PERGAMON

Journal of Structural Geology 21 (1999) 1285–1302

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

'Forebergs', flower structures, and the development of large intra-continental strike-slip faults: the Gurvan Bogd fault system in Mongolia

Amgalan Bayasgalan[a], James Jackson[a,*], Jean-François Ritz[b], Sebastien Carretier[b]

[a]Bullard Laboratories, Madingley Road, Cambridge CB3 0EZ, UK

[b]Laboratoire de Géophysique et Tectonique, Université Sciences et Techniques de Languedoc, Place E. Bataillon, 34060 Montpellier Cedex, France

Received 11 September 1998; accepted 1 March 1999

Abstract

The Gurvan Bogd mountains of the Gobi–Altay, Mongolia contain a system of strike-slip faults with a reverse component, part of which moved in a large earthquake ($M_w \sim 8.0$) in 1957. Adjacent and sub-parallel to the main ranges are numerous thrust-related folds, thrust faults, and elongated low ridges ('forebergs'), all of which result from the shortening component on the fault zone. The appearance of these thrust-related structures is varied, depending on their stage of development, preservation, and exposure. Evidence from geomorphology and surface ruptures suggests that they may all serve a common function, which is to broaden the deforming zone by creating new structures that are able to accommodate both the strike-slip and the shortening components of motion. The geomorphology further suggests that these new structures then evolve by lateral propagation and increase in amplitude, to eventually merge and form through-going new faults subparallel to the old. In their early stages the new faults and related structures appear to be influenced by the underlying sediments adjacent to the main range, which may include weak layers such as lake beds that can ultimately cause the collapse of foreberg ridges in landslides. The migration of faulting away from the main range is likely to be driven by stresses associated with topography, which in turn is a consequence of the shortening component. The evolution described here is thus peculiar to strike-slip faults with a reverse component, and can form many of the features of the 'flower structures' that are often described in such oblique-shortening zones. Although the shortening component is often localized in restraining bends, its origin may ultimately be related to rotations about vertical axes, which are common in deforming continental regions.

1. Introduction

The Gurvan (*lit.* 'three') Bogd mountains, containing the massifs of Ih Bogd, Baga Bogd and Artz Bogd, are at the eastern end of the E–W Gobi–Altay range in SW Mongolia (Fig. 1). The active deformation of the Gobi–Altay is dominated by E–W left-lateral strike-slip faulting, which forms a conjugate system with the dominantly NW–SE right-lateral strike-slip faulting in the Mongolian Altay to the west (e.g. Tapponnier and Molnar, 1979; Baljinnyam et al., 1993; Cunningham et al., 1996a, 1996b, 1997). The deformation in both ranges also contains a shortening component, manifested as numerous reverse or thrust faults, folds, or oblique slip on the strike-slip faults. It is probable that both the Gobi–Altay and the Mongolian Altay (and their strike-slip faults) rotate about vertical axes to accommodate the expected N- to NNE-shortening in this part of Asia (see inset to Fig. 1 and Bayasgalan et al., 1999), and this rotation may be the fundamental cause of the reverse component on the strike-slip systems. From a geomorphological and structural point of view, the reverse-slip component on these fault systems is very useful because it creates topography whose morphology, drainage and associated sedimentation allow insights into

* Corresponding author.
E-mail addresses: niceba@old.magicnen.mn (A. Bayasgalan), jackson@esc.cam.ac.uk (J. Jackson)

0191-8141/99/$ - see front matter
PII: S0191-8141(99)00064-4

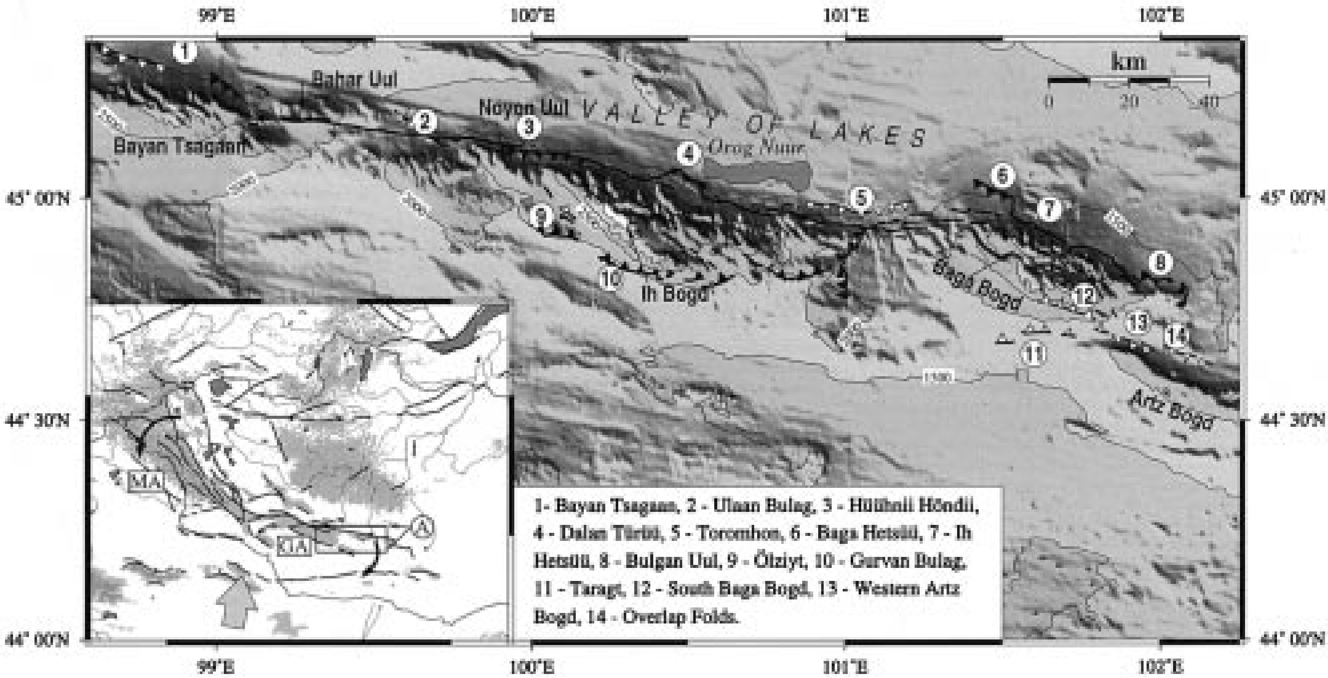


Fig. 1. Inset map shows the location of the Gurvan Bogd fault system (box A) within the Gobi Altay (GA) range of western Mongolia. Curved arrows show the inferred senses of rotation within the Mongolian Altay (MA) and Gobi–Altay (relative to Siberia in the north), and the big shaded arrow shows the approximate direction of overall shortening (e.g. Holt et al., 1995; England and Molnar, 1997). The main map (box A in the inset) identifies locations within the Gurvan Bogd mountains. Faulting in the 1957 earthquake is shown by solid black lines and thrust-related structures that moved in this earthquake are identified by filled black triangles. Open white triangles identify other thrust-related structures that did not move in the 1957 earthquake. Numbers in circles are locations referred to in the text.

how the fault systems evolve with time, which is the subject of this paper.

The Gurvan Bogd fault system is the best studied and most celebrated in the Gobi–Altay, mainly because it ruptured over a distance of about 260 km in an earthquake of $M_w \sim 8$ in 1957 (Florensov and Solonenko, 1963). The main 1957 surface ruptures were described by Florensov and Solonenko (1963) and Baljinnyam et al. (1993), and then in a critical synthesis involving precise re-measurement of scarps, by Kurushin et al. (1997). In addition to the main range-bounding oblique strike-slip faults, all these authors also describe sub-parallel ruptures separated from the main range fronts by typically 2–8 km and on which the dominant component of slip appeared to be thrusting on faults dipping towards the nearby high massifs. Some of the 1957 thrust scarps are at the foot of much larger escarpments displacing alluvial fans, while others are associated with rows of low hills, called 'forebergs' by Florensov and Solonenko (1963) and later authors. On the edges of the Gurvan Bogd mountains are other young scarps and ridges that are similar to those associated with the 1957 thrust scarps, but which did not rupture the surface in that earthquake. Both the 1957 and the pre-1957 thrust-related features vary in their geometry, appearance and geomorphological setting, and it is improbable that a single generic model of their structure and development can account for all of them. Yet they have all contributed to the topography and morphology of the Gurvan Bogd mountains, and they all pose the same essential questions regarding the evolution of this fault system, namely: (1) what is the relation between the thrusting and the strike-slip motion, and (2) how do the thrusts develop with time? In this paper we use our own observations of the 1957 and pre-1957 fault scarps and associated geomorphology to supplement the detailed description of the 1957 ruptures reported by Kurushin et al. (1997) and attempt to address these questions. As Bayasgalan (1995) and Cunningham et al. (1996a, 1997) point out, the internal geology of the Gobi–Altay ranges resembles the 'flower structures' that are often described in regions of oblique shortening (e.g. Woodcock and Fischer, 1986; Sylvester, 1988; Woodcock and Schubert, 1994), and the questions posed above may help us understand how flower structures evolve. Finally, as Bayarsayhan et al. (1996) emphasize, the Gurvan Bogd fault system is probably typical of many large, active, continental strike-slip systems, and understanding what the relation between geomorphology and ruptures in earthquakes has to tell us about their behaviour is of more than local interest.

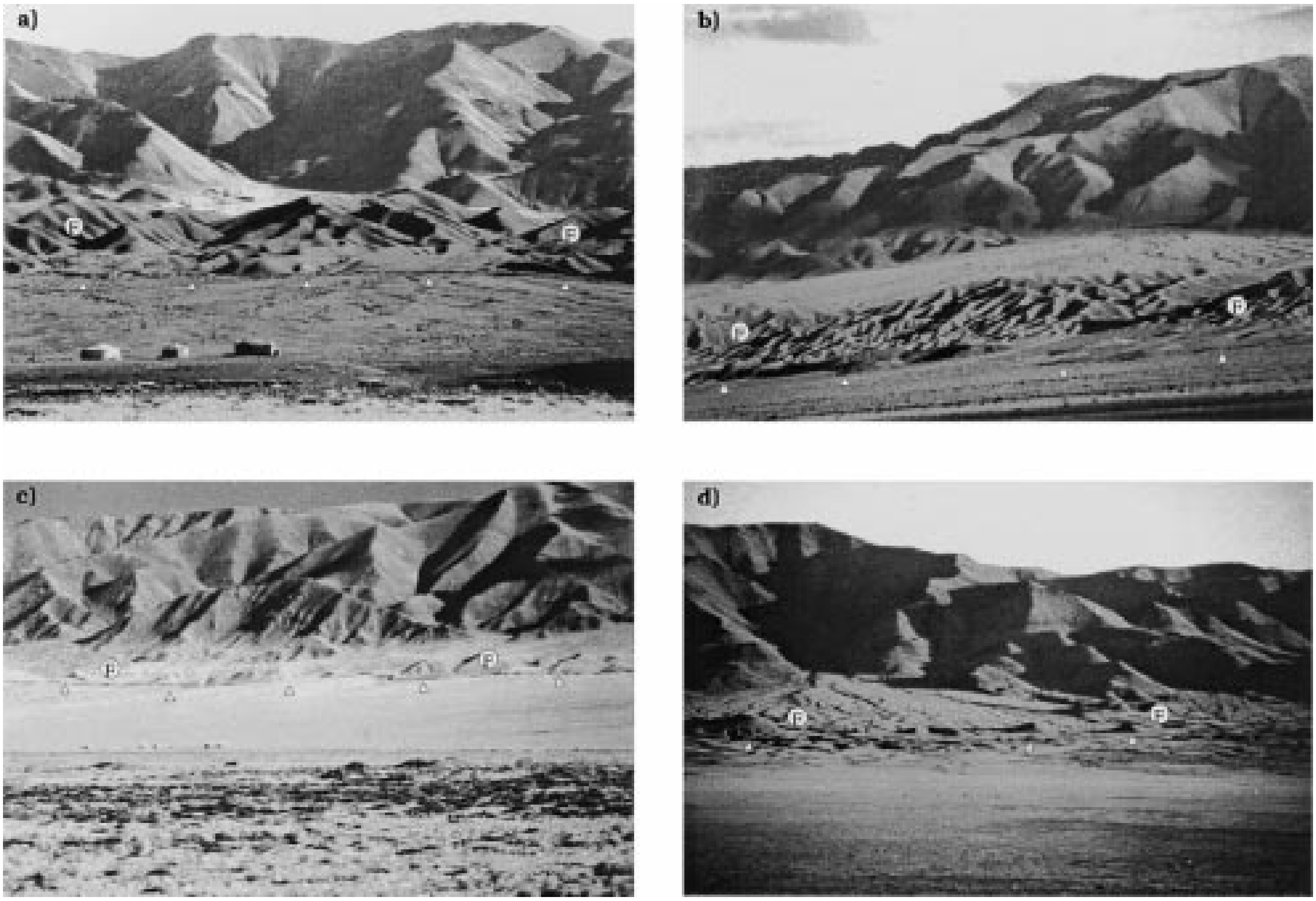


Fig. 2. Photos of foreberg ridges, identified by F in each picture. (a) View looking south at the eastern end of Dalan Türüü (#4 in Fig. 1). The main 1957 surface rupture is the line marked by arrows following the foot of the subdued hills in the foreground. In the background is Ih Bogd. Tents are about 3 m high. (b) View looking southeast at the western end of Dalan Türüü. Note the dissected hills of the foreberg rising above the fan surfaces between the foreberg and the main range front. The line of the 1957 ruptures is marked by arrows. (c) View of the Gurvan Bulag foreberg (#10), looking north. The main 1957 surface ruptures (marked by arrows) follow the base of the subdued foreberg ridge. (d) View looking south at the forebergs on the northeast side of Bayan Tsagaan (#1). Arrows mark the subdued foreberg hills.

2. General setting of the shortening structures

Fig. 1 shows the faulting in the 1957 earthquake and other features associated with thrusting but which did not rupture the surface in 1957. Of the thrust-related features referred to by numbers (#1–14) in Fig. 1, those at Dalan Türüü (#4), Baga Hetsüü (#6), Ölziyt (#9), Gurvan Bulag (#10) are all 'forebergs', or narrow ridges of hills rising up to 100 m above the surrounding alluvial fans and situated typically 5 km from the neighbouring mountain (Fig. 2). Thrusting associated with each of these features ruptured the surface in 1957 to form scarps upthrown on the mountain side and ranging from about 2 m (#4, 6, 9) to 4–5 m (#10) in height. At Bayan Tsagaan (#1) is a similar foreberg but, if it ruptured in 1957, the surface scarps were smaller (Kurushin et al., 1997). These forebergs share some general features: They all strike 110–130°, oblique to the average horizontal projection of the slip vector in the 1957 earthquake (thought to be in the range 080–090° because of the correlation between the vertical component of slip and the strike of the fault; Baljinnyam et al., 1993; Kurushin et al., 1997). With this orientation, the forebergs would therefore be expected to have a thrust component. Some of them (e.g. #4 and 6) are at obvious restraining bends in the fault system. Nearly all the forebergs and thrusts in Fig. 1 occur near the high and relatively wide massifs of Bayan Tsagaan, Ih Bogd and Baga Bogd, which suggests they are related to the way in which these mountains increase their width with time.

At the eastern end of Baga Bogd and the western end of Artz Bogd are other folds (#14), scarps (#12) and forebergs (#8, 11, 13) of which only #8 ruptured in 1957. Along Artz Bogd, folds and forebergs are found only in this location (#13 and #14). Bayasgalan et al. (1999) suggest that their formation is related to this special structural position between the two rotating massifs of Baga Bogd and Artz Bogd. Their left-stepping en échelon arrangement (discussed later, Fig.

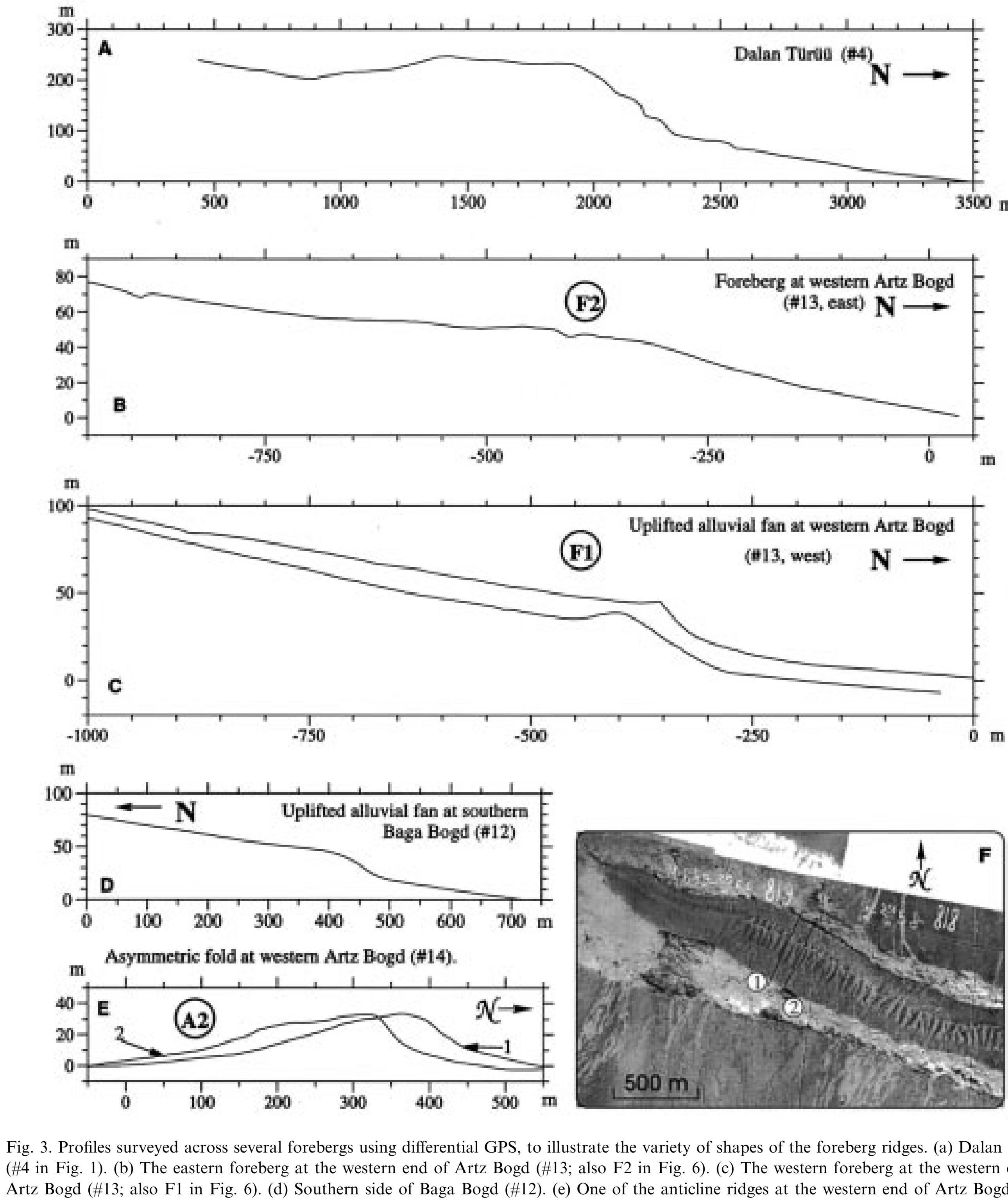


Fig. 3. Profiles surveyed across several forebergs using differential GPS, to illustrate the variety of shapes of the foreberg ridges. (a) Dalan Türüü (#4 in Fig. 1). (b) The eastern foreberg at the western end of Artz Bogd (#13; also F2 in Fig. 6). (c) The western foreberg at the western end of Artz Bogd (#13; also F1 in Fig. 6). (d) Southern side of Baga Bogd (#12). (e) One of the anticline ridges at the western end of Artz Bogd (#14; also A2 in Fig. 6). (f) Air photo of the fold profiled in (d): see also A2 in Fig. 6.

6) suggests a component of left-lateral strike-slip along the Artz Bogd range.

In addition, we identified four places, at Ulaan Bulag (#2), Hüühnii Höndii (#3), Toromhon (#5) and east of Ih Hetsüü (#7), where we suspect earlier thrust-related structures have been abandoned or modified during the evolution of the main 1957 strike-slip fault [called the Bogd fault by Florensov and Solonenko (1963) and later authors] as a through-going feature.

The forebergs and other thrust-related structures show both similarities and differences with each other. It is not our intention to produce a single model that explains all their features, nor do we believe that one exists. Different aspects of their geometry, kinematics and evolution are revealed in the different localities, and we hope that when taken together, they may allow generalizations to be made that are valid in principle, even though they may not apply to each structure in detail.

3. Structural generalizations

3.1. Shortening

The cores of the main basement massifs of Ih Bogd, Baga Bogd and Artz Bogd consist of metasedimentary rocks, volcaniclastics and felsic intrusions deformed in the late Paleozoic, followed by early Mesozoic foreland basin deposits that are uncomformably overlain by later rift-related Mesozoic clastic sedimentary rocks and volcanic rocks (e.g. Florensov and Solonenko, 1963; Hendrix et al., 1996; Cunningham et al., 1997). The region was peneplained in the late Cretaceous or early Tertiary, and there is speculation that the late Cenozoic deformation has involved inversion of Mesozoic extensional basins, possibly by reactivation of normal faults as thrusts (Cunningham et al., 1997). However, most of the thrust-related scarps that are the subject of this paper cut Quaternary fan material or bedded Tertiary sediments. Where exposed near the frontal thrust scarp, the bedded sediments generally dip toward the mountain at up to 30–40° (at #4, 6, 7, 13), but sometimes adjacent to the scarp itself (#4), the bedding dips away from the mountain and the foreberg has the internal structure of an anticline. The tilting, uplift and folding of the rocks within the foreberg are responsible for elevating it above the fans that lie between it and the mountain. However, the shapes of the emergent forebergs or ridges can be quite variable (Fig. 2). Some, such as #4 (Fig. 3a), 6 and 7, form ridges with slopes on the mountain side that are quite clear (~10°), though much less steep than the valley-facing slope at the thrust scarp itself. Other ridges are barely emergent above the fan surfaces behind them (e.g. #13 in Fig. 3b and c and #12 in Fig. 3d), and resemble more localized displacements in those surfaces. Many forebergs are internally deformed, especially by normal faults subparallel to the thrust scarps. The normal faults dip both toward and away from the mountain, and some ruptured the surface in the 1957 earthquake (#4, 9, 10). In addition, at least two forebergs (#4 and 10, and possibly 9) contain 'backthrusts' which moved in 1957. The backthrusts dip away from the mountain, and are situated on the mountain side of the foreberg ridge.

What can be deduced from these generalizations? The shape of the foreberg ridge is always asymmetrical, with its steepest flank away from the mountain, suggesting it overlies a thrust dipping toward the mountain. However, the shape and wavelength of the exposed ridge is clearly affected by several factors, including: (1) the internal deformation of the ridge (especially backthrusts, which can accentuate the mountain-facing slope, as at #4 and #10); and (2) the rate of uplift relative to (a) the sedimentation rate on the fan systems between the ridge and the mountain and (b) the incision rate of the outwash streams that cross the ridge. Some foreberg ridges are partially or almost completely buried beneath the outwash (#7, 13), and their internal structure is only evident in the gorges that cross them. The interplay between the rates of sedimentation and erosion allows some elevated fans between the foreberg ridges and the mountains to be much less dissected than would otherwise be expected, because the fans are protected by the rising foreberg, which only a limited number of streams succeed in crossing (see also Owen et al., 1997). From this point of view, the asymmetric folds and ridges (#14 in Fig. 3e and f) in the region between Artz Bogd and Baga Bogd are informative, since they are well away from the fans coming from Artz Bogd. These ridges are asymmetric folds, vergent away from the mountain, but their cores contain substantial internal deformation including structural repetition on thrusts (Cunningham et al., 1997). Their wavelength of about 500 m is typical of the 500–1000 m wavelength seen in several other forebergs (e.g. #1, 4, 6, 10), even though some of these are partially buried beneath outwash sediments on their mountain side. This relatively short wavelength, combined with the tilting of young sediments toward the mountain and the ability of the foreberg ridge to act as a barrier to the outwash (because its uplift rate exceeds that of the region between it and the mountain) all suggest that, in general, the thrusts beneath the forebergs flatten or decrease their dips at depths of 1–2 km (e.g. White et al., 1986; Avouac et al., 1993; Kurushin et al., 1997; Meyer et al., 1998). In addition, the numerous normal faults adjacent to several of the frontal scarps (e.g. #4, 10) may indicate that some thrusts also decrease their dips at very shallow depth (perhaps less than 100 m) causing them to produce a sinuous scarp at the surface (Kurushin et al., 1997). In at least one place (#6), the thrust exposure at the surface follows a weak layer of gypsum interbedded with red beds and outwash gravels.

In summary, the foreberg shapes are probably related to changes in the dip of the underlying thrust faults in the near surface (perhaps shallower than 100 m) and also at greater depths (1–2 km), thus including features of fault-bend and fault-propagation folds. A representative fault dip beneath the foreberg ridges may be in the range 30–40°, which is commonly seen in the tilted sediment and in a few exposures of

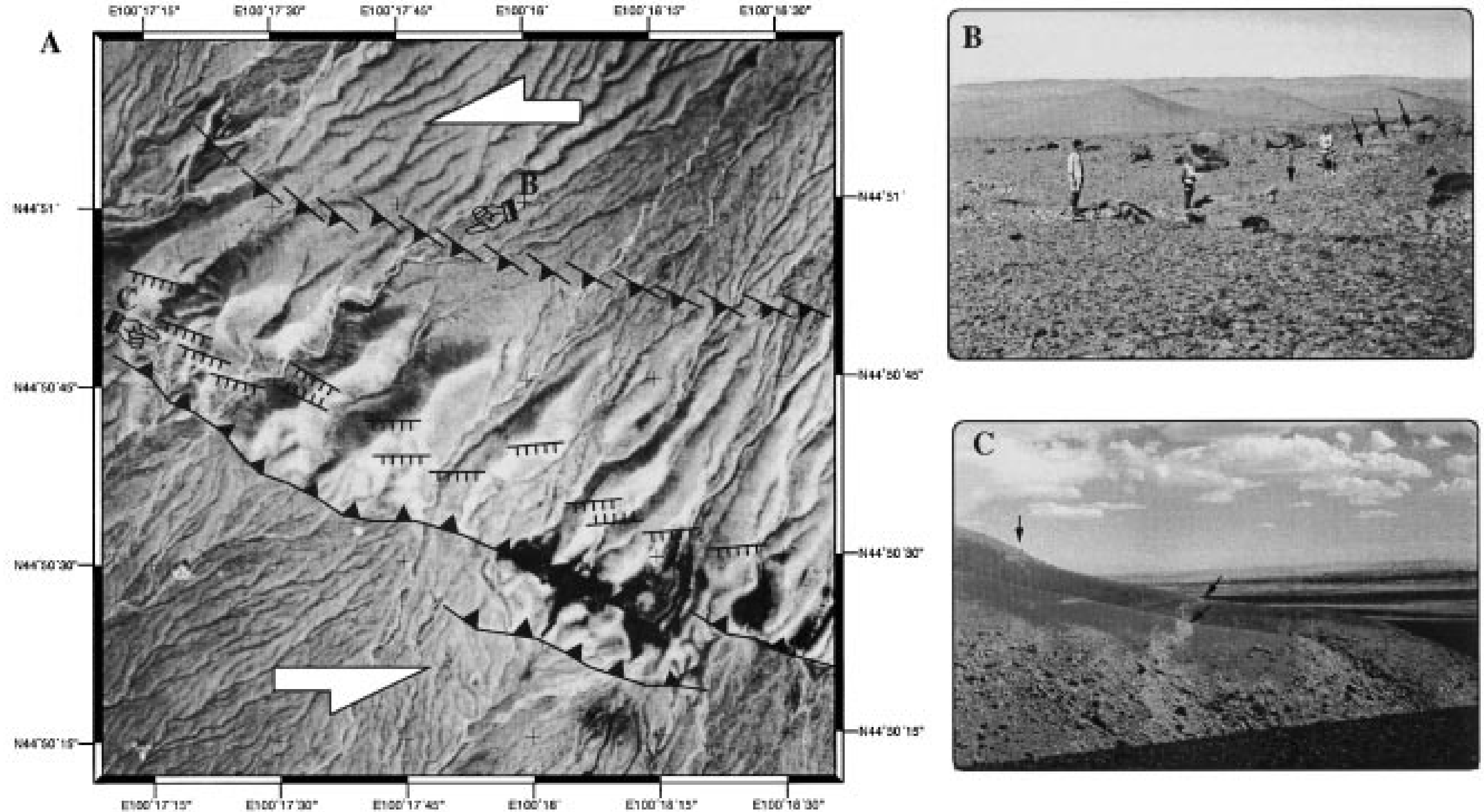


Fig. 4. (a) Sketch map of the geometry of the internal deformation within the Gurvan Bulag foreberg (#10 in Fig. 1). The main 1957 surface rupture is the almost continuous scarp up to 5 m high and striking 120–130° along the base of the southern edge of the ridge, marked as a continuous line with black triangles. Along the northern edge of the ridge, but within the fan material, is a zone of left-stepping backthrusts (dipping south) and moletracks with a general trend of ~120°. The zone is shown schematically here as short lines with single triangles: the location of the zone is correct on the air photograph, but the individual ruptures are neither this regular nor visible in the photo. Individual backthrust scarps are up to 50–100 cm high, sometimes at the base of an older scarp up to 3 m high. Between the two zones of thrusting are normal faults dipping both north and south, often arranged in right-stepping groups, with typical strikes of 080–090°. Typical scarps are 50 cm high and 100–200 m long. The regular orientation and stepping of the small thrusts and normal faults within the foreberg suggests a left-lateral component of slip along the foreberg (white arrows). The pattern described here is not restricted to this part of Gurvan Bulag, but continues a further 4 km to the west. (b) View of a backthrust scarp, (identified by arrows) looking SW at point B in (a). Note the foreberg hills rising above the fans in the background. (c) Normal faults (arrows) on the southern edge of the foreberg at C in (a), looking ESE.

the 1957 faulting (e.g. at Gurvan Bulag, #10 in Fig. 1; Kurushin et al., 1997). However, the appearance of the structurally controlled shapes are also modified by sedimentary and erosional processes, which Owen et al. (1997) argue are climatically controlled. It is probable that, at least in some cases, the thrusts follow bedding planes within the Tertiary–Quaternary sedimentary sequence adjacent to the mountains.

3.2. Accommodating the strike-slip component

At Dalan Türüü (#4), Baga Hetsüü (#6), Ölziyt Uul (#9) and Gurvan Bulag (#10), no significant strike-slip component was observed on the 1957 scarps at the foot of the forebergs (Kurushin et al., 1997). Of these, Dalan Türüü (#4) and Baga Hetsüü (#6) are both at obvious compressional jogs ('restraining bends') in the main through-going strike-slip rupture of 1957 on the north side of Ih Bogd and Baga Bogd. With the exception of the special case at Ih Hetsüü (#7, discussed later), we do not believe the forebergs are simply the toes of landslides coming off the high mountains, as there is no sign of normal faulting or back-rotation of the fan systems at the main range fronts. The lack of strike-slip motion on the main foreberg scarps raises the possibility that the shortening and strike-slip components are spatially separated, or 'partitioned', into strike-slip faulting along the range front and thrust faulting in the forebergs, analogous to the known fault geometry in some subduction zones (Fitch, 1972; McCaffrey, 1992). However, of the four main 1957 foreberg ruptures (#4, 6, 9, 10), strike-slip motion was seen at the range front between the mountain and the foreberg only at Baga Hetsüü (#6) (Kurushin et al., 1997). If partitioning occurs, and if the strike-slip and thrust faults are to meet within the seismogenic upper crust, the geometrical requirements for their stability as a system of internally rigid blocks are very severe: the slip vector on the strike-slip fault must be exactly parallel to the line where the strike-slip and thrust faults meet. We suspect that this necessary condition for separation of the strike-slip and reverse components is too restrictive to apply outside subduction zones, and leads instead to distributed deformation within the weakest part of the system, which is probably at shallow depths within the hanging wall of the thrusts.

There is evidence that, at least in some cases, the expected strike-slip component is taken up within or beneath the forebergs themselves. Firstly, at Gurvan Bulag (#10) the internal deformation within the foreberg ridge is organized systematically into en échelon sets of right-stepping normal faults and left-stepping mole tracks (backthrusts) in zones sub-parallel to the frontal thrust scarp (Fig. 4). To us, this suggests a component of left-lateral motion along this foreberg ridge. The Gurvan Bulag example is very important:

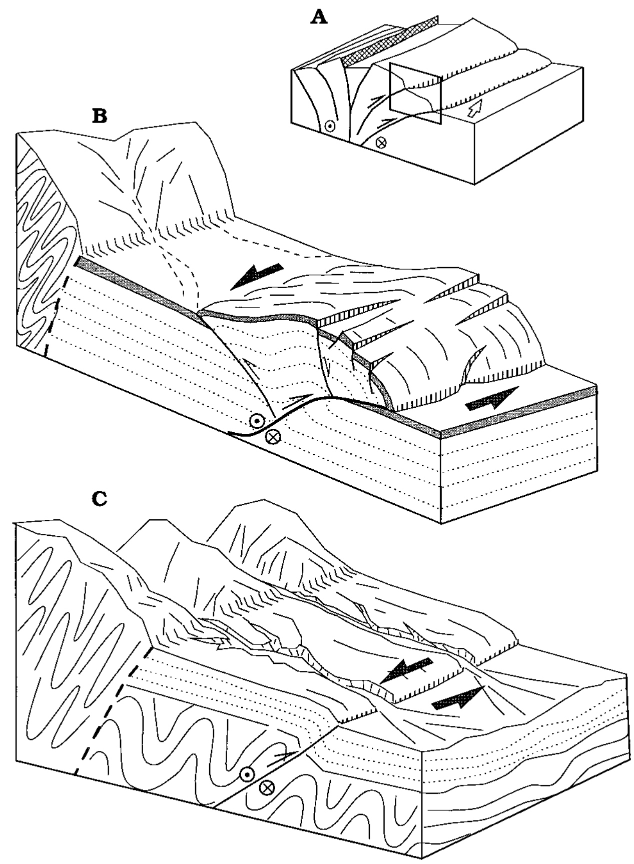


Fig. 5. (a) Cartoon of a transpressional 'flower structure', adapted from Sylvester (1988). (b) Cartoon of the internal deformation within a foreberg, based on observations at Gurvan Bulag. Note the flattening of the underlying thrust at very shallow depths, which is probably responsible for the collapse of the thrust 'nose' by normal faulting (Kurushin et al., 1997) and the left-stepping backthrusts and right-stepping normal faults, which suggest a component of left-lateral slip. (c) Cartoon showing the migration of active faulting away from the main range front, leaving uplifted and dissected fans in the hanging wall of the new fault and older, abandoned faults and shear fabrics within the uplifting range (see the description of Hüühnii Höndii in Fig. 9). This may be an important process in forming 'flower structures', giving rise to the geometries represented in the box outlined in (a).

the pattern there is easy to recognize where the 1957 ruptures break the surface, but would be much harder to demonstrate where scarps have been degraded. At Gurvan Bulag, the front of the foreberg consists of large outwash boulders. We suspect that at shallow depths this material lacks the strength to form a coherent through-going shear, and takes up the strike-slip component as a series of multiple fractures and fissures, while still producing a vertical step at the frontal scarp because of the shortening (Fig. 5b). Other forebergs could contain internal structures capable of accommodating strike-slip like Gurvan Bulag, but they are much harder to see if they do not rupture the surface in earthquakes. Secondly, at the western end of Artz Bogd the northeast-vergent forebergs and folds

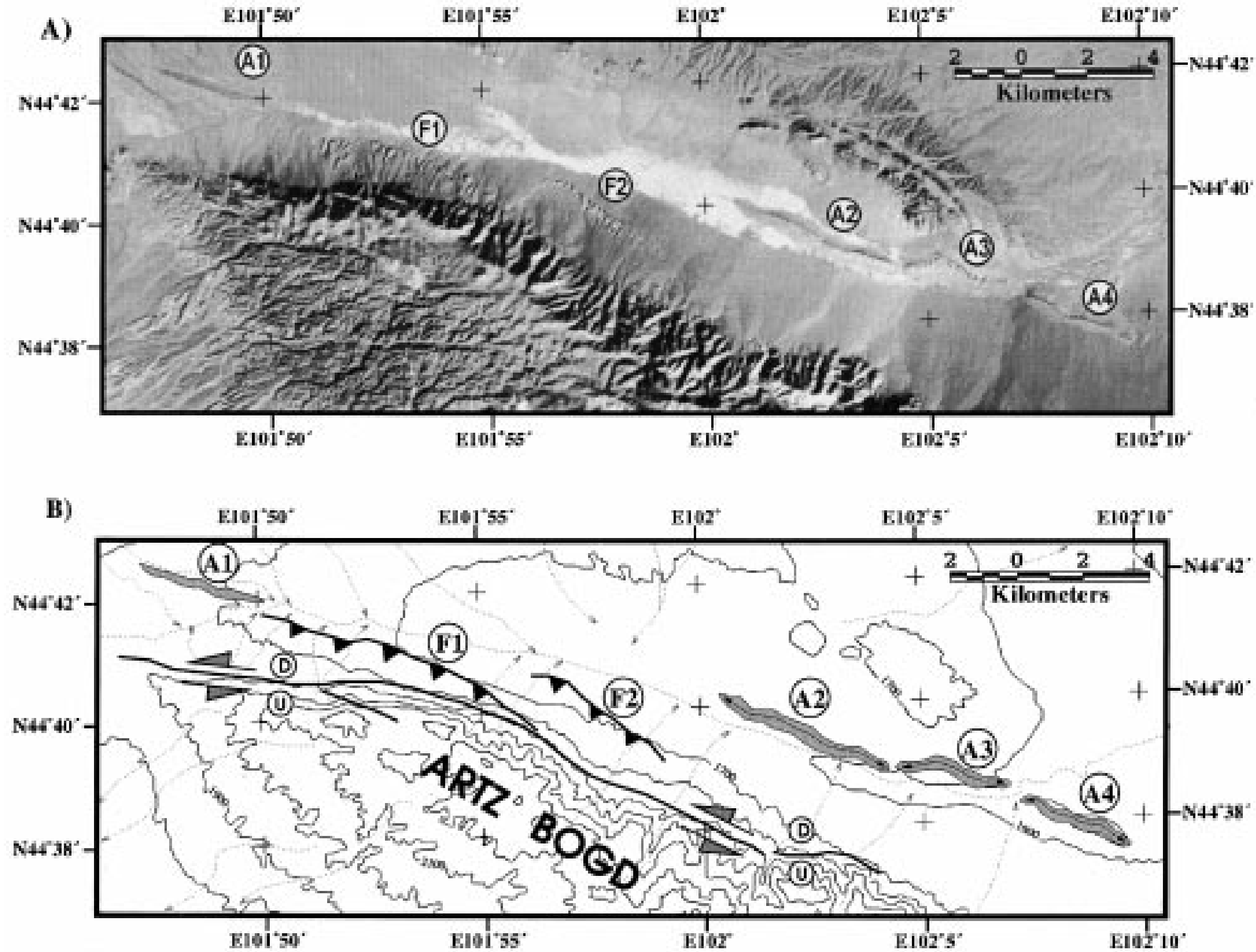


Fig. 6. The overlap area between southeast Baga Bogd and northwest Artz Bogd (#13 in Fig. 1). (a) Landsat TM image. (b) Map of the principal young faults and folds in (a), including forebergs (F1, F2) and anticlines (A1–A4). Anticlines A2–A4 are all steeper on the northern side (see Fig. 3d, e), presumably above south-dipping thrusts emanating from Artz Bogd. F1, F2 and A2–A4 are arranged in a left-stepping en échelon pattern, suggestive of left-lateral strike-slip. A1 is steeper on the south side, and is part of the north-dipping thrust system on the south side of Baga Bogd (#12 in Fig. 1).

(#13 and #14) are arranged in a left-stepping en échelon pattern (Fig. 6), suggesting left-lateral motion along the Artz Bogd range.

The elevations of all the foreberg ridges decrease toward at least one of their ends. At both Dalan Türüü (#4) and Baga Hetsüü (#6) the ridge crest height decreases toward the northwest, the end farthest from mountain range, and this is mirrored in the measured vertical offsets on the 1957 scarps, which in each case decrease from maximum of ~2 m to nothing over a distance of ~10 km. From these observations Kurushin et al. (1997) suggest that the hanging wall blocks of the Dalan Türüü and Baga Hetsüü thrusts are rotating anticlockwise (relative to the footwall block to the north) about an axis near their northwest ends. Such anticlockwise rotations of small blocks may be expected in a broad left-lateral shear zone, but we suggest these displacement gradients may have another significance as well. Firstly, they are expected in any series of en échelon, left-stepping thrusts within a left-lateral shear zone, as can be seen in Fig. 6, where all the northeast-vergent folds and forebergs die out to the northwest. Secondly, all dip-slip faults tend to show displacement gradients along their length, probably as a natural consequence of their growth from smaller, shorter faults (e.g. Walsh and Watterson, 1988; Cowie and Scholz, 1992). Certainly such gradients in displacement require strain to be taken up in the surrounding region, but they do not require the blocks bounding large faults to rotate coherently if they deform internally instead. In short, we believe that the displacement gradients along the forebergs may be related to their growth and propagation, which we discuss in the next section.

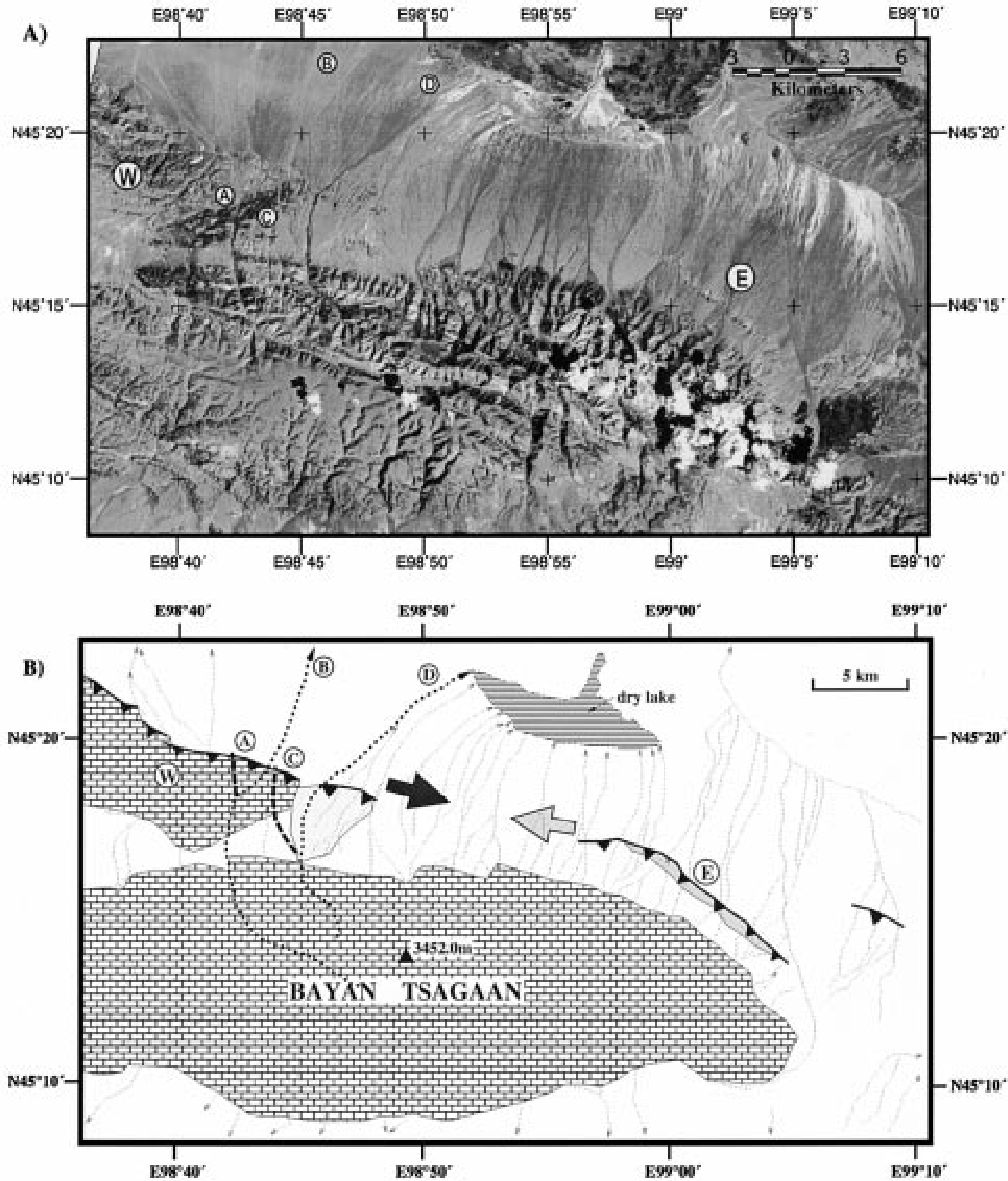


Fig. 7. (a) Landsat TM image and (b) map of the northeast side of Bayan Tsagaan (#1 in Fig. 1). The brick symbol is bedrock, the shaded area is the uplifted and inactive fan surface abandoned as the western foreberg ridge (W) propagated east, causing streams B and D to move from their former positions A and C to leave behind dry valleys (wind gaps).

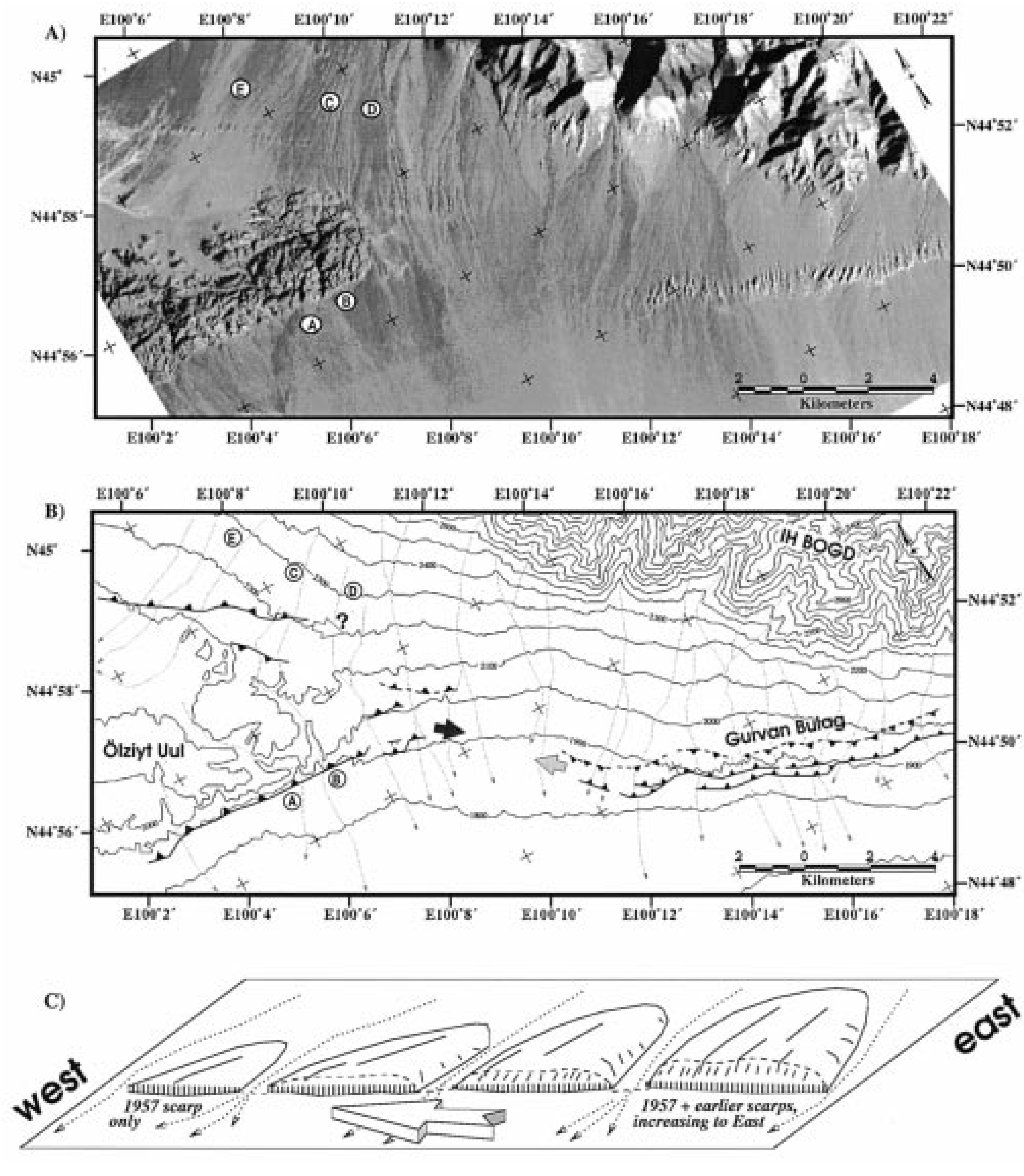


Fig. 8. (a) Landsat TM image and (b) map of Ölziyt Uul and Gurvan Bulag forebergs on the southern side of Ih Bogd (#9 and 10 in Fig. 1). The deep gullies A and B have lost their upstream catchments, we suspect because the eastward propagation of Ölziyt Uul deflected streams to the east (C and D) or west (E): see text. (c) Cartoon to illustrate the progressive increase in height of the Gurvan Bulag ridge toward the east, with the 1957 ruptures extending 2 km west beyond the topographic expression of the foreberg. This is consistent with (but does not prove) a lateral westward growth of the ridge.

3.3. Summary

The available evidence suggests to us that the forebergs are able to take up a substantial part (possibly all) of the strike-slip component of motion that would be expected from their orientations and a regional slip vector of around 080°. They can achieve this either by internal deformation within the hanging wall anticlines above the thrusts or by forming en échelon sets of thrusts that rotate about a vertical axis. In these cases, it will always be easier to detect the vertical component associated with shortening than the horizontal component associated with strike-slip. An important consequence of this conclusion is that the motion accommodated by the forebergs is of the same type as that on the main through-going, range-bounding fault that ruptured in 1957, namely oblique left-lateral strike-slip. Yet it is obvious that the total strain accumulated on the forebergs is much less and that they are in a relatively early stage of development. In the next section we look for indications of how they grow with time, and how their evolution is related to longer-term behaviour of the Gurvan Bogd fault system.

4. Foreberg and thrust evolution

In the normally erosive environment of thrust faults, drainage patterns can sometimes be used to infer the processes of fault growth and propagation (e.g. Jackson et al., 1996; Gupta, 1997; Mueller and Talling, 1997). In this section, we show evidence of this kind that suggests the forebergs are not structures of fixed length, but that they grow and propagate laterally, with consequences for the evolution of the topography and faulting in the Gurvan Bogd mountains.

4.1. Bayan Tsagaan

On the north side of Bayan Tsagaan (#1), the highest massif at the western end of the 1957 ruptures, are two foreberg ridge systems, which both die out laterally toward a region of apparently undeformed fan surfaces that separates them (Fig. 7). At the eastern end of the western foreberg two prominent streams (B and D in Fig. 7b) have been deflected east to leave behind two dry valleys, or wind gaps (A and C), and a now-inactive fan surface (shaded). A simple explanation for this pattern is that the western foreberg ridge (W) propagated to the east, perhaps eventually to join with the eastern foreberg ridge, E, which Kurushin et al. (1997) suggest may have been reactivated in 1957. The eastern foreberg dies out toward its western end, and may in turn be propagating to the west, though there is no direct evidence for this.

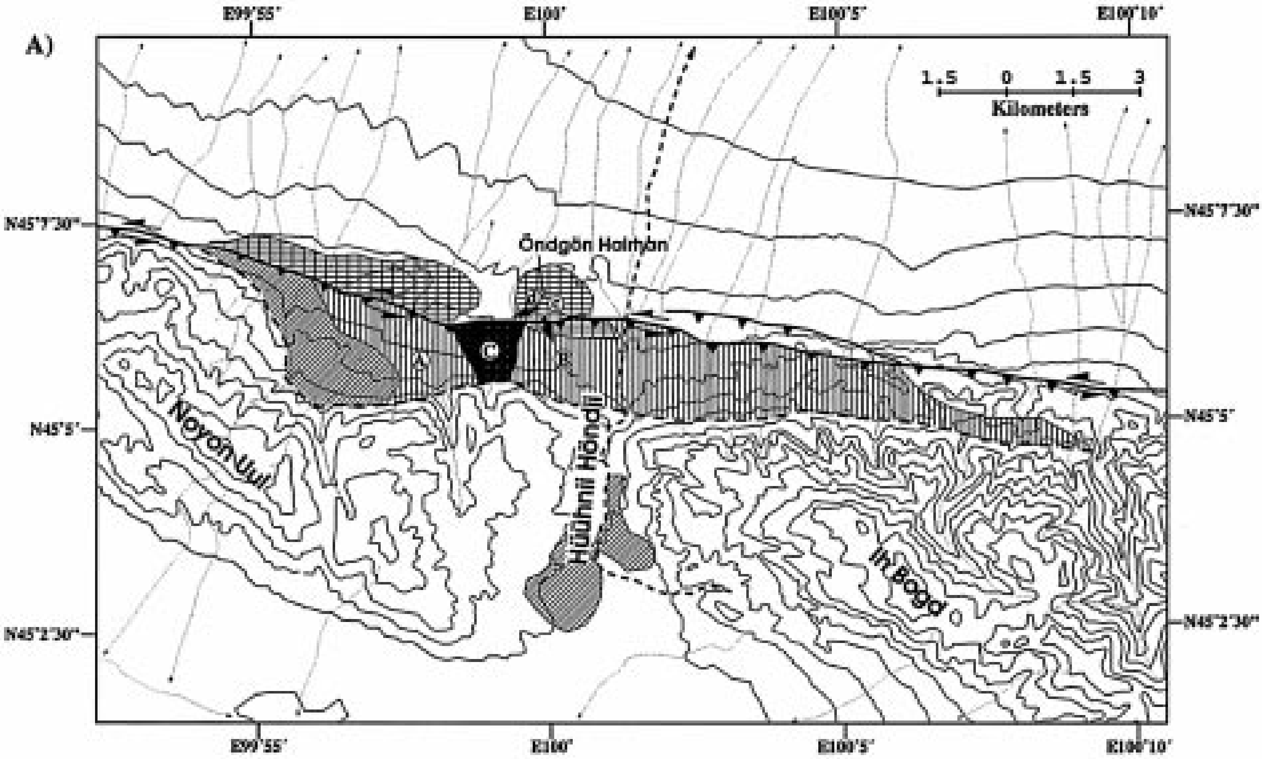
4.2. The Ölziyt Uul–Gurvan Bulag system

A similar pattern is seen at Ölziyt Uul (#9) and Gurvan Bulag (#10, Fig. 8). Both forebergs die out toward the apparently undisturbed region that separates them. The eastern end of Ölziyt Uul is crossed by a number of deep gullies (e.g. A and B) that have apparently lost most of their catchments and are barely able to sustain a flow through the range. We speculate that their head-water catchments have been diverted as the Ölziyt Uul ridge propagated eastward toward Gurvan Bulag. This process may have proceeded in two stages: streams from regions C and D appear to have been diverted to the east, and may once have fed gorges A and B. Other streams, from the region marked E, which may once also have crossed Ölziyt Uul, appear to have been defeated by the rising ridge and are now diverted west (and in fact ultimately north) to enter the Valley of Lakes through a gully west of Noyon Uul (see Fig. 1). As Ölziyt Uul continues to propagate and increase in height, streams from C and D are likely to also join the westward-flowing system marked E.

Both the 1957 scarp heights and the total elevation of the eastern foreberg ridge (Gurvan Bulag) above the fan surfaces die out toward the west (Kurushin et al., 1997). The 1957 surface ruptures continue as thrusts and backthrusts for about 2 km west beyond the topographic expression of the Gurvan Bulag ridge. We speculate that the underlying fault may be propagating in that direction (Fig. 8c).

4.3. Hüühnii Höndii and Toromhon

In the two examples above, at Bayan Tsagaan and at Ölziyt Uul–Gurvan Bulag, the eventual result of foreberg and thrust propagation will be a longer continuous ridge that isolates and protects the alluvial-fan system in the uplifted hanging wall between the new ridge and the main range. At the same time, as displacement on the underlying thrust increases, it is possible that accommodation of the (inferred) strike-slip component may change from distributed deformation within the foreberg ridge to localized slip on a through-going oblique strike-slip fault. We suspect this happened at Hüühnii Höndii (#3, Fig. 9). At this location, the 1957 ruptures form a through-going continuous fault north of the main range front and separated from it by a series of uplifted, and now heavily dissected, fans (Figs. 9 and 5c). This geometry would be expected if forebergs north of the massifs of Noyon Uul and Ih Bogd propagated towards each other, merged, and then became the main fault as the range-bounding fault was abandoned. As the cumulative displacement on each foreberg decreases toward its tip, the final result when the forebergs merge is a saddle in the main ridge of the Noyon Uul–Ih Bogd range, through which the stream of Hüühnii Höndii now flows in a canyon.



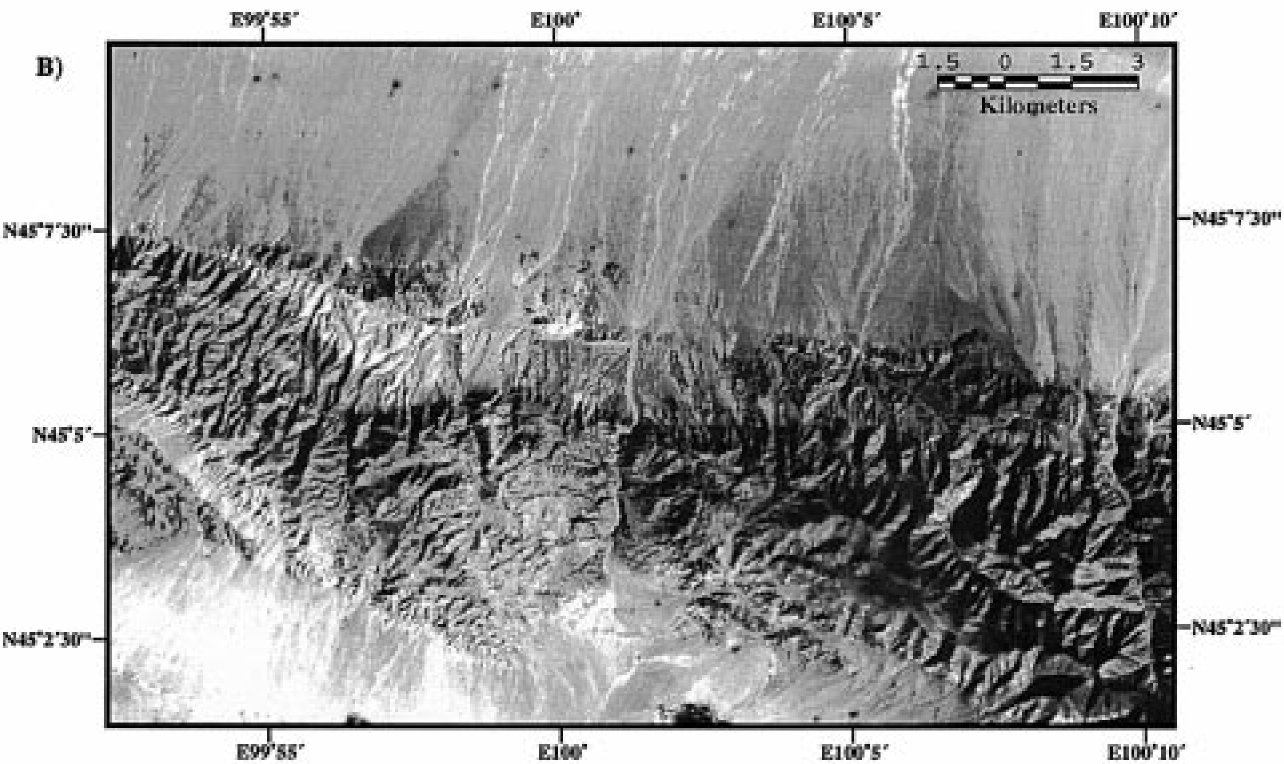


Fig. 9. (a) Morphological map of Hüühnii Höndii (#3 in Fig. 1), between Noyon Uul and Ih Bogd. Vertically striped areas A and B are regions of uplifted and now dissected fans between the 1957 surface rupture (solid line, with triangles) and the main range front (dashed), which marks an older, now inactive, fault. Preservation of these fans is related to the cross-hatched areas of ?Mesozoic volcanics, which protect the fan systems between the faults (see Fig. 9c). Where these volcanics are missing north of the fault, the fans have been destroyed, as in area C (see Fig. 9d). Diagonal striped areas are late Mesozoic red beds. (b) Landsat TM image of the region in (a). (c) Photo looking southeast from Öndgön mountain; see (a) for location. In the foreground is the scarp from the 1957 earthquake, with ~4 m of vertical and ~5 m of left-lateral slip at this location. Between this scarp and the main range front in the background (black arrow) are uplifted and dissected fans (white arrow), protected by the volcanics of Öndgön mountain. (d) Photo looking west along the 1957 ruptures (one person on each side) at Öndgön mountain; see (a) for location. In this case we are looking over the region C in Fig. 9(a) between the two faults (white arrows), where the fans equivalent to A and B have been destroyed by more recent outwash, as they were unprotected by the volcanic rocks north of the 1957 fault.

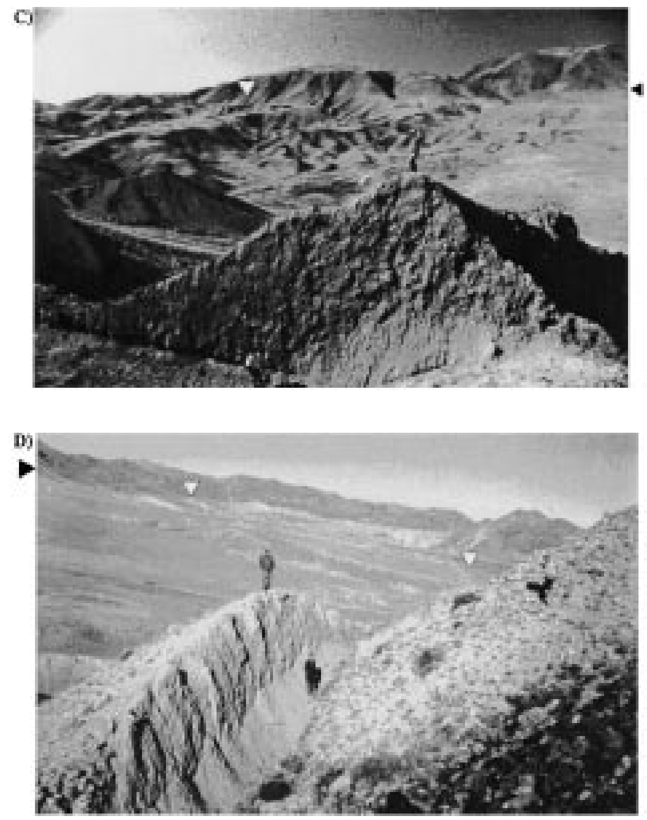


Fig. 9. (*continued*).

An earlier stage in the development that led to the faulting at Hüühnii Höndii may be seen in another major saddle in the mountain system followed by the 1957 thrust fault at Toromhon (#5), between Ih Bogd and Baga Bogd (Fig. 10). Here there are two forebergs (A and B) north of the through-going 1957 rupture. These were apparently not reactivated at the surface in 1957 and their state of development is unclear. The relatively dissected appearance of the western one (A) may indicate that it has now been abandoned. Bayasgalan et al. (1999) speculate that the faults bounding Ih Bogd and Baga Bogd may once have been separate, but then joined together through lateral propagation. If this is correct, then the forebergs may have been abandoned at that time.

4.4. Landslides: the ultimate fate of some forebergs?

On the north side of Baga Bogd, and adjacent to the highest topography of that massif, Philip and Ritz (1999) described a giant landslide with an estimated volume of 50 km^3 (#7 and Fig. 11). The landslide predates the 1957 earthquake, but is obviously young (Late Quaternary) as it has led to a complete rearrangement of the drainage and fan systems (see also Owen et al., 1997). Philip and Ritz (1999) describe the geometry of the landslide in detail and attribute it to collapse triggered by an earlier earthquake. Of interest to us here is that the landslide is adjacent to, and

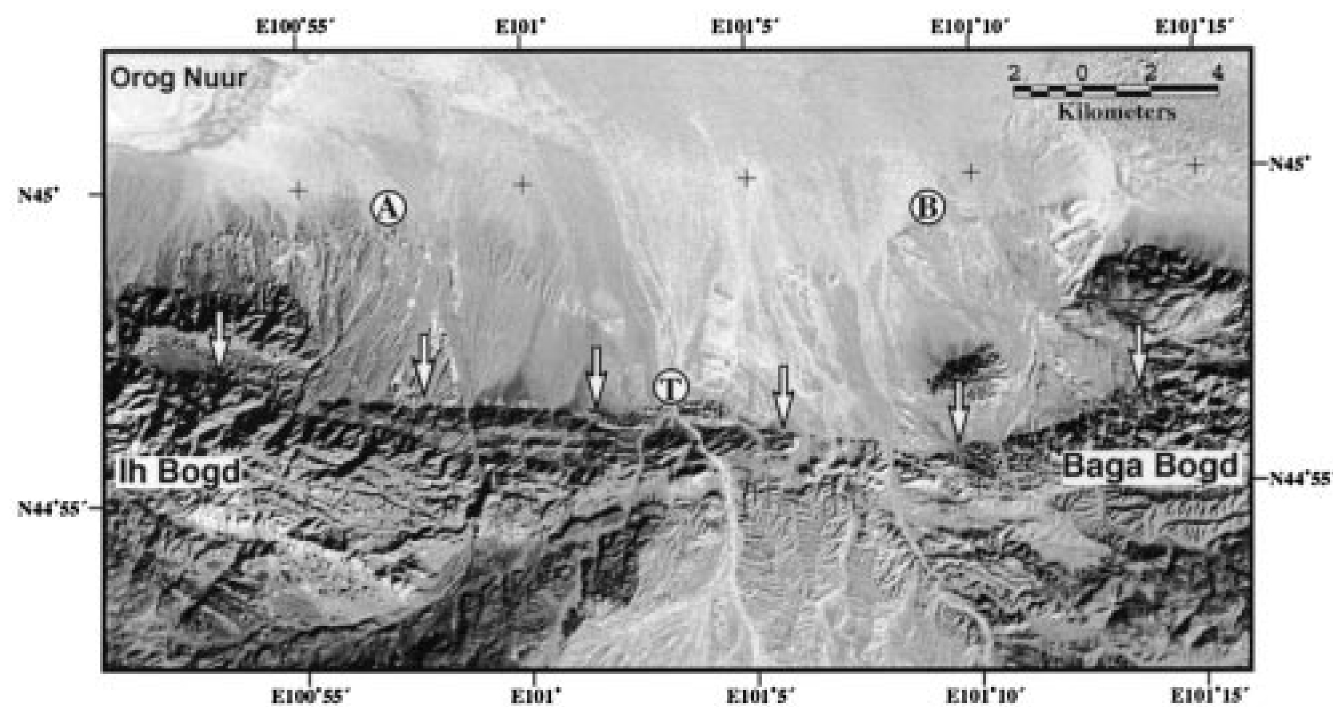


Fig. 10. Landsat TM image of possibly abandoned forebergs (A and B) near Toromhon Sayr (T), between Ih Bogd and Baga Bogd (#5 in Fig. 1). Arrows mark the line of the 1957 surface ruptures.

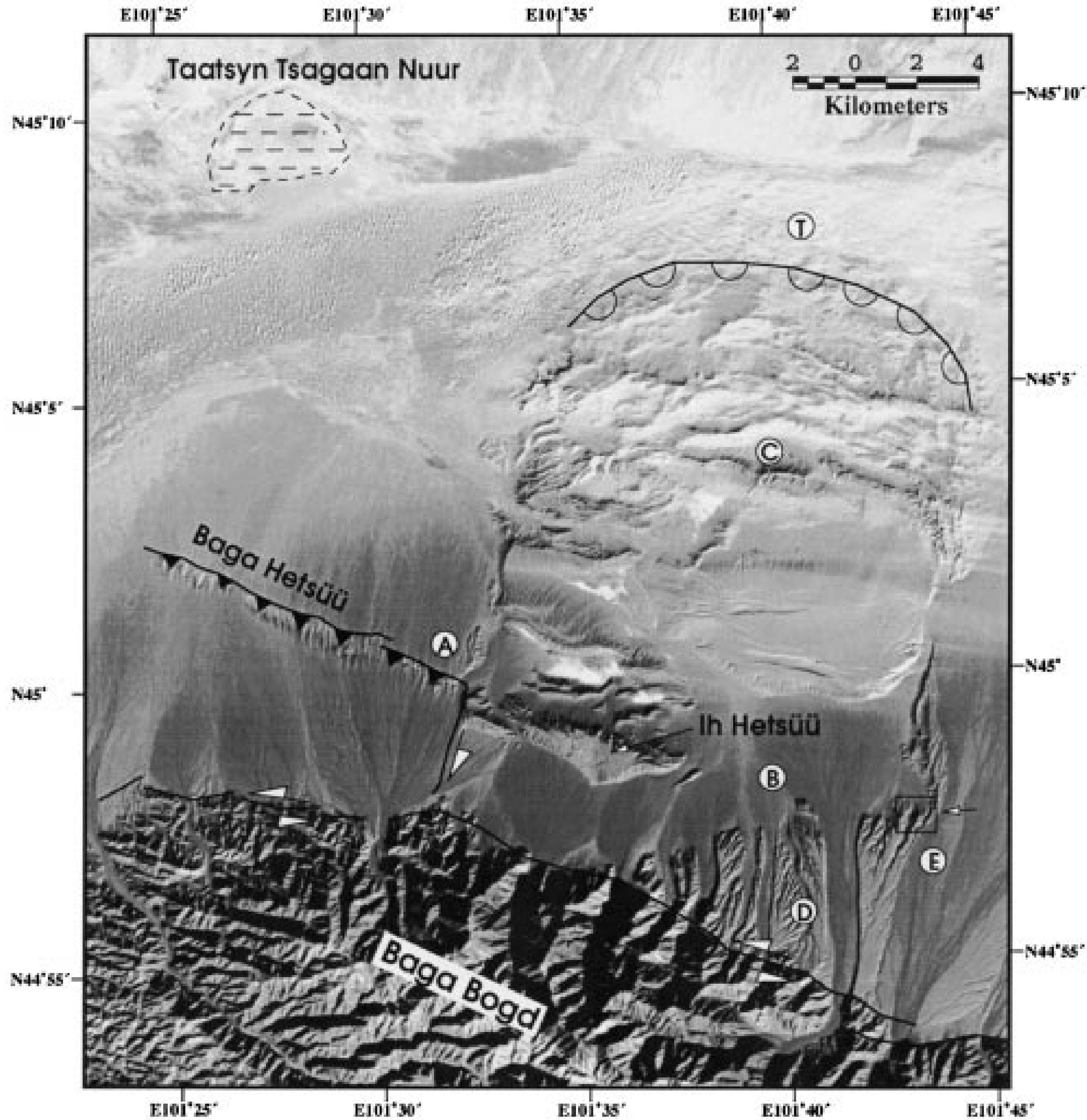


Fig. 11. Landsat TM image of the landslide at Ih Hetsüü (#7 in Fig. 1). The 1957 surface ruptures at Baga Hetsüü and along the Baga Bogd range front are marked with black lines. The line marked T, with semicircle ornamentation is the approximate toe of the landslide (Philip and Ritz, 1999).

along strike from, the foreberg, which was activated at the surface in 1957.

The height of the Baga Hetsüü foreberg increases from west to east, mirroring the vertical displacement on the 1957 surface ruptures, which increases from the western end, where they die out, to reach a height of ~2 m at the eastern end (point A in Fig. 11). At that point, the thrust ruptures join a N–S right-lateral strike-slip fault with ~3 m of offset in 1957 that links Baga Hetsüü with the Baga Bogd range front (Kurushin et al., 1997). The area affected by the landslide extends for 15 km east of the N–S strike-slip fault, and involves a large mass of material, now internally deformed by folding and faulting (C in Fig. 11), that slid away from the range front to leave a deep hole (B) ~150 m below the surrounding fans (D), which have since become deeply incised and abandoned. Another block, called Ih Hetsüü, subsequently

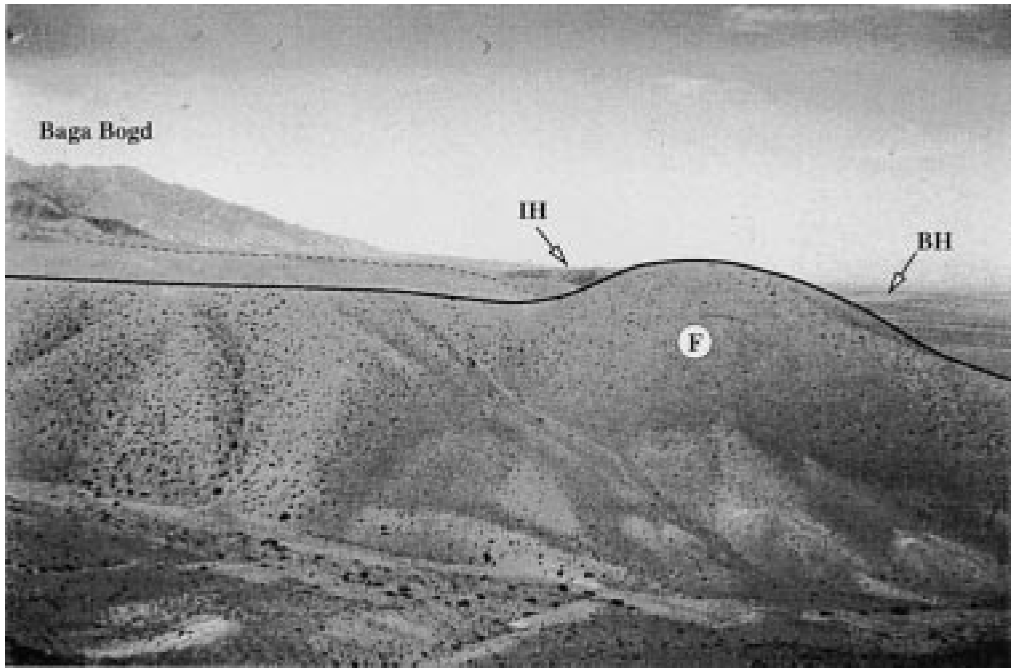


Fig. 12. Photo of the remnant foreberg at location E in Fig. 11. Note the ridge (F) rising above the now abandoned fan surfaces on the left (south), the big hole on the right (B in Fig. 11) and Baga Bogd in the background. Arrows show the positions of Ih Hetsüü and Baga Hetsüü.

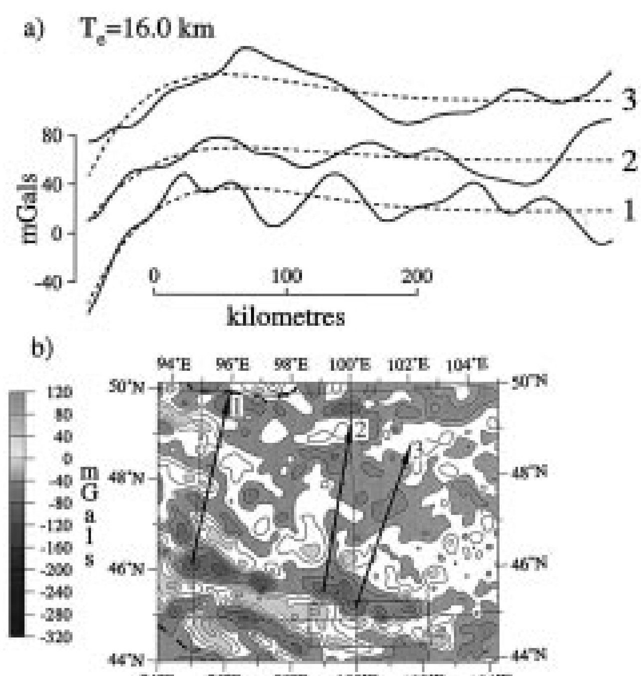


Fig. 13. Free-air gravity profiles (a) and map (b) of the Valley of Lakes. The map is contoured at intervals of 20 mGal. The numbered lines show the location of the profiles in (a), and the outlined box shows the area of Fig. 1. The observed free air gravity profiles are shown as continuous lines, together with the best fitting elastic plate models as dashed lines. A single value of $T_e = 16$ km was used for each profile. Details of the elastic plate model and fitting procedure can be found in McKenzie and Fairhead (1997), and are unimportant here: the point of this figure is the clear gravity signal indicating a flexural origin for the Valley of Lakes.

slid from the range front into the hole left behind by the main landslide (Philip and Ritz, 1999). All trace of the material originally along strike from Baga Hetsüü has now vanished, incorporated into the deformed landslide mass to the north (C) or covered by rejuvenated outwash deposits in the hole (B), except at one location, marked E, on the eastern edge of the landslide. At this point, a small remnant of a former foreberg ridge survives, elevated ~30 m above the now abandoned and incised fan to the south (Fig. 12). Not only does this ridge have a morphology similar to the range-front sides of the Dalan Türüü, Gurvan Bulag and Baga Hetsüü foreberg ridges, but preserved in the bottom of the incised canyons that cross it are bedded sediments, including red beds and fine white silts, dipping ~40°SSW. This remnant back (i.e. range-front) side of the ridge strikes 290°, and is along strike from the Baga Hetsüü foreberg.

The landslide appears to have destroyed a foreberg that was along-strike from, and possibly a continuation of, the Baga Hetsüü foreberg. A clue to why this may have happened lies in the presence of lakes in the long valley (called the 'Valley of Lakes') north of the Bayan Tsagaan–Ih Bogd–Baga Bogd massifs (Fig. 1). The long, linear and asymmetric gravity anomaly associated with the Valley of Lakes (Fig. 13) suggests it originated as a flexural foredeep basin in front of the rising load of the Gurvan Bogd mountains. Gravity profiles across the valley can be matched by bending an elastic plate 16 km thick. The elevated flat tops of Ih Bogd and Baga Bogd may even be the uplifted remnants of an old surface warped down to make the Valley of Lakes (Baljinnyam et al., 1993; Kurushin et al., 1997). Lakes forming in this closed basin are presumably responsible for the fine white silts and gypsum-rich sediments that are exposed in the foreberg ridges at Baga Hetsüü (where the 1957 thrust ruptures break the surface along a gypsum-rich bed), Dalan Türüü and the remnant foreberg at the eastern end of the landslide at Ih Hetsüü. These lake beds form an obvious weak layer which can be exploited by faulting at shallow depths. Our suggestion for the evolution of the forebergs on the northern side of Ih Bogd and Baga Bogd is as follows (Fig. 14): (1) in the early stages, when the main mountain ridge is small, the lakes will be close to the range, but will then migrate out (2) into the valley as they are overridden by outwash from the rising range; (3) the older lake sediments are progressively buried, leaving a series of (probably discontinuous) weak horizons stacked such that they have a general dip back toward the range; (4) these horizons are then exploited by faults (oblique-slip thrusts) that give rise to foreberg ridges; (5) internal deformation of the foreberg ridges by numerous faults, especially by normal faults as at Dalan Türüü and Gurvan Bulag, provide readily-available surfaces that allow the ridge to later collapse as landslides (6). Clearly, such an evolution depends on the existence of weak lake beds, which may not be preserved everywhere. If the foreberg becomes high enough, landsliding may perhaps be expected whether or not there are lake beds present; however, there is no evidence for landsliding on the lake-free south side of the Gurvan Bogd mountains.

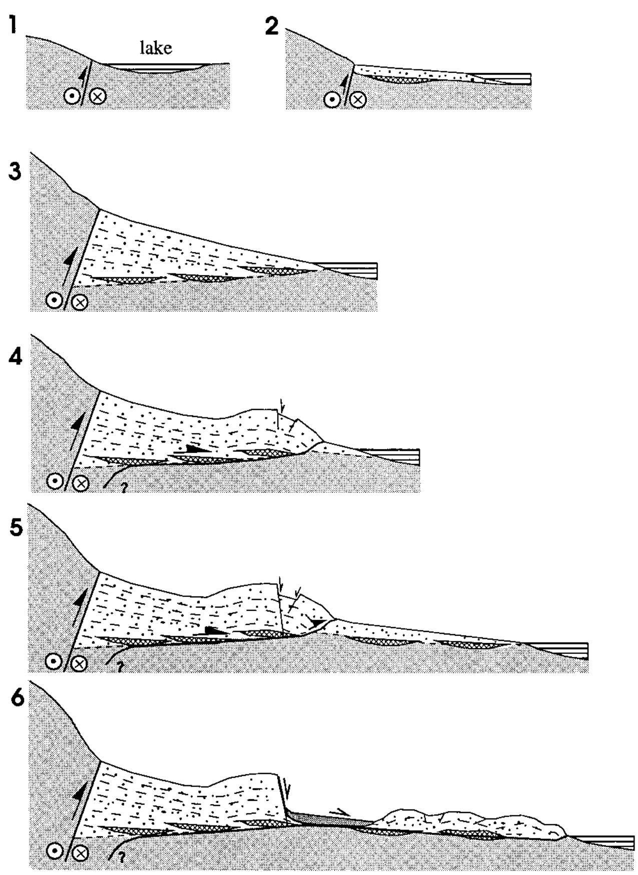


Fig. 14. Cartoon showing how the evolution of a foreberg may lead to landsliding. The lake is striped, the crossed ornament represents old lake beds. See text for details.

5. Discussion

We emphasize that no single description or model can apply to all the forebergs, folds, and thrusts of the Gurvan Bogd mountains: they clearly exhibit a variable range of characteristics. However, by looking at different aspects of these features throughout the region, we conclude that some of this variability arises because the structures are in different stages of development, or in different sedimentary environments, or are variably exposed. More specifically: (1) the interaction between fault slip rate, fan sedimentation, and the ability of the drainage to downcut affects the physical appearance of the foreberg ridges; (2) internal deformation of the ridges by normal and thrust faults, and their role in accommodating a strike-slip component, is much easier to see in the 1957 earthquake ruptures than in structures that were not reactivated in 1957; (3) the presence or absence of shallow weak layers, such as lake beds, is likely to affect the near-surface geometry of the foreberg thrust faults, and their ultimate destruction in landslides; and (4) some forebergs or thrusts are in early stages of development, whereas lateral propagation and growth may have led to the merging of others and the creation of new through-going structures.

Thus, in spite of their apparent variability, we suspect that the forebergs, folds and thrusts of the Gurvan Bogd mountains all accommodate shortening and strike-slip motion across these ranges. Of these, the shortening is unequivocal, and is represented by folding, thrusting and uplift. The strike-slip component is more subtly expressed, but is represented as an en échelon arrangement of forebergs (as at the western end of Artz Bogd), as a regular obliquity of the forebergs to the regional slip vector of 080–090° (Fig. 1), and especially as distributed internal deformation of the forebergs in the form of en échelon tension cracks and backthrusts, as at Gurvan Bulag. The association of many forebergs with the highest topography of Bayan Tsagaan, Noyon Uul, Ih Bogd and Baga Bogd strongly suggests they represent an attempt by the thrust faulting to move away from the high ground in response to stresses generated by topography. This is seen in many places, including elsewhere in central Asia (e.g. Avouac et al., 1993), and is no surprise. However, we believe it is not just the thrust component, but the strike-slip component as well, which is taken up on these new faults, and that the shift away from the main range front is a process that leads to a permanent migration in the position of the main active faulting. Thus the general lack of strike-slip surface ruptures along the main range fronts behind the forebergs in 1957 may be because those range-front faults are no longer active. We cannot say whether the new faults remain connected to the earlier faults at depth, or (if they do) whether this happens within or below the seismogenic upper crust. In their early stages, the appearance of the new faults and ridges is much influenced by the near-surface sediments, but the new structures then grow in amplitude and evolve by lateral propagation, eventually merging to form new through-going faults, as at Hüühnii Höndii. The evidence of their former state may be preserved only in the uplifted and abandoned fans and drainage systems (Figs. 9 and 5c) and the saddle left in the topography where they joined. It is easy to see how migration of the faulting away from the range front, if repeated several times, can lead to a series of now-abandoned, parallel, older faults within the range, as described by Cunningham et al. (1997) in Artz Bogd. On such faults the thrust component is expected to be more obvious than the strike-slip component.

Thus we see the foreberg systems as fundamental features in the development of the oblique-slip structures in the Gobi–Altay, and not as superficial surface manifestations of a partitioned shortening component that is taken up in sediments adjacent to the ranges. The evolution we have described can produce the sub-parallel series of faults within and on the edges of the main ranges that, together with the variable width of the ranges along strike, make up the essential features of the ‘flower structures’ in the Mongolian and Gobi–Altay (Cunningham et al., 1996a, 1996b, 1997) and also elsewhere (e.g. Sylvester, 1988; Woodcock and Schubert, 1994; and Fig. 5a). It is the stresses generated by topography that are likely to make the deformation spread out and increase the width of the ranges with time, but this process takes with it the strike-slip component, leaving behind older faults and an abandoned shear fabric within the ranges. A consequence of this evolution is that the migration of the faulting onto new sub-parallel, through-going faults means that only a small part of the total strike-slip offset on the system will be concentrated on any single fault strand, which is an essential feature of strike-slip duplexes (e.g. Woodcock and Fischer, 1986).

The evolution we describe here is thus likely to be peculiar to strike-slip systems with reverse components, as without the topography generated by shortening there is nothing to make the deformation spread out. We agree with Kurushin et al. (1997) and Cunningham et al. (1997) that many of the forebergs along the 1957 earthquake fault are located in obvious restraining bends relative to the regional slip vector on the fault. However, in the case of the Gobi–Altay the shortening component may also arise, and increase with time, because of the (postulated) rotation of the strike-slip faults within the wider deforming region (inset to Fig. 1), and it is possibly misleading to think of the slip vector as constant in orientation relative to the fault throughout its lifetime. Rotation of strike-slip faults about vertical axes is a process that is common elsewhere, for example in eastern Tibet (England and Molnar, 1990), eastern Iran (Jackson et al., 1995) and California (e.g. Luyendyk et al., 1980, 1985; Jackson and Molnar, 1990), so the evolution of oblique-slip systems with time is of more than local significance.

6. Conclusions

We conclude that the fold, thrusts and foreberg ridges of the Gurvan Bogd mountains offer an insight into how strike-slip systems with reverse components evolve with time. The outward variability of these thrust-related structures is, to some extent, a reflection of their different preservation, development and evolution, and hides an underlying common function, which is to broaden the zone of oblique-slip deformation. They achieve this by creating new faults, away from the main range front, that can accommodate both the strike-slip and shortening components of motion, and which then evolve by lateral propagation and merge to create new through-going faults. The result of this process is to form a range containing several abandoned faults and associated shear fabrics, each one of which may only accommodate a small part of the total motion. The migration, growth, and merger of the faults we describe here can produce many of the features described as ‘flower structures’ on other strike-slip faults. This development is fundamentally driven by the stresses generated by topography, which is in turn a consequence of the reverse component on the strike-slip system. The origin of the shortening component may be linked to local geometrical effects (‘restraining bends’), but also to the rotation of large, intracontinental, strike-slip systems about vertical axes.

Acknowledgements

We are grateful to Trinity College and Amerada Hess for supporting Bayasgalan with a studentship and supporting fieldwork in Mongolia, and to the Informatics Center of the Mongolian Academy of Sciences for field support. We thank Derek Fairhead, who kindly provided the gravity data in Fig. 13, and Dan McKenzie, who helped with its analysis. We are grateful to W. Lund and J. Evans for careful reviews. Landsat TM images were provided by the National Science Foundation under grant EAR-9260603. Collaboration between Cambridge and Montpellier was facilitated through the British Council Alliance scheme. Cambridge Earth Sciences contribution no. 5578.

References

Avouac, J.-P., Tapponnier, P., Bai, M., You, H., Wang, G., 1993. Active thrusting and folding along the northeastern Tien Shan, and rotation of Tarim relative to Dzungaria and Kazakhstan. Journal of Geophysical Research 98, 6755–6804.

Baljinnyam, I., et al., 1993. Ruptures of major earthquakes and active deformation in Mongolia and its surroundings, Geological Society of America Memoir 181.

Bayarsayhan, C., Bayasgalan, A., Enhtuvshin, B., Hudnut, K.W., Kurushin, R.A., Molnar, P., Ölziybat, M., 1996. 1957 Gobi–Altay, Mongolia, earthquake as a prototype for southern California's most devastating earthquake. Geology 24, 579–582.

Bayasgalan, A., 1995. Application of remote sensing techniques for the regional geology and neotectonics of the Gobi–Altay range, south-western Mongolia. MS thesis, Enschede, The Netherlands, International Institute for Aerospace Survey and Earth Sciences (ITC), 105 pp.

Bayasgalan, A., Jackson, J.A., Ritz, J.-F., Carretier, S., 1999. Deformation at the ends of intracontinental strike-slip faults. Tectonics (in press).

Cowie, P.A., Scholz, C.H., 1992. Growth of faults by accumulation of seismic slip. Journal of Geophysical Research 97, 11085–11095.

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

Cunningham, W.D., Windley, B.F., Dorjnamjaa, D., Badamgarav, G., Saandar, M., 1996b. Structural transect across the Mongolian Altai: active transpressional mountain building in central Asia. Tectonics 15, 142–156.

Cunningham, W.D., Windley, B.F., Owen, L.A., Barry, T., Dorjnamjaa, D., Badamgarav, J., 1997. Geometry and style of partitioned deformation within a late Cenozoic transpressional zone in the eastern Gobi–Altay Mountains, Mongolia. Tectonophysics 277, 285–306.

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

England, P., Molnar, P., 1997. The field of crustal velocity in Asia calculated from Quaternary rates of slip on faults. Geophysical Journal International 130, 551–582.

Fitch, T.J., 1972. Plate convergence, transcurrent faults and internal deformation adjacent to southeast Asia and the western Pacific. Journal of Geophysical Research 77, 4432–4460.

Florensov, N.A., Solonenko, V.P. (Eds.), 1963. The Gobi–Altay earthquake. Akademiya Nauk USSR, Moskow (in Russian; English translation by Israel Program for Scientific Translations, US Department of Commerce, Washington, DC, 1965).

Gupta, S., 1997. Himalayan drainage patterns and the origin of fluvial megafans in the Ganges foreland basin. Geology 25, 11–14.

Hendrix, M.S., Graham, S.A., Amory, J.Y., Badarch, G., 1996. Noyon Uul syncline, southern Mongolia: early Mesozoic sedimentary record of the tectonic amalgamation of central Asia. Geological Society of America Bulletin 108, 1256–1274.

Holt, W.E., Li, M., Haines, A.J., 1995. Earthquake strain rates and instantaneous relative motions within central and eastern Asia. Geophysical Journal International 122, 569–593.

Jackson, J.A., Molnar, P., 1990. Active faulting and block rotations in the western Transverse ranges, California. Journal of Geophysical Research 95, 22073–22087.

Jackson, J., Haines, A.J., Holt, W., 1995. The accommodation of Arabia–Eurasia plate convergence in Iran. Journal of Geophysical Research 100, 15205–15219.

Jackson, J.A., Norris, R., Youngson, J., 1996. The structural evolution of active fault and fold systems in central Otago, New Zealand: evidence revealed by drainage patterns. Journal of Structural Geology 18, 217–234.

Kurushin, R.A., et al., 1997. The surface rupture of the 1957 Gobi–Altay, Mongolia, earthquake. Geological Society of America Special Paper 320.

Luyendyk, B.P., Kammerling, M.J., Terres, R.R., 1980. Geometric model for Neogene crustal rotations in southern California. Geological Society of America Bulletin 91, 211–217.

Luyendyk, B.P., Kammerling, M.J., Terres, R.R., Hornafius, J.S., 1985. Simple shear of southern California during Neogene time suggested by paleomagnetic declinations. Journal of Geophysical Research 90, 12454–12466.

McCaffrey, R., 1992. Oblique plate convergence, slip vectors, and forearc deformation. Journal of Geophysical Research 97, 8905–8915.

McKenzie, D., Fairhead, D., 1997. Estimates of the effective elastic thickness of the continental lithosphere from Bouguer and free air gravity anomalies. Journal of Geophysical Research 102, 27523–27552.

Meyer, B., Tapponnier, P., Bourjot, L., Metivier, F., Gaudemer, Y., Peltzer, G., Shunmin, G., Zhitai, C., 1998. Crustal thickening in Gansu–Qinghai, lithospheric mantle subduction, and oblique, strike-slip controlled growth of the Tibet plateau. Geophysical Journal International 135, 1–47.

Mueller, K., Talling, P., 1997. Geomorphic evidence for tear faults accommodating lateral propagation of an active fault-bend fold, Wheeler Ridge, California. Journal of Structural Geology 19, 397–411.

Owen, L.A., Windley, B.F., Cunningham, W.D., Badamgarav, J., Dornjnamjaa, D., 1997. Quaternary alluvial fans in the Gobi of southern Mongolia: evidence for neotectonics and climate change. Journal of Quaternary Science 12, 239–252.

Philip, H., Ritz, J.-F., 1999. Giant paleolandslide associated to active faulting along the Bogd fault (Gobi–Altay, Mongolia), Geology 27, 211–214.

Sylvester, A.G., 1988. Strike-slip faults. Geological Society of America Bulletin 100, 1666–1703.

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

Walsh, J., Watterson, J., 1988. Analysis of the relationship between displacements and dimensions of faults. Journal of Structural Geology 10, 239–247.

White, N.J., Jackson, J.A., McKenzie, D., 1986. The relationship between the geometry of normal faults and that of the sedimentary layers in their hanging walls. Journal of Structural Geology 8, 897–909.

Woodcock, N., Fischer, M., 1986. Strike-slip duplexes. Journal of Structural Geology 8, 725–735.

Woodcock, N., Schubert, C., 1994. Continental strike-slip tectonics. In: Hancock, P.L (Ed.), Continental Deformation. Pergamon Press, Oxford, pp. 251–263.