit of observation). From the map pattern depicted in Plate 1, it is arguable that the contact between the Tethyan strata directly south of Pali and the Greater Himalayan belt rocks to the south might have been an early strand of the STDS, which was obliterated by subsequent intrusion of the Gaowu granite. We found no compelling evidence for such an interpretation.

The field observations along the west slope of the Chomolhari range together with the regional outcrop pattern indicate that Tethyan belt and structurally underlying Greater Himalayan belt allochthons have been warped into a north-northeast striking, west-northwest dipping monocline coincident with the range. The strata within the monocline have locally been ductily deformed in dip-slip shear (west-northwest azimuth) and are cut by a system of west-northwest dipping normal faults (CFS). We conclude that the ~70-km strike separation of the STDS along the Chomolhari range is an apparent offset produced by differential vertical displacement of the Tethyan belt/Greater Himalayan belt contact along the Chomolhari range (shallower to the east). The available observations militate against the YCS being a late strike-slip fault that offsets the STDS or being a strike-slip fault that separates segments of

Table 1. U-Pb Isotopic Data for Monazites From the Wagye La and Gaowu Leucogranites

				Atomic Ratios								Ages, Ma			
Analysis	Total U, ng	Total Pb, pg	Total[a] Common Pb, pg	$^{206}\mathrm{Pb}^{b}/^{204}\mathrm{Pb}$	$^{206}\mathrm{Pb}^{c}/^{208}\mathrm{Pb}$	$^{206}\mathrm{Pb}^{c}/^{238}\mathrm{U}$	Error, %	$^{207}\mathrm{Pb}^{c}/^{235}\mathrm{U}$	Error, %	$^{207}\mathrm{Pb}^{c}/^{206}\mathrm{Pb}$	Error, %	$^{206}\mathrm{Pb}/^{238}\mathrm{U}$	$^{207}\mathrm{Pb}/^{235}\mathrm{U}$	$^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$	Rho[d]
							Wagye La Leucogranite								
A (30)	80.8	630	44	252.1	0.2986	0.001941	0.897	0.01146	1.15	0.04281	0.680	12.5	11.6	-178.9	0.81
B (29)	83.2	792	36	316.8	0.2276	0.001944	0.476	0.01148	0.600	0.04282	0.344	12.5	11.6	-177.8	0.82
C (15)	47.1	398	16	396.8	0.2679	0.001983	0.780	0.01196	1.14	0.04376	0.783	12.8	12.1	-124.4	0.73
D (15)	1100	6481	205	721.6	0.4598	0.002035	0.225	0.01198	0.282	0.04271	0.167	13.1	12.1	-184.6	0.81
							Gaowu Leucogranite								
E (1)	58.5	1040	63	237.4	0.2345	0.003650	0.390	0.02281	0.741	0.04532	0.602	23.5	22.9	-38.3	0.59
F (10)	44.7	555	64	190.0	0.4274	0.003818	0.732	0.02406	1.11	0.04571	0.789	24.6	24.1	-17.4	0.70
G (7)	23.7	281	22	283.9	0.4305	0.003879	1.38	0.02435	1.59	0.04552	0.754	25.0	24.4	-27.5	0.88
H (20)	301	4239	320	259.8	0.3641	0.003982	0.251	0.02516	0.394	0.04582	0.292	25.6	25.2	-11.7	0.67
I (33)	98.4	1520	73	430.0	0.3910	0.004745	0.372	0.03144	0.437	0.04805	0.219	30.5	31.4	101.8	0.87
J (3)	134.5	3300	109	704.9	04916	0.008906	0.246	0.06347	0.307	0.05168	0.178	57.2	62.5	271.5	0.81

Monazite analyses are indicated by letters. The number of grains in each analysis is shown in parentheses. Monazites were dissolved in 10.5 M HCl for 48 hours at 200°C. Pb was separated using a double pass through 100 µl ion exchange columns in 0.55 M HBr. U was separated using a single-column pass in 6M HCl. Data reduction follows *Ludwig* [1989].

[a] Includes common Pb in monazite and laboratory blank.

[b] Measured ratio is corrected for mass bias only. The mass bias correction used is 0.18 % (± 0.07%) per atomic mass unit.

[c] Corrected for mass bias, spike, blank, and initial common Pb. Quoted errors are at the 2σ confidence level (percentage for atomic ratios and absolute for ages). Pb blank ranged from 5-10 pg (±50%) during the course of the study; U blank is 0.5 pg (± 50%). Initial common Pb composition was determined by analyzing a HF acid-leached K-feldspar separate from each rock. The values determined for the Wagye La leucogranite are $^{206}\mathrm{Pb}/^{204}\mathrm{Pb} = 19.21$, $^{207}\mathrm{Pb}/^{204}\mathrm{Pb} = 15.81$, and $^{208}\mathrm{Pb}/^{204}\mathrm{Pb} = 39.64$. The values determined for the Gaowu leucogranite are $^{206}\mathrm{Pb}/^{204}\mathrm{Pb} = 18.67$, $^{207}\mathrm{Pb}/^{204}\mathrm{Pb} = 15.76$, and $^{208}\mathrm{Pb}/^{204}\mathrm{Pb} = 39.32$.

[d] The $^{207}\mathrm{Pb}/^{235}\mathrm{U}$ - $^{206}\mathrm{Pb}/^{238}\mathrm{U}$ error correlation coefficient is calculated following *Ludwig* [1989].

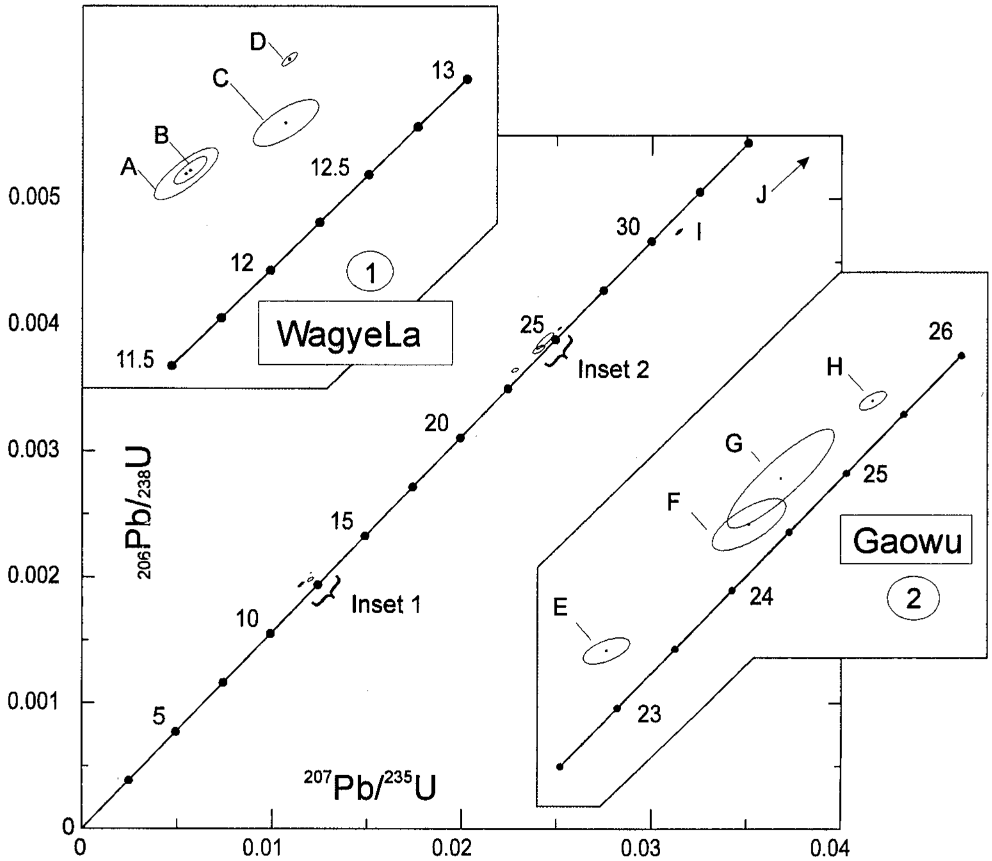

Figure 4. U-Pb concordia diagram for monazite analyses of the Wagye La and Gaowu leucogranites. Labeled ellipses correspond to letters in Table 1. Analysis of fraction "J" of the Gaowu leucogranite lies off the diagram (indicated by arrow).

the STDS that slipped at different times (i.e., strike-slip fault restricted to the hanging wall of the STDS). Both of these hypotheses require that the YCS continue within the Tethyan belt north of the Chomolhari range as a strike-slip fault, and both imply that transcurrent shear sense should be observed along the Chomolhari range; neither appears to be the case.

The regional map pattern and our field observations can be rationalized in a structural model incorporating a west-northwest dipping lateral ramp in the south directed thrust system that underlies the Greater Himalayan allochthon (Figure 5). We suggest that the Greater Himalayan allochthon and structurally overlying Tethyan belt strata are draped across this inferred lateral ramp, which we term the "Yadong ramp." The Chomolhari range is the surface expression of the monoclinal flexure of the upper plate. The north-northeast trending CFS is superimposed on the upper plate monocline and, in principle, could be the result either of extension of the upper plate produced by bending or entirely unrelated Neogene-Quaternary east-west regional extension (or both). In the interpretation shown in Figure 5, the Yadong ramp connects offset frontal ramps on the Main Central Thrust (MCT). A frontal ramp on the MCT, in approximately the position shown west of the YCS, is exposed in eastern Nepal and along much of the Himalaya to the west [e.g., *Schelling and Arita,* 1991; *Schelling,* 1992; *Srivastava and Mitra,* 1994]. We infer that the equivalent frontal ramp is offset to the north across the YCS and underlies the crest of the Bhutan Himalaya to the east. Perusal of *Gansser's* [1983] map of the Bhutan Himalaya indicates that a frontal ramp on the MCT is not exposed in Bhutan. However, the regional northward dip of the Greater Himalayan belt and Tethyan belt strata along the north slope of the Bhutan Himalaya, coupled with the regional flattening of these strata to the south, implied by the map pattern in Bhutan [*Gansser,* 1983], is suggestive of a frontal ramp at depth in this position.

The height of the Yadong ramp is poorly constrained, but the available data suggest that it may be about 10 km. Along the west side of Duoqen valley, gently folded Cretaceous carbonates crop out at the latitude of the east-west cross section shown in Figure 5 (~28°N latitude). Published estimates of the stratigraphic thickness of the Tethyan series (Ordovician through Cretaceous) in the southern Tethyan Himalaya are in the range of 7-13 km [*Li et al.,* 1988; *Lin et al.,* 1989]. In principle, the stratigraphic thickness of the Tethyan series on the west side of Duoqen valley gives a minimum depth to the top of the Greater Himalayan allochthon at this position and, because crystalline rocks of the Greater Himalayan belt are exposed to the east in Bhutan, a minimum height of the Yadong ramp. The reported stratigraphic thicknesses for the Tethyan series, however, are based on sections measured a substantial distance west of Duoqen valley (Nyalam and Dinggye-Dingri areas), and the extent to which faulting has been accounted for

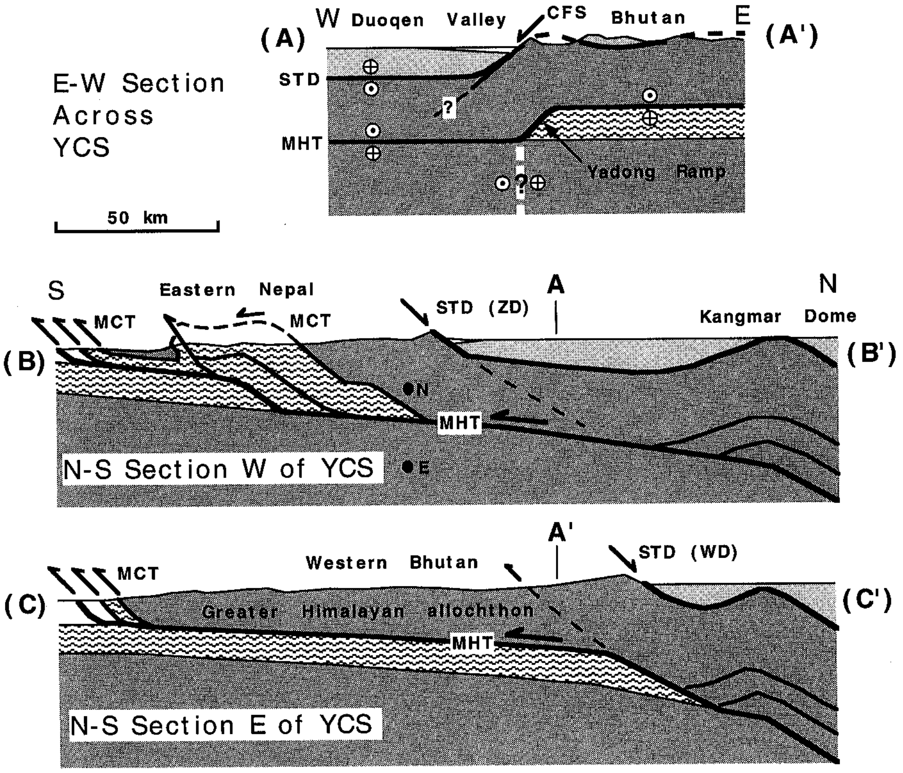

Figure 5. Interpretive geologic cross sections across and on either side of the Yadong cross structure (YCS). The YCS is interpreted to be the surface manifestation of a lateral ramp ("Yadong ramp") connecting offset frontal ramps on the Main Himalayan Thrust (MHT). The two north-south sections are simplified from *Hauck* [1997, Figure 3.6]. The north-south section west of the YCS is interpreted from the geologic cross sections of *Acharya and Ray* [1977] and *Schelling and Arita* [1991] crossing the south slope of the Himalaya and recent INDEPTH seismic reflection results to the north. The north-south section east the YCS is interpreted from *Gansser's* [1964] geologic cross-section of western Bhutan south of the Himalayan crest [Gansser, 1964] and INDEPTH reflection data to the north [*Hauck*, 1997]. Abbreviations are as follows: MHT, Main Himalayan Thrust; MCT, Main Central Thrust; STD, South Tibetan Detachment (locally: ZD, Zherger La detachment and WD, Wagye La detachment); and CFS, Chomolhari Fault System. Dark shading indicates Indian-affinity crystalline basement (present-day Indian continental crust below the MHT and Greater Himalayan belt allochthon above); light shading indicates Tethyan belt sedimentary strata; and wavy pattern indicates Lesser Himalayan belt metasedimentary strata. The circles labeled "N" and "E" in cross section B-B' illustrate the focal depths for the November 19, 1980 Yadong earthquake determined by *Ni and Barazangi* [1984] and *Ekstrom* [1987], respectively. The dashed strike-slip fault in the lower plate of the MHT, shown in cross section A-A', is required if the actual focal depth for the Yadong earthquake is greater than about 30 km.

in these estimates is not clear. Our reconnaissance mapping along the west side of south Duoqen valley suggests only moderate structural thickening (shortening) of the Tethyan strata in this area. Hence a stratigraphic estimate of the depth to the top of the Greater Himalayan allochthon beneath Duoqen valley should only "moderately" underestimate the actual depth to the allochthon beneath the valley and hence height of the ramp. Interpretation of the Tethyan belt/Greater Himalayan belt contact north of Zherger La on the INDEPTH reflection profile in Duoqen valley is problematic. *Hauck* [1997] has tentatively picked the contact along a series of bright but discontinuous reflections occurring at about 9 km depth along the section, which generally separates relatively less reflective crust above (interpreted deformed Tethyan strata) from more reflective crust below (interpreted Greater Himalayan belt). While none of these observations are compelling, together they are suggestive of a substantial height for the ramp, in the vicinity of 10 km.

The lateral ramp interpretation accounts for (1) the regional map pattern in which Tethyan belt strata are exposed west of the Chomolhari range (west of Duoqen valley), whereas structurally underlying Greater Himalayan belt strata are exposed at the same altitude over much of Bhutan to the east; (2) the north-northeast striking monoclinal flexure of the Tethyan belt/Greater Himalayan belt strata along the YCS; (3) the strike offset of the STDS and topographic crest of the Himalaya across the YCS; (4) the field observations indicating west-northwest azimuth (normal-sense) shear along the YCS; and (5) the observation that the YCS does not continue north of the Chomolhari range as a strike-slip fault. The interpretation also has several corollaries. One of these is that the north-northeast trending segment of Tethyan belt/Greater Himalayan belt contact exposed along the Chomolhari range between the projections of the Zherger La and Wagye La detachments is a modified part of the STDS. We have not observed the contact along this segment of the range closely enough to determine whether evidence for northerly directed slip is preserved along it. Given our observations along the Chomolhari range to the south, we suspect that STDS fabric along this segment of the contact will have been largely overprinted or cut out by later west-northwest dipping shear fabric. A second corollary is that the southern extrapolation of the YCS within the Greater Himalayan belt strata comprising the south slope of the Himalaya is also not a strike-slip fault. The available geologic mapping in Sikkim is supportive of this inference; in that regional map, units are not shown to be offset substantially across the southern extrapolation of the YCS [*Gansser,* 1964, 1983; *Acharya and Ray,* 1977].

9. Discussion

9.1. Yadong Cross Structure

Lateral ramps are a ubiquitous feature of thrust belts and have been recognized at a number of localities within the Lesser Himalaya [e.g., *Johnson,* 1994]. The inferred Yadong ramp is notable because of its scale and because it apparently is the cause of the largest along-strike discontinuity in the topography and bedrock geology of the Himalayan chain. Its existence may bear on several other features of the belt as well.

The lateral ramp interpretation provides a regional context for interpreting outliers of Paleozoic and Mesozoic sedimentary strata cropping out north of the surface trace of the MCT in Bhutan [*Gansser,* 1983]. On the basis of *Gansser's* [1983] descriptions of these strata, we infer that these are erosional outliers of the Tethyan series lying atop the Greater Himalayan belt. Of particular interest would be to determine whether any or all of these outliers are soled by top-to-the-north ductile shear zones, that is the STDS, or alternatively lie depositionally on the Greater Himalayan belt. From the descriptions provided by *Gansser* [1983], it appears that at least one of these outliers is soled by a ductile shear zone (Tong Chu outlier [*Gansser,* 1983, Figure *54; Edwards et al.,* 1996]).

It seems likely to us that the 1980 Yadong earthquake occurred on the Yadong ramp and manifests contemporary southward transport of the Greater Himalayan allochthon parallel to it. Taken strictly, *Ekstrom's* [1987] reported focal depth for this earthquake appears to be marginally too deep for this interpretation, given the INDEPTH seismic reflection constraint on the depth to the MHT to the north (about 25 km deep beneath Pali valley [*Zhao et al.,* 1983; *Hauck,* 1997]) (Figure 5). However, if the focus of the earthquake was marginally shallower and/or slightly north of the reported ISC location, it would be compatible. The alternative interpretation is that an active left-lateral strike-slip fault exists in the underthrusting Indian crust beneath the Yadong ramp (lower plate of the MHT). Further study of the seismicity in the region would seem to be of interest, particularly as the latter interpretation would imply that the Indian crust in the lower plate of the MHT is differentially shortening as it underthrusts the Himalaya.

Yin et al. [1994] have recently drawn attention to the fact that the Xigaze Group forearc basin strata border the north side of the Yarlung-Zangbo suture for approximately 2000 km west of the Yadong-Gulu rift but are absent east of the rift. Additionally, they have shown on the basis of thermochronologic data and relative preservation of volcanic cover that the degree of denudation of the Gangdese batholithic belt, lying immediately to the north of the Xigaze Group/Yarlung-Zangbo suture, is substantially greater east of the rift than to the west. Both observations, they argue, imply that magnitude of Tertiary north-south shortening was greater east of the rift than to the west. They suggest that this discontinuity in the thrust belt was caused by the impingement of a promontory in the Indian continental margin in the area now lying east of the rift [see *Yin et al.,* 1994, Plate 8].

Our inference of a large lateral ramp in the Himalayan thrust system beneath the southern Yadong-Gulu rift is supportive of their hypothesis. While the precise reason the Yadong ramp formed is unknown, its origin could well reflect a substantial lateral discontinuity in the precollisional structure of the Indian continental margin. This could be the side of the promontory hypothesized by *Yin et al.* [1994] or, as a variation on this theme, a substantial lateral change in the thickness (because of different amounts of stretching) of the rift-stage crust along the Indian margin (paleotransfer fault). In turn, this rift-stage structure, whatever its precise nature, was probably localized along an older Precambrian structure within the Indian crust. A number of north trending Precambrian faults have been identified in the Indian basement underlying the Ganga basin on the basis of geophysical data [e.g., *Valdiya,* 1976]. One of these, the Kishangang Basement Fault, lies approximately along the southern extrapolation of the YCS [*Mather and Evans,* 1964; *Ni and Barazangi,* 1984]. At a larger scale, the existence of the Shillong basement uplift in the foreland of the Himalaya east of the YCS, versus the lack of any equivalent structures in the foreland for some 2000 km to the west, implies an east-west change in the physical properties of the underthrusting Indian lithosphere at approximately the longitude of the YCS. This gross difference presumably reflects a variation in Precambrian crust/lithosphere structure.

9.2. Granite Intrusion and Slip on the STDS

As noted above, sheared leucogranites in the immediate footwall of the STDS generally appear to have been intruded, deformed, and denuded in a relatively short interval (less than a few million years). That this was true for the Khula Kangri and Wagye La granites is suggested by the near coincidence of their monazite U-Pb and Th-Pb ages with the ^{40}Ar/^{39}Ar mica ages for the Khula Kangri granite reported by *Maluski et al.* [1988] and *Guillot et al.* [1997]. Thus the ~12-Ma monazite age for these granites is regionally significant because it implies that granite emplacement and subsequent ductile normal shear in the footwall of the STDS took place substantially later in footwall exposures east of the YCS than in those to the west [*Edwards and Harrison,* 1997] (compare 12 Ma versus >16 Ma). The ~23-Ma monazite age for the Gaowu granite, which lies in the footwall of the STDS just west of the YCS, further suggests that this age break takes place across the YCS. Additional geochronological investigation of the immediate footwall of the Zherger La detachment needs to be undertaken to test this inference.

The observation that the age of granite intrusion and near-contemporaneous ductile deformation in the exposed footwall of the STDS varies along the Himalaya might be taken to indicate that different along-strike segments of the STDS slipped at different times [*Edwards and Harrison*, 1997]. This hypothesis, however, would seem to require the existence of some type of accommodation structure(s) within the Tethyan Himalaya to accommodate the differential slip in the STDS hanging wall (e.g., tear faults). As yet, such structures have not been identified. More to the point, the YCS, which presumably would be the most obvious candidate, is not such a structure.

Another possibility is that the apparently large east-west variation in ages actually reflects, at least in part, a general northward younging in the crystallization age of the granites emplaced into the top of the Greater Himalayan allochthon. The relatively young Wagye La and Khula Kangri granites are substantially farther north (closer to the Yarlung-Zangbo suture) than the dated STDS footwall granites to the west. We have argued elsewhere on the basis of INDEPTH geophysical observations that a zone of partial melting exists within the middle crust of southern Tibet and that this partial melt zone has existed since at least middle Miocene time [*Nelson et al.*, 1996]. Apparently, collisional crustal thickening and attendant thermal relaxation have acted to warm the doubly thickened crust of southern Tibet sufficiently for it to begin to melt. It follows from this hypothesis and the crustal-scale geometry of the STDS and MCT outlined by *Burchfiel et al.* [1992] that the Greater Himalayan belt allochthon is effectively being extruded southward from this partial melt zone. The evolution of the footwall of the STDS in this model is essentially similar to that described for core complexes in the western United States [e.g., *Davis and Lister,* 1988]. This evolution is schematically illustrated in Figure 6. Granites emplaced near the top of the Greater Himalayan allochthon within the partial melt zone are progressively drawn out of the zone, frozen, ductily deformed in normal-sense shear, and finally brittlely deformed in normal-sense shear as the top of the allochthon (STDS footwall) approaches the surface. Given that the STDS footwall granites west of the YCS are both older and farther south than those east of the YCS, they could simply represent more distal portions of the STDS footwall that were "extracted" from depth earlier.

This hypothesis is undoubtedly simplistic. Combined field geological and geochronological investigation near Annapurna has shown that several alternations between extension and shortening occurred along the top of the Greater Himalayan allochthon in that area within a time span of a few million years [*Hodges et al.*, 1996]. These relatively rapid alternations presumably reflect short-term temporal variations in erosion rate and/or the mechanical properties of the Himalayan thrust wedge. It seems likely that similarly complex "short-period" oscillations may have occurred along the length of the Himalaya. We suggest, however, that the longer-term evolution, averaged over 10 or more million years, is likely to be as depicted in Figure 6. This hypothesis is intriguing because it suggests the possibility that an average slip rate for the STDS might be estimated by dating granites in exposures of the footwall that are substantially separated in the STDS slip direction. For example, allowing that the ~23-Ma date for the Gaowu granite and ~12-Ma date for the Wagye La granite are crystallization ages and taking a north-south separation between them of 80 km yields an implied average slip rate of about 7 mm/yr. Similarly, allowing that the North Himalayan domes are exposures of the Greater Himalayan allochthon (suggested by INDEPTH data [*Hauck et al.,* 1995]) and taking *Scharer et al.'s* [1986] monazite ages of about 17 Ma for deformed granite in the footwall of the STDS near Nyalam and about 9.5 Ma for granite exposed in Majia dome, ~50 km to the

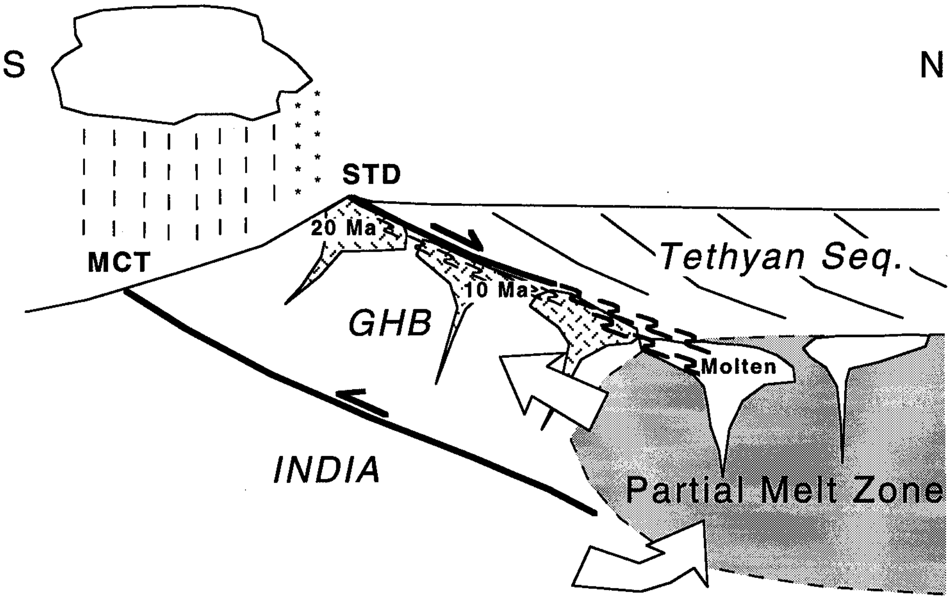

Figure 6. Schematic cross section illustrating progressive "extraction" of the Greater Himalayan belt allochthon (GHB) from a midcrustal partial melt zone beneath southern Tibet. This evolution produces a northward younging of the crystallization ages of granites intruded into the footwall of the South Tibetan Detachment.

north, yields an implied average slip rate of about 6 mm/yr. Given the ambiguities inherent in interpreting crystallization ages of Himalayan granites and the few data points presently available, we would not argue that a systematic north-south age variation for Himalayan granites has yet been demonstrated. Nor would we argue that the average STDS slip rates calculated from the few data points presented here should be considered significant. We do note, however, that they are a "not unreasonable" fraction of the 10 to 15 mm/yr convergence rate across the Himalaya for the past 15 to 20 million years, estimated from progradation of the Himalayan foreland basin sediments *[Lyon-Caen and Molnar,* 1985]. In principle, the hypothesis can be tested through further geochronological studies of STDS footwall granites in areas where the footwall is exposed for a substantial distance in the STDS slip direction. Areas where this might be undertaken include along the Chomolhari range (YCS) in Bhutan, along the STDS between Rhombuk and Dinggye, and along the STDS near Ghurla Mandhata. If the hypothesis proves correct, the data so obtained would yield substantial new insight into the temporal evolution of the STDS and the mode of formation of the High Himalayan granites, both of which are fundamental features of the Himalayan orogen.

10. Conclusions

The YCS, the largest along-strike discontinuity in the geology and topography of the Himalaya, is the surface manifestation of a lateral ramp in the MHT. This ramp underlies the north-northeast trending Chomolhari range, has an inferred height of about 10 km, and faces west-northwest. The plan view offset of the STDS of about 70 km across the YCS is defined by the map offset of the Wagye La detachment mapped by *Burchfiel et al.* [1992] at the south end of the Nieru valley and the Zherger La detachment identified by us on the west side of Duoqen valley. This apparent offset is not due to transcurrent motion on the north-northeast trending range-front fault system bounding Duoqen valley (CFS) but, rather, arises from differential vertical displacement of the Greater Himalayan belt and overlying Tethyan belt strata across a lateral ramp. The CFS is a late down-to-the-west normal-fault system superimposed on the west facing homoclinal flexure of the Greater Himalayan belt and Tethyan belt strata overlying the ramp. Strike-slip seismicity along the southern extrapolation of the Yadong ramp implies continuing slip subparallel to the ramp. The spatial coincidence of the Yadong-Gulu rift with the Yadong ramp lends support for *Yin et al.'s* [1994] contention that the Yadong-Gulu rift formed on a lateral discontinuity in the Himalayan thrust system. This, in turn, was likely controlled by a substantial precollisional lateral discontinuity in the structure of the Indian continental margin. Finally, the crystallization ages of sheared granites in the footwall of the STDS appear to be substantially younger east of the YCS than to the west. These observations can be rationalized in a kinematic model involving progressive slip on the STDS, which if correct can yield an average slip rate for the STDS.

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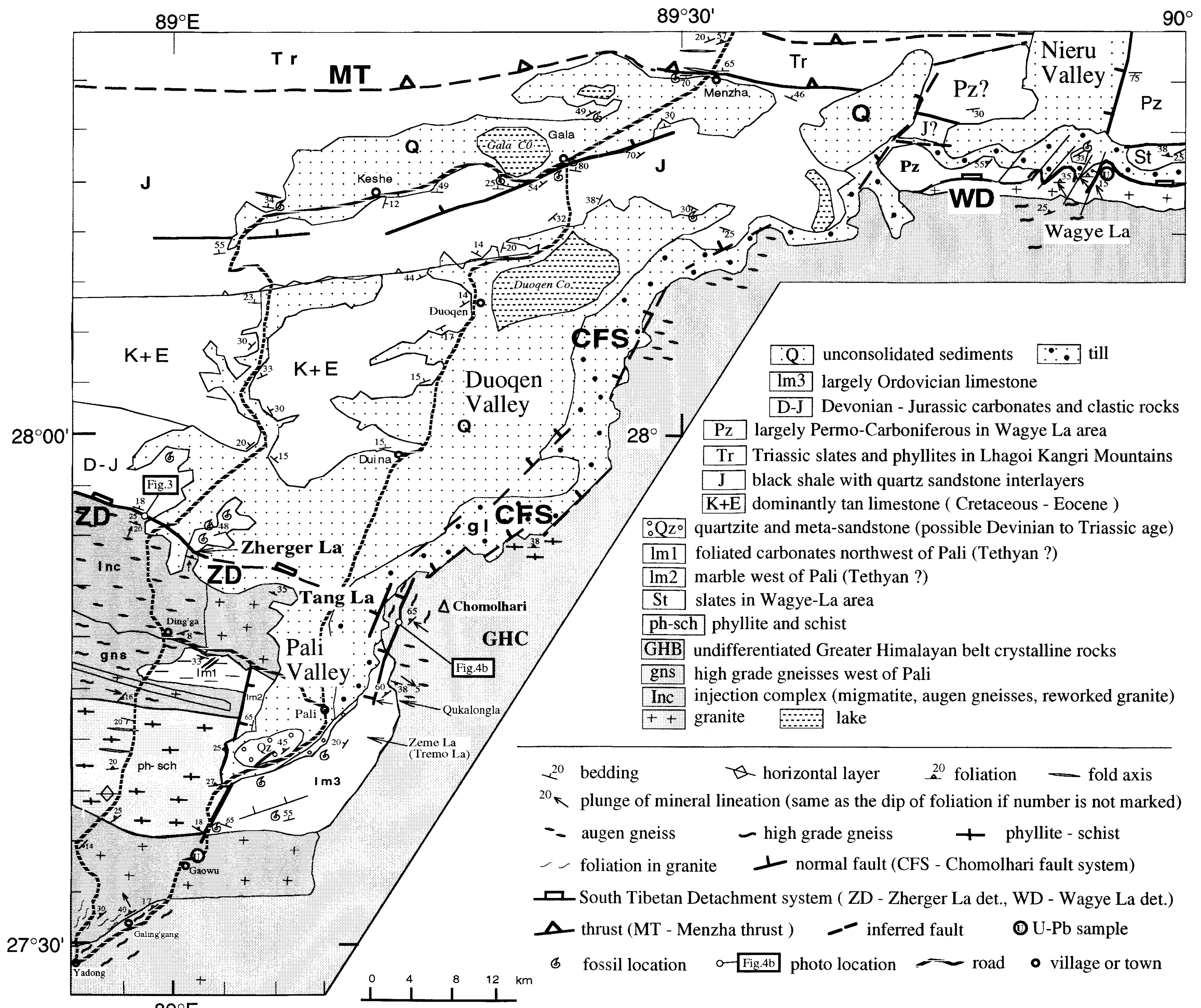

Plate 1. Geologic map of the southern Yadong-Gulu rift area.