AMOUNT AND STYLE OF LATE CENOZOIC DEFORMATION IN THE LIUPAN SHAN AREA, NINGXIA AUTONOMOUS REGION, CHINA


Abstract. The structures of the Liupan Shan area are characterized by numerous active thrust and strike-slip faults that suggest thin-skinned deformation. The structural history of this area can be divided into three phases that probably overlap one another in time and are parts of a single protracted deformation. The oldest Cenozoic deforming phase occurred probably between late Pliocene and early Quaternary time and produced some of the folds and thrust faults in the Liupan Shan and Yueliang Shan. During this phase, deformation was the result of approximately N50°E shortening, and the amount of shortening seems to have been about 1-2 km. The second phase of deformation was dominated by left-lateral strike-slip faulting (left slip) on the N60°W striking Haiyuan fault zone and shortening on north-south trending structures; shortening was associated with a transfer of the left-slip displacement on the Haiyuan fault zone to shortening in areas farther east. Shortening occurred by thrust faulting in the Liupan Shan and Xiaoqian Shan and by folding in the Madong Shan. During this phase the orientation of shortening changed to N60°W. The average amount of shortening on the north-south trending faults in the Madong Shan is about 6.3-7.8 km. Most of the shortening on the Liupan Shan and Xiaoqian Shan thrust faults also occurred during this phase and amounted to a minimum of 4.8-6.3 km and 6.6-7.6 km, respectively, also with an orientation of N60°W. During the third phase of deformation, about 1.5 km of late Pleistocene to Recent left slip occurred on the Xiaokou fault, which was transferred into oblique left-slip thrusting in the Liupan Shan. At this time, deformation in the Madong Shan and Xiaoqian Shan ceased or was reduced to a very slow rate. The present, active left-slip on the Haiyuan fault zone is accommodated by shortening in the Liupan Shan area. The total displacement along the Haiyuan fault is essentially the same as the total amount of shortening in the Liupan Shan area. The sequence and interaction of strike-slip and thrust faults in the Liupan Shan area seem to apply to the folds and thrust faults farther north in the southern Ningxia region. Thus the northeastern margin of the Tibetan Plateau appears to grow by shortening oriented northeast and by left slip faulting that transfers material from farther to the west. The total left-slip in the entire southern Ningxia region probably is less than 20-25 km and may be absorbed by shortening within this region. Thus the eastward displacement of crustal fragments in the northern part of the Tibetan Plateau may not extend east of southern Ningxia, and if large-scale eastward displacement has occurred, it must lie farther south.

INTRODUCTION

One of the most important questions in Earth science today is the nature of intracontinental deformation and its relation to plate tectonics. In order to understand intracontinental deformational processes we need to know the geometry, timing, and magnitude of intracontinental deformation and its relation to plate boundaries. Studies of modern plate boundaries and related active intracontinental deformation is a logical approach to understanding these processes. The collision of Asia by the Indian subcontinent about 40-55 m.y. ago and the continued convergence between India and Asia [e.g., Molnar and Tapponnier, 1975, 1978; Tapponnier and Molnar, 1976; 1977; Tapponnier et al., 1986] resulted in the development of a broad zone of intracontinental deformation that offers an excellent place to study such phenomena.

The Liupan Shan area, which includes the Liupan Shan, Xiaoguan Shan, Yuejiang Shan, and Madong Shan, is located along the northeastern margin of the Tibetan Plateau in north central China (Figures 1 and 2). The tectonics of the region from the Liupan Shan to the west are characterized by numerous active strike-slip and thrust faults. Slip on these faults contributes to continuing uplift and seismic activity of the northeastern margin of the Tibetan Plateau. East of the Liupan Shan is the relatively stable Ordos Plateau that tectonically belongs to the North China Block, a region that seems to share a common late Precambrian to Cenozoic geological history but that has undergone regional extension during Cenozoic time. Thus the Liupan Shan area forms a transition from thrust and strike-slip faulting in the west to regional extension in the east.

Deng et al. [1984, 1986], Burchfiel et al. [this issue], Zhang et al. [1987], Zhang et al. [1988a, 1988b] and Zhang et al. [1990] discussed the basic tectonics, the surface rupture and displacement associated with the 1920 Haiyuan earthquake, and the total displacement, Holocene slip rate, and earthquake recurrence intervals on the Haiyuan fault. In this paper, attention is focused on the geology and tectonic evolution of the Liupan Shan area, which lies east of the Haiyuan fault zone discussed by Burchfiel et al. [this issue].

GEOLOGICAL SETTING OF THE LIUPAN SHAN AREA

The area east of the Liupan Shan forms the southwestern margin of the Ordos Plateau, a plateau bounded by thrust faults east of the Liupan Shan area and by extensional grabens on its other margins (Figure 1). The similarity of the stratigraphic sequence present in the Ordos Plateau to that of the rest of the larger North China Block indicates that the entire region has undergone a common depositional and tectonic evolution.
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 emph where Cenozoic. Dotted areas are underlain by thick Cenozoic deposits. 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 Plateau is nearly surrounded by narrow Cenozoic extensional basins. These basins form 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 indicated.

[Ningxia Geological Bureau, 1974; Huang, 1980]. In the southern Ordos Plateau the oldest exposed rocks are unmetamorphosed dolomite and cherty dolomite of late Precambrian age (assigned to the Sinian, 1950-800 Ma [Huang, 1980; Zhang et al., 1984]). Cambrian to Middle Ordovician rocks are shallow marine carbonate rocks with some terrigenous interbeds. The contact between the Sinian and Cambrian rocks is not exposed in the area, but elsewhere in the North China Block it is marked by a paraconformity. The absence of Upper Ordovician to lower Carboniferous rocks characterizes the North China Block, and Permian coal-bearing littoral and terrestrial strata paraconformably overlie the Middle Ordovician limestone. Lower and Middle Triassic rocks are also missing, and Upper Triassic conglomerate paraconformably overlies Permian sandstone. Jurassic coal-bearing clastic rocks overlie the Triassic rocks with a slight angular discordance. At the end of Jurassic time a major orogenic event (the Yanshanian event) occurred throughout the North China Block, and almost all preexisting strata were folded and faulted. Lower Cretaceous terrestrial rocks are sandstone, siltstone, mudstone, and conglomerate in southwestern part of the Ordos Plateau and unconformably overlie all older rock units; middle and upper Cretaceous rocks are missing. Tertiary red beds were deposited only in grabens and depressions around the boundaries of the Ordos Plateau. Quaternary loess blankets the entire Ordos Plateau, while other Quaternary sediments were deposited only locally.

The Liupan Shan area forms the northeastern margin of the Tibetan Plateau and the eastern margin of the Paleozoic Nanshan fold belt (Figure 1). The complete stratigraphic sequence of the Nanshan fold belt is present about 100-150 km to the west and northwest [Li et al., 1978; Wei, 1978], but in the Liupan Shan area only part of this sequence is exposed. Basement rocks for the Nanshan fold belt are poorly known, but some high-grade metamorphic rocks of unknown age are exposed in a few places within the fold belt. The oldest sedimentary rocks exposed in the fold belt appear to be slightly metamorphosed Cambrian marine clastic rocks with some basic volcanic interbeds. The Ordovician rocks consist of cherty limestone, granular limestone, and some elastic rocks. They
Fig. 2. Geological map of the Ningxia region showing major structural features and mountain ranges (see Figure 1 for location). PK, pre-Cretaceous rocks. Kl, Cretaceous Sanqiao Formation. Klh, Cretaceous Heshangpu Formation. KlI, Cretaceous Lisanwa Formation. Klms, Cretaceous Madong Shan Formation. Kl's, Cretaceous Naijiahe Formation. Ors, Eocene or Oligocene Shikouzi Formation. Orb, Oligocene Qinshuiyin Formation. Mrb, Miocene Hongliugou Formation. Peg, Pliocene Ganhegou Formation. Unmarked area is covered by loess and other Quaternary sediments. Thick lines with ticks are normal faults, and thick lines with solid triangles are thrust or reverse faults. Thick lines with arrows are strike-slip faults. Dashed thick lines are inferred faults. Major folds are also shown with standard symbols. Locations of Plates 1 and 2 are indicated.
are slightly metamorphosed and contain a thick sequence of basic volcanic rocks west of the Liupan Shan area. Silurian rocks are shallow marine carbonate rocks, red sandstone, and grits. A major deformatinal event occurred after the deposition of Silurian rocks (Li et al., 1978; Wei, 1978). Devonian red conglomerate was deposited unconformably on all older units. West and northwest of the Liupan Shan area, Carboniferous to Cretaceous rocks consist conglomerate, sandstone, siltstone, shale, mudstone, and coal-bearing strata. These rocks formed mainly in terrestrial basins and lakes, and they cannot be distinguished from those in the Ordos Plateau and North China Block. Farther west in the Nanshan fold belt, rocks of the same age consist of marine clastic and carbonate rocks that are completely different from those near the Liupan Shan area. During Tertiary time, most of the Liupan Shan area was the site of terrestrial deposition that extended over a large part of north central China (Burchfiel et al., this issue; Zhang et al., 1990). These Tertiary red beds are overlain by Quaternary rocks that were deposited during deformation in the area and consist of locally derived deposits except for the loess that blankets the entire area. Rock units exposed in the Liupan Shan area are described briefly in Table 1.

STRUCTURE OF THE LIUPAN SHAN AREA

Because the pre-Cretaceous rocks are poorly exposed in the Liupan Shan area and the major structures were formed during late Cenozoic deformation, the focus of this paper is on the Cenozoic deformatinal and tectonic history of the area. The Cenozoic geological structure in the Liupan Shan area is dominated by thrust or reverse faults and related folds.

Liupan Shan Thrust Fault

The north trending Liupan Shan thrust fault is exposed along the eastern foot of the Liupan Shan and is characterized by the eastward displacement of the Cretaceous Liupan Shan Group over the Tertiary red beds (Figures 2 and 3 and Plate 1). The Cretaceous rocks in the hanging wall form the Liupan Shan, and the footwall consists of Tertiary red beds and Quaternary sediments forming an eastward sloping lowland.

The Liupan Shan thrust fault apparently dies out at its northern end near Xiaokou (Plate 2), where part of its displacement has been taken up by a northwest trending fault, the Xiaokou fault (Figure 2). How the displacements are transferred from one fault to the other near Xiaokou is not clear, but the offset on Cretaceous rocks near Xiaokou (Plate 2) suggests a small pull-apart structure may mark the transition between these two faults.

The northern part of the Liupan Shan thrust fault strikes about N20°W and generally consists of two strands south of Haizikou (Plate 1). The southwestern strand is located along the foot of high mountains, and the northeastern strand is commonly about 200-300 m to the east in the low hills. The Cretaceous rocks exposed between the two strands are strongly deformed and brecciated. Small folds are present near the thrust and trend northwest or northeast. Numerous small faults of varied orientation are also present. Although the fault surface is not well exposed, it can be inferred to dip to the southwest from its topographic trace. At Haizikou the Liupan Shan thrust fault is exposed where it crosses a stream (Plate 1).

Here the Cretaceous Lisanwa Formation (Table 1) and fault breccia are thrust on young Quaternary sediments in the bench of a stream along a fault dipping 44° southwest.

The main segment of the Liupan Shan thrust fault is characterized by a single fault. Different formations of the Liupan Shan Group are thrust over the Tertiary red beds and Quaternary sediments on the east. In a few places a fault surface dipping 50°-60°W is exposed, but three-point solutions at several places along the fault indicated it dips about 45°W and locally as little as 20°W near its south end.

The hanging wall of the Liupan Shan thrust fault consists mainly of west dipping Cretaceous rocks of the Liupan Shan Group (Table 1) with progressively older parts of the group present at the thrust trace to the southeast (Plate 1). The oldest rocks exposed in the Liupan Shan, the Cretaceous basal conglomerate of the Sanqiao Formation (Kls, Table 1), are discontinuous and appear only in two places (Plate 1). Because the conglomerate is massive, structures within it are difficult to detect. In some places it dips about 30° to the west or southwest. The overlying Heshangpu Formation (Khs, Table 1) generally dips 15°-30° to the west, but three small folds (wavelength ~ 300-500 m) are present near the thrust fault in the southern part of the mapped area (Plate 1). The exposed Lisanwa (KIl) and Madong Shan formations (Klm) dip 45°-50°W. The upper part of the Madong Shan Formation and the entire Naijiayi Formation (Krm; exposed in the footwall) are missing in the Liupan Shan, and the Tertiary red beds overlie the lower part of the Madong Shan Formation along an irregular erosion surface. The Tertiary red sandstone (Ors) dips to the west at about the same angle as the Cretaceous rocks, but its dip becomes gentle toward the west. The red siltstone and mudstone west of the sandstone dip only about 15°, and farther west beyond the mapped area, it gradually becomes almost horizontal. These relations in the hanging wall suggest the Liupan Shan thrust fault ramps generally upward to the east beneath the Liupan Shan (see below).

The major trends of rocks in the hanging wall block of the Liupan Shan thrust fault are from N20°W to north-south, but near the fault the strikes of these rocks are often deflected to N30°W-N50°W and N45°-90°E, and some small folds are commonly present. These folds are more common in the north-northwest trending part of the Liupan Shan than in the north-south trending part where the rocks near the fault are mainly massive conglomerate. All of these folds are small, generally several hundred meters in length, and plunge either to the northwest or southwest (Plate 1). In one place near Haijiazhuang a syncline near the Liupan Shan fault is overturned to the northeast. In two places along the Liupan Shan thrust fault, north of Haijiazhuang and Yanglin, a few small folds trend northeast. The axes of all these small folds make an angle of 30°-60° to the strike of the thrust, and we interpret them to be structures associated with oblique movement along the Liupan Shan thrust fault. Regional kinematic analysis of the Liupan Shan thrust suggests that its early movement had a dextral component and its late movement had a sinistral component (see below). Although the two fold sets are not superposed, we suggest they formed during the two periods of oblique thrusting.

The footwall of the Liupan Shan thrust fault consists of Tertiary red beds, some Quaternary sedimentary rocks, and, in the east, Cretaceous rocks that form the Xiaoguan Shan. The
<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Paleozoic Rocks</strong></td>
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<td><strong>Mesozoic Rock</strong></td>
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<tr>
<td>Sanqiao Formation (K1s)</td>
<td>Grey poorly sorted pebble to cobble conglomerate with angular clasts. Upper part tan, brown, red, and purple. Clasts consist of Ordovician limestone, granite, and quartzite. Thickness 20-800m.</td>
<td>Contains <em>Estheria</em> sp.: Early Cretaceous</td>
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<tr>
<td>Heshangpu Formation (K1h)</td>
<td>Dark red cross-bedded sandstone interbedded with siltstone in the lower part and purple mudstone and light blue to grey siltstone, shale and marl in the upper part. Conformable above Sanqiao Formation. Thickness 560m.</td>
<td>Contains <em>Plagiophyllum</em> sp., <em>Otozamites</em> sp.: Early Cretaceous</td>
</tr>
<tr>
<td>Sandstone of Sikouzi (Ors)</td>
<td>Dark to medium red, more rarely pale red, orange and tan, conglomerate, sandstone and rare siltstone. Conglomerate most common near the base, contain pebbles to cobbles of resistant rock types with quartz-rich matrix. Unconformable on underlying Cretaceous rocks. Thickness 270m.</td>
<td>No fossils, latest Eocene to early Oligocene (?) as conformably overlain by Oligocene.</td>
</tr>
<tr>
<td>Unit</td>
<td>Description</td>
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<td>Red Beds of Sikouzi (Orb)</td>
<td>Dark red to maroon quartz-rich sandstone, siltstone and mudstone with inerbedded evaporites. Thin beds of white or green siltstone.</td>
<td>Contain *Cyprimites formalis, Cyprimites beljaewskyi, Eucypris longa, Baluchitherium sp., Tsaganomys altaicus, Bithynia sp., Unio sp., Darwinula sp.: Oligocene.</td>
</tr>
<tr>
<td>Red Beds of Hongliugou (Mrb)</td>
<td>Red, pale red to tan, massive mudstone and siltstone with sandstone in upper part. Pebble conglomerate with clasts of resistant rock types in upper few hundred meters. Thickness 930m. Conformable above Oligocene rocks.</td>
<td>Contains Mastodon sp., Testudo sp., Cyprimites sp., Limnothyere sp.: Miocene.</td>
</tr>
<tr>
<td>Conglomerate of Yangjuanpu (Pcg)</td>
<td>Tan sandstone and conglomerate. Pebbles to boulders of resistant rock types and matrix of quartz, feldspar and lithic grit. Thickness approximately 630m.</td>
<td>Contain *Hyocypris cf. bradyi, Cardona sp., Limnothyere luculenta, Cardoniella sp., Cyprimites sp., Chara sp., Catharica sp.: Pliocene.</td>
</tr>
<tr>
<td>Conglomerate of Yangzhongpu (Qcg)</td>
<td>Dark grey conglomerate several tens of meters thick that crops out only at the southeastern foot of Madong Shan. Angular pebbles and cobbles of grey to brown siltstone, sandstone, marl, and limestone derived from local Cretaceous rocks.</td>
<td>No fossils. Conformable above Pliocene rocks and conformable below loess, probably latest Pliocene or early Quaternary.</td>
</tr>
<tr>
<td>Loess (QI)</td>
<td>Tan massive silt to dust-sized deposit. Thickness 0-30m.</td>
<td>No fossils. Base could be as old as 2.4 Ma [Heller and Liu, 1984] or as young as 1.3 Ma [Burbank and Li, 1985].</td>
</tr>
<tr>
<td>Conglomerate of Liupan Shan (Qcl)</td>
<td>Tan to grey interbedded conglomerate, sandstone and siltstone. Conglomerate contains pebbles to cobbles of dark grey to grey-brown Cretaceous rocks. Upper part is interbedded with loess or reworked loess. Rests unconformably on all older pre-Quaternary rocks east of the Liu Pan Shan.</td>
<td>No fossils. Oldest part could be as old as late Pliocene, and upper part is intraloess (Quaternary).</td>
</tr>
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</table>

All fossil listings are from Ningxia Geological Bureau [1974].

*Although there are numerous local units, only the important units are listed.

Tertiary red beds just below the Liupan Shan thrust fault have been folded into a footwall syncline whose axial trace is approximately parallel to the thrust fault (Plate 1 and Figure 3). The asymmetric syncline has a steep western limb that suggests a relative northeast movement of the hanging wall of the thrust fault.

Present displacement of the Liupan Shan thrust fault determined by seismological data is unclear because of the lack of well-constrained fault plane solutions, but our work provides some information on the fault displacement in Holocene time. In many places along the fault a series of ridges and streams appear to be deflected left laterally where they cross the fault (Figure 4), but for most of them the offset cannot be measured accurately. Some of the deflections may be fortuitous due to the meandering of the streams and the irregularity of the ridges, but the presence of many consistent deflections suggests a component of left slip along the Liupan Shan thrust fault during late Pleistocene or Holocene time.

At Haiizikou, clear evidence is present for left slip along the Liupan Shan thrust fault. The fault trends about N20°W and is
clearly marked by a zone of gouge about 2-4 m wide. The
gouge zone and Cretaceous rocks are thrust above Quaternary
terrace deposits along a fault dipping 44° SW. Along a stream
flowing northeast from the mountains, the upstream part of the
channel is incised into the Cretaceous rocks, and its
downstream part is incised into young Quaternary terrace
deposits. The stream has been offset in a left-lateral sense
14±3 m where it crosses the fault (Figure 5), and the offset
part of the stream flows along the fault zone. There is a bench
about 1 m above the channel bed. This bench is offset about 5-
6 m along the fault within the 14±3 m of total stream offset
(Figure 5). The offset seems to be very young but,
unfortunately, we cannot determine its age.

In summary, the geological evidence indicates the Liupan Shan thrust fault has had a complex kinematic history.
Generally, the hanging wall of the thrust fault moved to the
east-northeast. In the early stage of thrusting a right-slip component may have been present, but in the later stage of
thrusting the Liupan Shan fault had a component of left slip.
The Xiaoguan Shan Fault

The Xiaoguan Shan fault is parallel to and lies about 14 km east of the Liupan Shan thrust fault (Figure 2 and Plate 1). The fault dips 40°-50° W and thrusts Cretaceous and Ordovician rocks relatively eastward over Tertiary red beds. Its hanging wall consists mainly of Cretaceous rocks from the Sanqiao Formation to the Naijiuhe Formation (Table 1). Ordovician limestone is exposed near the Xiaoguan Shan fault in the core of an anticline. The eastern limb of the anticline is steeper than its western limb, which is cut by a west dipping high-angle normal fault. The relation between the high-angle normal fault and the Xiaoguan Shan fault is unknown. West of the anticline both Cretaceous and Tertiary rocks dip generally to the west. The exposed footwall of the Xiaoguan Shan fault consists of Tertiary red beds and Cretaceous rocks.

No detailed work was done along this fault, and its evolution is unclear. Topographically, the hanging wall and footwall crop out at about the same elevation. No ridge or stream offsets were observed and none have been reported. We interpret these data to suggest that the fault is inactive or its slip rate is very small. Most of the recent tectonic activity in this area has taken place along the Liupan Shan and Xiaokou faults.

Xiaokou Fault

The Xiaokou fault strikes about N40°W (Figure 2 and Plate 2) and can be traced from Xiaokou northwest for about 60 km, where it steps left through the Laohuyiaoxian basin, then crosses the Nanhu Shan, and intersects the Haiyuan fault southwest of Youfangyuan, just where the N60°W trending left-slip Haiyuan fault zone changes its character (Figure 2; for details see Burchfield et al. [in this issue]). East of the Xiaokou fault is the Madong Shan fold zone that trends about N20°-30°W. The Xiaokou fault apparently dies out at Xiaokou or transfers displacement to the Liupan Shan thrust fault (see above).

The Xiaokou fault is clearly marked by the juxtaposition of Cretaceous Naijihe Formation (Kln) to the west with Tertiary red beds to the east (Plate 2). The light blue mudstone and marl of the Naijihe Formation form the Yueliang Shan on the
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southwest side of the Xiaokou fault, and the Tertiary red beds (Mrb) to the northeast commonly form basins and small hills separated by wide valleys. The difference in elevation across the fault is usually about 100-200 m. Only in one place, at Caixangpu, is the fault exposed. The width of the fault zone is about 60 m. The Cretaceous Naixiahe Formation has been intensively brecciated, and gypsum and other evaporites are common near the fault. The Tertiary massive mudstone (Mrb) is also brecciated and has been injected into fractures along the fault zone. The dip of the Xiaokou fault is about 40°-50° southwest, but its dip is poorly determined.

The hanging wall of the Xiaokou fault consists of Cretaceous rocks, but its structure has not been well studied. According to previous work [Ningxia Geological Bureau, 1959], the Cretaceous rocks extend about 30 km to the west from the Xiaokou fault across the Yueliang Shan, and all the formations present in the Liupan Shan Group are exposed in Yueliang Shan. Devonian red conglomerate and granodiorite of unknown age are reported farther southwest of the Cretaceous outcrops.

The footwall block of the Xiaokou fault mainly consists of Tertiary red beds (Mrb and Orsb) that were intensively folded near the southeast end of the fault (Plate 2). The axes of these folds are approximately parallel to the fault. Along the middle segment of the fault, the Tertiary rocks are massive mudstone, and they are not folded but are gently warped. Farther to the north, the outcrops are very poor due to cover by loess and other Quaternary sediments, but gentle folds are present beneath the loess.

Near the southeastern end of the Xiaokou fault, at Xangshuiqousui, the Cretaceous rocks in the hanging wall adjacent to the fault have been intensely folded. These folds disappear away from the fault. The folds trend about N30°-35°W, parallel to the trend of the Xiaokou fault. About 15 km northwest of Xangshuiqousui, at Shangdazai, folds in the hanging wall adjacent to the Xiaokou fault also are parallel to the fault. About 4 km northwest of Xangshuiqousui, folds are developed in the Tertiary red beds in the footwall and are parallel to the Xiaokou fault. The parallelism of the folds and the faults suggests that the Xiaokou fault probably was a thrust fault or had an important component of thrusting across it in its early stage of displacement.

Late Pleistocene and Holocene features show evidence of left slip along the Xiaokou fault. At Xangshuiqousui a stream channel has been offset about 27±5 m left laterally along the Xiaokou fault (Figure 6). Both the upstream and downstream parts of the channel are straight, and terraces are well developed on both sides of the channel. The fault is clearly marked by the juxtaposition of Cretaceous and the Tertiary rocks. At the fault the Cretaceous rocks are vertical and form a small waterfall, but the fault surface is covered by alluvium.

Near Shangdazai a series of streams have been offset left laterally (Figure 7). The fault surface is not exposed because alluvium covers all older rocks. The stream offsets at the location shown in Figure 7 were measured to be 380±30 m. Although we have not been able to date any of these stream offsets, they indicate that the Xiaokou fault has had a significant component of left slip during its later history.

Fig. 6. The left-lateral stream offset along the Xiaokou fault at Xangshuiqousui. The view is to the northeast. The stream flows from southwest to northeast, and is offset where it crosses the fault. The measured offset is 27±4 m. The fault is marked by the juxtaposition between Cretaceous rocks and Tertiary red beds, but fault surface is not well exposed. This stream offset is typical of stream offsets along the Xiaokou fault.
Madong Shan Fold and Fault Zone

The Madong Shan is a roughly northerly trending range located northeast of the Xiaokou fault (Figure 2 and Plate 2). The folds in the northern part of the Madong Shan trend approximately N20°W, whereas in the wide southern part they trend about N20°E. East of the Madong Shan is the north-south trending Qinshuihe Basin (Figures 2 and 8) which is filled with Quaternary sediments and is underlain by Tertiary conglomerate. The thickness of Quaternary sediments in the basin is generally between 100 and 200 m. The eastern boundary of the Qinshuihe Basin is covered by loess. Cretaceous rocks and Tertiary red beds are exposed east of the basin and dip west [Ningxia Geological Bureau, 1974]. Thus the Qinshuihe basin is a buried open syncline. To the south the Madong Shan ends near the transition between the Xiaokou fault and the Liupan Shan thrust fault. To the north the area is covered by thick loess, but on the satellite images a linear feature extends eastward from the Haiyuan fault zone across the loess covered area and merges with the northern end of the Madong Shan (Figure 8).

The higher part of the Madong Shan is formed by rocks from the lower Cretaceous Madong Shan (Klm) and Naijiahe (Kln) formations that crop out in the cores of the major folds. The lower flanks of the mountains are formed mainly by Tertiary strata of Oligocene to Pliocene age. All these rocks are intensely deformed into three en echelon major anticlines. From south to north they are the overturned Taozigou anticline, the box-shaped Chenzhuang anticline, and the faulted Sikouzi anticline (Plate 2 and Figure 9). Some small folds are developed between and adjacent to these major folds. Along the eastern side of the Madong Shan there is a scarp, but it is not clear if it is a fault scarp or an erosional feature.

The Taozigou Anticline

The Taozigou anticline consists of the Cretaceous Madong Shan and Naijiahe formations and Tertiary red beds (Plate 2 and sections AA', and BB' in Figure 9). The oldest rocks exposed are pink siltstone and mudstone of the Cretaceous Lisangwa Formation (KII) that crops out at only two places in deeply incised canyons. The subunits of Madong Shan and Naijiahe formations form most of the core of the fold.
Fig. 8. (Top) Satellite image of the Haiyuan and Liupan Shan areas, and (bottom) generalized map showing the major structures mapped on the ground.
The anticline is doubly plunging and overturned to the southeast. The northwestern limb of the Taozigou anticline is upright and dips 30°-50° NW. On the northern part of its western limb the Naijiaha Formation (Kln) crops out in a wide region where it is folded on a smaller scale between the Taozigou anticline and the Chenzhuang anticline to the northwest (Plate 2). The southeastern limb of the anticline is more complex. Rocks of the Cretaceous and the lower Tertiary are overturned and dip 70°-80° NW. The Tertiary rocks farther east are upright and dip 50°-70° SE. Quaternary conglomerate (Qcg) on the eastern limb of the fold contains debris of the Cretaceous rocks and records the beginning of deformation in the Madong Shan. The northern part of the eastern limb of fold is also overturned and dips 70°-80° SW.

The Taozigou anticline can be divided into two segments: a southern segment that trends about N20°E and a northern segment that trends about N20°W. At its north end the fold plunges gently northwest, but at its south end the fold plunges steeply southwest and contains several parallel folds. At its very southern end the fold is deflected to a southeast trend and plunges steeply southeast.

The Chenzhuang Anticline

The Chenzhuang anticline (Plate 2) is formed by the Cretaceous Madong Shan and Naijiaha formations and Tertiary red beds. The anticline trends about N15°E, but like the Taozigou anticline, its northern segment trends more northwesterly than the southern segment. The Chenzhuang anticline is a doubly plunging box-type fold (Figure 9, section BB'). The broad crest of the anticline is about 2 km wide and has been gently warped into three small anticlines. The
anticline is asymmetric in its central and northeastern parts: its northeastern limb dips 50°-85° NE, and its western limb dips 20°-40° NW.

The Tertiary red beds of the western limb are covered by loess and Quaternary sediments, but a few outcrops indicate a progressively more gentle dip northwest, decreasing from 30°-40° in Oligocene red sandstone and red beds to 10°-20° in Miocene massive mudstone.

At its south end the Chenzhuang anticline plunges south and breaks up into a series of small south plunging folds (Plate 2). To the northeast the anticline is deflected to a northwest trend, its amplitude is reduced, and some shortening has been transferred into the adjacent Sikouzi anticline. Farther north, the Chenzhuang anticline and the syncline west of it are probably connected with the anticline and syncline east of the Sikouzi anticline. We did not complete the mapping between them, but the folds generally project into one another.

The Sikouzi Anticline

The Sikouzi anticline (Plate 1 and section CC' in Figure 9) trends about N15°-20°W and differs considerably from the main structural orientation of the Madong Shan, but its trend is similar to the northwest segments of the two other folds. The Sikouzi anticline folds Tertiary red beds and Cretaceous Naijiaye Formation (Kln). To the north it plunges beneath loess and Quaternary sediments where the eastern extension of the Hailun fault zone ends as traced on the satellite image (Figure 8). To the south it overlaps with the northwest trending northern segment of the Chenzhuang anticline and its southern end curves to trend northeast. If its southern end is projected southwest, it should connect with the northeastern trending anticline west of the Taozigou anticline. However, the exposure in that area is very poor.

The Sikouzi anticline can be divided into southern and northern segments. The southern segment is cored by the Naijiaye Formation. Its eastern limb generally dips 40°-50° NE and connects with the northern part of the Chenzhuang anticline through an open north plunging syncline (Figure 9, section BB'). Its western limb dips steeply southwest. Farther west the Miocene massive mudstone is only gently warped but does not appear to have involved in the folding of the Madong Shan. Most of the southern segment of the Sikouzi anticline apparently is not overturned. In one well-exposed cross section near the crest of the anticline on its western limb, however, in the lower unit of the Naijiaye Formation, rocks dip to northwest, but rocks in the upper part of the formation are overturned to the northeast. It is possible that the axial surface of the fold is upright at depth but is overturned upward and that most of the overturned rocks have been removed by erosion.

The northern segment of the fold is more complex than the southern segment even though there is no change in strike between the two segments. The west limb of the fold is cut by an east dipping thrust fault that trends parallel to the anticline (Figure 9, section CC'). The fault places the lower units of the Cretaceous Naijiaye Formation over the Tertiary red beds. The Cretaceous rocks in the hanging wall near the fault are overturned and dip northeast. The eastern limb of this segment dips 40°-50° NE and contains an anticline-syncline pair; the western limb of the anticline dips more gently than the eastern limb (Plate 2 and section CC' in Figure 9). West of the thrust fault the rocks are also folded. In northern part (north of Sikouzi) a west-vergent overturned footwall syncline is present below the thrust fault, and an open anticline is present farther west. West of this anticline the Miocene massive mudstone is only gently warped and dips less than 10°. In southern part (south of Sikouzi) a tight doubly plunging anticline cored by the Naijiaye Formation is developed west of the thrust fault and its footwall syncline.

In summary, the Madong Shan fold zone has a different structural style and evolution from the structures in the Liupan Shan, Xiaoguan Shan, and Yueliang Shan. The major structural pattern in the Madong Shan is formed by three anticlines with curved axial traces and other smaller folds that parallel the anticlines. We suggest that the Sikouzi anticline is connected with the anticline west of the Taozigou anticline to the south, and the Chenzhuang anticline is connected with the anticline east of the Sikouzi anticline to the north. The northern segments of the three anticlines are all deflected to the northwest, and we suggest that they have undergone left-lateral shear during and/or after their formation.

The folds can be interpreted as fault propagation folds [Suppe and Chang, 1983] (Figure 9). The southern part of the Madong Shan, the Taozigou anticline, is east vergent, whereas the northern part, the Sikouzi anticline is west vergent. The box-shaped Chenzhuang anticline formed between the other two folds as the crest of the fault propagation fold where the vergence changes. Shortening within these folds is progressively transferred from the Sikouzi anticline in the north to the Taozigou anticline in the south. Because of the changes in vergence and the gently Z-shaped axial traces, we suggest that these folds formed with a component of left-lateral shear.

TIMING RELATIONS OF STRUCTURES IN THE LIUPAN SHAN AREA

Based on the data presented above, the structural evolution in the Liupan Shan area can be divided into three stages (from oldest to youngest): (1) folding and thrust faulting along the Liupan Shan and Xiaokou fault, with a possible right-lateral component of displacement along the Liupan Shan thrust fault, (2) formation of the fold zone in the Madong Shan, thrust faulting in the Xiaoguan Shan, and continued thrusting in the Liupan Shan, and (3) left-lateral strike-slip along the Xiaokou fault and northern part of the Liupan Shan fault and continued thrusting in the Liupan Shan (Figure 10). These stages should not be considered isolated stages; they are interrelated and probably diachronous.

Stage 1: Folding and Thrust Faulting With Associated Strike-Slip Motion

The oldest Cenozoic structures recognized are the folds and thrust faults in the Liupan Shan and Yueliang Shan (Figure 10-stage 1). Their ages can only be estimated on the basis of the age of the youngest sedimentary rocks that were involved in these structures. The Liupan Shan and Xiaokou faults all offset the contact between Cretaceous and Tertiary red beds, which is a paraconformity, throughout the Liupan Shan area and northeastern margin of the Tibetan Plateau. Rocks above the paraconformity contain only rare fragments of the underlying Cretaceous rocks, and most of the pebbles and cobbles in the
early Tertiary conglomerate are quartzite, gritty red sandstone, red conglomerate, and other resistant rock types. This suggests that no significant tectonic event occurred within the mapped area during the hiatus represented at the paraconformity. The mapped area as well as the northeastern part of Tibetan Plateau was the site of continued deposition of fine-grained terrestrial red sediments from early Oligocene to Pliocene time [Burchfiel et al., this issue; Zhang et al., 1990] and this indicates deformation did not begin in this area until Pliocene time. The Pliocene conglomerate contains debris from all underlying units and probably marks the onset of Cenozoic deformation in this area. Therefore the age of this deformation is probably Pliocene and younger.

During this earliest deformational phase the thrust faults and related folds involved rocks as old as the Ordovician limestone. Relative displacement along thrust faults was to the east-northeast and may have been associated with right-lateral displacement in the Liupan Shan.

Stage 2: Formation of the Fold Zone in the Madong Shan and Thrust Faulting in the Liupan Shan and Xiaoguan Shan

The Madong Shan fold zone consists of three major anticlines each with a different geometry. Vergence is both to the southeast and northwest, and the axial traces of most of the folds are curved. The folds probably formed in part later than the earliest structures in the Liupan Shan and Yueliang Shan. In the eastern limb of the Taozigou anticline the Quaternary conglomerate (Qcg) has been involved in the folds. The Quaternary conglomerate conformably overlies the Pliocene conglomerate, and it contains the first abundant debris of grey, yellow, light blue mudstone, siltstone, marl, and fine-grained sandstone that clearly were eroded from the nearby Cretaceous rocks. The source for the clasts in the Quaternary conglomerate may have been from the Cretaceous rocks in the deformed and uplifted areas such as the Madong Shan, Yueliang Shan, Liupan Shan, and Xiaoguan Shan. The uppermost part of the folded Quaternary conglomerate is interbedded with loess, whereas the loess in the other adjacent ranges rests unconformably on older rocks. This suggests that folding in the Madong Shan began later than the folding and thrust faulting in the adjacent areas. For reasons given below, we interpret much of the thrusting in the Liupan Shan and Xiaoguan Shan to have been contemporaneous with folding in the Madong Shan (Figure 10-stage 2). The younger part of the loess does not appear to be involved in the Madong Shan and Xiaoguan Shan structures.

Stage 3: Left-Lateral Faulting Along the Xiaokou Fault and Continued Thrusting On The Liupan Shan Fault

The youngest phase of deformation in this area is left-lateral strike-slip faulting along the Xiaokou fault and thrusting in the Liupan Shan with a left-slip component in its northern part (Figure 10-stage 3). This deformation is still active. An important question is when this left-slip motion started, because the development of left slip on the Xiaokou fault has probably been responsible for ending or slowing the rate of deformation in the Madong Shan and Xiaoguan Shan, where the loess does not appear to be involved in active structures. When left-slip displacement began on the Xiaokou fault is difficult to determine within the map area. Although a series of streams across the fault have been offset, no material was found to date them. Data presented by Burchfiel et al. [this issue] have suggested that left slip on the Xiaokou fault may have begun no more than 150,000 to 300,000 years ago.

KINEMATICS AND STRAIN EVOLUTION IN THE LIUPAN SHAN AREA

From the descriptive geology and timing constraints presented above, a kinematic evolution of the Liupan Shan area can be developed. This kinematic evolution must be related to the evolution of adjacent areas in southern Ningxia, particularly the Haiyuan area. Furthermore, most of the magnitude of the deformation in the Liupan Shan area can be shown quantitatively to be associated with the left-slip displacements on the Haiyuan fault zone.
The first structures to form were the thrust faults and related folds in the Yueliang Shan (Xiaokou fault) and Liupan Shan. These structures trend north in the Liupan Shan and about N40°W in the Yueliang Shan. They are parallel to the earliest structures that formed in the Haiyuan area [see Burchfiel et al., this issue] and also parallel to most of the other structures in southern Ningxia (Figure 2) that began to develop at about the same time. The trends of these structures indicate a N50°-60°E direction of shortening. Such a shortening direction would produce thrusting on the Xiaokou fault but thrusting with right slip on the Liupan Shan thrust fault. The magnitude of this shortening is difficult to determine. A total thrust displacement of about 2 km (or horizontal shortening of 1.4 km) on the Xiaokou fault was calculated using the present fault dip and stratigraphic separation, but not all of this displacement need have occurred during this early stage of deformation. If some of the shortening is related to oblique strike slip during the youngest stage (see below), then about 0.8 km of horizontal shortening could have occurred in this earliest stage. Such a magnitude of shortening is reasonable for the earliest phase structures in the Haiyuan area [see Burchfiel et al., this issue]. We infer that perhaps about 1-2 km of horizontal shortening would have occurred at this time on the Xiaokou fault and on the Liupan Shan thrust fault (Figure 10).

Following formation of these early stage structures, movement on the Haiyuan fault began, and the kinematic evolution in the Liupan Shan area changed. Because the movement on the Haiyuan fault zone is almost purely strike slip along N60°W, shortening along the more northerly trending structures in the Liupan Shan area can be expected to have changed to about the same direction. The total displacement on the Haiyuan fault zone, the dominant structure in the southern Ningxia area, is from 10.5 to 15.5 km [Burchfiel et al., this issue]. The largest magnitude of shortening in the Liupan Shan area is present in the folds and thrust faults in the Madong Shan, Liupan Shan, and Xiaoguan Shan. The geometric and timing relation between structures in the Liupan Shan and Haiyuan area clearly indicates structures in the two areas are related, and we interpret that left slip on the Haiyuan fault zone has been transferred into shortening in the folds and thrust faults in the Liupan Shan area (Figures 8 and 10). Stratigraphic relations presented above indicate that shortening in the Madong Shan followed the development of the oldest Cenozoic structures in the Liupan Shan area. From the calculations of shortening in the Liupan Shan area, we infer that most of the folding and thrust faulting in the Liupan Shan and Xiaoguan Shan were contemporaneous with the deformation in the Madong Shan.

The minimum shortening can be measured from the two cross sections constructed through the Madong Shan (Figure 9). Sections A-A' and B-B' were constructed parallel to the strike of the Haiyuan fault zone. Restoring the folded beds in these cross sections yields shortening magnitudes of 7.7-3.5 km and 63-7.8 km, respectively.

Horizontal shortening across the Liupan Shan thrust fault can be measured from the cross section shown in Figure 3. The shortening calculated parallel to the Haiyuan fault is 7.8 km. About 1-2 km of this displacement may have occurred during the earliest stage of deformation and another 1-2 km in the youngest stage (see below); thus during the folding in the Madong Shan (stage 2), about 4.8-6.3 km of shortening occurred on the Liupan Shan thrust fault in the direction parallel to the Haiyuan fault. Since this amount is close to that obtained from the Madong Shan, we infer that this shortening was contemporaneous in the two areas.

Structures in the two areas are not continuous. Structure in the Liupan Shan is dominated by thrust faults, whereas that in the Madong Shan is dominated by folds. The folds at the southern end of the Madong Shan plunge steeply south and are not aligned with the Liupan Shan thrust fault. We interpret this relation to result from the early stage of deformation, possibly thrust faulting, in the Liupan Shan that was not present in the Madong Shan. Later when both areas were deformed, shortening continued by thrust faulting in the Liupan Shan but occurred by folding in the Madong Shan. A zone of accommodation between these two structural styles, with a possible left-slip component, occurred between Xiaokou and Yangzhongpou where structures from both mountain ranges show a sinistral deflection.

Displacement on the Xiaoguan Shan thrust fault east of the Liupan Shan is difficult to determine because the structure of the footwall is incompletely exposed (Plate 1 and Figure 3). A hanging wall cutoff of the oldest Cretaceous formations is present, and assuming the simplest structure for the footwall yields a minimum east-west displacement in a N60°W direction of 8.6 km, of which about 6.6-7.6 km would have occurred during stage 2.

Thus folding and faulting in the Madong Shan and Liupan Shan during stage 2 would account for 6.3-7.8 km and 4.8-6.3 km of shortening, respectively, and when combined with shortening in the Xiaoguan Shan (6.6-7.6 km), they yield a total shortening of 11.4-15.4 km in the direction parallel to the Haiyuan fault zone.

Left slip on the Xiaokou fault occurred during the youngest stage of deformation. Displacement began in late Pleistocene time and is active today. Strike-slip displacement on this N30°W trending fault is a maximum of 1-1.5 km [Burchfiel et al., this issue]. Since left-slip movement on the Xiaokou fault became active, deformation in the Madong Shan and Xiaoguan Shan either has ceased or has proceeded at a very slow rate. The left slip on the Xiaokou fault would add 1-2 km to the horizontal shortening on the Liupan Shan thrust fault (parallel to N30°W) and perhaps a small amount to the shortening (0.5 km) at the latitude of the Madong Shan. If added to the earlier displacements, it would yield a total shortening in the Liupan Shan area of 12.9-17.4 km parallel to the Haiyuan fault zone.

Left slip on the Haiyuan fault and Xiaokou fault is along two faults that intersect at an angle of about 30°. In order to maintain a compatible strain relationship some shortening is required east of the Xiaokou fault. This shortening may be along the Xiaokou fault itself but may also occur by deformation along the continuation of the Haiyuan fault east of its intersection with the Xiaokou fault or within the broad syncline along the Qinshuihe valley (Figure 2) [see Burchfiel et al., this issue].

If the thrust fault in the Xiaoguan Shan takes up shortening related to movement southeast of the Haiyuan fault zone, then the Haiyuan fault must have continued southeast from the northern end of the Madong Shan to the northern end of the Xiaoguan Shan (Figure 10). Presently there is no evidence for the fault between the Madong Shan and Xiaoguan Shan (Figure 8). The fault would cross the Qinshuihe valley. The valley is
located along the axis of a broad north plunging syncline that can be traced northward to Zhongnin (Figure 2). This syncline is one of several synclines that form topographic lows with active uplift in adjacent ranges. The Qinshuihe basin was thus a topographically low area that has been filled with loess and other sediments. If the southeastern extension of the Haiyuan fault became inactive during late Pleistocene time, when movement began on the Xiaokou fault, the trace of the Haiyuan fault in the Qinshuihe basin would have been concealed beneath these young sediments (Figure 10). We infer that the Haiyuan fault did continue to the Xiaoquan Shan, because the only structures present to accommodate the shortening transferred from the Haiyuan fault zone in this region are the structures in the Liupan Shan, Madong Shan, and Xiaoquan Shan. Thus the concordance of the shortening in these two structural zones in the direction of the Haiyuan fault zone (12.9-17.4 km) with the magnitude equal to the left-slip displacement on the Haiyuan fault zone (10.5-15.5 km) implies that slip on that strike-slip fault is nearly completely absorbed by folding and thrust faulting. The Z-shaped trace of the Madong Shan folds clearly reflects the left-slip strain.

DEPTH OF DEFORMATION BENEATH THE LIUPAN SHAN AREA

Shortening in the Liupan Shan area occurs by listric thrust faulting and fault propagation folding, both of which suggest a thin-skinned style of deformation. Constructing cross sections on the Liupan Shan and Xiaoquan Shan thrust faults based on a thin-skinned geometry indicates the depth to the decollement would be at about 5 km below the present land surface (Figure 3). This would place the decollement zone below the Cretaceous rocks exposed in the area. Ordovician rocks are exposed in the hanging wall of the Xiaoquan Shan thrust fault; thus the level of decollement is within or below the Ordovician strata.

For the Madong Shan folds, cross sections based on fault propagation fold geometry yields a depth to decollement that ranges from about 5 to 7.5 km below the present land surface (Figure 9). The geometry of these folds is reasonably well constrained, and errors of about 1 km to the decollement are possible. This would place the decollement at or about 1 km below the Cretaceous rocks; a stratigraphic level similar to that in the Liupan Shan and Xiaoquan Shan thrust faults. Depth to decollement using the excess area method [Laubscher, 1962 and 1969; Dahlstrom, 1969], as recently expanded by Hossack [1979], Suppe [1985], Woodward et al. [1985] and Mitra and Namson [1989], can be applied. By measuring the area beneath the folds for three cross sections, the average depth to decollement is about 4.4 km and ranges from 3.5 km along section A-A' to 5.1 km along section G-G'. This depth is comparable to that obtained from the cross sections for the thrust faults and folds in the area.

The geometry of the Madong Shan folds indicates a complication at depth. The western limb of the folded zone at the depth of the inferred decollement is consistently about 1 km shallower than the eastern limb. There are several ways that this could be interpreted. Because of the limits of our mapping we can only suggest that this change in depth is the result of broad warping during formation of the Qinshuihe basin.

The thin-skinned geometry of the structures in the Liupan Shan area might be applied also to the folds and thrust faults in the southern Ningxia region (Figure 2). Folds and thrust faults in the region expose rocks as old as Cambrian metasedimentary rocks or pre-Silurian metamorphic rocks. This suggests that if there is a decollement zone beneath these structures, it cuts through the structurally complex pre-Cenozoic rocks and structures in the region and that much of the Pliocene-Quaternary structural development in southern Ningxia has a style similar to that of the Haiyuan-Liupan Shan area where left-lateral strike-slip displacement is transferred to north or northwest trending zones of shortening [Zhang et al., 1990].

CONCLUSION

Stratigraphic relations in the Liupan Shan region indicate that deformation began in Pliocene time. If this deformation is related to the Indian/Asian collision zone, deformation began here about 40-45 m.y. after the collision started.

The Liupan Shan thrust fault trends generally north-south except in its northern part where it trends north-northwest. It is characterized by the eastward displacement of Cretaceous Liupan Shan Group above the Tertiary red beds. The hanging wall has been folded into an anticline near the thrust fault, but to the west the rocks dip gently west, and farther west they become horizontal. This relation suggests that the Liupan Shan thrust fault is a decollement-style thrust fault that ramps gently upward to the east and that the folds were developed only near the thrust fault. In the hanging wall west of the fault there are a series of small folds that trend obliquely to the Liupan Shan fault and intersect it with acute angle facing to the southeast. These relations suggest that the earliest phase of thrust displacement may have been accompanied by a component of right slip. Along the northern part of the Liupan Shan thrust fault, several left-lateral stream offsets are present. The clearest left-lateral offset is 14±3 m, and a bench within the same stream is offset about 5 m. Thus the youngest phase of thrusting on the Liupan Shan thrust fault has had a component of left slip.

The Xiaoqian Shan fault is parallel to the Liupan Shan thrust fault. The Cretaceous and Ordovician rocks in its hanging wall have moved relatively eastward over Tertiary red beds. No detailed work was done on this fault, and its evolution is poorly known.

The Xiaokou fault trends about N40°W and lies north of the Liupan Shan thrust fault. Cretaceous rocks are thrust eastward over Tertiary red beds. Small folds parallel to the Xiaokou fault in both hanging wall and footwall suggest that no lateral displacement was associated with the thrust faulting in its earliest phase of deformation. A series of ridges and streams that cross the fault have been offset left laterally in Pleistocene and Holocene time, and a stream offset of 380±30 m was measured at one place. Thus its youngest phase of deformation is associated with left slip.

The Madong Shan fold zone is located east of the Xiaokou fault. It trends about N20°W and consists of three anticlines with gentle Z-shaped axial traces. Each of the anticlines in the zone has a different geometric style. The Taoziqin anticline is overturned to the southeast, the Chenzhuang anticline is a box-shaped fold, and the Sikouzi anticline is cut by an east dipping thrust fault. The southern part of the fold zone is east vergent,
whereas the northern part is west vergent. The geometry of these folds can be interpreted to be the result of complex fault propagation folding where the shortening in the Madong Shan appears to be progressively transferred to more easterly structures southward.

The tectonic history of the Liupan Shan area can be divided into three interrelated stages. During the first stage, folds and thrust faults along north-western trends were associated with right-slip motion. This stage probably occurred between late Pliocene and early Quaternary time, because the Pliocene conglomerate has been involved in the folds and thrust faults, but Quaternary rocks unconformably overlie the folds. Such structures were formed in the Liupan Shan and Yueliang Shan. Shortening during this stage was about 1-2 km in a NS00-60°E direction. During the second stage, folding began in the Madong Shan and thrust faulting began in the Xiaoguan Shan and continued in the Liupan Shan. In the folds of the Madong Shan the Quaternary conglomerate (Qeg) conformably overlies the Pliocene conglomerate and contains detritus from Cretaceous rocks indicating the Madong Shan folds are probably younger than the initial deformation in the Yueliang Shan and Liupan Shan. Most of the shortening (11.4-15.4 km) in the Liupan Shan area occurred a this time. During the third stage, about 1-1.5 km of late Pleistocene to Recent left slip occurred on the Xiaokou fault and then was transferred to left-slip oblique thrusting on the Liupan Shan fault. Deformation ceased or was reduced to a very slow rate in the Madong Shan and Xiaoguan Shan.

Left slip on the N60°W striking Haiyuan fault zone has been transferred into shortening on the generally north trending structures in the Liupan Shan area. The 10.5-15.5 km of left slip on the Haiyuan fault zone is comparable to the 12.9-17.4 km of shortening in the Liupan Shan structures. The structures in the Liupan Shan area are probably thin-skinned, and the depth to the decollement zone is about 5-7.5 km, a depth that places the decollement within a varied complex of pre-Cretaceous rocks.

Interpretations of the geology in the Liupan Shan area can be applied to the folds and thrust faults in southern Ningxia that form the developing northeastern margin of the Tibetan Plateau. The structural pattern in this region suggests that this part of the plateau has formed by shortening oriented northeast and by left-slip faulting that has transferred material from farther west into northeast and east-west shortening along folds and thrust faults that are detached within the upper crust [Burchfiel et al., 1989; Zhang et al., 1990].

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Plate 1. Geological map along the Liupan Shan thrust front.
fault and vicinity.
Plate 2. Geological map of the Madong Shan area. The thrust fault south of the Xiaokou is the north continuation of the Liupan Shan thrust fault in Plate 1. Plates 2 and 1 ajoin and are at the same scale.