Figure 1.

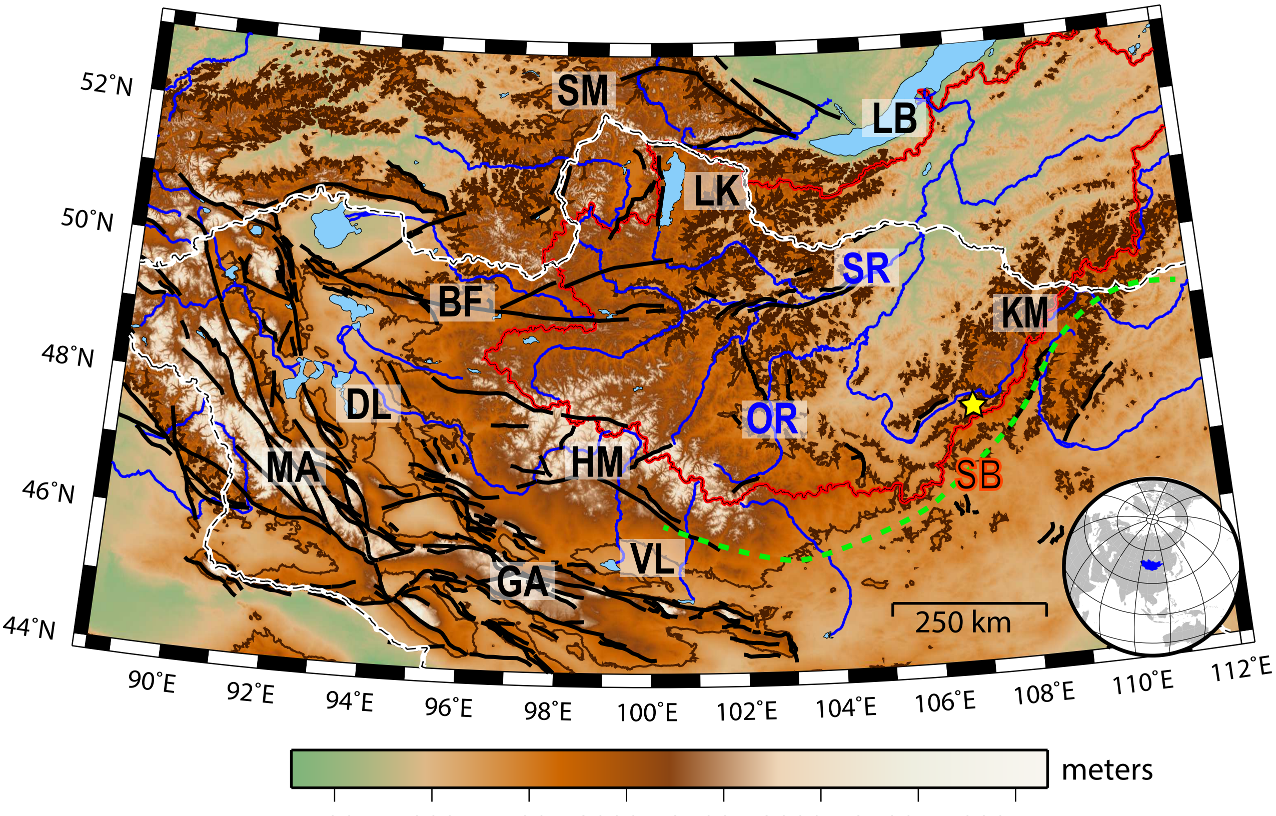
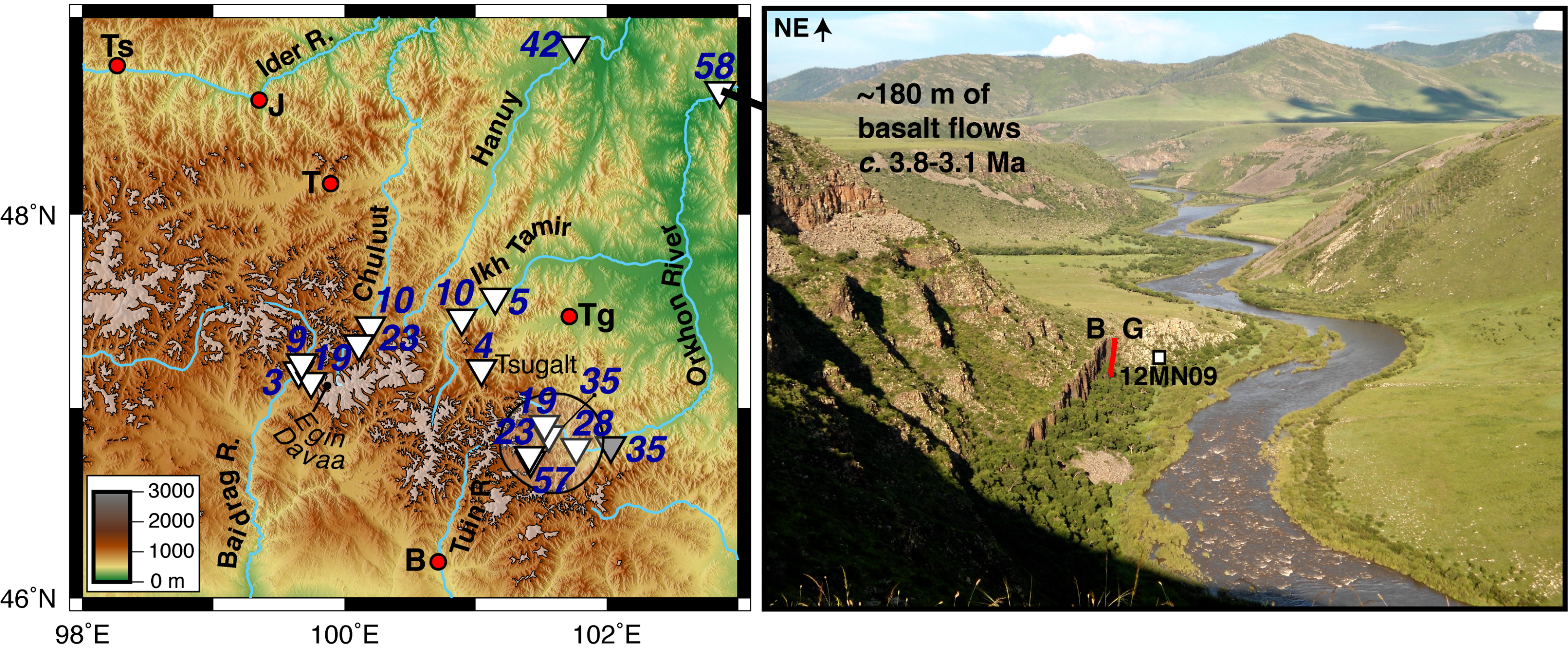

SM
LB
LK
SR
BF
KM
DL
OR
MA
HM
SB
VL
GA
250 km
52°N
50°N
48°N
46°N
44°N
90°E
92°E
94°E
96°E
98°E
100°E
102°E
104°E
106°E
108°E
110°E
112°E
meters
500
1000
1500
2000
2500
3000
3500
4000

Figure 2.



Ts
Ider R.
J
T
Hanuy
Chuluut
Ikh Tamir
Orkhon River
Tg
Tsugalt
Egin Davaa
Baidrag R.
Tuin R.
B
42
58
10
10
5
23
9
19
3
4
35
19
23
28
35
57
3000
2000
1000
0 m
48˚N
46˚N
98˚E
100˚E
102˚E
NE
~180 m of basalt flows c. 3.8-3.1 Ma
B
G
12MN09

Figure 3.

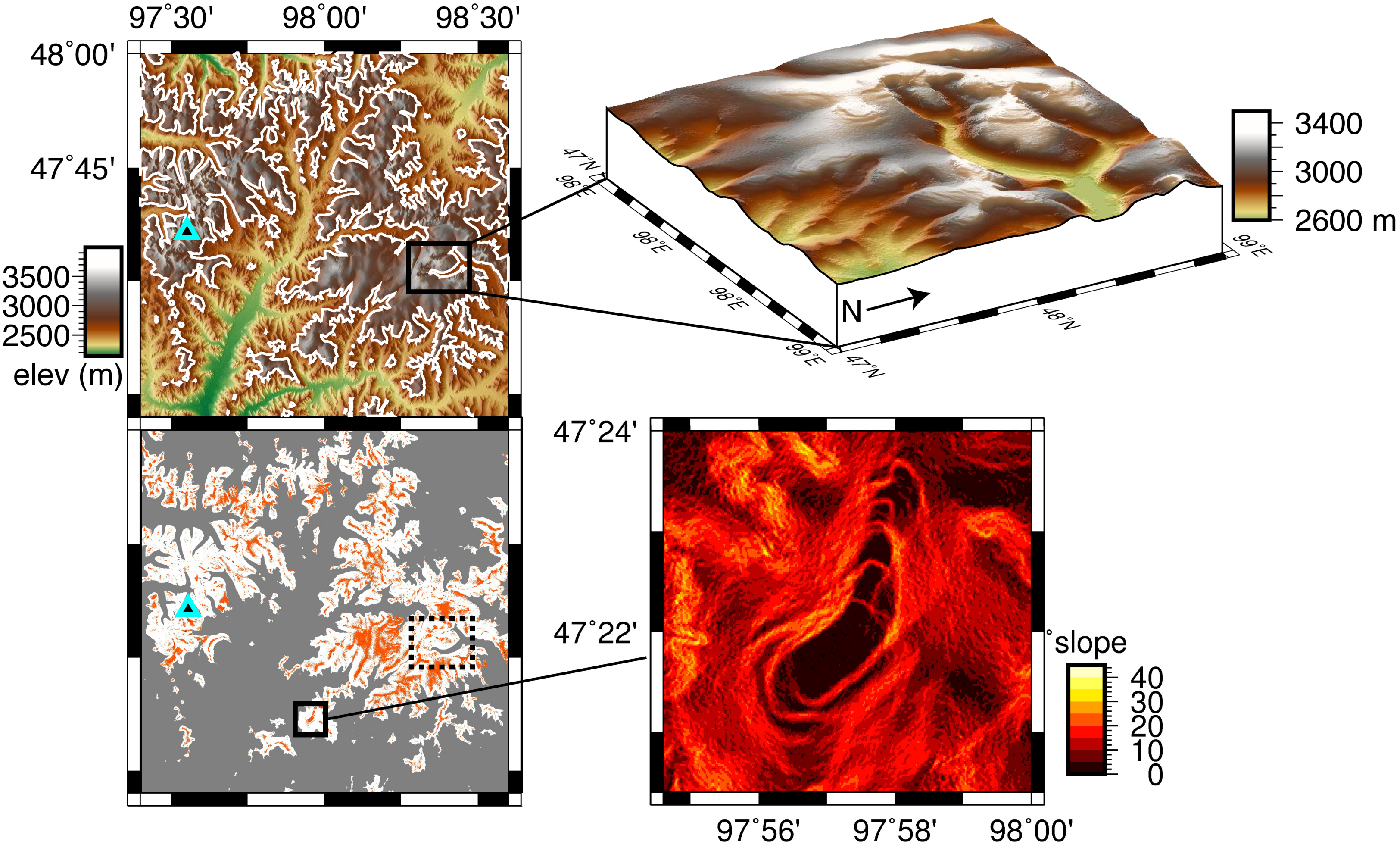

97˚30'
98˚00'
98˚30'
48˚00'
47˚45'
3500
3000
2500
elev (m)
47°N
98°E
98°E
98°E
99°E
47°N
48°N
99°E
N
3400
3000
2600 m
47˚24'
47˚22'
97˚56'
97˚58'
98˚00'
˚slope
40
30
20
10
0

Figure 4.

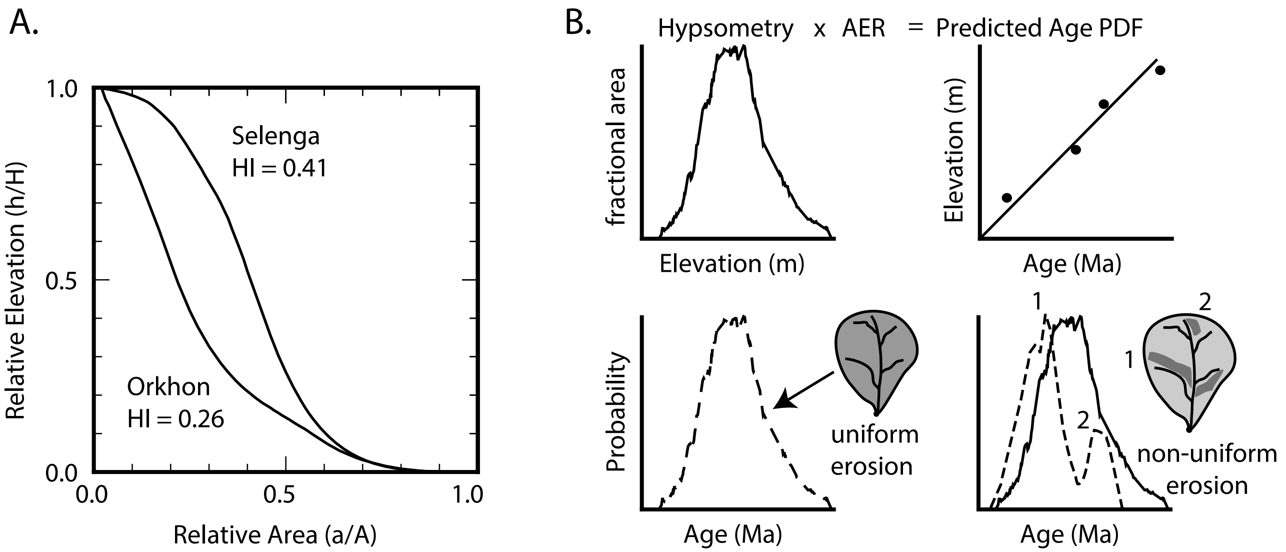

A.
1.0
0.5
0.0
Relative Elevation (h/H)
0.0
0.5
1.0
Relative Area (a/A)
Selenga
HI = 0.41
Orkhon
HI = 0.26
B.
Hypsometry x AER = Predicted Age PDF
fractional area
Elevation (m)
Elevation (m)
Age (Ma)
Probability
Age (Ma)
uniform
erosion
1
2
1
2
Age (Ma)
non-uniform
erosion

Figure 5.

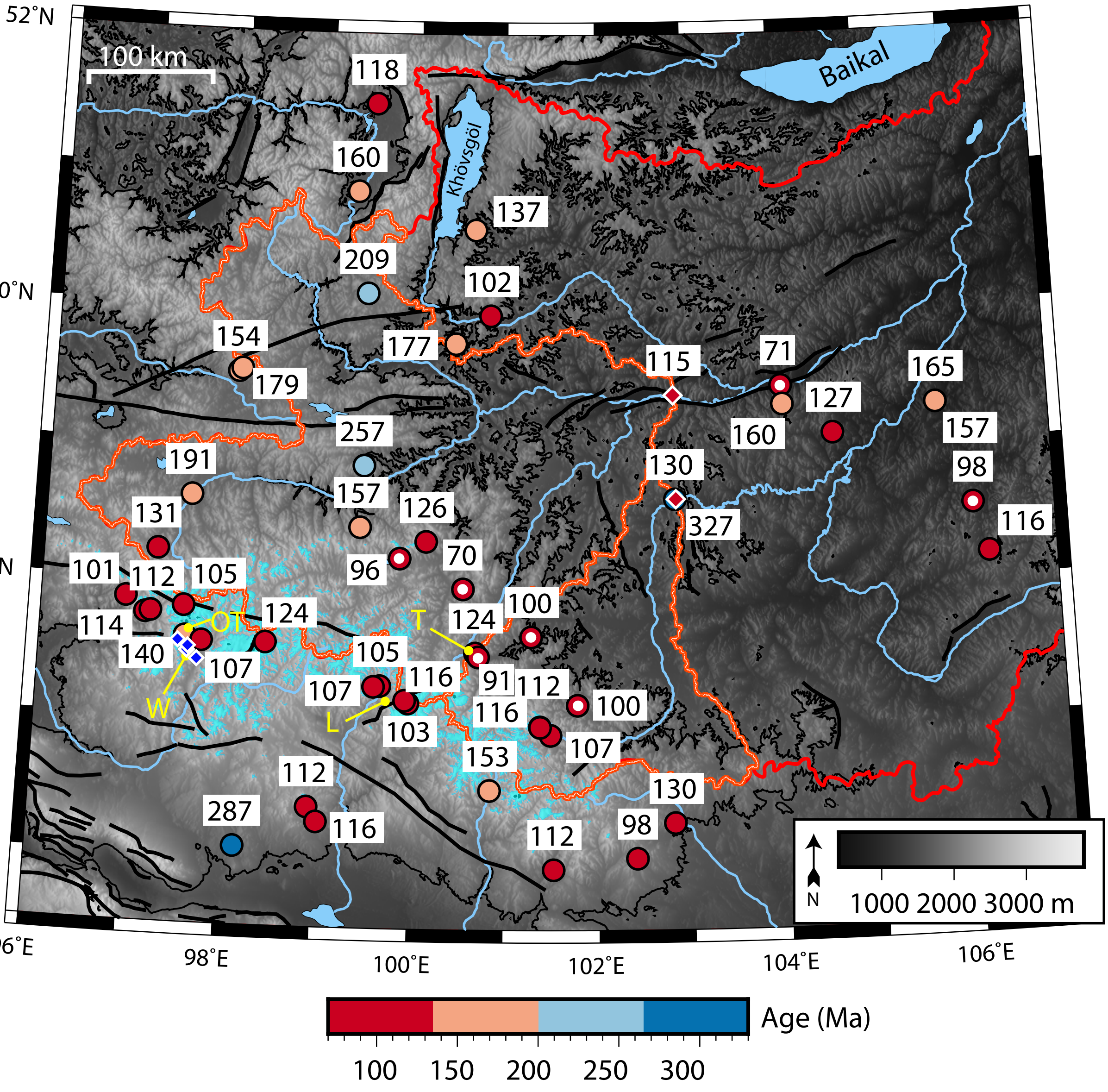
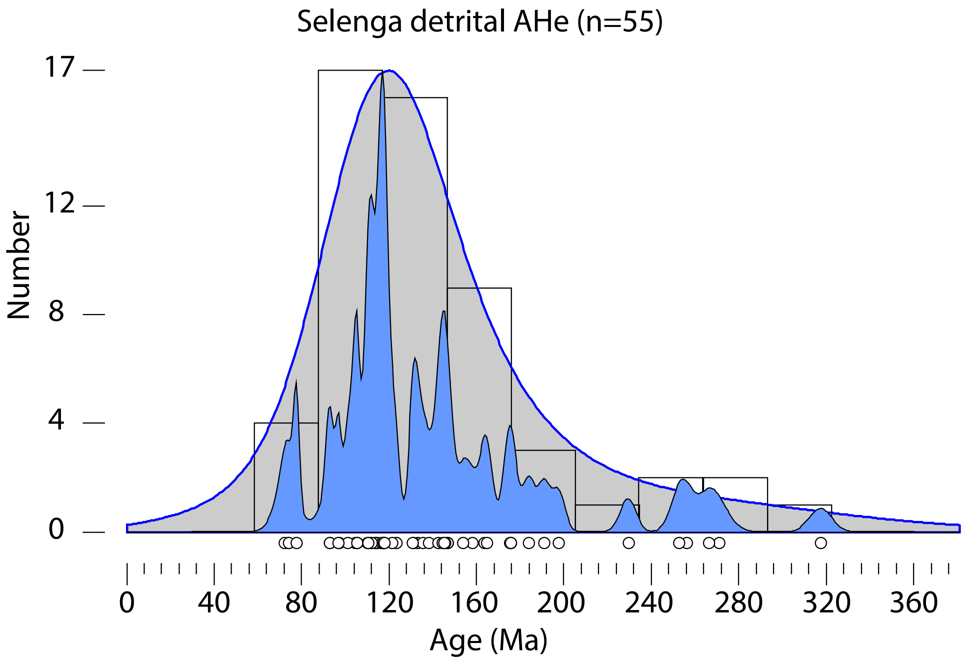
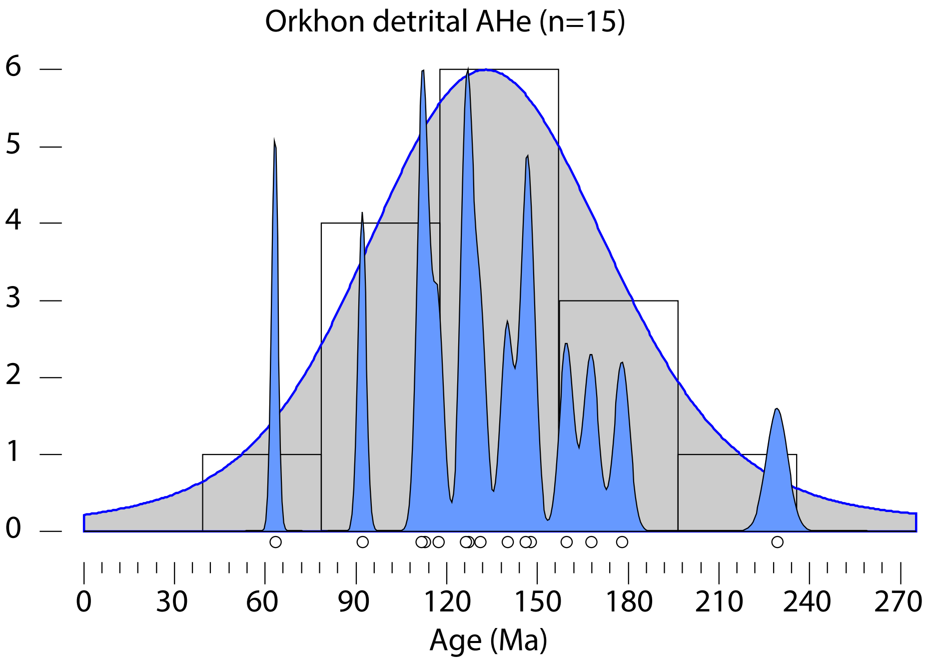

52˚N
50˚N
48˚N
46˚N
96˚E
98˚E
100˚E
102˚E
104˚E
106˚E
100 km
Baikal
Khövsgöl
118
160
137
209
102
154
177
179
115
71
165
127
257
160
157
191
130
98
131
157
126
327
116
101
112
105
96
70
100
114
OT
124
T
124
140
107
105
116
91
112
W
107
L
116
100
103
107
153
112
130
287
116
98
112
N
1000 2000 3000 m
Age (Ma)
100 150 200 250 300

Figure 6.



Selenga detrital AHe (n=55)



Orkhon detrital AHe (n=15)

Figure 7.

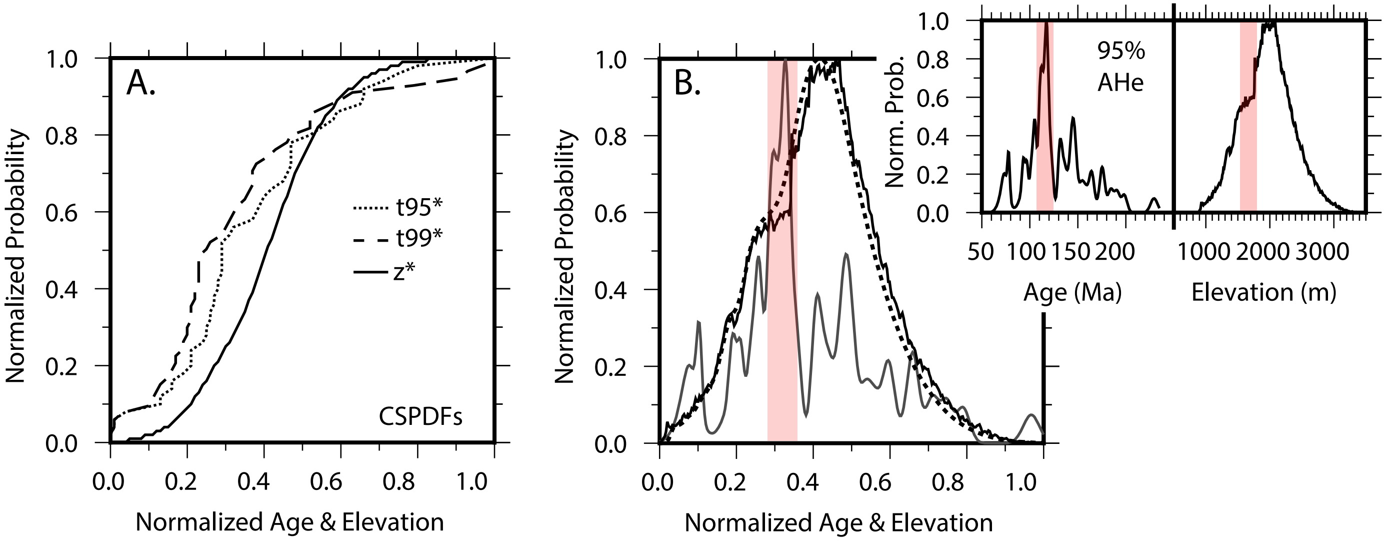

A.
Normalized Probability
0.0
0.2
0.4
0.6
0.8
1.0
Normalized Age & Elevation
t95*
t99*
z*
CSPDFs
B.
95%
AHe
Norm. Prob.
50
100
150
200
Age (Ma)
1000
2000
3000
Elevation (m)

Figure 8.

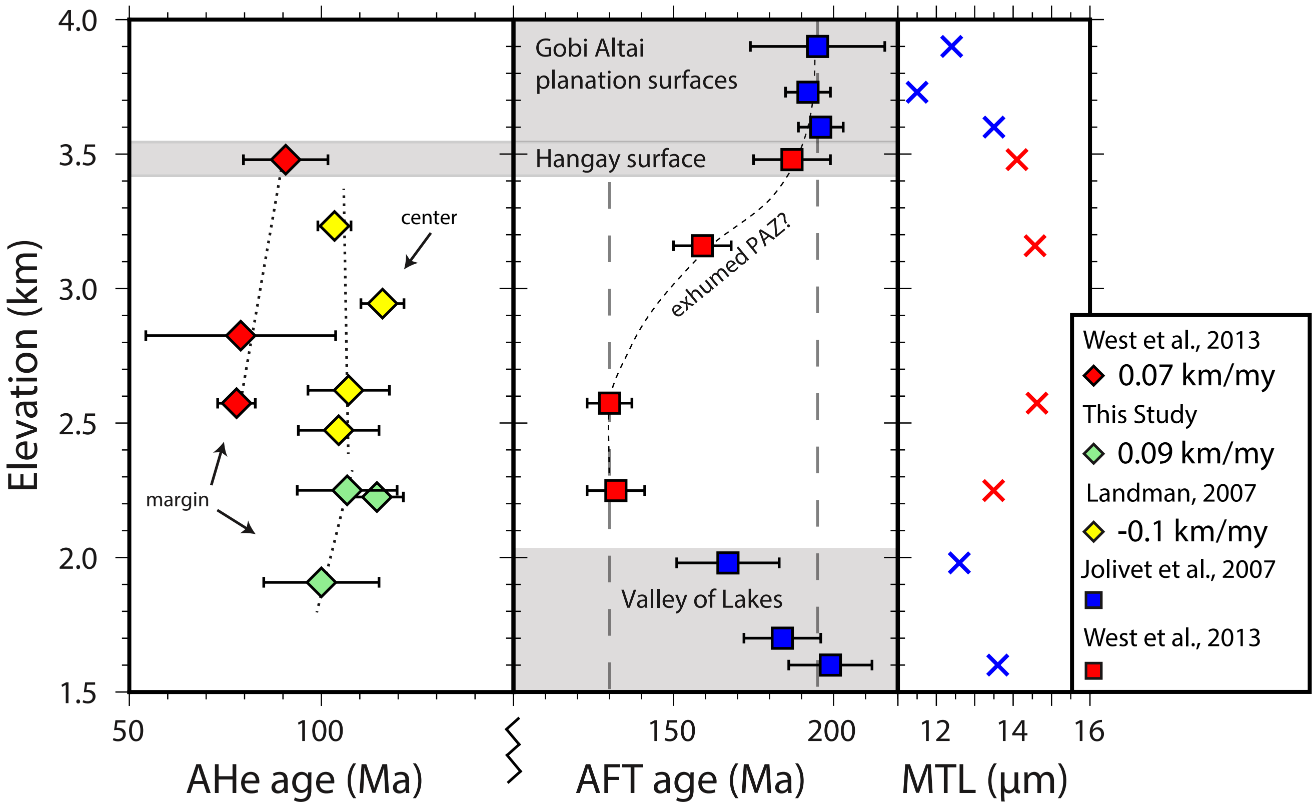

4.0
3.5
3.0
2.5
2.0
1.5
Elevation (km)
50
100
AHe age (Ma)
150
200
AFT age (Ma)
12
14
16
MTL (μm)
center
margin
Gobi Altai
planation surfaces
Hangay surface
exhumed PAZ?
Valley of Lakes
West et al., 2013
◆ 0.07 km/my
This Study
◆ 0.09 km/my
Landman, 2007
◆ -0.1 km/my
Jolivet et al., 2007
■
West et al., 2013
■

Figure 9.

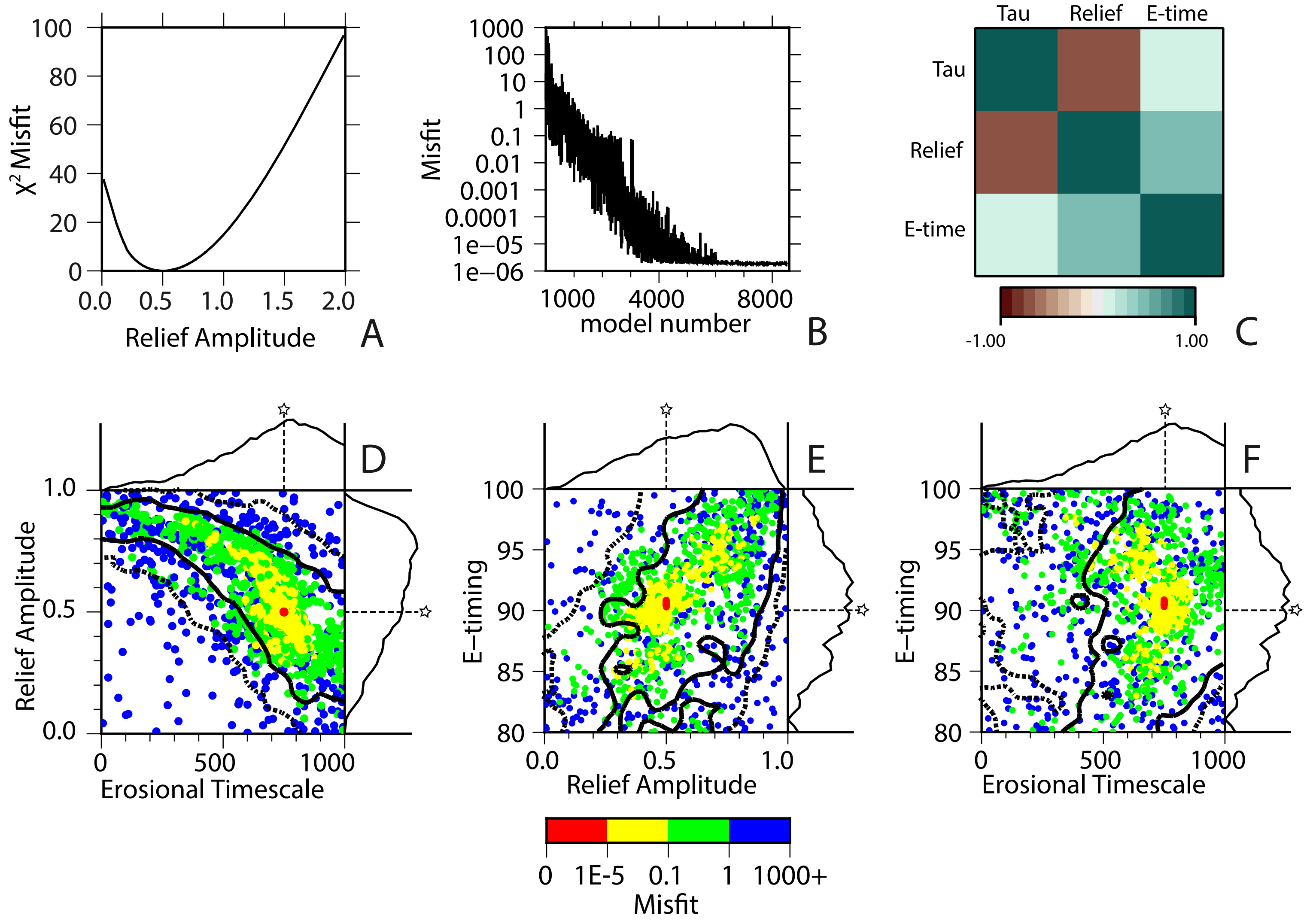
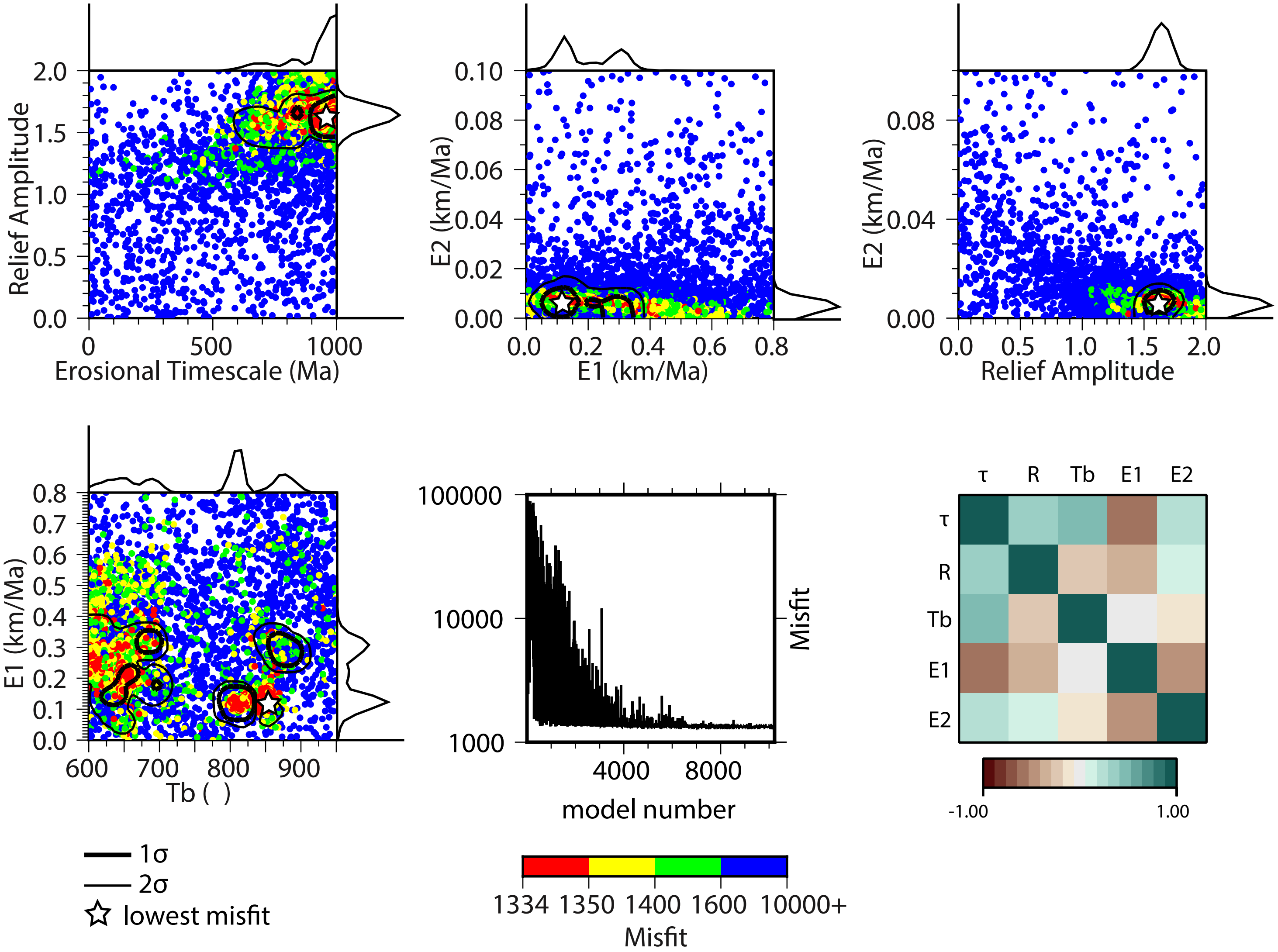

χ² Misfit
100
80
60
40
20
0
0.0
0.5
1.0
1.5
2.0
Relief Amplitude
A
Misfit
1000
100
10
1
0.1
0.01
0.001
0.0001
1e−05
1e−06
1000
4000
8000
model number
B
Tau
Relief
E-time
Tau
Relief
E-time
-1.00
1.00
C
D
Relief Amplitude
1.0
0.5
0.0
0
500
1000
Erosional Timescale
E
E−timing
100
95
90
85
80
0.0
0.5
1.0
Relief Amplitude
F
E−timing
100
95
90
85
80
0
500
1000
Erosional Timescale
0
1E-5
0.1
1
1000+
Misfit

Figure 10.



Relief Amplitude
2.0
1.5
1.0
0.5
0.0
0
500
1000
Erosional Timescale (Ma)
E2 (km/Ma)
0.10
0.08
0.06
0.04
0.02
0.00
0.0
0.2
0.4
0.6
0.8
E1 (km/Ma)
E2 (km/Ma)
0.08
0.04
0.00
0.0
0.5
1.0
1.5
2.0
Relief Amplitude
E1 (km/Ma)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
600
700
800
900
Tb ( )
100000
10000
1000
4000
8000
model number
Misfit
τ
R
Tb
E1
E2
τ
R
Tb
E1
E2
-1.00
1.00
1σ
2σ
☆ lowest misfit
1334
1350
1400
1600
10000+
Misfit

Figure 11.

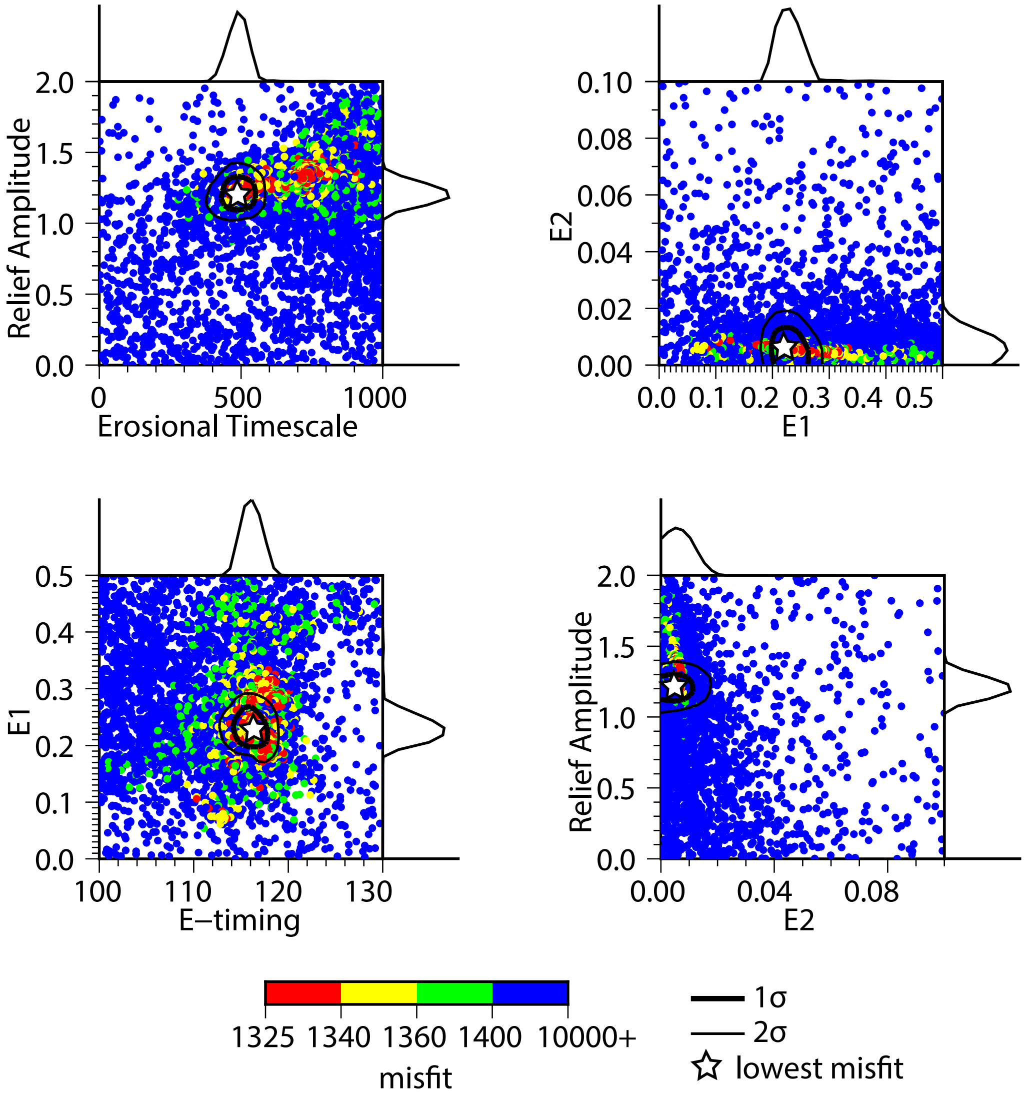

Relief Amplitude
2.0
1.5
1.0
0.5
0.0
0
500
1000
Erosional Timescale
E2
0.10
0.08
0.06
0.04
0.02
0.00
0.0 0.1 0.2 0.3 0.4 0.5
E1
E1
0.5
0.4
0.3
0.2
0.1
0.0
100
110
120
130
E–timing
Relief Amplitude
2.0
1.5
1.0
0.5
0.0
0.00
0.04
0.08
E2
1325 1340 1360 1400 10000+
misfit
1σ
2σ
☆ lowest misfit

Figure 12.

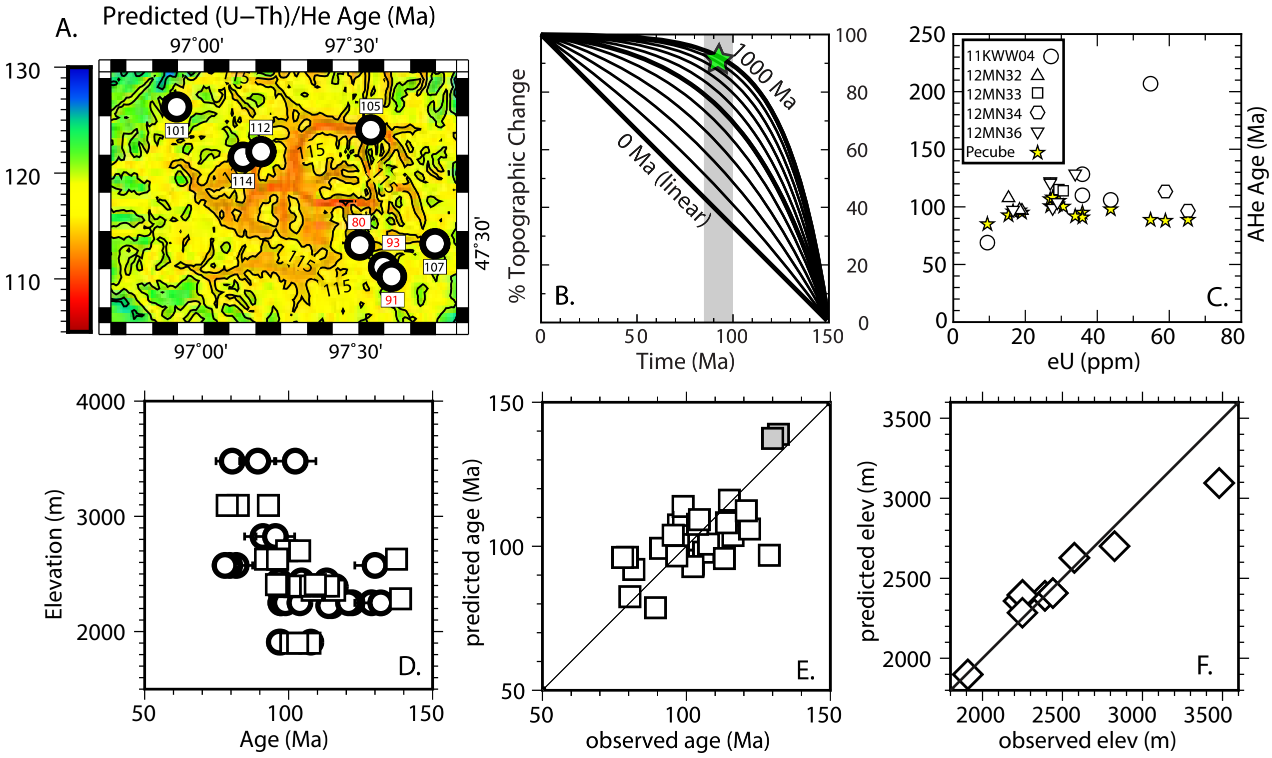

A.
Predicted (U–Th)/He Age (Ma)
130
120
110
97°00'
97°30'
47°30'
101
112
114
105
115
80
93
91
107
B.
% Topographic Change
Time (Ma)
0
50
100
150
0
20
40
60
80
100
1000 Ma
0 Ma (linear)
C.
AHe Age (Ma)
eU (ppm)
0
50
100
150
200
250
0
20
40
60
80
11KWW04 ○
12MN32 △
12MN33 □
12MN34 ⬡
12MN36 ▽
Pecube ☆
D.
Elevation (m)
Age (Ma)
2000
3000
4000
50
100
150
E.
predicted age (Ma)
observed age (Ma)
50
100
150
F.
predicted elev (m)
observed elev (m)
2000
2500
3000
3500

Figure 13.

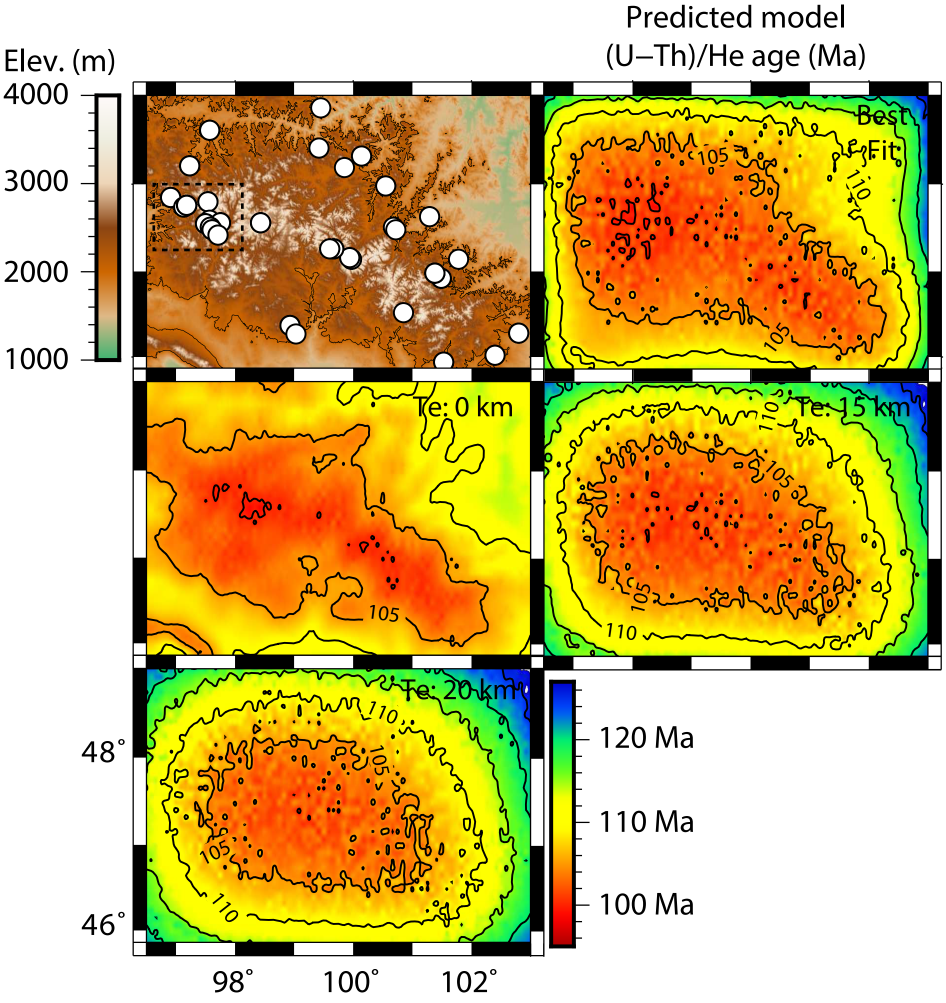
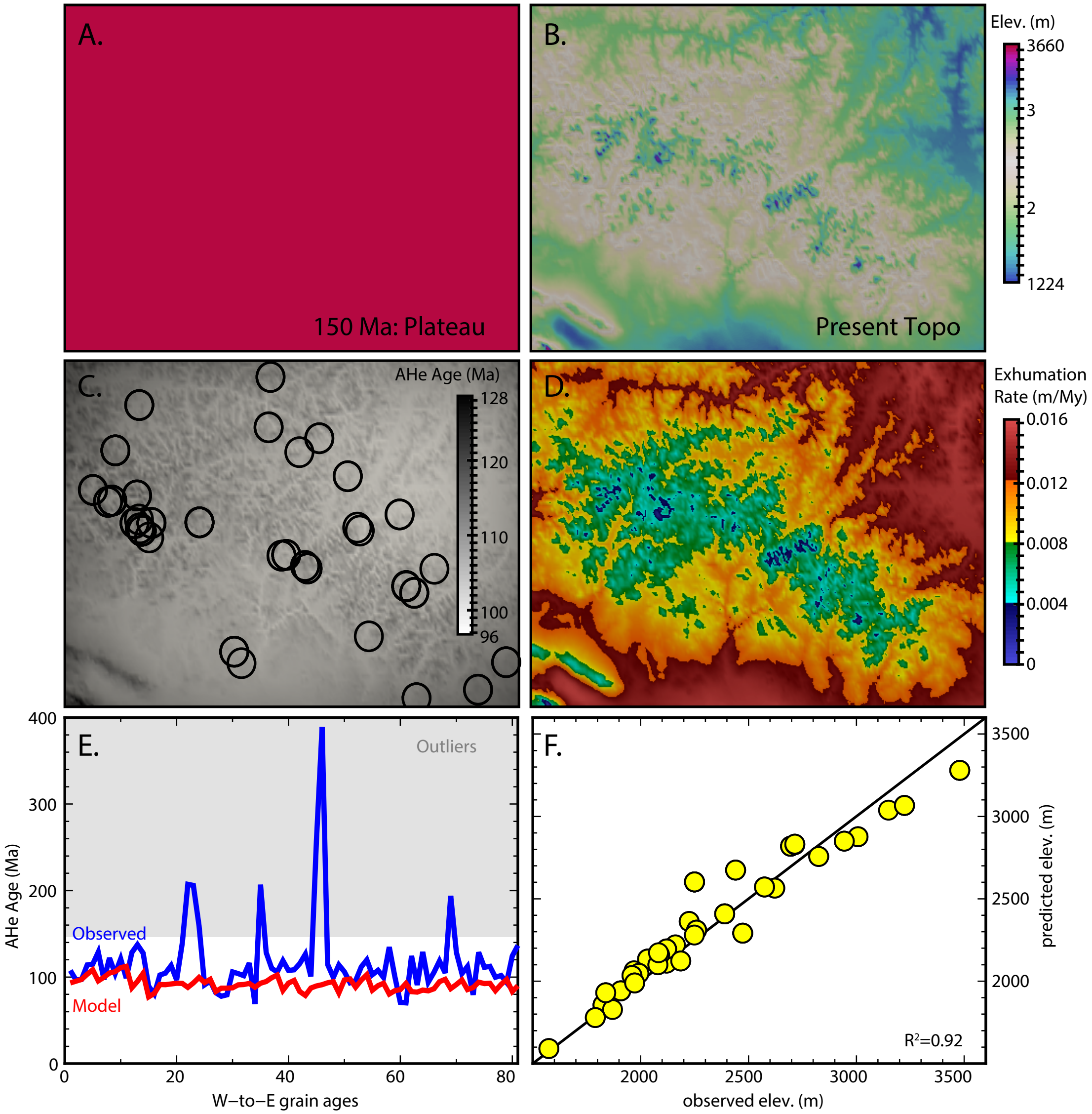

Predicted model
(U–Th)/He age (Ma)
Elev. (m)
4000
3000
2000
1000
Best Fit
105
110
Te: 0 km
105
Te: 15 km
105
110
Te: 20 km
110
105
120 Ma
110 Ma
100 Ma
48˚
46˚
98˚
100˚
102˚

Figure 14.



A.
150 Ma: Plateau
B.
Present Topo
Elev. (m)
3660
3
2
1224
C.
AHe Age (Ma)
128
120
110
100
96
D.
Exhumation Rate (m/My)
0.016
0.012
0.008
0.004
0
E.
Outliers
Observed
Model
400
300
200
100
0
AHe Age (Ma)
0
20
40
60
80
W–to–E grain ages
F.
$R^2=0.92$
2000
2500
3000
3500
observed elev. (m)
predicted elev. (m)
3500
3000
2500
2000

Relict topography within the Hangay Mountains in central Mongolia: Quantifying long-term exhumation and relief change in an old landscape

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Key Points

- New bedrock and detrital apatite (U-Th)/He cooling ages were determined for the Hangay Mountains and central Mongolia
- Thermo-kinematic modeling suggests relief change in the Mesozoic with slow exhumation rates on the order of <20 m/My since the Cretaceous
- Coupled Pecube-Neighborhood Algorithm modeling is successfully applied in a slowly eroding setting

Abstract

The Hangay Mountains are a high-elevation, low-relief landscape within the greater Mongolian Plateau of central Asia. New bedrock apatite (U-Th)/He single-grain ages from the Hangay span ~70 to 200 Ma, with a mean of 122.7 ± 24.0 Ma (2σ). Detrital apatite samples from the Selenga and Orkhon Rivers, north of the mountains, yield dominant (U-Th)/He age populations of ~115 to 130 Ma, as well as an older population not seen in the Hangay granitic bedrock data. These low-temperature data record regional exhumation of central Mongolia in the Mesozoic followed by limited erosion of <1-2 km since the Cretaceous, ruling out rapid exhumation of this magnitude associated with any late Cenozoic uplift. Apatite (U-Th)/He age-elevation patterns suggest long-term thermal stability of the upper crust, and thermal model inversions require late Mesozoic uplift and spatially variable exhumation driven by isostasy in concert with relief evolution to produce the observed cooling ages in the Hangay region. Regionally, modeling suggests reduction of topography in the Jurassic followed by rapid relief growth that was completed by the mid-Cretaceous. These results support Mesozoic topographic evolution and relative stability of the landscape throughout the Cenozoic with very little subsequent exhumation. Alpine cirques and intact moraines are indicative of more recent, modest climate-driven erosion in the higher peaks of the western Hangay. These data reinforce the notion that in the absence of strong tectonic or climate forcing, erosion is limited and remnant landscapes can persist over 10s-100s of millions of years in a state of disequilibrium.

Keywords: Thermochronology, (U-Th)/He, Hangay, Mongolia, landscape evolution, Pecube

1. Introduction

The topographic evolution of landscapes offers a top-down perspective on understanding mountain-belt development through time. In recent decades, we have begun to understand that deformation, erosional unroofing, and climate can be coupled in active settings and that their system dynamics inherently regulate landscape geometries, [e.g., *Molnar and England*, 1990; *Raymo and Ruddiman*, 1992; *Zeitler et al.*, 2001]. Studies of exhumation in active mountains have shown that orogenesis can take place quite rapidly at rates and durations consistent with plate convergence, and that surface processes can remove large relief rapidly [*Montgomery and Brandon*, 2002]. Conversely, ancient mountains and the records of their origins are often different from their modern counterparts, making the analysis of orogenic and topographic development a challenge.

Over orogenic timescales, the primary control on erosion and landscape evolution in active regions is tectonic uplift [e.g. *Koppes and Montgomery*, 2009]. In slowly eroding landscapes, where there is little tectonism, isostasy is the primary contributor to exhumation and under typical crustal and mantle density conditions reduction of surface topography requires significant erosion [e.g. *Braun and Robert*, 2005]. The overall density structure of the lithosphere, in turn, controls the magnitude and distribution of isostatic adjustment to erosion, with less buoyant lithosphere demonstrating an inhibited isostatic response [e.g. *Fischer*, 2002]. Post-orogenic topography has been found to survive over extended timescales through various surface process interactions including landslide-erosion feedbacks [*Egholm et al*., 2013], and when sediment mobilization shear stresses are low and fluvial systems are transport-limited [*Baldwin et al.*, 2003]. These phenomena allow topographic and geodynamic aberrations to persist over hundred million-year timescales, rather than disappear within tens of millions of years after tectonism ceases.

Clues to the exhumation and relief history of a landscape are held in the thermochronologic record of surface rocks across both short and long topographic wavelengths [*Braun*, 2002; *Mancktelow and Grasemann*, 1997; *Stüwe et al.*, 1994]. Topography affects the upper-crustal thermal structure, with the severity of the thermal disturbance decreasing with depth and proportionally with the topographic wavelength [*Braun*, 2002]. At long topographic wavelengths (10s-100s of km) and low topographic relief, isotherms conform to the broad shape of the topography, whereas at very short wavelengths (≤10 km) with high relief, low-temperature isotherms do not fully conform to topography. Rocks that are exposed at peaks have traveled a greater distance after crossing closure-temperature isotherms and therefore a cooling age increase with elevation is expected and provides a direct estimate of the exhumation rate for short topographic wavelengths [*Stüwe et al.*, 1994; *Braun*, 2002]. Sampling at short wavelengths across steep valleys can be used to directly estimate the mean exhumation rate when higher temperature systems are used or in regions characterized by slow exhumation. An observed positive age-elevation relationship (AER) becomes flattened with respect to steady-state topography if there has been relief growth, or steepened and even inverted if topographic relief has been reduced [*Braun*, 2002]. Therefore, short wavelength AERs are suitable for exhumation-rate estimation, while sampling long topographic wavelengths can provide estimates of relief change [*Braun and Robert*, 2005].

The Hangay Mountains of central Mongolia are high-elevation (>3500-4000 m), low-relief topography within the Asian continental interior. Broad, low-relief topographic surfaces that stand prominently above median continental base level are common features of continental interiors. How these apparently epeirogenic areas reach and maintain high elevations is puzzling because of their great distance from plate boundaries. Several studies suggest that the Hangay Mountains were uplifted recently in the mid-late Cenozoic [e.g. *Cunningham*, 2001; *Windley and Allen*, 1993; *Yanshin*, 1975] or rapidly within the past 5 Ma [*Yarmolyuk et al.*, 2008]. Questions remain about the exact timing of surface uplift and whether the current topography is a youthful feature. To test this, inferences about topographic change and the erosion history of the upper crust can be made from spatial patterns in low-temperature thermochronology data. Here, we explore the ability of the apatite (U-Th)/He thermochronometer to constrain long-term, long-wavelength exhumation and relief evolution in the Hangay Mountains, where there is a lack of penetrative deformation, limited mass transport, and the regional climate has become increasingly arid from the Jurassic through the Cenozoic [*Hendrix et al.*, 1992; *Caves et al.*, 2014; *Jolivet et al.*, 2015]. The elevated Hangay landscape itself thus shows no evidence for significant exhumation (more than 1-2 km) associated with any possible younger surface uplift, and likewise detrital age data show no evidence of such exhumation anywhere in the extensive

Selenga River catchment. This study suggests that the topography in the Hangay region is not young, but a relict feature that has persisted since the late Mesozoic. This work is part of a multi-institutional collaboration to study the development of high topography in intracontinental settings and the geodynamic and biologic implications of surface uplift in central Mongolia, specifically, addressing lithosphere-asthenosphere character and dynamics, Asian climate change, and climatic-tectonic forcing of landscapes [*Ancuta*, 2017; *Carlson and Ionov*, 2014; *Caves et al*., 2014; *McDannell*, 2017; *Meltzer et al.*, 2012; *Meltzer et al.*, 2015; *Sahagian et al.*, 2016; *Smith et al.,* 2016; *Stachnik et al.,* 2014; *Wegmann et al*. 2014].

2. Regional setting and geologic history

The Hangay Mountains are a high-elevation region in the Asian continental interior and offer the unique opportunity to study an old landscape in a setting affected by recent tectonism (fig. 1). The Hangay Mountains sit within the Mongolian Plateau (2.6 million km^2) between the Siberian craton to the north and the Tarim and North China cratons to the south. The Hangay are also situated between the Altai Mountains (transpressional zone) and northern extensional zone of the Khövsgöl and Baikal rifts. The ranges in central Mongolia and southern Russia form the northernmost extent of the Central Asian Orogenic Belt (CAOB), which was a long-lived accretionary system, ca. 1000-250 Ma [*Windley et al.,* 2007]. The CAOB is composed of accretionary complexes including micro-continent blocks, volcanic arcs, back-arcs, and fore-arcs. This accretionary phase is believed to have lasted from Late Precambrian to Late Permian time when terrane suturing and closure of the Paleo-Asian Ocean was complete [*Kroner et al.*, 2007; *Lehmann et al.*, 2010]. The Mongol-Okhotsk Ocean was located between the Siberian and Mongolian (Amuria) blocks during Paleozoic-Mesozoic time and closed along a scissor-like suture in the eastern CAOB [*Tomurtogoo et al.*, 2005]. The exact timing of closure is debated, as the Late Jurassic-Early Cretaceous appears to represent a period of rapid Mongol-Okhotsk closure based on the apparent clockwise rotation of Siberia during collision with the North China block [*Cogné et al.*, 2005], while Late Triassic-Early Jurassic exhumation was driven by Mongol-Okhotsk convergent margin tectonism [*Yang et al.*, 2015; *Cunningham*, 2017], followed by terminal collision in the Late Jurassic-Cretaceous. *Yang et al.* [2015] assessed the Jurassic-Cretaceous transition and propose that a brief (ca. 10 Ma), but significant collision occurred in the Late Jurassic-Early Cretaceous driven by collision of Siberia with the Kolyma-Omolon (Russia-Mongolia) block and terminal closure of the Mongol-Okhotsk seaway. Subsequently, there was a change in the regional stress field as regional compression ceased within the CAOB, allowing vast regions of over-thickened crust with high gravitational potential energy and elevated geothermal gradients to exist throughout central Asia [*Cunningham*, 2017]. Strike-slip system development and gravitational collapse of the upper crust gave way to the continental-scale extensional setting in East Asia accommodating India-Asia collision [*Yin*, 2010]. Seismic analysis in the Tugrug Basin (Valley of Lakes region) also supports a rapid change from orogenic thickening to collapse in the Late Jurassic [*Johnson et al.*, 2015]. Thermochronologic data from the Kyrgyz Tian Shan and Siberian Altai-Sayan confirm regional cooling during the initial stages of the Mongol-Okhotsk orogeny and contemporaneous Lhasa collision at about 150 Ma, with orogenic collapse occurring afterwards around 100 Ma [*Glorie and De Grave*, 2016].

Mongolia is divided into two major geologic domains: a northern zone of Precambrian basement rocks and a southern zone of Paleozoic sedimentary and volcanic rock. The basement of the Hangay Dome is Archean to Early Proterozoic and is composed of metamorphic rocks unconformably overlain by Cambrian through Devonian (meta)sedimentary units. The crystalline and sedimentary rocks were intruded by Permian and Jurassic post-orogenic granitoids and underwent deformation during major Late Paleozoic compression [*Lehmann et al.*, 2010]. The granitoid massifs of the Hangay batholith yield zircon U-Pb crystallization ages of 260-242 Ma [*Yarmolyuk et al.*, 2008] while the Khentiyn batholith (abbrev. KM; fig. 1) is 220-200 Ma [*Yarmolyuk et al.*, 2001]. Formation of the Hangay batholith is believed to be related to magmatism associated with the Mongolian-Siberian craton collision [*Zorin*, 1999] or from post-orogenic intraplate magmatism [*Jahn et al.*, 2000].

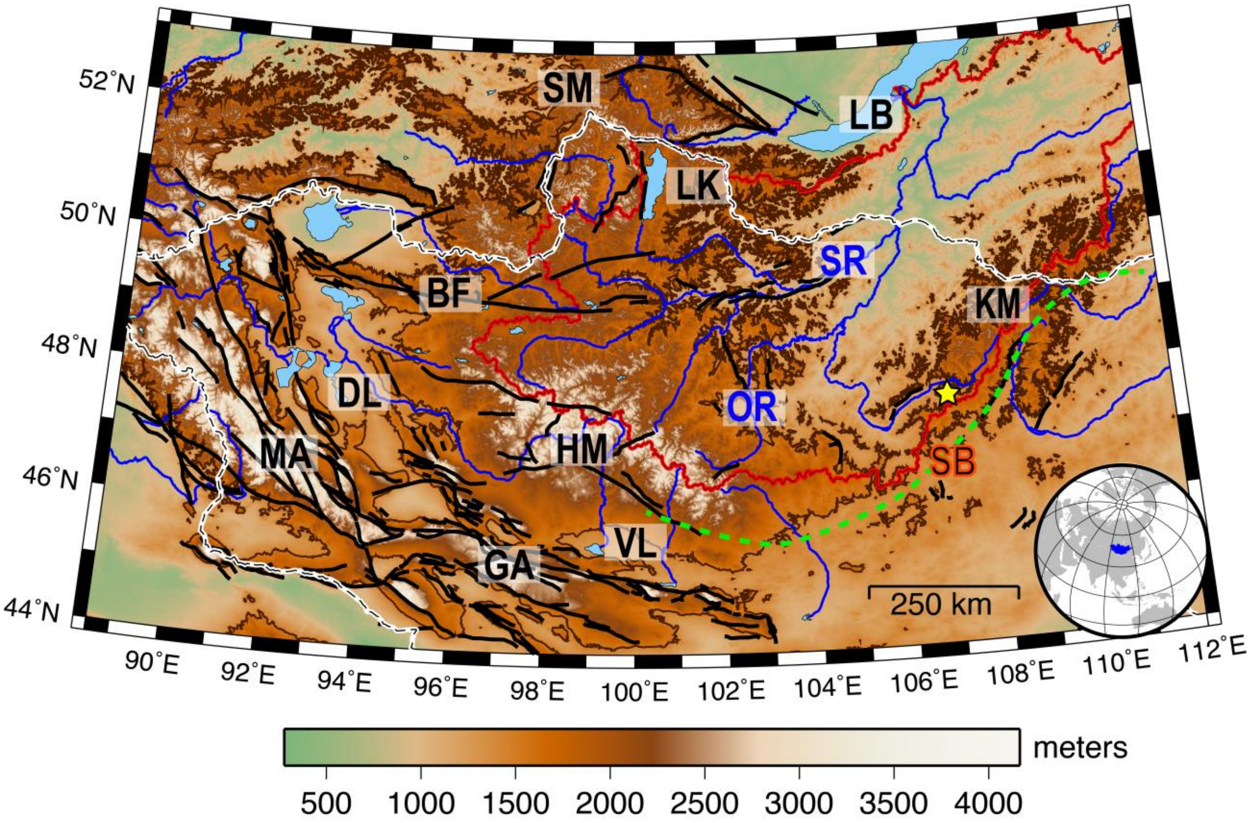

Figure 1: Regional map showing areas of high topography within Mongolia and southern Russia. The mean elevation in this view extent is 1500 ± 563 m and shows that the Hangay, Khövsgöl, Khentiyn, and Sayan Mountains (Russia) are a region of long-wavelength, high topography that has been dissected by the Selenga River network that drains the northern flank of the Hangay into Lake Baikal. Note that the deformation patterns vary regionally, i.e. the strong, large fault control in the Altai versus the diffuse,

smaller faults of the Hangay. The dark brown line denotes the 1500 m topographic contour. Regional fault systems are also shown; the sinistral Bulnai (BF) is the major strike-slip fault north of the Hangay separating the Sayan/Khövsgöl from the Hangay. The Mongolian (MA) and Gobi Altai (GA) ranges south of the Hangay are within a major transpressional fault system. The Siberian craton margin begins just north of the Sayan Mountains in the < 500 m elevation region (green) near the Mongolia-Russia border and Lake Baikal at ~53ºN latitude. Blue lines are major permanent streams draining higher elevations and the red line denotes the Selenga River system drainage divide. Heavy white line is Mongolian political border. Green dashed line is approximate Mongol-Okhotsk Ocean suture after *Van der Voo et al.* [2015]. Yellow star is Ulaanbaatar, the capital city. (MA=Mongolian Altai; GA=Gobi Altai; DL=Depression of Lakes; VL=Valley of Lakes; HM=Hangay Mountains; LK=Lake Khövsgöl; KM=Khentiyn Mountains; SM=Sayan Mountains; OR=Orkhon River; SR=Selenga River; LB=Lake Baikal; SB=Selenga basin). Major towns in Hangay region shown on figure 2.

Gravity data along with seismic tomography and mantle xenolith information have allowed interpretation of the lithospheric structure below the Hangay-Khövsgöl region [*Ionov et al.*, 1998; *Petit et al.*, 2002; *Zorin et al.*, 1990]. The lithosphere is thinner in Mongolia relative to the Siberian craton, and cratons to the south. Gravity anomalies are associated with localized lithospheric flexure from the current compressional stress regime [*Petit et al.*, 2002]. Deep ($\geq$100 km) anomalous buoyant lithosphere is causing a long-wavelength, low-amplitude negative gravity signal with regional uplift of ~400 m, crustal velocity dampening, and a low-density lower crust-upper mantle beneath the Hangay, that results in a high amplitude gravity residual and localized uplift of ~700 m [*Petit et al.*, 2002; *Petit et al.*, 2008]. The uplifted high topography of the Mongolian Plateau (and central Mongolia) has mainly been described as a distal expression of the India-Asia collision [*Molnar and Tapponnier*, 1975; *Vassallo et al.*, 2007]. However, other proposed uplift mechanisms include, Pacific plate subduction [*Yanovskaya and Kozhevnikov*, 2003], localized mantle plume activity [*Windley and Allen*, 1993], asthenospheric upwelling and support [*Cunningham*, 2001; *Petit et al.*, 2008; *Tiberi et al.*, 2008; *Chen et al.*, 2015], delamination of the lithospheric mantle [*Hunt et al.*, 2012], and thickened crust resulting from mafic underplating [*Stosch et al.*, 1995; *Petit et al.*, 2002].

2.1 Regional thermochronology

During the Middle to Late Mesozoic, parts of central Asia were characterized by a topographic planation surface [e.g. *Cunningham*, 2001; *Hetzel et al.*, 2011; *Jolivet*, 2017]. The Hangay Mountains, Sayan-Baikal ranges, and the Altai systems all show preserved Jurassic through Paleogene planation surfaces at elevations ranging from a few hundred meters to up to 4000 m [*Cunningham*, 2001; *Jolivet et al.*, 2007; *Vassallo et al.*, 2007; *De Grave et al.*, 2009; *Jolivet et al.*, 2013; *West et al.*, 2013; *Glorie and De Grave*, 2016]. In the Hangay Mountains, Valley of Lakes, and Gobi Altai, rocks from these relict erosional surfaces have Jurassic-Early Cretaceous apatite fission-track (AFT) ages [*Jolivet et al.*, 2007; *Vassallo et al.*, 2007]. The similarity in AFT ages at peak summits in the Mongolian-Gobi Altai, Hangay, and the adjoining Valley of Lakes piedmont suggests that cooling below ca. 110°C occurred at roughly the same time across this region and these surfaces were at the same paleo-depth (see fig. 8; *Jolivet et al.* [2007]).

Central Mongolia also shares similarities with mountains in neighboring southern Russia. The mountains around Lake Baikal record AFT ages between ~140-100 Ma and experienced rapid cooling in the Early Cretaceous, indicated by thermal-history modeling of AFT length distributions [*van der Beek et al.*, 1996; *Jolivet et al.*, 2009]. AFT ages from the Siberian Altai and Western Sayan of Russia are Jurassic to Cretaceous in age [*De Grave et al.*, 2009; *Jolivet et al.*, 2013; *Glorie and De Grave*, 2016]. Apatite fission-track thermal models for the Sayan suggest long-term erosion rates of 17.5 m/My, while ^{10}Be cosmogenic data suggest short-term (10^5 years) rates of 12-20 m/My [*Jolivet et al.*, 2013]. ^{10}Be cosmogenic data from basins in the eastern Hangay also show erosion rates between 12-20 m/My [*Hopkins*, 2012]. Short and long-term rates are similar and at first-order imply an extended period of nearly constant, slow erosion since the Mesozoic across Mongolia and southern Russia.

2.3 Hangay geomorphology

Stratigraphy and basin analysis of the Tian Shan Mountains (see supplement for location) shows that the aforementioned Late Mesozoic tectonic reorganization and surface uplift shut off the monsoon system in central Asia, and aridification occurred through the Late Jurassic [*Hendrix et al.*, 1992; *Jolivet et al.*, 2015]. This region of central Asia has been arid through the end Mesozoic and Cenozoic and much of the aridification is attributed to the uplift of the Tibetan Plateau and corresponding intraplate mountain belts extending to the north towards the Siberian craton [*Molnar et al.*, 2010]. Observed shifts in regional isotopic aridity signatures support the timing of Hangay surface uplift to be at least as old as Oligocene, and Late Miocene for the Altai range [*Caves et al.*, 2014].

The ages of tilted sediments and volcanic rocks exposed on the flanks of the Hangay also support Oligocene doming and surface uplift of the Hangay, which is also broadly coincident with the initiation of regional volcanic activity [*Devyatkin*, 1975; *Cunningham*, 2001]. Basalt vesicle paleo-altimetry shows the surface of the Hangay may have been modestly uplifted by up to 1 km over the past ~10 Ma [*Sahagian et al.*, 2016]. Stratigraphic relationships between basalt flows and granitic bedrock document the existence of ~700 m of local paleo-relief in central Mongolia [*Smith et al.*, 2016], and this pre-existing topography is similar to the modern topography. Basalt ^{40}Ar/^{39}Ar ages constrain the minimum age of the Hangay landscape to the Oligocene [*Ancuta*, 2017], while ^{14}C dating indicates that material in lacustrine deposits overlying basalt flows near Tariat (fig. 2 for location) are as young as ~5 Kya [*Logachev et al.*, 1982].

The central Mongolian fluvial network comprises alluvial streams with high sediment loads and limited transport ability due to many factors, including prolonged high aridity and spatially variable fluvial network integration. The Selenga River has a large drainage network (447,000 km^2) that sources the entire northern flank of the Hangay and most of central Mongolia and flows north into Lake Baikal, contributing a large volume of the lake water supply. The Orkhon River is one of the major Selenga tributaries flowing out of the glaciated eastern Hangay (fig. 1 and fig. 2). The river network has modestly eroded most of the northern Hangay since minor late Cenozoic surface uplift. *West et al.* [2013] recognized two major river profile knickpoints near the northern and southern Hangay margins at ~2500 m elevation and estimate that up to 1-1.5 km of total erosion (relative to reconstructed “pre-incision” remnants at high elevations) have occurred below these knickpoints and in other areas in the eastern Hangay.

Geomorphic observations coupled with $^{40}Ar/^{39}Ar$ dated whole-rock basalt stratigraphy [*Ancuta*, 2017] allow us to calculate minimum incision rates in the Hangay region (fig. 2). The Orkhon River headwaters show rates of ~20 m/My through the late Pliocene to Holocene, while Orkhon headwater tributaries show late Pliocene through Holocene rates of ~30-60 m/My. At the Orkhon River waterfall (Ulaan Tsutgalan) basalts are ~700 Ka in age and yield incision rates of ~35 m/My. The northern flank of the Hangay shows rates of ~10 m/My in 13-14 Ma basalts exposed along the Ikh Tamir River, a tributary of the Orkhon. The Chuluut River valley, to the west, shows variable incision rates of 10-23 m/My over the past ca. 8-10 Ma. Basalt incision rates are similar to the aforementioned cosmogenic erosion rates in adjacent drainages and those estimated at Egiin Davaa in the central Hangay of ~25-77 m/My over the past 9 Ma [*Smith et al.*, 2016]. Basalt damming of river valleys in the past few million years establish that isolated flows caused accelerated incision (fig. 2), but overall these rates are comparable to those seen in old orogens such as the Appalachians [e.g. *Matmon et al.*, 2003; *McKeon et al.*, 2014].

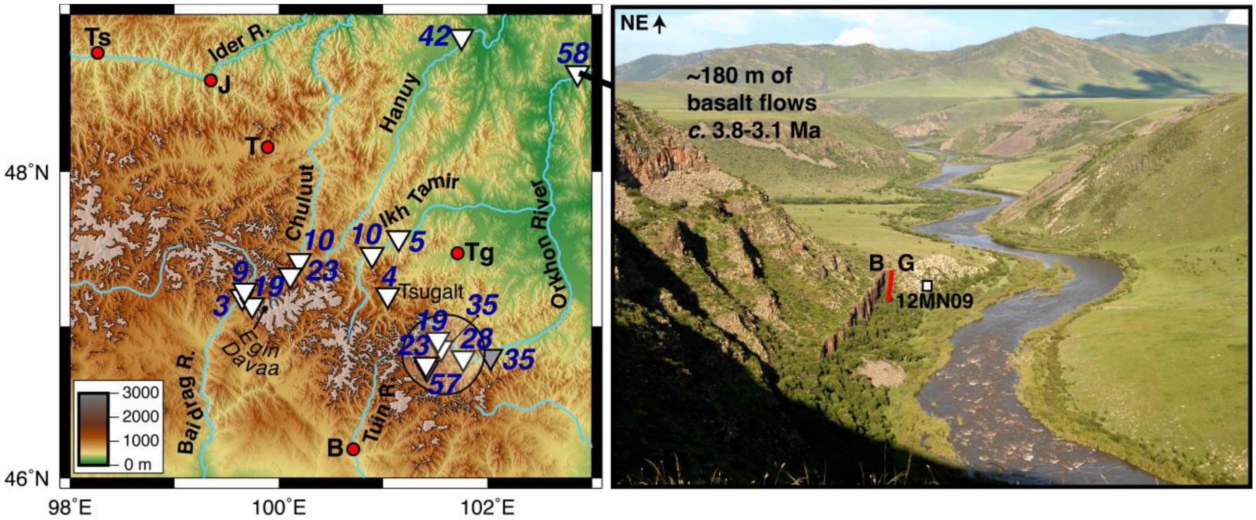

Figure 2: The eastern Hangay Mountains and major rivers (blue lines) with high elevation areas glaciated in the LGM shown in gray. River incision estimates at locations (triangles) from basalt age data presented in *Ancuta* [2017]. Numbers shown are in incision rates in m/My. Circled area in the southeast is the headwaters of the Orkhon River. Gray triangle is the Orkhon waterfall location (Ulaan Tsutgalan). Photo on the right shows a canyon location along the Orkhon River, at lower elevations in the Selenga River basin, where the higher incision rates (~58 m/My) are due to local basalt flow damming (~180 m total thickness) over the past 3 m.y. Red dots mark major towns in the area. B = Bayankhongor; J = Jargalant; T = Tariat; Tg = Tsetserleg; Ts = Tosontsengal. Photo: The contact between granitic basement and the basalt flows is shown by the red line in the photo. Apatite (U-Th)/He sample 12MN09 is from the granite bedrock [mean (U-Th)/He age of ~325 Ma].

The Hangay Mountains were glaciated in the Pleistocene during the Last Glacial Maximum [*Lehmkuhl et al.*, 2004]. Evidence for this exists in the form of well-defined cirques and preserved moraine deposits. There are currently no permanent alpine glaciers in the Hangay, but cryoplanation features, patterned ground, and other glacial features exist at high elevations and advocate a more recent climate-driven erosion signal in the past few million years. Cryoplanation terraces are typically just below relict planation surfaces at high elevations (fig. 3) [*West et al.*, 2013]. *Lehmkuhl* [1998] estimates the equilibrium line altitude (ELA) of the last glacial maximum (LGM) to be at ~2700-2800 m elevation. Current ELA estimates are ~3700 m [*Lehmkuhl and Lang*, 2001], which is ~1000 m higher than the Pleistocene ELA and at fairly high elevations relative to the highest peaks of the Hangay (~4000 m), thereby limiting the potential for modern glaciation. The highest peaks show evidence of cryoplanation terraces down to 3100-3300 m elevation, while most glacial processes below 2600 m in the Hangay are limited in extent and mainly restricted to frost shattering of bedrock [*Lehmkuhl and Lang*, 2001]. Presumably, glaciation in the western Hangay near Otgontenger (fig. 3) has recently created more dramatic topographic relief, which is almost twice the relief observed in lower elevations near the Selenga River headwaters (see suppl. figure S2).

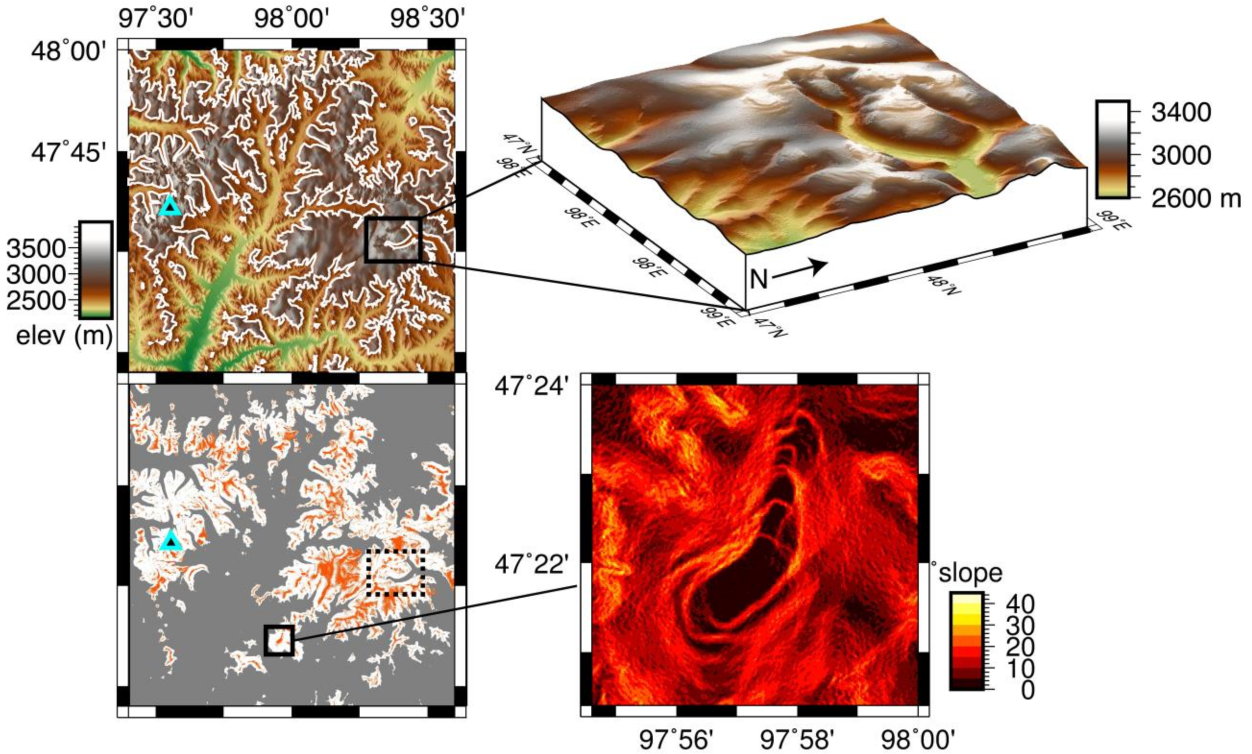

Figure 3: Imagery showing the regional topography near the highest Hangay peak, Otgontenger Uul (triangle). The areas outlined in white are the ELA for the LGM at 2800 m elevation. The image below is of the same area as above but showing elevations >2800 m (gray area is <2800 m) and areas with slopes ≤5° (orange). Enlarged digital elevation model (DEM) inset (top right, looking 240° at 20° inclination)

shows example of high elevation relict planation surface and associated cryoplanation features east of Otgontenger. Bottom panel is a slope map of another such area to the south with a flat, relict surface and cryoplanation terraces. See *West et al.*, [2013] for other examples.

3. Methodology

3.1 Apatite (U-Th)/He thermochronology

Granitic bedrock and detrital sediments were collected for apatite (U-Th)/He (AHe) analysis throughout central Mongolia. Igneous bedrock samples went through standard procedures for rock crushing, sieving (<250 microns), Frantz magnetic splitting, and heavy-liquid separation using lithium polytungstate and methylene iodide. Unbroken, symmetric apatite grains without visible inclusions were selected under a high-power petrographic microscope at 250-300X magnification. Samples were digitally photographed in order to record their 3D morphology for determination of alpha-correction factors using a cylindrical geometry. Grains were then placed in small Nb tubes whose ends were crimped and loaded into the extraction system in the Lehigh University noble gas laboratory for analysis following conventional methodology (see below) or underwent continuous ramped heating treatment [*Idleman et al.*, 2018; *McDannell et al*., 2018]. ^{4}He and the ^{3}He spike were measured using a Balzers bakeable quadrupole mass spectrometer designed for UHV operation, fitted with both Faraday and electron-multiplier detectors. For helium extraction, a double-vacuum resistance furnace was used for heating, and an all-metal sample dropper permits multiple samples to be loaded for sequential analysis in the resistance furnace. Helium evolved from heated samples was purified in an all-metal extraction line pumped by an ion pump during routine operation as well as a 70 l/s turbo-molecular pump with a small rotary backing pump used during bake-out. An SAES GP50 getter in the extraction line removes active gases, while a smaller SAES getter in the mass spectrometer volume is used to minimize hydrogen loads. Reservoirs containing a ^{3}He spike and a ^{4}He/^{3}He standard are attached to the line behind all-metal pipettes while two temperature-stabilized capacitance manometers provide the precise, accurate pressure measurements needed for spike preparation (the extraction line ^{4}He blank is 1x10^{-16} moles or less). ^{4}He was measured by isotope dilution, using a ^{3}He spike, and also by manometric peak-height comparison against a mass-discrimination standard. Generally these approaches agree to better than 1% and the dual calibrations provide an internal crosscheck. Over periods spanning the analysis of sample batches, the ^{4}He/^{3}He ratio for the standard was precise to within 0.3%, with a value of about 0.795 (the true ^{4}He/^{3}He ratio of standard is 1.000). For the current spike preparation, the size of a typical spike is 4 x 10^{-13} moles. Following helium extraction, U, Th, and Sm measurements were obtained from the University of Arizona in the laboratory operated by Dr. Peter Reiners, where samples were dissolved, spiked, and analyzed using isotope-dilution ICP-MS [*Reiners and Nicolescu*, 2006]. U, Th, and Sm were measured on the same aliquots of apatite that were used for He determinations, eliminating any uncertainties contributed by weighing errors and sample heterogeneity. A mean age of 31.85 ± 0.24 Ma (2 SE, n=78) for the Durango apatite age standard has been acquired over repeated experiments in the Lehigh noble gas laboratory. *McDowell et al.* [2005] obtained a direct ^{40}Ar/^{39}Ar reference age of 31.13 ± 0.42 (2 SE) for Durango apatite.

3.2 Detrital apatite (U-Th)/He modeling

3.2.1 Inference of detrital cooling age distribution components

The BayesMixQt program allows Bayesian inference of probability distributions regarding the number of component age distributions from a set of individual mineral cooling ages and their associated errors under Gaussian or Skew assumptions [*Jasra et al.,* 2006]. More simply, it allows identification of discrete age components (mixture modeling) in a larger age distribution and is well suited for the heterogeneity often encountered in detrital age datasets. The modeling infers the proportion of each individual distribution that contributes to the total distribution as well as the parameters that define each distribution (i.e. mean and standard deviation). The approach implements Reversible Jump Markov chain Monte Carlo methods that employ an iterative sampling scheme and allow changes in the problem-space dimensionality (i.e. component distributions). This approach requires defining prior and proposal distributions for the dataset and allows a "burn-in" phase for exploratory sampling of the model space, which is used to infer the component distribution parameters (i.e. post-burn-in phase). Refer to *Jasra et al.* [2006] for a more complete overview of mixture modeling.

3.2.2 Catchment-averaged erosion rates and topographic relief histories from detrital data

The age distribution of detrital mineral cooling ages provides a proxy for the erosional history of mountain catchments [e.g. *Avdeev et al.*, 2011; *Brewer et al.*, 2003]. The range of cooling ages can also provide information about erosion timing and magnitude. The detrital age range for a catchment is proportional to the time needed to erode the total relief in the source region [*Brewer et al.*, 2003; *Ruhl and Hodges*, 2005], while narrow or broad age spread is interpreted as rapid or slow erosion rate, respectively [*Stock and Montgomery*, 1996]. Assuming uniform erosion and a positive trend AER, the observed elevation distribution in a catchment should produce a predicted age probability density function (PDF) that matches the hypsometry (fig. 4) [*Brewer et al.*, 2003; *Ruhl and Hodges*, 2005; *Stock et al.*, 2006]. If there is non-uniform erosion in a catchment then the predicted age PDF will be out of phase with the hypsometric curve or have multiple peaks corresponding to the areas of the catchment that are being more heavily eroded (fig. 4) [*Stock et al.*, 2006; *Ehlers et al.*, 2015]. Equations (1-3) after *Ruhl and Hodges* [2005] describes this relationship:

$$PDF = \frac{1}{\sigma t_m \sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{t - t_m}{\sigma t_m}\right)^2\right] \tag{1}$$

Where *t* is the PDF of the age, t_m is the measured age with the analytical uncertainty, σ. The synoptic probability function (SPDF) is the summation of all individual grain PDFs multiplied by the reciprocal of the number of detrital grains normalized to unity.

$$SPDF = \frac{1}{n}\sum_{i=1}^{n} PDF\ (i) \tag{2}$$

The shape of the SPDF should mimic the hypsometric curve if bedrock erosion scales with surface area and the cooling ages accurately reflect the eroded sediment signal. The cumulative synoptic probability function (CSPDF) represents the probability that the age takes on a value less than or equal to *t*, the PDF of the cooling age. The CSPDFs are normalized hypsometric curves of elevation, *z**, and cooling age, *t**, and assuming uniform erosion, should overlap.

$$CSPDF = \sum_{i=0}^{t} SPDF\ (j) \tag{3}$$

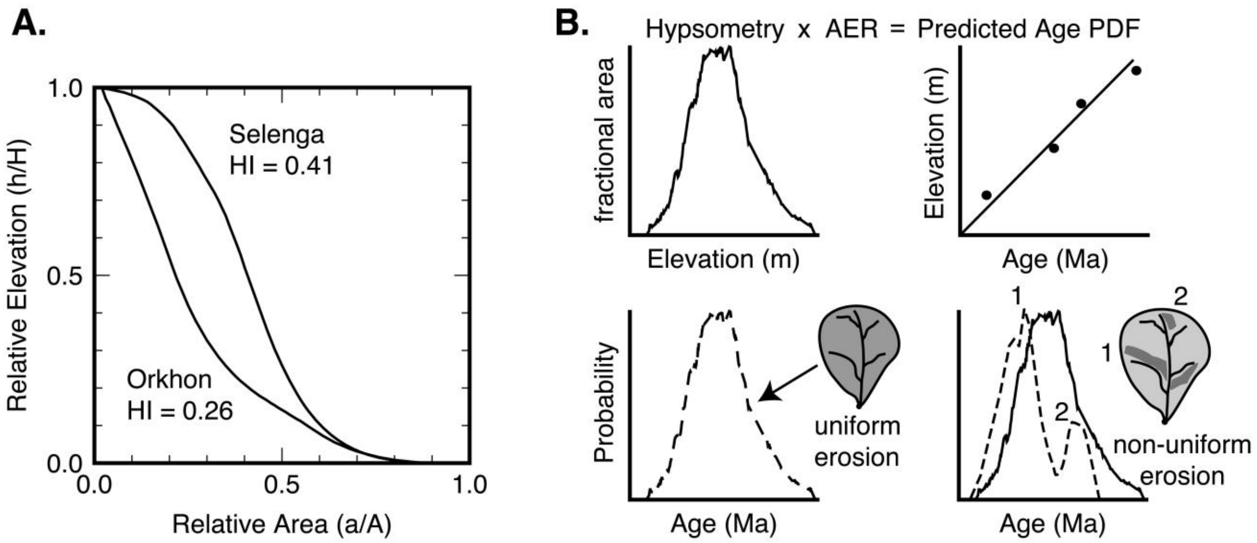

Figure 4: **(A)** Hypsometry of the Selenga and Orkhon River sub-catchments sampled for detrital AHe (see figure 5 for locations; section 5 for discussion). **(B)** Schematic diagram illustrating the relationship between detrital thermochronometer data and the hypsometry of a catchment given an assumed positive age-elevation relationship where cooling ages should match the hypsometric curve if erosion is uniform, i.e. all points on the topography produce cooling ages that correspond to the basin AER. If there is non-uniform erosion, then the elevations on the landscape contributing sediments will affect the SPDF curve accordingly, modified after *Stock et al.* [2006].

3.3 Methods: Coupled Pecube-Neighborhood Algorithm modeling

Pecube [*Braun*, 2003] is a finite-element thermo-kinematic model that solves the 3D heat transport equation in a crustal block with the allowance of a time-variable surface boundary condition (topography) including the effects of isostasy. Pecube predicts thermochronometric ages for crustal scenarios involving erosional or fault-driven exhumation. In our Pecube inversions we adopt spatially constant material properties for the crust (table 1) and a sub-region of central Mongolia is modeled as a single uplifting block, as the entire Hangay and thermochronology dataset coverage are too large to model efficiently (see section 5.4 for location and discussion). A SRTM digital elevation model of central Mongolia resampled to 1 km resolution was used as the topographic input. The conventional volume diffusion model of *Farley* [2000] has typically been used for AHe age prediction, and in the case of grains with low (<20-30 ppm) effective uranium (eU) content [*Flowers et al.*, 2009], and/or rapid cooling this model is satisfactory and does not require more sophisticated age prediction models that account for compositional or radiation damage effects [e.g. *Flowers et al*., 2009; *Gautheron et al*., 2009]. Since radiation damage tends to suppress partial He loss, the closure temperature varies in proportion to the eU and cooling rate, thus contributing to the observed apatite cooling age dispersion commonly seen in slowly cooled settings. The *Flowers et al.* [2009] radiation damage model was incorporated for age prediction within Pecube for modeling of our Mongolia data similar to code used in *Fox et al.*, [2014]. Pecube and previous applications are reviewed thoroughly in *Braun et al.* [2012]. Here we summarize some of the main features relevant to this study.

During a Pecube model inversion, the use of a two-step *Neighborhood Algorithm* (NA) inverse approach is employed, where during the sampling stage the multi-dimensional prior model space is efficiently sampled to find the best-fitting parameter combinations that produce the lowest user-defined misfit between observed and predicted data [*Sambridge*, 1999a]. The appraisal stage then allows robust measures of parameter resolution to be extracted in the form of Bayesian marginal posterior probability density functions (PPDF) during resampling of the model ensemble [*Sambridge*, 1999b]. During the sampling stage an initial model ensemble is randomly generated using the prior parameter range (assumed uniform distribution) of the Pecube variables. The misfit is assessed and Voronoi cells are created about nearest neighbor models that are subdivided after successive iterations as the algorithm focuses on regions of lower misfit by resampling the previous iteration. We employed an objective function or χ^2 misfit of the form:

(4)

$$\mu = \sum_{i=1}^{n} \left(\frac{m_i - o_i}{\sigma_i}\right)^2$$

Where μ is the misfit value, n is the number of data, and for each datapoint i, o_i is the observed age, m_i is the model age, and σ_i the observed age error. During the NA appraisal stage the entire sampling-stage ensemble is resampled to gain Bayesian estimates of parameter values and assess the lowest misfit via the Likelihood function, L, to assess the likelihood of different model predictions, given in the simplified form as:

(5)

$$L = \exp(-\tfrac{1}{2}\chi^2)$$

In the case of χ^2 misfit, the simplified form of the *log (L)* is equal to -0.5 multiplied by the misfit value [*Glotzbach et al.*, 2011]. The motivation for examining individual model misfit during the appraisal stage is that the lowest misfit can be misleading, for example, the lowest misfit may be identified for an individual parameter, but in the multi-dimensional case the overall misfit is a combination of several parameters where the identified best fit may have a single parameter value that is associated with a large misfit due to trade-offs in multi-dimensional space. Posterior probability accounts for this, because although it is a function of all parameters, it may be integrated over one or more parameters to examine the probability of that parameter in relation to the other parameters in the form of a 1-D marginal PPDF curve. Parameters plotted as 2-D marginal PPDFs examine potential correlative tradeoffs between different parameters. In the case of a purely Gaussian PPDF the results are interpreted as a mean/mode value at the peak maximum, and in the case of a skewed PPDF, the mode is at the maximum probability peak of the PPDF curve.

The sampling stage has typically been performed iteratively but here we use the MPI-enabled parallelized version of the code that does away with 'formal iterations' and instead of the misfit being assessed at the end of an iteration, it is continuously assessed during the inversion, leading to more efficient algorithm performance [*Rickwood and Sambridge*, 2006]. The number of iterations, the number of models in each iteration step, and the resampling rate all control the NA-sampler stage and influence the NA search. Although there are no specific rules for these configurations, a lower resampling rate allows faster convergence, albeit with the danger of prematurely converging on local minima, while a greater resampling rate allows more thorough exploration of the ensemble space but is slower to converge. Generally, inversions with a greater number of free parameters require a larger number of iterations to converge on the best fitting parameter combination.

The relief amplitude, R, in Pecube is fairly simplistic as it assumes the planform geometry of the topography does not change, only the amplitude varies, i.e. valleys and ridges do not migrate laterally [*Valla et al.*, 2010; *van der Beek et al.*, 2010]. This assumption is justified in equilibrated landscapes with low erosion. R is defined as the ratio between the relief amplitude (Δh_i) when rocks passed through the closure isotherms and the modern-day relief amplitude (Δh_0). Where: (6)

$$R = \frac{\Delta h_i}{\Delta h_0}$$

According to the model definition, where $R = 1$ is the modern topography, when $R = 0$ the initial topography is a plateau (no relief) at the highest elevation; for $R < 1$ relief has grown from the past to present; while for $R > 1$ relief has decreased from past to present [*Beucher et al.*, 2012; *Valla et al.*, 2010]. The erosional (or relief change) timescale, τ, is a function that describes how relief evolves through time, either in an exponential or linear fashion (see fig. 12), where 0 is a linear change in relief in the model between time steps (equation 7). When values are highly positive, relief change will take place rapidly at the model onset, and if τ is highly negative the relief change will take place close to present day [*Beucher et al.*, 2012].

$$\Delta h_t = \Delta h_0 + \left[(R-1)\Delta h_0 \frac{1-e^{\left(-\frac{t\tau}{t_{f^2}}\right)}}{1-e^{\left(-\frac{\tau}{t_f}\right)}} \right] \tag{7}$$

Pecube-NA inversions have been applied successfully to high-relief regions that have experienced relatively high exhumation rates and recent relief development such as the European Alps [*van der Beek et al.*, 2010] and Southern Alps [*Herman et al.*, 2010]. There has been varying success in applying this approach to determine relief histories accurately and difficulties are attributed to incomplete sampling of topography at multiple wavelengths, and the insensitivity of low-temperature thermochronometers to rapid topographic change or high exhumation rates [e.g. *Valla et al.*, 2010; *Reverman et al.*, 2012]. *Valla et al.* [2010] explored the efficacy of estimating denudation rates and relief histories using the Pecube-NA inversion and the resolving power of the AFT and AHe low-temperature thermochronometers. They suggest that settings where relief development is approximately two to three times higher than background exhumation rates, or where background exhumation rates are generally low, as being more suitable for relief-change investigations. Central Mongolia is a setting where the latter is likely to be true throughout the latest Mesozoic and Cenozoic.

4. Apatite (U-Th)/He thermochronology results

4.1 Bedrock (U-Th)/He data

Granitoid bedrock samples were collected across the Hangay and areas to the north (fig. 5; suppl. table S1 for data). We dated 106 single-crystal aliquots of apatite (44 bedrock samples) and also report 12 multi-grain aliquots (5 bedrock samples) dated at Lehigh University during pilot Mongolia sampling presented in *Landman* [2007]. For mean age calculations, bedrock ages that were older than reported Hangay U-Pb ages of ~250 Ma were discarded as outliers. However, there is a lack of age control for granitoids to the north, and those found in the Altai in southwest Mongolia have older zircon U-Pb populations spanning 289-317 Ma and 350-398 Ma [*Cai et al.*, 2015], considerably older than the ~240-250 Ma granites in the Hangay. This allows for the possibility that there are older granites to the north that exhumed prior to those in the Hangay.

Age dispersion in slowly-cooled settings is a common issue [e.g., *Fitzgerald et al.*, 2006; *McDannell et al.*, 2018] that is often attributed to factors such as fluid and mineral inclusions [e.g. *Farley*, 2000], U-Th zonation [e.g. *Farley et al.*, 2011], and radiation damage effects [e.g. *Shuster et al.*, 2006]. We ran a number of replicate grains for each sample in order to identify any dispersion, and it does occur in a few samples. The convention is to analyze 2-5 replicate single grains for each sample; however, robust averaging methods are difficult to justify for small sample sizes less than 10 grains due to the effects of age dispersion and outlier treatment [e.g. *Vermeesch*, 2010]. Additionally, because factors such as U content, radiation damage, and grain size control kinetic properties and He retentivity [*Farley*, 2000; *Shuster et al.*, 2006], each grain from the same rock is in effect a separate thermochronometer, so statistical averaging is not always warranted. We report arithmetic mean ages only for the purpose of an overview of regional age patterns. Mean ages are not used in thermal modeling (see later sections), as it is a requirement to model single grains because each analyzed grain is unique in its kinetic properties and slow cooling amplifies these kinetic effects.

Single-grain ages replicate well within the central Hangay and cluster around ~100-120 Ma at various elevations with a few exceptions, while data outside the Hangay show greater variation and generally older ages (fig. 5). The cooling ages from the north flank of the range are marginally younger than elsewhere in the higher elevations (<100 Ma), which coincides with the focus of modern erosion and precipitation leading to peak height asymmetry in the Hangay [*West et al.*, 2013]. This regional cooling age pattern is similar to that of the Dabie Shan in China [*Reiners et al.*, 2003] where significant age differences exist between the range core and flanks, with a progressive younging of cooling ages toward the mountain interior. Modeling of these data may be explained by a twofold decrease of topographic relief over the past ~100 m.y. to produce observed age patterns [*Braun and Robert*, 2005].

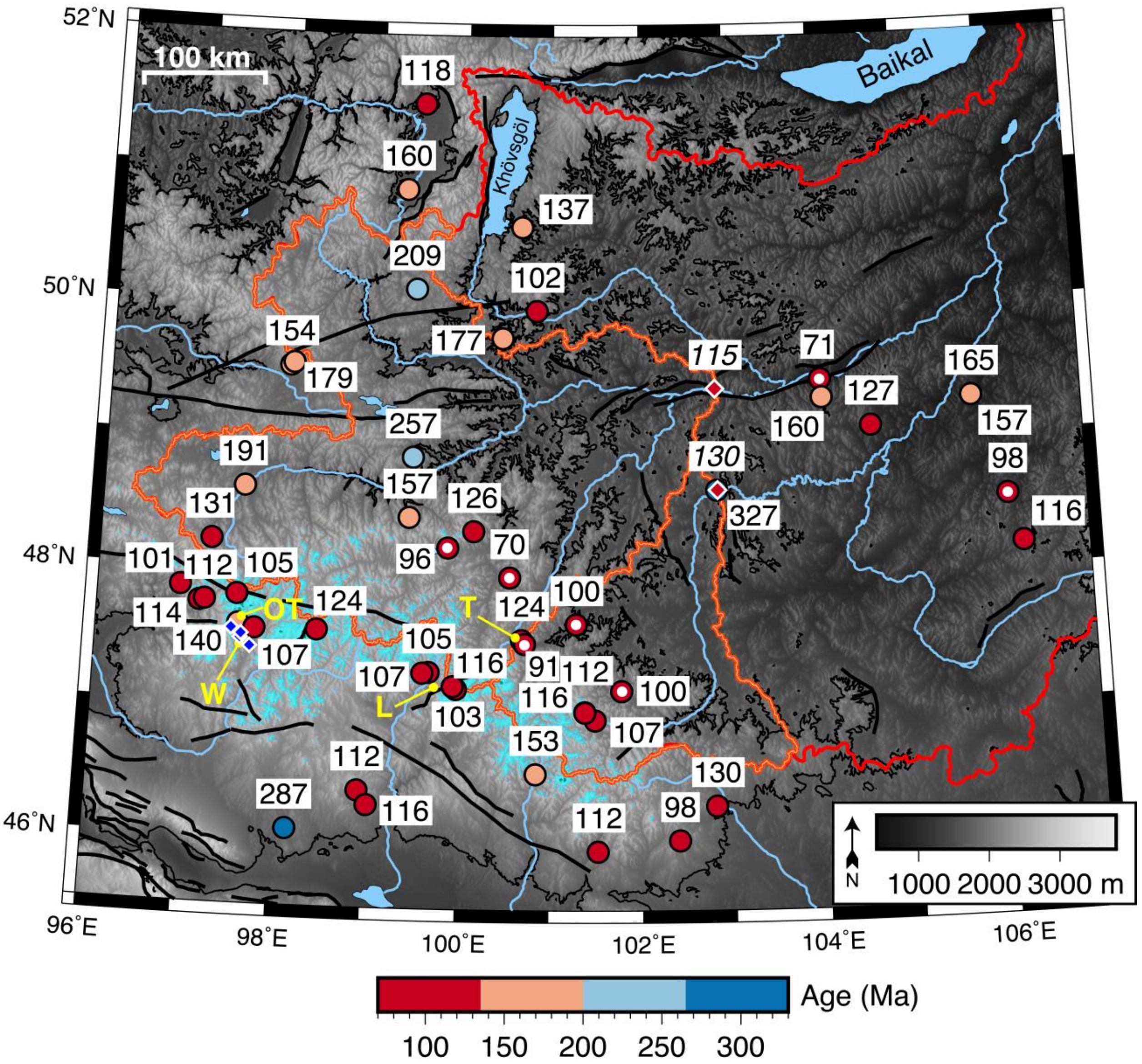

Figure 5: Granitic-bedrock mean AHe ages across the Hangay Mountains and north-central Mongolia colored by age. The majority of cooling ages in the Hangay are ca. 100-120 Ma, with a slightly younger grouping <100 Ma on the north flank (red/white center). Off the Hangay, ages are similar, albeit with greater scatter and an older component greater than ca. 120 Ma. Detrital sample locations are shown as diamonds (mean age in italics). The red line shows the Selenga watershed and sub-catchments with respect to detrital samples for the Selenga and Orkhon are the orange lines. Points tagged in yellow are AHe/AFT transect (W) of *West et al.* [2013] shown in blue diamonds, transect (L) of *Landman* [2007] near Egiin Davaa, and transect (T) discussed with figures 7 and 8. OT = Otgontenger Uul. Grayscale 90 m DEM with 1700 m contour to mark higher elevations above the regional background and onset of 'regional knickpoint elevation zone' discussed in text and with fig. 7. Glaciated high elevations areas shown in cyan blue, derived from the ELA during the LGM from *Lehmkuhl* [1998]. Major faults from *Tomurtogoo* [1999] geologic map of Mongolia shown by heavy black lines. See supplement for full age dataset.

4.2 Detrital (U-Th)/He data

The lower reaches of the Orkhon and Selenga Rivers were sampled to survey regional detrital apatite cooling ages (suppl. table S2 for data). The corresponding watersheds of the sampled locations are shown in figure 5. The motivation for detrital dating was to establish the age distribution that may be expected from bedrock ages, and to assess any dominant subsets. There was also an added motivation to determine if younger detrital ages were expressed that were missed by bedrock sampling. The Selenga and Orkhon Rivers (fig. 6) show similar age distributions with dominant peaks at ~115-120 Ma for the Selenga and a broad peak centered at ~130 Ma for the Orkhon (this central value is likely controlled by the low number of data).

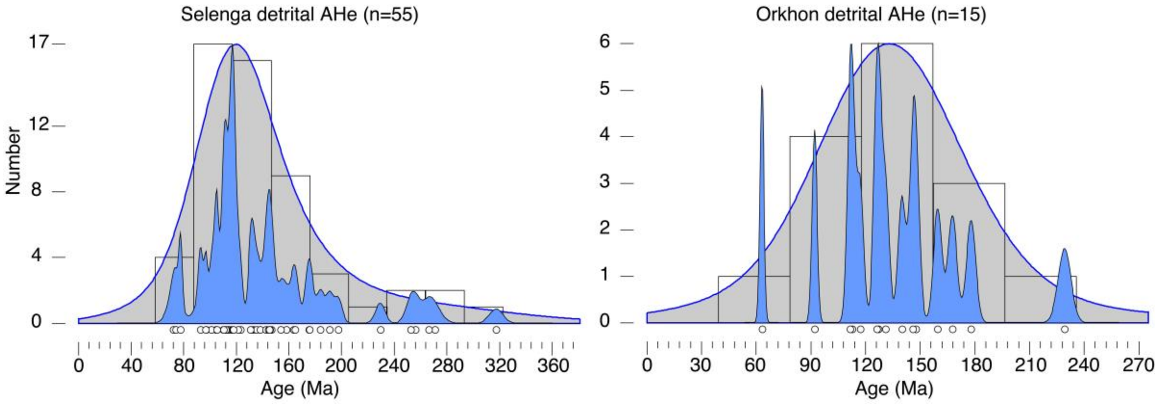

Figure 6: Selenga and Orkhon River detrital apatite (U-Th)/He cooling age populations shown by kernel density estimator (KDE) (smooth, gray envelope) and probability density functions (PDF) (shaded blue) from DensityPlotter [*Vermeesch*, 2012] using a Gaussian kernel and adaptive bandwidth (varied based on local data density). White dots show individual grain ages for the datasets. The y-axis is number of grains.

5. Modeling and interpretations

5.1 Detrital apatite (U-Th)/He modeling

Inference of the probability distribution of the number of detrital cooling age components was performed via BayesMixQt using Reversible Jump Markov-Chain Monte Carlo methods [*Jasra et al.*, 2006]. There are two major age components identified in the Selenga River sample with an expected model mean of 124 ± 29 Ma, representing 83% of the detrital population and an older component at 227 ± 51 Ma, representing 17% of the population (200,000 iterations, post burn-in). The Orkhon sample has very few grains and is less resolved, but mixture modeling reveals a single component maximum posterior peak at 131 ± 29 Ma, showing overall agreement between both rivers. The Selenga detrital population contains a few dates that may reflect the end of CAOB orogenic exhumation, while the majority of grains are from the last major exhumation event in the early Cretaceous during Mongol-Okhotsk suturing. The notable outcome from the detrital dating is that the area supplying sediment to these two locations contains an older age component that is not reflected in the Hangay bedrock samples, implying that the older ages are potentially coming from bedrock in the lower reaches of the catchments or that older cooling ages are sourced from glacially-eroded relict surfaces.

The hypsometry of the Selenga and Orkhon catchments relative to the detrital sample locations are quite different (fig 4). Both drainage basins have been glaciated (fig. 5), but the glaciation is limited in extent to only the highest elevations, compared to the overall basin areas. Based on the shape of the hypsometric integral, the Orkhon basin would be “mature or old,” with the majority of the catchment area at low elevations, while the Selenga would represent a younger stage of development [*Strahler*, 1952]. Nevertheless, caution is required during interpretation because the influence of tectonics or fluvio-glacial processes, along with basin size and tectonic activity can render basin hypsometry non-unique [*Brocklehurst and Whipple*, 2004].

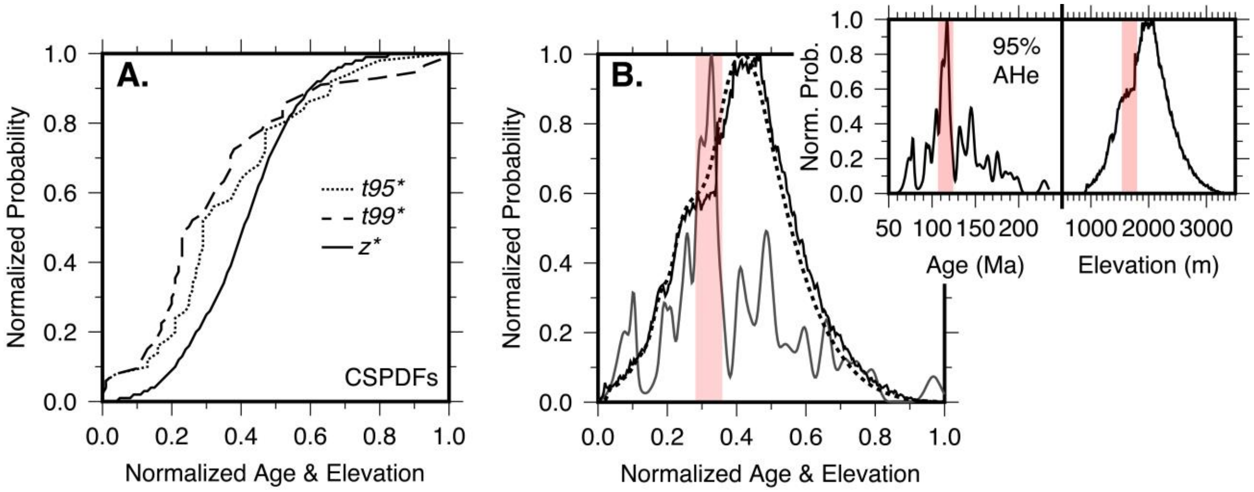

Figure 7: **(A)** Normalized CSPDF curves of Selenga detrital ages (dashed lines, t*) and catchment elevations (solid line, z*) for the Selenga River, using 95% and 99% of the detrital dataset, after *Ruhl and Hodges* [2005]. **(B)** SPDF curves for normalized age (gray) and elevation (solid black line) distributions with inset age and elevations (upper right). Dashed line in (B) is the 'ideal' age SPDF obtained from inverting the observed age SPDF and hypsometric curves with respect to the regional AER from the northern Hangay (figure 5, transect labelled T). Small inset panels show ages for 95% of the detrital AHe dataset and the elevations in the Selenga sub-catchment and red shading shows the dominant mismatch in age/elevation from the ideal age SPDF, see text for details.

Figure 7 show plots of detrital cooling age PDFs from equation 1-3 after *Ruhl and Hodges* [2005]. To minimize the mismatch between normalized age and elevation curves due to uncertainty in cooling ages, both the 95% and 99% detrital SPDF were used to construct the *t** CSPDFs, which effectively removes a small component of the older age signal. The CSPDF$_{t*}$ curves are slightly offset from the CSPDF$_{z*}$ curve for the Selenga basin, suggesting non-uniform erosion and a preferential erosional zone at elevations between ~1600-1800 m in the northern Hangay landscape. *Whipp et al.* [2009] showed through 3D thermal modeling that an increase in relief amplitude (with a constant minimum elevation) causes a shift in the detrital age population towards older ages relative to steady-state relief, whereas a relief decrease would have an opposite trend. This is directly linked to the higher or lower effective denudation rate between each respective relief change scenario. The mismatch/shift towards younger ages in fig. 7B may be in line with the relief-decrease age shift of *Whipp et al*. [2009]. The Orkhon basin curves are not shown due to the limited number of dated grains.

We solve for the expected uniform erosion AER by dividing the observed detrital PDF by the hypsometry to obtain the slope of the ideal AER to match the hypsometry. This produces a predicted slope of 0.068 that is then compared to a bedrock age-elevation transect on the north flank of the Hangay in the Selenga sub-catchment (see fig. 5 for location), which yields a slope of 0.060 (dashed predicted age SPDF curve in fig. 7B). Another short bedrock age transect from the valley floor to the Orkhon headwaters cirque yields a slope of 0.059. Near Otgontenger Uul, the highest elevation peak in the glaciated interior of the Hangay, age-elevation transects are shown in figure 8 using our data and cooling ages from *West et al.* [2013], *Jolivet et al.* [2007], and *Landman* [2007]. Here, AER slopes are greater but still similar to the predicted and measured AER slopes in the Selenga basin. The slight mismatch in the PDF curves could be due to:

1) Sampling bias or outlier ages: The Selenga basin sources not only the Hangay, but lower elevations to the north that have a slightly older, albeit scattered, cooling age signal and therefore are eroding more slowly than the Hangay. Bias could be introduced from the dating process itself or be naturally occurring if a higher proportion of 'younger' Hangay sediments were being supplied to the lower reaches of the basin. Naturally occurring bias may be a reflection of alpine cirque cutting and higher erosion along steeper slopes of the Hangay. There is also the possibility of sampling other Mesozoic-Paleozoic bedrock and older, recycled sediments. If this were the case, it would seem that this is a fairly small proportion of dated grains. Alternatively, some of these slowly-cooled apatites could be

cooling age outliers that are skewing the age PDF; this situation is apparent in the 95% CSPDF_{t*} curve, which more closely matches the hypsometry by removing only the oldest ages from the detrital population.

2) Detrital under-sampling: The Selenga CSPDFs are reminiscent of those presented by *Ruhl and Hodges* [2005] for the Marsyandi trunk stream in Nepal where there is also departure of the CSPDF_{t*} from the elevation range. This was attributed to sediments not capturing the full bedrock age signal in a very large catchment. This could very well be the case here as well, since the sampled Selenga catchment is >95000 km^2 in size.

3) The ‘spike’ in the measured detrital age PDF is the only main point of deviation between the PDFs and occurs at a large step in the hypsometric curve, which roughly aligns with the shift from the background low-lying elevations in the deeper basin to the elevated landscape of the Hangay. This shift likely signifies a regional, preferential cooling age ‘erosional zone’ that is the current focus of incision at the crossover into higher elevations of the Hangay where more sediment of the primary detrital peak is being sourced. In line with this, the mismatch between hypsometry and the age CSPDF may also signify a change in erosion rate at ~120-130 Ma, which agrees to first-order with the *West et al.* [2013] apatite fission-track AER (fig. 8).

The large spread in our observed detrital ages suggests that erosion has been slow, of low magnitude, and operative over a prolonged period since the Mesozoic. In a simplistic 1-D case where lateral advection is ignored, an erosion rate over the time represented by the detrital population can be calculated by simply dividing the total catchment relief by the cooling age range, which in this case is quite long, >150 Ma. Long-term slow erosion and low modern relief suggest that the shallow isotherms have conformed to the topography, and a simple 1-D technique is adequate for erosion rate estimation [*Whipp et al.*, 2009]. To reduce the influence of potential outlier ages, only cooling ages falling within 95% of the detrital population mean were used. The detrital apatites from the Selenga catchment that source the majority of the western Hangay and northern Mongolia show a time-integrated erosion rate ($\dot{E}$) ≈ 17 m/My, which decreases to ~10 m/My if the entire detrital dataset is used. This is in agreement with the independently derived basalt incision rates for the late Cenozoic and previous thermochronologic and cosmogenic estimates for the region cited in section 2, all in accordance with a long-term history of slow erosional exhumation.

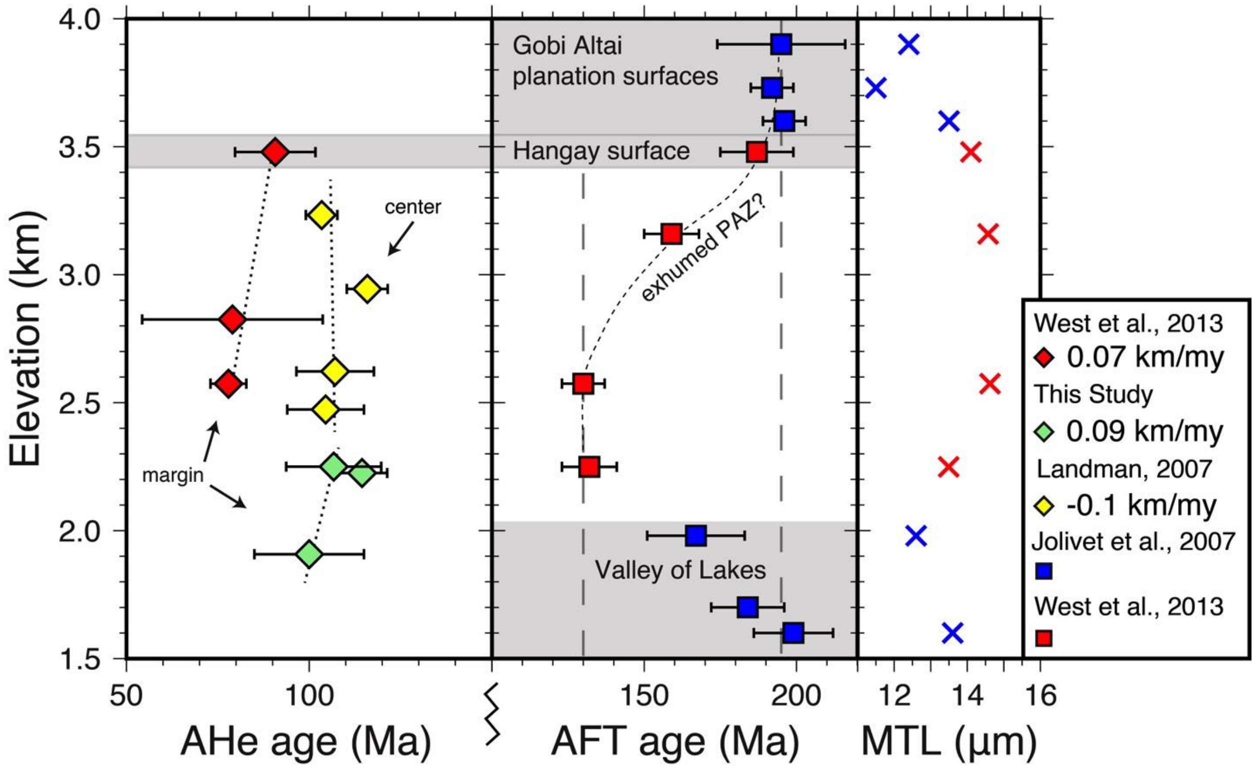

Figure 8: Apatite AERs (left panel) from the western Hangay near Otgontenger (highest peak; figs. 3 and 4) incorporating a short transect from this study and from *West et al.* [2013] and *Landman* [2007] datasets (see fig. 5 for transect locations). Positive AERs suggest valley-scale topographic wavelengths do not affect low-T isotherms. Right panels show AFT and mean fission-track lengths (MTL) for *Jolivet et al.* [2007] and *West et al.* [2013] datasets. Planation surfaces in the Gobi Altai, Valley of Lakes, and W. Hangay (gray) are all similar in age suggesting regionally coincident exhumation and that highest elevations are preserved remnants from an older event. *West et al.* AFT transect suggests the period

between ~180-130 Ma being governed by a moderate exhumation rate. Our rates and those published on the right are for the AHe transects and overestimate the true exhumation rate.

Conversely, the detrital cooling age range and the AER can be used to estimate the paleo-relief of a catchment [*Stock and Montgomery*, 1996]. On the large scale in the slowly-eroding Hangay, isotherms would presumably now be parallel to the surface, and assuming horizontal isotherms, the exposed bedrock ages divided by the modern relief yields the change in cooling age with elevation. By the same token, the detrital age range divided by the AER provides estimates of the paleo-relief. The apatite fission-track AER of *West et al.* [2013] spans 46.34 ± 0.24 Ma over 1.23 ± 0.01 km of modern elevation (using 10 m elevation errors from 90 m DEM) in the western Hangay. Using the 95% spread about the mean Selenga detrital age approximates catchment paleo-relief of 3.39 ± 0.1 km, or a 0.79 ± 0.1 km decrease in relief in the time represented by the sub-basin detrital dataset. However, two potential caveats exist for interpreting AERs throughout the Hangay, (1) the rivers sample the flank of a long wavelength topographic structure, which presumably means the isotherms conform to the topography to some degree, and (2) the remnant planation surfaces imply that the landscape underwent modest uplift and has been deformed since the development of the low relief surface, therefore the cooling ages could vary as a function of depth below the surface and not with elevation. We see both positive and negative AERs across the landscape, which collectively suggest either paleo-relief change or incision of a thermally stable upper crust.

Our detrital age sample population is too small to allow a definitive assessment of landscape change, although assumptions of widespread steady-state erosion in the Hangay are invalidated. It is reasonable to suspect that the landscape has experienced variable, finite erosion since the Cretaceous that has been more focused in certain areas of the landscape. The continued existence of the remnant planation surfaces across the Hangay is further evidence that an erosional steady state has yet to be reached. The recent surface uplift has potentially complicated the erosional history and provided a “regional knickpoint” at the uplifted Hangay margins for focused incision, which is supported by knickpoints in river profiles at elevations of ~2000-2500 meters [*West et al.*, 2013]. The eastern Hangay and Orkhon watersheds contain the majority of Cenozoic valley-filling basalts that have dammed valleys and locally disrupted the fluvial system by resetting base level in the last ca. 10-15 Ma. Our geomorphic observations, detrital data, and the findings of *West et al.* [2013] agree and support modest glaciation, recent surface uplift, modern precipitation gradients, and structural or lithologic controls as the cause of localized erosional variability in this setting. Our detrital AHe ages also suggest areas of the Hangay landscape near ~1600-1800 m elevation are the focus of erosional unroofing.

5.2 Pecube-NA thermo-kinematic modeling

We are interested in not only the long-term exhumation of the region but also the relief evolution through time. We performed modeling analogous to the Dabie Shan study of *Braun and Robert* [2005] to ascertain the topographic and thermal histories necessary to produce the observed AHe dataset for central Mongolia using Pecube. Modeling was carried out as an exploration of plausible scenarios rather than an attempt to rigorously invert for actual values that are free of assumptions, including inferences about the state of relief earlier in the Mesozoic or spatial variability in timing, magnitude, and phases of exhumation during that time. Our thermo-kinematic models are inherently non-unique and should be viewed as an assessment tool that aid in ruling out extremes, and to assess whether our AHe data permit any ‘young’ exhumation scenario.

5.3 Inversion resolution tests

As a first step, we ran a Pecube-NA sensitivity test inversion in the same model domain as our true inversions in the western Hangay to primarily assess model performance and the ability of the model to efficiently evaluate if exhumation rates and relief could be adequately constrained to first order. Values for erosional timescale (τ), relief amplitude (*R*), and exhumation rate timing (E-timing) were set and run through a forward Pecube model to produce synthetic AHe and AFT cooling ages. These synthetic ages were then used as input in a Pecube inversion to determine if the true values could be recovered (with 6% and 10% synthetic measurement uncertainties derived from the output ages, 2σ; results shown in table 2). The sensitivity test recovered the true parameter values and the overall misfit was very good, however the assigned synthetic age errors were larger than the observed analytical errors on our data, and so were more permissive of good fits.

We then tested whether moderate relief change in a slow exhumation setting is adequately modeled using Pecube-NA (fig. 9). We set background exhumation rates from exhumation phase #1, E_1, from 180-90 Ma at 0.1 km/My and a second slower phase, E_2, from 90-0 Ma at 0.03 km/My. The relief amplitude, *R*, is set to 0.5 (50% of modern relief) at the model start, and the erosional timescale, *τ*, to 750 Ma. These variables are fixed and a Pecube forward model predicts model AHe and AFT cooling ages output at the same locations as observed data applying 6% AHe and 10% synthetic AFT age errors. The model ages and respective errors are then supplied back into two NA inversions, one where the relief amplitude is the only free parameter varying between 0-2, and the other with τ, *R*, and E-timing set free. This second test is to examine the ability to identify the true parameter values and any tradeoff effects. The second resolution test initially allowed E_1 and E_2 as free parameters but during initial tests the “true” rates were quickly identified, therefore during later inversions the background exhumation rates were fixed.

The relief amplitude-only sensitivity test inversion (fig. 9A) was set to run for >6000 total models with 96 models in an initial iteration and 96 models in each subsequent iteration with a 96% resampling rate. Convergence on the true value of $R = 0.5$ was found within a few hundred models but the algorithm was allowed to run to ~850 models before the run was stopped due to adequate convergence. This result verifies that in the case of low model complexity (dimensionality), well-known thermo-kinematic parameters and high quality thermochronometric data can accurately resolve relief change in a post-orogenic setting to within 2% in a short number of iterations, in this example the best 50 models resulted in an $R = 0.49 \pm 0.02$ (1σ).

The sensitivity test inversion for τ, R, and E-timing was run with an initial and subsequent pool of 112 models over 75 iterations with a 68% resampling rate for a total of 8504 models (fig. 9B-F). The lowest misfit values matched the true values very accurately, suggesting the absence of synthetic noise in the resolution test. The model appraisal shows that relief amplitude was well resolved with a mode and standard deviation of 0.57 ± 0.23 for R and E-timing mean of 90.2 ± 5.5 Ma. The erosional timescale showed considerable scatter but was within one standard deviation of the true value. Trade-offs between parameter combinations can be noted in figure 9C. Under fixed exhumation rates, relief amplitude decreases non-linearly as the relief-change timescale increases, while the timing of exhumation rate change is positively correlated with both relief amplitude and relief-change timescale.

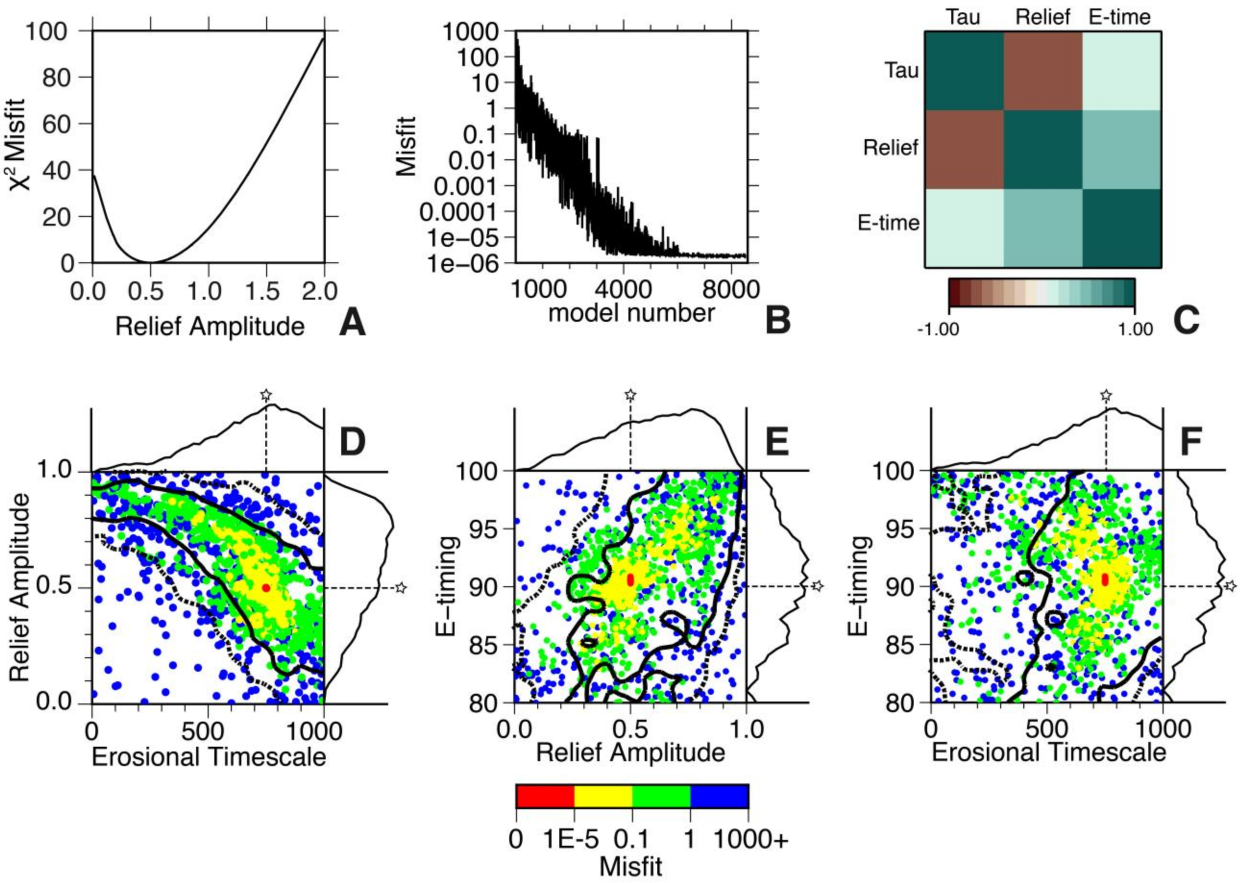

Figure 9: Pecube-NA sensitivity test of variables controlling relief to assess the ability to resolve relief change in this type of slow exhumation setting. For tests, a two-phase exhumation scenario was used with fixed rates of 100 m/My and 30 m/My. **(A)** Sensitivity test for *relief amplitude-only* showing least-squares misfit and relief amplitude between 0 (no relief) to 2 (two times modern relief) with a defined misfit minima at the true value of 0.5X the modern relief in the Hangay. **(B)** Misfit evolution over the sensitivity test inversion where τ, R, and E-timing are allowed free, exhibiting optimal convergence after >6000 models. **(C)** Correlation matrix for the free inversion parameters using NA-plot [*Sambridge*, 1999b]. Values approaching (-1)+1 show greater (anti)-correlation while values near 0 show no relationship or dependence. Erosional timescale and relief amplitude are highly anti-correlated, while both the exhumation rate change timing and relief amplitude have a slight positive correlation with erosional timescale. These trends can also be seen in the PPDFs in panels D to F. **(D-F)** Scatter plots showing misfit between τ, *R* and E-timing, the 2-D PPDF 1σ (solid) and 2σ (dashed) contours shown as overlays and the corresponding 1-D marginal PPDF curves for each parameter on the corresponding axes. In each case the star marks both the ‘true parameter value’ and in this case, the respective lowest misfit of the 1-D PPDF, which in this synthetic example is also the mean or modal value.

5.4 Pecube-NA model inversion results

Following the sensitivity tests, we then applied Pecube-NA modeling to learn about the landscape evolution in Mongolia. The AHe thermochronologic data suggest low background exhumation rates have been sustained over the past ~100 m.y., so here we test the resolving power of the Pecube-NA model to estimate timing and magnitude of long-term exhumation rates and paleo-relief histories using a modest data subset in the western Hangay. We used representative values for model (crustal) thickness, basal temperature, etc. for central Mongolia (table 1) and our data input consists of replicate single grain AHe cooling ages and those reported in *West et al.,* [2013]. Figures 10 and 11 and table 2 show inversion results. We ran ~10,000 models for each inversion with a resampling rate between ~60-70% to obtain adequate convergence and sampling of the model space.

We report results for two inversions that simulate the last 150 Ma in the western Hangay (see figs. 12 and 13 for location). One inversion (run 1-TSW) held the major exhumation phase timing fixed from 150-130 Ma, which was derived from the modeled AFT thermal history of *West et al.* [2013]. The optimal relief history and basal temperature of the model (geothermal gradient) were investigated in this run. The inversions allowed relief to evolve in one of three ways, either (1) relief stays fixed through time (same as modern topographic relief), (2) start as a plateau at low elevations with simulated 'incision' to grow the modern topography, or (3) topography is at higher elevations (than modern peaks) at the model start and is then incised to form the modern topography. A second inversion attempt allowed the end of the exhumation phase to be a free parameter (run 1-C). The second inversion with the unrestricted exhumation phase was mainly for comparative purposes, as delayed or prolonged exhumation may have been possible in different parts of Mongolia during the end of the Mongol-Okhotsk orogeny in the Jurassic through the Cretaceous.

Table 1: Model parameters used in Pecube-NA inversions

Fixed Parameter	Value	Units	Reference
Model initiation	150	Myr	
Basal temperature, *Tb*	850	°C	*Ionov et al.*, 1998; *Ancuta*, 2017
Volumetric heat production, *H*	0.7	μW m^{-3}	*Lysak and Dorofeeva*, 2003
Radiogenic heat production, *A*	8	°C Myr^{-1}	
Thermal diffusivity, κ	25	km^{2} Myr^{-1}	
Specific heat capacity, *Cp*	800	J kg^{-1} K^{-1}	
Surface Temperature, *Ts*	0	°C	
Atmospheric lapse rate	0	°C km^{-1}	
Crust/Mantle density, $\rho c/\rho m$	2800/3300	kg m^{-3}	
Model Thickness, *Zc*	49	km	*Stachnik et al.*, 2014
Effective elastic thickness, *Te*	6.1	km	*Bayasgalan et al.*, 2005
Model domain	80 x 60	km	
1 km grid resolution	0.00833	degrees	
Vertical node spacing	1	km	

Table 1: Fixed model parameters used in Pecube inversions to calculate the isostatic and thermal response to varying relief.

Table 2: Pecube-NA inversion results

SENSITIVITY TEST

Inversion Parameter	**True value**	**Inversion Results**	**Mean ± SD**
Erosional timescale (Myr), τ	750	750.1 (0:1000)	608 ± 260
Relief amplitude, R	0.5	0.50 (0:1)	0.57 ± 0.23
Exhumation change timing (Myr), E-timing	90	90.4 (100:80)	90.2 ± 5.5
Exhumation rate 1 (km Myr^{-1}), E_1	0.1	-	-
Exhumation rate 2 (km Myr^{-1}), E_2	0.03	-	-
Number of models	8512		
Lowest misfit, μ	1.8E-06		
Misfit type	χ^2		
Free parameters	3		
Models/Iterations	112/75		
Resample rate	68%		

FULL INVERSIONS	**INVERSION 1**		**INVERSION 2**	
Inversion Parameter	**Run 1-TSW**	**Mean ± SD**	**Run 1-C**	**Mean ± SD**
τ	**930** (0:1000)	890.6 ± 110	**482** (0:1000)	491.7 ± 43
R	**1.58** (0:2)	1.62 ± 0.08	**1.24** (0:2)	1.20 ± 0.07
E-timing	130	-	**116.5** (130:100)	116.0 ± 1.1
E_1	**0.13** (0:0.8)	0.21 ± 0.09	**0.22** (0:0.5)	0.23 ± 0.03
E_2	**0.0071** (0:0.1)	0.0064 ± 0.0029	**0.0056** (0:0.1)	0.0078 ± 0.0046
T_b (basal temp, ºC)	**860.5** (600:950)	760.7 ± 92.8	850	
Time Step	1		1	
Run time (Ma)	150		150	
Number of models	10224		9504	
Lowest misfit, μ	1334.2		1325.5	
Number of Data	28		28	
Misfit type	χ^2		χ^2	
Free parameters	5		5	
Models/Iterations	144/70		144/65	
Resample Rate	63%		70%	

Table 2: Pecube-NA inversion results for sensitivity test and full inversions. Values separated by a colon are the prior search ranges during the NA sampling stage while those in bold are the best-fit parameter values (lowest misfit). Mean and standard deviation represent the resampling results from the NA

appraisal of the model ensemble. *R* = relief amplitude; τ = erosional timescale; E-timing is the time of exhumation rate change; E_1 and E_2 = exhumation rate 1 and exhumation rate 2. See text for details.

Model inversion 1-TSW (fig. 10) shows paleo-relief ~50% greater than the modern relief (1.62 ± 0.08) is required to explain the AHe ages. The *τ* (erosional timescale) parameter is a primary control on the evolution of relief, as the relief amplitude and erosional timescale show a positive correlation. The large positive value for *τ* suggests exponentially rapid relief evolution following the main exhumation phase with the majority of paleo-relief (~90%) reduced by ca. 100-85 Ma (see fig. 12).

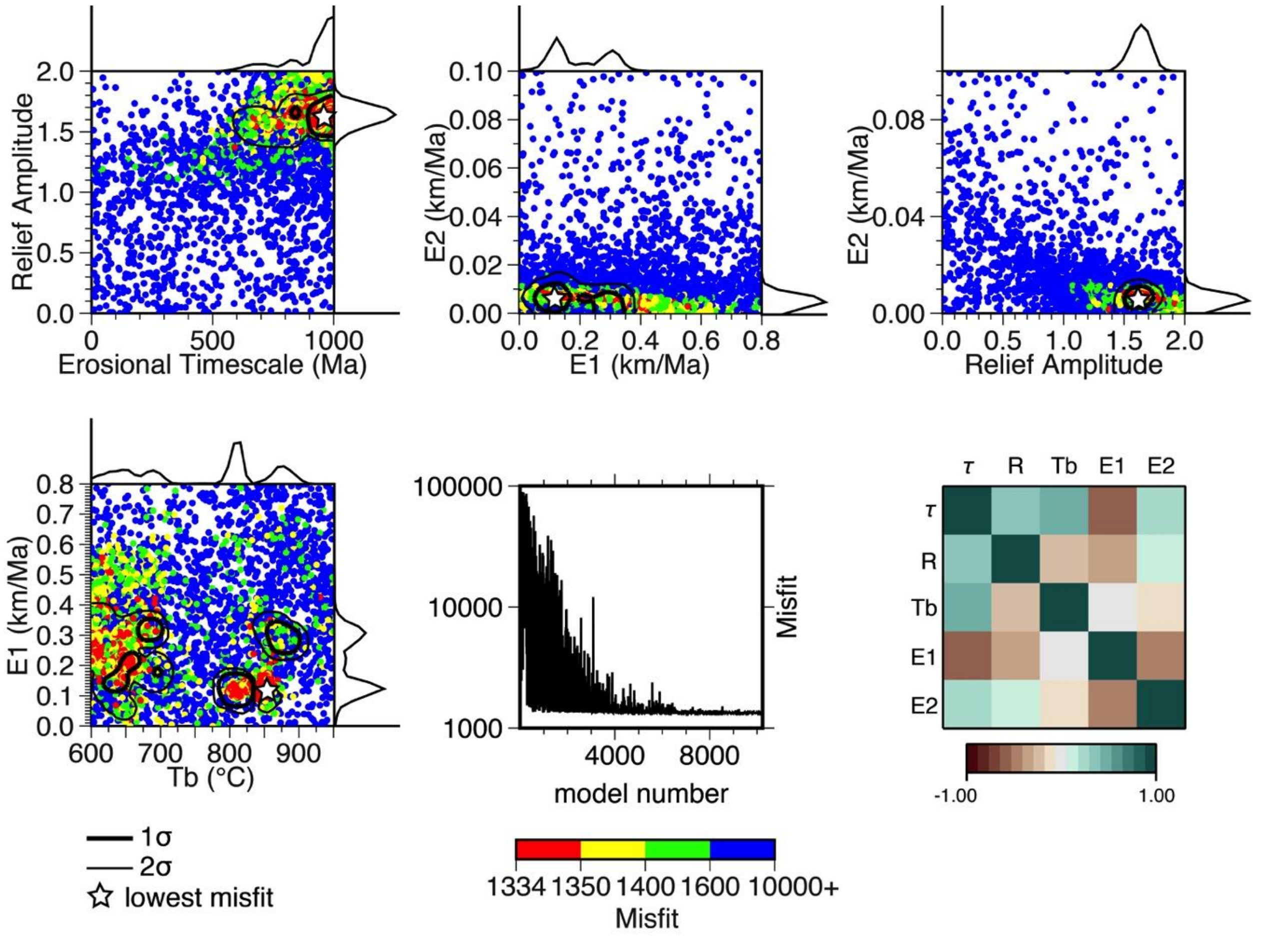

Figure 10: Pecube-NA inversion results for Run 1-TSW. Scatter plots are 2-D projections of the 5 dimensional parameter space on planes defined by combinations of two parameters. 1-D posterior curves show probability density within the parameter search range. See supplementary material for additional plots of other variables. Each dot represents a forward model from the inversion and is colored by the χ^2 misfit value. Stars denote the lowest misfit model while heavy/thin black lines are 1σ (67% confidence)

and 2σ (95% confidence) errors, respectively. Bottom middle panel shows misfit evolution and convergence during the inversion and the bottom right shows the correlation matrix between difference parameters between -1 to +1 signifying strong (negative) anti-correlation or positive correlation, with values near zero having no relationship. Pecube physical modeling domain shown in fig. 13 inset box, see text for discussion.

Inversion 1-C results are in good agreement with inversion 1-TSW, where the only difference is in the delayed timing in exhumation rate change at ~116 Ma (lowest misfit), which appropriately constrains the predicted relief reduction to be lower and approaches a relief amplitude of 1.0, suggesting very little to no relief change by the end of the Cretaceous (fig. 11). A two-stage exhumation scenario was applied for simplicity and because more complicated exhumation histories are unnecessary to explain the data. If exhumation is shorter in duration, i.e. 150 to 130 Ma versus 150 to ~115 Ma, the required paleo-relief is also greater. Both inversions suggest background exhumation was never extremely rapid during this time, on the order of ~100-200 m/My during the primary phase and very low since the Early Cretaceous at ≤10 m/My (table 2). The E_1-E_2 scatterplot (fig. 11; table 2) shows that the secondary phase of exhumation is required to be very low at ~6 ± 3 m/My, regardless of what the E_1 exhumation rate is. The erosion rates for the Hangay, which account for background exhumation, isostasy, and relief evolution, suggest rates in the higher elevations (fig. 12A) of up to 16 m/My since the Early Cretaceous. The geothermal gradient, which is controlled by the basal temperature (T_b) shows two distinct regions of either a cooler or hotter temperature, where neither has a clear relationship with the primary exhumation phase (E_1), however larger values of R require a lower (E_2) exhumation rate. The best-fit model has a basal temperature of 860°C, which is in agreement with local geochemical data [e.g. *Ionov et al.*, 1998; *Ancuta*, 2017] and produces a geothermal gradient in agreement with paleo- and modern estimates of 15 and 21°C/km, respectively [*Ionov et al.*, 1998; *Kopylova et al.*, 1995; *Lysak and* Dorofeeva, 2003; West *et al.*, 2013].

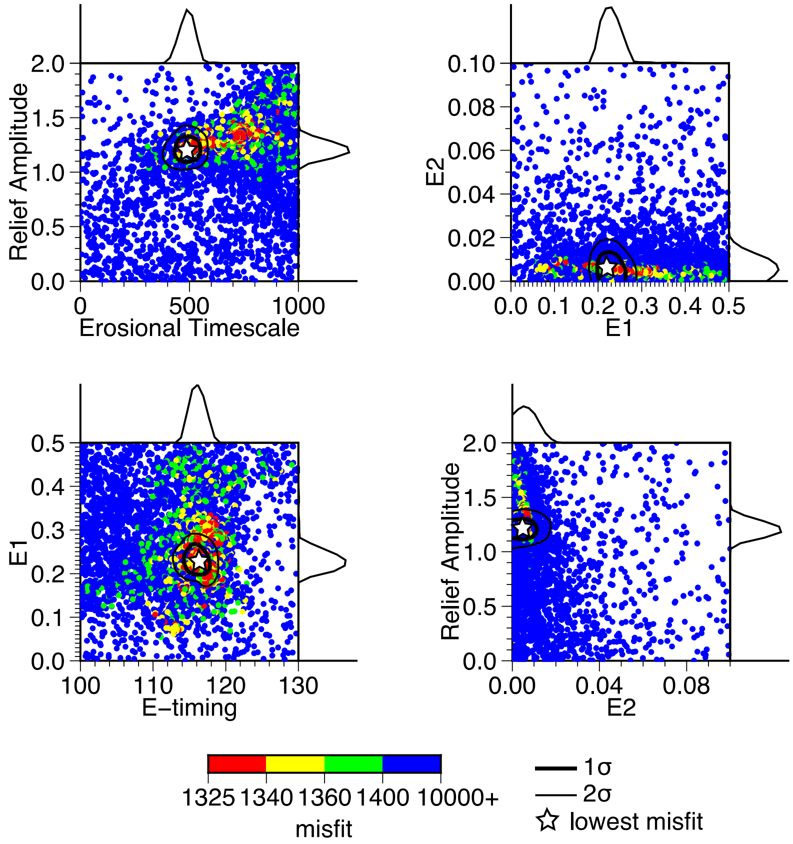

Figure 11: Pecube-NA Run 1-C inversion results for 9504 models. The same figure scheme as figure 9. The difference between Run 1-TSW is that the exhumation rate change timing is allowed free in this inversion.

The misfit values reported for the full inversions are higher than the sensitivity inversion because the sensitivity test allowed much greater variance in the synthetic age uncertainties. The full inversions used the analytical error, which is typically ≤ 2 Ma. The observed and predicted ages agree very well, generally within 2%, except for a few cases where the reported AHe age is slightly older (~10%) than the predicted age, which drove the misfit up (fig. 12; suppl. table S4). The reported multi-grain aliquot AHe data from *West et al.* [2013] were over-predicted and were the main contributors to the higher overall misfit values, stressing the importance of single-grain (U-Th)/He data in old, slowly-cooled regions.

We ran Pecube forward models using the best-fit parameters of inversion 1-TSW to predict model regional AHe cooling ages (fig. 12), since our inversions are focused on a small area of the western Hangay and the flexural response to exhumation will be variable depending on the size of the area modeled. Figure 12C-F shows observed versus predicted cooling ages using the best-fit parameters from inversion 1-TSW for the western Hangay and the age-eU relationship using the RDAAM for age prediction. The major discrepancy in age agreement (higher associated misfit) lies between the *West et al.* [2013] multi-grain aliquot AHe ages and those modeled at high elevations (fig. 12A and 12D). This is likely due to the cooling age ‘averaging’ bias from using multiple grain aliquots, and in combination with the known scatter in slowly cooled samples, produces ages that do not adequately represent the ‘true’ single grain cooling ages. In this case, it seems that the *West et al.* [2013] AHe ages are younger in comparison to nearby samples from this study. Potential outlier ages from our dataset that are anomalously old and not readily explained by radiation damage, grain size, etc., also cannot be fit adequately (fig. 12C and fig. 14E). The elevation for the highest samples is also under-predicted (fig. 12F), which may be convolved with the errors associated with the age prediction itself, or indicates that the predicted relief evolution is too simplistic and does not fully capture the nuanced topography (see regional model in fig. 14).

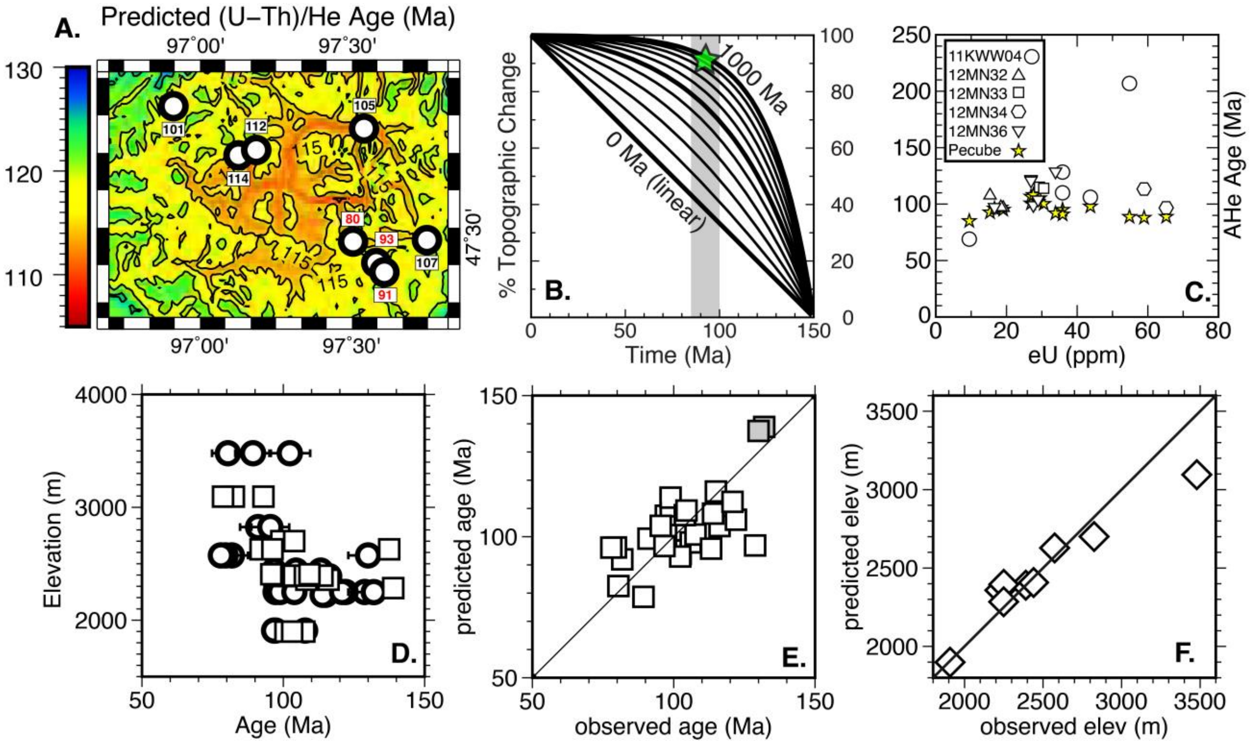

Figure 12: **(A)** Contoured age map (5 Ma interval) of Pecube-NA Run 1-TSW in the western Hangay (see fig. 13 for location, inset box). Locations of samples are circles with mean ages shown, ages in red are multi-grain aliquots from *West et al.* [2013]. Note that single grain ages were used in the inversion. Single grains shown in panel D. **(B)** Plot showing how topography changes in the model according to equation 6. Our model inversion 1-TSW exhibits highly positive best-fit values for τ, suggesting relief decayed rapidly and was ≥90% of the modern relief by ca. 100-85 Ma. **(C)** A plot of single-grain AHe ages with respect to eU for a few samples in the modeling domain. The Pecube model predictions (stars) are fairly consistent with observed age-eU patterns. **(D)** Observed and predicted cooling ages and corresponding elevations are in good agreement except mainly at the highest elevations which are derived from Pecube forward models using our best-fit or maximum likelihood values from the model inversion. Black circles are observed single-grain age replicates with errors, while squares are predicted cooling ages. **(E)** 1-to-1 line for predicted vs. observed cooling ages; gray squares are AFT samples. **(F)** observed versus predicted elevations using best-fit 1-TSW inversion relief scenario in Pecube forward model.

The optimum inversion 1-TSW model parameters for the western Hangay were held fixed and extrapolated to the entire Hangay and forward modeled (fig. 13). Four different model scenarios explored changes in effective elastic thickness. This was done to test the flexural response to erosional unloading, which is magnified or isostatically-enhanced when the elastic thickness is low (in local isostatic equilibrium), compared to a high elastic thickness of 20 km or more (strong lithosphere). These results highlight the complexity between relief evolution and isostasy and deconvolving the two in a slowly-eroding setting where isostasy is a primary contributor to rock uplift over long timescales. Regional variations in lithospheric thickness and mechanical properties, as well as varying depths of seismicity and changes in regional faulting character, cause effective elastic thickness variability in Mongolia [*Bayasgalan et al.,* 2005]. The Pecube-predicted age surface maps were resampled at the 10 km length scale to smooth age gradients (fig. 13). Contouring the predicted age surfaces allowed comparisons of regional cooling age spatial patterns. The effective elastic thickness from *Bayasgalan et al.* [2005] is shown in the upper right panel (Te of 6.1 km), while the other panels show results using elastic thicknesses of 0 (local isostasy), 15, and 20 km. Local isostasy (Te = 0) produces uniform predicted ages across the Hangay, closely following the topography but with less age variation in the broad sense (fig. 13). Increasing Te (panels 15 and 20 km) yield concentric 'bulls-eye' patterns of increasing cooling ages away from the range center with less topographic correlation. However, this pattern is partially due to an edge effect modeling artifact because of the 'zero exhumation' model domain boundary but would be theoretically expected if Te increases away from the Hangay high elevations. The overall misfits for each model are fairly similar and fit the data within analytical error (reduced chi-squared misfit 0.8-0.9), demonstrating that varying Te has little effect on the match between observed and predicted ages for low exhumation rates. However, at the orogeny-scale an elastic thickness of 20 km yields a marginally better misfit compared to the other models, which agrees with the findings of *Bayasgalan et al.* [2005] that the elastic strength of the lithosphere increases away from the central Hangay.

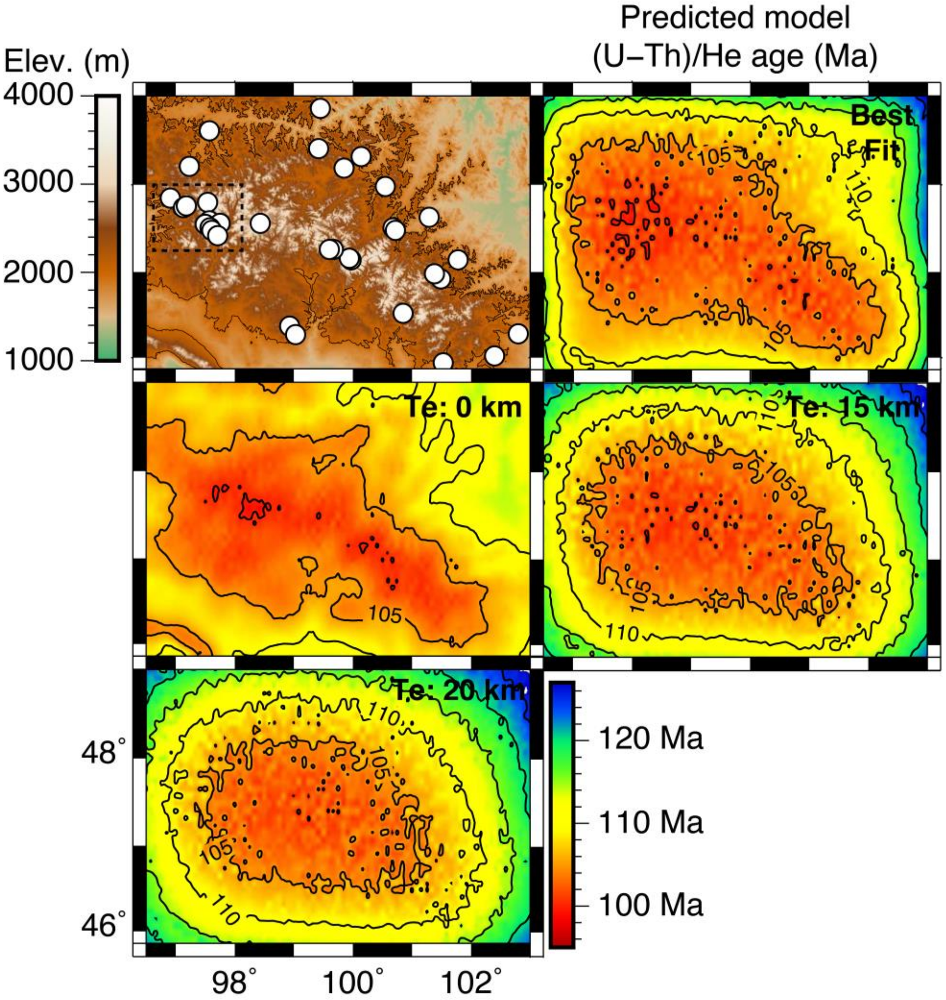

Figure 13: Pecube forward model age predictions using inversion run 1-TSW best-fit parameter values with the main exhumation stage from 150-130 Ma after *West et al.* [2013] model thermal history. Inset box shows location of western Hangay bounds used in Pecube-NA inversion. Regional forward models are resampled at 10 km to smooth ages and are shown with a 5 Ma contour interval. (Top left) Elevations from 90m SRTM DEM (2000 m elev. contoured) with white dots showing sample locations used in Pecube modeling of the entire Hangay, (top right) the ages predicted by the best-fit model results of inversion 1-TSW shown in table 1 (Te = 6.1 km). Other panels show the effects of varying the effective elastic thickness (Te) while holding all other best-fit variables constant.

To investigate relief evolution in a more regional sense and to reproduce the relict planation surfaces, we ran a Pecube forward model for central Mongolia using our full AHe dataset that begins at 150 Ma with a flat plateau at the highest modern elevation, similar to *Valla et al.* [2010] (fig. 14A and 14B, same regional model domain as shown in fig. 13). This simulates a regional relief increase through preferential valley incision, where highest peaks stay at a fixed point but valley bottoms are lowered. Forward modeling was necessary because a full inversion over such a large area would be computationally infeasible. For simplicity, late Cenozoic surface uplift (elevation change) is ignored because it amounts to only on the order of a few hundred meters, accompanied by minor erosion, and occurs very late in the overall history, so it is of little consequence for AHe age prediction. We used a DEM resampled to 4 km resolution for faster computation over this large area, an elastic thickness of 20 km, and the E_1/E_2 exhumation phases and best-fit background exhumation rates from inversion 1-TSW (fig. 14). All other forward model parameters were the same as the inversions. The forward model MSWD misfit is very high (>>1) for models involving an exponentially rapid late change in topography (i.e. young relief creation) or a linear change through time, which is expected since our AHe data are old and require cooling through closure isotherms in the Mesozoic. We used a value of 930 My for the erosional timescale (τ), which indicates rapid relief change early in the model (fig. 12B) and is the best-fit value from inversion 1-TSW. The major assumption here is that differential exhumation across the region is not high, however we know this is likely the case given our detrital modeling results, older bedrock AHe ages outside the Hangay, and the effects of isostasy in the Hangay compared to the outlying area. This model is simplistic and meant to reproduce observed regional cooling age spatial patterns to first order and the predicted AHe ages are in agreement with observed data (MSWD=0.92), especially in the Hangay high elevations (fig. 14C and 14E). However, older observed ages outside of the Hangay to the northeast would be predicted too young under these exhumation conditions, suggesting more complexity is required to fully capture subtleties, including differential uplift/regional tilting or spatially varying exhumation. The model is able to reproduce older planation surface remnants that are not eroded while the rest of the topography shows higher exhumation rates into the lower elevations and in the modern incised channels (fig. 14D), furthermore, the observed and predicted Hangay ages (14E) and elevations are in excellent agreement (14F).

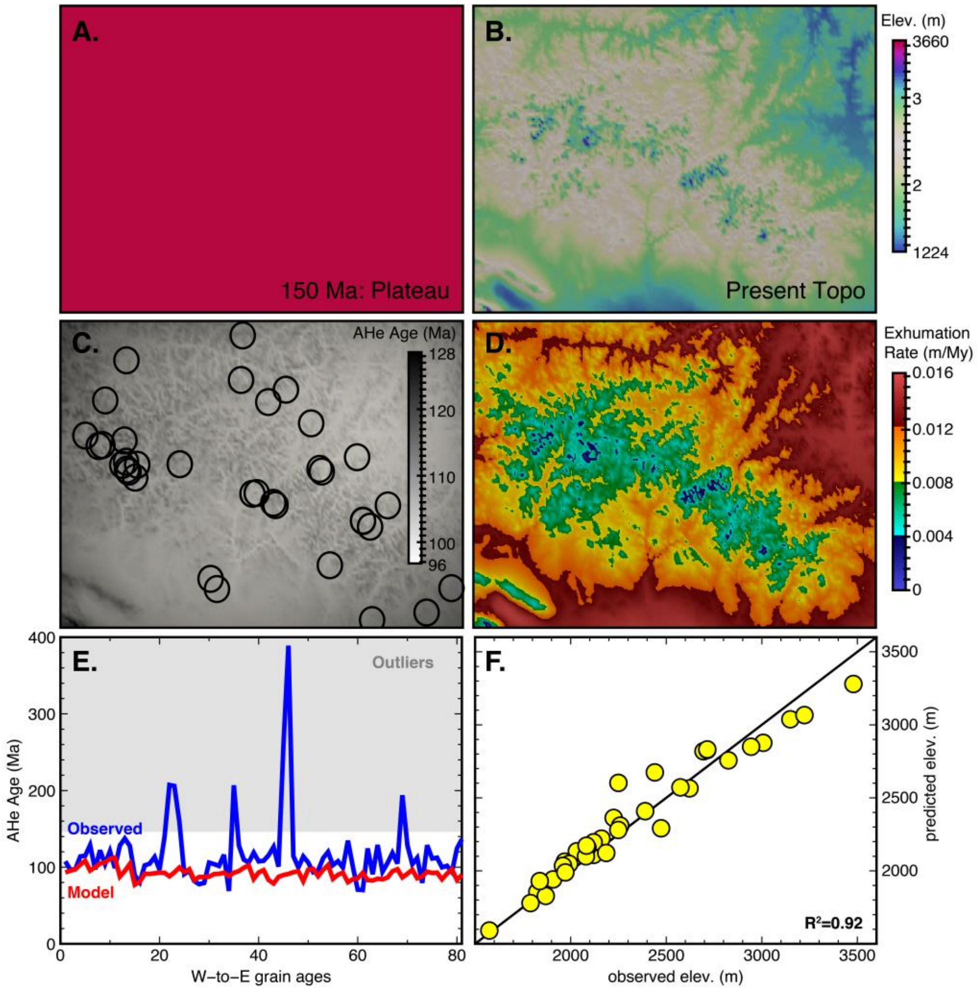

Figure 14: Pecube forward model results for a planation surface and carving of topographic relief **(A)** The model starting condition for topography is a high plateau at the highest modern elevation (slightly lower than actual due to grid resampling). See elevation scale in panel B. **(B)** The end of the model run showing the modern topography. This relief was created using an erosional timescale of 930 My, which created the modern topography (within 90%) by 100-85 Ma. Note: although difficult to see, there are remnant surfaces (red) at highest elevations in panel B. **(C)** The predicted AHe age map across the region. Ages are best predicted in the Hangay but suggest younger ages outside of the Hangay, which is not in total agreement with real AHe data. Circles are the locations of real data used in the model **(D)** The predicted exhumation rates over the single time step with two phases of exhumation using the best-fit values from inversion 1-TSW. The rates are spatially variable and show no erosion at highest peaks and more focused/higher exhumation in the incised topography. Exhumation rates are on par with previously mentioned long-term estimates and inversion results between 4-16 m/My. **(E)** The observed and predicted single-grain AHe ages going from west to east in panel C showing a good match (also refer to fig. 5 for AHe age reference). The MSWD model misfit is 0.92 between observed/predicted and shaded gray denotes single-grain age outliers. **(F)** The observed and predicted elevations for a 'planation surface'

exhumation model displaying excellent correlation (R^2=0.92) and suggesting the exhumation/relief evolution model is viable at orogeny-scale. Line is 1-to-1 for reference.

6. Discussion

Some first-order conclusions about the regional relief history of the Hangay can be made from the thermochronology and modeling results. Apatite (U-Th)/He cooling ages and regional patterns from this study document Mesozoic cooling based on spatial relationships across central Mongolia. Modest relief lowering in the western Hangay in the latest Jurassic through Cretaceous could expose younger ages at high peaks while valley bottoms are older, producing an orogen-scale, inverted age-elevation relationship but maintained valley-scale positive AERs. The steep trend of positive AERs also suggests a low elastic-plate thickness in the central Hangay (<20 km), which has been previously advocated [*Bayasgalan et al.,* 2005]. These AER trends have been documented in other old, post-orogenic mountains in central Asia with similar exhumation histories, such as the Dabie Shan [*Reiners et al.,* 2003]. This age relationship is observed in the Hangay as well, where cooling ages are generally uniform in the mountain core, while away from the higher topography ages are slightly older, which points to modest, localized relief change within the highest peaks, spatially variable regional exhumation, or the combined effects of both to produce the observed cooling age patterns. A regional model for the Hangay is that there was regional ‘peneplanation’ in the Jurassic and then relief was created rapidly in the Cretaceous, which is consistent with the geology and tectonic models for the main cooling and exhumation phase for central Mongolia [e.g. *Jolivet et al.*, 2007; *West et al.*, 2013]. In either scenario, relief evolution is completed by the end of the Cretaceous and the landscape remains in disequilibrium throughout the Cenozoic.

The regional bedrock cooling age trends and the detrital AHe data point to erosion following the last major tectonic event in the Late Jurassic-Early Cretaceous. Cooling-age patterns are explained by preferential exposure of younger rocks at higher elevations through modest summit relief lowering or variable exhumation of the Hangay Mountains and central Mongolia that mainly occurred during the initial post-orogenic phase in the Cretaceous. “Total exhumation” rates that combine relief change and isostasy with the background rates are on the order of 4-16 m/My. One could instead argue that relief lowering, recent surface uplift accompanied by some amount of erosion could produce similar age patterns however there is no evidence to support a Cenozoic history involving accelerated, high-magnitude (>1-2 km) erosion of the Hangay. Moderately higher erosion rates from basalt age data are only found in isolated cirques and glacial valleys (river headwaters regions), or valleys that have experienced local base-level changes due to Cenozoic basalt emplacement.

The suturing of Mongolia and collision with the Siberian craton created high mountain peaks in central Mongolia in the early Mesozoic, which eroded rapidly through the Cretaceous. The peaks were heavily eroded and subsequent uplift drove the creation of regional relief during the Cretaceous (setting our AHe ages) followed by minimal exhumation since that time. This allowed the landscape to remain as an erosional remnant throughout the Cenozoic. In either case, an important conclusion is that relief was rapidly changed to within 10% of the modern relief by ca. 100-85 Ma. Erosional proxies in the form of detrital cooling ages agree to first-order with thermo-kinematic models and indicate extended, low erosion since the end Mesozoic and that Jurassic-Early Cretaceous paleo-relief may have been modestly greater than the present in the western Hangay. Holding the current landscape geometry fixed through time, the current approximated mountain relief of the Hangay is approximately 2500 m, which would be approaching 4000 m in the Mesozoic using the modeled paleo-relief relative to current elevations. Relief 50-60% greater than the modern value would produce ancient elevations in the Hangay >5000 m at the highest peaks, roughly on par with the modern Tian Shan to the southwest.

Exhumation rates estimated from Pecube inversions suggest a period of moderate exhumation in the Early Cretaceous followed by low rates of ~4-16 m/My since that time. This history agrees with shorter-term cosmogenic estimates of erosion and implies that the Hangay have been subject to a long regime of very slow erosion, similar to other old orogenic landscapes, such as the Appalachians in the eastern USA [e.g. *McKeon et al.*, 2014]. The high-elevation regions of the Hangay have experienced topographic rejuvenation because of recent enhanced erosion from alpine glaciation that is minimal in magnitude and regional extent (supplement fig. S2).

In summary, thermochronological evidence provides support for either minor high-elevation peak relief loss or formation of the central Mongolian landscape in the Mesozoic through variable exhumation and relief change subsequent to Late Jurassic through Early Cretaceous tectonism associated with terminal Mongol-Okhotsk suturing. During the Cretaceous there was a phase of relief evolution completed by ca. 100-85 Ma followed by minor erosion since the Oligocene due to regional “doming,” glacial cirque cutting, and fluvial incision (i.e. valley cutting leaving non-dissected plateau remnants). There is no evidence for Cenozoic compressional deformation in the Hangay and limited normal faulting, which suggests that the modern landscape was formed in two main stages, with the second stage being entirely epeirogenic. All of the other regional Asian mountains are dominated by horizontal tectonic forces, (e.g. transpressional: Altai, Gobi Altai, eastern Tian Shan; transtensional: Transbaikalia, Longshan, etc.; [*Cunningham*, 2013; Cunningham, 2017]), while the Hangay are not. The Hangay Mountains may be tectonically unique due to the Archean basement that is exposed and underlies much of central Mongolia, which may be important in terms of long-term stability and preservation of the landscape. Remnant landscapes may persist over hundred million year timescales if the landscape is built upon old, rheologically strong lithosphere that may respond to vertical forces but resist or focus horizontal tectonic stresses creating deforming belts around their margins.

7. Conclusions

The termination of the Mongol-Okhotsk orogeny in the Cretaceous and synchronous rapid relief change produced the observed pattern of progressively older cooling ages away from the highest topography of the Hangay Mountains. Bedrock apatite (U-Th)/He age spatial patterns in the Hangay Mountains are reinforced by detrital (U-Th)/He ages and indicate <1-2 km of exhumation since the Cretaceous, while detrital age distributions and geomorphic relationships suggest that current elevations between ~1600-1800 m at the Hangay margins are the current focus of incision across the landscape. A regional Pecube forward model suggests the landscape was heavily eroded through the Jurassic, followed by subsequent uplift and exhumation that drove creation of topography and was completed by the end of the Cretaceous. This is in agreement with other published data that suggest some amount of regional relief planation in the Mesozoic followed by topographic rejuvenation. Pecube thermo-kinematic inversions and detrital age modeling suggests western Hangay paleo-topographic relief was between ~10-70%

greater than the modern relief in high elevations and that total exhumation rates have been up to 16-17 m/My since the late Mesozoic. The magnitude of relief loss in Pecube model inversions is highly correlated with the timing of the shift to very low exhumation rates, with more extended high-rate periods (i.e. delayed exhumation rate change) requiring minimal relief loss. We prefer conservative model predictions towards the middle to lower end of this range due to complexity arising from the combined effects of isostasy and relief change. Relief has presumably been stable throughout the Cenozoic due to high aridity, with a modest amount of surface uplift probably occurring in the Oligocene-Miocene. The Hangay Mountain landscape is an old feature that has recently undergone surface uplift of a few hundred meters, which locally imprinted a younger, more dramatic landscape through glacial cirque cutting in the highest topography. This mountain belt is an excellent example of a relict erosional landscape and demonstrates that mature topography can endure for prolonged periods when there is little forcing from tectonics, climate, or surface processes.

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FIGURE CAPTIONS

Figure 1: Regional map showing areas of high topography within Mongolia and southern Russia. The mean elevation in this view extent is 1500 ± 563 m and shows that the Hangay, Khövsgöl, Khentiyn, and Sayan Mountains (Russia) are a region of long-wavelength, high topography that has been dissected by the Selenga River network that drains the northern flank of the Hangay into Lake Baikal. Note that the deformation patterns vary regionally, i.e. the strong, large fault control in the Altai versus the diffuse, smaller faults of the Hangay. The dark brown line denotes the 1500 m topographic contour. Regional fault systems are also shown; the sinistral Bulnai (BF) is the major strike-slip fault north of the Hangay separating the Sayan/Khövsgöl from the Hangay. The Mongolian (MA) and Gobi Altai (GA) ranges south of the Hangay are within a major transpressional fault system. The Siberian craton margin begins just north of the Sayan Mountains in the < 500 m elevation region (green) near the Mongolia-Russia border and Lake Baikal at ~53ºN latitude. Blue lines are major permanent streams draining higher elevations and the red line denotes the Selenga River system drainage divide. Heavy white line is Mongolian political border. Green dashed line is approximate Mongol-Okhotsk Ocean suture after *Van der Voo et al.* [2015]. Yellow star is Ulaanbaatar, the capital city. (MA=Mongolian Altai; GA=Gobi Altai; DL=Depression of Lakes; VL=Valley of Lakes; HM=Hangay Mountains; LK=Lake Khövsgöl; KM=Khentiyn Mountains; SM=Sayan Mountains; OR=Orkhon River; SR=Selenga River; LB=Lake Baikal; SB=Selenga basin). Major towns in Hangay region shown on figure 2.

Figure 2: The eastern Hangay Mountains and major rivers (blue lines) with high elevation areas glaciated in the LGM shown in gray. River incision estimates at locations (triangles) from basalt age data presented in *Ancuta* [2017]. Numbers shown are in incision rates in m/My. Circled area in the southeast is the headwaters of the Orkhon River. Gray triangle is the Orkhon waterfall location (Ulaan Tsutgalan). Photo on the right shows a canyon location along the Orkhon River, at lower elevations in the Selenga River

basin, where the higher incision rates (~58 m/My) are due to local basalt flow damming (~180 m total thickness) over the past 3 m.y. Red dots mark major towns in the area. B = Bayankhongor; J = Jargalant; T = Tariat; Tg = Tsetserleg; Ts = Tosontsengal. Photo: The contact between granitic basement and the basalt flows is shown by the red line in the photo. Apatite (U-Th)/He sample 12MN09 is from the granite bedrock [mean (U-Th)/He age of ~325 Ma].

Figure 3: Imagery showing the regional topography near the highest Hangay peak, Otgontenger Uul (triangle). The areas outlined in white are the ELA for the LGM at 2800 m elevation. The image below is of the same area as above but showing elevations >2800 m (gray area is <2800 m) and areas with slopes ≤5° (orange). Enlarged digital elevation model (DEM) inset (top right, looking 240° at 20° inclination) shows example of high elevation relict planation surface and associated cryoplanation features east of Otgontenger. Bottom panel is a slope map of another such area to the south with a flat, relict surface and cryoplanation terraces. See *West et al.,* [2013] for other examples.

Figure 4: **(A)** Hypsometry of the Selenga and Orkhon River sub-catchments sampled for detrital AHe (see figure 5 for locations; section 5 for discussion). **(B)** Schematic diagram illustrating the relationship between detrital thermochronometer data and the hypsometry of a catchment given an assumed positive age-elevation relationship where cooling ages should match the hypsometric curve if erosion is uniform, i.e. all points on the topography produce cooling ages that correspond to the basin AER. If there is non-uniform erosion, then the elevations on the landscape contributing sediments will affect the SPDF curve accordingly, modified after *Stock et al.* [2006].

Figure 5: Granitic-bedrock mean AHe ages across the Hangay Mountains and north-central Mongolia colored by age. The majority of cooling ages in the Hangay are ca. 100-120 Ma, with a slightly younger grouping <100 Ma on the north flank (red/white center). Off the Hangay, ages are similar, albeit with greater scatter and an older component greater than ca. 120 Ma. Detrital sample locations are shown as diamonds (mean age in italics). The red line shows the Selenga watershed and sub-catchments with respect to detrital samples for the Selenga and Orkhon are the orange lines. Points tagged in yellow are AHe/AFT transect (W) of *West et al.* [2013] shown in blue diamonds, transect (L) of *Landman* [2007] near Egiin Davaa, and transect (T) discussed with figures 7 and 8. OT = Otgontenger Uul. Grayscale 90 m DEM with 1700 m contour to mark higher elevations above the regional background and onset of ‘regional knickpoint elevation zone’ discussed in text and with fig. 7. Glaciated high elevations areas shown in cyan blue, derived from the ELA during the LGM from *Lehmkuhl* [1998]. Major faults from *Tomurtogoo* [1999] geologic map of Mongolia shown by heavy black lines. See supplement for full age dataset.

Figure 6: Selenga and Orkhon River detrital apatite (U-Th)/He cooling age populations shown by kernel density estimator (KDE) (smooth, gray envelope) and probability density functions (PDF) (shaded blue) from DensityPlotter [*Vermeesch*, 2012] using a Gaussian kernel and adaptive bandwidth (varied based on local data density). White dots show individual grain ages for the datasets. The y-axis is number of grains.

Figure 7: **(A)** Normalized CSPDF curves of Selenga detrital ages (dashed lines, t*) and catchment elevations (solid line, z*) for the Selenga River, using 95% and 99% of the detrital dataset, after *Ruhl and Hodges* [2005]. **(B)** SPDF curves for normalized age (gray) and elevation (solid black line) distributions with inset age and elevations (upper right). Dashed line in (B) is the ‘ideal’ age SPDF obtained from inverting the observed age SPDF and hypsometric curves with respect to the regional AER from the northern Hangay (figure 5, transect labelled T). Small inset panels show ages for 95% of the detrital AHe dataset and the elevations in the Selenga sub-catchment and red shading shows the dominant mismatch in age/elevation from the ideal age SPDF, see text for details.

Figure 8: Apatite AERs (left panel) from the western Hangay near Otgontenger (highest peak; figs. 3 and 4) incorporating a short transect from this study and from *West et al.* [2013] and *Landman* [2007] datasets (see fig. 5 for transect locations). Positive AERs suggest valley-scale topographic wavelengths do not affect low-T isotherms. Right panels show AFT and mean fission-track lengths (MTL) for *Jolivet et al.* [2007] and *West et al.* [2013] datasets. Planation surfaces in the Gobi Altai, Valley of Lakes, and W. Hangay (gray) are all similar in age suggesting regionally coincident exhumation and that highest elevations are preserved remnants from an older event. *West et al.* AFT transect suggests the period between ~180-130 Ma being governed by a moderate exhumation rate. Our rates and those published on the right are for the AHe transects and overestimate the true exhumation rate.

Figure 9: Pecube-NA sensitivity test of variables controlling relief to assess the ability to resolve relief change in this type of slow exhumation setting. For tests, a two-phase exhumation scenario was used with fixed rates of 100 m/My and 30 m/My. **(A)** Sensitivity test for *relief amplitude-only* showing least-squares misfit and relief amplitude between 0 (no relief) to 2 (two times modern relief) with a defined misfit minima at the true value of 0.5X the modern relief in the Hangay. **(B)** Misfit evolution over the sensitivity test inversion where τ, R, and E-timing are allowed free, exhibiting optimal convergence after >6000 models. **(C)** Correlation matrix for the free inversion parameters using NA-plot [*Sambridge*, 1999b]. Values approaching (-1)+1 show greater (anti)-correlation while values near 0 show no relationship or dependence. Erosional timescale and relief amplitude are highly anti-correlated, while both the exhumation rate change timing and relief amplitude have a slight positive correlation with erosional timescale. These trends can also be seen in the PPDFs in panels D to F. **(D-F)** Scatter plots showing misfit between τ, *R* and E-timing, the 2-D PPDF 1σ (solid) and 2σ (dashed) contours shown as overlays and the corresponding 1-D marginal PPDF curves for each parameter on the corresponding axes. In each case the star marks both the 'true parameter value' and in this case, the respective lowest misfit of the 1-D PPDF, which in this synthetic example is also the mean or modal value.

Figure 10: Pecube-NA inversion results for Run 1-TSW. Scatter plots are 2-D projections of the 5 dimensional parameter space on planes defined by combinations of two parameters. 1-D posterior curves show probability density within the parameter search range. See supplementary material for additional plots of other variables. Each dot represents a forward model from the inversion and is colored by the χ^2 misfit value. Stars denote the lowest misfit model while heavy/thin black lines are 1σ (67% confidence) and 2σ (95% confidence) errors, respectively. Bottom middle panel shows misfit evolution and convergence during the inversion and the bottom right shows the correlation matrix between difference parameters between -1 to +1 signifying strong (negative) anti-correlation or positive correlation, with values near zero having no relationship. Pecube physical modeling domain shown in fig. 13 inset box, see text for discussion.

Figure 11: Pecube-NA Run 1-C inversion results for 9504 models. The same figure scheme as figure 9. The difference between Run 1-TSW is that the exhumation rate change timing is allowed free in this inversion.

Figure 12: **(A)** Contoured age map (5 Ma interval) of Pecube-NA Run 1-TSW in the western Hangay (see fig. 13 for location, inset box). Locations of samples are circles with mean ages shown, ages in red are multi-grain aliquots from *West et al.* [2013]. Note that single grain ages were used in the inversion. Single grains shown in panel D. **(B)** Plot showing how topography changes in the model according to equation 6. Our model inversion 1-TSW exhibits highly positive best-fit values for τ, suggesting relief decayed rapidly and was ≥90% of the modern relief by ca. 100-85 Ma. **(C)** A plot of single-grain AHe ages with respect to eU for a few samples in the modeling domain. The Pecube model predictions (stars) are fairly consistent with observed age-eU patterns. **(D)** Observed and predicted cooling ages and corresponding elevations are in good agreement except mainly at the highest elevations which are derived from Pecube forward models using our best-fit or maximum likelihood values from the model inversion.

Black circles are observed single-grain age replicates with errors, while squares are predicted cooling ages. **(E)** 1-to-1 line for predicted vs. observed cooling ages; gray squares are AFT samples. **(F)** observed versus predicted elevations using best-fit 1-TSW inversion relief scenario in Pecube forward model.

Figure 13: Pecube forward model age predictions using inversion run 1-TSW best-fit parameter values with the main exhumation stage from 150-130 Ma after *West et al.* [2013] model thermal history. Inset box shows location of western Hangay bounds used in Pecube-NA inversion. Regional forward models are resampled at 10 km to smooth ages and are shown with a 5 Ma contour interval. (Top left) Elevations from 90m SRTM DEM (2000 m elev. contoured) with white dots showing sample locations used in Pecube modeling of the entire Hangay, (top right) the ages predicted by the best-fit model results of inversion 1-TSW shown in table 1 (Te = 6.1 km). Other panels show the effects of varying the effective elastic thickness (Te) while holding all other best-fit variables constant.

Figure 14: Pecube forward model results for a planation surface and carving of topographic relief **(A)** The model starting condition for topography is a high plateau at the highest modern elevation (slightly lower than actual due to grid resampling). See elevation scale in panel B. **(B)** The end of the model run showing the modern topography. This relief was created using an erosional timescale of 930 My, which created the modern topography (within 90%) by 100-85 Ma. Note: although difficult to see, there are remnant surfaces (red) at highest elevations in panel B. **(C)** The predicted AHe age map across the region. Ages are best predicted in the Hangay but suggest younger ages outside of the Hangay, which is not in total agreement with real AHe data. Circles are the locations of real data used in the model **(D)** The predicted exhumation rates over the single time step with two phases of exhumation using the best-fit values from inversion 1-TSW. The rates are spatially variable and show no erosion at highest peaks and more focused/higher exhumation in the incised topography. Exhumation rates are on par with previously mentioned long-term estimates and inversion results between 4-16 m/My. **(E)** The observed and predicted single-grain AHe ages going from west to east in panel C showing a good match (also refer to fig. 5 for AHe age reference). The MSWD model misfit is 0.92 between observed/predicted and shaded gray denotes single-grain age outliers. **(F)** The observed and predicted elevations for a 'planation surface' exhumation model displaying excellent correlation (R^2=0.92) and suggesting the exhumation/relief evolution model is viable at orogeny-scale. Line is 1-to-1 for reference.

Table 1: Fixed model parameters used in Pecube inversions to calculate the isostatic and thermal response to varying relief.

Table 2: Pecube-NA inversion results for sensitivity test and full inversions. Values separated by a colon are the prior search ranges during the NA sampling stage while those in bold are the best-fit parameter values (lowest misfit). Mean and standard deviation represent the resampling results from the NA appraisal of the model ensemble. R = relief amplitude; τ = erosional timescale; E-timing is the time of exhumation rate change; E_1 and E_2 = exhumation rate 1 and exhumation rate 2. See text for details.