Sedimentary record and tectonic implications of Mesozoic rifting in southeast Mongolia

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ABSTRACT

The East Gobi basin of Mongolia is a poorly described Late Jurassic–Early Cretaceous extensional province that holds great importance for reconstructions of Mesozoic tectonics and paleogeography of eastern Asia. Extension is especially well recorded in the structure and stratigraphy of the Unegt and Zuunbayan subbasins southwest of Saynshand, Mongolia, where outcrop and subsurface relationships permit recognition of prerift, synrift, and postrift Mesozoic stratigraphic megasequences. Within the synrift megasequence, three sequences developed in response to climatic and rift-related structural controls on sedimentation. Where best exposed along the northern margin of the Unegt subbasin, each of the synrift sequences is bounded by unconformities and generally fines upward from basal alluvial and fluvial conglomerate to fluvial and lacustrine sandstone and mudstone. Resedimented ashes and basalt flows punctuate the synrift megasequence. Rifting began in the Unegt subbasin prior to 155 Ma with coarse alluvial filling of local fault depressions. Subsidence generally outstripped sediment supply, and fresh to saline lacustrine environments, expanding southward with time, dominated the Unegt-Zuunbayan landscape for much of latest Jurassic–Early Cretaceous time. Episodic faulting and volcanism characterized the basin system for the balance of the Early Cretaceous. A brief period of compressional and/or transpressional basin inversion occurred at the end of the Early Cretaceous, prior to deposition of a widespread Upper Cretaceous overlap sequence.

The driver(s) of Late Jurassic–Early Cretaceous extension remain uncertain because southeast Mongolia occupied an intraplate position by the beginning of the Cretaceous. Extension in the East Gobi basin was coeval with collapse and extension of early Mesozoic contractional orogenic belts along the northern and southern borders of Mongolia and probably was a linked phenomenon. Strike-slip faulting associated with collisions on the southern Asian and Mongol-Okhotsk margins likely also played a role in late Mesozoic deformation of the East Gobi region, perhaps partitioning the Gobi from apparently coeval large-magnitude contractional deformation in the Yinshan-Yanshan orogenic belt south of the study area in Inner Mongolia.

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INTRODUCTION

Rifting, usually ascribed to extension in the backarc region of the Pacific margin, dominated much of eastern China during the late Mesozoic (e.g., Watson et al., 1987). The most obvious manifestation of this period of extension is a family of well-developed rift basins in eastern China (Chen and Dickinson, 1986; Liu, 1986) (Fig. 1) that contain the majority of the petroleum reserves of China, notably Daqing oil field in Songliao basin. As a result, the structure and fill of the Chinese extensional basins are relatively well known (e.g., Ma et al., 1989; Zhai, 1993).

This family of Mesozoic extensional basins extends into Mongolia, >1000 km from the Pacific margin (Fig. 1). Various broad discussions of the Mesozoic basins of southeast Mongolia have characterized them as extensional or transtensional (e.g., Traynor and Sladen, 1995; Zorin, 1999), but comparatively little substantiating evidence has been published in either the Russian-Mongolian–language or English-language literature. This lack of documentation is an important matter, because Mongolia spans the region between the realm of Mesozoic contractional tectonism of western China and that of extensional tectonism of eastern China (Zhang et al., 1984; Chen and Dickinson, 1986; Watson et al., 1987). In addition, a temporal change from compression to extension is recorded in the Jurassic geology of southern Mongolia (Graham et al., 1996; Hendrix et al., 1996; Zheng et al., 1996; Johnson et al., 2001). Thus, a more detailed consideration of the evolution of the rift basins may illuminate the timing and causes of these tectonic changes. Finally, because the only proven oil fields in Mongolia occur in Mesozoic strata of eastern Mongolia, a more explicit documentation of the region will permit better forecasting of the petroleum resource potential.

In this paper, we present the results of our field studies of Jurassic–Cretaceous strata of southeast Mongolia (Figs. 1, 2). We sought (1) to test the hypothesis that these strata are rift-related, (2) to describe synrift sequence-stratigraphic architecture, (3) to interpret synrift depositional systems, and (4) to assess the influence of tectonics and climate on rift-fill evolution. To accomplish these goals, we visited all major outcrops of Jurassic and Cretaceous strata in the Gobi region in 1993–1995 and 1997–1998, and we examined core and reflection seismic lines from the region. On the basis of our findings and interpretations, we conclude this paper with a discussion of the Mongolian rift basins in the larger context of the tectonics of Mesozoic eastern Asia.

Basin Structure in the Gobi Region

The southeastern quadrant of Mongolia (Fig. 1) makes up much of the region termed the ‘‘Gobi Desert’’ (also spelled ‘‘Govi’’ in some transliterations). Little Cenozoic sedimentary rock cover is preserved in southeast Mongolia, so the Upper Cretaceous postrift sequence, famed for its remarkable dinosaur fauna (e.g., Berkey and Morris, 1927; Novacek et al., 1994; Dashzeveg et al., 1995), is widely exposed over the entire region (Fig. 1). Upper Jurassic–Lower Cretaceous synrift facies are exposed along the margins of many uplifts, and a few spectacular badlands-style exposures permit close study of the synrift facies. No geologic maps more detailed than 1:1 500 000 have been published, although unpublished recent mapping is available for some areas.

Areas covered by Upper Cretaceous strata generally reflect residual structural and/or topographic depressions within a broad region rifted during the Late Jurassic–Early Cretaceous (Fig. 1). Although few of these depressions have been studied in detail, most are probably underlain by grabens and half grabens, typically 100 to several hundred kilometers in length, 20–50 km in width, and filled with 1–3 km of synrift and postrift strata (Figs. 1–4). Taken together, this family of depressions in Mongolia is termed the Gobi basin, and it appears to be the continuation of the Erlian basin of China (Jerzykiewicz and Russell, 1991; Traynor and Sladen, 1995), although the two are separated by the large Toto Shan basement block (also called Hutag Uul) (Fig. 1). Mongolian and Russian workers sometimes divide the Gobi basin into several smaller basins, including the South and East Gobi basins, although the structural basis for this subdivision is not well established. Neither balanced structural cross sections nor estimates of total extension across the Gobi basin are available, but extension of 20%–40% was suggested as typical in adjacent China by Sladen and Traynor (2000).

Pre-Mesozoic basement rocks of southeast Mongolia are heterolithic and structurally complex, reflecting their origins as diverse terranes that were accreted to Eurasia during the Paleozoic (Lamb and Badarch, 1997; Badarch and Orolmaa, 1998). Paleozoic accretion imparted a structural fabric that rifting followed in the Mesozoic (Traynor and Sladen, 1995). Inherited structural controls on younger deformation such as in this instance are common in Asia, where polycyclic deformation typically follows the fabric of accretionary substrates (Graham et al., 1993).

The presence of unexposed rift basins is inferred from maps of the structure of the basement (i.e., usually the top of the Paleozoic), based on regional gravity surveys, measurement of outcropping sedimentary sections, and limited borehole and reflection seismic data (Fig. 4). Seismic data in the vicinity of Tsagaan Els and Zuunbayan oil fields provide critical evidence of the style and timing of structural development. The seismic line in Figure 3 images the Tsagaan Els antiformal uplift, which is dominated by normal-fault tilt blocks indicating northwest-southeast extension, consistent with fault azimuths observed in adjacent outcrops (Figs. 1, 2). Structural closure for petroleum entrapment was enhanced by an episode of postrift structural inversion (Traynor and Sladen, 1995), reflected by drag folding developed in response to inversion uplift (Fig. 3). Significantly, both rift and inversion structures are overlapped by undeformed Upper Cretaceous strata, as is evident on both seismic lines (Fig. 3) and geologic maps of southeast Mongolia (Figs. 1, 2).

The timing of extension in southeast Mongolia currently is best inferred from studies of Mesozoic volcanic rocks. These are described as bimodal basalt-rhyolite (often alkalic or subalkalic) localized in grabens and along faults and are inferred to be related to mantle-plume upwelling and continental rifting (Filippova et al., 1984; Enkhtuvshin, 1999; Kovalenko et al., 1995; Geral, 1998). These rocks constitute part of the South Hangay and East Mongolia volcanic provinces of Kovalenko et al. (1995), which include Late Jurassic and Early Cretaceous (155–140; 136–120; 122–115; 118–105 Ma) phases of volcanism.

The Zuunbayan fault is the most prominent fault in southeast Mongolia on the 1:1 500 000 geologic map of Mongolia (Yanshin, 1989); the fault forms the northwestern boundary of the Toto Shan block (Fig. 1). Mapped as cutting Lower Cretaceous but not Upper Cretaceous strata (Fig. 1), recent unpublished mapping at 1:50 000 by local Mongolian mapping teams (G. Altagerel, 1998, personal commun.; J. Olziybayan and G. Bomoboroo, 1999, personal commun.) depict the fault with much less surface continuity than the 1:1 500 000 geologic map. The fault forms the southern boundary of a linear array of connected subbasins from the Zuunbayan subbasin in the northeast to the Galb Govi subbasin in the southwest (Figs. 1, 2); thus, it

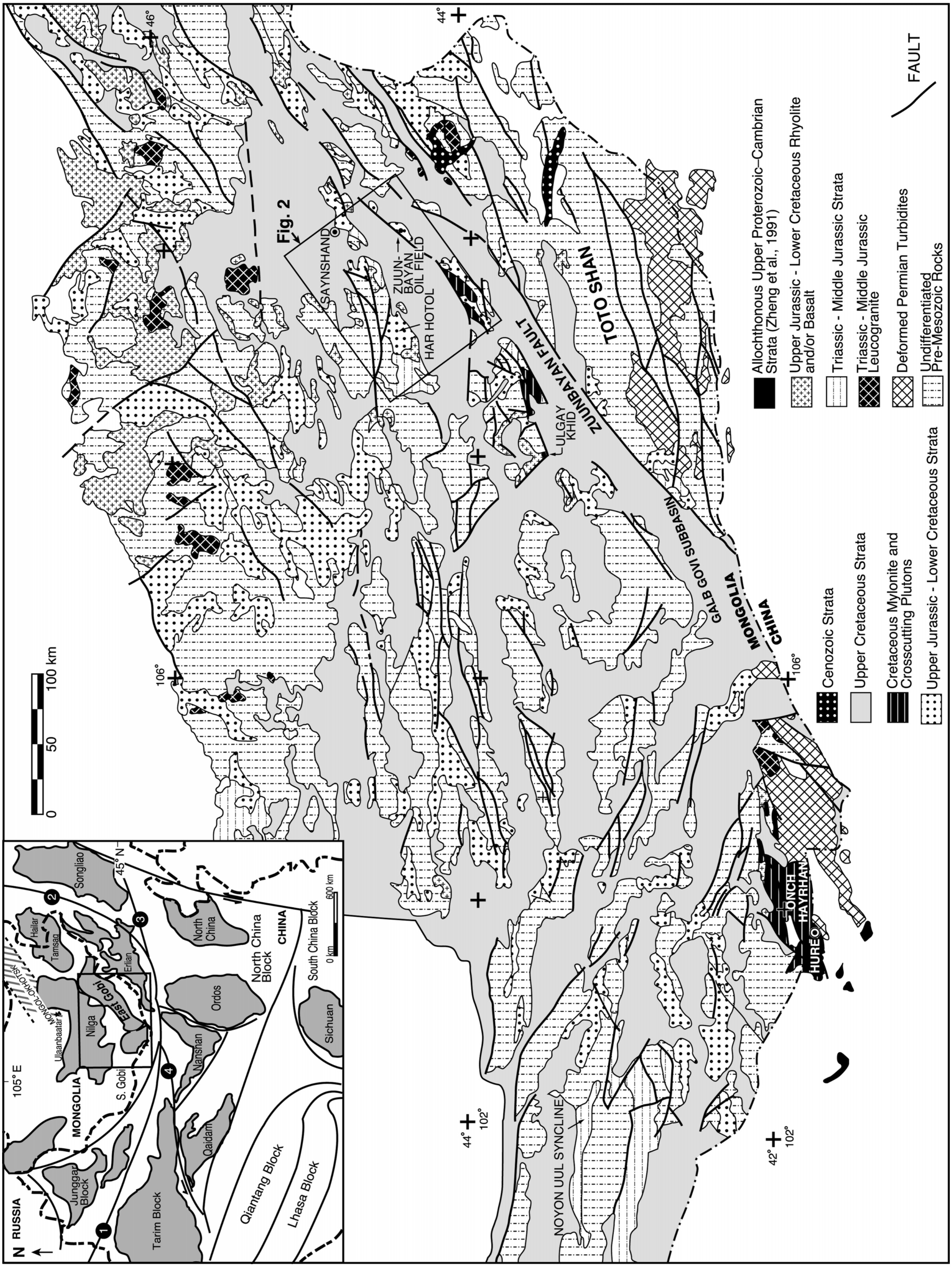


Fig. 2
SAYNSHAND
ZUUN-BAYAN OIL FIELD
HAR HOTOL
ZUUNBAYAN FAULT
TOTO SHAN
ULGAY KHID
GALB GOVI SUBBASIN
MONGOLIA
CHINA
ONCH HAYRHAN
HUREO
NOYON UUL SYNCLINE
0 50 100 km
46°
44°
42°
106°
102°
Allochthonous Upper Proterozoic–Cambrian Strata (Zheng et al., 1991)
Upper Jurassic - Lower Cretaceous Rhyolite and/or Basalt
Triassic - Middle Jurassic Strata
Triassic - Middle Jurassic Leucogranite
Deformed Permian Turbidites
Undifferentiated Pre-Mesozoic Rocks
Cenozoic Strata
Upper Cretaceous Strata
Cretaceous Mylonite and Crosscutting Plutons
Upper Jurassic - Lower Cretaceous Strata
FAULT
N
RUSSIA
MONGOLIA
CHINA
105° E
45° N
Ulaanbaatar
Nilga
East Gobi
S. Gobi
Tamsag
Hailar
Erlian
Songliao
North China
North China Block
Ordos
Nanshan
Qaidam
Junggar Block
Tarim Block
Qiantang Block
Lhasa Block
South China Block
Sichuan
MONGOL-OKHOTSK
0 km 600 km
1
2
3
4

may be the master half-graben bounding fault for all of these Mesozoic basins. The length, linearity, and presumed continuity of the Zuunbayan fault, as well as its regional tectonic context, hint at a possible strike-slip history. Suvorov (1982) suggested that the Zuunbayan fault was active as a left-slip fault principally in the Mesozoic, and Lamb et al. (1999) argued that it accrued 185–235 km of left slip during the Mesozoic on the basis of offset belts of Paleozoic rocks and fault-overlap relationships. In contrast, Yue and Liou (1999) posited 400 km of Cenozoic left-slip on the fault (their ''East Mongolia fault system'').

Mesozoic Stratigraphy

Mongolian and Russian geologists and paleontologists have established a stratigraphic framework for the Mesozoic of the Gobi region (e.g., Martinson et al., 1969; Martinson and Shuvalov, 1973; Shuvalov, 1975; Sochava, 1975), which remains reconnaissance in nature owing to remoteness, poor exposure, and problems attendant with nonmarine strata such as rapid facies changes and poor chronostratigraphy. Traynor and Sladen (1995) couched Mongolian stratigraphy in a modern sequence stratigraphic framework by emphasizing stratigraphic megasequences bounded by unconformities and tied to tectonic episodes or phases.

The Upper Jurassic–Lower Cretaceous stratigraphic megasequence (megasequence 4 of Traynor and Sladen, 1995), the focus of this paper, developed during rifting and is an exclusively nonmarine sequence of alluvial, fluvial, and lacustrine strata with interbedded basaltic and felsic flows and tuffs. Unfortunately, few of the volcanic rocks have been radiometrically dated, and faunal and floral endemism in the Gobi region during parts of the Mesozoic make correlations difficult, even when fossils are present (Jerzykiewicz and Russell, 1991). In addition, the Russian approach of erecting ''suites'' with chronostratigraphic significance works relatively poorly below the megasequence level in small isolated half grabens in which nonmarine facies can vary rapidly and fossils usually are quite rare or nonage diagnostic. Jerzykiewicz and Russell (1991), in the most extensive and best-documented discussion of Mesozoic stratigraphy of Mongolia in the English-language literature, employed a dual rock-stratigraphic and biostratigraphic nomenclature (Fig. 5).

Figure 1. Geology of the East Gobi basin region of southeast Mongolia, simplified from Yanshin (1989) to emphasize lithologic and tectonic elements that are key to Mesozoic rifting. Inset map: Schematic map of sedimentary basins (shaded) of China and Mongolia; box shows location of larger map of this figure. Tectonic blocks, suture zones, and faults (modified from Li [1982] and Watson et al. [1987]): 1—Junggar (Tian Shan) suture, 2—Hegen suture, 3—Yinshan-Yanshan orogenic belt, 4—Altyn Tagh fault.

Despite these correlation problems, there has been a certain consistency in nomenclatural practice, which we think reflects a regional sedimentary response to climatic and rift tectonic events as previously proposed by Traynor and Sladen (1995). Hence, in this paper we elect to de-emphasize traditional stratigraphic names in favor of a nomenclature couched in terms of genetic sequence stratigraphy and chronostratigraphy, and so we subdivide the synrift megasequence of our study area into stratigraphic sequences SR-1 through SR-3. For ease of comparison, we correlate the nomenclature we have used in the Unegt and Zuunbayan subbasins with traditional formation names in Figure 5. Our usage is shaped by new radiometric ages that we present in this paper. These ages are important and illuminating. They indicate that, in some cases, previous stratigraphic assignments in our study area are in error by as much as 40 m.y.!

GEOLOGY OF THE UNEGT AND ZUUNBAYAN SUBBASINS

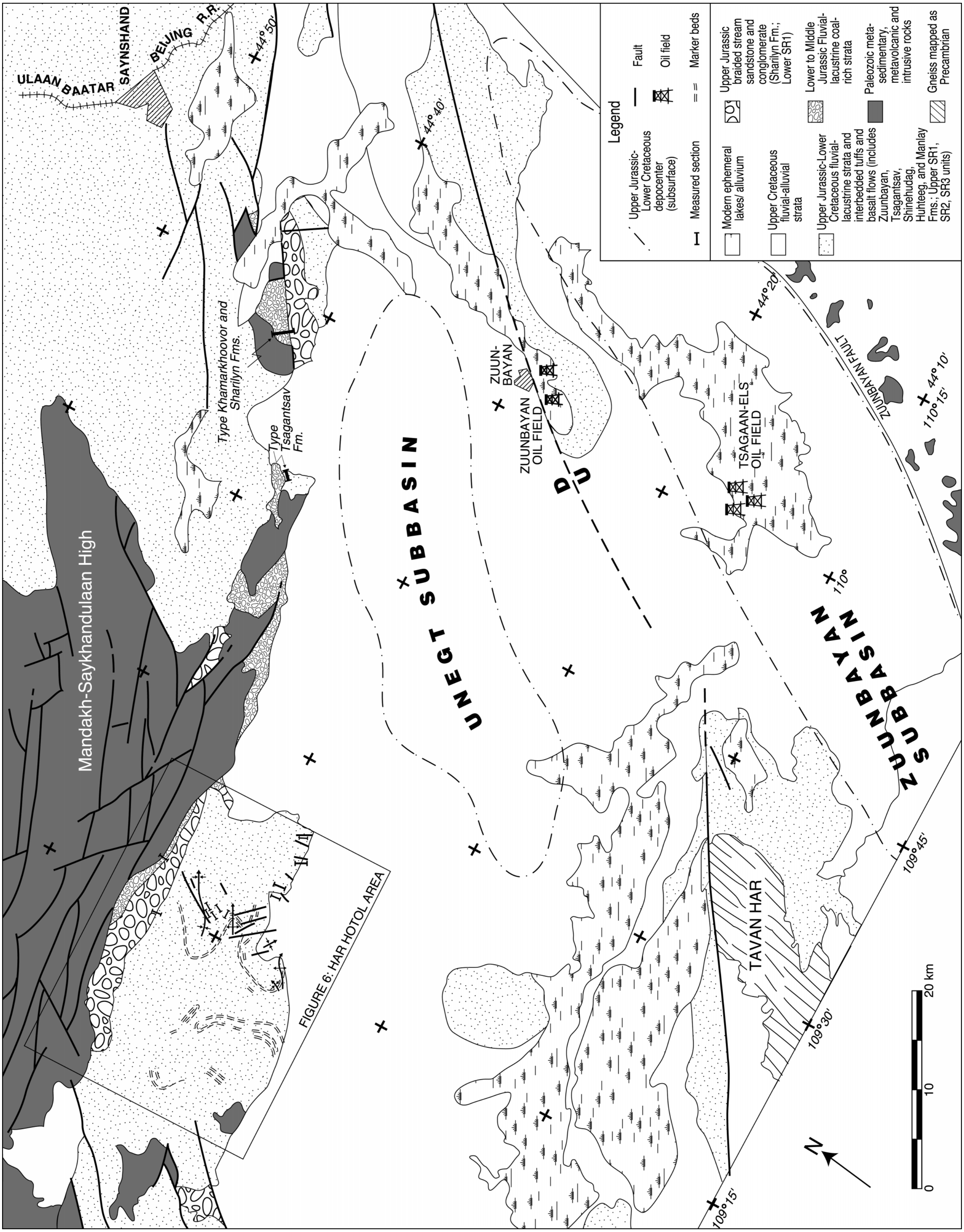
The linked Unegt-Zuunbayan subbasin pair (Figs. 1, 2) is the best locality for study of rifting in the East Gobi basin because (1) structural inversion after rifting created locally excellent exposures of synrift strata (Figs. 2, 6), and (2) it contains the only oil fields in southeast Mongolia—Zuunbayan and Tsagaan Els, discovered in 1941 and 1953, respectively (Pentilla, 1992, 1994); therefore, some borehole and seismic data exist. Our field studies in 1993–1995 and 1997–1998 included measurement of stratigraphic sections and local mapping, particularly in the northwest corner of the Unegt subbasin in an area called ''Har Hotol'' (Fig. 2; ''Black Pass'').

Subbasin Structure

Pre-Mesozoic basement rocks consist of sedimentary and slightly to highly metamorphosed rocks reflecting a complicated history of accretionary tectonics. The Tavan Har uplift (Fig. 2), cored by schistose-gneissic-mylonitic quartzofeldspathic rocks mapped as Precambrian on the basis of metamorphic grade, has been taken as the easternmost exposure of the South Gobi microcontinent (Lamb and Badarch, 1997), but it includes a mylonite zone dated as latest Triassic (209 ± 2 Ma, Lamb et al., 1999). By far the most extensively exposed pre-Mesozoic rocks are Devonian–Carboniferous volcanic and volcaniclastic rocks, locally metamorphosed to greenschist grade, which are associated with the late Paleozoic South Mongolia arc system described by Lamb and Badarch (1997). These make up the exposed basement of the Mandakh-Saykhandulaan high to the north of Har Hotol (Fig. 2).

In general, a network of northeast–striking curviplanar faults cuts the region of the Unegt-Zuunbayan subbasins (Figs. 1, 2). The Har Hotol outcrop area apparently is separated from the main Unegt subbasin by blind faults (Fig. 4), and a structural high partitions the Unegt and Zuunbayan subbasins. Mesozoic strata as thick as 3 km may be present in intervening depressions, although nowhere has the full section been penetrated by drilling. More typically, subbasin fill is 1–2 km thick. Pre-Mesozoic basement of the structural partition between the two subbasins crops out at Tavan Har (Fig. 2). The northeast continuation of the Tavan Har trend partitioned the Unegt and Zuunbayan subbasins at times during rifting as shown by our analysis of proprietary seismic data. The Zuunbayan oil field structure is a complexly faulted anticline that developed on the southeast side of the partition (Fig. 2). It formed during pre–Late Cretaceous inversion in response to compression against the backstop formed by the partition. Our study of a lengthy core cut through the reservoir section in the Zuunbayan field revealed thick successions of depocenter facies (e.g., lacustrine facies, Fig. 7B), confirming inversion from a depocenter to a partition position. Tsagaan Els oil field (Figs. 2, 3) occurs on a structural nose within the Zuunbayan subbasin. It is underpinned by a tilt block that was covered during synrift deposition. Later, the structure was mildly inverted, especially on its eastern limb, where a thrust fault displaced strata cut by synrift normal faults (Fig. 3).

Evidence of progressive rifting is found in subcrop and outcrop stratal geometries. In the subsurface of the oil fields, early rift faults show stratal growth, and the entire synrift section is cut by normal faults (Fig. 3), indicating that faulting occurred there still later in the Early Cretaceous, according to new $^{40}Ar/^{39}Ar$ age determinations (whole rock) of 126 ± 1


ULAAN BAATAR
SAYNSHAND
BEIJING R.R.
44°50'
44°40'
44°20'
44°10'
110°15'
110°
109°45'
109°30'
109°15'
Mandakh-Saykhandulaan High
Type Khamarkhoovor and Sharilyn Fms.
Type Tsagantsav Fm.
ZUUN-BAYAN
ZUUNBAYAN OIL FIELD
TSAGAAN-ELS OIL FIELD
UNEGT SUBBASIN
ZUUNBAYAN SUBBASIN
ZUUNBAYAN FAULT
D
U
TAVAN HAR
FIGURE 6: HAR HOTOL AREA
N
0
10
20 km
Legend
Upper Jurassic-Lower Cretaceous depocenter (subsurface)
Fault
Oil field
Measured section
Marker beds
Modern ephemeral lakes/ alluvium
Upper Cretaceous fluvial-alluvial strata
Upper Jurassic-Lower Cretaceous fluvial-lacustrine strata and interbedded tuffs and basalt flows (includes Zuunbayan, Tsagantsav, Shinehudag, Huhteeg, and Manlay Fms.; Upper SR1, SR2, SR3 units)
Upper Jurassic braided stream sandstone and conglomerate (Sharilyn Fm.; Lower SR1)
Lower to Middle Jurassic Fluvial-lacustrine coal-rich strata
Paleozoic meta-sedimentary, metavolcanic and intrusive rocks
Gneiss mapped as Precambrian

and 127 ± 2 Ma from tuffs cored in a Zuunbayan field well (Fig. 8). In an outcrop in the southwestern Har Hotol area, aerial photos reveal that folded ash marker beds are truncated beneath synrift conglomerate (lower left corner of Fig. 6). At ground level, outcrops are too poor to unambiguously determine whether this relationship is an angular unconformity or postdepositional shearing, but if the former, our new $^{40}Ar/^{39}Ar$ age of 155 ± 1 Ma for one of the ash beds and a 131 ± 1 Ma age for an overlying synrift basalt (Fig. 8) indicate that the angular unconformity developed in latest Jurassic to earliest Cretaceous.

An episode of structural inversion associated with at least minor shortening occurred prior to the cessation of deformation but before deposition of the Upper Cretaceous overlap sequence (cf. Pentilla, 1992). Reflection seismic profiles demonstrate that rift-phase structures were the loci of nucleation for later shortening, leading to structural inversion (Fig. 3). The overlap megasequence was deposited near the onset of the Late Cretaceous, although poor faunal control in the basal element, the Saynshand Formation, precludes precise dating (Jerzykiewicz and Russell, 1991). In the Unegt-Zuunbayan area, these beds are little deformed and nearly flat lying in most places, as shown on the seismic line of Figure 3. Thus, rift deformation and inversion were completed by about the start of the Cenomanian (Fig. 5, ca. 98 Ma).

In sum, current data, including our new radiometric dates, permit the following structural interpretation. Rifting commenced in Late Jurassic, prior to 155 Ma, and structural development likely was influenced by late Paleozoic basement structures. Rift deformation, in multiple phases, continued through the Early Cretaceous. The Unegt and Zuunbayan subbasins are structurally partitioned and likely were separate depocenters at times during rifting. A phase of basin inversion, reactivating some normal faults as reverse faults, occurred in late Early Cretaceous prior to 100 Ma and enhanced the structural partition that now separates the two subbasins. Thereafter, deformation waned and an Upper Cretaceous overlap sequence accumulated. Strike-slip faulting during rifting and/or inversion is possible, even likely, on the basis of flower structures we have observed on proprietary reflection seismic data.

Figure 2. Geologic map of the Unegt and Zuunbayan subbasins of the East Gobi basin, simplified from unpublished 1:200 000 mapping by the Mongolian Academy of Sciences (1985) and modified by our mapping in the Har Hotol area.

Stratigraphy and Facies of the Subbasins

We have developed a composite stratigraphic column, based on field measurements and new geochronologic data, for the northern margin of the Unegt subbasin (Fig. 9). The section derives largely from the contiguous 2.2-km-thick outcrop section of synrift strata at Har Hotol, but also includes important elements from the type sections of the Khamarkhoovor (Fig. 10A), Sharilyn (Fig. 10B), and Tsagantsav (Fig. 10F) Formations on the northeast basin margin (Fig. 2).

Lower to Middle Jurassic Prerift Megasequence

The Mesozoic synrift megasequence rests unconformably on Paleozoic rocks in many places along the exposed margins of basement uplifts. Locally, however, and especially along the northern margin of Unegt subbasin, a nonmarine Lower to Middle Jurassic prerift stratigraphic megasequence occurs that is typically less than 1 km thick. We measured the upward-fining Khamarkhoovor Formation where best exposed at its type locality in the northeast corner of the basin (Figs. 2, 9, 10A). Overlying the basal sandstone-conglomerate member is a generally fine-grained sequence of shale, carbonaceous shale, sandstone, and thin coal seams (Fig. 10A). The coal beds distinguish this sequence from younger Mesozoic strata, all of which lack coal beds in outcrop in the Unegt and Zuunbayan subbasins.

We interpret the megasequence to reflect sandy braided-stream settings that evolved to meandering-stream flood-plain and palustrine environments. Imbrication and cross-bedding are south directed (Fig. 9), consistent with a position along the northern basin margin, and conglomerate consists of metagraywacke clasts derived from basement to the north. From these findings it is apparent that a depocenter toward which these streams flowed existed to the southwest in the direction of the center of the modern Unegt subbasin. These prerift Lower to Middle Jurassic beds are coeval with an extensive foreland-basin sequence exposed to the west at Noyon Uul (Hendrix et al., 1996, 2001) (Fig. 1), and although now isolated in outcrop, it is possible that they originally were part of the same basin system. Fluvial-lacustrine sequences and coaly intervals indicate that a humid environment prevailed during deposition of the prerift Mesozoic megasequence, consistent with organic-rich Lower to Middle Jurassic strata that are well developed elsewhere in Mongolia and adjacent China (Hendrix et al., 1992, 1996; Graham et al., 1997).

Upper Jurassic–Lower Cretaceous Synrift Megasequence

The synrift stratigraphic megasequence exposed along the northern margin of the Unegt subbasin consists of sedimentary and volcanic rocks well over 2 km thick (Fig. 9). However, stratal truncation patterns indicate that the youngest synrift facies were eroded from the northern basin margin prior to deposition of the Upper Cretaceous overlap megasequence. The youngest synrift strata, rocks of late Early Cretaceous age, are exposed poorly elsewhere along the basin margin, as at Tavan Har and around the Zuunbayan and Tsagaan Els oil fields (Fig. 2). Conglomerate tends to occur abruptly in discrete stratigraphic packets overlying unconformities within the synrift megasequence, signaling coarse-grained pulses of sedimentation likely related to basin structural events. Hence, they form a reasonable basis for subdividing the synrift megasequence into several stacked synrift sequences (SR-1, SR-2, SR-3) reflecting stages of rift evolution, as previously suggested by Traynor and Sladen (1995).

To provide a chronostratigraphic framework for the synrift sequence, we have begun a campaign of radiometric dating of the basalt flows and numerous ashes in the section (Figs. 8, 9). A thick, prominent, orange-colored, very slightly reworked, tuffaceous sandstone that forms an important stratigraphic marker yielded a $^{40}Ar/^{39}Ar$ date on biotite of 155 ± 1 Ma (sample 94-HH-26C). One of the basalt flows in the Har Hotol basalt sequence yielded a $^{40}Ar/^{39}Ar$ age on plagioclase of 131 ± 1 Ma (93-HU-22), and a basalt at the base of the type section of the Tsagantsav Formation contains plagioclase dated by $^{40}Ar/^{39}Ar$ at 126 ± 1 (93-TS-1) Ma (Figs. 8, 9). Thus, the northern-basin synrift section is equivalent to the Sharilyn and Tsagantsav Formations of Jerzykiewicz and Russell (1991) and Badamgarav et al. (1995) (Fig. 5). Our new dates clarify much past confusion: The 131 ± 1 Ma basalt has been proposed to be pre-Tsagantsav (i.e., Tithonian) on the basis of an insect fauna (A.G. Ponomarenko, 1998, personal commun.), but is mapped as Saynshand Formation (i.e., Cenomanian) on 1:200 000 unpublished interagency mapping (G. Bomboroo, 1999, personal commun.); the underlying section enclosing the 155 ± 1 Ma ash has been considered Shinehudag Formation (i.e., late Neo-

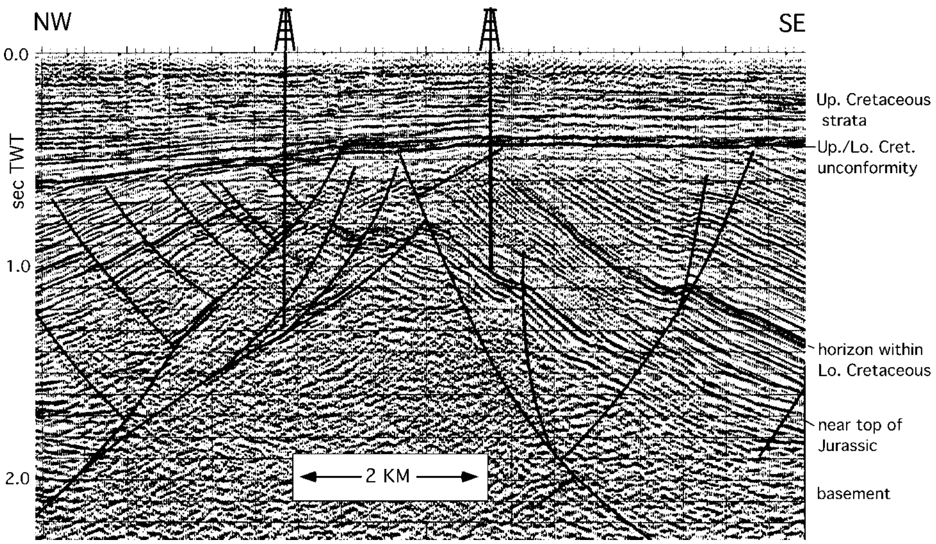


Figure 3. Northwest-southeast–oriented reflection seismic profile across Tsagaan Els oil field. See Figure 2 for location of seismic line. The section is a migrated time section from data collected in the 1980s and reprocessed in 1995. The seismic section reveals a thick Upper Jurassic–Lower Cretaceous synrift sequence cut by late-rift normal faults in part subsequently reactivated as reverse faults during inversion prior to deposition of the Upper Cretaceous overlap megasequence. TWT—two-way traveltime.

comian–Aptian) on the basis of ostracods (Y. Khand, 1995, personal commun.).

First Synrift Sequence (SR-1). Facies, grain size, and chronostratigraphic correlation to rift-attributed volcanic sequences elsewhere in southeast Mongolia (e.g., Kovalenko et al. 1995) form the basis for our assignment of this unit to the synrift megasequence, although we currently lack outcrop or subcrop data that conclusively demonstrate that SR-1 is a synrift deposit. SR-1 is an overall upward-fining siliciclastic sequence that is 1.35 km thick at Har Hotol (Fig. 9). The basal 200–300 m of the sequence is pebble to cobble conglomerate conventionally mapped as Sharilyn Formation. At the type section at Sharilyn Uul (Fig. 2), the conglomerate appears to rest with angular unconformity on the Lower to Middle Jurassic prerift megasequence, although the contact locally is sheared. The pebble-cobble-boulder conglomerate is grain supported, moderately to poorly sorted, and massive to imbricated (Figs. 10B, 11A). Maximum clast size is 1.5 m, and the clasts are significantly larger than those in prerift conglomerates, indicating that they have not simply been reworked from the prerift Mesozoic sedimentary sequence. Clasts are composed of pre-Mesozoic basement rocks and appear to lack synrift volcanic types.

We interpret the basal SR-1 conglomerate as the deposits of braided streams or the upper reaches of stream-dominated fan systems on the basis of the dominance of very coarse grained, organized to poorly organized conglomerate (e.g., DeCelles et al., 1987; Blair and McPherson, 1994). The section lacks matrix-supported units that might be interpreted

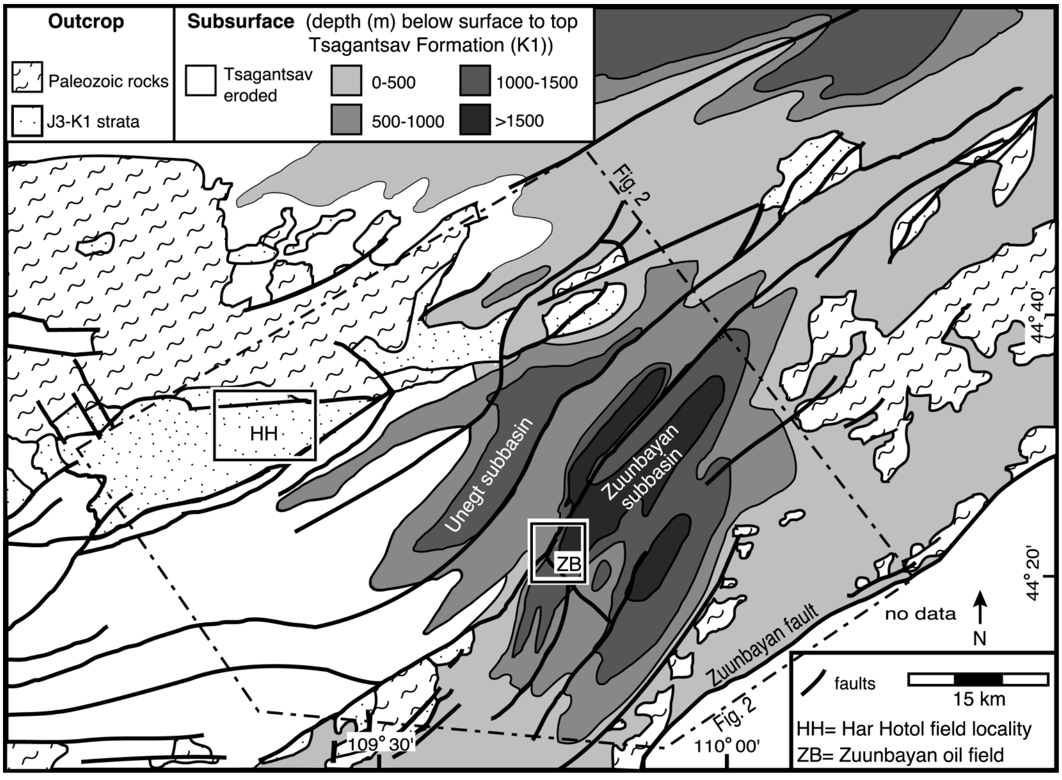


Figure 4. Subsurface structure map of the top of the Tsagantsav Formation (Lower Cretaceous) of the Zuunbayan and Unegt subbasins, East Gobi basin (Shirakov and Kopytchenko, 1983). Shaded contours represent meters below present-day ground surface to the top of the Tsagantsav Formation, as compiled from outcrop, seismic, magnetic, and borehole data. See Figure 1 for location encompassing the Figure 2 location. Har Hotol area is mapped in Figure 6.

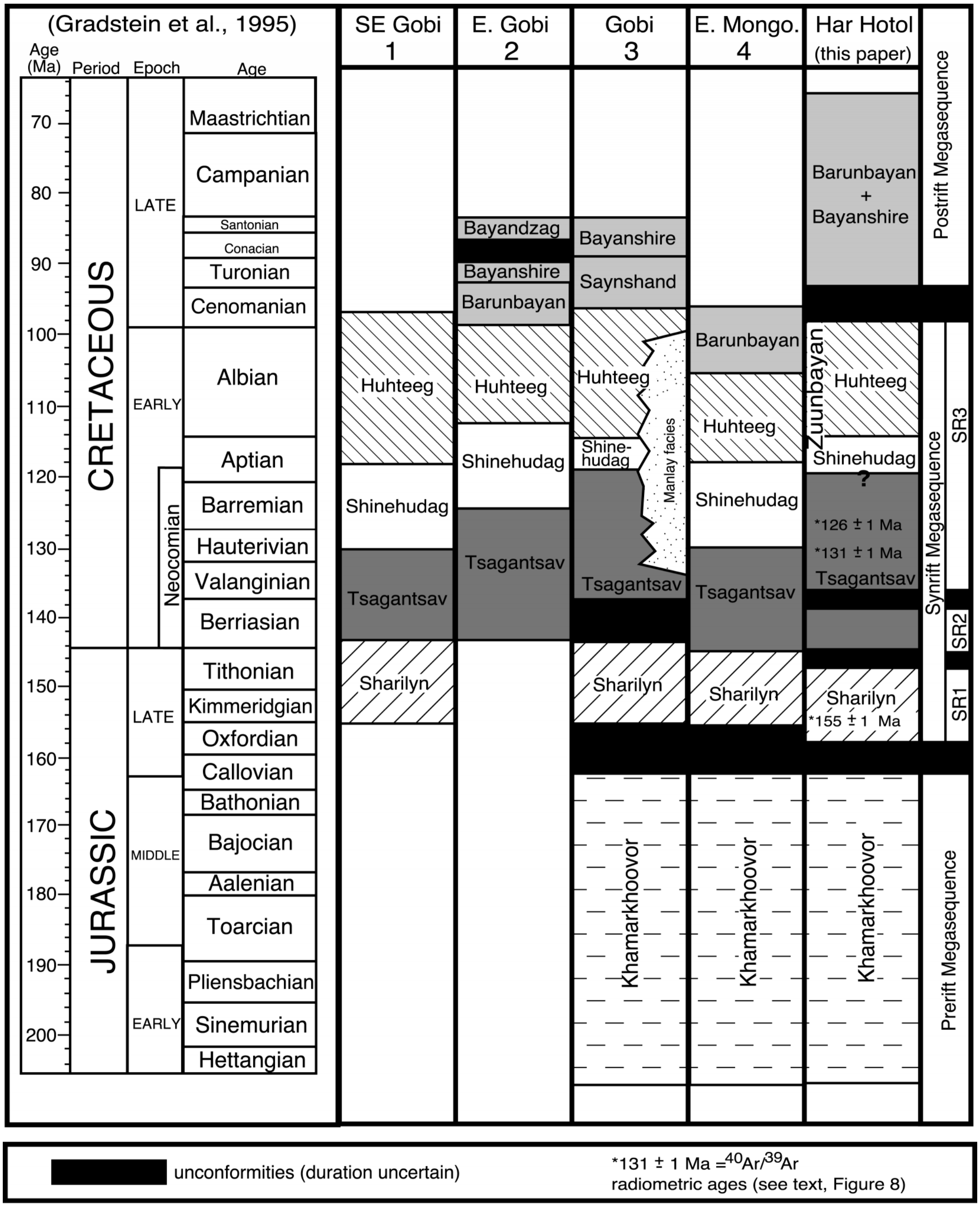


Figure 5. Comparison of stratigraphic nomenclature used in southern Mongolia. References for columns: 1—Martinson and Shuvalov (1973), 2—Badamgarav et al. (1995), 3—Jerzykiewicz and Russell (1991), 4—Yamamoto et al. (1993), 5—this study. Shading and patterns are only intended to facilitate correlation and do not signify lithology.

as debris-flow deposits. Provenance, clast size, lack of fines, and paleocurrent indicators (Fig. 9) suggest that stream headwaters lay at most a few kilometers to the north.

The basal conglomerate abruptly fines upward to a very poorly exposed section that contains red and green mudstone with some nodular carbonate horizons we interpret as Calcisols (cf., Mack et al., 1993). Above ~800 m in the SR-1 section at Har Hotol (Fig. 9), exposures improve dramatically in a set of rimrock cliffs (the ''amphitheater'' section of Johnson et al., 2000; circled ''A'' in Fig. 6). The section begins with an ostracod-bearing gray mudstone section containing rare decimeter- to 2-m-thick fine sandstones that thicken and become more numerous upward (Figs. 9, 10C). The sandstone beds sometimes are graded, but are pervasively characterized by soft-sediment deformation (Fig. 10C). The lower part of the amphitheater cliff section consists of thinly interbedded, very fine grained sandstone and siltstone bundled in lenticular packages up to a few meters thick and tens of meters wide. The upper half of the amphitheater cliff is made of fine- to medium-grained sandstone that occurs in channel-form bodies, scour fills, and lenticular wedges (Figs. 10C, 11B). These sandstone bodies in many places consist entirely of stacked sets of ripple-drift deposits, and soft-sediment deformation is very common to pervasive. West of the amphitheater, the section is dominantly shaly (Johnson et al., 2000). Paleocurrent indicators suggest flow to the south and west (Fig. 9). The amphitheater cliffs are capped by the prominent orange tuffaceous cross-bedded and rippled sandstone unit that we have dated at 155 ± 1 Ma (Fig. 9). Silicified transported logs are common to abundant in the upper part of the amphitheater section. Disarticulated dinosaur remains, the oldest and first Jurassic

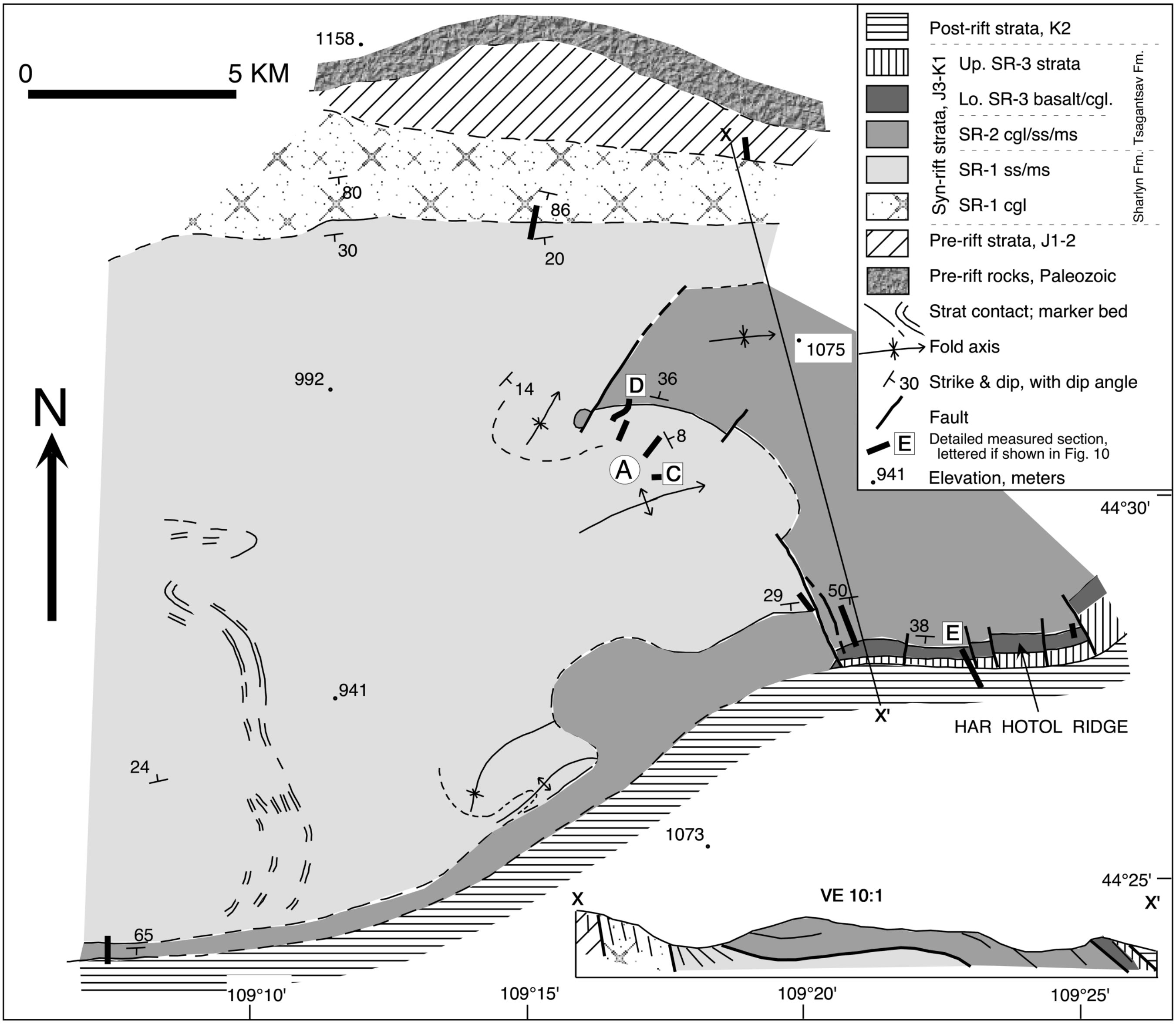


Figure 6. Geologic map of the Har Hotol area based on field investigations in 1993–1995, 1997–1998. Circled "A" location is termed the "amphitheater" in the text. See Figure 2 for location.

remains found in southeast Mongolia, occur at the base of the amphitheater cliff (Fig. 10C).

We interpret the amphitheater section as a progradational delta on a lacustrine shoreline (Johnson et al., 2000). The basal shaly unit represents deeper-water, well-oxygenated, prodelta environments. Interbedded sandstone contains structures consistent with origins as prodelta turbidite and slump deposits. Delta progradation is indicated by upward thickening and coarsening sandstone beds that begin as prodelta deposits, give way upward to delta distributary-channel deposits, and culminate in the fluvially redeposited orange tuffaceous sandstone. Upper sandstone bodies are typified by channel-fill geometries and large surfaces that we interpret as lateral-accretion (point-bar) surfaces. Pervasive rippling and abundant slumping are consistent with a fluvial-lacustrine interface (Castle, 1990). The rapid change from dominantly distributary-channel sandstone to shale from east to west across the amphitheater and the southwest-directed paleocurrent data support the lacustrine-shoreline interpretation and indicate that the main lake body lay to the west, where we have observed thick shale sequences with thin turbidites that belong to SR-1 (vicinity of folded marker beds within SR-1 in Fig. 6).

The lacustrine deltaic sequence of the amphitheater serves as a stratigraphic and depositional motif for most of the overlying SR-1 sequence (Fig. 9). The stacking of multiple progradational deltaic sections above the 155 ± 1 Ma ash imparts a cyclic aspect to the upper part of SR-1 (Fig. 9). All of the 13 recognizable cycles are very similar in terms of successions of sedimentary structures. Phyllopods and ostracods occur in most of the transgressive shales that separate deltaic sandstone units and that we infer to be of lacustrine origin. Some of the lenticular, slumped, rippled deltaic sandstone units are noteworthy for exceptionally large (0.5 × 4 m), parallel-aligned, silicified logs (Fig. 11C), which presumably reflect flood events. Many of the cycles are capped by analcite-cemented, laterally continuous, orange tuffaceous sandstones sim-

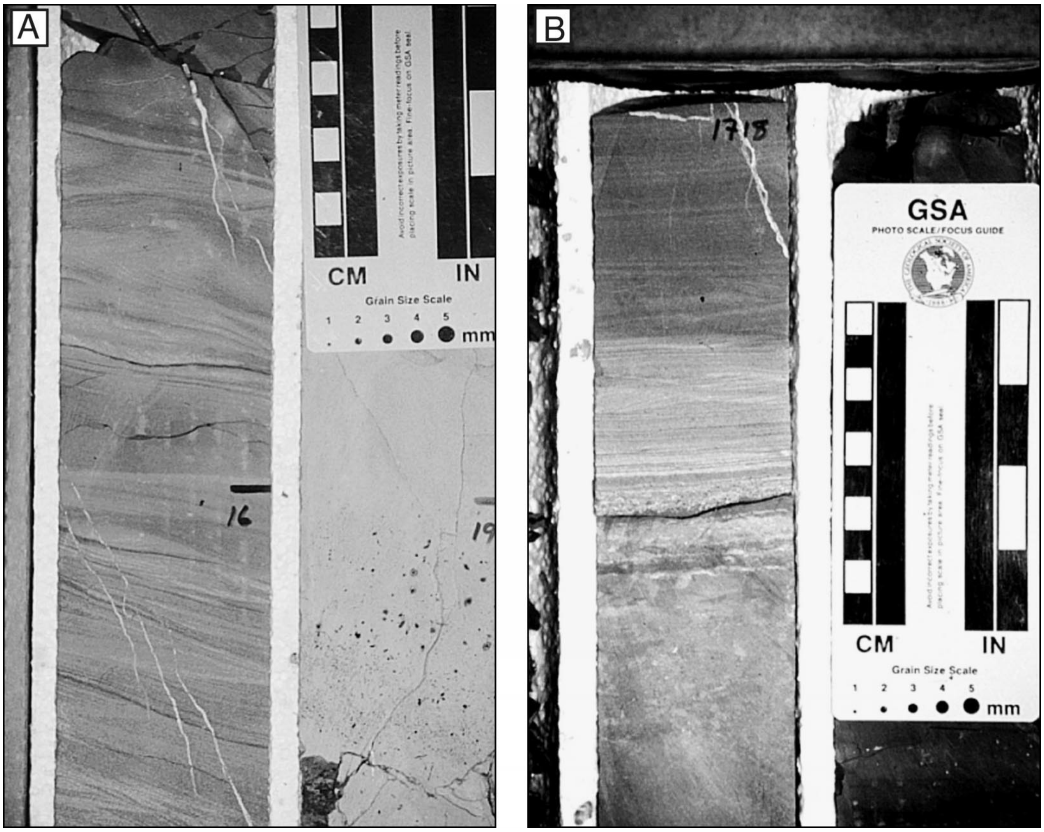


Figure 7. Borehole cores from strata equivalent to the Tsagantsav Formation in the Zuunbayan oil field (location in Fig. 2). (A) Fluvial levee deposits characterized by ripple-drift cross-lamination (left), and paleosol horizon (massive, light-colored, mottled carbonate interval sampled by core segment on right). (B) Lacustrine turbidite bed characterized by normal grading and Bouma intervals, beginning with coarse shelly debris (white granular material) at base of bed.

ilar to the 155 ± 1 Ma tuffaceous sandstone. The protracted cyclicity indicates waxing and waning phases of lake development during a period when the mean shoreline was generally located at Har Hotol.

The SR-1 sequence is capped by a cycle that marks the end of lacustrine history at Har Hotol. The uppermost lacustrine cycle begins like those below with lacustrine mudstone and deltaic sandstone, but the section passes upward into red mudstone and thin lenticular sandstone beds (Fig. 10D). Common nodular carbonate horizons in the locally root-mottled red mudstone likely are Calcisols (cf., Mack et al., 1993). These features indicate an end of lacustrine conditions in the face of a seasonally wet or semiarid climate. The red-bed sequence is sharply truncated by the unconformity beneath the conglomeratic lower member of SR-2 (Figs. 9, 10D, 11E).

Second Synrift Sequence (SR-2). SR-2, 580 m thick at Har Hotol, fines upward from basal pebble-cobble conglomerate, through a dominantly sandy middle member, to an unexposed but presumably fine-grained upper member (Fig. 9). Thin basalt flows locally occur in strata we have mapped as SR-2 in the southwestern corner of the Har Hotol area (Fig. 6). The basal contact is locally a paraconformity with modest local erosional relief (Figs. 9, 10D), but as already discussed, an angular relationship with older synrift strata exists at map scale (Fig. 6). Some unpublished Mongolian geologic maps of the Har Hotol area assign the SR-2 conglomerate to the Saynshand Formation, but we map the unit as underlying a 131 ± 1 Ma basalt, and so SR-2 should instead be assigned to the Tsagantsav Formation (Fig. 5). We interpret the basal conglomerate of SR-2 to be alluvial-fan deposits, on the basis of conglomerate textures that vary from breccia-like and very poorly sorted to grain-supported and imbricated.

The middle part of SR-2 is dominated by two medium-grained sandstone units separated by a red and green shale unit. Prominent buff-colored outcrops of the upper unit are pervasively trough cross-bedded sandstone and reworked ash that contain abundant silicified wood fragments and logs. Disarticulated dinosaur remains, previously unreported, occur locally in abundance in the upper sandstone, as well (Fig. 9). We interpret these strata as sandy braided stream deposits akin to the South Saskatchewan type of Miall (1978), which developed in a climate sufficiently humid to support forests and a dinosaur fauna. The uppermost part of SR-2 is completely covered beneath a strike valley, but most probably is shaly. Whether it represents muddy fluvial flood-plain or lacustrine environments is uncertain, but either way, SR-2 represents an overall decrease in depositional gradient over time.

Third Synrift Sequence (SR-3). The basal conglomerate of the third synrift sequence sharply overlies the fine-grained uppermost strata of the underlying sequence, but unlike the two older synrift sequences, the SR-3 conglomerate includes ∼50 m of interstratified basalt flows at Har Hotol, as well as lenticular sandstone and shale units (Figs. 6, 9, 10E). Conglomerate below the basalt is polymict and basement derived, whereas intraflow conglomerate contains abundant basalt clasts, as well. All conglomerate yields southwest-directed paleocurrents (Fig. 9). The grain-supported, locally imbricated, pebble to cobble conglomerate units are consistent with a braided-stream setting.

The basalt intervals in SR-3 at Har Hotol include multiple flows, as evinced by baked basal contacts and weathered and vesicular tops. The basalts are generally fine grained, and columnar jointing is widely but crudely developed (Fig. 11F). We obtained a $^{40}Ar/^{39}Ar$ age of 131 ± 1 Ma on plagioclase (weighted mean age) in the upper basalt. K/Ar ages of 145 Ma for the lower basalt and 119 Ma for the upper basalt were previously reported by

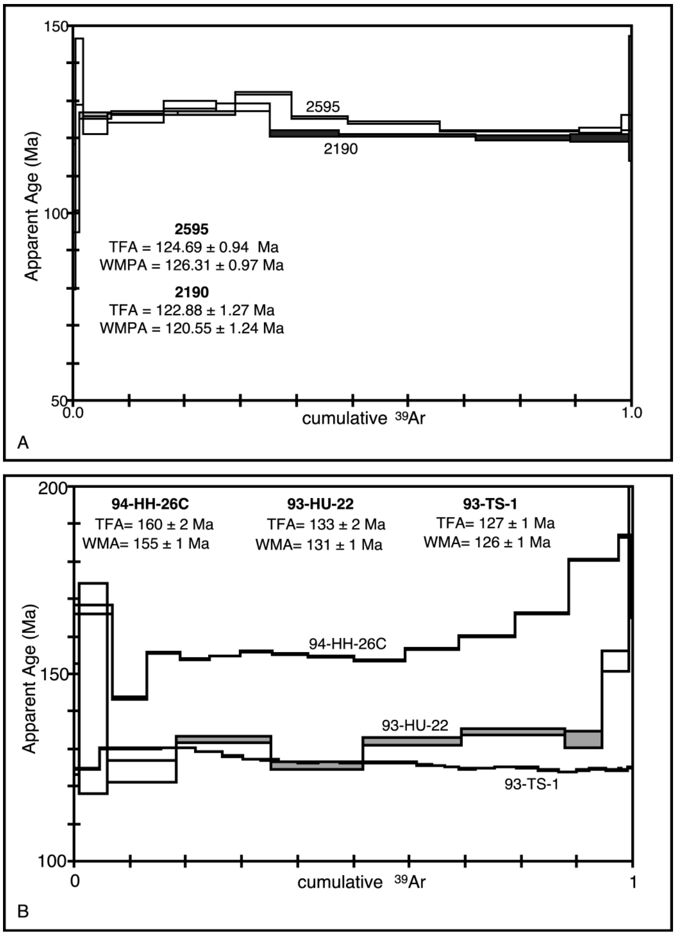


Figure 8. $^{40}Ar/^{39}Ar$ apparent age spectra for Mesozoic samples from Unegt subbasin and Zuunbayan oil field obtained following the analytical procedures outlined in Hacker et al. (1996). TFA—total fusion age, WMPA—weighted mean plateau age, shown with $\pm 1\sigma$; (A) Samples of fluvially reworked ashes encountered in core samples of the reservoir section of Zuunbayan oil field; these whole-rock ages demonstrate that this subsurface section is generally coeval with the type Tsagantsav Formation (e.g., sample 93-TS-1 in part B of this figure, and section F of Fig. 10); (B) Outcrop samples from the northern margin of the Unegt subbasin. These samples set limits on ages of the synrift sequences (Figs. 5, 9); 94-HH-26C (biotite) is from section C, Figure 10, 93-HU-22 (plagioclase) is from section E, Figure 10, and 93-TS-1 (plagioclase) is from section F, Figure 10.

Shuvalov (1980, 1982). The intimate association of basalt and conglomerate likely indicates that the basalt flows occupied the stream valleys in which the basal conglomerate of SR-3 was deposited.

Overlying the basalts at Har Hotol is an 80-m-thick section of conglomerate, sandstone, and mudstone that persists upward to the overlap unconformity of Upper Cretaceous strata (Figs. 6, 9, 10E). Lithofacies within this section vary rapidly laterally and lack cyclicity. Conglomerate beds tend to be poorly sorted, and some are matrix supported. Sandstone and conglomerate units typically are cross-bedded, relatively thin, and lenticular (Fig. 10E). Silicified wood is uncommon. We interpret the common nodular carbonate horizons, especially thick horizons 60–70 m above the top of the basalt, as Calcisols. The SR-3 sequence above the basalt likely reflects an alluvial fan or plain characterized by shallow, probably ephemeral, streams, on the basis of the abundance of mudstone, lenticularity of coarse-grained units, and paucity of organic remains.

We have examined two other sections of the SR-3 sequence, one in outcrop and one in the subsurface. The type section of the Tsagantsav Formation crops out ~25 km northeast of Har Hotol (Fig. 2). The section includes amygdaloidal basalt we have dated at 126 $\pm$ 1 Ma (Figs. 8, 9, 10F). The section differs from the Har Hotol section in that it contains conglomerate only at its base and is dominated by sandstone and finer-grained lithologies that display common cross-bedding, ripples, and soft-sediment deformation. Most of the upward-fining section is tuffaceous (Fig. 10F), and zeolite mineralization is common (Anonymous, 1986). We interpret the section as reflecting expansion of a lake system over a gravelly alluvial surface, on the basis of the presence of subaerial basalt flows and conglomerate overlain by an upward-fining sequence. The latter includes abundant soft-sediment deformation in sandstone-siltstone units, consistent with a lacustrine-delta setting (e.g., Castle, 1990), as well as a capping sequence of tabular siltstone-mudstone likely representing open-lacustrine settings.

Younger Lower Cretaceous units, such as the Huhteeg and Shinehudag formations, are not preserved at Har Hotol and so must be evaluated elsewhere in the subbasins. We have observed them in poor exposures around Tavan Har and on the Zuunbayan anticlinal uplift (Fig. 2). Fine-grained lithologies, including some organic-rich laminated shales and marly horizons representing deeper-water lacustrine environments, are dominant at Tavan Har. Volcanic flow units are absent, and ashes are few and undated.

Synrift sections are penetrated and oil productive in the Tsagaan Els and Zuunbayan oil fields. We have studied a 450-m-long core cut from the SR-3 section at Zuunbayan field (Zuunbayan and Tsagantsav Formations of oil-field usage). The lower half of the section penetrated by the cored well is coeval with the type section of the Tsagantsav Formation (Figs. 2, 5, 9, 10F) according to our dating of fluvially reworked ashes in the core of 126 $\pm$ 1 Ma and 127 $\pm$ 2 Ma (Fig. 8). However, in contrast to the outcrop sections along the north basin margin, the Zuunbayan oil-field section lacks basalt flows and conglomerate. Our analysis of sedimentary structures in the core suggests that the SR-3 section of Zuunbayan field consists of braided fluvial strata dominated by pebbly, coarse-grained, trough cross-bedded sandstone low in the section, grading upward to thick, organic-rich, finer-grained, meandering fluvial to lacustrine deposits (Fig. 7A). Lacustrine strata characterized by mudstone with occasional slump and turbidite deposits (Fig. 7B) dominate the section younger than 126 Ma.

Inversion Megasequence

Analysis of proprietary reflection seismic profiles from the area of the oil fields reveals the development of an off-structure stratigraphic wedge that we believe preserves detritus eroded from the Tsagaan Els–Zuunbayan antiform during late Early Cretaceous basin inversion. This section has not been identified in outcrop, but it has been penetrated by drilling; presumably, it is restricted to buried parts of basin depocenters.

Overlap Megasequence

Upper Cretaceous strata of the Unegt subbasin lap onto the third synrift sequence exposed along the Har Hotol ridge. These generally fine-grained nonmarine strata are poorly lithified and typically are poorly exposed. We did not study them in detail, but they appear to overlap a synrift fault that offsets the west end of the Har Hotol basalt ridge (Fig. 6). Fossils from Har Hotol, verifying the Late Cretaceous age of the megasequence, include the segnosaur *Enigmosaurus barsbold* Perle, an unidentified sauropod, turtles, and the freshwater trigonioidid mollusk *Plicatotriponioides multicostatus* Barsbold.

IMPLICATIONS

Evolution and Paleogeography of the Unegt-Zuunbayan Subbasins

Rifting commenced in the Unegt-Zuunbayan subbasins of the East Gobi basin prior to 155 Ma, the age of the orange ash marker bed in the middle of SR-1. If we assume (1) an average undecompacted sediment-accumulation rate of 50 m/m.y. (derived from radiometric ages for the middle SR-1 to lower SR-3 strata) and (2) comparable accumulation rates earlier in the rift history, the lower undated 800 m of SR-1 may have begun to accumulate as early the beginning of the Late Jurassic. This conclusion is consistent with angularly unconformable relationships between Middle and Upper Jurassic strata across much of southern Mongolia (Shuvalov, 1968, 1969), as well as the onset of rift volcanism by 155 Ma in the South Hangay volcanic province (Kovalenko et al., 1995).

A dominance of southwest-oriented paleocurrents and intervals of coarse conglomerate (Figs. 9, 10B, 11A) indicate that strata exposed along the northern margin of the Unegt subbasin represent environments close to the original northern basin margin, beyond which lay the uplifted basement of the Mandakh-Saykhandulaan high (Fig. 2). The Zuunbayan fault likely was the master fault on the southern side of the linked Unegt-Zuunbayan subbasins, on the basis of our interpretation of reflection seismic data and because that fault separates the Zuunbayan subbasin from the large Toto Shan basement block. Basin topography was irregular and deposition was localized during initial phases of rifting: The basal SR-1 Sharilyn conglomerate facies varies in thickness and is not everywhere present along the northern basin margin. The streams represented by the Sharilyn facies perhaps fed lakes recorded by coeval parts of the lacustrine ‘‘Manlay facies’’ (Fig. 5, Jerzykiewicz and Russell, 1991). By 155 Ma, lakes certainly occupied at least the Unegt subbasin. A persistent southwest-facing lacustrine shoreline at Har Hotol provides evidence for the position of the northern margin of the Unegt subbasin, but the stacked progradational deltaic cycles of SR-1 (Fig. 9) indicate that the Unegt lake frequently expanded to the north beyond current outcrops during a 10 m.y. period. Forcing factors for this cyclicity are uncertain, but the pattern of ashes capping many of the progradational parasequences suggests that episodic eruptive events may have periodically overwhelmed fluvial systems and forced rearrangement of drainage systems.

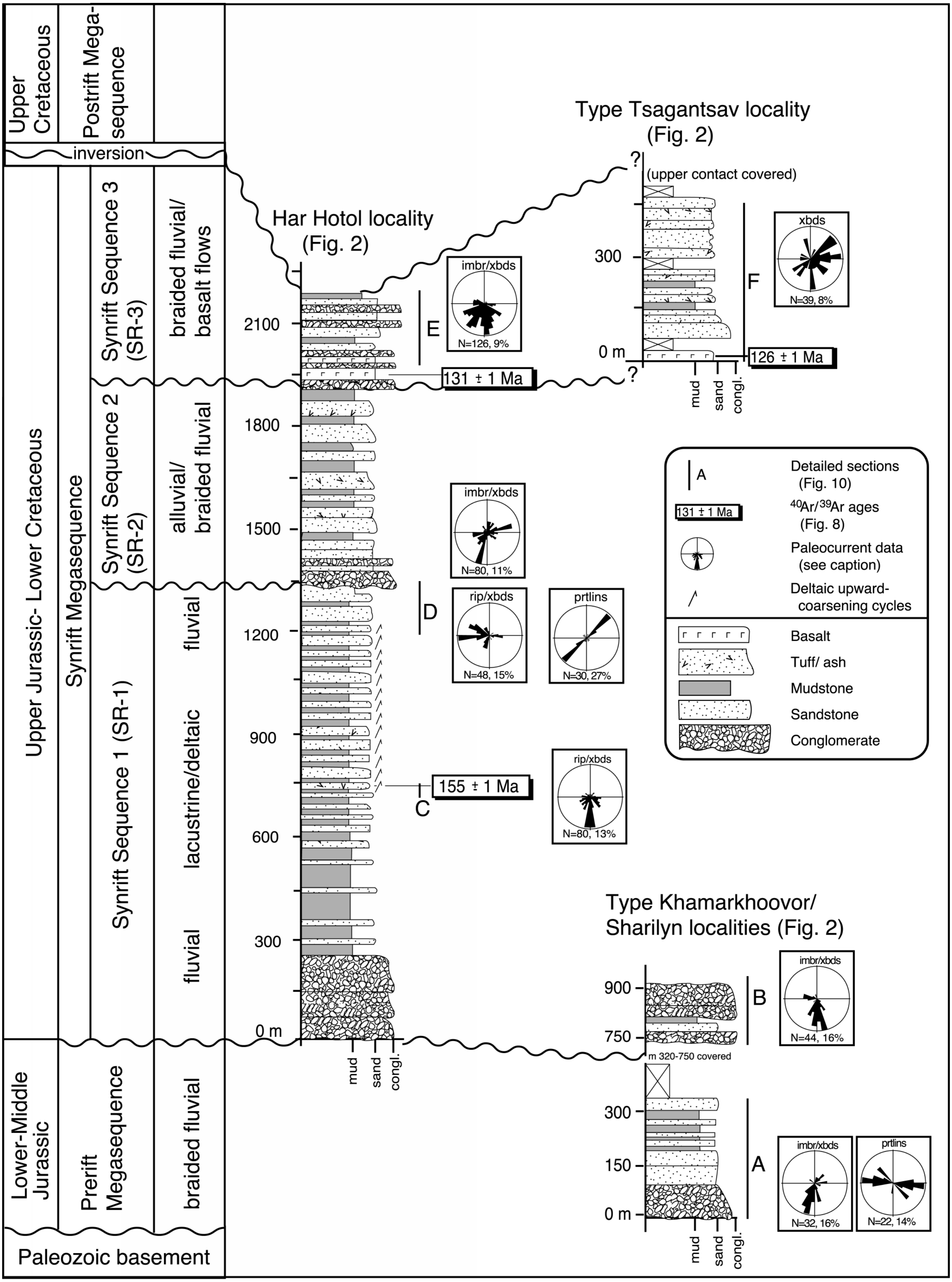
The unconformable base of the second synrift sequence (SR-2) signals structural rejuvenation along the northern margin of the Unegt subbasin. The basal SR-2 conglomerate (Fig. 9) and possible map-scale angular unconformity between SR-1 and SR-2 (Fig. 6) suggest deformation and uplift; southwest-directed paleocurrents and the locally breccia-like character of the SR-2 conglomerate (Figs. 9, 10D) signal immediate proximity to the basin margin. As with SR-1, basal SR-2 gravelly braided-fluvial systems at Har Hotol evolved to sandy fluvial systems.

The unconformity between SR-2 and SR-3 signifies a structural event of at least basin-margin significance. Associated eruptive activity along the northern subbasin margin (Figs. 9 and 10, E and F) presumably was related to extension and faulting. Basal SR-3 gravelly deposits reflect southwest-flowing braided streams whose valleys periodically were clogged by basalt flows. Faulting, volcanism, and gravel deposition persisted for at least 10 m.y., according to our dates from SR-3 basalts at Har Hotol and the type Tsagantsav Formation (Figs. 8, 9). No lacustrine elements occur in the truncated SR-3 strata preserved at Har Hotol, but fine-grained lacustrine and flood-plain deposits crop out at the type Tsagantsav locality, as well as occur in the subsurface of the oil fields. As mapped at Tavan Har, the Tsagantsav Formation (i.e., SR-2 and SR-3) is fine grained and includes laminated, fish-bearing, paper shales, reflecting relatively deep, poorly oxygenated lacustrine water columns. We also have observed thick lacustrine mudstone intervals with minor turbidites in the core from Zuunbayan oil field (Fig. 7B). Thus, the Tavan Har–Zuunbayan trend was at least partly covered by offshore lacustrine deposits prior to uplift in the late Early Cretaceous. SR-3 ended with structural inversion, evident on reflection seismic data (Fig. 3).

Our interpretation of facies and stratigraphic architecture suggests structurally controlled, internally drained subbasin paleogeography throughout much of synrift time, consistent with Traynor and Sladen’s (1995) general reconstruction of the Gobi region during rifting. The extent of fluvial and lacustrine connections between the numerous subbasins of the East Gobi basin is quite uncertain at present. Periods when lakes occupied little or none of the Unegt basin seem generally to correspond to pulses of faulting and volcanism. At other times, lakes certainly expanded beyond current erosional subbasin boundaries. Mesozoic Gobi lake history likely was akin to that of the Pleistocene-Holocene Lake Bonneville–Salt Lake system of the U.S. Basin and Range which, depending on climate, sometimes formed a single vast lake that connected across structural sills to numerous rift subbasins, but at other times (as at the present) was a series of lakes (some saline) occupying isolated rift subbasins (Oviatt, 1997).

Nevertheless, the role of climate in stratigraphic development in the East Gobi basin is less certain than that of tectonism, because the history of climate change in central Asia during the Mesozoic is only broadly known. Central Asia was subject to major drying from Middle Jurassic to Late Jurassic, apparently related to changing continental configuration and global circulation patterns (Hendrix et al., 1992). The record in the Unegt subbasin is consistent with these regional trends: Prerift Lower to Middle Jurassic coaly strata (Fig. 10A) suggesting high water tables and abundant flora are overlain by Upper Jurassic synrift strata that include indicators of at least seasonality of rainfall, if not semiaridity, such as red beds and Calcisols (Figs. 10D, 11E).

Three other lines of evidence support the inference of semiarid conditions during the synrift period. (1) Sladen and Traynor (2000) provided geochemical data in the form of organic biomarkers from oils and source rocks that indicate that the Gobi lacustrine systems were at alternate times saline and fresh. (2) The presence of common analcite cement in ashes and sandstones is consistent with at least periodically alkaline and/or saline lakes with volcanic input (Surdam and Sheppard, 1978; Parrish, 1998). Finally, dendroclimatologic inferences of a seasonally wet, rather than perennially humid climate, derive from a fossil



Upper Cretaceous
Postrift Mega-sequence
inversion
Upper Jurassic- Lower Cretaceous
Synrift Megasequence
Synrift Sequence 3 (SR-3)
braided fluvial/ basalt flows
Synrift Sequence 2 (SR-2)
alluvial/ braided fluvial
Synrift Sequence 1 (SR-1)
fluvial
lacustrine/deltaic
fluvial
Lower-Middle Jurassic
Prerift Megasequence
braided fluvial
Paleozoic basement
Har Hotol locality (Fig. 2)
2100
1800
1500
1200
900
600
300
0 m
mud
sand
congl.
131 ± 1 Ma
155 ± 1 Ma
E
D
C
imbr/xbds
N=126, 9%
imbr/xbds
N=80, 11%
rip/xbds
N=48, 15%
prtlins
N=30, 27%
rip/xbds
N=80, 13%
Type Tsagantsav locality (Fig. 2)
(upper contact covered)
300
0 m
126 ± 1 Ma
F
xbds
N=39, 8%
Detailed sections (Fig. 10)
$^{40}Ar/^{39}Ar$ ages (Fig. 8)
Paleocurrent data (see caption)
Deltaic upward-coarsening cycles
Basalt
Tuff/ ash
Mudstone
Sandstone
Conglomerate
Type Khamarkhoovor/ Sharilyn localities (Fig. 2)
900
750
m 320-750 covered
300
150
0 m
B
A
imbr/xbds
N=44, 16%
imbr/xbds
N=32, 16%
prtlins
N=22, 14%

forest entombed by a volcanic event at 156 ± 1 Ma at Ulgay Khid (Fig. 1; Keller and Hendrix, 1997) ~125 km to the southwest of Har Hotol (possibly the same eruptive event or sequence of events responsible for the 155 ± 1 Ma orange ash marker bed at Har Hotol). The climate was nevertheless sufficiently wet to support some forests and dinosaurs, and lacustrine bodies persisted much of the time from 160 Ma to 125 Ma. Thereafter, climate may have been more arid, as suggested by Lower Cretaceous, Calcisol-bearing, alluvial facies above the basalt at Har Hotol (Fig. 10E). A return to wetter climates in the late Early Cretaceous is suggested by widespread, large and deep lakes across the Gobi region, reflected by the Manlay facies (Fig. 5; Jerzykiewicz and Russell, 1991) and the faunas found at Har Hotol previously discussed.

In sum, rifting of Unegt and Zuunbayan subbasins lasted at least 35 m.y., but no longer than 60 m.y., on the basis of currently available geochronologic constraints, and was followed by a period of inversion tectonics. The fill of the basin is divisible into genetic sequences related to episodes of basin structuring, although climate and sediment supply likely also played important roles in controlling styles of sedimentation and patterns of stratigraphic architecture. Internal drainage was a persistent feature of the subbasins.

Southeast Mongolian Subbasins in the Context of Mesozoic Tectonics of Eastern Asia

Relationship to Extended Areas of Southern Mongolia and Adjacent China

Late Jurassic–Early Cretaceous extension characterized a large part of southeast Mongolia, although there are significant differences in structural and sedimentary style along trend (Johnson et al., 2001). An extensional metamorphic core complex characterized by mylonitic deformation at 129–125 Ma (Webb et al., 1999a) occurs at the southern edge of the Gobi basin at Onch Hayrhan (Figs. 1, 12); this pronounced extension is coeval with SR-2 of the Har Hotol area. The core complex extends across the border into China, where it includes metamorphic and igneous rocks that date from 161 to 128 Ma (Zheng et al., 1991, 1996, 2001; Zheng and Zhang, 1994), equivalent to SR-1 through SR-3 of the Unegt subbasin (Fig. 5).

The Songliao and Erlian basins of adjacent China (Figs. 1, 12) rifted in the Late Jurassic and early Early Cretaceous and expanded during a late Early Cretaceous ''sag'' phase during which faulting was diminished or absent (Zhai, 1988, 1993; Ma et al., 1989). The onset of extension is best known in the Songliao basin, where seismic profiling reveals rift structuring and growth faulting that localized synrift volcanic rocks. These rocks are dated at 160–136 Ma and are characterized as alkalic and rift related on the basis of rare earth elements (Zhai, 1993). The ''sag'' phase of Songliao basin history was noteworthy for large deep lakes, reflecting increased accommodation space attributed to thermal-cooling subsidence (Zhai, 1993). The widespread Manlay lacustrine facies of southeast Mongolia (Fig. 5) likely in part represents this phase of late- to postrift subsidence. Thus, the Mongolian and Chinese basins display similarities in timing and character of rift structure and deposition that suggest common underlying genetic drivers.

Drivers of Late Mesozoic Extension

Identifying the tectonic drivers for Late Jurassic–Early Cretaceous deformation in the East Gobi basin and adjacent areas of Asia is difficult because (1) the geology of the remote deserts of the region remains poorly known; (2) both extensional and contractional structures occur in the same general areas and are close, if not overlapping, in time (e.g., Traynor and Sladen, 1995; Hendrix et al., 1996; Yin and Nie, 1996; Davis et al., 1998a; Vincent and Allen, 1999; Zorin, 1999: Johnson et al., 2001); and (3) eastern Mongolia and adjacent China occupied an intracontinental position by the end of the Jurassic, with continental margins (some involved in collision) at a considerable distance to the east (Pacific), north (Mongol-Okhotsk) and south (southern margin of Asia). No tectonic mechanism can yet be argued with confidence, but some combination of at least five factors may have driven extension in eastern Mongolia and eastern China. Nevertheless, the spatial position of the Mongolian rift system and the timing of rifting we document in this paper help to discriminate among these five factors, as discussed next.

Pacific Margin Backarc Extension. The most frequently cited driver for the extension of Chinese basins such as Songliao (Figs. 1, 12) is backarc extension behind the late Mesozoic continental margin arc that faced the Pacific Ocean from South Korea to southeastern China (e.g., Watson et al., 1987; Ma et al., 1989). This mechanism seems plausible for eastern Chinese basins such as Songliao, but the East Gobi basin of Mongolia was ~1200 km (nonpalinspastic distance) continentward of the axis of the Cretaceous Chinese maritime arc, thus inviting consideration of other driving forces for rifting in Mongolia.

Extension Associated with Closing of the Mongol-Okhotsk Seaway. Alternatively, extension in the Gobi region might have been related to the evolution of the continental margin that faced the Mongol-Okhotsk Seaway to the north (Figs. 1, 12). Parallel belts of Mesozoic marine strata and igneous and metamorphic rocks trending northeast from Ulaanbaatar through Siberia to the modern Sea of Okhotsk record the western end of the Mongol-Okhotsk Seaway (Kosygin and Parfenov, 1981; Zonenshain et al., 1990; Figs. 1, 12). Paleomagnetic data (Zhao et al., 1990; Enkin et al. 1992) suggest that northeastern Siberia and eastern China were widely separated at the beginning of the Mesozoic (by ~50° of latitude), but that the intervening Mongol-Okhotsk Seaway was closed by the Early Cretaceous (135–95 Ma window of Enkin et al., 1992). Zonenshain et al. (1990) and Yin and Nie (1996) inferred that the seaway closed diachronously from west to east by oroclinal rotation.

The geologic record of the closure of the Mongol-Okhotsk Seaway in Mongolia is poorly documented. A magmatic belt (220–180 Ma [K/Ar]) occurs parallel to, but north of, marine Triassic strata in northeast Mongolia (Fig. 35 of Kovalenko et al. 1995). Marine Mesozoic strata occur very sparsely northeast of Ulaanbaatar, are no younger than Triassic, and are structurally associated with ultramafic rocks of undocumented ages (Yanshin, 1989). No Mesozoic marine strata are reported west of Ulaanbaatar, consistent with

Figure 9. Generalized composite Jurassic–Lower Cretaceous stratigraphic column of the northern margin of the Unegt subbasin. See Figure 2 shows location of sections A, B, and F; see Figure 6 shows locations of sections C, D, and E. Detailed sections A–F are shown in Figure 10. Paleocurrent insets: North is up; N—number of measurements; diameter of circle scaled to most-frequent-occurrence sector, expressed as % of total measurements; rip—ripples, imbr—imbrication, prtlins—parting lineations, xbeds—trough and tabular cross-stratification.

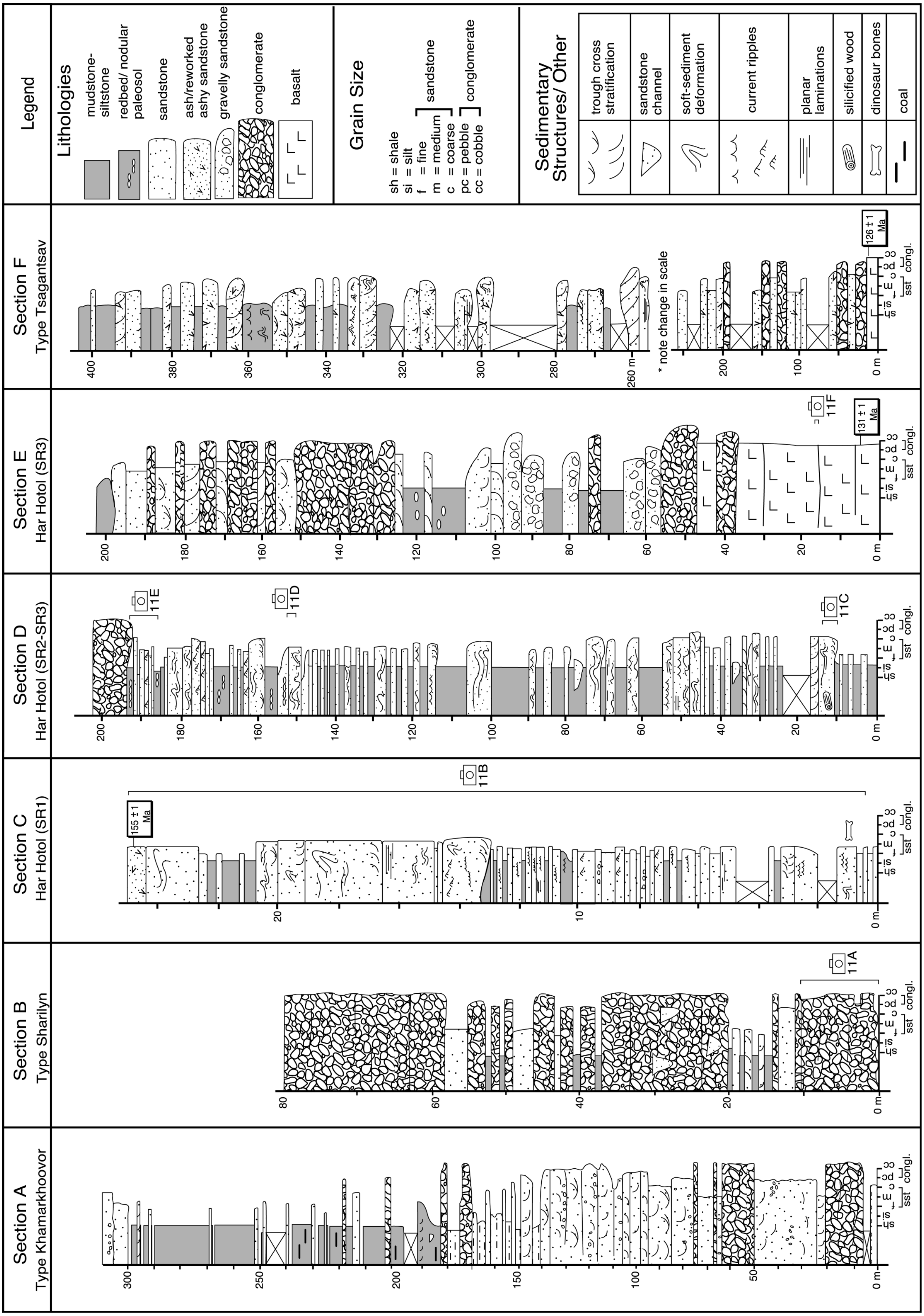


Figure 10. Detailed measured sections of selected intervals of the composite section of Figure 9. See Figure 2 for location of sections A, B, and F; see Figure 6 for sections C, D, and E.

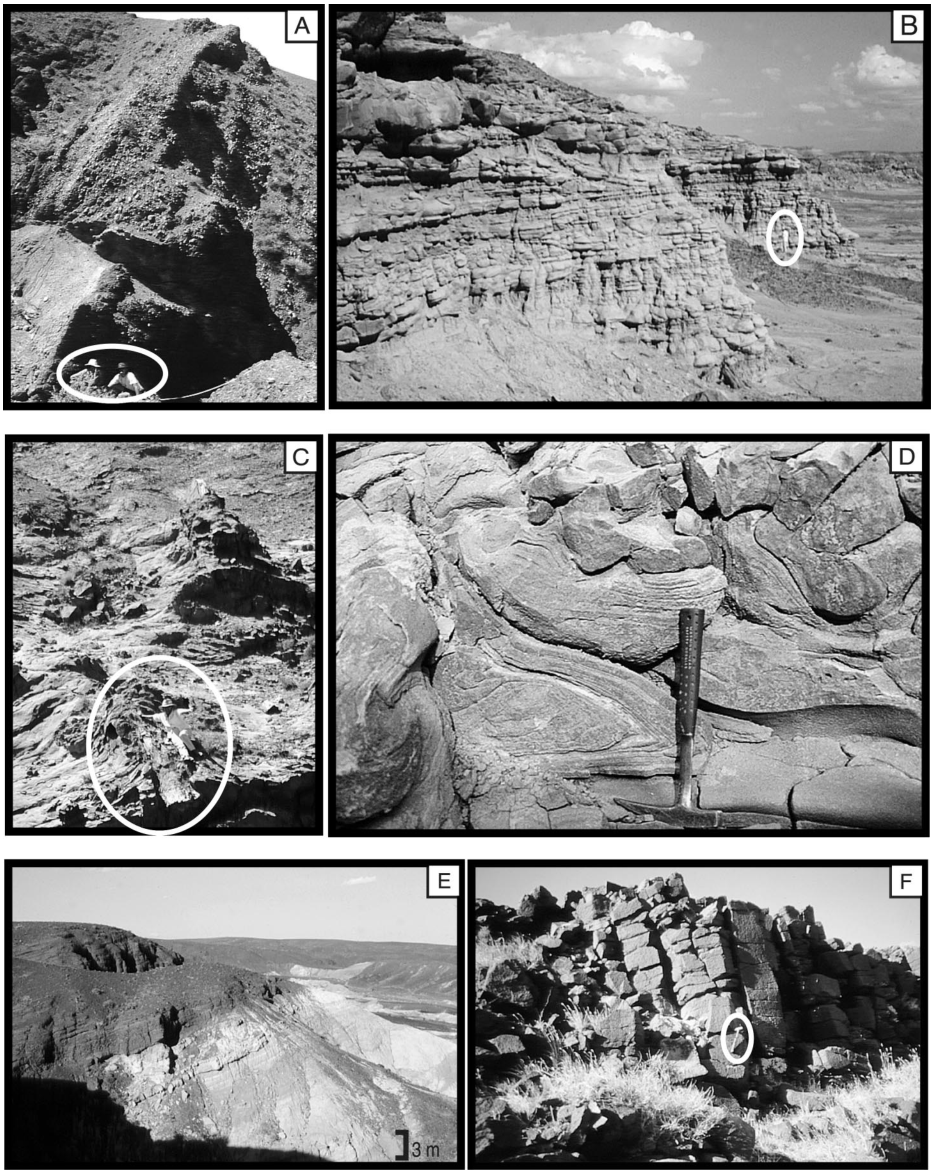


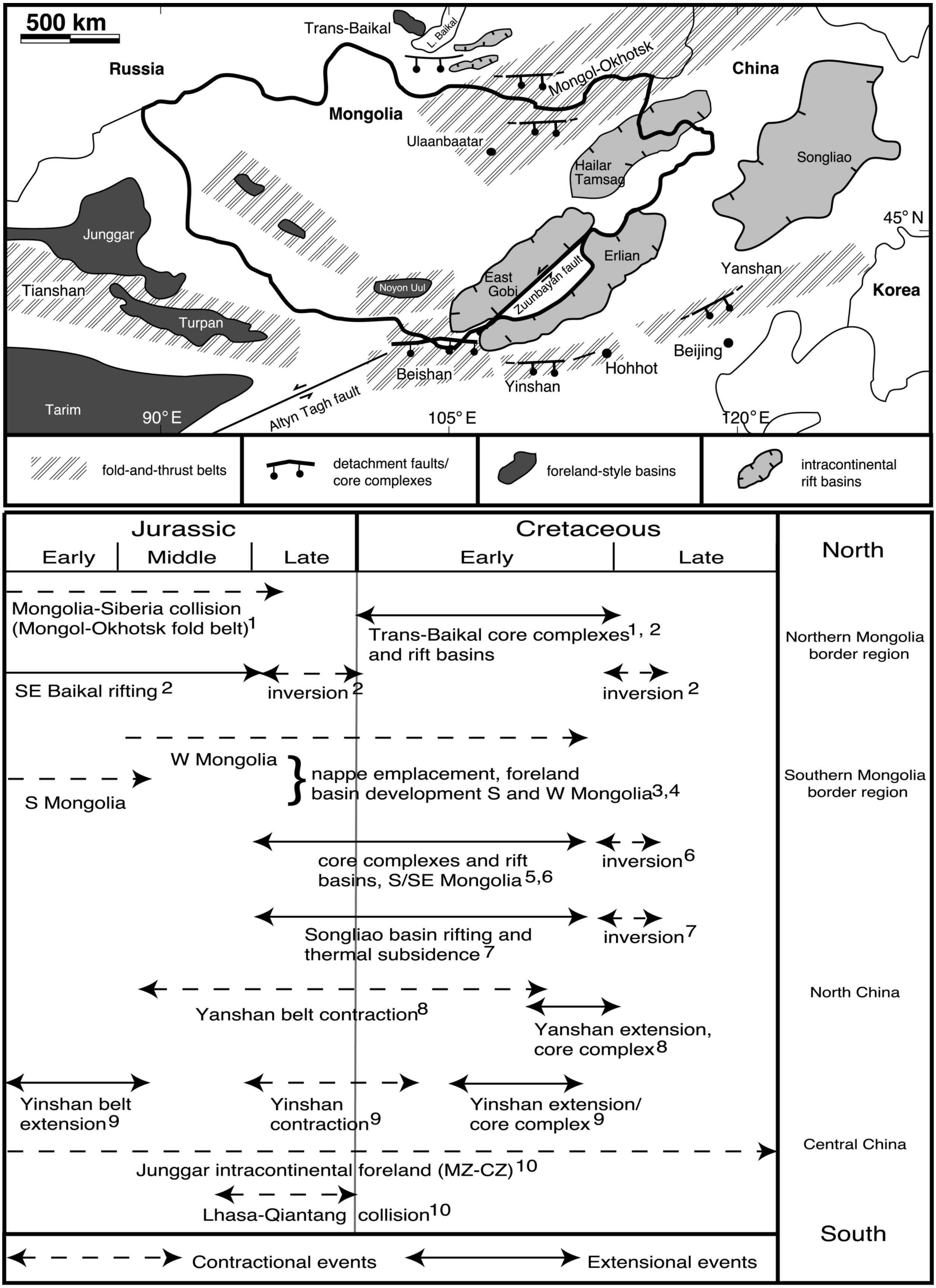
Figure 11. Outcrop photographs from the northern margin of the Unegt subbasin. (A) Upper Jurassic boulder conglomerate of the basal Sharilyn Formation; stratigraphic up is to the left; persons (circled) in foreground for scale; see column B of Figure 10 for stratigraphic position. (B) Upper Jurassic upward-coarsening lacustrine deltaic sequence exposed on the east margin of the "amphitheater;" section is capped on the skyline in right distance by reworked 155 ± 1 Ma ash; person (circled) for scale; see column C of Figure 10 for stratigraphic position. (C) Large, aligned, silicified logs in slumped lacustrine deltaic sandstone unit; person (circled) lying on nearest log; see column D of Figure 10 for stratigraphic position. (D) Slumped lacustrine deltaic sandstone; see column D of Figure 10 for stratigraphic position. (E) Unconformable contact between coarse alluvial deposits of basal SR-2 (dark upper left) and underlying red-bed sequence of upper SR-1 (lower right); see column D of Figure 10 for stratigraphic position. (F) Columnar jointing in basalt of SR-3; hammer (circled) for scale; see column E of Figure 10 for stratigraphic position.

our studies of Mesozoic strata of Mongolia (Hendrix et al., 1996; Graham et al., 1997; Sjostrom et al., 1996, 2001; Johnson et al., 2001; see also Fig. 35 of Kovalenko et al., 1995), although some regional tectonic syntheses (e.g., Enkin et al., 1992; Van der Voo et al., 1999) misleadingly show otherwise. On the basis of geologic and paleomagnetic constraints, Zorin (1999) concluded that closure of the Mongolian sector of the ocean basin was complete by the Early Jurassic–Middle Jurassic boundary; we accept this time as the best estimate currently available (Fig. 12).

Two tectonic mechanisms associated with the southern margin of the Mongol-Okhotsk Seaway can be hypothesized for extension in the East Gobi region in the Late Jurassic–Early Cretaceous. One possibility is backarc extension behind (to the south of) an arc that faced north toward the Mongol-Okhotsk Seaway (Yin and Nie, 1996). However, the timing of extension in the southeast Gobi region, as we document here, is later than collision as construed by Zorin (1999), and this mechanism is in any event invalid if there was no arc along the southern margin of the seaway (Zonenshain et al., 1990). Alternatively, the oroclinal rotation that closed the seaway in Mongolia may have promoted extension or transtension in southeast Mongolia. Late collisional post–Early Cretaceous sinistral shear is documented along the suture zone to the northeast of Mongolia (Halim et al., 1998), and major Mesozoic strike-slip faulting in southeast Mongolia was proposed by Suvorov (1982) and Lamb et al. (1999).

Compressional or transpressional inversion in the Unegt-Zuunbayan subbasins in the late Early Cretaceous also may reflect closure of the Mongol-Okhotsk Seaway. The inversion we document in Mongolia was coeval with inversion in the Chinese rift basins; the rather complete stratigraphic record in Songliao basin indicates inversion near the Early Cretaceous–Late Cretaceous boundary (Zhai, 1993) (Fig. 12). Continued shortening in the Mongol-Okhotsk collision zone in the late Early Cretaceous (Halim et al., 1998) may have affected the Gobi region and adjacent China.

Escape Tectonics Associated with Collision along the Southern Margin of Asia. Another potential driver for Late Jurassic–Early Cretaceous extension or transtension in the Gobi region is related to tectonism along the southern margin of Asia, where the South China, Qiantang, and Lhasa blocks were accreted during the Mesozoic (e.g., Watson et al., 1987; Yin and Nie, 1996; Fig. 12). Analogous to "escape tectonics" of the Cenozoic Himalayan collision (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979), accretion of these blocks promoted extensive intracontinental deformation within Mesozoic Asia (see papers in Hendrix and Davis, 2001). Vincent and Allen (1999), Lamb et al. (1999), and Webb et al. (1999b, 2001) applied the escape-tectonics model to the Late Jurassic–Early Cretaceous accretion of the Lhasa block and proposed that collision-driven strike-slip faulting and associated transtensional basins char-


500 km
Trans-Baikal
L. Baikal
Russia
Mongolia
Mongol-Okhotsk
China
Ulaanbaatar
Songliao
Hailar
Tamsag
45° N
Junggar
Erlian
Yanshan
Korea
Tianshan
Noyon Uul
East
Gobi
Zuunbayan fault
Turpan
Beijing
Hohhot
Beishan
Yinshan
Tarim
90° E
Altyn Tagh fault
105° E
120° E
fold-and-thrust belts
detachment faults/
core complexes
foreland-style basins
intracontinental
rift basins
Jurassic
Cretaceous
Early
Middle
Late
Early
Late
North
Mongolia-Siberia collision
(Mongol-Okhotsk fold belt)1
Trans-Baikal core complexes1, 2
and rift basins
Northern Mongolia
border region
SE Baikal rifting 2
inversion 2
inversion 2
W Mongolia
S Mongolia
nappe emplacement, foreland
basin development S and W Mongolia3,4
Southern Mongolia
border region
core complexes and rift
basins, S/SE Mongolia 5,6
inversion6
Songliao basin rifting and
thermal subsidence 7
inversion7
North China
Yanshan belt contraction8
Yanshan extension,
core complex8
Yinshan belt
extension9
Yinshan
contraction9
Yinshan extension/
core complex 9
Central China
Junggar intracontinental foreland (MZ-CZ)10
Lhasa-Qiantang collision10
South
Contractional events
Extensional events

acterized much of eastern Asia. Specifically, Lamb et al. (1999) suggested that an ancestral Altyn Tagh fault was linked with a transtensional Zuunbayan fault (Fig. 12), and as noted previously, we have observed flower structures suggestive of strike slip on proprietary seismic profiles in the Zuunbayan subbasin.

Contractional Orogen Collapse. Gravitational collapse of a contractional orogen may have contributed to extension in the East Gobi region. As noted earlier, a major zone of late Paleozoic crustal thickening associated with a closed late Paleozoic ocean basin (Junggar-Hegen or Suolon suture) lies along the Mongolia-China border (Mueller et al., 1991; Amory, 1996), then trends eastward beneath the Erlian basin (Zhang et al., 1984; Fig. 1). This region was further shortened in the early to middle Mesozoic, as evinced by nappes emplaced prior to 155 ± 10 Ma along the international border at Hure and Onch Hayrhan (Zheng et al., 1991, 1996; Johnson et al., 2001; Figs. 1, 12). Significantly, a Mesozoic extensional metamorphic core complex is superposed on the contractional systems at Hure-Onch Hayrhan (Zheng et al., 1991; Webb et al., 1999a; Johnson et al., 2001). The extension we describe in this paper apparently commenced within a few million years of Jurassic nappe emplacement (Fig. 12) and may even have been overlapping in time, given the uncertainty of available geochronologic data. These relationships are reminiscent of other settings, such as the Caledonides of Norway (Seguret et al., 1989) and the Tertiary Basin and Range province of the United States (Constenius, 1996), where extension has been attributed to gravitationally driven collapse of orogenically thickened and heated continental crust. This mechanism, first suggested for southeast Mongolia by Traynor and Sladen (1995), may account for localization of extensional features superposed on the suture region, such as specific basins and zones of high-strain extension.

In addition, crustal thickening associated with closure of the Mongol-Okhotsk Seaway may have played a role in extension in the Gobi region. Zorin (1999) attributed trends of extensional metamorphic core complexes (140–110 Ma) in the region between Lake Baikal and the northern Mongolian border (Fig. 12) to collapse of crust thickened and heated during the Mongol-Okhotsk collision. He further suggested that coeval rift basins in southeast Mongolia, such as we describe in this paper, reflect the same driver but more modest extension. We thus envision the Mesozoic East Gobi as a plateau-like region characterized by internally drained, fault-controlled subbasins and bounded to the north and south by collapsing orogenic belts.

Relationship to Tectonism in the Yinshan-Yanshan Belt

Any consideration of drivers of late Mesozoic extension in southeast Mongolia and adjacent China must reconcile one other currently enigmatic aspect of Asian geology. The Yinshan-Yanshan belt is an east-trending, intracontinental Mesozoic contractional orogen (Davis et al., 1998a, 1998b, 2001; Darby et al., 2001) that lies just south of the Mesozoic extended region of southeastern Mongolia (Figs. 1, 12). Where closest to the East Gobi basin, near Hohhot, China, the belt includes the Daqing Shan thrust, which reflects shortening in the Late Jurassic–Early Cretaceous (before 119 ± 2 Ma; Zheng et al., 1998). Yin and Nie (1996) and Davis et al. (1998b) speculated that Yinshan-Yanshan shortening was driven by closure of the Mongol-Okhotsk Seaway, 800 km to the north. However, extension in the East Gobi basin and related Chinese basins occurred in the intervening area (Figs. 1, 12) in the same time frame, seemingly rendering this idea difficult. Perhaps strike-slip faulting associated with collisions on the southern Asian and Mongol-Okhotsk margins partitioned the Gobi extensional province from generally coeval large-scale contractional deformation in the Yinshan-Yanshan orogenic belt.

CONCLUSION

On the basis of our outcrop and subsurface studies of Jurassic and Cretaceous strata in the Unegt and Zuunbayan subbasins of the East Gobi basin of Mongolia, we conclude the following:

1. A Jurassic prerift megasequence of upward-fining, coal-bearing fluvial facies deposited in southeast Mongolia may be part of the early Mesozoic foreland basin developed in south-central Mongolia (Hendrix et al., 1996, 2001).

2. New radiometric ages from volcanic units indicate that rifting in southeastern Mongolia began prior to 155 Ma and possibly as early as the onset of the Late Jurassic. Rifting ended after 126 Ma (possibly as late as 110 Ma), but before deposition of a Cenomanian overlap sequence.

3. On the basis of our analysis of facies and structural-stratigraphic relationships, we recognize three synrift sequences, interpreted to be related to episodic structural rejuvenation along basin margins. Each of the synrift sequences is an upward-fining facies succession that records the transition from basin-margin alluvial-fan and braided-fluvial deposition to meandering-fluvial and lacustrine deposition.

4. A brief period of compressional or transpressional basin inversion is demonstrated by normal faults reactivated with reverse drag that are observed on seismic lines from the East Gobi basin. The Early Cretaceous–Late Cretaceous unconformity truncates these faults and older extensional structures.

5. Our study confirms Late Jurassic–Early Cretaceous rifting in southern Mongolia, but the tectonic drivers for that extension remain uncertain, in large part because the area occupied an intraplate position >1000 km from the nearest continental margin by Early Cretaceous time. We favor the idea that Late Jurassic–Early Cretaceous extension of the East Gobi plateau region was facilitated by collapse of bounding orogenic belts to the north and south, modified by collision-driven strike slip that partitioned the Gobi from coeval shortening deformation in northern China.

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Figure 12. Spatial relationships and temporal sequencing of Mesozoic tectonic elements surrounding the East Gobi basin. Refer also to inset map of Figure 1 for location of terranes to the south. References to features (superscript labels): 1—Zorin (1999); 2—Van der Beek et al. (1996); 3—Sjostrom et al. (2001); 4—Hendrix et al. (1996), Zheng et al. (1991, 1996); 5—Webb et al. (1999a); Johnson et al. (2001); 6—this paper; 7—Zhai (1993); 8—Davis et al. (1996); 9—Darby et al. (2001); G. Davis (2000, personal commun.), 10—Hendrix et al. (1992).

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