Extension rates impact on endorheic drainage longevity and regional sediment discharge

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Tectonic and climate drivers exert co-equal forces on the evolution of tectonic sedimentary basins. The Rio Grande rift and its drainages provide a backdrop for discussing which drivers drive the transition from endorheic or closed drainage basins to exorheic or open, through-going drainage basins, with both climatic and tectonic drivers being proposed by researchers. With a dearth of regional scale extensional landscape modeling studies to draw from, we explore the impact of tectonic extension on endorheic-exorheic transitions and regional sediment and water discharge in both a "dry" and "wet" runoff regimes. We show that holding climate-induced runoff constant, that greater extensional rates correspond to a longer period of sedimentation capture, tectonically induced gradients significantly increases sedimentation long after tectonic activity has terminated, and that developing an endorheic basin is very difficult in high runoff regimes.

Implementation of FastScape into reusable software components

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We present ongoing work on the development of open-source software around FastScape, a name used to designate a set of efficient algorithms for solving common problems in landscape evolution modelling. The software suite is divided into components that can be reused in many different contexts including experimentation, model coupling and direct integration within various scientific software ecosystems. As a core component, *fastscapelib* is a C++ library that aims to provide a robust implementation of the FastScape algorithms accessible through a basic API with bindings for Python/Numpy and potentially other languages such as R, Julia or Fortran, thanks to *xtensor* on which this library depends. Another component, *xarray-simlab*, provides a generic framework that allows to build, extend and couple computational models very easily by automating aspects such as workflow dependencies, model i/o interface and possibly more (e.g., parallel execution, command-line interface or graphical interface). Via its *xarray* interface, this framework is highly connected to the Python scientific stack, which may greatly help in streamlining the process of setting / running simulations and analysing / visualizing the outputs. We also wish to explore how these software components may interplay with other open-source tools used in landscape evolution modelling and topographic analysis (e.g., Landlab, LSDTopotoolbox).

Highly efficient methods to solve the Stream Power Law including sediment transport, local minima resolution and multi-direction flow

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Over the past few years we have continued the development of efficient methods and algorithms to model landscape evolution. The main purpose of our efforts is to obtain methods that can be inserted into an optimization (Bayesian) scheme to invert geological observations such as present-day landform, thermo-chronological and barometric data or sedimentary flux data, in order to obtain relevant constraints on local uplift rate, its evolution through time, as well as the value of model parameters. This often requires that hundreds of thousands to millions of forward model runs be performed to explore parameter space. This can only be achieved if the forward model run takes a few minutes of compute time, at most, to simulate tens of millions of years of landscape evolution at a spatial resolution that is relevant for the process being modeled (i.e., grid size or number of points used to discretize the model, n, of 1000×1000 or more). This is why we are currently developing methods that are implicit in time and thus allow for very large time step lengths ($10^4 - 10^6$ yrs), and are $O(n)$, i.e., where the number of operations increases linearly with n.

Here we will show improvements we have brought to the FastScape algorithm (Braun and Willett, 2013) previously developed to solve the Stream Power Law (SPL) implicitly and in $O(n)$ operations. These include (1) a new algorithm to include the theory of Davy and Lague (2009) concerning the effect of sediment transport and deposition in channels, (2) two new algorithms that find local minima and the geometry of the associated "lakes," the first being $O(n + N \log N)$ (N being the number of detected local minima) and the second $O(n)$, as well as several algorithms to drain water, and transport and deposit sediment across the lakes, and (3) a new algorithm to compute the drainage area and solve the SPL for distributed flow routing (i.e. Multiple Flow Direction instead of D8 or steepest descent flow direction). We have also added an efficient method to solve the equation governing diffusive hillslope transport that is implicit and $O(n)$, based on an ADI (Alternating Direction Implicit) algorithm. We are currently working on the development of an algorithm that improves accuracy when the SPL and the hillslope diffusion equation are solved sequentially.

Braun, J. and Willett, S.D., 2013. A very efficient, $O(n)$, implicit and parallel method to solve the basic stream power law equation governing fluvial incision and landscape evolution. Geomorphology, 180-181, pp., 170-179.

Davy, P. And Lague, D., 2009. Fluvial erosion/transport equation of landscape evolution models revisited. Journal of Geophysical Research: Earth Surface, 114:2003-2012.

Quantifying Effects of Lithospheric versus Deep-Mantle Dynamics on Surface Processes using Landscape Evolution Modeling

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Driving mechanisms of the formation of large intra-continental sedimentary basins remain elusive, with proposed models including lithospheric deformation and deep-mantle induced dynamic topography. One way to tackle this problem is through running landscape evolution simulations coupled with subsidence histories characteristic to these tectonic processes. From model predictions we can identify the characteristic effects of each subsidence mechanism on landscape evolution. We then use surface observations, e.g., sedimentation records, land erosion, and drainage evolution, to backtrack the likely tectonic histories and the underlying mechanisms.

In practice, we use Badlands to simulate the evolution of surface processes with synthetic setups and literature-based topography data, with a target being the Cretaceous Western Interior Seaway (WIS) in western North America. We first examine key features in the resulting sedimentation due to different subsidence scenarios and evaluate the effects of critical factors in sedimentation such as flexural rigidity, isostatic adjustment and the nature of the subsidence. Then we further quantify different driving forces behind the formation of the WIS using observations in the sedimentation history. Preliminary results suggest that only a geographically migratory subsidence scenario can produce the shifting depocenters and tilted strata in the WIS. Ongoing research will focus on understanding the quantitative relationship between a specific subsidence history and the resulting sedimentation records. Eventually, we aim to use coupled landscape evolution modeling to place more constraints on the mechanisms that formed large intra-continental sedimentary basins.

Controls on the disequilibrium condition of mountain gravel-bed streams

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Statistical steady-state for rivers is commonly defined in terms of bedload sediment mass equivalence over channel reaches of many channel widths in length, or longer. Proposals for fluvial equilibrium commonly extend the steady-state condition with the requirement that rivers express a longitudinal bed profile which varies around some well-defined mean condition. Although this definition of equilibrium has merit at relatively large spatial scales, it neglects the key underlying and local physical processes that govern bedload deposition and entrainment, the implications of which can lead to multiple equilibrium profiles. Furthermore, we lack a formal definition of equilibrium based on these processes, which we frame as depositional and entrainment filters acting on the local upstream supply of bedload sediment. We address this knowledge gap and use physical scaling theory with mass conservation statements for the bulk riverbed and the sediment particles which comprise the riverbed to derive two new dimensionless numbers which quantify the rates of bed topography (N_t) and bed sediment texture (N_p) adjustment to upstream water and sediment supplies. Bed sediment texture as used here is defined by the local spatial distribution of grain sizes for bed surface areas that scale as the local width squared. We hypothesize that an equivalence of N_t and N_p is indicative of fluvial equilibrium, and non-equivalence suggests disequilibrium (the more general state). We quantify this perspective as the ratio N_t/N_p, which we term the channel response number N_e. The use of N_t and N_p as disequilibrium metrics can be scaled up to reaches of many channel widths and to larger spatial scales. Calculation of N_t and N_p depends on only four quantities: the rate of topographic adjustment, the rate of particle composition adjustment, the local channel width and a sediment texture term which quantifies the degree of difference between the fractional composition of the local bedload supply and the sediments stored in the bed substrate, in relation to the fractional composition of the long-term average sediment supply. We apply our new view to experiments conducted to examine pool-riffle formation along variable width channel reaches. Among other things we find that equilibrium conditions are achieved for relatively high bed sediment mobility's, but a majority of time disequilibrium conditions prevail. We also show that following upstream supply perturbations, the local response is governed by topographic adjustments which persist for time scales that scale as 5-10 times the initial perturbation response time scale. The bed sediment texture response plays a more critical role in setting the disequilibrium condition only after the rate of topographic adjustment has tended toward some steady condition. In our talk we will review how we set the problem up, the details of the channel response number N_e, and testing of the idea with experimental data. We will end with ideas of how this new framework can be applied at the landscape scale.

A local description of landscapes

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Two models stand out in quantitative geomorphology: the diffusion model for hill-slopes and the stream power model for fluvial erosion. Though highly debated and often criticized for over-simplifying surface processes, these two models have provided some of the most powerful tools in geomorphology, including river long-profile analysis, steepness index, chi analysis, and equilibrium hill-slope profiles. More recently these models have been applied together as a diffusion-advection equation yielding other important advances, such as an understanding of the spacing of first order channels in simple landscapes. A powerful aspects of both models is their simplicity, as they depend solely on the characteristics of the surface describing the landscape, rate coefficients and exponents. As a result, these models are easily calibrated to real landscapes, manipulated for theoretical treatments, or applied in landscape evolution models. One of the most interesting features of the stream power model in particular is the dependence on both local conditions, quantified by slope, as well as non-local conditions, quantified by contributing catchment area. This non-locality is the source of much of the richness observed in the model behaviour, but it is also challenging to deal with both numerically and theoretically. In particular, contributing area cannot currently be cast in terms of standard mathematical forms, preventing the application of modern mathematical tools.

We revive and expand an old approach to provide a second constraint on contributing area based on the conservation of mass. This allows us to rewrite models such as the stream power model or the diffusion-advection model as PDEs without explicit dependence on contributing area. One of the most exciting aspects of this is that these models are in terms of local derivatives of topography. As a result of this, we show that for equilibrium landscapes, it should be possible to determine erosion rate at all points on the landscape from local derivatives of topography plus knowledge about the rate coefficients. The application of the technique may provide new ways of generating hypotheses to compare model to real landscapes, and opens landscape evolution equations to the study using established methods in differential function analysis.

How dynamic topography influences the landscape evolution and stratal architecture on passive continental margins – insights from stratigraphic modelling in a source-to-sink framework

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Quantifying the interaction between surface processes and tectonics/deep Earth processes has been one critical aspect of landscape evolution modelling (LEM). Both observations and results from numerical modelling indicate that dynamic topography – the surface expression of time-varying deep Earth processes, plays a significant role in shaping landscape through geological time. Recent research suggests that dynamic topography also has profound effects on stratigraphic architecture since it influences surface processes and thus the sediment supply to continental margins. Moreover, dynamic topography contributes to modifying coastal accommodation which is one primary force on building up stratigraphic sequences.

We use *Badlands* 1) to investigate the landscape evolution respond to dynamic topography (transient uplift/subsidence); 2) to model the stratigraphic development on passive continental margins respond to sea-level change, thermal subsidence and dynamic topography. One critical parameter linking these two aspects is sediment flux. For the post-processing, we first present the evolving catchments, longitudinal river profiles and chi value to evaluate the dynamic response of drainage systems to dynamic topography. We then calculate the amount of cumulative erosion and deposition, and sediment flux at shoreline position, with the coupling of various precipitations and the erodibility coefficient. Finally, we show the stratal stacking pattern and Wheeler diagram on vertical cross-sections at continental margin. Our preliminary results indicate that 1) dynamic topography has considerable influence on drainage reorganization by redirecting rivers; 2) dynamic topography also contributes to shoreline migration and the distribution of depositional packages by modifying the accommodation space; 3) dynamic topography slightly affects the sediment flux. Transient uplift contributes to gentle increase of sediment supply. In contrast, the subsidence leads to more deposition in coastal area, which would decrease the sedimentation on the continental margin.

Effect of Pre-existing Structures on the Seismicity of the Charlevoix Seismic Zone, Quebec, Canada

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The Charlevoix Seismic Zone (CSZ) occurs along the early Paleozoic St. Lawrence rift zone in southeastern Quebec at the location of a major Devonian impact crater. The crater superimposed major, steeply dipping basement faults trending N35°E. Many earthquakes are recorded each year in the CSZ and are concentrated within and beneath the impact crater. Some large-magnitude earthquakes associated with the rift faults occurred outside the crater. The primary goal of this research is to investigate combined effects of the pre-existing structures and regional stresses on earthquake activity in the CSZ. We set up some models using PyLith, an open-source finite-element code for simulations of crustal deformation. Our models will be compared with those of Baird et al. (2010), which took a different numerical approach for the same purpose of relating the regional structures, stresses, and seismicity. Adopting the results from recent hypocenter relocation study, we will modify the locations and dips of the rift faults and assess the effect of the new fault geometries on stress distributions. Finally, we will discuss whether modeled stress distributions can explain the seismicity distribution in the CSZ and published focal mechanism solutions. As a part of our efforts to enhance the reproducibility of these types of complex geodynamic models, selected models in this study will be made available in the form of sharable and reproducible packages. Such packaging is enabled by GeoTrust, an EarthCube-funded project that aims to automate the creation of a self-contained metadata package that provides a complete description of all data elements associated with a computational experiment.

Glassy dynamics of landscape evolution

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Soil creeps imperceptibly downhill, but also fails catastrophically to create landslides. Despite the importance of these processes as hazards and in sculpting landscapes, there is no agreed upon model that captures the full range of behavior. Here we examine the granular origins of hillslope soil transport by Discrete Element Method simulations, and re-analysis of measurements in natural landscapes. We find creep for slopes below a critical gradient, where average particle velocity (sediment flux) increases exponentially with friction coefficient (gradient). At critical there is a continuous transition to a dense-granular flow rheology. Slow earthflows and landslides thus exhibit glassy dynamics characteristic of a wide range of disordered materials; they are described by a two-phase flux equation that emerges from grain-scale friction alone. This glassy model reproduces topographic profiles of natural hillslopes, showing its promise for predicting hillslope evolution over geologic timescales.

Morphotectonics in a low tectonic rate area: analysis of the southern Portuguese Atlantic coastal region

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South Portugal is characterized by low tectonic rates (<0.3 mm/a), with infrequent large seismicity. Recent studies indicate a coastal region in southwest Portugal uplifting at higher rates (0.11 ± 0.01 mm/a) than the remaining southern portion of Portugal (~0.04 mm/a); however, the mechanisms that drive this uplift are poorly understood. With the purpose of investigating the regional Quaternary deformation and its patterns, as well as the difference in the uplift rate, 77 exorheic drainage basins along 460 km of the southern Portuguese coastline were analysed through the application of geomorphic indices. In this study we applied stream channel sinuosity *S*, basin relief ratio *Rh*, elongation *Re*, basin shape ratio *Bs*, valley height-width ratio V_f, basin asymmetry factor *AF*, hypsometry *HI* and, the stream-length gradient index *SL*, and we propose the terminal basin shape index *TBS*. This study aims to (1) identify Quarternary deformation along presumed tectonic structures; (2) recognize uplift or subsidence along the coastline; and (3) test the application of geomorphic indices in low deformation rate environments. The cross-correlation of results led to the recognition of the São Teotónio-Aljezur-Sinceira fault system and the São Marcos-Quarteira Fault as major regional Quaternary faults, as well as to the interpretation of Quaternary activity for other structures. Spatial differences in uplift rates are identified through basin shape indices and valley height-width ratios, even for low vertical motion rates, whereas other indices were found to be not as sensitive to variations in uplift rate.

Lithologic controls on focused erosion and intraplate earthquakes in the Eastern Tennessee Seismic Zone

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Intraplate seismicity does not conform to plate tectonic theory and its driving mechanisms remain uncertain, yet it is recognized as a relevant seismic hazard to heavily populated regions, such as Eastern North America. A variety of models have been proposed to explain this enigma, but conclusive supporting evidence remains elusive. In order to identify high hazard areas and derive predictive models it is imperative to identify the underlying processes responsible for intraplate seismicity. Here we present results from an interdisciplinary study of the Eastern Tennessee Seismic Zone (ETSZ), the second most seismically active region east of the Rocky Mountains in the North American continent to clarify the potential mechanisms driving intraplate seismicity in post-orogenic and passive margin settings. Previous studies document that the Upper Tennessee Drainage basin, which lies directly above the ETSZ, is in a transient state of adjustment to ~150 m of base level fall provoked by river capture in the Late Miocene. Using quantitative geomorphology, we demonstrate that base level fall has focused erosion in a ~70 km wide ~350 km long corridor of the highly erodible rocks in the ancient fold-thrust belt of the Late Paleozoic Alleghanian orogeny. The total volume of rock removed above the ETSZ since ~9 Ma is ~3,550 ± 800 km^3. Stress modeling indicates that spatially focused erosion reduced fault clamping stress at 15 km depth on average by ~2.5 MPa, with average annual unclamping rates of ~0.3 Pa yr^{-1}. Under the assumption that the crust is critically stressed, we argue that preferential erosion of less competent overburden in response to base level fall has created a zone reduced clamping stress allowing for slip on pre-existing basement structures in the ambient stress field. This model for surface process induced intraplate seismicity is generally transferable to other continental settings where complex geology and landscape dynamics conspire to produce spatially focused erosion and unloading of pre-existing bedrock structures.

An examination of landscape evolution driven by subduction initiation in Haida Gwaii, Canada

Philip Schoettle-Greene

The Pacific and North American plates are colliding offshore the Haida Gwaii archipelago of coastal British Columbia. A number of lines of evidence, from the M7.8 2012 earthquake on a shallowly dipping thrust fault under a nascent accretionary prism to the strong gravity gradient across the continental margin, support the hypothesis that this collision is initiating subduction. If true, Haida Gwaii is a singular example of forced, oblique subduction initiation on a predominantly strike-slip plate boundary. According to plate motion models, the Pacific plate began obliquely colliding with North America in this region approximately 10 million years ago, resulting in a wedge-shaped zone of underthrusting extending up to 120 km into the North American plate interior. I am examining the upper plate deformation and landscape evolution of Haida Gwaii driven by this underthrusting. Using apatite and zircon helium thermochronometry, I hope to determine the timing and magnitude of recent uplift and exhumation and use this information to calibrate a flexure model of uplift driven by subduction initiation. The 150+ islands of Haida Gwaii are unusual – rising upwards of a kilometer in elevation from the edge of the continent, they served as a biological refugia during Pleistocene glaciation and a stepping stone for the human settlement of the Americas. It is likely Haida Gwaii's unique role in the biological, geographical, and human history of western North America is tied to equally particular neotectonic deformation.

A new experimental apparatus for exploring the effect of differential tectonic uplift rate on fluvial landscape evolution

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The effect of tectonic rock uplift rate on fluvial landscape dynamics at the scale of a mountain range is a key problem in tectonic geomorphology. Physical experiments of fluvial landscape evolution at this scale are relatively little used despite their many strengths that are complementary to the more classical approaches of field observations and analysis and numerical modeling. In physical experiments, the input tectonic and climatic conditions are set by the experimentalist and the output dynamics can be correlated to the input parameters, this is rarely the case in field settings, where the history of the tectonic rates is seldom known and the present landscape form is an integral of its evolution. In physical experiments, the landscape dynamics emerges naturally from the boundary and the initial conditions as well as from the experimental material. This means that, unlike in numerical experiments, the experimentalist does not need to impose erosion and transport laws.

Existing experimental facilities for physical mountain-range scale landscape evolution have so far targeted spatially uniform uplift rates. However, in natural settings, the uplift rate at the scale of a mountain range is spatially variable. In order to simulate more realistic tectonic settings in laboratory experiments, a novel experimental apparatus has been constructed. The new apparatus has a flexible base, consisting of six elements, and each element can be independently uplifted. The space and time variable uplift rate history can be coded in a computer program that controls the elements. During an experiment, the experimental material, saturated silicon powder, is uplifted with respect to the boundaries of the experimental box, and erosion is facilitated by water discharge that originates from a mist system that is mounted above the box. This configuration allows us to experimentally simulate complex tectonic scenarios of space and time variable uplift rates.

Preliminary results show that the main water divide continuously migrates towards the high uplift rate region during tectonic tilt experiments, and depending on the tilt magnitude, intermountain basins transiently form close to the high uplift rate side.

Using roughness to date alluvial fans is not a smooth process: A new method for morphologic dating of alluvial fan sequences

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On active alluvial fans, the depositional morphology of debris flows, large boulders, and frequent avulsions produce a rough topographic surface. Abandoned alluvial fans become progressively smoother with time, producing textural differences useful in delineating relative age criteria for fans. We expand on this recognition by defining a quantitative, numerical chronology for fan surfaces reliant on predictions from the assumption that fans are smoothed by local, linear diffusion. Specifically, by comparing the surface roughness of active and older alluvial fan surfaces measured from spectral transformations of topography, we directly estimate a fan's 'morphologic age:' the product of the duration and efficiency of diffusive modification by surface processes. In testing this method on a suite of alluvial fans in the San Luis Valley, Colorado, USA, we highlight that while morphologic ages obey stratigraphic constraints and imply reasonable efficiencies of sediment transport, some aspects of the topography are inconsistent with model expectations. The oldest fan surfaces observed here, constrained to be older than 100 ka by U-series dating of pedogenic carbonates, have morphologic ages near the method's saturation point. In addition, many fans have morphologies that are not entirely consistent with a purely diffusive modification from the initial fan morphology recorded on active fan surfaces, likely due to post-depositional modification by wind- and overland flow-driven sediment transport. However, we remain optimistic that morphologic dating can provide useful insights into the history of alluvial fan activity, in particular because our method provides a means for both computing a morphologic age and assessing the validity of some of the assumptions required for that computation from analysis of topography alone.

Do landscapes have good memories?

Jeffrey Kwang and Gary Parker

Numerical landscape evolution models (LEMs) are deterministic; therefore, the model's output results are dependent on their initial conditions. An example of an initial condition for a LEM is the initial topography of a landscape, and commonly, the landscape is initialized as a horizontal surface with small randomized perturbations. By applying a uniform and steady precipitation and rock uplift, this initial topography evolves into a landscape made up of dendritic drainage basins. Since the model is deterministic, the forms of these drainage basins are dependent on the initial condition. However, by eye, the final condition bears little resemblance to its initial conditions. To clearly demonstrate that LEMs are deterministic, we add a non-randomized, Euclidian signal to our initial condition in the form of a planform sinusoidal channel. This signal persists throughout the entire landscape evolution and is finally preserved indefinitely as the landscape achieves a topographic steady state. A LEM is capable of remembering its initial conditions, but do physically-scaled experiments similarly retain a legacy from its initial conditions? We compare our numerical results to physical experiments that were conducted in the eXperiment Landscape Model (XLM) at the Saint Anthony Falls Laboratory at the University of Minnesota. This facility holds a 0.5m x 0.5m x 0.3m (WxDxH) block of sediment under a precipitation generator containing multiple evenly spaced misters, and rock uplift is simulated by the gradual lowering of a weir in the sediment box. The evolution of the experimental landscape is documented by planform images and digital elevation maps with 0.5 mm resolution every 5 minutes. In our experiments, we imprint the same sinusoidal channel into the initial surface and subject the landscape to a steady uniform precipitation rate and a gradual lowering of the base level. Our preliminary results of the physical experiments show dramatic differences in the evolution when compared to the numerical results, which suggests that LEMs are missing key physical mechanisms for describing landscape evolution.

Modeled glacial erosion in orogenic belts and its implication for climate-erosion-tectonics interaction

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The relationship between late Cenozoic cooling and the dynamics of mountain building has been in debate for decades, and glacial erosion is a critical component that links climate to tectonic deformation. Glaciers may limit the height of mountain ranges through an efficient denudation mechanism known as "glacial buzzsaw." This theory is supported by a correlation between the equilibrium line altitudes (ELA) and maximum height of mountain ranges. However, the correlation between ELA and mountain heights breaks down in high-latitude regions, where mountain peaks attain elevations above the ELA of Last Glacial Maximum (LGM) and erosion is slower than mid-latitude regions. The specific mechanisms responsible for such observations remain unclear. One hypothesis is that toward high-latitude region, glaciers are more frequently frozen to the bed and these cold-based glaciers will protect topography from erosion due to their low sliding velocity. This research uses a state-of-the-art numerical model to test whether the differences in glacial thermal regimes have impact on the rates and patterns of glacial erosion. We conduct a series of numerical experiments using the Parallel Ice Sheet Model (PISM) that model the glaciation under a steady climate of a fixed mountain topography, and the experiments cover a range of climatic conditions represented by different values of mean annual sea-level temperature and mean annual precipitation. The potential glacial erosion rate is estimated using a common linear erosion law in which the erosion rate is proportional to the basal sliding velocity. Preliminary analysis of the results shows that when the ELAs in different climate conditions are similar, the glaciers in colder climate have lower potential erosion. This finding is consistent with the hypothesis that cold-based glaciers are less erosive than warm-based glaciers.

Stream network fragmentation by faults and effects on species evolution

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Changes in stream network habitat connectivity are known to affect species macroevolution processes. We use the Landlab modeling library to explore the conditions that simulated networks rearrange in response to faults, and when networks do rearrange, what are the regional-scale geomorphological controls on species macroevolution. Network fragmentation reduces gene flow and increases rates of speciation. The organisms of a species can disperse across a greater geographic range when the stream network expands. Conversely, a shrinking range increases the likelihood of species extinction. We model these processes of macroevolution (dispersal, speciation, and extinction) in scenarios with different fault orientations and slip rates, and different erosion patterns. The outcome of hundreds of model runs shows that channel captures occurred within a limited combination of parameters and conditions. Captures were larger when topographic relief was low, and stream topology strongly affected capture occurrence. Large captures were more common above a threshold of the erodibility parameter in the stream power model, and speciation events increased with the quantity of large captures.

Towards joint modeling of tectonics, geomorphology, geochemical cycles and climate

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For decades, silicate weathering and associated oceanic carbonate precipitation and burial is thought to be the negative feedback avoiding extreme greenhouse gases variations. Understanding the way this feedback operates is key to understanding climate variation during Earth history. It is based on chemical reaction between continental silicate rocks and rainwater. As such, the strength of the feedback depends on continent locations, atmospheric dynamics and silicate availability, itself depending on continent lithology, tectonics and erosion of landscapes. All of these elements interact with each other: mountain rise modifies atmospheric circulation, which influences erosion, itself affecting topography and possibly tectonic uplift through controversial positive feedback.

Accurately modeling silicate weathering in order to predict the evolution of Earth's climate in the past would theoretically require modeling these interactions. Moreover, it has to be done at global scale, in spite of the inevitable loss of resolution. Models for each component exist — though not all are applicable to the global scale: General Circulation Models (climate), Reactive Transport models (mineral weathering), Landscape Evolution Models, Virtual Earth models (tectonics). However, combining them is not easy, mainly because they operate at time and spatial scales that are not compatible: climate model can hardly be run more than a thousand years while landscapes evolve during million years, carbon cycle model need to be global whereas the high resolution needed by LEM limit their application to regional scales.

GEOCLIM model (geoclimmodel.wordpress.com) is an attempt to investigate these interactions. At this time, it resolves geochemical cycles, climate and regolith evolution by combining three models. Yet, the only connection from "geological models" to climate model is atmospheric CO_2. This means that even if the model "sees" continent locations and topography, neither of them can evolve freely within the model. They are just forcings of the model. Moreover, the influence of deep Earth (tectonic uplift, onset of pluton, volcanic arc or trap) is currently missing, as well as sediment transport and deposition across continents.

Within this framework, we start by linking weathering to erosion, improving the reliability of weathering computation. As will be shown, it is now possible to better understand the effects of orogens on climate and weathering in addition to continent locations. Accounting for dynamic evolution of regolith have also shown that their response time may significantly affect the response of global climate to carbon cycle perturbation, depending on the contribution of fast and slow responding places. For instance, the raise of continental plants during Devonian could have a short-term effect by increasing weatherability, but also long-term effects by decreasing erodibility and modifying weathering profiles.

Orocline formation above retreating subduction zones: effect of surface process interaction in large-scale coupled numerical models

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The effect of surface processes on the evolution of topography related to subduction zones but also on the overall dynamics of these systems remains poorly constrained. The origin and formation conditions of curved subduction zone topography – oroclines – is not well understood at orogenic scales, where the interaction with surface processes is expected to be most relevant. On the other hand, sediment supply to the trench and potentially into the subduction zone can have large effects on the subduction dynamics, feeding back with mass redistribution at regions of high relief.

Here we employ high-resolution 3D numerical simulations of narrow retreating subduction zones in an oceanic domain using the viscoplastic thermomechanical code I3ELVIS (Gerya and Yuen, 2007) coupled to a diffusion-advection surface process code (FDSPM) to investigate their effect on retreating subduction zones.

We investigate the influence of surface processes intensity and initial sediments thickness on the evolution of the retreating subduction zone. We observe variations in the kinetics of slab retreat as well as changes in the resulting topography (oroclines): Slab retreat is slower with a 4 km thick sedimentary cover than with no sedimentary cover. The presence of sediments considerably reduces topography, especially in the trench where an accretionary prism forms. Sediments also influence strain patterns at the surface. After 3 Ma of slab retreat, we observe a curved trench for both simulations. However, the smoothing effect of sediments, which may be mechanically buffered in the accretionary wedge, is also seen laterally, and the curvature is stronger in the simulation with no sedimentary cover.

Investigating modern glacial erosion-tectonic interactions within the St. Elias Mountains, Alaska using marine sediment provenance

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The coastal St. Elias Range in Alaska is home to large temperate glaciers, making it an exceptional location to study the interaction between glacial erosion and tectonics in an active orogen. Glacial erosion scales with ice flux and bedrock erodibility that is affected by regional faulting and tectonic strain. Previous work in this region has focused on the Malaspina-Seward and Bering-Bagley ice fields, using exhumation rates derived from detrital and bedrock zircon and apatite thermochronology to constrain regions of increased glacial erosion and uplift. Within the Malaspina-Seward, erosion is concentrated in regions with both fast sliding velocities (Seward Throat), and concentrated tectonic strain (Seward ice field) (Headley et al., 2013; Enkelmann et al., 2015). For the Bering-Bagley, erosion is thought to be concentrated on the windward side of the range based on thermochronology (Berger et al., 2008). This study uses geochemical provenance of silt-sized (15-63μm) surficial sediments collected throughout the Gulf of Alaska to test if the same erosion patterns are also observed in the fine-grained fraction. Onshore bedrock elemental data is used to create a Bayesian Composition Estimator (Van den Meersche, 2008) mixing model for Gulf of Alaska sediments offshore the Bering-Bagley and Malaspina-Seward ice fields. Our results show a majority of fine-grained sediment deposited by the Bering Glacier during the 1994-1995 surge event originated from an ultra-mafic metabasalt zone and the low-grade metamorphic Orca-Valdez formation rocks underlying the Bagley ice field. This suggests that the tectonic-erosion coupling within the Bagley ice field, which overlies the Contact fault, may be stronger than what is observed from thermochronology. Sediment deposited by the Malaspina-Seward glacial system appears to reflect a mixed provenance representing the Yakataga formation that underlies the Seward throat, and Chugach Metamorphic Complex and Orca-Valdez rocks that underlie the Seward ice field. Our results support global observations that temperate glacial erosion in an active orogen is concentrated in regional fault zones.

The effect of sediment fluxes on the dynamics and style of convergent margins

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Subduction zones represent the only major pathway by which continental material can be returned to the Earth's mantle. Quantifying the sediments mass flux through subduction zones is not only important to the general problem of petrogenesis of continental crust (i.e., Dewey and Windley, 1981, Plank and Langmuir, 1993), but also to the understanding whether large volumes of existing continental crust are ever recycled back into the mantle over long periods of geologic time.

When sediments are considered, convergent margins appear to fall into one of two classes: accretionary and erosive (Clift and Vannucchi, 2004). Accretionary margins are dominated by accretion of thick piles of sediments (>1km) from the subducting plate, while tectonic erosion is favored in regions where the sedimentary cover is <1 km. However, as data help define geometry of the global subduction system, the consequences of the two styles of margins on subduction dynamics remain poorly resolved. In this study, we run systematic 2D numerical simulations of free-subduction to investigate how sediment fluxes influence subduction dynamics. We aim to understand the factors that cause convergent margins to either accrete continental material delivered by the subducting plate or, alternatively, to subduct the trench sediment pile and even erode the basement of the upper plate.

We parameterize the effect of weak sediments by varying the thickness and viscosity of the sediment layer and upper plate. Our results show three modes of subduction interface: a) Tectonic erosion margin (high viscosity sediment layer), b) Low angle accretionary wedge margin (low viscosity, thin sediment layer), and c) High angle accretionary wedge margin (low viscosity, thick sediment layer). We find that the properties of the sediment layer modulate the extent of viscous coupling at the interface between the subducting and overriding plates. When the viscous coupling is increased, an erosive style of margin will be favored over an accretionary style. On the other hand, when the viscous coupling is reduced, sediments are scrapped-off the subducting slab to form an accretionary wedge. By increasing the thickness of the sediments, more sediment is available to create a thicker wedge (high angle and width). The velocity field at the subduction interface suggests internal counter-flow inside high-angle wedges, different from low-angle accretionary or tectonic erosion margins.

Extracting erosion rates from steepland catchments to reconcile long-term uplift and the Cascadia earthquake deformation cycle

Penserini, B., J.J. Roering, and A. Streig

In unglaciated steeplands, valley reaches dominated by debris flow scour and incision set landscape form as they often account for N80% of valley network length and relief. While hillslope and fluvial process models have frequently been combined with digital topography to develop morphologic proxies for erosion rate and drainage divide migration, debris-flow-dominated networks, despite their ubiquity, have not been exploited for this purpose. Here, we applied an empirical function that describes how slope-area data systematically deviate from so-called fluvial power-law behavior at small drainage areas. Using airborne LiDAR data for 83 small (~1 km2) catchments in the western Oregon Coast Range, we quantified variation in model parameters and observed that the curvature of the power-law scaling deviation varies with catchment-averaged erosion rate estimated from cosmogenic nuclides in stream sediments. Given consistent climate and lithology across our study area and assuming steady erosion, we used this calibrated denudation-morphology relationship to map spatial patterns of long-term uplift for our study catchments. By combining our predicted pattern of long-term uplift rate with paleoseismic and geodetic (tide gauge, GPS, and leveling) data, we estimated the spatial distribution of coseismic subsidence experienced during megathrust earthquakes along the Cascadia Subduction Zone. Our estimates of coseismic subsidence near the coast (0.4 to 0.7 m for earthquake recurrence intervals of 300 to 500 years) agree with field measurements from numerous stratigraphic studies. Our results also demonstrate that coseismic subsidence decreases inland to negligible values N25 km from the coast, reflecting the diminishing influence of the earthquake deformation cycle on vertical changes of the interior coastal ranges. More generally, our results demonstrate that debris flow valley networks serve as highly localized, yet broadly distributed indicators of erosion (and rock uplift), making them invaluable for mapping crustal deformation and landscape adjustment.

Flexural Isostatic Response to Landscape Evolution during Glacial Cycles on the U.S. Atlantic Passive Margin

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Elevations of Pleistocene paleo-shorelines that lie across the South Carolina and northern Georgia coastal plain lie well above those of reconstructed past sea levels. These enigmatic surfaces have been attributed to some combination of tectonics, glacial isostatic adjustment, and/or deviations in estimated ocean volumes derived from the marine δ18O record. To reconcile these anomalous elevations, we combine a landscape evolution model with models of coupled ice-sheet, sea level and solid Earth deformation along the southern U.S. Atlantic passive margin to estimate erosion, deposition and corresponding flexural response since Marine Isotope Stage (MIS) 11 (~410 ka). We find that along-shore changes in modeled paleo-shoreline elevations are similar to measured elevations along 100s of kilometers. Up to 10 m of shoreline uplift since MIS 11 may be attributed to flexural isostatic feedback in response to erosion and deposition.

Exploring river response to tectonic perturbations with the open-source, 2-D SPACE model

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Over geologic time, nearly all river channels transition between alluvial, bedrock-alluvial, and bedrock states in response to tectonics. Understanding landscape response to tectonic perturbation requires models that can evolve both sediment and bedrock. However, most models of river channel evolution only treat erosion into a single substrate or are constrained by assumptions of detachment or transport limitation. Most of the few existing models that treat coupled sediment transport and bedrock erosion do so at the reach scale rather than the landscape scale. We present a new algorithm (the SPACE model) for modeling the simultaneous evolution of sediment and bedrock in river channels in 2-D. SPACE explicitly incorporates sediment entrainment, transport, and deposition as well as bedrock erosion, rather than parameterizing the effects of sediment on bedrock erosion into a sediment-flux-dependent function. The model tracks mass in three reservoirs: the water column, the sediment bed, and the underlying bedrock. SPACE allows self-organization of sediment flux, channel slope, and sediment thickness in response to model forcings. SPACE can therefore transition freely between, and match known analytical solutions for, both detachment-limited and transport-limited behavior. We develop steady-state analytical solutions for channel slope, sediment thickness, and sediment flux in the more complex case of a mixed bedrock-alluvial river, and show that the 2-D numerical implementation of SPACE matches the predictions and need not be constrained by detachment-limited or transport-limited assumptions. SPACE is particularly useful for modeling landscape response to tectonic forcing as it can treat the storage and evacuation of sediment and the accompanying episodic bedrock incision. We present two examples. First, SPACE is coupled with a hillslope diffusion model to explore the dynamics of erosion and sedimentation resulting from topographic growth and decay. Second, we couple SPACE with models for soil production and depth-dependent hillslope diffusion to investigate landscape response to Basin and Range style rock uplift patterns.

Examining transient thermal-rheological interaction during collisional orogenesis using numerical modeling

Stephanie A. Sparks and J. Ryan Thigpen

Two quantitatively-supported models, critical wedge and channel flow, have been applied to the Himalaya and proposed for other large collisional systems as mechanisms for shortening accommodation during orogen evolution. These two models are fundamentally distinct and until recently have been viewed as mutually exclusive. While there remains support for these mechanisms being incompatible end-members, in more recent studies it has been proposed that either: (1) both geodynamic mechanisms may operate simultaneously yet in spatially distinct parts of the larger composite orogenic system or (2) both mechanisms are present yet they operate at temporally distinct intervals, wherein the orogen progressively develops through stages dominated by mid-crustal channel flow followed by shallow thrust stacking and duplex development. In both scenarios, the mechanism active at each stage in orogen evolution is presumably dependent upon local to regional scale rheological conditions (as a function of orogen dynamic and thermal evolution) that are likely to be transient in both space and time. Additionally, these rheological conditions are strongly dependent upon surface processes driving exhumation rates. Here, we present results from numerical experiments of a 2-D large collisional orogen that focus on the how thermal structure affects rheological conditions – which vary both spatially and temporally – and attempt to explain the mechanical and thermal-kinematic linkages between the two aforementioned mechanisms. Finally, we assess the possibility of using thermokinematic models built from Himalayan-Tibetan orogenic system thermochronologic data to simulate the effect of variable exhumation and better understand relationships between surface and tectonic processes.

Bridging erosion rate measurements across timescales

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Understanding the processes shaping the Earth's topography requires detailed reconstructions of erosion, climate and tectonic histories on different spatial and temporal scales. In that context, and particularly for glacial landscapes, there is an ongoing debate on how erosion rate measurements can be compared across timescales (Ganti et al., 2016). Because of the stochastic nature of erosional processes, a timescale bias might cause apparent changes in erosion rates through time. However, this bias occurs primarily when erosion rates are acquired with independent methods and averaged over different timescales. Therefore, methods that enable to quantify time series of erosion rates, rather than erosion integrated over a single timescale are needed. Thermoluminescence thermochronology (TLT) offers this possibility. This method uses the signal emitted by the temperature-stimulated release of electrons previously ionized due to ambient radioactivity and trapped in different energy levels. It enables us to constrain the high-resolution temperature-time path of a rock sample during exhumation by using several closure temperatures ranging from about 80° to 30°C. TLT thus bridges the erosion rates constrained by apatite (U-Th)/He thermochronology and by denudation rates inferred from ^{10}Be. In the Western Cordillera of the Central Andes, at 26°-35°S latitude, new and previously published low-temperature thermochronological data (AHe, AFT, ZHe, ZFT) show a Pleistocene increase in erosion rates at the latitude of 33.5°S latitude. TLT measurements confirm this increase in erosion, but show additionally a later decrease of the erosion rates towards present. Interestingly, the inferred erosion rates are similar to published erosion rates (0.28 mm/yr) derived from ^{10}Be and sediment yield measurements. Our study implies that TLT offers the link between Ma- and ka-scale erosion rates by avoiding problematics posed by a possible timescale bias.

A Plastic Formulation of Rate and State Dependent Friction: Emergence of Slip Transient and Earthquakes

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At subduction zones, the elastic energy released during an earthquake is mostly expressed as energy carried by seismic waves, kinetic energy released as slip along a frictional interface, energy needed to form new fractures, and the energy dissipated by heat generation along the frictional interface. For the last two decades, slow slip events (SSEs) have been observed at many subduction zones including Western Japan, Cascadia, Hikurangi, Central America, and Alaska. Like megathrust earthquakes, SSEs are phenomena that represents shear slip on the plate interface. Unlike fast earthquakes, SSEs are mostly observed through long-term geodetic observations. When taken into account over multiple seismic cycles, SSEs can be seen as part of the total energy release process and should be taken into consideration when studying seismic hazard at convergent margins. For this reason, SSEs are believed to be critical to our understanding of megathrust interseismic loading because they occur in areas adjacent to the source of very large earthquakes, hence, potentially loading the seismogenic locked patch. SSEs differ from classical earthquakes in that when they release seismic waves they do so at lower frequency, they slip at rates 7 to 10 order of magnitude slower than earthquakes and SSEs' rupture propagation associated with new fractures seems to occur at much slower rates than that of shear fractures associated with fast earthquakes. These observations point to the first order observation that the elastic energy loaded interseismically is released in fundamentally different ways during SSEs and fast earthquakes. At first order, to understand the different slip behaviors of a fault over secular time scales and the interaction between long term tectonic and seismic processes we need to constrain the partitioning between kinetic energy and strain energy that are respectively associated with the release of elastic energy in slip and in permanent deformation on fault zones.

Not Feeling The Buzz: Tectonic Limits to Mountain Heights

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The potential to rapidly denude topography at and above the glacier Equilibrium Line Altitude (ELA), irrespective of uplift rates, rock type or pre-existing topography, is explored in the glacial buzzsaw hypothesis (e.g., Brozović et al., 1997). This hypothesis emerged from correlations between mountain heights and ELAs and has been fueled by numerical landscape evolution models that can make glacial erosion control mountain height (e.g., Egholm et al., 2009). Some of the interest in this hypothesis has foundations in a separate hypothesis that global cooling during the onset of Northern Hemisphere glaciation during the Plio-Pleistocene is thought to increase rates of erosion in moun_tain belts (e.g., Molnar 2004). This climate-driven erosion hypothesis has the potential to feedback to long-term climate by accelerating erosion, thus silicate weathering, and the sequestration of atmospheric CO_2, further decreasing temperatures (Raymo and Ruddiman, 1992). Together, the effects of these two hypotheses (if both true) would send the Earth into a deep freeze.

Here, we present a bottom-up analysis of the buzzsaw hypothesis. We compiled tectonic, topographic, and erosion rate data from Arc-Continent convergent margins (Andes, Central America, Cascadia, British Columbia, Alaska) to discover the drivers controlling mountain height. We regressed plate convergence against average and maximum mountain heights and erosion rates derived from the ages of copper porphyry deposits emplaced at 2-km depth. Erosion rates and elevation maxima correlate linearly with plate convergence rates. Importantly, mountain peaks in three heavily glaciated mountain ranges (Alaska, Cascadia, and South Chile) do not deviate from the trend which includes unglaciated mountain ranges such as the Central Andes. That mountain ranges with different climatic characteristics fall within the same trend implies that tectonics is the primary control of mountain range mass and heights–not glaciers.

What caused the Miocene-Pliocene unconformity in the Rio Grande rift?

Jolante van Wijk

The Rio Grande rift zone in the southwestern U.S. started opening around 24 Ma. Our tectonic subsidence curves show that subsidence was rapid until ~8 Ma, and that this phase of rapid subsidence was followed by a slow-down of subsidence or uplift, resulting in an unconformity. Tectonic subsidence resumes again ~5 Ma. This Late-Miocene-Early Pliocene unconformity was previously described in several basins of the Rio Grande rift; this study shows that this unconformity is more widespread than previously thought within the rift zone, and that it is present also outside of the rift zone. The age of its associated lacuna is spatially variable but falls within 8–3 Ma (mostly 7–5 Ma). This is synchronous with eastward tilting of the western Great Plains. We explain the spatial distribution and timing of the unconformity, as well as eastward tilting of the western Great Plains, by dynamic mantle uplift. Earlier explanations include climatic variations and slowing down of rift opening. The mantle-driven uplift explanation for the unconformity is supported by geoid-to-elevation ratio analyses that suggest that topography of the northern Rio Grande rift region is compensated by a component of mantle-driven dynamic uplift.

Active tectonic influence on the evolution of drainage and landscape in the Kenya Rift, East African Rift System

Liang Xue, Mohamed Abdelsalam

The evolution of drainage systems and landscape in continental rift settings reflects a complex process combining tectonic uplift of rift shoulders, propagation of border faults, and changes in climate. The mechanisms that drive the interactions between Earth's endogenous and surface processes, in regions of the continental rift, is poorly understood. Furthermore, the differential uplift in both spatial and temporal scales in the Kenya Rift still lacks geologic constraints. This works applied the landscape evolution module using Landlab, a python-based moedling environment, in an effort to: (1) elucidate the influence of tectonic forcing on the topographic relief and drainage systems, (2) examine the system response through time to tectonic parameters, and (3) determine the uplift rate and patterns for the three sections in the Kenya Rift. Results of the landscape evolution model suggested that the magnitude of uplift rate has a significant control on the development of border fault derived rift relief and drainage patterns in the rift valley and shoulders. Therefore, it can, in turn, provide some insights on the tectonic uplift distribution in the Kenya Rift. This work found that the streams in the rift valley retreat towards Central Kenya, and the border fault derived rift relief in the North and South Kenya are highly dissected by the rift valley streams. This observation suggested the North Kenya Rift is approaching steady state and uplift rate of rift shoulders is similar to that of the rift valley. Differently, the Central Kenya Rift exhibited a well-expressed topography relief and active rift border faults. This analysis supports the emerging view that the Central Kenya Rift represents a more recent and tectonically active uplift phase which is different from that in North Kenya Rift. This phase may be related to the Pliocene volcanism in this region and possibly linked to the major paleoenvironment shift in East Africa.

Base level signal propagation through a block-controlled landscape

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Canyons developed in layered rock are often shaped by interactions between fluvial and hillslope processes in the presence of large blocks of rock. In landscapes such as the Colorado Plateau, canyon walls are composed of resistant caprock overlying weaker rock. Large blocks derived from the resistant layer mantle the hillslopes and channels below. We present a 2-D numerical model of the evolution of a river reach developed in horizontal, layered. Here we drive our model with constant base level incision, and explore the resulting signals of fluvial and hillslope erosion in the presence of blocks. At early times, when the river first cuts through the resistant rock and exposes the weaker rock underneath, blocks enter the channel with great enough size and frequency to inhibit channel incision. This in turn slows the rate of hillslope evolution and cliff retreat, which then decreases the amount of blocks entering the channel and allows further incision. These initial autogenic fluctuations in erosion rate shred base level signals. After cliffs retreat further from the channel, any blocks reaching the channel are smaller and do not stall channel incision, allowing the system to better adjust to the base level signal. We show that feedbacks between hillslopes and channels in the presence of blocks control the style and pacing of canyon evolution.

GeoTrust: Improving Sharing and Reproducibility of Geoscience Applications (geotrusthub.org)

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Recent requirements of scholarly communication increasingly emphasize the reproduce-bility of scientific claims. Given the computational nature of science, text-based research papers are considered poor mediums to establish reproducibility. Papers must be accom-panied by “research objects”— aggregation of digital artifacts such as code, data, scripts, and temporary experiment results — that together with the paper provide an authoritative and far more complete record of a piece of research. We will present GeoTrust Hub (http://geotrusthub.org), a platform for creating, sharing, and reproducing reusable research objects. GeoTrust Hub provides tools for scientists to create ‘geounits’— reusable research objects. Geounits are self-contained, annotated, and versioned contain-ers that describe and package computational experiments in an efficient and lightweight manner. The geounits can be shared on public repositories such as HydroShare and FigShare, and also using their respective APIs reproduced on provisioned clouds. The latter feature enables science applications to have a lifetime beyond sharing, where in they can be independently verified and trust be established as they are repeatedly reused.