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Great Jurassic thrust sheets in Beishan (North Mountains)—Gobi areas of China and southern Mongolia

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Abstract—Jurassic thrust sheets with minimum displacements of 120–180 km have been discovered within the 'Hercynian–Indosinian' orogenic belt of the Beishan of China and south Gobi area. The thrusts strike E–W, extend over 1200 km in length, and carried Meso-Proterozoic massive dolomitic limestones over strata ranging from Neo-Proterozoic (Cryogenian and Terminal Proterozoic) to Lower–Middle Jurassic. Slip-linear plots based on kinematic indicators, such as slickenlines and groove lineations, fiber lineations and 'drag folds' adjacent to the fault surface, vergence of folds and imbricated thrusts in the upper plate, indicate northward movement in the Beishan area to the west and southward movement in the South Gobi area to the east. The two major thrust faults, the Beishan thrust and South Gobi thrust, are presumably separated by a major tear fault, the Ruo Shui fault. The major thrust faults were later deformed into a series of E–W antiforms and synforms and the sheets are separated, due to erosion, into a number of klippen mainly located on synforms of the major faults. The Yagan metamorphic core complex, which is a result of an extensional event that postdates the thrust event, yields an ^{40}Ar–^{39}Ar plateau age of 155.1 ± 10 Ma, and Rb–Sr isochron age of 153 ± 6.2 Ma. The thrust sheets formed during the late Middle Jurassic, long after the closure of any oceans in the study area previously reported for this region, and are ascribed to a phase of intracontinental deformation. The closing of the Jurassic Tethys or retroarc deformation behind an active continental margin at the southern edge of Asia, prior to the Tethyan collision, or/and the closing of Mongolo–Okhotsk oceans might be responsible for this event. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Thrust sheets have been recognized for over a century (Ferry *et al.* 1984, Coward *et al.* 1986). Almost without exception the examples discovered so far occurred during convergence of lithospheric plates, and the collision of thick crustal blocks (e.g. Scandinavian Caledonides, European Alps, Oman, Himalayas and Appalachian systems). Two enormous Mesozoic thrust sheets with displacement over 120–180 km were recently discovered within the Late Palaeozoic–Early Mesozoic orogenic belt in the Beishan of China and the South Gobi (Sino–Mongolia boundary) area (Figs. 1 and 2, Zheng *et al.* 1991, Zuo *et al.* 1992, Zheng & Zhang 1992). The thrust sheets occurred long after the elimination of oceanic lithosphere in the area and are interpreted to be post-Indosinian (the term is commonly used for Early Mesozoic events in China) and an expression of intracontinental deformation. Some studies have described Cenozoic intracontinental deformation in central Asia and attributed to the indentation of India into Asia (Molnar & Tapponnier 1975, Allen *et al.* 1993, Avouac *et al.* 1993, Yin *et al.* 1993, Molnar 1994); however, there are few reports on Mesozoic thrusts in the area. We describe in some detail their kinematic characteristics and discuss the possible driving force responsible for such features.

TECTONIC SETTING

The two thrust sheets, the Beishan sheet (Fig. 3) and the South Gobi sheet (Fig. 4), are situated in what is known as the Sino-Mongolian 'Hercynian' (the term broadly refers to Late Paleozoic orogenies in China, e.g. Wang *et al.* 1990, Wang & Mo 1995)—Indosinian Orogenic Belt (Huang 1978, Ren *et al.* 1984, Ruzhentsev & Badarch 1988, Ruzhentsev *et al.* 1989, Badarch 1990, Zheng *et al.* 1991). They extend c.1200 km E–W from longitude 93° to 108° E, and are separated by a major strike-slip fault, the Ruoshui fault (Fig. 2). The Beishan thrust sheet lies south of the earlier Palaeozoic suture

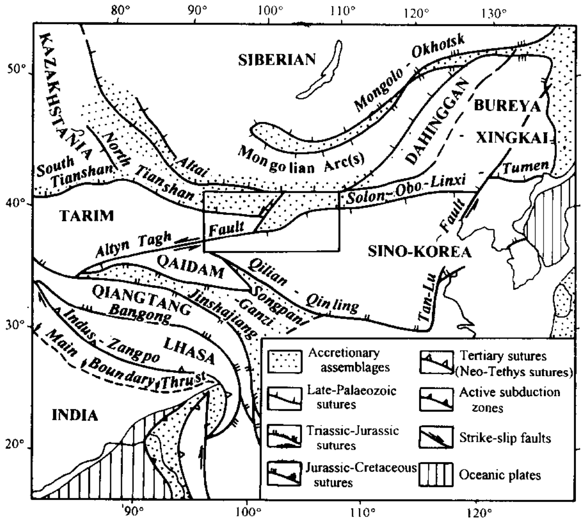


Fig. 1. Tectonic sketch map of Central Asia (after Peyve *et al.* 1976, Stocklin 1980, Otsuki 1985, Nie *et al.* 1990, Yin & Nie 1993), with location of the studied area (framed).

between the Kazakhstan composite Block and the Tarim Block (Zuo *et al.* 1992, Wang & Mo 1995), whereas the South Gobi thrust sheet lies north of the later Palaeozoic convergence zone between the Tarim Block and the Sino-Korean Craton (Wu & He 1992, Wang *et al.* 1994, Wang & Mo 1995). Stratigraphic units in the study area range in age from Archaean to Mesozoic. These units can be grouped into two parts according to their rock types, structural styles and metamorphic grades (Fig. 5). The lower part includes Proterozoic and Paleozoic strata that mainly consist of marine sedimentary and submarine volcanic rocks, that were metamorphosed in the lower greenschist facies and have penetrative fabrics, commonly, a slaty cleavage (Fig. 6a). Over 100 pieces of deformed coral fossils (*Disphyllum* and *Sinodisphyllum*) collected from Devonian limestone under the thrust sheets show that ratio of principal strain axes $X{:}Y{:}Z$ is 3:2:1, indicating about 60% shortening in the direction of Z (N–S) axis (Zheng *et al.* 1991). A series of rhythmic successions, similar to the Bouma cycles, are preserved in the Upper Permian turbidite sequence (Fig. 6a). The upper part, *in a stratigraphic sense*, has no penetrative fabrics and consists of Upper Triassic molasse, a Lower–Middle Jurassic coal-bearing unit, an Upper Jurassic clastic unit, and Cretaceous red beds. In contrast to the lower stratigraphic units, the rocks of the upper part have not experienced metamorphism and show brittle deformation behavior (Fig. 6b).

The sharp contrast and unconformity between the upper and lower parts and the absence of Lower and Middle Triassic strata in the areas show that the main orogeny took place after the Permian and before the end of the Triassic; it is, therefore, traditionally referred to as the 'Hercynian–Indosinian' orogeny (Ren *et al.* 1984, Wang *et al.* 1990, Zheng *et al.* 1991).

THRUST KINEMATICS

Beishan thrust sheet

Large scale structures. The Beishan area lies to the north of the well-known Gansu or Hexi Corridor ('Silk Road'). Numerous klippen of varying sizes, mainly composed of Meso-Proterozoic dolomitic limestone containing stromatolites, are widely scattered through the area. These klippen roughly fall in three E–W trending belts from north to south (Fig. 2). The northernmost one is the Pochengshan klippe (Figs. 2 and 3a). Several small klippen are separated by erosion from the major klippe to the north. (Fig. 3b). The Pochengshan klippe consists mostly of massive dolomitic limestone dipping steeply to the north. Stromatolite geometries indicate the sequence in the sheet is right side up. Neo-Proterozoic (Cryogenian and

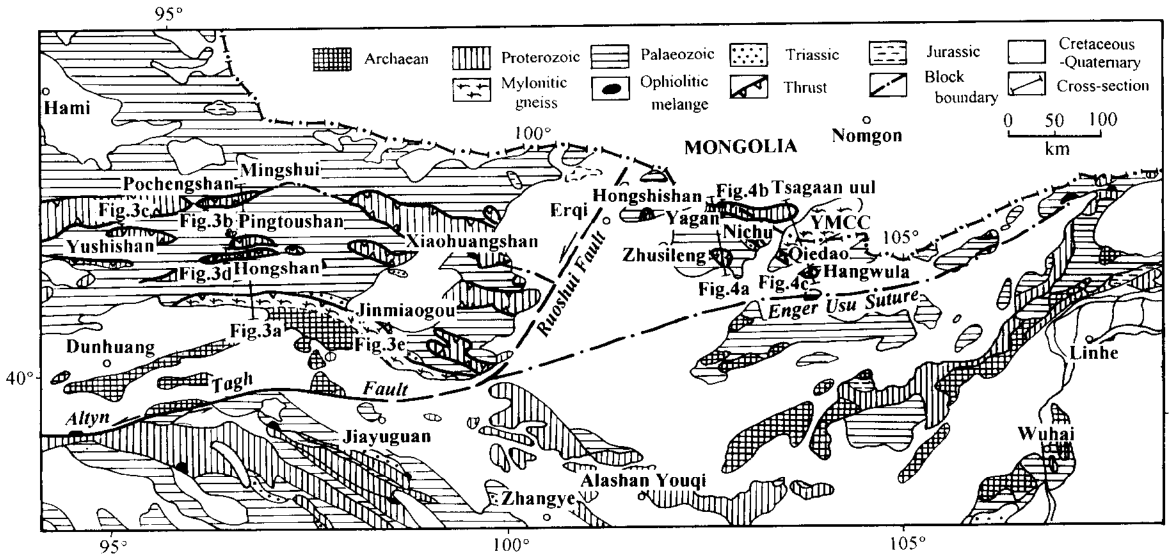


Fig. 2. Simplified geological map of Beishan–Southern Gobi areas. YMCC—Yagan Matamorphic Core Complex.

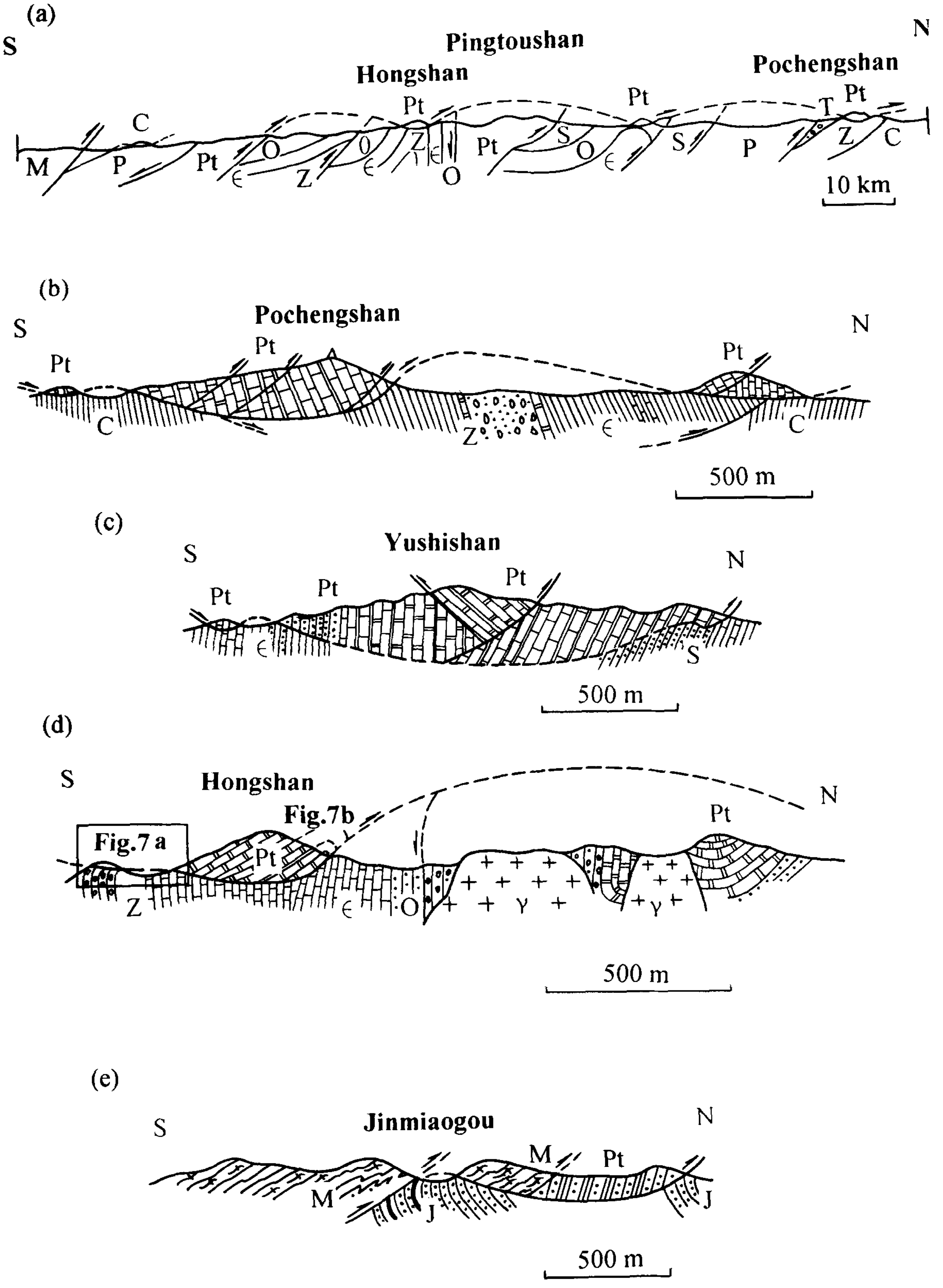


Fig. 3. Cross-sections of the Beishan thrust sheet. M—mylonitic gneiss; Pt—Meso-Proterozoic dolomitic limestone; Z—Neo-Proterozoic tillite; ε—Cambrian slaty limestone and slate; O—Ordovician sandstone; S—Silurian turbidite; C—Carboniferous slate; P—Permian turbidite; T—Triassic molasse; J—Jurassic coal bearing unit; γ—granite. See Fig. 2 for locations.

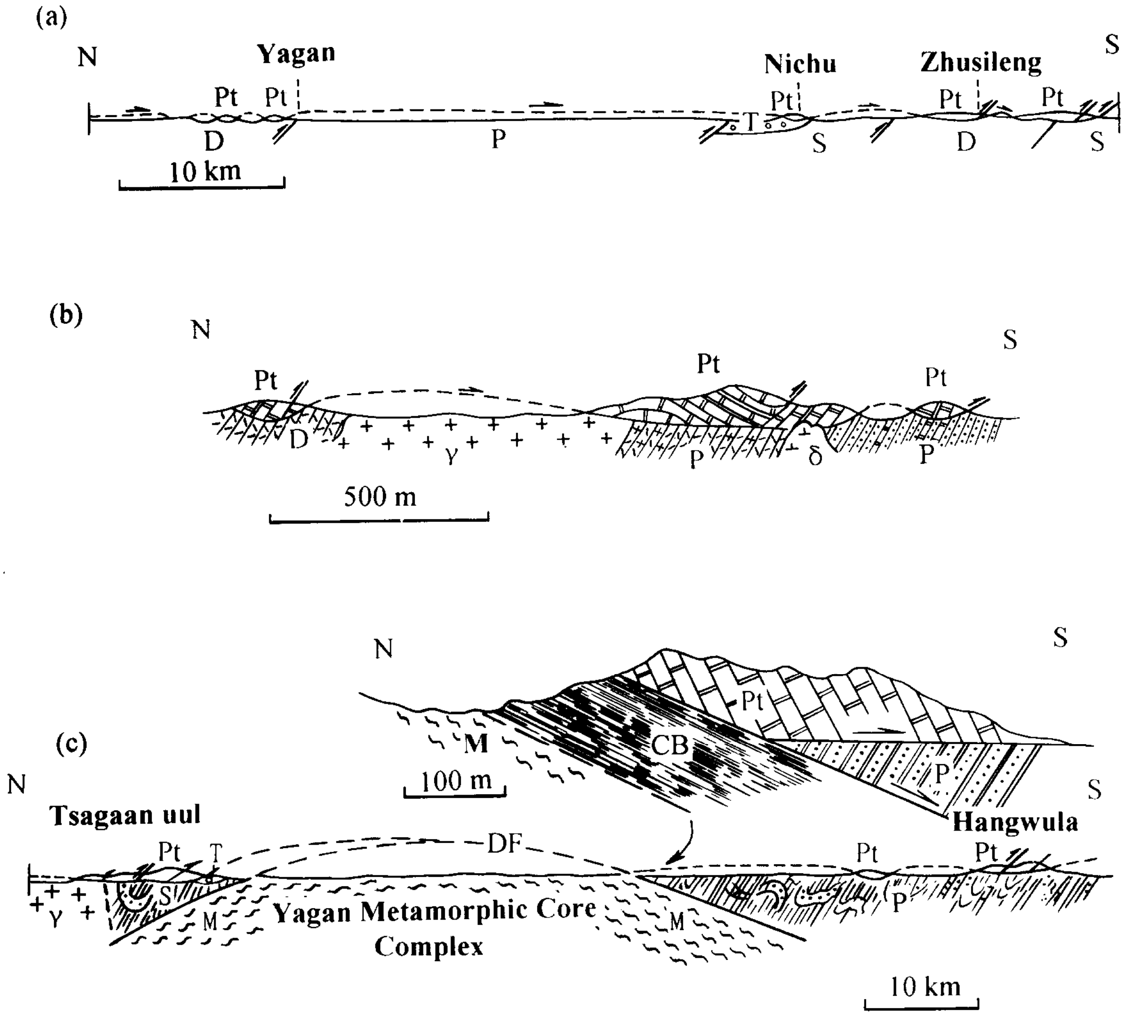


Fig. 4. Cross-sections of the South Gobi thrust sheet. M—Mylonitic gneiss; Pt—Meso-Proterozoic dolomitic limestone; S—Silurian turbidite; D—Devonian slaty siltstone, tuffaceous slate and limestone; P—Permain turbidite; γ—granite rocks; δ—diorite; CB—chloritic breccia; DF—detachment fault. See Fig. 2 for the locations.

Terminal Proterozoic) tillite and Cambrian slaty limestone containing *Eoredlichia sp.* crop out north of the major klippe, forming a half-window with an opening to the west. A layer of gouge and incohesive breccia approximately 2.5 m thick runs along the fault zone.

Southwest of the Pochengshan klippe is the Yushishan klippe, which trends E–W over a large area covering 75 km and several kilometers N–S (Fig. 2). The fault with Cambrian limestone and Silurian sandy slate as its footwall crops out in places along the north and south hillsides and constitutes a synform. Several micro-windows where the footwall-rocks crop out, however, are found inside the klippe near to the north and south margins, suggesting a more complicated geometry of the fault surface. Several small klippen are separated from the main body to the south (Fig. 3c). A 50 cm thick gouge layer lies along the fault and the fault surface is grooved or fluted, giving rise to large corrugations with wavelength of 1 or 2 m, and a depth in centimeters. Such corrugations are aligned N–S, and may give the displacement direction (e.g. Power & Tullis 1989, 1991, Wu & Bruhn 1994). At the western end, the fault is lifted nearer to the earth surface and the klippe is dismembered into a swarm of small klippen by erosion. These klippen lie on hill-tops and synforms of the fault surface (Fig. 6c). The fault surface at the best outcrop on a southern hillside is grooved or fluted in the dip direction at 30° to the north (Fig. 6d). Slickenlines on the fault surface are parallel to the shallow U-shaped grooves. On the northern hill-sides, the fault surface dips to the south at 20–70°. The fault surface is deformed into antiforms and synforms and the dismemberment of the Yushishan klippen is the result of folding and differential erosion.

The Hongshan klippe lies c. 70 km to the southeast of the Yushishan klippe (Fig. 2), and forms an E–W trending range. Meso-Proterozoic massive dolomitic limestone lies mainly on Cambrian slaty limestone. A small separate klippe to the south, however, lies above Neo-Proterozoic tillite and the fault surface here dips 28° north (Figs. 3d and 7a). The cleavage in the tillite is generally vertical and strikes E–W, but progressively flattens northward into the fault surface, forming a 'drag fold' within a zone of about 10 m thick (Figs. 3d and 7a). Such a flexure indicates the upper plate moved northward

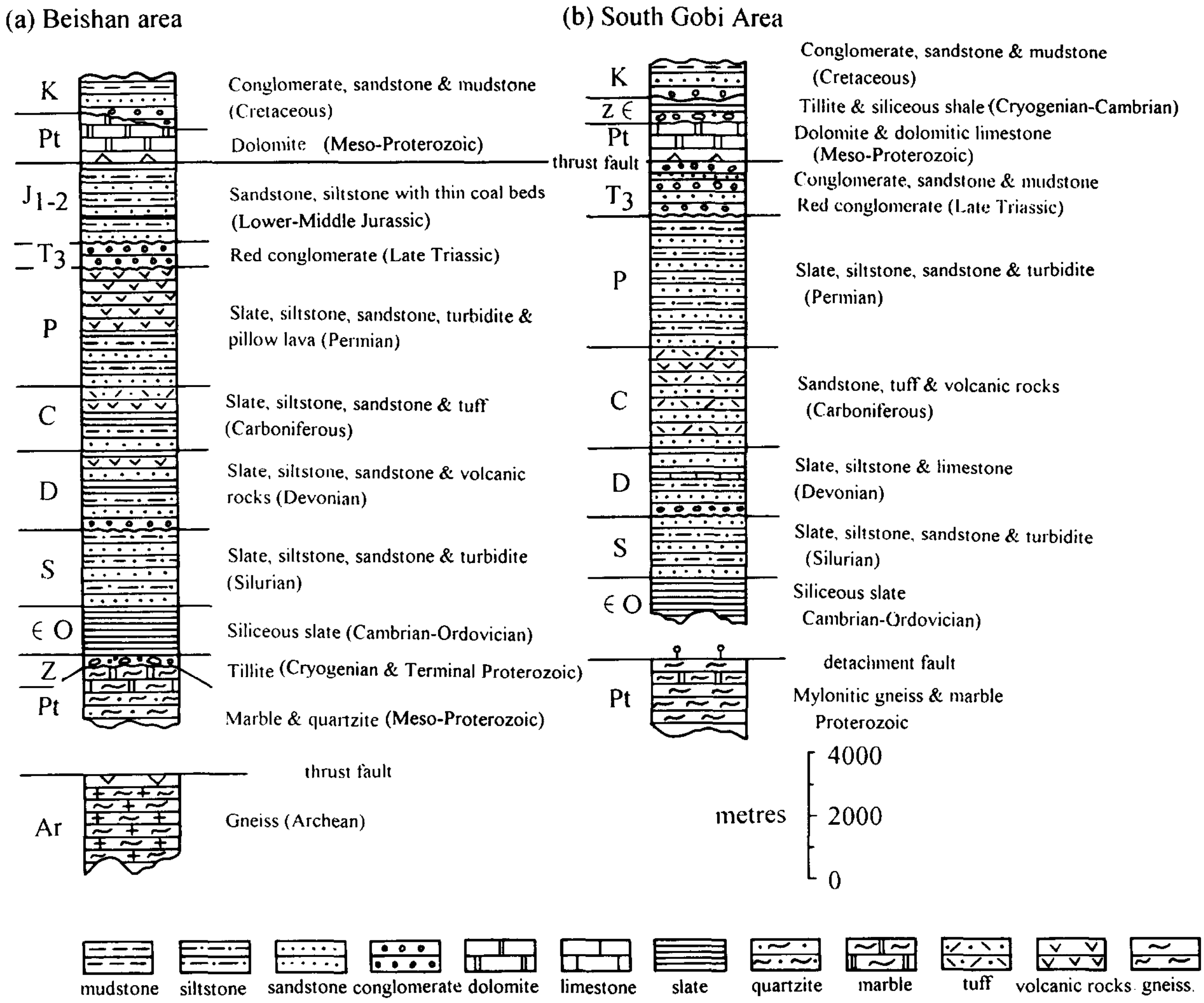


Fig. 5. Stratigraphic columns of the Beishan and the South Gobi area.

with respect to the lower plate. The fault surface that crops out on the north margin of the main klippe dips 45° towards 170°. The upper plate dolomitic limestone takes the shape of an antiform adjacent to the thrust and is compatible with northward thrusting (Figs. 3d and 7b).

Between the Hongshan and Pochengshan klippen are Proterozoic quartz schist (lower part) and dolomitic marble (upper part) which are obviously different from the dolomitic limestone of the klippen and form the E–W Pingtoushan culmination above a south-dipping thrust fault (Fig. 3a). The thrust places Proterozoic dolomitic marble, and overlying Cambrian slaty limestone and Ordovician turbidite on top of Silurian turbidite (Fig. 3a). The fault dips southward at 10–50° and has a 40–50 cm thick gouge layer along it. The subvertical Cambrian and Ordovician strata of the upper plate constitute the footwall of the Hongshan klippe (Fig. 3d). This implies that Pingtoushan thrusts are an imbricated fault under the Pochengshan–Hongshan thrust, branching from an inferred floor thrust at depth.

The stereogram (Fig. 8a) of the attitudes of the main thrust fault (open circles) and imbricated faults in the upper plate (dots) implies that the main thrust fault was folded into anti- and synforms after its emplacement and that synthetic- and antithetic-imbricated thrusts developed in the upper plate. The anti- and synforms of the thrust surface with E–W axes are compatible with observations in the field and the E–W elongated shapes and distribution of klippen (Fig. 2). The separated klippen are probably caused by the later folding and erosion afterwards, and the parts of the thrust sheet located on the synforms of thrust surface are generally preserved as klippen.

Small-scale structures. Certain structures, such as slickenlines or slip lineations and fiber lineations on faults, asymmetric folds and a number of small-scale structures in mylonites, may provide evidence for determining shear sense on a shear zone or fault.

The slip-linear plot (Fig. 8a), has the symbol for the pole to a fault plane decorated by a line that indicates direction of slip, or an arrow that indicates the direction and sense of slip (Hoeppener 1955, Marshak & Mitra 1988), shows that the upper plate generally moved northwards relative to the lower plate.

Most sedimentary and volcanic rocks in lower plate display a weak to moderate subvertical slaty cleavage, striking E–W (Fig. 8b). Such a fabric geometry is kinematically compatible with northward thrusting. However the facts that the thrust faults marked by a layer of incoherent gouge truncate the slaty cleavage and related folds in Paleozoic rocks and that Triassic molasse lies unconformably on the slaty rocks and tectonically under the thrust sheet suggest that the thrusts and the cleavage belong to different tectonic events. We used the Hansen slip-line method (Hansen 1971, Marshak & Mitra 1988) for data of mesoscopic folds in the slaty rocks to determine the kinematics of the thrust (Fig. 8c). The fold axes do not lie exactly on a unique great circle but fall in a zone around an E–W great circle that is parallel to the average attitude of cleavage (Figure 8b). The clockwise and anticlockwise folds do not lie in their respective fields but both lie in E and W fields. It is not unexpected since these folds lie in different limbs of larger folds and those with ambiguous vergence (dots without an arrow) are located in hinge areas. There is a gap (separation arc), between the two fields, and the slip direction within the separation arc is obviously subvertical. It is more reasonable, therefore, to ascribe these small folds to buckling under a N–S compression related to the Late Paleozoic orogeny (Zheng *et al.* 1991). The kinematic coincidence between the folds and the slickenlines indicates that the thrusting events might have inherited the earlier tectonic orientation.

Mylonitic foliation in the postulated root zone has formed a series of north-vergent folds (Fig. 9a) and poles to the foliation fall around a great circle of the stereogram (Fig. 8d), whereas the most of mylonitic lineations plunge to ESE at low angles. Shear sense in most outcrops and samples could be determined by S–C fabric relations and asymmetric feldspar-augens that exhibit evidence for sinistral shear. In places, however, stretching lineations are paralleled to both the dips of mylonitic foliation and the axes of shear folds in the mylonitic rocks (Fig. 9b). This inconsistency of lineation in orientation presumably reflects kinematic complexity or heterogeneity of deformation and a transpressional movement.

South Gobi thrust sheet

Large scale structures. A number of klippen dominantly composed of Meso-Proterozoic massive dolomitic limestone are scattered throughout the area from Hongshishan (Fig. 2) near the Town of Eqi to north of the Linhe county (covering over 400 km E–W and 60–70 km N–S). Among the main klippen are those at Hongshishan, Yagan, Zhusileng, Qiedao-Haobiru of China and Tsagaan-uul of Mongolia (Fig. 2).

East of Eqi, the Hongshishan klippe forms an N–S trending range that is 10 km long, 1.5 km wide and 50–60 m high above the average local topographic level. Near its center, a N–S running dry valley exposes the fault and Devonian foliated limestone below it. The attitude of the fault surface is subhorizontal (5–7° dip to the north) and along it is a layer of flinty micro-breccia (1–3 m thick; Fig. 10a). The foliation in the lower plate is generally subvertical, strikes E–W and curves upwards and southwards into the fault, and thus indicates southward thrusting (Fig. 10b). Several small imbricated thrusts are present in the upper plate and dip northward at 30–58°. Restraining steps and releasing steps with fibrocalcite filled on the faults (Marshak & Mitra 1988) are also compatible with southward thrusting.

The Yagan klippen extend from 15 km west of Yagan discontinuously for 50 km and continue into Mongolia at longitude 103° E (Fig. 2). A cross-section through the klippe to the west of Yagan is shown in Fig. 4b. The upper plate consists of Meso-Proterozoic dolomitic limestone (locally marble), while the lower plate is composed of Devonian andesitic rocks in the north and Permian rhyolitic rocks and turbidites in the south. The fault surface is wavy and subhorizontal as a whole. A layer of gouge c. 10 cm thick lies along the fault. The imbricated thrust faults in the upper plate imply that the upper plate moved southward with respect to the lower plate.

According to our recent reconnaissance on the Mongolian side of the China–Mongolia border, the Tsagaan-uul klippe (area of 70–80 km E–W and over 10 km N–S), which consists of Meso-Proterozoic dolomitic limestone and some quartzite, is thrust over Silurian slaty turbidite and Upper Triassic molasse (Figs. 2 and 4c). Small windows are found within the klippen and the fault crops out subhorizontally on hillsides or along the foot of hills. Several imbricated thrusts have slickenlines in the upper plate that dip northwards (Fig. 7c), and related folds verge southwards (Fig. 7d).

Meso-Proterozoic dolomitic limestone containing chert bands crops out near Nichu (Fig. 2) in the central part of the area as an E–W range. The dolomitic limestone is faulted over Upper Triassic sandstone and conglomerate. A layer of gouge along the thrust is over 50 cm thick.

Dolomitic limestone with some stromatolite comprises a N–S hill-belt near Zhusileng (Fig. 2) where it rests structurally on top of the Silurian–Devonian sandstone, silty slate and thin-bedded limestone. The klippe is up to 150 m high above the local surface (Fig. 10c). Bedding and slaty cleavage in the lower-plate rocks generally strike nearly E–W and dip northwards at high angles. The thrust fault crops out on the hillsides or along the base of small hills and extends for 5–6 km. The fault surface crops out along the southern side of the klippe, and fault gouge up to 2–3 m thick occurs along it (Fig. 10d). Several imbricated thrusts dipping north at 40–50° are found in the upper plate. Up-dip-directed slickenlines and fiber lineations (Fleuty 1975, Power & Tullis 1989, 1991, Wu & Bruhn 1994) on some of the exposed fault surfaces also indicate southwards thrusting.

The stratigraphic position of strata in the upper plate becomes higher eastwards in the Qiedao–Haobiru area. Meso-Proterozoic strata including the uppermost siliceous shale member are thrust over the Silurian turbidite in the north part of the area, whereas the klippe in the south part contains Neo-Proterozoic tillite and Cambrian black siliceous shale lying above Carboniferous clastic rocks. The upper plate strata are deformed into a pair of folds whose axial planes verge southwards (see fig. 3 in Zheng *et al.* 1991).

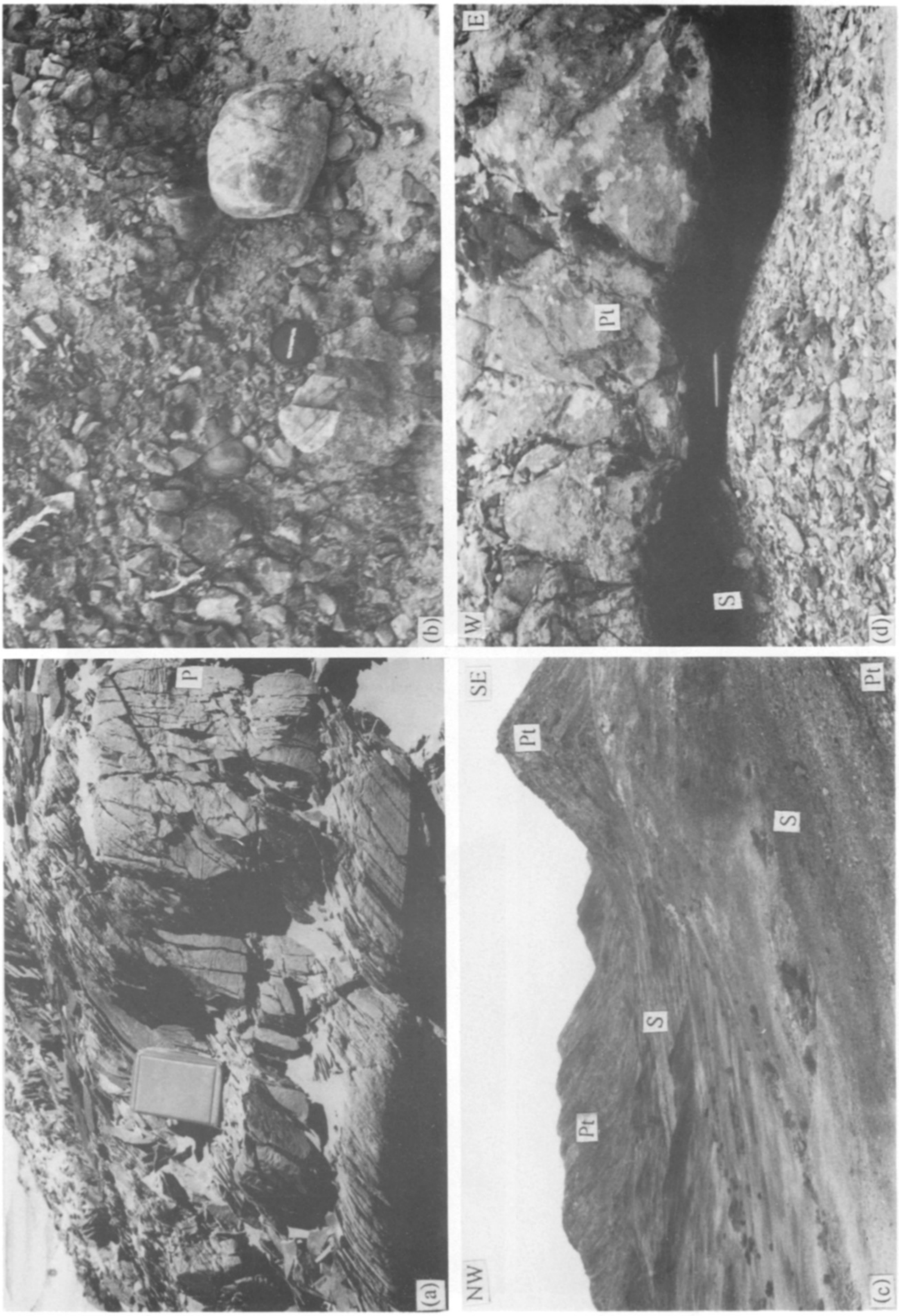


Fig. 6. (a) Slaty cleavage and rhythmic succession in Upper Permian turbidites near Nichu. Note current ripple laminations of a Buoma cycle at place P. (b) An outcrop of Upper Triassic molasse in Beishan. Note the conjugate fracture system in pebbles showing brittle behavior. (c) Small klippen with dolomitic limestone over Silurian slaty rocks at the western end of the Yushishan klippe. The thrust fault crops out along the hillsides. (d) The thrust fault at the best outcrop on the southern hillside to south of (c) is grooved or fluted in the dip direction at 30° to the north.

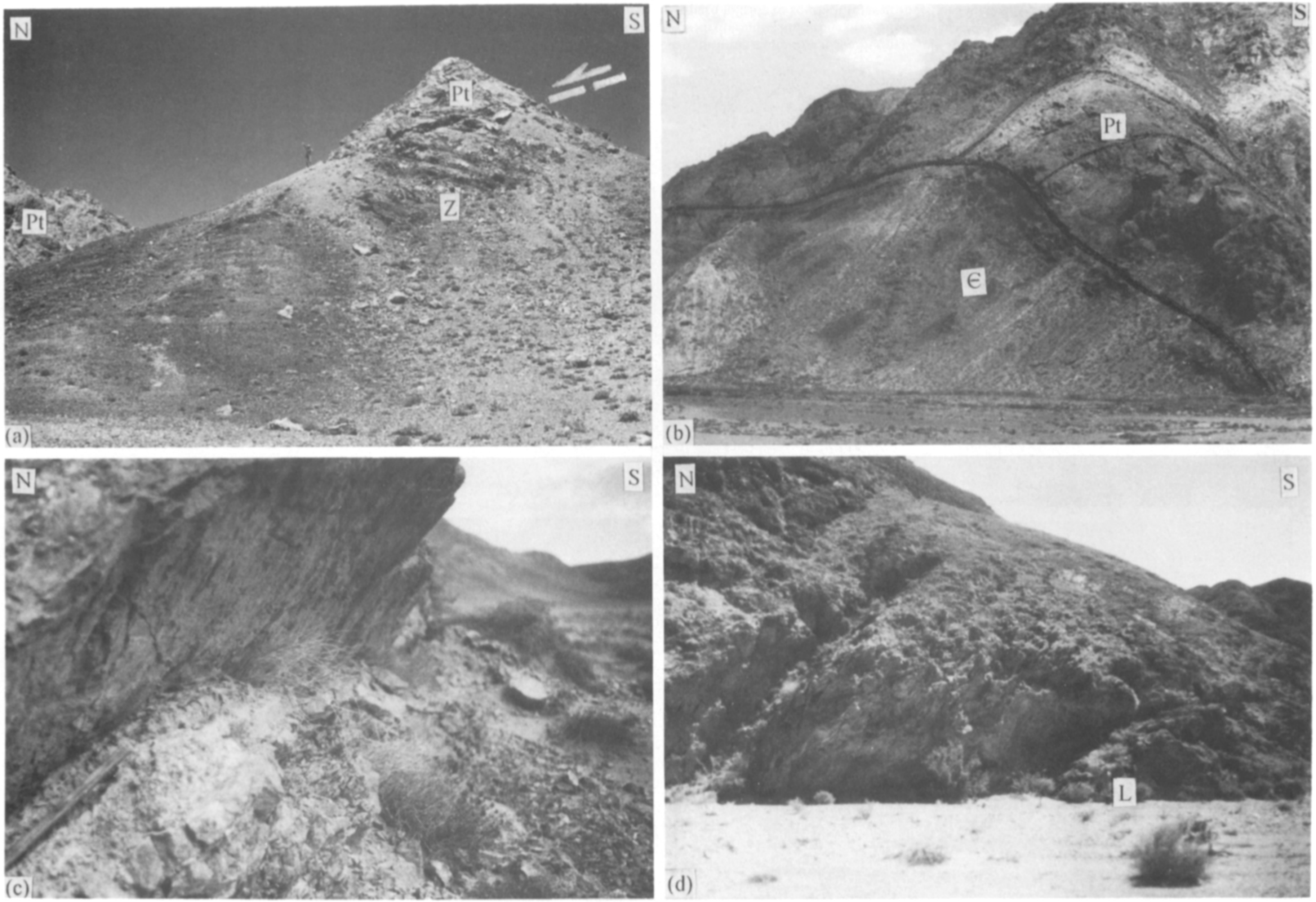


Fig. 7. (a) A small klippe (south of the Hongshan klippe) with Meso-Proterozoic dolomitic limestone over Neo-Proterozoic tillite. Note the 'drag fold' adjacent to the thrust. (b) The 'drag fold' in upper plate to the thrust fault on the north margin of the Hongshan klippe. (c) An imbricated fault with obvious slickenlines in dip-direction in the north part of the Tsagaan-uul klippe. (d) Two imbricated faults in the south part of the Tsagaan-uul klippe. Note the S-vergent folds in between and near Lkaasuren at place (L).

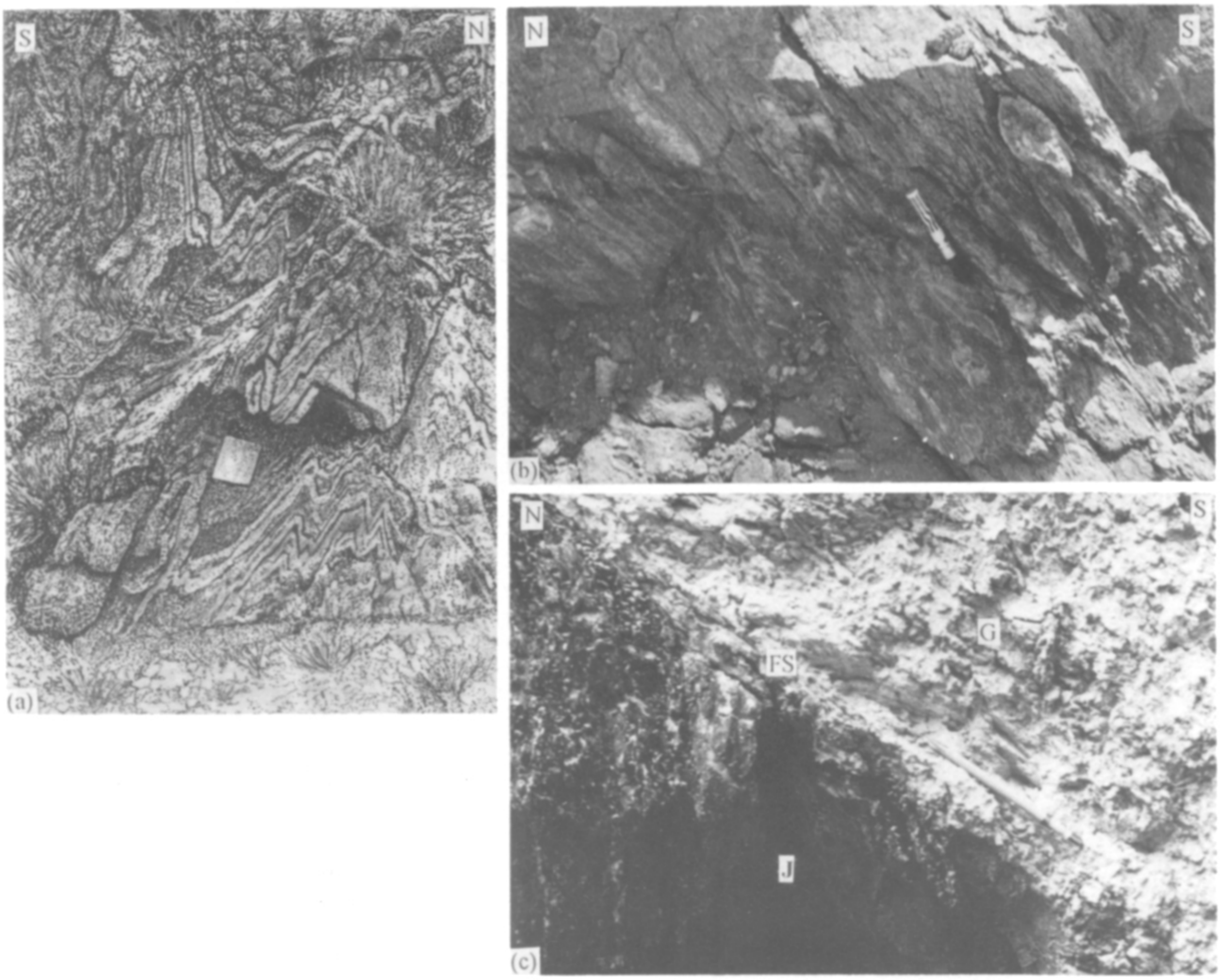


Fig. 9. (a) Asymmetric folds in mylonitic gneiss in the root zone (near Jinmiaogou). (b) A swarm of sheath folds in mylonitic gneiss in the root zone (south of Hongshan), (c) The thrust surface (FS), fault gouge (G) and 'drag fold' revealed by an exploratory trench at Jinmiaogou. The vertical Jurassic coal seams (J) in the footwall take the fault as an asymptote rolling backwards and northwards.

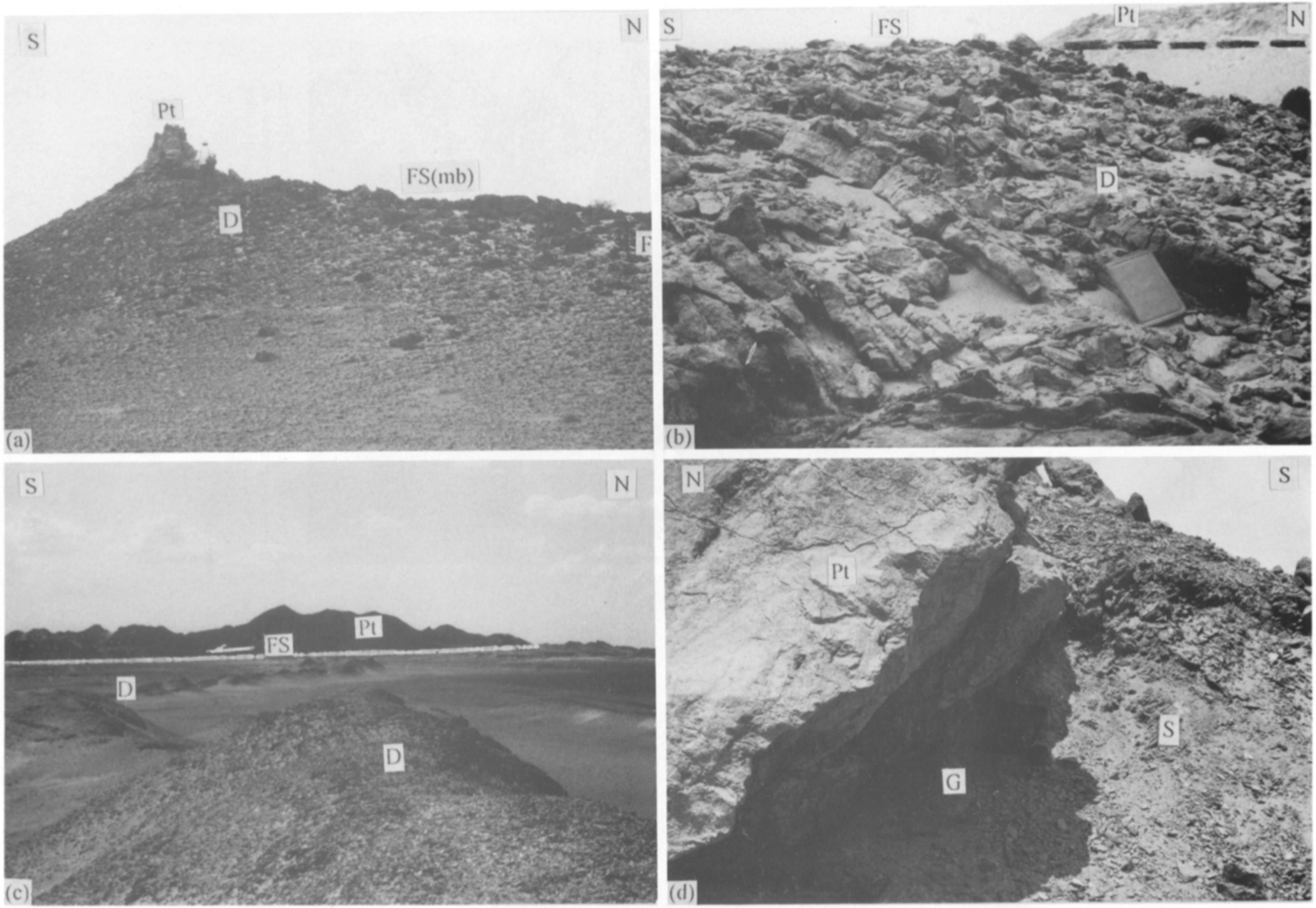


Fig. 10. (a) A 'microklippe' with Meso-Proterozoic limestone over Devonian slaty limestone and siltstone at Hongshishan. The fault surface (FS) is subhorizontal and along it is a layer of flinty breccia or microbreccias (mb). (b) A 'drag fold' beneath the fault. (c) The thrust surface cropping out along the Zhusileng hill–foot for 5–6 km. Meso-Proterozoic dolomitic limestone in upper plate and Devonian slaty siltstone and thin-bedded limestone (the E–W running range) in lower plate. Western view. (d) The southern front of the Zhusileng klippe. The well-exposed thrust surface dips northward at 48° and c. 4-m-thick gouges along the fault.

Small-scale structures. The slip-linear plot for the South Gobi area (Fig. 8e) is similar to that of the Beishan area except that it contains more north-dipping faults. In contrast to the latter, however, it shows that the upper plate moved southward to the lower plate. Since the poles to the main fault surface (open circles) lie closer to the center of the plot, it implies that the fault surface is less folded.

Similar to the Beishan area, most sedimentary and volcanic rocks in lower plate display a weak to moderate subvertical slaty cleavage, striking E–W (Fig. 8f), and meso-scopic folds in the rocks have similar attitudes (Fig. 8g). Since both the slaty cleavage and the folds are truncated by the thrust sheet, it seems unreasonable to take them as reliable kinematic indicators of the thrust event even though cleavage mainly dips to the north.

There is no outcrop of lower-plate Proterozoic rocks in the South Gobi area except for the Yagan area where mylonitic rocks constitute a metamorphic core complex under an extensional detachment fault (YMCC in Fig. 2). Over 200 attitudes of foliation and lineation in the mylonitic rocks have been measured (Fig. 8h). As shown in Figs. 2, 4(c) and 8(h), mylonitic foliation forms a NE dome-like antiform; it dips SSE in the south flank and NNW in the north flank. The lineation generally trends NNW–SSE and plunges NNW in the north and SSE in the south. Most of the shear sense indicators in the mylonitic rocks (Simpson 1986, Hanmer & Passchier 1991), including macro- and micro S-C fabric, asymmetric augen, asymmetric 'mica-fish', and oblique foliation in dynamically recrystalized quartz aggregates, demonstrate the SSE-directed shear (higher structural levels relative to lower) along the penetrative mylonitic lineation (Zheng *et al.* 1991, Zheng & Zhang 1994). Since the metamorphic core complex has truncated the thrust as shown in Fig. 4(c) and occurred closely after the latter (see Age of Thrusting), it is regarded here as a post-thrust extensional event and its movement sense may have no *direct* relationship with the thrust event.

Postulated root zone

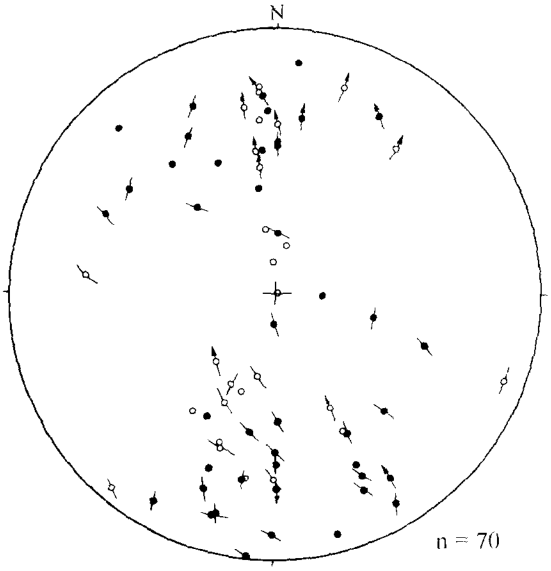
The root of a thrust surface is where the thrust dives from view for the last time (Boyer & Elliott 1982). Archaean gneiss, quartz schist, amphibolite and mylonitic gneiss crop out along the southern margin of the Beishan area for nearly 500 km in an E–W direction (Fig. 2). The mylonitic rocks are thrust over Lower Carboniferous, Permian and Lower–Middle Jurassic strata and covered unconformably by Upper Jurassic sandstone. In contrast to the abovementioned outcrops of the klippen, the rocks show striking ductile behavior. South of Hongshan, the mylonitic gneiss containing a swarm of sheath folds (Fig. 9b) is thrust upon Carboniferous slate and dacitic pyroclastic rocks (Fig. 3a). The mylonitic gneiss dips southwards at 60°, showing strong stretching lineation in the dip direction. The S–C fabric and asymmetric augen system of the mylonite indicate northwards thrusting. In the Jinmiaogou area to the east, the mylonitic gneiss is thrust over the Lower–Middle Jurassic coal-bearing unit. There is a 'micro'-window composed of the Jurassic coal-bearing unit within the area of mylonitic gneiss (Fig. 3e). The fold vergence in the mylonitic gneiss indicates northwards thrusting (Fig. 9a). Exploration trenches cutting on the north margin of the thrust reveal the Jurassic coal-bearing unit in the lower plate and a layer of gouge up to 2 m thick along the fault surface. The fault surface dips at 40° toward 170° and lies parallel to the foliation of mylonitic gneiss in the upper plate. The coal-bearing unit commonly has a regional dip of 25° northward and steepens as it approaches the fault, and is vertical adjacent to the fault. Incompetent coal seams in the unit seam bend into the fault surface as an asymptote extending along it for several metres (Fig. 9c). This arrangement provides strong evidence for displacement on the fault surface from south to north.

Since the non-cohesive gouges related to the thrust event were probably formed at shallow levels (e.g. Sibson 1977, 1982) and are juxtaposed by the mylonitic rocks, the thrust with mylonitic rocks in the upper plate is older than the brittle thrust fault which truncates it, and the thrust fault with metamorphic rocks in its hanging wall cuts across the brittle thrust system. The root zone of the thrust sheet probably lies somewhere to the south buried beneath the younger thrust plate that carries metamorphic and mylonitic rocks in its upper plate (Figs. 3a & e).

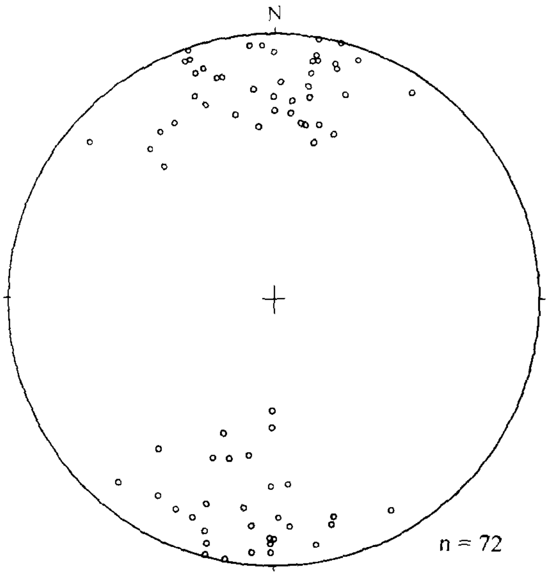
Although it is not yet clear where the root zone is for the South Gobi area, it is probably on the Mongolian side of the international border because most indicative features, such as 'drag folds' (Fig. 10b), vergence of imbricated thrusts and the folds (Figs. 4, 7c & d), and the upper plates with southwards cutting up-section of strata (Elliott & Johnson 1980, Elliott 1983), imply the southward thrusting in the area. What is more, the Sinian tillite and the Cambrian black siliceous rocks in the Qiedao–Haobiru klippen provide strong evidence for southward thrusting, for no Neo-Proterozoic tillite and Cambrian black siliceous rocks are found on the North China craton to the immediate south. Similar klippen of Meso-Proterozoic dolomitic limestone are found in the Nomgon area of Mongolia (c. 120 km north of the Sino–Mongolia border and 180 km north of the Hangwula klippe) and there is no outcrop of lower-plate Proterozoic rocks in the South Gobi area except for the Yagan area where mylonitic rocks belong to the lower plate of the main thrust fault as earlier mentioned. It is almost certain that all the klippen of the South Gobi area constituted a mega-thrust-sheet or allochthon. It appears to be an orphan, a great far-traveled horse, like those described in southwestern Virginia (Bartholomew *et al.* 1994).

The South Gobi and the Beishan sheets are terminated on the east and the west by the Roushui fault. Since the thrust direction of the Beishan sheet is opposite to that of the South Gobi sheet, the Roushui fault in between, which is regarded as the north part of the Altyn Tagh transcurrent fault by Wang & Mo (1995), seems a major tear fault that transferred the movement from one sense

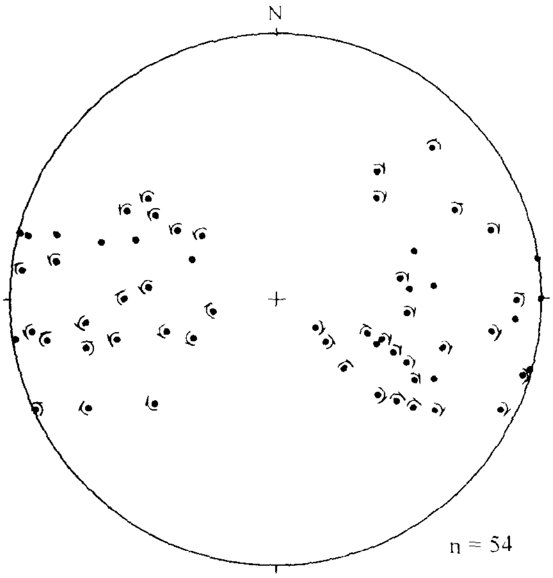
(a) Fault Surfaces, Beishan



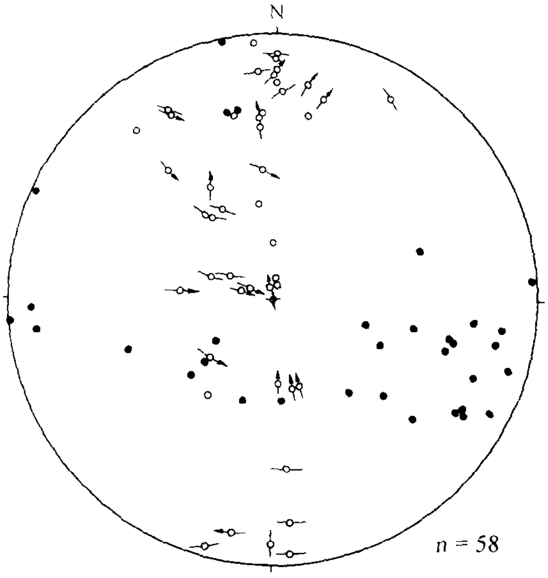
(b) Slaty cleavages, Beishan



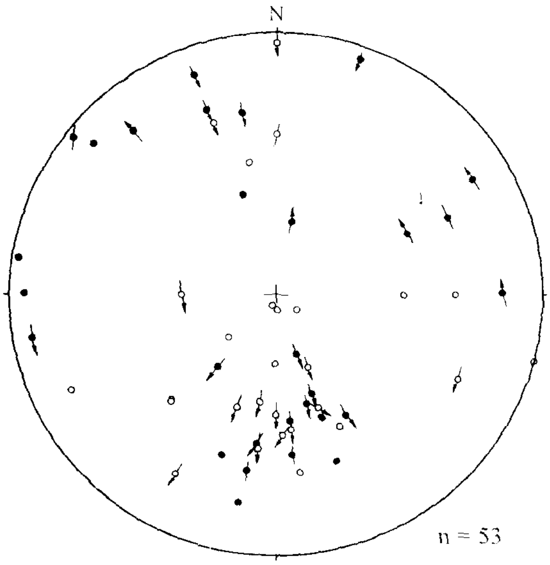
(c) Small folds, Beishan



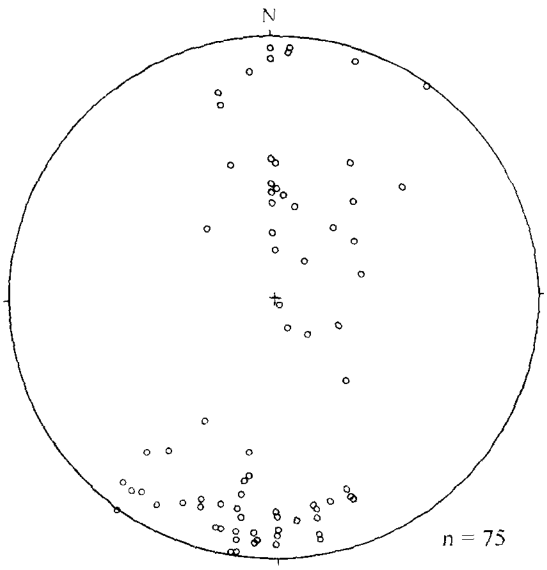
(d) Mylonitic foliations and lineations, Beishan

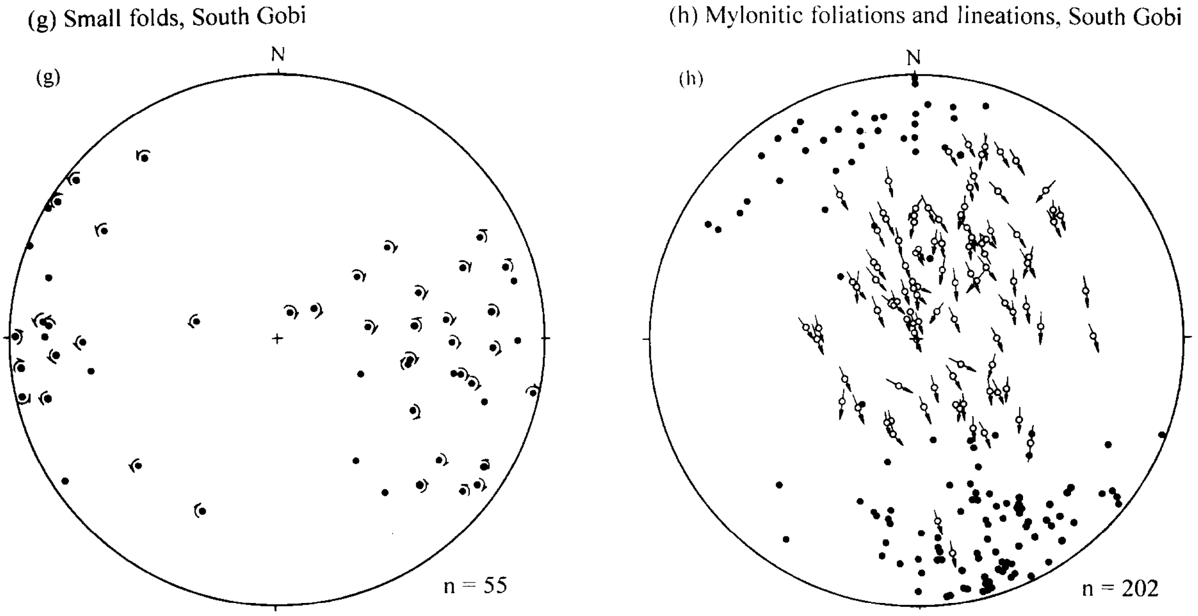


(e) Fault Surfaces, South Gobi



(f) Slaty cleavages, South Gobi





(g) Small folds, South Gobi

(h) Mylonitic foliations and lineations, South Gobi

Fig. 8. Stereograms of structural data from the Beishan (a–d) and the South Gobi (e–h) (Schmidt projection, lower hemisphere). Poles to the main fault surfaces (open circles) and imbricated faults (dots) in (a) and (e); poles to slaty cleavage in (b) and (f); orientation and symmetry of small-scale folds in (c) and (g); poles to mylonitic foliations (open circles), slip-linears (arrows) and stretching lineations (dots) in (d) and (h). See text for discussion.

to the other (Figure 2). Although the fault is, unfortunately, covered with sand, it can be recognized by obvious discontinuity structures and the reversal of vergence. This reversal of vergence is quite similar to that observed for the Dil Jabba and Domeli thrusts in the eastern Potwar Plateau of Pakistan (Pennock *et al.* 1989) and for the Foothill thrust in northwest India (Yeats & Lillie 1991).

Summary of structural analysis

Several lines of evidence enable determination of the direction and sense of the thrust movements. The distribution of the klippen, the attitude of imbricated thrust, the trend of major folds of the thrust-fault surface, and striation and groove or flutes on the fault surface all indicate a nearly N or S directed movement. Slickenlines on the main fault surfaces and imbricated faults are probably the most reliable kinematic indicator for the thrust event (Figs. 8a & e). The slickenlines or fiber lineations and grooves or flutes on the fault surfaces in the South Gobi area suggest that the relative slip-direction of the upper plate was generally to the south. The distance between the southernmost klippe at Hangwula (Fig. 2) and the northernmost one at Tsagaan-uul or possibly at Nomgon, seems to give a 120–180 km displacement of the thrust. Given the subsequent (post-thrusting) event—the extensional dismemberment—the real displacement might be less than this estimate. 'Drag folds' adjacent to the main thrust fault (Figs. 7a & b, and 9c), the main vergence of imbricated thrust and folds in the upper plates (Figs. 3b & e, and 9a) and the postulated locations of the root zone (Fig. 2) show that the upper plate of the Beishan thrust sheet moved northwards relative to the lower plate. The distance between the root zone and the northmost outcrop of the klippe at Pochengshan might give a minimum value of the thrust displacement (over 120 km).

AGE OF THRUSTING

The youngest stratigraphic unit truncated by the klippen is a Lower–Middle Jurassic coal-bearing unit. The klippen are in places covered by Upper Jurassic clastic units and Cretaceous red beds. Unfortunately, the illite and kaolinite (main clay minerals in the fault gouges) appear as mineral fragments and micro-spherical particles and are not suitable for dating (Kralik *et al.* 1987, Wang *et al.* 1995). However, the Yagan metamorphic core complex (Zheng *et al.* 1991, Zheng & Zhang 1994) which is a result of an extensional event that postdates the South Gobi nappe (Fig. 6c), yields a ^{40}Ar–^{39}Ar plateau age of 155.1 ± 10 Ma and partly mylonitic granite plutons in the complex are 153 ± 6.2 Ma in Rb–Sr isochron age. A vast amount of rock fragments from the metamorphic core complex are found in nearby conglomerate. Jurassic fossils, such as *Mongolianella*, are collected from siltstone alternating with the conglomerate. The thrust event might, therefore, have occurred during a short span in late Middle Jurassic times.

PROBLEM OF DRIVING FORCE

As Boyer & Elliott (1982) pointed out, it is usual to explain the creation and emplacement of major thrust nappes as a consequence of collision between a continent and an arc, microcontinent, or continent. Frequently, but wrongly, the dominant thrust fault is equated with a plate boundary or subduction zone.

Paleozoic rocks in the study area have ubiquitously experienced a lower greenschist facies metamorphism and commonly have penetrative fabrics. In sharp contrast, overlying Mesozoic strata lack penetrative fabrics and their bedding usually has lower dips than underlying Paleozoic units. Because there is no record of Early and Middle Triassic strata in the region and the youngest of the metamorphic units is Upper Permian, the main deformation–metamorphic event in the area probably took place at the end of the Paleozoic or early Triassic, long before the Middle Jurassic thrust event commenced. From studies of the ophiolite suites in the area, a 302.2 ± 51 Ma isotopic age of a pillow basalt from ophiolitic melange in the Enger Usu zone (Fig. 2) was obtained with the Rb–Sr method. Gabbro has a K–Ar age of 356.4 ± 6.5 Ma and a zircon U–Pb age of 380 Ma (Zuo *et al.* 1992), while an S-type granite in the Mingshui–Xiaohuangshan zone (Fig. 2) gives an earlier Palaeozoic age (405 ± 37.5 Ma) with the U–Pb isochron method (Wu & He 1992, Wang *et al.* 1994). The two zones are regarded as Paleozoic collision zones between the Mongolia arc(s), Tarim block and North China craton. The pre-Triassic tectonic events may be associated with these episodes of Paleozoic subduction and collision. Since the Mongolian arc(s), Tarim block and North China craton had become an amalgamated plate by the end of Late Paleozoic, the Middle Jurassic thrust event in the area may be related to Jurassic subduction and collision zones to the far north or south. As such, it can be regarded as an intracontinental deformation similar to those found in the Andes (Jordan *et al.* 1983a, b), the Laramide orogeny and the Sevier orogenic belt of western United States (Burchfiel & Davis 1975, Burchfiel *et al.* 1992), and the Tertiary deformation in the Tian Shan (Hendrix *et al.* 1992, Allen *et al.* 1993, Avouac *et al.* 1993, Yin *et al.* 1993).

The major Tertiary tectonic features of Central Asia have been thought to be related to collision with the Indian continent (Molnar & Tapponnier 1975, Tapponnier *et al.* 1986). The initial collision appears to have taken place during the Eocene when the leading edge of the Indian continent first made contact with the southern margin of the Eurasian continent. Prior to this event, however, the intervening oceanic lithosphere, site of the Neo-Tethyan ocean, was being subducted below the Eurasian plate (e.g. Mitchell 1981, Zheng *et al.* 1983, Sengor 1985). Recent studies (Li 1987, Liu *et al.* 1990, 1994, Lu *et al.* 1990, Nie *et al.* 1990, Sengor 1990, Li *et al.* 1991, Sengor *et al.* 1993, Yin & Nie 1993, Mo *et al.* 1994, Wang & Mo 1995, Xiao & Li 1995) suggest a more complicated story of Tethys. Three suture zones are recognized from north to south in the Tethys: the Jinshajiang suture (Fig. 1) between the Songpan–Ganzi region to north and the Qiangtang block to south, the Bangong suture between the Qiantang block and the Lhasa block, and the Indus–Zangbo suture between the Lhasa block and the Indian plate. There are ample geological data to support that the Jinshajiang suture is the boundary between Gondwana and Eurasia and many geologists now believe that the north Tibet terrane(s) was once part of Gondwana. Liu *et al.* (1994) infer from the sedimentary characteristics and temporal evolution of each terrane (or block) that the Qinghai–Tibet plateau formed by amalgamation of terranes at different periods: the closing of the Paleo-Tethys ocean during the Triassic led to the formation of the Jinshajiang suture zone with accretion of the Qiangtang terrane onto the Eurasian continent. In the Early to Middle Jurassic, with the closing of Meso-Tethys, the Bangong suture zone was formed and the Lhasa terrane accreted onto the Qiangtang terrane. The Indus–Zangbo ocean (Neo-Tethys) closed from the late Cretaceous to Eocene, earlier than in the Eocene, as previously considered. It is beyond the scope of this paper to provide a detailed discussion of these issues. The Jurassic thrust event in the study area is possibly an expression in the interior of Eurasia of one of the Tethyan events. It is note worthy that the crust shorting from the Lhasa block to Qiangtang block is more than that between the Himalaya and Lhasa terranes (Xiao & Li 1995). The Lhasa–Qiangtang collision possibly provided the driving force for the Jurassic event. Some authors (e.g. Dewey *et al.* 1988, Wang & Mo 1995), however, placed this collision in the Late Jurassic. If the timing is correct, it is too late for the thrust event in the study area. An alternative mechanism is that the deformation in the Beishan may corresponds to retroarc deformation or back-arc compression behind an active continental margin at the southern edge of Asia, prior to the Late-Jurassic collision. This style of tectonics is similar to that seen today in the Andes and is just as plausible a driving force.

Davis *et al.* (in press) evaluated an alternative scenario for Mesozoic contractional deformation in the eastern part of North China (Yunmeng Shan, 100 km north of Beijing) and noted that there is growing recognition that the continent–continent suturing of an amalgamated Mongolia–North China craton to Siberia may have occurred much later than the Permian age traditionally assigned to this event. Although collision of the craton with a Mongolian arc(s) in the late Permian appears likely, closure of the Mongolo–Okhotsk ocean between Siberia and the North China–Mongolian arc terranes may not have occurred until the Late Jurassic. Davis' conclusion was based on both geological studies (e.g. Kosygin & Parvenov 1981) and on paleomagnetic investigations (e.g. Zhao *et al.* 1990, Enkin *et al.* 1992, Nie & Rowley 1994, Nie *et al.* 1994). Although the Yunmeng Shan contractional zone may lie too far south of this possible Mesozoic suture to be the direct result of convergence across it, the possibility should not yet be dismissed that the Jurassic thrust(s) described in this paper may be a previously unrecognized expression of this continental collision.

CONCLUSIONS

The Beishan thrust and the South Gobi thrust are of large scale thrust tectonics. Slip-linear plots based on kinematic indicators indicate northward movement in the Beishan area and southward movement in the south Gobi area. The major thrust faults were later deformed into a series of E–W antiforms and synforms and the sheets are separated, due to erosion, into a number of klippen mainly located on synforms of the major faults. The thrust sheets formed during the late Middle Jurassic, long after the elimination of oceanic lithosphere in the study area. The Jurassic thrusting might occur as a result of the vast and long-lived India–Asia collision, and is ascribed to a phase of intracontinental deformation. Orogens and tectonic stresses may not be confined to narrow zones and large scale thrust tectonics can take place a long way from continental margins at the time.

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