Full length article

Plate interior polyphase fault systems and sedimentary basin evolution: A case study of the East Gobi Basin and East Gobi Fault Zone, southeastern Mongolia

Matthew J. Heumann\textsuperscript{a,b}, Cari L. Johnson\textsuperscript{b}, Laura E. Webb\textsuperscript{c}

\textsuperscript{a} Apache Corporation, 2000 Post Oak Blvd \#100, Houston, TX 77056, USA
\textsuperscript{b} Geology and Geophysics Department, University of Utah, 115 South 1460 East FASB 383, Salt Lake City, UT 84112, USA
\textsuperscript{c} Department of Geology, University of Vermont, 180 Colchester Ave., Burlington, VT 05405, USA

1. Introduction

Localized deformation along plate-interior fault systems is an important mechanism in intraplate deformation (Johnston and Schweig, 1996; Célérier et al., 2005). These fault systems typically have polyphase histories recorded in structural elements and associated sedimentary basin fill (e.g., Tarim and Ordos basins; Graham et al., 1993; Ritts et al., 2009). In southern Mongolia, the East Gobi Basin and its main defining structural element, the East Gobi Fault Zone (EGFZ), together form an example of a long-lived basin and fault system that records multiple phases of deformation and subsidence (Fig. 1; Johnston and Ritts, 2012). Unlike end-member strike-slip fault systems defined by a single tectonic setting (Sylvester, 1988; Mann, 2007), the EGFZ evolved from a plate margin to a plate interior tectonic setting over a period of \(\sim\) 300 million years. The record of this dynamic tectonic history underscores the role of pre-existing structures and crustal fabrics as mechanisms for the distribution of strain (Sykes, 1978).

The EGFZ formed within accreted arc complexes of the Central Asian Orogenic Belt, or Altaids (Fig. 1; Şengör et al., 1993; Jahn, 1999; Jian et al., 2010). Several studies provided evidence for multiple phases of deformation in this region from Mesozoic-early Cenozoic, including sinistral shear, contraction, and extension (e.g., Johnson, 2004, 2015; Webb and Johnson, 2006; Webb et al., 2010; Heumann et al., 2012; Graham et al., 2012). Building on this and related regional work, this study details the manifestation and timing of these events, offering insight into an under-studied class of polyphase fault systems. The results illustrate how such systems record the behavior of plate interiors as they respond to evolving plate boundary conditions and other driving factors.

This study presents data collected from the correlation of field mapping to 2-D seismic reflection surveys in southeastern Mongolia. The deformation and subsidence phases and fault generations identified here shed light on models for Mesozoic-Cenozoic deformation in eastern-central Asia. A better understanding of the full deformation history of the EGFZ is necessary for evaluating the role of analogous polyphase, intracontinental fault and basin systems. The importance of preexisting fabrics is also emphasized as a control on subsequent Mesozoic-Cenozoic intracontinental deformation.
Accreted arc terranes and synorogenic intrusive suites comprise the basement for much of southern Mongolia (Lamb and Badarch, 1997; Badarch et al., 2002; Lehmann et al., 2010; Taylor et al., 2013). These amalgamated terranes are bound by the Siberian craton to the north, along the Mongol-Okhotsk suture (Zorin et al., 2002; Van der Voo et al., 2015; Johnson, 2015), and by the North China block to the south (Fig. 1). There is debate regarding nature of the southern boundary with the North China block, including the number of terranes and timing of the associated suture zones. Many publications interpret the boundary between the Mongolian terranes and the North China block in Inner Mongolia and southern Mongolia as the late Paleozoic Solonker suture zone (e.g., Zhang et al., 1984, 2014; Chen et al., 2009; Jian et al., 2010; Xiao et al., 2003, 2015; Lin et al., 2014). In contrast, other studies favor an earlier suture prior to the Late Devonian (Xu et al., 2013; Zhao et al., 2016), and that sedimentary and magmatic rocks interpreted by others as evidence for the Solonker suture zone instead formed in an intracontinental setting (Zhao et al., 2016; Luo et al., 2016). Our own studies, which include geochronologic constraints, support a time-transgressive closure of a Permian marine basin between the Mongolian terranes and North China, with the marine-to-non-marine transition occurring in southernmost Mongolia by the end of the Early Triassic (Johnson et al., 2008; Heumann et al., 2012). Regardless of which model is favored, the EGFZ and associated Mesozoic-Cenozoic strata of the East Gobi Basin are superimposed on the various Paleozoic terranes, in a distinct northeast-southwest trending fault-bounded structural corridor (Fig. 2).

The term ‘phase’ is used throughout this study to describe a subset of interpreted deformation and/or basin subsidence events which reflect a specific geologic time frame and tectonic setting (e.g., rifting in the Late Jurassic-Early Cretaceous). Groups or ‘generations’ of faults can be linked to these phases. Previous investigators identified at least four distinct tectono-stratigraphic packages deposited during phases of deformation responsible for post-assembly (Mesozoic-Cenozoic) basin development and the EGFZ’s current architecture. These events include: (1) sinistral ductile shear in the Late Triassic (Webb and Johnson, 2006; Webb et al., 2010); (2) Late Jurassic- Early Cretaceous rifting (Graham et al., 2001); (3) mid-Cretaceous transpression and basin inversion (Johnson, 2004); and (4) Late Cretaceous to early Tertiary left-lateral strike-slip faulting (Webb and Johnson, 2006). Prost (2004) suggested an additional deformation phase of right-lateral strike-slip faulting lasting from Late Cretaceous–Holocene time. This study further investigates these phases by documenting their subsurface and outcrop structural expressions and associated basin fill, and considers evidence for additional events not previously recognized.

The terms Zuunbayan fault (Lamb et al., 1999; Graham et al., 2001) and the Alxa-East Mongolia fault system (Yue and Liou, 1999) have been used to broadly define prominent structures in the study area. Both names predate more detailed field and subsurface mapping, and each refers to multiple faults of the EGFZ rather than a single structure. One important revision is the recognition of the North Zuunbayan fault as distinct from the ‘main’ Zuunbayan fault (Johnson, 2004). The North Zuunbayan Fault forms the northern structural boundary of the Zuunbayan subbasin of the main East Gobi Basin, i.e., the northern margin of the Tavan Har basin uplift, and this structure was active during the latest phase of deformation observed in the study area (Fig. 3; Webb and Johnson, 2006). The Zuunbayan fault forms the southern boundary of the Zuunbayan subbasin and is only identified in the subsurface because it is overlapped by Upper Cretaceous-Recent strata (Fig. 3; Lamb et al., 1999; Johnson, 2004). Other individual fault segments have been identified throughout the study area, specifically around Tavan Har (Fig. 3; Webb and Johnson, 2006). These individual structures (such as the Zuunbayan and North Zuunbayan faults) are cited here as necessary for clarity, but for the purposes of this study the whole system is broadly characterized as the EGFZ.

The Uegt and Zuunbayan subbasins are located on either side of the North Zuunbayan fault at Tavan Har in the northeastern part of the East Gobi Basin (Fig. 3). The Uegt subbasin is the larger in areal extent of the two subbasins, approximately 40 km wide and 120 km long, and forms a broad low relief area north of the EGFZ. In contrast, the Zuunbayan subbasin is more narrow (~20 km) and elongate (~100 km). Prost (2004) estimates total depth to Paleozoic basement of up to 4000 m for the deepest parts of the basins. The Uegt-Zuunbayan subbasin pair provide excellent exposures of sedimentary and volcanic rocks deposited during Late Jurassic-Early Cretaceous rifting (Graham et al., 2001; Johnson and Graham, 2004a,b), correlated here to subsurface borehole and seismic reflection data (Johnson, 2004).

3. Methods

Two dimensional (2-D) seismic reflection data are currently available only from the Uegt and Zuunbayan subbasins (Fig. 3). A Soviet exploration survey (~800 km, early 1990s) and a private industry survey (~2400 km, 1998–1999) provide sufficient areal coverage of both subbasins that structures can be correlated to previously-mapped regional features with high confidence (Lamb et al., 1999; Johnson et al., 2001; Johnson, 2004; Webb and Johnson, 2006). All 2-D seismic data presented here are post-stack migrated, time seismic profiles first published by Johnson (2002). Accurate velocity data are not readily available and therefore seismic lines have not been depth converted. The available migration file shifts the data downward approximately 400 ms at the surface, and interpretations have not been corrected for this shift.

Digitized well-logs available for this study (Johnson, 2002) include 76 of the total penetrations for the East Gobi Basin. The majority of these are from the Zuunbayan subbasin where the main hydrocarbon-producing fields are located. Only six are within the Uegt subbasin and only eight are continuously logged to the top of the Paleozoic basement. The main interval for hydrocarbon production in the East Gobi Basin is the Lower Cretaceous synrift section and this is commonly the only logged interval (Johnson and Graham, 2004a; Wang et al., 2014).

Palinspastic reconstructions are not currently possible for the Uegt and Zuunbayan subbasins due to structural complexity and lack of a
regional velocity model for depth conversions. The subsurface data are used here specifically to determine relative life-spans and ages of faults. Faults were interpreted using Halliburton-Landmark’s SeisWorks® 2-D Seismic Interpretation software and IHS’s Kingdom suite following standard interpretation techniques. Automated triangulation operations were used to interpolate fault surfaces between fault segments in separate seismic profiles. The triangulated fault mesh was exported in AutoCAD format and imported into ESRI’s ArcMap geospatial software for outcrop correlations. First-order observations of fault geometries were made from the seismic data, and a youngest age of activity was assigned to a fault segment based upon crosscutting, overlap, and stratigraphic relationships.

Fig. 2. Simplified geologic map of southeastern Mongolia modified from Webb and Johnson (2006) and Tomurtogoo (1999). The Unegt and Zuunbayan subbasins are outlined in narrow dashed lined. Documented large-scale faults within the EGFZ are show in bold black lines (dashed where inferred). The China-Mongolia political boundary is outlined in red. Abbreviations for localities are as follows: BU – Bulgan Uul, HH – Har Hotol, NO – Nomgon, OH – Onch Hayrhan, TH – Tavan Har, TS – Tsagan Subarga, UB – Unegt subbasin; UK – Ulgay Khid, UR – Urgun, ZB – Zuunbayan subbasin. Approximate location of Fig. 3 is outlined by the dashed box.

Fig. 3. Detailed geologic map for the study area based on field observation (this study) and adapted from Webb et al. (2010), Graham et al. (2001), Tomurtogoo (1999), Lamb et al. (1999) and Borzakovskiy et al. (1982). Map units have been grouped according to discussion points in the text; Paleozoic rocks and intrusive suites, Late Triassic shear zone, Lower - Middle Jurassic sedimentary rocks, Upper Jurassic - Lower Cretaceous sedimentary rocks, and Upper Cretaceous Quaternary sediments. Generalized basin outlines are show in dashed-lines for the Unegt and Zuunbayan subbasins. Abbreviations for localities are as follows: NZB – North Zuunbayan Fault, UR – Urgun, HH – Har Hotol, TH – Tavan Har, TS – Tsagan Subarga, UK – Ulgay Khid, ZB – Zuunbayan Fault.
Fig. 4. (A) Simplified tectonostratigraphic summary for the study area. Blackened intervals correspond to mapped unconformities with estimated duration. Radiogenic age constraints are from volcanic ashes and basalts by Johnson and Graham (2004a), Graham et al. (2001) and metamorphic tectonites by Webb et al. (2010). Geologic time scale is from Gradstein et al. (2012). (B) Uninterpreted and interpreted seismic cross-section (shown in two-way travel time); inset map shows approximate location. See tectonostratigraphic column for fill patterns; faults are shown in bold black lines and horizons mapped within major stratigraphic packages are delineated by thin black lines. Examples of phases of deformation discussed in the text are identified with large black arrows. Early Jurassic foreland deposits are absent in this portion of the subbasin, and Phase 4 extension is poorly developed here. The mid-Cretaceous basin inversion event (Phase 5) is well illustrated in folding of the synrift strata and reactivated basement faults. Inset map shows location of seismic profile; TH - Tavan Har.

Fig. 5. Uninterpreted and interpreted seismic cross-section (shown in two-way travel time); inset map shows approximate location. Simplified tectonostratigraphic summary for the study area is included from Fig. 4A; for discussion see Fig. 4A caption. Faults are shown in bold black lines and horizons mapped within major stratigraphic packages are delineated by thin black lines. Examples of phases of deformation discussed in the text are identified with large black arrows. Paleozoic basement which reaches the surface in the center of this seismic profile has been correlated to the Late Triassic shear zone (Phase 2; Webb et al., 2010). Inset map shows location of seismic profile; TH - Tavan Har.
Four seismic profiles were chosen for this publication (Figs. 4–7; original publication and data release in Johnson (2002)). These profiles are all oriented roughly NW-SE, i.e., dip sections across the Cretaceous rift basin, and they step sequentially from southwest to northeast across the EGFZ. The profiles highlight the key structural and temporal relationships for each phase of deformation. A fault generation map (Fig. 8) was also created to represent the five brittle phases of deformation. Fault traces have been simplified for display, and only major basin-forming faults are included (i.e., faults that can be correlated along strike across multiple seismic profiles). As will be discussed, displaying these deformation phases together in map view highlights notable differences in the distribution and orientation of fault generations across the EGFZ, and helps illustrate kinematic relationships and reactivation patterns between them.
To supplement the subsurface interpretations, geologic transects and area mapping were conducted in locations along the Unegt and Zuunbayan subbasin margins, particularly where mapped subsurface features appeared to crop out (e.g., Ulgay Khid, Nomgon, Tsagan Subarga, Tavan Har, Har Hotol, Urgun; Fig. 2). Fault plane orientation and kinematic indicators for sense of slip were collected where possible (Taylor et al., 2009), in addition to the age and type of rocks involved in faulting. The correlation of structures observed in outcrop to those interpreted in seismic profiles was most successful around Tavan Har, the structural and basement high between the Unegt and Zuunbayan subbasins (Fig. 2). Additional field transects targeted linear features observed in SRTM LandSAT imagery along strike (to the northeast and southwest) of Tavan Har. Several faults crosscut Paleogene or younger strata and alluvium, and palynology samples were collected for age and environmental determination of these units.

4. Results

4.1. Phase 1

The oldest stage of deformation is defined by faults that cut mainly Devonian, Carboniferous and Permian basement rocks of the East Gobi Basin (Figs. 6 and 7). Devonian and Carboniferous units include greenschist-grade sedimentary successions, volcanic rocks, and some intrusions (Fig. 2; Badarch et al., 2002). Silurian and Ordovician sedimentary units have been reported in isolated outcrops but are poorly represented in the study area (Yanshin, 1989; Lamb and Badarch, 1997, 2001; Tomurtogoo, 1999; Blight et al., 2010). These arc assemblages are indistinguishable in the seismic dataset and have not been penetrated by boreholes, so the Paleozoic units are largely undifferentiated in our subsurface interpretations.

Faults that moved during this earliest phase of deformation are mainly northwest-dipping thrusts. The seismic data presented here only extend to 4 s depth (TWTT) and the quality/resolution of imaging rapidly deteriorates with depth. Therefore, décollement surfaces and boundaries between fault blocks at depth are largely inferred in the interpreted seismic cross sections. There is little or no offset of the Mesozoic and younger strata that overlap these structures (Fig. 6). The oldest strata deposited unconformably over Phase 1 structures are Early Jurassic prerift sequences; Triassic strata are absent in much of the study area (Figs. 2 and 4; Tomurtogoo, 1999). Several subsequent deformation phases for the EGFZ exploit the faults formed during Phase 1 deformation, mainly the basin-bounding faults.

Phase 1 thrust faults are common beneath the Unegt subbasin, north of the EGFZ (Fig. 3), but the structures are notably absent beneath the Zuunbayan subbasin (Fig. 7). The fault generation map best highlights this relationship (Fig. 8), as the most continuous of the interpreted Phase 1 faults are located beneath the Unegt subbasin. In part, this contrast is a result of deeper burial of the Paleozoic sections beneath thick Mesozoic rift sections in the Zuunbayan subbasin (and thus more difficulty in imaging), but it may also reflect later strike-slip faulting and juxtaposition of different basement blocks (see Phases 2, 5, 6).

Field transects at Har Hotol, Ulgay Khid and Tsagan Subarga (Fig. 3) in Paleozoic igneous and sedimentary rocks, including locally dated
Carboniferous arc units near Har Hotol (Blight et al., 2008, 2010), also show localized evidence for faulting corresponding to this earliest phase (Fig. 9A). Faults located in these areas proved difficult to map over distances beyond 10’s of meters due to poor exposures, but exposed fault planes strike northeast and do not displace overlying Mesozoic and younger strata (Fig. 3). Regional maps (Borzakovskiy, 1982) suggest that related thrust structures are present to the south of the EGFZ (i.e., Nomgon area, Fig. 2).

4.2. Phase 2

The Unegt and Zuunbayan subbasins are separated by an exposed basement high at Tavan Har (Fig. 3). Webb et al. (2010) identified the horst as an exhumed sinistral shear zone and dated the main phase of ductile deformation via 40Ar/39Ar geochronology as Late Triassic (ca. 225–210 Ma). Seismic profiles cross the northeastern margin of the exposed basement block at Tavan Har study area, but the deep subsurface structure is poorly resolved (Fig. 5) due to acquisition and processing problems (e.g., edge-effects), as well as difficulty in imaging steeply dipping foliation. The shear zone is also heavily overprinted by later brittle deformation (Webb and Johnson, 2006; Taylor et al., 2008).

The exposed shear zone at Tavan Har is part of a zone of tectonites that can be traced roughly 250 km along the EGFZ to Ugaly Khid, Tsagan Subarga and Urgun (Fig. 3). As at Tavan Har, along-strike outcrop exposures of the shear zone have been previously mapped as Precambrian crystalline basement (Tomurtogoo, 1999). Webb et al. (2010) report Late Triassic 40Ar/39Ar ages (225–210 Ma) from shear zone samples collected at Tsagan Subarga, similar to Tavan Har. Differing cooling rates inferred from the 40Ar/39Ar data suggest different uplift histories for the two basement blocks during Late Jurassic-Early Cretaceous extension (Webb et al., 2010). The ductile shear zone is dominated by steeply dipping northeast-striking foliation and lineation that plunges to the WSW or ENE (Fig. 9B; Webb and Johnson, 2006). Foliation measurements at Urgun also dip steeply and lineation plunges WSW. The shear zone is also heavily overprinted by shearing ductile deformation (Jerzykiewicz and Russell, 1991; Yamamoto et al., 1993).

4.3. Phase 3

A thick (maximum ~2 s TWTT) assemblage of folded and faulted reflectors is prominent in the subsurface dataset along the northeastern margin of the Unegt subbasin between 0.5 and 2.5 s TWTT (Fig. 6). The reflectors correspond to the Early-Middle Jurassic prerift megasequence described in Johnson (2004) and Graham et al. (2001) (Fig. 4). Locally named the Khamarkhoovor Formation (Jerzykiewicz and Russell, 1991; Yamamoto et al., 1993), these are dominantly alluvial-fluvial strata and are mainly observed in the subsurface along the northern margin of the Unegt subbasin in a wedge-shaped, northward-thickening section (Fig. 6). The seismic dataset shows that these deposits are generally absent or notably thin in the Zuunbayan subbasin, although the formation is mapped in small outcrops to the south of the EGFZ (e.g., Nomgon, Fig. 3).

The seismic cross-sections lack evidence for syn-depositional deformation of this prerift assemblage. Deformation recorded in the prerift deposits partially exploits the lower unconformity with Paleozoic basement as a basal décollement, and ramp-flat fault geometries and broad folds are present within the prerift unit (Figs. 5 and 6). Comparison of the three seismic lines (Figs. 4, 6 and 7) demonstrates the lack of inferred Early Jurassic strata in the Zuunbayan subbasin, and illustrates increasing strain (broad into tight folds) and increased internal faulting, as well as basement-involved faulting to the northwest, as compared to the Unegt subbasin. These observations argue for reactivation of existing faults in the Paleozoic basement, presumably the southwest-striking, northwest-dipping structures identified in Phase 1. Major fault planes interpreted to accommodate Phase 3 deformation were correlated throughout the seismic survey northeast of Har Hotol, where they occur along a subparallel strike to the mapped Phase 1 fault observed in the Unegt subbasin (Fig. 8). Additionally, the seismic cross-sections in Figs. 6 and 7 illustrate an unconformable relationship between Early Jurassic prerift strata and the synrift strata deposited during Phase 4 (i.e., late Mesozoic rift phase).

Low-angle faults with several meters of apparent reverse offset of sedimentary layers are exposed in the prerift megasequence at Har Hotol (Fig. 9C). The faults are interpreted to correspond with the deformation observed in the subsurface, which is consistent with the increasing degree of faulting and folding of the unit from southwest to northeast through the seismic cross sections (Figs. 5, 7 and 8). The prerift megasequence includes discontinuous outcrops mapped as Lower Jurassic Khamarkhoovor Formation by Graham et al. (2001). All documented occurrences of the prerift megasequence in the study area strike northeast with variable dips, although exposures are limited.

The rocks comprising the prerift megasequence include thick (meter scale), fining upward conglomerate sequences with grain sizes ranging from sand matrix to well-rounded cobble and boulder-sized clasts (Fig. 9C). Locally, the conglomerates are interbedded with thinly bedded (decimeter scale) sandstone channels, consistent with alluvial-fluvial environments as interpreted by previous investigators (Jerzykiewicz and Russell, 1991; Yamamoto et al., 1993; Graham et al., 2001). The Khamarkhoovor Formation has been interpreted by previous investigators (Graham et al., 2001; Johnson, 2004) as a possible foreland basin deposit, coeval with an extensive foreland basin succession exposed ~1000 km to the west at Noyon Uul (Fig. 1; Hendrix et al., 1996, 2001). Although deposits of the prerift megasequence occur in isolated exposures, it has been suggested that these units were once part of the same regional basin system (Graham et al., 2001).
unconformably on Paleozoic basement and post-dates the final thrusting associated in Phase 1. Thus the lower (oldest) age limit for deposition must postdate the Late Triassic ductile shearing (Phase 2 deformation; ~210 Ma) and also predates Late Jurassic-Early Cretaceous extension (Phase 4). Additionally, apatite fission track dating suggests that cooling below ~150 °C was not achieved at Tavan Har until the Middle Jurassic (Taylor et al., 2009). This observation is consistent with relatively slow cooling during the Early Jurassic as indicated by Webb et al. (2010). Therefore, the timing of Phase 3 deformation and development of the regional unconformity likely occurred during the later Early Jurassic as a minimum age.

4.4. Phase 4

The Late Jurassic through Early Cretaceous is a well-documented period of extension in the study area (Graham et al., 2001; Johnson et al., 2004), in addition to much of East Asia (Dong et al., 2015). Late Mesozoic rifting in southeastern Mongolia is contemporaneous with extension throughout central and eastern China, and the formation of large rift basins that contain significant petroleum reserves (Watson et al., 1987; Traynor and Sladen, 1995; Wei et al., 2010; Graham et al., 2012; Lin et al., 2013) as well as uranium deposits (Bonnetti et al., 2016). The synrift deposits are further subdivided into several sequences, each reflecting a different period of extension marked by the occurrence of a conglomerate unit in outcrop or other evidence of a renewed basin subsidence and deposition phase (Fig. 9D; Graham et al., 2001; Johnson et al., 2004). In this study, the synrift megasequence is left unconformably on the prerift megasequence and locally on Paleoecic basement (Fig. 7). Interbedded bimodal volcanic units provide absolute age constraints on the timing of extension from at least 155 to 121 Ma (Fig. 4; Graham et al., 2001; Johnson and Graham, 2004). Slow along the high-angle basin bounding faults of the Zuunbayan subbasin (Phase 4 deformation) is primarily dip-slip and subparallel to steeply dipping shear zone fabrics developed during the Late Triassic (Webb and Johnson, 2006). Thus, the high-angle fabrics associated with the Late Triassic shear zone (Phase 2) were exploited during extension by basin-bounding faults as observed in the field (Webb et al., 2010) and in the subsurface 2D seismic dataset. Extension resulted in horst and graben architecture throughout the study area. Deposition of strata is contemporaneous with normal faulting along main basin bounding faults, as illustrated by the packages of growth strata formed along subbasin margins (Figs. 4, 6 and 6). The Unegt subbasin occupies a poorly developed half graben to the north of the horst block at Tavan Har (i.e., the EGFZ), and the Zuunbayan subbasin occupies a well-developed graben system to the south (Figs. 7 and 8). The Unegt subbasin lacks a significant basin-bounding fault system and extension across the area is therefore relatively minor. Preserved ‘acoustic thickness’ of synrift fill in the Zuunbayan subbasin is more than double that of the Unegt (~2.25 s vs ~1 s TWTT; Fig. 7). Thickness of exposed synrift strata based on outcrop studies is ~2–3 km in the Zuunbayan subbasin (Graham et al., 2001). The difference in thickness of depositional packages across the EGFZ may partly indicate of differential exhumation during Phase 5 (basin inversion). However, there appears to be a fundamental structural control favoring deep basin development in the Zuunbayan subbasin, and this primarily reflects reactivation of structures inherited from previous deformation phases. More specifically, slip along the high-angle basin-bounding faults of the Zuunbayan subbasin is primarily dip-slip and sub-parallel to steeply dipping shear zone fabrics developed during the Late Triassic (Phase 3). This further argues for reactivation of the shear zone during late Mesozoic extension (Webb et al., 2010).

4.5. Phase 5

A regional unconformity truncates the synrift and older assemblages of the East Gobi Basin, above which a Late Cretaceous-Paleogene postrift or overlap megasequence was deposited (Fig. 9E; Graham et al., 2001; Johnson et al., 2004). The synrift strata were inverted during a period of regional shortening or transpression along the EGFZ. Regional scale reverse and thrust faults of this phase (post-unconformity) have not been identified in the field, nor in the subsurface (Fig. 8), so it is likely that contraction during this phase included an oblique component. Folds and faults beneath the regional unconformity are oriented in geometries inconsistent with thermal subsidence or progressive rotation during normal faulting; instead the shallowest synrift units dip steeply basinward, whereas the deepest synrift units are reverse-faulted internally for space accommodation (Figs. 6 and 7). Within the Unegt subbasin, anticlinal features were formed during this phase (Fig. 1), but at Tavan Har the overlap megasequence onlaps the basement high (Fig. 5). Drag folds indicative of reverse sense of slip across inferred normal faults during Phase 4 are present at the margins of the Zuunbayan subbasin (Figs. 6 and 7). We infer basin inversion was accomplished mainly by folding and reverse-sense reactivation of synrift normal faults.

Phase 5 deformation was likely brief, lasting perhaps ~1–5 million years during Cenomanian or Turonian time (Graham et al., 2001; Johnson et al., 2004). Similarly, multiple basin inversion events beginning at ~95 Ma have been documented in Songliao and Erlain Basins in China (Li et al., 1997; Lin et al., 1997, 2001; Feng et al., 2010; Wei et al., 2010). The magnitude of total shortening across the Unegt and Zuunbayan subbasins during the basin inversion event is uncertain but probably relatively minor overall (crude, line-length restoration across several inverted structures suggests ~3%), and most pronounced along the main structures of the EGFZ (Fig. 6). Thermal maturation modeling by Johnson (2004) suggested up to 1700 meters of eroded synrift strata in one well at the Zuunbayan oilfield. Therefore, although lateral shortening was minor, significant inversion may have occurred along basin bounding faults.

This period marks a significant change in deformation style observed in the subsurface dataset. Only the major basin-bounding faults (in particular, along Tavan Har) remained active following the inversion event and unconformable deposition of the postrift sequences (Figs. 8 and 9E). Otherwise, minor anthetic and synthetic faults locally offset the unconformity (Fig. 7).

4.6. Phase 6

The final and youngest phase of deformation observed along the EGFZ corresponds to Cenozoic strike-slip faulting and minor basin deposition. The seismic cross sections shown in this study indicate that the mid-Cretaceous unconformity (Phase 4) is locally deformed, as are overlying Upper Cretaceous and Paleogene strata (Fig. 9F). Faults of this phase are typically reactivated basin-bounding faults of Phases 4 and 5. These relationships are best illustrated in Figs. 7 and 8, where the overlying strata are folded and faulted along the EGFZ (specifically, the North Zuunbayan fault near Tavan Har). The faults corresponding to Phase 6 deformation juxtapose distinct packages of basin fill along steeply dipping faults, with sudden changes in the apparent amount and sense of offset shown on 2-D seismic sections (cf. Figs. 4, 6 and 7). Such relationships are common in the subsurface expressions of strike-slip fault zones in other regions (Zolnai, 1991; Webb and Johnson, 2006). The generation of faults corresponding to Phase 6 deformation presented here commonly reaches the surface, are northeast striking and can be mapped for several kilometers within the seismic data set.

Surface expressions of Phase 6 faults include multiple zones of fault gouge reaching tens of meters in width (Figs. 3 and 9F). Gypsum and related minerals were found in several locations growing alongstriated fault planes in Paleogene or younger strata. Several faults identified
outside the seismic survey boundaries at Ulgay Khid and near Urgun (Fig. 3) are also consistent with a northeast trending left-lateral strike-slip fault zone.

Strata cut by Phase 6 faults range from Upper Cretaceous through Paleogene, although regional maps imply (perhaps incorrectly) only minor Cenozoic deposition. The youngest units are typically poorly lithified, poorly sorted sandy to conglomeratic successions deposited in alluvial environments. Clasts within the units appear to be locally derived (mainly volcanic lithic fragments). These strata thicken away from the bounding fault systems (Figs. 4–7) and may represent a period of post-inversion thermal subsidence.

A key observation is that the youngest strata involved in faulting are quite distinct from the well-lithified, generally finer grained, fossil-bearing and volcanioclastic Cretaceous units of the synrift sequences. One successful palynological sample was recovered from deformed red beds that are currently mapped as Upper Cretaceous (postrift), near a Phase 6 fault zone at Ulgay Khid (Fig. 3). Sample 04UK114 contained pollen forms of *Bombacaceae*, *Chenopodiaceae*, and *Betulaceae*. These three families are derived from temperate-tropical trees and angiosperms that are most common in the Oligocene-Miocene of China and Mongolia (Song et al., 2004). They were largely extint in the region by the end of the Paleogene (Wang et al., 1990). These new data suggest some of the mapped ‘Upper Cretaceous’ basin fill is in fact at least Paleogene (likely Oligocene-Miocene) in age, and therefore there may be more of a sedimentary record of this deformation phase than has been recognized. Recorded seismicity for southeastern Mongolia since 1958 (beginning of recording as per the Advanced National Seismic System [ANSS] Worldwide Earthquake Catalog) is sporadic and minor recorded seismicity for southeastern Mongolia since 1958 (beginning of recording as per the Advanced National Seismic System [ANSS] Worldwide Earthquake Catalog) is sporadic and minor.

5. Discussion

The results of subsurface and outcrop interpretation presented here summarize nearly 270 million years of deformation and basin evolution recorded in Paleozoic through Cenozoic rocks of southern Mongolia (Fig. 3). The six distinct phases of deformation shed light on modes of intracontinental deformation. In this example of a long-lived intracontinental deformation zone, local and regional tectonics couple with dynamic boundary conditions to drive polyphase deformation and basin evolution. The main deformation phases and possible tectonic driving forces are summarized in Fig. 10. Furthermore, we argue that preexisting fabrics favor the localization of successive deformation phases along the EGFZ. Multiphase, localized deformation occurring under dynamic boundary conditions suggests that deep-rooted crustal fabrics are the main control on where and how deformation is manifested along the EGFZ.

5.1. Deformation phases and tectonic driving forces

5.1.1. Phase 1: Paleozoic arc accretion and basement structural development

Structures identified as Phase 1 deformation correspond to the late Paleozoic period of arc accretion and rapid growth of the Altaiads (Fig. 10; Şengör et al., 1993; Windley et al., 2007; Guy et al., 2014). Where observed in the subsurface and in outcrop, mainly in the Unegt subbasin, Phase 1 faults dip north and deform mainly Ordovician through Carboniferous rocks. The structural fabric in these units likely originated during subduction of arc terranes in the Devonian and Carboniferous (Lamb and Badarch, 1997; Taylor et al., 2013). The terminal Late Permian collision in southern Mongolia was likely southward-directed with partial subduction of the Altaiads beneath the North China Block (Fig. 10; Cope et al., 2005; Zhang et al., 2007; Johnson et al., 2008), although regionally the broader suture zone has evidence for collision ranging from pre-Late Devonian (Xu et al., 2013; Zhao et al., 2016) to Middle or Late Triassic (Chen et al., 2009; Li et al., 2014). Although Permian units do not crop out in the study area immediately surrounding the subsurface dataset, they are present to the southwest at localities such as Bulgan Uul and Nomgon (Fig. 2). At these localities, Permian strata are deformed by reverse faulting and tight folding associated with penetrative cleavage, dissimilar to the deformation observed in the Unegt and Zuunbayan subbasins (Johnson et al., 2008; Heumann et al., 2012). Thus the arc accretion phase can be distinguished from final closure of the remnant ocean basin in southern Mongolia.

5.1.2. Phase 2: Late Triassic shear zone formation

Outcrops of the Late Triassic sinistral shear zone can be mapped along trend of the EGFZ for ~250 km in outcrop (Fig. 3; Lamb et al., 1999; Webb et al., 2010), and possibly more than 1000 km based on subsurface magnetic data (Maus et al., 2009). The main phase of shear zone activity occurred between ~225 and 210 Ma, as determined by 40Ar/39Ar thermochronology by Webb et al. (2010) and Lamb et al. (1999). The age of ductile deformation thus postdates Late Permian (and older) arc-continent collision along the Solonker suture and occurred in an intracraton setting (Johnson et al., 2008). Estimates for left-lateral displacement during Phase 2 are ~250 km based on piercing point studies along the EGFZ by Heumann et al. (2014).

Such magnitudes of displacement and the continuity of the shear zone suggest regional-scale processes rather than just local drivers. Southeast of Tavan Har, proximal to the Solonker suture zone (Fig. 1), Davis et al. (2004) have documented high strain NNE-SSW extension along a low-angle detachment fault in the Late Triassic. E-W Late Triassic extension has also been documented in N-NE striking faults along the northwest portion of Ordos basin (Ritts et al., 2009). Sinistral shear along NE striking faults is documented in north-central China (Zhou et al., 2012; Zhang et al., 2013; Zhao et al., 2015), and in northwest China (Wang et al., 2010). These regional extensional features may have been kinematically linked with the EGFZ shear zone, along a regional scale left-lateral fault zone or series of fault zones, the brittle component of which has since been eroded (cf., Zhao et al., 2015).

Timing and modes of closure of the Mongol-Okhotsk ocean is highly controversial, but in the vicinity of northern Mongolia it likely occurred during the Late Triassic, probably suturing from west to east (Zhao et al., 1990; Zorin et al., 2002; Johnson, 2015; Van der Voo et al., 2015). Timing of final Mongol-Okhotsk collision in the vicinity of northeastern Mongolia remains a point of controversy between Late Triassic (Zonenshain et al., 1990), Middle-Late Jurassic (Zhao et al., 1990; Zorin et al., 2002; van der Meer et al., 2010), and Early Cretaceous (Van der Voo et al., 1999, 2015). In any case, collision was apparently ongoing along its western portion (in Mongolia, Fig. 1) during Phase 2. Also possibly influencing boundary conditions at this time is terminal collision between the North and South China blocks, resulting in the Qinling-Dabie orogen between ~240 and 220 Ma (Fig. 10; Ames et al., 1993, 1996; Hacker et al., 2000; Pullen et al., 2008), and perhaps ongoing deformation along the northern margin of the North China Block (Tian et al., 2015). Therefore we infer that oblique movement between two rigid bodies (Siberia and the combined North China Block-South China Block) was focused along a narrow region (i.e., the EGFZ shear zone) of recently accreted arc systems.

5.1.3. Phase 3: Early Jurassic foreland basin

The Early Jurassic pre rift megasequence forms a north-thickening wedge (Fig. 6) along the northern margin of the Unegt subbasin. Available outcrops of this succession are poorly preserved (Fig. 3) but where studied in the Unegt subbasin, the pre rift megasequence is nonmarine and likely Early Jurassic in depositional age (e.g., the fluvial-lacustrine Khamarkhoovor Formation; Jerzkykiewicz and...
Russell, 1991; Yamamoto et al., 1993). The prerift megasequence lies unconformably between Paleozoic basement rocks and late Mesozoic rift successions, and thus it post-dates the Permian ocean closure in southernmost Mongolia and predates rifting. The prerift megasequence also lacks extensive bimodal volcanics and obvious normal faults that characterize the later rift succession. These observations, along with the observed northward thickening wedge-shape and evidence for south-directed shortening (Fig. 6), suggests the prerift succession may have been deposited in a foreland basin setting.

Phase 3 deformation is consistent with regional contractional tectonics in the Early Jurassic (Yin and Nie, 1996) and contemporaneous with N-S shortening during the Early Jurassic to the southwest of the study area near the Beishan and Noyon Uul (Fig. 1; Zheng et al., 1996; Hendrix et al., 1996; Webb et al., 1999; Dumitru and Hendrix, 2001; Liu et al., 2002, 2003).
5.1.4. Phase 4: Late Jurassic-Early Cretaceous extension

Late Mesozoic extension is well documented across most of east-central Asia (e.g., Meng et al., 2003; Ritts et al., 2010; Graham et al., 2012). Modes and strain magnitudes for Late Jurassic through Early Cretaceous extension vary. A metamorphic core complex at Yagan-Onch Hayrhan metamorphic core complex (Fig. 2), where top-to-the-southwest sense of shear in ductile fabrics are likely early Mesozoic in age (they are overprinted by the Early Cretaceous detachment fault fabrics dated by Webb et al. (1999)). Field observations from Johnson et al. (2001) suggest these overprinted fabrics are coeval with Mesos-Neproterozoic carbonate klippe emplacement in the Beishan orogen (Zheng et al., 1996). Apparently localized deposition of pre rift strata along the northern margin of the Unegt subbasin, and southward propagation of basement thrusting (Fig. 8), suggest that Phase 3 deformation reactivated a select subset of steeply-dipping Paleozoic faults north of the Unegt subbasin.

During Early Jurassic time, regional shortening was likely driven by continuing closure of the Mongol-Okhotsk Ocean to the north (Zorin et al., 1993; Zorin et al., 2002; Van der Voo et al., 1999, 2015; van der Meer et al., 2010), and collision of the Qiantang block to the southwest (Fig. 10; Dewey, 1988; Hendrix et al., 1992; Matte et al., 1996). These distant collisional events may have influenced plate boundary conditions at this time, thus driving intracontinental deformation along the EGFZ.

5.1.6. Phase 6: Paleogene strike-slip faulting

Phase 6 deformation along the EGFZ has only recently been characterized (Webb and Johnson, 2006; Heumann et al., 2008, 2009; Taylor et al., 2009). Left-lateral strike-slip faulting and associated shortening and extension features are observed along large zones of fault gouge that cross-cut deformed (in places) Paleogene alluvium (Fig. 9F). The lower age limit for initiation of strike-slip faulting is poorly known. However, strike-slip faults observed in the subsurface (Figs. 6 and 7) clearly cross-cut the middle Cretaceous unconformity, implying faulting may have initiated as early as post ~95 Ma, although potential tectonic driving mechanisms for strike-slip activity at ~95–100 Ma are lacking (Fig. 10). This study documents unconsolidated alluvium (distinctly different from Upper Cretaceous strata in the region) that is also cross-cut by northeast striking left-lateral strike-slip faults. The single palynology result presented by this study suggests that some of this alluvium is Oligocene-Miocene in age. Earthquake data and a lack of neotectonic features in both field and remote-sensing (e.g., LandsAT) observations suggest the EGFZ is mostly inactive today (Adiy et al., 2003; cf. Li et al., 2016). Therefore, although the maximum age range for strike-slip activity across the EGFZ during Phase 6 is Late Cretaceous through Miocene, we tentatively favor late Oligocene through early Miocene as most probable. This favored timing is also easier to explain by possible drivers (Fig. 10), as discussed below.

The magnitude of left-lateral strike-slip displacement across the EGFZ is likely ~100 km, from piercing point studies by Heumann et al. (2014), with a proposed approximate age of Late Oligocene-Early Miocene. Post-Cretaceous displacement magnitude across the EGZ contrasts with total displacement across the Altyn Tagh fault presented by Yue et al. (2001, 2005) of ~400–350 km, although the timing for displacement across each system is similar, beginning in the Late Oligocene. Interpretation by Yue and Liou (1999) suggested that slip across a linked Altyn Tagh-East Mongolia (i.e., the EGFZ) fault system essentially ceased in the mid-Miocene, replaced by a second stage of Altyn Tagh movement and significant crustal thickening in the Qilian Shan. The discrepancy in magnitudes of displacement across the Altyn Tagh Fault and EGFZ likely results from coeval displacement occurring across multiple strike-slip faults systems throughout southwestern Mongolia and northern China (e.g., the Tost and Onon faults and east-striking faults in the Alxa region (Fig. 1; Lamb et al., 1999; Darby et al., 2005; Zhang et al., 2009). Therefore, large-magnitude displacement across a single fault zone (the Altyn Tagh) was perhaps transferred to multiple structures in horsetail geometry with smaller individual offset magnitudes during the late Oligocene. Several east-
striking faults were documented by Darby et al. (2005) in the western Alxa region, where they interpreted ~70 km of offset magnitude (Fig. 1).

Tectonic driving forces responsible for strike-slip initiation across the EGFZ (Phase 6) are difficult to determine. Pacific Plate velocities relative to Eurasia decreased at ~65 Ma by more than 40 mm/yr and began to increase in the Eocene before reaching modern rate of ~100 mm/yr at ~20–10 Ma (Northrup et al., 1995; Zhuang et al., 2010). Collision of the India subcontinent with southern Asia is contemporaneous to the period of decreased relative Pacific Plate velocity (Rowley, 1996). In agreement with proposed driving forces for initiation for strike-slip activity along the Altyg Tagh Fault (Yin et al., 2002), it is likely similar forces associated with the collision are responsible for faulting initiation across the EGFZ. Following a brief period of left-lateral displacement across the EGFZ, an increase in Pacific Plate velocity and a shift from transtension to transpression along the northeastern Pacific margin during the Miocene removed the necessary free surface (Jones et al., 1997) for the continuation of lateral extrusion along the EGFZ (Fig. 10; Jolivet et al., 1994; Worrall et al., 1996; Webb and Johnson, 2006). This shift in boundary conditions is inferred to cause the end (or significant slowing) of Phase 6 deformation in the East Gobi basin, while allowing for deformation observed in western Mongolia to remain active today (Fig. 10; Cunningham et al., 2003; Howard et al., 2003, 2006).

5.2. Reactivation of preexisting crustal fabrics

Multiple phases of deformation identified by this study are evident along a defined structural corridor in southeastern Mongolia (the EGFZ), and occurred during a long term range of boundary conditions and far-field stress regimes (Fig. 10). The correlation of the EGFZ to a linear magnetic anomaly present in the EMAG2 survey (Maus et al., 2009), suggests the EGFZ is a significant and well defined feature (~1000 km long) with regional implications. The recurrence of six distinct deformation phases along EGFZ suggests that several deformation phases may exploit structures that were formed or modified during preceding deformation phases. We infer that the focused nature of the deformation phases described here reflects inherited crustal weaknesses that played a major role in defining the long term, polyphase evolution of the East Gobi basin and the EGFZ. Such controls likely originated as a deep crustal fabric created during Paleozoic arc-arc and arc-microcontinent amalgamation (Badarch et al., 2002; Johnson et al., 2008). Crustal-scale features are indicative of relatively weak crust in southeast Mongolia, resulting from the heterogeneous oceanic arc terranes of the Altaiids as well as a fluctuating geothermal gradient formed during terrane accretion and rifting. Faults observed in the Paleozoic basement beneath the Unegt subbasin are likely restricted to a single terrane (Badarch et al., 2002), helping to explain why similar faults are apparently absent in the subsurface south of the EGFZ (Fig. 8). In the subsurface and in outcrop, faults of Phase 1 are interpreted as bimodal in how they control later phases of deformation. Specifically, these faults provide either a preexisting weakness enabling continued deformation (typically at the basin margins), or they remain intact beneath the basin thus partitioning and localizing strain elsewhere.

Steeply dipping foliation in the shear zone (Phase 2) characterized by Webb et al. (2010) and Lamb et al. (1999) strikes southwest, approximately parallel to the strikes of faults characterized as Phase 1 and the orientation of the regional linear feature in the magnetic anomaly dataset. Therefore, we infer that the shear zone exploited some weakness in the accreted arc system, possibly a terrane boundary (Badarch et al., 2002). During Phase 3 deformation (shortening phase resulting in an Early Jurassic foreland deposits; Fig. 5), we infer that Phase 1 high-angle basement faults were reactivated in a reverse sense (south-directed) as basin uplifts along only the northern margin of the Unegt subbasin.

High-angle normal faults of Phase 4 deformation (rifting) formed along pre-existing high-angle structural fabrics inherited from Paleozoic accretion (Phase 1), Late Triassic shearing (Phase 2) and along basement uplifts formed during the Early Jurassic (Phase 3). Subduced extension in the Unegt subbasin (relative to the Zuunbayan) is partly controlled by the thrust sheet beneath the basin, which is inferred to have an orientation unfavorable for reactivation for high-angle normal faulting (Fig. 6). Faults within the Unegt subbasin show minor displacement in comparison to the Phase 4 extensional faults observed in the Zuunbayan subbasin (Fig. 7).

Middle Cretaceous basin inversion (Phase 5) resulted from regional contraction and reverse movement along those same basin bounding faults exploited during Phase 4. Drag folds present in the synrift strata against the basin-bounding faults are indicative of a reverse sense of displacement (Figus. 6 and 7). Magnitudes of displacement along basin bounding faults remain undetermined. Potential differences in thickness of the synrift strata between the Unegt and Zuunbayan subbasins may be linked to asymmetrical inversion during Phase 5 (as observed in the Songliao basin; Feng et al., 2010). Finally, left-lateral strike-slip displacement during the late Oligocene (Phase 6) continued exploitation of basin bounding faults, locally reactivating the high-angle fabrics of the Late Triassic shear zone (Phase 2; Webb and Johnson, 2006).

The six successive deformation phases presented here encompass disparate far-field tectonic driving forces over some ~270 million years, and thus we infer that a deep-rooted crustal fabric (possible a terrane boundary or series of arc-system boundaries) favored multiphase reactivation of the EGFZ. Such occurrences are documented in other rifted regions (e.g., South Africa, South America; Tommasi and Vauzech, 2001; Paton, 2006), suggesting that the propagation of deformation is not random, but rather controlled by orogenic fabrics and structure within the lithosphere.

6. Conclusions

Six main deformation phases are linked to the EGFZ, beginning with late Paleozoic continental assembly of southeastern Mongolia via arc and terrane accretion, four phases of Mesozoic reactivation including Triassic sinistral shear, early Jurassic contraction, Late Jurassic-Early Cretaceous extension, mid-Cretaceous inversion (oblique contraction), and finally left-lateral strike-slip in the Paleogene. Sedimentary basin response to each of these is recorded in stratigraphic fill as well as unconformities and cross cutting and overlapping relationships with structures. Despite the obvious complexity associated with this long-lived intracratonic deformation zone, these discrete features and phases are elucidated by a multi-proxy approach that incorporates outcrop to subcrop correlations, fault generation maps, and published analytical data. Tectonic drivers for these phases largely reflect far-field and plate boundary effects of the ongoing Mesozoic-Cenozoic growth of Eurasia, although the causes of some remain enigmatic. Polyphase reactivation of the EGFZ is likely controlled by basement structures and fabrics inherited from previous deformation events, which define the strong northeast fabrics of the EGB.

Acknowledgements

This work was supported by the National Science Foundation – United States grant numbers EAR-0537318 to C. Johnson and EAR-0537165 and EAR-0929902 to L. Webb. The research also benefited from a Petroleum Research Fund (American Chemical Society) grant 40193-G8 to C.L. Johnson. We thank Joshua Taylor, Ian Semple and Megan Frederick for their help in the field during the 2006–2009 field seasons. We also thank Bolortsetseg Minjin, director of the Institute for the Study of Mongolian Dinosaurs, Ivanhoe Mines, and Rio Tinto for logistical support while in South Gobi in our 2005–2008 field seasons. IHS, Halliburton, and ESRI provided academic licenses of interpretation software that made this study possible. Thorough reviews and editorial comments by John Bartley, Michel Faure, and Bradley Ritts greatly

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