Abstract. We summarize evidence for Quaternary and active faulting collected in the field during three Sino-French expeditions to southwestern Tibet (1980-1982). Detailed mapping of Quaternary and active faults as well as microtectonic measurements indicate that normal faulting has been the dominant tectonic regime north of the Himalayas in the last 2 ± 0.5 m.y. The maximum horizontal principal stress in south Tibet appears to be only the intermediate principal stress \( \sigma_2 \), \( \sigma_1 \) being vertical. South of the "chord" joining the eastern and western syntaxes of the Himalayan arc, extensional strains are principally localized within seven regularly spaced rift zones, three of which have been studied in some detail. The extension direction is determined to be N9\(^\circ\)E \( \pm 5^\circ \) mainly from statistical averaging of strikes of newly formed normal faults. Throw rates on normal faults are evaluated for different time spans (2 ± 0.5 m.y., 60 ± 40 kyr, and 10 ± 2 kyr B.P.), using structural and topographic reliefs, as well as synglacial and postglacial vertical offsets. The rate of Quaternary extension is about 1 cm/yr along a 1100-km-long ESE traverse across southern Tibet. This corresponds to an "spreading" rate of 1 ± 0.6 cm/yr. This rate and the divergent horizontal projections of slip vectors of earthquakes along the Himalayan front constrain the rate at which rigid India underthrusts southern Tibet to be 2 ± 1 cm/yr. Although most of the normal faults appear to be independent of, and nearly orthogonal to, the E-W Mesozoic-Tertiary tectonic fabric, the Yadong-Gulu rift appears to be guided for over 130 km by the older, oblique (NE-SW) Nyainqentanglha range and fault zones along it. This reactivated zone is the most prominent left-lateral strike-slip fault system in SE Tibet. Excepting this zone, and the vicinity of the SE extremity of the Karakorum fault, Quaternary strike-slip faulting is rare in south Tibet, i.e., south of the chord between the syntaxes of the Himalayan arc. North of the chord, the tectonic style is different. There is a major zone of active right-lateral, en echelon strike-slip faults (Karakorum-Jiali fault zone) probably reflects the greater facility of eastward extrusion in north central Tibet, in response to the northward push of India. The eastern Himalayan syntaxis may be an obstacle to such extrusion movements south of the chord.

1. Introduction

Landsat image interpretation and earthquake fault plane solutions imply that normal faulting characterizes the present tectonics of the Tibetan plateau [e.g., Molnar and Tapponnier, 1978; M1 and York, 1978; Romanowicz, 1982]. Such an extensional regime contrasts with active thrust faulting in areas of lower elevation to the north and south. Besides, it seems to have started only recently, after important episodes of crustal shortening and thickening. Indeed, much of the overall structure, high elevation, and thickened crust of Tibet appears to be the result of three subduction-collision cycles which, since the Palaeozoic, have accreted Gondwanan or Cathaysian continental blocks to Laurasia [Chang and Cheng, 1973; Stöcklin, 1980; Sengör, 1981a, 1984; Tapponnier et al., 1981a; Allègre et al., 1984; Hirn et al., 1984]. A better comprehension of the development of postorogenic extension in Tibet is important to understanding the way in which high plateaus evolve during continental collision but has so far been hampered by the scarcity of direct evidence.

As a step toward such a comprehension, we present a field study of active and Quaternary tectonics performed during the 1980-1982 Sino-French expeditions to Tibet. Much of the work described in this paper was done in areas near Kung Co and Dinggye and between Yadong and Nagqu (Plate 1). It involved a combination of approaches. Structures deforming Quaternary sediments, or exhibiting youthful morphology in the field, and on air photographs were mapped at a scale of 1:100,000. Morphological observations were gathered to constrain offsets of different sizes on faults. Measurements of small-scale features reflecting tectonic strains (slickensides, tension gashes, etc.) were also made, usually near the faults in Quaternary sediments or in fractured bedrock and cataclasites. Finally, we tried to relate recent surface breaks to historical and instrumental seismic records [Institute of Geophysics, 1976].
The data collected are used to place quantitative constraints on the direction and rate of Quaternary extension in southern Tibet. We also examine the implications of our results on the recent tectonics of Asia, particularly, the link between extension in Tibet and the contrasting tectonic strains induced in adjacent areas by the northward penetration of India into Asia.

2. Major Features of South Tibetan Cenozoic Stratigraphy

Despite problems in regional correlation, the Cenozoic stratigraphic record appears to be different from one another; they are now isolated from one another, they are now isolated from one another, they are now isolated from one another. This change probably followed the onset of a new tectonic regime: normal faulting appears to have helped Gangetic drainage to dissect the east-west Miocene-Pliocene basins by creating outlets through the Himalayan barrier [Armijo and Tapponnier, 1985]. The late Pliocene-early Pleistocene age of the Gongba conglomerate which caps the ponded Miocene-Pliocene sediments in most basins [Wang and Li, 1982] may be taken as a lower bound for the onset of such faulting. Indeed, except for high-level veneers of morainic and alluvial deposits [Ambolt and Norin, 1982] the bulk of Quaternary sediments (lacustrine and fluval) are accumulated mostly within north-south trending rifts or half-grabens. Moreover, we are not aware of the occurrence of sediments older than Pleistocene in the north-south grabens south of YZS except where they intersect the east-west Miocene-Pliocene basins [e.g., Gyirong and Thakkhola basins [Chen, 1981; Fort et al., 1981].

3. Relationship Between Morphology and Recent Tectonics

3.1. Planation Surfaces and Tectonic Movements

In contrast with the Colorado Plateau, the Tibetan plateau does not owe its morphology to the existence of distinct structural horizons. Instead, this morphology appears to be a combination of planation surfaces [e.g., Li et al., 1981]. Since wide planation surfaces may only form and persist near the base level, the generally flat morphology of Tibet implies the persistence of a high relative base level. Internal drainage must therefore have prevailed over much of the plateau, for several million years. It was probably maintained by mountain building and uplift along structural edges of the plateau where overthrusting occurred (Himalayas, Kun Lun, Lung Men Shan). This inference is supported by the fact that three of the largest rivers now escaping from Tibet (Jinsha, Lancang, Nu) flow through the plateau where overthrusting occurred (Himalayas, Kun Lun, Lung Men Shan). Where the plateau lacks such an edge, probably as a result of dominant Tertiary strike-slip movements [Tapponnier et al., 1982, 1986]. The headwaters of those rivers, however, have not yet reached the far interior of the plateau.

A dry climate such as that which now exists in central and northern Tibet may have added to the isolation of the high-altitude drainage by starving it. The preservation of wide, uniformly high planation surfaces also implies that tectonic differential uplift was more subdued within the plateau than along its rims. Thus, although it remains difficult to constrain precisely the way in which the Tibetan plateau formed, grew, and rose during the collision, its surface probably had little more than a thousand meters of interior relief in the late Miocene-early Pliocene because of extensive internal levelling [Li et al., 1981]. In fact, south of YZS, that surface corresponds to the eroded top of the older 10 m old Maluski (Xing) and the N-S trending ridges (Figures 2, 3a, 3b, and 3a). In south Tibet, linear, N-S trending ridges
and troughs with up to 2.5 km of steep relief appear to have subsequently dismembered the above-mentioned surface, as normal faulting prevailed over competing leveling processes. Most of the short-term normal faults documented in this study display remarkably “long-term” evidence of Pleistocene activity on the rising footwall and “short-term” evidence of Holocene and historic movements on the subsiding hanging wall (Figure 1). Outstanding triangular facets (Figures 1 and 3) usually mark the sharp mountain fronts along the major faults and other regions of dry climate. The 100- to 1000-m-high facets may correspond to offsets accumulated during the last 10^6 to 10^7 years [Wallace, 1977, 1978]. Other long-term features that testify to Quaternary uplift on the normal fault footwalls are “wineglass” and “hanging” alluvial and glacial valleys (Figure 1). The shorter-lived traces of active faulting are smaller scarps which cut piedmont slopes (average elevation of 4700 m, above the level of the “high plains” which lack traces of glacial erosion or deposition). In contrast with the uniformly high elevation of terminal moraines on the plateau, terminal moraines of late Pleistocene glaciers on the south flank of the Himalayas and Karakorum are found at variable but always lower elevations (3500 and 3000 m, respectively) [Gansser, 1964; Ambolt and Norin, 1982] (Figure 2). This difference might result from the difference in relief and climate. Because the mountain barriers which ring the Tibetan plateau collect more snowfall and because the base level in the lowlands surrounding Tibet is lower than the plateau base level, glaciers at the periphery of Tibet should be larger and should flow and erode faster to lower elevations. Glaciers on most of the plateau, on the other hand, might be starved. Their imprint on the morphology would remain moderate, and their drainage networks local.

The puzzling lack of clear glacial traces at the high relative base level of the plateau might be interpreted in other ways. Glaciations might have involved dry base glaciers or large masses of stagnant ice, ponded at the plateau base level by internal drainage. Since convincing evidence for extensive glacial events of this type has yet to be found, however, we infer here that as elsewhere in the world, the readily observable glacial erosion morphology, whose imprint on the morphology would remain moderate, and whose drainage networks local.

3.2. Magnitude and Timing of Glacial Events on the Plateau

Over most of the Tibetan plateau the traces of large active faults lie at altitudes high enough to cut glacial drainage networks. It is thus important to characterize specific features of the late stages of the Quaternary glaciation there. Such features are apparent in the Lhagoi Kangri range (Figures 2 and 5a), only about 60 km north of the Himalayas. Along this range, Miocene granites (= 10 Ma [Maluski, 1984]) form a string of isolated domes, several hundred meters higher than the surrounding host rocks (Figures 2 and 5a). Because they lie north of, and lower than, the Himalayan climatic barrier, these domes display a pattern of glacial erosion different from that observed on the south flank of the Himalayas. Although little ice and snow now subait the domes, Landsat images reveal, on each of them, a scalloped upland morphology with a radial network of glacial valleys (Figures 2 and 5a). This implies that an initially smooth surface, the top of the domes and was subsequently covered and carved by ice caps which fed peripheral, now extinct, glaciers.

Normal faults that cut the Lhagoi Kangri domes appear to have controlled this extinct glacial drainage because glacial valleys adjacent to such faults were cut at high angles (sires 1, 11, and 14; Figures 2 and 5a). The position of terminal moraines at 4700 ± 100 m on the piedmont slopes shows that glaciers crossed the normal faults but did not reach the flat floors of the corresponding graben. Several hundred meters below (Figures 2 and 5a). The glaciations were thus on "trunk" glacial valleys, in fact often corroborated by their asymmetry (Plate 1 and Figures 2 and 5a). Ambolt and Norin [1982] found a similar situation in central and northwestern Tibet (Qangtang, Plate 1). Terminal moraines there also lie at an average elevation of 4700 m, above the level of the "high plains" which lack traces of glacial erosion or deposition.

At a more detailed level, two main glacial advances named Qomolangma I (Guxiang or Jilong stadial) and Qomolangma II (Baiyu or Rongpu stadial) are documented on the northern slopes of the Himalayas [Zheng and Shi, 1982]. They are separated by a major interstadial marked by weathering of the older (Qomolangma I) moraines and formation of a soil on them [Academia Sinica, 1980]. Within the younger set of moraines (Qomolangma II), two interstades are recognized by Chinese authors. A similar distinction of two main glacial advances during the last glaciation
Fig. 1. Summary of typical morphological features along normal faults in Tibet. Left side represents faulted graben floor (e.g., Figure 10) and mountain front with steep young scarp but degraded triangular facets (t) (e.g., Figure 24). Right side represents mountain front with steeper facets (t) and perched glacial valleys (g) (e.g., Figure 3). m, moraines; k, knick; a,p, alluvial fan, plain; tr, travertine ridge.
Fig. 2. Map of Quaternary faults in Kung Co and Beiku Co area. Topographic contours from Tactical Plotage chart H-9B (1972). Qomolangma glacial network interpreted from Landsat images. Miocene granites in Lhagoi Kangri from Burg [1983]. Faults from field observations and Landsat images. Symbols are the same as in Figure 5a. Numbers refer to sites in text.

has been made in the Tanggula range of central Tibet (Za'gya Zangbu and Basicuo stadials [Xu, 1981]) and may hold in the Nyainqentanglha range where air photographs reveal two sets of end moraines in front of large glacial valleys.

Since none of the above glacial pulses has been dated so far, only broad correlations with other parts of the world may be used to constrain their age. The morphology of the receding sequence of moraines in Tibet is reminiscent, for instance, of that of the Wisconsinan sequence in the eastern Sierra Nevada, where two main pulses (Tahoe and Tenaya-Tioga) are recognized, with a major interstadial between 65 and 45 kyr B.P. [Gillespie, 1982]. On a global basis, well-dated coral reef terraces (principally in New Guinea and Barbados) reveal five interstadials during the last glaciation, roughly around 30, 40, 60, 83, and 105 kyr B.P. [Bloom et al., 1974]. Although none of the observations above allows us to specify the age of the main interstadial observed in Tibet, 105 and 30 kyr B.P. probably represent safe upper and lower bounds. Correlations between oxygen isotopic stratigraphy, calcium carbonate analysis, and planktonic foraminiferal species percentages in North Atlantic cores [Ruddiman and McIntyre, 1984], which support the idea that the interstadial at 60 ± 10 kyr B.P. is the most prominent of the last glaciation, may allow us to place tighter constraints. If the moderate glacial imprint north of the Himalayas resulted from a starved glaciation, perhaps only major fluctuations within this glaciation were recorded on the Tibetan Plateau. The age of the main interstadial separating the Qomolangma I and Qomolangma II glacial advances might then be 60 ± 10 kyr B.P., roughly as in the eastern Sierra Nevada.

4. Kung Co and Pum Qu Normal Fault Systems

Although the Kung Co and Pum Qu fault systems are traceable without major discontinuities to
Fig. 3a. Kung Co fault mountain front (site 1, Figure 2).
Fig. 3b. Sketch of mountain front in Figure 3a. F, trace of master fault (thick barbed lines represent small scarps); a, slickensides on fault plane; c, crest; ch, secondary rain wash channel; m, young moraine; ot, older till; other symbols as in Figure 1.
about 32°N (Plate 1), we were able to study them mostly south of YZS. In this region the faults traverse the Tethys Himalayas, from the Precambrian basement of the greater Himalayas to the deformed Paleozoic to Tertiary sedimentary cover. The faults are nearly orthogonal to the regional E-W trend of south vergent, Tertiary folds and thrusts [e.g., Tapponnier et al., 1981a] and to the Lhagoi Kangri structural high, which probably corresponds to an E-W ramp anticline [Burg, 1983]. Locally, the faults cut the Miocene Lhagoi Kangri granites (Figures 2 and 5a).

4.1. Kung Co Half Graben

The Kung Co half graben (Figure 3) displays many features typical of other south Tibetan rifts.

1. It is assymetric: There is one prominent master fault (Figures 3a and 3b) at the base of the sharp mountain front on the eastern side. In contrast, on the western side, only minor, approximately N-S trending, conjugate normal faults offset Quaternary silts, sands, and conglomerates several centimeters to a few meters (Figure 2, site 2; site 3, Figure 3d). The Quaternary layers generally dip gently to the east and appear to onlap a flexed, also east dipping erosional surface (Figure 2). The average width of the Quaternary basin is about 10 km, and the elevation difference between the highest point on the uplifted footwall (6041 m) and the swampy valley floor (=4400 m) is approximately 1600 m.

2. On the uplifted footwall, a series of large triangular facets, visible on Landsat images [Tapponnier et al., 1981b, Figure 2c], separate glacial U-shaped valleys. The flatish longitudinal profiles of the glacial valleys and of the spur crests between them appear to be inherited from the initially smooth erosion surface which topped the adjacent granite dome in the latest Miocene and Pliocene (Figures 2 and 3). The facets are about 600-800 m high with slopes of the order of 2°-3°. Along the lowermost parts of the facets, the master fault plane, dipping 5°-6°W is exposed as polished surfaces or slickensides on foliated or crushed granites.

3. The glacial valleys are hanging, and each one exhibits only one major knickpoint upstream from the master fault trace (Figures 3a, 3b, and 3c). Both the hanging position and the knickpoint are related to tectonic uplift along the fault. The knickpoint, which was the site of a receding ice fall, must have resulted either from a rapid increase in the rate of normal faulting or a rapid decrease in the rate of glacial downcutting, concurrent with a temporary retreat of the glacier. Since there is no detectable trace, within the facets, of a morphological discontinuity testifying to a rapid change in the rate of normal faulting, the existence of the knickpoint may be ascribed to a large climatic change during the glaciation, probably the last major Qomolangma interstadial or the last interglacial. In any event, the mere existence of one large glacial knickpoint in each valley implies that average glacial downcutting rates in the Lhagoi Kangri belt have been slower than normal faulting rates. By contrast, in the Greater Himalayas farther south, the absence of marked knickpoints (Figure 7a) appears to be a consequence of the more active glacial erosion.
Plate 1. Seismotectonic map of Tibet. Major fault systems include the Main Boundary Thrust along the Himalayan Front, the Altyn Tagh and Kun Lun faults at the boundaries of Tibet with Tarim and Qaidam, respectively, and, in southern Tibet, the Karakorum-Jiali strike-slip fault zone (KJFZ, Figures 32 and 33) and seven principal rift systems (Figure 28). In northern Tibet, conjugate strike-slip faults are generally less conspicuous. Landuse coverage was of poor quality between 33°–35°N and 89°–91°E. Young volcanics appear to be concentrated SW of western tips of Altyn Tagh and Kun Lun faults. Seismicity is from Institute of Geophysics [1976] and fault plane solutions (lower hemisphere, compressional quadrants in black) from Molnar and Tapponnier [1978], and Molnar and Chen [1983]. The two fault plane solutions west of Lhasa (lighter) correspond to subcrustal events. Elevations are in meters. Names in China follow pinyin transcription.
Plate 2. Transverse cross sections (oriented between N95° and 105°E) in Yadong-Galu rift. See maps for locations (Figures 6, 8, 13a and 26). Topographic reliefs across faults are given by vertical bars, and minimum cumulative throws (?) are in kilometers. Vertical exaggeration is 2.5. Geology is mainly from Ministry of Geology [1980], Burg [1985], and Girardeau et al. [1986]. A is Quaternary; N, Neogene volcanics; UK-FO, Palaeogene ignimbrites; UK, upper Cretaceous melanges; IK, lower Cretaceous; J, Jurassic; T, Triassic; P, Permian; Pz, Palaeozoic; PC, Precambrian (?) gneisses; YT, YMa, Tertiary and Mesozoic granites; y5Ma, Mesozoic granodiorites; 0, ophiolites.
Fig. 3d. Small ENE dipping normal fault within Quaternary sediments in Kung Co half graben (site 3, Figure 2).

which, for the climatic and topographic reasons discussed earlier, has apparently kept pace with normal faulting.

4. A till wedge, at least 300-500 m thick (elevation difference between valley floor and master fault trace), lies along the base of the mountain front. The surface of this wedge is rather smooth and its upper part is cut by numerous small scarps. The overall continuity and linearity of the scarps (Figures 3a and 3b) which follow the master fault indicate a recent tectonic origin. In front of the hanging glacial valleys the fresh Qomolangma terminal moraines lie on top of the till wedge, which therefore represents the principal trace of glacial deposition older than Würm in the Kung Co half graben.

The observations above allow us to estimate two quantities which can be used to constrain the rates of normal faulting on the Kung Co master fault: (1) The total throw on the fault (H, Figure 3c) is at least 1600 m, and (2) the throw since the formation of the knickpoints has been about 200 m (h, Figure 3c).

To the south, the Kung Co fault appears to die out in the vicinity of site 4 (Figure 2) where a system of fissures feeds active hot springs which have built up travertine ridges 4-8 m high (Figure 4). The longest ridges (seve-

Fig. 4a. Schematic map of travertine ridges, open fissures, and springs south of Cangmuda (site 4, Figure 2). Average azimuth of the main set of fissures is N10.4°E; standard deviation is 10.8° (32 samples for ~1500 m of fissure length).
ral hundred meters) trend N10°E ± 1°. In addition, however, shorter approximately E-W ridges branch off the principal, most active fissure, particularly near its northern extremity (Cangmuda health resort). An open crack, 10-40 cm wide, runs along the top of each travertine ridge (Figure 4b), indicating that periods of travertine buildup may be triggered by shorter episodes of tectonic extension. This suggests that the Cangmuda fissure system is a result of tectonically induced hydrofracturing, a process analogous to magma fracturing in rift volcanoes such as Krafla in Iceland [Björnsson et al., 1979] or Ardokoba in Afar [Tarantola et al., 1980]. One may thus infer the orientations of principal tectonic stresses from the geometry of the fissures: the minimum principal stress σ3 should be oriented approximately N100°E perpendicular to the average orientation of the main set of fissures, while the maximum principal stress σ1 should be vertical, parallel to the intersection between the two sets of fissures.

The main fissures of the Cangmuda system form an overall dextral en echelon array (Figure 4a). Together with the Kung Co fault, faults southeast of Cangmuda also form a large, right-lateral array (Fig. 3). In the latter area, however, the evidence for Quaternary faulting is less clear, particularly at the foot of the high Himalayan range where normal fault scarps cannot be easily distinguished from the edges of glacial valleys which they may have guided (site 6, Figure 2). Nevertheless, at site 5 (Figure 2) a west dipping normal fault appears to have offset a conglomerate mesa, inducing a gentle eastward tilt in the downthrown block.

4.2. Pum Qu Faults

The principal Quaternary fault in the Pum Qu-Dinggye region (Figure 5a) cuts into the Himalayas, allowing the Pum Qu (Arun) river to flow through. In contrast with other interpretations [e.g., Wager, 1937; Holmes, 1965], we believe that the Arun captured, at site 7 (Figure 5a), a large, formerly internally drained catchment, located north of the Himalayas and south of the Lhagoi Kangri belt [Armijo and Tapponnier, 1985]. In fact, a case can be made here for the Quaternary drainage reversal which seems to have occurred in many of the Miocene to Pleistocene basins along the Himalayan northern piedmont. The drainage of such basins is unstable because it is controlled by two competing processes. On one hand, regional northward tilting, induced by uplift of the Himalayas, favors northward, internal, or Zangbo-directed
Here, the post glacial capture point is revealed by the improbable geometry of the present outlet of the Pum Qu river through the Himalayas. The river crosses the Pum Qu fault twice (A, B, Figure 5a), flowing into and out of, respectively, the footwall. Within the footwall the river follows adjacent valleys initially carved by two, now extinct, glaciers which used to flow northward (to A) and westward (to B), respectively (Figure 5a). Between A and site 7, the Pum Qu river thus now flows in a direction opposite to that of the formerly northward flowing glacier. The elbow of capture (7, Figure 5a), which formed across the crest of the spur separating the two glacial valleys, coincides with a knickpoint along the river profile. Whereas upstream of A (Figure 5a), the river meanders in marshlands at a uniform elevation above 4100 m, it drops about 300 m near site 7, between A and B (Figure 5a).

Continuing activity on the principal Pum Qu fault is clear at site 8 (Figure 5a), where scarps cut the postglacial piedmont morphology. Other clear Quaternary scarps cut an alluvial fan (site 9, Figures 5a and 5b) and stepped terraces (site 10, Figure 5a) along a smaller fault to the west. Faults at sites 11, 12, and 13 also show signs of Quaternary activity. Only the faults at sites 12 and 13 dip to the east. Together with the Pum Qu fault, the fault at site 13 delimits a large horst, whose crest is about 2300 m higher than the adjacent basins. In map view the series of faults including the Pum Qu fault, the fault at site 14 (Figure 5a), and the faults northwest of Xigaze (Plate 1) may form a large, left-lateral, en échelon array. Also, the central, N70°E trending segment of the Pum Qu fault probably accommodates a component of left-lateral displacement.
5. Faulting Along the Yadong-Gulu "Rift"

The normal fault system which extends about 500 km from Yadong in the Himalayas to Gulu (Yadong-Gulu "rift") (Plate 1 and Figures 6, 8, and 13a) is the longest rift system of Tibet. It runs nearly continuously across several major structural zones: The Tethys Himalayas, the Zangbo suture zone, the Lhasa block and Gangdise batholith, and the Nuijiang zone of Jurassic tectonics. Although the overall trend of the rift is about N30°E, it is segmented into smaller, generally asymmetric grabens oriented N10°E on the average. Major normal faults bounding these grabens have individual lengths between 20 and 60 km. The Yadong-Gulu rift system may be subdivided into three structurally different sections. South of the Zangbo suture, the major normal faults dip to the west (Figure 6). Between the suture and the Nyainqentanglha range, the rift is nearly symmetrical (Figure 8). Along the Nyainqentanglha, major faults dip to the east and have a large component of left-lateral movement (Figures 8 and 13a). This subdivision is convenient for presenting field observations.

5.1. Southern Section

Between Yadong, near the border with Sikkim, and the Zangbo river, several west dipping normal faults form a regular left-lateral en échelon array (Plate 1, and Figure 6). The uplifted hanging walls to the east make a high range which culminates at Njinkangsang (7191 m) and merges with the Himalayas in the area of Chomolhari (7313 m) (Plate 1 and Figure 6).

Yadong fault zone. The 130-km-long, 4500-m-high, marshy corridor which is entrenched in the Himalayas between Yadong and Gala (GA) (Plate 1, and Figure 6) is bordered to the east by a series of en échelon, N15°E trending, normal faults. As in the Kung Co area, the fault cuts through the gneissic Precambrian basement, its deformed Paleozoic to Eocene cover, and the intrusive, Miocene leucogranites. Triangular facets are well developed along the fault, particularly near the foot of Chomolhari (site 1, Figures 6 and 7a). Although fault scarps clearly offset moraines of the last Qomolangma glacial pulse (near sites 1 and 3, Figure 6) glacial valleys here are not hanging valleys (Figure 7a). At site 2 (Figure 6), hot springs and fissures are outlined by travertine ridges. Although this hydrothermal system is comparable to that observed at Cangmuda (Figure 4), its geometry is less clear, with fissures oriented between N135° and N160°E. The present topographic relief along the Yadong fault zone is about 2.6 km (section aa', Plate 2). Since published maps show only a thin veneer of Quaternary sediments in the southern part of the Yadong graben [Ministry of Geology, 1980], the total throw on the fault may not be much greater than the present relief.

Nyeyo fault. Northeast of Gala, the Nyeyo fault (N, Figure 6) makes the eastern boundary of a Quaternary half graben about 45 km long. This is an area where south vergent overthrusting induced by the collision is prominent; Mesozoic shales south of Yamzho Yumco (Plate 1, Y, Figure 6) are affected by kilometric overturned folds [Tapponnier et al., 1981; Burg, 1983] and south of Kangmar (KA, Figure 6) the gneissic basement and its cover have been overthrust onto the Mesozoic to lower Tertiary sediments [Burg, 1983]. This thrust contact (Kangmar thrust) is offset by the Nyeyo fault [Burg, 1983] (section bb', Plate 2), which
Fig. 6. Map of Quaternary faults in southern section of Yadong-Gulu rift. Elevations are from 1:100,000 PRC topographic maps (not accurate in Bhutan, south of peaks at 7000 m and 7168 m). Numbers refer to sites discussed in text. GA, Gala; N, Nyeyo; KA, Kangmar; X, Karila; Y, Yamzho Yumco; Z, Zangbo. Circled lowercase letters (e.g., aa') refer to sections of Plate 2.
implies a total vertical displacement on the fault about 500 m greater than the present topographic relief (1.4 km) (Plate 2). At site 4, fresh parallel scarps cut alluvial fans developing on top of a till wedge. Within the Nyeyo half graben, at site 5, fluvioglacial gravel beds with gentle (1°-1°) dips to the west are offset = 30 m by an east dipping normal fault whose scarp is covered by a more recent wedge of Quaternary conglomerates (Figures 6 and 7b). Other minor NE trending faults displace the gravel beds a few tens of centimeters. Slickensides on these faults indicate normal left-lateral movement.

Karila fault. The third major fault of the southern "en echelon" section of the Yadong-Gulu rift is located west of Yamzho Yumco, near Karila (Y, K, Figure 6). At the base of the mountain front, loose Quaternary silts and gravels lie in fault contact against the Mesozoic shales. Quaternary activity is attested by truncated spurs. South of site 6, small (1-2 m high) discontinuous and eroded scarps along the upper part of the piedmont slope may mark the trace of the last faulting event.

At site 6 (Figure 6), near the major fault contact, many small normal faults cut the well-bedded Mesozoic calc-schists and limestones, here intruded by a large dolerite sill. These faults, which trend NE on the average, may be separated into two roughly conjugate subsets (Figure 29). ESE dipping tension gashes associated with these small normal faults are perpendicular to the WNW dipping Mesozoic beds. Dispersion of bedding plane poles is compatible with folding about an axis oriented roughly N115°E and plunging 20° to the WNW. A rotation of approximately 20° about a horizontal axis oriented = N25°E, nearly parallel to the strike of the Karila fault, brings the gashes to a vertical position and the fold axis to a horizontal ESE direction. It also rotates the average strike of bedding planes from NE to ESE. The orientation of the fold axis and of the bedding thus becomes identical to that of the regional Tertiary folding south of Yamzho Yumco. The above rotation may therefore be interpreted as cancelling the effects of drag in the vicinity of the Karila fault, and the extension direction prior to that drag may be taken as perpendicular to the tension gashes (N115°E) (Figure 29). Slickensides on the small normal faults are compatible with such an extension direction although movement on some of the SE dipping normal fault planes may have been guided by the intersections of such planes.

Topographic relief along the Karila fault...
Fig. 7b. Minor eastward facing normal fault (site 5, Figure 6) within west tilted Quaternary beds in Nyeyo half graben. View to north, fault plane and offset (30 m) are concealed by wedge of younger alluvium.

Fig. 7c. Schematic topographic profile across Karila fault. Adjacent highs are projected along longitudinal profile of ancient Yamzho Yumco drainage into Zangbo. Present water divide (4456 m) corresponds to site 7, Figure 6.
Fig. 8. Map of Quaternary faults in central section of Yadong-Gulu rift (Angang and Yangbajain graben, southern part of Damxung corridor). Topography and symbols as in Figure 6. Dashed contour (4300 m) outlines here and in Figure 13a the two main rhomb-shaped basins of Damxung corridor. A, Angang; YA, Yangbajain; NA, Nam Co.
reaches a maximum value of about 2.5 km (Plate 2, section cc'). Stratigraphic mismatch between the undeformed late Cretaceous melange on the downthrown side of the fault and the metamorphic early Jurassic "Spiti" shales on the upthrown side suggests that the total vertical displacement on the fault has been at least 500 m greater.

The topographic highs on the east side of the Karila and Nyeyo faults appear to be balanced by topographic depressions on the west side. The width (10-40 km) and oval shape of such topographic deflections and highs imply a flexural origin (Figure 6). A regional, flexural tilt of the upthrown block (a few degrees to the east) along the Karila fault may account for the formation of the Yamcho Yumo lake. The lake now floods a complex network of narrow fluvial valleys at 4400 m. Its ancient, antecedent outlet across the Karila fault used to flow toward the Yarlung Zangbo. There exists now in the area of site 7 (Figure 6) a subtle water divide (Figure 7c) along the longitudinal profile of this outlet. This divide does not correspond to damming of the valley by a landslide or moraine and may be ascribed to tilting rather than faulting. Tilting of the upthrown block may also account for a = 20-km-long stretch of rapids along the Zangbo (Z, Figure 6). This stretch begins at site 8 (Figure 6), where the river enters a narrow gorge, as it crosses the Karila fault.

5.2. Central Section

Between the Zangbo river (Z, Figure 8) and the Nyaiqentanglha range, the central section of the Yadong-Gulu rift has a symmetrical structure, with faults dipping east and west. Immediately north of the Zangbo suture (YZS), normal faulting is distributed over a region about 50 km wide (Figure 8 and Plate 2, dd'). Average elevations there are generally lower, possibly because of more diffuse tectonic subsidence and because of increased erosion rates near the Yarlung Zangbo valley (≈ 3700 m). Farther north, however, extension becomes localized again in a unique, well-defined graben (Yangbajain graben, Yangbajain graben, Figures 6 and Plate 2, dd'). Average faulting there is distributed over a region about 50 km wide (≈ 25 km) along the Yadong-Gulu rift. As observed south of YZS, normal faulting in this region is also overprinted on a nearly orthogonal Mesozoic-Cenozoic tectonic fabric: the faults cut the Gangdise batholith, which forms along the Mesozoic-Andean margin of the Lhasa block, as well as its folded upper Paleozoic to Paleocene sedimentary cover and the more recent, unconformable andesites and ignimbrites (Tapponnier et al., 1981a; Burg, 1983).

Angang graben. Within the zone of more distributed extension North of YZS, the Angang graben is a small (4 X 21 km) rift (A, Figures 8 and 9a) located south of the western master fault. This graben, aligned approximately parallel to the main fault which bounds the Angang graben on its west, is thus more prominent than its eastern counterpart. That fault is well exposed at site A (Figure 9a), where Quaternary gravels and silts are in fault contact with crushed granodiorites in which there are numerous slickensides. The slickensides indicate movements with both normal and left-lateral components even on planes trending roughly N-S (Figure 29). Here, the resulting extension direction thus appears to be ENE (HSPF) rather than ESE as in Karila or farther north. In the graben itself, three levels of Quaternary terraces, well developed on the western piedmont slope, can be recognized (Figure 9a). There is a suggestion that these terraces might be tilted because the surface of the highest (oldest) terrace (T3) appears to dip slightly to the west (B, Figure 9a) and because the eastward dip of the surface of the middle terrace (T2) is smaller than that of the lowest terrace (T1). A large, perhaps earthquake-triggered landslide (E in Figures 9a and 9b) covers the youngest terrace (T1) as well as the western master fault and a prominent fault on the graben floor (B in Figures 9a and 9b). Although not much degraded by erosion and thus probably rather young, the absence of small-scale normal faults, the lower unit is densely faulted at places and exhibits significant dips (between 30° and 60°) toward the east and west or southwest (Figure 9c). At least two small faults, trending NS and NW-SE, (near β and γ on Figure 9c) show reverse sense of slip in their present attitude. The absence of small-scale folding and the apparent conjugate geometry of the faults with respect to the bedding (α, β, Figure 9c) suggest to us that deformation in unit I may result from a complex sequence of extensional faulting followed by local tilting, perhaps in relation with drag and/or gravity sliding adjacent to the YZS in a flexural regime such as in Karila.

The top surface of unit II at site C corresponds to the surface of the youngest terrace (T3), the age of which is thus 10 kyr (Figures 9a and 9b). Since that time, the cumulative throw on the several single event or multievent scarps which cut this terrace west of site C (Figure 9a), may be crudely estimated at 20 ± 10 m. Addition of topographic reliefs across the principal normal faults in profile dd' (Plate 2) yields a total of about 3.9 km with a cumulative uncertainty greater than the uncertainties (100-200 m) in other sections of the Yadong-Gulu rift.

Yangbajain Graben. North of Angang, the Yangbajain graben (YA, Figure 8) forms a well-defined N-S trough which widens from about 12 km in the south to 28 km in the north where it abuts against the NE trending Nyaiqentanglha range. The floor of this trough, at an average elevation of 4300-4400 m is cut by numerous normal faults. It is limited to the east and west by two larger faults of opposite dips and truncated to the north by another, SE dipping...
Fig. 9a. Schematic map of Quaternary deposits in Angang graben. Three terrace levels (T1, T2, T3) are offset by normal faults. Capital letters indicate sites discussed in text and shown in Figures 9b and 9c. Site A corresponds to site 9, Figure 8.

Faulting within Quaternary sediments is particularly well developed in the south central part of the Yangbajain graben (Figure 8, sites 10, 11, Figure 10). A dense network of subparallel scarps, oriented N12°E ±16° (Figures 10a, 10b, and 10c) disrupts the topographic surface of the graben floor and eastern piedmont. Most of the faults dip to the west, as does the eastern master fault and separate major steps. The lowest part of the graben, which forms a marshy depression, thus lies close to the western master fault (Figure 8 and Plate 2, ee'). Normal offsets on individual scarps range from a few tens of centimeters to a few tens of meters (Figure 10c). Scarps near the lowest, depositional part of the graben, under Quaternary gravels, sands, and silts. Such volcanics might be as young as Miocene [Zheng et al., 1985] and thus comparable to those found west of the graben in the Machiang area (Coulon et al., 1986).

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grabens is probably older than a few hundred years. The entire series of steps is carved by transverse, glacier-fed rivers, whose valleys provide exposures into older, uplifted Quaternary gravel beds and their volcanic basement. Tilts within these gravel beds appear to be minor and some normal faults exhibit well-preserved slickensides (site 10, Figures 8 and 28, and Figure 4a of Tapponnier et al. [1981b]).

The central zone of dense faulting described above extends northward to the Nyainqentanglha range front fault. Although most normal faults keep a similar orientation (NI$^2$E), the overall geometry of faulting is more complicated towards the North, and the surfaces of the more numerous steps appear to be slightly tilted outward both to the east and west. The whole zone is obliquely cut by a major fault striking ENE which truncates, at site 13 (Figure 8), a NE trending, west dipping fault plane. Slickensides on this plane, which brings the underlying Tertiary volcanics against the Quaternary gravel beds, indi-

Fig. 9b. Aerial view around site B (Figure 9a) in Angang graben. Faults cut youngest terrace (B) as well as recent landslide (E).
Fig. 9c. Schematic sections of Quaternary deposits in one canyon near eastern edge of Angang graben (site C, Figures 9a and 9b).
Fig. 10b. Schematic map of fault scarps in Figure 10a. Azimuthal distribution diagram (upper left) represents 241 samples (totaling 83 km of scarp length). Average azimuth (arrow) is N12.4°E; standard deviation, 16°.

Predominant fault scarps are west dipping. Shorter antithetic faults locally isolate small grabens.

cate a composite normal left-lateral movement (Figure 29). Both the absence of volcanic basement just north of site 13 and the surface morphology imply that the graben floor south of the ENE transverse fault has been uplifted along it. Such an uplift may have produced the threshold dividing, WSW of site 13, the western, most subsident depression of the Yangbajain graben into two distinct ponds (Figure 8). Many small normal faults, parallel to those in the central zone, are exposed along this threshold. The ENE transverse fault zone probably extends farther westward into a large WSW valley (Figure 8). North and south of this valley, the western edge of the Yangbajain graben (Nyainggentangla frontal fault and western master fault, respectively) is offset about 4 km left laterally (Figure 8). The transverse fault zone and its inferred extension may belong to a system of ENE trending faults that are well developed farther north along the Nyainggentangla range in the Damxung corridor (Figures 8 and 13a). A combination of left-lateral and normal movements has apparently occurred on most such faults in the Quaternary and probably also the Tertiary.

North of the threshold, a broad till apron slopes gently from marshlands at about 4400 m, up to the Nyainggentangla frontal fault which forms here the western edge of the Yangbajain graben. This master fault, which is marked by prominent triangular facets, curves from a NNE direction near site 12, to a nearly E-W direction, northwest of site 14 (Figure 8). Its southern extremity (south of site 12) appears to splay into several smaller branches (Figure 11a). A sharp surface break, about 5 km long, outlines one such branch, oriented N140°-150°E (B on Figure 11a). The grass-covered piedmont slope (F) as well as the channels of small transverse gullies (C) are offset 5-6 m vertically along this fault scarp (Figure 11b), implying that it probably represents a single event. The thick grass turf has not grown back on the disrupted ground near the scarp. On the other hand, the small juniper shrubs which
Scarps of similar size and morphology appear to run nearly continuously along the southwestern extremity of the Nyainqentanglha fault north of B and past C and E (Figure 11a), which may bring the total length of the surface rupture to more than 10 km, if it is entirely related to the same event. Although a shock of magnitude = 6 1/2, of unknown focal depth and of uncertain location a few tens of kilometers to the west, occurred on October 9, 1924 (Plate 1), it may be too recent and too small to account for the surface break described here.

The NNE trending range front in the vicinity of site 12 (Figures 8 and 11a) displays most of the large morphological features described at Kung Co (Figures 3a, 3b, and 3c). Three hanging glacial valleys with gently sloping longitudinal profiles (at an average elevation of 5400-5600 m) have been uplifted by normal faulting (Figures 11a, 11c, and 11d). In each valley, major knickpoints lie about 150 m above the master fault trace, here at an elevation of ~5200 m (Figure 11c and 11d). The triangular facets are about 500 m high. As in Kung Co, the absence of slope break in the facets implies that the knickpoints may be related to the last major interstadial (or interglacial). The throw (h, Figure 3c) on the fault since that time is thus about 100 m, roughly half the corresponding displacement at Kung Co. North of site 12, larger and longer glacial valleys in which rates of glacial downcutting must have been higher are not hanging and are flanked by higher (= 1000 m), triangular facets.

Evidence for Holocene activity along the Nyainqentanglha fault near site 12 is much clearer than along the Kung Co master fault. A continuous, steep scarp about 15 m high runs along the base of the triangular facets and across the lateral moraines (essentially Qomolangma II) where it becomes more diffuse, less steep, and thus of greater apparent height (Figures 11c and 11d). The most recent scarps, only a few meters high and mostly devoid of vegetation, which may be correlated with the surface break identified farther south (B, Figures 11a and 11b) are observed near the base or more rarely near the top of this Holocene scarp (Figures 11c and 11d). Both types of scarps may be followed at least as far as E (Figure 11a) to a large valley where postglacial lateral terraces are offset vertically 15-20 m, while the valley floor itself is displaced only a few meters. Slickensides exposed by the recent break

follow the crest of the scarp must have grown since its formation. Such changes in the vegetation cover are probably related to the still high angles (up to ~37°) of the debris-controlled scarp slope (Figure 11b). All these observations concur to suggest that the earthquake during which this scarp formed is at most several hundred years old [Wallace, 1977].
Fig. 11a. Aerial view of Nyainqentanglha frontal fault, Yangbajain graben, at site 12 (Figure 8). Note fresh N140°-150°E scarps at B and prominent triangular facets and perched glacial valleys in uplifted basement rocks NW of C.
south of C indicate predominantly dip-slip faulting on NE trending planes (Figure 29).

Near site 14, the traces of normal faults of the central zone meet the Nyainqentanglha frontal fault trace at an angle of 50°-70° in map view (Figures 8 and 12). In this area, the latter master fault curves back to a more northeasterly strike (Figures 8 and 12). The master fault plane, which juxtaposes basement rocks with Quaternary tills, is well exhumed and displays two sets of striations. Thinner and younger striations with steeper pitches overprint everywhere larger, older grooves. Both sets indicate a combination of left-lateral and normal slip. The larger displacements correspond to the grooves and entail a greater strike-slip component. The slip vector represented on Figure 29 (NFF) corresponds to these larger displacements. Since the master fault here is oriented N80°E and dips 50°S, the measurements above locally rule out N-S shortening during the Quaternary. As at Cangmuda, they imply that the horizontal, NNE component of the stress tensor is the intermediate principal stress σ2. Measurements on faults located lower down, within the Quaternary fill (site 14 and sulfur mine northwest of the Yangbajain geothermal power plant), show predominantly normal slip with small right-lateral components on planes oriented north to slightly west of north (Figure 29).

The Yangbajain geothermal field lies in the transition area (Figure 8) where the roughly N-S Yangbajain graben narrows and gives way to the oblique Damxung corridor. The large, west dipping fault system that can be followed almost continuously from the Himalayas across the Zangbo suture comes to an end here. The geothermal reservoir appears to be located within Pleistocene sediments on top of a basement high that may represent an extension of the minor horst observed farther south, just west of the eastern master fault (Figures 8, and Plate 2, ee'). On this high, the Quaternary deposits rest directly upon 49 Ma granites [Zheng et al., 1985] similar to the 40-50 Ma leucogranites sampled near Yangbajain village [Allègre et al., 1984] and is only about 300 m thick [Academia Sinica, 1980; Zheng et al., 1985]. Northeast and west of the high, the depth of the basement appears to increase to over 1200 m [Zheng et al., 1985]. All the reliable slickenside measurements made either on faults within Quaternary deposits or on faults separating these deposits from older rocks in the Yangbajain graben are assembled in the diagram of Figure 29. Although the measurements were collected at distant sites and on faults with different attitudes, they are compatible with a regional direction of Quaternary extension and a least principal stress σ3 oriented about N105°E. The average strike
of the most recent scarps within the Quaternary fill of the graben (Figures 10a and 10b) may be taken as another independent indicator of the orientation of the maximum horizontal principal stress $\sigma_2$. The fact that these two directions are nearly orthogonal confirms that both are well constrained and represent more accurately than elsewhere along the Yadong–Gulu rift the regional kinematics and state of stress.

The particularly clear evidence for youthful faulting in the Yangbajain graben is suggestive of larger cumulative displacements across it in the last 100,000 years than elsewhere in SE Tibet. Although our observations yield a quantitative estimate of such high displacements only on the Nyainqentanglha frontal fault near site 12, the existence of other faults with comparable morphology (Figure 8 and Plate 2, ee') supports this inference. Estimates of cumulative topographic relief and minimum vertical displacements of geological markers suggest that cumulative throws are also maximum across this graben. On profile ee' (Plate 2) the cumulative topographic relief is about 4.9 km. This high value may be related to the fact that Quaternary faulting only: Part of the present relief of the oblique Nyainqentanglha range, which maintains its high topographic identity as it diverges from the Yangbajain graben toward the SW, may be a consequence of combination of Tertiary strike-slip and normal or thrust movements [Tapponnier et al., 1986]. About 10 km south of ee', nevertheless, the cumulative topographic relief along an E–W profile across the graben is still about 4.4 km. In addition, the fact that the Tertiary volcanics, which appear to underlie part of the Quaternary fill of the Yangbajain graben, are found perched at high elevations in the adjacent mountains suggests several kilometers of cumulative basement offset. Such an offset cannot be estimated more precisely since the poorly mapped base of the volcanic pile may have flooded an irregular surface. The apparent thickness of alluvial sediments just W and NE of the geothermal site (= 1000–1500 m [Zheng et al., 1985]) implies still greater thicknesses (= 25–35 m) in the western, more subsiding portion of the graben. If all those sediments were of Quaternary age, such large thicknesses would concur to indicate several kilometers of cumulative basement offset across the normal faults of the graben. Alternatively, it is possible that some of these alluvial sediments were deposited before the Quaternary, as a consequence of oblique movements along the Nyainqentanglha fault system. In any event, cumulative Quaternary normal throws in the Yangbajain graben are likely to be at least of the order of 5 km, mostly because of the existence of two conjugate master faults. This minimum throw is smaller than twice the offset cannot be estimated more precisely since the poorly mapped base of the volcanic pile may have flooded an irregular surface. The apparent thickness of alluvial sediments just W and NE of the geothermal site (= 1000–1500 m [Zheng et al., 1985]) implies still greater thicknesses (= 25–35 m) in the western, more subsiding portion of the graben. If all those sediments were of Quaternary age, such large thicknesses would concur to indicate several kilometers of cumulative basement offset across the normal faults of the graben. Alternatively, it is possible that some of these alluvial sediments were deposited before the Quaternary, as a consequence of oblique movements along the Nyainqentanglha fault system. In any event, cumulative Quaternary normal throws in the Yangbajain graben are likely to be at least of the order of 5 km, mostly because of the existence of two conjugate master faults. This minimum throw is smaller than twice the

5.3. Northern Section

North of Yangbajain, the main zone of active and Quaternary faulting follows the Nyainqentanglha range to about 91°30' E, where it takes a sharp turn to the east, creating the roughly Y-shaped morphology observed in the southern and central sections (Figures 8 and 13). Around 31°10' N 91°35' E, North of Gulu (C, Figure 13a), the Yadong–Gulu rift loses its morphological and structural identity, where it interferes with two large right-lateral strike-slip faults (Plate 1 and Figure 13a). North of these strike-slip faults, normal faulting appears to be more distributed than south of them (Plate 1 and Figure 26). Along the Nyainqentanglha range, a combination of normal and left-lateral strike-slip faulting is observed, mostly along the western edge of two large rhomb-shaped basins (outlined by dashed 4300 m contours, Figures 10a and 13a), which together form the Damxung (D) corridor (Figures 8 and 13). The sharp bend at 30°35'N, 91°30' E marks an abrupt change between this strike-slip regime and predominant east dipping normal faulting along the Gulu half graben. Although the Nyainqentanglha is one of the major mountain ranges in the interior of Tibet, its structure is poorly known. Metamorphic rocks appear to crop out along most of it [Ministry of Geology, 1980]. They include, north of Yangbajain, biotite gneisses with NE striking foliation and stretching lineations dipping $\approx 39^\circ$ to the SE [Burg, 1983; Tapponnier et al., 1986] intruded by 40 m.y.-old granites [Allègre et al., 1984] and, north of Damxung, granodiorites and conglomerates of probable Tertiary age with steep, E–W striking foliation and horizontal stretching lineations [Tapponnier et al., 1986] that the Yangbajain graben does not cut this major range suggests the existence of crustal scale structures along it. In fact, the Yadong-Gulu rift system north of the Nyainqentanglha range only where it narrows (east of Damxung) and appears to be truncated by an E–W striking Tertiary fault zone extending at least 200 km eastward, to Jiali [Ministry of Geology, 1980; Tapponnier et al., 1986]. Farther north, active faults along the Gulu half graben cut across folded Jurassic black shales with steep E-W axial cleavage, intruded by an E-W belt of 100 m.y.-old granites [Allègre et al., 1984].

Damxung corridor. The combination of normal and strike-slip faulting which characterizes the Damxung corridor is already apparent at site 15 (Figures 8, 14a) and site 12, the continuation of the strike-slip regime and predominant east dipping normal faulting along the Gulu half graben. North of that corridor, numerous Quaternary scarps oriented $\pm 120^\circ$ with offsets of the order of 1–10 m form an overall left-lateral array. The faults are primarily normal and dip mostly to the east. Those that dip to the west, opposite to the piedmont slope, retain small ponds (d, Figure 14). The east dipping front fault (Figure 14), about 1 km to the west, strikes more easterly (N35° E). The south-eastern structural edge of the corridor is a linear, N65° E trending fault (AB, Figure 14) with comparatively little vertical relief. It dams a perpendicular SE–NW trenched drainage creating a series of marshy depressions (d, Figure 14). There is evidence for left-lateral strike-slip movements on this fault at A (Figure 14), where the outlet of one such depression is sharply kinked and offset 30–40 m. The existence of a now beheaded stream, about 500 m NE of A, south of the fault (Figure 14) suggests that such larger left-lateral offsets if this starved stream is interpreted as the former outlet of
that depression. The rectilinear fault trace described above extends about 50 km, almost continuously, along the southeastern edge of the corridor, to 91°E (Figures 8 and 13a).

Topographic relief on the Nyainqentanglha range front master fault is here about 3 km (ff', Plate 2). As previously noted, however, this relief may not result from Quaternary faulting alone. The vertical component of displacement along the predominantly strike-slip fault along the other side of the corridor is more difficult to assess. Fluvial terraces southeast of this fault are uplifted several meters, and the marshy area around trig point 4208 (Figures 8 and 13a) may be a consequence of occasional damming of the tributary of the Lhasa river by uplift along the fault. Several small but steep triangular facets south of point 4208 suggest that the topographic relief created by the fault is of the order of 500 m.

South of Damxung, approximately at 91°E, a bottleneck analogous to that north of Yangbajain marks the structural limit between the two main rhomb-shaped basins of the corridor. North of this bottleneck, Quaternary faulting is particularly prominent along the Nyainqentanglha mountain front and its piedmont (Figures 13a and 13b). In contrast, faulting along the southeastern edge of the corridor, if any, is not marked by clear traces in the surface morphology.

At site 16 (Figures 13, 15a, and 15b), in the bottleneck area, active fault scarps, oriented N70-80°E cut the till wedge, here perched at an elevation of about 5000 m. Major movements appear to take place along two subparallel fault...
zones that merge east of a rhomb-shaped depression filled with a lake. The depression and lake, which lie in front of a triangular facet, are not of glacial origin. They appear to form a left-lateral pull-apart (Figures 15a and 15b), between two particularly linear, mostly strike-slip fault segments. The en échelon geometry of faults along the range front, which have important normal throws, is additional evidence for a left-lateral component of movement.

Partition into two major fault zones is also characteristic of active faulting at sites 17 and 18 (Figures 13, 16, and 17). As clear on the picture shown in Figure 16c, a linear fault trace, located about 1 km downslope on the Nyainqentanglha piedmont, runs parallel to a zone of multiple scarps along the range front (site A, Figure 16b). These scarps cut moraines which flank wineglass valleys at the base of large triangular facets (Figures 16a, 16b, and 16c). Although both fault zones strike 70°–80°E, displacements on the south dipping range front fault appear to be mainly downdip, whereas drainage offsets (o near A, Figures 16b and 16c) and a comparatively small (antithetic) normal throw imply dominant left-lateral strike-slip movement on the rectilinear piedmont fault. Such geometry and kinematics of faulting are also clear at sites 20 and 21 (Figures 13, 19, and 20).

Figure 16d illustrates one simple way to explain coeval movements on a dominantly normal fault parallel to a dominantly strike-slip fault located at a short distance within the downthrown block. Parallelism of the surface traces is easily accounted for if the two faults splay from one single master fault plane at depth. Splaying into two distinct faults may result from the existence, on top of the basement, of a layer of sediments with markedly lower cohesion and strength. In such a circumstance, bulk displacements of the hanging wall respective to the footwall in the basement are unlikely to be transmitted rigidly into the weaker sediment layer. This layer is more likely to rupture...
Fig. 12. Nyainqentanglha front fault W of site 14 (Figure 8). The master fault trace bends from nearly E-W (left) to NNE-SSW (right). Note smaller NNE-SSW fault scarps cutting obliquely till wedge before merging with master fault.

along a steeper secondary fault, originating at the intersection between the basement top and the master fault. If the movement on the basement master fault at depth is oblique and if the attitudes of both faults do not change with ongoing deformation, the secondary fault will be purely strike slip and is likely to take up most of the strike component of slip. Figure 16d shows the limiting case in which that fault is vertical and absorbs all the strike component of slip. Minor complications may arise if the master fault surface is curved (Figure 16d). Partition of slip into parallel, almost purely normal and strike-slip faults near the surface probably accounts for the nearly dip-slip striations on south dipping, approximately EW striking fault planes in the diagram of Figure 29. Note that if the basement fault surface has been sufficiently exhumed, it should bear a younger set of striations with steeper pitches overprinting an older set with a larger strike component of slip. A mechanism of this type may have produced the double set of slickensides observed on the Nyainqentanglha frontal fault North of site 14 (Figures 8 and 29). A similar mechanism may also account for the partition of oblique slip into parallel strands along major, reactivated faults elsewhere in the world. One example may be the active Red River fault of Yunnan (south China), where a range front (predominantly dip-slip) fault and a mid valley (predominantly strike-slip) fault run approximately parallel to each other for 150 km between Chun Yuan and Hong He [Allen et al., 1984].

With the simple geometry of Figure 16d, the depth of the basement beneath the strike-slip fault trace would be 1-3 times the distance separating this trace from that of the master fault if the average dip of the latter above that depth were between 45° and 75°. This would yield sediment thicknesses of about 2 ± 1 km in sites 17 and 20, somewhat less in site 21, but perhaps as much as 5 km west of site 16. If the dip of the approximately N80°E basement fault were constant along strike, the sediment layer would thus thin progressively from site 20 toward the eastern tip of the Damxung rhomb-shaped basin (Figures 13, 19, and 20). It would also pinch out in the bottleneck separating the two basins of the corridor, immediately east of the lake at site 16 where the two main fault traces merge (Figures 13 and 15). The rather large thicknesses estimated here suggest that as west of Yangbajain, perhaps not all the sediments filling those basins are of Quaternary age. The existence of exhumed red sandstones and
Fig. 13a. Map of Quaternary faults in northern section of the Yadong-Gulu rift (Dammung corridor and Gulu half graben). Data and symbols as in Figures 6 and 8. D, Dammung; G, Gulu; B, Beng Co. Note the two subparallel active fault zones along Nyainqentanglha.
shales overlying deformed (Tertiary?) volcanics on top of a minor fault step adjacent to the range front fault (F on Figures 16b and 16f) might imply that parts of such thick fills were deposited in the Tertiary.

At site 18 (Figure 13a, B on Figures 16a and 16b), the piedmont strike-slip fault cuts a young alluvial fan (lower terrace, it). The scarp is oriented mostly N80E and the vertical offset on it (6-8 m) is opposite (i.e., downthrown block to the south) to that observed at site 17 (A in Figures 16a and 16b). Adjacent to this scarp, a double rhomb-shaped depression, which is most simply interpreted as a double asymmetrical pull-apart (Figures 16a, 16b, 17a, and 17b) confirms the existence of the left-lateral component of movement observed on all ENE faults along the Damxung corridor. The depression is located within a step in the piedmont fault, the two offset segments of which are connected by approximately N30E striking faults. If the floor of this depression was, before being blanketed by colluvium, about 3 m lower than the level of the downthrown block adjacent to it (As, Figure 17a) and the N50E and N80E faults had respective dips of 60° and 90°, this additional downthrow would correspond to as much as 4-5 m of left-lateral movement along the N80E fault (Figure 17a, insert). The rather sharp morphology of the debris-controlled scarp slope and the fact that its distal part has not yet concealed the pull-apart depression suggest that this scarp formed between several hundred and a few thousand years ago, perhaps as a result of one earthquake of large magnitude. Other neighboring scarps in the lower terrace probably formed during the same time interval. The absence of free faces on the scarps at site 18 suggests that none of them is related to the October 15, 1921, shock (M = 6 1/4) reported to have occurred west of Damxung (Plate 1).

The principal scarp along the piedmont fault swings to a N20°-30°E orientation, several hundred meters east of the site 18 pull-apart, near the edge of the lower terrace (Figures 16a, 16b, and 17a). It appears to cut the most recent alluvial fan and can be followed across the lower and middle terrace into the next valley to the north (Figures 16a and 16b, site C, and Figure 17c). This bend of the piedmont fault zone appears to correspond to a change in its nature: From rectilinear and mostly strike-slip west of B (Figure 16b), it becomes a left-lateral array of en échelon, SE dipping, and mostly normal faults northeast of B. This array remains roughly parallel to the range front master fault, the trace of which also swings to an approximately N30°E direction upstream of B (Figure 16b). Moreover, the dips of the piedmont normal faults appear to remain steeper than that of the range front master fault (Figures 15a and 16b). Such steep dips (60°-70°) are particularly clear on the large fault of site 19 (Figure 18). The distance between the two fault zones increases to about 2.5-3 km. They bound a well-defined wedge of thick and coarse Quaternary gravel beds capped by the uppermost terrace (qt in Figures 16a and 16b). This terrace has been uplifted at least =200 m along the piedmont fault zone. In
the wedge the thick gravel beds are uniformly tilted $10^\circ$ to $20^\circ$ to the northwest, the most coherent and clearly normal fault-related tilt we could find in the SE Tibet.

The fact that the piedmont fault bends in the same area as the range front fault, while keeping a surface trace roughly parallel to, and a dip steeper than, those of the latter, implies that NE of that bend, both faults may continue to splay from a single master fault in the basement. If that master fault had a dip of $6^\circ$ where it strikes N80$^\circ$E and if slip vectors on both the N80$^\circ$E and the N30$^\circ$E striking parts of the basement master fault were the same, the dip of the fault NE of the bend could not exceed $5^\circ$ because there appears to be no right-lateral component of slip along the N30$^\circ$E striking piedmont faults (Figure 16d). Dips of less than $5^\circ$ are consistent with the geometry of the range front fault and massive, often at about midheight of the main scarp itself offsets an erosion surface near the eastern tip of the Damxung basin, Quaternary faulting appears to be concentrated mostly in a single, linear fault trace along the range front (site 23, Figure 13). Although it is difficult to evaluate here the importance of strike-slip movements from the morphology, throws corresponding to faulting during three different time spans may be distinguished within the main, steep scarp (Figures 22a and 22b). The main scarp itself offsets an erosion surface 10-30 m (e, Figures 22a and 22b), which has a much gentler slope than usual triangular facets. In the valleys carved into that surface, alluvial fanheads are only offset 2-4 m. Finally, a barren break 0.5-1.5 m high runs continuously, often at about midheight of the main scarp, along the top of a scree wedge (s, Figure 22b). This break, which exposes crushed bedrock a few cm thick, extends for hundreds of meters along the scarp face (f) is the freshest of all surface breaks observed in the Yalong-Gulu rift and probably is only a few decades old. A discontinuity in annual growth rings of partially uprooted or inclined juniper shrubs along it [Han, 1983b] supports the inference that it corresponds to the shocks of September 3 (M = 6 1/2) and October 4, 1940 (M = 6), east of the Gulu graben and south of the Damxung Basin respectively (Plate 1).

Slickensides measured principally near site 23 and north of site 18, mostly in the crushed or fractured bedrock along the range front master fault are consistent with the combination of
Fig. 14a. Aerial view of faults near site 15, southern extremity of Damxung corridor (Figure 8).

Figure 14a shows an aerial view of faults near site 15, located at the southern extremity of the Damxung corridor. The faults observed in the vicinity of site 15 exhibit left-lateral and normal movements. For instance, at site 23, the pitches of striations on faults striking N60°-65°E, antithetic to the master fault, are 4°-5°W, and the direction of movement is clearly downdip (Figure 22d) [Petit et al., 1983]. It is noteworthy that a set of steep, N10°-11°E striking faults with a right-lateral component of slip, absent on diagrams farther south, have been observed. The least principal stress compatible with all slickenside measurements is oriented approximately N100°E (Figure 29).

Gulu half graben. A few kilometers east of site 23, the strike of the zone of active faulting changes about 90° from nearly E-W to nearly N-S. North of this corner, the faults, primarily normal, dip to the east along the western edge of a narrow (6-9 km wide) half graben (Figure 13). An oval topographic high, about 20 km wide at 5300 m, flanks the Gulu (G) half graben to the west (Figure 13). This high, which is comparable in shape and dimensions to those observed along the Kung Co, Nyeyo, Karila, and Dong Co faults (Figures 2 and 6, DO, Figure 26) probably has a similar flexural origin. The present topo-
Fig. 14b. Sketch map corresponding to Figure 14a. F is range front fault. Piedmont slopes are cut by NNE-SSW normal faults and by NW-SE, more linear fault trace (AB), bearing evidence for left-lateral displacement. Attitudes of fault AB and en échelon array are summarized in stereogram (left). Average azimuth of dip-slip scarps within array is N11.9°E, standard deviation 6.9° (37 samples for = 10 km of fault length). t, triangular facet; l, landslide; d, closed depression; o, offset stream; b, beheaded stream.

graphic relief along the Gulu master fault is about 2.2 km (Plate 2, profile gg').

Immediately north of the corner, four main parallel scarps, striking N10°E, form a right-lateral en échelon array oriented approximately N17°E (site 24, Figures 13, 23a and 23b). Although these fault scarps are mostly normal, they appear to offset transverse channels in a dextral sense (Figures 23a and 23b). In addition, the uppermost fault steps are cut obliquely by a N17°E striking, right-lateral array of smaller, en échelon scarps (Figure 23). West of site 24, another array of minor en échelon scarps, also with a right-lateral geometry, cuts
Quaternary alluvium in the valley (Figure 13a). The kinematics of faulting just north of the corner thus imply right-lateral components of movement on faults oriented N170°-N100°E. Since the major approximately E-W fault trace at site 23 overruns the corner only a few hundred meters and thus does not really cut the N-S faults, one may assume that as at the bend of site 18 north of Damxung, slip on both the approximately E-W and approximately N-S faults occurs mostly in the same direction, parallel to the intersection of these faults.

In this event, all plausible values of dips toward the east on the approximately N-S fault and toward the south on the approximately E-W fault will account for the observed components.

Fig. 15b. Sketch map corresponding to Figure 15a. Lowercase letters as in Figure 14b.
of right- and left-lateral movements, respectively, on these two faults (Figure 23c). At a more detailed level, the linearity of the surface trace of the N80ºE fault at site 23 implies that it dips more steeply and has a greater strike-slip component than the N170ºE fault zone north of the corner. In addition, the slight right-lateral component observed on faults striking N10ºE requires that the azimuth of the common slip vector be at least N100ºE. Slip vectors

Fig. 16a. Aerial view of piedmont fault bend north of Damxung (sites 17 and 18; Figure 13a).

Fig. 16b. Sketch map corresponding to Figure 16a. Active faults (thick lines) form two main strands: the range front fault (F) and the piedmont fault (ABC). A, site 17; B, site 18 (Figure 13a); ut, mt, lt are upper, middle and lower terraces, respectively; q, tilted Quaternary gravels; P, alluvial plain. Other lowercase letters and symbols as in Figure 14b.
Fig. 16c. Photograph of the two subparallel active fault strands at site 17 (Figure 13a). Multiple normal fault scarps mark range front fault (F), while linear fault trace below corresponds to piedmont fault. Streams in center are offset left laterally (~10 m) along the latter (near A, Figures 16b and 16a).

Fig. 16d. Fault bifurcation at basement (crosses)-sediment (dots) interface: two coeval faults with parallel traces and different kinematics splay from single fault at depth. Block diagram represents the simple case of planar faulting between rigid blocks discussed in text. Profiles represent curved basement faults and corresponding tilts in deforming sediment wedge.
Fig. 16e. Stereogram of rigid fault kinematics at bend of site 18 (Figures 13a and 16b). Azimuth range of slip vectors (N94°-120°E) is constrained by left-lateral arrangement of N30°E piedmont faults north of bend and probable minimum dips of basement fault west and north, respectively, of bend. Narrower range corresponds to preferred estimate in text.

Fig. 16f. Balanced section of tilted Quaternary wedge north of B (Figure 16b). Initially, sediments are horizontal and dips of basement and secondary faults 45° and 70°, respectively. Dashed line corresponds to situation in which all movement on basement fault takes place on secondary fault above bifurcation point. Isovolumetric collapse of sediment wedges parallel to small arrows (upper diagram) yield tilts of = 6° and 15°. Edge of undeformed sediment layer on top of basement has arbitrary dip of 70°W. Solid arrows indicate net slip on basement fault. Probably not all sediments in cross section are of Quaternary age (lower diagram, to scale).
Fig. 17a. Idealized block diagram of faulting near small pull apart at B, north of Damxung (Figure 16b). Insert shows main components of motion. Lowercase letters as in Figure 16b.
which account best for the observed geometry and kinematics of surface faulting are thus likely to have azimuths between N10° and 12° E (Figure 23c), in accordance with the regional direction of Quaternary extension elsewhere along the Yadong-Gulu rift.

It was generally difficult to determine the sense of slip on slickensides at site 24. In addition, since all of them were measured in Mesozoic black shales, most of them may not correspond to Quaternary movements. Nevertheless, on the four SE striking, NE dipping fault surfaces for which the sense of movement was clear (Figure 29), the observed combination of right-lateral and normal slip is compatible with the Quaternary kinematics deduced from surface faulting. Such ESE to SE striking surfaces, already detected north of Damxung (Figure 29) probably correspond to the linear N10°-14° E faults which become apparent in the regional tectonic fabric north of 33°N (Figure 13a).

The morphology of the large scarps at site 24 closely resembles that of the single fault scarp at site 23. Each of the four, 10- to 20-m-high main scarps visible on Figure 23 cuts the gentle erosion surface of the triangular facet. In addition, the channels of the transverse streams are uplifted several meters along the two uppermost scarps, while their alluvial fans are truncated by the lowermost one. Finally, the small (several tens of centimeters high) surface breaks which run at about midheight along most of the large scarps appear to correspond, as in site 23, to the 1951-1952 (or 1940) earthquake sequence.

The multiple, en échelon scarps of site 24 disappear to the North. Near site 25, normal throws are localized along a unique fault scarp (Figures 13 and 24). At this site, as south and north of it (sites 23, 24, and 26, Figure 13a), the average slope of the eroded triangular facets is particularly gentle (1°-2°, Figure 24) and generally concave upward (Figure 1, left part of block diagram) in contrast with the steep (2°-3°) morphology of facets at Kung Co or Yangbajain (Figures 3b, 3c, 11c, and 11d). Nevertheless, the normal fault scarp is the largest and steepest scarp that we have observed in Tibet (A in Figure 24b). Its upper part is a 20- to 30-m-high free face, cut in the bedrock (locally Jurassic granites). The steep slope of a debris wedge of comparable height (Figures 24c and 24d) constitutes its base. As at sites 23 and 24, the main dislocation of the 1951-1952 (or 1940) earthquake sequence generally runs along the limit between the free face and the wedge, where the fault reaches the surface. Near A (Figure 24b), the crest of the main scarp is...
barely incised by small stream channels perched on the lowermost part of the spur (Figures 24c and 24d). At B (Figures 24a and 24b) the height of this fault scarp does not decrease much across the flat, wide floor (g) of a large glacial valley. In this valley, even the narrow fluvial channel of the present outwash is uplifted several meters where it crosses the fault.

The similar morphological features observed at sites 23, 24, and 25 differ from those observed elsewhere in SE Tibet in one important respect (Figure 1). The large size, freshness, and steepness of the most recent scarps contrast sharply with the gentle slopes and degraded forms of the mountain fronts. This difference between the short- and long-term imprints of faulting in the morphology cannot be easily ascribed to a specific erosional or geological environment between Damxung and Gulu. Instead, it may reflect a singularity in the Quaternary tectonic regime. The large throws on the recent scarps appear to be mostly a result of sustained, rapid Holocene movements. Moreover, all the faults appear to have broken during recent earthquakes. Thus, since the important degradation of the triangular facets is not in keeping with fast postglacial movements, a marked acceleration in the rates of normal faulting may have occurred recently along this segment of the Yadong-Gulu rift.

North of C (Figure 24) the master fault trace climbs above 4800 m on large morainic accumulations (ot) deposited on a faulted basement step (Figures 13a, 25a, and 25b). This step is limited to the east by another fault whose northern extension is outlined by fissural hot springs and geysers (A, Figure 25b). This fault, which appears to be less active than the master fault, marks the edge of a marshy area, in the center of the Gulu valley. On the moraine and mudslide-covered step, the master fault trace splays into multiple scarps (B, C, Figure 25). Much of that splaying, which resembles that observed along the mountain front NW of Damxung (Figures 13a, 16a, 16b, and 16c), may be related to the lack of cohesion between the boulders which compose the morainic surface layer (B, Figure 25b). The geometry of faulting, however, is also consistent with an increase in the total amount of extension toward the north and with a right-lateral component of displacement, as at site 24 (Figure 13a), within a roughly N170°E striking zone. From south to north, the most numerous normal fault scarps, which strike N120°E ± 11°, are disposed in three, west stepping clusters whose width increases to about 2 km (C,
Fig. 18. Piedmont fault at site 19 (Figure 13a). Note steep eastward dip of fault plane between coarse gravels (left) and drag-tilted sands and silts (right).

Figure 25b). Many of the scarps in cluster C (Figure 25b) seem to cut the bedrock in the lowermost part of the triangular facet, as at site 24, and a few correspond to west dipping, antithetic faults. Cumulative throw on the particularly large scarps across this cluster appear to be of the order of 150 ± 50 m. The fact that the scarps disrupt the lateral walls of the most recent, still active glacial valleys (Figures 25b and 25c) implies that most of this large cumulative displacement is of Holocene age. This indicates, as at sites 23, 24, and 25, particularly fast rates of postglacial normal faulting. Surface breaks similar to those attributed, farther south, to the 1951-1952 (or 1940) earthquake sequence apparently follow the fault zone north of site 25 at least to site 26 (Figure 13a). It was not possible, however, to establish the continuity of such breaks as clearly as between sites 23 and 25 (Figure 13a).

North of site 26, the main normal fault zone crosses the mountain range which flank the Gulu graben to the west and joins the Beng Co strike-slip fault (Beng Co is B on Figures 13a and 26). This fault, along which the "Damxung" earthquake (November 18, 1951) produced as much as 12 m of right-lateral slip (32, Figure 13) also appears to have been the site of particularly large Holocene displacements (31, Figure 13a) [Armijo et al., 1983, also manuscript in...
preparation, 1986]. The junction between the two fault zones takes place through a series of interconnecting, oblique fault segments within the mountain range (Figure 13a). In the junction area, a couple of passes below 5500 m interrupt obliquely the N-S trending crest of the range (Figure 13a). North of these passes, the crest and eastern frontal fault of the range (27, Figure 13a) appear to be offset 6 km toward the east. The junction area thus coincides with an overall dextral shift of the western edge of the Gulu graben (Figure 13a).

The master fault along the northernmost segment of the Gulu graben (27, Figure 13a) is outlined by triangular facets smaller and steeper than those observed south of the junction. Holocene scarps along it also appear to be smaller than along faults south of the junction. Nevertheless, this fault seems to have ruptured recently, possibly in 1951-1952. It is faced by

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**Fig. 19a.** Aerial view of parallel fault strands at site 20 (Figure 13a), east of Damxung.

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**Fig. 19b.** Sketch map corresponding to Figure 19a. Note left laterally disturbed drainage along piedmont fault. Symbols as in Figure 14b.
the only west dipping normal fault observed to cut clearly the Quaternary morphology along the eastern edge of the Gulu graben (28, Figure 13a). At about 30° 05' N, the western master fault bends into an approximately N130° E strike-slip fault zone which vanishes 6-8 km to the west (29, Figure 13a). The freshness, on aerial photographs, of a right-lateral array of surface breaks along this zone suggests that such breaks also formed in 1951-1952.

At this point, the intermontane passageway which extends continuously from the Zangbo valley to Gulu opens onto the wide, flat surface of the Tibetan plateau proper. Farther north, for

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**Fig. 20a.** Aerial view of parallel fault strands at site 21 (Figure 13a), east of Dam-xung.

**Fig. 20b.** Sketch map corresponding to Figure 20a. Triangular facets imply normal offset along range front fault, while rhomb-shaped sags and displaced stream channels are consistent with left-lateral slip along more linear piedmont fault. Note landslides from range front cut by piedmont fault trace. Symbols as in Figure 14b.
at least 100 km, we found no prominent, Quater-
nary normal faults along the projected trend of
the Gulu graben. Instead, we could map, mainly
from aerial photographs, the 100-km-long, linear
trace of a Quaternary fault across which relief
was generally less than a few tens of meters
(Fig. 13a). This fault strikes N13°-14°E
nearly parallel to the average direction
(N12°E) of the Beng Co fault, and small pull-
out sags along it indicate that its strike
component of slip is also right lateral (Figure
13a). This suggests that the Yadong-Gulu rift,
which begins in the Himalayas, terminates around
31°10'N, against two prominent, en échelon
right-lateral strike-slip faults.

6. Faulting North of Beng Co

The highlands surrounding Nagqu, as well as
those farther west toward Siling Co (Plate 1)
have the flat and smooth morphology which cha-
racterizes the central Tibetan plateau (Figure
26). The average elevation is above 4800 m, with
maximum relief of the order of 1000-1500 m
(Figures 26 and Plate 2). Although the eastern-
most part of this area corresponds to the upper-
most reaches of the Nu Jiang (Plate 1), most of
it is internally drained, as is the greater part
of the plateau to the west. In the region of
Figure 26, for instance, several large lakes lie
within N-S half grabens. By contrast, there is
no such lake in the Yadong-Gulu rift, now almost
entirely drained by tributaries of the Yarlung
Zangbo. The smoother topography may thus partly
be a consequence of this difference. At the same
time, since, as elsewhere in Tibet, the most
significant reliefs are related to N-S normal
faulting, the rather small local variations of
altitude also imply more distributed and/or
smaller amounts of normal faulting. On the pro-
file across the northern half of the area in
Figure 26 for instance (hh', Plate 2), reliefs
on individual faults are smaller than 1300 m,
and total only about 2.5 km along the entire
profile, although it is nearly twice as long as
most other profiles across the Yadong-Gulu rift
(Plate 2).

Quaternary faulting north of Beng Co (B,
Figure 26) postdates a complex sequence of Mesoz-
ocic and Tertiary deformations. The dismembered
ophiolite massifs which outline the eastern seg-
ments of the Bangong-Nujiang suture [Girardeau
et al., 1984] have been thrust onto folded
Jurassic flysch and black shales with generally
steep, N10°-14°E striking axial cleavage. NE
to SE trending, mostly upright folds affect the
lower middle Cretaceous red sandstones and
limestones (equivalent to Takena formation)
which were deposited unconformably upon the Jurassic structures. In the mountains surrounding Dong Co and Peng Co (DO, P, Figure 26), chiefly north dipping, probably Tertiary thrusts have emplaced the Jurassic shales and ophiolites onto the Mesozoic-Tertiary fabric (Figure 26). The most prominent faults dip west along the Dong Co (DO) and Daru Co (DA) basins, not far north from the western branch of the Beng Co fault zone (Figure 26). There is no clear link, however, between that branch of the Mesozoic-Tertiary fabric, north of the Beng Co pull-apart, and the surface traces of those two normal faults. This contrasts with the intimate connection between normal and strike-slip fault segments at sites 18, 23, and 26 along the Damxung corridor and Gulu graben (Figure 13).

Similarly, although the surface break on the great 1951 earthquake extends beyond site 33 (Figure 26) [Tapponnier et al., 1981b; Armijo et al., 1983, also manuscript in preparation, 1986], no such break seems to exist along the Dong Co and Daru Co normal faults. Traces of Quaternary faulting on either side of the Peng Co basin are scarce. At site 35 (Figure 26), however, the complexly deformed, large-beded sandstones, of probable Quaternary age, are cut by steep normal faults, extensional fissures, and sedimentary dykes striking N28°E-40°E on the average.

Faults east of Dong Co form a left-lateral, en échelon array, on a large and small scale. Two of the three major faults (Figure 26) are about 1 km north of and several km east of the Dong Co basin, disrupting alluvial fan surfaces. There are two fault traces that are arrays of shorter scarp segments (Figures 27a and 27b). These scarps strike N72°E ± 10°E (Figure 27b). The parallel traces of ancient, regressive lake shorelines (a1, Figure 27b) outline the shapes of alluvial fans on the lower terrace but do not reach the youngest scarp. The development of the smaller stream channels (ch, Figure 27b) seems to be driven by that of vertical relief along the fault scarp. Pounding of water at the places where such channels cross the fault traces (d, Figures 27a and 27b) is indicative of a slight eastward tilt of the downthrown upper terrace. As near Yangbajain or Damxung (sites 10, 11, Figure 8; site 8, Figure 13a), the absence of free face on one hand and, on the other hand, the youthful morphology of both the steep small scarps and the gentle large one imply that they formed mostly between 10° and 100° years ago [Wallace, 1977]. The fact that the wide, funnel-shaped valley of the largest stream is filled by a young alluvial fanhead (Figure 27a) suggests that the total offset of the upper terrace across the fault may exceed 100 m. If aggradation of this valley occurred in the beginning of the Holocene when the lake level was high, fault scarps across the fanhead may be less than a few thousand years old.

Evidence for Holocene normal faulting is similarly clear along the major scarps east of Daru Co (36, Figure 26). By contrast, other less prominent normal faults as that west of Daru Co or that north of Peng Co (at -90°E) display mostly long-term signs of Quaternary activity. Such appears to be also the case of approximately N-S striking normal faults along the southern part of the Rami Co basin (BA, 37, Figure 26), although the shock of December 26, 1951 (M = 6 1/2) [Plate 1], could have occurred on one of them.

7. Kinematics of Quaternary Faulting and Implications for Collision Mechanics

7.1. Geometry of Faulting and Regional Tectonic Styles, New Versus Reactivated Faults

The observations presented in this paper help define accurately the nature and style of Quaternary tectonics in southeastern Tibet. Moreover, because such direct field evidence allows to calibrate and test different Quaternary geologic maps, it permits us to assess the major traits of Quaternary tectonics over the entire plateau with confidence. Those traits are apparent on Plate 1, where faults have been represented using the area of our field survey as a standard of reference, a procedure which may account for differences between this and previously published maps [e.g., Rothery and Drury, 1984].

For instance, the two prominent right-lateral strike-slip faults mapped near the northern end of the Yangdong-Gulu rift (Figure 26) make, together with other faults that we also mapped in the field (Gyaring Co and Jiali faults, R. Armijo et al., manuscript in preparation, 1986) and Landsat images, it permits us to assess the major traits of Quaternary tectonics over the entire plateau with confidence. Those traits are apparent on Plate 1, where faults have been represented using the area of our field survey as a standard of reference, a procedure which may account for differences between this and previously published maps [e.g., Rothery and Drury, 1984].

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Similarly, our field observation that Quaternary and active normal faulting is less prominent and more distributed north of the Beng Co fault than south of it (Figures 13 and 26 and Plate 2) characterizes a difference visible, on Landsat images, across the entire KJFZ. On such images (Plate 1), prominent normal fault traces are fewer, shorter, less continuous, and with less relief north of KJFZ than south of it. Normal faults north of KJFZ are mostly into long and narrow rift zones. Instead, most of them lie either en échelon along, or near, the junction between short strike-slip fault segments of conjugate trends (Plate 1). Normal faulting thus appears not only to be more diffuse and subdued north of KJFZ than south of it but also to be subordinate to strike-slip dis-
placements along minor approximately NW-SE or NE-SW right- or left-lateral faults respectively (Plate 1); see also Molnar and Tapponnier [1978]. This difference between the southern and north central parts of the plateau is apparent in fault plane solutions too (Plate 1). Some of the modest E-W extensional strain in north central Tibet may thus be interpreted to balance Quaternary, N-S shortening [Rothery and Drury, 1984], with little net crustal thinning. The smaller morphological development of Quaternary strike-slip faults within this region than along its southern and northern limits (KJFZ and Kun Lun-Altyn Tagh, respectively, Plate 1) implies, however, that such shortening has been less than estimated by these authors.

South of KJFZ the Quaternary tectonics are characterized by large, approximately N-S normal faults with only few, subordinate strike-slip segments, along the Nyainqentanglha or northwest of Gyirong for instance (Plate 1). The normal faults have kilometric offsets and are arranged along seven principal rift zones (Plates 1 and Figure 28). The rifted region, about 1100 km long from west to east (A-B on Figure 28), is limited by KJFZ and the greater Himalayan arc and thus narrows toward the west (Plate 1 and Figures 28, 32, and 33). Within this wedge-shaped region, individual rifts are more widely spaced (up to ≈200 km) and progressively longer (up to ≈500 km) toward the east (Plate 1). The southern extremity of the Yadong-Gulu rift, in particular, comes closest to the Main Boundary Thrust (less than 50 km, Plate 1 and Figure 33). The northern extremities of six of the rifts meet with strike-slip faults of the Karakorum-Jiali zone (Plate 1). The main normal fault along the northern segment of the Yadong-Gulu rift, in particular, joins the Beng Co strike-slip fault (Figure 13a). As other rifts of Asia, which have been interpreted to grow, like cracks, from the extremity of strike-slip faults [e.g., Tapponnier and Molnar, 1977, 1979; Peltzer et al., 1985], most rifts in south Tibet thus appear to branch off the southeastern extremities of the main faults of KJFZ (Plate 1 and Figure 33).

Although movement on approximately E-W, Quaternary faults along and north of KJFZ may include minor thrust components [Sengör, 1981b; R. Armijo et al., manuscript in preparation, 1986], we found no evidence of Quaternary thrusting or folding south of it. In at least three areas of the rifted southern region (site 4, Figure 2; NW of site 14, Figure 8; sites 20, 21, and 23, Figure 13a), the approximately N-S principal stress appears to be only the intermediate one (σ2), the maximum principal stress (σ1) being vertical, as expected from the regional dominance of N-S normal faults. The presence of approximately E-W travertine fissures at Cangmu-da (Figure 4a), and of a normal component of slip along the approximately E-W Nyainqentanglha...
range front fault north of Yangbajain and NE of Dazhuxing (Figures 8, 13 and 29), argues against the often postulated existence [e.g., Sengör and Kidd, 1979], of N-S, late Quaternary shortening between KJFZ and the greater Himalayas and implies that E-W stretching there reflects upper crustal thinning.

At a more subtle level, faulting along the rifts of south Tibet has distinct characters north and south of the Zangbo suture. Although most of the rift zones cross the suture, they are less developed and more asymmetric south of it, being usually reduced to single master faults, or "échelons" of master faults dipping in the same direction (Plate 1). Between the suture and KJFZ, on the other hand, the rift zones are complex, wider arrays of more numerous, nearly parallel master faults, often with opposite dips. Accordingly, cumulative throws are largest between YZS and KJFZ (Figure 30a). Note that in spite of this difference, reliefs on individual normal faults appear to be consistently larger south of YZS than north of KJFZ (Plate 2 and Figure 30a).

Such variations in the distribution and magnitude of normal faulting, particularly the inference that there has been more crustal stretching, over a larger time span or at faster rates, between the Zangbo suture and the Karakorum-Jiali Fault Zone than elsewhere in Tibet, may partly result from regional differences in the age-dependent rheology of the Tibetan crust and/or lithosphere [Molnar and Tapponnier, 1981]. South of the Zangbo suture, in the Tethys Himalaya thrust wedge, imbrication of slices of the Triassic passive margin of Precambrian India started only in the Eocene. The wedge is intruded only by recent (Miocene) granites. In addition, it is probably underlain by the strong lithosphere of India which keeps plunging under Tibet [e.g.; Lyon-Caen and Molnar, 1983; Mattleer, 1983; Molnar, 1984]. By contrast, the area between the Zangbo suture and KJFZ (which roughly follows the Pangong-Nujiang suture, Plate 1 and Figures 32 and 33), appears to have been the site of several tectonic and magmatic episodes between the Jurassic and the Miocene [Sengör, 1981a, 1984; Tapponnier et al., 1981a; Allegrè et al., 1984; Girardeau et al., 1984; Coulon et al., 1986] and is less likely to be underlain by thick, cold (Asian or Indian) lower crust and upper mantle [Chen and Molnar, 1981].

North of the Pangong-Nujiang suture, the Qangtang platform was apparently an area of shelf sedimentation after the Triassic orogeny [Sengör, 1984]. This period of relative tectonic quiescence probably ceased only when the effects of the India-Eurasia collision became widely

Fig. 22b. Sketch of range front at site 23. Thick barb line marks last surface break. s is steeper part of Holocene scarp; sc, scree wedge; a, alluvial fan; ch, transverse channel; ps, piedmont slope; e, erosion surface, probably relict of incipient pediment.
felt, presumably later than in south Tibet since the widespread alkaline volcanics of northern Qangtang [Ministry of Geology, 1980], are of Quaternary age. Thus, the area between YZS and KJFZ, where Quaternary normal faulting is more developed, may correspond to a weaker region of more "continuous" magmatic and tectonic activity from 150 Ma to the present, interposed between stronger areas whose lithospheres, deformed mostly prior to 150 Ma, have only been reactivated recently.

The two latter regions share another common characteristic: 60-70% of the large Quaternary normal faults there dip to the west (Plate 1). This asymmetry may result from the eastward flow of a more ductile layer at depth, either in the lower crust or upper mantle [Faugère and Brun, 1984]. The fact that the asymmetry is clear only in areas where extensional faulting is incipient implies that it may have been obliterated by the greater development of such faulting between YZS and KJFZ.

Most of the normal faults along the rifts of southern Tibet appear to be newly formed faults. The regular spacing of the rifts (Plate 1 and Figure 28) implies that their formation, even south of the Zangbo, has not been triggered by ancient, N-S trending structures in the underthrust Indian plate. In general, the Quaternary normal faults do not follow such ancient structures or fault zones in the Tibetan crust either but cut them at a high angle.

Nevertheless, there is one important exception to the above pattern. The fault system which limits, without interruption, the Nyainqentanglha range between sites 12 and 24 (Figures 8 and 13) probably follows and reactivates a prominent older fault zone (Plate 2, profiles ee' and ff') connected with the formation of this range [Tapponnier et al., 1986]. Several observations corroborate this inference. First, although Quaternary strike-slip faulting is rare in southeastern Tibet, outstanding strike-slip movements take place along this fault system (Figures 8 and 13). Moreover, it is the only large fault system in south Tibet on which such movements are clearly left lateral (Plate 1).

Second, this system is composed of complex, zig-zagging faults which splay in map view (Figure 13a), bifurcate in cross section (Figure 16), and often display oblique slip (Figure 29). Third, the NE striking, metamorphic backbone of the Nyainqentanglha range appears to deviate and guide the Yadong-Gulu rift for over 130 km. Finally, the obliquity of this range, the largest one in the interior of Tibet, and the alignment of three pull-apart basins at its base (north Damxung, south Damxung, and west Yangbajain basins, Figures 8 and 13a) with similar Oligocene basins SW of it (Wuyu and Wulong basins [Ministry of Geology, 1980; Hsu, 1976]) may imply Tertiary left-lateral movements along it. In fact, the geometry of faulted ridges and basins along Nyainqentanglha is reminisc-

Fig. 22c. Detail of surface break at site 23, right bank of creek (Figures 22a and 22b). Free face (f) is at base of scarp (s, Figure 22b), on plane separating crushed bedrock (C) from Quaternary scree wedge (Q) (sc in Figure 22b).
cent of that observed NE of 35° N, 80° E near the SW extremity of the active, left-lateral, Altyn Tagh fault system (Plate 1). The reactivation, along the Nyainqentanglha range, of a prominent discontinuity in the Tibetan crust and lithosphere may also account for the exceptional development and southward propagation of the Yadong-Gulu rift, for the left-lateral, en échelon arrangement of faults along the southern section of this rift (Plate 1 and Figure 6), as well as, perhaps, for the existence and focal mechanisms of subcrustal (90 km deep) earthquakes NE of Xigaze (Plate 1). Ultimately, even the left-lateral strike-slip mechanism of the M=6, November 19, 1980, shallow earthquake near Yadong in the lesser Himalayas may be related to the propagation of this discontinuity within the Asian plate rather than to the existence of a large fault within the underthrusting Indian plate (Kishangang Basement Fault [Nl and Barazangi, 1984]).

7.2. Quantitative Constraints on Quaternary Extension in South Tibet

Extension direction. The average, regional direction of extension is constrained by different kinds of results, plotted together on Figure 30b. Those results include, first, orientations of least principal stresses obtained at single sites or groups of sites (Figure 29)(see also J.L. Mercier et al. (manuscript in preparation)) by inversion of large enough sets of unambiguous, coeval slickenside measurements [e.g., Carey, 1979; Etchecopar et al., 1981; Armijo et al., 1982a]; second, ranges of orientations of horizontal projections of slip vectors fixed by kinematic compatibility requirements at rigid fault bends and corners (Figures 16e and 23c) along the Damxung corridor (sites 18 and 23-24, Figure 13a); and third, directions orthogonal to average strikes of predominantly dip-slip, Quaternary fault scarps. It is justified to consider the latter directions to coincide with those of maximum extension since the majority of normal faults, whether in Quaternary sediments or basement, are not reactivated and hence do not owe their orientations to the pre-Quaternary crustal fabric. Azimuthal distributions of dip-slip fault traces were thus statistically analyzed at sites 10 and 11 (Figures 8 and 10) south of Yangbajain, site 15 (Figures 8 and 14) North of Yangbajain, site 26 (Figures 13a and 25) West of Gulu, site 34 (Figures 26 and 27) east of Dong Co, as well as in the whole region north of Beng Co (Figure 26), and in the entire region between KJFZ and the Himalayas (Plate 1 and Figure 28). The orientation of the least principal stress at Cangmuda, in the Kung Co half graben (site 4, Figure 2), was similarly deduced from the average azimuth of the principal set of fissures (Figure 4).

Except for that at site 34 (Figure 26), the average directions deduced from small fault traces or fissure azimuthal distributions lie between N100° and 105° E (with standard deviations...
between \( P \) and \( 1 \theta \). The difference between the average at site 34 and the regional average north of Beng Co (DOC, DAC, Figure 30b) probably results from the local, left-lateral, en échelon arrangement of fault scarps at this site (Figures 26 and 27) and underlines the principal shortcoming of this type of statistical averaging: the presence of a lateral component of slip may deviate the average orientation of individual surface scarps. As visible south of Yangbajain (Figure 10) and north of Beng Co (Figures 26 and 27), the existence of such components also increases the standard deviation (Figure 30b). Admissible orientations of slip vectors at fault corners north of Damxung and south of Gulu, although they provide looser constraints, are consistent with extension directions between N10°E and 120°E (sites 18, 23-24, Figure 30b).

The majority of orientations of principal stresses deduced from slickenside sets similarly lies between N10°E and 119°E. Such estimates are biased, in particular, by departures from the assumption that slip on all planes results from the same state of stress, a condition which may not hold where most slickensides are in the basement or even cataclasites near major Quaternary faults. This is perhaps the case at Karila (site 6, Figures 6 and 29) and more clearly at Angang (site 9, Figure 8) where slickensides in the crushed granite probably include Tertiary, NE striking faults with significant components of left-lateral slip (Figure 29). The most reliable result (N10°E), deduced from Quaternary measurements only, at Yangbajain (Figure 29) is closest to the majority of statistical averages obtained from scarp azimuthal distributions (Figure 30b).

Irrespective of the data from which they derive, the results plotted on Figure 30b are mutually consistent. If, for the reasons discussed above, results at sites 6, 9, and 34 are excluded, the extension direction which fits best all quantitative observations at and north of Yangbajain is N10°E. Within a few degrees, this direction is perpendicular to the strike of normal fault scarps in the Quaternary floor of the Angang graben (about N12°E, Figure 9a), to individual strikes (about N1°E) of large normal faults in the southern section of the Yadong-Gulu rift (Figure 6), and to the average orientation (about N1°E) of the Pum Qu faults (Figure 5a). A N10°E-105°E extension direction requires a right-lateral component of slip along the N17°E striking Kung Co fault (Figure 2), in agreement with the geometry of the fissure array.
Fig. 23b. Sketch of mountain front of Figure 23a. Most scarps bear recent surface breaks. Lowercase symbols as Figure 22b.

Fig. 23c. Stereogram of rigid fault kinematics at Damxung-Gulu corner between sites 23 and 24 (Figure 13a). Steeper dip of master fault west of corner and right-lateral component of slip on N10°E scarps north of corner fix range of possible slip vectors. Value of master fault dip is arbitrary (70°).
observed near the southern extremity of that fault at the Cangmuda hot springs (Figure 4).

The N105°E extension direction characteristic of the Yadong-Gulu rift corresponds to one of two modes in the large-scale azimuthal distribution of normal faults south of KJFZ (Figures 28 and 30b). Except for faults east of Lhasa (VII, Figure 28) this mode appears to be representative of normal faulting in SE Tibet, particularly along rift zones V and VI (Figure 28). The second mode (N92°E), on the other hand, seems to typify such faulting in SW Tibet, mostly along rift zones I and III and along the southern sections of rift zones II and IV (Figure 28). The existence of two such modes may be related to the distinct left- and right-lateral, respectively, en echelon arrangement of normal faults in the western Gangdise on one hand, and in the Pum Qu-Gyaring Co and Yadong-Gulu rift zones (V and VI) on the other hand (Plate 1 and Figure 28). If the majority of Quaternary normal faults in SW Tibet had small components of right-lateral slip however, the well-constrained N105°E average direction determined in SE Tibet rather than the overall south Tibetan average (N96°E ±7°, Figures 28 and 30b) might characterize extension throughout the region south of KJFZ.

The standard deviations of the statistical averages discussed here locally reach 19° (Figure 30b). The great consistency of average values obtained with a large number of diverse measurements at different scales suggests, however, that such averages might weigh more than estimates relying on a small number of fault plane solutions whose dip-slip nodal planes have poorly constrained strikes [Molnar and Chen, 1983; Molnar and Deng, 1984].

Throw and "extension" rates. Bounds on either short or long-term rates of movement on the approximately N-S normal faults may be deduced from the offsets of various types and magnitudes specified in the text and plotted on Figures 30a and 31. At the kilometric scale the near orthogonality between the normal faults and the regional, approximately E-W trends of the pre-Quaternary morphologic and structural fabrics

Fig. 24a. Air photograph stereo pair of mountain front near site 25 (Figure 13a), Gulu half graben. Deeply eroded facets contrast with high, sharp and steep scarp at their base.

Fig. 24b. Sketch map of right side image of Figure 24a. Note offset of floor of glacial valley (g) and fluvial channel at B. A is location of Figures 24c and 24b. Symbols as in Figure 16b.
Fig. 24c. View of mountain front at site 25 (Figure 13a) (A, Figure 24b), Gulu graben.

Fig. 24d. Sketch of mountain front of Figure 24c. Smooth mountain slope (e) is cut dramatically by ~50 m high scarp. Small channels (ch) remain perched. Thick barbed lines follow last surface break. Symbols as in Figure 22b.
makes the use of such fabrics as displacement markers more reliable than in regions where this particular geometry does not exist (e.g., Basin and Range).

Topographic reliefs across large master faults (H in Figure 3a; Plate 2 and Figure 30a) are thus a good measure of minimum throws on them. Reliefs for all normal master faults in the region of our study are plotted on Figure 31. The average minimum throw on such faults is \( \bar{H} = 0.6 \text{ km} \). The sums of minimum throws along sections across rift zones IV, V, and principally VI (Yadong-Gulu rift, Plate 2), are projected on Figure 30a as a function of distance from the Main Boundary Thrust. For the entire Yadong-Gulu rift such minimum cumulative throws, which are largest \((\approx 5 \text{ km})\) between Angang and Damxung, average \( 3.1 \pm 1 \text{ km} \). This average is not much different from that obtained including the few other sections in the Pum Qu, Kung Co, Gyaring Co, and Dong Co areas \((3.06 \pm 1.15 \text{ km}, \text{Figure 30a})\).

Upper bound estimates for total throws on the master faults require finer structural constraints such as offset horizons, sediment thicknesses within the rifts, or amounts of eroded basement on rift shoulders. Although major traits of the regional geology are represented on Plate 2, the absence of detailed mapping and subsurface information in most areas makes such structural constraints rare and imprecise. Nevertheless, the moderate incision of the Miocene-Pliocene planation surface [Zhang et al., 1981; Armijo and Tapponnier, 1985], and the preservation of patches of Tertiary volcanics in the mountains shouldering the rifts (Plate 2, ee') suggest that the average footwall erosion along the master faults has been limited to probably less than 1000 m. In addition, except near
Fig. 25c. Multiple scarps cutting glacial valleys and spur in between, north of C in Figure 25b (site 26, Figure 13a).

Yangbajain and Damxung (e, f, Figure 30a) and perhaps at places between YZS and KJFZ along other rift zones, the thickness of Quaternary fills is unlikely to exceed about 1000 m, given the asymmetry and narrow width (~5-10 km) of most flexural rift basins and the lengths (~40 ± 20 km) of most individual master faults. Thus in the absence of further evidence, it seems reasonable to consider the average, cumulative, structural relief along the Yadong-Gulu rift, and probably other south Tibetan rift zones as well, to be between 3.5 and 4 km.

The generally similar dimensions of faulted range fronts and adjacent basins (Plate 1 and Figures 2,5a,6,8,13a, and 30a) suggest that normal faulting started roughly at the same time in most parts of the Tibetan plateau, although perhaps first between KJFZ and YZS. The fact that the Miocene-Pliocene sedimentation was confined to approximately E-W trending basins implies that the approximately N-S rift zones developed mostly after the Pliocene. More precisely, if, as inferred by Wang et al. [1981, 1982], the Gongba conglomerate, which caps the Miocene-Pliocene sequence in the string of basins just north of the greater Himalayas (Yagru-Xongla, Gyirong, etc.) was deposited during the Matuyama reversed epoch, the corresponding regime of E-W trending sedimentation could not have ended before about 2.5 Ma. On the other hand, the large (~1000 m high) triangular facets observed along several normal master faults are unlikely to have formed in less than about 1 m.y. [e.g., Wallace, 1978]. The combined stratigraphic and morphological evidence available thus suggest to us that rifting in south Tibet started approximately 2 ± 0.5 m.y. ago. Given this rifting onset date, uniform rates of 1 ± 0.6 mm/yr would account for the average minimum throw on individual master faults (Figure 31), and the average cumulative structural relief in the Yadong-Gulu rift would result of vertical movements at uniform rates of 1.9 ± 0.6 mm/yr.

Although shorter-term rates deducible from synglacial to postglacial offsets on faults remain poorly constrained in the absence of an accurate time scale of glacial events and of direct calibration of scarp degradation rates in Tibet, they may also be evaluated. The values plotted on Figure 31 (boxes) include all reliable estimates of morphological offsets to which acceptable ages could be ascribed. In keeping with inferences discussed earlier, the assessment of those ages rests on the following assumptions: first, offsets of the tectonically hanging glacial valleys (h, Figure 3c) probably represent throws on master faults since the major interstadial of the Würm glaciation (~60 kyr B.P.). They could at most be a measure of throws since the Last interglacial (~120 kyr B.P.), and are unlikely to correspond to movements younger than the latest sizeable Würm interstadial (~30 kyr B.P.). Second, the age of the beginning of the Holocene (present interglacial) in Tibet is taken to be 10 ± 2 kyr B.P. [Zheng and Shi, 1982]. Finally, we estimate the ages of Holocene scarps in fanglomerates on the dry, high plateau to be in broad correlation with ages based on shapes of degradation profiles in the arid Basin and Range [Wallace, 1977, Figure 7].

Given such assumptions, the most probable
Fig. 26. Map of Quaternary faults West of Nagqu. Data and symbols as in Figure 6. B is Beng Co; P, Peng Co; DO, Dong Co; DA, Daru Co; BA, Bamu Co.
Average azimuth of major normal fault traces is N12.5°E, standard deviation, 17.7° (25 samples for ~ 125 km of fault length).
values of uniform throw rates during the period between 60 kyr and the present on the Kung Co and West Yangbajain master faults (1, Figure 2; 12, Figure 8) are 3.3 and 1.6 mm/yr (Figure 31, KUC(1) and YBWX(12)), respectively, whereas the latter fault has the same throw rate (>1.5 mm/yr) is obtained for just the Holocene period, at the same site (Figure 31, YBWN(12)). Offsets of the youngest terrace (T3, >10 kyr B.P.) near Angang (Figure 9, B) yield cumulative Holocene rate of 1 mm/yr for faults within the graben floor (Figure 31, ANG(B)). Holocene rates on the western Gulu master fault appear to be faster and to increase northward toward the junction with the Beng Co strike-slip fault from >6 mm/yr at site 25 and >15 mm/yr at site 26 (Figure 31 GULS(25), GULN(26)). At site 23 on the other hand, just west of the Damxung-Gulu corner (Figure 13a), the Holocene throw rate on the Damxung master fault is probably only 2 mm/yr (Figure 31, DAM(23)). Finally, the apparent acceleration visible in the lower-left corner of Figure 31 simply outlines the fact that recent scarps have no reason to be multiples of recurrence periods. Thus like moment tensors of large continental earthquakes integrated over short periods of time (e.g., 100 years [Molnar and Deng, 1984]), morphological offsets younger than about 5 kyr cannot easily be interpreted in terms of rates.

Long-term and short-term throw rates on the west Yangbajain fault (>1.5 mm/yr) are mutually consistent and comparable to those found on the Wasatch fault in Utah (1 mm/yr [Swan et al., 1980]), and on the Cordillera Blanca fault in Peru (2-3 mm/yr [Yonekura et al., 1979]). Other short-term throw rates in Figure 31 appear to be somewhat faster than the long-term ones. This may partly reflect the fact that they represent local, not average values at sites where morphological offsets are abnormally large. Other explanations must be sought, however, for the much faster recent rates on the Gulu and Kung Co faults: The Gulu fault may absorb a much faster recent rate on the master fault than does the earlier rate (>1.5 mm/yr); specifically, 3 x 10^{-16} s^{-1} (=12 m.y. -1).

The average Quaternary rate of relative movement between eastern and western Tibet (A-B, Figure 28) obtained here is about twice that derived from cumulative rates of the much faster recent rates on the Gulu and Kung Co faults: The Gulu fault may absorb a much faster recent rate on the master fault than does the earlier rate (>1.5 mm/yr); specifically, 3 x 10^{-16} s^{-1} (=12 m.y. -1).

7.3. Stress Variations and Combination of Collision-Induced Strains in Tibet and the Himalayas

The occurrence of normal faulting on the high plateau of Tibet appears to be mostly a consequence of the great thickness of its hot and therefore weak crust [e.g., Molnar and Tapponnier, 1975]. The observation that starting just north of the Greater Himalayas (Figures 4a and 4b), the maximum principal stress (σ1) in south Tibet is now vertical and the approximately N-S horizontal stress intermediate (σ2) supports this inference and emphasizes the contrast between the tectonic regime on the high plateau and that characterized by thrust faulting (σ1 north-south, σ3 vertical) in the lesser Himalayas and other low areas surrounding this plateau [Tapponnier and Molnar, 1976]. The roughly EES direction of extension in Tibet appears to result from the small resistance opposed to eastward extrusion at the Pacific margin of the Asian continent [e.g., Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977]. The subduction of oceanic lithosphere there probably transmits smaller horizontal stresses to the interior of Asia than does that of the more buoyant Indian lithosphere along the Himalayas. The uniform orientation of normal faults in southeastern Tibet, and perhaps over most of the plateau (Plate 1 and Figures 28 and 30b), appears to reflect an equally uniform orientation of the regional least principal stress (σ3) resulting from such distant boundary forces. Apparently, such an orientation is not altered by the differences in regional tectonic styles discussed earlier.
At a more detailed level, the average direction of extension in SE Tibet (≈N102°E) remains nearly parallel to the two great circles which join the present, and more ancient, eastern and western syntaxes of the Himalayan belt (Hazara-Assam, and Nanga Parbat-Namche Barwa syntaxes, Figures 32 and 30b). This may simply reflect the fact that such great circles, by definition, smooth out the curvature of the Himalayan arc. Thus between the syntaxes, the average azimuth (N15°-20°E) of directions perpendicular to these circles may be taken to represent approximately that of the resultant horizontal force applied to Tibet by the Indian indenter (Figure 32). This azimuth is different from either directions of relative motion between India and Asia, or horizontal projections of average slip vectors from fault plane solutions of earthquakes, along the Himalayas (Figure 32).

Within Tibet, the difference in regional tectonic styles north and south of the Karakoram-Jiai Fault Zone and the location of this zone between the two great circles above (Figure 32) probably implies a difference in boundary conditions north and south of such circles. In fact, by analogy with two-dimensional plane geometry, these circles outline the "chord" of the Himalayan "arc" (Figure 32). The occurrence of right-lateral shear along this chord, and of minor strike-slip faulting within the plateau north of it, probably reflects the greater facility of eastward extrusion north of this chord. By contrast, the presence of the Namche Barwa syntaxis, which may now oppose such extrusion movements south of this chord, might account for the scarcity of active strike-slip faults in SE Tibet. The south Tibetan rifted region might thus be viewed as a thick and weak crustal zone, "contained" between the above chord and the greater Himalayan arc, and "left to flow" onto...
Fig. 27b. Sketch map of Figure 27a. sl, lake shorelines. Other symbols as in Figures 16b and 22b. Average azimuth of scarps is N20.5°E, standard deviation, 14.8° (20 samples for = 12 km of fault length).

The flexed, more rigid Indian plate in the divergent manner represented on Figures 32 and 33.

Kinematically, rifting in south Tibet may account for the divergence of thrust earthquake slip vectors in the lesser Himalayas (Plate 1 and Figures 32 and 33) [Armijo et al., 1982b; Molnar and Chen, 1983; Baranowski et al., 1984; Tapponnier et al., 1986]. The fact that such slip vectors remain approximately orthogonal to the Himalayan arc and Main Boundary Thrust requires "spreading" between southeastern and southwestern Tibet in a reference frame fixed to rigid India (Figure 33). The angle (=30°) between the average horizontal projections of those slip vectors in Kumaon and the Miri Hills (K, M, respectively, south of A, B, Figure 33) and the regional direction (=96°E) and average rate (=1 cm/yr) of Quaternary movement between regions A and B, inferred from the field observations described in this paper, constrain the rate of underthrusting of India along the Himalayas to be =2 cm/yr (insert in Figure 33). Clearly, the use of the average spreading rate above is justified only if the instantaneous slip vectors characterize thrust movements along the Himalayan arc for a sizeable part of the Quaternary. The uncertainties on either the south Tibetan "spreading" rate or the slip vector directions allow between =1 and =3 cm/yr of underthrusting at the Himalayas (Figure 33, insert). Even the fastest rate of underthrusting, however, remains short of the total convergence between India and stable Asia (Figure 32) [Armijo et al., 1982b; Molnar and Chen, 1983; Tapponnier et al., 1986].

The boundary between the north and south Tibetan regions along the Karakorum-Jiali Fault Zone is complex. Although it may be a zone of right-lateral decoupling between India and south Tibet and the rest of Tibet (Figure 32), strains along and on either sides of this zone are not independent. Besides, right-lateral decoupling along KJFZ appears to be mechanically connected.
Fig. 28. Simplified map of Quaternary normal fault traces in southern Tibet. Diagram (insert) represents azimuthal distribution for 153 samples (totalizing 2550 km of fault length). All faults taken into account show clear evidence of predominant normal Quaternary slip (see Plate 1). Average azimuth is N5.9°E (arrow); standard deviation, 7.5°. Roman numbers point to the seven main rift systems. Total Quaternary extension in text is integrated along profile AB.
Fig. 29. Microtectonic measurements at five locations in Yadong-Gulu rift. Lower hemisphere, equiangular projection. All reliable measurements (i.e., for which sense is clear) are included. Thin lines when less reliable (Gulu). Thick line on Angang diagram is only reliable slickenside in Quaternary upper unit of east edge of graben, a on Figure 9d. Thick, dashed lines represent regional attitudes of master faults. Small arrows indicate slip of hanging wall relative to footwall. Large open arrows indicate azimuth of $\sigma_3$ from inversion of slickenside data sets. Crosses and dots at Karila site are poles to tension gashes and bedding, respectively. Numbers on Yangbajain diagram indicate locations on Figure 8; NFF is Nyainqentanglha frontal fault.
Fig. 30a. Cumulative throws. Throws (discussed in text) from sections (circled lowercase letters, Plate 2) across Yadong-Gulu rift are plotted as a function of distance from Main Boundary Thrust (MBT) on profile perpendicular to it. Data corresponding to section 10 km south of ee' is also plotted. Small horizontal bars are topographic reliefs (minimum throw). Corresponding average and standard deviation are shown to the right. Solid squares include maximum estimated Quaternary fills. Arrows, constraints from bedrock geology. Dashed vertical lines indicate range of probable values. HIM is Greater Himalaya; PUQ (about 2 X 2.3 km on profile just south of sites 7 and 13, Figure 5a), KUC and GYC (1.8 km (R. Armijo et al., manuscript in preparation, 1986) are data projected from Pum Qu, Kung Co, and Gyaring Co.

Fig. 30b. Extension directions. Data from sites along Yadong-Gulu rift (discussed in text) are plotted as in Figure 30a (numbers refer to sites). Dots with unbounded bars are azimuths of \( \phi_3 \) from inversion of slickenside data sets (Fig. 29). Dashed bounded bars represent ranges of slip vector azimuths at "rigid" fault corners. Dots with bounded bars are averages, with standard deviations, of normal fault trace or fissure azimuths. Regional average and principal modes for entire region between KJFZ and Himalayas (Figure 28) are shown to the right. Dotted band spans azimuths of Hazara-Assam great circle (Figure 32). Hatched band, those of small circle approximating KJFZ (Plate 1 and Figure 32). Note that all azimuths are less than average direction (dashed line) of Beng Co fault (BCF). KAR, Karila; ANG, Angang; YBJ, Yangbajain; YBJN, Yangbajain North; DAM, Damxung; GULS, GULN, Gulu south and north; DO, DAC, Dong Co, Daru Co (Figure 26). KUC is data projected from Kung Co (Cangmuda fissures azimuths).
Fig. 31. Throw rates. Shaded boxes are for observations at given sites along single master faults. Point in center is mean with corresponding error bars. Open dashed boxes are for observations on secondary or groups of secondary faults. Brackets with arrows pointing upward represent minimum Quaternary throw. Bracket with arrow pointing to left, probable maximum age of scarps in Yangbajain graben floor (YBJ). See discussion in text and Plate 2 and Figure 30a. GUL is Gulu; NYO, Nyeyo; NYE, Nyaingentanglha; YAD, Yadong; YBJE, YBJW, Yangbajain east and west. Other symbols as in Figure 30b. Numbers and letters in parentheses refer to sites on figures of corresponding areas.
Fig. 32. Regional difference in Tibetan Quaternary tectonics and relationship with plate movements. KJFZ separates southern zone of predominant rifting (light shade) from northern zone where normal faulting (in Tibet) is subordinate to minor strike-slip faulting (dark shade). Shaded bands represent south China and Sunda cratons. Northern zone is extruded eastward along KJFZ and Altn Tagh fault (large open arrow). Segmented great circles join active Hazara (H) and Assam (A) syntaxes and older Nanga Parbat (NP) and Namche Barwa syntaxes (NB). Small circles with north directed arrows indicate present motion of India relative to stable Asia [Minster and Jordan, 1978]. South directed arrows along Himalayan Front are horizontal projections of average slip vectors from fault plane solutions of Plate 1 (M, Miri Hills; K, Kumaun). Thin lines within continent represent faults (symbols as in Plate 1).
Fig. 33. Kinematics of active faulting in southern Tibet and Himalayas. Bold lines on simplified fault map correspond to KJFZ, MBT, and major south Tibetan rifts. Open arrow is average extension direction in southern Tibet (Figures 28 and 30b). Bold arrows along MBT and K, M, as in Figure 32. Velocity triangle (insert) is constructed with data from Plate 1 and Figures 31 and 32 (discussed in text), assuming India rigid under Ganga foredeep. Shaded areas represent uncertainties.
with movements along the northern edge of Tibet (Altyn Tagh, Kun Lun faults) and along other major strike-slip faults within eastern China. Thus both the evidence for complex Quaternary and active deformations along KJFZ and the causes of such deformations need to be discussed at length and will be presented elsewhere (R. Armijo et al., manuscript in preparation, 1986).

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