GEOLOGY OF THE HAIYUAN FAULT ZONE, NINGXIA-HUI AUTONOMOUS REGION, CHINA, AND ITS RELATION TO THE EVOLUTION OF THE NORTHEASTERN MARGIN OF THE TIBETAN PLATEAU

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Abstract. The Haiyuan area, located along the northeastern margin of the Tibetan Plateau in north central China, provides a laboratory for studying how the plateau has grown in late Cenozoic time. Rocks in the area range from pre-Silurian (Precambrian?) to Recent; the pre-Silurian and Cenozoic rocks form the most extensive outcrops. The pre-Silurian rocks consist of amphibolite- and gneisschist-grade metasedimentary and metaigneous rocks unconformably overlain by Silurian and Devonian red beds. All of these rocks are intruded by granodiorite of unknown age. Cenozoic rocks consist of 2.6-3.0 km of Eocene to Miocene red beds that were deposited over an extensive area in this part of China. Pliocene conglomerate contains clasts from all older formations and is interpreted to have been derived from highlands developed during the beginning of Cenozoic deformation in the Haiyuan area. Except for the widespread loess deposits, Quaternary rocks reflect deposition in local tectonic environments. The oldest Cenozoic structures in the Haiyuan area are folds and small thrust faults that generally strike N30°-45°W and involve mostly pre-Quaternary rocks. These structures and all the Quaternary rocks are cut by the Haiyuan left-lateral strike-slip (left-lap) fault zone that generally trends N60°-65°W and is nearly vertical. At the western end of the mapped area a fault zone, which strikes N75°-90°W, forms a left-stepping transfer zone that connects with another segment of the Haiyuan fault zone, which continues N60°-65°W west into Gansu Province. A small basin, the Salt Lake Basin, is marked by active faults in the area of the transfer zone and is interpreted as a pull-apart basin along the left-lap Haiyuan fault zone. At its eastern end the Haiyuan fault zone has an irregular surface trace; east of Luzigou an active fault striking N35°-45°W branches to the south. This southern branch appears to be a younger fault and now accommodates most of the left-lap deformation that formerly occurred on the easternmost part of the Haiyuan fault zone. This younger fault connects through a left-stepping transfer zone to a parallel fault, the Xiaokou fault, that can be traced into the Liupan Shan about 60 km to the southeast. The Laohuaxian Basin is interpreted as a very young pull-apart basin in the area of the transfer zone. Matching different geological features across the Haiyuan fault zone yields a total left-lap offset of between 10.5 and 15.5 km, and the best constrained offsets yield 12.9-14.8 km. If left slip began near the end of the Pliocene time or earliest Pleistocene time, it indicates an average slip rate between 5 and 10 mm/yr. Progressively smaller offsets can be determined on progressively younger geological features, but dates for these younger features are too imprecise to constrain slip rates through time. Surface ruptures that formed during the 1920 Haiyuan earthquake (M = 8.7) show mostly left-lap displacement with magnitudes of more than 10 m in some places. Active faulting in the region suggests the Tibetan Plateau may be extending to the northeast in time. In the Haiyuan area, deformation probably began in Pliocene time, compared with a likely earlier initiation to the southwest; thus deformation began about 40-45 m.y. after collision between India and Asia. Formation of the low ranges to the northeast of the Haiyuan area, however, may have developed at different times and deformation may not have propagated regularly to the northeast. A total displacement of 10.5-15.5 km on the Haiyuan fault zone indicates that this fault zone does not accommodate large-scale eastward lateral transfer of continental fragments in the northern Tibetan Plateau.

INTRODUCTION

The Tibetan Plateau, with its high elevation and thick crust, appears to have been built by crustal shortening beginning when India collided with southern Eurasia in early Cenozoic time. At present, however, much of the active deformation of the plateau occurs by normal and strike-slip faulting. An important question is: How does the change from shortening to strike-slip deformation occur? Clearly a good place to examine this is on the margins of the plateau, where such changes have occurred recently. The Haiyuan area of the Ningxia region is such a place.

The Ningxia region is characterized by numerous active faults and contains the transition from strike-slip and thrust faulting within the broad northeastern margin of the Tibetan Plateau to normal faulting that dominates the tectonics of northeastern China (Figures 1 and 2). Thrust faulting dominates the northern boundary of the western Qinling (Maxian fault zone) in the south and in the north and northwest trending mountains in the eastern part of the region (Figure 2). All of these active faults contribute to the continuing uplift of the northeastern margin of the Tibetan Plateau. The thrust faults in the Yantou Shan, Dalou Shan, and Niushou Shan lie northeast of the main topographic front of the plateau and may foreshadow future northeastward migration of the plateau [Zhang et al., 1990]. The Helan Shan in the northeastern part of the region is bounded by normal faults, and the Yinchuan valley is underlain by a graben with at least 1609 m of Quaternary sediment and more than 6000 m of Cenozoic rocks, some of which were penetrated by a drill hole 10-20 km north of Yinchuan [Ma et al., 1982]. This area of active extension is only part of the regional area of extension that surrounds three
Fig. 1. Regional tectonic map of China showing many of the major Cenozoic structural features. Strike-slip and thrust faults shown by conventional symbols. Lens-shaped areas are folds: solid where known to be late Cenozoic and empty where Cenozoic. Dotted areas are underlain by thick Cenozoic deposits. The morphological margin of the Tibetan Plateau is limited by the surrounding Cenozoic basins and passes along the north slope of the Nan Shan and through the southern Ningxia area (SNA). The Ordos Block is nearly surrounded by narrow Cenozoic extensional basins and belongs to the North China Block. It forms part of a Cenozoic extensional region that includes much of northeast China. QB, Qaidam Basin, which is morphologically part of the Tibetan Plateau. H, Haiyuan fault zone. Location of Figure 2 is shown.

sides of the Ordos Plateau and that extends farther into northeast China (Figure 1). Numerous earthquakes with $M \geq 6$ are known from historical records to have occurred within the Yinchuan Basin and the northeast margin of the Tibetan Plateau (Figure 2) [Lee et al., 1976; Li et al., 1960; Tapponnier and Molnar, 1977]. Of specific interest to the present study was the December 16, 1920, Haiyuan earthquake ($M = 8.7$), which was associated with a surface break 220 km long and was followed by an aftershock of $M = 7.5$ in the region of the Dalachi Basin (Figure 2).

The Haiyuan area is located along the northeastern margin of the Tibetan Plateau in the Ningxia-Hui Autonomous Region of north central China (Figure 1). This margin of the Tibetan Plateau drops irregularly in elevation from 3600 m in the south to 1200 m along the Huang He in the north and along the Qingshui He in the east (Figure 2). To the north lies the Gobi desert, Helan Shan, and Yinchuan Valley, and to the east is the Ordos Plateau. The land surface on this margin of the Tibetan Plateau is characterized by smooth, rounded slopes with narrow, steep-walled modern stream valleys. This morphology is the result of deposition of a blanket of windblown Pleistocene loess that has only recently been incised by present day streams that generally follow the more ancient loess-buried valleys (Figure 3). The loess cover makes mapping difficult because exposure of older rocks is commonly discontinuous and present only beneath the loess in the valleys or within the higher mountains.

Deng et al. [1984] described our reconnaissance study of several faults in the Haiyuan area, with some details on the displacements on the Haiyuan fault during the 1920 earthquake. In this paper we discuss the geological history of the Haiyuan fault from its inception to Holocene time. The relation of the Haiyuan fault to the active north trending thrust belt in the Madong Shan and Liupan Shan to the east (Figure 1) is presented in a companion paper by Zhang et al. [this issue].

REGIONAL TOPOGRAPHY OF THE HAIYUAN FAULT ZONE

The present study describes the geology of a zone 2-7 km wide along 60 km of the Haiyuan fault zone (Plate 1). Mapping was done on topographic maps at scales of either
Fig. 2. Map of the major structural features and epicenters of large earthquakes in the southern Ningsxia area and adjacent regions. Dotted area is the northeast margin of the Tibetan Plateau. Location of geologic map, Plate 1, is indicated along the Haiyuan fault zone. Dates refer to the 1920 Haiyuan earthquake and historically documented earthquakes of $M = 6$ and greater. See Figure 1 for location.

1:50,000 or 1:25,000 with a 10 m contour interval. Plate 1, however, contains only 50 m contour intervals.

At the western end of the mapped area at 2000 m elevation is a small basin that has interior drainage and contains a small saline lake, which we refer to informally as the Salt Lake Basin (Figure 4). It is flanked by a low ridge about 100 m high along its southwest side and by a higher range of mountains, the eastern part of the Huangjiawa Shan, that rise more than 200 m above the basin on its northeast side (Figure 4). The Haiyuan fault zone follows the base of the northeast slope of the Xihua Shan and Nanhua Shan southeast of the Salt Lake basin to the end of the map area. The Xihua Shan rise to an elevation of a little more than 2800 m, and the Nanhua Shan crest is at slightly more than 2955 m. These mountains are separated by the Yuan River, which flows eastward through the Xianzhou Basin. Northeast of the Haiyuan fault zone are gently rolling hills with smooth topography reflecting a thick loess cover (Figure 2), and outcrops of pre-Quaternary rocks are sparse.

ROCK UNITS OF THE HAIYUAN AREA

Rock units in the Haiyuan area range in age from pre-Silurian (possibly Precambrian) to Recent (Table 1) with the pre-Silurian metamorphic rock and Cenozoic strata forming the most extensive outcrops (Plate 1). Only brief descriptions of rock units are presented in Table 1, but discussions of some rock units occur in the text where they are relevant to the structural history. Previous work in the area has been of a reconnaissance nature. Thus, although there are established rock units within the region, the type sections of most of the
Fig. 3. Photograph in the Haiyuan region showing the characteristic morphology developed by the thick loess cover in areas between and adjacent to higher mountain ranges. Photograph taken 2 km northeast of the town of Haiyuan.
established rock units lie outside the Haiyuan area, and we have chosen to use informal local names. Correlation of mapped units with the type sections is difficult, particularly in the nonmarine rocks, because ages of the rock units in the Haiyuan area are not well established. The pre-Silurian and Cenozoic rocks have been the most useful in deciphering the history of the Haiyuan fault.

**STRUCTURE OF THE HAIYUAN FAULT ZONE AND HAIYUAN AREA**

The pre-Cenozoic structural history of the Haiyuan area has not been studied in detail during our work and will be discussed only briefly. The main structural features that are important to an understanding of the evolution of the Haiyuan fault zone appear to be of Pliocene and younger age.

*Pre-Pliocene Deformational Events and Structure of the Haiyuan Area*

The oldest structural event in the area is associated with folding and metamorphism of the thick sequence of pre-Silurian metasedimentary rocks of the Haiyuan Group (Table 1). These rocks contain folds formed in several deformational phases, which we did not study. Prior to deformation the sedimentary rocks were intruded by mafic dikes, sills, and small plutons. In the Huangjiawa Shan the two main rock assemblages in the Haiyuan Group (PSg and PSm) are juxtaposed by a north trending, steeply dipping fault. The age of this fault is not known, but it is probably pre-Oligocene, because it does not appear to offset Oligocene red beds ( Orb; red beds of Shaojiawang; see Table 1 ) on the north slopes of the Huangjiawa Shan. Silurian and Devonian red beds (Table 1; see red beds of Youfangyuan (Srb) and Conglomerate of Tangjiapo (Deg)) unconformably overlie rocks of the Haiyuan Group and therefore date the deformation and metamorphism as pre-Silurian. The Silurian and Devonian red beds are tilted and locally dip steeply but are not generally folded. The Silurian rocks were intruded by the coarse-grained hornblende-biotite granodiorite of Yehupo (Table 1), and in the mapped area the age of intrusion can only be determined as post-Silurian and pre-Cenozoic. Intrusive relations between the granodiorite of Yehupo and the rocks of the Haiyuan Group and Silurian red beds are clearly exposed in the southeastern part of the Nanhu Shan (Plate 1).

Eocene (Erb; sandstone of Guannen Shan) and Oligocene red beds (Orb; red beds of Shaojiawang) unconformably overlie all older rocks. The thin, 1-3 m thick, basal conglomerate is exposed only in the eastern Huangjiawa Shan, the southeastern Xihua Shan, and the western Nanhu Shan south of Caiyuan. The widespread distribution of the Oligocene-Miocene red beds in the Ningxia Autonomous Region and adjacent areas indicates that they override all the older rocks in the region (Figure 5) and that the lower part of the red bed sequence was deposited on a surface of low relief. The extensive, uninterrupted deposition of fine-grained sand, silt, and mud in this part of China suggests that deformation did not begin in this region until after Miocene time. The Pliocene conglomerate of Dagoumen (Figure 6 and Table 1) contains cobbles and boulders of all older rock units and probably records the beginning of deformation and the creation of relief in the Haiyuan and adjacent areas.

*Pliocene to Recent Structure of the Haiyuan Area and Haiyuan Fault Zone*

Structures associated with the Pliocene to Recent deformation will be discussed in two parts: (1) structures adjacent to the Haiyuan fault zone and (2) structure along the Haiyuan fault zone itself.

**Structures adjacent to the Haiyuan fault.** These include structures of the Huangjiawa Shan, those southwest of the Salt Lake Basin and in the Xihua Shan, and those of the Nanhu Shan.

**Structure of the Huangjiawa Shan:** North of the Salt Lake Basin the Huangjiawa Shan are underlain by rocks of the pre-Silurian Haiyuan Group and in the east by Oligocene red beds (Plate 1 and Figure 4; Orb, red beds of Shaojiawang). Loess blankets these rocks and dips gently away from the mountains into the adjacent lowlands.
<table>
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<tr>
<th>Unit</th>
<th>Description</th>
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| **Paleozoic and (?)**  
**Precambrian Rocks** | Coarse-grained garnet-biotite-muscovite-quartz feldspar schist and gneiss retrograded to chlorite-bearing assemblages. Layered greenstones both parallel and crosscut foliation, probably originally dikes and sills. Irregular crosscutting bodies of amphibolite (PSa). Rare marble. In northwest Nanhua Shan near Caifu is dark grey slate, phyllite, sandy phylite, and rare blue-grey marble. | Uniformly overlain by Silurian red beds. K/Ar age of 540 Ma [Gansu Geological Bureau, 1972]. |
| Haiyuan Group (pre-Silurian)  
(P5gn, P5m, PSa)  
Schist and gneiss association (P5gn) | Marble and quartzite association (P5m) | |
| | Yellow, tan, orange and white weathered mable interlayered with white, tan and blue-grey weathered quartzite. Locally contains black graphitic schist. Amphibolite dikes and sills retrograded to greenschist. | |
| Silurian-Devonian Red Beds  
(Srb, Dcg) | Red beds of Youfangyuan (Srb). Only in eastern Nanhua Shan. Basal red conglomerate unconformable on pre-Silurian metamorphic rocks, overlain by several hundred meters of coarse-grained red arkosic sandstone. Conglomerate of Tangjiapo (Dcg). Several hundred meters of pebble to boulder red conglomerate with clasts from pre-Silurian metamorphic rocks, red conglomerate and sandstone from older parts of the red bed sequence, and rock types not present in the mapped area. | Fossils from similar rocks in Gansu Province; (Gansu Geological Bureau, 1965, 1972). Conformably overlies pre-Silurian metamorphic rocks south of Salt Lake Basin. Fossils from similar rock in Gansu Province [Gansu Geological Bureau, 1965, 1972]. |
| Late Devonian Limestone  
(Dls) | Thick bedded cherty limestone that weathers tan and orange; overlies conglomerate of Tangjiapo only south of Salt Lake Basin. | Fossils in Gansu [Gansu Geological Bureau, 1973]. |
<p>| Granodiorite of Yehupo and Yao Xian (Pgr) | Coarse-grained, hornblende-biotite granodiorite, weathered white and locally red. | Intrudes pre-Silurian metamorphic rocks and Silurian red beds in the Nanhua Shan. Early Paleozoic [Ningxia Geological Bureau, 1980]. |
| | Dark to medium red, but locally pale red, orange or tan, conglomerate, sandstone, siltstone, mudstone and rare breccia. Minimum 100-200m thick. Conglomerate mainly in middle and upper part, clasts mainly from pre-Silurian. | |</p>
<table>
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<tr>
<th>Unit</th>
<th>Description</th>
<th>Age</th>
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<tr>
<td>Red Beds of Wanjiasi (Mrb)</td>
<td>Massive red to tan sandstone, siltstone and mudstone with rare pebble conglomerate in upper 100m that contains only rounded resistant rock types. Thickness about 2000m.</td>
<td>Correlates with fossiliferous Miocene rocks at Zhongning [Ningxia Geological Bureau, 1976].</td>
</tr>
<tr>
<td>Conglomerate of Dagoumen (Pcg)</td>
<td>Pebble to boulder light brown and tan conglomerate with clasts derived from all older formations particularly pre-Silurian metamorphic rocks set in a quartz, feldspar, and lithic grit. At least 200m thick but top not exposed.</td>
<td>Correlates with Pliocene rocks at Zhongning [Ningxia Geological Bureau, 1980].</td>
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<tr>
<td><strong>Quaternary Rocks</strong></td>
<td></td>
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<tr>
<td>Yuan River Conglomerate (PQcg)</td>
<td>Fluvial tan and yellow sandstone, siltstone, and pebble to boulder conglomerate; pale red at the base where it unconformably overlies Miocene red beds. Conglomerate clasts dominated by metamorphic rocks near the base, but more resistant rock types near the top. Interbedded with loess or reworked loess in the upper part. Unit is at least 200-300m thick. Deposition took place during folding as there is a progressive change of about 50° in dip of beds upward in the syncline along the Yuan River. Present only along the Yuan River.</td>
<td>Pre-loess to intra-loess.</td>
</tr>
<tr>
<td>Conglomerate of Salt Lake (Qa)</td>
<td>Dark grey or greyish brown, poorly sorted cobble and boulder conglomerate dominated by clasts of chloritized schist and gneiss, except near base where it is tan or red and dominated by clasts from underlying Devonian red beds. Thickness 20-30m, but thickens rapidly south beyond the mapped area. Present only southwest of the Salt Lake Basin.</td>
<td>Largely or entirely pre-loess, but not folded.</td>
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<tr>
<td>Loess (Ql)</td>
<td>Tan massive fine-grained silt to dust sized deposits of variable thickness. Interbedded with reworked bedded loess and siltstone. Most widespread unit in the map area.</td>
<td>Within northern China considered to be as old as 2.4 Ma [Heller and Liu, 1984] or no older than 1.3 Ma 350 km to the west [Burbank and Li, 1985]. Everywhere unfolded.</td>
</tr>
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</table>
In the eastern part of the Huangjiawa Shan the Cenozoic structure consists of an open southeast plunging anticline in the Oligocene red beds. This structure becomes more complex toward the northwest; the red beds are folded on a smaller scale, and attitudes are locally vertical. Fold axes are difficult to define in the red beds because these beds are massive and often slumped. Where the pre-Silurian rocks crop out in two large and several smaller areas in fold cores, they are in both fault and depositional contact with the red beds. The southwestern outcrop of pre-Silurian rocks is bounded on its northeast side by a thrust fault that dips southwest at about 30°. It can be traced for 3 km to the northwest where it is covered by loess. Toward the southeast the thrust fault passes into the pre-Silurian rocks and cannot be traced further. Where the fault passes into metamorphic rocks, its footwall contains a syncline overturned toward the northeast, in which both the Oligocene red beds and the metamorphic rocks are folded. The depositional unconformity between the two units is inverted and dips 70° southwest.

Northeast of the thrust fault, both the metamorphic rocks and red beds are cut by northwest striking, nearly vertical faults. The faults have a consistent southwest-side-down separation. A narrow sliver of brecciated metamorphic rocks along a fault within the red beds suggests that some of the displacement may have been strike slip, but most of the contacts between the red beds and metamorphic rocks in this area are depositional, planar, and unfolded. The northwest trending nearly vertical faults cannot be traced far to the southeast where they appear to die out within folds in the red beds.

We interpret the faults and folds in the Huangjiawa Shan to be related to shortening within rock units of different structural behavior and at different structural levels. Within the metamorphic rocks, shortening occurred by brittle faulting, with both thrust and possible strike-slip displacements, whereas shortening of the overlying red beds occurred largely by folding. The complex structural relations near the contact between the red beds and the metamorphic rocks form a transition between the two structural styles. All these structures trend south-southeast, obliquely into the Haiyuan fault near Shaojiazhuang (Plate 1).

Between Shaojiazhuang and Dagoumen, 10 km to the southeast, the structure of the rocks northeast of the Haiyuan fault zone is relatively simple. The Tertiary rocks beneath the loess cover and mainly exposed in the stream valleys strike north and dip east in a homoclinal section containing both Oligocene and Miocene red beds. Between Saomayin and Dagoumen the Pliocene strata and the upper part of the Miocene red beds (Pcg: conglomerate of Dagoumen and Mrb; red beds of Wanjiashu; see Table 1) contain northwest trending folds with subhorizontal axes. The folds are asymmetric with steep east limbs and are cut by the Haiyuan fault zone. Quaternary loess unconformably overlies the folds and is not folded.

Structure southwest of the Salt Lake Basin and in the Xihu Shan: Southwest of the Salt Lake Basin the Quaternary conglomerate of the Salt Lake (Qs; see Table 1) dips 10°-35° to the southwest and unconformably overlies pre-Silurian and Devonian rocks (Plate 1). The conglomerate forms a ridge with a gentle southwest slope and a steep northeast slope that is marked along its base by active traces of the Haiyuan fault zone. Imbrication of clasts in the conglomerate indicates a source to the north or northeast. The clasts consist of the schist and gneiss assemblage (PSgn) of the pre-Silurian rocks and of Devonian conglomerate of Tangjiapo (Dcg). No clasts from the marble and quartzite assemblage (PSm) of the pre-Silurian rocks were found even though they are exposed in the projected source area of the eastern Huangjiawa Shan. The conglomerate presently is higher than the basin and dips away from it. These relations indicate that the basin was not present when the
conglomerate of the Salt Lake was deposited. The lack of marble and quartzite clasts in the conglomerate suggests that a strike-slip component of faulting was necessary to move the conglomerate into its present position.

The conglomerate is not folded and is unconformably overlapped by loess that dips into the Salt Lake Basin along the northeast side of the low ridge held up by the conglomerate. Where the ridge slopes southwest, the loess dips southwest. These relations indicate that the Salt Lake Basin had formed by the time the loess was deposited. Thus the time of formation of the Salt Lake Basin is bracketed between the deposition of the conglomerate of Salt Lake Basin and the deposition of the loess.

Along the southeast side of the Salt Lake Basin the loess dips gently northwest into the basin along a ridge that gently rises into the Xihua Shan. The northwest part of the Xihua Shan is covered by loess, but southeast of the Salt Lake Basin, pre-Silurian rocks of the schist and gneiss assemblage (PSgn) of the Haiyuan Group crop out on its northern slopes (Plate 1). Only in the southeastern part of the Xihua Shan where Cenozoic rocks crop out, however, were structures mapped in detail.

South of Dagoumen and south of the Haiyuan fault zone the Oligocene red beds (Orb) are in both fault and depositional contact with the pre-Silurian metamorphic rocks. Where a depositional contact is present, it is folded and overturned in some places. The fault contacts between the two units are both high angle and low angle. Low-angle thrust faults strike about N50°W and dip both northeast and southwest (Plate 1). High-angle faults have the same strike. Eastward the faults project into an area where outcrops of preloess rocks are scattered, but southeast plunging folds can be mapped in the Oligocene and Miocene red beds (Plate 1). Folds are not present in these rocks farther south where the Oligocene red beds strike northeast and dip 40°-50° southeast and rest unconformably on the metamorphic rocks. The structural relations here are similar to those in the eastern part of Huangjiawa Shan where shortening was accommodated in the pre-Silurian metamorphic rocks by thrust faulting and in the overlying Oligocene and Miocene red beds by folding. These structures near Dagoumen strike obliquely into the Haiyuan fault zone to the northwest. They are over lain unconformably by the Quaternary conglomerate units (Liu Wen conglomerate (Qtw) and the conglomerate south of Dagoumen (Qb); see Plate 1 and Table 1), both of which are gently warped but not folded.

The main body of the Xihua Shan is underlain by the pre-Silurian schist and gneiss assemblage, which contains only rare, thin (1-2 m) zones of marble, except in the area 1 km
south of Dagoumen, which is the only place in the Xihua Shan where the marble and quartzite assemblage is present. One kilometer south of Dagoumen the marble and quartzite assemblage of the Haiyuan Group crops out above a northeast dipping fault that places the metamorphic rocks above the Oligocene red beds. Farther east the red beds rest unconformably on both assemblages of the pre-Silurian rocks (Plate 1), and the unconformity shows no significant displacement. Thus the offset on the thrust fault cannot be large, and the two pre-Silurian assemblages must have been in contact before Oligocene time. This relationship is important when rock units are correlated across the Haiyuan fault zone to determine its total offset (see below).

Structure of the Nanhua Shan: The central part of the Nanhua Shan is underlain by the pre-Silurian metamorphic rocks of the gneiss and schist assemblage (PShg) of the Haiyuan Group. Details of the internal structure of these rocks are unknown. Toward the west the grade of metamorphism gradually decreases until the assemblage consists of slates and phyllites with rare limestone beds; farther west it is unconformably overlapped by the basal conglomerate of the Oligocene red beds (Plate 1, Orb; red beds of Shaojiazhua).

In the eastern Nanhua Shan both assemblages of the Haiyuan Group are present and are unconformably overlapped by the Silurian red beds (Sr; red beds of Youfangyuan). Both the Silurian red beds and the overlying Devonian red beds dip steeply and are cut by faults, but essentially they are not folded. The Silurian rocks are intruded by the granodiorite of Yehuo (Pgr).

In the northwestern Nanhua Shan, thick loess covers Cenozoic rocks that are mainly exposed in the deeply eroded valleys. The Oligocene and Miocene red beds are folded about N20°-25°W axes that plunge gently northwest. Locally the beds are overturned. Near the Yuan River the Pliocene (?)-Quaternary Yuan River conglomerate (PQcg; see Table 1) rests unconformably on the youngest part of the Miocene red beds and is also folded. The basal part of the Yuan River conglomerate does not contain loess interbeds and resembles the Pliocene conglomerate of Dagoumen. These conglomerates may be partly equivalent. The upper part of the Yuan River conglomerate contains loess interbeds and is folded, but the dips are less than in the lower part indicating that the formation was deposited during folding. All the folds are unconformably overlain by thick, undeformed loess. Folds in the Cenozoic red beds both west and east of the Yuan River have a similar trend and styles. They probably formed during the same folding event. The folds in the Cenozoic rocks on both sides of the Yuan River and west of Dagoumen curve 10°-15° toward the trend of the Haiyuan fault, suggesting some left-slip drag is present.

From 1.5 to 4 km west of Caiyuan and about 500 m south of the Haiyuan fault zone a syncline trends about N60°-W, parallel to the fault zone (Plate 1). It might be the eastward continuation of the syncline that trends N25° farther west, but the area where they would join is cut by several faults and the outcrop is poor. They are probably not the same fold, however, because another syncline of N25°W trend is present farther south. We consider the syncline that parallels the Haiyuan fault zone to have formed by a component of convergence across the fault zone. The fold dies out to the southeast near the pre-Silurian metamorphic rocks, suggesting that the sedimentary rocks are folded but that the metamorphic rocks have accommodated the shortening differently.

Part of the southwest slope of the Nanhua Shan was mapped to determine its structure. On the Landsat imagery the southwest side of the Nanhua Shan is very straight and parallel to the Haiyuan fault, suggesting that it is controlled by a fault. West of Yiao Xian (Plate 1) the mountain front is formed by the red Eocene sandstone (Erb; sandstone of Guan Men Shan) resting unconformably on rocks of the Haiyuan Group. The sandstone strikes N60°-45°W and parallels the mountain front. No fault could be demonstrated, and the mountain front can most easily be interpreted to be the result of differential erosion of the soft Oligocene red beds and the more resistant older rocks.

Southeast of Yiao Xian the granodiorite of Yiao Xian (Pgr; see Table 1) forms two hills south of the linear part of the mountain front, but again no fault could be demonstrated on either side of the hills. Faults of small displacement could be present on the northeast side of the granodiorite, such as those present 1.5 km farther southeast, but dikes and sills from the pluton are present within the Haiyuan Group as much as 0.5 km from the intrusion, indicating no fault of large displacement follows the topographic mountain front.

North of Guan Men Shan the Eocene sandstone rests unconformably on the metamorphic rocks of the Haiyuan Group in small fault blocks bounded by nearly vertical faults that strike N60°W (Plate 1). No Eocene sandstone is present northeast of the most easterly fault, and consequently the amount of displacement is unknown. The mountain front here is partly controlled by faults. We do not consider the faults to have large displacement, because 1.5 km farther to the southeast the Eocene sandstone rests unconformably on the Haiyuan Group. The sandstone strikes parallel to the mountain front, and no faults could be demonstrated along the front.

About 4 km from the southeast end of the Nanhua Shan, rocks of the Haiyuan Group (PSgn and PSm) and, in one
place, the Devonian conglomerate of Tangjiapo (Dcg) are in fault contact with the Tertiary rocks. The fault dips 35°-40°N and the Eocene sandstone is folded beneath the fault. The fault can be traced to the southeast end of the Nanhua Shan. We interpret this fault as a thrust fault that begins about 4 km from the end of the Nanhua Shan and increases in displacement to the southeast, because progressively younger rocks are present in its footwall. Oligocene rocks below the fault are overturned and contain small-scale folds that trend N60°W, indicating a southwest direction of movement of the hanging wall of the thrust fault. We saw no evidence that the thrust fault was active during the 1920 earthquake.

Our mapping indicates the linear mountain front on the southwest side of the Nanhua Shan is controlled partly by high-angle and thrust faults of small displacement and partly by differential erosion. On a broader scale the Tertiary rocks appear to continue northwest from Xiao Xian to connect with the Tertiary rocks in the Yuan River Valley, but we have not actually mapped the connecting segment. The Tertiary rocks form a northwest plunging anticline with the rocks of the Haiyuan Group of the central Nanhua Shan in the core of the anticline. We interpret the folds in the Tertiary rocks of the Yuan River Valley to be parasitic folds on its plunging nose. The southeastern end of the Nanhua Shan may be formed by a southeast plunging anticline that had a thrust fault along its southwest flank. The existence of this plunging anticlinal nose is difficult to demonstrate because it has been disrupted by younger displacement on the faults bounding the Laohuyaobao Basin.

On the eastern part of the Nanhua Shan southwest of Youfangyuan (Plate 1), a fault zone trends N45°-53°W and can be followed through the Nanhua Shan to the small Laohuyaobao Basin. Along the southern part of this fault zone, several faults are marked by tension gashes, mole tracks, and offset streams within loess that probably formed during the 1920 earthquake. Combined displacements of the different faults could be as much as 10 m. The fault zone forms the southwest side of the Laohuyaobao Basin, and its northeast side is formed by a linear zone of active faults that can be traced for tens of kilometers to the Liupan Shan [see Zhang et al. this issue]. The Laohuyaobao Basin and a slightly higher, loess-covered, flat area to the northwest are partly bounded by active fault scarps, suggesting that the Laohuyaobao Basin is a pull-apart basin. Boulder conglomerate (Qm, see Plate 1) dips 37°-42°N into the basin at its southeastern corner. We tentatively regard these conglomerates as Quaternary, but we found no fossils in the rocks. If they could be dated, they would provide a lower limit on the age of formation of the Laohuyaobao Basin. The conglomerate is overlain unconformably by horizontal conglomerate interbedded with loess. The west trending active fault at the southeast corner of the basin cuts both conglomerate units.

The evidence suggests that the more recent displacement on the southeast continuation of the Haiyuan fault zone is being taken up on the fault zone between Youfangyuan and the Laohuyaobao Basin. This fault zone steps east across the Laohuyaobao Basin to continue farther southeast. This relationship explains why active fault segments along the Nanhua Shan mountain front east of Luzigo are difficult to follow (see below) and are of small magnitude. Furthermore, the southeastern continuation of the Haiyuan fault east of Luzigo is curved, whereas the rest of the fault zone is extremely linear. We interpret the curvature as deformation of the older trace of the Haiyuan fault zone after the more northwesterly trending fault southwest of Youfangyuan became active. The arcuate fault traces suggest that this part of the Haiyuan fault zone may have a significant component of northeast directed thrust movement during the younger part of its history. The northeast front of the Nanhua Shan continues to the southeast. Because it is arcuate and trends more to the north than the rest of the Nanhua Shan, it may be marked by thrust faults. However, no active faults could be found along this segment of the mountain front. On Landsat images a lineament, not identifiable on the ground, continues east from the Nanhua Shan to the north end of the Madong Shan (Figure 2) [see Zhang et al., this issue]. This lineament might be an inactive connecting structure between the left slip on the Haiyuan fault zone and the folds in the Madong Shan [Zhang et al., this issue].

Structure of the Haiyuan fault zone. The Haiyuan fault zone is only one of many northwest trending faults that are present within the extensive northeastern margin of the Tibetan Plateau (Figure 2). From the study of Landsat imagery and geological maps of the region we think the faults tend to occur within belts that separate crustal blocks containing fewer and more discontinuous faults. In the region shown in Figure 2, five belts of west to northwest trending faults can be recognized. From north to south they are the belts passing through (1) the Niushou Shan-Dalou Shan, (2) the Yantong Shan, (3) the Tianjina Shan, (4) the Xihua Shan-Nanhua Shan, and (5) the Maxian Shan.

The Haiyuan fault zone is one of several faults present in the Xihua Shan-Nanhua Shan belt. It forms a clear trace on the Landsat imagery (Figure 7). The surface trace that broke during the 1920 earthquake follows parts of two parallel faults that can be seen on the Landsat imagery and regional geologic maps. Figures 7 and 8 show that two faults, 5-7 km apart, are present north and south of the Salt Lake Basin, and Xihua Shan. A linear feature that could be the possible continuation of the more southern fault along the southwest side of the Nanhua Shan is present, but our mapping discussed above could find no evidence of a throughgoing or active fault along this part of the Nanhua Shan. During the 1920 earthquake, surface rupture occurred on the northern fault along the Nanhua Shan, Xihua Shan, and northern margins of the Salt Lake Basin and on the southern fault west of the Salt Lake Basin. The displacement shifts from one fault to the other at the west end of the Salt Lake Basin along a series of ruptures that define a transfer zone. The parts of the northern and southern faults northwest and southeast of the Salt Lake Basin, respectively, were not active during the 1920 earthquake, and their history is presently unknown.

The part of the Haiyuan fault zone we have mapped is that part of the Xihua Shan-Nanhua Shan belt of faults that ruptured during the 1920 earthquake (Plate 1). This zone has probably been active since about early Pleistocene time. Surface ruptures during the 1920 earthquake occurred within a band that varies from tens of meters (and less in some places) to 1000 m wide and thus define a fault zone rather than a single surface break.

The strike of the fault zone is generally N60°W, but locally it can vary by 15°-20°. Displacements of surface features, such as streams, valleys, and farming walls are clearly left slip.
Measured offsets associated with the 1920 earthquake reach a maximum of about 10 m [Deng et al., 1984, 1986; Zhang et al., 1987].

The Haiyuan fault zone enters the mapped area from Gansu Province in the west as a narrow zone (100-200 m wide) of surface ruptures [Deng et al., 1986]. It continues along the southwest side of the Salt Lake Basin for about 3 km where surface ruptures end (Plate 1). Along this part of the fault zone there is clear evidence of left slip as well as down-to-the-north dip slip. At the very western end of the map area, surface ruptures striking N75°W to N90°W extend to the east for 6-7 km, where the more characteristic strike of N60°-65°W for the Haiyuan fault zone is found again along the southern front of the Huangjiawa Shan. This zone of surface ruptures, about 1 km wide, defines the transfer zone. Surface breaks show both strike-slip and dip-slip displacement. Dip-slip displacement is dominantly down to the south, but down-to-the-north displacement is clear on some scarp. Between the more continuous N75°-N90°W ruptures are shorter ruptures that trend between N40° and 60°E and have small (1 m or less) dip-slip displacement.

Along the northeast side of the Salt Lake Basin and the southern slopes of the Huangjiawa Shan are numerous ruptures across a zone about 1 km wide. Evidence is clear for both left-slip and dip-slip displacement. Dip slip appears to be dominantly down to the south although locally down-to-the-north displacement is also present. Ruptures generally strike N60°-65°W, but some small ruptures trending N30°-15°W are present. These latter ruptures bound small grabens on alluvial fans and may be related to local slumping. Another rupture striking N75°W branches from the main fault zone and trends into the lower southwest slopes of the Huangjiawa Shan. A
few short rupture segments trend N90°-60°W between the more continuous ruptures and have small dip-slip displacement. This part of the Haiyuan fault zone appears to connect gradually into the transfer zone (Plate 1). A continuation to the northwest of ruptures along the fault zone on a N60°-65°W strike can be followed about 2 km beyond the transfer zone where evidence for active ruptures is not present.

Between Shaojiazhuang and Dagoumen, ruptures form a straight, continuous zone 100-500 m wide and striking N60°-N65°W. Small scarps are present adjacent to the main continuous rupture. Generally the north side is down, but the major component is left slip and has been measured at 10 m in several places along this segment [Zhang et al., 1987]. For about 2 km west of Fangjiahe and north of the 1920 ruptures is a fault that dips southwest 45°-70° and places pre-Silurian metamorphic rocks above the Miocene red beds (Mrb). This thrust fault was not active during the 1920 earthquake, and there is no evidence that it cuts the overlying loess, but exposures of the important relations are poor. This fault may be an older part of the Haiyuan zone, and slip on it may be responsible for the relative uplift of the Xihua Shan south of the fault.

Commonly in this region, however, fault contacts have been strongly modified by downhill creep so they appear to be thrust faults that dip toward the mountains. The loess and rocks just below the loess are strongly affected by down slope movement, because groundwater is preferentially concentrated and moves along the base of the loess. Downhill creep rotates originally steep fault contacts to progressively lower angles such that they appear to be low-angle thrust faults (Figure 9).

Two kilometers south of Dagoumen the strike of the surface ruptures changes to about N70°W. Within 1 km to the east all evidence for the surface trace of the fault disappears for the next 3 km. Two small, poorly developed scarp is present west of the Yuan River and mark the only evidence for the fault in the area.

East of the Yuan River to Caiyuan, continuous surface ruptures and narrow grabens define the fault zone. Evidence for left slip is common along a zone 200-750 m wide. At Caiyuan, two clear ruptures about 500 m apart bound a small graben. The graben appears to be a small pull-apart structure where for about 1 km the strike of the more northerly fault is N70°W.

From Caiyuan to Luzigo there are several long parallel ruptures across a zone 1 km wide that define the Haiyuan fault zone. In many places the ruptures and small scarps are clear, but in the middle of this segment these features are hard to recognize in the recent colluvium and reworked loess. Several stream valleys are clearly offset in a left-slip sense. Minor dip-slip components on scarps are both down to the north and down to the south and form conspicuous grabens.

From east of Luzigo to the eastern end of the mapped area, surface ruptures become more difficult to follow and a continuous trace cannot be seen. Some surface ruptures in this segment strike N40°W but are poorly defined. Moreover, when exposures of surface ruptures are connected across areas where there is no evidence for the fault trace, the inferred trace is more sinuous than to the west. As mentioned above, we infer that an inactive fault once connected left slip on the Haiyuan fault zone to shortening in the Madong Shan farther east [Zhang et al., 1990 and this issue].

One to two km northwest of Luzigo the Silurian red beds (Srb; red beds of Youfangyuan) crop out north of the Haiyuan fault zone. The relationship of these outcrops to the fault requires an explanation. They lie along the projected trend of the same rocks south of the fault zone south of Luzigo. Such a relationship would require very little if any left slip on the Haiyuan fault zone. As an alternative explanation we suggest that the Silurian rocks may have been moved north of the projected continuation of the Haiyuan fault zone by movement on the fault zone that passes S40°E through the Nanhua Shan into the Laohuyaoxian Basin. The eastward continuation of an older part of the Haiyuan fault zone would then lie buried and inactive about 1 km north of the present Nanhua Shan topographic front. As described above, east of Luzigo the active trace of what appears to be the southeastward continuation of the Haiyuan fault zone is difficult if not impossible to find until the vicinity west of Youfangyuan. From Youfangyuan to the southeast, surface ruptures caused by the 1920 earthquake appear to be present but make irregular sinuous trends. The curvature of the fault trace in this area suggests that either the fault has a thrust component or it is a segment of the Haiyuan fault zone that has been offset and deformed, after movement on the fault zone through the Laohuyaoxian Basin developed, or a combination of both.

The characteristics of fault rocks along the Haiyuan and related faults depends upon the rock units adjacent to the faults. The pre-Silurian metamorphic rocks are strongly brecciated and chloritized and form gouge that may extend for several meters to several tens of meters away from fault surfaces. Some brecciation may be the result of downhill creep, but the contribution of this process to brecciation, while probably very
Fig. 9. Downhill creep of pre-Silurian metamorphic rocks of the Haiyuan Group beneath loess cover (Base of loess shown by vertical arrowhead). The metamorphic rocks have moved downslope with loess both above and below. Layering in the metamorphic rocks (white rocks at left side of photo; arrowhead pointing left marks position of fault) is nearly vertical but bends over as it moves downhill, where it still retains original but thinned layering (white and gray bands that taper to the right just below the cave). Downhill creep occurs across a secondary fault (at arrowhead) of the Haiyuan fault near Clergou. The right hand side of fault is relatively down, and loess was faulted against the metamorphic rocks. Downhill creep has occurred across the fault and postdates its last movement. Cave in loess shows evidence of former human occupation. Rucksack in lower center of photo for scale.

important, cannot presently be evaluated. Paleozoic red beds are generally brecciated and often form sandy or clay gouge, but are generally less disrupted than the metamorphic rocks. Tertiary formations are cut rather cleanly by the faults, and seams of clay gouge 0.01-1 m wide commonly occur along the faults. The loess responds to faulting in such a way that the fault surfaces often are invisible. Displacements below the loess and at the surface may be clear, but where the fault surface must connect the two through the loess, there is no obvious evidence for faulting. Clear evidence for faulting is present only where the loess has been reworked and is bedded. All of these fault rock characteristics suggest that the portions of the faults now exposed along the Haiyuan fault zone formed at very shallow crustal levels even though they are associated with deeper crustal processes. Our mapping also indicates that the fault zone was not controlled by any pre-Cenozoic structures in the mapped area at the present level of exposure.

GEOLOGICAL HISTORY OF THE HAIYUAN FAULT ZONE

From the descriptions presented above, the following structural evolution (from the oldest to youngest events in Cenozoic time) for the Haiyuan area can be proposed: (1) northeast-southwest shortening by folding and thrust faulting, (2) initiation of left-slip displacement on the Haiyuan fault zone and perhaps on a parallel fault zone south of the Xihua Shan, (3) formation of the transfer zone and development of the Salt Lake Basin, and (4) development of a S35°E trending fault zone in the eastern Nanhu Shan that has changed the geometry of the left-slip movement on the Haiyuan fault zone. The Haiyuan area was the site of continuous deposition of fine-grained terrigenous sediments from early Oligocene to Pliocene time (Plate 1 and Table 1), and deformation did not begin in the Haiyuan area, or in this northeastern part of the Tibetan Plateau, until Pliocene time. The conglomerate of Dagoumen of probable Pliocene age records the relative uplift and erosion of pre-Silurian rocks. We regard these conglomerates as marking the onset of deformation in this area, which has continued to the present.

Folding and Thrust Faulting

The oldest Cenozoic structures recognized in the mapped area are the northwest trending folds and thrust faults in the Huangjiawa Shan, Xihua Shan, and Nanhu Shan. The Pliocene conglomerate of Dagoumen (Peg) and the Yuan River conglomerate (PQcg) are folded and are unconformably overlain by the horizontal Quaternary loess (QI), Conglomerate south of Dagoumen (Qb), and Lien Wen conglomerate (Qlw). The older part of the Yuan River conglomerate was deposited during the youngest part of the folding and may be equivalent to the upper part of the Pliocene conglomerate of Dagoumen.
Rock units regarded here as Quaternary in age are not folded, with the exception of the youngest part of the Yuan River conglomerate, but they may be broadly warped. We associate the Pliocene conglomerate of Dagoumen and the Yuan River conglomerate with the exposure of pre-Silurian metamorphic rocks in highlands created by thrust faulting and folding. Thus we date this deformation as Pliocene to early Quaternary in age. More generally, the elevation of the Huangjiawa Shan, Xihua Shan, and Nanhua Shan may also be associated with the folding and thrust faulting. Shortening was by brittle thrust faulting in pre-Cenozoic rocks and largely by folding of the overlying Cenozoic sedimentary rocks.

The folds and thrust faults formed in response to northeast-southwest shortening similar to active deformation occurring in the structural belts northeast of the Haiyuan area (see below). Because the area is now dominated by left-slip faulting, it is possible that some shortening was a manifestation of regional left-slip strain along northeast trending boundaries. The folds and thrust faults make an angle of 15°-40° to the Haiyuan fault zone and are in the correct orientation to be part of the same strain field as that resulting from left slip on the Haiyuan fault zone.

Left-Slip Faulting

The folds and thrust faults are cut and displaced by left slip on the Haiyuan fault zone. Because there is very little accentuation or drag of folds or thrust faults adjacent to the Haiyuan fault zone, we conclude that the left-slip zone of faulting followed the development of the folds and thrust faults and that after this fault zone had formed, all or most of the succeeding deformation was taken up by left slip. This is supported by the displacement of all Quaternary formations, which otherwise are only slightly tilted or broadly warped but are not folded. Only the fold that parallels the Haiyuan fault zone west of Caiyuan and the thrust faults west of Fangjiaba suggest convergence across the fault zone after its inception.

Left slip probably developed on N60°-65°W trending faults in the Haiyuan area as well as other faults in the region (Figure 8). Unfortunately, we have little data on the fault segments that were not activated by the 1920 earthquake. We found no evidence that the southern fault of the Haiyuan fault zone continued east south of the Nanhua Shan. Even if the southern fault were present south of the Nanhua Shan, but covered by the youngest loess, its displacement can not be large because none of the structures in Liupan Shan area which lie along the projection of this fault show any displacement [Zhang et al., this issue]. A similar argument can be made to suggest that none of the other faults in the Xihua Shan-Nanhua Shan belt continue to the southeast. Thus only the northern fault of the Haiyuan fault zone continues to the southeast beyond the Nanhua Shan. The beginning of strike-slip displacement can only broadly be dated as early Pleistocene.

Formation of the Transfer Zone and the Salt Lake Basin

The development of the zone that transfers displacement between the two parallel faults in the Haiyuan area apparently began after the deposition of the conglomerate of Salt Lake (Qa) and before deposition of the loess. Pebble imbrications in the conglomerate of Salt Lake indicate source areas to the northeast, the present location of the topographically lower Salt Lake Basin. Rocks presently exposed farther to the northeast in the Huangjiawa Shan contain abundant outcrops of the marble and quartzite assemblage (PSm) of the Haiyuan Group, but the conglomerate of Salt Lake contains no debris from this assemblage. This suggests that the conglomerate of Salt Lake was deposited farther west with respect to this assemblage and then was moved to its present position. Alternatively, the conglomerate source may lie beneath the Salt Lake Basin. The next younger unit in the area, the loess, dips into the Salt Lake Basin from all sides, indicating that the basin was present by the time of deposition of the loess.

We interpret the Salt Lake Basin to have formed as a pull-apart basin at the time the transfer zone was initiated. Left slip on the N60°-65°W striking segments of the fault zones that are connected by the transfer zone would result in extension across the transfer zone. The formation of the Salt Lake Basin has continued to the present. The displacements on surface ruptures of the 1920 earthquake are consistent with the active formation of the Salt Lake Basin as a pull-apart structure.

The relationship of the Salt Lake Basin to the development of the transfer zone suggests that both features began to form after the deposition of the conglomerate of Salt Lake (Qa) but before the deposition of the loess (Q1). Uncertainties in dating of these units only broadly suggests that these features began to form in about middle Pleistocene time. Whether this is also the time at which segments of the two parts of the faults beyond the transfer zone became inactive is unknown. The active ruptures that formed during the 1920 earthquake follow faults that have been active since the formation of the transfer zone.

Left-Slip Fault Zone of the Laohuyaoxiao Basin

The youngest part of the left-slip displacement in the eastern Nanhua Shan has taken place on the fault zone that bounds the two sides of the Laohuyaoxiao Basin (Plate 1). This fault zone trends N35°-45°W and intersects and may offset the Haiyuan fault zone near Luzigo just where the Haiyuan fault zone changes its character. Development of this fault zone has caused a significant change in the deformation occurring in the southern part of the Nanhua Shan and areas to the southeast [see Zhang et al., this issue]. Left slip on this more northerly trending fault zone has caused offset, warping, and/or thrust faulting on the continuation of the Haiyuan fault zone east of Luzigo. The Laohuyaoxiao Basin is interpreted as a pull-apart basin along this fault zone. The amount of displacement required to form the basin is very small (a maximum of 1.5 km). Using a slip rate of 5-10 mm/yr, the fault zone that bounds the basin probably was initiated no more than 150,000-300,000 years ago.

DISPLACEMENT HISTORY OF THE HAIYUAN FAULT ZONE

From our mapping we can determine the total offset on the Haiyuan fault zone as well as offsets of rocks and topographic features progressively younger than the age of inception of the faulting. Most of the features that are used to determine the total offset are present between the Huangjiawa Shan and the Xihua Shan (Figure 10). The total displacement on the fault zone can be measured by matching the structures, contacts, and
rock units from north of the fault zone in the area north of Shaojiazhuang to similar features south of the fault zone and south of Dagoumen. The thrust faults and folds in these two areas are very similar in style, and they involve the same rock units. Nowhere else along the fault zone do a group of similar rocks and structures occur. These structures strike obliquely into the fault and also cannot be matched uniquely across the fault, thus yielding only a general displacement of about 10.5-15.5 km (Figure 10). The only outcrops of the marble and schist assemblage of the Haiyuan Group south of the fault occur south of Dagoumen (Figure 10), and in the eastern Nanhua Shan south of Yehupo (Plate 1). In the eastern Nanhua Shan the rocks are associated with the Silurian-Devonian red beds and the granodiorite of Yehupo. None of these rocks are present in the Huangjiawa Shan, but the marble and quartzite south of Dagoumen contains irregular bodies of graphitic schist similar to those in the Huangjiawa Shan, north of the fault. The only two large amphibolite bodies present in the Haiyuan Group occur on opposite sides of the fault and in both areas crop out west of the marble and quartzite (Plate 1 and Figure 10). Matching of the western limits of the marble and quartzite unit and of the amphibolites across the fault zone yields displacements of 14.5-14.8 km and 12.9-13.8 km, respectively (Figure 10). Finally, the apparent separation of the steeply dipping (60°SE) contact between the Oligocene red beds and the Haiyuan Group is 14 km. Thus our estimate of the total offset on the Haiyuan fault zone in its western part is between 10.5 and 14.8 km, and the better constrained measurements imply offsets of between 12.9 and 14.8 km.

A similar but slightly larger magnitude for the total offset can be measured in the Nanhua Shan. The only outcrop of the granodiorite of Yehupo present north of the fault is 1.5 km east of Caiyun. This is 15.5 km from the closest outcrop of the same rocks where they make contact with the fault on its south side (Plate 1), but the contact between granodiorite and its country rock is not exposed north of the fault. The eastern contact must lie no more than 500 m east of the granodiorite where an outcrop of Haiyuan Group rocks is present, but the western contact is not exposed. Thus the displacement is not well constrained.

On the north side of the fault 1 km west of Fangjiaye, is an ancient stream channel (labeled Qc in Plate 1) that cuts into Miocene red beds and lies below the main loess cover. The channel conglomerates contain boulders up to 55 cm in diameter of marble, weathered yellow and tan, in addition to schist and gneiss from the Haiyuan Group. About 20% of the clasts are marble. Their most probably source is the outcrop or marble south of Dagoumen, because we have found no other major source for marble in the Xihua Shan south of the fault. If this correlation is valid, it yields a left-slip displacement between 5.8 and 7.6 km. The channel conglomerate contains interbeds of reworked loess near its base, and thus it is an intraloess unit. The main body of the loess overlies the channel, suggesting that it was deposited during the early stages of loess deposition. We have tried to date the loess interbeds but have been unsuccessful. This offset on the channel indicates that about half the movement on the Haiyuan fault zone occurred after deposition of the channel conglomerate.

Many of the large stream valleys show left-slip offsets of 2-3 km, and lesser offsets on smaller stream valleys and terraces of 550-700 m and 50-120 m can also be documented [Deng et al., 1984; Zhang et al., 1988] (one such terrace (Qta) about 0.5-1 km east of Saomayin is shown in Figure 10). Intraloess channel and fan conglomerates yield similar offsets. For example, the intraloess fan conglomerate north of the fault zone 2 km west of Caiyun (Qd in Plate 1) contains only cobbles of schist and gneiss. It is in contact with Miocene red beds south of the fault zone. The closest source for these clasts would be the rocks of the Haiyuan Group at Caiyun. It is possible that
the conglomerate Qd represents the offset piece of the beheaded intraloeus fan conglomerate Qf 0.5 km west of Caiyun (Plate 1). In the eastern part of the map area east of Youfangyuan, several intraloeus channel conglomerates labeled Qi in Plate 1) north of the fault contain cobbles from only the Silurian-Devonian red beds. These channels are offset 1-1.5 km from their source, which is the large stream valley that cuts through the red beds in the eastern Nanhua Shan and passes through Luandeizi. These intraloeus conglomerates also have not been dated.

Our mapping shows progressively smaller offsets on younger rock units. Unfortunately, only one of the Quaternary units has yielded a definitive date. If we assume 4.5 km of slip faulting began near the end of Pliocene or the beginning of Pleistocene time and offset 1.8 ± 0.15 Ma, then offsets of 10-15.5 km yield an average slip rate of 5-10 mm/yr. This rate is analogous to the Holocene offsets of stream valleys [Zhang et al., 1988].

RELATION OF THE HAIYUAN AREA TO THE NORTHEAST MARGIN OF THE TIBETAN PLATEAU

We have mapped the Madong Shan, part of the Liupan Shan [Zhang et al., this issue], and segments along the northeastern boundaries of the Tianjing Shan and the Mibo Shan, and we have visited the Yantong Shan and the Niushou Shan north of the Haiyuan area [Figure 2; Zhang et al., 1990] to determine their structure and evolution. Together with the Haiyuan area they form most of the active structural elements of the northeastern margin of the Tibetan plateau in Ningxia. It is important to note briefly the geology of the Haiyuan area to the development of the northeastern margin of the Tibetan Plateau. The Haiyuan fault zone continues to the southeast where the southeastward movement of its southern block is taken up by the Madong Shan and the Mibo Shan [Zhang et al., this issue]. The Madong Shan is formed by complex folds that are vergent both to the east and west. The Liupan Shan contains an east-vergent thrust fault zone along its eastern side. The two mountain ranges are separated by a complex zone of northwest trending faults and folds that are the southeastward continuation of the left-slip fault that passes through the eastern Nanhua Shan. Deformation in the Madong Shan and Liupan Shan are about the same age as that in the Haiyuan area. Thus we conclude that the two areas are closely linked and that the eastward component of movement of the block south of the Haiyuan fault zone is being taken up by east-west shortening in the Madong Shan and Liupan Shan [Zhang et al., this issue].

The topographic fronts of the Tianjing Shan and the Mibo Shan are dominated by northwest trending folds, mostly vergent to the northeast and associated with gently dipping, northeast-vergent thrust faults [Figures 2 and 9; Zhang et al., 1990]. The two ranges overlap in the same way as the Madong Shan and Liupan Shan, but the nature of their structural connection is not clear because the outcrop there is very poor. The amplitudes of the folds in the Tianjing Shan and Mibo Shan are less than those of the Madong Shan and Liupan Shan. Toward the west the topographic front of the Tianjing Shan curves to trend west, and evidence indicates that a component of left slip is present on faults along the range front. The structural relations are similar but not identical to those in the Haiyuan-Madong Shan-Liupan Shan area to the south. A block bounded by left-slip faults on its northern side and by folds and thrust faults on its northeast and east side seems to move east or northeast with respect to the area northeast of it. The rates of deformation in the Tianjing Shan and Mibo Shan are about 1-5-2.7 mm/yr, notably less than in areas to the south [see Zhang et al., 1990].

Evidence for east-vergent thrust faulting is present along the Yantong Shan, Niushou Shan and Dalou Shan farther to the northeast (Figure 2). These ranges are topographically lower than those to the southwest. Observations by two of us (Wang Y. and Zhang W.) suggest that the beginning of deformation in the Niushou Shan is perhaps a little older than that in the Haiyuan area, but the ages of deformation in these northern ranges are not well constrained. If the deformation in these ranges occurred throughout the same period, or during a slightly longer interval of time as that in the Haiyuan area, the rates of deformation in these northern areas might be less than those in both the Tianjing Shan-Mibo Shan and Haiyuan-Madong Shan-Liupan Shan areas to the southwest.

Our present study suggests that the northeastern margin of the Tibetan plateau is actively being elevated by shortening mainly concentrated along several structural belts that follow mountain ranges. The shortening is concentrated along north to northeast trending folds and thrust faults at the margins of northeast moving blocks of crust that are bounded by left-slip faults along their northern sides. Elevation of the plateau in this area may not have proceeded by shortening that migrated progressively to the northeast. Rather, the growth of the margin during latest Tertiary and Quaternary time appears to have taken place by shortening that may have begun in different places, at different times, and in no apparent order. At present all the ranges appear to be structurally active, but the deformation occurs at a lower rate in the more northerly ranges. The structures in the ranges to the northeast of the Haiyuan area are similar to what we envisage for the early structures in the Haiyuan area. This may be the reason for the rates of deformation are less, and they have not evolved as far as those in the Haiyuan area over the same period of time.

CONCLUSIONS

The Haiyuan area is part of a region in the southern Ningxia-Hui Autonomous Region and adjacent terrane that was the location of a large area in which a thick sequence (2.6-3.0 km) of early Oligocene to late Miocene, nonmarine, fine-grained sedimentary rocks were deposited. There is no evidence of structural activity or high relief in this area during this period.

Coarse conglomerates of Pliocene age are the oldest Tertiary rocks suggestive of high relief and therefore probably of tectonic activity in the Haiyuan area. We associate these conglomerates with the development of folds and thrust faults in the Huangjiawa Shan, Xiahua Shan, and Nanhua Shan. The northwest trending structures are characterized by brittle thrust faults in the metamorphic basement and folds in the sedimentary cover. They formed as a result of northeast-southwest shortening similar to that now occurring in the structural belts northeast of the Haiyuan area. They may also have been accompanied by some left-slip shear strain along an easterly or east-southeasterly trending zone.

Left-slip faults began to develop during late-stage folding
and thrust faulting, but the major displacement on west-northwest to west striking strike-slip faults followed this period of folding and thrust faulting. The Haiyan fault zone cuts the folds and thrust faults, and there is no indication of local accentuation of those structures near the fault zone. Pliocene and, very locally, Quaternary rocks are folded, but most of the Quaternary rocks are not; thus left-slip faulting probably began in late Pliocene or early Pleistocene time. Apparently, several left-slip faults developed in a band about 25 km wide in the Haiyan area. Two subparallel faults along the north side of this band were connected by a transfer zone at some time near the middle of the Pleistocene epoch. This transfer of displacement complicates the study of fault zones in the Haiyan area because each segment of a fault zone must be studied in order to understand the complete history of that particular fault zone. Such complications may be applicable in general to the study of other fault zones.

Formation of the transfer zone led to the development of the Salt Lake pull-apart basin. Surface ruptures formed during the 1920 Haiyan earthquake show components of both strike- and dip-slip displacements along the margins of the Salt Lake Basin and therefore indicate continuing development of the pull-apart structure.

Left-slip faulting began on a more northerly trending fault zone in the eastern Nanhu Shan, probably after formation of the transfer zone in the Salt Lake Basin and possibly only about 100,000 years ago. A small pull-apart basin, the Laohujiaoxian Basin, formed along this fault zone. Formation of this fault zone has led to offset, warping, and/or thrust faulting along the easternmost part of the Haiyan fault zone in the mapped area.

Total displacement on the mapped part of the Haiyan fault zone ranges from 10.5 km to 15.5 km. If left-slip faulting began near the end of Pliocene time, it indicates an average slip rate of between 5 and 10 mm/yr. The best constrained offsets of 12.9 km-14.8 km yields a preferred range of slip rate of between 7 and 10 mm/yr for the Quaternary period. We have determined a series of progressively smaller offsets on progressively younger geologic features. Those for the Holocene Epoch yield a similar rate of 8±2 mm/yr (Zhang et al., 1988).

Active faulting in the region suggests the Tibetan Plateau may be growing toward the northeast in time. Structures in the Tianshan Shan and Mibao Shan may be similar to the folds and thrust faults that developed in the Haiyan area during Pliocene time. Thrust faults farther to the northeast in the Yantun Shan, Duluo Shan, and Niushou Shan may be at an even younger stage. Initiation of deformation in these ranges developed at different times, but probably in Pliocene time, and apparently did not progress regularly toward the northeast. The differences in the stages of evolution of these ranges appear to be a function of a progressively slower rate of deformation in the ranges toward the northeast. Thus the elevation of the plateau may be extending progressively to the northeast, but the initiation of the deformation responsible for shortening and elevation of the crust may proceed irregularly. Dating of the Tertiary and Quaternary rocks in these areas is poor so that this conclusion must remain at present speculative.

If structures in this area result from the collision and convergence between India and Asia, they did not begin to form until about 40-45 m.y. after the initial collision. A magnitude of 10.5-15.5 km of left-slip displacement on the Haiyan fault zone suggests that this fault zone has not accommodated significant eastward movement of crustal fragments in this part of the Tibetan Plateau. If significant eastward movement has occurred, the bounding faults must be sought south of the Haiyan area.

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Plate 1. Geological map and legend of the Haiyuan fault zone and adjacent region.
CORRECTION TO "GEOLOGY OF THE HAIYUAN FAULT ZONE, NINGXIA-HUI AUTONOMOUS REGION, CHINA, AND ITS RELATION TO THE EVOLUTION OF THE NORTHEASTERN MARGIN OF THE TIBETAN PLATEAU" BY B. C. BURCHFIEL ET AL.

In the paper "Geology of the Haiyuan Fault Zone, Ningxia-Hui Autonomous Region, China, and its Relation to the Evolution of the Northeastern Margin of the Tibetan Plateau" by B. C. Burchfiel et al. (Tectonics, 10(6), 1091-1110, 1991), Plate 1 was printed without a scale. The plate with a scale is included loose in this issue so that it may be inserted in place of the incomplete plate.
Plate 1. Geological map and legend of the Haiyuan fault zone and adjacent region.