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# Quaternary alluvial fans in the Gobi of southern Mongolia: evidence for neotectonics and climate change

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ABSTRACT: Alluvial fans in southern Monglia occur along a group of narrow discontinuous mountain ranges which formed as transpressional uplifts along a series of strike-slip faults. They provide information on the nature of neotectonic activity in the eastern Gobi Altai range and on palaeoclimate change. Alluvial fan formation was dominated by various geomorphological processes largely controlled by climatic changes related to an increase in aridity throughout late Quaternary times. Their sedimentology shows that initially they experienced humid conditions, when the sedimentary environments were dominated by perennial streams, followed by a period of increasing aridity, during which coarse fanglomerates were deposited in alluvial fans by ephemerial streams and active-layer structures were produced by permafrost within the alluvial fan sediments. With climatic amelioration during early Holocene times, the permafrost degraded and fan incision and entrenchment dominated. Sedimentation was then confined to the upper reaches of the fans, adjacent to steep mountain slopes, and within the entrenched channels. The alluvial fans have been neotectonically deformed, faulted and their surface warped by small thrust faults that propagate from the mountain fronts into their forelands. Localised uplift rates are in the order of 0.1 to 1 m Ka$^{-1}$. © 1997 John Wiley & Sons, Ltd.

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alluvial fans; neotectonics; Gobi; Mongolia; cryoturbation.

## Introduction

Impressive alluvial fans in the Gobi cover an extensive area that stretches from the Hangay Dome southwards to the Qilian Shan, and eastwards from Bogda Shan to the eastern border of Mongolia (Fig. 1). These alluvial fans prograde from a series of narrow mountain ranges, which include the the Gobi Altai Mountains and the Gurvan Sayhan Nuruu. The geomorphology of the alluvial fans in the Gobi was first described by Berkey and Morris (1927). Although they recognised a series of phases of fan development, little attention was paid to their mode of formation with respect to tectonics or climate change. This paper will, therefore, examine the geomorphology, sedimentology and the neotectonic setting of the alluvial fans in order to provide a model for their formation and to aid in the elucidation of the tectonic history of the Gobi Altai Mountains in southern Mongolia. In addition, southern Mongolia is important palaeoclimatologically, because variations in the intensity of the Mongolian High Pressure System (MHPS), which develops over the region and has a strong control on the regional climate of central Asia, have occurred throughout Quaternary times. Changes in the MHPS are recorded in the Chinese loess sequence because the majority of loessic silt on the Loess Plateau in China is derived from the Gobi and carried by western winds produced by the MHPS. Yet, despite the importance of this pressure system for understanding the climate of central Asia, little is known of the nature of climate change within Mongolia itself. This paper will examine the alluvial fans and their associated landforms and sediments in the Gobi in order to determine the nature of their formation and to help reconstruct the palaeoclimatic conditions in which they formed. The alluvial fan record and the inferred palaeoclimatic conditions are compared with the existing palaeoclimatic data base in central China to aid providing a chronological control on their formation.

## Regional tectonics

The Gobi Altai and Gurvan Sayhan ranges are transpressional uplifts that have formed in the Cenozoic along a series of

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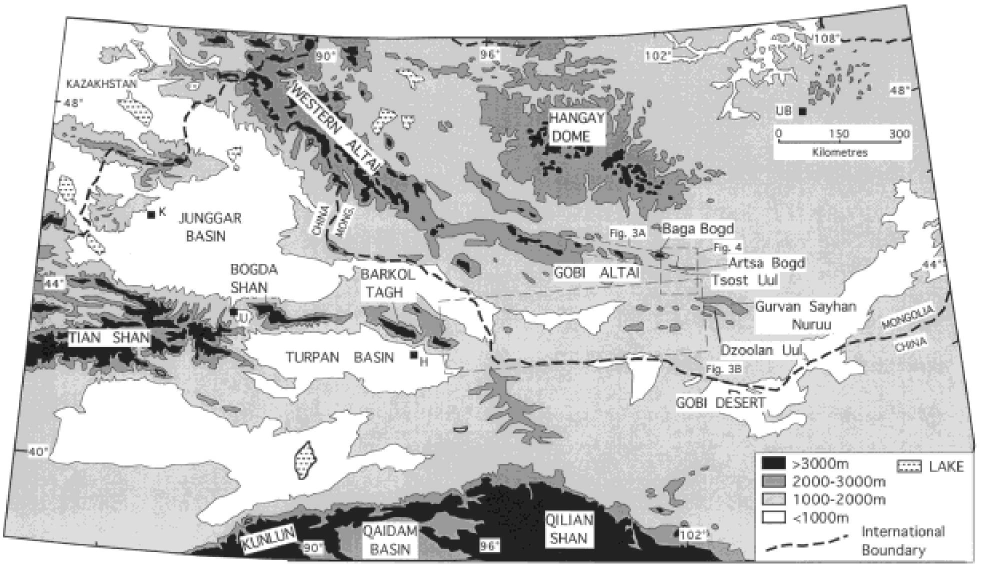

**Figure 1** Topographic map of part of central Asia showing study areas. UB = ulaan Baatan; H = Hanai Dome; K = Karamay.

strike slip faults that define a corridor of transpressional deformation extending from southern Mongolia to northwest China (Cunningham *et al.*, 1996; Fig. 2). The fault systems are clearly visible on Landsat images. Two dominant systems are present, the North Gobi Altai fault system and the Gobi–Tian Shan fault system. The former continues for over 300 km from the eastern Gobi Altai to the western Altai mountains, whereas the latter continues for over 1200 km into China, where it passes through the easternmost Tian Shan in the Barkol Tagh and Bogda Shan ranges (Figs 2 and 3). Cunningham *et al.* (1996) propose that these fault systems are probably distant responses to the continued northeastward indentation of India into Asia since approximately 50 Ma (Tapponnier and Molnar, 1979; Tapponnier *et al.*, 1986; Dewey *et al.*, 1989; Burchfiel and Royden, 1991). These faults are similar in orientation and scale to other major left-lateral strike-slip systems throughout Central Asia, such as the Kunlun and Altyn Tagh faults in China (Molnar *et al.*, 1987; Zheng, 1991), and the Bolnai fault in northwest Mongolia (Baljinnyam *et al.*, 1993). Using both field evidence and the results from experiments with scaled models, Tapponnier *et al.*, (1982) and Peltzer and Tapponnier (1988) proposed that much of Central Asia has been expelled eastward along sinistral faults during a process of continental escape that resulted from the indentation of India into Asia. Dewey *et al.* (1989) argued, however, that the amount of eastward extrusion has been minor in comparison with north–south shortening accommodated by the late Cenozoic uplift of the Tibetan plateau and such mountain ranges as the Himalaya, Pamirs, Kun Lun and Tian Shan. From long baseline interferometry, Molnar and Gipson (1996) concluded that crustal thickening absorbed most of India's convergence. In contrast, Cobbold and Davy (1988) used experiments to demonstrate that eastward escape and crustal contraction and thickening may have been approximately equal. Accordingly, understanding the dynamics of the Gobi–Tian Shan and Bulgan–North Gobi fault system will help to elucidate the Cenozoic tectonic history of Central Asia, which is perhaps the principal region in the world for understanding active processes of intracontinental deformation and uplift resulting from a distant continental collision. Such information will also help in understanding the landscape evolution of this and other active fault zones elsewhere in the world.

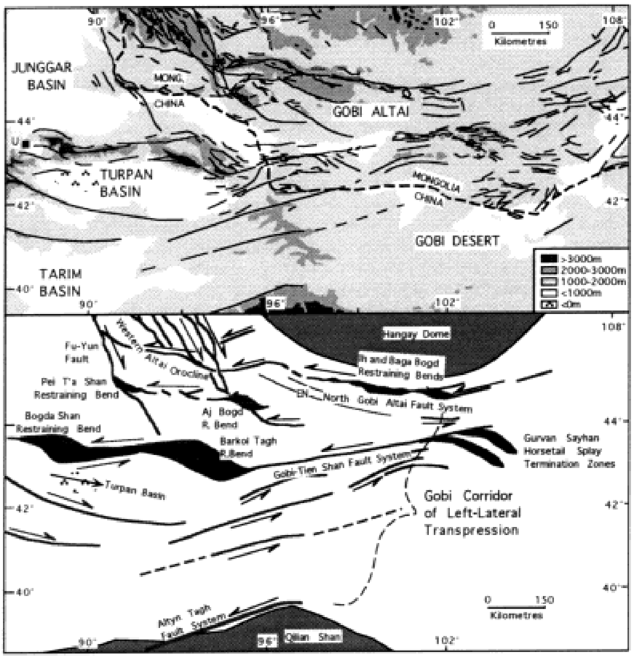

**Figure 2** Major Cenozoic fault systems identified in southwest Mongolia and northwest China (from Cunningham *et al.*, 1996).

On the basis of field mapping and the interpretation of Landsat images of the Gobi Altai Mountains, Cunningham *et al.* (1996) showed that the North Gobi Altai and the Gobi–Tian Shan fault systems link east–west-trending with northwest- and northeast-trending faults to form an interlinked wrench fault system (Fig. 2). In addition, many sigmoidal-shaped double restraining bends are visible on Landsat images (Fig. 3). These are structural pop-ups or push-ups that link the tips of step-overs of an en échelon fault system that has undergone left-lateral transpression. Field observations confirm that these are restraining bends, with thrusted margins and strike-slip terminations, and that they have flower structure cross-sections (Cunningham *et al.*, 1996). They link the strike-slip parts of the fault system that display prominent sinistral drag on many Landsat scenes. Cunningham *et al.* (1996) proposed that the formation of many

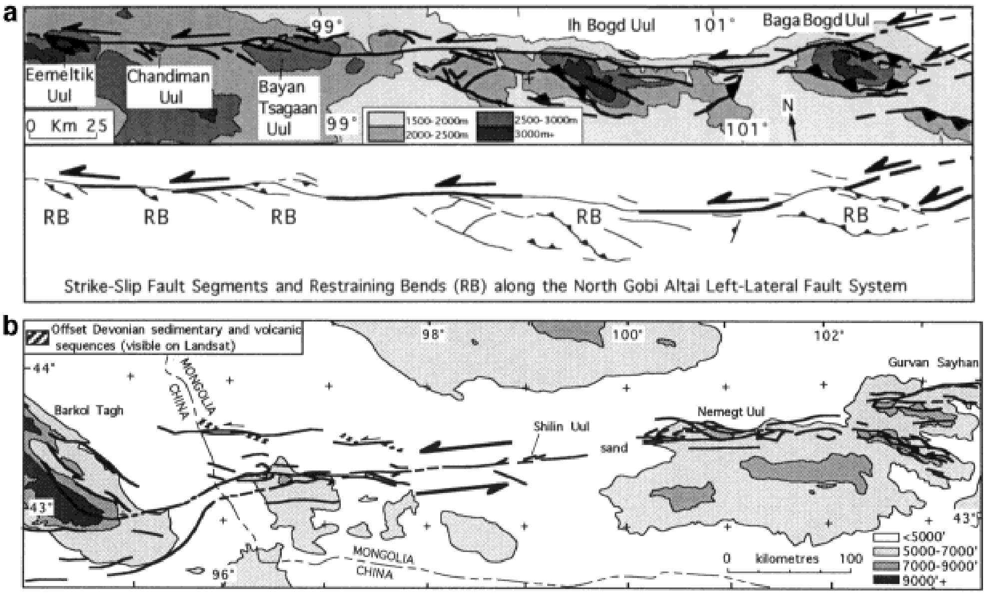

**Figure 3** (A) Topographic map showing location of left-lateral Gobi–Tian Shan strike-slip fault system. Sharply defined faults visable on Landsat imagery and documented in the field are shown. Location of map shown in Fig. 1. (B) Topographic map showing location of left-lateral North Gobi Altai Fault system. Highest mountains in the region occur at restraining bends along the system. (After Cunningham *et al.*, 1996.)

ranges in the Gobi Altai Mountains was, therefore, the result of transpressional forces along the North Gobi Altai and the Gobi–Tian Shan fault systems. From a Mongolian perspective the Gobi–Tian Shan fault system continues westwards into Xinjiang in China, where the mountains of Barkol Tagh and Bogda Shan display the sigmoidal map view geometry of restraining bends. The fault system appears to terminate eastward in a series of ranges (Gurvan Sayhan Nuruu) that have the geometry of a horse-tail splay zone (Fig. 3). The North Gobi Altai and Gobi–Tian Shan fault systems occupy the central part of a largely unrecognised, wide corridor of left-lateral crustal movement between the Hangay Dome to the north and the Qilian Shan on the north side of the Tibetan plateau. There appears to be a kinematic transition from the western-central Tian Shan, where north–south shortening in the Cenozoic is well recorded (Ni, 1978; Tapponnier and Molnar, 1979; Allen *et al.*, 1994), to transpression in the eastern Tian Shan, where Bogda Shan and Barkol Tagh are probably restraining bends with prominent thrusting and uplift, to the predominantly strike-slip movements in southern Mongolia. This transition may be reflected by the decreasing elevation along this 1200 -km-long fault system.

The formation and deformation of alluvial fans within this corridor of left-lateral transpression is an important expression of the Cenozoic tectonism and allows the nature and magnitude of tectonic processes to be determined.

## Geomorphological setting

The region comprises a series of discontinuous mountain ranges that trend approximately east–west and rise from an extensive desert surface, which has elevations of between 1000 and 2000 m a.s.l., to a maximum of 4231 m a.s.l. in the western Altai Mountains, ca. 3900 in the Gobi Altai Mountains, 4925 m in the Barkol Tagh, 5445 m in Bogda Shan and 6995 m in the Tian Shan. The climate is of semi-arid continental type with summer temperatures that exceed 40°C and winter temperatures that frequently drop below –40°C. In the winter, the region is influenced by the Mongolian High Pressure System (MHPS), which drives strong westerly wind systems and produces snow. The desert is dominantly of reg type, comprising alluvial fans and deeply weathered Palaeozoic, Mesozoic and early Tertiary bedrock with badlands topography. Areas of active sand dunes are restricted in extent. One of the best developed dune areas is north of Dzoolan Uul, and is known locally as the 'Sea of Sand'. The dunes are controlled by the dominant western wind systems and are of barchan and seif type. Most streams are ephemeral, filling during heavy rainstorms and/or as snow melts at higher locations within the mountains during spring time. The few perennial streams are located at spring lines and generally can be traced only for several hundred metres. There are many wells thoughout the region, which have high water levels, with the water table being approximately 2 to 3 m below the surface. Large lakes north of Baga Bogd Uul and Ih Bogd Uul include Orog Nur and Boon Tsagaan No. These are internally drained and have brackish to saline waters. Vegetation is relatively sparse, being usually restricted to xerophytes and grasses, but lush grassy pastures are present where the water table is very high or along spring lines and at higher altitudes within the mountains.

## Methods

Field work was undertaken along the North Gobi Altai and Gobi–Tian Shan fault systems, in southern Mongolia. This included geological and geomorphological mapping and the analysis of structures and landforms, aided by the use of handheld global positioning system receivers, Landsat MSS images and aerial photographs. Selected fault zones were studied to examine the style of deformation and landform associations. These were mapped at scales of 1:20 000 to 1:5000 following established procedures using field survey techniques and a global positioning system to establish location, aided by barometric altimetry and levelling (cf. Owen *et al.*, 1995, 1996). Detailed sedimentological and geomorphological analyses of the alluvial fans and terraces, together with the lacustrine, mass movement and aeolian deposits were undertaken in order to provide important information on the rates and timing of tectonic and climatic events. Unfortunately, suitable material for radiocarbon dating was not found within the research area, and so far the fluvial and aeolian sediment samples that have been used for dating by optically stimulated luminescence (OSL) at Royal Holloway have not exhibited the strong or characteristic OSL signals that are necessary for the dating technique to be successful. Hence, an absolute chronology is not available. Five main study areas include: Gurvan Sayhan Nuruu, Baga Bogd Uul, Artsa Bogd, Tsost Uul and Dzoolan Uul (Fig. 1).

## Alluvial fan sedimentology

The Landsat image in Fig. 4 illustrates the characteristics of alluvial fans within the study areas. They are generally very large, reaching more than 10 km in radius, and converge to form extensive bajadas along most mountain fronts. Most alluvial fans within this region have been deeply incised to their heads. The entrenched channels are generally a few metres deep and several tens of metres wide. This incision provides abundant sections where the alluvial fan sedimentology can be examined. The main alluvial fan sediments comprise angular to subrounded cobbles and pebbles which are clast-supported or supported in a matrix of medium to coarse sand. Many clasts are imbricated, the bedding is gradational, with crude decimetre-thick units that dip between 1 and 4°C, subparallel to the surface of the alluvial fan (Figs 5 and 6). Throughout the region these beds are involuted and ice-wedge casts are locally present. The involutions occur in a variety of lithologies ranging from coarse gravels to silts, and they range in shape from Vandenberghe (1988) type 2, 4 and 6 involutions, and in some cases they are over a metre in diameter. The majority of the fan surfaces are extremely smooth, comprising small pebbles and sand. Boulders on the surface of the fans have been deeply weathered, producing small pebbles and sand. These surfaces are deflated of fine sand and silt, and some fan surfaces are calcreted to a depth of approximately 50 to 100 cm (e.g. at the western end of Gurvan Sayhan Nuruu, 43°38′N, 102°19′E). On some of the fan surfaces (e.g. at 44°23.2′N, 102°24.8′E; 44°20.4′N, 102°25.6′E; and 44°23.7′N, 102°18.9′E) there are jasper flake artefacts. The artefacts have undergone little or no modification since the period that they were produced. All these observations suggest that in most regions the alluvial fans are no longer actively aggrading.

The fan head entrenchment allows an estimate of the thickness of the alluvial fan sediments to be determined because the channels frequently erode into the underlying bedrock. Most Quaternary fanglomerates were found to be no more than 3 m thick. This suggest that the fans form a thin veneer over most of their extent. However, debris flow cones and scree slopes that mantle the hill slopes above the alluvial fans provide much more debris to the apex of the fan, thus thickening and steepening the fans. The fan surfaces at these locations are very rugged, as a result of large recent debris flow levees and rock avalanche deposits.

Within the main entrenched channels a series of terraces at lower elevations rise in elevation from a few decimetres to several metres above the active channel (Fig. 7). The terraces consist of sediments similar to the main alluvial fan deposits, which contain dominantly angular to subrounded cobbles and pebbles that are clast-supported or supported in a matrix of medium to coarse sand and constitute decimetre-thick crudely defined beds that dip subparallel to the surface of the fan. The clasts within these beds are frequently imbricated.

The floors of the entrenched channels and the recent ephemeral channels comprise angular to subrounded cobbles and pebbles which are clast-supported or supported in a matrix of medium to coarse sand. The clasts are frequently imbricated within metre-wide channels.

## Alluvial fan deformation

Landsat images show clear lineaments across many of the alluvial fans, which were identified as faults in the field (Fig. 4). These are picked out by spring lines, offset streams and surface ruptures. Locally, fault systems occur as a single fault trace, but along other segments, deformation and displacement are distributed across a wide zone containing numerous subfaults and splays, together with restraining bends, push-up ridges and small basins. Surface deformation of alluvial fans, however, was not commonly observed in the areas visited. The best examples of fault scarps were observed along the north side of Baga Bogd, where rupture scarps up to several metres high are present, resulting from the 1957 earthquake (Baljinnyam *et al.*, 1993) (Fig. 8A). Deformation of recent sediments is limited to a few locations. The following examples characterise the style of deformation throughout the study region.

### North Artsa Bogd

The northern edge of Artsa Bogd is delimited by a series of thrust faults that propagate into the foreland of the mountains, forming a series of laterally continuous ridges of red marlstones, sandstones and conglomerates (Fig. 8B). One of the best examples of neotectonically deformed Quaternary sediments occurs within a ridge approximately 4 km north of the main mountain front. Here fanglomerates and associated fine-grained sediments are deformed. This can be seen in Fig. 9, where the marlstones and Quaternary sediments have been faulted and there is a clear surface warping resulting from the propagation of the thrusts towards the surface. Nearer the mountain front (44°40′N, 101°58′E) pre-Quaternary rocks have been progressively eroded and redeposited because they have been deformed into an open fold with axes trending subparallel to the mountain front.

### North Baga Bogd Uul

The most impressive deformed Quaternary sediments are along the northern edge of Baga Bogd, where a series of small faulted escarpments have formed in the foreland of the mountains. The escarpments comprise polymictic subangular to subrounded pebbles and cobbles which have crude

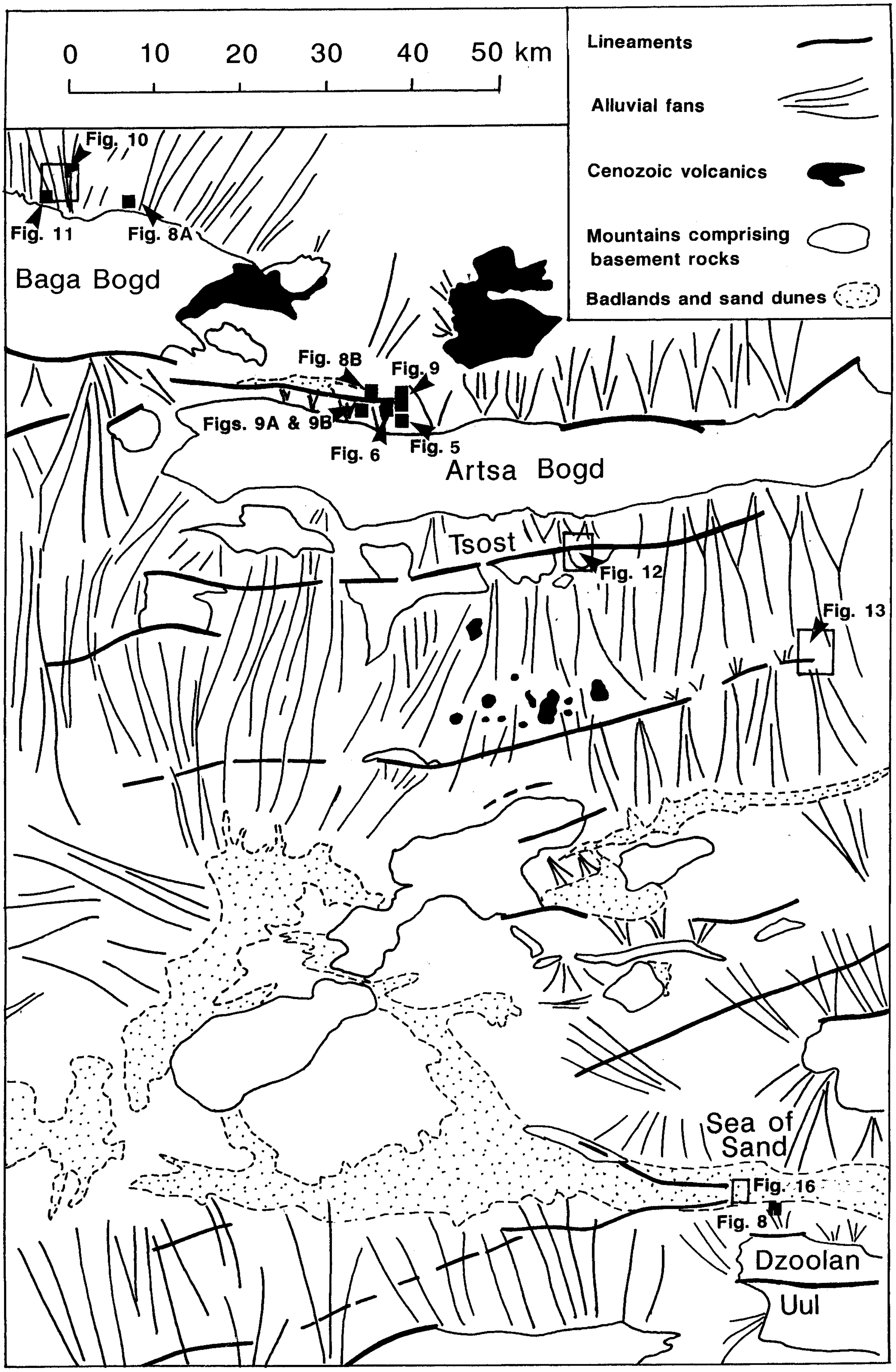

**Figure 4** (B) Interpretation of the Landsat image shown in Figure 4(A).

**Figure 5** Section through an alluvial fan on the northern side of Artsa Bogd (44°35.6′N, 102°14.8′E) showing typical Holocene fanglomerates dominated by imbricated angular to subangular large pebbles and cobbles. Location shown in Fig. 4B.

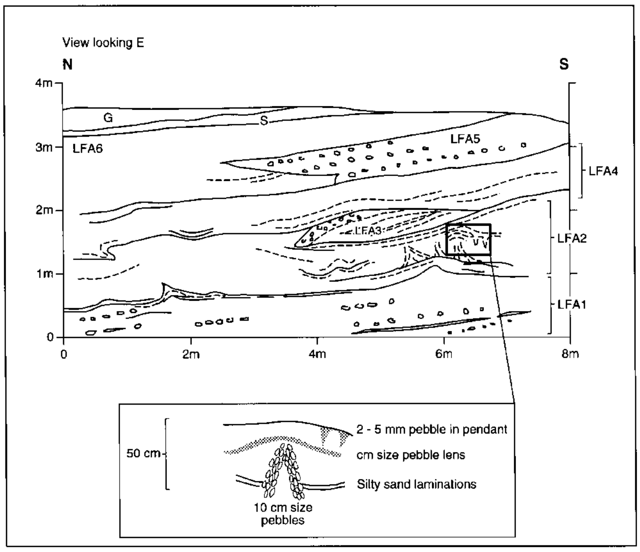

**Figure 6** Section through an alluvial fan on the north side of Artsa Bogd (44°38.2′N, 102°07.0′E) illustrating the sedimentology that is typical of alluvial fans in the Gobi Altai Desert. Location shown in Fig. 4B. *Lithofacies Associations*. LFA1: crudely stratified decimentre- to centimetre- thick bed of poorly imbricated matrix-supported subangular to subrounded pebbles (5–10 cm diameter) with occasional <1-cm-thick lenses of planar laminated fine sand. The stratification is subparallel to the present fan surface. LFA2: planar cross-bedded pebbly silty sand with deformed pebble lenses (centimetres thick, decimentres wide to m wide). LFA3: channel-fill approximately 30 cm deep and 2.5 m wide comprising matrix-supported pebbles. LFA4: crudely stratified, imbricated clast-supported pebbles (2 to 10 cm diameter). The stratification is subparallel to the present fan surface. LFA5: channel-fill approximately 1 m deep and > 4 wide comprising matrix-supported pebbles. LFA6: crudely stratified matrix-supported gravel. The stratification is subparallel to the present fan surface.

decimetre- to metre-thick bedding that dip southwards, subparallel to the dip surface of the small escarpments (Fig. 10). Figure 11 shows the geomorphological characteristics of this region. Lacustrine sediments immediately south of each of these faulted blocks represent ponding of water after the initial formation of each escarpment and prior to breaching of the escarpment by streams. Alluvial fans have subsequently aggraded around each of the fault blocks, but have not completely buried the lacustrine deposits.

## Tsost Uul

An impressive series of narrow mountain ridges comprising Palaeozoic and Mesozoic rocks are present in this region. Their formation is related to transpression within a well-delimited fault zone (Cunningham *et al.*, 1997). Figure 12 shows the characteristic of the alluvial fans immediately north of the main mountain ridge at Tsost. Here the main Quaternary alluvial fans have been deeply incised at their toes by a ephemeral stream which trends eastward subparallel to a mountain ridge before it breaches the ridge southwards. The alluvial fan sediments comprise involuted matrix-supported subangular to subrounded imbricated pebbles and cobbles. South of the alluvial fans and the ephemeral channels, an impressive, but deeply dissected planation surface slopes between 1 and 2° towards the south. The surface of planation is very smooth, comprising angular small pebbles and sand derived from the weathering of larger clasts. Locally, thin (<50 cm thick) deposits of calcreted conglomerates cap the surface. These deposits unconformably overlie steeply dipping red marlstones, sandstones, conglomerates, and phyllites. Figure 12 shows an extrapolation of this surface northwards, and an extrapolation of the more recent alluvial fans surfaces towards the south. The relative displacement of these two surfaces is at least 10 m. This suggests that the planation surface has been uplifted differentially as the mountain range at Tsost developed in respect to the Quaternary alluvial fans. The uplift was also important in controlling the trend of the ephemeral stream.

About 15 km east of the latter location, at the western end of a series of major mountain ridges along another fault zone (44°15′N, 102°35′E), impressive cresent-shaped ridges comprising red standstone and conglomerates of Cretaceous age rise to elevations of approximately 4 to 5 m above the surrounding alluvial fan surfaces. Figure 13 shows the characteristics of these landforms. It is likely that these ridges are the surface expression of thrusts associated with a horsetail splay termination zone at the eastern end of the fault system (Cunningham *et al.*, 1997).

## Northwest Bayan Tsagaan, Gurvan Sayhan Nuruu

This is a complex fault zone at the western end of Gurvan Sayhan Nuruu. Cunningham *et al.* (1996) proposed that ranges in this region form a horsetail splay termination zone at the eastern end of the Gobi–Tian Shan fault system. Impressive alluvial fans are present along the northern front of Bayan Tsagaan. Figure 14 shows an example of a deeply eroded alluvial fan which overlies red sandstone and conglomerates and which is folded into an open anticline that has a wavelength of approximately 2 km. The main alluvial fan sediments are involuted, but the smaller terraces that are within the entrenched channel are not. Figure 14 and 15 shows that the surface of the fan is subtly deformed above the crest of an anticline within the bedrock.

# Fluvial sedimentation north of Dzoolan Uul

North of Dhoolan Uul, impressive exposures of sands and gravels underlie the 'Sea of Sand' (Fig. 16). These sediments

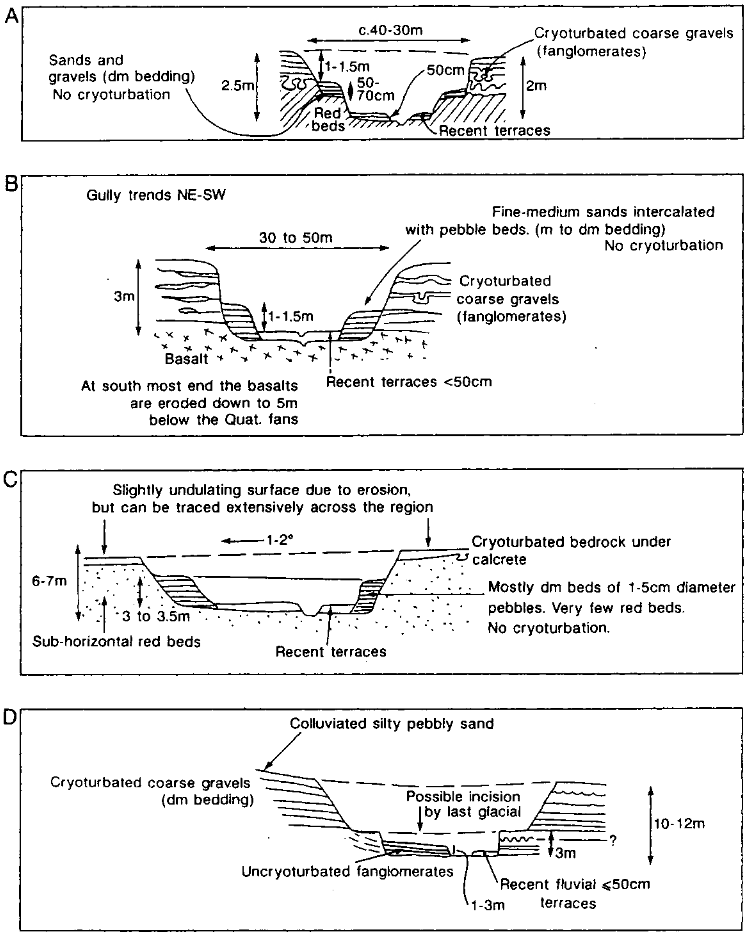

**Figure 7** Schematic sections through alluvial fans from selected areas. (A) Southeast of Tsost on the southern side of the Tsost Uul Mountain range (44°15.35′N, 102°31,42′E at approximately 1370 m a.s.l.), the fan slopes towards the south. (B) Southeast of Tsost village on the southern side of the Tsost Mountain range (44°22.58′N, 102°26.16E at approximately 1370 m), the fans slope towards the south. (C) Southwestern end of the Dzoolan Uul (43°37.93′N, 102°19.10′E at about 1830 m), the alluvial fan surfaces slope towards the south, but the incised channels trend westwards. (D) North–south section through the valley in Bayan Tsagaan (43°48′N, 103°12′E at approximately 2100 m). Note the recurrent pattern of incised cryoturbated Quaternary fan deposits, small terraces of Holocene sediments which are not cryoturbated, and very low recent terraces.

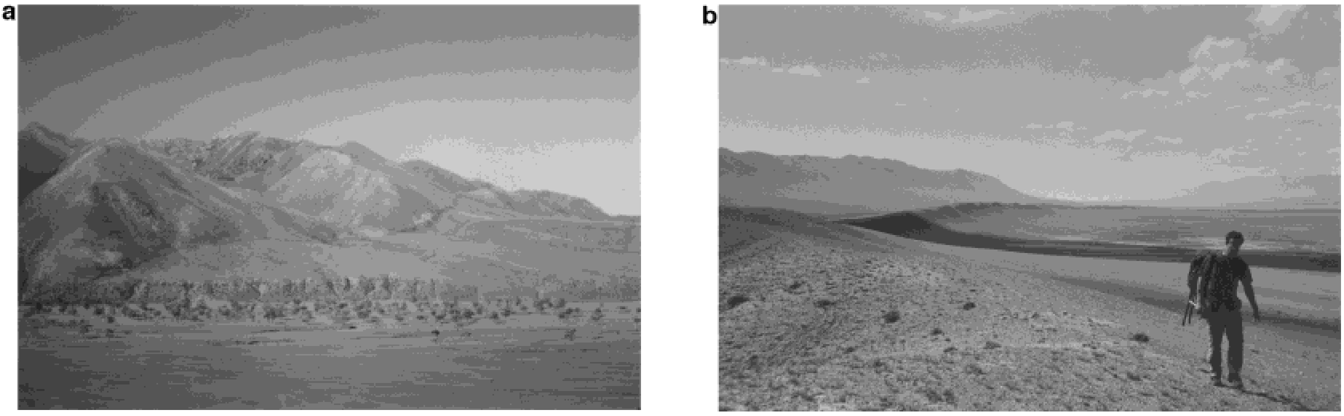

**Figure 8** (A) View south of an alluvial fan on the north side of Baga Bogd showing part of the surface rupture associated with the 1957 earthquake (44°54.4′N, 101°41.4′E). Location shown in Fig. 4B. (B) View looking west along a neotectonic ridge north of Artsa Bogd (44°38.9′N, 102°05.1′E). Location shown in Fig. 4B.

dip gently (<2°) to the south and probably represent the surface expression of a northerly propagating blind thrust fault that is associated with the transpressional uplift of Dzoolan Uul. Figure 16 shows the sedimentology of these deposits. They comprise well-sorted sands and polymictic gravels, which are rippled and have graded beds constituting decimetre-size sets. Well-defined channel fills are several metres wide and have steep channel sides, decimetres to a metre in depth. Along the southern edge of the exposures, poorly sorted, subangular polymictic gravels with centimetre- to decimetre-thick, low-angled stratified and cryoturbated fanglomerates clearly overlie the finer units described above.

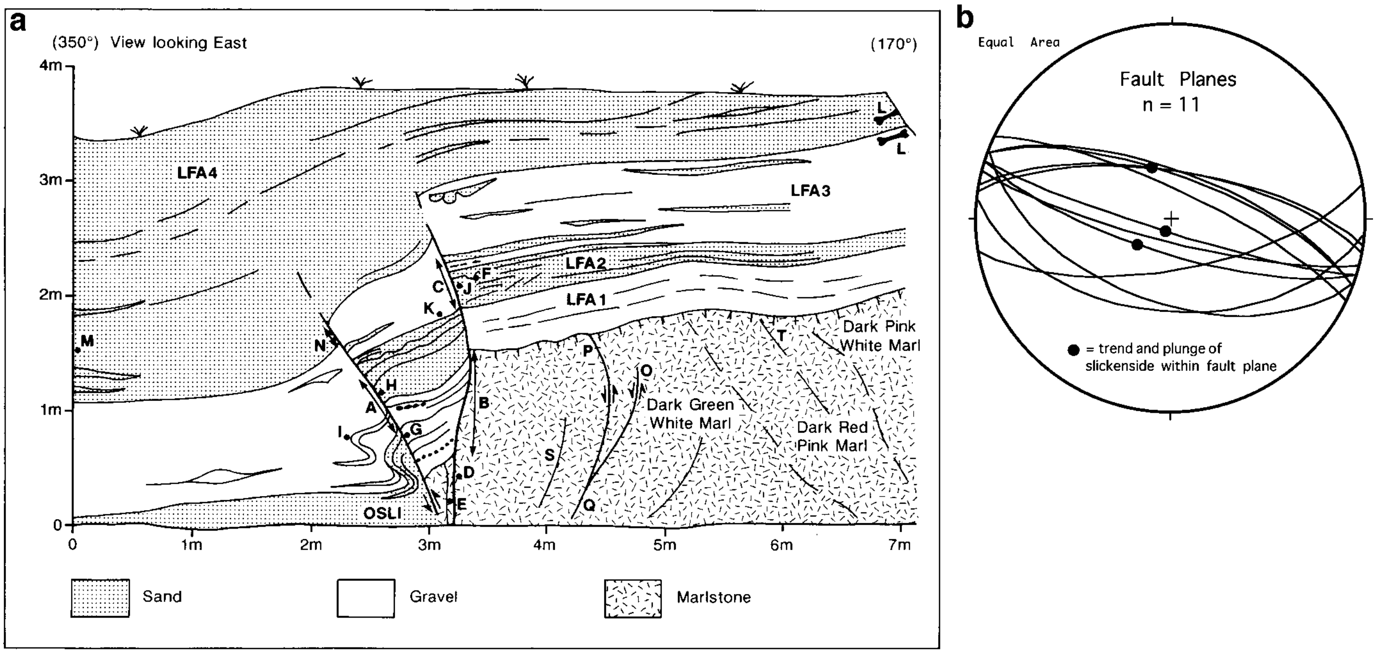

**Figure 9** (A) Recent faulting in Quateernary sediments at 44°38.40′N, 102°07.29′E showing the main structures and lithofacies association. Location shown in Fig. 4B. (B) The lower hemisphere stereonet plots of the fault plane orientations that were measured at positions D, E, G, H, O, P, Q, R, S, T and U. Vertical fault offsets at position: A = 45 cm; B = 95 cm; C = 47 cm; and N = 23 cm. Bedding planes are orientated at position: K = 100°/48°N; L = 110°/8°N; and M = 105°/48°N. *Lithofacies Association.* LFA1: metre-thick planar bed of small subangular to subrounded pebbles with occasional < 1-cm-thick beds of sand, which thin out laterally and drape underlying pebbles. Along some of the horizons the pebbles are clast-supported, although most are matrix-supported. LFA2: planar bedded, planar laminated fine sand with occasional course sand grains. The top centimetre is ironed stained. In places fine <1-cm-amplitude and 2-cm-wavelength ripples are present. The unit thins southwards. LFA3: Dominantly < 1 to 7 cm diameter pebbles with centrimetre-thick crude planar stratification. These are intercalated with finely rippled cross-laminated centimetre-thick lenticular beds of fine to course sand. Some silt beds can be traced for severalmetres and are < 10 cm thick Pebbly beds are dominantly matrix-supported by medium sand to coarse sand. The ratio of sand to pebbles is approximately 3:7. LFA4: dominantly decimetre-bedded with planar laminated fine sand and coarse silts. These are intercalated with lenses of pebbles ca. 5 cm thick and several metres long. The pebbles are polymictic; limestone is the dominant lithology.

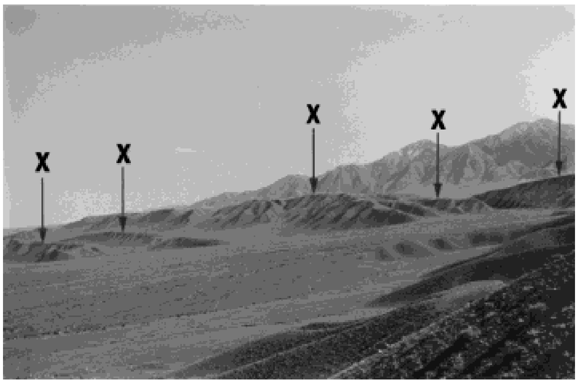

**Figure 10** View looking south-southeast at part of the alluvial fans north of Baga Bogd (ca. 44°54′N, 101°41′E), showing the deformed blocks of Quaternary sediments (labelled X) buried within the most recent alluvial fan. Location shown in Fig. 4B.

## Discussion

Most alluvial fans in this region are ancient, being deeply incised to their heads, and active deposition is constrained within the entrenched channels and along the margins of the mountain fronts, where mass movement processes dominate. The presence of involutions and ice-cast wedges within the majority of alluvial fan deposits suggests that the fanglomerates were subjected to permafrost processes. The styles of involution vary considerably, but they are characteristic of those produced by active layer processes (Vandenberghe, 1988; Van Vliet Lanoë, 1988). The presence of ice-wedge casts within the same horizons as the involutions supports the view that these structures have a permafrost origin. Furthermore, the criteria of Sim (1975) that is used to attribute such structures to seismic events is not satisfied. Rather, the involutions are not laterally continuous throughout the entire length an of exposure, the involutions are not confined to one particular lithology or to a unique stratigraphic horizon, there is no spatial concentration of involutions or spatial distribution of particular involution types. The younger, smaller terraces within the alluvial fan channels comprise fanglomerates and are not cryoturbated. These were, therefore, not subjected to permafrost conditions. This strongly suggests that the majority of alluvial fan sedimentation took place during the Pleistocene, when permafrost developed in a cold climate. In contrast, the fan head entrenchment and formation of terraces within the alluvial fan channels occurred during Holocene times when fan incision dominated. The cryoturbated sediments are, therefore, a useful stratigraphic horizon, which can be used to help correlate and constrain the rates of deformation in southern Mongolia.

The fluvial sediments north of Dzoolan Uul have a very different style of deposition from those of the Holocene and Pleistocene alluvial fans. The sedimentology is suggestive of a period of sedimentation when surface waters were more abundant and well-constrained streams flowed across the region. Structurally, these sediments are clearly older than most of the alluvial fans. It is unlikely that the sedimentology reflects a period when the mountains were lower and sediment supply was less. The polymictic nature of the conglom-

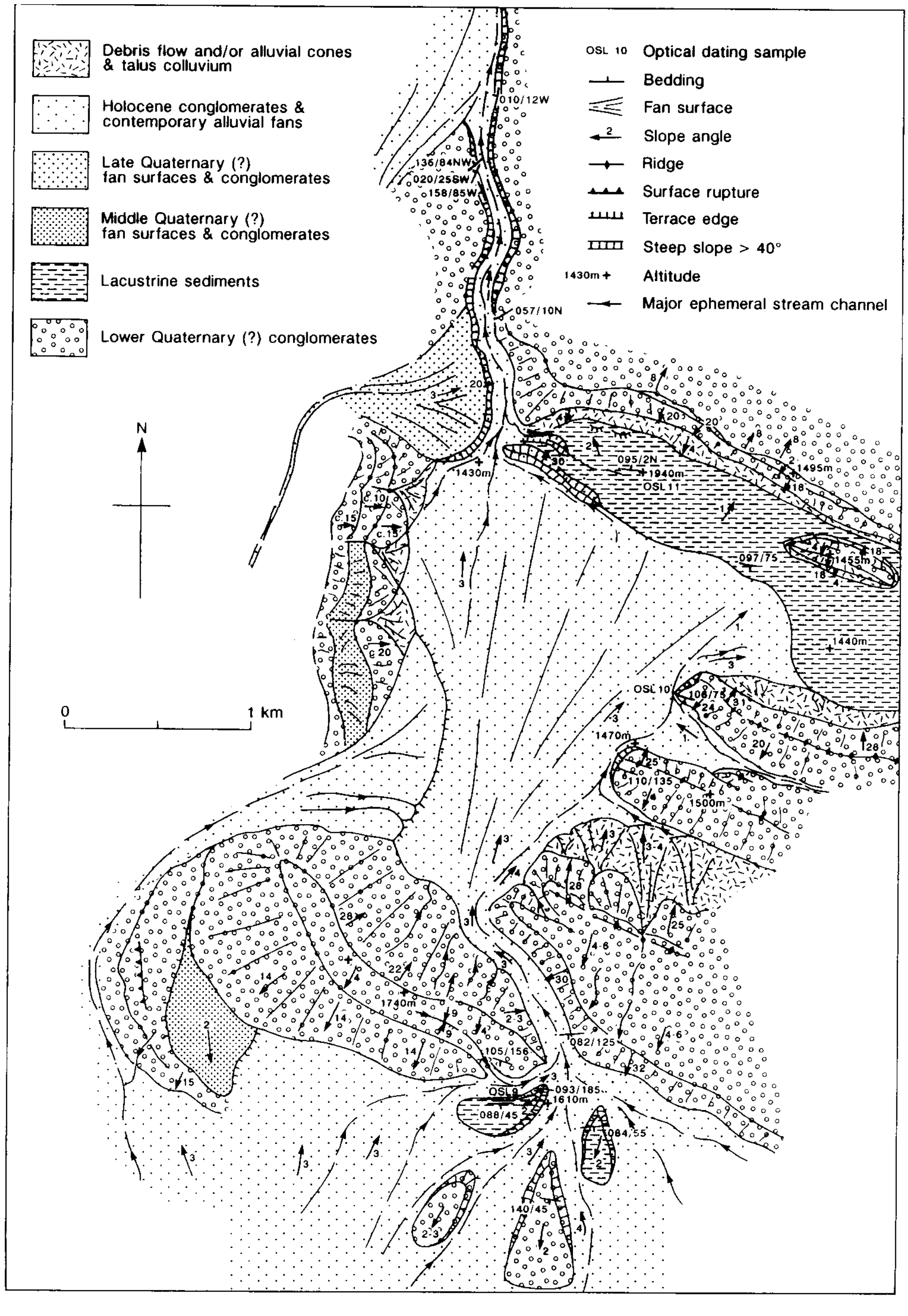

**Figure 11** Geomorphological map of part of the alluvial fans north of Batga Bogd (ca. 44°54′N, 101°41′E), showing the main Quaternary formations and illustrating the nature of the neotectonic deformation. Location shown in Fig. 4B.

erates under the 'Sea of Sand' supports the assertion that the Dhoolan Uul mountains were sufficiently high to allow the lithologies within these sediments to be derived from the erosion of a relatively high mountain range. This pattern of alluvial fan formation is therefore considered to be strongly controlled by climate.

Attributing alluvial fan aggradation to climatic period is difficult. The fluvial sediments north of Dhoolan Uul suggest that climate was sufficiently wet to allow perennial streams to develop before the alluvial fans formed. Clearly, the main sedimentation and alluvial fan formation must have occurred before Holocene times, during a period when flash flooding dominated the fluvial regime allowing the transportation of large amounts of sediments. It must have also been sufficiently cold to allow permafrost to develop. This suggests that this region has become more arid during the late Quaternary times. This assertion is difficult to prove, however, because of the lack of any absolute dating. To the south on the Tibetan Plateau and in the Himalayas, other proxy evidence supports the view that aridity increased throughout late Quaternary times. On the basis of the lacustrine sedimentology within Qaidam Basin, northern Tibet, Chen and Bowler (1986) recognised a period of lake expansion from before 40 ka to about 25 ka, after which there was a phase of desiccation to about 9 ka. On the basis of palaeoshorelines and the geochemistry of Ostracoda in lacustrine sedi-

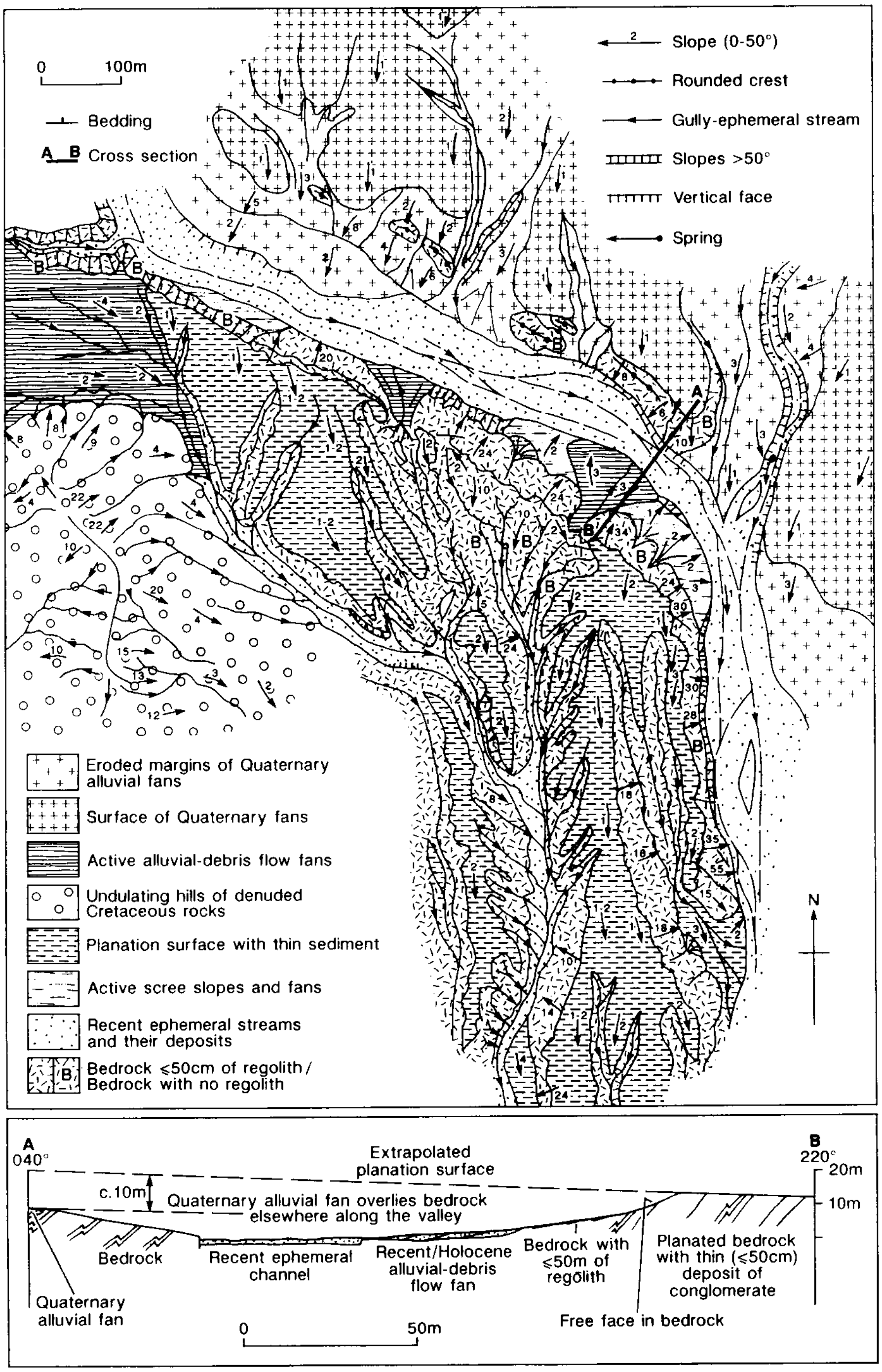

**Figure 12** Geomorphological map of area around Tsost (44°25′N, 102°20′E), showing landforms and the relative displacement of an early Quaternary planation/alluvial fan surface as compared with the position of the late Quaternary alluvial fans (section A–B). Location shown in Fig. 4B.

ments in the Tengger Desert, north of the Qilian Mountains, Pachur *et al.* (1995) inferred humid/cool conditions from about 39 $^{14}$C ka to about 23 $^{14}$C ka. After which, the climate became dry and aeolian activity dominated as lake levels dropped. This was followed by the reestablishment of wet conditions after ca. 13 000 yr BP. Similarly, Lister *et al.* (1991) showed, on the basis of sedimentological evidence and the oxygen isotope record for Ostracoda, that Qinghai Lake in northern Tibet was experiencing a phase of aridity from before about 14.5 ka until about 10.2 ka, after which time lake levels rose substantially due to increased precipitation. In addition, the the Zunggar Desert, northern Xinjiang, western China, Rhodes *et al.* (1996) showed on the basis of lacustrine sediments from Lake Manas, that at between 37 $^{14}$C ka to 32 $^{14}$C ka humid conditions prevailed and that this was followed by a period of extreme aridity until about 12 ka.

On the basis of glacial evidence, Owen *et al.* (1996, 1997) and Derbyshire and Owen (1997) have shown that glaciation became progressively less extensive and more constrained in the mountains of high Asia during late Quaternary times. They suggest that this may be the result of differential uplift of the Himalayas restricting the supply of moisture from the Indian monsoon into the Greater Himalayas and Tibet, or that it may be a function of global climate change that had a widespread effect on central Asia. Such correlations are highly tentative. However, it seems unlikely that Himalayan uplift directly influenced climate

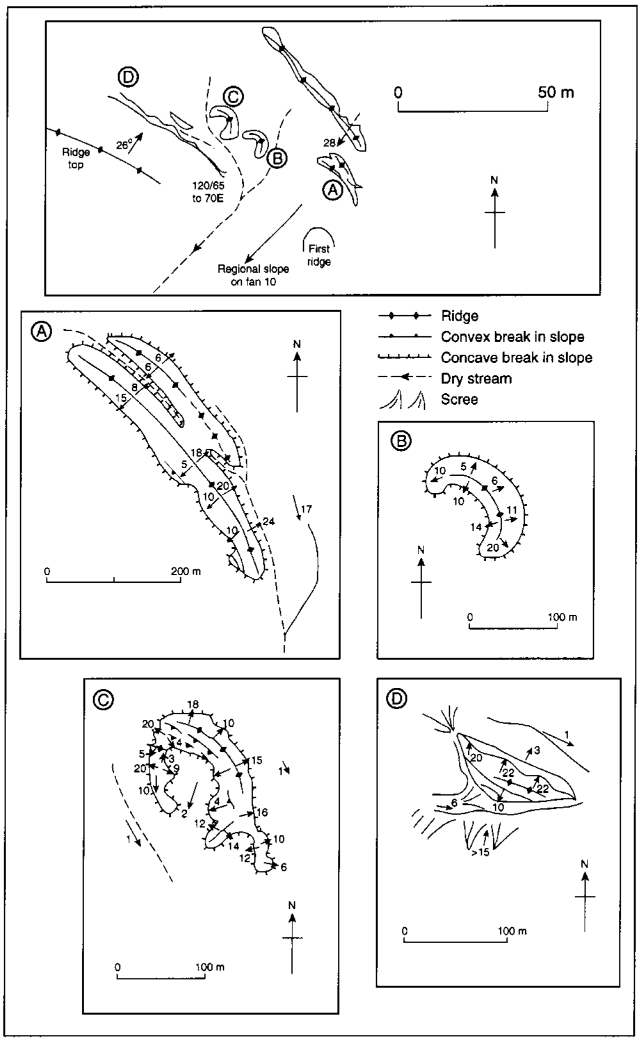

**Figure 13** Geomorphological map showing the characteristics of small push-up ridges at the western end of a fault segment, 15 km west of Tsost. Location shown in Fig. 4B.

**Figure 14** View looking southwest across main valley exit from the Bayan Tsagaan showing the deformed fan surface. Note how the surface tilts towards the mountain front.

change in Mongolia. Even if the Himalayas were substantially lower during the Pleistocene the effects of the Indian monsoon in Mongolia would have been minimised by the blocking effect of the MHPS. This increased aridity, therefore, may be a regional trend for central Asia, suggesting that the growth of Northern Hemisphere ice sheets during Oxygen Isotopic Stage 2 may have been reponsible for the increased aridity in central Asia. Thus, the sediments under the 'Sea of Sand' might be correlated tentatively with the high lake levels of Qaidam, Tengger, and Zunggar before about 40 ka and up to about 23 ka. Care must be taken with this correlation, because the sediments within the 'Sea of Sand' could, of course, represent an older humid phase. The lack of any sediments between the perrennial channelled sands and the main ephemeral alluvial fan sediments suggests that this time gap is small and that the 'Sea of Sand' sediments were deposited between 40 ka and 23 ka.

Bull (1977) highlighted that periods of alluvial fan accumulation may coincide with climatically controlled times of increased sediment yield of the source area or decreased competence of transportational processes. During periods of

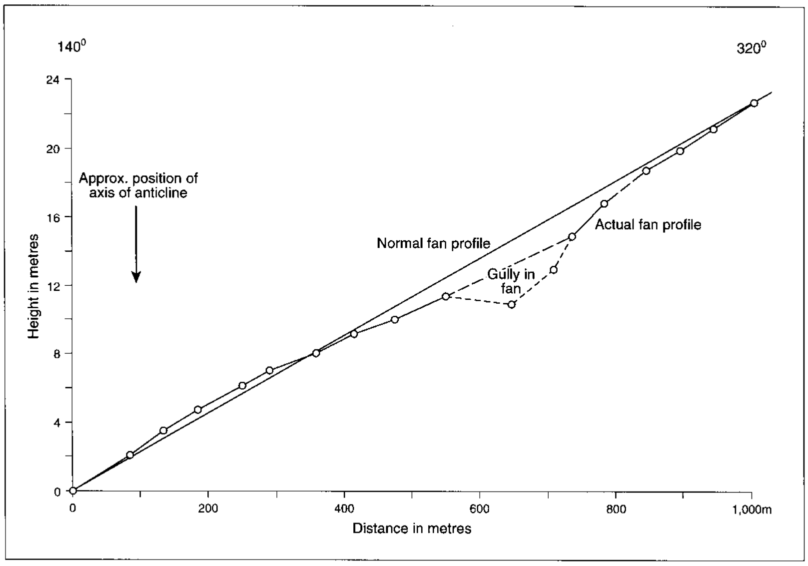

**Figure 15** Profile of the fan surface south of the main valley exit from the Bayan Tsagaan.

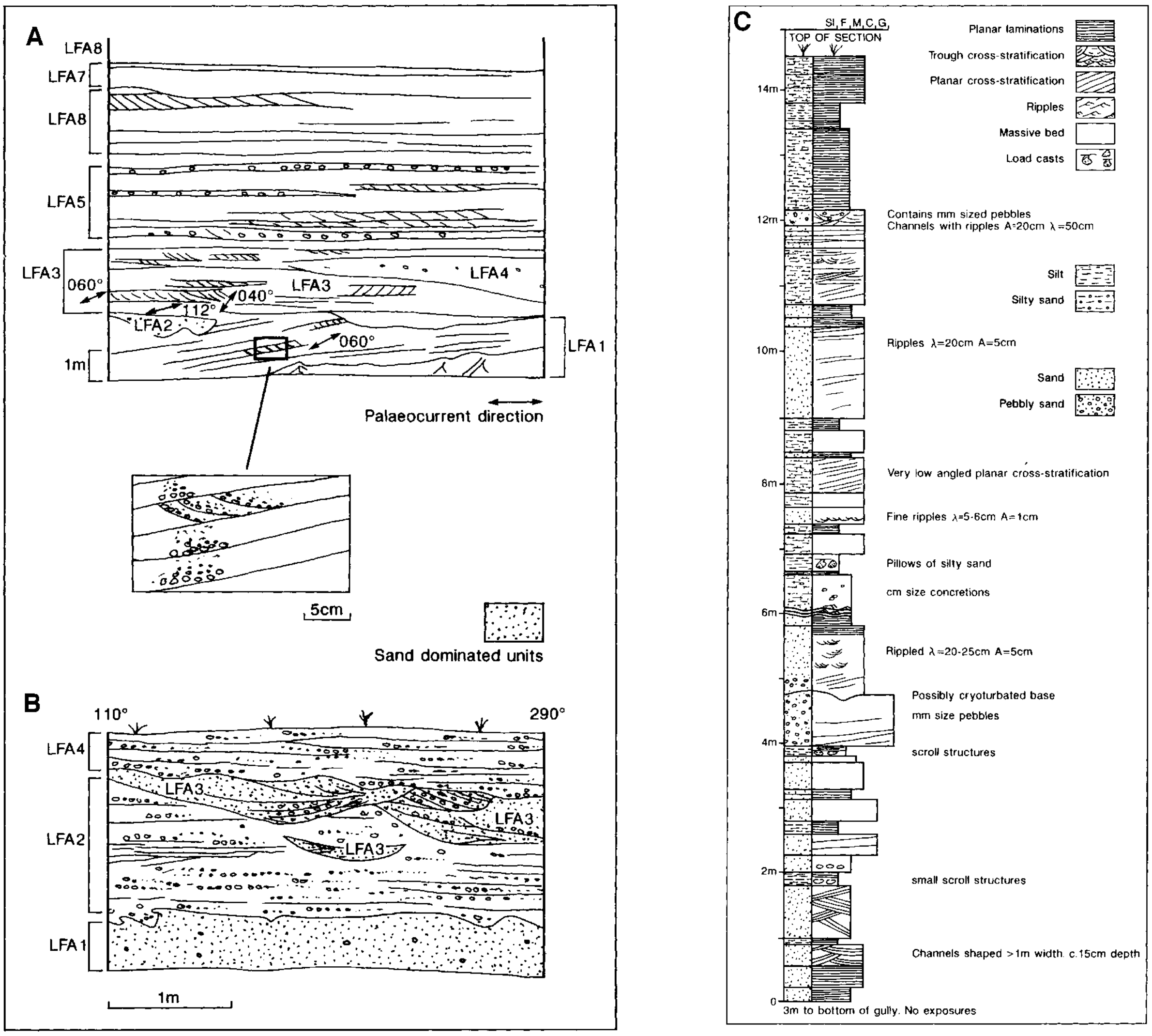

**Figure 16** Section through Quaternary deposits north of Dzoolan Uul, within the 'Sea of Sand': (A) looking northeast at 43°43.54′N, 102°22.50′E with an elevation of 1500 m. LFA1: ≤1-cm size pebbles in a sandy matrix, with planar cross-stratified sets between 10 and 15 cm thick. LFA2: channel fills 0.5 m to 1.5 m deep and 3 m to 15 m wide with irregular erosional lower contacts. These are planar stratified with 10-cm-size pebbles, matrix-supported in coarse to medium sand together with occasional large pebbles (≤30 cm) and interclasts of sand. LFA3: decimetre-thick beds of planar cross-stratified silty medium to coarse sand with metre-wide channel fills. LFA4: large channel fill >60 m wide and 1.5 m deep, comprising a massive unstratified pebbly (millimetre and centrimetre size) medium to coarse sand. The upper 5 cm are crudely stratified. LFA5: decimeter-thick beds of alternating cross-stratified coarse to medium sands and channel fills >20 to 30 m wide and ≪1 m deep comprising matrix-supported pebbles (1 cm size). LFA6: planar decimetre-thick beds of coarse to fine sand with trough and very low-angled planar cross-stratification. The beds are draped with centimetre-thick beds of laminated silt with desiccation cracks. Millimetre to ≤1-cm-size pebbles are present with low-angled cross-stratified horizons in some beds together with interclasts of desiccated silt. Overall this LFA fines upwards. LFA7: 0.5- to 1-m thick planar bed of silty coarse sand with horizons of millimetre-size pebbles, with an erosive base. Very crude low-angle cross-stratification is picked out by the pebbles. LFA8: not shown on diagram! 3 m of decimentre- to metre-size planar beds of sand with horizons of centimetre-size pebbles interbedded with centimetre-thick planar beds of laminated silt. Lithoclasts: jasper, greenschist, psammites, serpentinite, quartz-feldspar pegmatite, grey and black chert, vein quartz, and slate. (B) Looking north at 43°37.42′N, 102°50.23′E) at an altitude of approximately 1737 m. LFA1: massive silty fine--medium sands with occasional millimetre-size pebbles. LFA2: erosive base, although in some places the lower bedding contact is loaded into the underlying beds. 1–5 cm diameter subangular pebbles, within very low-angled planar stratified and occasional very low-angled cross-stratification 1–3 cm sets. The pebbles are imbricated and matrix-supported by sand. The sandier layers help pick out the stratification. LFA3: Trough cross-stratified channel fills, 10 cm to 30 cm deep and 0.5 m to 5 m wide. These comprise mainly fine to course sand which fines upwards, often containing 1 cm size pebbles at the base. LFA4: massive silty fine–medium sands with occasional millimetre-size pebbles. Lithoclasts: Ophiolithic dolerite, greenschist, greenstone, red sandstone, red marlstone, red conglomerate, jasper, granite porphyry, calcite nodules and quartzite. (C) Graphic sedimentary log of the sediments in (A). Location shown in Fig. 4B.

greater aridity the spatial continuity of fluvial systems would be less and the relative effectiveness of major storms for the transportation of sediment would be greater, hence leading to a more consistent aggradation in drier regions (Baker, 1977; Wolman and Gerson, 1978; Brunsden and Thornes, 1979). In contrast, wetter periods coincide with increased incision. Bull (1964), for example, showed that increased channel incision since 1855 in the alluvial fans of western Fresno County (California) could be attributed to periods of above-normal stream flow caused by large rainfall. Many workers (e.g. Beaumont, 1972; Lustig, 1965; Harvey, 1984, 1990; Wells *et al*, 1987) have shown that alluvial fan aggradation in semi-arid regions is usually associated with dry conditions during glacial times, whereas fan degradation or stabilisation is dominant during interglacial times. The main Quaternary alluvial fans in the Gobi probably formed between 23 ka and about 13 to 9 ka, when the region was more arid and flash flooding dominated the fluvial regime. During this period, temperatures would have been sufficiently cold to allow the development of permafrost. In the Late Pleistocene–Early Holocene (after about 13 to 9 ka) the permafrost would have degraded, allowing incision of the alluvial fans and formation of terraces within the entrenched channels.

The distribution of alluvial fans is clearly controlled by tectonics because they develop from tectonically uplifted mountain ranges. Unfortunately, the alluvial fans are of only limited use for calculating rates of strike-slip movements. This is because there is little evidence of strike-slip faulting within the alluvial fans, and deformation is restricted to warping and thrust faulting related to the development of positive flower structures. Figure 17 summarises the characteristic landforms associated with the fault zones in southern Mongolia. Vertical displacements landforms associated with the fault zones in southern Mongolia. Vertical displacements of Quaternary fan surfaces are also difficult to assess but, given the examples described above, a maximum value for uplift can be calculated. For example, the minimum displacement at Tsost Uul is about 10 m and, given that the Quaternary alluvial fans are probably younger than 25 ka, the uplift rate with respect to the higher planation surface gives a maximum value of 0.4 mm yr$^{-1}$ (10 m 25 ka$^{-1}$). The maximum relative elevation of escarpments north of Baga Bogd is approximately 130 m. However, the age of the deformed sediments here is more difficult to determine. This is because they are much thicker than the main alluvial fan sediments, so they may be much older. Their likely period of deposition is probably much longer than 14 000 yr (25 ka to 13–9 ka). If these sediments are contemporaneous with the alluvial fan sediments elsewhere in the region, they provide a maximum uplift rate of 5.2 mm yr$^{-1}$ (130 m 25 ka$^{-1}$). The sediments under the 'Sea of Sand' have a relative relief of approximately 15 m compared with the elevation of the surrounding desert floor. Given that these sediments probably antedate 40 ka, they give a maximum uplift rate of 0.37 mm yr$^{-1}$ (15 m 40 ka$^{-1}$). These maximum uplift rates provide values of between approximately 0.37 and 5.2 mm yr$^{-1}$, although it must be recognised that they may represent localised uplift rates only.

## Conclusions

Alluvial fans in southern Mongolia have formed as a consequence of sedimentation along a series of narrow mountain ranges which are the result of transpression along major Cenozoic strike-slip fault systems. Their sedimentology and geomorphology, however, are mainly products of processes that were controlled by climatic changes. The alluvial fan sedimentology and geomorphology suggest that southern Mongolia became progressively more arid during late Quaternary times. Tentative correlations with the Qaidam Basin on the northern edge of Tibet, the Zunggar Desert in northern Xinjiang and the Tengger Desert north of the Qilian Mountains suggest that, prior to about 40 ka and up to about 23 ka, the region may have experienced humid conditions. During this time the alluvial fan environment may have been dominated by perennial streams and hence the early alluvial fan sedimentology reflects these conditions, and may be dated tentatively as between 40 ka dn 23 ka, although the alluvial fan sedimentology may represent an earlier humid phase. These humid conditions were followed by a period of increasing aridity, when alluvial fans formed as ephemeral streams deposited coarse fanglomerates and permafrost developed to produce active-layer structures. With climatic amelioration during early Holocene times, the permafrost degraded and fan incision and entrenchment dominated, with sedimentation confined to the upper reaches of the fans, adjacent to steep mountain slopes, and within the entrenched channels.

The alluvial fans have been neotectonically deformed, faulted and warped by small thrust faults that propagate from the mountain front into the foreland. Localised uplift rates are of the order of 0.1 to 1 m ka$^{-1}$. More detailed geomorpholocial and geological mapping as well as precise dating is required to help constrain the timing of these events and to quantify rates of uplift.

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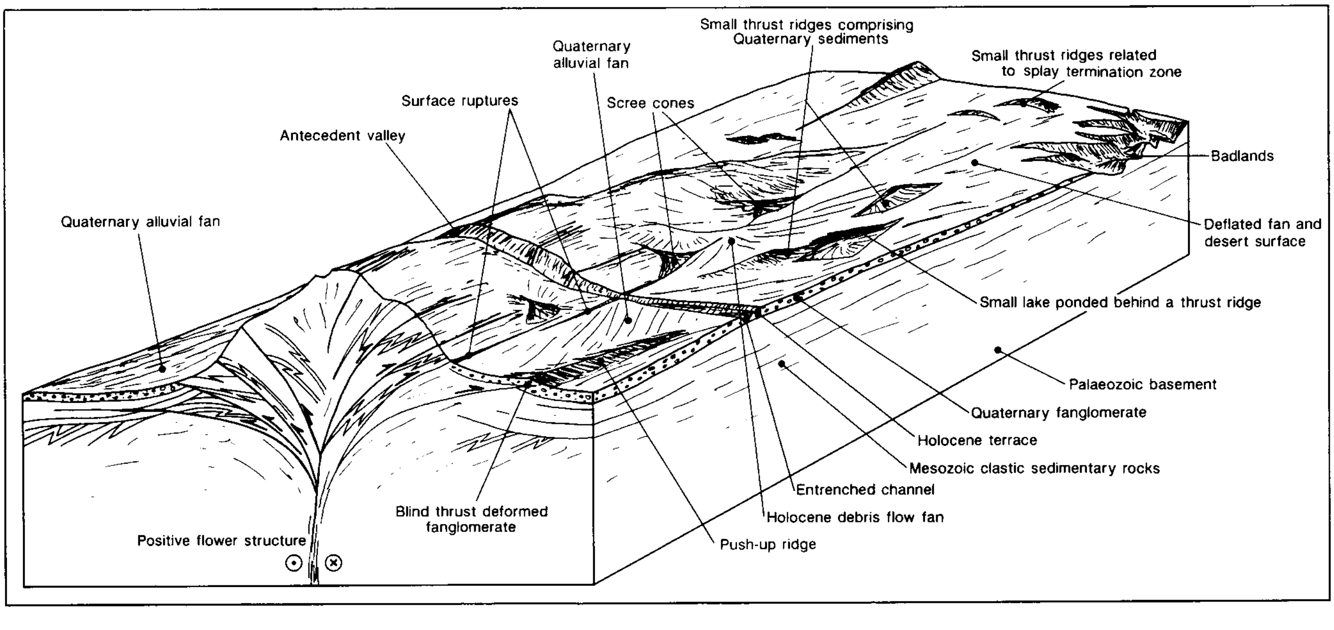

**Figure 17** Schematic model for the structures and landforms associated with a typical fault zone in southern Mongolia.

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