



EFEL 1.0: An integrated set of components for Landlab to simulate landscape evolution from fault creep, earthquakes, and coseismic landslides

Adam M. Forte¹

¹Department of Geology & Geophysics, University of Louisiana, Baton Rouge, LA

Correspondence: Adam M. Forte (aforte8@lsu.edu)

Abstract. I present a suite of new numerical model components for use with Landlab, collectively the *Elastic Fault, Earthquake, and Landslide (EFEL)* model that enable users to simulate surface deformation related to both interseismic creep and seismogenic events on faults of variable geometry and include the effects of coseismic landslides. The surface deformation from either interseismic creep or individual earthquakes are simulated as discrete, rectangular dislocations within an isotropic, linear elastic half-space. The location of coseismic landslides are determined through the implementation of several different empirical ground motion prediction equations coupled with a Newmark style sliding-block analysis. Used together, the components allow for the generation of either dipping or vertical faults of variable geometries with independent kinematics, the generation of earthquake catalogs with varying levels of complexity for simulating surface deformation, and coupling these with existing Landlab libraries for simulating surface processes. I present a variety of examples using these components, including landscape evolution above both an aseismic and seismogenic shallow dipping thrust fault, considered without and with coseismic landslides, landscape evolution above both aseismic and seismogenic simple high angle normal faults and listric normal faults, and landscape evolution along both aseismic and seismogenic strike-slip faults with or without a restraining bend. These components fill an important gap within existing Landlab libraries, and landscape evolution models more broadly, providing a prepackaged method for users to simulate complicated deformation of single-fault systems in concert with surface processes.

1 Introduction

Topography developed in actively deforming regions can encode details of the driving tectonic rates, structural geometries of responsible faults, and even aspects of the seismic hazard of the underlying fault systems (e.g., Kirby et al., 2008; Kirby and Whipple, 2012; Whittaker, 2012; Ellis and Barnes, 2015; DeLong et al., 2017; Pavano, 2025). However, in many cases, the way in which we interpret, and in turn numerically simulate, the evolution of tectonically active topography do not capture many of these details that we expect to be important in controlling landscape evolution. Specifically, the representation of the underlying tectonic driver of surface deformation, which is in most cases reflects a mixture of interseismic creep, coseismic slip, and postseismic deformation occurring on faults (e.g., Segall, 2010; Avouac, 2015), are instead often simplified to vertical block uplift at constant rates or spatially and/or temporally variable vertical uplift rate functions (e.g., Shikakura et al., 2012;



25 Gasparini and Whipple, 2014; Forte et al., 2015; Adams et al., 2016; Yuan et al., 2022; Zhang et al., 2026; Wang et al.,
2026). A more limited set of studies have emphasized the importance of including semi-realistic fault geometry and/or lateral
advection when simulating landscape evolution in tectonically active settings, (e.g., Miller et al., 2007; Goren et al., 2015;
Duvall and Tucker, 2016; Gray et al., 2018; Harbert et al., 2018; Hoskins et al., 2023; Eizenhöfer et al., 2019; Aránguiz-Rago
et al., 2025), but still have largely considered what amounts to steady-creeping faults, i.e., making the explicit assumption that
30 earthquakes, or the seismic cycle more broadly, is not necessary to simulate to understand landscape evolution. At the same
time, a growing variety of results highlight that various aspects of the seismic cycle could impact the evolution of topography,
for example through "incomplete seismic cycles" wherein there are long-term mismatches between interseismic and coseismic
deformation (e.g., Meade, 2010; Simpson, 2015), the extent to which rheology related to the seismic cycle plays a critical role in
landscape evolution (Baden et al., 2022; Oryan et al., 2024), or more indirectly through the importance of coseismic landslides
35 in long-term erosional process of tectonically active regions (e.g., Li et al., 2014, 2019; Marc et al., 2019; Croissant et al.,
2019; Wang et al., 2020).

Recognition of the potential for individual earthquakes summed over geologically relevant time periods to impart more
nuanced landscape evolution has prompted a narrow set of efforts simulating topography driven, at least in part, by individual
earthquakes across a range of tectonic settings. Some of the pioneering efforts in this regard comes from Densmore et al.
40 (1998) and follow up work (e.g., Allen and Densmore, 2000; Densmore et al., 2003) using the 'ZSCAPE' model that simulated
landscape evolution related to earthquakes on a normal fault and where surface deformation from individual earthquakes were
treated as elastic dislocations in an isotropic elastic half-space (e.g., Savage, 1983; Okada, 1992) and that included simulation
of hillslope diffusion, bedrock landslides, and fluvial incision, but which did not consider interseismic fault creep, considered
relatively simplistic earthquake behavior, and did not explicitly model landslides from earthquake shaking. More recently, a
45 variety of efforts have considered aspects of landscape evolution driven by individual earthquakes, for example; the evolution
of single river profiles related to spatially and temporally variable earthquake ruptures on a thrust fault with interseismic creep
but with relatively simple treatment of surface deformation and where the surface processes portion was restricted to 1D fluvial
profile evolution (Steer et al., 2019), triangular facet evolution of normal faults through simple block punctuated slip along
a dipping fault (Tucker et al., 2020), or 2D landscape evolution of a strike-slip fault driven by individual earthquakes but
50 again which did not consider background interseismic creep and made a variety of simplifying assumptions with respect to
individual earthquakes (Reitman et al., 2019). Broadly, these efforts produce interesting results that highlight the potential
importance of directly simulating the long-term development of landscapes in the context of individual earthquakes, but are
often more "bespoke" implementations of landscape evolution models as opposed to easily adaptable tools and/or consider
overly simplified or idealized versions of the seismic cycle.

55 Here I build upon these prior efforts, specifically taking inspiration from 'ZSCAPE' (Densmore et al., 1998), and introduce
a set of components designed for use in Landlab (Hobley et al., 2017; Barnhart et al., 2020) to generate faults of variable
geometry and kinematics and simulate landscape evolution related to interseismic fault creep, earthquakes, and coseismic
landslides, collectively the *Elastic Fault, Earthquake, and Landslide (EFEL)* model. As with 'ZSCAPE', earthquake (and
interseismic) deformation in *EFEL* are simulated with elastic dislocations in an isotropic, linear elastic half-space, and identical



60 to 'ZSCAPE', use the solutions of Okada (1992) for these dislocations. The components within *EFEL* are fully integrated with
Landlab, and as such are able to take advantage of the wide array of existing surface process models within that library,
and are designed to simulate either dip-slip or strike-slip faults, filling an existing gap within Landlab in terms of providing
a mechanism for driving simulations with semi-realistic tectonics on a single fault-scale. In this paper, I present the theory
underlying the design of the various components included within *EFEL* and a suite of example simulations to highlight potential
65 uses of these new components.

2 Description of Model Components

The *EFEL* model described here is organized into a set of distinct Landlab components designed to both work with each other,
but also with other Landlab components taking advantage of the modular nature of the Landlab library (Hobley et al., 2017;
Barnhart et al., 2020). Specifically, there are two components for establishing fault geometry and kinematics and for calculat-
70 ing surface deformation resultant from constant fault creep, a component for generating quasi-realistic earthquake sequences
and calculating surface deformation resultant from individual earthquakes within these sequences, and a coseismic landslide
component that determines the expected location of landslides that then fails and routes material. The fault components can
operate independently from the other components described here, but the earthquake component requires an instance of one of
the two fault components and in turn the coseismic landslide component requires an instance of the earthquake component to
75 run.

Internally, surface deformation for both the fault and earthquake components are built around an implementation of the
3-dimensional analytical solutions for rectangular dislocations in an isotropic elastic half-space from Okada (1992) (e.g., Fig.
1) as implemented by Jolivet (2024) in *okada4py*, which additionally makes use of a method for making simple topographic
corrections for surface velocities from Langer et al. (2020). It should be noted that while the solutions of Okada (1992) as
80 implemented by Jolivet (2024) consider displacement resultant from dislocations that can have components of dip-slip, strike-slip,
and tensile motion, at present, the components in *EFEL* internally fix the tensile component to zero. Both fault components and
the earthquake component use the Landlab component *AdvectionSolverTVD* to use the horizontal components of the velocities
produced by the implemented elastic dislocation code to deform the topography and associated fields within a Landlab grid. As
described in the Landlab documentation, the *AdvectionSolverTVD* uses a total variation diminishing numerical finite-volume
85 method to solve the 2D advection equation. One advantage of the *AdvectionSolverTVD* is that it allows for surface deformation
to occur even when horizontal displacement over a time step is less than the grid resolution. Internally, the coseismic landslide
component uses the *BedrockLandslider* component (Campforts et al., 2020, 2022) to identify material that would be expected
to fail above "critical sliding nodes" and routing failed material through the landscape.

All components follow the suggested Landlab practice to have a primary "run_one_step" method that takes only a time step
90 length as an argument and is designed for use within a model loop. The outcome of the "run_one_step" method is different for
each component, but generally, for the fault component it calculates and applies surface deformation resultant from fault creep,
for the earthquake component it calculates and applies surface deformation resultant from earthquakes from a pre-generated

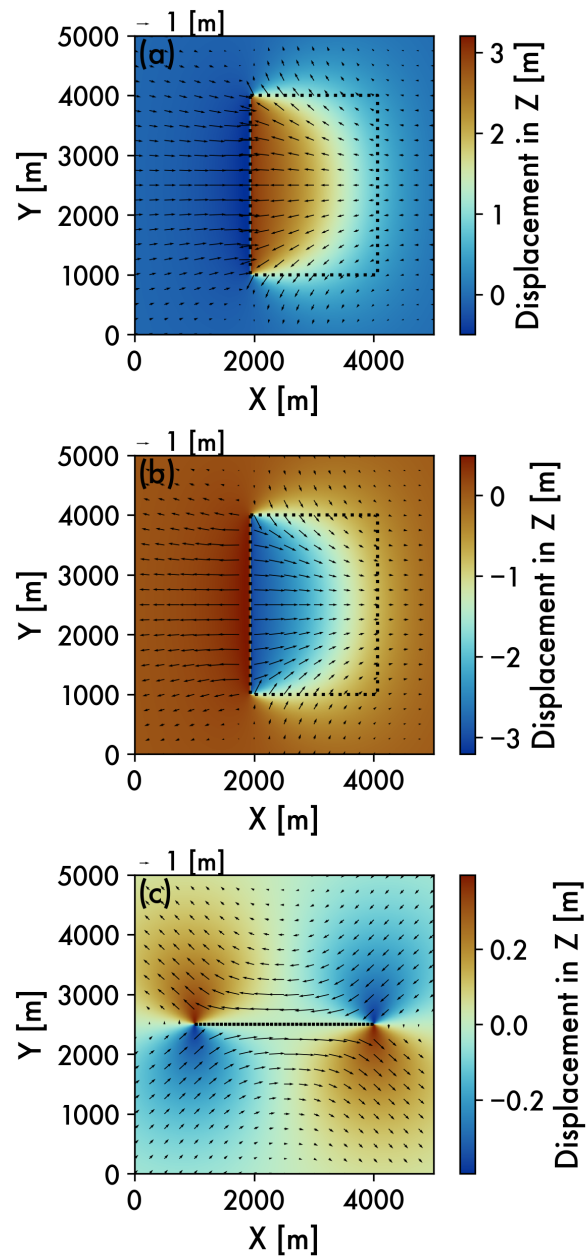


Figure 1. Example surface displacements from a rectangular elastic dislocation using *okada4py* (Jolivet, 2024). In all plots, black dotted line marks the outline of the dislocation projected to the surface and black arrows are horizontal displacement vectors scaled by magnitude. (a) Example surface displacements resultant from a 5 meter reverse-sense displacement on a 3 km x 3 km dislocation dipping at 45° to the east with a tip near the zero surface. (b) Example surface displacements with identical geometry for the dislocation as (a), but with a 5 meter normal-sense displacement. (c) Example surface displacement on a 3 km x 3 km vertical dislocation with a left-lateral sense displacement.



catalog that would occur during a given time step, and for the coseismic landslide component it identifies areas of potential failures and routes this material in the landscape. In the sections that follow, I describe the detailed behavior and design principles of each of the three component types.

3 Fault Components

The *EFEL* model includes two distinct fault components, *DippingFault* and *VerticalFault*, both of which allow for the generation of single faults and where a single fault is idealized as a set of rectangular planes that share one to two edges. A fault defined by an instance of the *DippingFault* component is constrained to having a single strike and constant fault length, and where by convention fault length refers to the dimension of the fault in the direction of strike, but which allows for an arbitrary number of fault panels with variable width and dip. Alternatively, a fault defined by an instance of the *VerticalFault* component is constrained to a dip of 90 and a constant fault width, where again by convention the fault width refers to the dimension of the fault plane in the direction of dip, but allows for an arbitrary number of fault panels with variable lengths and strikes.

The definition of kinematics of a fault instance is independent of its geometry, and for both types of fault components, the kinematics of the fault in question are defined by providing average rates of slip in the direction of strike and the direction of dip. This means that while geometrically one would typically consider faults generated with an instance of the *DippingFault* component to have either predominantly normal or reverse sense motion and faults generated with an instance of *VerticalFault* to have predominantly strike-slip sense motion, nothing in the model definition requires this and a user could prescribe pure strike-slip motion to a *DippingFault* instance or pure dip-slip motion to a *VerticalFault* instance, or combinations thereof, i.e., oblique-slip can be prescribed by providing non-zero components for both the dip- and strike-slip rates. I describe the details of the *DippingFault* component first and then highlight the differences between it and the *VerticalFault* component.

3.1 Dipping Fault Component

3.1.1 Fault Geometry

The definition of an instance of a *DippingFault* component and the associated fault geometry is referenced to the location of the center of the upper tip of the fault within the coordinate system defined by a provided instance of a Landlab grid. The user must provide an X, Y, and Z coordinate for this "tip location" where the X and Y coordinate are interpreted within the same coordinate system as the provided Landlab grid. Instances of *DippingFault* are not constrained to being within the Landlab grid, but surface deformation that results from motion on the fault (or from subsequent earthquakes produced by the related *EarthquakeSequence* component) will only be computed for nodes within the Landlab grid. The Z coordinate of this tip location is interpreted as the positive depth below a zero surface. Because of the nature of the underlying elastic dislocation models, this depth must be positive or equal to zero, i.e., a fault cannot be defined that goes above the zero surface. Single values define the fault length and strike, where the fault will extend in the direction of strike for half of the fault length from the tip location coordinate, i.e., the tip location defines the center of the upper tip line of the fault. While an instance of *DippingFault*



can only have a single length and strike, the user can define an arbitrary number of "panels" of the fault with variable widths
125 and dips as two separate lists provided upon instantiation. These lists of dips and widths are interpreted in the context of the
right-hand rule, i.e., the fault will dip in the direction to the right of the strike line if facing the azimuth provided as the strike,
and sequentially, i.e., the first set of widths and dips will define the upper most panel of the fault and so-on.

3.1.2 Fault Kinematics

The simplest version of an instance of *DippingFault* assumes a single slip-rate across the entire fault surface. Slip-rates and
130 kinematics are parameterized via a magnitude of strike-parallel motion and a magnitude of dip-parallel motion. The component
follows the conventions within the underlying elastic dislocation implementation (Jolivet, 2024) such that positive values
for dip-parallel slip will produce reverse-sense displacement, negative values for dip-parallel slip will produce normal-sense
displacement, positive values for strike-parallel slip will produce left-lateral-sense displacement, and negative values for strike-
parallel slip imply right-lateral-sense displacement.

135 To provide added realism, when instantiating an instance of *DippingFault*, the user can specify one of several slip-rate
functions that define how the slip-rate should vary along-the fault length. The default behavior is a boxcar function which
implies constant slip-rate along the fault length, but parabolic, triangular, blunt parabolic, and blunt triangular functions are
also defined within the component (Fig. 2). For all but the boxcar, the slip-rate effectively goes to zero at either end of the
fault in the strike direction, however, because motion on the portion of the fault that is creeping, defined in more detail in
140 the following section, is still simulated as a rectangular dislocation with constant magnitude of slip, for any of the slip-rate
functions besides the boxcar it is necessary to discretize the smoothly varying slip-rate function into a set of equal width
rectangles. As such, the "patches" of the fault at the lateral tips of the fault will still generally have non-zero effective slip-rates,
meaning that in practice, slip-rate will not truly be zero at the fault tips.

3.1.3 Fault Behavior

145 Each part of a fault as defined by a *DippingFault* instance is assigned to being one of three types that will dictate the behavior
of that portion of the fault during a Landlab simulation; above the coseismic ("A"), coseismic ("C"), or interseismic ("I").
"A" portions of the fault are treated as sections of the fault that do not creep and cannot nucleate earthquakes, meaning that
the center of simulated earthquake ruptures cannot be located within "A" portions of the fault, but that simulated earthquake
ruptures can extend into this portion of the fault. "C" portions of the fault are regions of the fault plane that also do not creep
150 but within which simulated earthquake ruptures can be centered, if used in conjunction with an instance of the earthquake
component as described later. Finally, "I" regions of the fault are portions of the fault envisioned as creeping interseismically.
A call to the primary "run_one_step" method of a *DippingFault* calculates the surface deformation resultant from movement, at
the defined slip-rate, of the interseismic portion of the fault treated as an elastic dislocation with a total displacement reflective
of the slip-rate and time step. For example, if an instance of *DippingFault* was defined with a slip rate of 0.001 m yr^{-1} and over
155 a time step of 10 yr, the "run_one_step" method of the *DippingFault* instance would treat any portion of the fault designated as

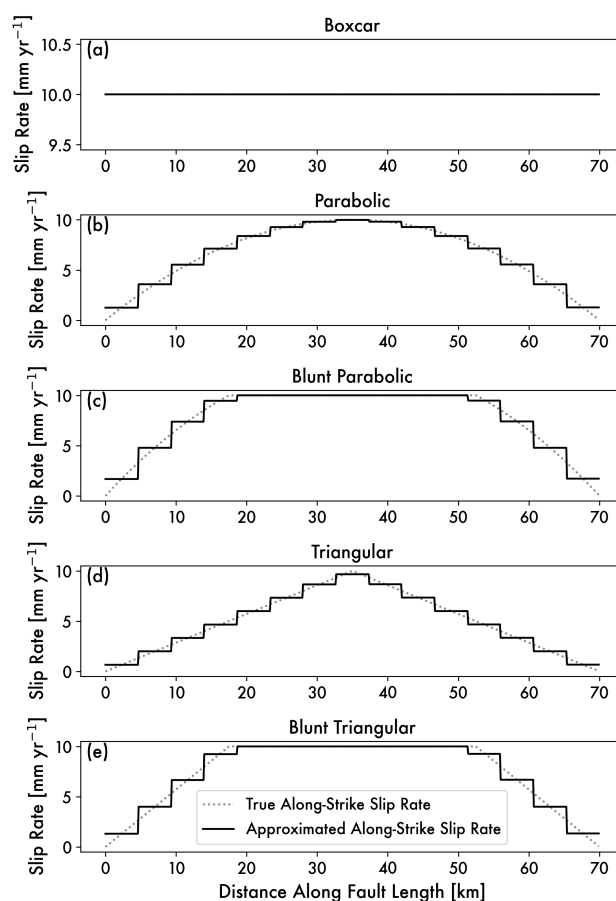


Figure 2. Example slip-rate functions that can be implemented to control how slip-rate varies along fault length. All examples consider a fault with a length of 70 km and a maximum slip-rate of 10 mm/yr and where slip along strike is discretized into 15 equal width patches. Slip-rate functions that are implemented are (a) boxcar, (b) parabolic, (c) blunt parabolic, (d) triangular, and (e) blunt triangular. For blunt style slip-rate functions, the user can specify the relative fraction of the slip-rate along strike that should be at the maximum slip-rate.



"I" as an elastic dislocation with a total of 0.01 m of displacement and calculate and apply the respective surface deformation to the Landlab grid.

All parts of a fault must be defined as one of the three types and can be assigned in one of two ways. The first methods assigns type specifically to panels as defined by the fault geometry, i.e., when instantiating an instance of the component, the user provides a list of types for each fault panel they are also defining with equal lengths lists of dip and fault width. Alternatively, the user can simply define a seismogenic zone specified by an upper and lower depth and the component automatically assigns any portion of the fault above the seismogenic zone as "A", any portion of the fault within the seismogenic zone as "C", and any portion of the fault below the seismogenic zone as "I". Any *DippingFault* instance must have at least one part of the fault that is defined as "I", but there are no formal requirements that an instance have any part that is defined as "A" or "C", though if an instance does not have a "C" section, the user cannot use that fault instance with an instance of the earthquake component defined later. If a user wished to treat the entire fault plane as creeping, as is shown in some of the example outputs discussed later, all fault panels can simply be designated as "I" during instantiation of the component.

3.2 Vertical Fault Component

The *VerticalFault* component shares much of the same logic as the *DippingFault* component but has some critical differences in implementation. The location and geometry of the fault is still tied to a tip location specified by a single set of X, Y, and Z coordinates, but this tip location defines the center of the upper tip of what is considered the first vertical panel of the fault. Any subsequent panels, defined by lists of strikes and fault lengths provided when instantiating an instance of *VerticalFault* will be appended to this first panel in the direction of strike of the preceding panel. By definition within the component an instance of *VerticalFault* will have a single fault width, measured down-dip, for all fault panels and the user does not specify a dip as it is set to 90. Slip-rates are specified in the same way and the same library of slip-rate functions are available within the *VerticalFault* component, with slip-rate still varying along fault length. An instance of *VerticalFault* has the same three definitions of types and subsequent behaviors as an instance of *DippingFault* internally, but the only way to specify these are by providing a top and bottom depth for the seismogenic zone. Because panel types are not directly assignable in the same way as the *DippingFault* component, if the user wishes for the entire fault surface to be treated as creeping, a separate boolean parameter can set this behavior.

4 Earthquake Component

The earthquake component, *EarthquakeSequence*, is designed to generate a sequence of earthquakes based on user defined parameters, place the ruptures on the coseismic portion of a fault plane defined by an instance of either the *DippingFault* or *VerticalFault* component, and then translate individual earthquake ruptures into surface deformation using the underlying elastic dislocation model (Jolivet, 2024) during a Landlab simulation. The *EarthquakeSequence* component works under the premise of pre-generation of a complete earthquake sequence prior to inclusion in a Landlab model. This is both by necessity to ensure that the earthquake sequence conforms to user defined properties, but also by design as it allows the user the opportunity



to inspect both the geometric and statistical properties of the earthquake sequence before incorporating it into a Landlab simulation. Specifically, several built in methods exist within the component to generate maps of rupture locations, slip-rate
190 histories, and earthquake catalog statistics to allow a user to interrogate the details of the generated earthquake sequence before using it in a Landlab simulation.

The component includes three different methods for generating earthquake sequences, but some details and assumptions persist across all generation methods. Specifically, across all generators, ruptures are treated as rectangular patches where the slip-magnitude is uniform across the entire patch. In cases where an individual rupture spans panels of a fault with different
195 geometries, the rupture is effectively broken up into a series of linked patches so that the underlying geometry of the fault is honored across the rupture. Additionally, all ruptures follow the uniform scaling relations of Leonard (2014), meaning that for a given earthquake moment magnitude or seismic moment, there is a unique rupture length, width, and displacement associated with an earthquake of that magnitude. Internally, the *EarthquakeSequence* component includes all four of the "fault types" considered by Leonard (2014), specifically stable continental region dip-slip, stable continental region strike-slip, interplate
200 dip-slip, and interplate strike-slip and which set of relations are used is controlled by the user when instantiating the respective fault component.

It should be emphasized that earthquake sequences generated by the *EarthquakeSequence* component are designed to mimic aspects of real earthquake sequences in a statistical sense, but are not dynamic rupture simulations and do not track expected stress changes on or near the fault plane that result from prior earthquakes. The placement of individual ruptures on the fault
205 plane follow very simple rules, including that the rupture center must be within the portion of the fault defined as coseismic and that no part of the rupture cannot extend beyond the dimensions of the fault, but beyond that, the placement of individual ruptures on the fault is random and fully independent in the sense that past earthquake locations do not influence locations of later earthquakes in the sequence. The earthquake sequences produced by the *EarthquakeSequence* component are also fully reproducible. That is to say, an earthquake sequence generated by an instance of the *EarthquakeSequence* will be exactly the
210 same every time if the geometry of the fault as defined in the provided fault component instance, total model duration, and the random number seed provided to the generator are the same.

4.1 Terminating Earthquake Sequences

It is necessary to define how an earthquake sequence terminates during the generation process and the component includes two main methods. The default method is to clip the sequence so that it does not exceed the total seismic moment (M_0^Σ [N – m])
215 expected for the fault. For this the component uses the relation

$$M_0^\Sigma = A\mu\bar{v}t \quad (1)$$

where A [m²] is the area of the fault that can host earthquakes, μ [Pa] is the rigidity, $\bar{v}$ is the average slip-rate [m yr⁻¹], and t [yr] is the duration of the model in question to define the maximum expected total seismic moment. The $\bar{v}$ is defined as the magnitude of the vector sum of the input dip-slip and strike-slip components of the slip rate, i.e.,

$$220 \quad \bar{v} = \sqrt{ssv^2 + dsv^2} \quad (2)$$



where ssv is the input strike-slip component magnitude and dsv is the input dip-slip component magnitude both in m yr^{-1} . In practice, the component, regardless of which generator is being used, defines a candidate earthquake sequence that includes more events than needed and then is trimmed such that the cumulative seismic moment of each event in the sequence is less than or equal to the total seismic moment as defined in Eq. (1).

225 While simple to calculate and geologically reasonable, because of the random placement of the earthquake ruptures, this can sometimes result in portions of the seismogenic section of the fault accumulating more total displacement than would be predicted from a simple product of the average slip-rate and the model duration (Fig. 3 and 4). As such, the component includes two ways to deal with this behavior. First, the user can specify a fraction of the total moment to use when truncating the earthquake sequence with a parameter provided to *EarthquakeSequence* that is constrained to be between 0 and 1. This is a crude fix to the over-estimation of slip, but it is also potentially a useful option if a user wishes to simulate a scenario with a specific long-term deficit in total released moment. As a more robust alternative, *EarthquakeSequence* also includes a method for clipping the earthquake sequence based on the total accumulated displacement within the seismogenic portion of the fault. To accomplish this, the seismogenic portion of the fault is discretized into a series of points on which the total accumulated displacement is calculated and then the earthquake sequence is truncated when any of these points exceeds the expected maximum displacement from the product of the slip-rate ($\bar{v}$) and total model duration (t). This generally means that there will be a moment deficit, meaning that the total accumulated moment across the fault and clipped earthquake sequence will be less than what is predicted by Eq. (1) (Fig. 3 and 4). In practice, clipping a sequence by total displacement is also significantly more computationally expensive than clipping by total moment and so the processing time to generate a model ready earthquake sequence using the total displacement clipping option will be much longer.

240 4.2 Earthquake Generators

There are three built in methods for generating an earthquakes sequence, described in detail in the following sections. All three generators have the total duration of the simulation as a required input in order to assign times for when the earthquakes will occur during a Landlab simulation and to ensure that the earthquake sequence conserves either total seismic moment or total displacement as described previously.

245 4.2.1 Fixed Maximum Magnitude

The fixed maximum magnitude generator produces an earthquake catalog where every earthquake is the same moment magnitude, which is the largest possible magnitude that can be hosted within the seismogenic portion of the fault and still conform to the self-similar scaling relationships from Leonard (2014). In practice, this means that the dimensions of any single rupture in the sequence often will not fill the entire seismogenic portion of the fault unless the length and width of the seismogenic area match exactly the relationship between width and length defined by the appropriate relation in Leonard (2014) given the chosen fault type. Despite this, given the random placement of ruptures, the entire seismogenic portion of the fault will still tend to experience at least some ruptures, though the edges of the seismogenic zone tend to experience less through random

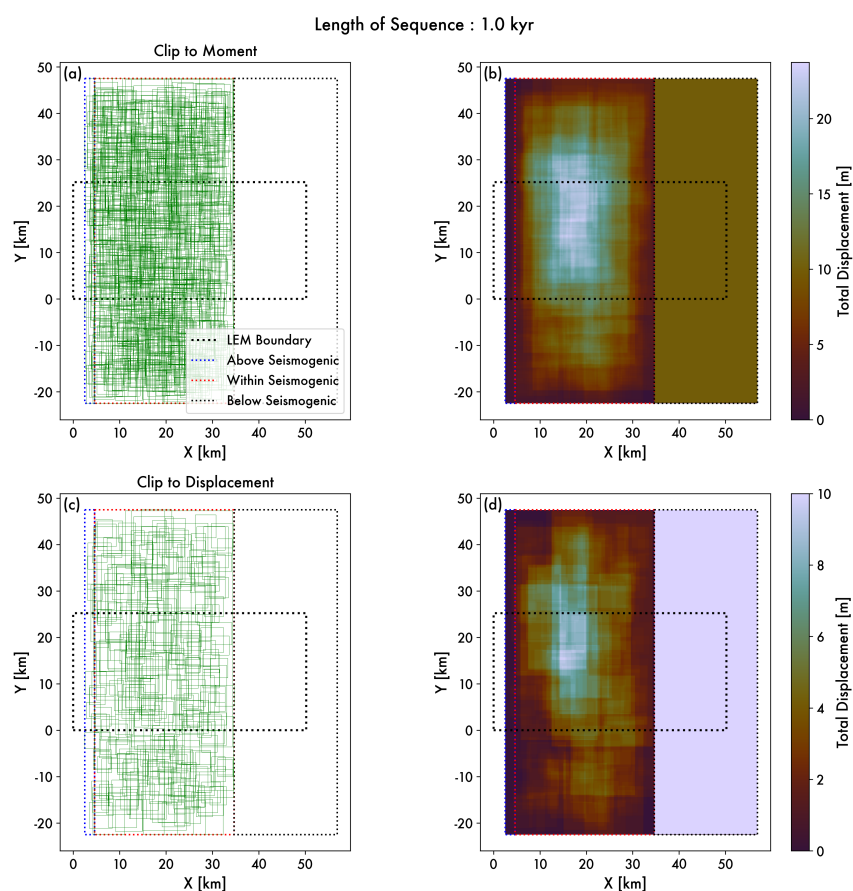


Figure 3. Visualization of individual ruptures on fault surface and total displacement from both earthquakes and fault creep at depth for a 1 kyr earthquake sequence on a fault identical to that used to generate the earthquake catalog in Figure 5. Top row (a-b) considers an earthquake sequence that is clipped to total moment, bottom row (c-d) considers an earthquake sequence that is clipped to total displacement. (a) and (c) display individual rupture patch outlines (green rectangles) projected to the surface. (b) and (d) map of total displacement on the fault surface. These figures represent outputs similar to what is generated by the built in "plot_ruptures" method of *EarthquakeSequence*.

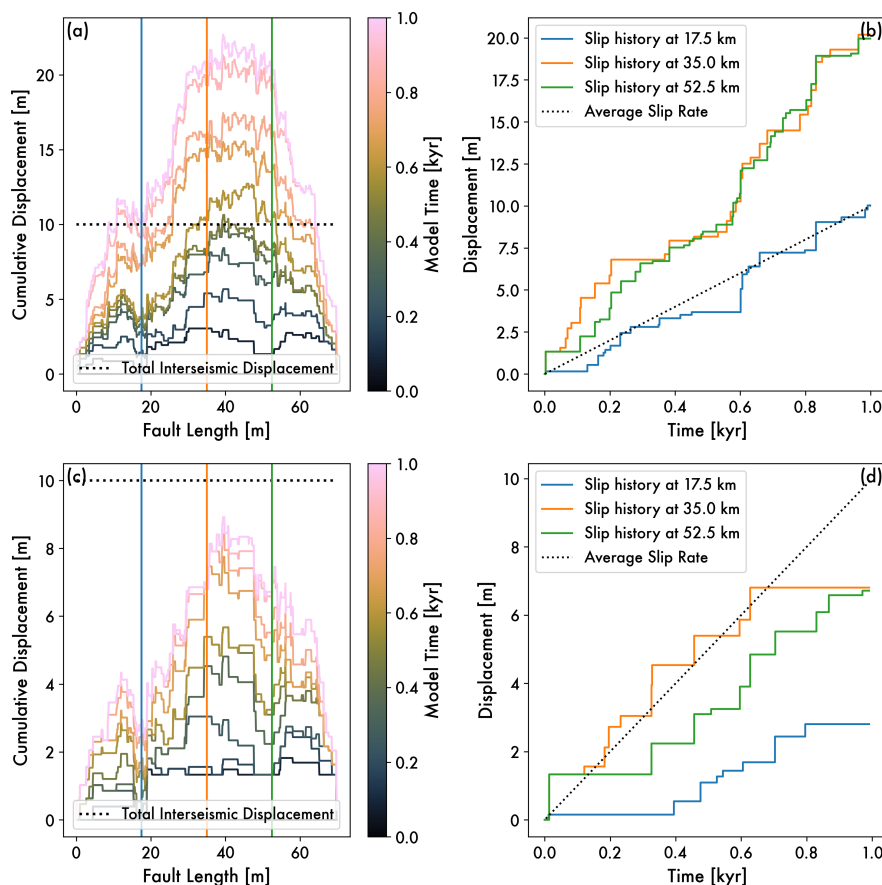


Figure 4. Slip through time on an example fault with two example 1 kyr long earthquake sequences, identical sequences as in Figure 3. Top row (a-b) displays details for the earthquake sequence clipped by moment, bottom row displays details for the earthquake sequence clipped by displacement. (a) and (c) show cumulative displacement along the fault length, sampled at a depth 0.5 half way through the seismogenic zone. Different colors correspond to different times within the model, vertical colored lines mark locations where slip histories are sampled in plots (b) and (d). Dotted horizontal line is cumulative displacement at the end of the 1 kyr sequence that would be expected to have accrued given the imposed slip-rate. (b) and (d) cumulative slip vs model time at the three locations on the fault marked in (a) and (c). These slip-rate histories are sampled at the same depth as (a) and (c). Dotted line is slip vs time based on the average slip-rate. These figures represent outputs similar to what is generated by the built in "plot_displacement_vs_time" method of *EarthquakeSequence*.



sampling. Time between events can either be set to be uniform, i.e the recurrence interval between events is exactly the same and will be a function of the duration of the model and imposed slip-rate, or drawn from a Poisson distribution.

255 4.2.2 Fixed Magnitude

The fixed magnitude generator is similar to the fixed maximum magnitude generator except that the magnitude of the single event is user defined as opposed to calculated by the component. If the user provided magnitude was set to the maximum possible magnitude that could be accommodated within the seismogenic portion of the fault, then this generator would produce identical behavior to that of the fixed maximum magnitude method. Similarly, as all earthquake generators by default restrict
260 the maximum magnitude of any earthquake in a sequence to be equal to or less than the maximum magnitude that can be hosted on the fault, if the user provided a value greater than the maximum magnitude, then similarly the behavior would be identical to using the fixed maximum magnitude generator.

An additional difference between the fixed maximum magnitude and fixed magnitude generators are the options for the temporal distribution of events. When using the fixed magnitude generator, a constant recurrence interval is not an option and
265 instead the default behavior is drawing time between events from a Poisson distribution. However, following results highlighting that earthquake catalogs tend to be temporally clustered (e.g., Kagan and Jackson, 2000), there is also an option to use a negative binomial distribution for defining temporal spacing between events. A negative binomial distribution has two shape parameters, τ and ν where $\tau > 0$, $0 \leq \nu \leq 1$, and ν effectively controls the degree of clustering. As ν approaches 1, the negative binomial becomes equivalent to the Poisson distribution. These shape parameters are in turn related to the average number of
270 earthquakes per year $E(k)f$ and the variance of the number of earthquakes per year $D(k)$ such that:

$$E(k) = \tau * \frac{1 - \nu}{\nu} \quad (3)$$

$$D(k) = \frac{E(k)}{\nu} \quad (4)$$

What this further implies is that the negative binomial distribution is only defined if the variance is equal to or exceeds the average and that if we consider a parameter ν such that $D(k) = \nu * E(k)$, ν becomes $\frac{1}{\nu}$. Within the component, the user can
275 set the value of ν , which if greater than 1 controls the degree of temporal clustering and where if $\nu = 1$, then the distribution becomes identical to the Poisson distribution per above.

4.2.3 Variable Magnitude

The most complicated, but arguably most realistic, generator is the variable magnitude generator. Here, the component uses one of several user selectable earthquake catalog distributions along with a minimum magnitude to generate an earthquake
280 catalog that conforms to basic expectations of Gutenberg-Richter scaling (e.g., Fig. 5). For this purpose, I use four distributions as defined in Kagan (2002), specifically a characteristic, a truncated Pareto, a tapered Pareto, and a modified form of a Gamma distribution. All of these distributions have a scale-invariant power law distribution for small to moderate sized earthquakes, but



differ in how they treat the frequency of large magnitude events. Generally, most of them predict fewer large magnitude events than what would be expected for a simple Gutenberg-Richter relationship, though not specifically the case for the characteristic distribution, consistent with observations of real seismic catalogs. I refer interested readers to Kagan (2002) for more complete discussions of these distributions, but the basic considerations and equations as implemented in the component are introduced in Appendix A. Within the component, the process of drawing events from the chosen distribution relies on methods associated with the *rv_continuous* class within SciPy (Virtanen et al., 2020) and where inherited versions of *rv_continuous* are created for each of the four implemented distributions within the *EarthquakeSequence* component. Custom distributions created in this way at minimum need a cumulative distribution function, but are faster if the inverse (percent point function) can be defined. In practice, only the truncated Pareto has an implemented percent point function and as such is the default behavior of the component.

All of the distributions include a minimum magnitude below which the distribution is truncated. In real seismic catalogs this would typically represent the magnitude of completeness, but within the *EarthquakeSequence* component, this is treated as the minimum magnitude event the user wishes to simulate. The implicit assumption here is that small events, with correspondingly small displacements, will not strongly influence the surface deformation or landscape evolution, but will significantly increase simulation time because of the power-law scaling of earthquake magnitude and frequency. The minimum magnitude is a user controlled parameter with a default of 4.0. It should be emphasized that changing the minimum magnitude will not change the magnitude of the value for truncating the earthquake sequence, i.e., the earthquake sequence will conserve either moment or displacement as described previously, but it will simply do it within the confines defined by the allowable magnitude events, specifically between the imposed minimum and the maximum set by the fault and seismogenic zone geometry.

The variable magnitude generator has identical options to that of the fixed maximum magnitude in terms of controlling temporal spacing of events, specifically these can be drawn from either a Poisson or negative binomial distribution. It should be emphasized that regardless of which distribution is used to set the temporal spacing, in the generic usage of the variable magnitude generator, each event is still considered independent and the selection of time between events is still fully random. In other words, using a negative binomial distribution for selecting temporal spacing will produce a more temporally clustered catalog, but not necessarily a temporally clustered catalog that guarantees clusters start with, or even include, larger events, i.e., this does not create aftershock sequences, though as discussed in later sections, a simple aftershock model can be implemented within the *EarthquakeSequence* component. If using the default behavior of a Poisson temporal distribution for events, though there is no formal consideration of the time since the last event, the resulting temporal distributions and average recurrence intervals of events of similar magnitudes will generally preserve basic expectations for real earthquake catalogs. Specifically, on average the time between rare, large events will be greater than the time between frequent, small events (e.g., Fig. 5).

4.3 Time Stepping

The end result of running any of the earthquake generators that are part of the *EarthquakeSequence* component is a synthetic earthquake catalog that contains the geometric details of the events (i.e., the locations and dimensions of the ruptures) along with their seismic moment, moment magnitudes, displacements, and the time of occurrence of each event within the model.

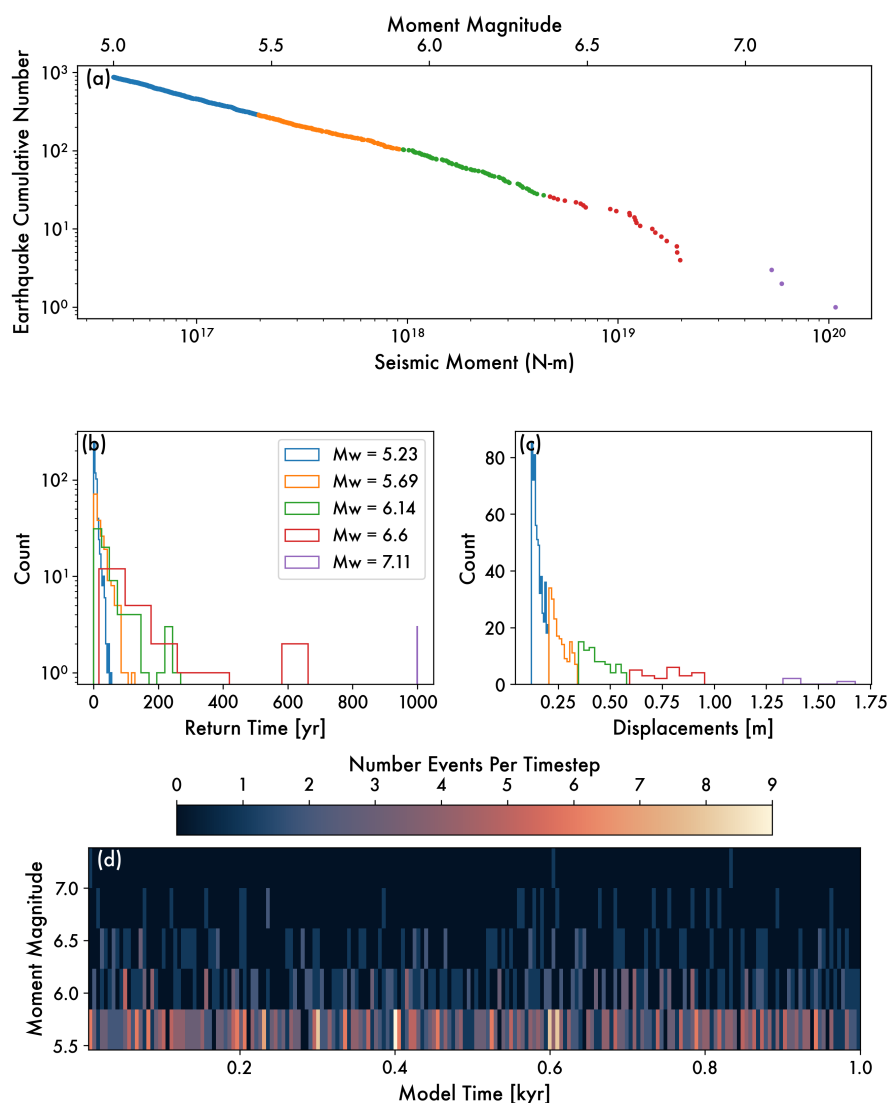


Figure 5. Example earthquake catalog generated for a 1 kyr earthquake sequence for a 70 km long fault, dipping at 25° , with a seismogenic zone between 1 and 15 km, with a slip-rate of 10 mm/yr. This example uses the default frequency-magnitude distribution, which is the tapered Pareto distribution from Kagan (2002). (a) Earthquakes plotted as cumulative number vs either moment magnitude or seismic moment. (b) Histogram of return times between events of similar magnitude within the 5 bins magnitude bins defined by the different color events in (a). (c) Histogram of displacements for events within the 5 magnitude bins from (a) and (b). (d) Visualization of how many earthquakes would be simulated by magnitude per time step assuming a 5 year time step. This figure is similar to what is generated by the built in method "plot_eq_catalog" within *EarthquakeSequence*.



During a call to the "run_one_step" method of the *EarthquakeSequence*, the geometric details and displacement magnitudes of selected events are provided to the underlying elastic dislocation model to generate surface displacements that update the Landlab grid and appropriate fields accordingly. In doing so, the component needs to identify which events to calculate during a given portion of the simulation. The most realistic approach to simulating the surface deformation resultant from individual earthquakes would be to effectively have a variable time step such that each earthquake interrupted an ongoing simulation at the exact time this earthquake was assigned to occur, deformed the surface according to the elastic dislocation, and then the other instantiated Landlab components continued the simulation with this updated topography. However, this is challenging to implement efficiently, especially with earthquake sequences produced by the variable magnitude generator as the time spacing between events can become quite small.

As a compromise, the component uses a binning approach to allow for a single time step length to be maintained throughout a simulation such that the component determines which events within the sequence should occur within a time step and the resultant surface deformation from all of the events during that time step are summed and applied during the "run_one_step" method of the *EarthquakeSequence* component (e.g., Fig. 5d). For example, if a simple earthquake sequence was generated with four events with times of occurrence of 1.2, 2.5, 5.6, and 7.5 years, for a simulation starting at time 0 and ending after 10 years, if the time step length was 5 years, the surface deformation resultant from the first two events would be summed and applied at the end of the first time step and the surface deformation from final two events would be summed and applied at the end of the second time step. If the time step was instead 10 years, the surface deformation resultant from all of the events would be applied at the end of the first (and only) time step. This implies that beyond normal considerations of numerical stability or numerical diffusion that are time step length dependent, the degree to which individual earthquake events can uniquely influence the surface deformation is potentially time step length dependent, a consideration I return to in the discussion.

4.4 Aftershocks

Aftershock sequences, and the resultant spatial and temporal clustering, are critical parts of realistic earthquake behavior, and as such, the *EarthquakeSequence* component includes a method for including them. For this purpose, I adapt the Branching Aftershock Sequence (BASS) model of Turcotte et al. (2007), a brief summary of the governing equations are provided in Appendix B. The BASS model shares many similarities with the more common epidemic type aftershock sequence (ETAS) models, but is simpler to implement, is well suited for Monte-Carlo style simulation as is employed here, and has fewer parameters, hence why I've chosen to use BASS over ETAS for simulation of aftershocks.

The BASS model simulates branching sequences of earthquakes by random selection from cumulative probability functions that define the magnitudes of aftershock events, the time of aftershock events (relative to the original parent event), and the radial distance of aftershock events (relative to the location of the original parent event). As implemented, the BASS model is recursive in that for a given parent event, it generates an original sequence of aftershocks above a minimum magnitude and then generates aftershocks of those aftershocks until all generated events are a magnitude such as to not generate further aftershocks given the imposed minimum magnitude. All three of the earthquake sequence generators include the ability to include aftershocks as determined by the BASS model and where the original sequence of earthquakes generated by the



respective generator will be used as parent events. If used in conjunction with the variable magnitude generator, the minimum magnitude is the same as for the original parent earthquake sequence, but if used in conjunction with either the fixed maximum magnitude or fixed magnitude generators, is a separate user input parameter. Because of the way the BASS model works, there is nothing to preclude a parent event, either an original parent or a subsequent aftershock treated as a parent during the recursive generation of events, from generating an "aftershock" that is larger than the parent, i.e., the BASS model can effectively treat some parent events as foreshocks through random sampling. As implemented within the *EarthquakeSequence* component, the aftershock generation model is still restricted from generating an earthquake with a magnitude larger than what is allowable on the fault as defined.

As described in more detail in Appendix B, additional modifications to the behavior of the BASS model are required to conform to the constraints of the model framework developed here. Specifically, without modification the BASS model will generate aftershocks that lie off of the fault plane and that occur after the total model duration, both of which are not easily allowable within the components described here and require modification.

5 Coseismic Landslide Component

The *CoseismicLandslider* component adapts common strategies from the natural hazards literature for estimating the likelihood of coseismic landslides based on the work of Newmark (1965). A standard Newmark, or rigid-block, analysis is based off a simple approximation of a landslide as rigid-block placed on a slope, with friction, that experiences acceleration at its base due to an earthquake (e.g., Jibson, 1993, 2007). The two parts to a Newmark analysis are considering the dynamic slope stability and the earthquake shaking itself. In the following sections, I review the relevant equations and discuss how these are implemented within the *CoseismicLandslider* component.

5.1 Dynamic Slope Stability

In the context of a Newmark analysis, dynamic slope stability is quantified as the critical ground acceleration necessary to overcome sliding resistance from basal friction. I follow Jibson (1993) and define this critical acceleration a_c [m s^{-2}] as

$$a_c = (FS - 1)g\sin(\alpha) \quad (5)$$

where FS is the dimensionless static factor of safety, g is acceleration due to gravity [m s^{-2}], and α is the hill slope angle at the point of interest. Within the component, for calculating FS I use the form of the static factor of safety from Pack et al. (1998) such that

$$FS = \frac{C + \cos\alpha[1 - wr]\tan\phi}{\sin\alpha} \quad (6)$$

where ϕ is the angle of internal friction of the soil, C is combined dimensionless cohesion such that



$$C = \frac{C_{eff}}{h\rho_s g} \quad (7)$$

380 and C_{eff} [N m^{-2}] is the effective cohesion representing the combined effects of root cohesion and soil cohesion, h [m] is soil thickness measured perpendicular to the slope such that $h = D \cos \alpha$ where D is the thickness of the soil measured vertically, and ρ_s [kg m^{-3}] is the wet soil density. The water to soil density ratio r within Eq. (6) is

$$r = \frac{\rho_w}{\rho_s} \quad (8)$$

385 where ρ_w [kg m^{-3}] is the density of water. The relative wetness w within Eq. (6) is dimensionless and varies between 0 and 1, reflecting the fraction of soil that is saturated such that

$$w = \frac{D_w}{D} = \frac{h_w}{h} \quad (9)$$

where D_w [m] is the thickness of saturated soil measured vertically and h_w is the thickness of saturated soil measured perpendicular to the slope such that $h_w = D_w \cos \alpha$.

The majority of terms within Eq. (5) and Eq. (6) are either values calculated from the Landlab grid fields (α , D , and h) or
390 are constant values reflecting material properties that are defined upon instantiation (C_{eff} , r , and ϕ). Within the component, w can either be asserted upon instantiation as a constant value between 0 (completely dry soil) and 1 (completely saturated soil) or computed dynamically. In the case that the user wishes the relative wetness to be a dynamic property, I have implemented a version of the TOPMODEL (Beven and Kirkby, 1979), which assumes that shallow lateral subsurface flow follows the local topographic slope, lateral discharge from one unit is always in equilibrium with a steady recharge rate herein assumed to be
395 equal to the runoff rate, and the capacity for lateral flux at each grid cell is a function of the transmissivity and surface slope. In this framework, the relative wetness w reflects a ratio between the surface discharge and the subsurface capacity such that,

$$w = \text{Min} \left(\frac{Ra}{T \sin \alpha}, 1 \right) \quad (10)$$

and R is runoff with units of length per time (typically m yr^{-1}), a reflects up-slope drainage area per unit contour width [$\text{m}^2 \text{m}^{-1}$] and where the grid size dx (or average node spacing if using a *HexModelGrid*) of the Landlab grid is used as the
400 normalizing factor instead of contour width, and T is soil transmissivity with units of length squared per time. Within the model, the user can either assert a single value for soil transmissivity or have this calculated based on the soil thickness where instead, a single value for hydraulic conductivity is provided and transmissivity is the product of this hydraulic conductivity and soil thickness within the local grid cell. Within the model component, R is assumed to be equal to whatever the value of the standard Landlab field `water__unit_flux_in` is within individual grid cells and as such, the typical units for R would be
405 m yr^{-1} , but depends on the time unit being used within the particular simulation. It should be noted that while in the hydrologic



literature, values for properties like soil transmissivity or hydraulic conductivity would typically be given with time units of seconds, hours, or days, within the component, these should instead be provided in the same time units as runoff. This implies that if desired, models with time varying w can be run if temporally (or spatially) variable magnitudes of *water__unit_flux_in* are provided during a model loop.

410 One detail that emerges from Eq. (10) is that in scenarios where surface discharge exceeds subsurface capacity, w will be set to 1 (i.e., the soil is fully saturated), but this situation implies that there should be overland flow of a magnitude equal to the difference between the numerator and denominator of Eq. (10). This effect can be included within simulations by activating an option with the *CoseismicLandslider* component which in turns sets the standard Landlab field that tracks discharge, i.e., *surface_water__discharge*, to this difference. It should be emphasized that this approach to calculating relative wetness is
415 very simple and does not include any "memory" in the sense that at each time step, the relative wetness is calculated using the current values of the relevant variables in Eq. (10) regardless of what the relative wetness was in that grid cell at the previous time step. Similarly, the subsurface component of each grid cell is effectively treated independently in that additions from lateral subsurface flow are not explicitly accounted for in the calculation of the denominator of Eq. (10). Recognizing the simplicity of this model, the component also allows the user to calculate relative wetness through alternative means, e.g.,
420 through a more realistic simulation of subsurface flow like the existing Landlab component *GroundwaterDuplunitPercolator* (Litwin et al., 2020), and simply provide and update values for relative wetness as a field stored within the Landlab grid to be used by the *CoseismicLandslider* component.

5.2 Earthquake Shaking

Within the context of a Newmark analysis, the strength of earthquake shaking is considered in relation to the dynamic slope
425 stability and results in an estimation of the magnitude of permanent displacement expected to be generated by this shaking (e.g., Jibson, 1993). In detail, a variety of strategies have been proposed for quantifying earthquake shaking (e.g., Jibson, 2007, 2011). In the context of the *CoseismicLandslider*, I choose to use the relatively simple framework presented by Jibson (2007) based on peak ground acceleration. Estimation of peak ground acceleration, using any number of ground motion prediction equations (GMPE), at points within the model domain are relatively straight forward as they largely incorporate details
430 that are already generated as part of the the synthetic earthquake catalog from the *EarthquakeSequence* component, namely location, orientation, dimension, and moment magnitude of individual earthquake events. I describe the calculation of peak ground acceleration in the following section, but at a given node, calculation of peak ground acceleration, along with estimation of a_c from Eq. (5), is used to calculate permanent displacements (D_N in cm) following Jibson (2007) either independent of event magnitude with,

$$435 \quad \log(D_N) = 0.215 + \log \left[\left(1 - \frac{a_c}{a_{max}} \right)^{2.341} \left(\frac{a_c}{a_{max}} \right)^{-1.438} \right] \quad (11)$$

or an alternate form that also accounts for the moment magnitude (M) of the triggering event,



$$\log(D_N) = -2.710 + \log \left[\left(1 - \frac{a_c}{a_{max}} \right)^{2.335} \left(\frac{a_c}{a_{max}} \right)^{-1.478} \right] + 0.424M \quad (12)$$

where a_{max} is the peak ground acceleration, which can either be in m s^{-2} or g and where this doesn't matter as long as a_c is in the same units. It should be noted that the original forms of both Equations 11 and 12 in Jibson (2007) include uncertainty values reflecting that these are derived from regressions of observations. Within the component, I omit the uncertainty bounds and treat the equations as median estimates of predicted displacements.

5.2.1 Ground Motion Prediction Equations

To calculate permanent displacements (D_N) from either Eq. (11) or Eq. (12) requires an estimation of peak ground acceleration for every node in the Landlab grid. For this purpose, I adapt a series of GMPE which are widely used in probabilistic seismic hazard analyses. In detail, there are a variety of GMPE of varying qualities and applicability and as such, choosing which GMPE to use in a given application, including the *CoseismicLandslider* component, is non-trivial (e.g., Cotton et al., 2006; Bommer et al., 2010; Delavaud et al., 2012; Douglas and Edwards, 2016). For the *CoseismicLandslider*, I largely follow the recommendations laid out in Stewart et al. (2015) which evaluated a suite of GMPE as part of development of the Global Earthquake Model, categorized these GMPE into three types based on the tectonic setting for which they were developed and/or were most appropriate, and made recommendations for preferred models for each of these settings. From these, I selected the Chiou and Youngs (2008) as the GMPE for generic active tectonic settings, Abrahamson et al. (2016) as the GMPE for subduction zone settings, and Pezeshk et al. (2011) as the GMPE for intracontinental settings, with the Chiou and Youngs (2008) GMPE set as the default choice for the *CoseismicLandslider* component. I refer interested readers to each of these respective publications for details of the development of these GMPE and some of their individual nuances, but review the governing regression equations for each in Appendix C, along with some specific considerations of how they are adapted for use within the *CoseismicLandslider*.

5.2.2 V_{s30} Estimation

Reviewing the equations for individual GMPE described in Appendix C reveals that the majority of non-constant terms reflect details of the earthquake itself (e.g., moment magnitude, depth) and the respective position of the particular node of interest with respect to some aspect of the earthquake rupture location or dimension. In other words, the majority of terms in the GMPE can be calculated easily from information stored within the earthquake catalog produced by the *EarthquakeSequence* component and the Landlab grid itself. However, the GMPE for active tectonic settings (Chiou and Youngs, 2008) and subduction zones (Abrahamson et al., 2016) both include a parameter V_{s30} , which is the average shear wave velocity in the top 30 meters of the Earth's surface, that must be estimated. V_{s30} is effectively a proxy for site response to seismic shaking that should reflect aspects of material properties and the path that seismic waves take to the spot of interest. In real world sites, it is a property that can be measured directly, but in a model context, it is a value that must be approximated. For this purpose, I adapt a variety of



methods for estimating V_{s30} based solely on topography, which is ideally suited for an application like the *CoseismicLandslider* component.

The default method uses the widely employed relationship developed originally by Wald and Allen (2007) for estimating V_{s30} based on topographic slope, but in detail uses the updated relationship presented by Allen and Wald (2009) that reformulated the relationships based on higher resolution topographic data. Both Wald and Allen (2007) and Allen and Wald (2009) demonstrate that where V_{s30} has been measured, it generally has a positive correlation with topographic slope. As opposed to developing a regression relationship between the quantities though, both Wald and Allen (2007) and Allen and Wald (2009) propose a series of slope bins that correspond to a median value of V_{s30} for any slope within that bin. It should be noted that because slope is a resolution dependent quantity, the exact relationships between slope and V_{s30} should similarly be resolution dependent, and this in large part reflects the difference between the relationships in Wald and Allen (2007) compared to Allen and Wald (2009) where the former developed relationships using 30 arc second topography (nominally 1000 meter resolution at the equator) and the latter developed relationships using 9 arc second topography (nominally 270 meter resolution at the equator). Here I use the relationships developed by Allen and Wald (2009) using the 9 arc second topographic data as this is a resolution that is comparable to what would be appropriate or typical in a landscape evolution models. Similarly, because of the binning approach used by Allen and Wald (2009), the differences that would result from moderately different resolutions should not impart significant bias in the V_{s30} , at least beyond the inherent bias that already exists because of the crudeness of the approximation. Allen and Wald (2009) present two sets of bin boundaries, those for active tectonic settings or stable continental settings, both are implemented in *CoseismicLandslider* with the active tectonic set being the default, but where the user can choose to use the alternative set for stable continental settings.

In addition to the simple slope based method from Allen and Wald (2009), I also implement two alternative methods of estimating V_{s30} which both rely on relationships between measured V_{s30} in California and the 16 category terrain classification algorithm of Iwahashi and Pike (2007), one developed by Yong et al. (2012) and the other by Yong (2016). The underlying terrain classification scheme from Iwahashi and Pike (2007) uses convexity, roughness, and slope to classify pixels within a DEM into 1 of 16 different numeric categories, that are argued to each correspond to a different type of terrain. In turn, Yong et al. (2012) and Yong (2016) present two different realizations of relationships between these terrain types and V_{s30} , such that for a given terrain classification, there is a single estimate of a V_{s30} value. Yong (2016) presents both a new version of this relationship and a comparison with the original relationship in Yong et al. (2012) and found them to be statistically indistinguishable, as such, I include both as options. It should be noted that neither Yong et al. (2012) or Yong (2016) provide a V_{s30} value for any pixel classified as terrain "13" because there were no site measurements of V_{s30} in areas classified as this terrain type in the underlying data. As applied in the *CoseismicLandslider*, in the event that a node is classified as this terrain type, the V_{s30} for that node is instead determined using the simple slope based approach from Allen and Wald (2009). Alternatively, a user can supply values for V_{s30} directly to the component if they wish to assert a constant value or calculate V_{s30} in some way other than the methods I have implemented.



500 5.3 Integration with *BedrockLandslider* and Time Steps

To summarize the processing steps within the *CoseismicLandslider* for evaluating the landslide potential for any given earthquake event, factor of safety is calculated for each node in the model using Eq. (6) which in turn dictates the critical acceleration via Eq. (5). Peak ground acceleration based on details of the triggering earthquake are calculated at every node using the relevant GMPE depending on user choice via the equations documented in Appendix C, which is used within Eq. (11) or Eq. (12) along with the critical acceleration to calculate a permanent displacement, D_N in cm. I follow the same strategy as employed in many hazard assessments by considering that there is some minimum permanent displacement that will result in a potential coseismic landslide (e.g., Jibson, 2011). By default, this minimum displacement is set at 5 cm, which is a value commonly used (e.g., Jibson, 2007), but this is left as a user controlled parameter so this can be set to a lower or higher value depending on preferences, see for example discussions in Jibson (2011) of potential alternative minimum displacement values.

510 Internally, the *CoseismicLandslider* uses the existing *BedrockLandslider* (Campforts et al., 2020, 2022) to identify areas of the landscape that will fail and route the failed material based on the calculated permanent displacements. Natively, *BedrockLandslider* takes a stochastic approach to identify areas that could fail by estimating unstable areas and flagging these as "critical sliding nodes", i.e., nodes that could fail and produce a landslide. *BedrockLandslider* internally also thins these critical nodes such that only the most down slope critical node is retained within a population. In other words, if a spot at relatively high elevation is flagged as being a critical node but is also up slope from a node that would also be predicted to fail, only the lower of the two critical nodes is retained. Within the *CoseismicLandslider* a similar process occurs, but where it considers any location within the Landlab grid with a D_N greater than or equal to the minimum displacement as a critical sliding node and then retains the most down slope set of critical nodes. These critical sliding nodes are then passed to an instance of *BedrockLandslider*, which circumvents the default stochastic behavior of *BedrockLandslider*, but uses it to fail and route material. It should be noted that not every critical node passed to *BedrockLandslider* necessarily will generate a landslide, as the *CoseismicLandslider* still relies on the internal criteria used by *BedrockLandslider* to determine if areas up slope of a critical node can fail.

As described previously, during a given time step and depending on the model details, more than one earthquake event may occur reflecting all the events within the catalog that would have occurred between the previous and the current time step. Unlike for how surface deformation is dealt with in the *EarthquakeSequence* component, for considering potential coseismic landslides within a given time step, each earthquake event is treated individually and in series for evaluating and routing landslides. This is largely to try to honor the idea that the order of events likely matters in controlling the location and magnitude of coseismic landslides. For example, if a given time step contains two events that with respect to the model domain, represents a close by, large magnitude event and a distant, smaller magnitude event, depending on the time since previous events that resulted in landslides, the smaller, more distant event might be more likely to trigger some amount of coseismic landslides if it precedes the larger event, but if it instead occurs after the larger event, then it might be less likely as material that could have failed in the smaller event likely already did during the closer, larger event. There is of course a mismatch between the surface deformation resultant from the earthquakes that occur during a given time step (which are treated as a composite event with a



single surface deformation field that is the sum of all events occurring during that time step) and the evaluation of landslides that might occur during that time step, but this is a necessarily simplification to keep the problem computationally tractable.

It should be noted that by default, the behavior of *CoseismicLandslider* is such that the only landslides that occur are a result of earthquakes. To include simulation of non-coseismic landslides as well, the user could run a normal instance of *BedrockLandslider* within their model loop, but I have also provided a simple logical flag which if set to true, will also perform the same stochastic landslide behavior native to *BedrockLandslider* at the conclusion of the time step.

Finally, to provide as much flexibility as possible, the *CoseismicLandslider* includes options such that it will calculate all of the details needed to determine critical sliding nodes (e.g., peak ground acceleration, factor of safety, Newmark displacements, etc.), but not actually invoke *BedrockLandslider* and instead can store these within an instance of the component during a time step. This is effectively to allow a user to choose an alternative method for identifying areas that would fail and routing those landslides but taking advantage of the calculations done within *CoseismicLandslider*.

6 Discussion

6.1 Example Models Using the Components

The combination of instances of *DippingFault* or *VerticalFault* with *EarthquakeSequence* with or without *CoseismicLandslider* have the potential to produce a wide array of model scenarios when used in concert with other Landlab components. Thus, it is not the intent here to provide an exhaustive set, or comprehensive analysis, of scenarios using the new components, but rather to provide a simple suite of models highlighting the types of scenarios that can be explored and examples of the differences in landscape evolution that result. In addition, while these new components are generally designed to work with a variety of existing Landlab components, in some cases, the combination of the type of deformation and associated behaviors that are simulated with the new components, produce more realistic landscapes when paired with particular existing Landlab surface process components or require non-traditional model design. As such, part of the goal of the example model scenarios is to document some of these idiosyncrasies and consider the importance of both component choice and the manner in which model scenarios are setup. A basic overview of parameters or setup details for all example models are provided in Appendix D and full input files are provided in the linked repository (Forte, 2026).

6.1.1 Simple Thrust Geometry Without Landslides

As a simple base example, I first present a suite of model runs (models TC, TFM, TVM, and TVD) simulating landscape evolution resultant from reverse-sense slip on a 70 km long, 25° dipping fault that comes near the surface at the "west" edge of the model and dips to the "east", with the tip of the fault located 10 m below 0 m elevation (Fig. 6). For scenarios with earthquakes, the seismogenic zone is defined as being between 1000 and 15000 m below 0 m elevation and all scenarios impose a dip-slip rate of 10 mm yr⁻¹ with no strike-slip component. Because motion on elastic dislocations that is predominantly dip-slip tends to produce both uplift and subsidence at the surface, it is beneficial to use surface process models that explicitly



565 track sediment and allow for deposition to allow surface depressions that form to be partially filled in by deposition. As such,
for all of the thrust-sense scenarios, flow accumulation, routing, and pit-filling is completed with the *PriorityFloodFlowRouter*
(Barnes, 2017), fluvial incision is modeled with the *SpaceLargeScaleEroder* (Shobe et al., 2017), weathering is modeled with
the *ExponentialWeatherer* (Barnhart et al., 2019), and hillslope diffusion is modeled with the *DepthDependentTaylorDiffuser*
(Barnhart et al., 2019), where, with the exception of the *PriorityFloodFlowRouter*, these components were chosen because
570 they track and/or modify sediment via a "soil__depth" field within the Landlab grid.

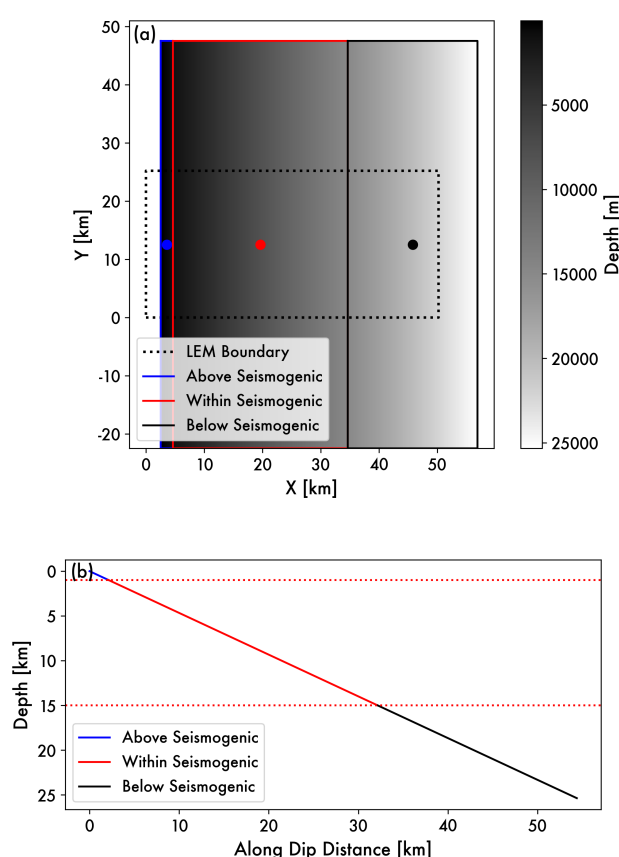


Figure 6. Geometry of thrust fault used in the example thrust simulations. (a) Map view of both LEM outline (box defined by dotted line) and the fault surface, colored by depth. Colored outlines show different parts of the fault defined by different behaviors as described in the text. (b) Cross-section of the fault showing the seismogenic zone as the region between the red dotted lines. This figure is similar to what is produced by the built in method "plot_fault_geometry" within the *DippingFault* component.

For comparison, I present the results of four versions of this simulation, one without earthquakes where the entire fault is modeled as creeping at the 10 mm yr^{-1} slip rate (model TC), one using the fixed maximum magnitude generator (model TFM), and two using the variable magnitude generator, one where the earthquake sequence is clipped by total seismic moment



(model TVM) and the other where the earthquake sequence is clipped by maximum displacement (model TVD). All four
575 models started from the same initial low relief, steady-state topography and were run for 1.5 Myr with 5 yr time steps and
outputs every 2500 yr. Despite the identical starting river network, fault geometry and slip rates, the final topography of these
four models differ in a variety of ways (Fig. 7).

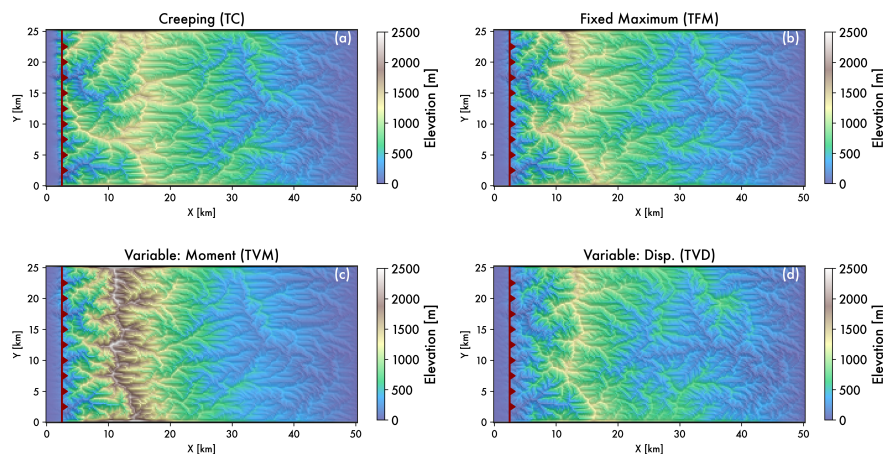


Figure 7. Topography of final time step after 1.5 Myr of model run time for simple example thrust models, where surface deformation is driven by (a) Model TC - creep along the entire fault, (b) Model TFM - fixed maximum magnitude earthquakes, (c) Model TVM - variable earthquakes with a minimum moment magnitude of 5 and where the earthquake sequence is clipped by moment, and (d) TVD - variable earthquakes with a minimum moment magnitude of 5 and where the earthquake sequence is clipped by displacement.

One of the more notable aspects of the differences in the resulting landscapes is the form of the respective drainage networks with general differences in the position of the main drainage divide and thus lengths of rivers on either side of this divide
580 (Fig. 8). Specifically, in all simulations the divide initially shifts from its original location, nominally near the center of the domain, to a position much further "west", reflecting the advection of topography in this direction from movement on the fault, however the divide is shifted the least in the TC model and the most in the TVM model. Similarly, tracking common topographic metrics, like gradient, mean local relief, or normalized channel steepness index, highlight quantitatively different resulting topography between the four models (Fig. 9). In detail, all of the simulations reach different quasi steady-state values
585 of the respective metrics and all of the simulations with earthquakes exhibit notable persistent unsteadiness in these metrics, which is not surprising given that the surface velocity is effectively changing every time step. The stark contrast in total relief and associated topographic metrics of the TVM model compared to the other models largely reflects the large accumulated total displacement related to the conservation of total seismic moment and the method of placing earthquake ruptures on the fault plane as described previously.

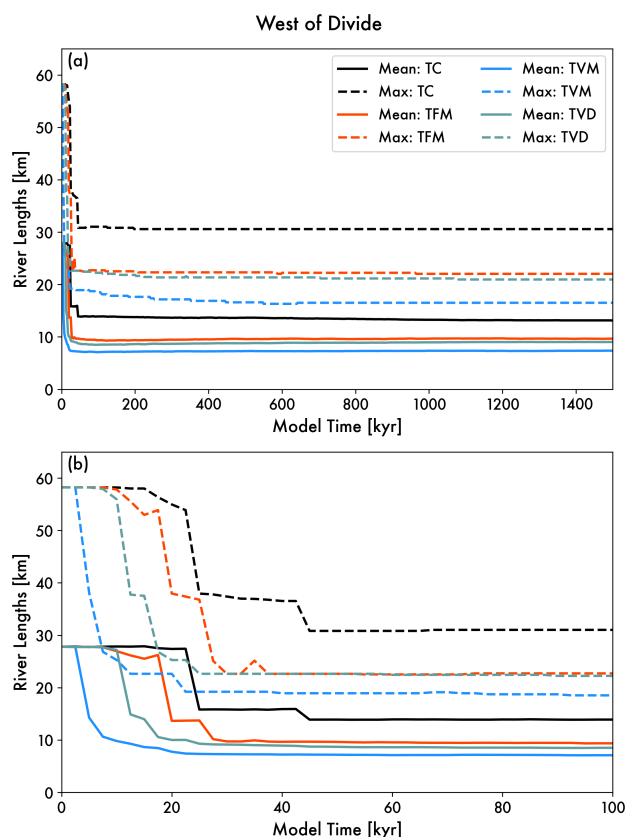


Figure 8. Mean and maximum length of streams draining west of the drainage divide for simple example thrust models. (a) Change in mean and maximum stream lengths during the entire 1.5 Myr run. (b) Change during the first 100 Kyr.

6.1.2 Simple Thrust Geometry With Landslides

To explore the effect of including coseismic landslides, I present an example of running an identical model to the variable magnitude scenario from above (e.g., Fig. 7c), including an identical earthquake catalog and other relevant details (e.g., both earthquake scenarios clipped by total moment, same initial topography, same time step length, etc.), but with coseismic landslides throughout the evolution of the topography (model TVMLa - Fig. 10). This model scenario is otherwise also identical in terms of the Landlab surface process components included. Of note here, while none of the implemented surface process components, i.e., *PriorityFlowFlowRouter*, *SpaceLargeScaleEroder*, *ExponentialWeatherer*, and *DepthDependentTaylorDiffuser*, were required for the thrust scenarios without landslides, in the case of *PriorityFlowFlowRouter* and *SpaceLargeScaleEroder*, that is not the case for models using *CoseismicLandslider*. Specifically, *CoseismicLandslider* requires the use of *PriorityFlowFlowRouter* for flow routing and pit-filling and *SpaceLargeScaleEroder* for fluvial incision because the underlying *BedrockLandslider* (Campforts et al., 2020, 2022) component requires fields produced and evolved by these components.

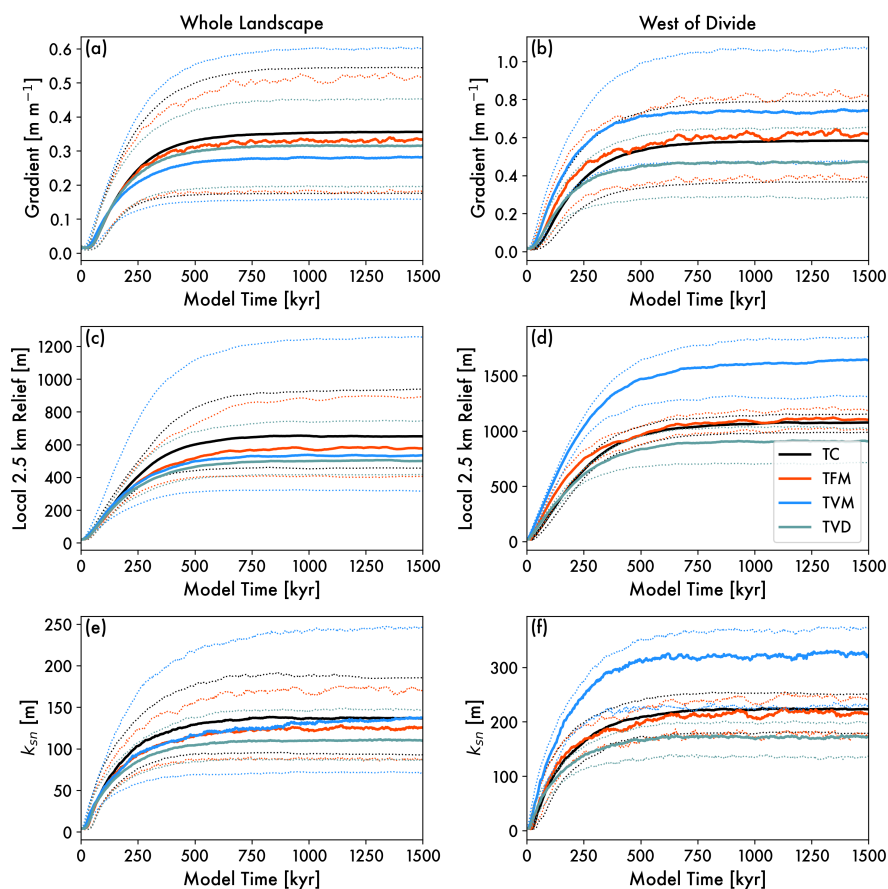


Figure 9. Time series of topographic metrics for simple example thrust models. Left column shows values calculated for the whole landscape at each output time step, right column show values calculated only for the area of the landscape west of the main drainage divide, i.e., the portion of the landscape "facing" the fault. Solid lines show the median value and dotted lines bound the interquartile range. (a) and (b) show gradient, (c) and (d) show local relief measured over a 2.5 km circular window, (e) and (f) show normalized channel steepness (k_{sn}) with a reference concavity of 0.5

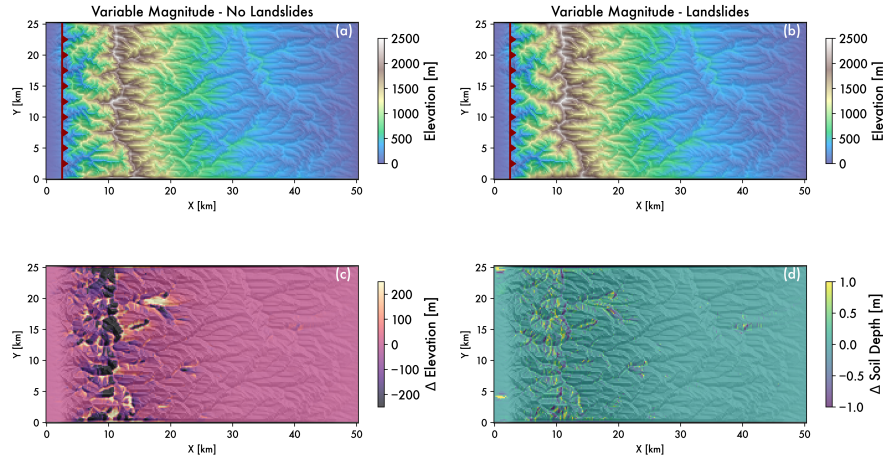


Figure 10. Topography of final time step after 1.5 Myr of model run time for simple example thrust models, where surface deformation is driven by (a) Model TVM - variable magnitude earthquakes without coseismic landslides or (b) Model TVMLa - variable magnitude earthquakes with coseismic landslides. Bottom row displays difference between (c) elevation and (d) soil depth of TVM - TVMLa.

The example simulation with coseismic landslides is run generally with the default choices for *CoseismicLandslider*, specifically using the GMPE from Chiou and Youngs (2008), the slope based estimate of V_{s30} from Allen and Wald (2009), an effective cohesion (C_{eff} in Eq. (6)) of 10,000 Pa, and a relative wetness ratio (w in Eq. (6)) of 0 that assumes completely dry soil. Comparison of the final topography between landscapes without and with coseismic landslides suggests extremely subtle differences in topographic evolution (Fig. 10). Direct differencing of the final elevations (Fig. 10c) or soil depth (Fig. 10d) between the two scenarios do show measurable and quantifiable differences, but not significant variations. Considering time series of topographic metrics like gradient, local relief, and k_{sn} highlight similar small levels of difference between models without and with landslides (Fig. 11). Generally, across all metrics, median values of these metrics suggest that the landscape experiencing coseismic landslides during the simulation are slightly steeper than the counterpart model without landslides, but the differences are again subtle and much smaller than the interquartile range of the two simulations.

Simulations using the *CoseismicLandslider* component can also take advantage of the underlying functionality of the *BedrockLandslider* (Campforts et al., 2020, 2022) to store statistics of landslides and in turn evaluate how these vary through time (Fig. 12). For the example simulation, Fig. 12 highlights some basic, and largely expected, behavior, namely that the total number of landslides, the total area of landslides, and total volume of landslides generally scale with the magnitude of the triggering event. The time series of the catalog also highlights that during the early stage of the simulation, when topographic relief and slope are still increasing, the number, area, and volume of landslides also increase with time and that these basic statistics reach a quasi-steady-state at a similar time as the general topographic metrics (e.g., around 500 kyr of simulation time).

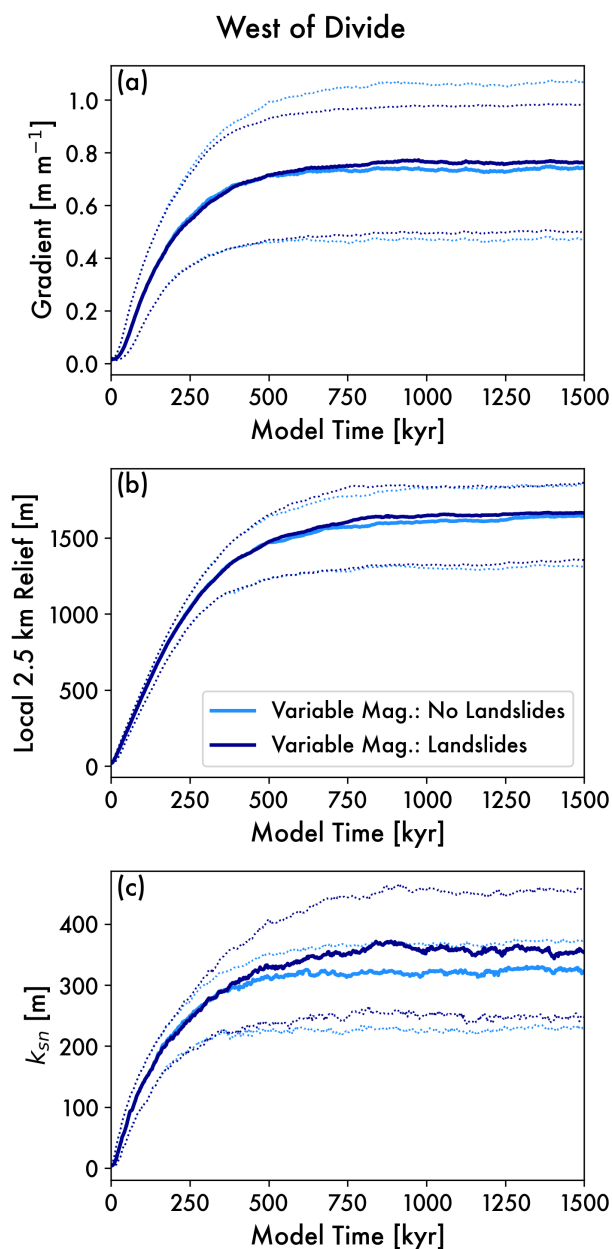


Figure 11. Time series of topographic metrics for models TVM and TVMLa. Graphs show median value (thick solid line) and interquartile range (thin dashed lines) and show (a) hillslope gradient, (b) local relief measured in a 2.5 km radius, and (c) normalized channel steepness (k_{sn}).

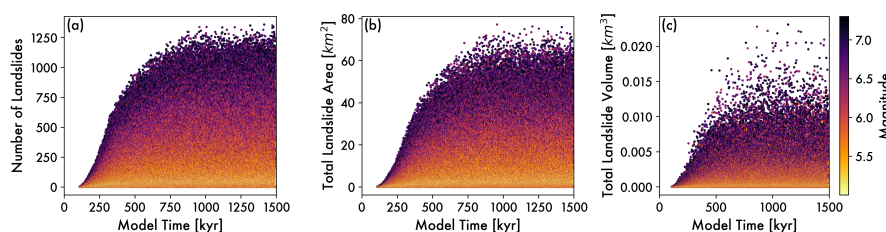


Figure 12. Landslide catalog with summative statistics for model TVMLa as a function of time showing (a) number of landslides per earthquake event, (b) total landslide area per earthquake event, and (c) total landslide volume per earthquake event. Each event is colored by its moment magnitude.

These basic aspects of the landslide catalog also allow for some direct validation of the extent to which the simulated landslides exhibit similar summative and statistical properties as natural coseismic landslides. Significant work has demonstrated that summative statistics, like either the total area or volume of coseismic landslides, generally positively scale with details of the triggering event, primarily magnitude and rupture depth (e.g., Keefer, 1984, 1994; Marc et al., 2016, 2017). Examination of total landslide area as a function of the magnitude and depth of the triggering earthquake from the example simulation reveals similar scaling behavior, but not that consistently matches observations from natural coseismic landslide catalogs (Fig. 13). It should be noted though that the simulated catalog and observed catalog generally overlap at low magnitude events. This is significant as it is only at low-magnitudes, and thus relatively small total rupture length for the underlying triggering event, where the simulated model domain strike-parallel length is significantly smaller than the size of the rupture. For natural landslide catalogs related to earthquakes, an essential aspect of an accurate catalog is that it covers the entire area affected by coseismic landslides (e.g., Harp et al., 2011), and as such, the relatively narrow simulated domain is likely artificially biasing summative statistics like total landslide area preferentially for larger magnitude, and thus longer rupture length, events. For the particular simulation, the simulated total landslide area for events with a M_w at and below 5.5 overlap with observations from natural events (Fig. 13).

An alternative method of comparison to natural events is considering the frequency-area scaling of the coseismic landslides. Populations of landslides, coseismically generated or otherwise, tend to display a power-law scaling between frequency and area, at least above a "cutoff" area (Malamud et al., 2004b, a). Compilations of the exponents on these power-law relations, often symbolized as β (distinct from the β that is common in equations for seismic moment distributions and represents the shape parameter of these distributions (e.g., Kagan, 2002)) for coseismic landslides reveal a relatively narrow range of β values between -2 and -3 (e.g., Tanyaş et al., 2019). Applied to either natural or the simulated catalog here, these measures should be less sensitive to total area of either simulated or mapped topography than summative statistics like total landslide area and thus may represent a more reliable method of validation of the behavior of the *CoseismicLandslider*. Comparison of fit β values for the entire simulated catalog to the compilation of natural β values from Tanyaş et al. (2019) as a function of either triggering earthquake depth (Fig. 14a) or magnitude (Fig. 14b) reveal a broad overlap in the central tendency of β values between simulated and natural events, despite a relatively restricted range of depths and magnitudes of the simulated

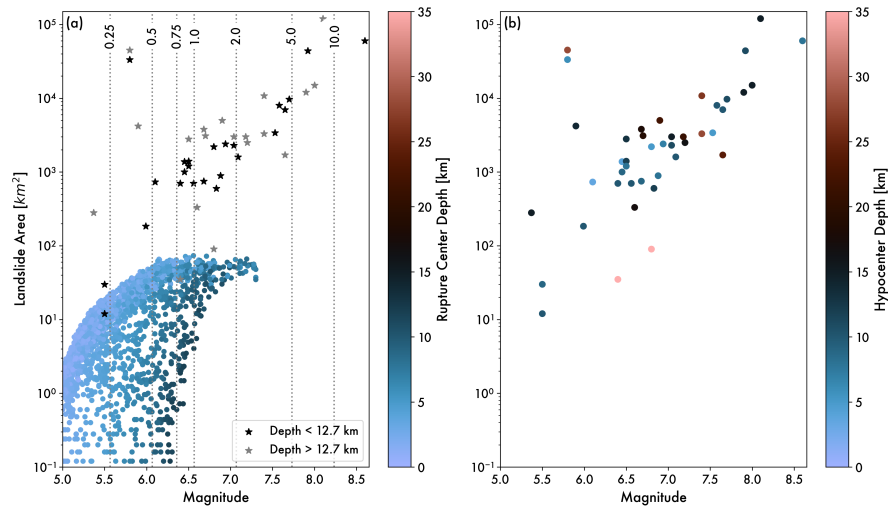


Figure 13. Comparison of total landslide area in model outputs vs. published catalogs. (a) Colored dots are total landslide areas compared to earthquake moment magnitudes of the triggering event for simulated events. This is a filtered version of the landslide catalog only displaying events with a rupture center within 500 m of the model domain and which occur after 1 Myr of run time, i.e., after the model topography has achieved a quasi-steady-state. Colors indicate depth of the rupture center. Black and gray stars are published total landslide area vs. earthquake magnitude from reverse events in the compilation in Marc et al. (2017). Black stars are events with hypocenter depths above 12.7 km, which is the maximum depth of rupture centers in the simulated catalog, gray stars are events with hypocenter depths below 12.7 km. Contour lines are ratio of rupture lengths, assuming Leonard (2014) scaling between seismic moment and length, to the along-strike model domain length, i.e., 25 km. (b) Reverse events from the compilation in Marc et al. (2017) colored by hypocenter depth on same scaled axes as (a).

events compared to the natural examples. Further restricting the events being compared to coseismic landslides triggered by earthquakes with rupture centers within 500 m of the center of the model domain and that occur after 1 Myr of model run time and breaking out by broad magnitude bins highlight that again, small events with magnitudes less than 5.5 are the most consistent with the natural catalogs and that events in larger magnitude bins tend to deviate more significantly than observed values β , specifically with lower (i.e., more negative) values of β . It should also be noted that many events, even in the filtered catalog, display β values well outside the observed range, including those with positive β values which would imply a higher frequency of large landslides than smaller ones.

Together the comparisons of either total landslide area (Fig. 13) or area-frequency decay exponents (Fig. 14) reveal acceptable levels of agreement between simulated and natural landscapes, but with some notable departures, specifically general under-prediction of total-landslide area and a wider range of β values. There are, however, a variety of reasons that this level of disagreement in both metrics are not necessarily surprising. For the summative statistics, as already discussed the domain size will play an important role in the accuracy of summative statistics and it would be expected that as domain size increases, respective to the size of possible ruptures given the imposed fault geometry, the degree of agreement between simulated

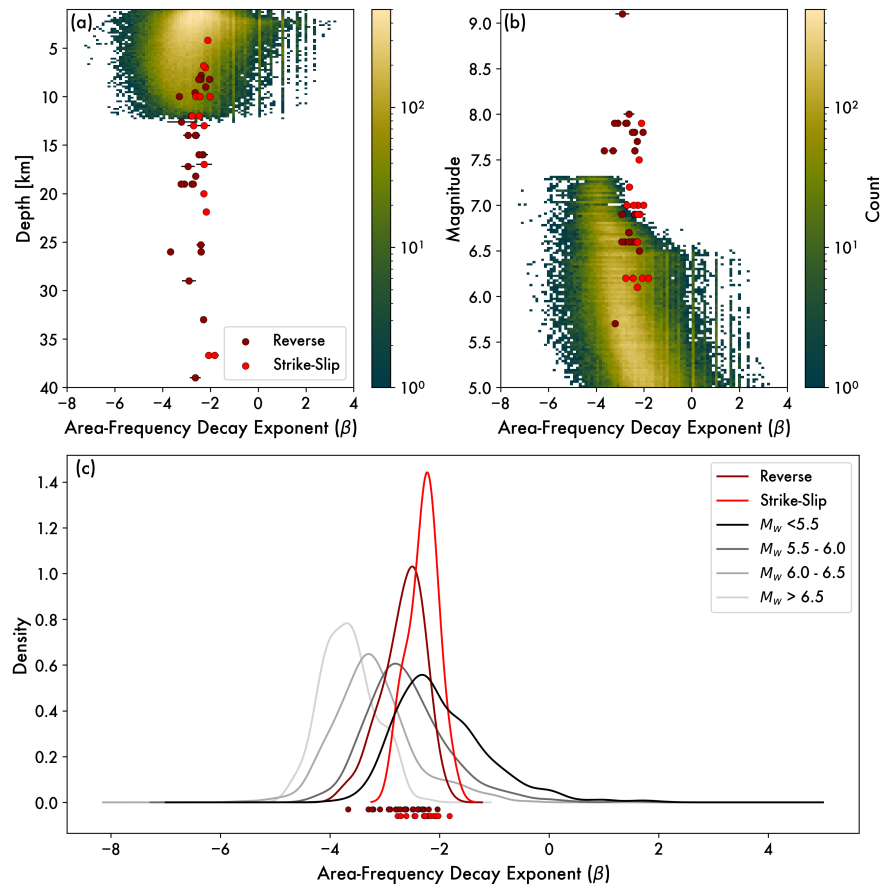


Figure 14. Comparison of area-frequency scaling in model outputs vs. published catalogs. (a) Colored area is 2D histogram of complete landslide catalog comparing the power-law exponent (β) and rupture center depth for model landslide catalog. Red dots are similar comparison for landslide catalogs analyzed and compiled by Tanyaş et al. (2019). Dark red dots are for reverse events, lighter red dots are for strike-slip events. All events show reported uncertainty in β reported by Tanyaş et al. (2019). (b) Same as (a), but comparing β and the moment magnitude of the respective triggering event. (c) Kernel density estimates of β values for real events from Tanyaş et al. (2019) (red lines) compared to filtered simulated events (black and gray lines). For the model landslides, these are first filtered in an identical manner as in Figure 13 and then separated by magnitude range.



summative statistics and natural examples would increase. For the observations of β , the comparison in Figure 14c similarly suggests that domain size may play a role, which is one possible reason that the β value for small magnitude events better matches that of natural β values despite the large differences in triggering magnitude for most of the natural events. For the area-frequency scaling, probably a larger factor is that the natural examples effectively represent continuous distributions in the sense that landslides of any size within the range covered by the distribution could occur, though there is an inherent scale in the sense of the resolution of the datasets used to generate the catalog, whereas there is a fixed scale for events (i.e., the grid size of the underlying LEM) in the simulated catalog. In the example scenario, the grid size is 200 m, implying that the smallest landslide that can occur has the same area as one pixel, i.e., $4\text{e}4 \text{ m}^2$. This is comparable to many "cutoff" areas above which natural landslide catalogs should exhibit power-law scaling (e.g., Tanyaş et al., 2019), but this also implies that landslides can only occur at discrete areas, i.e., a two-pixel landslide with an area of $8\text{e}4 \text{ m}^2$, a three-pixel landslide with an area of $1.2\text{e}5 \text{ m}^2$, etc., and as such, this has the potential to bias estimations of frequency-area scaling relationships. Thus, it is expected that simulations with smaller grid sizes, which would allow for less discretization of the distribution of landslide areas, would likely generate landslide catalogs with better matches to observed natural landslide catalogs. Finally, there are any number of details that are easily controllable within the *CoseismicLandslider* or the other components which could explain some degree of the variation. For example, the events in catalogs of either total landslide area (e.g., Marc et al., 2017) or frequency-area scaling (e.g., Tanyaş et al., 2019) likely reflect a mixture of relative C_{eff} and w that differ substantially from the values used in the representative simulation, but where these would be expected to influence total area more than frequency-area scaling. Similarly, the representative example used the very simple slope based method for V_{s30} estimation from Allen and Wald (2009), whereas the more nuanced topographic classification method from Yong et al. (2012) or Yong (2016) could influence landslide catalog statistics, and similarly the choice of GMPE, especially considering that many of the events in the Tanyaş et al. (2019) compilation of β values would be considered to be subduction related events and thus might be more comparable to outcomes of instead using the subduction related GMPE of Abrahamson et al. (2016). Similarly, details of the earthquake or general fault behavior could lead to some of the deviations. For example, Marc et al. (2016) highlight that total landslide area will be sensitive to both rupture depth and average topographic slope. For rupture depth, the majority of the simulated events are more shallow than their natural counterparts (e.g., Fig. 13, 14) which is largely an outcome of the seismogenic depths used in the model setup, but may also reflect that because of the simple nature of the simulated events, rupture depth is always the center of the ruptured patch, whereas hypocenter depth may or may-not be near the center of the rupture extent of a real earthquake event. In terms of average topographic slope, this will reflect aspects of both the surface processes components (e.g., the erosional efficiency), but also the average slip-rate imposed on the fault. Ultimately, it is beyond the scope of this work to provide a comprehensive exploration of simulated and natural coseismic landslides using the *CoseismicLandslider* component, but this simple example demonstrates that while not a perfect representation of reality, the extremely simple approach of the *CoseismicLandslider* reproduces many core aspects of natural coseismic landslides.



6.1.3 Normal Faults of Variable Geometry

To illustrate different kinematics for a model using instances of the *DippingFault* component, I also consider a suite of models simulating landscape evolution resultant from normal-sense slip on a 70 km long, 60° "east" dipping fault with an upper fault tip at the center of the model domain (Fig. 15a & b). Motion on a normal fault as simulated by an elastic dislocation poses some particular challenges for landscape evolution models because the predominant feature of the deformation field, especially in steeply dipping scenarios like the one simulated here, is downward motion of the hanging-wall, leading to significant subsidence. As such, this requires consideration of which Landlab components are necessary to produce semi-realistic landscapes. Specifically, components that track and deposit sediment, like *SpaceLargeScaleEroder* (Shobe et al., 2017) are essential to allow subsidence to be in part counter-balanced with sedimentation. As such, the normal-sense motion scenarios generally use the same Landlab surface process components as the thrust-sense scenarios, i.e., *SpaceLargeScaleEroder* for fluvial incision, *ExponentialWeatherer* for weathering and sediment generation on hillslopes, and *TaylorDepthDependentDiffuser* for hillslope diffusion. However, instead of flow-routing and pit-filling being accomplished with *PriorityFloodFlowRouter* as in the thrust-sense scenarios, the normal-sense scenarios use a combination of the *FlowAccumulator* and *LakeMapperBarnes* (Barnes et al., 2014) components. These were chosen as they produced the most realistic deposition behavior, whereas the *PriorityFloodFlowRouter* (Barnes, 2017) component produced non-reasonable sediment geometries in the presence of large depressions to be filled with sediment. However, even with these components, simulations driven by normal-sense motion on a dip-slip fault tends to produce a landscape entirely below sea level and with non-realistic topography in the foot-wall of the normal fault (Fig. 16a & b). However, a critical aspect of the topographic evolution of a normal fault system not explicitly considered in this model setup is a flexural or isostatic response to fault movement (e.g., Wernicke and Axen, 1988). To include this in a simplistic way, I incorporate the *Flexure* (Hutton and Syvitski, 2008) component within Landlab to these example model and approximate a time dependent flexural response with the exponential form suggested by Peltier (1998):

$$w(t) = w_0 \left(1 - e^{\left(\frac{-t}{t_0} \right)} \right) \quad (13)$$

where $w(t)$ is the flexural response at a given time t after the change in load, w_0 is the total flexural response from the change in the load, and t_0 is a mantle relaxation time in yr. In the presented models, the *Flexure* component is used to calculate w_0 and then at each time step, the appropriate flexural response given the time since a change in load that results from fault related deformation, erosion, or deposition, is applied. In detail, during a simulation the load changes at every computation time step and due to the form of Eq. (13), amount of flexure to be applied at a future time step asymptotically approach, but never reach, the total flexure. Thus for efficiency, incremental flexural responses for a given change in load at a time t are only considered up until the $w(t)$ is 99.9% of the value of w_0 . Also for efficiency, and taking advantage of the time delayed response implicit in Eq. (13), I use a separate 500 yr time step for calculating and applying flexural responses. At each node of the model, three components of the load are computed based on the bedrock elevation above a fixed crustal datum, the soil (here treated as sediment, including sediment infilling the basin that develops in the hanging wall), and the depth of a hypothetical water column for anywhere below 0 elevation and above the topographic surface. For all of the models shown, the density of



bedrock is assumed to be 2800 kg m^{-3} , sediment is assumed to have a density of 2600 kg m^{-3} , and water is assumed to have a standard density of 1000 kg m^{-3} . For all simulations, I assume a mantle relaxation time (t_0) of 2500 yr.

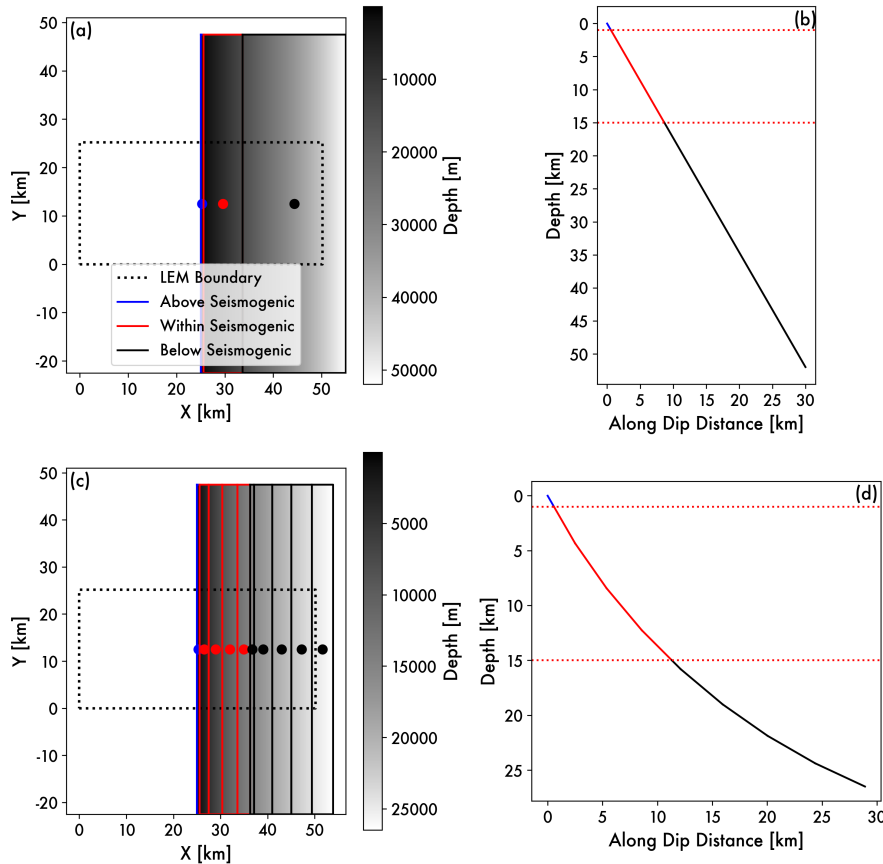


Figure 15. Geometry of normal faults used in the example normal-sense slip simulations. (a) Map view of both LEM outline (box defined by dotted line) and the fault surface, colored by depth for a simple 60° dipping fault for the fault used for models NC, NCTe10, NCTe30, NCTe50, NVDTe30. Colored outlines show different parts of the fault defined by different behaviors as described in the text. (b) Cross-section of the fault showing the seismogenic zone as the region between the red dotted lines. (c) Map view of fault surface for the listric fault example used for models NCLTe30 and NVDLTe30. (d) Cross-section of the listric fault showing the seismogenic zone for simulations with earthquakes.

As shown in Figure 16, including a simple flexural response produces much more reasonable topography and where the exact topographic response, and the corresponding shape and depth of the sedimentary basin that develops in the hanging wall depends on the effective elastic thickness (T_e) used within the *Flexure* component. I show results with a creeping fault and T_e of 10 km, 30 km, and 50 km (Fig. 16), but for subsequent models, I use a T_e of 30 km. In all of these simple creeping simulations with flexure, many hallmarks of normal fault bounded ranges develop, specifically a relatively steep topographic

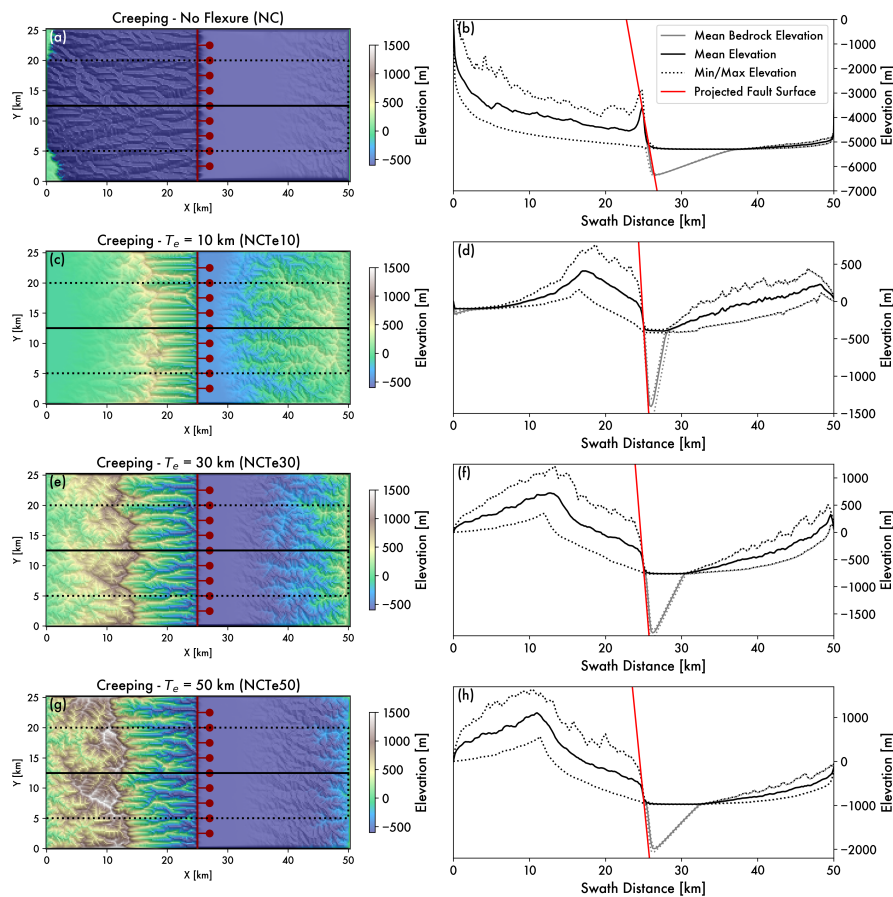


Figure 16. Left column, final topography after 1 Myr of model time with different effective elastic thicknesses (T_e). Right column, swath profile through both the topographic surface and bedrock surface, boundary of 15 km wide swath shown on corresponding panel to the left. (a) Topography and (b) swath profile through model NC without flexure. (c) Topography and (d) swath profile through model NCTe10 with a T_e of 10 km. (e) Topography and (f) swath profile through model NCTe30 with a T_e of 30 km. (g) Topography and (h) swath profile through model NCTe50 with a T_e of 50 km.



flank within the foot-wall facing the fault that in places are adorned with flat-iron like structures, a more gently sloping portion of the topography inclined away from the fault across the drainage divide, and an asymmetric basin developed within the hanging-wall.

As with the thrust models, it is similarly possible to consider the resulting differences in landscape evolution on a creeping fault compared to one with earthquakes. For the earthquake simulation (TVDTe30), I use the variable magnitude generator and clip the sequence by maximum displacement, and as with the thrust models, simulations with earthquakes produce decidedly different topography (Fig. 17, 18). In these simulations, as with the thrust scenarios (e.g., Fig. 9), models with earthquakes generally produce less steep topography than models driven by steady creep. Here it is also useful to consider differences not only in topography, but basin structure in models developed either with creep or earthquakes (Fig. 17). Here I also demonstrate that while many of the simulations presented as examples use very simple fault geometries, the components allow for simulations using complicated fault geometries by considering an analogous set of examples, but in comparing the topography developed either as a result of creep or earthquakes on a normal fault with a listric geometry (Models NCLTe30 and NVDLTe30 - Fig. 15c and d, 19). Examination of the time evolution of these different model outputs (Fig. 20) highlight the importance of fault geometry in dictating topographic response, even when that topography is primarily developed within the foot-wall block of a normal fault, i.e., not above the fault surface itself.

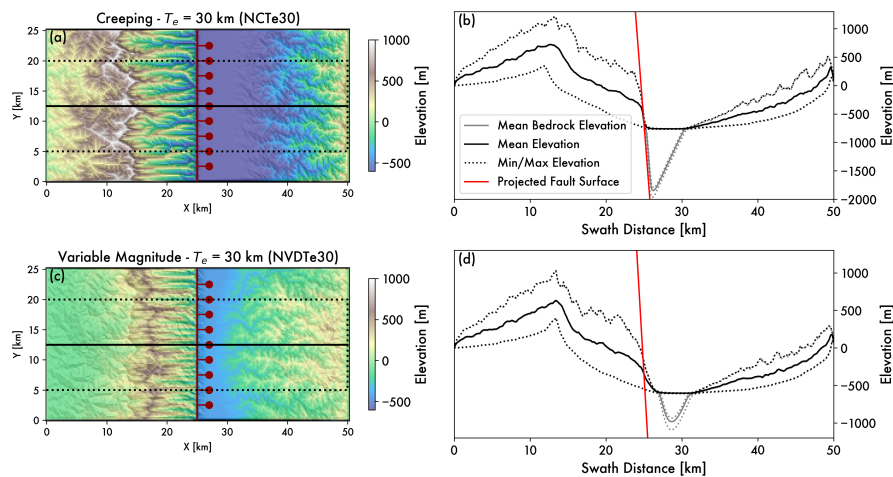


Figure 17. Comparison of model results of models NCTe30 and NVDTe30. (a) Model topography after 1 Myr of steady fault creep of model NCTe30. (b) Swath profile through topography and bedrock topography of model NCTe30. (c) Model topography after 1 Myr of model NVDTe30. (d) Swath profile through topography and bedrock topography of model NVDTe30.

Finally, it is important to consider that while the incorporation of a simple flexural model does produce more realistic landscape evolution when using a normal-sense instance of *DippingFault*, this is still an overly simplified model. Perhaps one of the largest simplifications is that while the flexural response is applied to the topography, and thus influences the simulated landscape evolution, the fault geometry is unaffected by flexure. In reality, rotation of normal faults as a response to flexure or

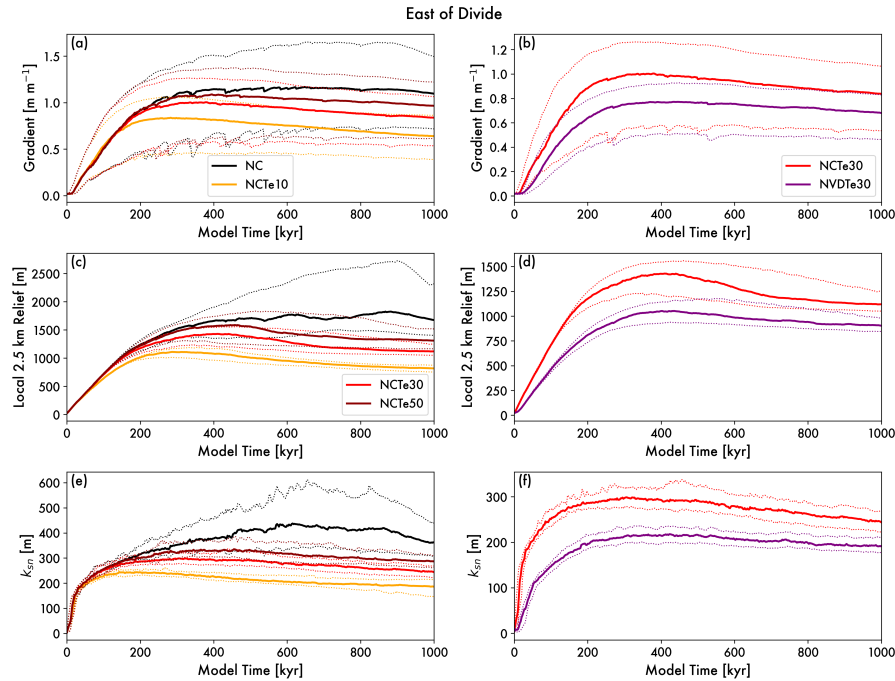


Figure 18. Time series of topographic metrics for simple normal fault models. Left column compares behavior between creeping models with and without flexure and with varying T_e , right column compares behavior between creeping and variable magnitude earthquakes. (a) and (b) show gradient, (c) and (d) show local relief measured over 2.5 km circular window, (e) and (f) show normalized channel steepness (k_{sn}) with a reference concavity of 0.5. All values are calculated only for the high relief portion of the landscape east of the main divide and west of upper fault tip, i.e., the portion of the landscape "facing" the fault and within the foot-wall block.

isostasy is recognized as an important process (e.g., Wernicke and Axen, 1988; Olive and Behn, 2014). Similarly, the *Flexure* component simulates response of an unbroken elastic sheet to an applied load, whereas simulations of flexure related to normal fault motion is more commonly simulated with a broken elastic sheet (e.g., Olive and Behn, 2014).

6.1.4 Strike-Slip Faults of Variable Geometry

As a final suite of examples, I consider landscape simulations using instances of *VerticalFault* with strike-slip sense motion. Similar to normal-sense faults, strike-slip faults pose unique challenges when incorporated into landscape simulations, but in the latter case, largely because of issues related to boundary conditions as opposed to high rates of subsidence in the former case. Specifically, because the dominant sense of motion is lateral, the resulting landscape evolution is highly sensitive to the nature of the boundaries on the edges of the model domain perpendicular to the strike-direction and thus the topography that is advected into the domain. Some of the challenges also result from how the underlying *AdvectionSolverTVD* Landlab component deals with closed boundaries, specifically that advected material cannot exit a closed boundary by definition and as

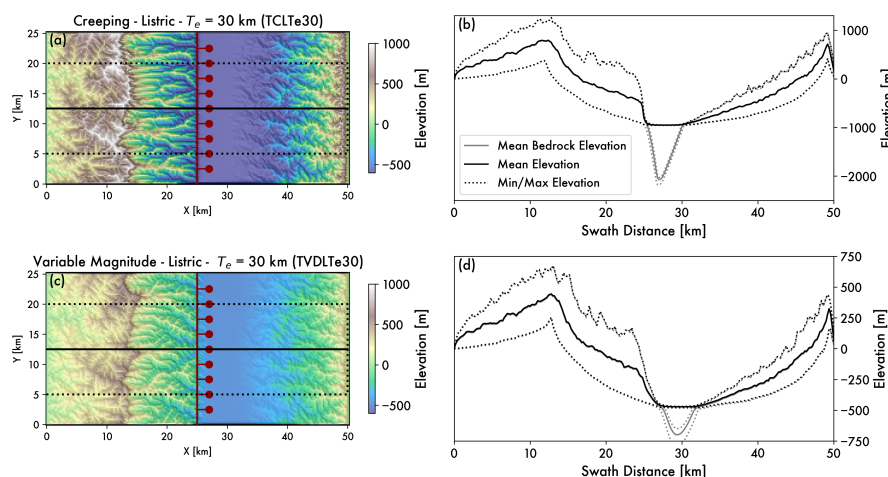


Figure 19. Comparison of model results from models NCLTe30 and NVDLT30 using a listric fault geometry. (a) Model topography after 1 Myr of model NCLTe30. (b) Swath profile through topography and bedrock topography of model NCLTe30. (c) Model topography after 1 Myr of model NVDLT30. (d) Swath profile through topography and bedrock topography of model NVDLT30.

such, having a closed boundary into which large amounts of material are advected will effectively cause material to "pile up",
 760 producing a large ridge along the closed boundary edge. One common solution for strike-slip landscape evolution models is to
 adopt something akin to a "looped" boundary condition, where material advected "out" of the model domain by motion on the
 fault is advected "into" to the model at the opposite side, producing effectively a conveyor of material with some topographic
 variation and avoiding simply advecting topography of a fixed elevation (e.g., Aránguiz-Rago et al., 2025). In the context of the
 presented components, a similar strategy works marginally well for either creeping or simple earthquake scenarios (e.g., fixed
 765 maximum magnitude), but it produces problematic behavior when earthquake sizes and locations are variable that ultimately
 leads to un-realistic topography in part because depending on where earthquakes occur within the domain, tracking whether
 material should be moved to one boundary from another becomes challenging. It additionally leads to challenges if a more
 complicated fault geometry is considered and specifically one where the fault does not "exit" the model at both sides at exactly
 the same position, e.g., a strike-slip fault with a releasing or restraining bend. Alternatively, a landscape could be simulated that
 770 spans the entire fault length, but in the context of the components presented here, this again poses some challenges. Specifically,
 because of the nature of elastic dislocations, the lateral tips of strike-slip faults produce paired uplifts and subsidence (e.g., Fig.
 1c), which in practice means that the topography that is advected "into" the fault, first passes through a subsidence field and
 thus starts at a generally low (often negative) elevation, leading again to unrealistic topography. This can be mitigated in part by
 applying a "slip rate function" as defined earlier where the slip-rate along the fault decreases towards the tips with or without
 775 the addition of flexure similar to normal-sense fault scenarios, but even this does not completely eliminate unrealistic landscape
 evolution.

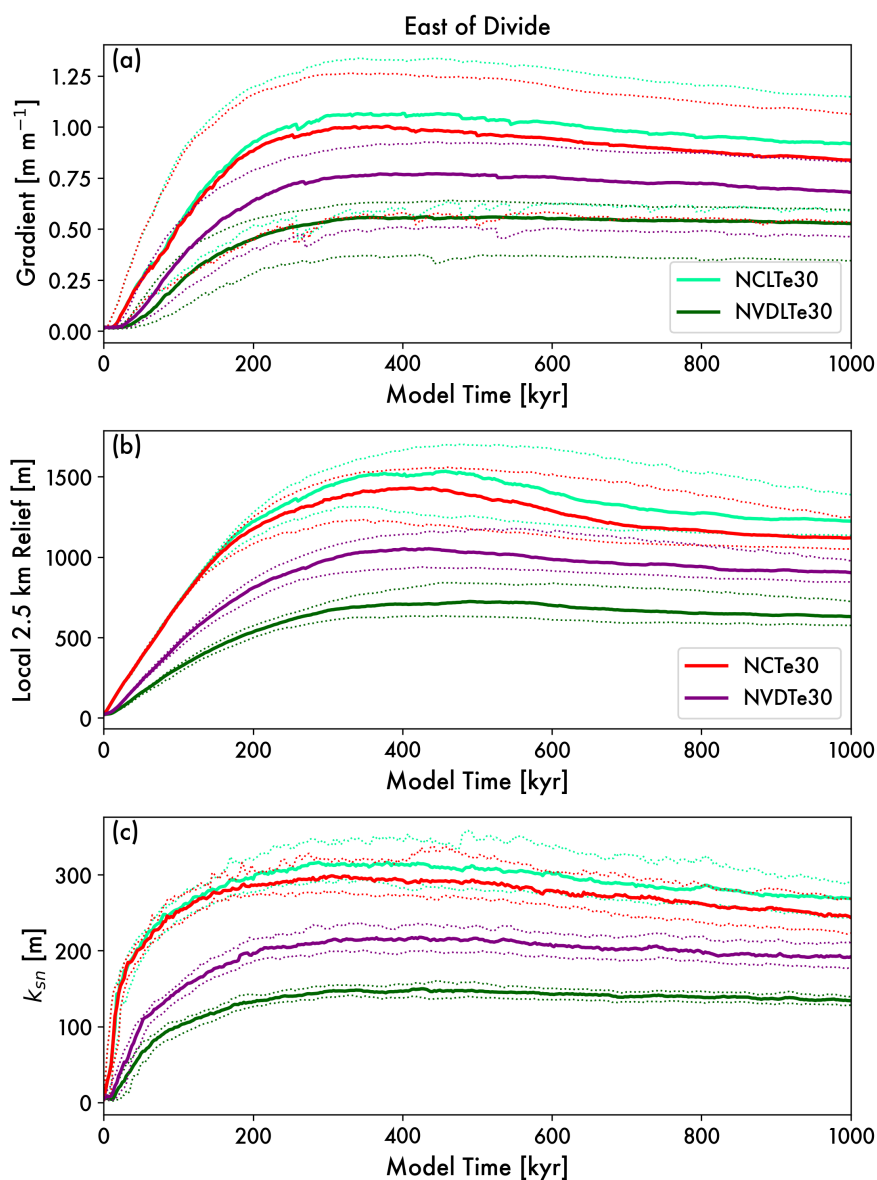


Figure 20. Time series of topographic metrics comparing models NCLTe30 and NVDLTe30 using a listric fault geometry. All models include flexure with a T_e of 30 km. (a) Gradient, (b) local relief measured over a 2.5 km radius, and (c) normalized channel steepness (k_{sn}) with a reference concavity of 0.5. All values are calculated only for the high relief portion of the landscape east of the main divide and west of the upper fault tip, i.e., the portion of the landscape "facing" the fault and within the foot-wall block.



As such, to produce semi-reasonable models using the *VerticalFault* and *EarthquakeSequence* component, especially when using a variable magnitude earthquake generator, an alternative approach is considered here that adapts some aspects of the quasi-looped boundary conditions described above. The strategy I adopt considers a model setup with a strike-slip fault that dominantly strikes parallel to the x-direction of the model domain. As opposed to looping material from one side to the other, during the simulations, I calculate the mean topography from a swath profile oriented perpendicular to the strike-slip fault, and use the mean topography to populate the lateral edges of the domain at each time step. In the first examples, this swath is centered at the center of the x-dimension of the domain (25 km) and is 20 km wide. This has the effect of ensuring that material advected into the model has topography somewhat consistent with adjacent nodes in a strike-direction sense, does not require tracking of magnitude and directions of displacement at the domain edges, and because the swath is updated at each time step, also ensures that the elevation of advected nodes are not a simple constant value. An additional detail of the simulation setup is that the boundary conditions of the model change during each step of the model loop. Specifically, all boundaries are opened prior to running the "run_one_step" method of instances of both the *VerticalFault* and *EarthquakeSequence* components to allow advected material to exit (or enter from the boundary nodes) the model domain, but then any boundaries that were closed (to force drainages in a particular direction) are re-closed before instances of erosional and depositional components are run.

Additionally, while in the case of both thrust-sense and normal-sense dip-slip scenarios, more traditional fluvial incision models that primarily consider vertical incision were able to produce realistic channel networks and behaviors (e.g., Fig. 7, 10, 16, & 19), this is generally not the case with strike-slip sense scenarios at comparable domain sizes and resolutions. Specifically, whether considering a surface process model that tracks sediment, like *SpaceLargeScaleEroder* that was used in the presented normal- and thrust-sense models, or a simpler detachment limited stream power component like *FastscapeEroder*, strike-slip sense models using either of these components tend to not exhibit clear translation and deflection of streams oriented perpendicular to fault strike, a hallmark of many natural streams crossing strike-slip faults (Fig. 21). Instead, simulating landscape evolution with these components produces streams oriented perpendicular to the fault that tend to become entrenched somewhat early in the model run and remain largely undeformed and where the lateral deformation the model surface is experiencing is largely reflected in lengthening or shortening of smaller tributaries oriented parallel to the strike of the fault. Notably, this differs from a variety of prior efforts simulating landscape evolution in the presence of strike-slip faults that produced offset channels, which used either comparable fluvial incision models (Duvall and Tucker, 2016) or some of the same Landlab components considered here (Gray et al., 2018; Reitman et al., 2019; Aránguiz-Rago et al., 2025). There are two possible explanations for this difference in behavior that themselves may be related. First, none of these prior efforts used the *AdvectionSolverTVD* to accomplish lateral motion and instead the majority took an approach of calculating when sufficient slip had been accommodated (given the imposed slip-rate and the grid size) to equal the size of a single grid cell and then effectively translated all of the grid cells on one side of the fault by one cell in the direction of slip, so it is possible that some aspect of this behavior is thus specific to the *AdvectionSolverTVD*. Tests implementing a much simpler creeping strike slip fault with just the *AdvectionSolverTVD* (i.e., not using the *VerticalFault* component or elastic dislocations) with otherwise the same model setups as the creeping strike-slip example here produced identical behavior as in Figure 21, suggesting that it is a behavior more related to the *AdvectionSolverTVD* component than anything having to do with the consideration of elastic dislocations.



Critically though, the model scenarios considered in the strike-slip examples here are run with a 1-2 order of magnitude larger grid resolution (100 m) than previous published examples with those using grid resolutions of 1 m (Reitman et al., 2019), 5 m (Duvall and Tucker, 2016; Gray et al., 2018), or 10 m (Aránguiz-Rago et al., 2025). Limited tests at comparable grid resolutions (on much smaller domains) suggests that this does contribute in a meaningful way, where strike-slip faults simulated using the *AdvectionSolverTVD* and these vertical incision rules were able to produce offset across-strike channels when resolution was much higher (i.e., smaller individual grid cells), but depended also on slip-rate and channel spacing. In contrast, even at the large spatial domains and the grid resolution as used in the main tests (Fig. 21), when the same strike-slip scenario is run using a surface process model that considers both lateral and vertical channel incision, specifically the *LateralEroder* (Langston and Tucker, 2018), streams oriented perpendicular to the strike direction of the fault tend to be deflected and deformed in a manner more consistent with natural streams crossing strike-slip faults (Fig. 21). To maintain a larger domain at lower resolution in the examples, I thus use *LateralEroder* to model fluvial incision for the remaining strike-slip scenarios, but emphasize that the choice of the "right" incision model in scenarios with large magnitudes of horizontal motion will likely be velocity, grid resolution, and channel network dependent. The *LateralEroder* component requires that flow accumulation and routing be done with the *FlowAccumulator* and I pair this with simple linear diffusion on hillslopes using the *LinearDiffuser*.

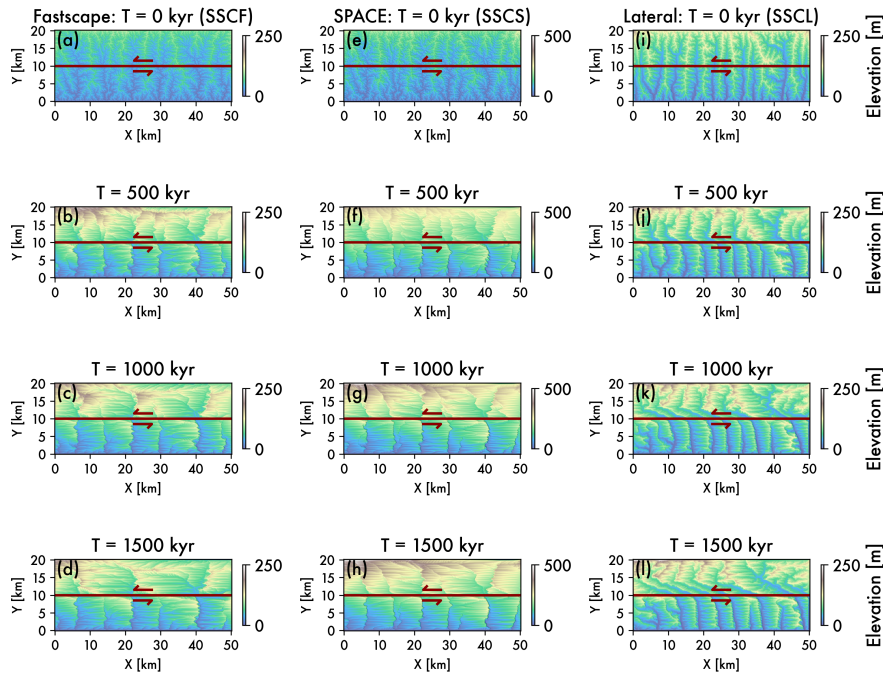


Figure 21. Comparisons of the evolution of left-lateral creeping strike-slip fault using different Landlab fluvial incision components at four representative time steps. (a-d) Model SSCF using the *FastEroder*. (e-h) Model SSCS using the *SpaceLargeScaleEroder* (Shobe et al., 2017). (i-l) Model SSCL using the *LateralEroder* (Langston and Tucker, 2018). All models have a resolution of 100 m.



For the first set of detailed examples (and the examples testing different incision rules, e.g., Figure 21), I compare landscape evolution after 1.5 Myr on a 100 km long fault, centered within the model domain. Unlike the thrust-sense and normal-sense scenarios, the initial topography for this scenario considered an entrenched drainage network with closed boundaries on all sides but the bottom edge to enforce drainages primarily flowing in one direction, perpendicular to the strike of the fault. Additionally, this initial topography was started with an initial slope, facing toward this bottom open boundary, with a total relief of 10 m, to force the development of narrow, quasi-linear drainages prior to initiation of fault movement, similar to the initial model setup used by Reitman et al. (2019). A final difference is that while the normal and thrust-sense models used a grid spacing of 200 m, the strike-slip simulations use a grid spacing of 100 m to provide finer resolution of the lateral motion of channels. The strike-slip fault was simulated as being 40 km wide, i.e., the fault extends to 40 km depth, with a 20 mm yr^{-1} left-lateral sense of slip. For scenarios with earthquakes, the seismogenic depth was considered to be between 1000 and 20,000 m depth. Similar to prior efforts simulating landscape evolution related to strike-slip deformation (e.g., Duvall and Tucker, 2016; Gray et al., 2018; Reitman et al., 2019), in addition to surface deformation from motion on the elastic dislocations, I also impose a steady 0.5 mm yr^{-1} vertical uplift rate to maintain relief within the model domain.

I first compare the result of a simulation with steady creep (model SSCL) over the whole fault surface with that of a simulation with earthquakes, using the variable magnitude generator and where the earthquake sequence is clipped by moment (model SSVML). In detail, model SSCL is the same as in the comparison with alternative fluvial incision models (e.g., Fig. 21i-l). As with the thrust and normal models, there are a variety of differences between the topography developed in creeping vs earthquake driven models (Fig. 22). One of the more noticeable aspects is that in model SSVML, rivers, and their corresponding interfluvies, tend to be more curved, especially downstream of the fault, when compared to the corresponding time step in the creeping model SSCL. While on average the total horizontal displacement accommodated by the two simulations are comparable (e.g., Fig. 22d & i), closer inspection shows that there is more across-strike variability in model SSVML, specifically with a more prominent decrease of total (absolute value) strike-parallel slip near the fault, which produces the curving nature of the streams.

Another noticeable difference between the creeping and earthquake model is that at any given distance from the fault, the former has more consistent relief than the latter. Specifically, in model SSVML there are noticeable lower relief and average elevation areas in the northeast and southwest corners of the model domain. Inspection of the total vertical displacement (Fig. 22e & j) at the end of the run reveals that in SSVML, these areas correspond to locations of local minima in the total vertical displacement. Ultimately, this reflects that over the accumulated time of the model, enough individual earthquake ruptures are located such that their lateral tips occur within (or near the edge) of the domain to impart some amount of the characteristic pattern observed in strike-slip elastic dislocations, namely a paired zone of positive and negative vertical displacements at the tips (e.g., Fig. 1c), within the total displacement field. Some of the strength of this signal may reflect details of the model setup, namely because the length of the fault (100 km) is relatively short with respect to the along-strike model domain (50 km), a relatively large proportion of ruptures will have at least one of their lateral tips that occur in the domain, whereas if the fault was longer (and thus could accommodate longer ruptures), fewer of the larger ruptures would have lateral tips that occurred in the domain. This also likely reflects some aspects of the simplifications made within the model structure itself, namely because

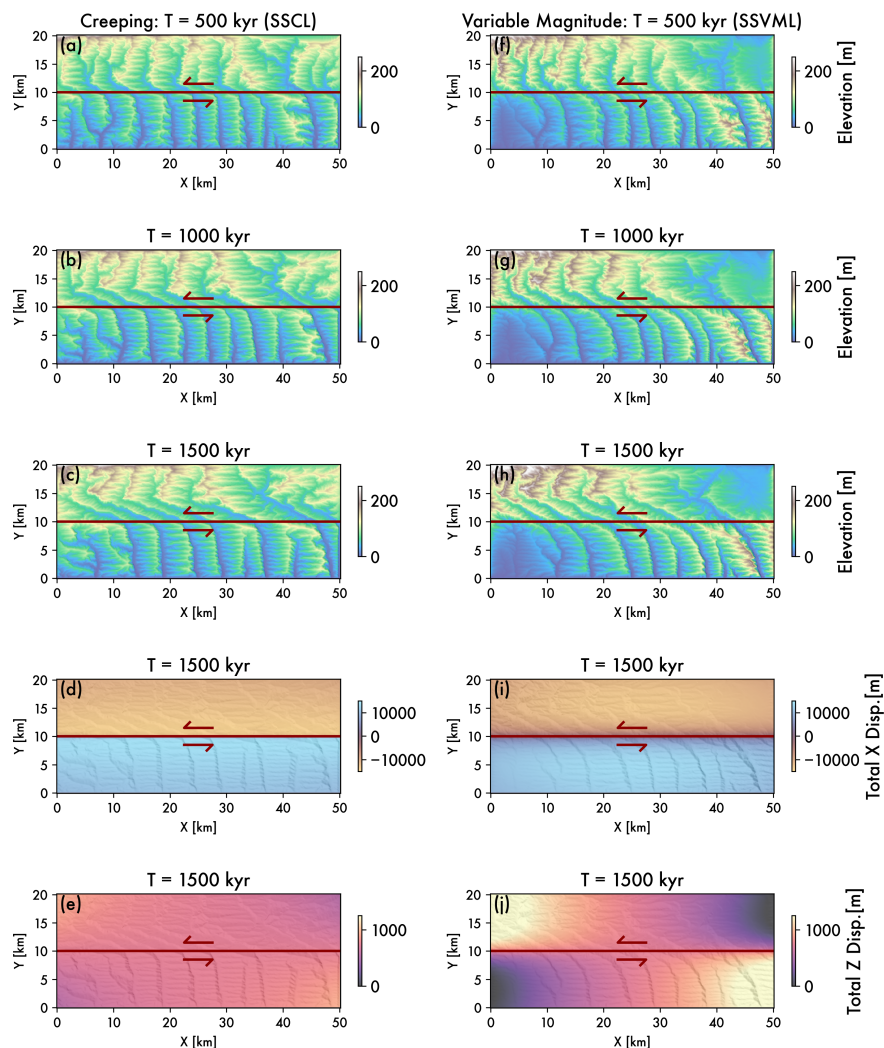


Figure 22. Comparisons of the evolution of models SSCL and SSVML. (a-c) Topography of model SSCL when time is 500, 1000, and 1500 kyr respectively, (d) Total displacement in the X-direction at the end of the 1.5 Myr run for model SSCL. (e) Total displacement in the Z-direction at the end of the 1.5 Myr run for model SSCL. (f-h) Same as (a-c) but for model SSVML. (i) Same as (d) but for model SSVML. (j) Same as (e) but for model SSVML.



ruptures are simulated as rectangular, constant displacement elastic dislocations, the paired uplift and subsidence signal at the lateral tips of ruptures will tend to be more extreme than more complicated, and realistic, ruptures, i.e., where displacement decreases toward the tips. While at present the model is not constructed in a way to allow ruptures with variable displacement, the behavior observed in this simulation could be partially addressed by applying a flexural model as in the normal-sense fault scenarios.

As a final example, I consider a similar comparison between simulations driven by steady creep over the whole fault surface (model SSCRBL) or variable magnitude earthquakes (SSVMRBL), but in the case with a left-lateral strike-slip fault with a right-step, i.e., a restraining bend, in the center of the model domain (Fig. 23) to highlight the capacity of the *EFEL* components to simulate more complicated fault geometries than prior efforts (e.g., Duvall and Tucker, 2016; Gray et al., 2018; Reitman et al., 2019; Aránguiz-Rago et al., 2025). The other details of the fault are similar to the simple strike-slip example with an identical total fault length, total fault width, and slip-rate. A similar swath approach is taken for generating suitable topography to impose along the lateral edges of the model to be advected in, but in this suite of models, the width of the swath is reduced to 15 km and the center of the swath is placed at 40 km from the left edge of the domain to avoid sampling through the center of the restraining bend. As one would expect, in both the creeping and earthquake models there is a zone of localized high total vertical displacement centered along the restraining bend that in turn forms a high topographic relief area along and extending outward from this restraining bend (Fig. 23). Similarly, as with the strike-slip model without the restraining bend, in model SSVMRBL low-relief areas develop in the northeast and southwest corners, which are co-located with local minima in the total vertical displacement (Fig. 23e & j). The reduction of relief is more extreme in the seismic restraining bend model, largely because this area of low relief is also being sampled within the swath used to populate the edges, so in effect, this low-relief area is reinforced by advecting in low-relief areas at a similar across-strike position. Thus, some of the behavior is more of an artifact of the model setup, which could be remedied by either sampling the model in a different place for the swath or modifying the mean topography before using it along the edge of the model.

6.2 Improving Computational Performance

Within *DippingFault*, *VerticalFault*, or *EarthquakeSequence* components, the most computationally intensive portion of any time step is the calculation of surface velocities resultant from movement on elastic dislocations. During an operation that only includes calculations for a small number of dislocations, the computation time is still generally quite small, though this will depend on the total number of nodes within the Landlab grid. However, depending on the details of how components were instantiated, the geometry of the fault, the length of the time step, or parameters set within earthquake generators, the number of individual dislocations that must be calculated during a single time step can become substantial. For this reason, an option to use parallel processing is provided, which relies on the Python *multiprocessing* module. Importantly, it should be noted that using parallel processing does not uniformly improve performance, effectively because there is significant "startup cost" from initiating a parallel pool. In cases where the time to start a parallel pool and assign jobs to the workers in the pool takes longer than if the calculation was simply done in series on a single processor, using parallel processing can actually degrade

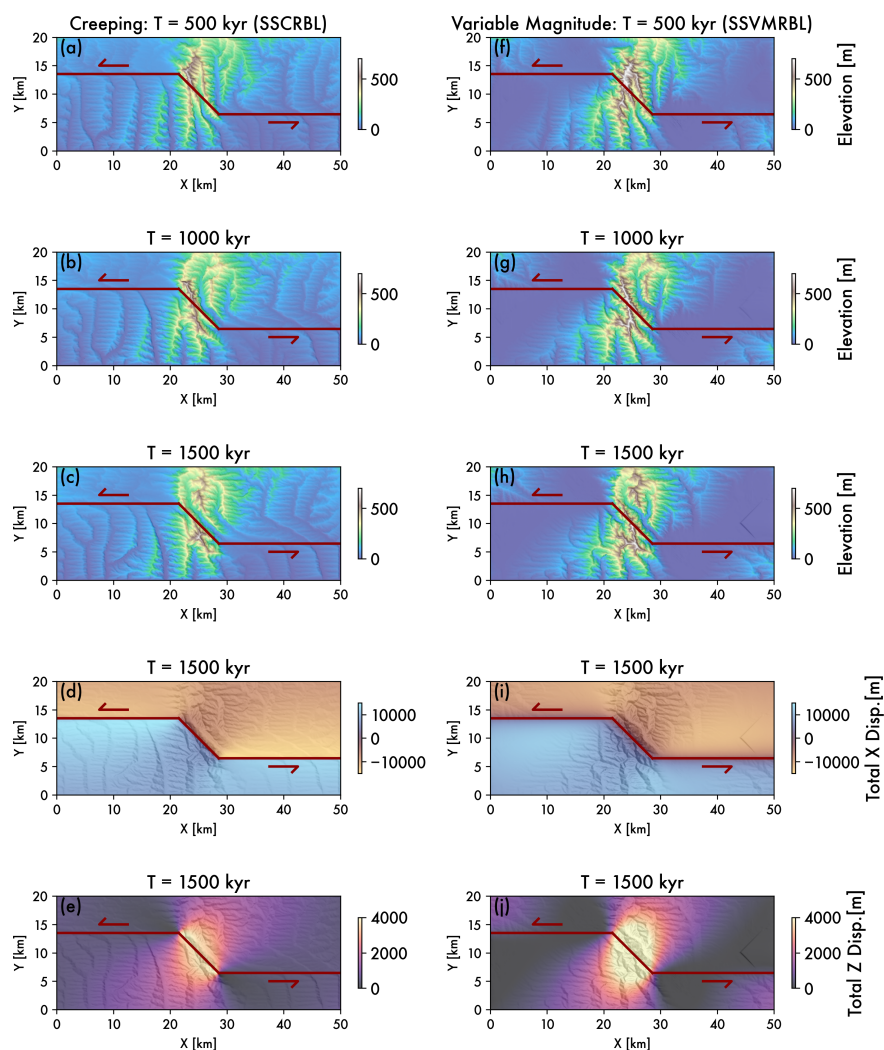


Figure 23. Comparisons of the evolution of models SSCRBL and SSVMRBL. (a-c) Topography of the SSCRBL when time is 500, 1000, and 1500 kyr respectively, (d) Total displacement in the X-direction at the end of the 1.5 Myr run for model SSCRBL. (e) Total displacement in the Z-direction at the end of the 1.5 Myr run for model SSCRBL. (f-h) Same as (a-c) but for model SSVMRBL. (i) Same as (d) but for model SSVMRBL. (j) Same as (e) but for model SSVMRBL.



performance. Similarly, there will generally be an optimum in terms of the number of processors added to the pool that will
895 actually continue to significantly improve performance.

To demonstrate this trade off, I present two sets of simulations with largely identical setups as those in the simple thrust
model scenarios. For all models in this set of experiments, I use the variable generator with a time step length of 5 yr, but for
one series this was run with a minimum moment magnitude of 4 whereas the other series used a minimum moment magnitude
of 5 as in the simple thrust experiments. Functionally this means that the number of dislocations needed to be calculated per
900 time step was significantly higher for the series with a lower minimum moment magnitude (Fig. 24). For all scenarios, I ran
the simulation in question for 1000 yr of model time but with either parallel processing turned off (i.e., simulations plotting
with 1 core) or parallel processing turned on and set to use between 2 and 16 processors, where 16 was the maximum number
of processors on the computer being used to perform the test. For all runs, the simulation in question was the only process
being run and all simulations were run on the same desktop machine (a 2025 Mac Studio with an Apple M4 Max processor
905 with 16 cores and 128 GB or RAM). As shown in Figure 24, for the scenario with a minimum moment magnitude of 5, and
generally less than 10 events per time step, using a single core and no parallel processing is actually the most efficient choice.
In contrast, when the minimum moment magnitude was 4 and generally there were between 20 and 50 events per time step,
running the model with a single core was the least efficient and running in parallel mode generally increased performance but
with relatively small increases above 6 cores included in the pool. Importantly, these results should not be viewed as a specific
910 recommendation for the number of cores or choice of single vs parallel processing as details will depend on the model setup and
computer specifications, but more a suggestion that small scale tests should be performed to determine whether using parallel
processing will increase or decrease performance for any given suite of simulations using the *DippingFault*, *VerticalFault*, or
EarthquakeSequence components.

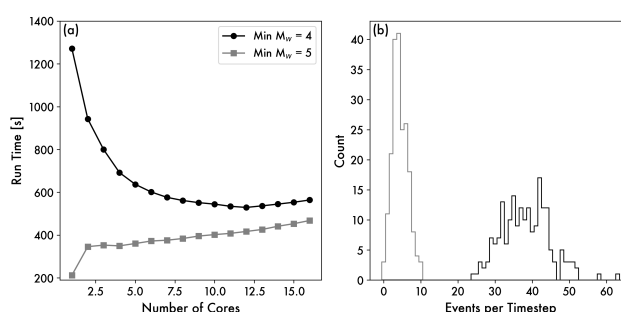


Figure 24. Results of tests for effect of parallel processing on computation time. (a) Computation time of the candidate 1000 yr of model
simulation using different total numbers of cores within the parallel pool. (b) Distribution of events per time step for the two different
scenarios considered in the experiment.



6.3 Evaluating Effect of Time Step Length

915 As with any landscape evolution model, another strategy for decreasing computation time is to increase time step length, however, for many process components, especially those that use a finite difference scheme, increasing the length of time step can lead to numerical stability issues. This is not specifically the case with any of the components presented here, though it can become an issue for the *AdvectionSolverTVD* component which is used internally in the *DippingFault*, *VerticalFault*, and *EarthquakeSequence* components, but for the *EarthquakeSequence* component, and specifically in cases using the variable
920 magnitude earthquake generator, increasing time step length also increases the number of earthquakes considered in a given time step. Increasing the number of events per time step has two effects; 1) it generally will increase the computation time per time step (which may be partially offset by use of the parallel processing option described previously and/or the resulting reduction of the total number of time steps for a simulation of a fixed length) and 2) it begins to average some amount of the "sharpness" of surface deformation fields from individual earthquakes as surface velocities of a greater number of earthquakes
925 are added together.

As a test of the impact of time step choice, I ran a suite of simulations with the same geometry and fault kinematics as the simple thrust tests using a variable earthquake generator with a minimum moment magnitude of 5, but ran this suite of models for 1 Myr and with time step lengths of 5, 10, 25, 50, 100, 250, or 500 yr. All of these time steps are still shorter than the maximum time step to maintain numerical stability given the grid size and other relevant model parameters, but they have
930 significantly different implications for the number of events per time step (Fig. 25). It should be emphasized that all of these models had identical earthquake catalogs, i.e., they all experienced the exact same earthquakes through the duration of the runs, but the timing of occurrence of those earthquakes effectively varied because of the accumulation of earthquakes during time steps. To a first order, Figure 25 highlights that the evolution of all the landscapes are broadly similar, but that finer details differ in some cases. Interestingly, examples can be found throughout the time series of portions of the record that are largely
935 the same, e.g., the majority of the different simulations show a positive or negative spike in one or more of the metrics at effectively the same time, and other examples of unique behavior, e.g., a spike in one metric for a particular time step length does not appear in other runs. Qualitatively, normalized channel steepness seems to be the most sensitive to time step choice in the sense that the time series of this metric is generally the most unique between time step lengths, whereas gradient appears less sensitive. Ignoring the higher order variability in the time series, with a time step below 100 yr, temporal evolution is
940 quite similar, but moving to larger time steps, the absolute magnitude of the topographic metrics begin to noticeably change, especially for local relief and to a lesser extent normalized channel steepness and gradient. Across all the simulations, it should be noted that the characteristic "noise" of simulating earthquakes remains when compared to simulations of steady fault creep without earthquakes (e.g., Fig. 9). Ultimately, this highlights that time step length choice does matter, but the extent to which it changes the outcome of simulations likely depends on the questions being asked with the simulations in question, but that
945 even at relatively long time steps, the stochastic nature of including earthquakes within landscape evolution is still preserved at least in a gross sense.

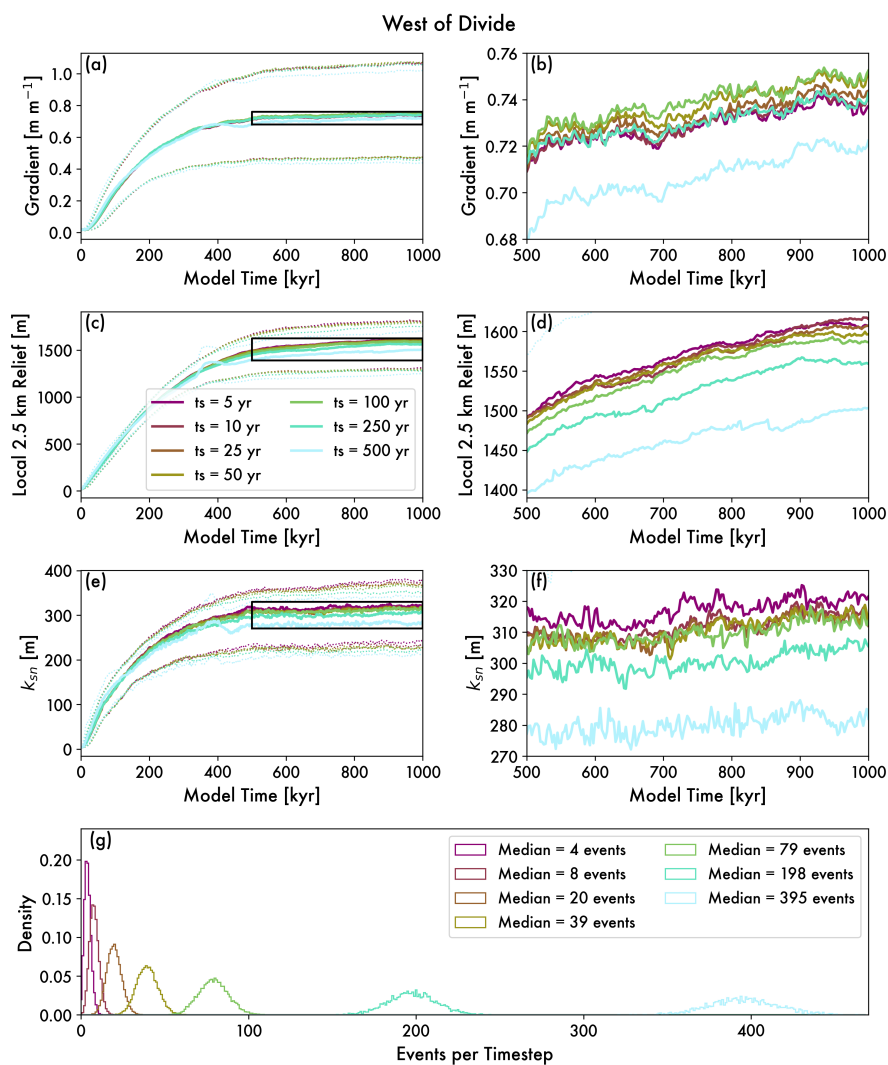


Figure 25. Quantification of (a-b) gradient, (c-d) local relief, and (e-f) normalized channel steepness as a function of model time for models with different time step lengths across the entire 1 Myr run duration. Black boxes show portion of time series examined in right column plots. (g) Distributions of events per time step for the runs with different time step lengths.



6.4 Model Component Limitations and Future Directions

As with any numerical model, a variety of simplifications, many of which have been described in some detail in previous sections of this paper, are necessary to make aspects of simulating the considered processes tractable, but which impose certain limitations on either the applicability of the model or the natural features that can be interpreted, or reproduced, with the model. Some simplifications and associated limitations are partially surmountable by creative model setups, while others are more inherent to the design of the components and less easily remedied. For example, the design of the fault component is predicated on the idea of simulating single faults with both static dimensions and slip-rates, where in reality, faults grow through time and their slip-rates similarly may vary through time. While neither the geometry or slip-rate of a modeled fault are designed to be mutable within a given instance of a fault component, because of the flexible design of Landlab, simulations using these components could be designed which include prescribed growth rates for faults wherein new fault instances with new dimensions are generated at a given time-interval and/or new instances with new slip-rates are similarly created and used. The binning of individual earthquakes within a given time step is another example of a simplification that can be partially remedied by model design or setup, specifically, as the length of the time step is decreased, the resulting simulations will better match reality as the temporal occurrence of earthquakes within the model get closer to the time of occurrence within the generated synthetic catalog, but which obviously begin to increase the number of time steps, and thus often the computation times, for model runs.

Other limitations are less easily solved through creative simulation design, like the limitation that all panels of a *DippingFault* instance will have the same strike or that all panels of a *VerticalFault* instance are restricted to having a vertical dip. Similarly, it is common for real active tectonic environments to have more than one active fault that can interact in complicated ways. There is nothing precluding a simulation from having more than one instance of a fault (and associated earthquake sequence, etc.) that is considered during a run, but at present, none of the components are designed to consider interaction of faults and their respective earthquake sequences, e.g., as currently implemented, the components here would not be able to simulate scenarios where earthquakes "jump" gaps between individual fault strands (e.g., Lozos et al., 2012; Biasi and Wesnousky, 2016; Rodriguez Padilla et al., 2024) and motion on one fault would not modify the geometry or likelihood of particular earthquakes on another fault within a simulation.

Similar sets of limitations exist for the treatment of coseismic landslides within the *CoseismicLandslider*. Specifically, while the simple Newmark sliding-rigid-block model that lies at the heart of the *CoseismicLandslider* is generally considered accurate in estimating the location of coseismic landslides to a first order, these estimations may be more robust when using a more integrative treatment of the seismic shaking, such as the Arias intensity (Arias, 1970) that accounts for the entire acceleration content of an event as opposed to a single measure like peak ground acceleration (e.g., Jibson, 1993, 2007, 2011) as the *CoseismicLandslider* uses. In detail, there are analogous GMPE designed to predict Arias intensity that require largely similar information to the set of GMPE I use here to predict PGA (e.g., Foulser-Piggott and Stafford, 2012; Campbell and Bozorgnia, 2012; Foulser-Piggott and Goda, 2015; Bahrampouri et al., 2021), and as such, incorporation of these into the *CoseismicLandslider* is a potentially fruitful next step in future development of the component. Additionally, more complicated



methods for calculating permanent displacements from earthquake shaking that acknowledge that landslide blocks themselves are typically non-rigid (e.g., Makdisi and Seed, 1978; Bray and Rathje, 1998) and/or that the movement of the landslide block may influence the earthquake induced ground motions (e.g., Bray and Travararou, 2007) could similarly produce more accurate estimations than the method employed here. Finally, there is a variety of evidence that critical material properties, like the friction coefficient of the hillslope material, may effectively be different values during earthquake shaking as opposed to during inter- or postseismic periods and may also evolve through time as a function of the earthquake history (e.g., Li et al., 2025). Integration of one or more of these more complex models or treatments of earthquake induced landslides might produce more accurate populations of coseismic landslides during simulations, but as with similar complexities of the underlying fault or earthquake models, also would likely increase computation time and require more parameters with increasing levels of uncertainty when applied to a wholly synthetic application. That being said, some alternative approaches that are still relatively simple, like supplementing PGA with Arias intensity, may still represent useful avenues for continued development of the *CoseismicLandslider*.

In terms of the fault and earthquake related aspects of *EFEL*, perhaps two of the largest simplifications are the treatment of both fault creep and individual earthquake events as solely elastic dislocations in a linear elastic medium and earthquake occurrence as a purely stochastic process. Considerable evidence highlights that more complicated rheologies, e.g., viscoelastic, and related consideration of effects like postseismic relaxation are necessary to explain detailed observed surface deformation related to earthquakes (e.g., Savage, 1983, 2000; Savage et al., 2005; Hetland and Hager, 2005; Avouac, 2015; Thompson and Parsons, 2016; Sobolev and Muldashev, 2017) and that consideration of the composite effect of these more complicated rheologies are likely important for understanding long-term landscape evolution (e.g., Cattin and Avouac, 2000; Simpson, 2015; Baden et al., 2022; Oryan et al., 2024). Similarly, treating earthquake locations on a fault as a purely stochastic process, as is effectively done within the *EarthquakeSequence* component, is also a large simplification and ignores that the location of future earthquakes will reflect the past location of earthquakes (e.g., Kanamori and Brodsky, 2004; Brodsky et al., 2020). The justification for the utility of the described components despite these simplifications is that to the extent that there is value in simulating long-term landscape evolution driven by individual earthquakes, using simple elastic dislocation models is still a large improvement over prior efforts that either do not directly simulate earthquakes (e.g., Goren et al., 2015; Duvall and Tucker, 2016; Aránguiz-Rago et al., 2025), represent earthquakes and fault creep largely as simple block motion (e.g., Steer et al., 2019; Reitman et al., 2019), or lack consideration of interseismic creep and coseismic landslides within a modern LEM framework (e.g., Densmore et al., 1998; Allen and Densmore, 2000; Densmore et al., 2003). Additionally, these existing limitations represent fertile avenues for future improvements or development of comparable components that model fault and earthquake slip with more realistic rheologies, e.g., through the replacement of elastic dislocations with existing software like PyLith (e.g., Aagaard et al., 2013; Walker et al., 2023), and/or replacing stochastic placement and timing of earthquake ruptures with outputs from dynamic rupture simulations (e.g., Harris et al., 2018; Jiang et al., 2022; Im and Avouac, 2024).



7 Conclusions

I present a suite of Landlab components, collectively *EFEL*, for simulating landscape evolution in the context of surface deformation resultant from steady fault-creep or individual earthquakes, where both are modeled as fixed displacement, rectangular dislocations in an isotropic elastic half-space, and additionally model coseismic landslides. The *DippingFault* and *VerticalFault* components allow generation of complex fault geometries of either a fault with a fixed length and strike but with an arbitrary number of panels that extend at depth with variable widths and dips or a fault with a fixed (vertical) dip and width but with an arbitrary number of panels that extend horizontally with variable lengths and strikes. The *DippingFault* or *VerticalFault* components can be used to simulate surface deformation of either fully creeping faults or the interseismically creeping portions of seismogenic faults. When used in concert with the *EarthquakeSequence* component, these can be used to simulate surface deformation resultant from a series of earthquakes over geologically relevant timescales. Toward that end, the *EarthquakeSequence* component can generate semi-realistic earthquake catalogs of varying complexity for use in landscape simulations. Finally, the *DippingFault* or *VerticalFault* and *EarthquakeSequence* components can be paired with the *CoseismicLandslider* component to simulate landslides that would be expected to result from individual earthquakes. The *CoseismicLandslider* incorporates a series of ground motion prediction equations, a simple approximation of seismic site effects (through estimation of V_{s30}), and a Newmark sliding-block analysis to predict where coseismic landslides would occur and use of the existing Landlab component *BedrockLandslider* to fail and route coseismic landslide material.

Together, the components have a wide range of possible applications, especially when paired with existing Landlab components for simulating other aspects of landscape evolution. I provide some basic examples of applications of these components to the simulation of landscapes developed above both aseismic and seismically active thrust faults, normal faults, and strike-slip faults. I also consider an example of a landscape developed with coseismic landslides formed above a seismically active thrust fault. In presenting these examples, I also consider some best practices and suggestions for pairing these components with existing Landlab components to produce geologically reasonable landscape evolution.

Code availability. The source code for the current version of the *Elastic Fault, Earthquake, and Landslide* Model is available from the project website http://github.com/amforte/elastic_fault_earthquake_and_landslide under the MIT License. A static version of the model, input files for the example models included in this contribution, and a series of tutorials as Jupyter notebooks are archived on Zenodo under <https://doi.org/10.5281/zenodo.21744823> (Forte, 2026). Though *Landlab* (<https://github.com/landlab/landlab> - last access: June 2026) is required to use *EFEL*, *EFEL* is not currently a part of *Landlab* releases, so *Landlab* must be installed to successfully use *EFEL*, and *EFEL* must be acquired from the standalone repository provided here. Similarly, *EFEL* requires a compiled version of *okada4py* (Jolivet, 2024) (<https://github.com/jolivet/okada4py> - last access: January 2025) to run, but this is not distributed with *EFEL* so also must be acquired separately and compiled prior to use of *EFEL*.



Appendix A: Earthquake Catalog Distributions

Below I review the four distributions that can be used within the *EarthquakeSequence* component if generating an earthquake
1045 sequence with the variable magnitude generator. The details of these distributions come from Kagan (2002).

A1 Characteristic

The characteristic distribution is effectively that defined by Youngs and Coppersmith (1985) which is largely a Gutenberg-Richter distribution that is truncated to only be defined above a minimum moment M_t and below a characteristic moment M_c . In terms of earthquake catalogs, M_t would roughly be equivalent to the magnitude of completeness, i.e., the minimum
1050 magnitude within the catalog for which it is considered that every event has been recorded. For the purposes of this component, M_t is treated as the minimum magnitude of earthquake the user wishes to simulate.

The survivor function (1 - cumulative distribution) for this distribution is:

$$S(M) = \frac{M_t^\beta}{M} \text{ for } M_t \leq M \leq M_c \quad (\text{A1})$$

In this (and subsequent distributions), β is the shape parameter of the distribution and is generally considered to be equal
1055 to $\beta = \frac{2}{3}b$, where b is the so-called *b-value* in the Gutenberg-Richter relation, typically assumed to be close to 1. As such, the default value for β is set to $\frac{2}{3}$ and it is generally suggested to not modify this value unless without fully understanding the implications (and reasons) for changing this parameter.

There has been significant debate on the appropriateness of the characteristic distribution for describing seismic catalogs, but it may be generally appropriate for describing the distribution of events on a single fault, as is considered in this component.

1060 A2 Truncated Pareto Frequency-Moment Distribution

The truncated Pareto distribution is a modified form of a standard Gutenberg-Richter distribution that is truncated to only be defined between a minimum moment M_t and a maximum moment M_{xp} , in many ways similar to the characteristic distribution. The survivor function (1 - cumulative distribution function) of this distribution is:

$$S(M) = \frac{(M_t/M)^\beta - (M_t/M_{xp})^\beta}{1 - (M_t/M_{xp})^\beta} \text{ for } M_t \leq M \leq M_{xp} \quad (\text{A2})$$

1065 Functionally, in empirical distributions, the M_{xp} parameter should be the maximum seismic moment observed within the catalog. In the implementation here, the default behavior is that M_{xp} is treated as the maximum moment that is able to be supported by the seismogenic portion of the fault. While referred to as a "truncated" Pareto, it effectively produces a very light tail that asymptotes to the M_{xp} compared to a hard cut off as observed in the characteristic distribution.



A3 Tapered Pareto Frequency-Moment Distribution

1070 The Tapered Pareto distribution is similarly truncated at a lower threshold moment M_t , but instead of having an upper truncation, it effectively has a taper applied to the tail of the distribution and where it deviates from a scale-invariant power law above a "corner moment", M_{cm} . This corner moment should largely be considered an independent parameter unrelated to the specific catalog being generated. It is a free parameter in the generator, but it is set by default to 8.1 as determined by Kagan (2002). The survivor function is:

$$1075 \quad S(M) = (M_t/M)^\beta \exp\left(\frac{M_t - M}{M_{cm}}\right) \text{ for } M_t \leq M < \infty \quad (\text{A3})$$

As implemented, the default behavior in the component will still remove any earthquakes that exceed the maximum supported by the fault regardless of what the corner moment is set to. The component has two alternate behaviors in this regard, it can either remove events that exceed the fault maximum from the generated catalog or replace events that exceed the fault maximum with events of the size of the fault maximum. The latter has the effect of tending to generate more earthquakes at the maximum magnitude the fault can allow and thus tends to produce a distribution that will be closer in form to the characteristic distribution.

A4 Modified Gamma Frequency-Moment Distribution

1085 The modified form of a Gamma distribution is broadly similar to the Tapered Pareto, but does not produce as strong a taper of the tail above the corner moment. It is similarly suggested that the value of the corner moment M_{cm} is not changed from the default of a M_w of 8.36 as determined by Kagan (2002). The survivor function is:

$$S(M) = C^{-1} (M_t/M)^\beta \exp\left(\frac{M_t - M}{M_{cm}}\right) * [1 - (M/M_{cm})^\beta \exp(M/M_{cm}) \Gamma(1 - \beta, M/M_{cm})] \quad (\text{A4})$$

where

$$C = 1 - (M_t/M_{cm})^\beta \exp(M_t/M_{cm}) \Gamma(1 - \beta, M_t/M_{cm}) \quad (\text{A5})$$

1090 and Γ is the upper incomplete gamma function. As with the tapered pareto, this distribution can produce earthquakes that exceed the fault maximum and these events are dealt with in the same way, i.e., they can either be removed or replaced depending on user choice.

Appendix B: Branching Aftershock Sequence Model

As described in more detail in Turcotte et al. (2007), the recursive Branching Aftershock Sequence (BASS) model functions mostly on the principle of random selection from a series of cumulative distribution functions. As implemented, this effectively



1095 means the underlying procedure selects a random value between 0 and 1 and then solving for the desired parameter of the particular aftershock. The BASS model first determines the expected number of aftershocks N_{dT} based on the magnitude of the parent event m_p , such that:

$$N_{dT} = 10^{b_d(m_p - \Delta m^* - m_{min})} \quad (B1)$$

where b_d and Δm^* are constants and m_{min} is the minimum magnitude earthquake that is considered able to generate an aftershock, functionally the minimum magnitude for any generated aftershock. To determine the magnitudes of aftershocks, BASS uses a cumulative distribution function P_{Cm} derived from a modified form of Båth's law, such that:

$$P_{Cm} = 10^{-b_d(m_d - m_{min})} \quad (B2)$$

where m_d are the magnitudes of the generated aftershocks. To determine the time of the aftershock relative to the parent event, BASS uses a cumulative distribution function P_{Ct} derived from Omori's law, such that:

$$1105 \quad P_{Ct} = \frac{1}{(1 + t_d/c)^{p-1}} \quad (B3)$$

where c and p are constants and t_d are the times of the aftershocks (in days) relative to the parent event. To determine the radial distance of the aftershock center from the parent earthquake center, the BASS model uses a cumulative distribution function P_{Cr} derived from a spatial Omori's law, such that:

$$P_{Cr} = \frac{1}{(1 + r_d/(d \cdot 10^{0.5m_p}))^{q-1}} \quad (B4)$$

1110 where d and q are constants and r_d is the radial distance, in meters, between the parent event and the aftershock. By default within the component, all values of the constants are set to those as suggested in Turcotte et al. (2007), specifically, $b_d = 1$, $\Delta m^* = 1.25$, $c = 0.1$ days, $p = 1.25$, $d = 4.0$ m, and $q = 1.35$. Selection of parameters for a given aftershock (i.e., its magnitude, time relative to the parent, and radial distance relative to the parent) are completely independent of each other, in other words, the randomly drawn magnitude of the aftershock has no bearing on the randomly drawn time or distance relative to the parent, etc.

It is necessary to modify some behaviors of the BASS model to function within the confines of the *EarthquakeSequence* and fault component structures, specifically that there need to be limits on both the location and timing of aftershocks, to keep them on the fault and to broadly restrict their occurrence to within the model time duration.

For distances, the BASS model calculates a distribution of radial distances of aftershocks that occur which in theory could occur in any direction with respect to the parent, i.e. a random selection of azimuths between 0 and 360 degrees. However, I modify this such that depending on where the parent is located on the fault (and the size of the aftershock), the potential



azimuths are restricted to ensure that the resulting aftershock will be located on the fault. If the radius is such that regardless of the azimuth, this event would not occur on the fault, then this aftershock (and any children of that aftershock) remain in the catalog, but where their magnitudes and other details are set to NaNs so they do not factor into deformation or other calculations.

For time, the BASS model calculates time of events with respect to the parent. The majority of these will occur very shortly after the event (following normal Omori decay behavior), but there is the potential for events to occur a very long time after the parent, even beyond the duration of the model depending on the length of the model and the timing of individual parent events. These will exist in the catalog, but will not be included in any landscape simulations that are run.

1130 Appendix C: Ground Motion Prediction Equations

A suite of three ground motion prediction equations (GMPE) are implemented within the *CoseismicLandslider*, one each for active tectonic environments, subduction zones, and stable continental regions, respectively. Each GMPE includes a variety of constants, which are hard coded into the component and calculate both the peak ground acceleration, but also spectral accelerations at a variety of periods. The PGA is the only value used directly by the *CoseismicLandslider*, but the spectral accelerations are accessible to the user if desired.

C1 Active Tectonic Environments

The GMPE from Chiou and Youngs (2008) were developed from observations primarily from California, but also include observations from other tectonically active environments, specifically excluding subduction zones as they generally have been found to have different behaviors requiring a dedicated set of GMPE. The equations for determining the median acceleration (y) in gravity units at a site (j) at a specific period or for the peak ground acceleration for a specific earthquake event (j) are given by:

$$\begin{aligned}
 \ln(y_{refij}) = & c_1 + [c_{1a}F_{RVi} + c_{1b}F_{NMi} + c_7(Z_{TORi} - 4)](1 - AS_i) \\
 & + [c_{10} + c_{7a}(Z_{TORi} - 4)]AS_i + c_2(M_i - 6) + \frac{c_2 - c_3}{c_n} \ln(1 + e^{c_n(c_M - M_i)}) \\
 & + c_4 \ln[R_{RUPij} + c_5 \cosh\{c_6 \max(M_i - c_{HM}, 0)\}] \\
 & + (c_{4a} - c_4) \ln(\sqrt{R_{RUPij}^2 + c_{RB}^2}) + \{c_{\gamma 1} + \frac{c_{\gamma 2}}{\cosh[\max(M_i - c_{\gamma 3}, 0)]}\} R_{RUPij} \\
 & + c_9 F_{HWij} \tanh(\frac{R_{Xij} \cos^2 \delta_i}{c_{9a}}) \{1 - \frac{\sqrt{R_{JBij}^2 + Z_{TORi}^2}}{R_{RUPij} + 0.001}\} \quad (C1)
 \end{aligned}$$



$$\ln(y_{ij}) = \ln(y_{ref_{ij}}) + \phi_1 \min(\ln(\frac{V_{S30j}}{1130}), 0) + \phi_2 \{e^{\phi_3(\min(V_{S30j}, 1130) - 360)} - e^{\phi_3(1130 - 360)}\} \ln(\frac{y_{ref_{ij}} + \phi_4}{\phi_4}) + \phi_5 (1 - \frac{1}{\cosh[\phi_6 \max(0, Z_{1.0} - \phi_7)]}) + \frac{\phi_8}{\cosh[0.15 + \max(0, Z_{1.0} - 15)]} \quad (C2)$$

where all of the c and ϕ terms are regression constants, M is the moment magnitude of the event, R_{RUP} is the closest distance to the rupture plane in km to a site (including the topographic elevation of the site), R_{JB} is the Joyner-Boore distance to the rupture plane in km which is the minimum distance between the projection of the rupture plane to a horizontal reference surface and the site coordinate and that is defined as zero for site coordinates within the projection of the rupture surface, R_X is the distance between the site coordinate and the up-dip edge of the rupture in km measured perpendicular to strike and defined as positive in the direction of dip, δ is the rupture dip, Z_{TOR} is the depth to the top of the rupture in km, F_{RV} is a flag for reverse faulting, F_{NM} is a flag for normal faulting, F_{HW} is a flag for if the site is in the hanging wall (i.e., if R_X is positive), AS is a flag for if the event is an aftershock, V_{S30} is the average shear wave velocity in the top 30 meters, and $Z_{1.0}$ is the depth to a shear wave velocity of 1.0 km s^{-1} . The majority of these non-constant terms are defined by either the event details itself (e.g., M), the orientation of the rupture (e.g., δ), or the spatial relationship between the rupture and the ground surface (e.g., R_{RUP} , etc.) which come from the event and rupture details as stored within an *EarthquakeSequence* instance. For ruptures on dipping faults that span multiple panels, the dip of the fault as calculated as the area weighted average dip of the individual component ruptures. The V_{S30} and $Z_{1.0}$ effectively reflect the seismic site response at particular locations. I describe how I estimate V_{S30} within model simulations in the main text, but I use the relationship between V_{S30} and $Z_{1.0}$ provided by Chiou and Youngs (2008), namely:

$$\ln(Z_{1.0}) = 28.5 - \frac{3.82}{8} \ln(V_{S30}^8 + 378.7^8) \quad (C3)$$

As this is an empirical regression model, there are a variety of sources of uncertainty on the estimate of the median acceleration. The total variance (σ_T^2) on the estimate of $\ln(y)$ is given by:

$$\sigma_T^2 = (1 + NL_0)^2 \tau^2 + \sigma_{NL_0}^2 \quad (C4)$$

$$NL_0 = b \frac{y_{ref}}{y_{ref} + \phi_4} \quad (C5)$$

$$b = \phi_2 [e^{\phi_3(\min(V_{S30}, 1130) - 360)} - e^{\phi_3(1130 - 360)}] \quad (C6)$$

$$\tau = \tau_1 + \frac{\tau_2 - \tau_1}{2} [\min\{\max(M, 5), 7\} - 5] \quad (C7)$$

$$\sigma_{NL_0} = [\sigma_1 + \frac{\sigma_2 - \sigma_1}{2} (\min\{\max(M, 5), 7\} - 5) + \sigma_4 AS] \sqrt{(\sigma_3 F_{Inferred} + 0.7 F_{Measured}) + (1 + NL_0)^2} \quad (C8)$$

where τ_1 , τ_2 , σ_1 , σ_2 , σ_3 , ϕ_2 , and ϕ_3 are constants and $F_{Inferred}$ and $F_{Measured}$ are flags to reflect the source of the V_{S30} estimation (this is hard-coded in the component to reflect that the V_{S30} is inferred as opposed to measured). In the context of the implementation within *CoseismicLandslider*, the default behavior is to ignore the variance and for a given node in the



1175 Landlab grid, to use the value of y as determined from Eq. (C2) as the value for the peak ground acceleration. Alternatively, the user can indicate that they wish to include the variance in the estimation of peak ground acceleration, and in this case, for each node, a value for peak ground acceleration is randomly selected from a normal distribution with a mean of y , as determined by Eq. (C2) and standard deviation σ_T .

C2 Subduction Zones

1180 Abrahamson et al. (2016) provides effectively two different GMPEs for subduction related events, one for slab interface events and another for intra-slab events. For interface events, the acceleration (y) is given by:

$$\ln(y_{interface}) = \theta_1 + \theta_4 \Delta C_1 + (\theta_2 + \theta_3(M - 7.8)) \ln(R_{RUP} + C_4 e^{\theta_9(M-6)}) + \theta_6 R_{RUP} + f_{mag}(M) + f_{FABA}(R_{RUP}) + f_{site}(PGA_{1000}, V_{S30}) \quad (C9)$$

$$f_{mag}(M \leq C_1 + \Delta C_1) = \theta_4(M - (C_1 + \Delta C_1)) + \theta_{13}(10 - M)^2 \quad (C10)$$

1185 $f_{mag}(M > C_1 + \Delta C_1) = \theta_5(M - (C_1 + \Delta C_1)) + \theta_{13}(10 - M)^2 \quad (C11)$

$$f_{FABA}(R_{RUP}) = [\theta_{15} + \theta_{16} \ln(\frac{\max(R_{RUP}, 100)}{40})] F_{FABA} \quad (C12)$$

$$f_{site}(PGA_{1000}, V_{S30} < V_{lin}) = \theta_{12} \ln(\frac{V_S^*}{V_{lin}}) - b \times \ln(PGA_{1000} + c) + b \times \ln(PGA_{1000} + c(\frac{V_S^*}{V_{lin}})^n) \quad (C13)$$

$$f_{site}(PGA_{1000}, V_{S30} \geq V_{lin}) = \theta_{12} \ln(\frac{V_S^*}{V_{lin}}) + b \times \ln(\frac{V_S^*}{V_{lin}}) \quad (C14)$$

$$V_S^* = 1000 \text{ for } V_{S30} > 1000; V_{S30} \text{ for } V_{S30} \leq 1000 \quad (C15)$$

1190 For slab events, the acceleration (y) is given by:

$$\ln(y_{slab}) = \theta_1 + \theta_4 \Delta C_1 + (\theta_2 + \theta_{14} + \theta_3(M - 7.8)) \ln(R_{HYPO} + C_4 e^{\theta_9(M-6)}) + \theta_6 R_{HYPO} + \theta_{10} + f_{mag}(M) + f_{depth}(Z_h) + f_{FABA}(R_{HYPO}) + f_{site}(PGA_{1000}, V_{S30}) \quad (C16)$$

$$f_{FABA}(R_{HYPO}) = [\theta_7 + \theta_8 \ln(\frac{\max(R_{HYPO}, 85)}{40})] F_{FABA} \quad (C17)$$

$$f_{depth}(Z_h) = \theta_{11}(\min(Z_h, 120) - 60) \quad (C18)$$

1195 where the various θ and C terms are constants as is ΔC_1 , b , and V_{lin} . R_{HYPO} is the distance between the site (including topography) and the hypocenter in km, Z_h is the depth of the hypocenter in km, F_{FABA} is a flag for whether the event is in the forearc (0) or backarc (1), and PGA_{1000} is the median peak ground acceleration for $V_{S30} = 1000 \text{ m s}^{-1}$. The location and



depth of the hypocenter for ruptures that span multiple panels is calculated as the area weighted average of the rupture surface. The component is flexible in terms of how events are treated with respect to whether they are considered "slab" or "interface" events, and the user can either indicate that all events should be treated as one or the other or randomly select whether events are considered to have occurred within the slab or on the subduction interface. Similarly, whether particular sites are treated as being in the forearc or backarc, and thus the value of F_{FABA} , can either be set to a single value (i.e., all nodes within the Landlab grid are considered either in the forearc or backarc), or the user can provide a distance which is interpreted as a map-view distance from the up-dip fault tip in the direction of dip to serve as a dividing line between forearc and backarc sites. For example, setting this parameter to 10 km would define any nodes within 10 km of the up-dip tip of the fault as being in the forearc and any nodes greater than 10 km in the direction of dip from the up-dip fault tip would be defined as being in the backarc.

As with the Chiou and Youngs (2008) model, there is also an associated estimate of the variance (σ^2) of $\ln(y)$, where:

$$\sigma^2 = \phi^2 + \tau^2 \quad (\text{C19})$$

and ϕ and τ are considered to have average values of 0.60 and 0.43 respectively such that $\sigma = 0.74$. As with the implementation of the Chiou and Youngs (2008) model, the default behavior of the *CoseismicLandslider* is to ignore the variance and use the value for y from either Eq. (C9) or Eq. (C16) for each node, but can similarly include the variance through random sampling of a normal distribution with a mean of y and a standard deviation σ .

C3 Stable Continental Interiors

Pezeshk et al. (2011) use observations of earthquakes from Eastern North America to estimate the median acceleration (y) such that:

$$\begin{aligned} \ln(y) = & c_1 + c_2M + c_3M^2 + (c_4 + c_5M) \times \min(\ln(R), \ln(70)) + (c_6 + c_7M) \times \max[\min(\ln(R/70), \ln(140/70)), 0] \\ & + (c_8 + c_9M) \times \max(\ln(R/140), 0) + c_{10}R \end{aligned} \quad (\text{C20})$$

1220

$$R = \sqrt{R_{RUP}^2 + c_{11}^2} \quad (\text{C21})$$

The estimate of the variance (σ^2) is:

$$\sigma^2 = (c_{12}M + c_{13})^2; M \leq 7 \quad (\text{C22})$$

$$\sigma^2 = (-6.95 \times 10^{-3}M + c_{14})^2; M > 7 \quad (\text{C23})$$



1225 As with the other GMPEs, the default behavior in *CoseismicLandslider* is to ignore the variance and use the value calculated from Eq. (C20), but the variance can be included through random sampling as previously described.

Appendix D: Example Model Parameters



Table D1. Description of major differences between example models discussed in the text. Abbreviations used in the table are: RB - Restraining Bend, FS - Fastescape, LE - LinearEroder, DDTD - DepthDependentTaylorDiffuser, LD - LinearDiffuser

Model ID	Fault Type	Earthquake	Slip Rate mm yr ⁻¹	Incision	Diffusion	dx m	dt yr	Duration Myr	Notes
TC	Thrust, 25°	Creeping	10	SPACE	DDTF	200	5	1.5	NA
TFM	Thrust, 25°	Fixed Maximum	10	SPACE	DDTD	200	5	1.5	NA
TVM	Thrust, 25°	Variable - Moment	10	SPACE	DDTD	200	5	1.5	NA
TVD	Thrust, 25°	Variable - Disp.	10	SPACE	DDTD	200	5	1.5	NA
TVMLa	Thrust, 25°	Variable - Moment	10	SPACE	DDTD	200	5	1.5	Landslides
NC	Normal, 60°	Creeping	10	SPACE	DDTD	200	50	1.0	NA
NCTe10	Normal, 60°	Creeping	10	SPACE	DDTD	200	50	1.0	Flexure, $T_e = 10$ km
NCTe30	Normal, 60°	Creeping	10	SPACE	DDTD	200	50	1.0	Flexure, $T_e = 30$ km
NCTe50	Normal, 60°	Creeping	10	SPACE	DDTD	200	50	1.0	Flexure, $T_e = 50$ km
NVDTe30	Normal, 60°	Variable - Disp.	10	SPACE	DDTD	200	50	1.0	Flexure, $T_e = 30$ km
NCLTe30	Normal, Listric	Creeping	10	SPACE	DDTD	200	50	1.0	Flexure, $T_e = 30$ km
NVDLT30	Normal, Listric	Variable - Disp.	10	SPACE	DDTD	200	50	1.0	Flexure, $T_e = 30$ km
SSCF	LL Strike-Slip	Creeping	20	FS	LD	100	50	1.5	$U = 0.5$ mm yr ⁻¹
SSCS	LL Strike-Slip	Creeping	20	SPACE	DDTD	100	50	1.5	$U = 0.5$ mm yr ⁻¹
SSCL	LL Strike-Slip	Creeping	20	LE	LD	100	50	1.5	$U = 0.5$ mm yr ⁻¹
SSVML	LL Strike-Slip	Variable - Moment	20	LE	LD	100	50	1.5	$U = 0.5$ mm yr ⁻¹
SSCRBL	LL Strike-Slip, RB	Creeping	20	LE	LD	100	50	1.5	$U = 0.5$ mm yr ⁻¹
SSVMRBL	LL Strike-Slip, RB	Variable - Moment	20	LE	LD	100	50	1.5	$U = 0.5$ mm yr ⁻¹



Author contributions. AMF conceptualized the model, designed the Landlab model code, designed and performed the simulations, and wrote all drafts of the paper.

1230 *Competing interests.* The author has no competing interests

Acknowledgements. The author thanks Gregory Tucker, Matthew Rossi, Eric Hutton, Karen Luttrell, and Mehran Basmenji for helpful conversations and comments during development of the presented model and example simulations.

Financial support. This research has been supported by the Directorate for Geosciences (grant no. 2237437) of the US National Science Foundation. Portions of development of the work described was completed during a Cooperative Institute for Research In Environmental
1235 Sciences Visiting Sabbatical Fellowship awarded to AMF.



References

- Aagaard, B. T., Knepley, M. G., and Williams, C. A.: A domain decomposition approach to implementing fault slip in finite-element models of quasi-static and dynamic crustal deformation, *Journal of Geophysical Research: Solid Earth*, 118, 3059–3079, <https://doi.org/10.1002/jgrb.50217>, 2013.
- 1240 Abrahamson, N., Gregor, N., and Addo, K.: BC Hydro Ground Motion Prediction Equations for Subduction Earthquakes, *Earthquake Spectra*, 32, 23–44, <https://doi.org/10.1193/051712EQS188MR>, 2016.
- Adams, B. A., Whipple, K. X., Hodges, K. V., and Heimsath, A. M.: In situ development of high-elevation, low-relief landscapes via duplex deformation in the Eastern Himalayan hinterland, Bhutan, *Journal of Geophysical Research: Earth Surface*, 121, 294–319, <https://doi.org/10.1002/2015JF003508>, 2016.
- 1245 Allen, P. A. and Densmore, A. L.: Sediment flux from an uplifting fault block, *Basin Research*, 12, 367–380, 2000.
- Allen, T. I. and Wald, D. J.: On the Use of High-Resolution Topographic Data as a Proxy for Seismic Site Conditions (VS30), *Bulletin of the Seismological Society of America*, 99, 935–943, <https://doi.org/10.1785/0120080255>, 2009.
- Arias, A.: A measure of earthquake intensity, in: *Seismic Design for Nuclear Power Plants*, edited by Hansen, R., Massachusetts Institute of Technology Press, Cambridge, MA, 1970.
- 1250 Aránguiz-Rago, T. F., Duvall, A. R., Tucker, G. E., and Campforts, B.: Climate Oscillation and Fault Slip Rate Control Sediment Aggradation and Channel Morphology Along Strike-Slip Faults, *Geophysical Research Letters*, 52, e2025GL118146, <https://doi.org/10.1029/2025GL118146>, 2025.
- Avouac, J.-P.: From Geodetic Imaging of Seismic and Aseismic Fault Slip to Dynamic Modeling of the Seismic Cycle, *Annual Review of Earth and Planetary Sciences*, 43, 233–271, <https://doi.org/10.1146/annurev-earth-060614-105302>, 2015.
- 1255 Baden, C. W., Shuster, D. L., Aron, F., Fosdick, J. C., Bürgmann, R., and Hilley, G. E.: Bridging earthquakes and mountain building in the Santa Cruz Mountains, CA, *Science Advances*, 8, eabi6031, <https://doi.org/10.1126/sciadv.abi6031>, 2022.
- Bahrapouri, M., Rodriguez-Marek, A., and Green, R. A.: Ground motion prediction equations for Arias Intensity using the Kik-net database, *Earthquake Spectra*, 37, 428–448, <https://doi.org/10.1177/8755293020938815>, 2021.
- Barnes, R.: Parallel non-divergent flow accumulation for trillion cell digital elevation models on desktops or clusters, *Environmental Modelling & Software*, 92, 202–212, <https://doi.org/10.1016/j.envsoft.2017.02.022>, 2017.
- 1260 Barnes, R., Lehman, C., and Mulla, D.: Priority-flood: An optimal depression-filling and watershed-labeling algorithm for digital elevation models, *Computers & Geosciences*, 62, 117–127, <https://doi.org/10.1016/j.cageo.2013.04.024>, 2014.
- Barnhart, K. R., Glade, R. C., Shobe, C. M., and Tucker, G. E.: Terrainbento 1.0: a Python package for multi-model analysis in long-term drainage basin evolution, *Geoscientific Model Development*, 12, 1267–1297, <https://doi.org/10.5194/gmd-12-1267-2019>, 2019.
- 1265 Barnhart, K. R., Hutton, E. W. H., Tucker, G. E., Gasparini, N. M., Istanbuluoglu, E., Hobley, D. E. J., Lyons, N. J., Mouchene, M., Nudurupati, S. S., Adams, J. M., and Bandaragoda, C.: Short communication: Landlab v2.0: a software package for Earth surface dynamics, *Earth Surface Dynamics*, 8, 379–397, <https://doi.org/10.5194/esurf-8-379-2020>, 2020.
- Beven, K. J. and Kirkby, M. J.: A physically based, variable contributing area model of basin hydrology / Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant, *Hydrological Sciences Bulletin*, 24, 43–69, <https://doi.org/10.1080/02626667909491834>, 1979.
- 1270 Biasi, G. P. and Wesnousky, S. G.: Steps and Gaps in Ground Ruptures : Empirical Bounds on Rupture Propagation, *Bulletin of the Seismological Society of America*, 106, 1110–1124, <https://doi.org/10.1785/0120150175>, 2016.



- Bommer, J. J., Douglas, J., Scherbaum, F., Cotton, F., Bungum, H., and Fah, D.: On the Selection of Ground-Motion Prediction Equations for Seismic Hazard Analysis, *Seismological Research Letters*, 81, 783–793, <https://doi.org/10.1785/gssrl.81.5.783>, 2010.
- 1275 Bray, J. D. and Rathje, E. M.: Earthquake-Induced Displacements of Solid-Waste Landfills, *Journal of Geotechnical and Geoenvironmental Engineering*, 124, 242–253, [https://doi.org/10.1061/\(ASCE\)1090-0241\(1998\)124:3\(242\)](https://doi.org/10.1061/(ASCE)1090-0241(1998)124:3(242)), 1998.
- Bray, J. D. and Travarasrou, T.: Simplified Procedure for Estimating Earthquake-Induced Deviatoric Slope Displacements, *Journal of Geotechnical and Geoenvironmental Engineering*, 133, 381–392, [https://doi.org/10.1061/\(ASCE\)1090-0241\(2007\)133:4\(381\)](https://doi.org/10.1061/(ASCE)1090-0241(2007)133:4(381)), 2007.
- 1280 Brodsky, E. E., Mori, J. J., Anderson, L., Chester, F. M., Conin, M., Dunham, E. M., Eguchi, N., Fulton, P. M., Hino, R., Hirose, T., Ikari, M. J., Ishikawa, T., Jeppson, T., Kano, Y., Kirkpatrick, J., Kodaira, S., Lin, W., Nakamura, Y., Rabinowitz, H. S., Regalla, C., Remitti, F., Rowe, C., Saffer, D. M., Saito, S., Sample, J., Sanada, Y., Savage, H. M., Sun, T., Toczko, S., Ujiie, K., Wolfson-Schwehr, M., and Yang, T.: The State of Stress on the Fault Before, During, and After a Major Earthquake, *Annual Review of Earth and Planetary Sciences*, 48, 49–74, <https://doi.org/10.1146/annurev-earth-053018-060507>, 2020.
- Campbell, K. W. and Bozorgnia, Y.: A Comparison of Ground Motion Prediction Equations for Arias Intensity and Cumulative Absolute Velocity Developed Using a Consistent Database and Functional Form, *Earthquake Spectra*, 28, 931–941, <https://doi.org/10.1193/1.4000067>, 2012.
- 1285 Campforts, B., Shobe, C. M., Steer, P., Vanmaercke, M., Lague, D., and Braun, J.: HyLands 1.0: a hybrid landscape evolution model to simulate the impact of landslides and landslide-derived sediment on landscape evolution, *Geoscientific Model Development*, 13, 3863–3886, <https://doi.org/10.5194/gmd-13-3863-2020>, 2020.
- 1290 Campforts, B., Shobe, C. M., Overeem, I., and Tucker, G. E.: The Art of Landslides: How Stochastic Mass Wasting Shapes Topography and Influences Landscape Dynamics, *Journal of Geophysical Research: Earth Surface*, 127, e2022JF006745, <https://doi.org/10.1029/2022JF006745>, 2022.
- Cattin, R. and Avouac, J. P.: Modeling mountain building and the seismic cycle in the Himalaya of Nepal, *Journal of Geophysical Research: Solid Earth*, 105, 13 389–13 407, <https://doi.org/10.1029/2000JB900032>, 2000.
- 1295 Chiou, B. S.-J. and Youngs, R. R.: An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra, *Earthquake Spectra*, 24, 173–215, <https://doi.org/10.1193/1.2894832>, 2008.
- Cotton, F., Scherbaum, F., Bommer, J. J., and Bungum, H.: Criteria for Selecting and Adjusting Ground-Motion Models for Specific Target Regions: Application to Central Europe and Rock Sites, *Journal of Seismology*, 10, 137–156, <https://doi.org/10.1007/s10950-005-9006-7>, 2006.
- 1300 Croissant, T., Steer, P., Lague, D., Davy, P., Jeandet, L., and Hilton, R. G.: Seismic cycles, earthquakes, landslides and sediment fluxes: Linking tectonics to surface processes using a reduced-complexity model, *Geomorphology*, 339, 87–103, 2019.
- Delavaud, E., Scherbaum, F., Kuehn, N., and Allen, T.: Testing the Global Applicability of Ground-Motion Prediction Equations for Active Shallow Crustal Regions, *Bulletin of the Seismological Society of America*, 102, 707–721, <https://doi.org/10.1785/0120110113>, 2012.
- 1305 DeLong, S. B., Hilley, G. E., Prentice, C. S., Crosby, C. J., and Yokelson, I. N.: Geomorphology, denudation rates, and stream channel profiles reveal patterns of mountain building adjacent to the San Andreas fault in northern California, USA, *Geological Society of America Bulletin*, 129, 732–749, <https://doi.org/10.1130/B31551.1>, 2017.
- Densmore, A. L., Ellis, M., and Anderson, R. S.: Landsliding and the evolution of normal fault-bounded mountains, *Journal of Geophysical Research*, 103, 15 203–15 219, 1998.
- Densmore, A. L., Dawers, N. H., Gupta, S., Allen, P. A., and Gilpin, R.: Landscape evolution at extensional relay zones, *Journal of Geophysical Research: Solid Earth*, 108, 1–15, <https://doi.org/10.1029/2001JB001741>, 2003.
- 1310



- Douglas, J. and Edwards, B.: Recent and future developments in earthquake ground motion estimation, *Earth-Science Reviews*, 160, 203–219, <https://doi.org/10.1016/j.earscirev.2016.07.005>, 2016.
- Duvall, A. R. and Tucker, G. E.: Dynamic Ridges and Valleys in a Strike-Slip Environment, *Journal of Geophysical Research: Earth Surface*, 120, 2016–2026, <https://doi.org/10.1002/2015JF003618>, 2016.
- 1315 Eizenhöfer, P. R., McQuarrie, N., Shelef, E., and Ehlers, T. A.: Landscape Response to Lateral Advection in Convergent Orogens Over Geologic Time Scales, *Journal of Geophysical Research: Earth Surface*, 124, 2056–2078, <https://doi.org/10.1029/2019JF005100>, 2019.
- Ellis, M. A. and Barnes, J. B.: A global perspective on the topographic response to fault growth, *Geosphere*, 11, <https://doi.org/10.1130/GES01156.1>, 2015.
- Forte, A. M.: amforte/elastic_fault_earthquake_and_landslide: EFEL v1.0.0, <https://doi.org/10.5281/zenodo.21744823>, 2026.
- 1320 Forte, A. M., Whipple, K. X., and Cowgill, E.: Drainage network reveals patterns and history of active deformation in the eastern Greater Caucasus, *Geosphere*, 11, <https://doi.org/10.1130/GES01121.1>, 2015.
- Foulser-Piggott, R. and Goda, K.: Ground-Motion Prediction Models for Arias Intensity and Cumulative Absolute Velocity for Japanese Earthquakes Considering Single-Station Sigma and Within-Event Spatial Correlation, *Bulletin of the Seismological Society of America*, 105, 1903–1918, <https://doi.org/10.1785/0120140316>, 2015.
- 1325 Foulser-Piggott, R. and Stafford, P. J.: A predictive model for Arias intensity at multiple sites and consideration of spatial correlations, *Earthquake Engineering & Structural Dynamics*, 41, 431–451, <https://doi.org/10.1002/eqe.1137>, 2012.
- Gasparini, N. M. and Whipple, K. X.: Diagnosing climatic and tectonic controls on topography: Eastern Flank of the Northern Bolivian Andes, *Lithosphere*, <https://doi.org/10.1130/L322.1>, 2014.
- Goren, L., Castellort, S., and Klinger, Y.: Modes and rates of horizontal deformation from rotated river basins: Application to the Dead Sea fault system in Lebanon, *Geology*, 43, 843–846, <https://doi.org/10.1130/G36841.1>, 2015.
- 1330 Gray, H. J., Shobe, C. M., Hobley, D. E. J., Tucker, G. E., Duvall, A. R., Harbert, S. A., Owen, L. A., Hills, M., and Fault, S. A. N. A.: Off-fault deformation rate along the southern San Andreas fault at Mecca Hills, southern California, inferred from landscape modeling of curved drainages, *Geology*, 46, 59–63, <https://doi.org/10.1130/G39820.1>, 2018.
- Harbert, S. A., Duvall, A. R., and Tucker, G. E.: The Role of Near-Fault Relief Elements in Creating and Maintaining a Strike-Slip Landscape, *Geophysical Research Letters*, 45, <https://doi.org/10.1029/2018GL080045>, 2018.
- 1335 Harp, E. L., Keefer, D. K., Sato, H. P., and Yagi, H.: Landslide inventories: The essential part of seismic landslide hazard analyses, *Engineering Geology*, 122, 9–21, <https://doi.org/10.1016/j.enggeo.2010.06.013>, 2011.
- Harris, R. A., Barall, M., Aagaard, B., Ma, S., Roten, D., Olsen, K., Duan, B., Liu, D., Luo, B., Bai, K., Ampuero, J., Kaneko, Y., Gabriel, A., Duru, K., Ulrich, T., Wollherr, S., Shi, Z., Dunham, E., Bydlon, S., Zhang, Z., Chen, X., Somala, S. N., Pelties, C., Tago, J., Cruz-Atienza, V. M., Kozdon, J., Daub, E., Aslam, K., Kase, Y., Withers, K., and Dalguer, L.: A Suite of Exercises for Verifying Dynamic Earthquake Rupture Codes, *Seismological Research Letters*, 89, 1146–1162, <https://doi.org/10.1785/0220170222>, 2018.
- 1340 Hetland, E. A. and Hager, B. H.: Postseismic and interseismic displacements near a strike-slip fault: A two-dimensional theory for general linear viscoelastic rheologies, *Journal of Geophysical Research*, 110, doi:10.1029/2005JB003689–doi:10.1029/2005JB003689, 2005.
- Hobley, D. E. J., Adams, J. M., Nudurupati, S. S., Hutton, E. W. H., Gasparini, N. M., Istanbuloglu, E., and Tucker, G. E.: Creative computing with Landlab: an open-source toolkit for building, coupling, and exploring two-dimensional numerical models of Earth-surface dynamics, *Earth Surface Dynamics*, 5, 21–46, <https://doi.org/10.5194/esurf-5-21-2017>, 2017.
- 1345 Hoskins, A. M., Attal, M., Mudd, S. M., and Castillo, M.: Topographic Response to Horizontal Advection in Normal Fault-Bound Mountain Ranges, *Journal of Geophysical Research: Earth Surface*, 128, e2023JF007126, <https://doi.org/10.1029/2023JF007126>, 2023.



- Hutton, E. W. and Syvitski, J. P.: Sedflux 2.0: An advanced process-response model that generates three-dimensional stratigraphy, *Computers & Geosciences*, 34, 1319–1337, <https://doi.org/10.1016/j.cageo.2008.02.013>, 2008.
- Im, K. and Avouac, J.-P.: Quake-DFN: A Software for Simulating Sequences of Induced Earthquakes in a Discrete Fault Network, *Bulletin of the Seismological Society of America*, 114, 2341–2358, <https://doi.org/10.1785/0120230299>, 2024.
- Iwahashi, J. and Pike, R. J.: Automated classifications of topography from DEMs by an unsupervised nested-means algorithm and a three-part geometric signature, *Geomorphology*, 86, 409–440, <https://doi.org/10.1016/j.geomorph.2006.09.012>, 2007.
- Jiang, J., Erickson, B. A., Lambert, V. R., Ampuero, J., Ando, R., Barbot, S. D., Cattania, C., Zilio, L. D., Duan, B., Dunham, E. M., Gabriel, A., Lapusta, N., Li, D., Li, M., Liu, D., Liu, Y., Ozawa, S., Pranger, C., and Van Dinther, Y.: Community-Driven Code Comparisons for Three-Dimensional Dynamic Modeling of Sequences of Earthquakes and Aseismic Slip, *Journal of Geophysical Research: Solid Earth*, 127, e2021JB023 519, <https://doi.org/10.1029/2021JB023519>, 2022.
- Jibson, R. W.: Predicting Earthquake-Induced Landslide Displacements Using Newmark’s Sliding Block Analysis, *Transportation Research Record*, 1411, 9–17, 1993.
- Jibson, R. W.: Regression models for estimating coseismic landslide displacement, *Engineering Geology*, 91, 209–218, <https://doi.org/10.1016/j.enggeo.2007.01.013>, 2007.
- Jibson, R. W.: Methods for assessing the stability of slopes during earthquakes—A retrospective, *Engineering Geology*, 122, 43–50, <https://doi.org/10.1016/j.enggeo.2010.09.017>, 2011.
- Jolivet, R.: okada4py, <https://doi.org/10.5281/zenodo.14170827>, 2024.
- Kagan, Y. Y.: Seismic moment distribution revisited: I. Statistical results: Seismic moment distribution: I, *Geophysical Journal International*, 148, 520–541, <https://doi.org/10.1046/j.1365-246x.2002.01594.x>, 2002.
- Kagan, Y. Y. and Jackson, D. D.: Probabilistic forecasting of earthquakes, *Geophysical Journal International*, 143, 438–453, <https://doi.org/10.1046/j.1365-246X.2000.01267.x>, 2000.
- Kanamori, H. and Brodsky, E. E.: The physics of earthquakes, *Reports on Progress in Physics*, 67, 1429–1496, <https://doi.org/10.1088/0034-4885/67/8/R03>, 2004.
- Keefer, D. K.: Landslides caused by earthquakes, *Geological Society of America Bulletin*, 95, 406–421, 1984.
- Keefer, D. K.: The importance of earthquake-induced landslides to long-term slope erosion and slope-failure hazards in seismically active regions, *Geomorphology*, 10, 265–284, 1994.
- Kirby, E. and Whipple, K. X.: Expression of active tectonics in erosional landscapes, *Journal of Structural Geology*, 44, 54–75, 2012.
- Kirby, E., Whipple, K. X., and Harkins, N.: Topography reveals seismic hazard, *Nature Geoscience*, 1, 2008.
- Langer, L., Ragon, T., Sladen, A., and Tromp, J.: Impact of topography on earthquake static slip estimates, *Tectonophysics*, 791, 228 566, <https://doi.org/10.1016/j.tecto.2020.228566>, 2020.
- Langston, A. L. and Tucker, G. E.: Developing and exploring a theory for the lateral erosion of bedrock channels for use in landscape evolution models, *Earth Surface Dynamics*, 6, 1–27, <https://doi.org/10.5194/esurf-6-1-2018>, 2018.
- Leonard, M.: Self-Consistent Earthquake Fault-Scaling Relations: Update and Extension to Stable Continental Strike-Slip Faults, *Bulletin of the Seismological Society of America*, 104, 2953–2965, <https://doi.org/10.1785/0120140087>, 2014.
- Li, G., West, A. J., Densmore, A. L., Jin, Z., Parker, R. N., and Hilton, R. G.: Seismic mountain building: Landslides associated with the 2008 Wenchuan earthquake in the context of a generalized model for earthquake volume balance: THE WENCHUAN COSEISMIC LANDSLIDE, *Geochemistry, Geophysics, Geosystems*, 15, 833–844, <https://doi.org/10.1002/2013GC005067>, 2014.



- Li, G., West, A. J., and Qiu, H.: Competing Effects of Mountain Uplift and Landslide Erosion Over Earthquake Cycles, *Journal of Geophysical Research: Solid Earth*, 124, 5101–5133, <https://doi.org/10.1029/2018JB016986>, 2019.
- Li, Y., Hu, W., Xu, Q., Luo, H., Chang, C., and Jia, X.: Metastable state preceding shear zone instability: Implications for earthquake-accelerated landslides and dynamic triggering, *Proceedings of the National Academy of Sciences*, 122, e2417840 121, <https://doi.org/10.1073/pnas.2417840121>, 2025.
- 1390 Litwin, D. G., Tucker, G., Barnhart, K., and Harman, C.: GroundwaterDupuitPercolator: A Landlab component for groundwater flow, *Journal of Open Source Software*, 5, 1935, <https://doi.org/10.21105/joss.01935>, 2020.
- Lozos, J. C., Oglesby, D. M., Brune, J. N., and Olsen, K. B.: Small intermediate fault segments can either aid or hinder rupture propagation at stepovers, *Geophysical Research Letters*, 39, L18 305–L18 305, <https://doi.org/10.1029/2012GL053005>, 2012.
- 1395 Makdisi, F. and Seed, H.: Simplified procedure for estimating dam and embankment-induced deformations, *ASCE Journal of the Geotechnical Engineering Division*, 104, 1978.
- Malamud, B. D., Turcotte, D. L., Guzzetti, F., and Reichenbach, P.: Landslides, earthquakes, and erosion, *Earth and Planetary Science Letters*, 229, 45–59, <https://doi.org/10.1016/j.epsl.2004.10.018>, 2004a.
- Malamud, B. D., Turcotte, D. L., Guzzetti, F., and Reichenbach, P.: Landslide inventories and their statistical properties, *Earth Surface Processes and Landforms*, 29, 687–711, 2004b.
- 1400 Marc, O., Hovius, N., Meunier, P., Gorum, T., and Uchida, T.: A seismologically consistent expression for the total area and volume of earthquake-triggered landsliding: MODELING EARTHQUAKE-TRIGGERED LANDSLIDES, *Journal of Geophysical Research: Earth Surface*, 121, 640–663, <https://doi.org/10.1002/2015JF003732>, 2016.
- Marc, O., Meunier, P., and Hovius, N.: Prediction of the area affected by earthquake-induced landsliding based on seismological parameters, *Natural Hazards and Earth System Sciences*, 17, 1159–1175, <https://doi.org/10.5194/nhess-17-1159-2017>, 2017.
- 1405 Marc, O., Behling, R., Andermann, C., Turowski, J. M., Illien, L., Roessner, S., and Hovius, N.: Long-term erosion of the Nepal Himalayas by bedrock landsliding: the role of monsoons, earthquakes and giant landslides, *Earth Surface Dynamics*, 7, 107–128, <https://doi.org/10.5194/esurf-7-107-2019>, 2019.
- Meade, B.: The signature of an unbalanced earthquake cycle in Himalayan topography, *Geology*, 38, 987–990, <https://doi.org/10.1130/G31439.1>, 2010.
- 1410 Miller, S. R., Slingerland, R. L., and Kirby, E.: Characteristics of steady state fluvial topography above fault-bend folds, *Journal of Geophysical Research: Earth Surface*, 112, 1–21, <https://doi.org/10.1029/2007JF000772>, 2007.
- Newmark, N.: Effects of earthquakes on dams and embankments, *Geotechnique*, 15, 139–159, https://ia800108.us.archive.org/view_archive.php?archive=/24/items/wikipedia-scholarly-sources-corpus/10.1680.zip&file=10.1680%252Fgeot.1965.15.2.139.pdf, 1965.
- 1415 Okada, Y.: Internal deformation due to shear and tensile faults in a half space, *Bulletin of Seismological Society of America*, 82, 1018–1040, 1992.
- Olive, J. and Behn, M. D.: Rapid rotation of normal faults due to flexural stresses: An explanation for the global distribution of normal fault dips, *Journal of Geophysical Research: Solid Earth*, 119, 3722–3739, <https://doi.org/10.1002/2013JB010512>, 2014.
- Oryan, B., Olive, A., Jolivet, R., Malatesta, L. C., Gailleton, B., and Bruhat, L.: Megathrust locking encoded in subduction landscapes, *Science Advances*, 2024.
- 1420 Pack, R. T., Tarboton, D. G., and Goodwin, C. N.: The SINMAP Approach to Terrain Stability Mapping, in: *Engineering geology and natural hazards*, vol. 2, pp. 1157–1166, A A Balkema, 1998.



- Pavano, F.: Fault geometry, strain partitioning and deformation history inferred by fluvial topography and marine terraces analyses, *Geomorphology*, 472, 109 583, <https://doi.org/10.1016/j.geomorph.2024.109583>, 2025.
- 1425 Peltier, W. R.: Postglacial variations in the level of the sea: Implications for climate dynamics and solid-Earth geophysics, *Reviews of Geophysics*, 36, 603–689, <https://doi.org/10.1029/98RG02638>, 1998.
- Pezeshk, S., Zandieh, A., and Tavakoli, B.: Hybrid Empirical Ground-Motion Prediction Equations for Eastern North America Using NGA Models and Updated Seismological Parameters, *Bulletin of the Seismological Society of America*, 101, 1859–1870, <https://doi.org/10.1785/0120100144>, 2011.
- 1430 Reitman, N. G., Mueller, K. J., Tucker, G. E., Gold, R. D., Briggs, R. W., and Barnhart, K. R.: Offset Channels May Not Accurately Record Strike-Slip Fault Displacement: Evidence From Landscape Evolution Models, *Journal of Geophysical Research: Solid Earth*, 124, 13 427–13 451, <https://doi.org/10.1029/2019JB018596>, 2019.
- Rodriguez Padilla, A. M., Oskin, M. E., Brodsky, E. E., Dascher-Cousineau, K., Herrera, V., and White, S.: The Influence of Fault Geometrical Complexity on Surface Rupture Length, *Geophysical Research Letters*, 51, e2024GL109 957, <https://doi.org/10.1029/2024GL109957>,
1435 2024.
- Savage, J. C.: A dislocation model of strain accumulation and release at a subduction zone, *Journal of Geophysical Research: Solid Earth*, 88, 4984–4996, <https://doi.org/10.1029/JB088iB06p04984>, 1983.
- Savage, J. C.: Viscoelastic-coupling model for the earthquake cycle driven from below, *Journal of Geophysical Research*, 105, 25,525,532–25,525,532, 2000.
- 1440 Savage, J. C., Svarc, J. L., and Yu, S.-B.: Postseismic relaxation and transient creep, *Journal of Geophysical Research*, 110, doi:10.1029/2005JB003 687–doi:10.1029/2005JB003 687, 2005.
- Segall, P.: Interseismic Deformation and Plate Boundary Cycle Models, in: *Earthquake and Volcano Deformation*, p. 44, 2010.
- Shikakura, Y., Fukahata, Y., and Matsu'ura, M.: Spatial relationship between topography and rock uplift patterns in asymmetric mountain ranges based on a stream erosion model, *Geomorphology*, 138, 162–170, <https://doi.org/10.1016/j.geomorph.2011.09.002>, 2012.
- 1445 Shobe, C. M., Tucker, G. E., and Barnhart, K. R.: The SPACE 1.0 model: a Landlab component for 2-D calculation of sediment transport, bedrock erosion, and landscape evolution, *Geoscientific Model Development*, 10, 4577–4604, <https://doi.org/10.5194/gmd-10-4577-2017>, 2017.
- Simpson, G.: Accumulation of permanent deformation during earthquake cycles on reverse faults, *Journal of Geophysical Research: Solid Earth*, 120, 1958–1974, <https://doi.org/10.1002/2014JB011442>, 2015.
- 1450 Sobolev, S. V. and Muldashev, I. A.: Modeling Seismic Cycles of Great Megathrust Earthquakes Across the Scales With Focus at Postseismic Phase, *Geochemistry, Geophysics, Geosystems*, 18, 4387–4408, <https://doi.org/10.1002/2017GC007230>, 2017.
- Steer, P., Croissant, T., Baynes, E., and Lague, D.: Statistical modelling of co-seismic knickpoint formation and river response to fault slip, *Earth Surface Dynamics*, 7, 681–706, <https://doi.org/10.5194/esurf-7-681-2019>, 2019.
- Stewart, J. P., Douglas, J., Javanbarg, M., Bozorgnia, Y., Abrahamson, N. A., Boore, D. M., Campbell, K. W., Delavaud, E., Erdik, M.,
1455 and Stafford, P. J.: Selection of Ground Motion Prediction Equations for the Global Earthquake Model, *Earthquake Spectra*, 31, 19–45, <https://doi.org/10.1193/013013EQS017M>, 2015.
- Tanyaş, H., Van Westen, C. J., Allstadt, K. E., and Jibson, R. W.: Factors controlling landslide frequency–area distributions, *Earth Surface Processes and Landforms*, 44, 900–917, <https://doi.org/10.1002/esp.4543>, 2019.



- Thompson, G. A. and Parsons, T.: Vertical deformation associated with normal fault systems evolved over coseismic, postseismic, and
1460 multiseismic periods: VERTICAL DEFORMATION FROM EXTENSION, *Journal of Geophysical Research: Solid Earth*, 121, 2153–
2173, <https://doi.org/10.1002/2015JB012240>, 2016.
- Tucker, G. E., Hobley, D. E. J., McCoy, S. W., and Struble, W. T.: Modeling the Shape and Evolution of Normal-Fault Facets, *Journal of
Geophysical Research: Earth Surface*, 125, e2019JF005305, <https://doi.org/10.1029/2019JF005305>, 2020.
- Turcotte, D. L., Holliday, J. R., and Rundle, J. B.: BASS, an alternative to ETAS, *Geophysical Research Letters*, 34, 2007GL029696,
1465 <https://doi.org/10.1029/2007GL029696>, 2007.
- Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J.,
van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., Carey, C. J., Polat,
İ., Feng, Y., Moore, E. W., VanderPlas, J., Laxalde, D., Perktold, J., Cimrman, R., Henriksen, I., Quintero, E. A., Harris, C. R., Archibald,
A. M., Ribeiro, A. H., Pedregosa, F., van Mulbregt, P., and SciPy 1.0 Contributors: SciPy 1.0: Fundamental Algorithms for Scientific
1470 Computing in Python, *Nature Methods*, 17, 261–272, <https://doi.org/10.1038/s41592-019-0686-2>, 2020.
- Wald, D. J. and Allen, T. I.: Topographic Slope as a Proxy for Seismic Site Conditions and Amplification, *Bulletin of the Seismological
Society of America*, 97, 1379–1395, <https://doi.org/10.1785/0120060267>, 2007.
- Walker, R. L., Knepley, M. G., Aagaard, B. T., and Williams, C. A.: Multiphysics modelling in PyLith: poroelasticity, *Geophysical Journal
International*, 235, 2442–2475, <https://doi.org/10.1093/gji/ggad370>, 2023.
- 1475 Wang, J., Howarth, J. D., McClymont, E. L., Densmore, A. L., Fitzsimons, S. J., Croissant, T., Gröcke, D. R., West, M. D., Harvey, E. L.,
Frith, N. V., Garnett, M. H., and Hilton, R. G.: Long-term patterns of hillslope erosion by earthquake-induced landslides shape mountain
landscapes, *Science Advances*, 6, eaaz6446, <https://doi.org/10.1126/sciadv.aaz6446>, 2020.
- Wang, L., Sun, Y., and Yuan, X.: Control of tectonic uplift and erosion on landscape evolution across the Longmen Shan: Insights from
numerical modeling, *Geomorphology*, 497, 110–188, <https://doi.org/10.1016/j.geomorph.2026.110188>, 2026.
- 1480 Wernicke, B. and Axen, G. J.: On the role of isostasy in the evolution of normal fault systems, *Geology*, 16, 848–851,
[https://doi.org/10.1130/0091-7613\(1988\)016<0848:OTROI>2.3.CO;2](https://doi.org/10.1130/0091-7613(1988)016<0848:OTROI>2.3.CO;2), 1988.
- Whittaker, A. C.: How do landscapes record tectonics and climate, *Lithosphere*, 4, 160–164, 2012.
- Yong, A.: Comparison of Measured and Proxy-Based V_{S30} Values in California, *Earthquake Spectra*, 32, 171–192,
<https://doi.org/10.1193/013114EQS025M>, 2016.
- 1485 Yong, A., Hough, S. E., Iwahashi, J., and Braverman, A.: A Terrain-Based Site-Conditions Map of California with Implications for the
Contiguous United States, *Bulletin of the Seismological Society of America*, 102, 114–128, <https://doi.org/10.1785/0120100262>, 2012.
- Youngs, R. R. and Coppersmith, K. J.: Implications of fault slip rates and earthquake recurrence models to probabilistic seismic hazard
estimates, *Bulletin of the Seismological Society of America*, 75, 939–964, 1985.
- Yuan, X., Huppert, K., Braun, J., Shen, X., Liu-Zeng, J., Guerit, L., Wolf, S., Zhang, J., and Jolivet, M.: Propagating uplift controls on
1490 high-elevation, low-relief landscape formation in the southeast Tibetan Plateau, *Geology*, 50, 60–65, <https://doi.org/10.1130/G49022.1>,
2022.
- Zhang, F., Yuan, X., Li, Y., Shen, X., and Liu-Zeng, J.: Uplift History of the Southeastern Tibetan Plateau Revealed by Cou-
pled Surface Processes and Orographic Precipitation Model, *Journal of Geophysical Research: Solid Earth*, 131, e2026JB033995,
<https://doi.org/10.1029/2026JB033995>, 2026.