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Active intracontinental transpressional mountain building in the Mongolian Altai: Defining a new class of orogen

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Abstract

Mountain ranges that are actively forming around the western and northern perimeter of the Indo-Eurasia collisional deformational field, such as the Mongolian Altai, comprise a unique class of intracontinental intraplate transpressional orogen with structural and basinal elements that are distinct from contractional and extensional orogens. Late Cenozoic uplift and mountain building in the Mongolian Altai is dominated by regional-scale dextral strike–slip faults that link with thrust and oblique–slip faults within a 300-km-wide deforming belt sandwiched between the more rigid Junggar Basin block and Hangay Precambrian craton. Dominant orogenic elements in the Mongolian Altai include double restraining bends, terminal restraining bends, partial restraining bends, single thrust ridges, thrust ridges linked by strike–slip faults, and triangular block uplifts in areas of conjugate strike–slip faults. The overall pattern is similar to a regional strike–slip duplex array; however, the significant amount of contractional and oblique–slip displacement within the range and large number of historical oblique–slip seismic events renders the term "transpressional duplex" more accurate. Intramontane and range flanking basins can be classified as ramp basins, half-ramp basins, open-sided thrust basins, pull-apart basins, and strike–slip basins. Neither a classic fold-and-thrust orogenic wedge geometry nor a bounding foredeep exists. The manner in which upper crustal transpressional deformation is balanced in the lower crust is unknown; however, crustal thickening by lower crustal inflation and northward outflow of lower crustal material are consistent with existing geological and geodetic data and could account for late Cenozoic regional epeirogenic uplift in the Russian Altai and Sayan regions.

Keywords: intracontinental mountain building; intraplate processes; transpression; Altai; Central Asia; active tectonics

1. Introduction

Major mountain ranges on the continents can be grossly subdivided into plate boundary and intraplate orogens. Modern orogens forming at plate boundaries include continent–continent collision belts (e.g., Himalayas, Alps), arc-continent collision belts (e.g., Taiwan, New Guinea), transpressional orogens (New Zealand, California), accretionary orogens (Makran, SE Alaska), continental magmatic arc orogens (Andes, Cascades), and rift shoulder ranges (Brazilian Highlands, Western Ghats). Intraplate orogens include dominantly contractional belts (Central Tien Shan), regions of rift inversion (Pyrenees), diffuse extensional basin and range belts (Utah–Nevada, Transbaikalia), plume-related domed highlands (Rhenisch Massif, Ethiopia), and unexplained plateaux (Guyana Highlands, Hangay Dome). A number of other active intraplate orogenic belts exist in Central Asia around the perimeter of the

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Indo-Eurasia deformation field such as the Hindu Kush, western spurs of the Tien Shan, Altai, Gobi Altai, Sayan, Stanovoy Belt, and bordering the Tibetan plateau (Qilian Shan, Yunnan ranges; Fig. 1). These intracontinental ranges are transpressional in nature and are distinguished from other orogenic types by specific structural, topographic and evolutionary characteristics. They constitute a unique class of intracontinental, intraplate transpressional orogen that is generally underappreciated by geologists.

One of the best examples of an intraplate intracontinental transpressional orogen is the Mongolian Altai.

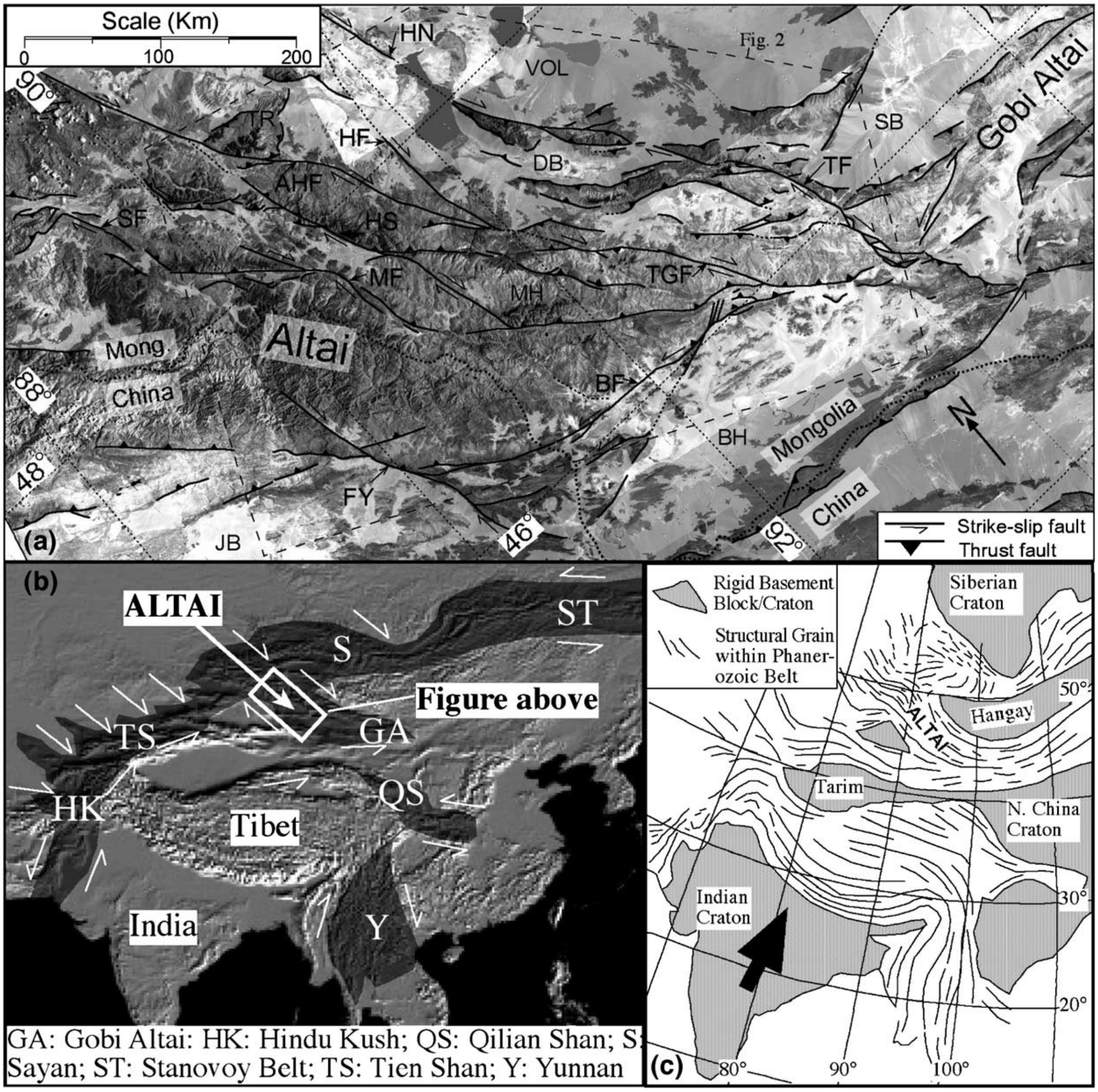

Fig. 1. (a) Landsat mosaic for Mongolian and Chinese Altai region showing late Cenozoic dextral transpressional fault array that is responsible for uplifting the mountain range during the late Cenozoic. Location of Fig. 2 shown. VOL: Valley of Lakes; SB: Shargyn Basin; DB: Dzereg Basin; TR: Tsambagarav Range; MH: Monkh Hayrhan; BH: Baruun Huuray Basin; JB: Junggar Basin; HN: Har Us Nuur Fault; HF: Hovd fault; AHF: Ar Hötöl Fault; HS: Hoh-Serkh Fault; SF: Sagsay Fault; MF: Mengildyk Fault; TF: Tonhil Fault; TGF: Turgen Gol Fault; BF: Bulgan Fault; FY: Fu-Yun Fault. (b) Map showing active intracontinental oblique deformation belts around the western and northern perimeter of the Indo-Eurasia deformation field and E and SE margin of Tibetan plateau (dark shaded areas). (c) Location of cratons/rigid blocks and Phanerozoic strike belts in Central Asia. Cratons have resisted internal deformation, whereas Phanerozoic belts like the Altai are regions of Cenozoic crustal reactivation and mountain building driven by India's continued indentation into Eurasia (thick arrow). J: Junggar Block.

The Altai is a northwest-trending belt of Palaeozoic arc terranes, accretionary complexes and continental fragments [1–3] that has been tectonically reactivated in the late Cenozoic (Oligocene–Recent) as a far-field deformational response to the Indo-Eurasia collision over 2500 km to the south (Fig. 1; [4–7]). Modern tectonic activity in the Altai is indicated by historical seismicity (for review see [5,8]), Quaternary surface fault ruptures, linear mountain fronts bordered by active alluvial fans, and other geomorphic indices of active tectonism [9,6,10,11]. The maximum horizontal stress (SHmax) in the region is NNE due to India's continued NNE indentation into south Asia [12,13] and limited GPS data for the Mongolian Altai region indicate NNE-directed crustal displacements relative to a fixed Siberia on the order of 5 mm/yr with velocities decreasing northwards towards Siberia [14]. Major terrane boundaries and the prevailing basement structural grain in the Altai strike NW [7,3]. The angular relationship between the NW-striking crustal grain and the NNE-directed SHmax promotes dextral transpressional deformation on the NW-trending strike–slip faults and linked oblique–slip and thrust faults (Fig. 1; [2,6,10,11,7]).

2. Tectonic geomorphology of the Altai

The geomorphology of the Altai is an important source of information for identification of active faults and folds and for interpreting fault kinematics and mechanisms of uplift. On the Mongolian side, the range contains distinctive topographic culminations and isolated massifs that are separated by large basins (Figs. 1, 2). There is neither a continuous range front nor obvious foredeep, and within the range, there are large uplifted areas with mature low-relief landscapes that show no surface evidence for neotectonic reactivation [10]. The Mongolian side of the range is arid, and low erosion rates, limited vegetation and a generally barren

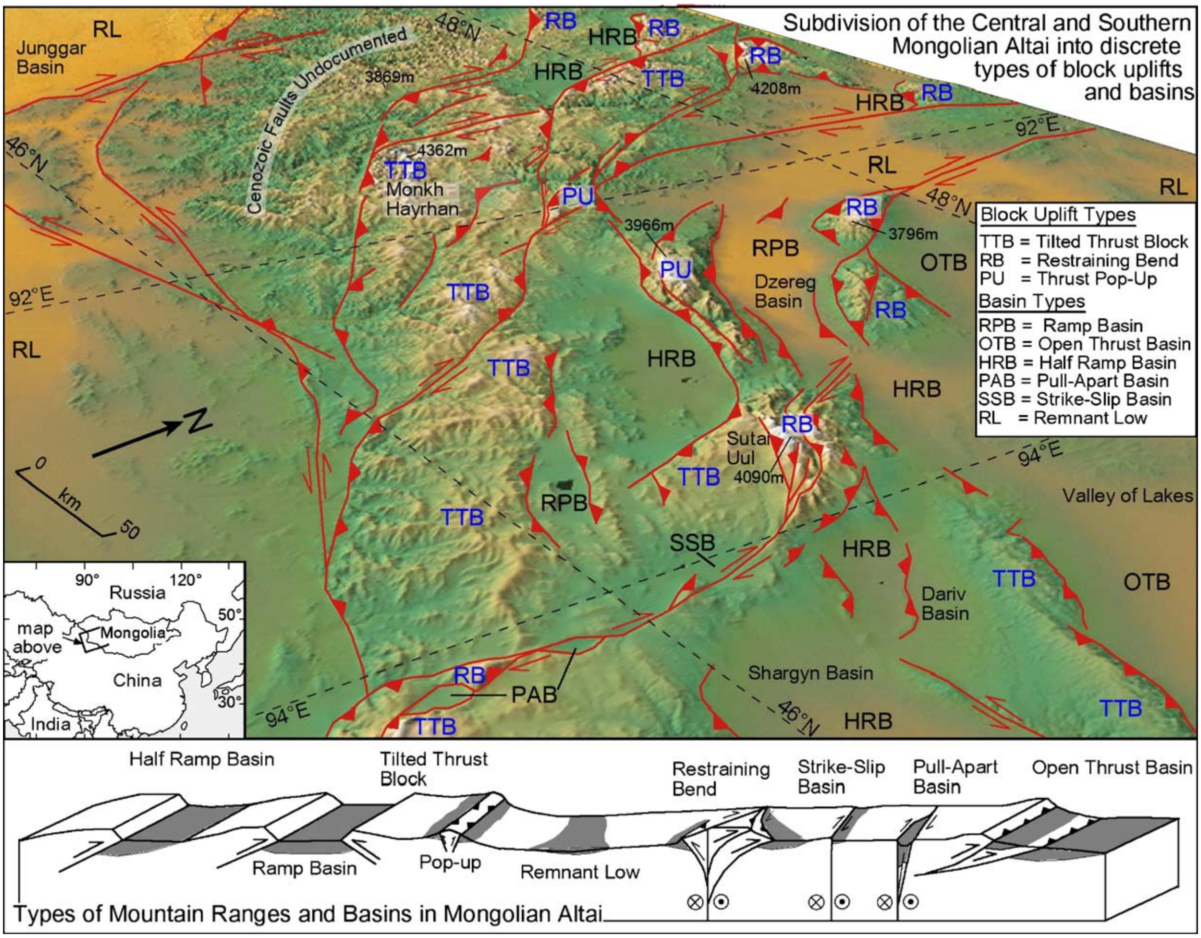

Fig. 2. Oblique DEM perspective of southern and central Mongolian Altai showing major late Cenozoic fault systems. The orogen can be subdivided into distinct mountain and basin types as defined in block model below. Location of image is shown in Fig. 1a.

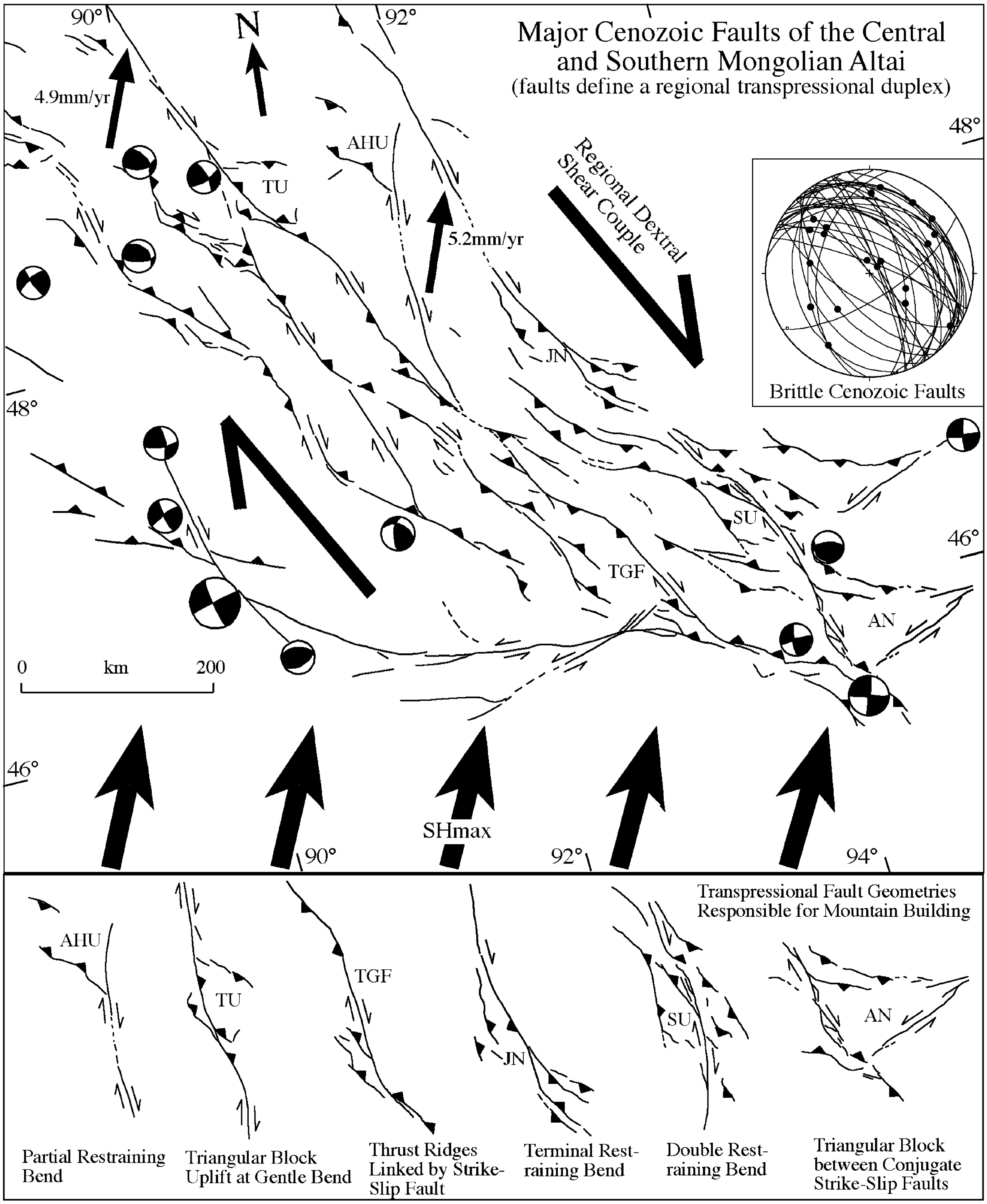

Fig. 3. Map of late Cenozoic fault systems in central and southern Mongolian and Chinese Altai and examples of transpressional fault geometries responsible for mountain building in the region. The central and southern Altai define a regional-scale dextral transpressional duplex. Solid arrows with velocities are GPS vectors relative to a fixed Siberia [14]. Earthquake focal mechanism solutions are taken from [8]. Inset shows equal-area lower hemisphere stereoplot of late Cenozoic faults and slickenlines on fault planes taken from outcrop data along transects reported in Cunningham et al. [6,10,11], and unpublished field data]. Earthquake and outcrop fault data indicate incompletely strain-partitioned oblique–slip deformation occurs within discrete deforming belts throughout the Mongolian Altai. AHU: Altun Huhey Uul; TU: Tsambagarav Uul; TGF: Turgen Gol Fault; JN: Jargalant Nuruu; SU: Sutai Uul; AN: Alag Nuruu.

landscape allow for clear identification of Quaternary fault scarps and older peneplain remnants. The Chinese side of the orogen is wetter, forested, more glacially and fluvially incised, has a more jagged mountainous physiography, and few Quaternary fault scarps have been identified there except at the range front [15]. Most of the highest mountains in the Mongolian Altai have flat summits or flat upland areas that are preserved remnants of older Cretaceous–Palaeocene erosion surfaces [16]. In parts of the Russian Altai, more than one-third of the elevated area consists of peneplain remnants and much of the region is essentially an eroded plateau that is locally faulted [17]. Almost all sediment eroded from the Mongolian Altai today is deposited in internal valleys or small confined marginal basins and not in the large depression to the east called the Valley of Lakes (Figs. 1, 2; [18]). In the southern Chinese Altai and along the south side of the southern Altai, there is also no significant foreland basin. Instead, exposed or shallow basement is found at the topographic mountain front and sediment eroded off of the Altai is deposited in individual fan complexes, or is transported away by river systems, or is removed by aeolian deflation (Fig. 1).

3. Fault systems and orogenic architecture

There has now been sufficient ground-truthing of geological features observed on satellite images to document the regional network of active faults and associated fault kinematics in the central and southern Mongolian Altai (Figs. 1–3). The DEM perspective in Fig. 2 differs from previous compilations because nearly all faults have been ground-checked by the author for confirmation of fault kinematics and connectivity [6,10,11,18,19], D. Cunningham, unpublished field data).

The modern Mongolian Altai does not have a thrust-wedge architecture, but rather is dominated by active NW-striking thrust faults and NNW-striking dextral strike–slip faults. In the central and southern Altai, between four and six major dextral fault systems with linked thrust blocks dominate the cross-strike structure of the range (Figs 1–3). On average, the major strike–slip fault systems are separated by 25 ± 5 km and intervening areas appear tectonically inactive at the surface [10]. Depending on the latitude of observation, these fault systems from SW to NE are the Fu-Yun, Sagsay-Mengildyk, Hoh-Serkh, Ar Hötöl, Turgen Gol, Hovd, Har Us Nuur, and Tonhil strike–slip systems (Fig. 1). The inter-linkage of these faults and associated splays leads to variable thrust directions and inconsistency in structural vergence throughout the range. Individual block uplifts and ranges can be classified as pure thrust ridges, terminal restraining bends, double restraining bends, partial restraining bends, triangular block uplifts along strike–slip faults, and triangular block uplifts between conjugate strike–slip faults (Figs. 1–3). Previous work has revealed that thrust ridges within the Altai are typically simple tilted blocks in cross section, whereas most restraining bends have positive flower structure cross sections which are asymmetric in their fault geometry and topography [6,10,11]. The vertical uplift and lateral coalescence of thrust ridges and flower structures has led to continuous mountainous topography in parts of the central and southern Mongolian Altai [6,10].

Of 21 historical earthquake events in the Altai region greater than $M_w = 5.0$ with reliable focal mechanism solutions, dextral strike–slip, thrust, and dextral-thrust mechanisms predominate [8]. Oblique–slip dextral thrust events with slip plane rakes between 20–70° and 110–160° comprise approximately 40% of the events suggesting incomplete slip partitioning during fault rupture (Fig. 3). Oblique–slip slickenlines on Quaternary fault scarps and late Cenozoic brittle fault surfaces within the Mongolian Altai further suggest incomplete slip partitioning during late Cenozoic transpressional deformation (Fig. 3; [6,10,11]). Thus, although the active fault array (Fig. 3) resembles a regional strike–slip duplex [20], the amount of oblique–slip and thrust–slip displacement associated with the active structures suggests that the system is best described as a “transpressional duplex” intermediate between a regional strike–slip and thrust duplex.

4. Altai basins

Various basin types occur within and along the flanks of the Altai and include (1) half-ramp basins where an active thrust bounds one side of an intramontane basin; (2) ramp basins where outward-directed active thrusts bound opposite sides of an intramontane basin; (3) open-sided small foreland basins where an active thrust bounds one side of the basin and the basin opens into a broad flat area: (4) pull-apart basins; (5) strike–slip basins where small depocentres occur along a regional strike–slip fault; and (6) remnant lows where sediment is accumulating in tectonically inactive low areas which simply have not been uplifted or down-dropped (Fig. 2). All but the remnant lows are dynamic systems that are receiving sediment and deforming at the same time. Some basins are in various stages of destruction and inversion forming low mountains and topographically uplifted areas (e.g., Dzereg Basin, Fig. 2; [21,18,19]). Exposed Oligocene–Recent stratigraphy in upturned belts within eastern flanking basins indicates that Cenozoic rejuvenation of the Mongolian Altai began in the Oligocene and continues today [18]. Fluvial systems in the Mongolian Altai are clearly influenced by recent fault movements; beheaded streams, fluvial offsets, and internally drained and confined basins all suggest immature networks [4,6,18]. In the Chinese Altai, higher rates of precipitation and erosion have led to steeper canyon cutting and dendritic tributary patterns supporting more linear trunk streams that empty directly into the Junggar Basin (Figs. 1, 2).

5. Discussion

Although the Altai has structural and basinal elements similar to continental transform systems undergoing transpressional deformation, such as the San Andreas system in southern and west-central California, it differs in several important aspects. The Altai is a reactivated mechanically weak belt between more rigid basement blocks in a continental interior (Fig 1). The Altai does not transfer plate motions, but terminally accommodates intraplate strain by oblique deformation. The Altai is a diffuse belt of deformation, but no singular strike–slip fault is dominant as is the case with the San Andreas Fault, Alpine Fault or Dead Sea Transform. Dextral transpressional deformation in the Altai is dictated by (1) an intraplate stress field driven by a distant continental collision, (2) the angular relationship between SHmax and the prevailing NW-striking basement structural grain, and (3) the shape of the Hangay basement block which acts as a passive indentor east and northeast of the Altai (Fig. 4; [22,10]).

Documentation of the extent of Cenozoic reactivation of older faults in the Altai region is incomplete, but appears to be a locally important process controlling the evolving architecture, structural vergence and topography of the range. Indeed, there is a first-order correlation between Cenozoic fault trends and Palaeozoic faults, terrane boundaries and the margins of the Hangay and Junggar blocks [7,23,2,3]. The prevailing basement grain throughout the Altai is defined generally by northwest-striking greenschist grade schistosity and phyllite cleavage and many faults appear to follow the metamorphic grain rather than a discrete fault [6,10,11,7]. In the Russian Altai, Delvaux et al. [24] report that segments of a number of major Palaeozoic strike–slip faults were neotectonically reactivated; however, other Cenozoic basin-bounding faults ignore and cut across older faults and basement folds. Likewise, in the Mongolian Altai, brittle thrust reactivation is reported for the Bulgan Fault, which defines the main southern range front, and the Ar Hötöl Fault along the SW front of the Tsambagarav Range (Fig. 1; [6,10]. Howard [18] and Howard et al. [19] argue on geometrical and stratigraphic grounds that Quaternary thrust faults in the Dzereg and Dariv Basins on the eastern edge of the Altai are reactivated Mesozoic normal faults (Fig. 2). However, all major ranges in the central and southern Mongolian Altai are cored by Palaeozoic

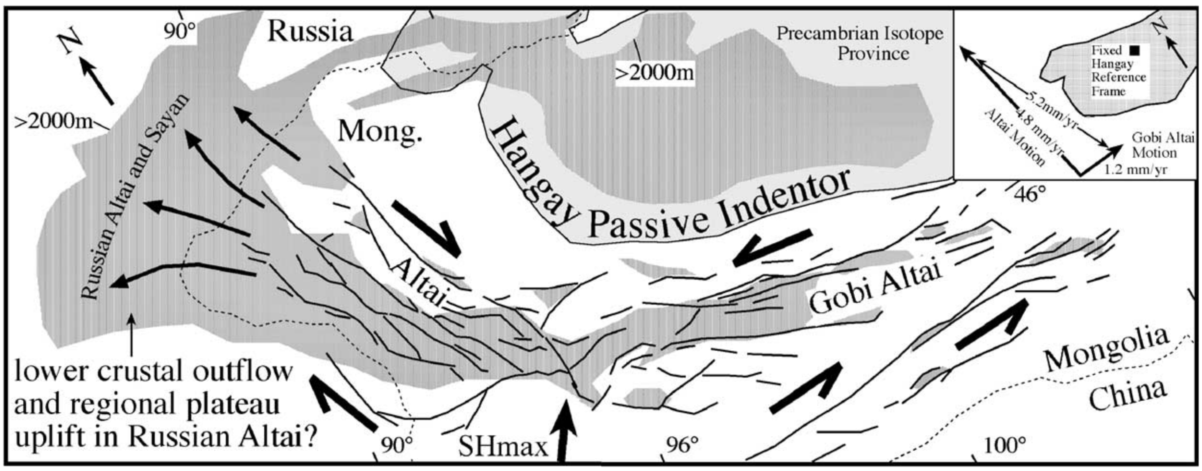

Fig. 4. Simplified model of active transpressional deformation in the Altai and Gobi Altai regions as a function of NE-directed SHmax impinging on the rigid curved boundary of the Hangay Precambrian block which acts as a passive indentor focussing dextral transpressional deformation in the Altai and sinistral transpressional deformation in the Gobi Altai. Possible northward outflow of lower crustal material from the Mongolian and Chinese Altai may explain late Cenozoic broad plateau uplift in the Russian Altai/Sayan region. See [40] for summary of isotopic data for Hangay block which suggests it is cored by rheologically strong Precambrian crust. Inset map shows relative motions for the Altai and Gobi Altai regions in a fixed northern Hangay reference frame using GPS data from the HOVD, KHAR and IKUL survey sites in [14].

basement rocks (often with preserved peneplained erosion surfaces) and significant reactivation of older rift-related normal faults is therefore unlikely because rift hanging-wall sedimentary strata are nowhere found at significantly elevated positions (i.e., >2700 m).

The manner in which the upper crustal transpressional deformation is balanced in the lower crust is unknown. No seismic anisotropy data exist for the Altai. However, in the neighbouring eastern Tien Shan and Gobi Altai, the parallelism of surface faulting and anisotropy data suggest that upper crustal deformation is coupled to upper mantle deformation [25–27]. Models of major intracontinental wrench belts that root into steep zones which penetrate the entire lithosphere are increasingly supported by geodetic, seismic and anisotropy data [28,29]. Active dextral transpression in the Altai best fits a bottom-driven block deformation model whereby discretely spaced fault systems are coupled to a continuously deforming substrate that is more NNE flowing (based on GPS and regional stress data; Fig. 3) relative to the NW-striking structural grain at the surface. Shortening beneath upper crustal flower structures and other oblique–slip fault systems requires non-plane strain solutions and is likely to be accommodated by vertical ductile thickening and orogen-parallel ductile flow. Vertical crustal thickening by lower crustal inflation may explain some of the elevated topography within the range where surface faulting is absent. This mechanism has been proposed for eastern Tibet and the Yunnan region and probably applies to the Altai region [30,31]. Northward outflow of lower crustal material from the Mongolian Altai region leading to lower crustal inflation in the Russian Altai is an appealing mechanism because it could explain late Cenozoic epeirogeny there which is suggested by regionally elevated plateaux and deep fluvial and glacial incision (Fig. 4; [17]).

The significant width of active transpressional deformation in the Altai (>250 km) may be fundamentally controlled by the width of mechanically weak Palaeozoic basement between the Hangay and Junggar blocks. However, another consideration is that because of low erosion rates in the region, mountains form faster than they are eroded as evidenced by the widespread preservation of elevated older peneplains. The simple conclusion is that it is less work against gravity and, thus, easier for the orogen to progressively widen than to force mountains higher. In addition, vertical axis rotations are expected in an orogen cut by regional-scale strike–slip faults [32] and anti-clockwise rotations up to 30° are documented in the southern Russian Altai [33]. They are also suggested by the regional anti-clockwise curvature of the southernmost Altai (Fig. 2) and local rotations adjacent to major fault systems are observed in the southern part of the range, for example, in Sutai Uul (Fig. 2; [11]). Although more evidence is needed to document block rotations in the rest of the Altai, if strike–slip faults rotate to an orientation more orthogonal to SHmax (more northwesterly), they are likely to turn off or change their slip vector and thrusting displacements will progressively predominate [11]. The implication is that with time, the Altai may have evolved an increasingly important shortening component of deformation and decreasingly important strike–slip component. This may have led to the widening of the orogen, coalescence of flower structures and ramp basin burial beneath thrust sheets.

The total amount of late Cenozoic NE–SW shortening in the central and southern Mongolian Altai is variable along strike (the range widens to the north) and is not well constrained because of the amount of NW–SE strike–slip displacement, lack of regionally extensive cover strata that could be used to balance cross sections, and lack of seismic data to document fault dips at depth. However, summit elevations of the regionally developed Late Cretaceous–Palaeocene peneplain help constrain the amount of late Cenozoic vertical topographic uplift for individual ranges. Thrust displacements for individual ranges are generally believed to be less than 5 km based on conservative downdip projections of range-bounding thrust faults, and total NE–SW shortening across the central and southern Mongolian Altai is estimated to be on the order of 20–30 km [10].

By converting published GPS data for Mongolia [14] to a fixed northern Hangay reference frame instead of a fixed Eurasia reference frame, crustal displacements for the central Mongolian Altai resolve to approximately 4.8 mm/yr towards 354°. Displacements in the Gobi Altai are approximately 1.2 mm/yr towards 091° (Fig. 4). These numbers must be regarded as very approximate for the Altai and Gobi Altai regions because several major east–west faults compartmentalise the Hangay and north Gobi Altai region into domains with different rates of eastward displacement (see discussion in [14]). Nevertheless, roughly speaking, the GPS data confirm that the Altai region is moving northward and the Gobi Altai region is moving eastward relative to the Hangay region. Displacement between the central Altai region and eastern Gobi Altai region in a fixed northern Hangay reference frame is approximately 5.2 mm/yr of NW–SE divergence at 340° (Fig. 4). This displacement must be accommodated by strike–slip faulting and block rotations in the southeastern Altai and western Gobi Altai (Cenozoic normal faults have not been found in these regions), but existing geodetic and fault slip data are insufficient to quantify the proportion of either mechanism.

Intracontinental, intraplate transpressional orogens like the Altai occur around the perimeter of the Indo-Eurasia deformation field and along the E and SE margins of Tibet [Fig. 1b; [9]. Active thrusting, oblique–slip deformation, and strike–slip faulting are indicated by the historical earthquake record and by structural field data in the Hindu Kush [34], western Tien Shan [35], Gobi Altai [5,36], Sayan [37], and Stanovoy Belt [38]. All of these regions consist of rheologically weak reactivated Phanerozoic accretionary belts that are sandwiched between more rigid basement blocks (Fig. 1). The principal driving force for orogenesis is India's continued NNE-directed indentation [4,9]. Late Cenozoic development of these perimeter belts is fundamentally controlled by the orientation of craton boundaries, prevailing structural grain, inherited fault architecture, orientation and progressive changes in direction of SHmax, fault kinematics and slip rates, and climate and erosion rates. Such regions are natural laboratories for studying the complex linkage of strike–slip, oblique–slip and thrust faults, extent of regional strain partitioning, and overall processes of oblique (transpressional) mountain building in a continental interior setting. Similar oblique deformation belts are likely to have formed around the edges of ancient intracontinental deformation fields associated with distant continental collisions. For example, late Palaeozoic continental interior deformation in central and western North America including development of the Ancestral Rocky Mountains in the western US was probably driven in large part by the Alleghanian–Ouachita collision [39]. It is likely that more ancient Palaeozoic and Precambrian continental collisions also produced oblique deformation belts in rheologically weak regions within or around the perimeter of the deformation field of the indented continent. However, because intracontinental oblique deformation belts generally contain lower mountains, shallower clastic basins, and very little magmatism or metamorphism compared to frontal collision belts, their geological expression is less likely to be preserved in the rock record.

Acknowledgements

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