Journal of the Geological Society, *London*, Vol. **163**, 2006, pp. 657–670. Printed in Great Britain.

Competing processes of clastic deposition and compartmentalized inversion in an actively evolving transpressional basin, western Mongolia

J. P. HOWARD[1], W. D. CUNNINGHAM[1] & S. J. DAVIES[2]

[1]*CASP West Building, 181a Huntingdon Road, Cambridge CB3 0DH, UK (e-mail: james.howard@casp.cam.ac.uk)*

[2]*Orogenic Processes Group, Department of Geology, University of Leicester, Leicester LE1 7RH, UK*

Abstract: The Dariv Basin is an actively evolving intracontinental transpressional basin located on the eastern flank of the Mongolian Altai. The basin occupies a complex tectonic position between a restraining bend, a thrusted basement block, and two major conjugate strike-slip fault systems. Structures and sedimentary strata exposed within the Dariv Basin suggest a Mesozoic and Cenozoic two-stage evolution. Jurassic–Cretaceous strata fine upward and record alluvial fan, fluvial and lacustrine depositional environments. The distribution of Mesozoic sedimentary rocks and the presence of a suspected Jurassic normal fault array suggest that the Dariv Basin initially formed as an extensional basin. Following Palaeogene tectonic quiescence, Oligocene–Recent basin fill is dominated by alluvial fan sediments derived from basin-flanking ranges. The modern basin is deforming by thrusting, normal fault inversion and folding along discrete belts expressed as intrabasinal ridges and domes. These belts define a rhomboid of active deformation that compartmentalizes the basin. Sediments derived from these discrete deforming belts and from basin flanking ranges continue to accumulate in the basin centre. Thus, modern fans contain reworked older basin fill and competing processes of sedimentation, deformation, erosion and resedimentation can be observed. The Dariv Basin is an excellent example of a transpressional piggyback basin in the early stages of basin inversion and destruction.

In this paper, the structural and stratigraphic characteristics of the Dariv Basin, an actively evolving transpressional basin along the eastern margin of the Mongolian Altai (Fig. 1), are described. Transpressional basins are a major sedimentary basin type, which form in tectonic settings where strike-slip, oblique-slip and contractional fault displacements dominate. Major transpressional basins that are developed along transform plate boundaries, such as the Ventura Basin along the San Andreas Fault (Yeats *et al*. 1994), are commonly petroliferous and are consequently well studied with good seismic reflection data. Conversely, transpressional basins that form in an intraplate and intracontinental setting have received less attention and their development and architecture are poorly understood. Intracontinental transpressional basins are found on all major continents and are potential sites of valuable economic resources including hydrocarbons, metallogenic commodities (i.e. placer gold, platinum), industrial minerals (e.g. salts, sands) and groundwater.

Transpressional basins in the eastern Altai region of Mongolia are linked to seismically active faults within a broad corridor of northwestward dextral strike-slip displacements and NE–SW shortening (Fig. 1). The basins occur in various stages of evolution from incipient to mature and represent depocentres adjacent to, and between, actively uplifting crystalline basement blocks, which are typically thrust over basin fill and laterally displaced by regional-scale strike-slip faults. Consequently, most basins are internally faulted or folded as revealed by tilted successions along their margins and within interior zones. The basins provide a superb opportunity for analysing the complex dynamic interplay between competing processes of clastic deposition, faulting, inversion, erosion, and resedimentation in an evolving system. For these reasons, the eastern Altai region is perhaps the world's finest natural laboratory for studying active processes of intracontinental, intraplate transpressional basin evolution.

Regional geology of western Mongolia

Transpressional basins in western Mongolia are constructed on basement rocks that comprise Palaeozoic subduction accretion belts and arc–back-arc complexes that accreted between older cratonic blocks in Siberia, China and central Mongolia (Badarch *et al*. 2002; Chen & Jahn 2002; Windley *et al*. 2002). Progressive terrane accretion resulted in the development of regional foliation and fault trends that are typically NW striking and NE dipping. This first-order basement fabric has exerted a strong influence on all later deformation within the region.

Basement rocks in the Dariv Basin region are exposed in the Sutai range (Fig. 2) and comprise lower Palaeozoic metasedimentary and metavolcanic slates, phyllites and schists intruded by undated granites and covered by a wide variety of middle Palaeozoic arc-related volcanic rocks (Zaitsev 1978). Basement rocks in the Dariv range to the east and NE of the Dariv Basin include amphibolite-grade continental gneisses, a lower Palaeozoic ophiolite complex and some younger volcanic rocks.

The Dariv Basin is one of about a dozen intramontane and external basins along the eastern flank of the Mongolian Altai, which have a combined Mesozoic and Cenozoic depositional history (Fig. 1). Sedimentary fill consists dominantly of fluvial, lacustrine and alluvial facies, and deposition continues today. The Dariv Basin stratigraphy correlates with that of other eastern Altai basins, e.g. the Dzereg Basin to the north (Graham *et al*. 1997; Howard *et al*. 2003). Age control for correlations within and between basins is based on vertebrate, plant and insect palaeontological data (Devjatkin 1970; Khosbayar 1973; Devjatkin *et al*. 1975; and summarized by Howard *et al*. 2003).

The tectonic setting of initial Mesozoic basin development along the NE flanks of the Altai is equivocal. It has been variously interpreted as compressional (Sjostrom *et al*. 2001) and extensional (possibly transtensional, Howard *et al*. 2003). SW of the Altai, late Palaeozoic crustal shortening occurred in the Tien

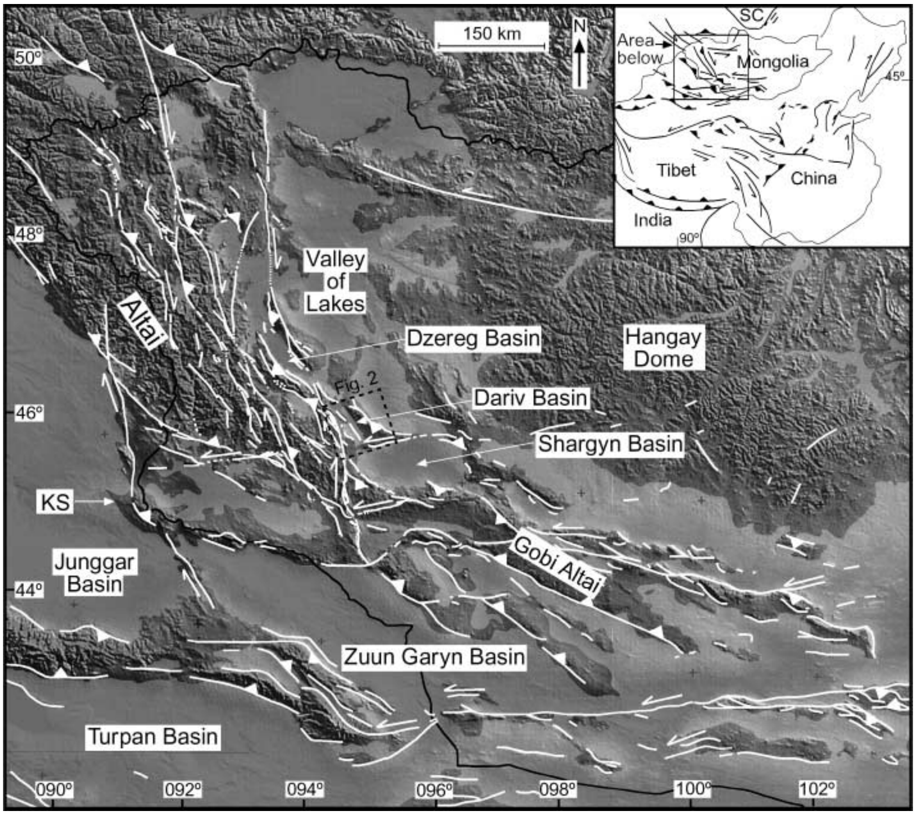


Fig. 1. Digital elevation model showing western Mongolia and adjacent parts of China and Russia. Sedimentary basins are shown in pale tones. Major Cenozoic thrust and strike-slip faults are also shown. The contrast between the dextral transpression in the Altai and the sinistral transpression in the Gobi Altai should be noted. The location of three studied basins is shown as well as the area covered by Figure 2. Inset map shows major Cenozoic faults within Asia. SC, Siberian Craton; KS, Kelameili Shan.

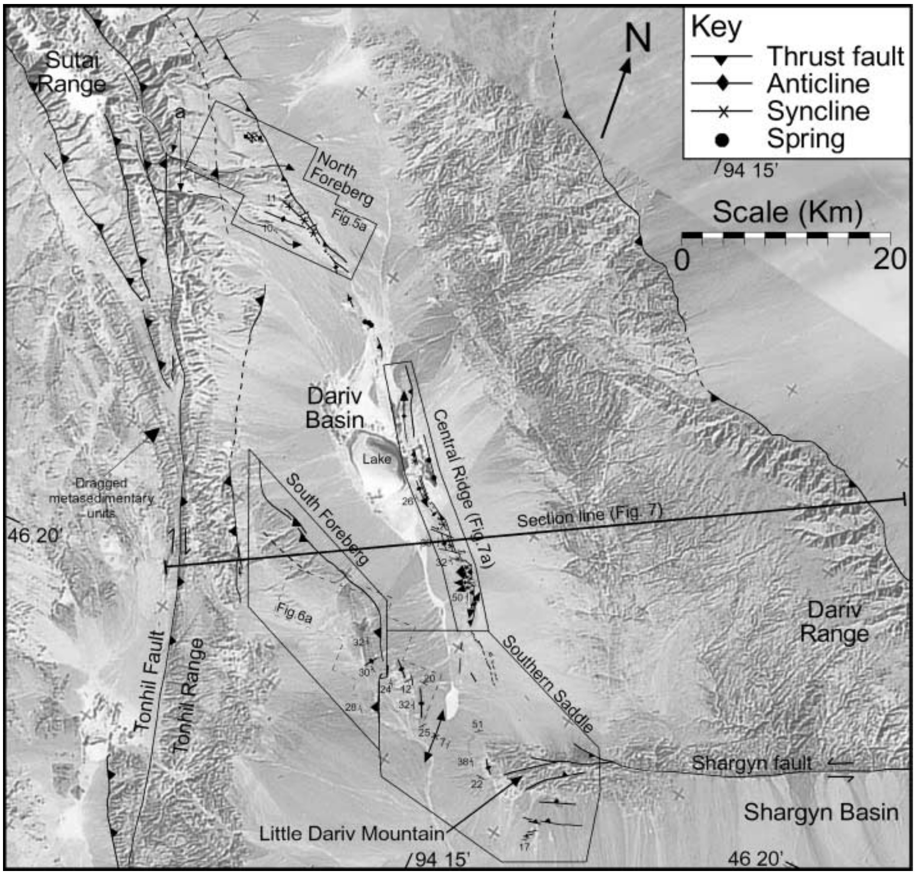


Fig. 2. Kosmos image covering the Dariv Basin, showing the major structural domains within the basin along with basin bounding structures. The change from west- to east-directed thrusting within the Sutai range should be noted; these faults are interpreted to define a flower structure geometry at depth. Location of Figures 5a, 6a, 7a and 8 are shown. Main drainage networks transporting sediment from the Sutai range into the Dariv Basin at ‘a’.

Shan and Bei Shan region in response to multiple collision events further to the south (Allen & Vincent 1997). The Tien Shan was a positive topographic feature for much of the Mesozoic (Zhang *et al*. 1984; Allen & Vincent 1997; Vincent & Allen 2001), and periodic uplifts produced sediment pulses recorded in adjacent basins (Hendrix *et al*. 1992). Vincent & Allen (2001) reported evidence for multiple Mesozoic compressional uplifts within the Kelameili Shan in the eastern Junggar Basin 275 km to the west of the Dariv Basin (Fig. 1). The existence of a thrusted Mesozoic palaeo-Altai with a foreland basin on its eastern margin is suggested by Sjostrom *et al*. (2001); however, structural evidence for Mesozoic shortening within the Mongolian Altai has not been documented (Cunningham *et al*. 1996*a*, *b*). Relict topography from Palaeozoic orogenic events may have been present during Mesozoic time. Sjostrom *et al*. (2001) proposed the existence of a west-vergent, contractional palaeo-Hangay range to the east of the Dariv Basin during the Early to Mid-Jurassic. However, no Mesozoic contractional structures have been identified in the Hangay range. Thomas *et al*. (2002) invoked a sharp variation in structural style between the Junggar and Altai domains corresponding to major faults or fault zones to explain variations in palaeomagnetically derived Cenozoic block rotations. It is possible that structural partitioning along these faults may have inhibited compressional uplift of the Altai during the Mesozoic.

In contrast, southern and eastern Mongolia and northeastern China are dominated by a broad belt of late Jurassic and Cretaceous extensional–transtensional basins (Traynor & Sladen 1995; Webb *et al*. 1999; Johnson *et al*. 2001; Meng 2003). In the northwestern Gobi Altai, Upper Jurassic continental deposits are interbedded with basalt in basins of probable extensional origin (Fig. 1; Shuvalov 1969). Within the Altai range, there is also some limited evidence to suggest that Mesozoic extension affected the region. Cunningham *et al*. 1996*a* reported structural evidence for a major pre-Cenozoic extensional event within the crystalline core of the high Altai west of the study area. Cenozoic thrust faults with pre-Cenozoic extensional histories were documented at two locations in ranges 130 km north of the Dariv Basin by Cunningham *et al*. (2003). Evidence for Mesozoic normal faulting within the neighbouring Dzereg Basin has also been documented (Howard *et al*. 2003).

The modern Dariv Basin is located in a region of active conjugate strike-slip faulting at the intersection between the Altai and Gobi Altai ranges (Tapponnier & Molnar 1979; Schlupp 1996; Fig. 1). Since the Oligocene, renewed deformation in western Mongolia is believed to have occurred in response to far-field stresses derived from the Indo-Eurasian collision over 2500 km to the SW (Tapponnier & Molnar 1979). The maximum horizontal compressive stress (SH_{max}) in western Mongolia is oriented NE as a result of India's continued northeastward indentation (Zoback 1992). This is confirmed by modern global positioning system (GPS) data that show NNE-directed crustal displacements in the Altai region at *c*. 4–5 mm a^{-1} (Calais *et al*. 2003). The central Mongolia craton, under the Hangay Dome region (Fig. 1), acts as a passive indentor, forcing lateral displacements around its margins along regional strike-slip faults. This results in NW-directed dextral displacement in the Altai and sinistral east–west displacement in the Gobi Altai (Fig. 1; Baljinnyam *et al*. 1993; Cunningham *et al*. 1996*a*, *b*) and possible anticlockwise crustal rotation relative to the applied NE SH_{max} in the Altai (Bayasgalan *et al*. 1999*a*). Ranges within the Altai represent discrete transpressional uplifts and thrust ridges, linked to regional strike-slip fault systems (Cunningham *et al*. 1996*a*, 2002, 2003). Many individual ranges comprise asymmetric flower structures with outward-directed thrusting at their margins (Fig. 2). Both the Altai and Gobi Altai are active, as indicated by historical seismicity, fresh fault scarps and alluvial fan deposits along their fronts, and low mountain front sinuosity (Baljinnyam *et al*. 1993; Cunningham *et al*. 1996*a*, *b*, 2003). All basins along the eastern flank of the Altai, including the Dariv Basin, record Late Cenozoic reactivation and uplift of the Mongolian Altai expressed as an Oligocene–Recent clastic basin fill sequence that is regionally unconformable above the older Mesozoic fill.

Local tectonic setting and physiography of the Dariv Basin

The Dariv Basin is a triangular-shaped depocentre containing Mesozoic and Cenozoic sedimentary rocks that is undergoing active deformation along thrust faults both within and adjacent to the basin margins (Fig. 2). The Sutai range that bounds the NW side of the basin is an actively forming restraining bend along the dextral Tonhil strike-slip fault (Fig. 2; Cunningham *et al*. 2003). This uplift, and the smaller Tonhil range that connects to the south, provide the major sediment input to the Dariv Basin. The Dariv range forms the northeastern margin of the Dariv Basin and is an uplifted and asymmetrically tilted block with an east-directed thrust on its eastern margin and an unfaulted western margin. Within the Dariv Basin, four structural domains are identified: the North and South Forebergs, the Central Ridge and the Southern Saddle. These domains are topographically connected at the surface and suspected to be structurally linked at depth; they appear to roughly define a rhomboidal area of active deformation adjacent to the Tonhil fault (Fig. 2).

Forebergs are thrust-bound ridges that form within sedimentary basins, adjacent to a throughgoing strike-slip or thrust fault that uplifts the bounding range (Bayasgalan *et al*. 1999*a*, *b*). Two forebergs project into the Dariv Basin from the west (Fig. 2) and define the southern and northern boundaries of the basin. In the basin centre the Central Ridge is a linear uplift, which is <40 m high and marked by spring lines, that links the Southern Saddle to the North Foreberg. Because the boundary between the Dariv range and Dariv Basin is unfaulted, the Central Ridge represents the eastern structural margin for the Dariv Basin (Fig. 2). The Dariv Basin floor is significantly higher than that of the adjoining Shargyn Basin to the south. The minor Southern Saddle uplift, extending from the Southern Foreberg to Little Dariv Mountain, forms the basin divide (Fig. 2).

Stratigraphy of the Dariv Basin

Exposure of the basin fill occurs only in the major deforming belts of the North and South Forebergs, the Central Ridge and the Southern Saddle (Fig. 2). No seismic or drill-hole data exist for the basin, so all information on the basin geology is based on analysis of surface outcrops. The Dariv Basin contains two major conformable successions separated by an angular unconformity: a Lower Jurassic to Cretaceous succession and an Oligocene–Present succession. A summary correlation panel in Figure 3 shows the stratigraphic sections investigated within the Dariv Basin, their location, and palaeocurrent data. A detailed facies analysis and environmental interpretation is beyond the scope of this paper and only a brief summary of the stratigraphy is given below.

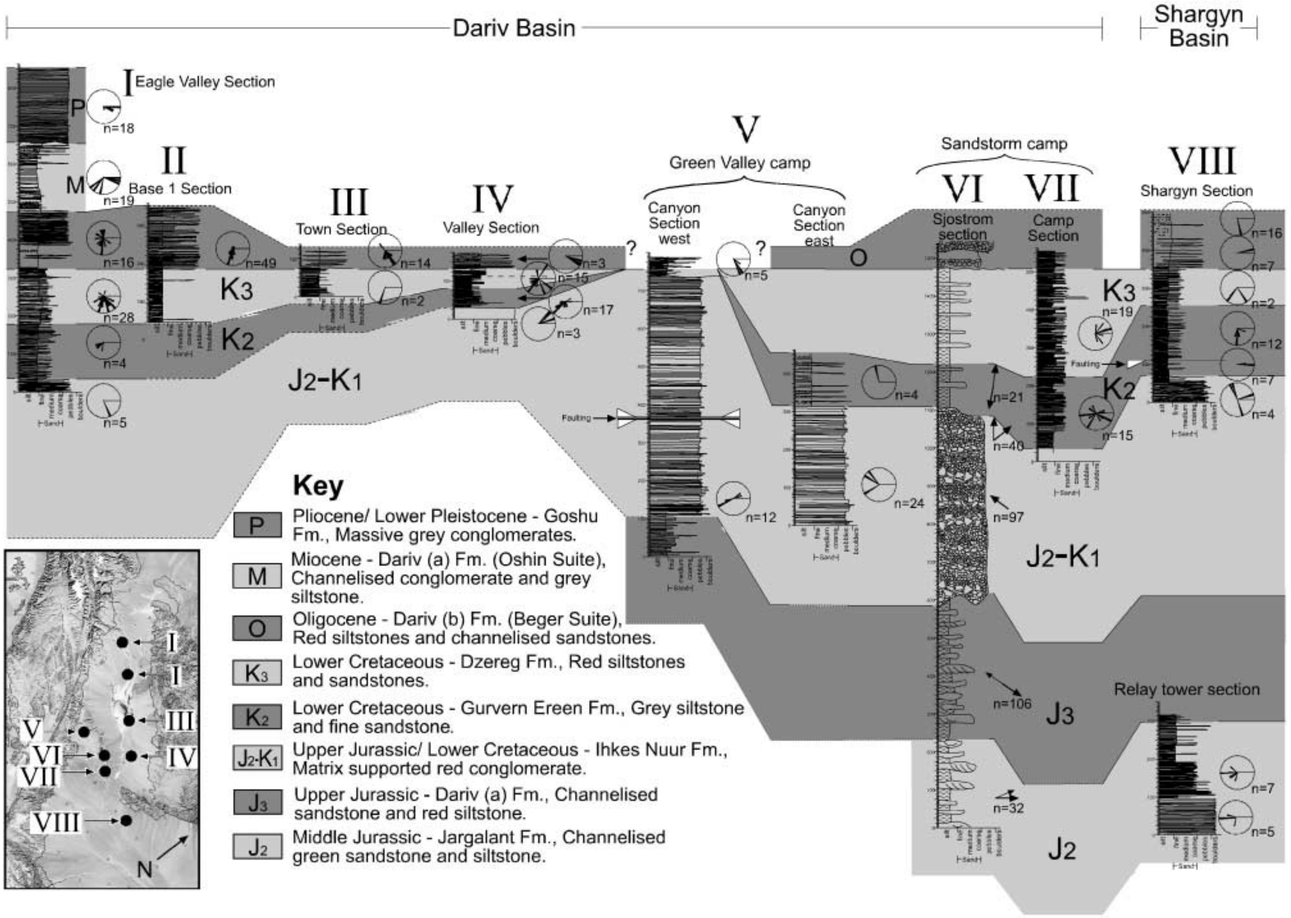


Fig. 3. Correlation panel showing the interpreted relationship between the sections investigated within the Dariv Basin and northern Shargyn Basin. Inset map shows the distribution of the sections investigated. The large thickness variation observed between sections in Upper Jurassic–Lower Cretaceous strata should be noted. Palaeocurrent data for each section are also shown and summarized in Fig. 4.

Jargalant Formation (Lower to Middle Jurassic)

The Jargalant Formation onlaps Palaeozoic rocks east of Little Dariv Mountain (Fig. 2) and consists of predominantly green-toned texturally mature cobble conglomerate beds with thin sandstone sheets that fine upwards into a siltstone-dominated succession containing conglomerate channels and minor sandstone sheets. The channels become increasingly broad and sandstone dominated towards the top of the formation. The Jargalant Formation is dated to the Early and Mid-Jurassic using ostrocodes and plant remnants (Devjatkin *et al*. 1975).

The facies observed in the Jargalant Formation are characteristic of a braided stream-dominated fluvial fan system (Nemec & Postma 1993). The fining-upward succession, associated with an increase in shallow, poorly confined, sandstone channels, may reflect changes in sediment source area or climate, or an increasingly distal position on the fan surface.

Dariv (a) Formation (Upper Jurassic)

This predominantly red coloured formation fines upward from medium-grained sandstone channels and interbedded siltstones into interbedded soft red siltstones and mudstone. The channels comprise massive, planar or trough cross-stratified poorly sorted sandstone. The siltstone successions contain plant remains and caliche horizons. The upper contact with the Ihkes Nuur Formation is locally scoured but broadly conformable. The formation is dated to the Late Jurassic based on dinosaur fossils (Khosbayer 1973; Graham *et al*. 1997).

The Dariv (a) Formation has previously been interpreted to represent the deposits of a shallow, sinuous, sand-bed river system within a mud-dominated overbank environment (Khosbayer 1973; Graham *et al*. 1997; Sjostrom *et al*. 2001); the observations in the present study are consistent with this interpretation.

Ihkes Nuur Formation (Upper Jurassic–Lower Cretaceous)

This formation is dominated by angular, poorly sorted, matrix-supported massive red conglomerate beds, which are 30–100 cm thick and have erosive basal contacts. Individual beds are laterally extensive over tens of metres. Inversely graded, matrix-supported pebble conglomerate beds are present along with the massive conglomerate, sandstone and siltstone horizons. The upper contact of the Ihkes Nuur Formation is generally conformable, except in the North Foreberg, where there is an angular unconformity. A Late Jurassic–Early Cretaceous age is assigned based on the stratigraphic position of the formation and palaeontologically dated correlative outcrops in adjacent basins (Khosbayar 1973).

The association of massive, laterally discontinuous conglomerate sheets, with abundant imbricated clasts, rare normally graded beds, and the limited preservation of fine material suggest that the Ihkes Nuur Formation represents a fluvial-dominated alluvial fan system (Harvey 1988; Nemec & Postma 1993; Sjostrom *et al*. 2001).

Gurven Ereen Formation (Lower Cretaceous)

This upward-fining formation consists of well-laminated grey siltstones containing gypsum, interbedded with sandstone sheets. At the basin margins, the unit comprises a coarser succession of interbedded red siltstone and sandstone with rare caliche horizons. The formation thickens westwards, forming an asymmetric wedge, and has a conformable upper contact (Fig. 3). It is dated as latest Jurassic to Early Cretaceous by ostracode, fish, insect and plant fossils (Khosbayer 1973; Devjatkin *et al*. 1975).

The siltstone beds contain lacustrine fossils, and thin sandstone sheets record periodic sheetflood events entering a lake. The absence of burrowing benthos, combined with gypsum horizons, may reflect a saline lake environment.

Dzereg (Zerik) Formation (Lower Cretaceous)

This formation is composed of predominantly massive siltstones interbedded with laminated siltstones. In the upper part of the formation, thick coarsening-upward sandstone layers overlain by caliche-rich siltstones are common. At the basin margins, caliche-rich red siltstones incised by channelized pebble conglomerate dominate. Early Cretaceous molluscs and ostracodes have been reported by Devjatkin *et al*. (1975) and Khosbayer (1973).

The formation records the evolution of a lake or lake margin environment. The succession is dominated by bioturbated lacustrine siltstones, which, combined with the red coloration, suggest an oxygenated lake bed. Periodic influxes of sand introduced via sheetflood events are interpreted from the formation's basal succession. The formation's upper section records the progradation of deltas into the lake supplied via a gravel bed fluvial system.

Cenozoic sediments

Dariv (b) Formation (Oligocene Beger Suite)

This formation is dominated by channelized conglomerate, interbedded with red–brown siltstone. Channels extend 40–50 m laterally, are spaced at <10 m vertical intervals and fine upwards between internal erosion surfaces. Thin pebble sheets that fine laterally are associated with channel margins. The siltstones are clay-rich, contain caliche and are extensively rooted. Channelized conglomerate bodies with multiple internal erosion surfaces suggest a long-lived, stable, fluvial channel. An Oligocene age is reported on published geological maps (Zaitsev 1978) and from correlative strata in adjacent basins (Devjatkin *et al*. 1975).

Dariv (c) Formation (Miocene)

Massive, multicoloured siltstone beds dominate this formation and two micritic, ostracode-rich limestone beds occur near its base. Fining-upward, laterally extensive, clast-supported, angular pebble conglomerate beds that are <50 cm thick become more dominant up-section. A Miocene age is assigned for this formation based on palaeontological and palynological evidence (Devjatkin 1981).

The formation records an unexpected pause in coarse sedimentation during the early Miocene, at a time when adjacent ranges were uplifting (Cunningham *et al*. 2003). Overbank floodplain deposits dominate; however, ostracode-bearing limestones suggest that lakes developed on the floodplain. The coarsening-upward trend and palaeocurrent data suggest that sediment was derived from a new source area in the evolving Sutai range west of the basin.

Goshu Formation (Pliocene to Lower Pleistocene)

This formation unconformably overlies the Dariv (c) Formation and comprises conglomeratic facies. It is exposed only in the Eagle Valley (Figs 2 and 5a). Clast-supported, grey pebble conglomerate sheets dominate and fine upward internally. They are interbedded with sandstone or matrix-supported conglomerate beds. The formation fines and thins to the east and is interpreted as the deposits of a sheetflood-dominated alluvial fan that prograded to the east in front of the Sutai range. The formation is undated, but is suggested to be Pliocene or Early Pleistocene in age, based on potentially correlative deposits elsewhere (Devjatkin 1981).

Modern Quaternary fill

The modern Dariv Basin has a radial drainage pattern and Holocene–Recent sedimentation is dominated by alluvial fans derived from the Sutai range and Tonhil range in the north and west (Fig. 2). Sediment from the Sutai range now bypasses the North Foreberg, where erosion and downslope redeposition of uplifted basin fill occurs. Five canyons incise the Southern Foreberg and transport sediment to the basin centre. The Dariv range, which is inactive on its southwestern side, supplies little sediment to the Dariv Basin at present. The basin lacks an outlet river and all drainages feed a small saline lake in the basin centre, which is ponded against the Central Ridge. Salt marshes and evaporate deposits surrounding the lake are visible on the imagery (Fig. 2).

Structure of the Dariv Basin

External basin bounding structures

The Tonhil dextral strike-slip fault defines the western margin of the Dariv Basin (Fig. 2). Relief along this fault (the Tonhil range) is low in the west where strike-slip motion dominates, but increases to the north as the fault curves westward, culminating in the Sutai range. The Sutai range restraining bend occupies a stepover zone between two segments of the Tonhil fault and includes the highest peak in the region, Sutai Uul (4090 m). The internal structure of the range is an asymmetric flower structure with most uplift accommodated by thrusting in the centre of the range and on its southwestern side (Cunningham *et al*. 2003). In the Dzereg Basin to the north (Fig. 1), the earliest Cenozoic sediment is derived from the Sutai range, suggesting that it was the initial locus of rejuvenated uplift in the region (Howard *et al*. 2003).

In contrast, the eastern Dariv Basin margin is characterized by sediments onlapping the gently tilted western flank of the Dariv range. The Dariv range is uplifted by a thrust fault on its eastern margin (Fig. 2) and the asymmetry of the range is clearly expressed in modern drainage patterns with short steep channels in the east or NE and longer, sinuous channels draining towards the west or SW. The southern front of the Dariv range is sharply defined by an active sinistral fault, the Shargyn fault. This fault extends westwards into the Dariv Basin, where it splays and curves NW as it approaches the Tonhil fault (Fig. 2). Little Dariv Mountain, which forms the southern margin of the Dariv Basin, is uplifted at this splay zone along the Shargyn fault.

Intrabasinal structures

The North Foreberg

The North Foreberg (Fig. 5a) is bounded on its NE side by a SW-dipping thrust fault. Thrust sense displacement is inferred from the uplift of the ridge relative to the basin floor, the asymmetric topography of the ridge, and westerly tilt of strata adjacent to the front. In addition, exposed tilted strata are younger to the SW and widespread folds and minor thrust faults are present within the ridge SW of the frontal thrust (Fig. 5b–d). In the northwestern part of the North Foreberg, near the Tonhil fault, a series of anticlines and synclines are present, deforming the Jurassic Ihkes Nuur and Lower Cretaceous Gurven Ereen and Dzereg Formations (Fig. 5b); these folds are upright, plunge SE at 05° → 130°, and have wavelengths of the order of 200 m. At the southeastern end of the foreberg, but still west of the frontal thrust, a prominent valley is underlain by an anticline with an axis that plunges 10° → 101° The anticline tightens eastwards toward the frontal thrust (‘Eagle Valley’ anticline, Fig. 5a).

Exposure is limited between the North Foreberg and the Tonhil fault. The Sutai range margin directly west of the North Foreberg contains several well-exposed east-directed thrust faults that cut Cenozoic alluvial sediments (Fig. 2; see Cunningham *et al.* 2003, fig. 6b).

The South Foreberg

The South Foreberg comprises an elongate ridge oriented 40° from the strike of the Tonhil fault and bounded by an east-directed thrust fault on its north and northeastern side (Fig. 6a). This thrust emplaces lower Jurassic Jargalant Formation sediments onto Cretaceous sediments of the Gurven Ereen and Dzereg Formations (Fig. 6b). The internal structure of the foreberg consists of a homoclinal section dipping 30° SW. The foreberg is truncated in the east by a series of NW–SE faults that separate the South Foreberg from the adjacent Southern Saddle domain (Figs 2 and 6a).

The Southern Saddle Domain

The geology of this area is poorly exposed, but it links the Southern Foreberg–Tonhil fault domain with a deforming belt associated with the sinistral Shargyn fault (Fig. 2). In the west of the domain, two low NW-trending domes of uplifted Mesozoic sedimentary rocks lie immediately adjacent to the Southern Foreberg (Figs 2 and 6). These domes consist of NW–SE periclines that deform Mesozoic–Cenozoic basin fill. The folds have a slight eastward vergence (Fig. 6a cross-section). East of the domes, limited exposures of Oligocene sediments form an open syncline that plunges both north and south (Fig. 2).

Little Dariv Mountain is uplifted where the Shargyn fault separates into a series of splays that curve both north and south within the range (Fig. 2). Several southward-directed thrust faults and asymmetric folds were identified in the Shargyn section south of Little Dariv Mountain (Fig. 2). These faults define an apparent flower structure within Little Dariv Mountain with uplift concentrated primarily on its southern side. The mountain is essentially a structural pop-up with sediments dipping away from it on each side.

Central Ridge section

The Central Ridge comprises a low ridge trending NW–SE through the centre of the Dariv Basin (Figs 2 and 7a). The Central Ridge rises to a maximum elevation of 40 m above the basin floor and exposes upwarped alluvial gravels and limited outcrops of Mesozoic–Cenozoic strata. The ridge is interpreted to be bounded on its northeastern flank by a NE-directed thrust fault. This fault is unexposed; however, its presence is strongly suggested by tilted and uplifted exposures of deeper basin stratigraphy and asymmetric, east-vergent folds. Spring lines around Dariv town provide further evidence for a fault rupture at the surface. The highest elevations of the Central Ridge occur in its southern part, where the sedimentary section is deformed by tight folds that have vertical or subvertical axes. In one location, two folds form an S-shape in plan view (Fig. 7b and c), whereas other folds form tight box structures. At the northern end of the Central Ridge, low gravel ridges trend towards the north and NW and the fault appears to be segmented and slightly sinuous (Fig. 7a). NW-trending ridges align with a series of springs, and beyond, link with the southern end of the North Foreberg (Fig. 2). South of the Central Ridge, a series of low ridges (Figs 2 and 7a) curves toward Little Dariv Mountain; these ridges lack stratigraphic exposures.

Mesozoic basin evolution

Mesozoic strata in the Altai region are exposed within an elongate belt on the eastern margins of the range that includes intermontane basins such as the Dzereg and Dariv Basins, and at a few locations within the Valley of Lakes (Graham *et al.* 1997; Tomurtogoo *et al.* 1999). No Mesozoic sediments have been identified within the interiors of ranges adjacent to the modern basins. This suggests that Mesozoic topographically low areas that received and stored Jurassic–Cretaceous sediments have not since been inverted to form the major mountain ranges of the eastern Altai. Instead, Mesozoic basins have been inherited and reactivated as Cenozoic depocentres.

Mesozoic strata within the Dariv Basin show marked lateral thickness variations (Figs 3 and 4). The basin fill is highly asymmetric, thinning to the east; for example, the Dzereg Formation thins by 80% over 10 km between the Dariv Section and the Central Ridge Section (Figs 3 and 4). Jurassic strata have a greater lateral extent than the overlying formations and have more uniform thickness. They are the only sediments exposed within Little Dariv Mountain. Mesozoic strata are not exposed east of the Central Ridge Section (Fig. 2); however, extrapolation of the thinning sediment wedge to the east suggests that the Mesozoic basin margin lay close to the Central Ridge.

The Central Ridge fault is the only known structure within the Dariv Basin that is likely to be a reactivated Mesozoic fault. The Central Ridge fault dips to the west and offsets both the Mesozoic and Cenozoic sedimentary fill. There appears to be no satisfactory mechanical reason why such an isolated thrust fault should initiate in the centre of the basin during late Cenozoic tectonism because it is too far to the east to be linked to an eastward propagating thrust wedge with a critical taper within the Tonhil range. This fault is therefore interpreted to be a

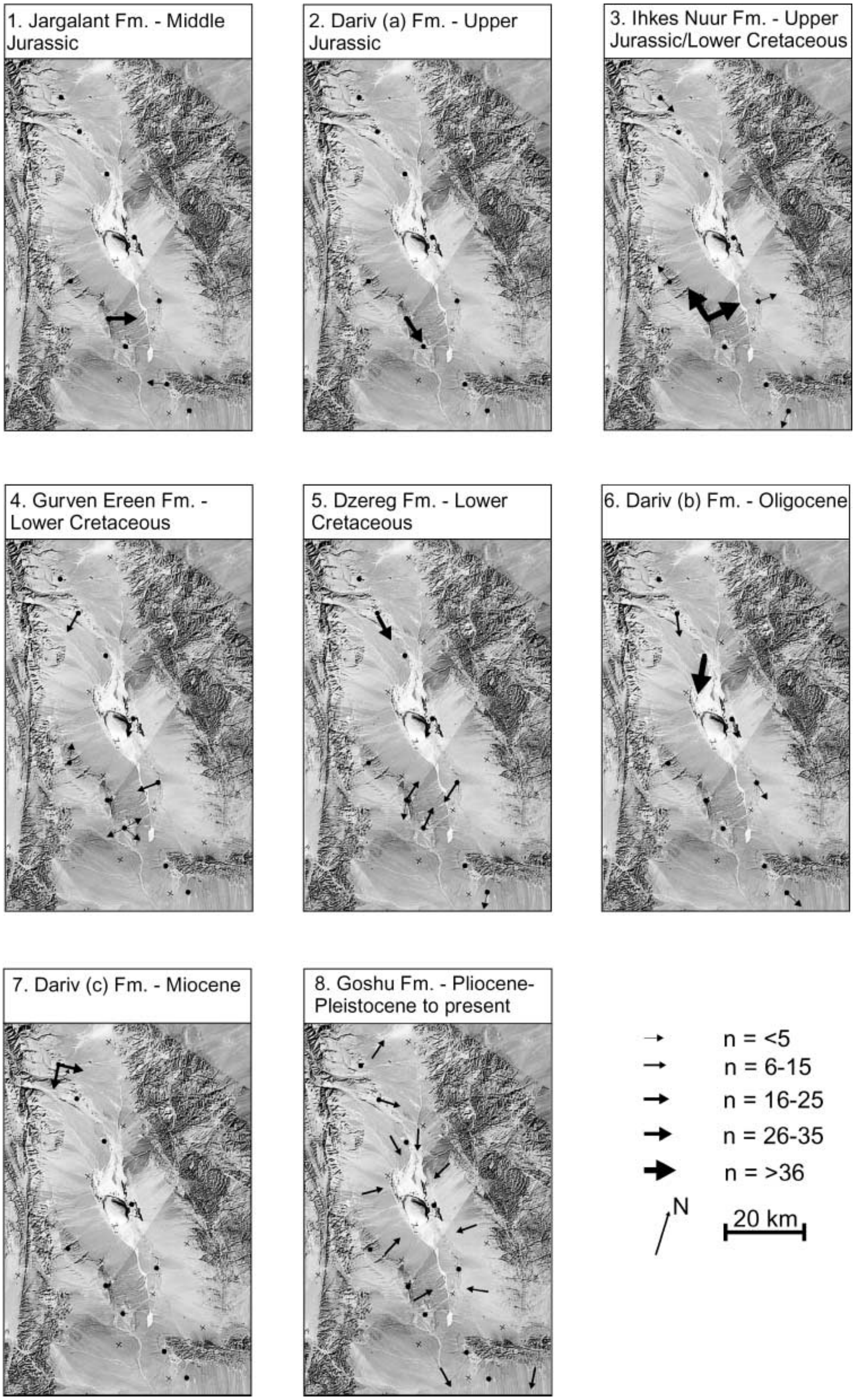
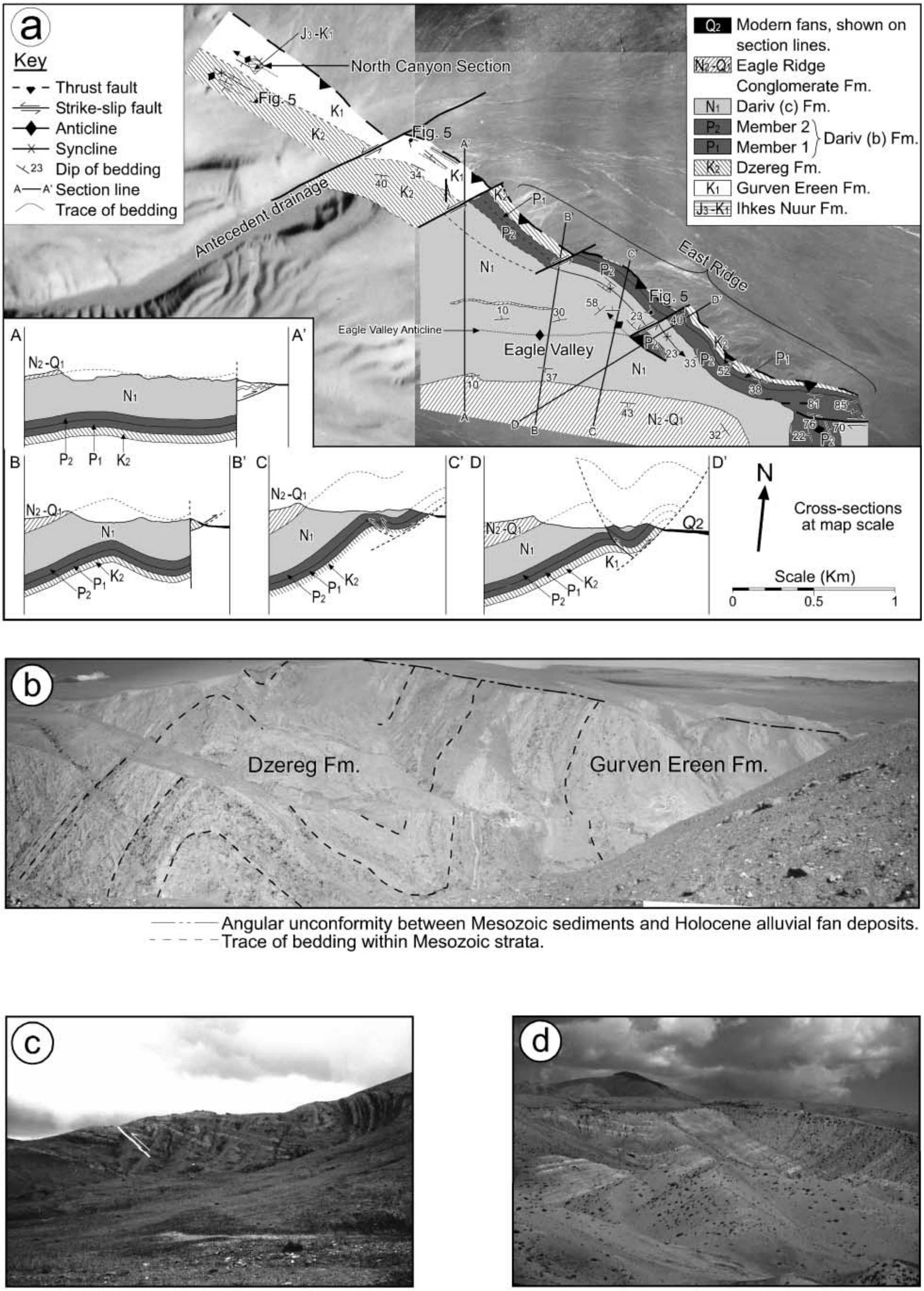


Fig. 4. Maps showing the geographical distribution of measured palaeoflow for each of the formations shown in Figure 3.

reactivated west-dipping normal fault. There may be other possible reactivated Mesozoic structures within the Dariv Basin that have not been recognized, or are present as blind structures at depth.

Based on consideration of exposed basin stratigraphy and structures, spatial trends in sedimentary characteristics and formation thicknesses, and palaeoflow indicators (Fig. 4), a model for the evolution of the Dariv Basin that begins with a


a
Key
Thrust fault
Strike-slip fault
Anticline
Syncline
23 Dip of bedding
A—A' Section line
Trace of bedding
Q2 Modern fans, shown on section lines.
N2-Q1 Eagle Ridge Conglomerate Fm.
N1 Dariv (c) Fm.
P2 Member 2
P1 Member 1
Dariv (b) Fm.
K2 Dzereg Fm.
K1 Gurven Ereen Fm.
J3-K1 Ihkes Nuur Fm.
J3-K1
North Canyon Section
Fig. 5
Fig. 5
Fig. 5
K1
K2
Antecedent drainage
East Ridge
Eagle Valley Anticline
Eagle Valley
N1
N2-Q1
P1
P2
A A'
B B'
C C'
D D'
Q2
Cross-sections at map scale
N
Scale (Km)
0
0.5
1
b
Dzereg Fm.
Gurven Ereen Fm.
Angular unconformity between Mesozoic sediments and Holocene alluvial fan deposits.
Trace of bedding within Mesozoic strata.
c
d

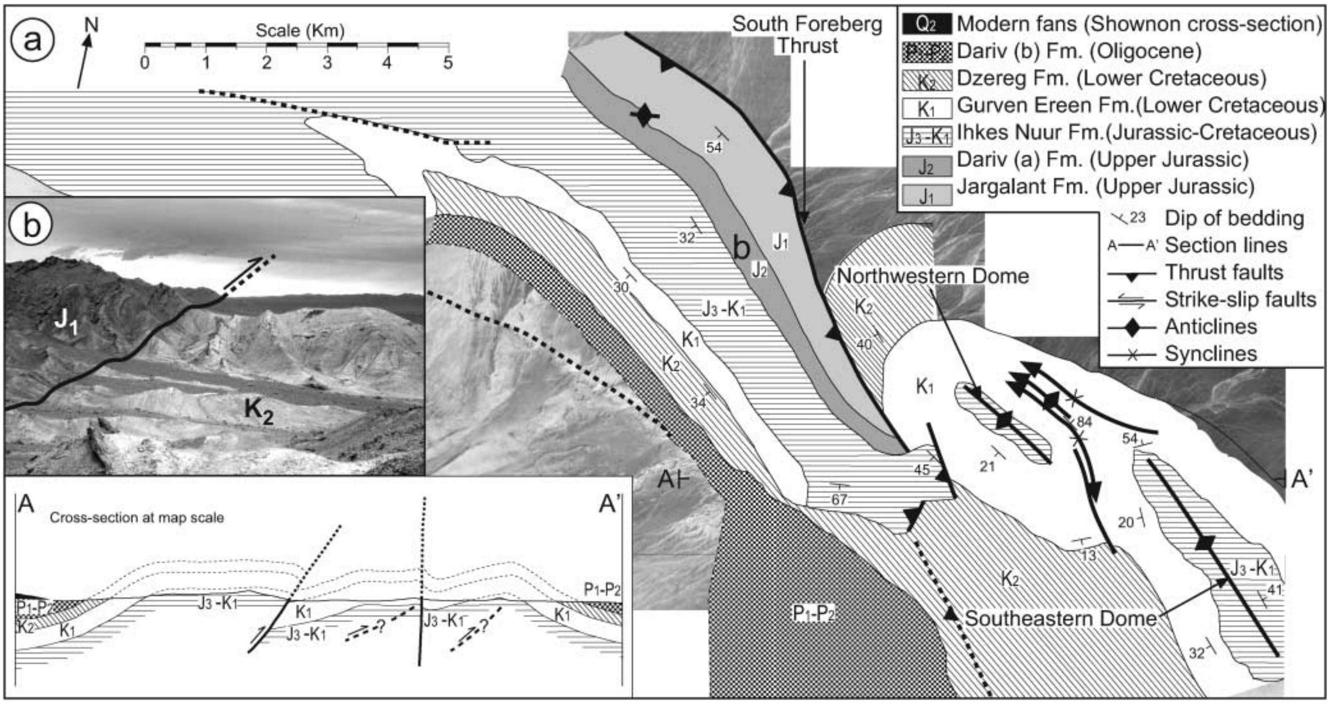


Fig. 6. (**a**) Aerial photograph of the South Foreberg overlain by geological map showing the distribution of stratigraphic units and geological structures. The foreberg is truncated at its eastern end by a series of north–south-trending faults. East of these faults lie two dome structures. (**b**) Photograph showing the Middle Jurassic Jargalant Formation thrust over Cretaceous beds. The syncline above the fault is an artefact of the image; beds curve into the dip-slip fault along a vertical fold axis.

period of Jurassic–Cretaceous crustal extension is proposed (Fig. 8). Initially, a half-graben developed bounded on the SW side by a system of normal faults that trend NW toward the Dzereg Basin, parallel to the basement structural grain. In the east of the Dariv Basin, sediments derived from the normal fault hanging walls were carried west, and in the west, sediments were carried east, forming alluvial or fluvial fans seen in the Jurassic Jargalant Fm (Fig. 4, (1)). It is likely that these fans flowed downslope to join the axial river system, exposed in the Dariv Formation, flowing toward the SE adjacent to the main bounding fault system in the west (Fig. 4, (2)). Extension continued during the Cretaceous and a westerly dipping antithetic normal fault formed in the east of the basin (Central Ridge Fault, Fig. 8b). The Ihkes Nuur Formation was deposited as small alluvial fans derived from the hanging-wall dip slope in the east and as large alluvial fans in the west derived from the footwall (Fig. 4, (3)). Although Sjostrom *et al*. (2001) interpreted the Ihkes Nuur Formation fans to have been derived from uplifted ranges in the south, coarser, more proximal conglomerates were not observed to the south in the Shargyn Basin section in this study (Figs 3 and 4). Instead, palaeocurrents within the Ihkes Nuur Formation in the Shargyn Section trend south (Fig. 4, (3)) and the formation is less coarse than the Dariv Section overall. It is suggested that fan systems derived from the Dariv Basin's southwestern flank flowed north as a result of subsidence adjacent to the proposed Central Ridge normal fault. Palaeoflow indicators in the Cretaceous rocks indicate that the Dariv Basin became internally drained and physically separated from the Shargyn Basin (Fig. 4). This separation is interpreted to record differential subsidence adjacent to different bounding normal faults. Stratigraphic data suggest that two distinct lacustrine depocentres formed that were each surrounded by an alluvial plain.

The upward-fining trend of the Cretaceous basin fill is characteristic of extensional basins (Leeder & Gawthorpe 1987) and the absence of any evidence for pre-Cenozoic contractional deformation within the Mesozoic basin fill further supports an extensional model for basin initiation. An extensional evolutionary model also best explains the asymmetric west–east thickness variations of the Mesozoic basin fill (Figs 3, 4 and 8). Unfortunately, the proposed basin bounding normal fault or faults that originally defined the western basin margin are not visible and may be either thrust truncated or buried beneath Cenozoic alluvial deposits.

Cenozoic basin development

Following a period of tectonic quiescence and development of a regional erosional peneplain in the Late Cretaceous–Palaeogene, the Altai was reactivated and uplifted in response to NE–SW

Fig. 5. (**a**) Aerial photograph of the North Foreberg overlain by geological map showing the distribution of major stratigraphic units and structures referred to in the text. It should be noted how strata exposed adjacent to the NE-directed frontal thrust fault become younger toward the SE. Locations of (**b**)–(**d**) are shown. (**b**) View north across the North Canyon Section (**a**) showing exposed basin stratigraphy in the North Foreberg. The lower unit is the Gurven Ereen Formation (Lower Cretaceous) overlain by the Dzereg Formation (Lower Cretaceous). (**c**) View south down the East Ridge showing asymmetric east-verging folds in the Cretaceous Dzereg Formation. Some fold hinges are locally broken by east-directed thrust faults. The major frontal thrust is unexposed, but lies left of the picture. (**d**) View NW up the East Ridge, showing the syncline behind the frontal thrust.

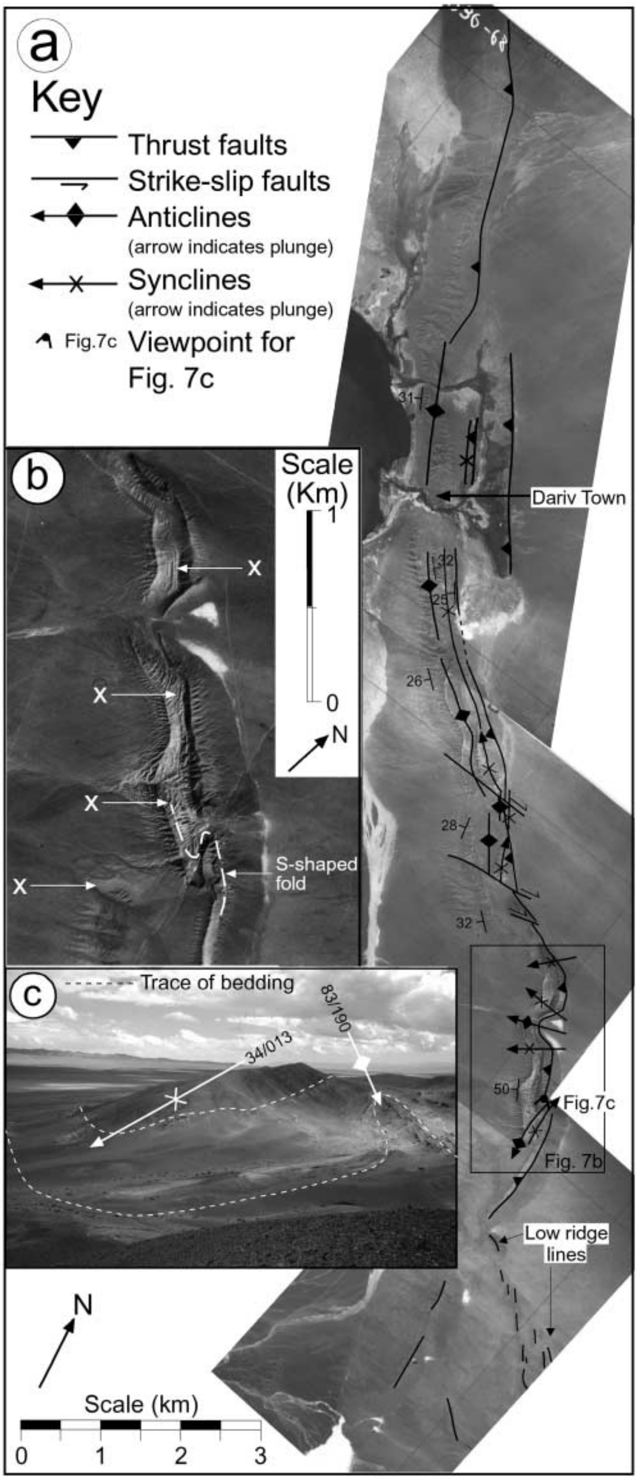


Fig. 7. (**a**) Aerial photograph mosaic and interpretation of the Central Ridge domain of the Dariv Basin. Thrust faults that uplift the ridge, folds and location of (**b**) and (**c**) are shown. (**b**) Aerial photograph showing part of the southern Central Ridge. Individual beds can be traced (x) and crest lines act as proxies for bedding. (**c**) View south over the southern Central Ridge. The ridge contains folds with steep or subvertical axes.

compression derived from the Indo-Eurasia collision (Tapponnier & Molnar 1979). Figure 9 is a block diagram with a conservative extrapolation to depth of surface fault and bedding attitude data. The model suggests that the Dariv Basin is similar to a piggyback basin between two thrust ranges, which in cross-section has architectural similarities to a foreland-style depocentre. However, because of the important strike-slip displacements on the Tonhil and Shargyn Faults, it is more accurate to regard the Dariv Basin as a transpressional piggyback basin that is also undergoing internal deformation in discrete structural compartments.

To explain the Cenozoic stage of Dariv Basin evolution, a model is proposed (Fig. 8, stages D and E, and Fig. 10) that relies on several assumptions. The four major structural domains within the Dariv Basin were initially distinct deformation zones that increasingly interacted as fault displacements increased and folds developed. Today they constitute a rhomboid of active deformation coupled to the Tonhil fault and the evolving Sutai range restraining bend to the west (Fig. 10). It is possible that they define an evolving strike-slip duplex coupled to the Tonhil fault and Sutai range (Cunningham *et al.* 2003), although evidence for strike-slip displacements was not found in the Central Ridge. However, vertical axis block rotations probably occurred in the two forebergs adjacent to the Tonhil fault as is typically observed in strike-slip and transpressional settings (Cobbold & Davy 1988; England & Molnar 1990; Bayasgalan *et al.* 1999*a*, *b*; Thomas *et al.* 2002). The NE-directed maximum horizontal stress is assumed constant throughout the mid- to late Cenozoic because the driving force is the continuous north-eastward indentation of India into Asia. Existing faults may also have been reactivated and inverted during a later stage of basin evolution (Holdsworth *et al.* 1997).

The majority of Cenozoic sediment was deposited as the basin flanking ranges were uplifted, but prior to intrabasinal deformation because Cenozoic sediment is uplifted and deformed by intrabasinal structures. There is a time lag between the onset of basin margin deformation in the Oligocene and widespread deposition of coarse sediment within the Dariv Basin. Oligocene fluvial sandstone and gravel beds with associated fine-grained overbank deposits (Dariv (b) Formation; Beger Suite) overlie the Palaeogene unconformity surface. Fluvial systems flowed axially SE through the Dariv Basin into the Shargyn Basin. This suggests that uplift along the Shargyn fault occurred later in the basin's evolution.

In the Dzereg Basin to the north (Fig. 1), the Cenozoic succession coarsened upward as the adjacent ranges developed; however, in the Dariv Basin, the Dariv (b) Formation shows upward fining. The Miocene Dariv (c) Formation records a broad alluvial plain periodically flooded by distal sheetfloods and rarely by more persistent lakes. The Sutai range is proximal to the North Foreberg locality and was supplying large amounts of coarse sediment into the Dzereg Basin during the Miocene (Howard *et al.* 2003). However, in contrast, the Dariv Basin received only limited coarse sediment during the Miocene. Two major drainages shown in Figure 2 (labelled 'a') incise the east ridge of the Sutai range and link this evolving catchment area to the Dariv Basin. If these drainages formed later in the basin's evolution, perhaps during the late Miocene, this might explain the lack of early Miocene coarse sediment in the Dariv Basin. Once these drainages were established, they captured much of the material being eroded from the Sutai range and provided a progressively coarser sediment supply to the Dariv Basin as fans prograded into the basin.

The Goshu Formation records a major alluvial fan system prograding SE from the Sutai range during the Pliocene–Early Pleistocene. The Goshu Formation conglomerate may have been derived from the same catchment area that is eroding today and, if so, progressive uplift of the Eagle Valley anticline has led to southward deflection of successive fans and depositional onlap onto the North Foreberg (Figs 2 and 5).

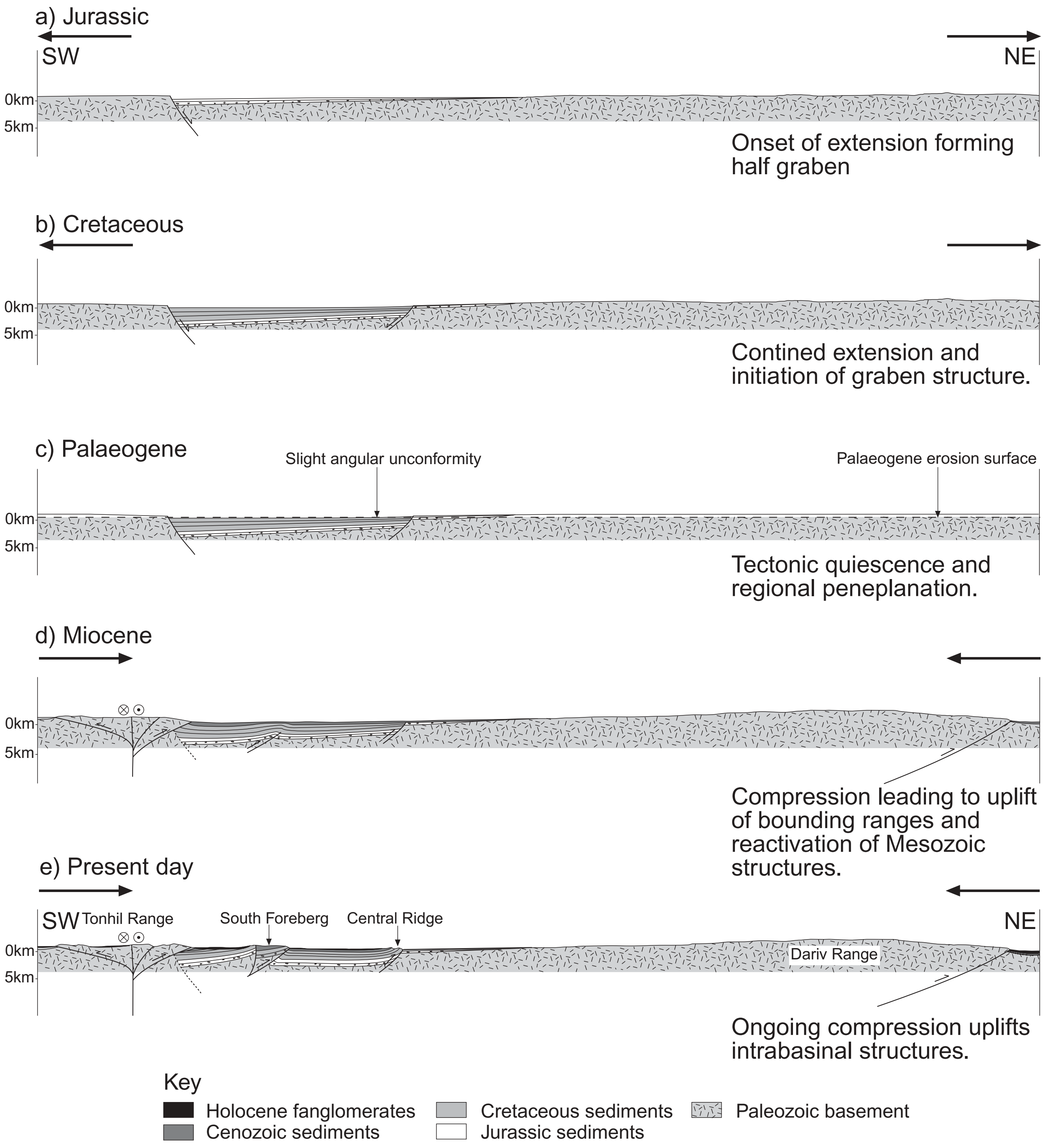


Fig. 8. Cross-sections showing an extensional model for Dariv Basin evolution; the section line is shown in Figure 2. (**a**) Regional crustal tension creates a Jurassic half-graben. (**b**) An antithetic normal fault forms in the Late Jurassic–Early Cretaceous confining Cretaceous sediment within the central part of the Dariv Basin. (**c**) Tectonic quiescence and regional peneplanation in the Palaeogene. (**d**) Onset of transpressional uplift of the Sutai Range and Dariv Range in the Oligocene. Many new faults form with only the Central Ridge fault reactivated and inverted as a thrust fault. (**e**) Continuing transpression results in intrabasinal deformation by foreberg evolution and uplift of the Central Ridge. Deformation causes uplift and erosion of the basin fill and its redeposition downslope.

The two forebergs within the Dariv Basin represent an outward progression of contractional deformation away from the Sutai range restraining bend and the transpressional zone associated with the Tonhil fault. The initial uplift is interpreted to have been at the mountain front (i.e. northwestern) end of the present-day forebergs because this is where the oldest basin sediments are exposed and where relief across the forebergs is greatest. Progressive range growth to the SE is indicated by progressively

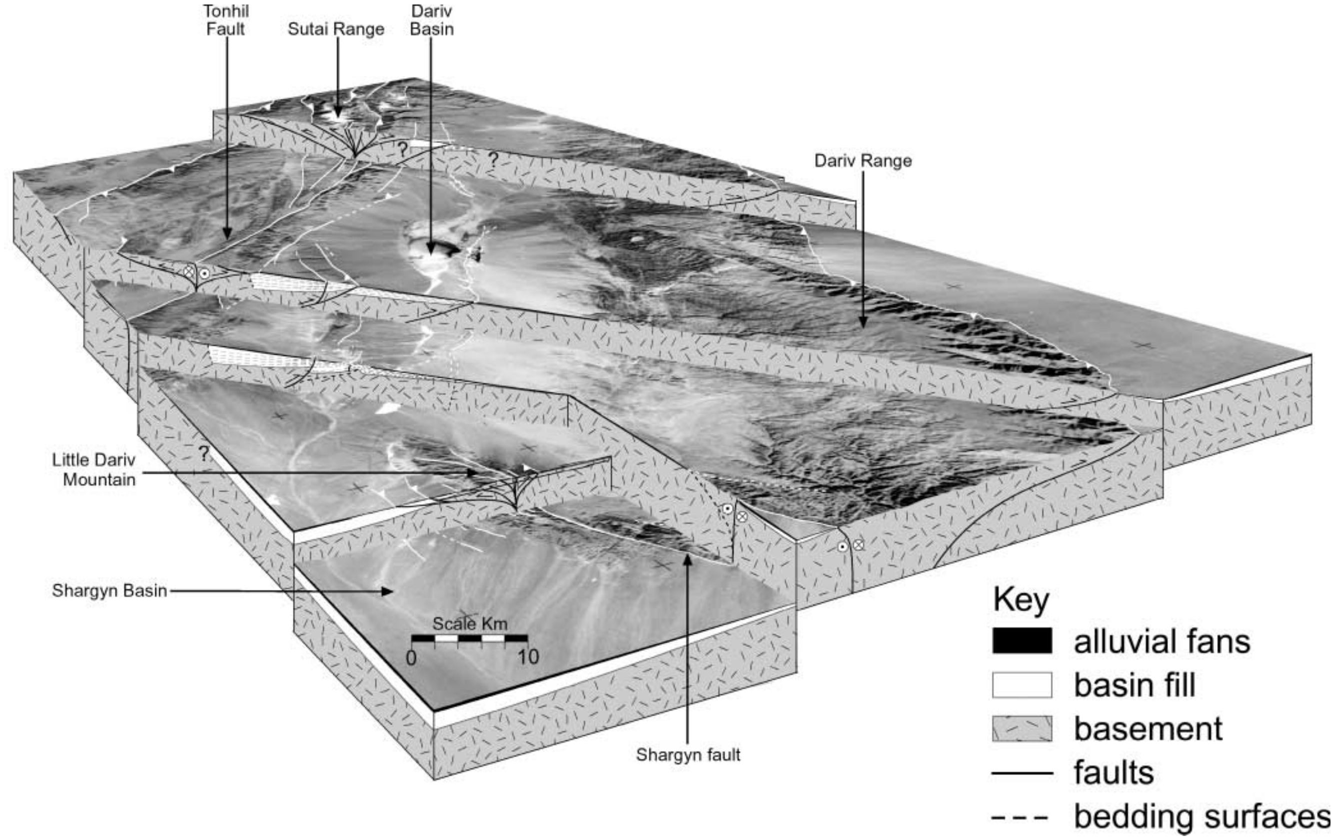


Fig. 9. A block diagram showing the interpreted 3D structure of the present-day Dariv Basin. The asymmetric flower structure geometry of the Sutai Range and Little Dariv Mountain and the asymmetric distribution of basin sediments should be noted.

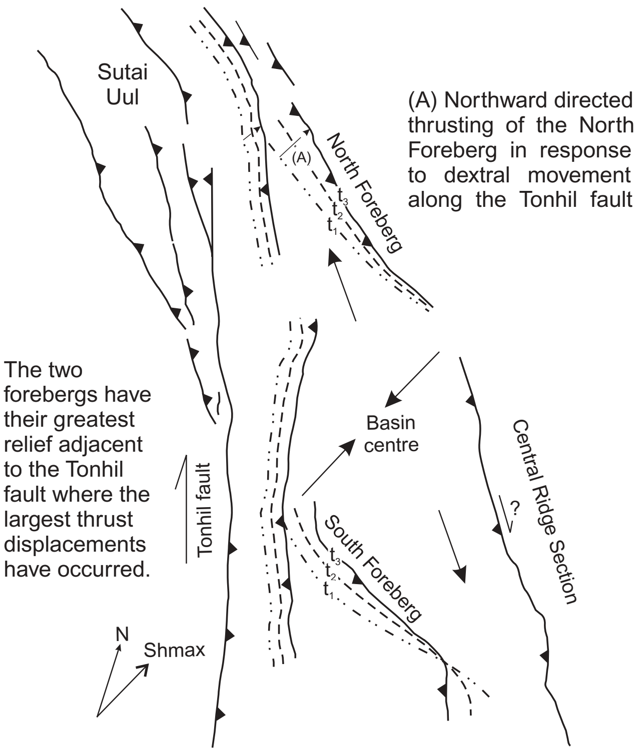
younger exposed strata in the North Foreberg, and decreasing topographic expression of the ridge. Block rotation of the forebergs relative to the Tonhil fault is interpreted to be a response to differential rates of thrusting along the strike of the frontal thrust (Fig. 10). This resulted in more rapid thrust propagation adjacent to the Tonhil fault and consequently clockwise rotation of the ridge. Such block rotations are expected in transpressional settings wherever a thrust fault with a gradient of displacement away from a linked strike-slip fault exists (Bayasgalan *et al*. 1999*b*).

The Southern Foreberg developed a slightly different geomorphological expression to the North Foreberg. Within the South Foreberg, shortening strain was accommodated on the frontal thrust faults and the foreberg consequently lacks an uplifted area between its frontal ridge and the Tonhil range. The southeastern end of the Southern Foreberg is truncated by a series of NW–SE-trending thrust and oblique-slip faults that form the boundary with the adjacent southern saddle domain (Fig. 6a). These NE-directed thrusts, in combination with the Northern and Southern domes that deform Mesozoic strata adjacent to the Southern Foreberg (Fig. 6a), are interpreted to accommodate stresses derived from east–west compression between the Tonhil and Shargyn fault systems (Fig. 2). The oblique displacements accommodated across the flower structure interpreted to underlie Little Dariv Mountain (Fig. 9), combined with the thrusts in the west, represent the complex termination zone of the Shargyn fault against the Tonhil fault and South Foreberg deforming zone (Figs 2 and 6).

Conclusions

The Dariv Basin is an actively evolving intracontinental basin positioned between a major restraining bend, a thrust mountain range and two major conjugate strike-slip fault systems. It has an interpreted polyphase history of probable Mesozoic rifting and late Cenozoic transpressional reactivation. The modern basin is receiving sediment while undergoing active deformation around its margins and within discrete compartments. Thrusting, folding, block uplift, and probable vertical axis rotations have led to erosion and redeposition of Mesozoic and Cenozoic basin fill. The basin provides a rare snapshot of an intracontinental transpressional basin at an early stage of destruction involving young faulting and folding, and reactivation of older faults and partial inversion. At first order, the basin is not simply a flexurally subsiding foredeep, but may be more accurately described as a transpressional piggyback basin. The basin geology reveals the complex interplay of major regional fault systems, local intrabasinal structures and evolving depositional systems.

We would like to acknowledge Tsogoo, Tsogoo and Oralmaa for their help in the field. This paper was improved following constructive reviews from J. Jackson and J. Turner, and comments and suggestions from J. Howell. This research was funded by Royal Society Grant 22077 and National Geographic Grant 6308-98 to W.D.C. and by a grant from the University of Leicester to J.P.H.



(A) Northward directed thrusting of the North Foreberg in response to dextral movement along the Tonhil fault

The two forebergs have their greatest relief adjacent to the Tonhil fault where the largest thrust displacements have occurred.

Fig. 10. Three-stage, progressive evolution of the North Foreberg, based on observed structures, taking into account NE-directed shortening and clockwise rotation adjacent to the Tonhil dextral strike-slip fault. t_1–t_3 indicate increasingly advanced stages of deformation.

References

Allen, M.B. & Vincent, S.J. 1997. Fault reactivation in the Junggar region, Northwest China; the role of basement structures during Mesozoic–Cenozoic compression. *Journal of the Geological Society, London*, **154**, 151–155.

Badarch, G., Cunningham, D. & Windley, B. 2002. A new terrane subdivision for Mongolia: implications for the Phanerozoic crustal growth of Central Asia. *Journal of Asian Earth Sciences*, **21**, 87–110.

Baljinnyam, I., Bayasgalan, A. & Borisov, B.A. et al. 1993. *Ruptures of Major Earthquakes and Active Deformation in Mongolia and its Surroundings*. Geological Society of America, Memoirs, **181**.

Bayasgalan, A., Jackson, J., Jean-François, R. & Carretier, S. 1999a. ‘Forebergs’, flower structures, and the development of large intracontinental strike-slip faults: the Gurvan Bogd fault system in Mongolia. *Journal of Structural Geology*, **21**, 1285–1302.

Bayasgalan, A., Jackson, J., Ritz, J.F. & Carretier, S. 1999b. Field examples of strike-slip fault terminations in Mongolia and their tectonic significance. *Tectonics*, **18**, 394–411.

Calais, E., Vergnolle, M., San’kov, V., Lukhnev, A., Mirotshnitchenko, A., Amarjargal, S. & Déverchere, J. 2003. GPS measurements of crustal deformation in the Baikal–Mongolia area (1994–2002): implications for current kinematics of Asia. *Journal of Geophysical Research*, **108**(B10), 2501, doi:10.1029/2002JB002373.

Chen, B. & Jahn, B. 2002. Geochemical and isotopic studies of the sedimentary and granitic rocks of the Altai origin of northwest China and their tectonic implications. *Geological Magazine*, **139**, 1–13.

Cobbold, P.R. & Davy, P. 1988. Indentation tectonics in nature and experiment: 2. *Central Asian Bulletin of Geology*, **14**, 143–162.

Cunningham, W., Windley, B.F., Dorjnamjaa, D., Badamgarov, G. & Saandar, M. 1996a. A structural transect across the Mongolian Western Altai: active transpressional mountain building in central Asia. *Tectonics*, **15**, 142–156.

Cunningham, W.D., Windley, B.F., Dorjnamjaa, D., Badamgarov, G. & Saandar, M. 1996b. Late Cenozoic transpression in southwestern Mongolia and the Gobi Altai–Tien Shan connection. *Earth and Planetary Sciences*, **140**, 67–82.

Cunningham, W.D., Dijkstra, A., Howard, J.P., Quarles, A. & Badarch, G. 2003. Active intraplate strike-slip faulting and transpressional uplift in the Mongolian Altai. *In:* Holdsworth, R.E. & Salvini, F. (eds) *Intraplate Strike-Slip Deformation Belts*. Geological Society, London, Special Publications, **210**, 65–87.

Cunningham, W.D., Davies, S. & Badarch, G. 2003. Crustal architecture and active growth of the Sutai Range, western Mongolia: a major intracontinental, intraplate restraining bend. *Journal of Geodynamics*, **36**, 169–191.

Devjatkin, E.V. 1970. *Mesozoic and Cenozoic Geology of Western Mongolia*. Joint Soviet–Mongolian: Scientific Research Geological Expeditions Transactions, Nauka, Moscow, **1**, [in Russian].

Devjatkin, E.V. (ed.) 1981. *The Cenozoic of Inner Asia Stratigraphy.* Combined Soviet–Mongolian Scientific Research Geological Expeditions Transactions, Nauka, Moscow, **27**, [in Russian].

Devjatkin, E.V., Nagibina, P. & Khosbayar, 1975. Neotectonic structures of western Mongolia. *In:* Yanshin, A.L. (ed.) *Mesozoic and Cenozoic Tectonics and Magmatism of Mongolia*. Combined Soviet–Mongolian Scientific Research Geological Expeditions Transactions, Nauka, Moscow, **11**, 44–102 [in Russian].

England, P. & Molnar, P. 1990. Right lateral shear and rotation as an explanation for strike-slip faulting in eastern Tibet. *Nature*, **344**, 140–142.

Graham, S.A., Hendrix, M.S., Barsbold, R., Badamgarav, D., Sjostrom, D., Kirschner, W. & McIntosh, J.S. 1997. Stratigraphic occurrence, paleoenvironment, and description of the oldest known dinosaur (late Jurassic) from Mongolia. *Palaios*, **12**, 292–297.

Harvey, A.M. 1988. Controls of alluvial fan development: the alluvial fans of the Sierra de Carrascoy, Murcia, Spain. *Catena*, **13** (Supplement), 123–137.

Hendrix, M.S., Graham, S.A., Carroll, A.R., Sobel, E.R., McKnight, C.L., Schulein, B.J. & Wang, Z. 1992. Sedimentary record and climatic implications of recurrent deformation in the Tien Shan: evidence from Mesozoic strata of the north Tarim, south Junggar, and Turpan basins, northwest China. *Geological Society of America Bulletin*, **104**, 53–79.

Holdsworth, R.E., Butler, C.A. & Roberts, A.M. 1997. The recognition of reactivation during continental deformation. *Journal of the Geological Society, London*, **154**, 73–78.

Howard, J.P., Cunningham, W.D., Davies, S.J. & Badarch, G. 2003. The stratigraphic and structural evolution of the Dzereg Basin, western Mongolia: clastic sedimentation, transpressional faulting and basin destruction in an intraplate, intracontinental setting. *Basin Research*, **15**, 45–72.

Johnson, C.L., Webb, L.E., Graham, S.A., Hendrix, M.S. & Badarch, G. 2001. Sedimentary and structural records of late Mesozoic high-strain extension and strain partitioning, East Gobi basin, southern Mongolia. *In:* Hendrix, M.S. & Davis, G.A. (eds) *Paleozoic and Mesozoic Tectonic Evolution of Central and Eastern Asia from Continental Assembly to Intracontinental Deformation*. Geological Society of America, Special Papers, **194**, 413–435.

Khosbayar, P. 1973. New data on Upper Jurassic and Lower Cretaceous sediments of western Mongolia. *Academy of Sciences of USSR, Doklady Earth Sciences Section*, **208**, 115–116.

Leeder, M.R. & Gawthorpe, R.L. 1987. Sedimentary models for extensional tilt-block/half-graben basins. *In:* Coward, M.P., Dewey, J.F. & Hancock, P.L. (eds) *Continental Extensional Tectonics*. Geological Society, London, Special Publications, **28**, 139–152.

Meng, Q. 2003. What drove late Mesozoic extension of the northern China–Mongolian tract? *Tectonophysics*, **369**, 155–174.

Nemec, W. & Postma, G. 1993. Quaternary alluvial fans in southwestern Crete; sedimentation processes and geomorphic evolution. *In:* Marzo, M. & Puigdefabregas, C. (eds) *Alluvial Sedimentation*. International Association of Sedimentologists, Special Publications, **17**, 235–276.

Schlupp, A. 1996. *Néotectonique de la Mongolie occidentale analysée à partir de données de terrain, seismologiques et satellitaires*. PhD thesis, Université Louis Pasteur, Ecole et Observatoire de Physique du Globe de Strasbourg.

Shuvalov, V.F. 1969. Continental red beds of the upper Jurassic of Mongolia. *Doklady Akademii Nauk, SSSR*, **189**, 1088–1091.

Sjostrom, D.J., Hendrix, M.S, Badamgarav, D., Graham, S.A. & Nelson, B.K. 2001. Sedimentology and provenance of Mesozoic nonmarine strata in western Mongolia: a record of intracontinental deformation. *In:* Hendrix, M.S. & Davis, G.A. (eds) *Palaeozoic and Mesozoic Tectonic Evolution of Central and Eastern Asia, from Continental Assembly to Intracontinental Deformation*. Geological Society of America, Memoirs, **194**, 361–388.

Tapponnier, P. & Molnar, P. 1979. Active faulting and tectonics of the Tien Shan, Mongolia and Baykal regions. *Journal of Geophysical Research*, **84**, 3425–3459.

Thomas, J.C., Lanza, R., Kazansky, A., Zykin, V., Semakov, N., Mitrokhin, D. & Delvaux, D. 2002. Paleomagnetic study of Cenozoic sediments from the Zaisan basin (SE Kazakhstan) and the Chuya depression (Siberian Altai): tectonic implications for central Asia. *Tectonophysics*, **351**, 119–137.

Tomurtogoo, O. (ed.) 1999. *Geological map of Mongolia. scale 1:1 000 000*. The Mongolian Academy of Sciences, IGMR & MRAM, Ulaan Baatar.

TRAYNOR, J.J. & SLADEN, C. 1995. Tectonic and stratigraphic evolution of the Mongolian People's Republic and its influence on hydrocarbon geology and potential. *Marine and Petroleum Geology*, **12**, 35–52.

VINCENT, S.J. & ALLEN, M.B. 2001. Sedimentary record of Mesozoic intracontinental deformation in the eastern Junggar Basin, northwest China: response to orogeny at the Asian margin. *In:* HENDRIX, M.S. & DAVIS, G.A. (eds) *Palaeozoic and Mesozoic Tectonic Evolution of Central and Eastern Asia, from Continental Assembly to Intracontinental Deformation*. Geological Society of America, Memoirs, **194**, 345–363.

WEBB, L.E., GRAHAM, S.A., JOHNSON, C.L., BADARCH, G. & HENDRIX, M.S. 1999. Occurrence, age, and implications of the Yagan-Onch Hayrhan metamorphic core complex, southern Mongolia. *Geology*, **27**, 143–146.

WINDLEY, B.F., KRÖNER, A., GUO, J., QU, G., LI, Y. & ZHANG, C. 2002. Neoproterozoic to Paleozoic geology of the Altai orogen, NW China: new zircon age data and tectonic evolution. *Journal of Geology*, **110**, 719–737.

YEATS, R.S., HUFTILE, G.J. & STITT, L.T. 1994. Late Cenozoic tectonics of the East Ventura Basin, Transverse Ranges, California. *AAPG Bulletin*, **78**, 1040–1074.

ZAITSEV, N.S. 1978. *Geological Map of the Mongolian Altai, scale 1:500 000*. Combined Soviet–Mongolian Scientific Research Geological Expeditions, Nauka, Moscow [in Russian].

ZHANG, Z.H.M., LIOU, J.G. & COLEMAN, R.G. 1984. An outline of the plate tectonics of China. *Geological Society of America Bulletin*, **95**, 295–312.

ZOBACK, M.L. 1992. First- and second-order patterns of stress in the lithosphere: the world stress map project. *Journal of Geophysical Research*, **97**, 11703–11711.

Received 15 June 2005; revised typescript accepted 7 November 2005.
Scientific editing by John Howell