Late Cenozoic tectonic evolution of the Ningxia-Hui Autonomous Region, China

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ABSTRACT

Part of the transition from active crustal shortening and strike-slip faulting in northwestern China to active extension in northeastern China takes place within the Ningxia Autonomous Region. Four arcuate zones of both strike-slip faults and thrust faults with associated ramp anticlines dominate the structures in southern Ningxia. Deformation in these zones indicates that a component of left-slip displacement is transferred into crustal shortening on north-south-trending folds and thrust faults. The average Quaternary slip rate along the Haiyuan–Liupan Shan fault zone is 5–10 mm/yr, and that along the Tianjin Shan–Mibo Shan fault zone is about 1.5–2.7 mm/yr. The amount of offset and rate of slip along the Yantong Shan and the Niushou Shan–Daluo Shan fault zones are unknown, but the topography of the mountains suggests that the rates of slip along these zones is lower than that of the Haiyuan–Liupan Shan fault zone. Deformation in northern Ningxia is dominated by normal faulting and extension. The Helan Shan rise about 2,000 m above the Yinchuan basin, reportedly filled with a few kilometers of Cenozoic sediments. The average rate of vertical separation in Quaternary time along the East Helan Shan fault is estimated to be at least 0.5–0.8 mm/yr. Opening of the Yinchuan graben is probably partly related to left-lateral slip on the Niushou Shan and Daluo Shan fault zone. The northeastern margin of the Tibetan Plateau is probably being elevated by the irregular growth of convergent and left-slip structural zones. The evolution of deformation along the Haiyuan–Liupan Shan structural zone probably foreshadows the future deformation in the ranges north of it. Left slip and shortening within the Ningxia region appears to accommodate less than 20–25 km of east or northeast displacement of crustal fragments of the northern Tibetan Plateau. Large-magnitude lateral transport of crust with respect to the area to the east has not taken place within the part of the Ningxia region covered by this study.

INTRODUCTION

The Ningxia-Hui Autonomous Region overlaps the areas of active crustal shortening and strike-slip faulting in western China and active crustal extension in northeastern China (Fig. 1; Tapponnier and Molnar, 1977; Huang, 1980; Zhang and others, 1984; Deng and others, 1979; Wang and others, 1985). The Cenozoic tectonics of western China, which includes the Tibetan Plateau and the area north of it, is dominated by thrust and strike-slip faulting, but in northeastern China, extension appears to be the dominant tectonic process. The Ordos block is surrounded by normal faults except along its southwestern side where it is bounded by thrust faults. Our studies in the Ningxia Hui Autonomous Region have focused on (1) the late Cenozoic geological evolution of the northeastern part of the Tibetan Plateau to try to understand how the plateau was developed, (2) determination of the magnitude and rate of eastward translation along strike-slip faults to test the hypothesis of eastward lateral transport of continental fragments within the plateau, and (3) understanding the transition between the regions of shortening and strike-slip faulting within the plateau and extension within northeastern China.

The neotectonics of southern Ningxia is dominated by strike-slip faulting and crustal shortening. The structures in southern Ningxia consist of four arcuate zones of both strike-slip faults and thrust faults with associated ramp anticlines (Fig. 2) along the northeastern margin of the Tibetan Plateau (Fig. 1). From south to north, the individual structures that comprise this arcuate system are the Haiyuan–Liupan Shan fault zone, the Tianjin Shan–Mibo Shan fault zone, the Yantong Shan fault zone, and the Niushou Shan–Daluo Shan fault zone (Fig. 2). Each of these fault zones consists of west-northwest–trending faults with major left-slip components and north-northwest–trending thrust faults or folds with minor strike-slip components.

North of the Niushou Shan–Daluo Shan fault zone, the structures are dominated by normal faults, which have formed along both the east and west sides of the Helan Shan. The Yinchuan graben lies east of the Helan Shan and is bounded on both sides by normal faults (Fig. 2). The graben is reported to be the site of more than 6,000 m of late Eocene or early
Oligocene to present sedimentary rocks, including 1–1.6 km of Quaternary rocks (Ma and others, 1982 and Zhang and others, 1986).

In a previous paper (Deng and others, 1984), we briefly described the active tectonics of the Ningxia region and adjacent areas based on our reconnaissance work and studies of Landsat imagery. Subsequently we studied the geological evolution; kinematic history; and amount, rate, and style of deformation in the Haiyuan and Liupan Shan area (Burchfiel and others, in press; Zhang and others, in press), which is the southernmost arcuate structural zone in southern Ningxia (Fig. 2). In this paper, we describe our field geological mapping of the Tianjin Shan–Mibo Shan zone, Niushou Shan–Daluo Shan fault zone, and the Helan Shan and Yinchuan graben, in order to understand when and how deformation occurred in different parts of the Ningxia region and its relationship to the development of the northeastern margin of the Tibetan Plateau.

ROCK UNITS IN THENINGXIA REGION

The ages of rocks exposed in southern Ningxia range from Cambrian (or possibly Precambrian) to Quaternary (Table 1). Paleozoic and Mesozoic rocks have been folded and faulted during pre-Cenozoic deformation. Petrological and structural features show that during Paleozoic and perhaps part of Mesozoic time, southern and northern Ningxia had different stratigraphic and tectonic histories. A fault zone through the Niushou Shan–Daluo Shan region separates these geological units (Wang and others, 1985; Huang, 1980), but the detailed geological history and kinematic features along this zone are poorly known.

After the deposition of Lower Cretaceous rocks, the entire Ningxia region appears to have been subject to erosion, as Upper Cretaceous rocks are missing from this area. A large Tertiary basin was formed in late Eocene or Oligocene time in what is now the northeastern margin of the Tibetan Plateau; that basin included much of Ningxia region (Fig. 3). From Oligocene to Pliocene time, this large Tertiary basin locally received more than 3 km of red mudstone, siltstone, and rare sandstone and conglomerate (Table 1). There are rare unconformities between Oligocene and Pliocene units, and transition from one formation to another is gradual.

Most of the Quaternary sediments were deposited during deformation and reflect deposition in local environments from local sources. They unconformably overlie all pre-existing rocks and structures (Burchfiel and others, in press; Zhang and others, in press). The Quaternary units in the Ningxia area will not be described, because the lack of age control on these units makes it impossible to correlate accurately the separate and locally restricted units. The similar lithological features and abundant fossils within most of the Tertiary formations enable us to correlate these formations in different areas, however, so that the time of initiation of Cenozoic deformation can be constrained, but it is much more difficult to correlate events within the Quaternary Epoch. Brief descriptions of the Tertiary and Paleozoic rocks are given in Table 1. All of the fossils listed in Table 1 were collected and dated by the Ningxia Geological Bureau (1974, 1976, 1980).

Figure 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; black where known to be late Cenozoic; unfilled 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 Precambrian 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 indicated.
Figure 2. (Left part is top part of map.) Geological map of the Ningxia region showing major structural features and mountain ranges (see Fig. 1 for location). PK = pre-Cretaceous rocks; Kls = Cretaceous Sanqiao Formation; Klb = Cretaceous Heshangpu Formation; Kl = Cretaceous Lisanzha Formation; Klm = Cretaceous Madong Shan Formation; Kls = Cretaceous Najiahe Formation; Ors = Eocene or Oligocene Sikouzi Formation; Orb = Oligocene Qinshuiyin Formation; Mrb = Miocene Hongliugou Formation; Pcg = Pliocene Ganhegou Formation. Blank area is covered by loess and other Quaternary sediments. Dotted area covers the Yinchuan Cenozoic extensional basin. Thick lines with ticks are normal faults; thick lines with solid triangles are thrust or reverse faults, with ticks on the upthrown side and triangles on the downthrown side. Thick lines with arrows are strike-slip faults. Dashed thick lines are inferred faults. Major folds are also shown with standard symbols. Letter A indicates the location of a 3.6 ± 1 km left-lateral offset along the Tianjin Shan fault zone mentioned in the text. Numbers refer to locations of Figures 4, 8, 9, and 10 shown by dotted areas.
Figure 2. (Continued). Bottom part of map. Note duplication of lower part of facing page.
TABLE 1. MAJOR ROCK UNITS OF THE SOUTHERN NINGXIA HUI AUTONOMOUS REGION

<table>
<thead>
<tr>
<th>PALEOZOIC ROCK UNITS</th>
</tr>
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<tbody>
<tr>
<td>Cambrian rocks (Cpb): 1,000+ m thick</td>
</tr>
<tr>
<td>Light green phyllitic, slate and marble, and</td>
</tr>
<tr>
<td>metamorphosed sandstone interbedded with deep</td>
</tr>
<tr>
<td>limestone and siliceous dolomite.</td>
</tr>
<tr>
<td>Form: Amphora sp., Metagryphus sp., Porostromella sp., Pumicius sp., and Pracryptophyllum sp. of Early Middle</td>
</tr>
<tr>
<td>Cambrian age.</td>
</tr>
<tr>
<td>Ordovician rocks (Orm): 500+ m thick</td>
</tr>
<tr>
<td>Dark gray, green limestone and layered clays.</td>
</tr>
<tr>
<td>Form: Gymnosiphon cf. winstein, Bathyperispora kastenholzi, Amphaius sp., Basalidion sp., and Pleuroglaupus sp.</td>
</tr>
<tr>
<td>Anisocrinus sp., and Nummulitidae sp. of Early Ordovician age.</td>
</tr>
<tr>
<td>Devonian red beds (Dbr): 500+ m thick</td>
</tr>
<tr>
<td>Red, quartz-rich sandstone, siltstone, and</td>
</tr>
<tr>
<td>conglomerate.</td>
</tr>
<tr>
<td>Form: Antartic sp., Bathyperispora sp., and</td>
</tr>
<tr>
<td>Actinocrinus sp. of Late Devonian age.</td>
</tr>
<tr>
<td>Carboniferous rocks (Cbc): 1,000+ m thick</td>
</tr>
<tr>
<td>Dark gray to black slate and siltsone</td>
</tr>
<tr>
<td>interbedded with abundant coal beds and gray</td>
</tr>
<tr>
<td>and white sandstone.</td>
</tr>
<tr>
<td>Form: Rhodon Antragnospora, Triphyllites</td>
</tr>
<tr>
<td>colubroides, Sandalhymenocarpus, Stereophyllites</td>
</tr>
<tr>
<td>lunguense, Lepidobrachion kirshunz, Cardiasteris quassembler, Schachneriella cf. normalis, Achlyon sp.</td>
</tr>
<tr>
<td>Theodosia sp., Concomelia sp., Tenuicornis sp.,</td>
</tr>
<tr>
<td>and Spinriphyllum sp. of Early Carboniferous age.</td>
</tr>
<tr>
<td>Permin sandstone (Pm): 50+ m thick</td>
</tr>
<tr>
<td>White and gray sandstone and siltstone.</td>
</tr>
<tr>
<td>Form: some reported.</td>
</tr>
</tbody>
</table>

MESOSOIC ROCK UNITS

Sanajo Formation (Km): Gray, very soft, pebble to cobble conglomerate with angular clasts. Upper part tan, brown, red, and purple. | Clasts consist of Ordovician limestone, granite, and quartzite. Thickness, 20-800 m. | Age: contains Echinaria sp., Early Carboniferous (7). |

Heishanu Formation (Km): Dark red, cross-bedded sandstone interbedded with siltstone in the lower part; purple mudstone and light blue to gray siltstone, shale, and marl in the upper part. | Conformable above Sanajo Formation. Thickness, 550 m. | Age: contains Pagiophyllum sp., Oxnampar sp., Early Carboniferous (7). |

Lianhe Formation (Kb): Light blue and gray mudstone, silt mudstone, mottled red mudstone and sandstone. | Thickness, 700 m. | Conformable above the Heishanu Formation. | Age: contains Pagiophyllum sp., Oxnampar sp., Spermophyllum, Brachyphyllum cf. obscurum, and Androstrachinum sp. of Early Carboniferous age. |

Madian Shan Formation (Kim): Four informal subunits: (1) White to light gray, muddy limestone and marl with siltstone interbedded oolitic limestone (Kishu). (2) Brown to gray mudstone and marl (Kilef). (3) Gray shale (Kilef). (4) Yellow to gray mudstone forms uppermost unit (Kishu). | Total thickness, 400 m. | Age: contains Cephalopora sp., Euophyllum sp., Cephalopora stromata, C. cf. percivalii, C. magna, Zygophycites cf. rugosus, Didemninae conchellus, C. cf. sterni, C. cf. liotae, and Mucrospirifer sp. of Lower Mississippian age. |

Najiske Formation (Kim): Light blue mudstone and marl in lower part; dark red and purple mudstone and siltstone interbedded with light blue to gray mudstone and sandstone in upper part. | Thickness, 650 m. | Age: contains Lyperophyllum sp., Bathyperispora sp., Kungangkakia, Zoobenthos sp., and Vauclisphoria sp. cf. procarniferae of Early Carboniferous age. |

CENOZOIC ROCK UNITS

Silurian Formation (Ox): 60-1,000 m thick | Haiyuan and Liupan Shan area: 60-1,000 m of red conglomerate with rounded clasts of reworked rock types and red, quartz-rich sandstone. | Age: contains Lyperophyllum sp., Bathyperispora sp., Kungangkakia, Zoobenthos sp., and Vauclisphoria sp. cf. procarniferae of Early Carboniferous age. |

Xiquan Formation: (Or): 60-1,000 m thick | Haiyuan and Liupan Shan area: 60-1350 m of red conglomerate with rounded clasts of reworked rock types and red, quartz-rich sandstone. | Age: contains Lyperophyllum sp., Bathyperispora sp., Kungangkakia, Zoobenthos sp., and Vauclisphoria sp. cf. procarniferae of Early Carboniferous age. |

Zhang and Others

STRUCTURE OF THE NINGXIA REGION

We have mapped in detail two large areas within the southern Ningxia region: one along the Haiyuan fault zone (Burchfiel and others, in press) and the second in the Liupan Shan area (Zhang and others, in press). In addition, we have mapped four small areas along the Tianjin Shan–Mibao Shan fault zone (Fig. 2), and we have visited all of the other structural zones in the Ningxia region (Deng and others, 1984). These data serve as a basis for understanding the structural development of these fault zones and their relationship and evolution of the eastern margin of the Tibetan Plateau.

The Haiyuan–Liupan Shan Fault Zone

The Haiyuan fault zone is located in southern Ningxia along the northern foot of the Nanhua Shan and Xihua Shan (Fig. 2). The strike of the fault zone is generally N60°–65°W. Slip on this fault is mainly left-lateral (Deng and others, 1984; Burchfiel and others, in press). The Liupan Shan area lies at the eastern end of the Haiyuan fault zone, where the tectonics is dominated by crustal shortening (Zhang and others, in press). The left-slip on the Haiyuan fault has probably been transferred into crustal shortening in the Liupan Shan, Madong Shan, and Xiaoguan Shan (Figs. 2; Burchfiel and others, 1989).

The oldest Cenozoic structures in the Haiyuan area consist of folds and thrust faults that generally strike N30°–45°W and involve mostly pre-Quaternary rocks. These structures are characterized by brittle thrust faults in metamorphic basement rocks and folds in the overlying sedimentary cover. Because Pliocene rocks are involved in the folds and thrust faults, but Quaternary rocks are not folded, the deformation probably occurred in latest Pliocene time. The left-slip faults, including the N60°W–trending Haiyuan fault, may have begun to develop during the late stage of this folding and thrust faulting, but the major left-lateral displacement on the strike-slip faults that trend west-northwest to west followed the formation of the folds and thrust faults (Burchfiel and others, in press).

Matching offset geological units, unconformities, and structures on both sides of the fault yields a total left-lateral displacement along the Haiyuan fault zone between 10.5 km and 15.5 km (Burchfiel and others, in press). If left-slip faulting began near the end of Pliocene time or in Quaternary time, the average slip rate over Quaternary time is between 5 and 10 mm/yr (Burchfiel and others, in press). The Holocene slip rate, determined by dating stream offsets, is 8 ± 2 mm/yr and is consistent with the average Quaternary slip rate (Zhang and others, 1988a).

The Haiyuan fault zone ends eastward, and its displacement is taken up by slip on the Xiaokou fault, Liupan Shan thrust fault, and Xiaoguan Shan thrust fault, and by folds in the Madong Shan (Zhang and others, in press). The earliest Cenozoic structures in the Liupan Shan area are thrust faults and folds in the Liupan Shan and Yueliang Shan. The youngest rocks involved in the folds and thrust faults are a Pliocene tan conglomerate probably equivalent to the Pliocene Ganhegou Formation (Table 1). Quaternary rocks unconformably overlie these structures. The orientation of shortening during this phase was N50°–60°E, and the amount of shortening was about 1 km. The shortening in the Liupan Shan and Yueliang Shan was contemporaneous with the early folds and thrust faults in the Haiyuan area (see Burchfiel and others, in press; Zhang and others, in press).

Following the formation of these structures, left slip on the N60°W–trending Haiyuan fault zone began, and it changed the kinematic evolution of the Liupan Shan area. The geometry and timing relationships
indicate that the structures in the two areas were related, and left slip on
the Haiyuan fault zone was transferred into shortening by the folding and
thrust faulting in the Liupan Shan area (Zhang and others, in press).
Stratigraphic relationships show that shortening in the Madong Shan fol-
lowed the development of the earliest Cenozoic structures in the Liupan
Shan area, and it was probably contemporaneous with the left slip on the
Haiyuan fault zone. The average amount of shortening across the Madong
Shan was 5.7 ± 0.7 km. Most of the shortening in the Liupan Shan and
Xiaoguan Shan was contemporaneous with the folding in the Madong
Shan. The magnitude of horizontal shortening across the Liupan Shan and
Xiaoguan Shan thrust faults was 6.8 to 7.8 km and 5.7 to 6.9 km, respec-
tively, in the direction parallel to the Haiyuan fault (Zhang and others, in
press).

Since late Pleistocene time, left slip on the Haiyuan fault has been
taken up by the slip on the Xiaokou fault (Fig. 2). As a result, the
deformation in the Madong Shan and Xiaoguan Shan either has ceased or
has proceeded at a very slow rate, and thrust faulting in the Liupan Shan
has continued with a left-slip component (Zhang and others, in press). The
1- to 1.5-km left slip along the Xiaokou fault probably requires that
shortening on the Liupan Shan thrust fault is 1–2 km more than that in the
Madong Shan region (Fig. 2). Thus, the total shortening, parallel to the
Haiyuan fault, during these three phases of deformation in the Liupan
Shan, Madong Shan, and Xiaoguan Shan areas, is 12.4–16.7 km; this total
is comparable to the 10.5–15.5 km of left slip on the Haiyuan fault zone.

The structures in the Liupan Shan area indicate a thin-skinned style
of deformation (Zhang and others, in press; Burchfiel and others, 1989).

The average depth to the décollement is about 4.5 ± 0.7 km, which
suggests that the décollement is well below the Cretaceous sedimentary
rocks that are exposed in the core of the folds and along the thrust faults.
This thin-skinned geometry of structures probably can be extended to
include the other zones of folds and thrust faults in the Ningxia region
(Burchfiel and others, 1989).

The Tianjin Shan–Mibo Shan Reverse Fault and Fold Zone

About 40–50 km north and northeast of the Haiyuan fault zone, lies
the Tianjin Shan–Mibo Shan arcuate zone of folds and reverse faults
(Fig. 2). The area between these two zones is covered by almost horizontal
or gently warped Cenozoic continental sedimentary rocks that form a
broad syncline or structural basin. Tectonic activity within this area is
generally mild in comparison with that in the surrounding structural zones,
and most of the deformation has occurred within the arcuate mountain
ranges, where folds and thrust or reverse faults are well developed. We
mapped several segments along the Tianjin Shan and Mibo Shan fold and
thrust zone (Fig. 2), where late Cenozoic deformation is similar to that of
the Haiyuan and Liupan Shan zone.

Hong Gou Liang. In the western part of Tianjin Shan (Fig. 2), the
structure is dominated by east-west– or northwest-trending thrust or re-
verse faults. Paleozoic formations have been thrust over one another and
over Tertiary red beds. Near Hong Gou Liang, four or five thrust faults are
present (Fig. 4).

Figure 3. Regional distribution of the Tertiary red beds (Oligocene to Pliocene) in the northeastern part of the Tibetan Plateau, China. Compiled from geologic maps of that area.
The southernmost fault strand is a thrust fault that dips about 45°–65° to the southwest. The hanging wall of this thrust fault consists of Cambrian light green metamorphosed phyllite, sandstone, and slate with some interbeds of marble, cherty limestone, and siliceous dolomite that have been thrust on dark gray Ordovician cherty limestone. This fault appears to be one of the major strands in the Tianjin Shan fault zone. At the west end of our map, the thrust fault places the Cambrian rocks above Carboniferous rocks. Farther west, it trends almost east-west, and the Cambrian phyllites have been thrust directly over Tertiary red beds (Fig. 2).

The next fault to the north at Hong Gou Liang crops out as a south-dipping high-angle (about 70°) reverse fault along which the Ordovician limestone is faulted against Devonian red beds (Fig. 4). About 20 m to the north, there is another southwest-dipping, high-angle, reverse fault along which Devonian red beds in the hanging wall are juxtaposed against Carboniferous black shale and siltstone in the footwall in the northwest and against Cambrian phyllite in the southeast. The displacements on this fault and on the one 20 m to the south are small, and both faults are cut at both ends by the large thrust fault south of them (Fig. 4).

To the north, Carboniferous rocks have been thrust over Permian sandstone and shale. To the east and west along the same fault, the Carboniferous rocks are thrust over Tertiary red beds (Fig. 4). The Tertiary red beds consist of Oligocene red mudstone and siltstone with gypsum layers and belong to the Qinshuiyin Formation (Table 1). They unconformably overlie the Permian rocks; in some places, however, there are minor faults present at the contact between them. Farther to the north, both the Tertiary red beds and Permian rocks are covered by loess and Quaternary alluvium. We infer the presence of another reverse or thrust fault, which lies underneath the cover at the front of the Tianjin Shan, because west of Hong Gou Liang the Tertiary red beds dip to the south at an angle of more than 80°.

Several stream channels appear to be offset across the fault that thrusts the Carboniferous rocks over Tertiary red beds and Permian sandstone. At one place near Hong Gou Liang, a channel about 5 to 6 m wide has been offset about 30 m left-laterally. Two adjacent small streams are both offset by 6 ± 2 m (Figs. 5 and 6), and the fault surface is exposed at the stream offset. Along this part of the fault, black Carboniferous rocks crop out on the south side of the fault, and red Tertiary rocks crop out on the northern side. Several ridges are also offset, but they have irregular morphology, and the amount of offset cannot be measured accurately.

West of the area that we mapped, there is an offset within the Cambrian rocks recently studied by two of us (Zhang Weiqi and Jiao Decheng). The unconformity between the Cambrian rocks and the Tertiary red beds has been offset left-laterally 3.6 ± 1 km (see point A in Fig. 2). Another series of small stream channels in this area has been offset left-laterally by 4 to 6 m.

About 2–3 km southeast of Hong Gou Liang, the major thrust fault splays into several strands. All of the faults dip about 70° to 80° to the

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Figure 4. Geologic map and cross section of Hong Gou Liang area along the Tianjin Shan (see Fig. 2 for location). Ėph, Cambrian phyllite; φlm, Ordovician limestone; Drb, Devonian red beds; Cbs, Carboniferous black shales and siltstone; Pss, Permian sandstone; Orb, Eocene or Oligocene red conglomerate (Silouzi Formation); Ors, Oligocene red beds (Qinshuiyin Formation). The thick lines are south-dipping thrust and reverse faults. Inferred faults are dashed.
The dips of Paleozoic rocks between these faults are also very steep. Along the foot of the mountains, Tertiary red beds unconformably overlie Devonian red beds (Fig. 4 and section A–A'). Low hills north of the main mountain front (Fig. 7) are underlain by Tertiary red beds and unconformably overlain by loess. Within the Tertiary red beds, there is a local low-angle unconformity between the red Oligocene conglomerate (Sikouzi Formation) and the Oligocene red mudstone (Qinghuaixian Formation). The Tertiary red beds are folded into a syncline (Fig. 4). Near the northern edge of these hills, the Tertiary red beds are tilted and dip southward toward the mountains, with steeper dips toward the north. This suggests that there may be a thrust fault or blind thrust underneath the low hills of Tertiary rocks. The modern alluvial fans that spread northward south of the low hills are deflected and end against the northernmost ridge of Tertiary rocks, indicating the very young age of the folding and faulting (Fig. 7).

In the Hong Gou Liang area there thus appears to be ~3 km of left slip on the east-west segment of the faults, and a comparable amount of shortening on the northwest-southeast segment.

Qinggeda. About 20 km southeast of Hong Gou Liang, near Qinggeda, the trends of both the mountain front and the structures are N30°–40°W (Figs. 2 and 8). The high mountains 3 km west of Qinggeda consist mainly of thick, dark gray Ordovician limestone (Ningxia Geol. Bureau, 1976). Tertiary red conglomerate, probably equivalent to the Sikouzi Formation (Table 1), unconformably overlies the Ordovician limestone (Fig. 8). A basal conglomerate, which contains angular boulders of dark gray limestone from the underlying rocks, is present near the contact. Farther from the contact, ~50 m above it, most of the cobbles and pebbles within the conglomerate are Devonian red sandstone and siltstone.

Near Qinggeda, a N45°W–trending, high-angle fault dips steeply to the east. Tertiary red conglomerate (Sikouzi Formation) in its foothills near the fault dips steeply to the west and forms a foothill syncline (Fig. 8, section A–A'). The geometry of the syncline and the fault suggests that the eastern side of the fault moved up, and therefore the fault is an east-dipping reverse fault, antithetic to most structures in this area. The east side of the fault consists of Ordovician to Carboniferous rocks that strike approximately east-west to west-northwest and are repeated several times. The lack of an obvious topographic expression along this fault implies that the displacement on it is less than that for the main range bounding fault to the west. Neither fault seems to be active.

The area east of Qinggeda is mostly covered by loess and Quaternary alluvial fans, but ~5 km northeast of Qinggeda, Tertiary conglomerate and Devonian red beds crop out (Fig. 8). Southwest of the Devonian red beds, Tertiary tan conglomerate, mapped as the Sikouzi Formation, dips to the west, but the relationship between the two formations is unknown because of Quaternary loess cover. The Devonian rocks have been folded; a syncline and an overturned anticline are present in the Devonian outcrop (Fig.
Figure 8. Geological map and cross sections near Qinggeda along the Tianjin Shan-Mibo Shan fault zone. Ølm, Ordovician limestone; Drb, Devonian red beds; Cbs, Carboniferous black shale and siltstone; Ors, Eocene or Oligocene red conglomerate (Sikouzi Formation); Orb, Oligocene red beds (Qinshuiyin Formation). The thick lines are faults; dashed thick lines are inferred faults.
tern is very different from that in the Qinggeda area (Fig. 9). About 2 km northwest of Xiao Hong Gou, Quaternary alluvium directly overlies Carboniferous rocks. At one place, it appears that Carboniferous rocks have been thrust over Quaternary sediments, but in most places, the fault is not clear. About 0.5 to 1 km northwest of Xiao Hong Gou, red beds of Oligocene, Miocene, and Pliocene age depositionally overlie the Carboniferous rocks, and the Quaternary sediments unconformably overlie all older rock units. The Tertiary rocks have been folded into a syncline and an overturned anticline within the Miocene red mudstone of the Honglugu Formation (Fig. 9; Table 1).

South of Xiao Hong Gou, the Carboniferous black shale and siltstone are unconformably overlain by Tertiary rocks both to the north and the south. Along the southern side, Permian sandstone and siltstone are faulted against the Carboniferous rocks (Fig. 9). A sequence of thick-bedded red conglomerate (Ocg in Fig. 9), which consists of cobbles mostly from Devonian red beds, unconformably overlies the Permian sandstone. The age of this conglomerate is unknown. This conglomerate has been cut by a west-dipping, high-angle fault and is juxtaposed against a very thick (at least several hundred meters) sequence of Tertiary red conglomerate that consists of cobbles and pebbles from both Devonian red beds and Permian sandstone. This thick conglomerate is tentatively correlated with the Sikouzi Formation (Table 1). Only in one place 750 m southwest of Xiao Hong Gou does the young Tertiary red conglomerate (Ors) unconformably overlie the older conglomerate (Ocg). The structures within the nearly vertical Carboniferous rocks southeast of Xiao Hong Gou are very complex. The black shales have been folded and sheared, and the over-all structural pattern within them is unknown. Because these rocks are much more intensely deformed than the Cenozoic rocks, the structures are probably pre-Cenozoic in age.

The over-all structure near Xiao Hong Gou is dominated by the frontal anticline, which is probably cored by Carboniferous rocks near Xiao Hong Gou. Beginning 1.5 km southeast of Xiao Hong Gou, only the Tertiary red conglomerate crops out, but the frontal anticline is clearly present, and its axis is parallel to the mountain front (Fig. 9). Its eastern limb generally dips more steeply than its western limb. This frontal anticline can be traced all the way to the south end of the Tianjin Shan. We infer that it is formed above a blind thrust fault at depth.

The late Cenozoic rocks 300 m south of Xiao Hong Gou in a profile well exposed along the south side of the river show well the progressive development of the structure (Fig. 10). Oligocene and Miocene red beds (Ors-Orm) dip steeply northeast, and all are overlain by tan conglomerate of probable Pliocene age (Pcg). The Pliocene conglomerate is unconformably overlain by more gently north-dipping tan conglomerate and sandstone (Qoal) that might be late Pliocene or early Quaternary in age.

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8). East of the Devonian outcrop, there is a valley covered by Quaternary sediment, and Tertiary conglomerate crops out east of the valley. The conglomerate dips 62° to the northeast at the eastern front of the outcrop, but about 20 m to the west, it dips only 15° to the northeast. From these relationships, we infer a thrust fault or blind thrust beneath the easternmost outcrops of the Tertiary conglomerate and probably another thrust fault west of these rocks.

**Xiao Hong Gou.** This area is located only about 4 km southeast of Qinggeda along the same mountain front (Fig. 2), but the structural pat-
(Fig. 11). To the north, light brown conglomerate interbedded with loess rests unconformably on the tan conglomerate, and these two units are folded into a syncline-anticline pair at the range front (Figs. 9, 10, and 11).

Lijiazhuizi and Mibo Shan. Lijiazhuizi is located at the southern end of the Tianjin Shan (Fig. 2). The major structure is a north-trending anticline (Fig. 12) in which Oligocene gypsiferous red beds (Qinshuiyin Formation) strike approximately north-south. At the eastern range front, the red beds dip 30° to 40° east, and in one locality, they become slightly overturned, dipping west at a steep angle (Deng and others, 1984). To the west, they dip west at angles of 40° to 50°, but farther west, the dip of the red beds becomes more gentle to horizontal. South of Lijiazhuizi, the anticline plunges south into the Quaternary loess. We infer that this fold is related to slip on a thrust fault at depth that dips west.

The Mibo Shan is about 4 km south of the end of the Tianjin Shan. These ranges are separated by a northwest-trending syncline filled with Quaternary rocks (Fig. 2). The Mibo Shan consists of two left-stepping en echelon anticlines separated by a syncline (Fig. 2; only the easternmost of the two anticlines is shown in Fig. 12). The anticlines are cored by Oligocene red beds and locally by the Eocene or Oligocene Sikouzi Conglomerate. The folds in the Mibo Shan are arcuate and trend north in their western parts and progressively more northwesterly to the southeast. They form a right-stepping pattern with the structures of the Tianjin Shan (Figs. 2 and 12).

We mapped the westernmost part of the eastern anticline in the Mibo Shan where it is cored by the gypsum-bearing Oligocene Qinshuiyin Formation (Figs. 12 and 13). Along the eastern foot of Mibo Shan, the Oligocene red beds dip steeply northeastward beneath the Quaternary loess and alluvium, and no evidence of faulting was found along this side of the Mibo Shan. To the south beyond the mapped area (Fig. 12), the red beds dip more gently toward the south; farther south, the overlying Miocene mudstone (Hongliugou Formation) is only gently warped and is nearly horizontal. The geometry of this anticline suggests that it is cored by a blind thrust ramp that dips west at depth. The anticline generally trends N30°–40°W and plunges moderately west. At its western end, the axial trace curves to the north before plunging beneath Quaternary alluvium and forms a left-stepping offset with the anticlines at Lijiazhuizi 5 km to the north (Fig. 12).

The Yanton Shan Fold and Thrust Fault Zone

The Yanton Shan arcuate thrust fault zone (Fig. 2) lies ~25 km northeast of the Tianjin Shan. Escarpments are clear on the Landsat image along the eastern side of the Yanton Shan. Field investigations show that the Devonian red beds have been thrust eastward over the Tertiary red beds and Quaternary sediments along the northern part of the Yanton Shan fault zone (Ningxia Geol. Bureau, 1976). The trend of this fault is about N40°W. To the south, the trend of the Yanton Shan becomes north-northwest, and the prominent thrust fault becomes a south-plunging anticline cored by Oligocene red beds (Fig. 2). Farther to the south, the range trends approximately north-south, and another anticline that trends north-northwest is present. The geometry of structures in the Yanton Shan is similar to that in the Tianjin Shan and the Mibo Shan (Fig. 2). Where the pre-Cenozoic rocks are exposed, the deformation is dominated by thrust faulting. The trends of thrust faults are about N40°–50°W. The deformation in the Tertiary red beds, however, is dominated by folding; the folds trend north-northwest and then curve to become nearly north-south toward the southeast. These folds also form a right-stepped en echelon pattern.

The Niushou Shan–Daluo Shan Fold and Fault Zone

The Niushou Shan–Daluo Shan structural zone is located northeast of the Yanton Shan (Fig. 2). It bounds two different geological terrains in Ningxia. North of the fault, the Paleozoic stratigraphy is similar to that of the North China block; south of the fault, it is similar to that of the Nanshan fold belt. Unfortunately, the geological history of this fault zone has not been well studied. Currently, it forms the southern boundary of the Yinchuan graben. Several earthquakes of magnitude 4 to 5 M, which have occurred at the southern end of the Yinchuan graben, may have been associated with movement on this fault.

In the Daluo Shan, thrusting on a N20°–30°W–trending, southwest-dipping fault places Paleozoic rocks on Miocene red beds. In the Niushou Shan, there are several thrust faults striking about N50°W and dipping southwest that make up a fault zone bounding the eastern side of the Niushou Shan. These faults carry gray, green, and black slate of Ordovician age over Miocene orange silty mudstone, probably the equivalent of the Hongliugou Formation, and locally the slate is thrust over Quaternary gravel. A reconnaissance study by Liao Yuhua (1986, unpub. data) has shown many subhorizontal slickensides within the fault zone that indicate a left-lateral, strike-slip component. Northeast of the Niushou Shan, Cretaceous rocks have been thrust over Oligocene red beds, and farther northwest, the fault is covered by Quaternary sediments in the Gobi Desert. Because this fault has not been well studied, its Cenozoic and recent kinematic history is poorly known, but the clear lineation on the
Landsat imagery and the horizontal slickensides suggest a large component of active strike-slip movement along this fault coupled with some thrust displacement.

THE YINCHUAN GRABEN AND THE HELAN SHAN HORST IN NORTHERN NINGXIA

North of the Niushou Shan–Daluo Shan fault, the dominant style of deformation includes a large component of normal faulting with a comparable, if not larger, right-lateral strike-slip component. The Helan Shan horst and Yinchuan graben are the major structural units that formed within the region (Figs. 1 and 2).

The Helan Shan trend north-northeast and consist of rocks that range from Sinian (pre-Cambrian) to middle Mesozoic in age. The major deformational phase that formed the pre-Cenozoic structures of the Helan Shan occurred in Jurassic time (Wang and others, 1986; Liao Yuhua, 1986, unpub. data). At present, the Helan Shan is bounded on both sides by high-angle normal faults. The normal faults on the western side have not been studied. On the eastern side, the Cenozoic and Quaternary rocks are displaced by normal faults (the East Helan Shan faults) that dip steeply eastward at the foot of the Helan Shan (Zhang and others, 1986). These same faults form the western boundary of the Yinchuan graben (Fig. 2).

The Yinchuan basin is a typical graben that is bounded on both sides by normal faults that dip into the basin (Fig. 2). It trends 160 km north-northeast and is 50 to 55 km wide. The graben is bounded on the west by the East Helan Shan fault zone, which consists of several north-northeast–trending normal faults. One of the major strands along the west side of the graben at the eastern foot of the Helan Shan clearly forms a prominent range-front scarp (Fig. 14). The alluvial fans are reported to have been cut by this fault. At one place, a small fan has been down-dropped to the east with about 50 m of apparent normal separation (Liao and others, 1982). To the north, the continuation of this fault has offset a segment of the “Great Wall” that was built about 4,000 yr ago with about 1.5 ± 0.5 m of right-lateral offset and 0.9 ± 0.2 m of vertical offset (He, 1982; Wang and others, 1982; Liao and others, 1982; Deng and others, 1984; Zhang and others, 1986). About 3 to 4 km east of the Helan Shan, another fault scarp 16.5 km long is present west of Yinchuan. The scarp faces southeast and trends generally northeast (Fig. 14). The vertical normal separation of the piedmont slope ranges from 2 to 4 m, and horizontal offset has been reported.

The major fault zone that bounds the eastern side of the graben is referred to as the “Huanghe fault.” Although there is no surface outcrop to locate this fault, geophysical studies have demonstrated its existence (Liao Yuhua, 1986, unpub. data; Zhang and others, 1986).

Geophysical studies and a borehole (more than 2,000 m deep) have indicated that the basement of Yinchuan graben is formed mainly by Ordovician limestone, and the graben fill consists of 1,000–1,600 m of
Quaternary sedimentary rocks and a total Cenozoic sedimentary accumulation reported to be more than 6,000 m thick (Liao Yuhua, 1986, unpub. data; Zhang and others, 1986). The Tertiary red beds within the graben can be correlated lithologically with those in southern Ningxia, suggesting that the floor of the Yinchuan graben was part of the large basin that was formed in Tertiary time in north-central China before the graben formed (Fig. 3). The average crestal elevation of the Helan Shan ranges from 2,000 to 3,000 m (maximum 3,557 m) above sea level. The surface of the Yinchuan graben is about 1,000 m above sea level. The total minimum vertical separation of Paleozoic rocks may therefore be more than 7,000 m to 8,000 m on opposite sides of the East Helan Shan fault zone.

Exactly when displacement on the Helan Shan faults began is not known. Tertiary gypsiferous red beds (possibly Oligocene in age and equivalent to the Qinshuixiu Formation) are preserved within the southern part of the Helan Shan (Fig. 15), which suggests that the displacement began after deposition of the Oligocene gypsiferous red beds. But inadequate knowledge of Tertiary deposition in the Helan Shan area makes it impossible to reasonably understand the history of the East Helan Shan fault. Using only the thickness of Quaternary rocks, the minimum vertical rate (in about 2 m.y.) on the East Helan Shan fault would be 0.5 to 0.8 mm/yr.

DISCUSSION

The major deformatonal phases that occurred in the Haiyuan and Liupan Shan area began after deposition of Pliocene conglomerate (Ganhiegou Formation) and before deposition of Quaternary deposits (Burchfield and others, in press; Zhang and others, in press). In the Tianjin Shan and Mibo Shan, the youngest rocks involved in the folds and thrust faults are also the Pliocene tan conglomerate. Near Xiao Hong Gou, the Quaternary conglomerate is involved in the folds, but it also unconformably overlies the Tertiary, probably Pliocene, conglomerate. This conglomerate could be derived from relief formed by the earliest part of the deformation that was later responsible for its deformation. The Pliocene tan conglomerate is not exposed in the Yantong Shan, Niushou Shan, and Daluo Shan, but we still infer that deformation began after deposition of Pliocene conglomerate in this area because there is no unconformity between any of the other Tertiary formations, and the youngest formation involved in each of the areas is the Miocene Hongliugou Formation. The onset of extension in the Yinchuan graben is uncertain, but we think that the deformation may also have begun after the formation of the Pliocene conglomerate. Deformation throughout the Ningxia region thus appears to have begun in Pliocene time, possibly late Pliocene time. The presence of the thick sequence of conformable fine-grained sediments that define the large Tertiary basin in north-central China (Fig. 3) suggests that deformation in most of the northeastern part of the Tibetan Plateau also did not begin until Pliocene time.

The Cenozoic structures in the Haiyuan and Liupan Shan area suggest a thin-skinned deformation (see Zhang and others, in press; Burchfield and others, 1989). The décollement zone beneath these structures cuts through structurally complex pre-Cenozoic rocks and structures in this region. If this thin-skinned geometry can be extended to include the folds and thrust faults in southern Ningxia (Fig. 16), much of the late Cenozoic structural development would have a style similar to that of the Haiyuan and Liupan Shan area, where the earliest phase of deformation was southwest to northeast convergence and was followed by late left slip along major fault zones. The displacement on the left-slip fault zone was
transferred to a north- or northwest-trending zone of shortening in the Liupan Shan, Xiaoguo Shan, and Madong Shan (Fig. 16).

The geometry of the Tianjin Shan–Mibo Shan fault zone is similar to that of the Haiyuan and Liupan Shan fault zone. Its western segment trends west-northwest to east-west. Pre-Cenozoic rocks exposed in the hanging wall of the western part of this zone contain structures that are dominated by thrust and reverse faults. The hanging wall consists mostly of Tertiary red beds, and the structures are dominated by frontal ramp anticlines parallel to the range front. Its eastern part trends north-northwest to north-south. The geometry of structures in the eastern segment of the Tianjin Shan–Mibo Shan fault zone is similar to that of structures in the eastern segment of the Yanton Shan, where the deformation is dominated by thrust faulting in pre-Cenozoic rocks and by folding in the Tertiary rocks, and the north-northwest–to north-south–trending folds in the eastern segments form a right-stepped *en echelon* pattern. Recently, a left-lateral displacement of $3.6 \pm 1$ km has been reported west of our mapped area along the Tianjin Shan–Mibo Shan fault zone (see above), but whether this displacement occurred after the thrust faulting and folding or in the early stage of deformation is uncertain. We suggest that the left slip on the fault did follow the early stage of thrust faulting and folding, because of very similar geometry between the Haiyuan–Liupan Shan fault zone and the Tianjin Shan–Mibo Shan fault zone. In one area near Hong Gou Liang, a ridge is offset by both thrust and left-slip displacement. The only difference between these two regions may be that the left-slip faulting on the Haiyuan fault offsets older thrust faults and folds, but along the Tianjin Shan fault, the left-slip faulting occurred on one of the thrust or reverse faults.

Evidence for northeast- and east-vergent shortening is present along the eastern segment of the Tianjin Shan–Mibo Shan fault zone and the northwest-trending Yanton Shan fault zone. We interpret the left-lateral offset along the western Tianjin Shan fault zone as being transferred into shortening in the eastern Tianjin Shan, Mibo Shan, and Yanton Shan. Unfortunately, insufficient mapping in these areas does not allow us to calculate the amount of shortening across them as we did in the Haiyuan–Liupan Shan area (Zhang and others, in press).

The evidence of northeastward thrust faulting is clear along the Niushou Shan and Daluo Shan fault zone. Their prominent lineation on the satellite imagery, along with recent reconnaissance work by Liao Yuhua (1986, unpub. data), suggests that there may be a large component of left-lateral strike slip along this fault. This fault zone bounds the Yinchuan graben on the south. The Quaternary extension and opening of the Yinchuan graben are probably in part related to the evolution of this fault zone.

The amplitude of displacement and topographic relief on the convergent and strike-slip structures in southern Ningxia decreases to the northeast, and the evidence for active faulting also becomes less clear in the same direction, even though the sharpness of the topographic range fronts suggests active deformation. The rate of deformation along these more northerly structural zones may be less than the rate in the Haiyuan and Liupan Shan area to the south. The average Quaternary left-lateral slip rate along the Haiyuan fault is 5–10 mm/yr (Burchfiel and others, in press). The left-lateral displacement along the Tianjin Shan fault appears to be $3.6 \pm 1$ km. Burchfiel and others (in press) suggested that the left slip on the Haiyuan fault began near the end of Pliocene time or the beginning of Pleistocene time (about 1.6 Ma). If we assume that the left slip along the Tianjin Shan fault zone is contemporaneous with that on the Haiyuan fault, the average slip rate would be about 1.5 to 2.7 mm/yr. The amount of offset and rate of slip along the Niushou Shan and Daluo Shan fault zone are unknown, but some evidence suggests a left-lateral, strike-slip component. The topography of the Niushou Shan and Daluo Shan is lower than that of the Liupan Shan, and even lower than that of the Tianjin Shan and Mibo Shan. Thus the rate of slip along the Niushou
Shan–Daluo Shan fault is probably less than that on the Tianjin Shan fault zone.

It appears that all of the ranges in southern Ningxia have been subjected to the same deformation processes: early northeasterly convergence followed by later increasing components of left slip on east-west – to northwest-southeast–trending faults. The left-slip displacement is transferred into crustal shortening on the north-south–trending zones. The rates of deformation, however, can be inferred to be less in the northern ranges than in the southern ranges. The northern ranges have therefore not evolved as fast or as far as those in the Haiyuan and Liupan Shan area over the same period of time. The tectonic evolution in the Haiyuan and Liupan Shan area thus probably foreshadows the future deformation in the northern ranges. If the interpretation presented above is correct, it suggests that the Ningxia region became the northeastern margin of the Tibetan Plateau in Pliocene time and that it is being elevated by the irregular growth of convergent and oblique-slip structures. The plateau may continue to grow toward the northeast, but in an irregular way.

Left slip and shortening within the Ningxia-Hui Autonomous Region accommodates probably less than 20–25 km of east or northeast displacement of crustal fragments of the northern Tibetan Plateau with respect to the area to the northeast. Large-magnitude lateral transfer therefore has not taken place within the Ningxia region studied by us. If such large-scale lateral transfer has occurred, it must be sought farther to the south.

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