Geological Society, London, Special Publications

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Geological Society, London, Special Publications 1999; v. 162; p. 201-218
doi:10.1144/GSL.SP.1999.162.01.16

The landscape evolution of Nemegt Uul: a late Cenozoic transpressional uplift in the Gobi Altai, southern Mongolia

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Abstract: The geomorphology and structural geology of Nemegt Uul, Southern Mongolia, is examined as an example of a mountain range that has formed within a restraining bend along a major intracontinental strike-slip fault system, the Gobi–Tien Shan fault system. Structural and geomorphological analysis demonstrates that the mountain belt is young and has been differentially tilted and eroded. A geomorphological model is developed showing that uplift and erosion have resulted in the formation of deeply incised mountains, alluvial fans, badlands, desert pavements and dunes.

The Gobi Altai Mountains of southern Mongolia comprise a series of discontinuous ranges that trend approximately east–west into northwest China (Fig. 1). The Gobi Altai rise from an extensive desert surface, which has elevations of between 1000 and 2000 m, to a maximum of 3957 m in Ih Bodg. Cunningham *et al.* (1996, 1997) and Cunningham & Windley (1995) have shown that these mountains are transpressional uplifts that formed during the Cenozoic along a series of strike-slip faults that define a corridor of left-lateral transpressional deformation from southern Mongolia to NW China. The longest fault system within this corridor is the Gobi–Tien Shan fault system which can be traced for over 800 km from the easternmost Tien Shan to the Gurvan Sayhan Ranges of the SE Gobi Altai. Cunningham *et al.* (1996) proposed that this corridor of left-lateral transpressional deformation represents a distant response to the continued northeastward indentation of India into Asia since approximately 50 Ma. Understanding the evolution of the Gobi–Tien Shan fault system, as well as other strike-slip fault systems, is important for understanding the overall Cenozoic deformation field of Central Asia (cf. Baljinnyam *et al.* 1993; Davy & Cobbold 1988; Tapponnier & Molnar 1979). The geomorphology of the Gobi Altai directly reflects the late Cenozoic active tectonics of southern Mongolia and provides important constraints on the geometry, style and timing of uplift in the region.

This paper describes the tectonic and geomorphological characteristics of one of the main mountain ranges, Nemegt Uul, situated in southernmost Mongolia (Fig. 1). In it, a model for the landscape evolution of the region is presented that may be applied to the other transpressional mountain ranges in Mongolia and in similar mountain regions elsewhere in the world.

Methodology

Geomorphological and geological field mapping was undertaken at a variety of scales ranging from 1:5000 to 1:20 000 following established procedures using field survey techniques aided by Global Positioning Systems, barometric altimetry and levelling in selected regions of Nemegt Uul (cf. Owen *et al.* 1997). Mapping was assisted by the use of Landsat MSS images (Fig. 2) and aerial photographs. Transects into the mountain range were made to study the structural geology, geomorphology and sedimentology.

Topographic maps (1:100 000 scale) were used to examine the regional geomorphology of Nemegt Uul. A geographical information system (GIS, using ARC/INFO) was used for digital terrain analysis and to calculate geomorphological indices for part of central Nemegt Uul (Fig. 2B). Using the GIS, hypsometric curves were constructed using the methods of Strahler (1952) for the whole of the Nemegt Uul study area, north and south of the main drainage divide, and for individual catchment areas. An index was then derived to assess the skewness of elevations (catchment area skewness) within individual catchment areas as an aid to assessing their relative geomorphological maturity. In addition, geomorphological indices

From: SMITH, B. J., WHALLEY, W. B. & WARKE, P. A. (eds) 1999. *Uplift, Erosion and Stability: Perspectives on Long-term Landscape Development*. Geological Society, London, Special Publications, **162**, 201–218. 1-86239-030-4/99/ $15.00

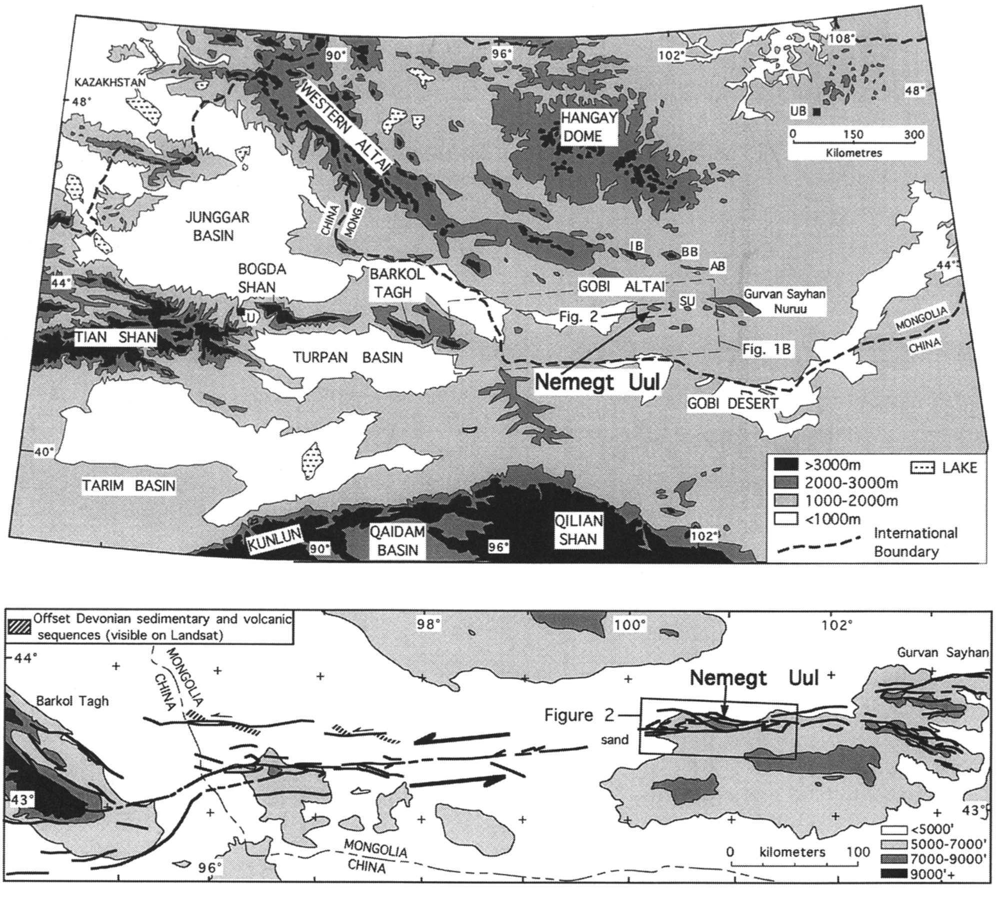

Fig. 1. (**A**) The geographical setting of Nemegt Uul in southern Mongolia within the Gobi Altai Mountains. IB, Ih Bogd; BB, Baga Bogd; AB, Arsta Bogd; SU, Severy Uul; UB, Ulaan Baatar; U, Urumchi. (**B**) Structural setting of Nemegt Uul along the Gobi–Tien Shan fault system (after Cunningham *et al.* 1996).

were used to compare regions throughout Nemegt Uul. These included mountain front sinuosity, using the methods of Bull & McFadden (1977), and a transverse topographic symmetry factor using Cox's (1994) method.

Tectonic setting

Two dominant left-lateral strike-slip fault systems are present in southern Mongolia and northwest China: the North Gobi Altai and the Gobi–Tien Shan fault systems (Cunningham *et al.* 1996). These fault systems occupy the central part of a 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. The North Gobi Altai fault system continues for over 300 km from the eastern Gobi Altai to the western Altai mountains. To the south, the Gobi–Tien Shan fault system can be traced for over 800 km and terminates in the east in a series of ranges (Gurvan Sayhan Nuruu) that have the geometry of a horse-tail splay (Fig. 1B), while in the west it passes into the easternmost Tien Shan terminating in the sigmoidal-shaped restraining bends of Barkol Tagh and Bogda Shan. The study area, Nemegt Uul, is near the eastern end of the Gobi–Tien Shan fault system and constitutes a broad sigmoidal-shaped restraining bend (Figs 1B and 2B).

Rock types and structural geology

Unpublished mapping by the Mongolian Geological Survey coupled with field observations

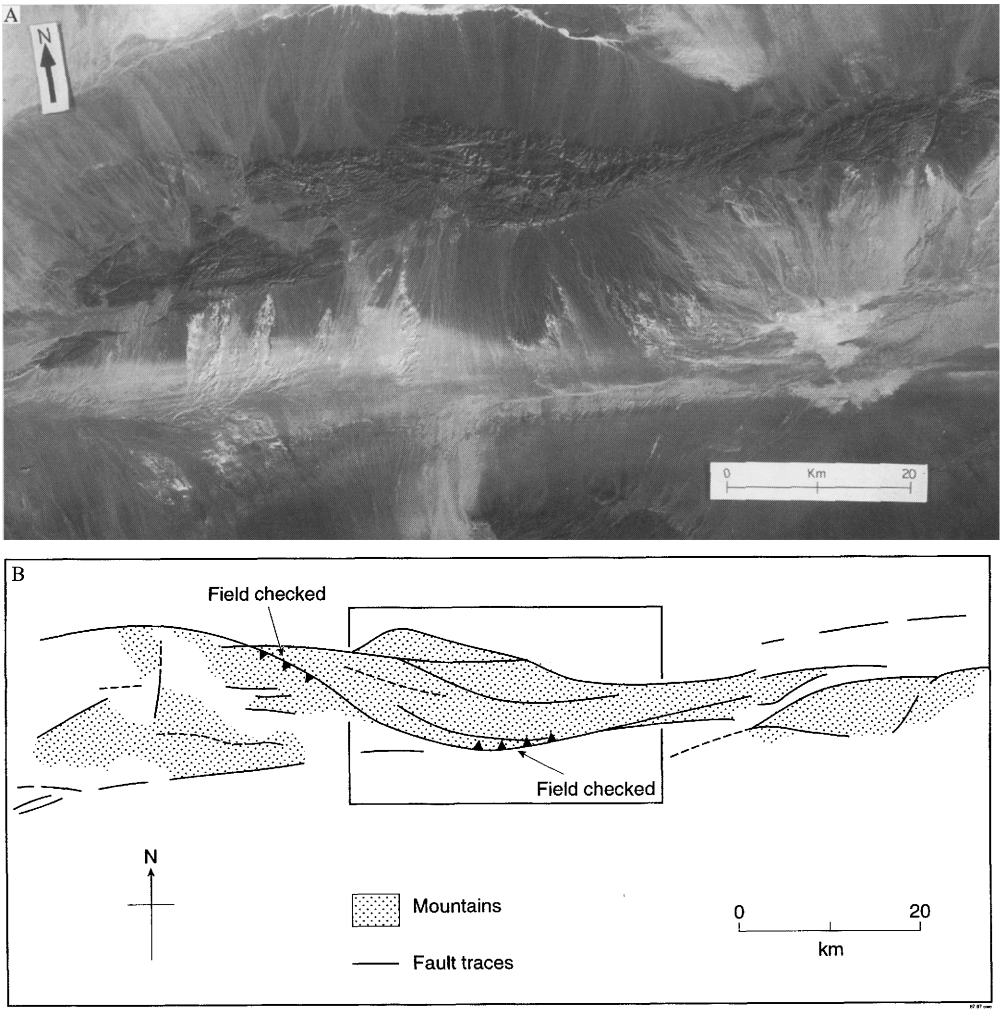

Fig. 2. (**A**) Landsat image of Nemegt Uul; (**B**) structural interpretation based on Landsat image and field checking. The area highlighted by the box is covered by the GIS.

from this study indicate that Nemegt Uul is dominantly composed of Devonian–Carboniferous greenschist-grade metasedimentary and metavolcanic rocks and unmetamorphosed volcanics and clastic sedimentary rocks. Subordinate lithologies include small granitic intrusions, serpentinite and ophiolitic rocks, and Mesozoic terrigenous deposits. The range lies along an E–W strike-belt dominated by low-grade metavolcanic, volcaniclastic and sedimentary sequences believed to have been deposited in an arc/backarc environment (Lamb & Badarch 1995).

The structural geology of the range is dominated by an array of approximately E–W trending faults that either cut through the range or help define the mountain fronts (Figs 2 and 3). The sigmoidal curvature of some of the longer faults has resulted in the sigmoidal shape of the range. This strongly suggests that the distribution of uplift is structurally controlled. Two structural transects were completed to gain an understanding of the kinematic nature of the major faults and the range's cross-strike structure (Fig. 3). Section A–B transects the northern half of the range, and is dominated by several large thrusts including a 0.5 km wide thrust zone that defines the northern mountain front and deforms recent alluvial deposits. Another major thrust zone has uplifted ophiolitic rocks in the centre of the range and forms a prominent topographic escarpment. The structural vergence

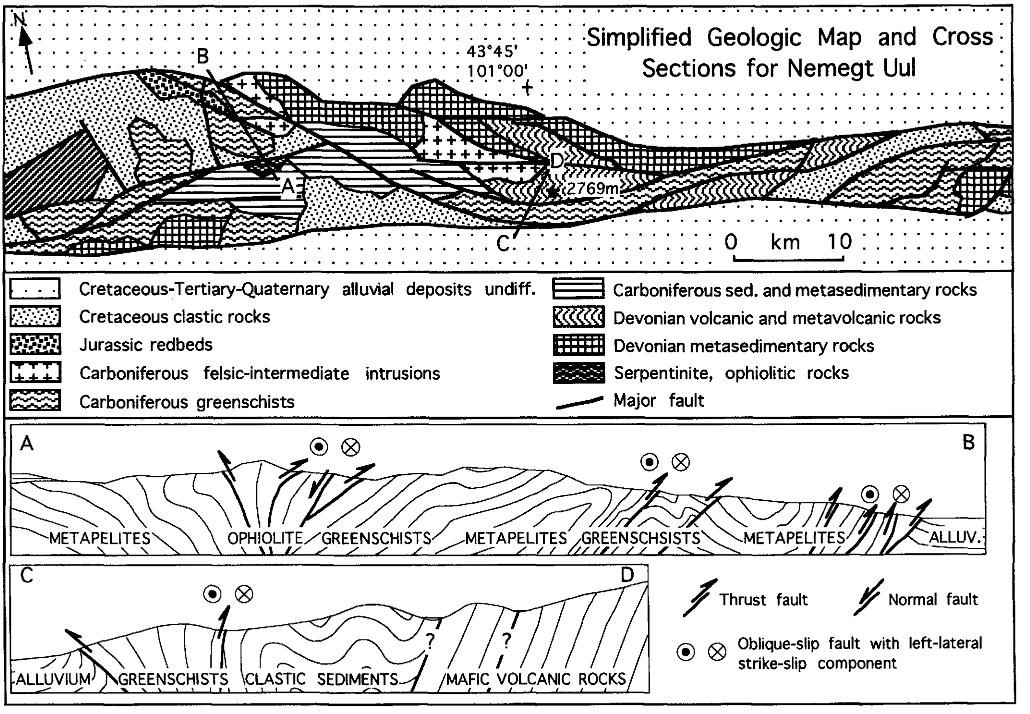

Fig. 3. Simplified geologic map and cross-sections of Nemegt Uul. Map largely taken from unpublished mapping by the Mongolian Geological Survey. Cross-sections completed by authors.

for most of the faults along section A–B is northward, whereas the geometry of large fold structures in compartments between major faults suggests that they are kinematically separate, and that they may be reactivated Palaeozoic structures.

The southern half of the range is dominated by a major S-directed thrust fault that has emplaced Palaeozoic phyllites and slates over undated foreland alluvial deposits (Fig. 3; Cunningham *et al.* 1996, fig. 12). Cross-section C–D indicates that the frontal ridge is a triangular wedge bounded by a steep left-lateral thrust on its northern side. North of this fault are unmetamorphosed sedimentary and volcanic rocks. Thus, along section C–D, the greatest amount of thrust-related uplift and exhumation of metamorphic basement rocks has occurred at the southern front and not in the centre of the range.

Our observations indicate that Nemegt Uul has bilateral thrust vergence with mountain-bounding thrusts dipping into the centre of the range. Extrapolation of these faults to depth suggests that the range has a complex flower structure geometry. Left-lateral components of motion have occurred on several major faults as indicated by oblique-slip slickenlines and stretching lineations suggesting a transpressional origin for the mountain along the trend of the Gobi–Tien Shan fault system (Cunningham *et al.* 1996).

Geomorphology

The discontinuous mountain ranges of the Gobi Altai rise from an extensive desert surface, which has elevations of between 1000 and 2000 m, to a maximum of 3957 m on Ih Bogd, 3590 m on Baga Bogd Uul, 2477 m on Artsa Bogd Uul, 2825 m on Gurvan Sayhan Uul, 2632 m on Sevrey Uul and 2769 m on Nemegt Uul (Fig. 1). The climate in the Gobi 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. 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.

Throughout the Gobi, the desert is dominantly of reg type, comprising alluvial fans and deeply weathered Mesozoic and early Tertiary bedrock with badlands topography. Owen *et al.* (1997) described the characteristics of the alluvial fans and showed their formation as dominated by climatically driven processes. Areas of active sand dunes are restricted in extent but, where present, are of barchan and seif type.

Most streams are ephemeral and have their source in the mountains. These fill during heavy rainstorms and/or as snow melts at higher locations within the mountains during springtime, particularly in alluvial fan areas, where the water table is locally as close as 2 m below the surface. Rare perennial streams are located at spring lines and generally can only be traced for several hundred metres. North of Baga Bogd Uul and Ih Bogd Uul are large lakes which are internally drained and have brackish to saline waters.

Figures 4 and 5 illustrate the main geomorphological characteristics of Nemegt Uul and the adjacent foreland. Figure 5 also shows the main lithofacies associations within each environment. Geomorphologically, Nemegt Uul and its foreland can be broadly divided into four zones: the mountains; the alluvial fan environments; badlands; and dunes and desert pavements (Fig. 5).

The mountains

Nemegt Uul is extremely elongate with a length–width ratio of approximately 1:8. Figure 6 shows the outline of Nemegt Uul with the calculated mountain front sinuosity for selected reaches. The mountain front is extremely straight where it is bounded by faults, particularly on the northern side of the range (cf. Figs 2B and 6). The mountain front sinuosity increases considerably within a number of embayments on the southern side of the range that mark stepover zones between the range-bounding faults.

Figures 7 and 8 illustrate the topography of the GIS study area. A clear asymmetry in the topography is picked out by the comparatively larger catchment areas north of the main east–west drainage divide compared with the smaller catchments to the south (Fig. 4). Furthermore, Fig. 8 shows that the distribution of elevations south of the main east–west drainage divide is more skewed towards the higher elevations compared with areas north of it. Towards the eastern and western ends of the main range, northward-flowing streams cross the whole range with much of their catchment on the southern foreland of the mountain range. This suggests that the northern margin of the mountain range has undergone a longer period of denudation than the southern margin, and it implies that uplift in the southern region is younger, or that the mountain belt as a whole has a northward tilt.

Figure 9 shows the area–altitude distributions and hypsometric curves of three different types of catchments within the study area, and Fig. 10 the catchment area skewness (CAS) for each catchment area in the GIS. Catchment areas with high positive CAS values are flat-iron-shaped catchments that correspond to fault facets, while catchment areas with negative CAS values approaching zero are well drained, with deep box-shaped valleys in their lower reaches.

Figure 11 illustrates the transverse topographic symmetry factor for each of the catchment areas. This shows that the streams are symmetrical within each catchment, and that they trend oblique to perpendicular to the main structural grain.

The high peaks are deeply weathered (LFA6 in Fig. 5) and, although they have steep sides ($>60°$), they are surrounded by extensive regolith and the valley heads open up into broad high pastures (Fig. 12A). Mass movement is mainly by rock fall and creep (Fig. 12B), and talus deposits up to 3 m thick with slopes of between 25° and 35° are common along most of the valleys. These talus deposits are commonly stratified (Fig. 12C) and in limestone-rich areas they are loosely cemented with calcite (LFA5 in Fig. 5); most are deeply incised by gulleys and rills, and the talus slopes are often truncated at their toes.

Low-angled ($<10°$) debris flow fans are present within broad valley stretches where small tributary valleys converge. These fans comprise angular, polymictic matrix-supported pebbles and cobbles that are crudely stratified parallel to the surface of the fan. Most fans are truncated at their toes (Fig. 13A) and incised towards their heads. River terraces are also present showing various phases of construction and incision (Figs 13B and 14).

Small pebbles and sands are dominant within the recent dry stream channels. In some valleys, however, large imbricated clusters of boulders (up to 2 m in diameter) are present representing large flood events (Fig. 13C).

Alluvial fans

Alluvial fans surround the mountain range and radiate from the main valleys to form extensive bajadas (Figs 2A and 4); they stretch for as much

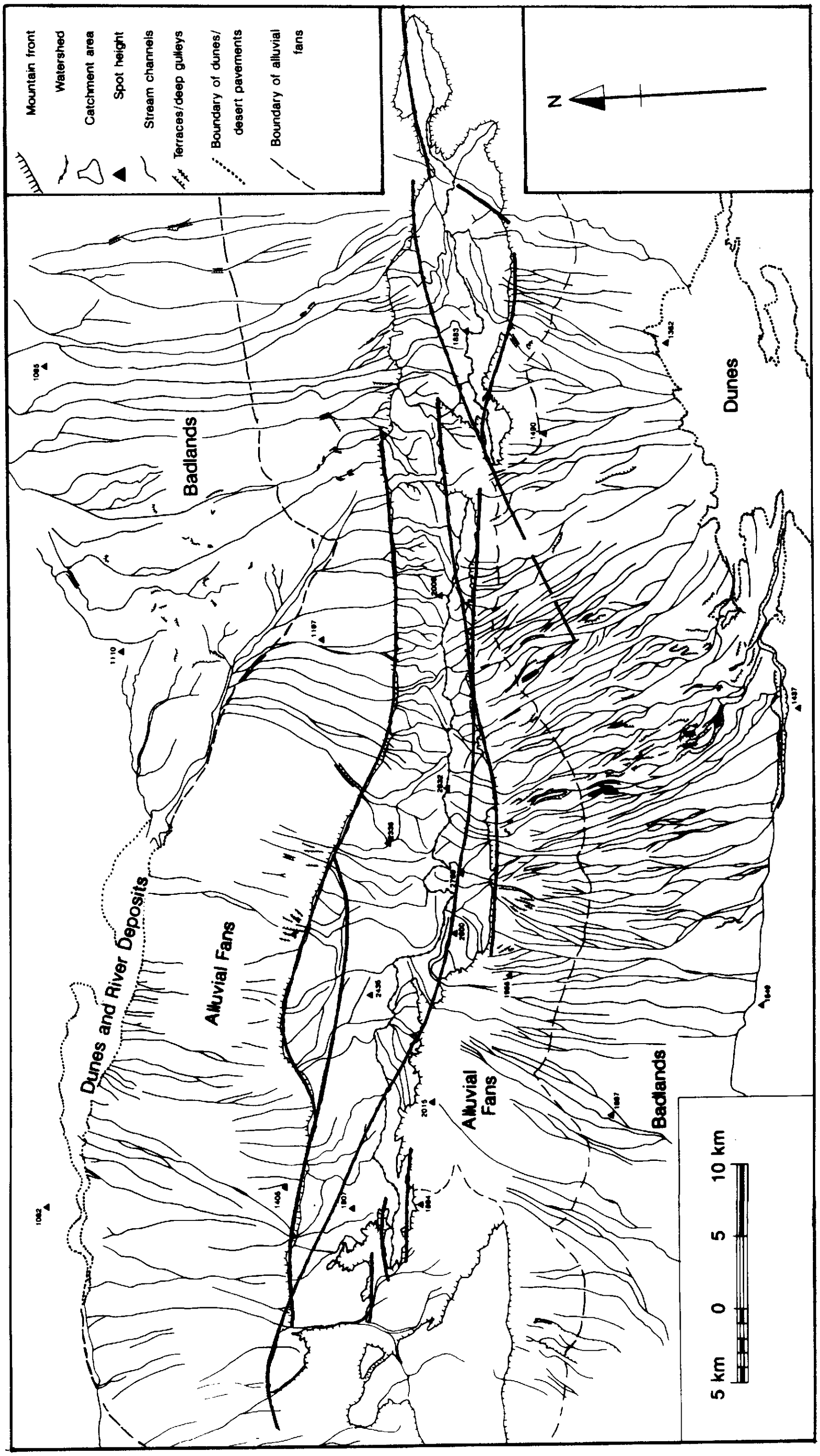

Fig. 4. Geomorphological map of Nemegt Uul and its forelands based on topographic maps and Landsat imagery. The bold dashed lines indicate major fault traces.

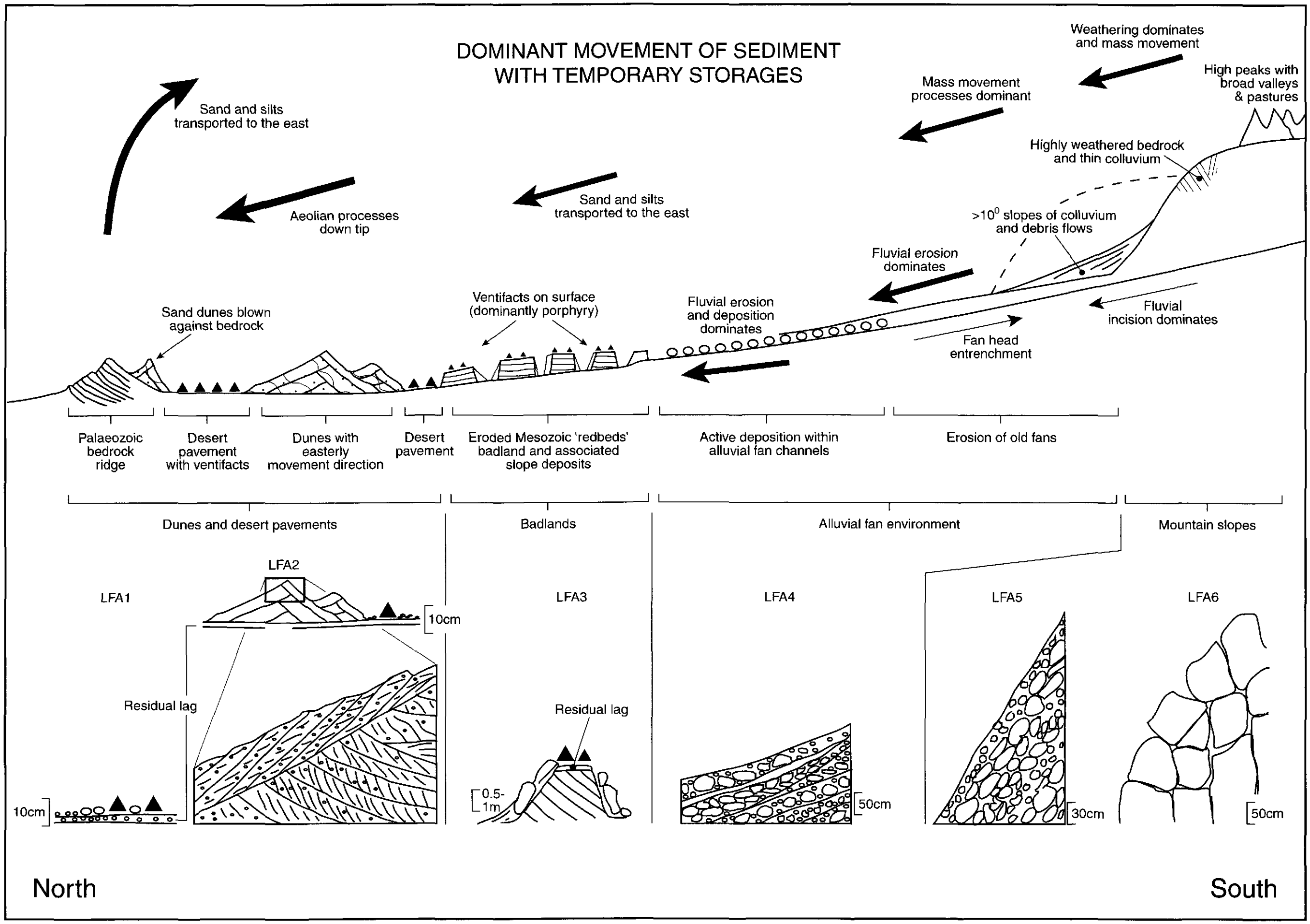

Fig. 5. Schematic section across the northern margin of Nemegt Uul and its pediment showing the main geomorphological characteristics, lithofacies associations (LFA) and the paths of sediment transfer.

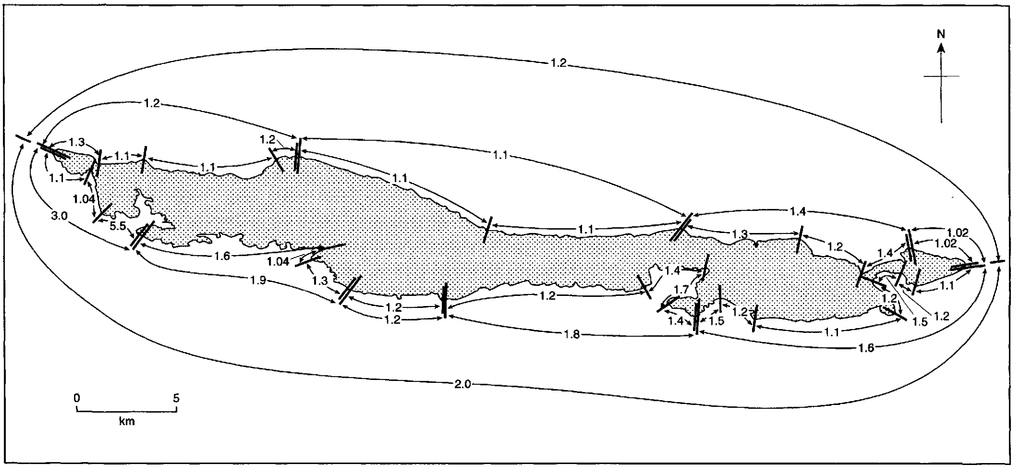

Fig. 6. Map showing the main Nemegt Uul range with the mountain front sinuosity (total length of the mountain front along its foot/straight-line length of mountain front) calculated for selected lengths of the range. The thick black lines mark major fault traces.

as 10 km away from the mountain front where they are replaced by desert pavements. Desert pavements also exist on some of the older alluvial fan surfaces. The alluvial fans are most extensive along the northern side of Nemegt Uul, whereas to the south they are steeper and stretch for only a few kilometres. Most of the major fans are entrenched at their heads to a depth of a few metres, frequently down to bedrock. The channels are several tens to hundreds of metres wide and comprise sand, pebbles and occasional small boulders. In some alluvial fans (e.g. NE corner of Fig. 4), entrenchment is concentrated in the mid-fan stretches. These probably represent areas of localized uplift associated with foreland propagating blind thrusts. The alluvial fan sediments comprise angular to sub-rounded cobbles and pebbles which are clast-supported or supported in a matrix of medium to coarse sand. Many of the clasts are imbricated and the bedding is gradational with crude decimetre-thick units which dip at 1° to 4° sub-parallel to the surface of the alluvial fan (LFA4 in Fig. 5 and Fig. 15). Small debris flows are present in the upper reaches of the alluvial fan, adjacent and near to the mountain front. Debris flows are rare in the mid-fan areas and the surfaces of the fans are depleted of fine sands and silts, and armoured with pebbles and cobbles. Basalt boulders are present on many of the fan surfaces, but have no obvious local source in Nemegt Uul. This suggests that they may be a residual deposit of former extensive basalt flows. In the distal fan areas the surfaces are depleted of fine sand and silt, and pebble-sized ventifacts are common. Calcretes have developed on some alluvial fan surfaces. Some alluvial fan sediments have been deformed by thrust faults (Fig. 16) that diverge away from the mountain range.

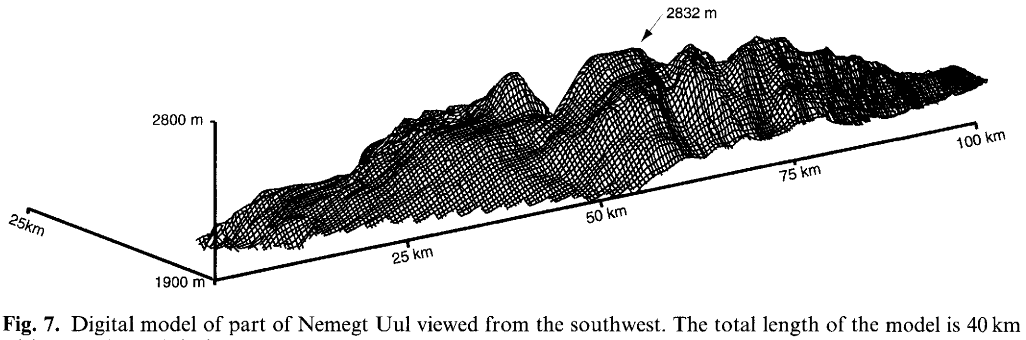

Fig. 7. Digital model of part of Nemegt Uul viewed from the southwest. The total length of the model is 40 km with a relative relief of 1300 m (vertical exaggeration is 10 times the horizontal scale).

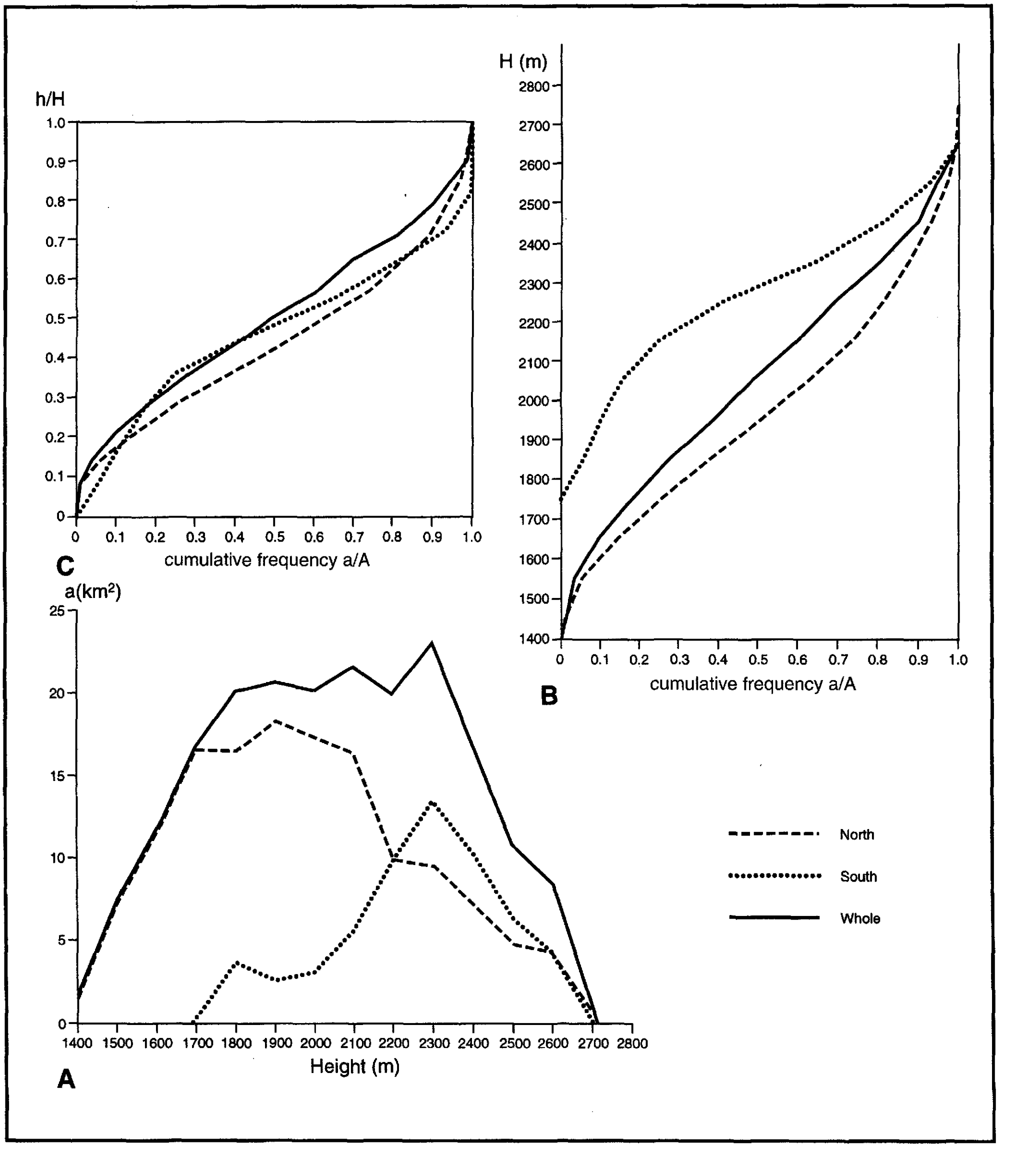

Fig. 8. (**A**) Area–altitude distribution and (**B** and **C**) hypsometric curves for the whole of the Nemegt Uul study area and the hypsometric curves for the areas north and south of the main watershed (A = total area of the catchment; a = area of catchment between 100 m contours; H = maximum elevation of the catchment area – minimum elevation of the catchment area; h = elevation of each 100 m contour).

Badlands

Badlands are best developed along the southern side of Nemegt Uul, where horizontal or gently dipping Cretaceous marlstones and sandstones have been deeply eroded. In some areas, the valleys reach depths of several tens of metres, with valley width exceeding hundreds of metres. Screes are thin (generally <1 m thick) and there is little sediment on the valley floors (LFA3 in Fig. 5).

Dunes and desert pavements

Dunes are present along the lowest elevations between the pediments of Nemegt Uul and the adjacent mountain ranges. The presence of

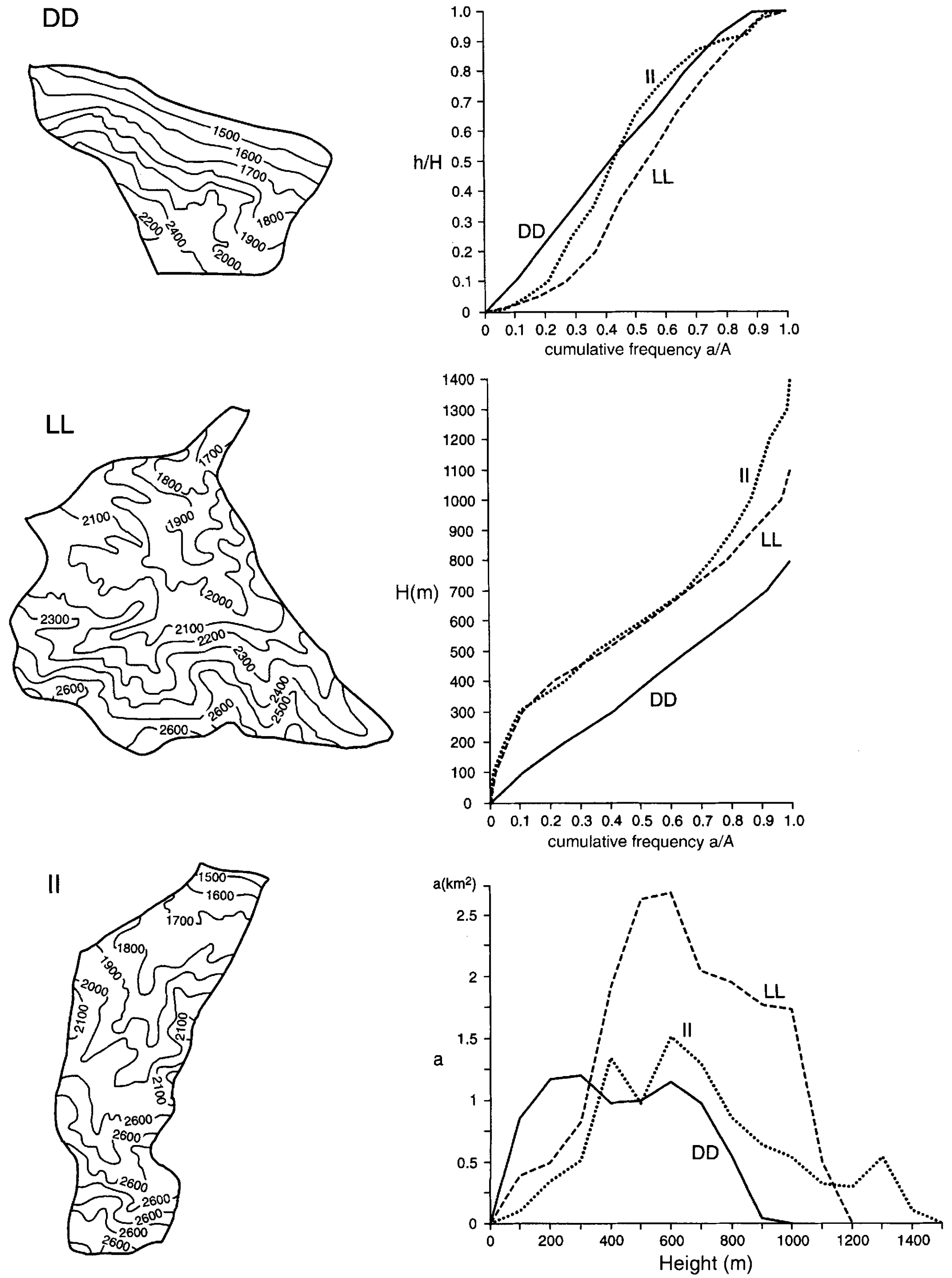

Fig. 9. Catchment areas and hypsometric curves for selected catchment areas in Nemegt Uul (A = total area of the catchment; a = area of catchment between 100 m contours; H = maximum elevation of the catchment area – minimum elevation of the catchment area; and h = elevation of each 100 m contour).

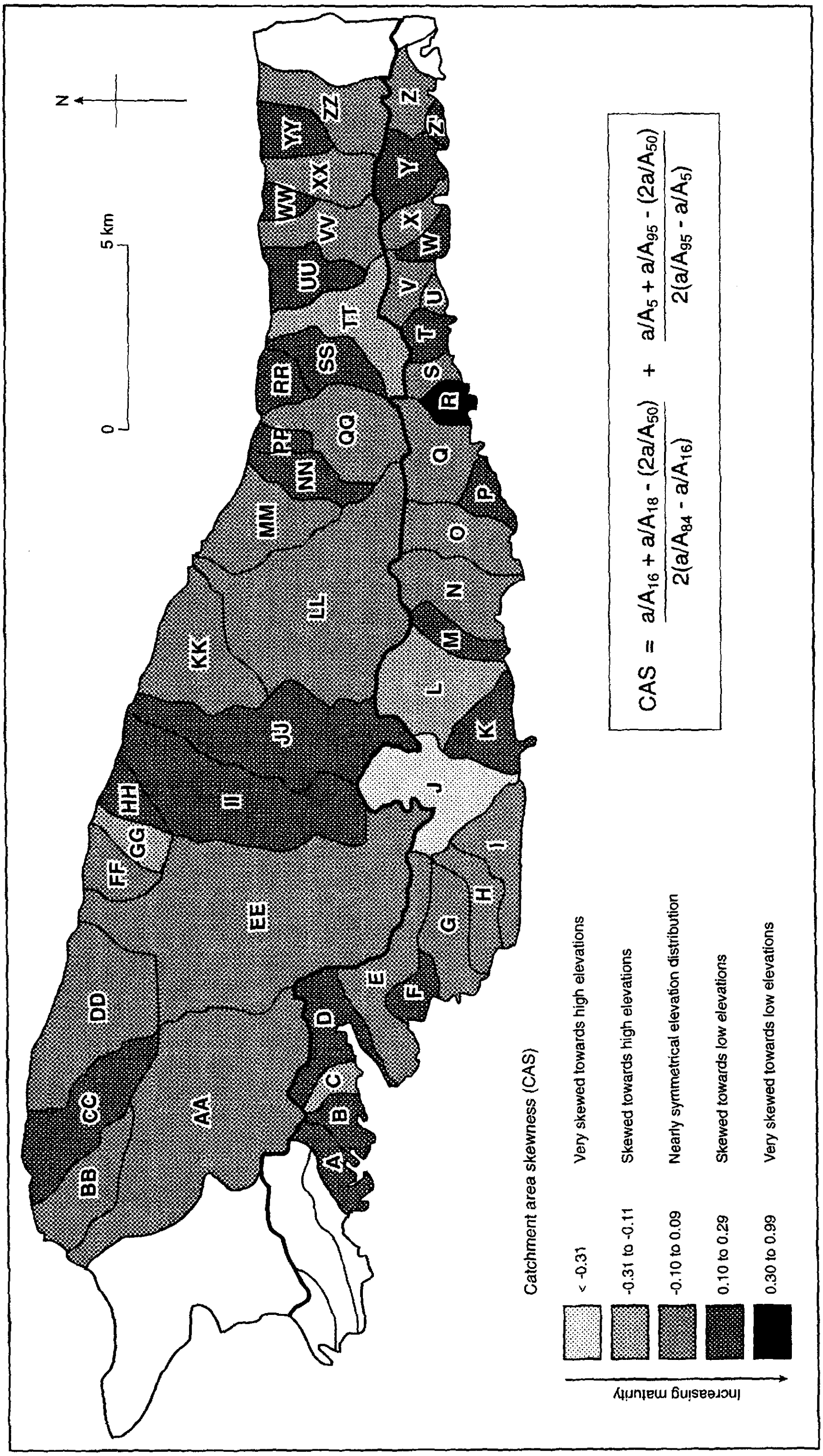

Fig. 10. Map showing the catchment area skewness (CAS) for catchment areas within Nemegt Uul. CAS is derived from the hypsometric curves of each catchment where a/A_x is altitude of the x percentile. The greater the skewness towards lower elevations, the greater the denudation of the catchment. (NB: CAS was not calculated for the unshaded catchment areas).

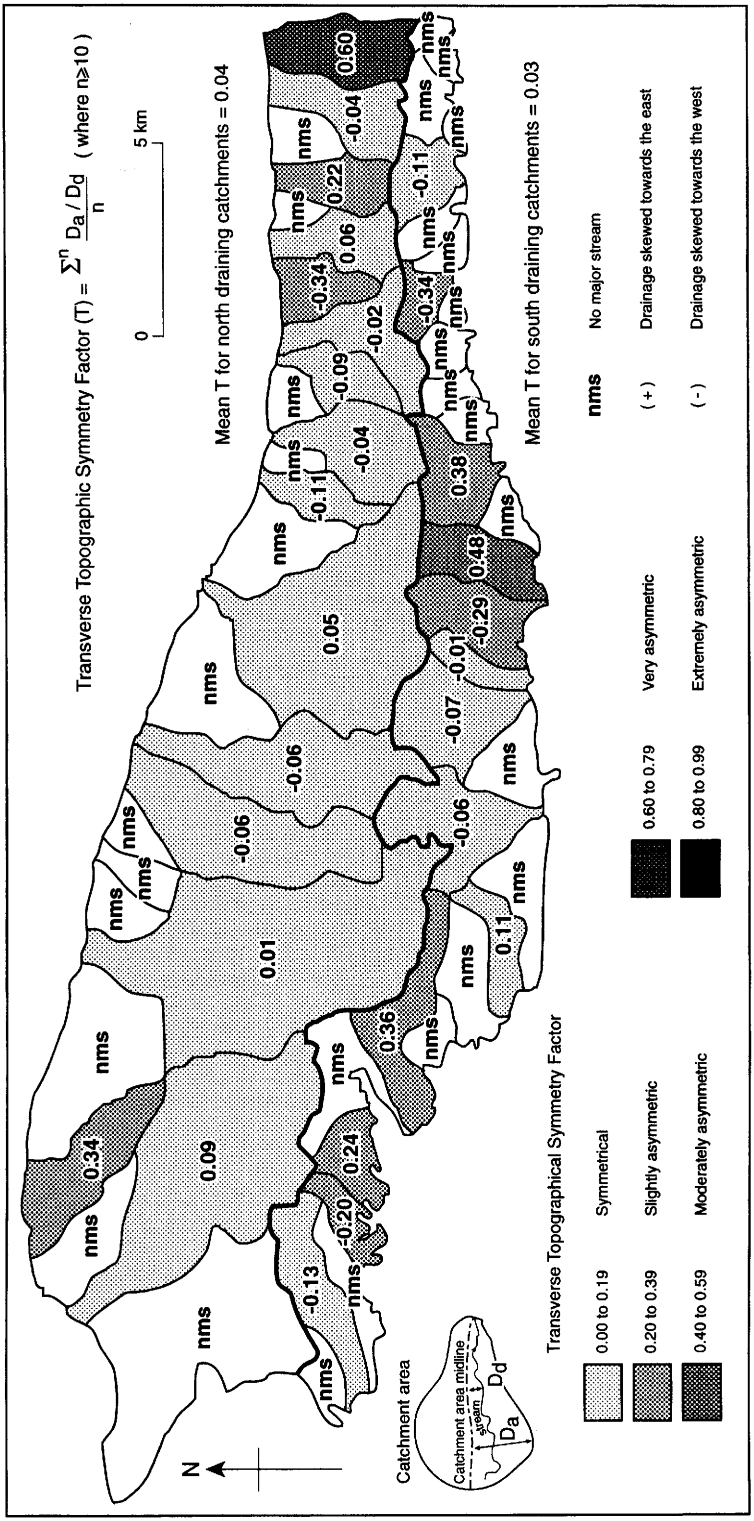

Fig. 11. Map showing the transverse topographic symmetry factor (T) for each of the catchment areas within Nemegt Uul.

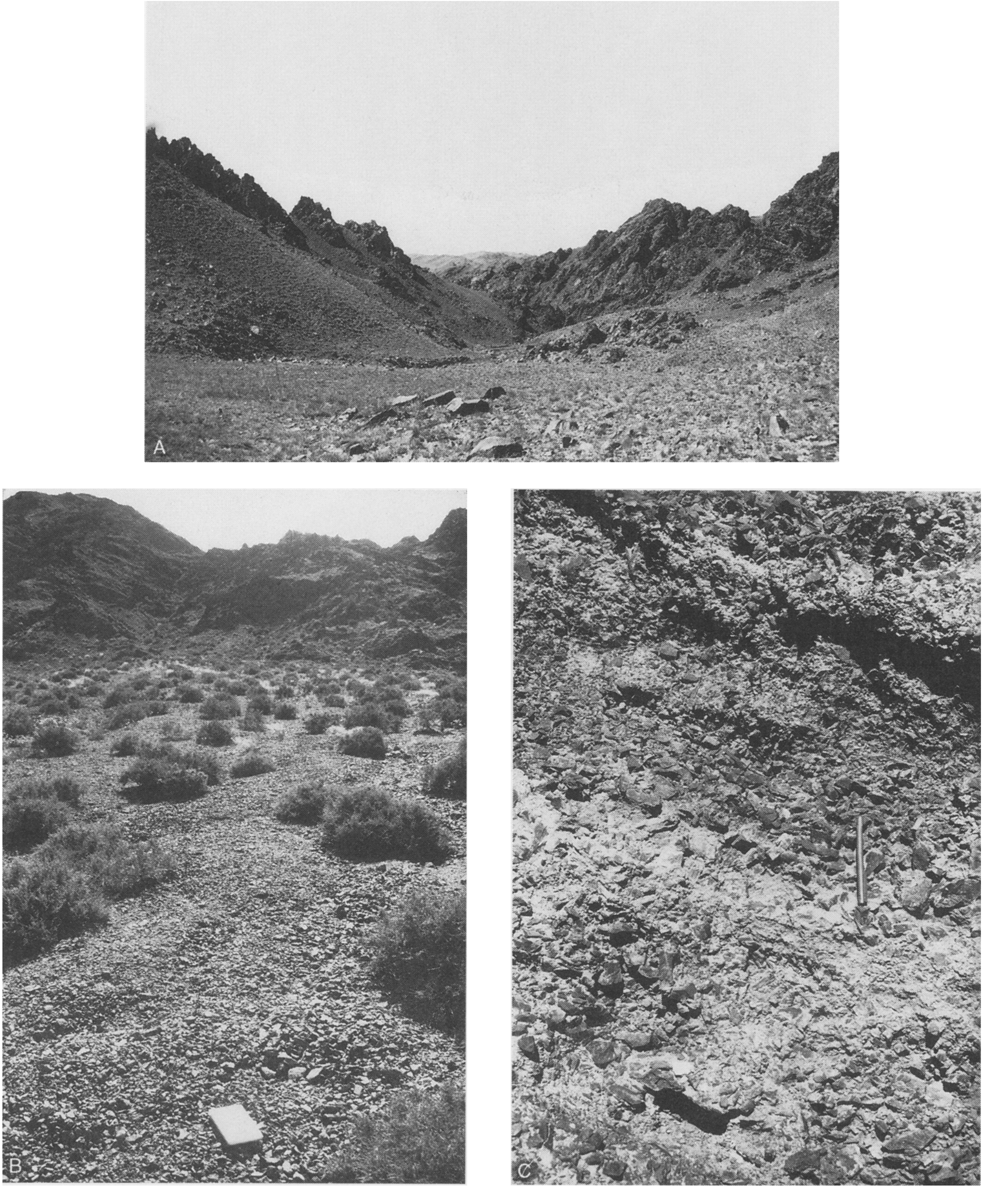

Fig. 12. (**A**) View looking south down one of the main tributary valleys from the top of Nemegt Uul (43°39.2′N 100°53.8′E, 2450 m). Note the craggy peaks surmounted by talus slopes. (**B**) Talus slope from near the top of Nemegt Uul. Note the lobate forms on the surface that indicate creep (43°39.2′N 100°53.7′E, 2450 m). (**C**) Stratified scree deposit from within one of the main valleys in Nemegt Uul (43°43.3′N 100°38.7′E, 1690 m).

both barchan and seif dunes indicates that westerly winds dominate. In some areas the dunes are partially vegetated and have become temporarily stabilized, but the majority are active and over-ride vegetation (LFA2 in Fig. 5).

Desert pavements are common on the distal fan surfaces, pediments and in the badlands. The pavements comprise armoured surfaces with abundant pebble-to boulder-sized ventifacts, but little silt-sized sediment (LFA1 in

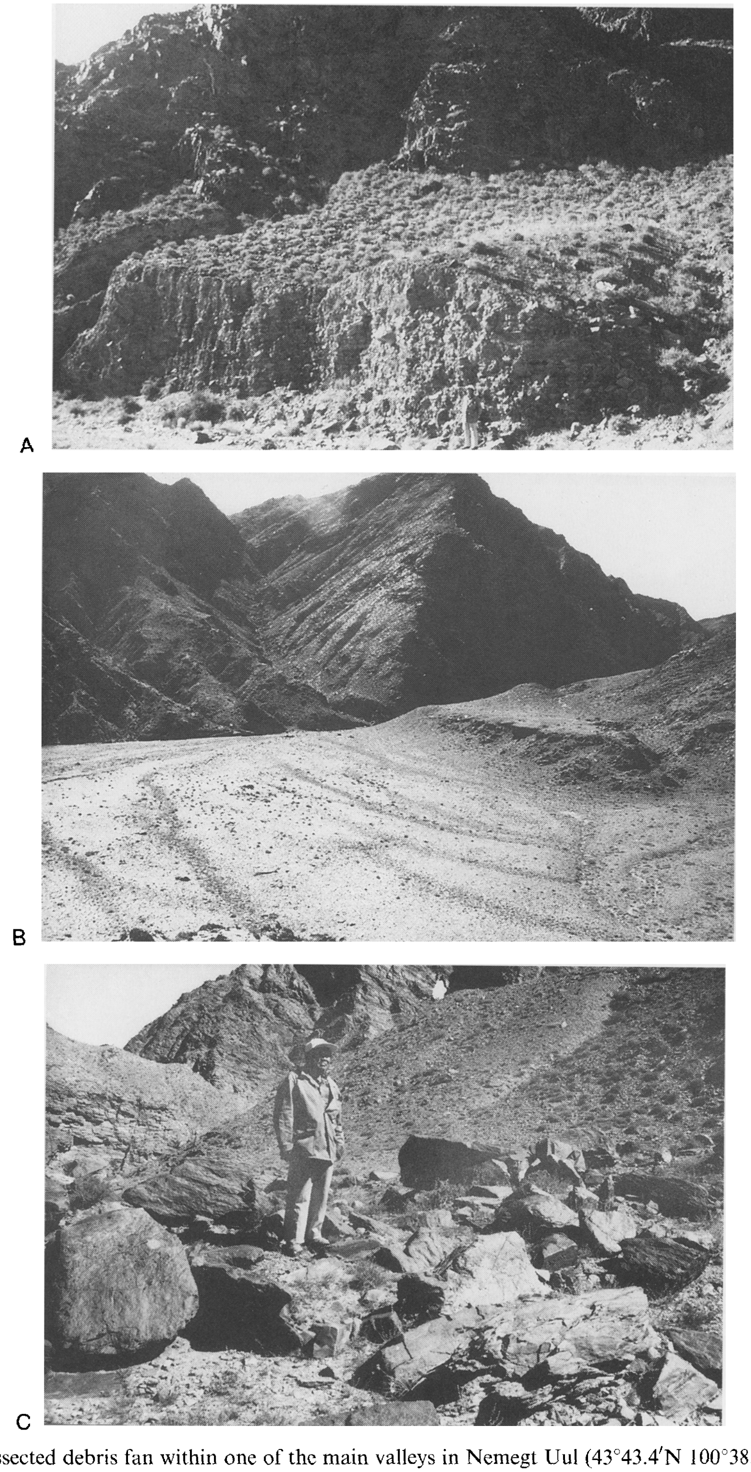

Fig. 13. (**A**) Dissected debris fan within one of the main valleys in Nemegt Uul (43°43.4′N 100°38.7′E, 1690 m). (**B**) High river terraces and dissected fans along one of the main valleys in Nemegt Uul (see Fig. 14 for detailed map) (43°42.9′N 100°39.1′E, 1690 m). (**C**) Flood deposit on one of the main valleys of Nemegt Uul (43°42.9′N 100°39.2′E).

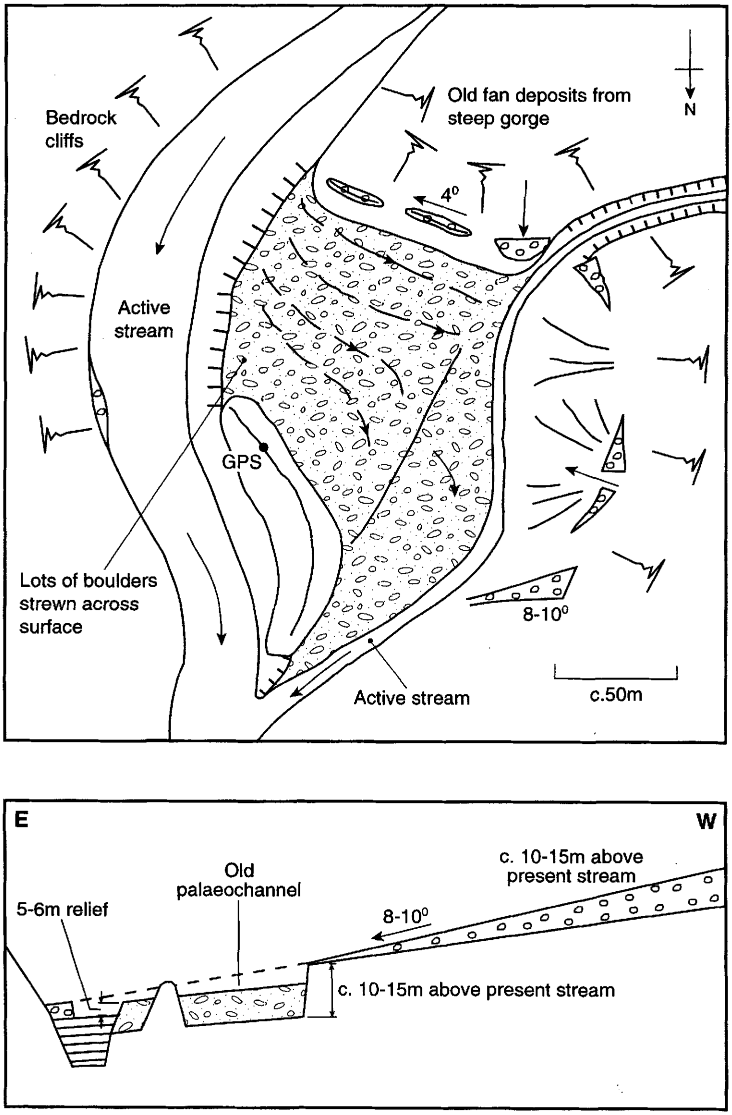

Fig. 14. Map and section showing river terraces and dissected fans in one of the main valleys of Nemegt Uul (GPS position: 43°42.9′N 100°39.1′E, 1670 m).

Fig. 5). Some of the pavements have poorly developed calcretes.

Discussion

Structural analysis shows that Nemegt Uul is an asymmetric flower structure that formed within a broad restraining bend. The straight stretches of the mountain front clearly support the assumption that the mountain range is very young and still active. Faulted Quaternary and Neogene alluvial fan sediments on the north and south sides indicate Quaternary faulting along the mountain belt. The straightness of the mountain front is attributed to thrust and oblique-slip faulting that has placed Palaeozoic rocks over Mesozoic and Cenozoic rocks. Mountain front sinuosity is higher, and embayments are present where there are stepover zones between the main faults. Deformation within the foreland is supported not only by faulted alluvial fan sediments, but by subtle changes in fan gradient picked out by entrenchment within the mid-fan

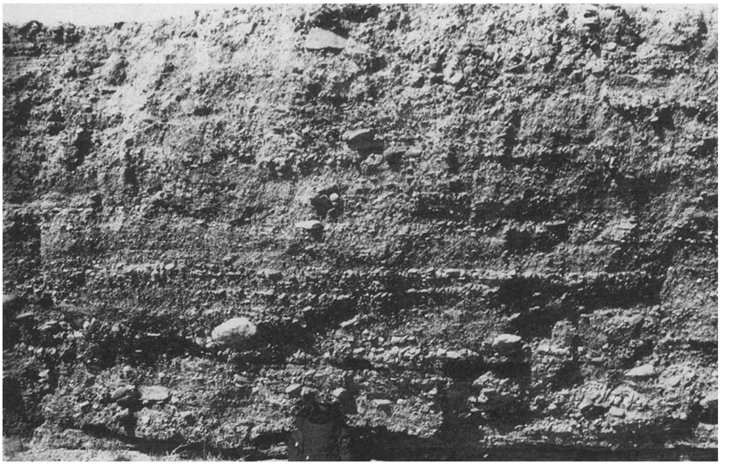

Fig. 15. View of typical alluvial fan deposits, showing centimetre- to decimetre-thick crude low-angled stratification (43°44.7′N 100°38.5′E, 1440 m).

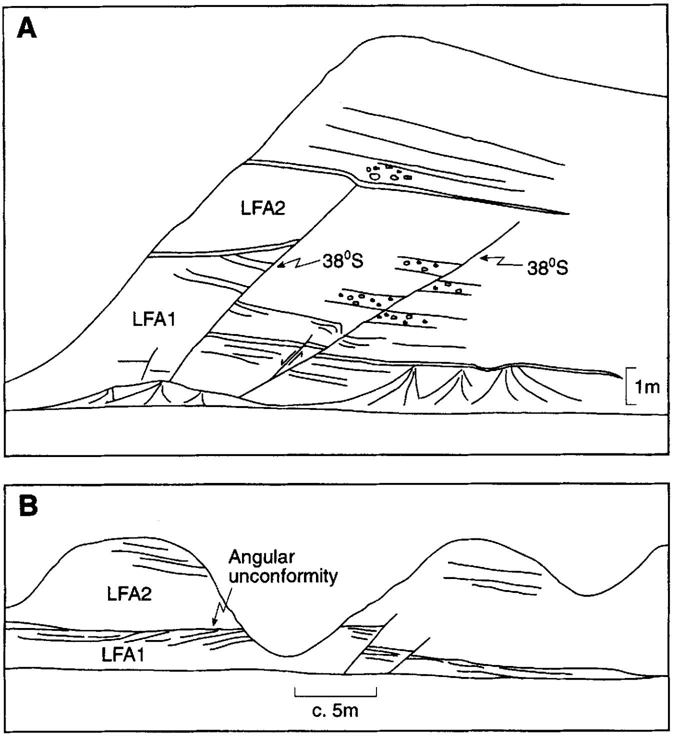

Fig. 16. Schematic section looking west at faulted alluvial fan deposits on the north side of Nemegt Uul (43°44.7′N 100°38.5′E, 1440 m): (**A**) details of the faulting; (**B**) the overall section. LFA1 – Brown coloured, poorly stratified, centimetre-thick beds of matrix-supported (sandy silt) sub-angular pebbles. Some of the clasts are imbricated. Occasional centimetre-thick lenses of silty sand are present. LFA2 – Grey coloured, crudely stratified, matrix-supported (sandy silt) polymictic medium to large pebbles (>3 cm diameter) with occasional cobbles and small boulders.

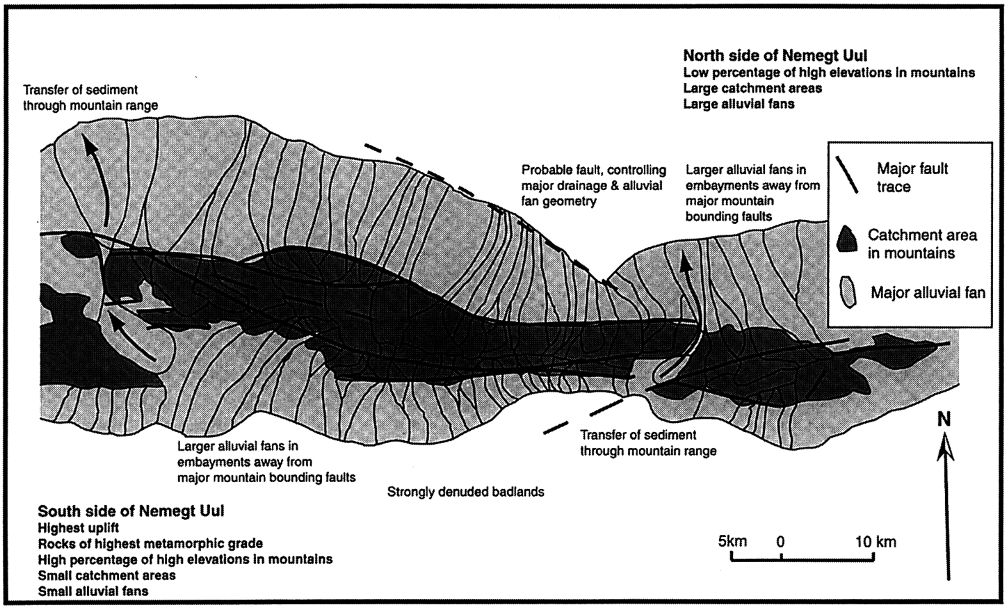

Fig. 17. Map showing the zones of sediment transfer and the relationship between catchment areas and alluvial fans with respect to the differential uplift and denudation across Nemegt Uul.

reaches and small terraces in the distal reaches of the foreland. In addition, a NW trending drainage channel north of Nemegt Uul (Figs 4 and 17), oblique to the northward regional slope, is probably controlled by faulting that parallels the northern edge of Nemegt Uul.

The geomorphological indices and digital terrain analysis support the view that the northern margin of the mountain range has been more deeply eroded and possibly reflects differential tilting of the mountain range. This is supported by the highest elevations concentrated in the southern half of the range. In addition, the highest grade metamorphic rocks along the cross-section crop out at the southern end (Fig. 3) suggesting greater uplift and exhumation in the south in this region. Consequently, the alluvial fans are larger on the northern side of the range, whereas alluvial fan development on the southern side is tightly constrained to areas near the mountain front and erosion in the distal reaches of the foreland is greater than the sediment supply from the mountains. The heterogeneity of rock types in the range (Fig. 3) precludes the possibility that the topographic asymmetry between north and south sides is due to differences in lithology-controlled resistance to erosion. Moreover, Owen *et al.* (1997) showed that the alluvial fans developed as a consequence of the tectonic setting, being adjacent to rapidly uplifting mountains, and that the main sedimentological and geomorphological characteristics of the alluvial fans were controlled by climate change and the associated changing hydrological conditions.

There is a clear geographical control of sedimentary facies associated with Nemegt Uul; this is shown in Fig. 5. Sediment produced by weathering and mass movement processes within the mountains is quickly transported to the foreland to form alluvial fans and there is little sediment storage within the valleys. The alluvial fans are themselves eroded by stream incision and their surfaces are deflated of fine sediment. Where alluvial fan sediments are very thin or absent, the Mesozoic bedrock has been deeply eroded by fluvial and aeolian processes. Eroded alluvial fan and pediment sediments are carried to the distal parts of the foreland where they form sand dunes. The dunes migrate eastward and the silt fraction is progressively deflated by aeolian processes.

Figure 17 shows the spatial relationships between sizes of catchment areas and alluvial fans on both the northern and southern sides of Nemegt Uul in relation to the major faults. The rocks with the highest grade metamorphism are present along the southern side of Nemegt Uul as a consequence of greater uplift. This is reflected in the higher percentage of land area at high altitudes, the smaller catchment areas and alluvial fans, and the more deeply eroded badlands on the southern side of the mountain range as compared with the northern side. The largest alluvial fans on both sides of the range, however, coincide with embayments away from major mountain bounding faults and towards the eastern and western end of the range in sediment transfer zones.

Conclusion

Nemegt Uul is an example of a desert mountain range that has formed within a restraining bend along a major left-lateral strike-slip fault system. Topography, valley development, drainage patterns, alluvial fans and badlands development are controlled by the rapid uplift, denudation and sediment transfer. Denudation by deep weathering, mass movement processes and the rapid transfer of sediment out of the mountain have produced deep valleys perpendicular or very oblique to the main structural grain of the mountain range. The greater catchment area and alluvial fan development on the northern side of the range, and the geomorphological indices and altitudinal distribution suggest that the mountain range has been differentially tilted to the north, possibly due to larger magnitudes of thrust displacement and greater uplift along the southern margin. Figure 17 shows the spatial relationships between the size of catchment areas and alluvial fans in relation to the major faults on both sides of Nemegt Uul. There is a clear relationship between the high percentage of land at high elevations, the smaller catchment areas and alluvial fans, and the more deeply eroded badlands on the southern side of the mountain range with the higher uplift that has exposed higher grade metamorphic rocks as compared with the higher percentage of lower elevations, larger catchment areas and larger alluvial fans on the northern side of Nemegt Uul. The largest alluvial fans on both sides of the range, however, coincide with embayments away from major mountain bounding faults and occur towards the eastern and western end of the range in stepover zones where there is transport of sediment from the southern foreland through the mountain range to the northern foreland.

This research was undertaken as part of NERC grant GR9/01881 awarded to B.F.W. and L.A.O. Thanks to Justin Jacyno for drafting the diagrams, British Petroleum for supplying the Landsat MSS images and two anonymous referees for their careful editting and constructive comments.

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