Earth Surf. Dynam. Discuss.,
https://doi.org/10.5194/esurf-2020-59-RC2, 2020

Earth Surface Dynamics Discussions

ESurfD

Interactive comment

Interactive comment on "Bias and error in modelling thermochronometric data: resolving a potential increase in Plio-Pleistocene erosion rate" *by* Sean D. Willett et al.

Anonymous Referee #2

Received and published: 5 October 2020

1 Overview

Willett et al. (present study; *W+PS*) argue that the analyses and conclusions of Herman et al. (2013; *H+13*) remain valid, despite the critiques of Schildgen et al. (2018; *S+18*) and Willenbring and Jerolmack (2016; *WJ16*).

But what is the conclusion of Herman et al. (2013)? Is their conclusion that some mountainous, glaciated regions were exhuming faster between 0-2 Ma compared with 4-6 Ma? Is their conclusion that most glaciated mountains were exhuming faster between these times? Most mountains? Or that there was a net increase in erosion rates globally?

The central argument of *H+13* / *W+PS* is that several regions have yielded low-T thermochronology data which support high-resolution reconstruction of exhumation from 6 Ma to present. When binned in 2 Ma intervals, these reconstructions show increased exhumation rate between two time periods, 4-6 Ma and 0-2 Ma, an increase coincident with the onset Northern Hemisphere glaciations.

2 Schildgen et al., 2018 critique

S+18 argued that erosion rate increases at these 'high-resolution' sites were often spurious, the result of *H+13* inadvertently grouping samples with very different geomorphic or tectonic histories. For example, a 20 Ma apatite (U-Th)/He (hereafter 'AHe') age taken from atop a plateau might constrain the "long term" exhumation rate, while a 1 Ma AHe age from a glacial valley bottom constrain the more recent exhumation rate. Even if the plateau and valley were eroding at different but constant erosion rates, they could be accidentally combined to calculate a shared exhumation history. The outcome of this 'spatial correlation bias,' *S+18* argued, was an apparent but false increase in erosion rate.

W+PS counter that the inversion routine of *H+13* (GLIDE; Fox et al., 2014) does not suffer from this effect. First, samples may only pass through the cooling temperature of each thermochronometer once and therefore disparate ages from the same thermochronometer cannot be grouped by GLIDE. Second, when low-T thermochronology data are simulated for a rapidly uplifting block adjacent to a slowly uplifting footwall, both rapid and slow exhumation are correctly inverted for and no spurious acceleration is observed, even though the rapid block has better calculated resolution. Finally, *W+PS* argue that *S+18* incorrectly compared ages from simulations with a fixed basal temperature (Pecube) and with a flux basal temperature (GLIDE). This mistake, *W+PS* argue, accounts for the false increase in exhumation rate presented by *S+18*.

3 Willenbring and Jerolmack, 2016 critique

WJ16 argued that the methodology of *H+13* is biased because only sites with rapid exhumation will precisely resolve a recent change in exhumation. Even if GLIDE perfectly identifies regions where thermochronology ages resolve a recent increase in erosion rate (a point contested by *S+18*), there will be many regions which have experienced constant or lower erosion rates that are cannot be resolved and are therefore under-represented.

In order to be collected, rocks must exhume up through the crust to Earth's surface after passing through the relevant closure temperatures at depth. The time required for this transit imposes a limit on which erosion rates can be measured across Earth's surface for any given time interval. Critically, the minimum resolvable exhumation rate for a given thermochronometer increases nonlinearly toward the present and the distribution of measurable erosion rates becomes increasingly truncated. *WJ16* argue that this effect biases the analyses of *H+13*, that any apparent increase in erosion rate toward the present actually signifies a progressive clipping of the measurable erosion rates for a given time interval.

W+PS mention this critique but grossly misrepresent the *WJ16* argument. Here is the original *WJ16* argument:

> "[W]e plot a variation of an idea of Anders et al. (1987) that describes two clipped distributions of sedimentation rate data both in the maximum depth of a population sampled and in the precision possible for the youngest ages. . .the conceptual analogy is useful."

and

> “The essence of the argument is that slower rates of exhumation are progressively clipped from the measured age distribution of rocks as one approaches the modern because of the precision of the technique. The reason is that thermochronometers measure the time since achieving an associated closure depth; rate is simply the measured time divided by this depth. If erosion rates have not been high enough to bring rocks to the surface, the rates associated with those buried rocks cannot be measured.”

And here is the response to this critique in *W+PS*:

> “. . .Willenbring and Jerolmack (2016) misinterpreted the meaning of the limit to resolution, or what they called “precision”. They took this concept from measurements of sediment layer thickness [the ‘idea of Anders et al., (1987)’ referenced in *WJ16* argument above], which can be biased by the inability to measure layer thicknesses below a specific precision (Anders et al., 1987).
>
> “Thermochronometric data are fundamentally different in that an age does not represent an estimate of rate at a point or across a closed interval of time such as represented by a stratigraphic layer, but rather, represents the integral of the exhumation rate. . .from the time of closure to the present day. Thus, rather than being unsampled, the region [from the youngest closure age until present] is actually the most heavily sampled part of parameter space. The better definition of the “limit to resolution” is that no change of exhumation rate can be resolved between this limit and time zero, because there is no sampling internal to this part of the parameter space, but the average rate across this interval is sampled and can be determined.”

This response misconstrues the legitimate criticism raised by *WJ16*.

More troubling, this limitation of only having access to rapid exhumation measurements for the time period in question (0 - 2 Ma) is never dealt with in a systematic way later in the manuscript. Given that GLIDE will assign high resolution values when “the time interval is resolved in the neighborhood of the point of interest” and will lower resolution values when “contamination enters from the other time intervals,” it is unsurprising that the regions for which there is good resolution since 2 Ma are largely regions which are exhuming very rapidly.

4 Sensitivity analysis

What remains to be demonstrated is whether the methodology of *H+13* / *W+PS* could resolve constant or decreasing erosion rates within a synthetic test. The analyses in Section 4 of *W+PS* indicate that constant but spatially distinct long-term erosion rates can be resolved, but similar tests are not provided for a recent change in exhumation rate.

If not all possible recent changes in exhumation can be resolved by the *H+13* / *W+PS* methodology, we are left with the original question of how to interpret the *H+13* observation that some regions appear to exhume faster during 0 – 2 Ma compared with 4 – 6 Ma. Presumably, some regions have also recently experienced slower exhumation and some have remained constant. Within even a single orogen this seems plausible.

5 The problem of still buried rocks

ll. 185-189. “[I]f one regresses age against depth (Figure 2d) with a moving depth window, one obtains the correct, unbiased regional mean erosion rate (Figure 2e, Average

1)."

This statement and the corresponding figure, *W+PS* Fig. 2d (reproduced here in Fig. 1), neglect the fact that a significant portion of rocks which passed through the closure depth after a recent change in exhumation rate will not yet have reached Earth's surface. *W+PS* Fig. 2d illustrates only a special case, where erosion is spatially varied but constant through time. This is unfortunate and misleading, because the question at hand is whether transient erosional signals (i.e., the onset of Northern Hemisphere glaciations) can be measured (in the midst of spatial variability).

If an instantaneous change in exhumation rate occurred recently, it will only be observable if rocks: a) began beneath the closure depth and b) were exhumed from that depth to the surface to be collected. This exhumation distance imposes a limit on which recent exhumation rates can be measured (Fig. 1).

The following thought experiment crudely estimates the magnitude of this 'still buried rock' bias effect (Fig. 2). *H+13* evaluated the difference in global erosion rates between the time periods of 4 – 6 Ma and 0 – 2 Ma. So, it is useful to consider what would happen if global erosion rates changed significantly and instantaneously at 2 Ma. Apatite (U – Th)/He is the lowest temperature system considered in *H+13* and would close at a depth of approximately 2 km, depending on the local exhumation rate and geothermal gradient. At 2 Ma, all rocks below this closure depth would begin their ascent according to the new surficial erosion rate. Therefore, a geologist collecting surficial samples today could only possibly collect samples which rose at a rate of (2 km) / (2 Ma) or greater. All other rocks would still be buried. This effect is illustrated in Fig. 2 for a range of times at which erosion rates could have instantaneously changed.

Extending this exercise, we could assume that if global erosion rates changed 2 Ma, they became similar to erosion rates observed today, a reasonable null hypothesis (whether global erosion accelerated or decelerated is immaterial for the exercise).

A global compilation of cosmogenic 10Be erosion rate estimates by Portenga and Bier-

Printer-friendly version

Discussion paper

man (2011) can serve as a primitive estimate of how global erosion rates are distributed today (Fig. 2). (Obviously, there are many caveats to this simplification, but the broad range of erosion rates represented and the relative rarity of erosion rates greater than 1 km/Ma should be uncontroversial.) In this scenario, only a small fraction of rocks from that 2 Ma erosion rate change would have travelled to the surface. The large majority would still be in transit.

From this exercise, two observations stand out. First, only terrains experiencing very rapid exhumation will inform the thermochronology record of erosion rate changes at 2 Ma. Second, it is much more likely to observe accelerations in exhumation than to observe constant or decelerating exhumation. To avoid confusion, note the following distinction. The approach of *H+13* / *W+PS* will register low erosion rates during the period of 2 Ma to present owing to old AHe and AFT ages (how 'resolved' low rates are depends on the GLIDE algorithm). What the *H+13* / *W+PS* approach will not register, however, are any decelerations down to rates below about 1km/Ma.

We must take as a null hypothesis the idea that global net erosion rate change was zero from 6 Ma until present. For the reasons outlined above, it is my view that the *H+13* / *W+PS* methodology is inherently incapable of resolving unchanging net erosion rates globally. The authors have not taken seriously this critique, initially outlined in *WJ16*, and have not demonstrated their ability to resolve a constant erosion rate or a decreasing erosion rate.

Figure captions

Fig. 1: *W+PS* Fig. 2d (left panel) is meant to illustrate that one can obtain an unbiased estimate of regional erosion by regressing cooling rates as a function of closure depth (rather than as a function of time). On the right-hand panel, it is shown that, even when regressing against closure depth, apparent cooling rates are inherently biased owing

to the fact that rocks exhuming below some minimum resolvable cooling rate (dot-dash line) will not be exposed at Earth's surface.

Fig. 2: For a closure depth of 2 km, approximate to apatite (U-Th)/He, the minimum resolvable exhumation rate is shown for an erosion rate change some time before present. For reference, these rates are compared with a global compilation of erosion rates from the CRONUS database, as presented by Portenga and Bierman, 2011 (right-hand panel). For example, if at 2 Ma (star), global erosion rates changed to the distribution shown on the right, only a small fraction of these rates would be represented at the surface within 2 Ma (shaded region); the majority of erosion rates would be 'archived' within rocks still in transit to the surface.

Interactive comment on Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2020-59, 2020.

Printer-friendly version

Discussion paper

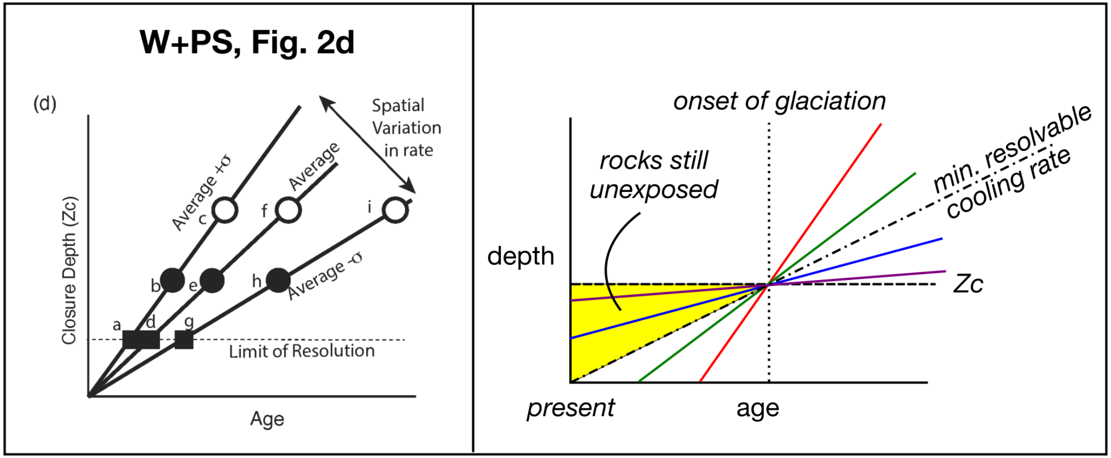
W+PS, Fig. 2d
(d)
Spatial
Variation
in rate
Average +σ
Average
Average -σ
Closure Depth (Zc)
Limit of Resolution
Age
onset of glaciation
rocks still
unexposed
min. resolvable
cooling rate
depth
Zc
present
age

Fig. 1.

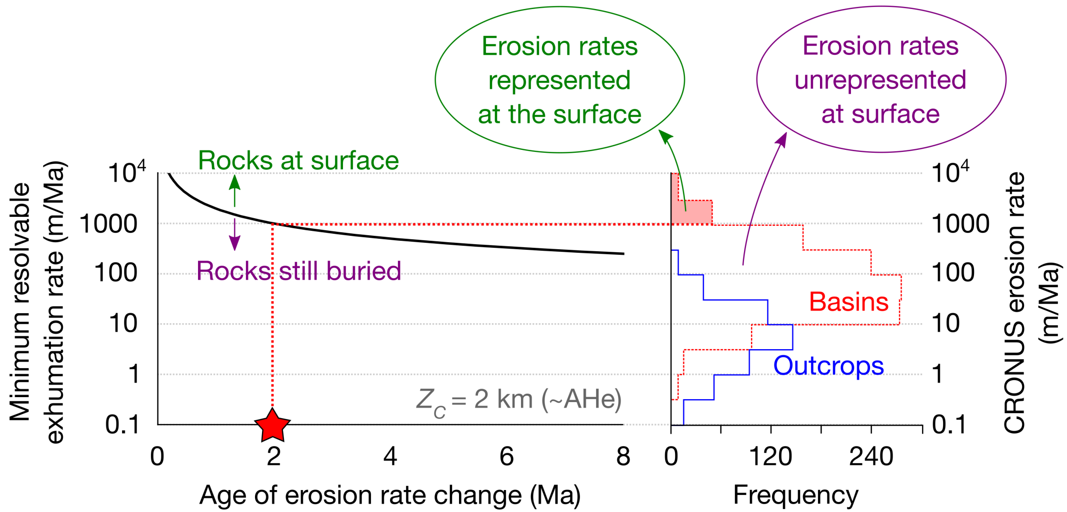
Erosion rates represented at the surface
Erosion rates unrepresented at surface
Rocks at surface
Rocks still buried
Basins
Outcrops
Z_C = 2 km (~AHe)
Minimum resolvable exhumation rate (m/Ma)
CRONUS erosion rate (m/Ma)
Age of erosion rate change (Ma)
Frequency
10^4
1000
100
10
1
0.1
0
2
4
6
8
120
240

Fig. 2.