Boulder Creek Critical Zone Observatory: Weathered profile development in a rocky environment and its influence on watershed hydrology and biogeochemistry

The first step in understanding how Earth surface processes are integrated in the critical zone—the heterogeneous carapace of rock in various stages of decay, overlying soil, and the ecosystems they support—is to understand the structure of the critical zone itself and the processes that produce this structure. Fundamental characteristics of the critical zone, such as its thickness, the character of the weathered rock and soil layers and the biological activity within them, together control the passage of water, the chemical processes operating, the material strength, and the function of subsurface ecosystems. Rarely is the architecture of the critical zone known outside of fortuitous exposures such as road and riverbank cuts or cliff edges. This lack of empirical constraint in turn hampers the development of our quantitative understanding of the landscape as a whole, and severely limits the degree to which we can predict the responses of landscapes to climate and land use change.

We propose to build a critical zone observatory designed *to understand how weathering (both physical and chemical) and transport processes control the structure of the critical zone itself*, and *to explore the impact of the critical zone structure on hydrological, geochemical and biological functions*. Our field site in the Boulder Creek watershed of central Colorado encompasses strong contrasts in erosional regimes, and therefore contains critical zone architectures that range from dominantly bare rock to deeply developed weathering profiles. We aim to exploit the natural experiment represented by these contrasts to examine the processes that shape the critical zone and the influence of the critical zone structure and character on hydrology and landscape evolution.

Background: In the simplest analysis, the critical zone is created by the interplay of processes that break down rock to produce weathered rock, and then regolith (material ready for transport); processes that transport mass through solution; and processes that drive physical erosion. Where erosional efficiency is high relative to the rate of advance of the weathering front, the critical zone may be vanishingly thin. Where the weathering front advances into fresh rock more rapidly than removal of material by erosion, the critical zone is thick and weathering is advanced. The problems of understanding how solid rock breaks down into transportable debris (regolith), and how this material is transported down hillslopes, are fundamental to both landscape evolution (Ahnert, 1970; Anderson & Humphrey, 1989), and to sedimentary systems, in which these processes encompass the sediment supply term (e.g., Blum & Törnqvist, 2000).

The critical zone is the region where surface processes enact changes in the physical, chemical or biological character of rock. Consider the system from the point of view of a rock parcel as the surface lowers toward it, or in the Lagrangian reference frame, follow the rock as it moves toward the surface. The rock will initially have some set of physical and chemical properties set by the geological and tectonic history of the rock parcel. As it moves toward the surface, at a rate set by either the local erosion rate or the downward advance of the weathering front, processes driven by meteoric water, thermal fields, stress fields, or biological agents will begin to occur. As they do so they will produce changes in the rock properties that may catalyze feedbacks that drive further and faster change. Once the rock parcel "feels" the surface in this way, it has entered the critical zone. With further transformation, eventually the strength of the rock is insufficient to prevent disintegration, and particles are freed from their parent rock mass and can move independently. This is regolith, and the particle motions are now driven by a suite of processes ultimately slaved to gravity.

In "rocky" landscapes, where any soil present develops from underlying bedrock, we have a qualitative understanding of how the interplay of physical or chemical weathering and erosional transport will produce a critical zone with particular characteristics. For instance, frost shattering on a low relief surface will produce a felsenmeer of broken boulders. Regions of low relief in warm wet climates are associated with deep weathering profiles (Stallard, 1985; Braun et al., 2005). Glacial removal of a weathered mantle produces thin weathering profiles and is associated with low solute fluxes (e.g., Millot et al., 2002). But few quantitative models capture the interactions of chemical, physical weathering and erosion processes. While there are no models of the evolution of rocks as they traverse the full critical zone, some have proposed "rules" for the production of regolith from rock. Regolith production rates are commonly considered to be a function of overlying regolith thickness (Carson & Kirkby, 1972), a model with empirical support (Heimsath 1997, 1999, 2000; Anderson, 2002). Models of this form, coupled with sediment transport, can describe the thickness of a soil mantle and spatial variation in chemical denudation rate on a hillslope (Mudd & Furbish, 2004, 2006; Yoo et al., 2004, in press). Missing, however, are the specific processes involved in regolith production, although some efforts have been made to show how particular processes ought to yield particular regolith production functions (Anderson, 1998; Gabet et al., 2003). Most models of regolith production are therefore incapable of capturing the undoubtedly strong dependence on both climate change and lithology. Perhaps more important for critical zone research, the focus on regolith production does not address the formation of the weathered rock zone underneath regolith, i.e. the formation of the critical zone itself. We wish to address these issues with an integrated approach to understand the processes that modify the rock as it passes upward into and through the critical zone, as well as those that disarticulate rock at the regolith interface.

The speed with which chemical weathering should proceed within rock might reflect the degree to which the rock is fractured for several reasons. First and foremost, fractures provide pathways for water to penetrate the rock. Chemical attack of intact rock can be treated as a diffusive process because its rate depends upon the diffusion of chemical species into and out of that rock (e.g. Fletcher et al., 2006; Hoke & Turcotte, 2002, 2004). The characteristic time scale for significant decay of the interior of the rock will therefore depend upon the square of the radius of the fracture blocks: $\tau \sim R^2/\kappa$, where κ is chemical diffusivity. The sensitivity of the critical zone to tectonic comminution (bottom-up, pre-conditioning), and to the density of surface-driven (top-down) fractures associated with topographic stresses (e.g. Miller and Dunne, 1996; Molnar, 2004) or biological agents (roots) or frost cracking, is therefore highlighted.

Surface water hydrology depends on the structure of the critical zone and plays key roles in shaping it. Gilbert (p. 99, 1877) noted that "deep soil acts as a .. reservoir for the water of rains, and tends to equalize the flow of streams", while in the absence of soil "nearly all the water runs off from the bare rock Solution becomes a slow process…" Recent work shows water residence time depends on critical zone thickness and upslope contributing area (Asano et al. 2002) and catchment topography (McGuire et al. 2005). Water drives chemical alteration, which in humid regions is the chief means of pushing the critical zone lower boundary, the weathering front, into fresh rock (Pavich, 1986; White et al., 1998; Gabet et al., 2006). Water is also necessary for a variety of predominantly physical processes that advance the weathering front, such as frost cracking and tree throw. Thus, not only does the structure of the critical zone control hydrologic response (Post & Jones, 2001; Uchida et. al, 2005) and the distribution of travel times within a catchment (Kirchner et al., 2001), but the nature of flowpaths will control the evolution of the critical zone architecture through their impact on all types of weathering and erosion processes.

Similarly, the biologically active zone, where soil biota and plant roots are directly involved in the net mobilization or immobilization of nutrients, will both depend on and shape the structure of the critical zone. We expect that biotic processes will become increasingly important (and abiotic processes less important) as the critical zone thickens. Abiotic processes will largely control nutrient mobilization and immobilization where fresh rock is close to the surface, and models of nutrient dynamics at these sites require knowledge of hydrologic, geochemical, and geomorphic characteristics of the watershed. In contrast, where the critical zone is thicker, subsurface biotic processes will have to be integrated into biogeochemical models in order to predict rates of immobilization and mobilization of nutrients as water moves through the weathered profile. This pattern will hold for both those nutrients with biologically driven dynamics (C, N) as well as those nutrients where abiotic controls on dynamics are relatively more important (Ca, K, Mg, and, to a lesser degree, P). Vegetation is involved in yet another feedback: supported by the nutrient supply and the upper soil, vegetation is a source of not only litter and root material but also of dissolved organic material (DOM) that moves with water through regolith to the weathering front. This DOM comprises organic substrates that support microbes and humic and fulvic acids; these in turn act as chemical weathering agents through electron transport and metal complexation, and hence advance the weathering front.

Boulder Creek

Boulder Creek drains 1160 km^2 from the Continental Divide in the Front Range of Colorado to its confluence with South St. Vrain River, and spans elevations from 1480 to 4120 m (Fig 1). The upper half of the watershed is a mountainous landscape of crystalline rocks, while the lower half crosses the piedmont and is underlain by sedimentary rocks and lined with alluvial terraces. The project will focus on the mountain portion, carved in Precambrian (1.7 by) granodiorite and older biotite gneiss (Lovering & Goddard, 1950), where three distinct erosion regimes arise (Birkeland et al., 2003). At the crest, the watershed was glaciated. U-shaped valleys, cirques (a few still with ice), and rock-dominated valley floors are found. Cosmogenic radionuclide (CRN) exposure ages on glacially polished bedrock in the valley floor document that glacial erosion removed the previous cosmogenic production layer, and that glaciers retreated from their maximum position at ~17ka to the divide between 14-12 ka (Ward et al., 2006). East of the glacial limit is a broad, high (2500-2750 m) post-Laramide surface of low relief (Bradley, 1987), in which weathered rock profiles are up to 15 m thick (Isherwood & Street, 1976; Dethier & Lazarus, 2005). Still further east, renewed bedrock channel incision over the last 5 My has progressed headward from the plains, cutting deeply into the post-Laramide surface, forming the

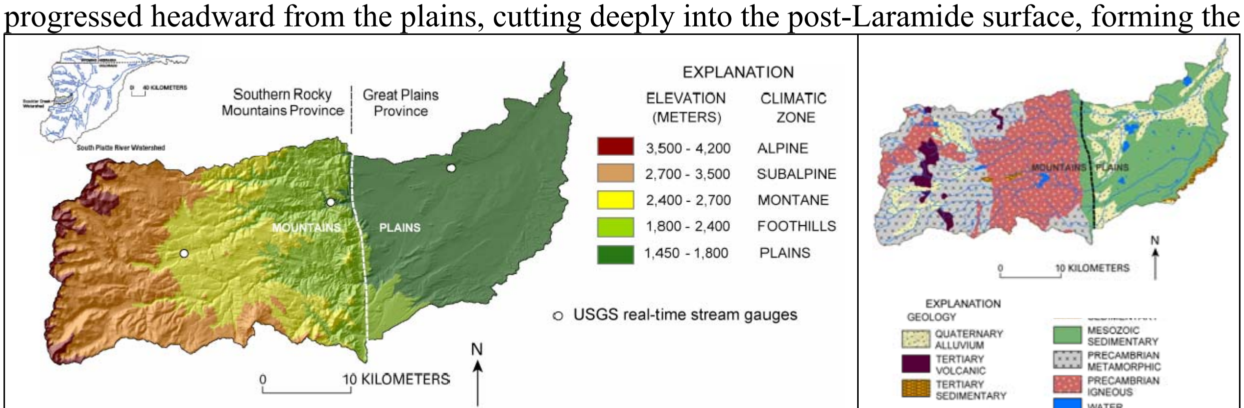

Fig. 1 Boulder Creek topography and geology. Inset map shows Boulder Ck within the South Platte watershed. From Murphy (2006).

steep slopes and deep canyons of the range front (Anderson et al., 2006).

The glacially scoured headwaters, the post-Laramide low relief surface, and the deeply-incised range front canyons are all in close proximity and are developed in similar granitoid rocks. The variation in weathered profile development resulting from these erosion regimes therefore constitutes a natural experiment that will enable us to test coupled models of weathering front advance, regolith production and sediment transport in an accessible field laboratory. The impacts of this spatial variation in the critical zone on hydrologic and biologic activities can also be documented, which will in turn constrain hydrologic and ecological models.

Hypotheses

The Boulder Creek CZO (BcCZO) will explore four questions:

- *How does critical zone development vary across erosional and ecological regimes?*
- *What controls the spatial variation in critical zone development?*
- *How does the distribution of critical zone development control the hydrologic response of the catchment to both snow and rainfall?*
- *How do weathering and nutrient fluxes vary with critical zone development?*

From these broad questions a number of hypotheses flow:

CZ development: -The rate of advance of the weathering front (and hence the base of the critical zone) is controlled either by bottom-up (tectonic cracking, topographic stress cracking) or top-down (chemical weathering, surface-driven mechanical weathering) processes. The strongest control is the degree of pre-fracturing of the protolith.

-The depth of glacial bedrock erosion during a glacial cycle is sufficient to maintain the CZ in the glacial portion of the landscape in a state of transience.

-Regolith production is dominated by *i)* biotite hydration driving mechanical breakdown, *ii)* frost cracking, *iii)* chemical alteration (perhaps hastened by organic acids), and/or *iv)* tree throw or fossorial rodent activity. Dominant weathering processes leave detectable signatures in the properties of a critical zone profile.

-Coupling of pore flow and chemical weathering in fractured rock leads to strong positive feedbacks between permeability, subsurface water flux, and weathering rate. These feedbacks lead to enhanced weathering in zones of initial weakness (e.g., around pre-existing fractures), and strong spatial variability in the degree of critical zone development.

-Chemical maturity (degree of alteration) of the regolith and underlying weathered rock will be greatest where low denudation rates promote long residence times for rock in the critical zone.

Hydrologic feedbacks: -Water flow paths will be deeper, and water residence times greater where the critical zone is most extensively developed. Alternatively, accumulation of weathering products (clays) where the critical zone is most extensively developed reduces deep penetration of water into the subsurface.

-The degree of CZ development strongly affects the hydrologic response and topographic evolution in rocky mountain drainage basins. For example, a deeper critical zone leads to reduced flood peaks, which in turn reduce water and sediment discharge in the stream network and lower catchment-wide erosion rates, and vice-versa.

Ecological feedbacks: -The spatial dependence of dominant weathering processes and rates are strongly tied to ecology. Sites with a better-developed critical zone will support greater plant productivity, resulting in greater fluxes of DOM. Enhanced microbial growth contributes to chemical weathering, thereby serving as a positive feedback for critical zone development.

Microbial activity within the critical zone will influence watershed-level aquatic ecology, and the magnitude of this influence will depend on both the hydrology and extent of development of the critical zone. Both inorganic weathering fluxes and biological activity will be greatest where the critical zone is most extensively developed.

Approach

Three sub-catchments within Boulder Creek, one for each of the major erosion regimes, will be focal points of the BcCZO. In these focus catchments we will characterize the thickness of the critical zone and its chemical and physical properties and biological activity. Tools will include geophysical surveying, deep coring, and hydrologic monitoring. These basic measurements will provide data needed to inform, design, and test models of weathering front advance, regolith production and landscape evolution, hydrologic function, and biological activity. In addition, we will take advantage of "fortuitous" critical zone exposures, particularly in road cuts within Boulder Canyon, where the upstream passage of a prominent knickpoint has left in its wake hillslopes in various stages of response to baselevel lowering. Boulder Creek watershed contains three active USGS stream gauges, one (in the headwaters) with a century of record (Fig 1), and 10 historic gauges with records that range from 4-20 years. A 1-m DEM of a 40 km^2 region of the alpine headwaters of Boulder Creek exists, and have requested the National Center for Airborne Laser Mapping (NCALM) to map the entire watershed at this resolution.

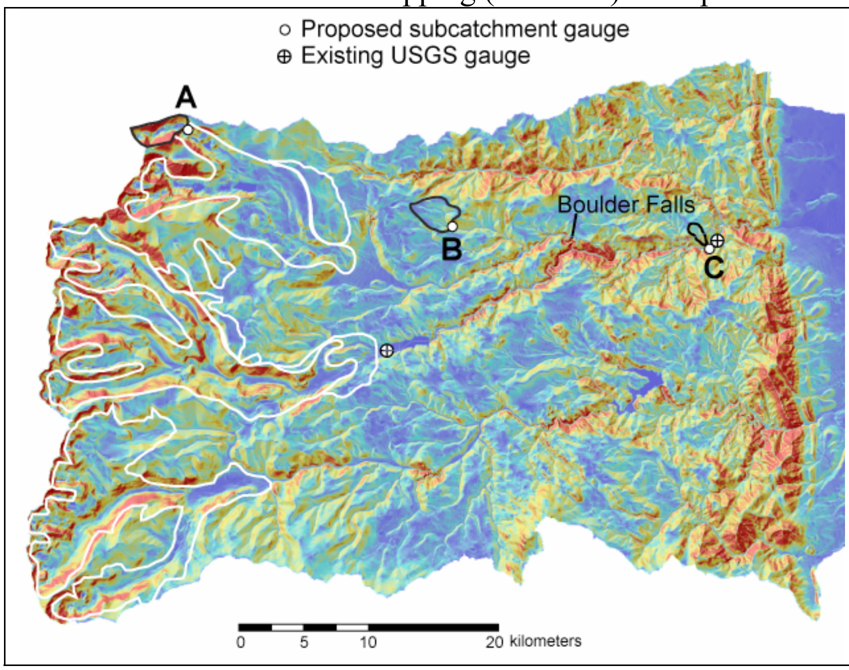

Fig 2. Shaded relief and slope map of mountainous portion of Boulder Creek. Steepest slopes shaded red; shallowest slopes are blue. Proposed subcatchments are **A**- Green Lakes Valley, which has been gauged since 1981, **B**- Gordon Gulch and **C**- Betasso cutoff. Pleistocene glacial limits (white), and two existing USGS gauges in this part of the watershed shown. Boulder Falls is a knickpoint on N. Boulder Creek; similar knickzones are seen as steep-walled canyons in other Boulder Creek tributaries.

Subcatchments: The three proposed subcatchments are A) *Green Lakes Valley* in the headwaters, B) *Gordon Gulch* on the post-Laramide surface, and C) *Betasso cutoff* in the steep outer canyon (Fig 2). All are free of mining activity and are accessible by car to at least the lower reaches (only Green Lakes, on the continental divide, lacks headwater auto access) and trails. Green Lakes Valley is a glaciated alpine watershed on biotite gneiss and granodiorite, continuously monitored for discharge and water chemistry for 26 years (Caine, 1995; Williams et al., 1996). The basin lies within the City of Boulder watershed, which has been closed to the public for a century. Gauges are present at 6 additional locations within the catchment and within a few km of it, and we have a 1 m DEM of the basin and surroundings. The other two subcatchments will be new installations. Gordon Gulch drains the low relief post-Laramide surface. It is underlain by biotite gneiss, and is forested; it lies within the Roosevelt Arapahoe National Forest. The Betasso cutoff is a steep, ephemeral gully stretching from Boulder Canyon into Betasso Preserve (a Boulder County Open Space park). The steep valley cut in granodiorite is dominated by bedrock in its lower reaches, and bedrock knobs occur at the canyon spurs, while deep weathering is found at the divide. The Betasso water filtration plant at the top of the site may prove a friendly location for deep drilling and met station installation.

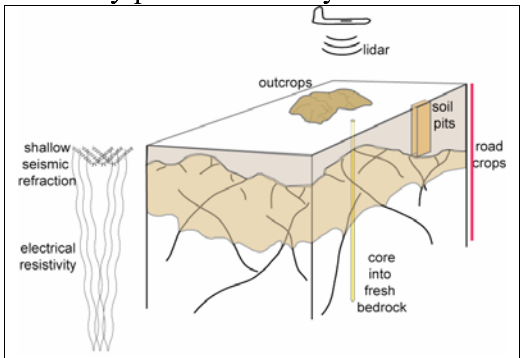

Fig 3. Subcatchment characterization

Measurements in subcatchments: Depth to bedrock and layering within the critical zone will be mapped using shallow geophysical techniques (seismic refraction, GPR, electrical resistivity) and deep drilling. Our goal is to characterize the full weathering profile chemically, as well as its geophysical, hydrologic and biological properties. We will core the full critical zone in at least 2 locations in each subcatchment; these cores will be analyzed for mineralogy and chemistry, fracture density, bulk density, conductivity, geophysical properties and biological activity. The boreholes will be developed and maintained as wells. Hydrologic monitoring in each subcatchment will include: a telemetered stream gauge; an automated water sampler; piezometers, tensiometers, and time domain reflectometry (TDR) probes at 15 sites; soil water samplers (lysimeters) in 4-5 clusters; met station measuring rain/snow amount, net radiation, soil temperature, relative humidity, wind speed, and wind direction. Samples from soil pits and outcrops will be analyzed for textural, chemical, and mineralogical properties and cosmogenic radionuclides.

Geophysical techniques: We propose applying a combination of diverse, complementary techniques (Table 1) to determine depth to bedrock, layering, and characteristics of weathered rock and soil (Burger et al., 2006). Shallow seismic refraction provides the fastest means of detecting competent bedrock with minimal post-processing, particularly for 1-D information. Difficulties arise where low-velocity layers occur (e.g., bouldery layers), or where depth to bedrock is shallow. GPR can provide cm-scale resolution of layering in the shallow subsurface when a common midpoint (CMP) sounding is performed. Although it is time intensive, electrical resistivity has greater depth resolution, and shows layers well. The technique works best where soils are > 0.2 m deep so that good connection can be established with electrodes. EM techniques will be used in reconnaissance to obtain lateral variations in ground conductivity.

Three levels of surveying will be conducted within each subcatchment, ranging from a very detailed survey to fast and rough estimates of depth to bedrock and composition of the critical zone. 1) *Calibration Site* (CaS). All four geophysical methods will be run in a 150x150 m grid around each deep drilling location to permit measurement of 3-D variation. The aim of a calibration site is to gather as much information as possible in a location where ground truth from the borehole is available. At each calibration site we will collect soil and rock samples and obtain laboratory measurements of density, porosity, electrical resistivity, water content, dielectric properties, and P wave velocity of the samples. The degree of sample disturbance and the moisture content are critical factors that affect the 'ground truth' measurements, and will be carefully accounted for. 2) *Core Sites* (CoS) CoS's provide some hard data for calibrating the geophysical measurements. They will be located either near drillings (wells, temperature loggers, etc., older road drilling or construction information) or close to road cuts, gullies or other natural sections. These sites will provide 2-D and 3-D data (interpolated by ~100-meter long parallel

Table 1. Proposed geophysical techniques

Method	Utility	Data collection and analysis
Seismic refraction	Efficient observation of regolith/rock boundary to 10s of meters.	Intercept time and wavefront inversion; both with network raytracing
Ground penetrating radar (GPR)	Local detailed information about layering in shallow subsurface.	Continuous or step-wise acquisition on transects, with common midpoint (CMP) soundings
Electrical resistivity (tomography)	Greater resolution and depth in soil-mantled areas than GPR. Good resolution of regolith/rock boundary, moist clay layers, ice cemented debris	Multi-switch system to measure 2-D section relatively rapidly.
EM	Useful for lateral variations in upper ~6m.	Lateral variations in ground conductivity.

lines and one or two cross lines). Again all three methods will be tested (GPR, Seismic Refraction, Electric Resistivity). Field work will show which combination of geophysical techniques works most effectively. 3) *Normal Site* (NoS) Rapid surveys will provide 2-D data along 200-400 m transects and 1-2 cross lines of about 50 m length in locations throughout the catchment. These fast surveys will mainly use seismic refraction and electric resistivity, as they provide good data for depth to bedrock and layering of the regolith.

We plan to conduct ~13 NoS surveys arrayed along three cross sections in each subcatchment, with survey sites in different slope positions and distributed along the catchment axis. These surveys along with 2-4 CoS's and 1-2 CaS in each subcatchment should provide a reasonable depiction of the critical zone thickness and layering in each subcatchment.

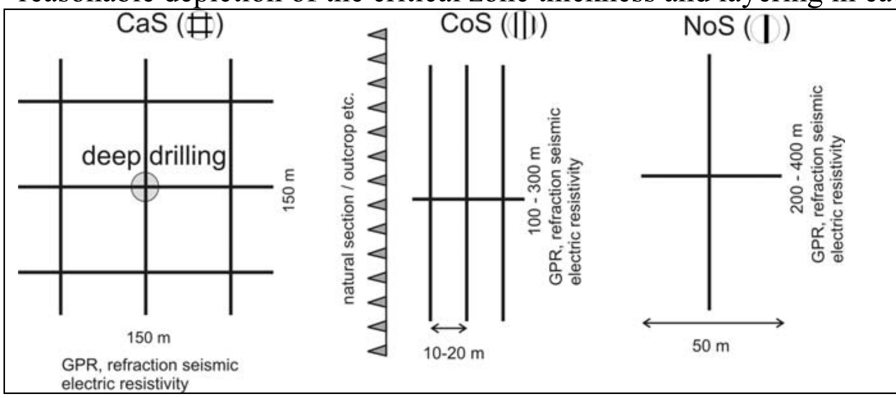

Fig 4. Shape, length and possible techniques applied to different geophysical sites. CaS = Calibration Site; Cos = Core Site; NoS = Normal Site;

Hydrologic and hydrochemical monitoring: Our hydrologic monitoring goals are to provide sufficiently detailed data to excite planned hydrologic simulations described below and to measure chemical fluxes within and out of the catchments. Characterization of topography, subsurface layering, and texture of soils are key boundary conditions in the hydrologic model. Our stream gauges will provide high-resolution observations of discharge from each subcatchment, to augment the larger scale data from the USGS. A full-time field coordinator hired by the project will oversee weekly monitoring of wells, piezometers, tensiometers and water content with TDR. Water samples from lysimeters and streams will be analyzed for major dissolved species as well as fluorescence (discussed below) on a weekly basis. These analyses will be supplemented by occasional measurements of strontium isotopic composition (to help unravel weathering sources, e.g., Singh et al., 2006) and tritium concentrations (to characterize water residence times, e.g., Michel 2004; Liu et al., 2004).

Weathered profile development: Deep cores, soil pits, and available rock exposures will be used to characterize the mineralogy and chemistry of the weathered profile, with particular attention given to changes in these properties through the critical zone. Samples will be analyzed using quantitative XRD (Srodon et al., 2001; Eberl 2004) for mineralogy and abundance, and using XRF for elemental abundances. These chemical analyses will be combined with physical descriptions of color, fracture density, texture, porosity, and bulk density to build comprehensive descriptions of the weathered profile, including elemental mass gains and losses relative to parent material (Brimhall and Dietrich, 1987; Anderson et al., 2002).

Vegetation and biological activity: We will explore how ecological systems supported by the critical zone impact weathering fluxes and advance the weathering front, and consider how these affect stream ecology. Vegetation can influence critical zone formation through the production of dissolved organic material (DOM) that is transported from litter into the weathered profile. DOM is a complex mixture, comprising many classes of organic compounds, such as carbohydrates and humic and fulvic acids. Humics can react with mineral surfaces through sorption and electron transport reactions. The sorption reactions preferentially remove more aromatic humic molecules with greater acidic functional group content, derived from the lignin and plant pigments abundant in above-ground vegetation. Meanwhile, heterotrophic microbes supported by labile fractions of the DOM produce new humic and fulvic acids, which have a lesser aromatic character than the humic material from leaf litter.

The litter-derived and microbial-derived humic fractions of DOM can be measured readily because their light absorbing and fluorescent properties differ. Measurement of ultraviolet absorbance divided by the DOM concentration, the *specific uv absorbance*, or SUVA, is typically made at either 250 or 300 nm. Similarly, the abundant fluorescent moieties in humic and fulvic acids include quinones, and in plant/soil the breakdown of pigments and lignin contributes to highly conjugated quinones, whereas quinones from microbial biomass are less conjugated (Cory & McKnight, 2005). These differences in the quinone moieties can be detected by simple fluorescence measurements at a single excitation wavelength (370 nm), referred to as the *fluorescence index* (McKnight et al., 2001). Thus, changing DOM sources with depth in the regolith and over time can be monitored by measuring DOM concentrations and spectroscopic characteristics of the DOM. These data will document the distribution of these humic substances within the regolith over time (sampled in the wells and lysimeters) and provide insight into the "biogeochemical hotspots" of humic-driven chemical weathering in the regolith. With more detailed measurements we can examine the transformation of DOM within the critical zone by in situ microbial growth. Fluorescence measured over a range of excitation (240 to 450 nm) and emission (240 to 600 nm) wavelengths, and analyzed using a statistical approach, can quantify the contributions of amino acids and quinones of different source and redox state. These measurements will be included in the analysis of waters collected from wells and lysimeters.

We anticipate that where the microbial activity is greatest, microbially derived humics will dominate, and reduced quinone moieties will be abundant, reflecting the electron shuttling role of these compounds. Down-flow from these zones, we expect to see greater concentrations of reduced metals, such as ferrous iron, liberated by the reduced quinones in the humic fraction. Yet further down-flow, if oxygen becomes available, these reduced metals may precipitate as oxides, with attendant influence on the geochemical and hydrologic properties of the regolith.

The composition and activity of subsurface microbial communities has received little attention despite the potential for microorganisms to mediate weathering reactions and nutrient dynamics many meters below the soil surface (Kieft & Phelps 1997, Fierer et al. 2005, Holden &

Fierer 2005). In order to evaluate the potential role of microbes on weathering processes, and as a complement to spectroscopic quantification of microbially-derived DOM, we will survey microorganisms and microbial activity in the subsurface environment. Samples will be collected aseptically from the deep drilling sites in each subcatchment at 0.5 m intervals down to bedrock. Only the inner portion of the cores will be used for microbiological analyses. Bromide (added as KBr to the borehole fluids) will be used as a solute tracer to determine if the collected samples are contaminated (e.g., Kieft et al., 1995). Total microbial biomass in each sample will be estimated by extracting and quantifying ester-linked phospholipid fatty acids (Fierer et al. 2003b). DNA will be extracted from the samples (e.g., Fierer & Jackson, 2006) with the abundances of specific functional groups of microorganisms (denitrifiers, ammonia oxidizers, methane oxidizers, Fe-reducers, Fe-oxidizers, H_2-oxidizers) determined using quantitative PCR assays (Kolb et al. 2003, Wallenstein & Vilgalys 2005, Schippers & Neretin 2006). Likewise, we will compare microbial community composition between samples by clone library construction/sequencing using 'universal' primers (Fierer et al., in review). We expect that the abundances of these functional groups and the overall composition of the microbial communities will be closely tied to the geochemical and hydrological characteristics of the collected samples.

To explore the role of microbially-produced carbonic acid as a weathering agent in the critical zone, we will incubate samples in the laboratory, under both aerobic and anaerobic conditions, to measure rates of microbial C mineralization with and without the addition of various organic carbon substrates (Fierer et al. 2003a). Likewise, we will estimate potential rates of denitrification using lab-based assays (Groffman et al. 1992) to estimate the potential for these microbial communities to remove nitrate from the pore water. While these assays do not allow us to estimate microbial activities *in situ* (due to the inherent difficulty of collecting undisturbed samples and then matching field conditions in incubation) they do provide comparisons of the potential rates of microbial activity within and between sites.

The fluorescence measurements, microbial community surveys, and microbial activity assays provide valuable data to develop conceptual models that can lead to process-based models of the critical zone in which interactions of vegetation and microorganisms are incorporated. For example, we evaluated the role of dissolved fulvic acids as electron shuttles between a stream and its hyporheic zone using field experiments and modeling in the headwaters of Boulder Creek (Miller et al. 2006). We plan to expand our models to address the importance of these DOM reactions and microbial processes along deeper flowpaths within the critical zone. These processes link to aquatic stream ecology issues, such as hydrologic and biogeochemical pathways that control stream P availability potentially responsible for blooms of invasive diatoms (e.g., *Didymosphenia geminata*, aka rock snot) (Greene et al., 2007; Vietti et al., 2007).

Cyberinfrastructure

All aspects of cyberinfrastructure will be represented in the BcCZO: numerical modeling, data organization and access, and data genesis and measurement (NSF, 2006). The first two of these components of cyberinfrastructure are discussed here.

Modeling evolution of the critical zone: We will develop models of the evolution of the critical zone that will serve to guide the collection of relevant field data, and to integrate the diversity of that data to gain insight into the active processes. We will start with simple 1-D models, and add complexity over the course of the project as guided by the data and our improved understanding of relevant processes.

1D vertical. The modeling will begin with a 1-D vertical Lagrangian model of weathering profile development in fractured, crystalline rocks. Here we embrace the view that exhumation drives vertical advection through a field of changing environmental conditions that are themselves strong functions of depth below the surface. The physical and chemical properties of a rock approaching the surface will depend upon the history of the processes and process rates it experiences along its path toward the surface. Starting with a 1D water and mineral mass balance framework, we will develop sub-models of property evolution, where properties include mineral abundances, permeability, crack density, etc. These models will require initial and boundary conditions (properties of the unweathered rock below the critical zone, to be constrained by field, geophysical and core observations), the mean rate of lowering of the surface (equivalent to the vertical speed toward the surface, to be determined by CRN–based erosion rates), and rules for the rate of change of these properties (e.g., crack generation, weathering of feldspar, hydration of biotite) as a function of depth below the surface. These processes will in turn be constrained with our best knowledge of geologic history, stress state, thermal state, chemical kinetics and hydrology of the column. Importantly, we can pose hypotheses about what properties are associated with deep weathering front advance as well as transformation of rock to regolith; at what level within this evolving profile is a threshold crossed that makes it possible to disarticulate rock? At steady state this model will result in a profile of properties (effectively, a critical zone boundary layer) that can then be tested against observations, and can be exercised to explore the dependence on the environmental drivers and material properties of a site. We can then exercise the model with 'events' that result in transient responses, such as by modulation of the rate of weathering or lowering processes. Glacial stripping of the profile represents an end-member experiment in which erosion returns the system to a transient state of re-growth of the critical zone. In these 1D models the lateral transfer of mass that occurs once regolith is produced are not considered.

2D cross section. Here we will both explore the interaction between lateral transport of regolith and production of regolith, and allow the regolith to evolve as it is transported down slopes. The starting point is conservation of regolith, which may be cast as $\frac{\partial H}{\partial t} = \frac{\rho_r}{\rho_b} w - \frac{1}{\rho_r} \frac{\partial Q}{\partial x}$, where H is regolith thickness, w production rate of regolith, Q regolith discharge per unit contour length, ρ_b and ρ_r bedrock and regolith bulk densities, and x is downhill distance. While this is the backbone of most landscape evolution models that explicitly account for hillslopes, we will go further in three ways: 1) we will lean on results from the 1D models to cast formalisms for the production of regolith; 2) we will write analogous conservation equations for individual mineral constituents within the regolith, such as feldspar, clay and quartz; and 3) we will explore coupling between permeability, water flux, and chemical weathering fluxes. Regolith properties in these 2D models will vary both vertically and downslope in the direction of regolith transport and will be diluted by inputs from the freshly detached subjacent rock at any position on the hillslope; the degree of vertical mixing will depend upon the geomorphic and biological agents. Again, these models can be used to guide the types of data to be collected, to interpret the data collected, and to develop insight into the relative importance of the various active processes.

3D drainage basin evolution. The channel network provides the lower boundary condition for hillslopes. Rates of channel incision (or aggradation) directly influence hillslope gradients and therefore control downslope fluxes of water and sediment into the fluvial system. Here, we wish to understand the strength of this coupling. Using information on hydrologic response derived from rainfall-runoff monitoring and integrated hydrology model (InHM) simulations (see below), we will use the drainage basin evolution model CHILD (Tucker et al., 2001) to study (a) the impact of hydrologic response on channel and hillslope evolution (Solyom & Tucker, 2004), and (b) the resulting feedbacks between regolith development, amplification/attenuation of flood peaks, rates of stream incision, and rates of hillslope erosion (and regolith thinning). The CHILD model simulates the evolution of a landscape surface under fluvial and hillslope erosion. Its stochastic hydrology module will be adapted to incorporate the results of Boulder Creek hydrologic analysis, and in particular to represent correctly the observed and InHM-modeled relationships between rainfall-runoff response and regolith conditions. Initial and boundary conditions and parameters will be informed by project data, including LiDAR based DEMs, regolith surveys (Table 1), and CRN analyses. This modeling will allow us to assess the potential magnitude of feedbacks between regolith development, hydrology, and landscape evolution, and will help us to interpret observed regolith and slope distributions.

Integrated hydrology model (InHM): The simulation approach to be taken in the proposed effort is *concept development*. The comprehensive InHM (VanderKwaak, 1999) was designed to quantitatively simulate, in a fully-coupled approach, 3D variably-saturated flow and solute transport in porous media and macropores (e.g., fractures, root holes, animal burrows) and 2D flow and solute transport over the surface and in open channels. The important and innovative characteristics of InHM include: (i) adaptive temporal weighting and time stepping, (ii) robust and efficient iterative sparse-matrix solution methods with the solution precision and mass-balance error stipulated by convergence tolerances, (iii) solution of one system of discrete equations with spatially variable properties and boundary conditions that requires no iteration between separate models or model components and no artificial boundary conditions, (iv) allowance for discontinuity of pressure across the subsurface/surface interface, and (v) no *a priori* assumption of a specific streamflow generation mechanism. The governing equations are discretized in space using the control volume finite-element method. Each coupled system of nonlinear equations in an InHM simulation is solved implicitly using Newton iteration. Efficient and robust iterative sparse matrix methods are used to solve the large sparse Jacobian systems.

We will conduct concept-development simulations (surface / subsurface fluid flow / solute transport) at the three Boulder Creek subcatchments designed to address the specific hydrologic-response differences between the subcatchments, variations in deep and shallow subsurface flow path contributions to runoff from differing critical zone architectures, and water residence times.

Data organization, storage and access: The BcCZO will hire a full time data manager responsible for establishing and maintaining data storage and access, compliance with NSF EAR Data Policy, as well as community standards. A computer dedicated to BcCZO data will be purchased in year 1, with sufficient memory and processor speed to handle the data streams we anticipate. All monitoring data will be made available through our website; some (e.g., streamflow) will be made available on a real-time basis, while other data (e.g., weekly catchment TDR, water levels, etc) will be released on an annual basis. LIDAR data will be posted to our website within a year of collection. Our data manager will work with the CZEN Cyberinfrastructure Program (D. Miller, Penn State University), the CUAHSI Hydrologic Information System (D. Maidment, UT Austin), and the Community Surface Dynamics Modeling System (J. Syvitski, CU) to provide seamless connection between our datasets and models and these community resources, and to insure that we comply with community metadata standards. Some of the data we generate will be available through the Boulder community website "BASIN" described below. These multiple outlets for BcCZO data provide the added benefit of data security through redundancy. We have budgeted for publication costs to support dissemination of data and results through journal articles.

Education and Outreach

Our education and outreach program seeks to reach the public, students and other scientists through programs operating at multiple levels. We will expand a highly successful community-based watershed website, work with educators to develop K-12 programs on the critical zone and hydrology, offer undergraduate research experiences, develop an interdisciplinary graduate-level critical zone course, offer graduate field fellowships for non-CU students, and lead field trips. The goal of these programs is to connect our science to the many communities we each are involved in, from our local neighborhoods, to schools, and to our professional colleagues across the country. Outcomes will be gauged with standard metrics.

Community Website. BASIN, the Boulder Area Sustainability Information Network, was established in 1999 through a grant from the U.S. Environmental Protection Agency. Pilot funding established an environmental information network for the Boulder Creek Watershed through partnerships within governmental, educational and research communities culminating in the website www.BASIN.org. The website provides a wealth of information about the watershed including streamflow, water-quality, snowpack, and air-quality data in real-time and archived, information on public water supplies, watershed history (photos, past floods, irrigation and water diversions), pollution prevention, learning activities tailored for the community and Colorado educational standards, and a calendar of local environmental events. BASIN website development has continued through volunteers and a small contract with the City of Boulder. Website content and information resources have expanded to cover emerging issues and continuous monitoring of Boulder-area environmental data, including an online database of 8 years of water quality data for Boulder Creek. Use of the BASIN has grown, with 2006 website traffic to-date *exceeding* 150,000 unique visitors logging in excess of 2 million page requests. The website has extensive local use, but also national and international users. Recent surveys indicate substantial use among the research and educational communities.

BcCZO will support the webpage coordinator for BASIN (Jim Waterman) to update the interface, and to coordinate the integration of BcCZO into BASIN webpages. BASIN will support the objectives of the BcCZO through:

1) Working with the project research team to identify public and educational connections between research goals and community interests, such as impacts on groundwater and municipal source water protection, flood prediction and mitigation, and the role of the critical zone in nutrient transport and surface water flow and quality.

2) Developing educational material to communicate project research objectives, procedures, analysis and conclusions to a range of grade levels and educational disciplines.

3) Working to integrate project data products within the context of the local environmental systems and community issues, including developing supplemental contextual material (text, maps and graphics) to support data presentation and derived information content.

4) Developing data management and posting procedures to support ongoing maintenance of project data in real and near real time and to insure data quality control and quality assessment.

5) Developing supplemental data presentation interfaces to support specific research team analytical and data sharing requirements.

6) Designing and implementing procedures to assess the effective communication of project objectives, procedures and conclusions.

7) Coordinating with BASIN partners (City of Boulder, Boulder Creek Watershed Initiative, Boulder Community Network, U.S.G.S., Cooperative Institute for Research in Environmental Sciences) to communicate project activities within the Boulder Creek watershed community.

8) Developing material to guide other communities in developing environmental information networks. This will build on an EPA technology transfer manual developed for BASIN in 2001 (EPA, 2001; see http://www.epa.gov/ttbnrmrl/).

K-12 outreach: 1) We will partner with the University of Colorado's *Science Discovery* program to engage K-12 students and teachers in the Boulder Creek CZO. Science Discovery, established in 1983, is an experience-based K-12 science outreach program, with a mission to *stimulate scientific interest, understanding, and literacy* among Colorado's youth. It serves over 30,000 students and 1,500 teachers annually throughout Colorado. Science Discovery programs support Colorado Model Content Standards for Science. BcCZO faculty and students will work with Science Discovery staff to develop and deliver new curriculum within three established Science Discovery programs in years 3-5 of the project.

Science Discovery's *Outdoor Classroom* program delivers a research-based curriculum to fifth graders in the classroom and in the field through repeated classroom visits and field trips. The goals are: 1) to connect economically disadvantaged and minority students to the natural world through a series of unique outdoor learning experiences related to the research, 2) to engage students with science professionals as role models, and 3) to increase student interest in, and understanding of, the natural sciences and scientific research. Activities will include: classroom visits by graduate students, field trips to the CZO subcatchments, and overnights at CU's Mountain Research Station in the watershed. Approximately 85 students per year will be served. An additional benefit will be the exposure of graduate students to these teaching roles.

Science Discovery's *Class Program* offers weeklong summer courses for kids aged 7-14. Three new Critical Zone courses will be added to Science Discovery's summer program of over 180 classes. The courses, taught by project graduate students, will explore the rocks and soils in the critical zone, water movement, nutrients and aquatic ecology. Courses will be taught two to three times each summer and will serve up to 210 students.

In year 5, BcCZO personnel will collaborate with Science Discovery's unique statewide teacher professional development program, *Science Explorers*. Project faculty will teach daylong, inquiry-based workshops based on BcCZO research and/or graduate students to 21 teams from throughout Colorado composed of five middle-school students and a teacher. Teachers and students will work side-by-side, and return to their schools to team-teach the curriculum with the materials provided by the project.

2) *Boulder Valley Children's Water Festival*. We will develop a program for this annual daylong extravaganza about water sponsored by the City of Boulder Water Quality and Environmental Services, the Northern Colorado Water Conservancy District, the U.S Bureau of Reclamation, and the University of Colorado. Approximately 1000 fifth-grade students and teachers from 17 Boulder Valley schools attend this event each year.

Educational video: In order to provide a vivid understanding of the world beneath our feet, we will develop a short animated video. It will involve a fly-over the watershed, and then drill down through soil and weathered rock to show how water moves through the critical zone. The video will touch on related environmental issues, such as septic system function, non-point source pollution, and flash flooding. The video will be modeled after "Ride Through the Storm Drain: The Adventures of H_2O Jo" available on the BASIN website. The video will be made available via BASIN and distributed to libraries, school groups and other interested parties.

Undergraduate research experience: Should this proposal be funded, we will submit an REU supplement request. A group of 10 students from across the country will be housed at CU's Mountain Research Station for an eight-week program that will include a week of lectures and field trips, student work on individual projects in the BcCZO, and culminate with poster presentations during the BcCZO Annual Meeting. Each student will have a graduate student and/or faculty mentor for their project to insure that all are successful.

Graduate critical zone course: An interdisciplinary course will be developed to introduce a broad array of tools used to study the critical zone. The team-taught course will use Boulder Creek as a laboratory to study coupling of geophysical, geomorphic, hydrologic, and ecological processes. Students will 1) collect data, 2) analyze datasets in the context of existing theory, 3) use analytical and numerical models of physical, chemical and ecological systems, and 4) synthesize observations in reports. Exposure and use of diverse tools such as data-logged field instruments, applied geophysical methods to probe the subsurface, and water chemistry, will empower students to incorporate diverse methods in their own research. Students will be encouraged to combine these with available resources, such as 1-m elevation data (currently available for 40 km^2; the remainder of the watershed to be mapped during this project), long-term data stream flow and meteorology data available from USGS and the Niwot Ridge LTER site, and the collection of numerical models of surface processes soon to be available through the Community Surface Dynamics Modeling System to address critical zone problems.

BcCZO Graduate Fellowships: To encourage other researchers to work in Boulder Creek, we will offer summer graduate fellowships (2/yr in yrs 3-5) for any aspect of critical zone study in Boulder Creek. These will provide $7800 summer stipend, lodging and meals at the Mountain Research Station, and travel from the home institution. Fellowships will be awarded based on intellectual merit as determined from a short proposal. BcCZO personnel will review proposals, and the Executive Committee will make the selections. CU students will *not* be eligible.

Geological Society of America Annual Meeting field trip: We will run a field seminar to visit the BcCZO and discuss critical zone processes during the GSA Annual Meeting in Denver in 2010. The event would be patterned after the 1st Annual Kirk Bryan Field Seminar, held during the 2006 GSA meeting, including a Pardee symposium on critical zone development.

Measuring outcomes: We propose to evaluate the outcomes and impacts of the outreach component on teachers, students, and the project team using both qualitative and quantitative methods (Frechtling and Sharp, 1997; Frechtling, 2002). The study will be conducted according to the Joint Committee Standards on Program Evaluation (1994). We will develop a detailed evaluation plan, including components to be carried out by the project team and by an external evaluator. The external evaluator will review and provide feedback on internal evaluation plans and report, and will conduct independent evaluation studies of project impacts. One potential independent evaluation would involve follow-up interviews of teachers attending CZO project workshops to assess teacher and student learning and implementation of workshop material.

Project Management, Annual Meeting, Advisory Board

PI Suzanne Anderson will be assisted by a 3-member *Executive Committee* chosen by co-PIs and senior personnel. The ExCom will meet at least 3 times annually to oversee budgetary allocations for the project, assess progress towards research goals and make adjustments in implementation plans, select BcCZO Graduate Fellows, and review site and data access issues.

A two-day, BcCZO *Annual Meeting* will be held each summer in Boulder. The purposes of the meeting are 1) to share findings among project members, 2) to review and refine plans for upcoming monitoring and experiments, 3) to inspire creative interdisciplinary thinking. As a means to engage the wider community and expand our thinking, we will invite 3 prominent researchers outside the project to participate in the annual meetings and give keynote talks.

The co-PIs will select a *Science Advisory Board* consisting of 3-4 members of the broader scientific community to provide feedback on the directions and success of the BcCZO at the 1, 3 and 5 year marks. The SAB will conduct their business at the Annual Meeting.

Results from Prior NSF support

Suzanne P. Anderson: *Collaborative research: The role of loess weathering in global geochemical cycles*. OPP-0345136, $255,310. 3/03-2/06. NCTE 5/2007 co-PI D. Mann (U Alaska Fairbanks). Used elemental mass balance in a deposequence of loess to show that silicate chemical weathering fluxes scale with deposition rate. One MS completed, 5 publications.

Anne F. Sheehan: *Collaborative Research: Seismotectonics and structure of creeping thrusts and mountain building of the Himalaya*. EAR-9903066, $343K, 4/00–9/05, co-PI's R. Bilham (CU), F. Wu (SUNY Binghamton). 29 broadband seismometers deployed in Nepal and Tibet in 2001-02 used to image the plate boundary, resolve crust structure, and record local events. 6 papers. Sheehan was IRIS/SSA Distinguished Lecturer on this work, and an advisor to Science Discovery workshops for >1700 middle school students in 17 communities in 2005-06.

Noah Fierer: *NSF Postdoctoral Research Fellowship in Microbial Biology*, DBI-0301773, $100,000, 7/03-6/05. Three related projects: controls on soil microbial community composition and function, continental-scale biogeography of soil bacteria, archaea, fungi, bacteria, and viruses in soil, and effects of C,N resources on soil bacterial communities. 8 papers published or submitted; one covered by *Discover*, *Sci News*, *Sci American* and NPR's All Things Considered.

Robert S. Anderson: *A geomorphic framework for interpreting continental interior mountain belt exhumation: The Laramide example*. EAR-0003604, $179,988, 4/01-3/04. This work combined field investigations with numerical modeling and cosmogenic dating to explore the late Cenozoic evolution of Ranges in the Laramide province and the associated basins. Supported one Ph.D. and 3 undergraduates. Produced 5 publications, 9 abstracts.

Greg Tucker: co-PI *Collaborative Research: Erosional Forcing of late Quaternary compressive strain, west central Taiwan*. PI: K. Mueller. EAR-0510971, $243,700, 2005-2008. Results to date include production of digital maps of stream-gradient anomalies and their correlation with known active faults, development of a model of cosmogenic radionuclide inventory in landslide-dominated drainage basins, and preliminary OSL field sampling.

Mark Williams: PI, *Niwot Ridge Long Term Ecological Research*, DEB-0423662, 2004-2010. Williams studies influence of increased snowpack and atmospheric N deposition on ecosystem processes. Approach combines isotopic tracers, plot experiments, and process modeling. 5 PhD, 5 MA and 12 undergraduates supported, 36 publications since 1998.

Keith Loague: *Process-based characterization of near-surface hydrologic response and hydrologically driven slope stability.* EAR-0409133, $249,681, 7/04-6/07. The focus of this study is concept-development numerical simulation with InHM, supported by field data from CB1. A PhD student is supported, and 3 publications have been produced.

David P. Dethier: *Collaborative Research: Late Cenozoic Evacuation of The Rocky Mountain Orogenic Plateau,* EAR-0106029, $70,079, 6/1/01-5/31/04. CRNs used to measure bedrock erosion rates in Laramide uplifts and adjacent basins and analyze their role on modern landscape development. Supported 5 undergraduates; produced 3 papers and 5 abstracts.

Diane McKnight: *Niwot Ridge LTER*, PI- M. Williams, DEB-0423662, 2004-10. McKnight studies phytoplankton in alpine lakes, nutrient dynamics, DOC transport and chemistry and runs Schoolyard LTER activities. 4 M.S. completed, and a paper submitted to ES&T.

Alex Blum, Matthias Leopold, Sheila Murphy, Jörg Voelkel, Cam Wobus: No NSF support in last 5 years