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Earth and Planetary Science Letters 173 (1999) 183–194

EPSL

www.elsevier.com/locate/epsl

Left-lateral sense offset of Upper Proterozoic to Paleozoic features across the Gobi Onon, Tost, and Zuunbayan faults in southern Mongolia and implications for other central Asian faults

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Received 15 April 1999; revised version received 14 September 1999; accepted 15 September 1999

Abstract

We present a preliminary study of Upper Proterozoic to Paleozoic features adjacent to, and offset across, three faults in southern Mongolia. Restoration of four offset stratigraphic units adjacent to the Gobi Onon fault indicates a left-lateral sense offset of 70–95 km. The Tost fault has a left-lateral sense offset of 95–125 km defined by three offset features. The Zuunbayan fault has seven offset features that display left-lateral sense offsets of 185–235 km. Deformation on these faults apparently occurred during the Mesozoic prior to the Late Cretaceous based upon the age of offset features, the age of overlap sequences, and inferred timing relationships with regional contractional structures. Although Cenozoic overprinting and reactivation has occurred along parts of these faults, thus complicating their restorations, we present a testable hypothesis which predicts possible connections between these faults and faults within China.

Keywords: left-lateral faults; Mongolia; Mesozoic; deformation

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1. Introduction

Major strike-slip faults, including the Altun Tagh and Ruoqiang faults in China and the Gobi Tien Shan and Gobi Altai faults in Mongolia, are prominent features of central Asia [1–6] (Fig. 1a). Many of these faults are demonstrably active and easily recognizable on satellite images, geologic maps, and in the field. Although progress has been made in understanding the current character and recent history of some of these faults [5,7], their pre-Pleistocene histories generally remain unconstrained. Several important aspects of the history of these faults are unknown: What is the history of timing of movement? Has the sense of movement changed through time? What is the magnitude of total slip? To what tectonic events are their origins and slip histories related?

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0012-821X/99/$ – see front matter
PII: S0012-821X(99)00227-7

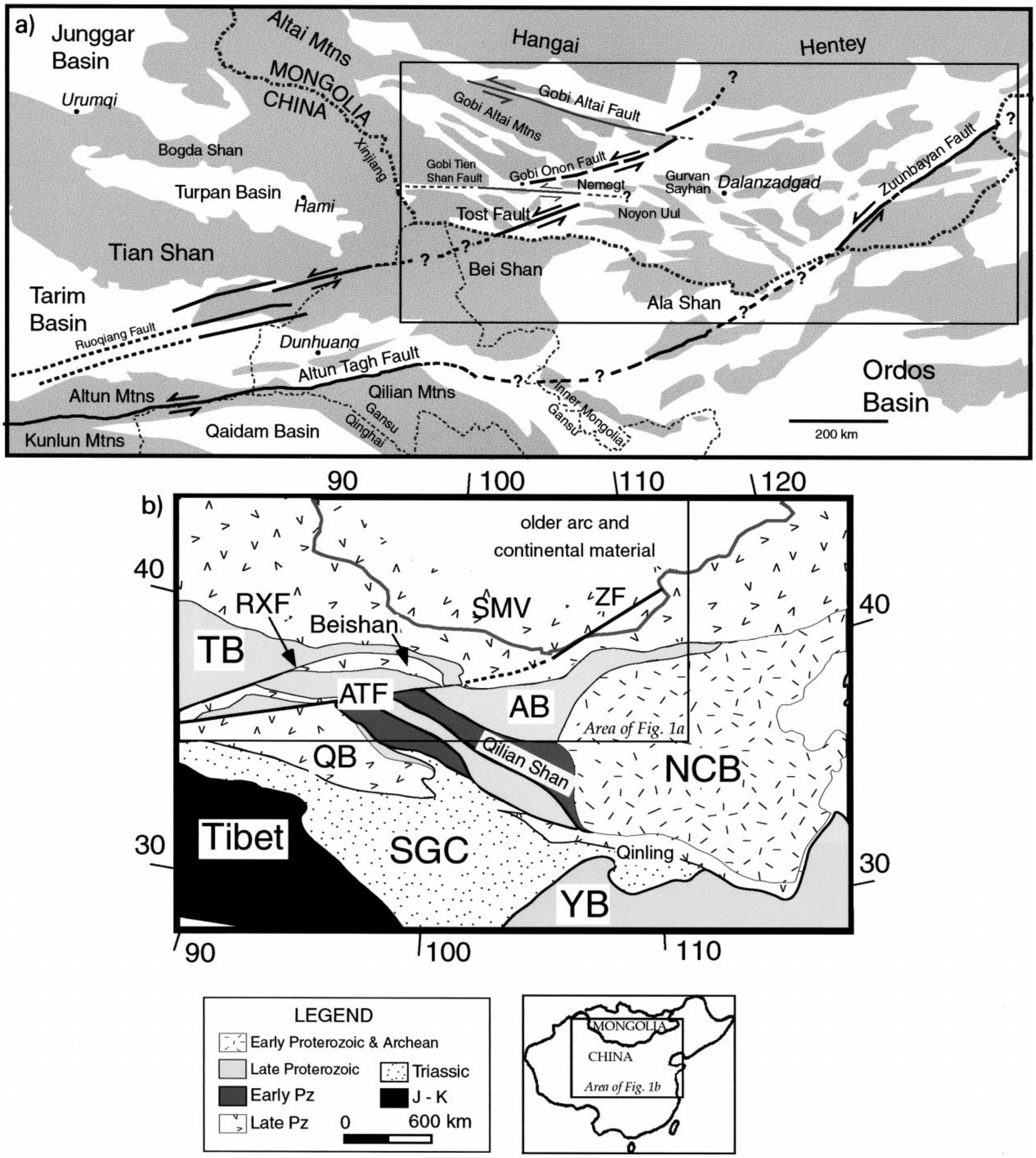


Fig. 1. (a) Map of central Asia, including southern Mongolia and portions of Inner Mongolia, Gansu, Qinghai and Xinjiang provinces of China. Shaded areas denote mountainous regions; white areas denote modern basins. Partially based on Yanshin [26], GBGMR [40], XBGMR [38], and NMBGMR [33]. Note that many place names have more than one commonly used English spelling, e.g. Tien vs. Tian and Altun vs. Altyn. We have used the spelling that is used by the government of the country in which the feature is located. (b) Major blocks and terranes of central Asia, after Zhou and Graham [15]. *AB* = Alashan block; *ATF* = Altun Tagh fault; *NCB* = North China block; *QB* = Qaidam basin; *RXF* = Ruoqiang Xingxingxia fault system; *SGC* = Songpan–Ganzi complex; *SMV* = southern Mongolia Paleozoic volcanic arcs; *TB* = Tarim basin; *YB* = Yangtze (South China) block; *ZF* = Zuunbayan fault.

These faults play major roles in many tectonic reconstructions of Asia [1,2,8–13]. Therefore, answers to these questions are critical to a complete understanding of the tectonic development of central Asia and figure prominently in consideration of intracontinental deformation and escape tectonics [11,14]. These large intracontinental strike-slip faults occur in regions along or near sutures between major Paleozoic terranes of central Asia, such as the North China block, Tarim block, Qaidam terrane, and the southern Mongolian Paleozoic volcanic arcs (Fig. 1b). The amalgamation of the terranes and the location of their margins most likely contributed to the development and localization of the faults, but the exact cause and effect relationships between amalgamation and faulting are unknown. Although previous studies have contributed greatly to our understanding of the geologic history of the individual terranes, the nature and timing of their amalgamation remains controversial (e.g. Zhou and Graham [15]). As a result, much work is currently focused on understanding the strike-slip faults of this region [16–21].

Many studies specifically focus on the Altun Tagh fault within China, in part because it has been more accessible than the faults of southern Mongolia. Few studies address the relationship of faults across the China–Mongolia border, and yet such relations are crucial to understanding the Phanerozoic history of Asia. Previous studies that have addressed structural relations across the international boundary were typically restricted by access issues that were in place until recently, and thus, few authors have conducted fieldwork in both countries.

In this paper, we identify numerous geologic features of Late Proterozoic–Paleozoic age that we infer to have been offset across three poorly known faults in southern Mongolia: the Gobi Onon, Tost, and Zuunbayan faults (Figs. 2 and 3), and discuss constraints on the timing of deformation. Although these faults have been previously recognized, this is the first attempt to constrain their sense of offset, timing and amount of offset using field data from southern Mongolia. Building on these data, we present a plausible and internally consistent, albeit preliminary, model of how these faults relate to the more widely known faults in China.

2. Methods

Our identified offset markers are based on data collected as part of two separate basin analysis studies, one in southern Mongolia (ML, GB, SG, LW) and one in southern Tarim, northern Qaidam, and the Altun Mountains (AH, SG, GB). Both studies included documenting sedimentologic and stratigraphic features, interpreting depositional environments, field-checking existing geologic maps, observing structural relations between units, and collecting and analyzing samples. Analyses included point-counting of sandstones for provenance, XRD and XRF analyses of igneous samples for geochemical study and tectonic indicators, ^{40}Ar/^{39}Ar dating in poorly dated sequences, and fossil identification for age determination and paleogeographic/climatic indicators. In sum, we use these original data to define distinctive petrotectonic features which have been offset by strike-slip faulting. We also discuss possible offset markers that we have identified from geologic maps, from other available data, and from previous workers.

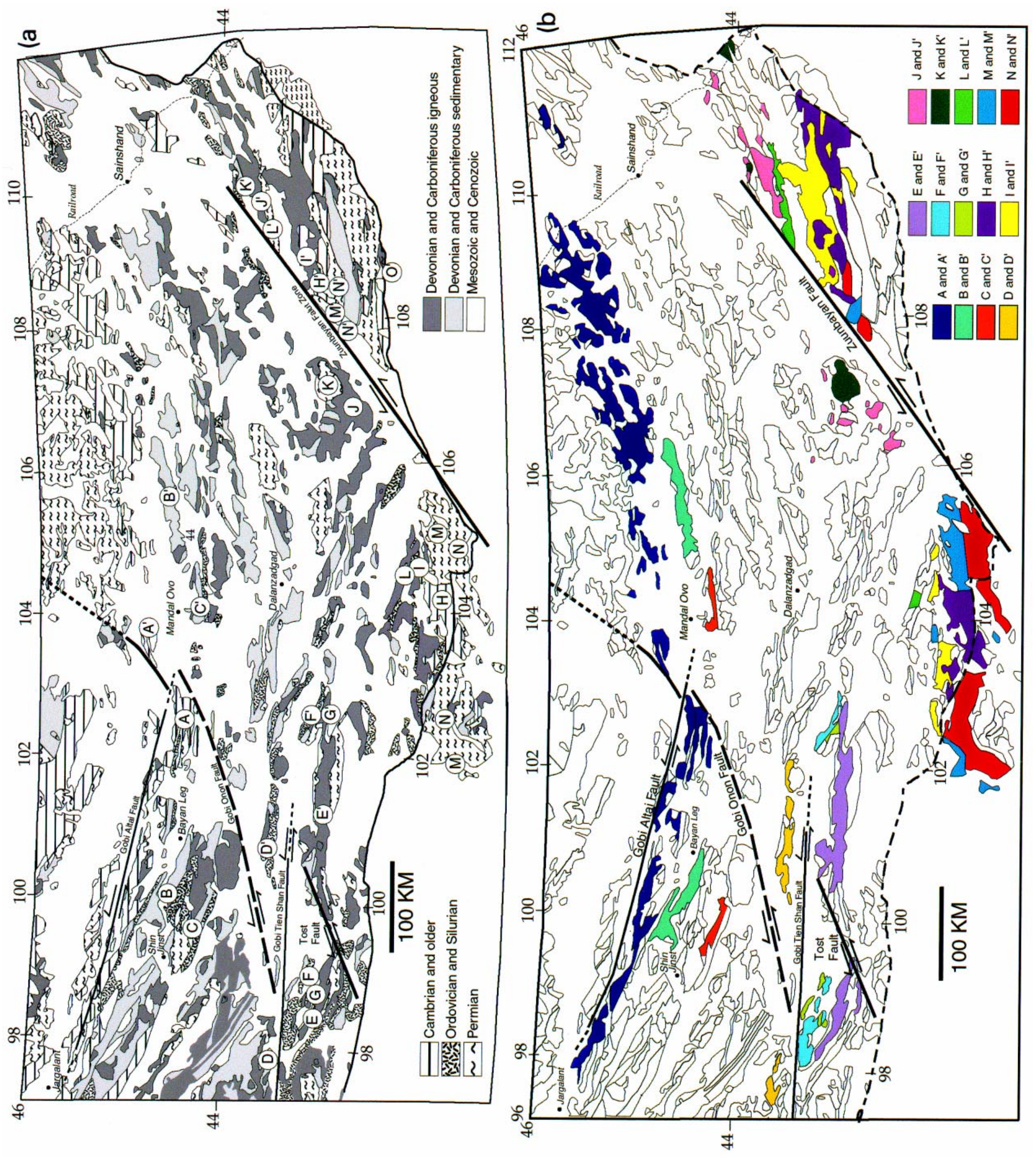
To simplify the use of long and unfamiliar names, offset markers are assigned letters, as shown in Figs. 2 and 3. Although none of our offset features are definitive piercing points in the sense of Crowell [22], they probably formed as continuous belts during the Paleozoic, and we believe can be treated as piercing points, because of their distinctive petrotectonic characteristics and the consistent amount of offsets that they record.

3. Offset geologic features

3.1. Gobi Onon fault

The Gobi Onon fault has been recognized as a fault by previous workers [23–26] and mapped as a left-lateral fault by Suvorov [24,25]. Suvorov [24,25] offered no estimates of the amount of displacement.

We recognize four offset markers on either side of this fault. Additionally, we suggest that the Gobi Onon fault has been offset by approximately 10 km of younger left-lateral slip on the Gobi Altai fault (Fig. 2). Our first offset marker, A/A″, is an east–west trending belt of Vendian–Cambrian limestone,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(b
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Shin Jinst
Bayan Leg
Mandal Ovo
Dalanzadgad
Sainshand
Railroad
Gobi Altai Fault
Gobi Onon Fault
Gobi Tien Shan Fault
Tost Fault
Zuunbayan Fault Zone
Zuunbayan Fault
100 KM
Cambrian and older
Ordovician and Silurian
Permian
Devonian and Carboniferous igneous
Devonian and Carboniferous sedimentary
Mesozoic and Cenozoic
A and A'
B and B'
C and C'
D and D'
E and E'
F and F'
G and G'
H and H'
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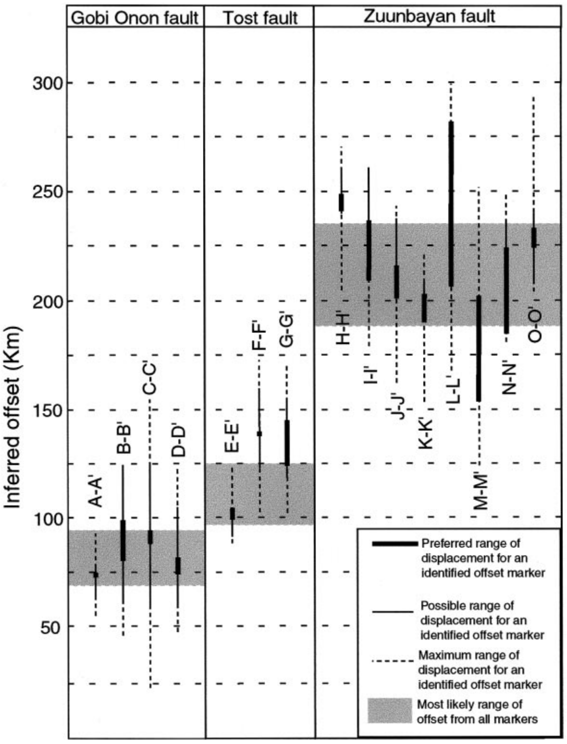

Fig. 3. Estimated amount of left-lateral offset for each geologic feature discussed in the text. Shaded area denotes our preferred range of the amount of displacement for each fault.

marble, and minor quartzites [26], the southern front of which best evinces the magnitude of offset.

Offset marker B/B″ consists of two similar east–west trending belts of slightly metamorphosed sequences of argillite and sandstone of presumed Middle to Late Devonian age. On the western side of the fault this belt includes deposits at Narin Sahir Mountain (B), and on the eastern side the Erdene Bayan Hural Formation (B″, Fig. 2a [27,28]).

Offset marker C/C′ consists of two similar Ordovician to Lower Carboniferous stratigraphic sequences (including deposits near the towns of Shin Jinst and Mandal Ovo described more fully in Lamb and Badarch [28]) which are intruded by granites that yield similar Triassic ages (our unpublished ^{40}Ar/^{39}Ar dates from potassium feldspars).

Offset marker D/D″ is a belt of Silurian and Devonian metasedimentary rocks, metavolcanics, ultramafic rocks, chert, and pillow lavas interbedded with volcaniclastic sandstones, and Lower Carboniferous interbedded siltstones, sandstones and debris-flow conglomerates. Small gabbroic bodies of uncertain age, possibly Silurian to Carboniferous, occur as structural inclusions within the Carboniferous section on both sides of the fault as well. On the western side of the fault, this belt includes deposits at Nomin Gobi (D) and on the eastern side, Nemegt, Zolen and Gurvan Sayhan ranges (D″, Figs. 1 and 2 [28,29]).

A restoration of 70–95 km of left-lateral separation along the Gobi Onon fault (Fig. 3) returns these markers to probable end-Paleozoic, pre-offset positions.

3.2. Tost fault

The Tost fault has been recognized by previous workers [23,26,30]. We recognize three markers offset by the Tost fault in a left-lateral sense (Fig. 2).

The first, E/E″, is an east–west trending belt of Carboniferous to Lower Permian arc-related volcanics, including andesite, dacite, rhyolite, and alkaline volcanics [26,28,31,32], that occur near Tsagan Uul (E) in the west and Noyon Uul and Tost Uul (E″) in the east (Figs. 1 and 2). The second, F/F″, consists of Silurian to Lower Devonian (?), mildly metamorphosed sandstones, siltstones, radiolarian chert and thin pillow lavas within Ih Havtsgai Nuru (F) to the west and Deng Nuru (F″) to the east (Fig. 2). A third marker, G/G″, consists of Carboniferous shallow-marine sandstones and conglomerates that unconformably overlie the marker beds of F/F″, and crop out west of the fault at Ih Havtsgai Nuru and Hutsyn Shand and east of the fault in the southern Deng Nuru [28]. Markers F′ and G′ crop out rather far away from the fault to the east, but combine with E′ to form a reasonable offset triad.

Fig. 2. (a) Simplified geologic map of southern Mongolia and the Ala Shan region of Inner Mongolia, China, emphasizing left-lateral faults discussed in text; after Yanshin [26] and NMBGMR [33]. Circled letters correspond to offset features discussed in text. (b) Upper Proterozoic and Paleozoic tectonostratigraphic features of southern Mongolia and the Alashan region of Inner Mongolia, China, offset along strike-slip faults discussed in this paper.

A restoration of 95–125 km of left-lateral separation along the Tost fault (Fig. 3) restores these markers as a contiguous Carboniferous to Lower Permian arc and its underpinning.

3.3. Zuunbayan fault

The Zuunbayan fault has been recognized by previous workers (e.g. Suvorov [24] and Yanshin [26]). Suvorov [24], without pointing to any specific features, speculated 100–150 km of offset on the Zuunbayan fault. Additionally, Suvorov [24], estimated 1–2 km of normal sense offset, with a component of left-lateral offset, to account for separation of Permian sediments and suggested that motion occurred in early Mesozoic time.

Mylonitic rocks related to the Zuunbayan fault zone were documented at Tavan Har by two of us (LW and GB; latitude: N43°58″16.5″; longitude: E109°32″07.3″). A sequence of basaltic and volcaniclastic rocks were deformed under greenschist facies conditions. Foliations dip subvertically or steeply to the north, and stretching lineations plunge moderately to the west (Fig. 4a). Sinistral shear sense is indicated by both mesoscopic and microscopic kinematic indicators such as σ and δ clasts, as well as S–C fabrics. We dated synkinematic biotite from the shear zone by the ^{40}Ar/^{39}Ar method and obtained a weighted mean age of 209 ± 2 Ma, the same within error of both the total fusion and inverse isochron ages for the sample (Fig. 4b). We interpret this age to define the timing of mylonitization.

We have identified a number of markers that support left-lateral offset. The oldest marker, H/H″, consists of a belt of Upper Proterozoic marbles, quartzites, and metasediments. The next marker, I/I″, is a belt of Devonian arc-related andesitic and dacitic volcanics, volcaniclastic sandstones, and deep-water sandstones and mudstones. To the north of these deposits are Carboniferous sub-alkaline granites, J/J″, and Permian alkaline granites, K/K″, including the Han Bogd pluton (K, Fig. 2).

Three Permian formations appear to be correlative. On the east side of the fault, the Lower Permian Bairam Ovo Formation (L′) consists of sandstone, siltstone and fusulinid-bearing carbonates which may correlate with similar but unnamed fusulinid-bearing strata (L) in Baga Uul and Ih Uul on the west side of the fault in Mongolia, as well as the Lower Permian Shuangbaotang Formation in Inner Mongolia [33]. The Lower Permian Jushitan Formation in Inner Mongolia and Bulgan Formation in southern Mongolia (M), both on the west side of the Zuunbayan fault, contain clastic and volcanic strata, and may correlate with unnamed and poorly dated volcanic and clastic rocks [34] on the east side of the fault (M′). The best constrained Permian offset feature may be the Upper Permian, turbidite-dominated Lugin Gol Formation, N/N′, found on either side of the fault in Mongolia [35,36]. This may

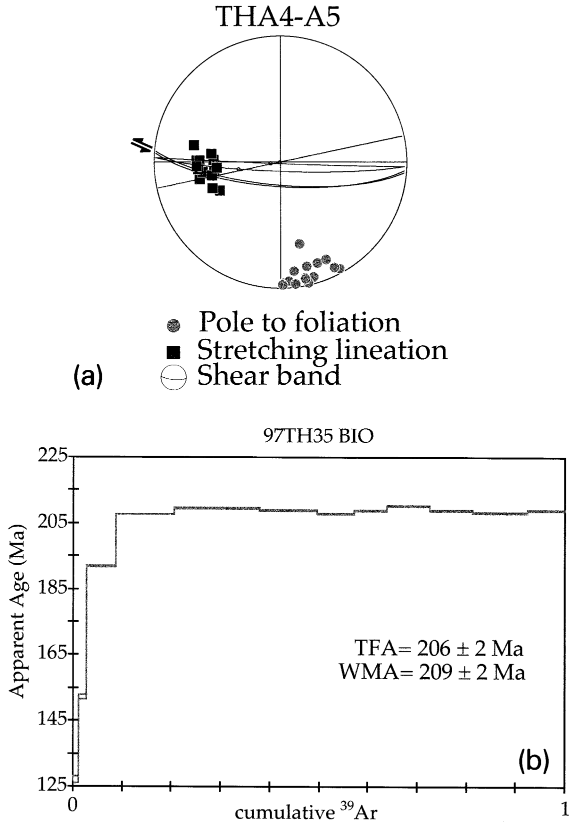

Fig. 4. (a) Typical structural data from mylonitic rocks related to the Zuunbayan fault zone represented in a lower-hemisphere, equal-angle stereonet projection. Data represent shear band orientations, and foliation and lineation measured in greenschist facies metavolcanic rocks. Sense of shear was universally left-lateral, oblique dip-slip. (b) ^{40}Ar/^{39}Ar apparent age spectra for biotite sample from mylonite related to the Zuunbayan fault zone. Release spectra show 1 sigma uncertainties without error in J. *TFA* = total fusion age; *WMA* = weighted mean age.

also correlate with the Upper Permian Fangshankou Formation of Inner Mongolia [33].

Some facies in this region lack obvious cross-fault correlative strata, perhaps reflecting Mesozoic thrusting in the Bei Shan [37], facies changes, or limited mapping. Nevertheless, we believe that our offset features are compelling and strongly suggest left-lateral offset with an estimated displacement of 185–235 km (Fig. 3). A younger extensional event, discussed below, in the vicinity of the Zuunbayan fault may have also contributed to displacement of these features.

4. Implications for faulting outside southern Mongolia

The fault offsets described above are derived mainly from features within southern Mongolia, where they are best constrained. Next, we use the offset amounts we established for the Gobi Onon, Tost, and Zuunbayan faults to address offset amounts to the southwest in China. We do not, however, address the northern extensions of the Gobi Onon and Zuunbayan faults, as these lie outside of our collective areas of direct observation.

4.1. Gobi Onon fault

We speculate on three alternative possibilities for the southern extension of the Gobi Onon fault. In the first scenario, the Gobi Onon fault continues southwestward into the Xinjiang Province of China where, via a system of splays, it may account for the mapped bend in the eastern end of the Chinese Bogda Shan [38]. A second possibility is that the Gobi Onon fault terminates (Fig. 2) and deformation is transferred via a left-step to the Tost fault, linking the Gobi Onon–Tost faults via an en-echelon step-over. The slight difference in offset amounts between the Gobi Onon and Tost faults may reflect decreasing strain further from the origin of deformation. Linkage of the Gobi Onon and Tost faults requires extension in the area that links the two faults: an area filled by post-Jurassic basin fill and occupied by the Gobi Tien Shan fault. The final possibility is that the Gobi Onon and Tost faults were originally one fault that has been subsequently offset by documented Cenozoic deformation on the Gobi Tien Shan fault [5]. Note that we place the eastern end of the Gobi Tien Shan fault south of Nemegt but north of Noyon Uul, as depicted by Yanshin [26] and Kovalenko et al. [39] (Figs. 1 and 2). It is also possible that the fault system runs through the Nemegt range, as depicted by Cunningham et al. [5]. Our satellite image analysis is not sufficient to resolve this question; additional fieldwork in this area is needed.

4.2. Tost fault–Ruoqiang fault

Projection of our predicted offset on the Tost fault south into China is somewhat problematic because of limited studies and exposure in the Bei Shan (Fig. 1). No mapped faults [33,40] link directly to the Tost fault. However, distinct lineaments on Landsat images [41–43] may be the southwestward extensions of the Tost fault through the Bei Shan. Strike-slip deformation on the Tost fault potentially was transferred to the Ruoqiang fault or associated en-echelon splays (Fig. 1a; also referred to as the Ruoquiang–Xingxingxia fault system). If the Tost fault extends into China, and if it was primarily active during the Mesozoic as we argue below, then timing on the Ruoquiang fault must be considered. Although Cenozoic strike-slip activity has been documented on the Altun Tagh, also discussed below, previous work suggests that Mesozoic activity in the Ruoquiang–Altun Tagh region is possible; sedimentary facies and paleocurrent analyses of Ritts and Biffi [44] suggest Mesozoic tectonic activity along the current trend of the Altun Tagh fault in Tarim, and Sobel [45] suggested strike-slip activity within the Altun Tagh–Ruoqiang corridor related to Mesozoic tectonic events south of Tarim. Alternatively, strike-slip deformation on the southern end of the Tost fault was accommodated by shortening related to Mesozoic contractile deformation within and adjacent to the Tian Shan (Fig. 1a). Although Cenozoic overprinting has obscured some features, Mesozoic contractile structures have been imaged and documented in the Tian Shan and Junggar, Tarim and Turpan basins [46].

At its northern terminus, deformation (1) could have been transferred to the Gobi Onon fault, as mentioned above, (2) been accommodated by deformation and faulting within Tost Uul and Noyon Uul [46], or perhaps most speculatively, (3) been accommodated by transfer into thrust faults within the Zolen and Gurvan Sayan ranges. This last scenario, however, would require extending the Tost fault further to the northeast than we have currently drawn it.

Northward vergent thrusting in the Bei Shan (Fig. 1a) [37] may have been bound on the northwest by the Ruoqiang fault. If this assumption is correct, and if the displacement on the Tost fault also occurred on the Ruoqiang fault, then total offset on the Ruoqiang fault would be at least 200–300 km: 95–125 km assigned to the Tost fault plus the 120–180 km in the Bei Shan (as will be discussed below). One test of this inference would be to measure the amount of offset between the southern pinchout of the Silurian in the subsurface of Tarim north of the Ruoqiang fault (AH, unpublished interpretation of proprietary seismic data) and the Silurian pinchout mapped in the southern Bei Shan [33].

4.3. Zuunbayan fault–Altun Tagh fault

We believe that the Zuunbayan fault may link with the Altun Tagh fault as shown in Fig. 1. This connection was also postulated by Yue [17,47], although his estimated displacement of 400 km is double our estimate of 185–235 km and is based on work done in China only, not work done on both sides of the border. Although this linkage results in a significant bend in the fault, a palinspastic restoration of the northwest–southeast oriented late Mesozoic extension in southern Mongolia [48] would decrease the apparent bend in the fault.

Cenozoic displacement on the Altun Tagh fault to the west of the Qilian Mountains is clearly apparent [1,2,49], and is currently being transferred to range-bounding thrust faults on the northeast side of the Qilian Shan [21]. As we will discuss below, data for the Zuunbayan fault, however, favor Mesozoic activity. A connection between the two faults would, therefore, suggest that the Altun Tagh may have experienced two episodes of faulting.

Ritts [50] documented post-Middle Jurassic displacement on the Altun Tagh fault southwest of the Qilian Mountains of 400 ± 60 km. It is conceivable that half of this displacement was coeval with movement on the Zuunbayan fault and that the remaining half has been accommodated in the Cenozoic by thrusting within the Qilian Shan.

5. Slip history

The youngest of our Paleozoic markers are Lower Permian deposits offset across the Tost fault and Upper Permian strata offset across the Zuunbayan fault, which constrain the maximum age of displacement to Late Permian and Early Triassic. Two contrasting Mesozoic tectonic regimes may account for the strike-slip offsets we have documented. The first of these is regionally extensive contractile deformation, manifested as thrusting in western China, Inner Mongolia and southern Mongolia, associated with the tectonic accretion of several Asian terranes during the first half of the Mesozoic [8,13,46,51–53]. In this view, the strike-slip faults would represent either transfer structures or escape structures analogous to those associated with the Cenozoic Himalayan collisional orogeny [1,3,54].

If strike-slip was related to regional compression, deformational events recorded in strata adjacent to the strike-slip faults may provide detailed constraints on timing. For example, a major foreland syncline and its overlap sequence east of the Tost fault, near Noyon Uul (Fig. 1a), indicate Middle to Late Jurassic deformation, with a second, apparently less intense, period of deformation during late-Early Cretaceous to early-Late Cretaceous [46]. To the south, in the Beishan, north-verging thrust faults with displacements of 120–180 km have been recognized and dated as late-Middle Jurassic [37]. In Tarim basin, Li et al. [53] presented reflection seismic evidence of Upper Jurassic strata that overlap deformed Lower and Middle Triassic strata along the Ruoqiang fault (Fig. 1a). The ^{40}Ar/^{39}Ar age of 209 ± 2 Ma from mylonite adjacent to the Zuunbayan fault falls within this timeframe of Late Triassic to Late Jurassic contractile deformation.

The second Mesozoic tectonic regime consists of widespread extension across southern and eastern Mongolia during the Late Jurassic–Early Cretaceous [55–57] followed by a late-Early Cretaceous post-extensional transpressional inversion recorded on reflection seismic transects of strata just south of Sainshand (unpublished observations of S. Graham). If related to this second period of Mesozoic deformation, the strike-slip faults may reflect partitioning of transtensional strain or be related to the second phase of contractile deformation which produced the inversion.

Sinistral shear sense indicators have been observed in Paleozoic (?) mylonitized rocks found adjacent to the Zuunbayan fault. No evidence of brittle deformation was observed in nearby outcropping Upper Cretaceous or Cenozoic strata, and reflection seismic profiles image faults nearby and parallel to the Zuunbayan fault which cut Lower Cretaceous strata but are overlapped by Upper Cretaceous strata (unpublished observations of S. Graham). Both observations support a pre-Late Cretaceous timing of faulting for the Zuunbayan fault.

Recent work has documented Quaternary activity on additional nearby faults, such as the Gobi Tien Shan and Gobi Altai faults [2,4,5]. It is possible that the three faults discussed in this paper also have been reactivated during the Cenozoic. However, currently available data suggest that the majority of activity occurred during the Triassic to Jurassic or Early Cretaceous. Of the two Mesozoic regimes with which strike-slip may have been coupled, we tentatively prefer an association with early Mesozoic regional compression because of the magnitude of accretionary events and demonstrated magnitude of shortening on thrust nappes in the Beishan [37], as well as our preliminary age data for a sinistral-sense mylonitic fabric near the Zuunbayan fault (Fig. 4).

Our preferred Mesozoic age of offset for these faults concurs with that of Suvorov [24] and Vincent and Allen [58]. Suvorov [24] presents three structural maps of Mongolia through time. The map of Triassic–Early Cretaceous faults (his fig. 2 [24]) includes the Gobi Onon, Zuunbayan and Tost faults and they are shown as major faults. The map of Late Cretaceous–Neogene faults (his fig. 3 [24]) depicts only the Gobi Onon and Zuunbayan faults. His final map, that of Neogene–Quaternary faults (his fig. 4 [24]), depicts only portions of the three faults and these sections are shown as minor faults. Suvorov [24], therefore, indicates a Mesozoic age of activity with possible Cenozoic offsets on some segments of each fault. Vincent and Allen [58] present field data from the Alashan region of China and conclude that Mesozoic basins formed in this region due to strike-slip activity.

We also point out that our conclusion of Mesozoic offset on the Zuunbayan fault differs from that of Yue and Liou [47] who favor only Cenozoic deformation for the Altun Tagh–Zuunbayan faults. (Note that they refer to the Zuunbayan fault as the East Mongolia fault.) As we have stated, it is possible that the Zuunbayan fault experienced some movement in the Cenozoic which would provide one explanation for the current topographic features that they cite as evidence for Cenozoic activity. Their only other line of evidence for Cenozoic activity states that “field mapping [in Mongolia] shows that most faulted rocks are Late Cretaceous in age” [47]. This is based solely on the map of Yanshin [26] and not by direct field observations. Yanshin’s map, however, places the Zuunbayan fault within Upper Cretaceous rocks but does not show them as offset. Our direct field observations suggest that in the region of the Zuunbayan fault, most deformation occurred within pre-Late Cretaceous rocks which are overlain by relatively undeformed Late Cretaceous and younger sediments.

6. Conclusions

Upper Proterozoic and Paleozoic rocks are interpreted as offset features which constrain the sense and amount of displacement on the Gobi Onon, Tost and Zuunbayan faults. Relative age relationships of the offset markers and overlying sequences apparently narrow timing of deformation from the Triassic to early-Late Cretaceous. Preliminary work on mylonitized rocks related to one of the three fault zones, as well as nearby deformed sequences on all three faults, suggest deformation during the Late Triassic to Early or Middle Jurassic. More extensive studies throughout this region, including additional and more comprehensive coupled thermochronologic/kinematic analyses of the fault zones, are needed to clarify slip histories and tectonic affinities. Understanding the history of faulting and deformation in southern Mongolia is crucial, not only to unravel the tectonic history of Mongolia, but also to address larger questions regarding the tectonic amalgamation of Asia. This model, although preliminary, presents testable hypotheses and implications for faults in China and Mongolia.

Acknowledgements

Our understanding of the geology of central Asia has benefited from discussions with many individuals, including Brad Ritts, Todd Greene, Cari Johnson, Bob Coleman, and Edmund Zhang. We thank Clark Burchfiel, Greg Davis and Dickson Cunningham for thoughtful and constructive reviews; Edmund Zhang for translating key literature; R. Barsbold, Badamgarav, Thomas Hickson, Juliet Crider, David Zinniker, A. Chimedtseren, D. Tomorhuu, Batar, Jaraa, Dorch, Dash, Dija, and Tulga for assistance in Mongolia; and the China and Mongolia Industrial Affiliates Program at Stanford University for financial support of this work. Contributing members have included AGIP, Amoco, Anadarko, Arco Oil and Gas Company, British Petroleum, BHP Petroleum, Canadian Hunter, Chevron Overseas Petroleum Inc., Conoco Inc., Enterprise Oil, Exxon Company International, Fletcher Challenge China Ltd., Japan National Oil Corporation, Mobil Exploration and Producing Services Inc., Nescor Energy, Occidental International Exploration and Production Company, Pecten International, Phillips Petroleum Company, Societé Nationale Elf-Aquitaine, Statoil, Texaco, Triton, Union Texas Petroleum, and Unocal International Oil and Gas. Additional funding was provided by Geological Society of America and American Association of Petroleum Geologists student grants, the Shell and McGee Funds of Stanford University, and National Science Foundation grant EAR-9315941. ***[RV]***

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