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Sliding–thrusting tectonics caused by thermal uplift in the Yunmeng Mountains, Beijing, China*

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Abstract—A ductile shear zone analogous to a normal fault with a low dip-angle occurs on the southeastern flank of the Yunmeng Anticlinorium north of Beijing in Huairou County. The southeast-dipping Shuiyu ductile shear zone is composed of mylonitic granitic gneiss and has an average width of about 1 km. The structures in the area show a symmetrical pattern. This pattern may be generated by a process of sliding and thrusting caused by thermal uplift. An alternative possible model for the area is that for the North American Cordilleran regions.

INTRODUCTION AND GEOLOGICAL SETTING

THE gently-dipping Shuiyu ductile shear zone lies in the area about 70 km north–northeast of the city of Beijing (Figs. 1 and 2). It has attracted the attention of Chinese and foreign geologists since 1981 when it was discovered by Wang (1981, 1985), who considered its internal sense of shear to be analogous to that of a normal fault. Shi & Chen (1984) inferred, on the basis of mineral assemblages, average sizes of subgrains and recrystallized grains, and dislocation densities, that the shear zone developed at a depth of 15 km and a temperature of 450–500°C. The estimates of differential stress on the basis of dislocation densities and average sizes of recrystallized grains range from 76.8 to 186 MPa (Feng *et al.* 1983). The analyses of oxygen isotopes show that the values of $\delta^{18}O$ in granitic rocks from outside the zone to granitic mylonites at its centre increased from 8‰ up to about 12‰, and that the metamorphic temperature of the zone increased from some 320°C near its margin to about 450°C at the centre. The shear zone, therefore, probably formed at a depth of 10–12 km (Shanguan *et al.* 1985).

Although the study of the shear zone has concerned the temperature conditions, confining pressure and differential stress, there is considerable controversy over the sense of shear within it. Shi & Chen (1984) considered that the sense of shear was compatible with thrust faulting. In the same year, however, Feng *et al.* (1983), Zheng & Chang (1985) and Zheng *et al.* (1986) made further studies on the macro- and microstructures of the shear zone and confirmed that the sense of shear resembled that of a low-angle normal fault; that is, higher levels were displaced downwards with respect to deeper levels. Disagreement has existed among foreign visitors as well. I. van der Molen (personal communication 1984), G. A. Davis (personal communication 1985) and B. E. Hobbs (personal communication 1985) have agreed with a normal shear zone geometry, whereas J. G. Ramsay and H. J. Zwart (personal communication 1983) thought that the shear zone was related to thrust faulting. A small-scale nappe that emplaces Cambrian sedimentary rocks, predominantly carbonates, on top of Jurassic volcaniclastic rocks (Figs. 3 and 4) was recognized in 1985 (Zheng *et al.* 1986) on the southeastern side of the shear zone.

The aim of this paper is to describe the shear zone and its relations to other structures, including the nappe, and to propose how the region has evolved.

The region (Fig. 2) involved is considered to be part of the Miyun uplift and the Yunmeng Anticlinorium on the Sino-Korean Craton. Its stratigraphy is similar to that of the rest of the craton but without the Ordovician, Carboniferous, Permian, Triassic and Cretaceous systems. The Yunmeng Anticlinorium has a NE–SW trend with a

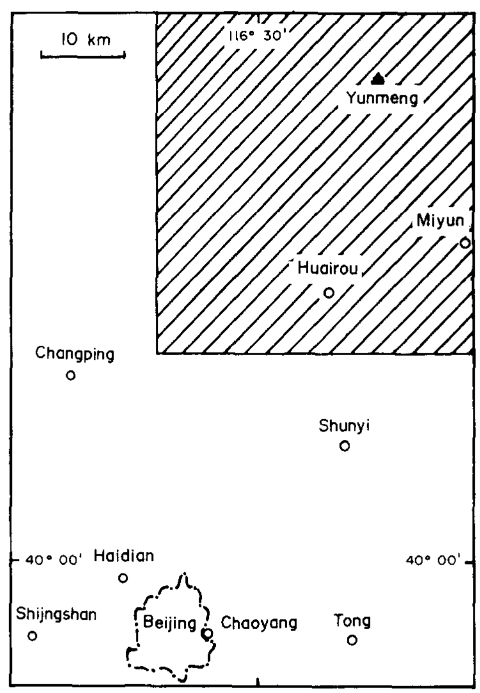

Fig. 1. Location map for the area involved (shaded area).

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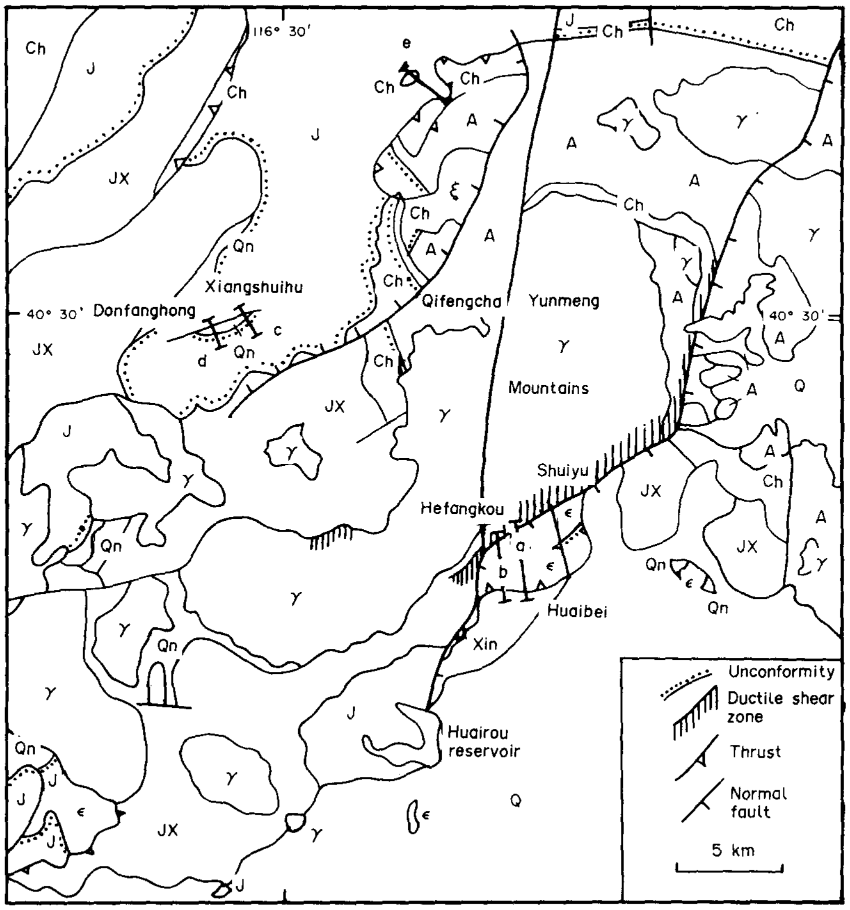

Fig. 2. Simplified geological map of the Yunmeng Anticlinorium. Q—Quaternary; J—Middle–Upper Jurassic volcanic and volcaniclastic rocks; ε—Cambrian; Qn—Qinbaikou system (lower part of Upper Proterozoic); JX—Jixian system (upper part of Middle Proterozoic); Ch—Changcheng system (lower part of Middle Proterozoic); A—Archean(?) or Lower Proterozoic schists; γ—Mesozoic granitic complex; ξ—syenite. a—Location of Fig. 4(a); b—Fig. 4(b); c—Fig. 14(a); d—Fig. 14(b); e—Fig. 15.

width of over 10 km and a length of approximately 40 km. Its core consists of a Cretaceous (106–114 Ma) peraluminous two-mica granitic pluton and an Archaean or Lower Proterozoic metamorphic complex. The inner sides of its flanks are mainly made up of Middle Proterozoic metasedimentary rocks, while the outer sides include Upper Proterozoic and Cambrian strata, and Middle Jurassic volcanic and volcaniclastic rocks. The Cretaceous granitic rocks have been overprinted by a ductile shear zone, the Shuiyu ductile shear zone, and are now best described as mylonitic granites. The ductile shear zone lies along the southeastern margin of the pluton on the SE flank of the anticlinorium. A high-angle normal fault, the Hefangkou Fault, dips SE on the SE flank, and another large high-angle normal fault, the Qifengcha Fault, dips NW on the NW flank. The rocks in the core of the anticlinorium have typically experienced penetrative ductile deformation (foliation and lineation), which is a result of deformation at deeper crustal levels. The rocks outside the Hefangkou and Qifengcha Faults are characteristically different. They have experienced brittle failure without any penetrative structures. This suggests that both high-angle faults played a significant role during the tectonic evolution of the region.

MOVEMENT SENSE OF THE SHEAR ZONE

The Shuiyu ductile shear zone strikes N50°–60°E over 12 km and has an average width of about 1 km. It dips to the southeast at an angle of 30–35° (Fig. 4). The zone is composed of mylonitic granite and granitic mylonite. Feldspar blasts in the rocks show brittle fractures, whereas quartz grains in the matrix show strongly ductile deformation. The ductile shear zone is truncated by the high-angle Hefangkou normal fault, which is probably connected with a fault situated in the western suburbs of Beijing 100 km to the south–southwest. The younger fault has 20–30 m of gouge zone and dips SE at an angle of about 60°. Drilling between Shijingshan and Beijing (Fig. 1) has confirmed that this fault has cut off the Cretaceous and Neogene strata with over 800 m of stratigraphic omission.

The ductile shear zone is considered here to have a normal sense of displacement; that is, higher structural levels down (SE) with respect to lower. Evidence for this conclusion is as follows.

(1) Two sets of foliations, *S* and *C*, can be recognized in the rocks within the zone and *S*–*C* fabrics are well developed in the mylonitic rocks. The *C*-foliation is parallel to the boundary of the shear zone. The *S*-

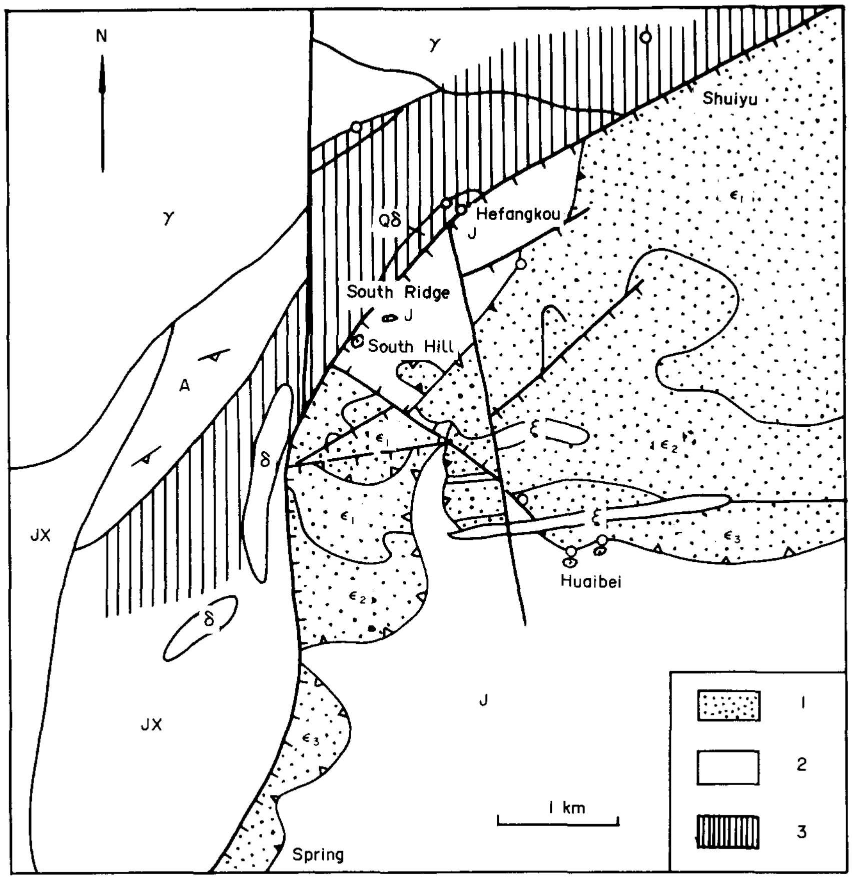

Fig. 3. Simplified geological map of Hefangkou area with the positions of main outcrops referred to in the text. Legend: 1—allochthon; 2—autochthon; 3—low-angle normal ductile shear zone; J—Middle–Upper Jurassic volcaniclastic rocks; ε—Cambrian; Qn—Qingbaikou system; JX—Jixian system; γ—Mesozoic granitic complex; ξ—syenite; δ—diorite.

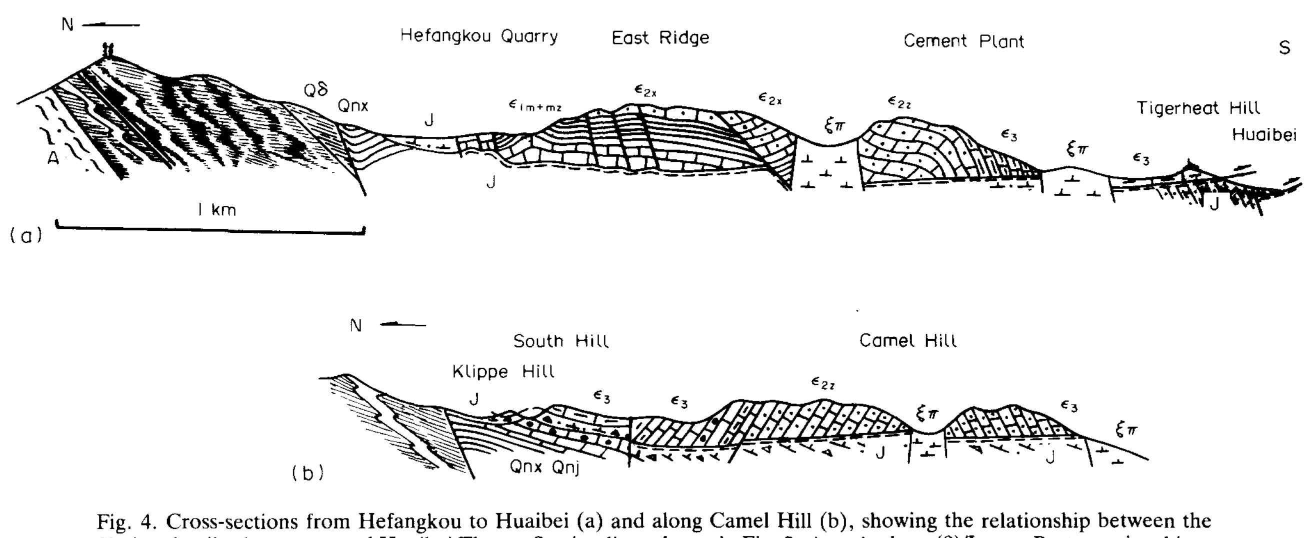

Fig. 4. Cross-sections from Hefangkou to Huaibei (a) and along Camel Hill (b), showing the relationship between the Shuiyu ductile shear zone and Huaibei Thrust. Section lines shown in Fig. 2. Ar—Archean(?)/Lower Proterozoic schists; Qnj—Qinbaikou system marl; Qnx—Qinbaikou system shale; ε1f—Lower Cambrian limestone; ε_{1m+mz}—Lower Cambrian red argillite; ε_{2x}—Middle Cambrian oolitic limestone; ε_{2z}—Middle Cambrian oolitic limestone and argillite; ε_3—Upper Cambrian limestone with banded argillite and Wormkalk limestone; J2t—Middle Jurassic volcaniclastic rocks; $\xi\pi$—porphyritic syenite; Qδ—mylonitic quartz diorite.

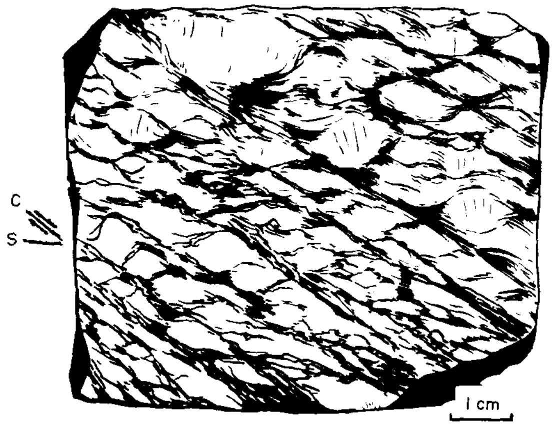

Fig. 5. A polished XZ-section with C- and S-foliation of mylonitized Cretaceous granitic rocks collected in the Shuiyu shuiyu shear zone, indicating normal shear sense. Both surfaces, S and C, dip southeastward in the field, but C has the steeper dip. Fabric relationships clearly indicate down-to-the-southeast movement of higher domains with respect to lower.

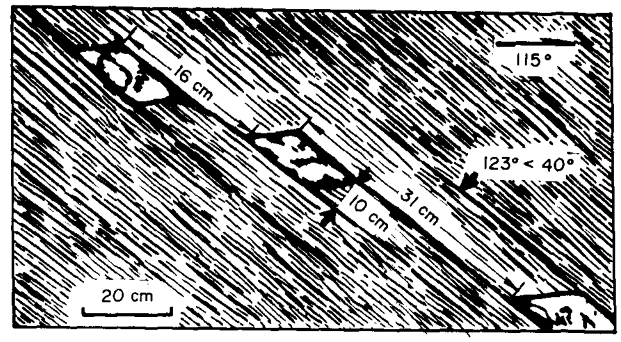

Fig. 7. A displaced felsic vein in mylonitic granite, indicating normal shear sense.

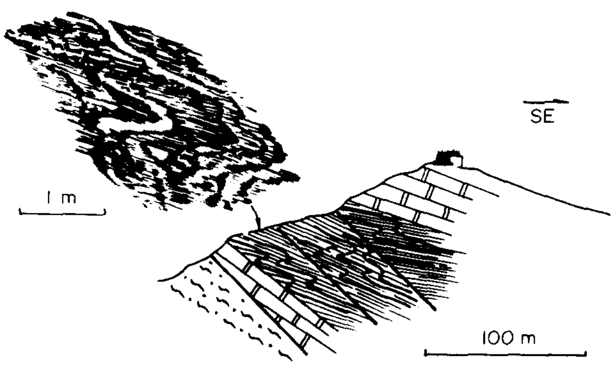

Fig. 8. The fold and foliation vergence in dolomitic limestone deformed by normal shearing.

foliation is defined by asymmetric feldspar porphyroclasts or augen and ribbon quartz grains around them. The relationship of the C- and S-foliations indicates a normal sense of shear, for the former dips more steeply SE (Passchier 1983, Simpson & Schmidt 1983) than the latter (Figs. 5 and 6). A prominent down-dip mylonitic lineation is present in the mylonitic rocks and is defined by elongate quartz grains and by trains of broken feldspar crystals. This SE-plunging lineation is interpreted as a stretching lineation within the shear zone.

(2) Asymmetric feldspar augen are commonly observed in the mylonitic rocks. The foliation surfaces are asymmetrically distributed around the augen, which have tails of finer grained material of the same composition, and can be used to determine shear sense (Simpson & Schmidt 1983) (Figs. 5 and 6).

(3) Domino structures, defined by displaced fragments of broken feldspar grains in the ductile matrix, occur commonly in the mylonitic rocks. The shear sense along the microfractures oriented oblique to the C-foliation is commonly opposite to the overall shear sense in the rocks (Etchecopar 1977). In some cases, however, opposite senses (sinistral and dextral) of displacement along microfractures coexist in the same thin sections of rock (Fig. 6b), thus limiting the usefulness of the shear sense along the microfractures as an overall shear sense indicator.

(4) The sense of displacement of veins along the C-foliation confirms the normal shear sense (Fig. 7).

(5) The direction of fold vergence (Bell 1981) in the shear zone is SE, the dip direction of shear zone (Figs. 8 and 17).

(6) The c-axes of quartz grains in the mylonitic gneiss are diffusely distributed within a single girdle which is oblique to the S-foliation. The shear sense can be inferred by the position of the pole to S-foliation relative to the c-axis girdle as shown in Fig. 9 (Lister & Hobbs 1980, Passchier 1983, Simpson & Schmidt 1983).

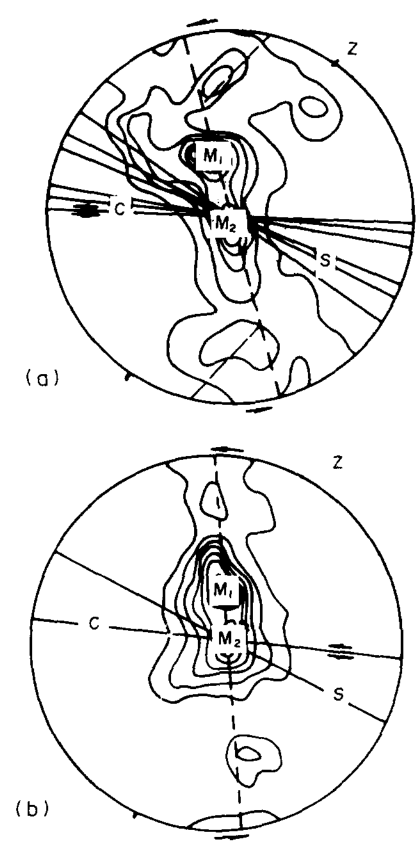

Fig. 9. Quartz c-axis diagrams of granitic mylonites in the Shuiyu ductile shear zone, indicating normal shear sense. Upper-hemisphere equal-area projections, 250 measurements, 2–4–6–8–10–12% contours.

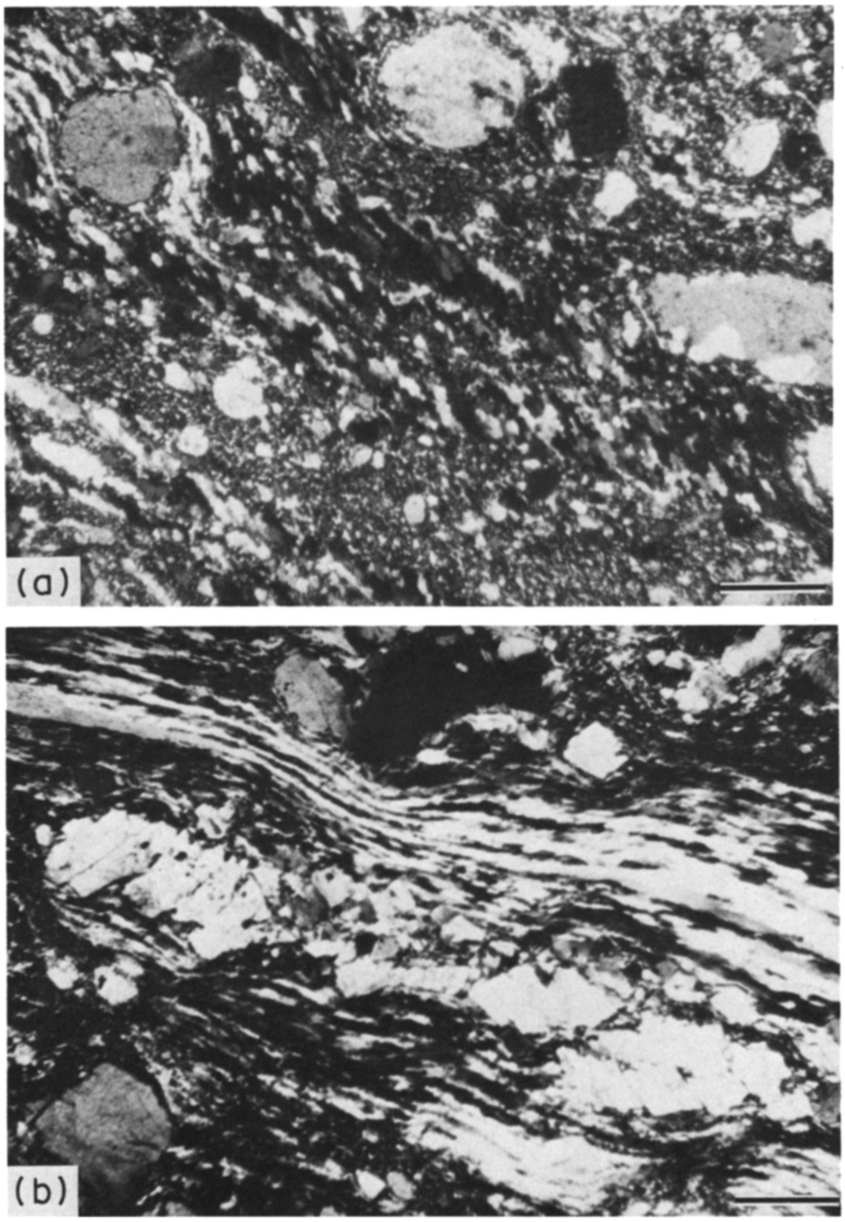

Fig. 6. Microscopic aspect of asymmetric feldspar augen and the *S*- and *C*-surfaces indicating normal shear sense. (a) Photomicrograph of optical thin section. Scale bar = 0.3 mm, crossed nicols. The top-left corner faces southeast. (b) There are two senses of shearing along microfractures oriented oblique to the *C*-surfaces in the augen. The right-hand side is to the southeast.

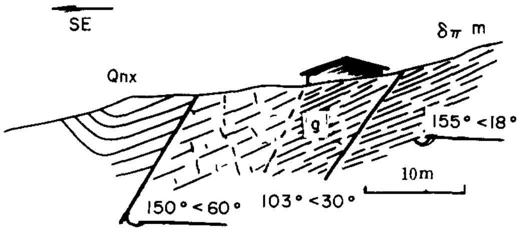

Fig. 10. Sketch profile of the Hefangkou Fault showing a 'drag fold' in the hangingwall, and the ribbon surfaces in fault gouge, with a dip-angle less than that of the fault. δπm—diorite mylonite; g—gouge. Dip and dip direction of foliations shown on figure.

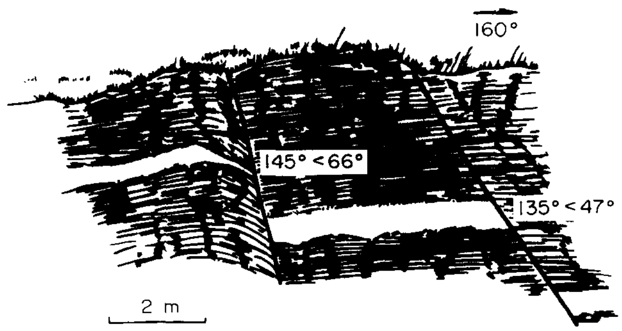

Fig. 11. Small-scale normal faults in the footwall close to the Hefangkou Fault. Slickenside striae on the faults are parallel to the fault dip.

The younger fault, the Hefangkou Fault, is also believed to be a normal fault. The reasons for this are as follows.

(1) The rocks of the footwall possess characteristics of deeper crustal levels, while the rocks of the hangingwall are of higher levels.

(2) The rocks of the footwall are older than those of the hangingwall.

(3) The colourful ribbons in the fault gouge have a lower dip-angle than that of the fault (Fig. 10). These ribbons are interpreted as a foliation analogous to *S*-foliation in mylonitic rocks.

(4) The small faults which are parallel to and close to the major fault are normal faults on the basis of observable offset of marker units (Fig. 11).

HUAIBEI–HEFANGKOU THRUST

A thrust fault crops out between Hefangkou and Huaibei village, extending over about 3 km from north to south, which represents the minimum displacement. It extends SW to Spring and probably to Xin village (Figs. 2 and 3). It dips to the northwest with a dip-angle of 20–25°. The hangingwall contains sedimentary rocks of the Cambrian System and the footwall consists mainly of Jurassic volcanic and volcaniclastic rocks.

The main outcrops of the thrust fault are the South Ridge Klippe, the South Hill Half Klippe, the Spring Thrust (Fig. 3), the Huaibei Thrust, the Cement Plant Microwindow, the Hefangkou Quarry Thrust (Fig. 4a), the Camel Hill Thrust and Klippe Hill (Fig. 4b). These

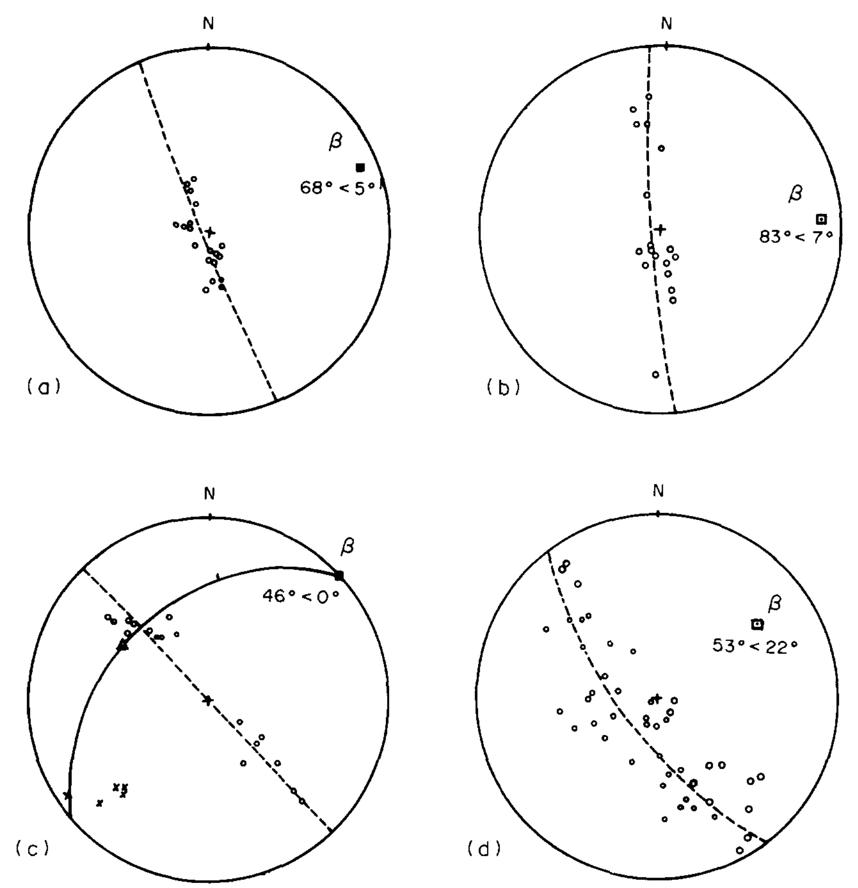

Fig. 12. *S*-pole (or Pi) diagrams of folds in the Huaibei Nappe showing that the fold axes plunge gently NE. Plunge and plunge direction of axes shown on figure.

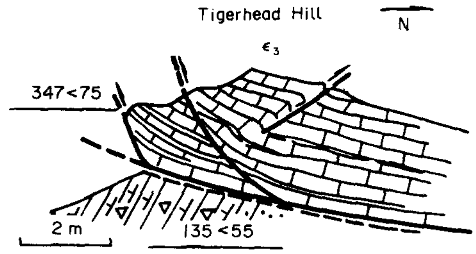

Fig. 13. Small-scale imbricates, an antithetic back thrust and the floor thrust as exposed at Tigerhead Hill. The angles subsidiary to the floor thrust are 36–45°.

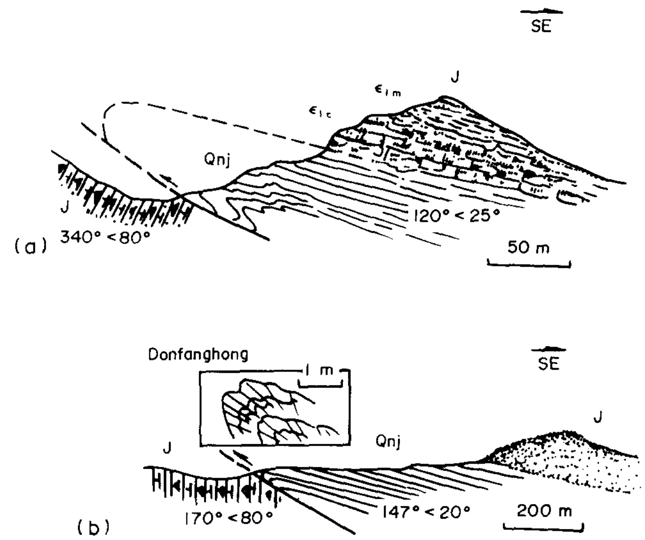

Fig. 14. Two sections across a thrust on the northwestern flank of the Yunmeng Anticlinorium. The folds verge NW. Section lines shown in Fig. 2. Chc-Chd—Changcheng system; Chc—Lower quartzite formation; Chcl—Shale formation; Cht—Dolomite formation; Chd—Upper quartzite formation. J_{2t}—Middle Jurassic volcanoclastic rocks.

outcrops indicate that their hangingwalls comprise a single nappe with an area of over 10 km^2.

The main structures in the hangingwall are asymmetrical folds which verge SE. Their axes vary from 0°, N46°E to 7°, N84°E (Fig. 12). The folds in the hangingwall involve the Jurassic strata and they therefore also formed after the Jurassic period. Considering that the fold axes are parallel to the strike of thrust as a whole, they may have a genetic relationship to the thrust. If so, it is reasonable to infer that the direction of thrusting was roughly SE from the vergence of the folds. This conclusion is supported by the fact that the thrust cuts the Lower, Middle and Upper Cambrian in order from north to south. According to the Elliott–Johnson law (1980), a thrust should cut up-section in the direction of thrusting. Additional evidence from the slickenside striae on the fault surface and the geometries of imbricate hangingwall thrusts, lateral ramps and antithetic thrusts (Boyer & Elliott 1982, Butler 1982) supports a SE sense of thrust displacement (Fig. 13).

The root zone, in this case, must lie northwest of the nappe. The nappe, however, has been offset by the Hefangkou normal fault, which exposes the low-angle normal ductile shear zone in its footwall. These relationships are discussed in greater detail below.

STRUCTURAL SYMMETRY OF YUNMENG ANTICLINORIUM

It is worth noting the following examples of structures on the northwestern side of the Yunmeng Anticlinorium that are similar to those on the southwestern side.

(1) The axial planes of folds on the northwestern flank of the anticlinorium verge NW without exception (Figs. 14 and 15).

(2) A thrust with several klippen and a displacement of 3–4 km lies northwest of the Qifengcha Fault (Fig. 15).

(3) There are some klippen characterized by a younger allochthon over an older autochthon (G. A. Davis personal communication 1985) (Fig. 16).

(4) As along the SE side of the anticlinorium, a large normal fault with a dip of about 70°NW lies along its NW side (Fig. 16).

(5) There is a ductile shear zone along the NW flank; it dips gently NW and its hangingwall moves down and NW with respect to the footwall, as indicated by the *C*-foliation, which dips at higher angles to the northwest than the *S*-foliation.

TECTONIC EVOLUTION

The above-mentioned symmetry may be explained as follows. A large fold, the Yunmeng Anticlinorium, began to develop above an intruding Mesozoic granitic pluton. Uplift was followed by gravity sliding down both flanks of the fold. Jurassic volcanic and volcaniclastic strata were deposited on the flanks of the fold.

The rocks at deeper levels behaved in ductile manner. Ductile shearing (mylonitization) of hot, crystallized upper levels of the pluton occurred along the flanks of the fold, producing the ductile shear zones with a normal shear sense. The mechanism of deformation at high

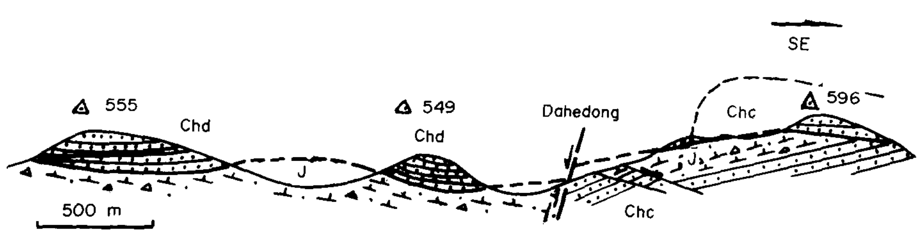

Fig. 15. The nappe on the northwestern flank of the Yunmeng Anticlinorium. Section line shown in Fig. 2. See Fig. 14 for legend.

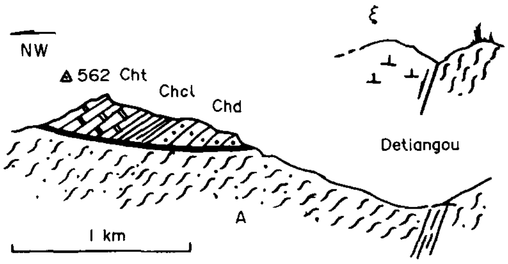

Fig. 16. Field sketch profile showing sliding-type klippe with the characteristic of younger allochthon over older autochthon. The Qifengcha high-angle normal fault is shown also.

levels, however, was different and the rocks showed brittle behaviour.

The upper strata above and around the plutonic core were squeezed outward and down the flanks of the fold along discrete surfaces. The sliding sheets were transformed into thrust nappes where the strata flattened out further away from the anticlinorium. This transformation can even be seen in outcrops, as shown in Fig. 17. In Fig. 17 a micronappe developed in dolomitic limestone within the Shuiyu shear zone. Note that there are two types of domino structures on the back of longer limb of the nappe, showing that compression and extension terrains are located at the front and back domains of the small nappe, respectively.

The process of tectonic evolution of the region is illustrated in Fig. 18. With post-Cretaceous high-angle normal faulting along the western and eastern flanks of the anticlinorium, the anticlinorium became a horst block between the western (Qifengcha) and eastern (Hefangkou) bounding faults, and dip-slip displacement along the Hefangkou Fault juxtaposed the mylonitic gneiss against rotated hangingwall units and structures.

An alternative tectonic model for the area is suggested by similarities of structures above and below the Hefangkou Fault with those found above and below Cordilleran detachment faults (G. A. Davis personal communication 1985, Davis & Zheng 1987). This alternative model would consider the Hefangkou Fault as a master detachment fault formed during post-granite (106–114 Ma) extension of northeastern China. According to this alternative, the structural elements above and below the fault are kinematically unified. Footwall mylonitic rocks may conceivably have been drawn upwards from beneath a distending upper plate (cf. Davis *et al.* 1986, fig. 4). The Yunmeng Anticlinorium (or antiform) may thus be a post-granite (possibly Paleogene) structure comparable to the detachment-bounded antiforms of Cordilleran metamorphic core complexes. Both our observations on the symmetry of the Yunmeng anticlinorium and the measurements of shear strain in the Shuiyu ductile shear zone (generally less than 4–5), however, clearly support the first tectonic hypothesis.

Fig. 17. A small-scale sliding 'nappe' exposed on the northeastern wall of a roadcut, 0.5 km NW of Hefangkou. Note that there are two kinds of domino structures in the top-right corner. Scale bar = 2 cm.

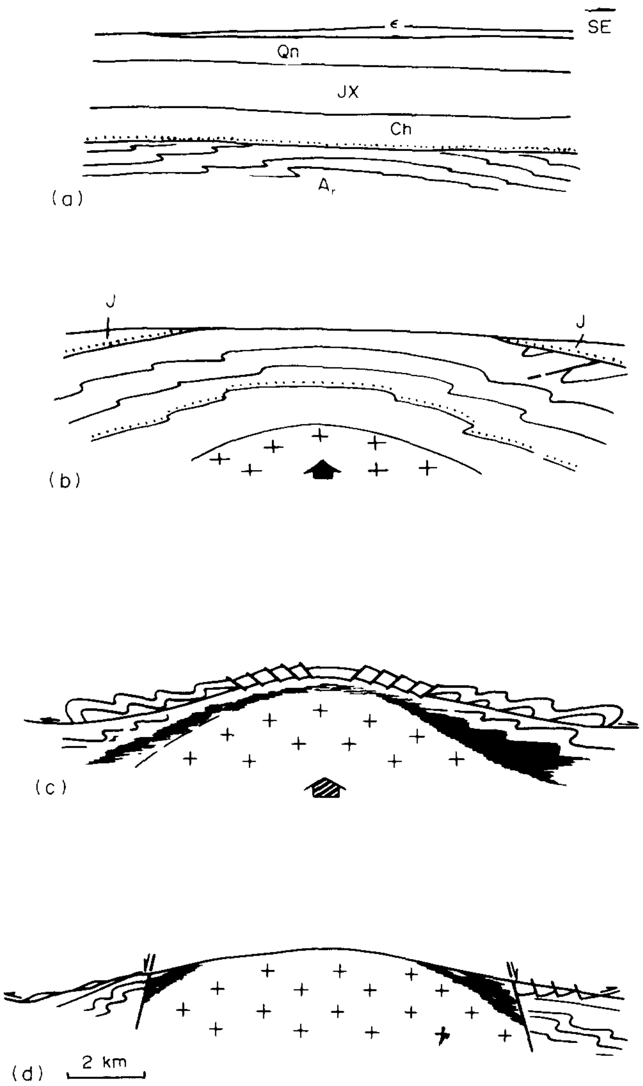

Fig. 18. Schematic tectonic evolution of the Yunmeng area. The main stages: a—Pre-Mesozoic; b—Jurassic period; c—Middle Cretaceous period; d—Late Cretaceous to recent time. Unit abbreviations as in Fig. 2. Scale bar = 2 km.

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