# Project Description

## Problem and Objectives

Earth surface dynamics in its broadest sense encompasses processes that span time scales from the impact of a single raindrop to the accumulation of the stratigraphic record over hundreds of millions of years, and the evolution of landscape topology over length scales from less than meters to thousands of kilometers. Because Earth landscapes are heterogeneous (rock, soil, sediment, biotic) systems whose evolution involves complex interactions among multiple fluid/solid/biological components conditioned by a host of external and boundary conditions (e.g. meteorological conditions, climate, tectonism, sea level), the breadth of topological and stratigraphic states of Earth's landscapes is exceedingly rich, and modeling their dynamical behavior in a predictive manner is one of the most exciting and challenging of tasks in the Earth sciences.

Toward this end, the overarching scientific goal of this project is to press our understanding of Earth surface dynamics and associated predictive modeling capabilities to an unprecedented level of sophistication, rivaling that of current (and next-generation) numerical modeling efforts in the ocean and atmospheric sciences. Three key items, however, distinguish this project from previous landscape modeling efforts and from analogous efforts in other fields. First, whereas in the atmospheric sciences and with certain engineered systems, for example, modeling starts from well known descriptions of fluid behavior, associated constitutive laws and equations of state, and with reasonably clear ideas of forcing and boundary conditions, these things generally are far more complex (and less constrained) in studies of surface dynamics. Second, the very nature of landscape dynamics, because it involves describing the continuously changing surface of Earth, with its mosaic of interacting sub-environments, at many scales, has meant that previous efforts at landscape modeling have been mainly piecemeal, focused on specific regions or time windows. A quantum step forward requires model integration on un unprecedented scale; this in turn requires that computational strategies be guided at ground level by the need to adaptively handle large domain deformation and to track dynamic internal fronts and boundaries. Third, the abundance of Earth-surface data now available from remote sensing invites a high level of integration between models and these rich data sets. This in turn requires novel approaches in diagnostic visualization and landscape pattern-recognition for application to landscape data.

We propose to develop a comprehensive framework — conceptual, theoretical, experimental and technical — to address *critical issues* in modeling of Earth landscape dynamics. We define a "critical issue" as being one of fundamental significance to modeling landscapes at a range of scales, with implications for many different types of landscapes, terrestrial and submarine. This reflects the philosophy of the entire project: the emphasis will be on general techniques applicable to a wide range of problems rather than on further development of regionally focused models. The goal is to develop new methods and to set the stage and tone for next-generation work in landscape modeling. Given the brevity of this pre-proposal, we therefore present *only key points and examples* below, with the understanding that these serve as *representatives* of numerous similar, important situations and applications.

- *Characterizing and modeling emergent large-scale behavior of erosion-sedimentation processes operating at small scales, including numerical sub-grid parameterization of these processes*.

One of the most important and exciting challenges facing this project is to develop insight and techniques for extracting essential dynamics from detailed simulations of small-scale processes to apply to large-scale models [e.g. *Werner*, 1999] that must accommodate concomitantly increasing system heterogeneity [*Howard et al.*, 1994] and temporal stochasticity of external forcing [*Benda and Dunne*, 1997]. At the heart of this is the problem of correctly parameterizing the emergent behavior of processes operating at scales finer than the (space/time) resolution of numerical grids (Figure 1). Whereas in analogous atmospheric modeling problems, for example, parameterization can involve suitable averaging of the underlying equations, adapting this technique to erosion-sedimentation systems has only just started [*Paola et al.*, 1992; *Niedoroda et al.*, 1995; *Paola*, 1996; *Paola et al.*, 1999]. The opposite problem of resolving sub-grid scale effects has been approached via "nested" models [*Giorgi and Mearns*, 1991]. In the simplest case, information flows

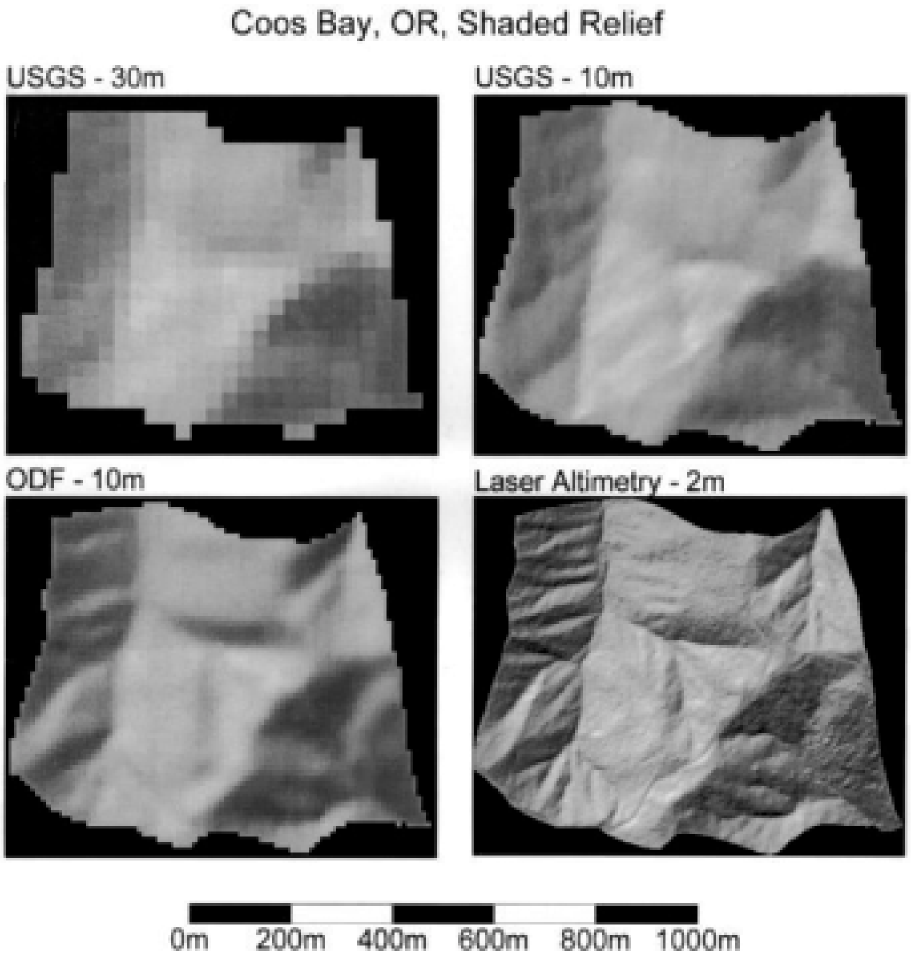


**Figure 1.** Much of the US has digital elevation data coverage at 30 m resolution, a much smaller part at 10 m, and only in special circumstances at 2 or 1 m. Because important processes in conjunction with topological details at the 1-2 m scale strongly influence emergent behavior at larger scales, extracting and parameterizing this sub-grid scale information is essential for landscape dynamics modeling.

downward; the solution at the large scale provides boundary conditions for a more detailed model of processes within a grid cell. Information can also propagate upward in so-called adaptive multi-grid methods, in which results of a fine-scale simulation can change parametric values at the larger scale [*Barros and Lettenmaier,* 1993]. Although model nesting has not yet been applied to morphodynamics, an example that is within reach involves large-scale, diffusional models of fluvial profile evolution [see *Paola*, in press] in which individual grid cells could be "opened" to examine details of individual stream channels.

Of particular interest are current formulations of long-term basin-scale (advective) sediment transport or erosion, heuristically based on power-law relations, normally involving a characteristic discharge (or a surrogate involving drainage area) and local bed gradient. In the subaerial case, small but random variations in the elevation on an initial surface are amplified by erosion, giving rise to discrete channels which, due to nonlinear effects over time evolve to a full drainage network. Examination of the basis of such formulations (as representing emergent behavior) is well suited to detailed simulation experiments using nested model techniques. In contrast, for well-developed channel networks in the submarine environment, which likely arise from erosional/deposition effects of turbidity currents that are generated on the shelf and flow over the slope, this problem may be well suited to the application of cellular discretization schemes, which have been applied (although not nested) to allow for the evolution of highly complex morphologies from relatively simple basic principles [e.g. *Willgoose et al.*, 1991; *Howard*, 1994; *Murray et al.*, 1994]. Such simulations will, in addition to providing a powerful approach to parameterization, also provide details of system behavior (e.g. downstream sediment fining) that go far beyond semi-empirical formulations of sediment transport. Also of particular note are situations involving mixtures of processes (e.g. hillslopes subject to soil creep, surface erosion and/or landsliding) that operate on different length/time scales, and which cannot be readily resolved (numerically) at all important scales simultaneously. Similarly, the scaling of diffusion-like behavior, which appears in numerous problem formulations at many sales (e.g. floodplain accretion, soil creep and rain splash, delta evolution), is well suited to examination by this approach.

- *Coupling erosion-sedimentation processes across highly dynamic process/landform interfaces and deforming boundaries*.

An essential part of an integrated modeling effort is treating the dynamics of interfaces between landscape environments, which in many problems manifest themselves numerically as moving boundary problems. Continental margins involve moving boundary problems for which the position of the shoreline, shelf-slope break and slope-rise break are all internal variables to be solved together with margin evolution in response, over long time scales, to external forcing (e.g. changes in relative sea level). Similarly, the gravel-sand transition in rivers [e.g. *Cui et al.*, 1997], which can mark a distinctive change in river morphology and behavior (e.g. a gravel-bed stream becomes a strongly meandering sand-bed stream), can prograde downstream or migrate upstream in response to sediment supply, tectonic setting and sea-level variation. Modeling these dynamic interfaces will require innovative moving-boundary techniques [*Swenson et al.*, 2000]. Particularly sharp, highly deformable interfaces occur in river/floodplain and alluvial fan systems, where detailed treatments of stream channel/floodplain/fan evolution can require separate (but highly interactive and highly deformable) computational meshes for flow in channels, flows on floodplain/fan surfaces, sediment exchanges between channels and floodplains, and valley wall erosion [e.g. *Howard*, 1996; *Sun et al.*, 1996; *Sun*, 1998]. The modeling becomes more sophisticated when considering individual flow events that pass over the landscape mesh until deposited. Of particular relevance are schemes developed for studying the behavior of flow fronts, and the use of Lagrangian-based Riemann solvers, which have been used to model the erosion, routing and deposition of debris flows [*Iverson*, 1997].

- *Testing and verifying landscape evolution models*.

Models of surface processes acting over sort terms generally have the great advantage of being rigorously testable using field and experimental data. This becomes difficult for longer time scales, for which relevant data must be extracted from the Earth's imperfect and often ambiguous stratigraphic record. Yet testing and verification on both scales are needed; and to this end a key aspect of this project will be its strong ties with experimental and field-based work involving Co-PIs and Affiliate Scientists. As one of many important examples, field-based cosmogenic isotope and optically stimulated luminescence techniques [e.g. *Heimsath et al.*, 1997; *Heimsath*, 1999] are proving to be key in modeling, estimating and calibrating soil production and diffusive transport processes, including creep. In addition, new experimental systems, such as the Experimental Earthscape (XES) facility at St. Anthony Falls Laboratory [SAFL; *Paola*, in press] offer the possibility of testing theories for long-term dynamics in controlled experimental systems that in effect compress time by a combination of reduced size and continuous, as opposed to episodic, forcing. Physical experiments are appropriate for testing model predictions that are either scale-independent or scale-distorted in known ways. They are also useful as test beds for evaluating, for instance, parameterization schemes over the range of scales in the experimental system. Although this proposal does not seek support for experimental studies, this ITR project will be closely coordinated with ongoing and independently funded experimental programs at SAFL.

- *Developing advanced algorithms, notably involving high-order methods (including, for example, discontinuous spectral techniques), for applications to coupled, deforming landform domains*.

With important exceptions, problems in landscape modeling mostly involve reduced/specialized forms of the Navier-Stokes equations, for example the shallow water equations and linear and nonlinear forms of advection-diffusion equations, applied at many different scales. The full richness of these equations, notably their unsteady two- and three-dimensional forms, can be examined effectively only by computational methods. Whereas numerous numerical schemes for treating these systems of equations are available, these normally involve low-order methods. Because of the possibility of sensitivity to nonlinear effects, we will examine applications of advanced numerical schemes [e.g. *Hussaini, et al.* 1987] based on high-order discontinuous Galerkin spectral methods designed for maximizing accuracy at a fixed grid resolution, thus requiring fewer nodes in dynamically adaptive, deformable meshes [e.g. *Hu et al.*, 1999]. These methods are robust, readily parallelized, and can easily accommodate complex boundary conditions.

- *Developing next-generation dynamically adaptive meshes that can readily accommodate these advanced algorithms as well as domain/boundary deformation involving exceedingly large strains.*

Large-scale landscape models thus far have utilized static rectangular meshes [e.g. *Willgoose, et al.*, 1991; *Howard*, 1994], static variable-resolution triangular meshes [*Braun and Sambridge*, 1997; *Tucker et al.*, 1999] and deforming (but not re-optimizing) meshes [*Willett*, 1993; 1994]. For time scales involving significant landform (and/or tectonic) deformation, it is imperative to develop deformable, dynamically re-optimizing meshes, including those designed for river/floodplain problems that involve a combination of large mesh strains and mesh regeneration during river meandering. Moreover, to fully treat certain three-dimensional aspects of landscape evolution will require terrain-conforming meshes that accommodate a mix of algorithms for calculating stresses, and routing of water (both above and below the land surface) and eroded debris, as well as steep to overhanging slopes [e.g. *Howard*, 1998].

- *Adapting current (as well as developing new) data retrieval/assimilation/management protocols and platforms for manipulating large data sets, including novel visualization techniques adapted to special needs of landscape modeling*.

Novel advances in information technology will be required to develop the protocol and diagnostic pattern-recognition algorithms necessary to adequately divide landscapes (images) into morphodynamic units as input to dynamics models. For example, individual hillslopes may contain colluvial hollows filled by creep processes, which are periodically evacuated by landslides [*Reneau et al.*, 1990]. Similarly, channels, floodplains and terraces have very different functions in riverine transport systems. Distinguishing such units with sufficient resolution for detailed nested modeling, for example, will require manipulating large data sets from various sources (e.g. elevation, soil/vegetation data, etc. on GIS platform), including laser altimetry (Figure 1) and field survey data; and it will require interactive visualization that simultaneously involves zoom, rotation, variable surface shading, animation, etc. capabilities.

- *Designing a modular, readily adaptable computations structure*.

A centerpiece of this project will be the development of a highly modular *Problem Solving Environment (PSE) for Landscape Dynamics* that incorporates many of the advances described above, and which serves effectively as a research tool as well as a platform for teaching across pedagogical levels. The modularity will be designed to allow a researcher/teacher to readily move among different aspects of a problem, from initial phases of diagnostic visualization to domain/mesh/algorithm specification to final visualization of results, computationally steering the simulation (e.g. modifying input, parameters, etc.). The PSE will also have a structure that allows for varying degrees of “run” sophistication, thereby making it accessible to different pedagogical levels (including computer platforms, memory availability, etc.), including options for students to perform interactive “What if?” experiments.

**Consortium Structure and Management**

To achieve the envisioned project goals will require a truly collaborative effort among Earth scientists, geophysicists, engineers, mathematicians and computational scientists; and it will be critical to have appropriate infrastructure and administrative programs in place that not only facilitate, but ensure, this collaborative effort. To this end, the Florida State University (D. Furbish, M. Hussaini, G. Fox, M. Schmeeckle) will serve as Lead Institution of the Consortium, administered under the School of Computational Science and Information Technology (CSIT). Within the context of CSIT, FSU is prepared to commit significant resources to this project, including access to outstanding computational facilities, ample modern office space and full administrative support staff. As part of a larger initiative to enhance advanced computations in the sciences at FSU, CSIT is also prepared to offer competitive Graduate Fellowships, and possibly to commit up to three of 30 new CSIT faculty positions, to the area of Earth surface dynamics; FSU has already committed resources for three Post-doctoral Associates in this area.

Four Node Institutions will serve as intellectual and administrative focal points: the University of California, Berkeley (W. Dietrich, J. Shewchuk), the University of Colorado (T. Pfeffer, J. Syvitski), the University of Minnesota (C. Paola, G. Parker, V. Voller) and the University of Virginia (A. Grimshaw, A. Howard, P. Wiberg). These represent a combination of key coverage of scientific specialties and intellectual resources, strength in computational and experimental resources, strong partnerships with members of Affiliated Institutions (see below) and diversity of geographic location facilitating accessibility among participants, including Affiliate Institution Scientists. This Consortium structure is administrative and not exclusionary; we envision involvement of many Affiliate Scientists who are not at Node Institutions (see below).

With input from appropriate advisory and steering groups constituted from Consortium and Affiliate members, the Consortium will administer five key, interrelated core programs:

1) *Shared Intellectual Resources*. This program will focus on supporting extended visits of senior scientists, post-doctoral associates and students involved in collaborative research among institutions, notably targeting arrangements for co-direction of student projects, and co-supervision of post-doctoral associates. The theme of this program will be to facilitate and enhance intellectual exchanges among participants and across disciplines, highlighting central themes (e.g. process scaling), and will serve an important role for involving Affiliate Scientists.

2) *Focus Topics*. This program will provide a mechanism for participants, including Affiliate Scientists, to focus on key problems (scientific, technical, educational) in workshop forums.

3) *Young Scientists*. This program will focus on early-career (e.g. untenured) scientists, facilitating their involvement in Consortium efforts. In addition to enhancing the future intellectual growth of the science community in the theme areas of this ITR project, this program will enhance transfers of information and technology among scientists at all career levels.

4) *Education*. This program will focus on implementation of a computationally centered learning platform that is adaptable across pedagogical levels and science backgrounds, and will sponsor internship and outreach programs.

5) *Partnerships*. This program will focus on enhancing intellectual exchanges with partners in government, industry and other key academic institutions. We have identified key, potential collaborations with scientists at Affiliated Institutions involving at least 11 US universities, five foreign universities, three national DOE labs, the US Forest Service, the US Geological Survey and the petroleum industry.

**Impact of Project**

This project will lead to an unprecedented step in our understanding of the dynamics of Earth's landscapes by addressing critical issues in landscape modeling, requiring new advances in the development of numerical algorithms, mesh generation, and data management and manipulation, including novel diagnostic visualization techniques. The Consortium is designed to provide international leadership in setting the stage and tone for next-generation work in landscape modeling, via its core programs involving partnerships with Affiliate Institutions, shared intellectual resources, education, and research-based training of young scientists. Results of the project will moreover have direct bearing on numerous environmental problems of critical national and international interest; examples include predicting flood, erosion and landsliding potential [e.g. *Pack et al.*, 1998; *Dietrich et al.*, submitted], and predicting transport, storage and release of critical substances (including contaminants) within the surface environment, including cycling and sequestration of organic carbon as this bears on the global carbon balance [e.g. *Jenkinson et al.*, 1991; *Trumbore et al.*, 1996; *Wang et al.*, 1996].