Eocene–Oligocene transition in Central Asia and its effects on mammalian evolution

Brian P. Kraatz[1] and Jonathan H. Geisler[2]
[1]Department of Anatomy, Western University of Health Sciences, Pomona, California 91766, USA
[2]Department of Geology and Geography, Georgia Southern Museum, Georgia Southern University, Statesboro, Georgia 30460, USA

ABSTRACT

The Eocene-Oligocene boundary (EOB) marks a period of dramatic global climatic change correlated with pronounced mammalian faunal change. The timing of these events is well constrained in North America and Europe, but the Asian record has yet to produce a synthetic section linking environmental change, mammalian fossils, and precise geochronological dates. Here we present the first magnetostratigraphic section for the Hsanda Gol Formation, Mongolia, which yields significant Oligocene fossils and also marks a pattern of aridification that is tightly correlated to the EOB (33.9 Ma), supporting a broader pattern of aridification in the central Asian plateau across the EOB. Oligocene faunas of Asia can now be confidently correlated to those of North America, Europe, and Africa. These results suggest that mammalian faunal turnover within Asia occurred slightly later than similar events within Europe, and question the influence of Asian immigrants on the Grande Coupure faunal turnover.

INTRODUCTION

The Eocene-Oligocene transition (EOT) represents the most significant global biotic reorganization since the end-Cretaceous extinction. In addition to shifts in the ocean current system and dramatic drops in sea level, large-scale positive oxygen isotope shifts have been recorded in the world's oceans (Zachos et al., 2001; Coxall et al., 2005) and from terrestrial sites in North America (Zanazzi et al., 2007), Europe (Grimes et al., 2005), and Asia (Graham et al., 2005). Eurasian land mammal communities were marked by the replacement of medium-sized ungulate communities with rodent- and lagomorph-dominated communities, known as the Grande Coupure ("Great Break") in Europe (Stehlin, 1909) and as the Mongolian Remodeling in Asia (Meng and McKenna, 1998).

The timings of the Eocene-Oligocene boundary (EOB) and EOT in Asia have been difficult to constrain due to the paucity of sediments that can be radioisotopically dated and correlated to the geomagnetic polarity time scale (GPTS). Several recent studies, however, have been able to correlate positive oxygen isotopic shifts (Graham et al., 2005) and substantial aridification on the Tibetan Plateau (Dupont-Nivet et al., 2007) to the GPTS (Fig. 1). To date, however, such studies have not included sediments that record the remodeling of mammalian communities, nor have they included magnetostratigraphic sections that are directly tied to the GPTS via radioisotopically dated layers.

The Tsagaan Nur Basin of Mongolia contains significant exposures of Paleogene nonmarine sediments, including the Oligocene Hsanda Gol Formation, which contains interbedded basalts and fossils that date the formation to the early Oligocene. Here we present the first magnetochronology for these faunas, showing that the earliest fauna of the Hsanda Gol Formation immediately postdates early Oligocene global cooling, is coincident with local and regional aridification, and is essentially contemporaneous with the postevent faunas of the Grande Coupure in Europe. The combined results demonstrate that extensive climatic change throughout Central Asia during the EOT was tightly correlated with, and likely drove, mammalian faunal change in Asia.

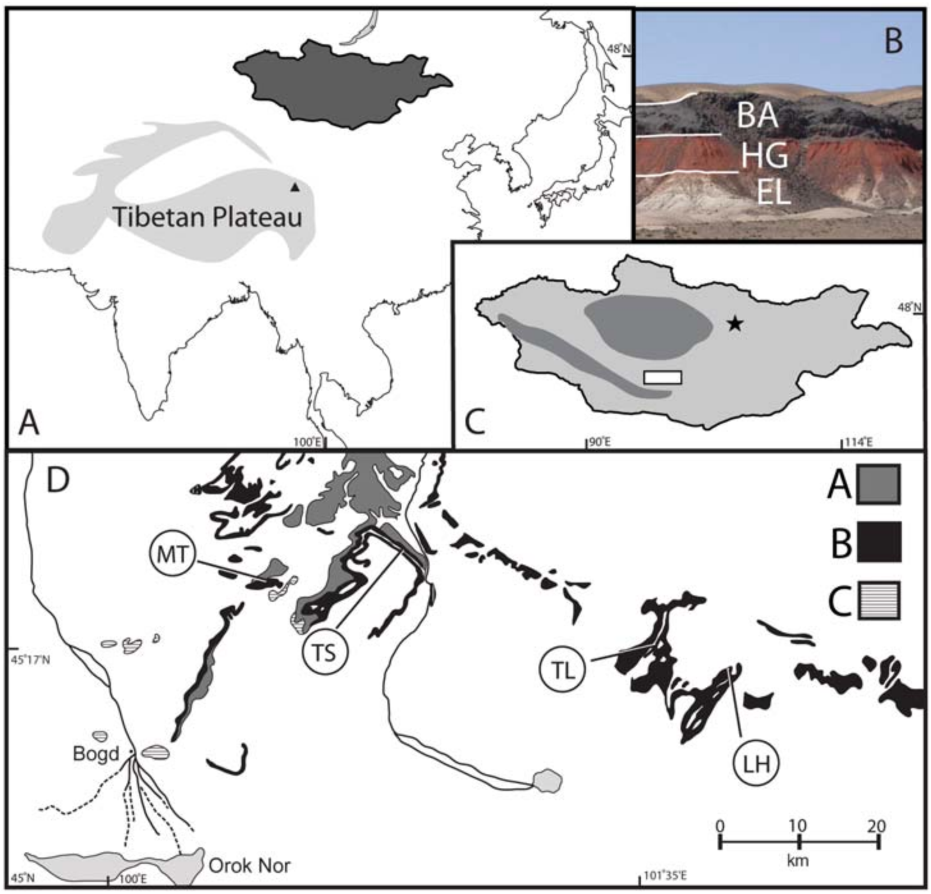

Figure 1. A: Location of recorded aridification in Tibetan Plateau (triangle; Dupont-Nivet et al., 2007). B: Contact between Hsanda Gol and Elegen Formations in section TGB; BA—basalt (~10 m), HG—Hsanda Gol Formation, EL—Elegen Formation. C: Study area within Mongolia. D: Geology of study area; MT—Menkhen Teg, TS—Taatsin Gol, TL—Tatal Gol, LH—Loh (area); A—Elegen Formation, B—Kholdbolzhi Formation, C—Hsanda Gol Formation (partially including Loh Formation) (modified from Russell and Zhai, 1987).

SEDIMENTOLOGY AND MAGNETOSTRATIGRAPHY OF THE EOT IN THE TSAGAAN NUR BASIN

The Hsanda Gol Formation is best exposed in the central portions of the Valley of Lakes area, Tsagaan Nur Basin, Mongolia (Fig. 1). Numerous studies have reported the geology and paleontology of the Hsanda Gol Formation (see Daxner-Höck and Badamgarav, 2007, for a summary), which intercalates with two Paleogene basalts. The older basalt, where present, is within the middle portions of the Hsanda Gol Formation and has been used to separate two members (Fig. 2).

The red beds of the Hsanda Gol Formation contrast sharply with the underlying gray sands of the Elegen Formation (Fig. 2). The lithologic contact between these two formations is conformable, with minor intertonguing of the fluvial sands of the Elegen Formation and fine red mudstones of the Hsanda Gol Formation. Sedimentological analysis has shown that the underlying fluvial deposits of the Elegan Formation are the source for the eolian dust sediments of the Hsanda Gol Formation (Höck et al., 1999), and thus mark a local pattern of aridification. Miocene fossils are known from the overlying Loh Formation (Höck et al., 1999), but a substantial unconformity makes its age unclear.

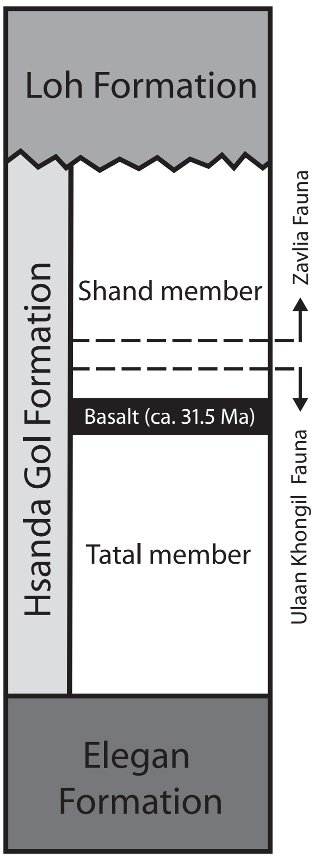

Figure 2. Elegan, Hsand Gol, and Loh Formations. Within Hsanda Gol Formation, basalt dated to ca. 31.5 Ma is present in places (Höck et al., 1999). Ulaan Khongil fauna of Bryant and McKenna (1995) = Biozones A + B of Höck et al. (1999).

OLIGOCENE MAMMALIAN FOSSILS OF THE HSANDA GOL FORMATION

The Hsanda Gol Formation contains abundant fossil mammals. After being grouped together as a single Hsanda Gol fauna in earlier studies (Mellett, 1968), two distinct faunas were recognized (Kowalski, 1974; Bryant and McKenna, 1995; Höck et al., 1999; Daxner-Höck and Badamgarav, 2007). The lower fauna occurs throughout the Tatal member and extends upward into the lower parts of the Shand member (Fig. 2). This fauna is considered to be the type of the Hsandagolian East Asian Land Mammal Age (EALMA; Meng and McKenna, 1998).

The Hsandagolian is recognized by the first appearance of rodent- and lagomorph-dominated faunas and is considered to represent the earliest post Mongolian Remodeling communities. Bryant and McKenna (1995) and Höck et al. (1999) found the sediments immediately below and above the basalt to be the most fossiliferous and dominated by typical Hsandagolian taxa. The Hsandagolian taxa (e.g., *Cricetops dormitor*) continue no more than 5 m above the basalt. An early Oligocene age for the Hsanda Gol Formation and its lower fauna was determined from dating the basalt found within the formation. Initial K/Ar ages were reported as 31.5–32 Ma (Evernden et al., 1964; Devyatkin and Smelov, 1979) with no error bars. These basalts were later redated using $^{40}Ar/^{39}Ar$ techniques and yielded ages that averaged 31.5 Ma (varying between 30.4 Ma and 32.1 Ma, with standard deviations of 0.3 and 0.8; Höck et al., 1999). These ages place the basalt in the early Oligocene during the upper parts of magnetochron C12r of the GPTS (Cande and Kent, 1995). Although the basalt radioisotopes reliably date the lower fauna within the Hsanda Gol Formation, these dates alone do not help to determine the age of EALMA boundaries, or the timing of related faunal changes.

RESULTS

The overall polarity sequence from the Valley of Lakes area includes five well-constrained magnetozones that are tied to the GPTS (Fig. 3) via two radioisotopically dated basalts that are stratigraphically delimited in sections TGB and TGAB and Bryant's Hill (for direction data, see Fig DR1 in the GSA Data Repository[1]). The basalts are of reversed polarity at TGB and TGAB (Fig. DR2), consistent with previous radioisotopic dates, and are thus correlated to the upper portion of magnetochron C12r and serve as strong tie points to the GPTS (ca. 31.1–33.3 Ma; Gradstein et al., 2004).

Below the basalt in sections TGB and Bryant's Hill is a prolonged reversed sequence that spans much of the lower Hsanda Gol Formation (Fig. 3) and is correlated to magnetozone C12r of the GPTS, as well as to the reversed zones in sections EHG and LOH. Sections EHG, TGB, and BO are correlated to one another via the presence of the Elegen–Hsanda Gol contact, and in each, a short normal magnetozone is present in the lowest portions of the Hsanda Gol Formation below C12r, here considered C13n (see Fig. DR3). Below the normal zone at TGB, a series of eight samples spanning ~12 m shows a persistent reversed zone entirely within the upper Elegen Formation and is considered to be C13r (ca. 33.7–34.8 Ma).

Above the basalt at both TGAB and Bryant's Hill a 10 m sequence of normal polarity sediments is correlated to magnetozone C12n (ca. 30.6–31.1 Ma). Reversed sediments are found above this zone in both sections, although only one reversed sample is observed in TGAB, and this overlying reversed zone is considered C11r at Bryant's Hill, where it persists for 10 m. Above C11r (ca. 30.2–30.6) at Bryant's Hill, two normal and one reversed magnetozones are present. These are tentatively referred to C11n.2n, C11n.1r, and C11n.1n, but additional specimens would be preferable, as each magnetozone is identified based on one sample level in this section. The magnetozones of North Ridge are shown, but correlations to Bryant's Hill are tentative.

Sections LOH and ULP are correlated based on a light-colored sandstone bed, and the normal magnetozone in ULP is directly correlated to the upper normal zone in LOH. The lack of basalt within this area makes it difficult to correlate these sections to others in the Valley of Lakes or to the GPTS. However, based on the known occurrence of fossils in this area (Höck et al., 1999), as well as the lithostratigraphy of the Hsanda Gol Formation, it is likely that the normal magnetozone observed in both LOH and ULP correlates to C12n, and that correlation is tentatively made here.

Hsandagolian fossils are frequently found immediately below the basalt, but they also occur throughout the lower portion of the Hsanda Gol Formation. Höck et al. (1999, their supplement 3) described Hsandagolian fossils near the base of the local section at TAT-C, and this section correlates to the Bryant's Hill section presented here. The base of these sections is likely near the base of the Hsanda Gol Formation, but the Elegen–Hsanda Gol contact

[1]GSA Data Repository item 2010023, methods and further results, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

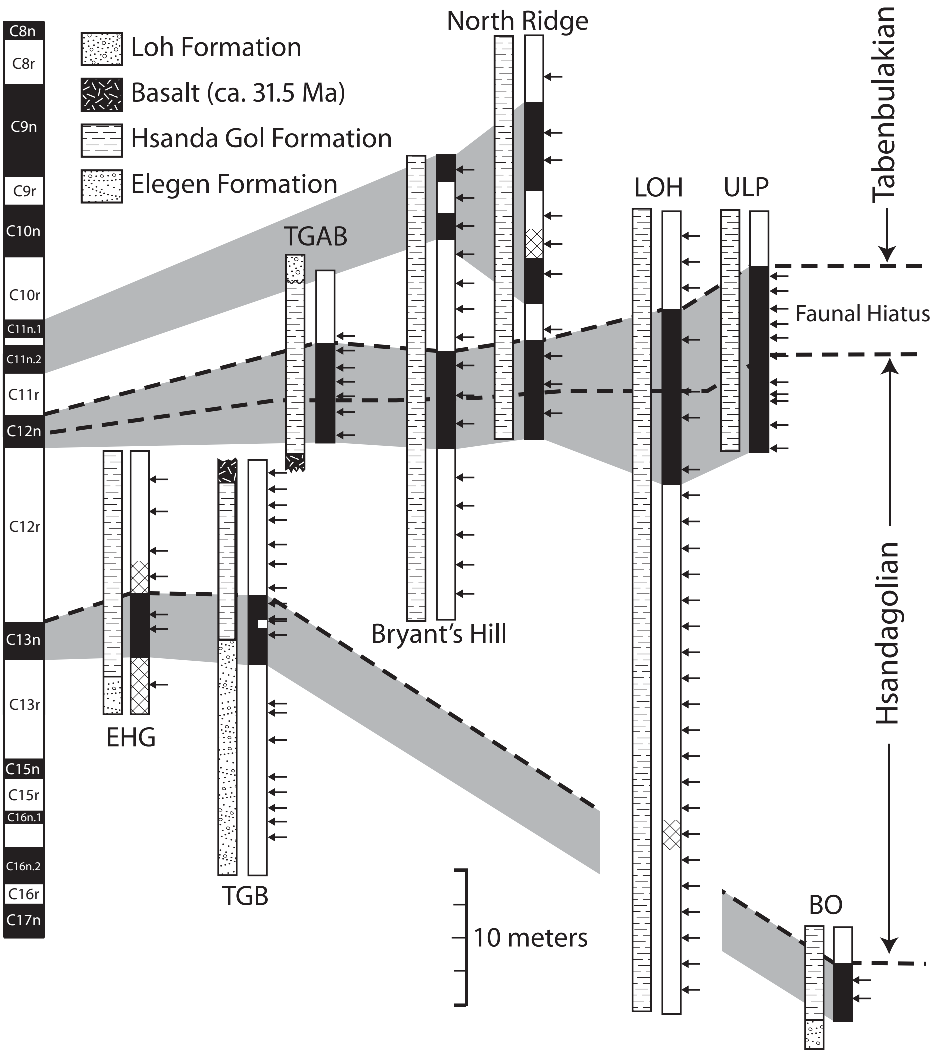

Figure 3. Correlations of eight stratigraphic (EHG, TGB, TGAB, Bryant's Hill, North Ridge, LOH, ULP, BO) sections measured for magnetostratigraphy within four areas (Menkhen Teg, Taatsin Gol, Tatal Gol, Loh; see Fig. 1) in Valley of Lakes, Mongolia. Sample levels marked by arrows (paleomagnetic direction data in Fig. DR4; see footnote 1). Dashed lines represent faunal boundaries. Cross-hachures indicate ambiguous samples.

is not present in the immediate area. The Bryant's Hill section did not show the presence of C13n, likely due to the absence of the lowermost Hsanda Gol Formation. Based on the distribution of Hsandagolian fossils at TAT-C and Bryant's Hill, the lower boundary of the lower fauna (and Hsandagolian EALMA) is placed within the lowest portions of C12r. Based on the upper stratigraphic occurrence of the lower Hsanda Gol fauna (Bryant and McKenna, 1995; Höck et al., 1999), the upper boundary of the Hsandagolian EALMA is in the middle portions of C12n of the GPTS.

DISCUSSION

Based on the identification of magnetochron C13n at the base of the Hsanda Gol Formation, the EOB (33.9 Ma; Gradstein et al., 2004) can for the first time be confidently placed in terrestrial sediments within Asia (Fig. 3). Magnetochron C13n was found within three sections in this study, including all that spanned the Elegen–Hsanda Gol contact. The placement of the EOB near the contact coincides with an abrupt local aridification event. By correlating these sediments to those of the Xining Basin of Tibet via the GPTS (Dupont-Nivet et al., 2007), a broader pattern of aridification across the EOB within Central Asia is also supported. It remains to be determined, however, if the regional aridification event was driven by tectonic activity, global climatic change, or both. Uplift of the Tibetan Plateau occurred around this time (Wang et al., 2008), and rain shadow effects could have influenced aridification patterns in Tibet and Mongolia. Regardless of mechanisms, this study supports a coordinated climatic change throughout Central Asia at the EOB.

Precise boundary dates for the Hsandagolian and Tabenbulakian EALMAs allow reassessment of the age of Oligocene faunas in Asia, and more important, better timing of the Mongolian Remodeling. The Hsandagolian and Tabenbulakian have been traditionally correlated to the early and late Oligocene, respectively. This study confirms that the Hsandagolian is an early Oligocene EALMA, but restricts it to the early-early Oligocene (30.6–33.3 Ma; Gradstein et al., 2004). The Tabenbulakian is significantly older than previously recognized; Tabenbulakian fossils are known from the base of the C11r and their first appearance is dated to the late-early Oligocene (30.6 Ma). Unfortunately, it is not yet clear how long Tabenbulakian faunas persisted in the Valley of Lakes, or elsewhere in Central Asia. Overall, our biostratigraphic revisions also help to date the timing of the Mongolia Remodeling because the lower fauna of the Hsanda Gol Formation (Hsandagolian EALMA) represents the first appearance of rodent- and lagomorph-dominated communities. Based on this study, the first post–Mongolian Remodeling faunas appeared by 33.3 Ma.

The revised biostratigraphic and geochronologic framework presented here also allows precise correlation of Oligocene mammalian faunas of Asia to others worldwide (see Fig. DR6 for summary). The Hsandagolian is now correlated to most of the Orellan and Whitneyan North American Land Mammal Ages (NALMAs) and the early Tabenbulakian is correlated to the early Arikareean NALMA (Woodburne, 2004). Several important fossil localities from Oman and Egypt have been correlated to the GPTS via magnetochronology and invertebrate paleontology (Seiffert, 2006), and directly correlate to the Hsandagolian.

Correlation to European mammalian faunas and the Grande Coupure can be made via the Hampshire, Paris, Belgian, and Ebro Basins (Hooker et al., 2004; Barberà et al., 2001). The Grande Coupure in all of these basins has been correlated to C13n of the GPTS via magnetochronology and/or calcareous nanoplankton zones. A positive oxygen isotope excursion is present near the Grande Coupure at the top of C13r in terrestrial sediments of the Hampshire Basin (Grimes et al., 2005), and correlates to global positive oxygen isotope excursion in marine sediments and to regional patterns of climatic change in Central Asia, as revealed in this study. The correlations to the GPTS in the Hampshire Basin, however, have been reassessed based on new magnetochronology (for summaries, see Gale et al., 2006; Hooker et al., 2007).

The recent work within Europe and this study allow the first precise timing of similar faunal turnovers across two continents. Meng and McKenna (1998) were the first to recognize the

Mongolian Remodeling within Asia and suggested that it occurred at or near the EOB and slightly before the Grande Coupure, because some taxa that diversified after the EOT in Europe had their evolutionary roots within Asia. The hypothesis that climatic change drove mammalian diversification in Central Asia is strongly supported here, as the origin of rodent- and lagomorph-dominated faunas coincides with regional aridification that is tightly correlated with global climatic change.

This study suggests, however, that the Mongolian Remodeling was nearly synchronous with the Grande Coupure. More precisely, the Mongolian Remodeling occurred by the beginning of magnetochron C12r and likely postdated the Grande Coupure by several hundreds of thousands of years. These new dates do not falsify the hypothesis that post–Mongolian Remodeling taxa immigrated to Europe and subsequently drove some European taxa to extinction while also serving as the stock for later European diversification, but it makes that scenario much more unlikely. This study lends support to two alternative hypotheses, however: (1) if Asian taxa influenced faunal reorganization within Europe, they were likely rodent and lagomorph representatives from the pre–Mongolian Remodeling faunas (i.e., late Eocene taxa or earlier); or (2) reorganization within Europe was largely driven by climatic change, and competition with Asian taxa had limited or no influence on European faunas. The conclusions here are limited by the fact that no late Eocene faunas are known from the Valley of Lakes, and the precise initiation of Mongolian Remodeling remains unclear. This will remain problematic as there are no stratigraphic sections known within Central Asia that document both late Eocene and early Oligocene faunas. To better understand faunal exchange between Asia and Europe such sections are needed, as well as better constraint on the retreat of the Turgai Strait, which served as a biogeographic barrier between Asia and Europe for much of the Eocene.

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REFERENCES CITED

Barberà, X., Cabrera, L., Marzo, M., Paré, J.M., and Agusti, J., 2001, A complete terrestrial Oligocene magnetobiostratigraphy from the Ebro Basin, Spain: Earth and Planetary Science Letters, v. 187, p. 1–16, doi: 10.1016/S0012-821X(01)00270-9.

Bryant, D., and McKenna, M.C., 1995, Cranial anatomy and phylogenetic position of *Tsaganomys altaicus* (Mammalia, Rodentia) from the Hsanda Gol Formation (Oligocene), Mongolia: American Museum Novitates, no. 3156, p. 1–42.

Cande, S.C., and Kent, D.V., 1995, Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic: Journal of Geophysical Research, v. 100, p. 6093–6095, doi: 10.1029/94JB03098.

Coxall, H.K., Wilson, P.A., Palike, H., Lear, C.H., and Backman, J., 2005, Rapid stepwise onset of Antarctic glaciation and deeper calcite compensation in the Pacific Ocean: Nature, v. 433, p. 53–57, doi: 10.1038/nature03135.

Daxner-Höck, G., and Badamgarav, D., 2007, Geological and stratigraphic setting, *in* Daxner-Höck, G., ed., Oligocene-Miocene vertebrates from the Valley of Lakes (Central Mongolia): Morphology, phylogenetic and stratigraphic implications: Annalen des Naturhistorischen Museums in Wien, v. 108A, p. 1–24.

Devyatkin, Y.V., and Smelov, S.B., 1979, Position of basalts in the Cenozoic sedimentary sequence of Mongolia: International Geology Review, v. 22, p. 307–317, doi: 10.1080/00206818209466888.

Dupont-Nivet, G., Krijgsman, W., Langereis, C.G., Abels, H.A., Dai, S., and Fang, X., 2007, Tibetan plateau aridification linked to global cooling at the Eocene–Oligocene transition: Nature, v. 445, p. 635–638, doi: 10.1038/nature05516.

Evernden, J.F., Savage, D.E., Curtis, G.H., and James, G.T., 1964, Potassium-argon dates and the Cenozoic mammalian chronology of North America: American Journal of Science, v. 262, p. 145–198.

Gale, A.S., Huggett, J.M., Pälike, H., Laurie, E., Hailwood, E.A., and Hardenbol, J., 2006, Correlation of Eocene–Oligocene marine and continental records: Orbital cyclicity, magnetostratigraphy and sequence stratigraphy of the Solent Group, Isle of Wight, UK: Geological Society of London Journal, v. 163, p. 401–415, doi: 10.1144/0016-764903-175.

Gradstein, F.M., Ogg, J.G., and Smith, A.G., 2004, A geologic time scale 2004: Cambridge, Cambridge University Press, 589 p.

Graham, S.T., Chamberlain, C.P., Yue, Y., Ritts, B.D., Hanson, A.D., Horton, T.W., Waldbauer, J.R., Poage, M.A., and Feng, X., 2005, Stable isotope records of Cenozoic climate and topography: Tibetan Plateau and Tarim Basin: American Journal of Science, v. 305, p. 101–118, doi: 10.2475/ajs.305.2.101.

Grimes, S.T., Hooker, J.J., Collinson, M.E., and Mattey, D.P., 2005, Temperatures of the late Eocene to early Oligocene freshwaters: Geology, v. 39, p. 189–192, doi: 10.1130/G21019.1.

Höck, V., Daxner-Höck, G., Schmid, H.P., Badamgarav, D., Frank, W., Furtmüller, G., Montag, O., Barsbold, R., Khand, Y., and Sodov, J., 1999, Oligocene–Miocene sediments, fossils and basalts from the valley of the lakes (Central Mongolia): An integrated study: Mitteilungen der Österreichischen Geologischen Gesellschaft, v. 90, p. 83–125.

Hooker, J.J., Collinson, M.E., and Sille, N.P., 2004, Eocene–Oligocene mammalian faunal turnover in the Hampshire Basin, UK: Calibration to the global time scale and the major cooling event: Geological Society of London Journal, v. 161, p. 161–172, doi: 10.1144/0016-764903-091.

Hooker, J.J., Collinson, M., Grimes, S., Sille, N., Mattey, D., Gale, A., Huggett, J., and Laurie, E., 2007, Discussion on the Eocene–Oligocene boundary in the UK: Geological Society of London Journal, v. 164, p. 685–688, doi: 10.1144/0016-76492006-098.

Kowalski, K., 1974, Middle Oligocene rodents from Mongolia: Palaeontologia Polonica, v. 30, p. 147–178.

Mellett, J., 1968, The Oligocene Hsanda Gol Formation, Mongolia: A revised faunal list: American Museum Novitates, no. 2318, p. 1–16.

Meng, J., and McKenna, M.C., 1998, Faunal turnovers of Paleogene mammals from the Mongolian plateau: Nature, v. 394, p. 364–367, doi: 10.1038/28603.

Russell, D.E., and Zhai, R., 1987, The Paleogene of Asia: Mammals and stratigraphy: Mémoires du Muséum National d'Histoire Naturelle, ser. C, v. 52, p. 1–488.

Seiffert, E., 2006, Revised age estimates for the later Paleogene mammal faunas of Egypt and Oman: National Academy of Sciences Proceedings, v. 103, p. 5000–5005, doi: 10.1073/pnas.0600689103.

Stehlin, H.G., 1909, Remarques sur les faunules de mammifères des couches Eocenes et Oligocenes du Bassin de Paris: Bulletin de la Société Géologique de France, v. 9, p. 488–520.

Wang, C., Zhao, X., Liu, Z., Lippert, P.C., Graham, S.A., Coe, R.S., Yi, H., Zhu, L., Liu, S., and Li, Y., 2008, Constraints on the early uplift history of the Tibetan Plateau: National Academy of Sciences Proceedings, v. 105, p. 4987–4992, doi: 10.1073/pnas.0703595105.

Woodburne, M.O., 2004, Late Cretaceous and Cenozoic mammals of North America: Biostratigraphy and geochronology: New York, Columbia University Press, 376 p.

Zachos, J.C., Pagani, M., Sloan, L., Thomas, E., and Billups, K., 2001, Trends, rhythms, and aberrations in global climate 65 Ma to present: Science, v. 292, p. 686–693, doi: 10.1126/science.1059412.

Zanazzi, A., Kohn, M.J., MacFadden, B.J., and Terry, D.O., Jr., 2007, Large temperature drop across the Eocene–Oligocene transition in central North America: Nature, v. 445, p. 639–642, doi: 10.1038/nature05551.

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Methods

To correlate fossil levels to the Geomagnetic Polarity Time Scale (GPTS), eight sections (Table A1) were measured in four areas of the Valley of Lakes (see Badamgarav et al. (1975) and Höck et al. (1999) for detailed descriptions of lithostratigraphy and sedimentology of the Hsanda Gol and related formations). Section EHG at Menkhen Teg spans the upper Elegen Formation and continues into the lower member of the Hsanda Gol Formation. Two sections were measured at Taatsin Gol, TGB and TGAB (directly corresponding to TGR-B and TGR-AB of Höck et al., (1999)). TGB spans the upper 15 m of the Elegen Formation and the Tatal member of Hsanda Gol Formation. The section is capped by 10 m of basalt, which can be traced to the base of section TGAB. TGAB is found only 50 m from TGB and includes the first 9 m of the Shand member of the Hsanda Gol Formation and is capped by an unconformable Loh Formation. The basalt was sampled for paleomagnetic analysis and was previously dated at 31.5 Ma (Höck et al., 1999)

Two sections were measured at Tatal Gol, Bryant's Hill and North Ridge. Bryant's Hill section is entirely within the Hsanda Gol Formation and includes a dated basalt (Höck et al., 1999) that is situated approximately 10 m from the base of the section. The section continues for nearly 20 m above the basalt. The base of North Ridge section is located just above the same basalt level as Bryant's Hill, although several interpretations of the correlation of these two sections are discussed below. Two sections were measured at Loh, LOH and ULP. The Loh section begins near the base of the

Hsanda Gol Formation and continues into the upper reaches of the Shand member. No basalt is exposed within this section. ULP is entirely within the Shand member of the Hsanda Gol Formation, and is found on the northeastern end of a prominent ridge of exposed Hsanda Gol Formation along the west side of the Loh drainage. The LOH section was measured on the southwestern end of this ridge. The two sections are correlated based on the occurrence of a white sandy layer that can be traced along the entire ridge. Section BO is across the Loh drainage from LOH and ULP and consists of several meters of sediments near the Hsanda Gol/Elegen contact.

Sediments from the Elegen and Hsanda Gol formations were collected from all measured sections in four different areas; radioisotopically dated basalt was found within the sections of two areas (Taatsin Gol and Tatal Gol). Oriented sediment samples for paleomagnetic study were collected in 1995 and 1997 (referred to as set A [n = 55], including Bryant's Hill, North Ridge, and LOH) and again in 2004 and 2006 (referred to as set B [n= 45], including Menkhen Teg, Taatsin Gol A and B, ULP, and BO). Field samples from 250 – 2,000 cm^3 were collected in 1 m to 1.8 m stratigraphic increments, although deviations from these increments occurred due to lithological considerations. All samples were cut into smaller specimens (~11 cm^3); two specimens for each sample for set A and three specimens from each sample from set B were prepared and demagnetized.

Remanence measurements of specimens from set A were made with a 2G Model 760 three-axis cryogenic magnetometer in a shielded room, which reduced the ambient field to < 300μT at the Paleomagnetic Laboratory at Lamont-Doherty Earth Observatory (Columbia University). The natural remnant magnetization (NRM) was measured for each specimen followed by a 14 step thermal demagnetization sequence: 200°, 300°, 400°, 500°, 525°, 550°, 575°, 600°, 625°, 650°, 660°, 670°, 680°, and 685° C. Between each demagnetization, the magnetic remanence as well as the susceptibility were measured. Remanence measurements of specimens from set B were made with a 2-G 755 cryogenic magnetometer in a magnetically shielded room (residual field < 2nT) at the Berkeley Geochronology Center. After measuring the NRM, specimens were demagnetized using both alternating field (AF) and thermal techniques; magnetic remanence was measured after each thermal step of demagnetization and before and after all AF demagnetization steps. AF was applied at 3, 6, 9, 12, and 15 mT to erase viscous remnant magnetization. Specimens were then thermally demagnetized beginning at 90°C and continuing to 625°C. All specimens were demagnetized (including AF and thermal) over 12 – 19 steps.

In general, each specimen began with a remanence that consisted of a low temperature/low coercivity component (aligned with the modern field direction) and a high temperature/high coercivity component (that was either of normal or reverse polarity) that was considered the Characteristic Remanent Magnetization (ChRM). Although it is difficult to distinguish the expected paleopole for the early Oligocene of this area (Hankard, et al., 2007) from the modern field due to their similar position, most normal samples did show two distinct normal components. Table A2 summarizes reverse and normal pole directs for each stratigraphic section. The low temperature component was typically removed by AF treatment (for set B) and heating to 200°C (AI Fig. 7, A). In some specimens, however, this component persisted into higher temperatures reaching 500°C and overlapped with a ChRM (see discussion below). Samples in which the modern component was easily removed, revealing a high temperature component, and then showed decay to the origin in orthogonal projection, are considered Class A (n = 55). Some samples, however, exhibited a demagnetization pattern that suggested a broad overlap of the low and high temperature components. These samples showed strong great circle trends in stereo projection; long, dispersed trends in specimens with a reversed high component, and short trends in specimens with a normal high temperature component. Samples in which all specimens exhibit this broad overlap are considered Class C (n = 36), and samples that consist of specimens of both types are considered class B (n = 9).

Directions of ChRM for specimens that exhibited clear separation of ChRM from a low temperature component were calculated using least squares analysis as described by Kirschvink (1980). AI Fig. 7 shows both reversed and normal samples in orthogonal projection. Directions of ChRM specimens in which a strong trend within stereographic projection occurred, but the ChRM did not decay toward the origin in orthogonal projection, were calculated by determining a mean direction (in stereographic direction) of representative thermal steps ((Fisher, 1953); Supp. Fig. 7, F). In one sample, a strong great circle trend was observed between secondary and ChRM components, but no series of steps represented a specific direction at higher temperatures. In these specimens, the end of streak method (Scott, et al., 2007) was used and a terminal step along the great circle trend was taken as the direction of the ChRM. All statistical analysis on the demagnetization data was conducted using PaleoMac (Cogné, 2003)

Polarity could be determined for all samples presented here, but because samples that exhibited overlapping components show a mixture of multiple components at high temperatures, the high temperature component is not specifically an ancient field direction. For this reason, Virtual Geomagnetic Pole (VGP) latitudes were not used. Instead, specimen and sample (mean for samples with multiple specimens) paleomagnetic directions were calculated as the angular difference (Δ) between the specimen (D_a, I_a) direction and the expected normal direction (D_b = 358.2°, I_b = 65.5°, from Hankard et al., (2007)), using the formula: $\Delta = \cos^{-1}(\cos I_A \cos D_A \cos I_B \cos D_B + \cos I_A \sin D_A \cos I_B \sin D_B + \sin I_A \sin I_B)$ from Butler (1992). In sample set A the characteristic specimen was typically used to determine direction rather than specimen means.

Results continued.

The placement of the upper fauna is more difficult as it is clear that a faunal hiatus occurs between the lower and upper faunas. The lowest stratigraphic positions of Tabenbulakian fossils within sections that can be related to those presented here occur at TGB and LOH, where Höck et al. (1999) show that Tabenbulakian fossils first appear ~10 m above the basalt (their TGL-A). TGL-A can be easily correlated to TGB via the basalt and due to the fact that the two areas were once stratigraphically continuous, but are now separated by erosion of the Taatsin Gol drainage. Based on the stratigraphic range of C12n within TGAB and the distribution of fossils at TGL-A, it is likely that the stratigraphically lowest Tabenbulakian fossils occur at the base of C11r. The upper age of the Tabenbulakan (and upper fauna of the Hsanda Gol Formation) is unclear due to the unconformity of the Hsanda Gol/Loh Formations.

Figure AI 8 shows the upper Elegen/lower Hsanda Gol sequence at TGB with associated stereographic summaries of paleomagnetic specimens. Important to note is the presence of a cryptochron (Cande and Kent, 1992) within the C13n (≈ 33.3 – 33.7 Ma) at the base of the Hsanda Gol Formation. One TGB sample produced two specimens of reversed and one of normal polarity. The specimens of reversed polarity were cut from the same level within the sample, but the specimen of normal polarity was cut from a different level. To clarify the presence of two different polarities within the same sample, four new specimens were prepared from the original sample; two from the initially recognized reversed layer and two from the normal layer. All four new specimens were demagnetized using the same methods and showed the same polarities as previous specimens from the same levels within the sample. Because the sample itself is bounded above and below by normal polarity samples, the sequence overall is still correlated to magnetozone C13n. However, as a small reversed layer is observed within an otherwise normal sample a minor cryptochron is inferred in magnetozone C13n.

The three highest samples in C12r at TGB are likely overprinted by the overlying basalt. Although these samples show a strongly reversed ChRM, their increased intensity relative to other sediments within this section and lack of a low coercivity component suggest that they retain a magnetization derived due to baking as the overlying basalt was deposited. The lowest sample from this sequence is found just 2.3 m below the 10 m thick basalt layer and all of the samples show some degree of discoloration believed to be from a baking event. Because the basalt and the three samples below it are reversed, it is likely that the entire sequence represents C12r. The polarities of the overprinted samples are marked as questionable in figure 5 (denoted by question marks) to show that the magnetization is likely derived from the basalt, and not a ChRM derived during initial lithification of sediments.

Table DR1. Longitude and latitude coordinates for sections referenced in text.

Sections	Latitude	Longitude
BO	45˚ 14’ 55”	101˚ 48’ 55”
ULP	45˚ 16’ 31”	101˚ 46’ 34”
LOH	45˚ 16’ 13”	101˚ 45’ 54”
North Ridge	45˚ 18’ 05”	101˚ 38’ 31”
Bryant’s Hill	45˚ 17’ 52”	101˚ 37’ 47”
TGAB	45˚ 24’ 49”	101˚ 15’ 25”
TGB	45˚ 24’ 53”	101˚ 15’ 44”
EHG	45˚ 24’ 31”	101˚ 04’ 03”

Table DR2. Fisher mean (1953) averages for normal and reversed specimens in each section

Sections	Specimen polarities	Direction means		n	k	α95
		Inc.	Dec.			
TGB	N	355.7	57.9	11	53.4	7.1
	R	174.8	-47.8	36	9..4	8.2
TGAB	N	348.7	65.4	19	24.7	6.9
	R	168.5	-50.2	2	1344.8	6.8
ULP	N	357.0	64.0	30	22.2	5.7
EHG	N	352.7	63.6	7	2.9	43.2
	R	187.2	-33.6	9	4.3	28.3
Tatal[a]	N	346.9	61.0	11	5.5	21.4
	R	204.4	-56.2	13	6.6	17.5
Loh	N	341.6	54	7	7.9	19.8
	R	173.8	-60.6	25	9.7	9.8
BO	N	4.3	65.3	5	133.1	6.7

[a]note: that Tatal refers to a combined Bryant's Hill and North Ridge sections

REFERENCES CITED

Badamgarav, D., Dashzeveg, D., Devyatkin, E. V., Zhegallo, V. I., and Liskun, I. G., 1975, Stratigrafiya Paleogena I Neogena Dolina Ozer (K vorposu o vydelenii sratotipicheskogo rayona dlya Paleogena I Neogena Tsentral'noy Azii),*in* Kramarenko, H. N., ed., Trudy - Sovmestnaya Sovetsko-Mongol'skaya Paleontologicheskaya Ekspeditsiya, p. 250–268.

Butler, R. F., 1992, Paleomagnetism: Magnetic Domains to Geologic Terranes: Blackwell Scientific Publications: Boston, pp. 319.

Cogné, J. P., 2003, PaleoMac: A Macintosh™ application for treating paleomagnetic data and making plate reconstructions: Geochemistry, Geophysics, and Geosystems, v.

4, p. 1007.

Fisher, R., 1953, Dispersion on a sphere: Proceedings of the Royal Society of London, Series A, No. 217, p. 295–305.

Hankard, F., Cogné, J. -P., Kravchinsky, V. A., Carporzen, L., Bayasgalan, A., and Lkhagvadorj, P., 2007, New Tertiary paleomagnetic poles from Mongolia and Siberia at 40, 30, 20, and 13 Ma: Clues on the inclination shallowing problem in central Asia, Journal of Geophysical Research, v. 112, B02101.

Höck, V., Daxner-Höck, G., Schmid, H. P., Badamagarav, D., Frank, W., Furtmüller, G., Montag, O., Barsbold, R., Khand, Y., Sodov, J., 1999, Oligocene–Miocene sediments, fossils and basalts from the valley of the lakes (Central Mongolia): An Integrates study: Mitteilungen der Österreichischen Geologischen Gesellschaft, v. 90, p. 83–125.

Kirschvink, J. L., 1980, The least-square line and plane and the analysis of paleomagnetic data: Geophysical Journal International, v. 62, p. 699–718.

Scott, G. R., Gibert, L., Gibert, J., 2007, Magnetostratigraphy for the Orce region (Baza Basin), SE Spain: New chronologies for Early Pleistocene faunas and hominid occupation sites: Quaternary Sciences Reviews, v. 26, p. 415–435.

Kraatz and Geisler_Figure DR1.jpg

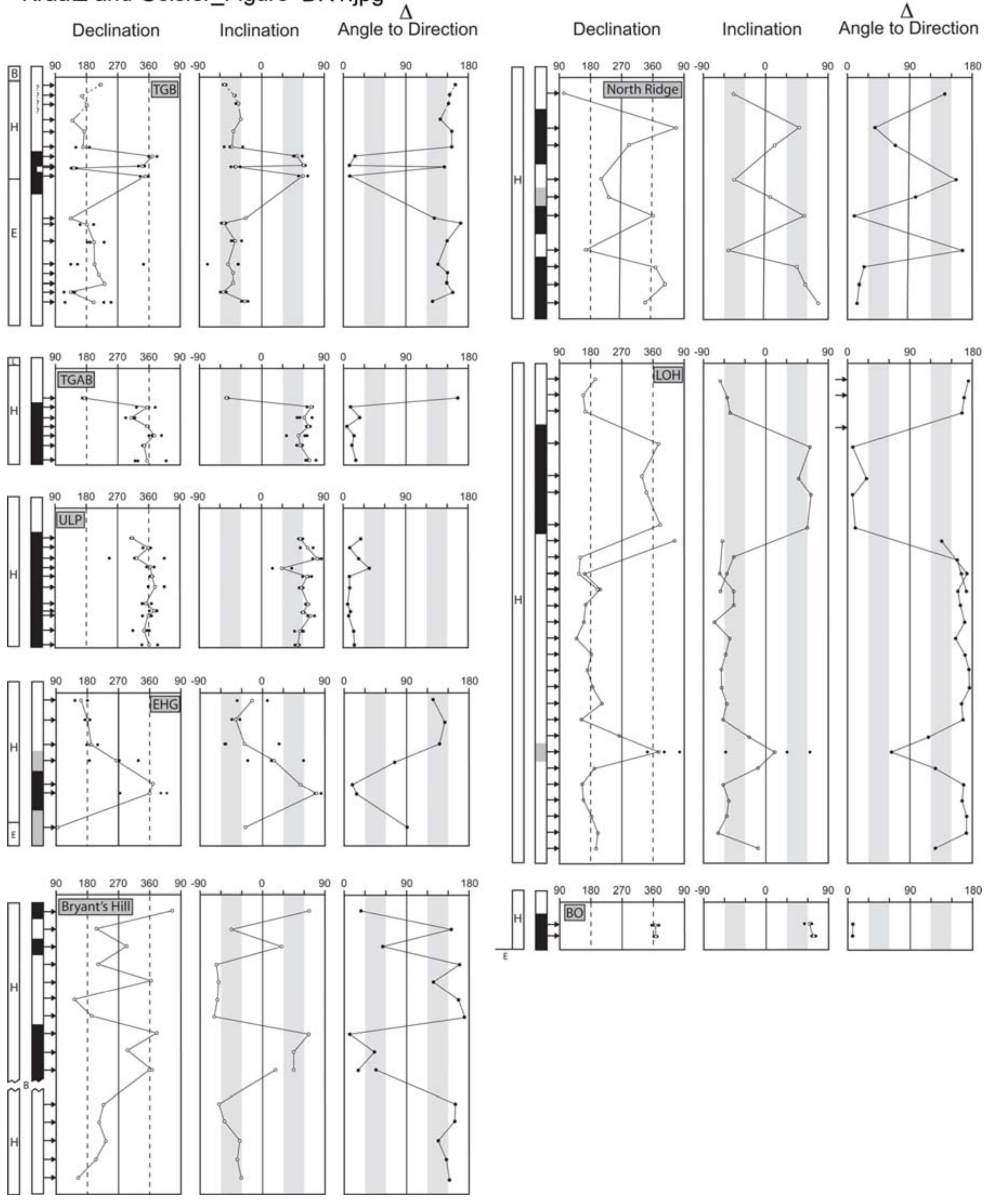

Figure DR1. Declination, Inclination, and Angle to Direction data for all samples in study. For samples with multiple specimens, sample means are marked by unfilled circle, and a solid circle marks individual specimens. On stratigraphic columns to the left of each section, B denotes basalt, L denotes Loh formation, H denotes Hsanda Gol formation, and E denotes Elegen formation. See supplemental text for a discussion of the Angle to Direction method.

Kraatz and Geisler_Figure DR2.jpg

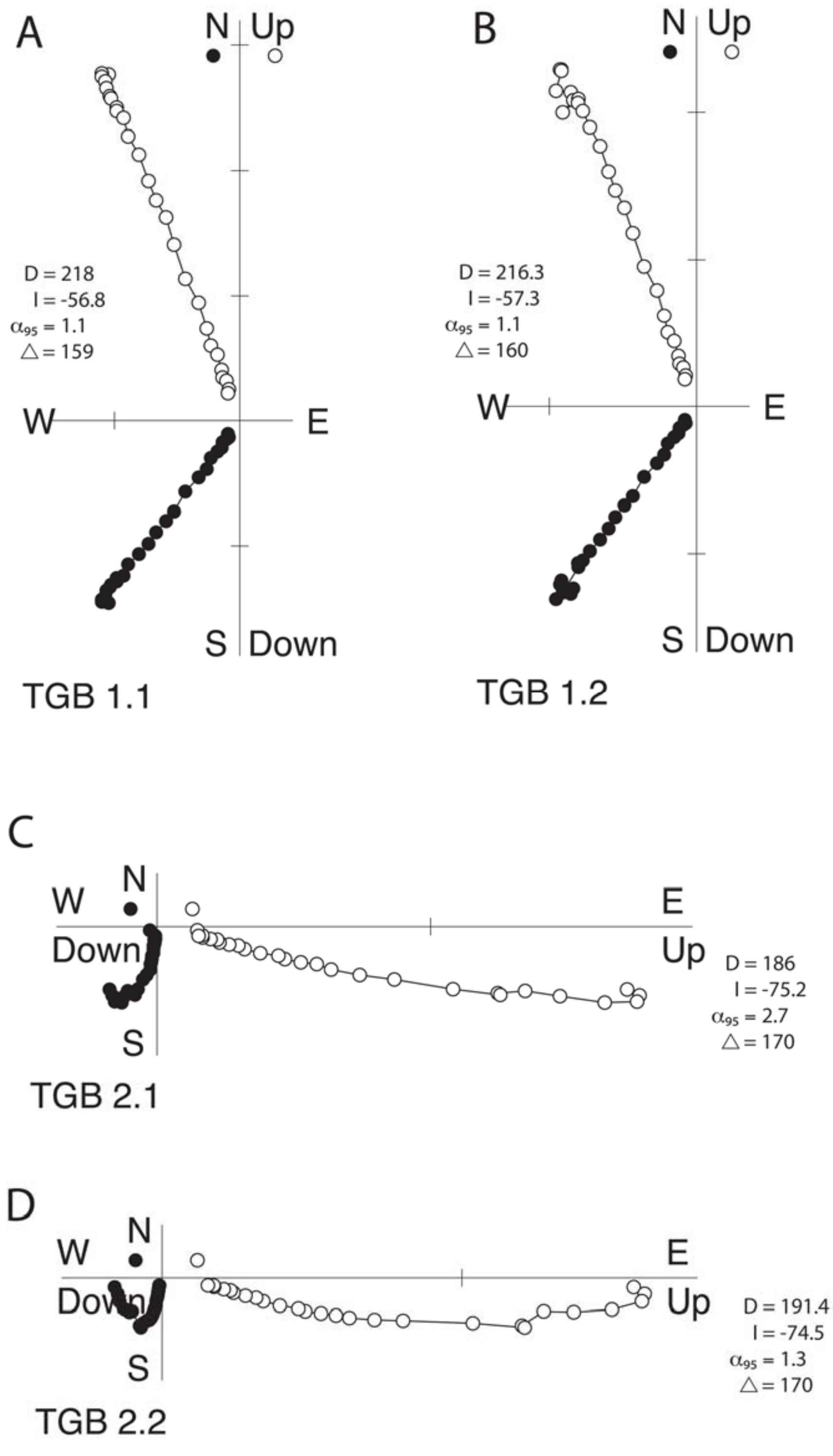

Figure DR2. Orthogonal projection of 4 specimens (two samples) taken from the basalt at TGB and TGAB. One sample (TGB.1, A and B of this figure) is from the top of the ~ 10 m basalt, the other (TGB.2, C and D of this figure) is from the bottom of the basalt.

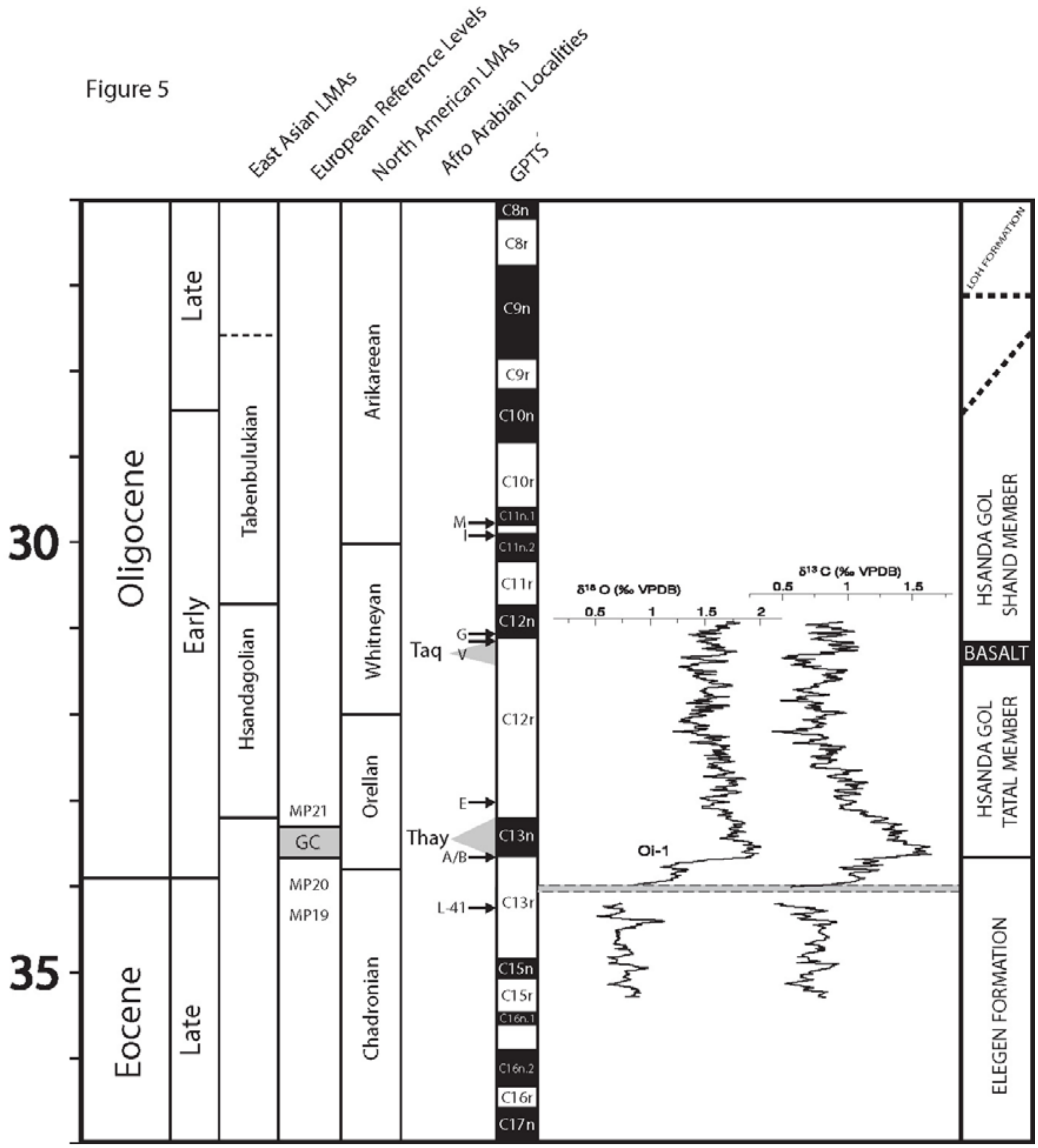

Figure DR3. Correlation of Hsanda Gol Formation to East Asian Land Mammal Ages as well as those from Europe, North America, and Afro-Arabia. Time scale and GPTS are taken from Gradstein et al., (Gradstein, et al., 2004). Placement of European reference levels are based on Hooker et al. (Hooker, et al., 2004). North American Land Mammal Ages and Afro-Arabian localities are taken from Woodburne (2004) and Seiffert (2006) respectively. The δ^{18} O and δ^{13} C curves are taken from Coxall et al. (2005) and mark major climatic excursions as well as the onset of Antarctic glaciation (Oi-1). The schematic of the Hsanda Gol Formation is not to scale.

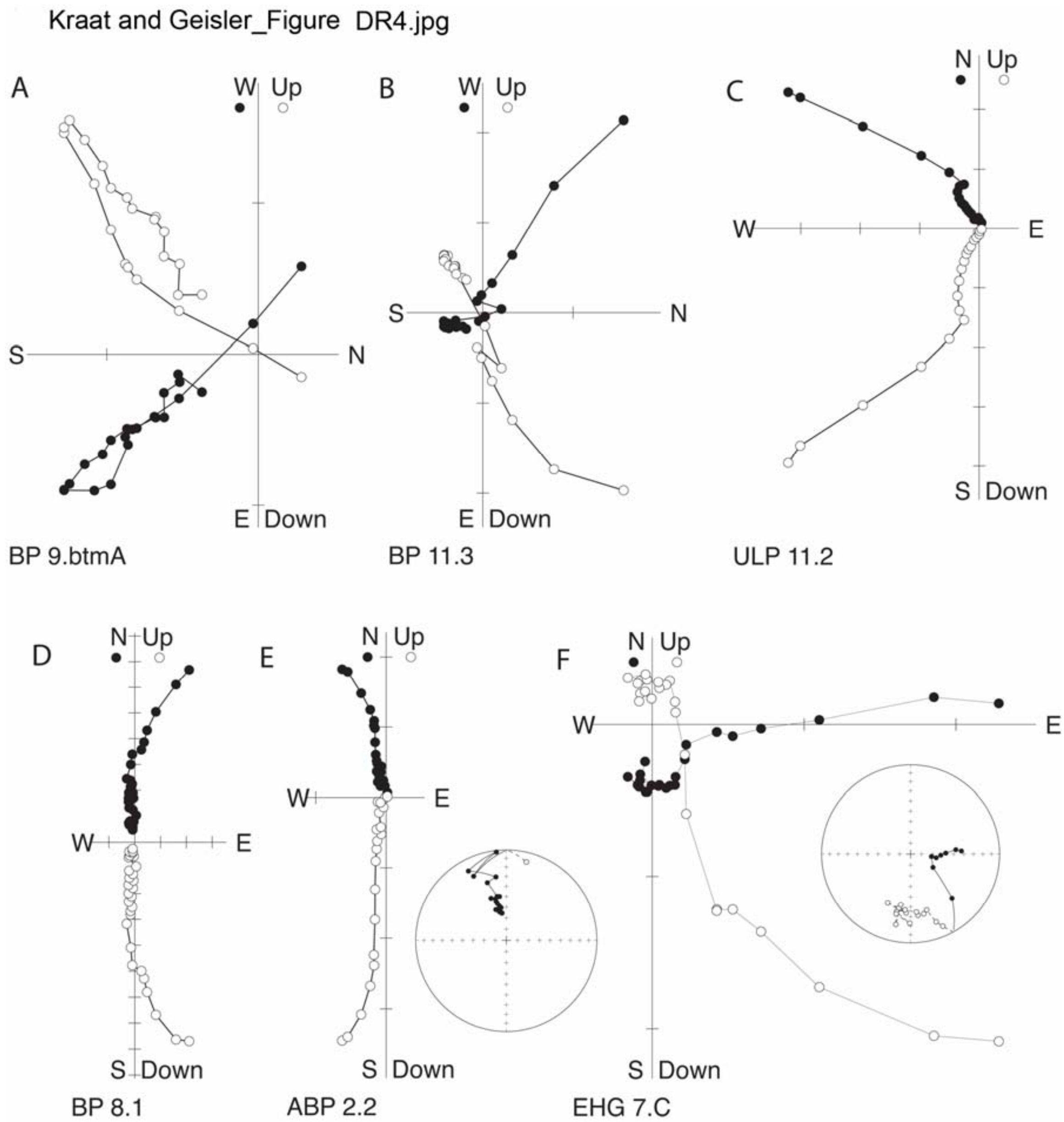

Figure DR4. Orthogonal projections of typical specimens, see supplemental text for discussion of what constitutes specimen types A, B, and C. A and B represent reversed specimens of type A. C and D represent normal polarity specimens of type A. F shows a sample (as discussed in text) in which a strong great circle trend during demagnetization is observed, but the specimen does not decay toward the origin (type C). Planes in stereographic projection represented by orthogonal axes are denoted in each graph.

Kraatz and Geisler_figure DR5.jpg

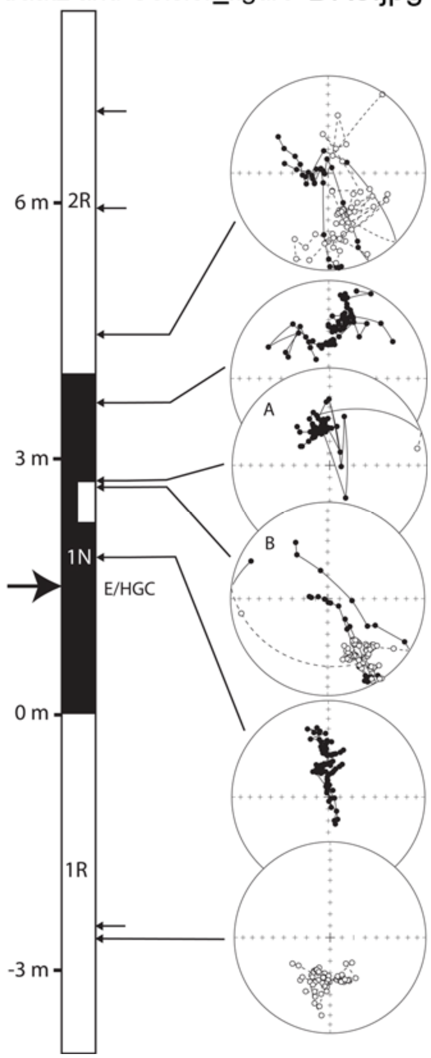

Figure DR5. A portion of section TGB that spans the Elegen/Hsanda Gol contact (denoted by arrow and E/HG in figure) and includes a normal polarity zone at the base of the Hsanda Gol Formation that is correlated to C13n of the GPTS. Arrows on right represent all levels from which paleomagnetic samples were taken. Stereographic projections are shown for six samples that illustrate the transition from reversed to normal and back to reversed polarities from stratigraphically low to high samples. Stereographic projections A and B also show two different specimens from the same sample that are of different polarity and have been interpreted to span a cryptochron (see text for discussion).