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Tectonophysics 331 (2001) 389–411

TECTONOPHYSICS

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Cenozoic normal faulting and regional doming in the southern Hangay region, Central Mongolia: implications for the origin of the Baikal rift province

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Received 25 February 2000; accepted 6 October 2000

Abstract

The Hangay Dome in central Mongolia is a mountainous region covering more than 200,000 km^2 with numerous flat-topped peaks over 3000 m that preserve a Late Cretaceous–Paleogene erosion surface. Doming began in the middle Oligocene producing more than 2000 m of regional topographic uplift. The range represents an important kinematic link between the Baikal rift province to the north and Altai transpressional ranges to the south and west. Structural field investigations of major faults visible on satellite imagery indicate that the southern Hangay Dome region is dominated by Late Cenozoic normal faults that bound small half-graben. Most faults are NE-striking and faults at the highest elevations are the most recently active. Most graben appear to be isolated systems that constitute small sediment sinks perched on the flanks and crests of the dome. The first-order feature is the dome itself and most sediment eroded off of the dome is deposited in the Mongolian Valley of Lakes or is carried northwards by the Selenga river and its extensive tributaries.

The basement of the dome is a Precambrian craton although the shape and dimensions of the craton are poorly constrained to the north and east. Late Cenozoic uplift of the southern dome region appears to be confined to the area underlain by cratonic basement whereas the Altai region to the south and west is underlain by mechanically weaker Palaeozoic arc and accretionary belts. With respect to the regional northeast directed S_{Hmax}, the Hangay craton appears to have acted as a rigid passive indentor focusing Late Cenozoic transpressional deformation around its west and southern margins. Models invoking a Late Cenozoic plume as the driving force for doming and widespread alkaline volcanism on the dome are not strongly supported by geochemical and isotopic data on Neogene–Recent volcanics and the spatial correlation between areas that are domed and older cratonic crust appears too coincidental to be ignored. Convective removal of an overthickened lithospheric root leading to adiabatically decompressed asthenosphere could explain regional doming and volcanism, however major crustal thickening last occurred in the Permian in the southern Hangay region and the time lag between thickening and postulated root removal and plateau uplift (>200 Myr) appears too long. An alternative model is explored based on speculated lithospheric mantle flow patterns driven by India's continued northeastward indentation. It is suggested that lithospheric mantle flow diversion around the overthickened Hangay craton crustal keel could cause lithospheric thinning beneath the craton and passive asthenospheric upwarp leading to regional topographic uplift and decompression melting/alkali volcanism. In general, the angular relationship

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PII: S0040-1951(00)00228-6

between Precambrian craton boundaries and the prevailing northeasterly S_{Hmax} appears to control the kinematics of late Cenozoic deformation throughout the Hangay, Altai, Sayan and Baikal regions.

Keywords: Hangay Dome; Mongolia; Baikal Rift; crustal extension; tectonics

1. Introduction

Current debate about the manner in which Central Asia internally partitions the strain resulting from India's northeastward motion has generally focused on individual mountain belts and specific fault systems in the huge region between the Himalayas and Altai to the north, and from the westernmost Tien Shan to Indochina in the east (Tapponnier and Molnar, 1979; Cobbold and Davy, 1988; Yin and Harrison, 1996, and references therein). Outside this area, to the north and northeast, lies a vast region that has also been tectonically active during the Cenozoic including the Sayan Belt, Hangay Dome, Lake Baikal rift system, and ranges east of Lake Baikal as far as Sakhalin and the Sea of Okhotsk (Tapponnier and Molnar, 1979; Worrall et al., 1996; Fig. 1). Although the style, kinematics, timing and rates of Cenozoic tectonic activity in these regions are now better documented (particularly with the Baikal rift system, e.g. Mats, 1993; Logatchev and Zorin, 1987, 1992; Petit et al., 1996, 1998; Delvaux et al., 1997), the kinematic link between active tectonism in these northern deforming regions and areas to the south and west (Altai, Tien Shan) has never been clearly documented. Despite early speculation that Cenozoic extensional deformation in the Baikal region is ultimately driven by stresses caused by the Indo-Eurasian collision (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979), other models invoking a mantle plume(s) have been introduced to explain the distribution of active faulting, uplifted topography and Cenozoic volcanism (Zorin, 1981; Yarmolyuk et al., 1990; Rasskazov, 1991; Windley and Allen, 1993; Ionov et al., 1998). The issue has not yet been resolved partly because the Cenozoic tectonic activity in the Hangay Dome region of central Mongolia, which lies between the Altai and Baikal regions and thus represents a critical kinematic link between these actively deforming regions, is poorly understood (Figs. 1 and 2). Specifically, field-based kinematic studies of Cenozoic fault systems in the Hangay region are limited to detailed studies of ground deformation associated with individual historic earthquake events on the Bolnai and Mogod strike-slip fault systems (and associated splays) in the northern Hangay and eastern Hangay regions, respectively (Baljinnyam et al., 1993; Bayasgalan and Jackson, 1999; Fig. 3). However, the Cenozoic tectonic activity of the entire southern Hangay region (Fig. 2) has received very limited previous attention (e.g. Devyatkin, 1975; Baljinnyam et al., 1993).

2. Objectives of this study

In order to better understand the Cenozoic deformation of the southern Hangay region, four weeks of field work were carried out during July 1998 to investigate major faults that appear on satellite imagery on the southern flanks and crest of the dome. Field investigations focused on documenting evidence for Cenozoic fault activity, fault kinematics, and tectonic geomorphology. The southern Hangay region was selected because it borders the northern Gobi Altai region, which is better understood in terms of its late Cenozoic tectonic activity (Baljinnyam et al., 1993; Cunningham et al., 1996, 1997; Kurushin et al., 1997; Bayasgalan et al., 1999). Faults were identified on the imagery as potentially active during the Cenozoic if (1) they have sharply defined traces, (2) clearly offset geological units or geomorphological features, (3) bound sedimentary basins, (4) have clear topographic expression, and (5) disrupt drainage systems.

The southern Hangay Dome region is reported to contain both normal and thrust faults of late Cenozoic age (Devyatkin and Smelov, 1979; Baljinnyam et al., 1993; Windley and Allen, 1993; Kopylova et al., 1995). However, these reports lack detailed information on individual faults and their kinematics. An open question has existed as to whether the southern dome

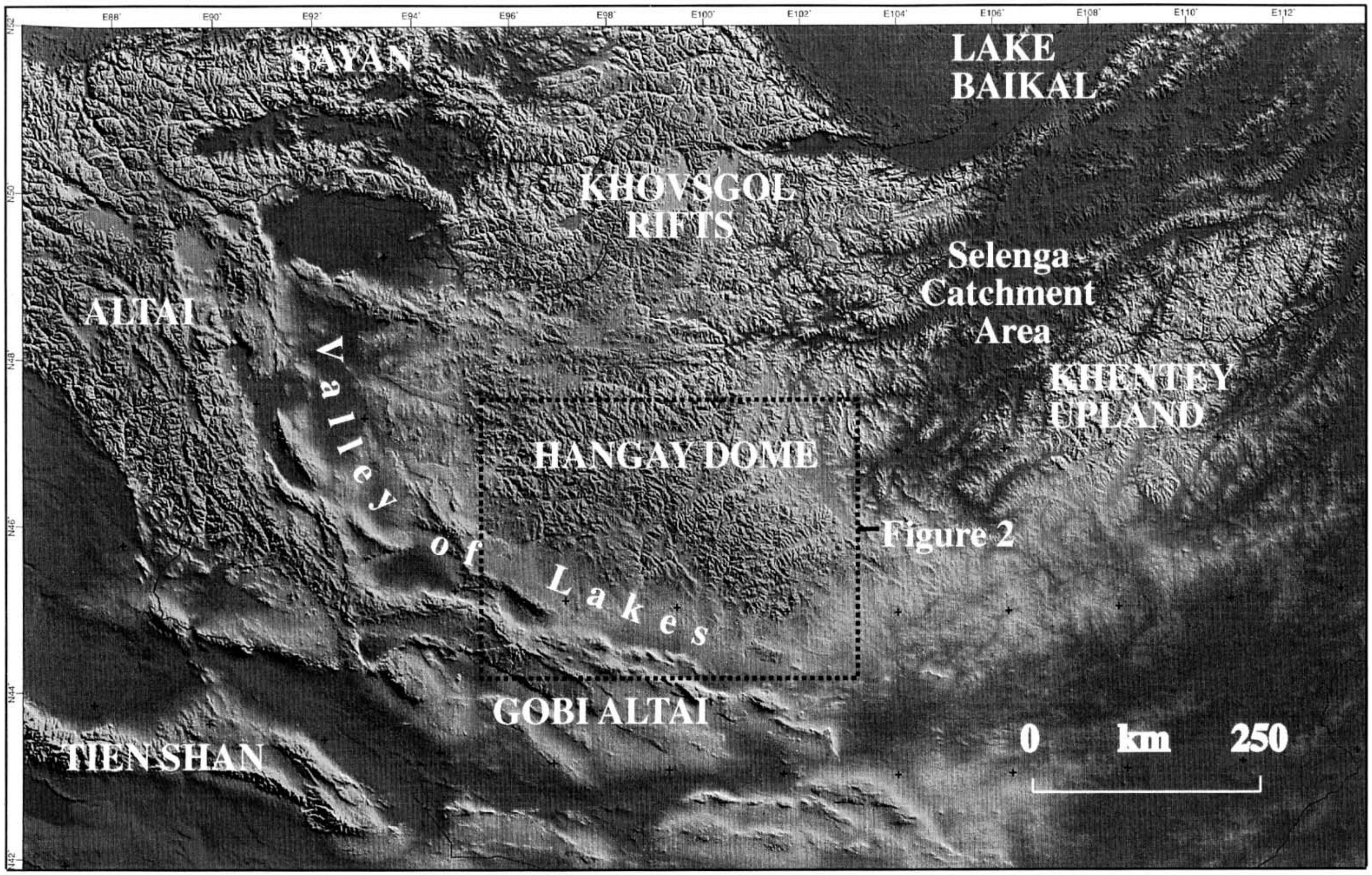

Fig. 1. Digital elevation model for the Hangay Dome region of central Mongolia and surrounding areas. Note the broad uplands of Hangay Dome, Khentey and Khovsgol regions and more linear ranges of Altai, Gobi Altai and Tien Shan. The Valley of Lakes separates the Hangay Dome from the Altai and the Gobi Altai and represents an important kinematic boundary between Late Cenozoic transpressional deformation in the Altai and Gobi Altai and regional doming and extensional deformation in the Hangay Dome.

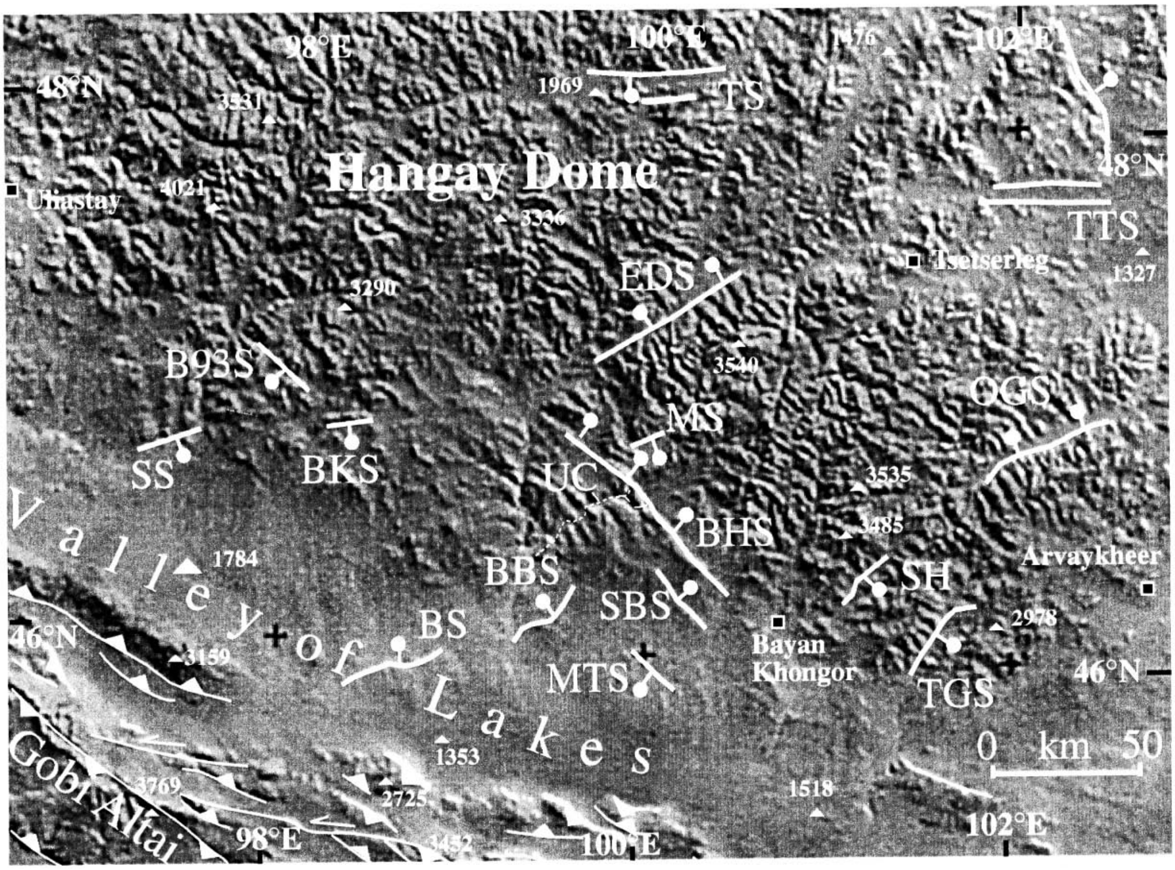

Fig. 2. Digital elevation model for the southern Hangay Dome region showing major Cenozoic normal faults. White thick lines are faults. Ball on down-dropped side. Thinner white lines are thrusts with teeth on upper plate. BBS: Bombögör scarp; BHS: Bayan Khongor basin scarp; BKS: Bayanbulak Valley scarp; BS: Boon Tsagaan Nuur scarp; EDS: Egiyn Davaa scarp; MS: Mandal scarp; OGS: Orkhon Gol scarp; SBS: Shar Burd scarp; SH: Shargaljuut scarp; SS: Shilüüstay scarp; TGS: Taatsyn Gol scarp; TS: Tariat scarps; TTS: Tsetserleg scarps; UC: Ulzit Gol Canyon. Elevation points in meters.

region is a product of actual doming ("arching", Devyatkin, 1975; Baljinnyam et al., 1993) or is a thrust stack with the Valley of Lakes representing a foredeep for the thrust belt. If the uplift is due to vertical forces and doming (e.g. Baljinnyam et al., 1993), the mechanism of doming either by broad regional flexure or by brittle normal faulting and step-like offsets, has not been documented. Thus the original purpose of this study was to better understand the mechanism of uplift of the southern Hangay Region and to compare and contrast it with the adjacent Gobi Altai to the south and Baikal rift province to the north.

3. Regional physiography

The Hangay Dome is a mountainous region covering over 200,000 km^2 with numerous peaks over 3500 m and one glacier-covered summit exceeding 4000 m (Figs. 1 and 2). The dome comprises the south and western end of what is sometimes called the Mongolian Plateau (Windley and Allen, 1993) and is separated from the domal Khentey Upland in northeastern Mongolia by the more deeply incised terrain of the Selenga river system and its tributaries, which drain north into Lake Baikal (Fig. 1). The drainage divide between water that flows into Lake Baikal

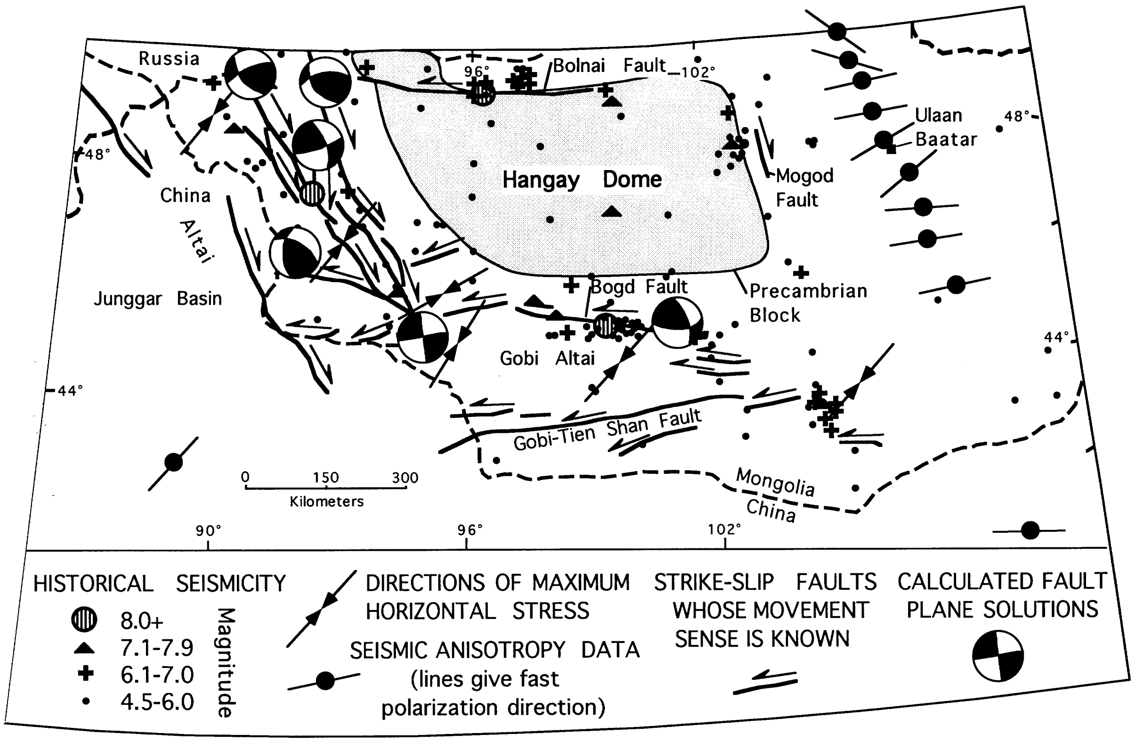

Fig. 3. Geological and geophysical data bearing on current tectonic activity in the Hangay Dome and Mongolian Altai regions. Historical seismicity taken from Mongolian National Atlas (1990), earthquake focal mechanism solutions taken from Baljinnyam et al. (1993), strike-slip faults from Cunningham (1998) and Baljinnyam et al. (1993), seismic anisotropy data from Gao et al. (1994) and Silver (1996), stress field data from Zoback (1992). Outline of Precambrian block beneath dome is approximate and is based on >1100 Ma Sm–Nd T_{DM} model ages for granitoids in central Mongolia (Kovalenko et al., 1996). Note the relative lack of recorded seismicity from the central and southern Hangay Dome regions compared to bordering areas.

(and ultimately the Arctic Ocean) and water that drains into the Mongolian Valley of Lakes and Gobi Desert is a northwest-trending belt of flat-topped peaks in the southwestern Hangay Dome region. These summits represent the remnants of a Cretaceous–Paleogene erosion surface that has been domed to 3000–3500 m elevations (Fig. 4; Devyatkin, 1975). The interpreted age of the peneplaned surface is based on the existence of overlying Oligocene and younger sedimentary and volcanic deposits that are now tilted and raised on the dome's margins and summits (Devyatkin, 1975; Barsbold and Dorjnamjaa, 1993). River systems on the north and northeast sides of the Hangay Dome are extensive, integrated and deeply incising, whereas on the south and southwestern sides of the range (more shadowed from Arctic moisture) rivers are shorter, have lower volumes, and have incised less deeply. Thus, in order to document the magnitude of Late Cenozoic topographic uplift of the dome (at least 2000 m, Devyatkin, 1975) and the extent of Cenozoic faulting, the crest and southern flanks of the dome provide a clearer impression because those areas have experienced less erosional denudation. If the river systems did not exist on the north side of the dome and uplifted topography was preserved and not deeply incised, then the dome would probably join the Khentey Uplands to form a much larger uplifted domain (Fig. 1). This is an important consideration when assessing the overall dimensions of late Cenozoic crustal uplift, and the crustal and mantle controls on Cenozoic tectonism in the Hangay and Baikal regions.

Fig. 4. Panoramic views of the Hangay Dome from 3500 m summit elevation at 47°04′N, 99°52.5′E. Top photo looking west, bottom photo looking north. Note summit peneplane defining domal topography. Rocks in foreground (both photos) are Permian granitoids overlain by Miocene basalts (bottom photo).

4. Regional geology of Hangay Province

The basement geology of the Hangay Dome consists of a Precambrian block that contains tonalitic and trondhjemitic gneisses, potassic granitoids (including rapakivi type) and various migmatites and high-grade schists and gneisses (Kepezhinskas, 1986). U–Pb zircon and Pb–Pb thermo-isochron ages have been determined for some of the basement complexes and have yielded late Archaean–Early Proterozoic ages (2.65–1.7 Ga, Mitrofanov et al., 1985; Kotov et al., 1995; Kozakov et al., 1997). The basement complexes are only locally exposed (Fig. 5), but are found throughout a wide region suggesting that Precambrian rock underlies the entire Hangay Province. This is supported by Sm–Nd isotope data for a wide region in central Mongolia where T_{DM} model ages for granite sources are all >1100 Ma (Kovalenko et al., 1996). This Precambrian block is generally referred to as the Tuva-Mongolia or Central Mongolia microcontinent or microcraton (Zorin et al., 1993; Sengör et al., 1993; Traynor and Sladen, 1995; Kovalenko et al., 1996). The actual size of the block is not well constrained and various authors draw it with different shapes and

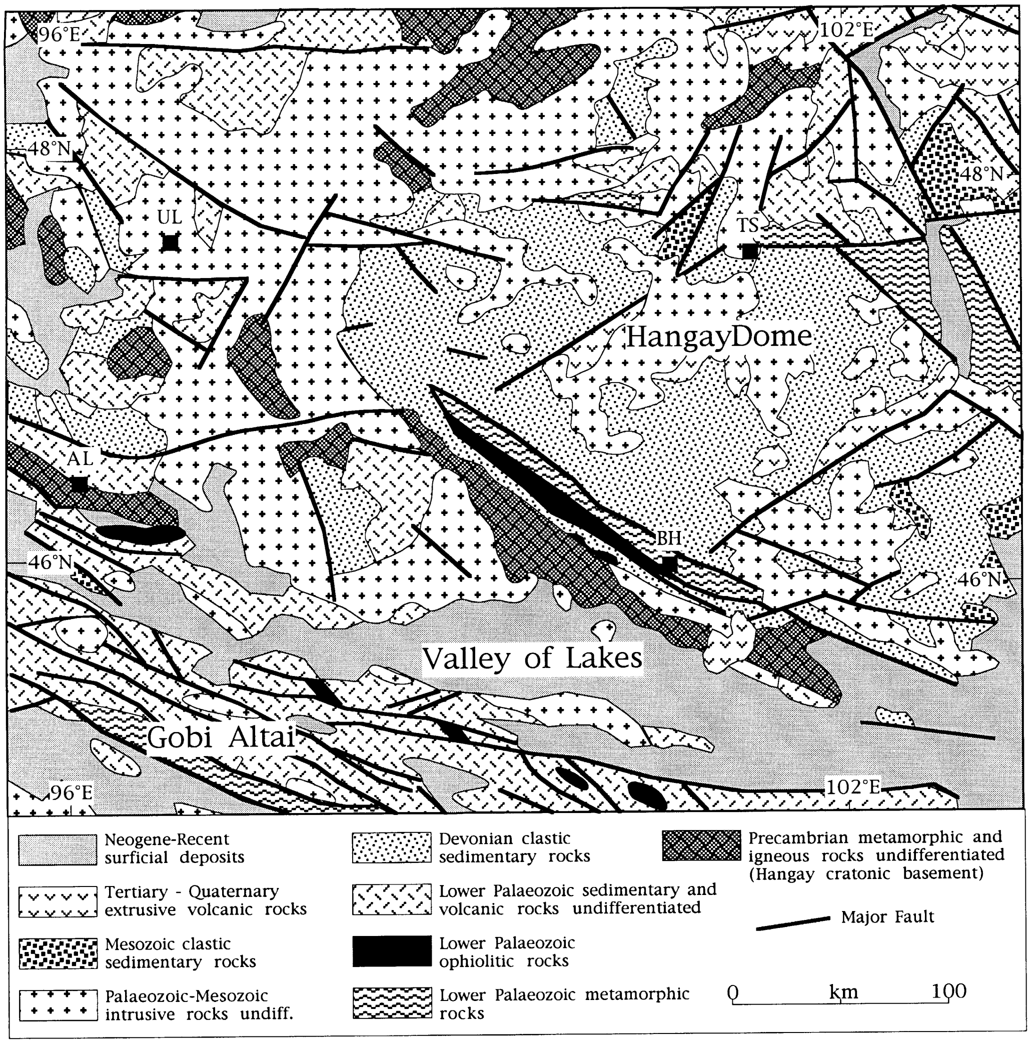

Fig. 5. Generalized geologic map of southern Hangay Dome region (taken from Badamgarav et al., 1998). Note scattered outcrops of Precambrian basement overlain by lower-mid Palaeozoic sedimentary and volcanic rocks. Voluminous undeformed Permian–Jurassic granitoids occur widely in the region. Faults shown do not necessarily correlate with results from this study. UL: Uliastay; BH: Bayan Khongor; TS: Tsetserleg.

dimensions (e.g. Zonenshain et al., 1990; Llyin, 1990; Sengör et al., 1993; Lamb and Badarch, 1997). The southern Hangay region is dominated by Cambrian–Devonian sedimentary rocks which were deposited on the basement complex (Fig. 5). These units were deformed into a northeast-vergent fold-and-thrust belt by a major late Palaeozoic contractional event (Zorin, 1999; C. Buchan, personal communication, 2000) and are extensively intruded by post-orogenic Permian and to a lesser extent, Jurassic granitoids (Zorin, 1999). The southern margin of the dome contains a Palaeozoic suture belt marked by a major ophiolitic complex (Bayan Khongor ophiolite) which separates continental fragments and arc/subduction complex terranes to the south from the Precambrian block that underlies the dome (Zorin et al., 1993). Mesozoic clastic rocks are preserved in a few scattered fault-bounded blocks on the dome and

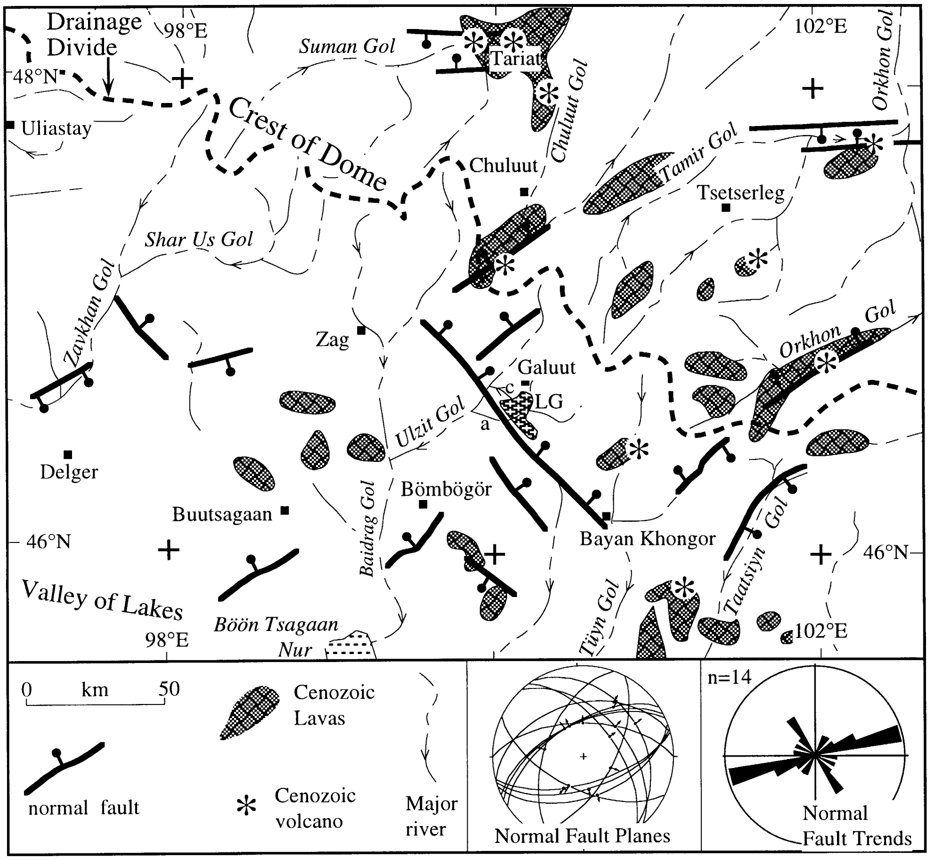

Fig. 6. Map showing major normal faults identified in this study and/or previously reported by others, locations of Cenozoic basalts and volcanic centres, and major river systems which flow off of the crest of dome. Area shown is approximately the same as in Fig. 2. Lower hemisphere, equal area stereoplot of normal fault planes with slip lineations and rose diagram plot are shown. Although only 14 faults are identified, NE trends dominate and major rivers flow dominantly NE or SW near the crest of the dome suggesting drainage is at least partially structurally controlled by Cenozoic normal faults. LG: drained Lake Galuut; a: abandoned Ulzit Gol tributary; c: canyon outlet for Lake Galuut.

are probably related to a Jurassic–Cretaceous regional extensional episode better developed in eastern and southern Mongolia (Fig. 5; Traynor and Sladen, 1995). Cenozoic deposits (Oligocene–Recent) are found in small basins and are commonly intercalated with volcanic rocks in the centre of the dome and along its southern flanks (Devyatkin and Smelov, 1979; Höck et al., 1998). Oligocene–Recent alkali basalt flows occur in many localities on the dome and on its southern flank and in the Khovsgul region (Fig. 5; Devyatkin and Smelov, 1979; Whitford-Stark, 1987; Höck et al., 1998). Small alkalic basaltic volcanoes are also preserved including several Holocene cones in the Tariat, Orkhon Gol and Chuluut regions (Fig. 6).

5. Modern seismicity, activity tectonics

Several major historic earthquakes have been recorded in the Hangay region along the eastern edge of the dome (Mogod fault) and in the northern Hangay region along the Bolnai fault and connecting splays (Fig. 3; Baljinnyam et al., 1993; Bayasgalan and Jackson, 1999, and references therein). These earthquakes were dominantly strike-slip events with associated thrusting and normal faulting at fault termination zones. For excellent summaries of these events and the associated ground deformation see Baljinnyam et al. (1993). Few earthquakes have been recorded from the centre and southern flank of the dome which is the focus of this study (Fig. 3). Despite previous remarks on the significance of normal faulting in the Hangay Dome region (Zorin et al., 1982; Baljinnyam et al., 1993), normal sense seismic events have not been recorded south of the Khovsgul graben and Bolnai fault system (Mongolian National Atlas, 1990). Active faulting in the northern Gobi Altai immediately south of the Hangay Dome is dominated by left-lateral strike-slip and thrusting displacements in an overal left-lateral transpressional regime (Baljinnyam et al., 1993; Cunningham et al., 1996; Kurushin et al., 1997; Bayasgalan et al., 1999). The maximum horizontal stress (S_{Hmax}) throughout the Altai, southern Hangay and eastern Tien Shan regions is interpreted to be northeasterly due to India's continued northeastward indentation (Zoback, 1992).

6. Crustal thickness and geophysical characteristics

Attempts to establish the crustal thickness under the Hangay region have produced varying results depending on the methods used. Assuming the region is under isostatic equilibrium (Zorin et al., 1990), the elevated topography suggests a thickened crustal root. Seismic refraction measurements and Rayleigh wave phase velocities for the Baikal/Hangay region indicate crustal thicknesses of 45–50 km with the lithosphere possibly thinned to crustal thickness under Hangay (Zorin et al., 1990). A revised crustal thickness map by Zorin (1999, Fig. 8) based on consideration of seismic data, topography and gravity anomalies suggests that the southern Hangay region is underlain by crust up to 60 km thick with average values exceeding 50 km. However, locally elevated heat flow data (Khovsgol region, Khutorskoy and Yarmoluk, 1990), widespread Late Cenozoic basaltic volcanism (Devyatkin and Smelov, 1979), and low P and S wave velocities (Rogozhina et al., 1983; Petit et al., 1998) suggest that the region is underlain by anomalously hot mantle which may provide dynamic support for the elevated topography without requiring the presence of a thick root (Baljinnyam et al., 1993). Temperature values for uppermost mantle spinel peridotite xenoliths applied to an empirical geotherm, derived from P–T estimates of different types of xenoliths taken from various alkali basalt flows in the Tariat region (Fig. 6), suggest the crust is about 45 km thick (Ionov et al., 1998). The derived geotherm for the southern Hangay region is elevated compared to most cratonic regions but is 50–100°C lower than for typical alkali basalt provinces worldwide (Kopylova et al., 1995). In general, the majority of evidence suggests that the region is underlain by thickened crust, but the degree to which the elevated topography is compensated by thermally buoyant mantle is unresolved. The greater than average crustal thickness may reflect Precambrian cratonization, Palaeozoic crustal thickening, and Palaeozoic–Mesozoic magmatic additions (Zorin, 1999), or it may reflect Tertiary basaltic underplating.

7. Cenozoic normal faults in the southern Hangay Dome region

The following section summarizes field observations of major fault scarps in the southern Hangay Dome region. All of the faults are normal sense and bound late Cenozoic sedimentary basins. Locations of faults are shown in Figs. 2 and 6.

7.1. NE Bayanbulak valley scarp (46°49.323′, 98°18.123′)

This prominent scarp bounds the north side of a 20 km long and approximately 5 km wide valley. The scarp trends 255° and is marked by triangular faceted ridge fronts which dip 25–35°SE (Fig. 7a). The upper plate consists of a vegetated apron of alluvial deposits that dips 12° basinward at the mountain front. The deposits are grass covered and incised with small channels but they are not obviously fan-shaped and fresh unvegetated deposits are rare. The footwall consists of granite which is variably brecciated with secondary chloritized and epidotized fractures. The most interesting structural feature in the granite is a set of parallel fractures at the mountain front that strike parallel to the scarp (250–255°) and dip 52°SE. Many of these surfaces contain down-dip slickensides. Other parallel surfaces lack slickensides

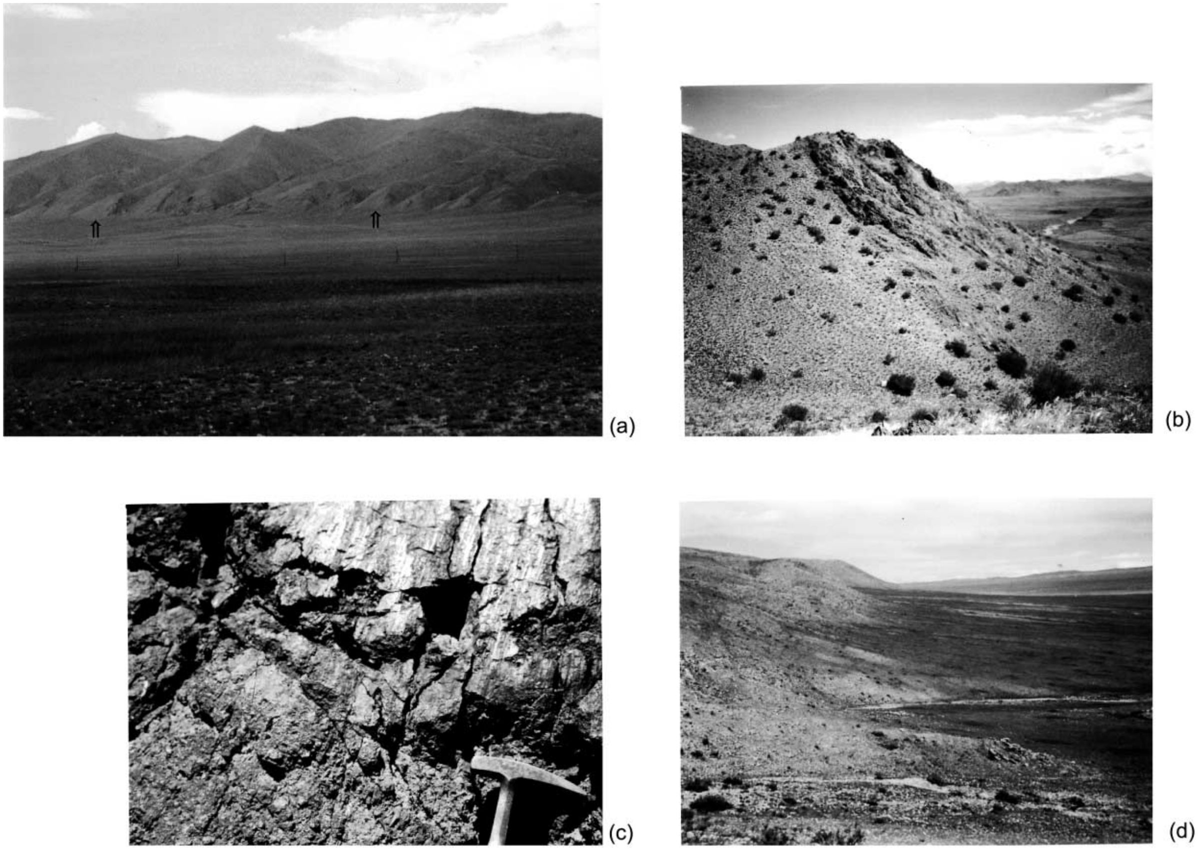

Fig. 7. (a) View looking north of Bayanbulak valley normal fault scarp. Note triangular facets on footwall block (arrows). (b) View ENE of Shilüüstay Valley scarp. Outcrop in centre consists of brecciated granite with basinward (S) dipping sheared surfaces which define parallel fabric. (c) Close-up view of brecciated granite from Shilüüstay Valley normal fault scarp with dominantly down-dip slickenlines on south-dipping sheared surface. (d) View looking NW of degraded Shar Burd scarp and Shar Burd valley to NE. Small outcrop near bottom right contains brecciated quartzofeldspathic gneisses cut by basinward dipping brittle sheared surfaces.

and appear to be relaxation joints. Although the main bounding fault is not exposed, it is interpreted to be a normal fault because of the presence of these fractures with their down-dip slickensides in the footwall block at the mountain front. Along strike to the SW, the valley divides and an en echelon left-stepping fault segment accommodates the extensional displacement.

7.2. *Shilüüstay scarp (46°43.013′, 97°17.482′)*

This 240–250° trending scarp is a major range bounding fault that separates rugged mountains to the NW from the smooth peneplaned south flank of the dome which runs uninterrupted down to the depression of the Valley of Lakes more than 30 km to the south (Fig. 2). The scarp runs for at least 30 km and produces 200–500 m of relief. The range bounding fault is best exposed about 350 m west of a perennial stream at 46°43.013′, 97°17.482′ that flows out of the range through a large canyon (Fig. 7b). The footwall is composed of blocky, massive coarse- to medium-grained pinkish brown granite. The fault zone is partially exposed and consists of highly brecciated and silicified granite containing sub-parallel and locally densely developed south dipping planar fault surfaces (255°, 50–80°SE). These fault planes are commonly slickensided (Fig. 7c) and small asymmetric steps on the sheared

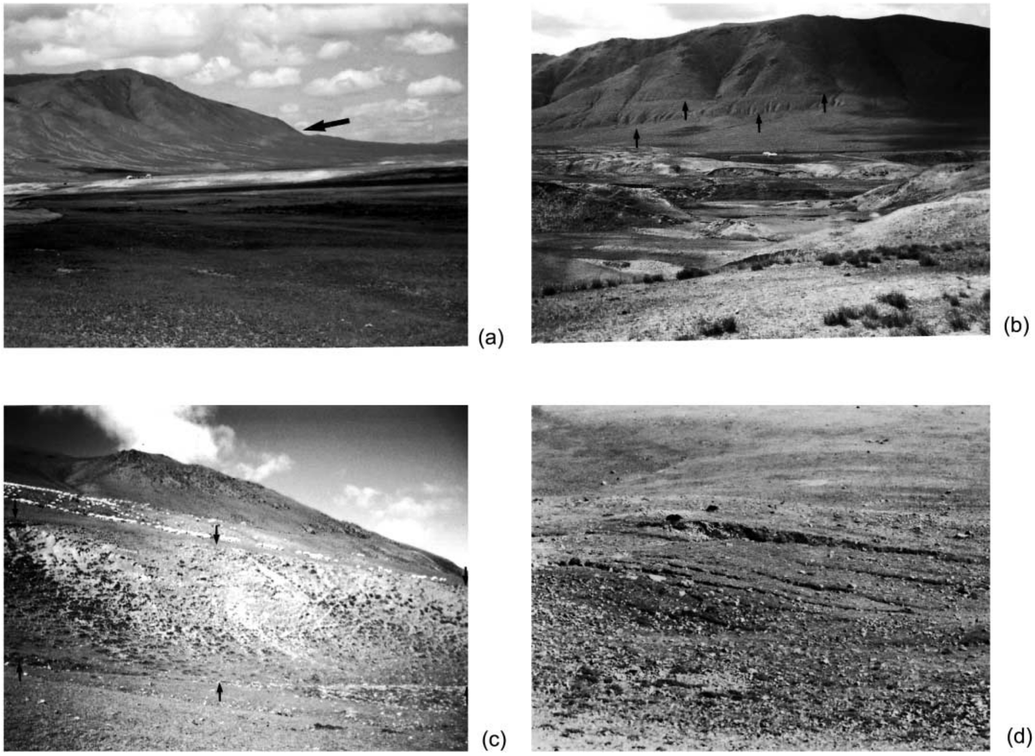

Fig. 8. Four different views of the Bayan Khongor Valley normal fault scarp: (a) View looking NW of footwall block and normal fault scarp where slope gradient changes (arrow). (b) View SW of Bayan Khongor Valley normal fault scarp where two segments overlap and double scarp exists (arrows). Eroded sediments in foreground are Quaternary lacustrine deposits of drained Lake Galuut. Lake Galuut ponded in front of the Bayan Khongor fault footwall block which acted as a natural dam for southward river flow off of the Hangay Dome. The lake drained to the NW into the Ulzit Gol and Baidrag river systems which are the most deeply incised canyons on the south flank of the dome. Draining of the lake was apparently sudden and is believed to have contributed significantly to Baidrag and Ulzit Gol canyon incision. (c) View NW of preserved Bayan Khongor normal fault scarp. Sheep above scarp give scale. Arrows show top and bottom of scarp which is >10 m high. (d) View looking N at tension cracks and small graben along the surface trace of the Bayan Khongor normal fault scarp. Black object above fresh exposure is backpack for scale.

surfaces indicate south-side down normal motion. On approximately half of the surfaces that were observed, slickensides plunge obliquely to the SW indicating a minor right-lateral strike-slip component to the extensional deformation. The silicified breccia locally forms a resistant ridge (Fig. 7b).

Upper plate lithologies are exposed in a few small inselbergs and consist of massive granite similar to the footwall rocks, and farther basinward, Neogene sediments. There is no significant accumulation of alluvial sediments at the mountain front itself instead, sediments that have been shed off of the mountain front have been transported farther downslope to the south to the Valley of Lakes depression. The lack of sediment accumulation on the immediate hanging wall (SE) side of the fault may indicate that the footwall and hanging wall were both uplifted and eroded, but that the footwall was uplifted more, thus producing the normal sense offset.

7.3. Shar Burd scarp (46°08.635′, 100°15.822′)

This erosionally degraded normal fault scarp trends 318° and can be traced for over 40 km on satellite imagery (Fig. 2). The orientation of the bounding mountain front suggests that the fault consists of several left-stepping segments. The scarp bounds a 5–10 km wide NW-trending alluvial valley and has up to 250 m of relief across it (Fig. 7d). The footwall block to the SW consists of a mixed igneous and metamorphic basement complex whereas the hanging wall consists of alluvial sediments. The mountain front to the SW slopes 28°NE whereas the alluvial cover on the hanging wall dips 9° or less towards the valley centre. The valley is markedly asymmetric with the river drainage shifted towards the SW side of the valley suggesting the greatest amount of downthrow has occurred along the SW side of the valley. The bounding normal fault was observed in only one location and consists of a zone of 295–300° striking, 60–90°NE dipping brittle sheared surfaces with down-dip slickensides. The fault rock is brecciated, strongly oxidized and generally poorly exposed.

7.4. Bayan Khongor basin scarp (46°36.252′, 99°56.188′)

The Bayan Khongor basin stretches NW of the city of Bayan Khongor for at least 250 km and averages 8–15 km wide (Figs. 2 and 6). It is a prominent feature on satellite imagery and the basin axis is roughly parallel to the NW-striking Palaeozoic basement structural grain. The basin is topographically asymmetric with a sharply defined southwestern boundary and high bordering mountain range (up to 600 m relief, Fig. 8a), whereas the northeastern boundary of the basin is irregular and bounded by erosionally denuded smaller ranges and hills. According to Baljinnyam et al. (1993) and after Devyatkin (1975), the basin is shallow (<150 m deep) and the bounding fault is a Palaeozoic structure reactivated in the Plio–Pleistocene. Devyatkin (1975) also apparently reported post-Oligocene thrusting along the fault, but this is questionable because the reported latitude and longitude coordinates for the zone of thrusting (46.5°, 101.2°) are well outside of the basin and therefore must be along some other fault.

Several segments of the fault were studied and convincing evidence was found for Cenozoic to Recent extensional activity. No evidence for thrusting was observed, nor evidence for reactivation of older structures, and the Bayan Khongor Basin is interpreted as a half-graben with a major normal fault along its SW margin.

The most impressive fault scarps occur along the basin bounding ridge to the SE and NW of the eastern Ulzit Gol Canyon (Figs. 2 and 6) which is an abandoned canyon outlet for the Bayan Khongor basin (Fig. 8a–d). The scarp separates folded and kinked Cambian greenschists from Quaternary alluvial fan deposits. At the scarp, short steep singular drainages divide into multiple channels that help define a series of coalesced grass-covered alluvial fans. Between drainages, triangular facets are developed. Locally, the surface trace of the scarp cuts across fan lobes and channels indicating that the fault must dip basinward (the scarp cuts upslope across the fans).

A spectacular exposure of the fault scarp is found at 46°35.628′, 99°56.833′ at approximately 2350 m elevation where the fault creates a 10 m high step in the topography (Fig. 8c). The surface slope above the scarp is inclined 12°NE whereas the scarp slope dips 32°NE and the slope below the scarp is 10° dipping to the NE. The scarp strikes 328° and has impressive ground deformation above and along its crest including surface tension cracks, small offset blocks and mini graben (Fig. 8d).

This major fault zone has had an important influence in landscape development along the southern flank of the Hangay Dome. The range along the SW margin of the basin represents the footwall block, however it is not anomalously high compared to the domed areas to the NE. Rather the basin floor has dropped down relative to the regionally domed topography. This appears to be a case of hanging wall collapse rather than footwall uplift relative to the level of the regionally domed Cretaceous/Palaeocene peneplane.

Between the eastern Ulzit Gol Canyon and the town of Galuut (Fig. 6), the basin is filled with thick Pleistocene lacustrine deposits now eroded into badland topography which contain fresh water gastropod (*Planorbis*) and bivalve (*Pisidium*) fossils. The half-graben was a Pleistocene sediment sink in which lakes formed and small lake remnants remain there today. The distribution of lacustrine deposits and the badland erosion pattern within the basin suggest that the lake system was drained rapidly. The outlet responsible for lake draining is the knife-like Galuut Canyon that now feeds the western branch of the Ulzit river system (Fig. 6). Draining of Pleistocene "Lake Galuut" robbed the eastern Ulzit Gol of its upstream catchment area and helps explain why the dry entrance to this large canyon is today perched above the Bayan Khongor Basin. Diversion of the Bayan Khongor basin drainage into the western Ulzit Gol system must have significantly increased the flow volume within the upper Ulzit Gol and Baidrag River (Fig. 6) into which it flows. The Baidrag River canyon system is much more deeply incised than any other river system on the south flank of the Hangay Dome (visible in Figs. 1, 2 and 6) and much of the deep incision along its lower stretches may have been caused by catastrophic flooding due to stream piracy and rapid draining of “Lake Galuut” in the Bayan Khongor Basin.

7.5. Mandal scarp (46°49.748′, 99°57.106′)

This impressive linear scarp shows up well on aerial photographs and consists of two *en echelon* normal faults that trend 240° and bound a small half-graben that opens to the south and links with the Bayan Khongor Basin (Fig. 9a). The graben varies from 2 km wide in the NE to 12–15 km wide in the SSW. The basin is filled with Quaternary alluvial and lacustrine deposits and a small lake. The bounding range rises more than 200 m above the basin to the NW and consists of Permian granitic and gabbroic intrusive rocks (Barsbold and Dorjnamjaa, 1993). Coarse-boulder-bearing alluvial fans occur along the triangular faceted range front at canyon outlets. The range bounding fault is exposed as a wide zone of brecciated footwall granite that is cut by many parallel brittle fractures (253°, 60SE) that dip toward the basin (Fig. 9b and c). These fractures are planar and iron oxide stained and were observed to have synthetic P-shear fractures that create small steps on the main fracture surface and indicate top to the SE extensional displacement. Slickensides plunge steeply SE. Other parallel non-striated SE-dipping fractures appear to be relaxation joints. Taken together, the extensional shears and joints form a densely developed brittle planar fabric that is exposed over a width of at least 20 m and defines the mountain front structure.

7.6. Egiyn Davaa scarp (47°07.345′, 99°44.350′)

This normal fault scarp was previously described by Baljinnyam et al. (1993) and Khil’ko et al. (1985) who published a geological map of the scarp and surrounding areas. Khil’ko et al. (1985) suggested that the fault ruptured 300–500 years ago based on


(a) (b) (c)

Fig. 9. Different views of the Mandal normal fault scarp: (a) Aerial photo of Mandal scarp (arrows). North is to top of page and width of photo is approximately 8 km. Basin opens to SW and normal fault displacement dies out to NE towards upper right corner. Bounding fault is in two segments. Left arrow points to triangular facets along front. (b) View SW of Mandal normal fault scarp. Note basinward dipping surfaces in foreground and distance, which are sheared faults and parallel joint planes. (c) View NE of brecciated footwall granite at Mandal scarp. Note subparallel basinward dipping surfaces which are discrete shear planes and relaxation joints.

surface deformation features and historical information. Where observed in the field for this study (GPS location above), the fault is expressed as a 074° striking, 42°NW dipping surface rupture on the SE side of a NE trending valley (Fig. 10a). Regionally, the fault strikes closer to 060°. This valley forms a major pass across the high crest and watershed divide of the Hangay Dome and is bounded by high peneplaned summits in excess of 3300 m. No fault was observed along the NW side of the valley so the valley appears to be a half-graben. The fault is 100% exposed (at GPS location above) because springs have stripped away the alluvial cover (Fig. 10a–c). The scarp slope dips 36°NW whereas the surface slope above the scarp is inclined at 20°NW and the lower slope below the scarp is inclined 7°NW. At this location, the footwall consists of fractured quartzite cut by pervasively developed sheared surfaces. Slickensides are well exposed and plunge 31°,032 indicating a subordinate right-lateral component to extension at this location (Fig. 10c). The hanging wall consists of valley fill sediments and Quaternary basalt flows and scoriaceous deposits. The scarp itself is up to 5 m high at this location (Fig. 10b).

This scarp is the freshest and most recently active scarp known in the southern Hangay region. It is perhaps significant that the youngest known rupture has occurred at the crest of the dome cutting across the highest elevations. Farther to the NE, the scarp continues for another 20 km where it cuts Quaternary deposits and Oligocene basalt flows (Khil'ko et al., 1985; Barsbold and Dorjnamjaa, 1993).

7.7. Shargaljuut hot springs area (46°19.992′, 101°13.491′)

This hot springs complex is found in a valley 45 km ENE of Bayan Khongor (Figs. 2 and 6). There are approximately 50 springs located on an east-facing slope at a slight bend in the valley. The outcrops at the springs consist of siliceous sinter and siliceous breccia which form a broken boulder pile on small ridges and depressions. The original host rock is fractured granite gneiss that is partially to wholly silica replaced. The complex is cut by a prominent set of planar extensional fractures that strike 060–080° and dip 70–80°SE producing a step-like topography. These fractures are also parallel to the overall valley

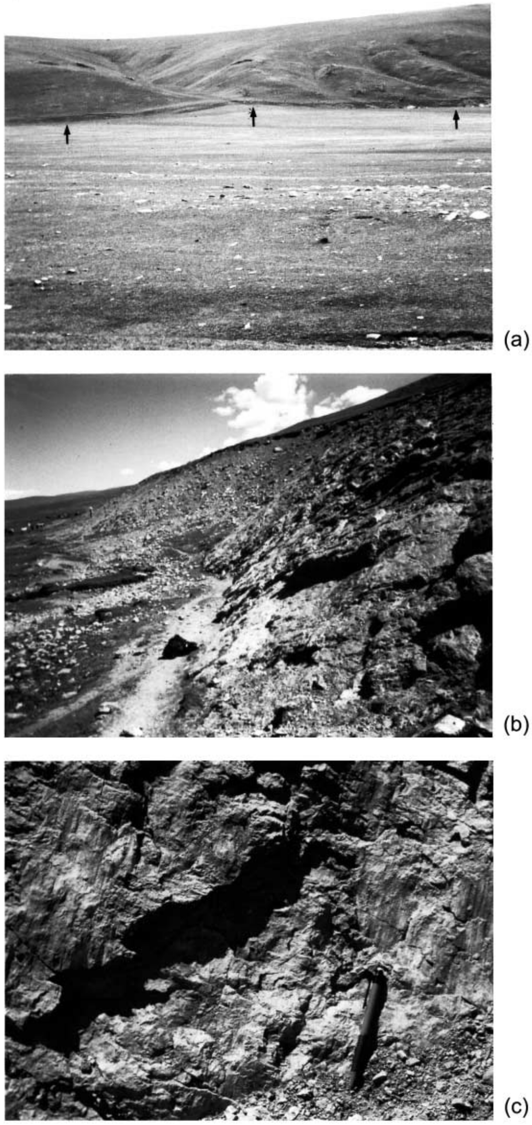

Fig. 10. Different views of Egiyn Davaa fault scarp: (a) View SE of active normal fault scarp (arrows) cutting Quaternary alluvial sediments at 2500 m elevation. Scarp defines SE side of major valley which cuts across crest of the dome. (b) View NE of exposed fault planes at Egiyn Davaa scarp where springs complex has removed overlying alluvium (small backpack in foreground for scale). (c) Closeup of normal fault planes at location shown in photo (b) with dominantly down-dip slickenlines on parallel sheared surfaces (pen for scale).

trend. The nearby slopes are mantled in fresh rockfalls and slide deposits that are not generally observed elsewhere in the region. The slope deposits and jumbled ground give the overall impression that the springs area has recorded geologically recent surface deformation and local ground shaking.

When seen from above, the springs follow linear N–S lines despite the prominent 070° fracture set. The entire complex is interpreted as a small N–S accommodation zone along a narrow NE-trending half-graben. Presumably fault intersections at the accommodation zone provide conduits that allow deep thermal waters to reach the surface.

7.8. Bombögör scarp (46°09.304′, 99°30.018′)

This remote scarp is visible on satellite imagery for a distance of at least 30 km and runs between the Baidrag Gol in the SW to a point 5 km SE of the town of Bombögör on the southern flank of the dome (Figs. 2 and 6). Despite its clear visibility from space, the scarp has only 100 m or less of relief and is thus a fairly subtle feature on the ground. Where studied, the fault trends 020°, dips 55°NW and separates footwall augen gneisses and variably foliated granitoids from hanging wall red beds and well indurated and cemented coarse-grained brown conglomerates. The best exposure of the fault zone is incomplete, but consists of three parallel brown-weathered and strongly silicified basinward-dipping breccia zones. On fresh surfaces, the breccia appears green due to a high degree of chloritization of micas and feldspars in the host granitoid. Slickensided surfaces are rare, however the entire fault zone is not exposed.

The basin deposits are not dated and form few exposures. The age of the extensional faulting is therefore not known and it is possible that the scarp is an exhumed Mesozoic feature and the sedimentary infill is Cretaceous, not Tertiary. Cretaceous clastic rocks have been mapped in the Valley of Lakes region to the southeast (Daxner-Höck et al., 1997). However, the footwall block forms a significant local drainage divide suggesting that even if the basin initially formed in the Mesozoic, there has been Cenozoic reactivation of the normal faults and consequent river diversion.

7.9. Mogoyn Toog Uul scarp (45°58.241′, 100°00.69′)

This remote scarp was identified on Landsat imagery and was ground-checked to determine its slip sense and evidence for Cenozoic activity. The scarp trends 300° and marks the southern front of a low mesa capped by several basalt flows dated at middle Miocene (Devyatkin, 1981). The scarp is linear and continuous for 10 km and has less than 100 m of relief. The entire region is one of subdued relief and slopes gently southwards towards the axis of the Valley of Lakes (Figs. 2 and 6). At the mesa front, the basalt flows dip up to 60°SW (296° strike) whereas only 100–150 m to the NE they are sub-horizontal. Thus they are dragged or flexed as in a monocline. The presumed bounding fault is covered by small grassy alluvial cones, basaltic colluvium and windblown sand and is not exposed and appears inactive. Despite never being seen, the fault is cautiously interpreted to be a normal fault because of the sense of drag and because other parallel-striking faults to the north (Shar Burd, Bayan Khongor; Figs. 2 and 6) are clearly normal sense. The age of faulting is unknown but must postdate the deformed Miocene basalt flows.

7.10. Other Cenozoic normal faults in southern Hangay

Several other prominent normal fault scarps in the southern Hangay region are visible on satellite imagery, but were not investigated in this study. The Taatsyn Gol Valley (46°15′N, 101°40′E, Figs. 2 and 6) is bounded on its northwest side by a NE striking normal fault system that can be traced on Kosmos images over a length of at least 100 km (observed by plane for this study, but not ground-checked). The valley appears to be a half-graben which varies in width from 2 to 7 km. Another major normal fault bounds the SE side of the Orkhon Gol Valley (46°35′N, 102°E, Figs. 2 and 6). This NE-trending fault is very sharp on satellite imagery and can be traced for at least 50 km. This valley also appears to be a half-graben and contains Pliocene volcanic centres and lava flows some of which are reportedly cut by the normal fault system (Devyatkin and Smelov, 1979). This fault appears to be approximately on strike with the Shargaljuut fault to the SW and may link up with it (as is shown on some published maps, e.g. Mongolian National Atlas, 1990; Badamgarav et al., 1998), however this linkage is not apparent on satellite imagery. Baljinnyam et al. (1993) reported the existence of a NW-trending, NE-dipping normal fault that crosses a high area (2500 m +) near 47°N, 98°E (Fig. 2) over a length of at least 30 km (see their Fig. 51). Finally, a sharply defined 40 km long NE-striking normal fault with NW side down displacement is visible on satellite imagery approximately 40 km NW of Boon Tsagaan Nuur (46°N, 98°40′E; Figs. 2 and 6). This fault bounds a basin 2–10 km wide which contains Cenozoic alluvial fill and dried up lake deposits.

8. Summary of fault observations

Although only 14 major Cenozoic normal faults are identified and reported here from the southern flank and crest of the Hangay Dome, it is likely that more exist, but have not yet been identified. The dominant normal fault trend is northeasterly (Fig. 6) and this is also the dominant river trend on the southern flank and crest of the dome suggesting structural control of the drainage pattern. Other NE-trending valleys and passes may also be normal fault controlled, but await further study. All of the major normal faults identified in this study bound small alluvial basins that appear to be half-graben. Symmetrical graben were not identified and all basins appear to be bounded by one individual master fault. Alluvial fill in the half-graben is mapped as Neogene or Quaternary on most geological maps and some scarps clearly deform Quaternary deposits indicating recent activity (Egiyn Davaa, Bayan Khongor). The depth of alluvial fill in most basins is unknown, however, Baljinnyam et al. (1993) reported that the Bayan Khongor basin has only 150 m or less of sedimentary infill based on electrical soundings reported in Devyatkin (1975). The other basins reported here are narrower and have lower footwall block ridges bounding them suggesting that they have experienced less total extension and thus probably have thinner sedimentary infill. Therefore, it appears that the half-graben reported here are only minor sediment sinks that are perched on the regionally south-sloping flank of the Hangay Dome. The major sediment sink for the southern flank of the Hangay Dome is farther downslope in the Valley of Lakes where Cenozoic alluvial fill is probably at least 1–2 km and possibly locally much greater (Baljinnyam et al., 1993). Significant Cenozoic alluvial sedimentation commenced on the northern margins of the Valley of Lakes in mid-upper Oligocene time (Yanshin, 1975) which is therefore the best indicator of when the Hangay region began to be topographically uplifted and became a major sediment source relative to regions to the south.

The first-order structural feature in the region is the dome itself. In contrast to the Gobi Altai directly to the south, no Cenozoic thrust belt or transpressional deformation was found on the southern flank of the dome which could have accommodated Cenozoic uplift. Mid-late Cenozoic regional doming has led to preservation of an elevated Cretaceous/Palaeogene peneplane at approximately 3500 m, development of NE- and NW-striking extensional faults and small half-graben, erosional exhumation of Precambrian and Palaeozoic basement rocks, and asymmetric development of river systems with extensive networks on the N and NE sides and short generally subparallel, non-integrated rivers on the south flank.

The normal faults with the clearest evidence for Holocene activity (Egiyn Davaa, Bayan Khongor) occur at relatively high elevations suggesting that the highest elevations are most actively extending. The Bayan Khongor Basin fault produces the highest relief of the scarps that were studied (up to 700 m) and therefore probably has accommodated the most displacement. Total displacements on all other faults appear to be less than 500 m based on topographic offsets and shallowness of alluvial fill on the hanging wall (for most scarps studied, the footwall preserves the regional summit peneplane). There is no evidence that deep-seated rocks are exhumed in the footwall blocks, nor are reactivated ductile mylonitic fabrics present within any of the observed fault zones which appear entirely brittle. There is no suggestion that the scattered normal faults are linked regionally with a deeper detachment fault. There may be structural linkage between the Egiyn Davaa, Bayan Khongor, Mandal and Shar Burd scarps which are spatially close to each other (Figs. 2 and 6), but elsewhere the graben appear to be isolated systems. Strike-slip faults were not identified in the area investigated here despite their importance in accommodating Cenozoic deformation in neighbouring regions.

Minor strike-slip components are suggested by slickenside orientations on some faults, but are clearly subordinate to the extensional displacements (Fig. 6).

A spatial association between Cenozoic graben development and alkali basalt centres may exist (Fig. 6). This has previously been reported for the Orkhon Gol and Tariat regions where cinder cones and vents locally line up along faults or dykes (Devyatkin and Smelov, 1979; Fig. 6), and was noted in this study in the Egiyn Davaa valley where three eruptive centres and a singular feeder dyke trend 296°. These areas and the rest of the region require much more detailed study to determine the relationship between faulting and localization of eruptive centres.

9. Discussion on origin of the Dome

The Hangay Dome has previously been interpreted to be underlain by a mantle plume that has buoyed up the topography and generated Cenozoic volcanism (Windley and Allen, 1993, and references therein). Support for this interpretation includes, regional doming, alkaline magmatism, locally elevated heat flow, rifting, and apparently thinned lithosphere. In addition, geophysical studies have shown low-velocity P wave, S wave and Rayleigh wave group anomalies beneath Hangay and the southern Baikal region (Zorin et al., 1982; Rogozhina et al., 1983; Petit et al., 1998). According to these ideas, doming could be supported dynamically or by basaltic underplating at the base of the crust.

Conversely, geochemical evidence from Cenozoic alkali basalts for the existence of a mantle plume beneath the dome is not compelling. Barry (1999) demonstrated that the mantle beneath the Hangay Dome was previously metasomatically enriched, probably during Palaeozoic–Mesozoic subduction-related continental assembly (Zorin, 1999). Generation of Cenozoic Hangay basalts could have occurred by only slight heating (50–100°C above ambient mantle temperatures) of hydrous mineral assemblages in the lithospheric mantle. In addition, helium isotope ratios are only slightly higher than MORB, but are significantly lower than typical plume signatures (Barry, 1999; Dunai and Baur, 1995). According to Barry (1999), a high-heat flux plume is not required to generate the Cenozoic volcanism. In addition, the existence of Cenozoic basalts with similar geochemical signatures over a much wider area that is not crustally domed including the Gobi Altai, eastern Mongolia and adjacent areas of northeastern China, suggests a more complex melting process (Barry and Kent, 1998).

It is therefore worth considering other mechanisms that could generate crustal doming and volcanism in the Hangay region without an active plume as the driving force. Long-wavelength whole lithospheric folding has been proposed as a mechanism to produce intracontinental topographic uplift elsewhere in Asia (Nikishin et al., 1993), but does not appear to be a likely mechanism for the doming in the Hangay region because there is no obvious long axis of the dome at a high angle to the northeasterly S_{Hmax}, nor does crustal folding explain the generation of Late Cenozoic volcanism. Delamination or convective removal of a thickened crustal root followed by partial melting of adiabatically decompressed aesthenosphere could cause the observed doming and volcanism as has been suggested for Tibet (Platt and England, 1993). However, major crustal thickening in the southern Hangay region last occurred in the Permian (Jurassic collision and crustal thickening is not documented in the southern Hangay region although it is documented further to the NE, see Zorin, 1999) and the time gap between Permian crustal thickening and Neogene plateau uplift and volcanism (>200 Myr) appears too great to be explained by this mechanism (Platt and England, 1993).

What does appear certain is that the change from linear mountain ranges formed by transpressional deformation in the Altai and Gobi Altai to regional doming and crustal extension in the Hangay region coincides with an important crustal boundary between the Hangay Precambrian block to the north and east and Palaeozoic subduction and arc complexes to the south and west (Fig. 5; Cunningham, 1998). This kinematic and topographic boundary (Valley of Lakes; Figs. 1 and 2) presumably reflects contrasting rheological properties on either side (strong craton vs. weak subduction/arc complexes). This is consistent with observations made elsewhere in Central Asia that the Cenozoic deformation field is strongly controlled by the geometry of Precambrian cratonic boundaries (Westaway, 1995; Clark and Royden,

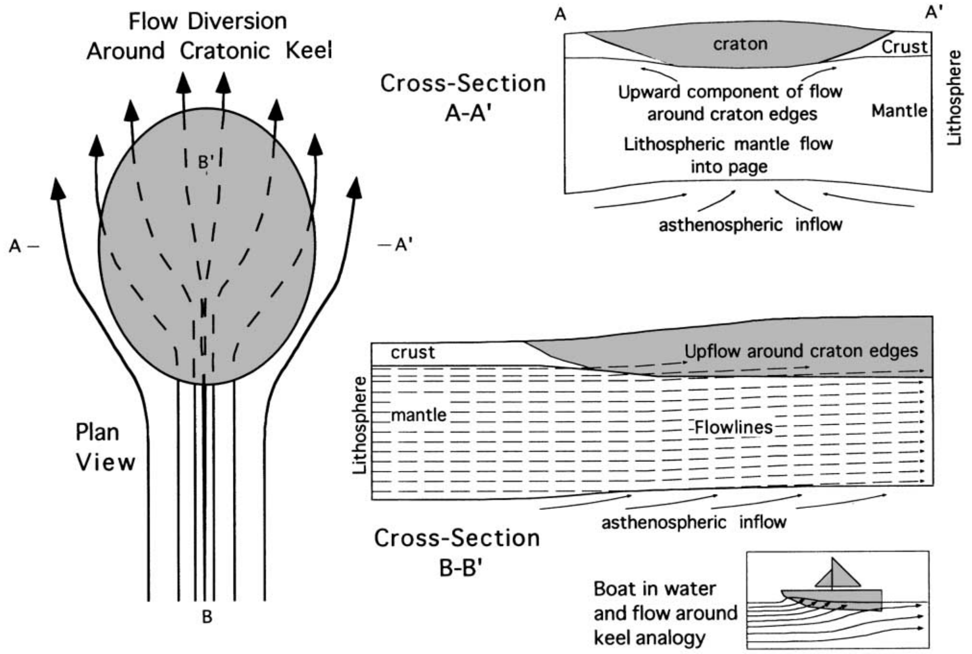

Fig. 11. Schematic diagram of how crustal doming may be a consequence of mantle lithospheric flow that is deflected by a thick, rigid, and cold Precambrian craton. Reverse topography at base of cratonic crust diverts ductile flow of lithospheric mantle around edges. Upwards component of flow around edges of craton will result in upwarp of lithosphere/asthenosphere boundary beneath craton (shown in cross-sections). Decompressed asthenosphere may partially melt and add a buoyancy force leading to doming of crust above. Degree of laterally and upwardly diverted flow of lithospheric mantle is critically dependent on shape and dimensions of craton, mantle strain rates, viscosity contrasts within the lithosphere, and whether the system is in dynamic communication with other plate boundaries.

2000). The way in which the Altai ranges encircle the Hangay Dome (Figs. 1 and 3) suggests that the dome acts as a rigid barrier and passive indentor that focuses transpressional deformation around its southern and western margins.

An alternative model for explaining doming and late Cenozoic alkaline volcanism in the Hangay Dome region is here proposed based on speculated patterns of lithospheric mantle flow in the region (Figs. 11 and 12). Geodetic studies from continental interiors increasingly show that long-term slip rates on continental strike-slip faults can be regarded as approximately the same as the velocity of a continuously deforming fluid below (Bourne et al., 1998). Accordingly, ductiley deforming lithosphere below is coupled to the discontinuously deforming seismogenic layer above by traction forces applied to the base of the seismogenic layer (England and Molnar, 1991). In the case of Mongolia, west of the Hangay Dome in the Altai region, N–S dextral displacements dominate the Cenozoic deformation field, whereas south of the dome in the Gobi Altai region, E–W sinistral displacements dominate (Fig. 3). These upper crustal displacements around the western, southwestern and southern margins of the dome are presumably matched by deeper similarly oriented flow patterns of lower crust and lithospheric mantle. This is supported by seismic anisotropy data in the eastern Gobi Altai and Tien Shan that suggest northeastwards directed lithospheric flow in these regions (Fig. 3; Gao et al., 1994; Silver, 1996). The driving force for these displacements is presumably India's continued northeastwards indentation relative to the more fixed and mechanically rigid Siberian and Hangay cratons (cf. Cunningham et al., 1996, 1997). If the upper and lower lithosphere in the region west, southwest, and south of the dome is moving together in response to India's continued push from the SSW, then it is important to consider the effects that the Hangay craton may have on deeper lithospheric flow.

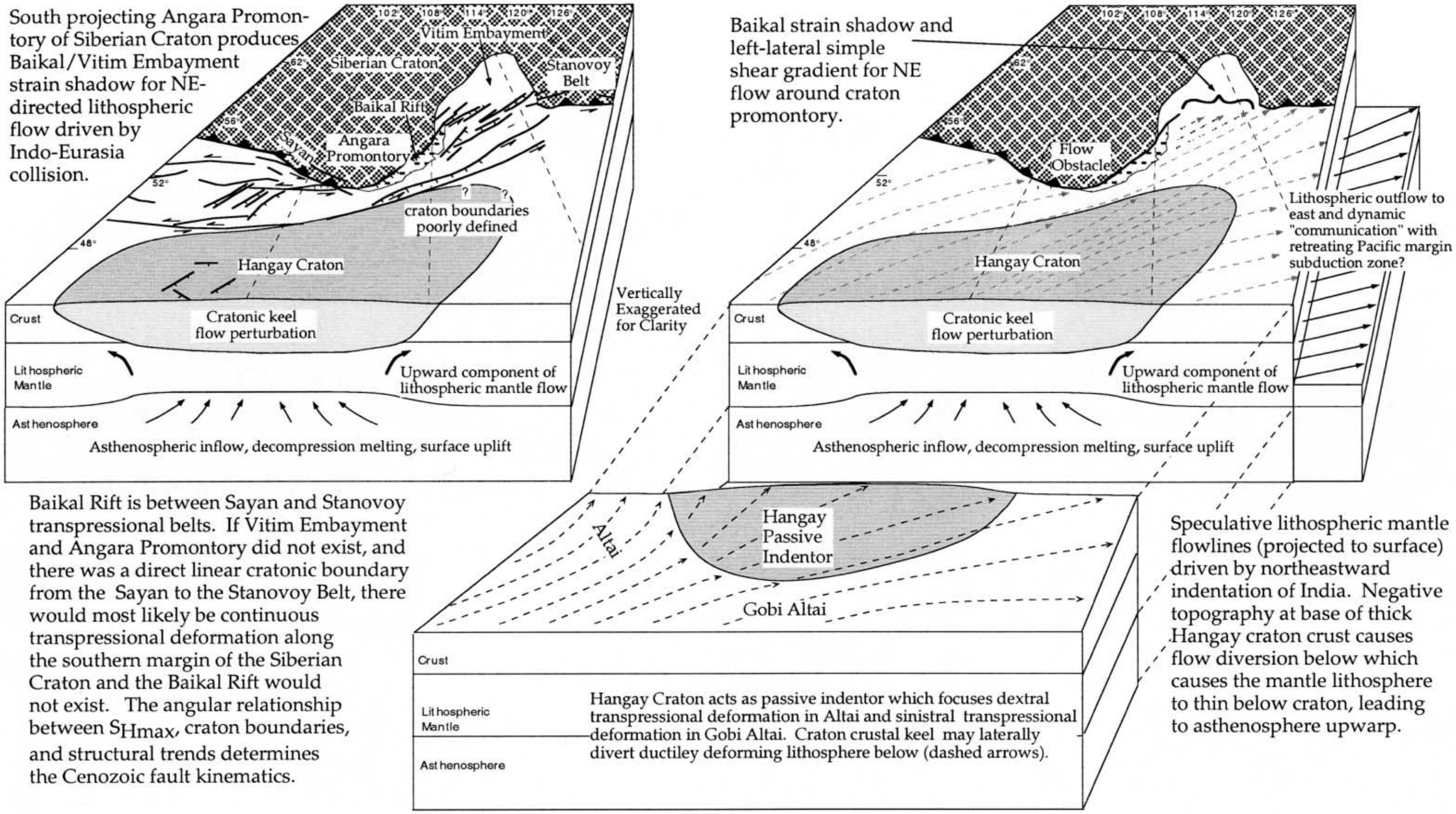

Fig. 12. Simplified lithospheric model for Hangay Dome and Baikal regions showing how Hangay crustal keel may deflect NE-directed lithospheric mantle flow driven by indentation of India. Diversion of flow around Hangay craton causes component of upward flow along craton edges and thinning of mantle lithosphere directly below craton. The asthenosphere/lithosphere boundary is consequently pulled up and rising asthenosphere decompresses and partially melts causing doming and volcanism above. The Baikal rift occupies a crustal scale strain shadow with regard to NE-directed lithospheric flow, E and NE of the Angara Promontory within the Vitim Embayment. See text for discussion.

The Hangay Dome is underlain by Precambrian crust which is thicker and older than crust to the south (Zorin et al., 1990, 1993) and was therefore presumably cooler, more rigid and elastically thicker *prior* to the onset of Cenozoic volcanism. It is speculated that this cratonic block has a crustal keel which initially impeded northeastward-directed lithospheric mantle flow driven by India's indentation into Eurasia. Flow diversion around the keel would have produced an upward component of lithospheric flow around the edges of the craton, analogous simplistically to the way in which water flows up and around the keel of a boat (Figs. 11 and 12). If the lithosphere under the dome was of normal thickness or was previously thinned (Permian delamination of lithospheric root now expressed by voluminous post-orogenic Permian granites in the Hangay region?), then this upward component of flow around the craton edges would have resulted in a net drawing up of the lithosphere/asthenosphere boundary as the mantle lithosphere diverts and thins under the craton (schematically shown in Fig. 11). This passive mechanism for asthenosphere upwarp under the craton would decompress the rising asthenosphere, generate partial melting, and create a buoyancy force which could dome the crust. Although this mechanism for doming and generation of alkali volcanism appears qualitatively plausible, it is critically dependent on various parameters which are difficult to quantify at this stage including, lithospheric mantle flow rates, lithospheric mantle viscosity under the dome, shape, dimensions and depth of penetration of the cratonic keel, original lithospheric thickness, ambient aesthenosphere, mantle lithosphere and crustal geotherms, the total amount of Cenozoic northeastward displacement in the region driven by India's northeastward indentation, and whether the system is in dynamic communication with the subduction zone along east Asia's Pacific margin which could generate forces (rollback, trench suction, etc.) that might influence the system under central Mongolia.

10. The Baikal extensional province from a Mongolian perspective

If deep lithospheric ductile flow patterns are affected by cratonic boundaries and the topography at the base of the brittle crust, and if divergent flow patterns have played a major role in the uplift of the Hangay Dome, then similar processes may be invoked to explain the pattern and kinematics of deformation in the adjacent Baikal rift province. As noted by others, the Baikal rift is located along the edges of the Siberian craton and within a large recess known as the Vitim Embayment (Fig. 12; Petit et al., 1996; Delvaux et al., 1997). To the west and east are the active transpressional orogens of the Sayan and Stanovoy belts (Fig. 11; Delvaux et al., 1997). These belts occur along segments of the Siberian craton margin that are at a high angle to the NE-directed S_{Hmax} (Zoback, 1992) and thus accommodate contractional and strike-slip components of deformation along the reactivated craton boundary. The Baikal rift is along a segment of the cratonic boundary that is roughly parallel to S_{Hmax} and thus the cratonic boundary and adjacent parallel strike belts are favourably oriented for extension and strike-slip displacements, but not contractional reactivation (Petit et al., 1996). One can imagine that if the Vitim embayment did not exist and the southern boundary of the Siberian craton was E–W oriented, then there would be a continuous transpressionally reactivated cratonic boundary instead of the Baikal rift. The Baikal rift can thus be imagined as a huge crustal strain shadow with respect to NE-directed S_{Hmax} partially protected by the *S*-directed Angara Promontory of the Siberian craton (Fig. 12). When considered from a Mongolian perspective, NE-directed lower lithospheric flow encounters two partial barriers, the Hangay and Siberian cratons. Together these constitute huge flow perturbations with crustal deformation focused along the cratonic margins with the relative kinematics determined by the angular relationship between flow direction and cratonic boundary. The combined Siberian and Hangay cratonic promontories may effectively divert lithospheric mantle flow, especially eastward where retreating Pacific margin subduction zones provide room for lithospheric extrusion (Worrall et al., 1996). Flow between the Hangay and Siberian cratons may be channelized and perhaps even accelerated causing the unexplained higher crustal strain rates in the Baikal rift (Calais et al., 1998) than predicted solely from the stresses due to the Indo-Eurasia collision to the south.

Acknowledgements

I thank T. Barry, C. Buchan, M. Allen, B. Windley, and G. Badarch for useful discussions and criticism. Thanks to D. Orolmaa for her help and companionship in the field. I am grateful to A. Swift for helping with fossil identification. A. Bayasgalan and K. Burke provided useful reviews. This project was supported by Royal Society Grant No. 19174 awarded to D. Cunningham.

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