Concepts and Objectives of Critical Zone Observatories

Soils and Geomorphology as Crucial Parts

Examples from the Boulder Creek CZO, Colorado U.S.A.

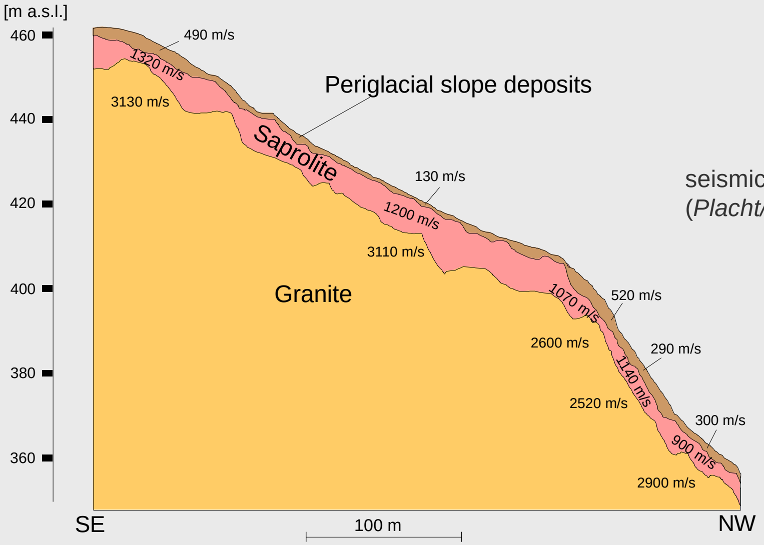
Jörg Völkel

25. Januar 2012

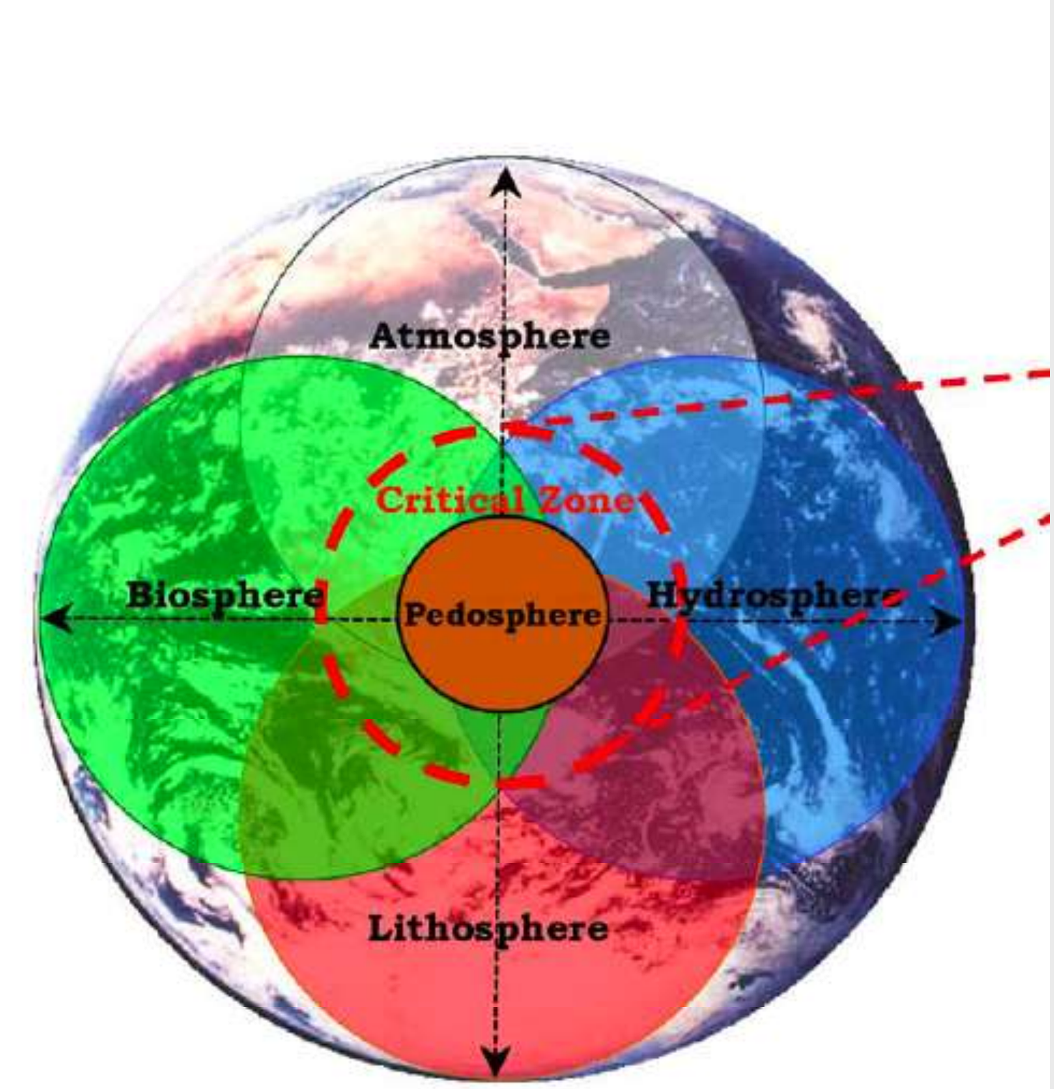
Critical Zone (CZ)

The *Critical Zone* (CZ) is defined as the external terrestrial layer extending from the outer limits of vegetation down to and including the zone of groundwater (e.g. Brantley et al. 2005). Therefore it is also called the Earth's weathering engine (Anderson et al. 2004). Biological, physical, and chemical processes transform bedrock and sediments into soil at the Earth's surface. (…) Processes within this zone regulate the transformation of minerals, solubilize nutrients for biota, buffer toxins, create water pathways, and ultimately sculpt the landscape on which we live (Hofmockel et al. 2007).

J. Völkel



seismic profile (*Placht/Leopold*)



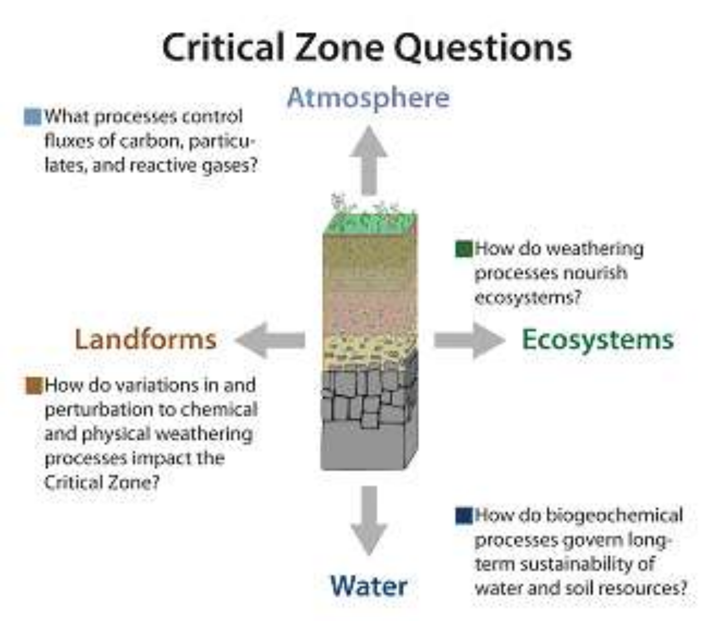
Wilding & Lin (2006) *Geoderma*

Critical Zone (CZ)

"the heterogeNeo$_u$s, near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources." (*National Research Council, 2001*)

THE CRITICAL ZONE: WHERE ROCK MEETS LIFE

The Critical Zone is Earth’s porous near-surface layer, from the tops of the trees down to the deepest groundwater. It is a living, breathing, constantly evolving boundary layer where rock, soil, water, air, and living organisms interact. These complex interactions regulate the natural habitat and determine the availability of life-sustaining resources, including our food production and water quality. (http://criticalzone.org/Research.html)



Critical Zone Questions

🟦 What processes control fluxes of carbon, particulates, and reactive gases?

🟩 How do weathering processes nourish ecosystems?

🟫 How do variations in and perturbation to chemical and physical weathering processes impact the Critical Zone?

■ How do biogeochemical processes govern long-term sustainability of water and soil resources?

- Schmitthüsen, J. (1942): Vegetationsforschung und ökologische Standortslehre in ihrer Bedeutung für die Geographie der Kulturlandschaft. - Zeitschrift der Gesellschaft für Erdkunde, 113-157.

- Troll, C. (1939): Luftbildplan und ökologische Bodenforschung. - Zeitschrift der Gesellschaft für Erdkunde, 241-298.

(http://criticalzone.org/Research.html)

Despite the Critical Zone's importance to terrestrial life, it remains poorly understood:

- **How does the Critical Zone form?**
- **How does it function?**
- **How will it change in the future?**

More specifically, too little is known about how physical, chemical, and biological processes in the Critical Zone are coupled and at what spatial and temporal scales. Many of these processes are highly nonlinear and can range across scales from atomic to global, and from seconds to aeons.

Understanding the complex web of physical, chemical, and biological processes of the Critical Zone requires a systems approach across a broad array of sciences: hydrology, geology, soil science, biology, ecology, geochemistry, geomorphology, and more.

How does the Critical Zone form, operate, and evolve?

MAIN GOALS (1/3)

1. ***DEVELOP A UNIFYING THEORETICAL FRAMEWORK* of critical zone evolution.**

   CZO is working toward a holistic conceptual model of critical-zone evolution that integrates new knowledge of coupled hydrological, geochemical, geomorphic, and biological processes. We are including both positive and negative feedbacks and their distribution in time and space.

National CZO Program
funded by NSF
CRITICAL ZONE OBSERVATORIES
studying the zone where rock meets life

How does the Critical Zone form, operate, and evolve?

MAIN GOALS (2/3)

2. *DEVELOP COUPLED SYSTEMS MODELS* to explore how critical zone services respond to anthropogenic, climatic, and tectonic forcings.

CZO is building systems models that quantitatively combine multiple processes, often spanning a whole watershed. These models typically track fluxes and storage of energy, water, carbon, sediments, and/or other materials.

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How does the Critical Zone form, operate, and evolve?

MAIN GOALS (3/3)

3. *DEVELOP AN INTEGRATED DATA/MEASUREMENT FRAMEWORK* sufficient for documenting a range of geologic and climatic settings, informing our theoretical framework, constraining models, and testing model-generated hypotheses across a CZO Network.

CZO is assembling the needed infrastructure for an integrated data/measurement framework. For more details on this integrated framework and a common infrastructure, see our data page and sites (infrastructure) page.

Summarizing CZO‘s Concept

This concept of Critical-Zone services expands on that of “ecosystem services” that was introduced in part as a framework for considering the many benefits or services provided by both near-natural and highly-managed ecosystems (Carpenter et al., 2009) by explicitly including the coupled hydrologic, geochemical, and geomorphic processes that underpin ecosystem processes.

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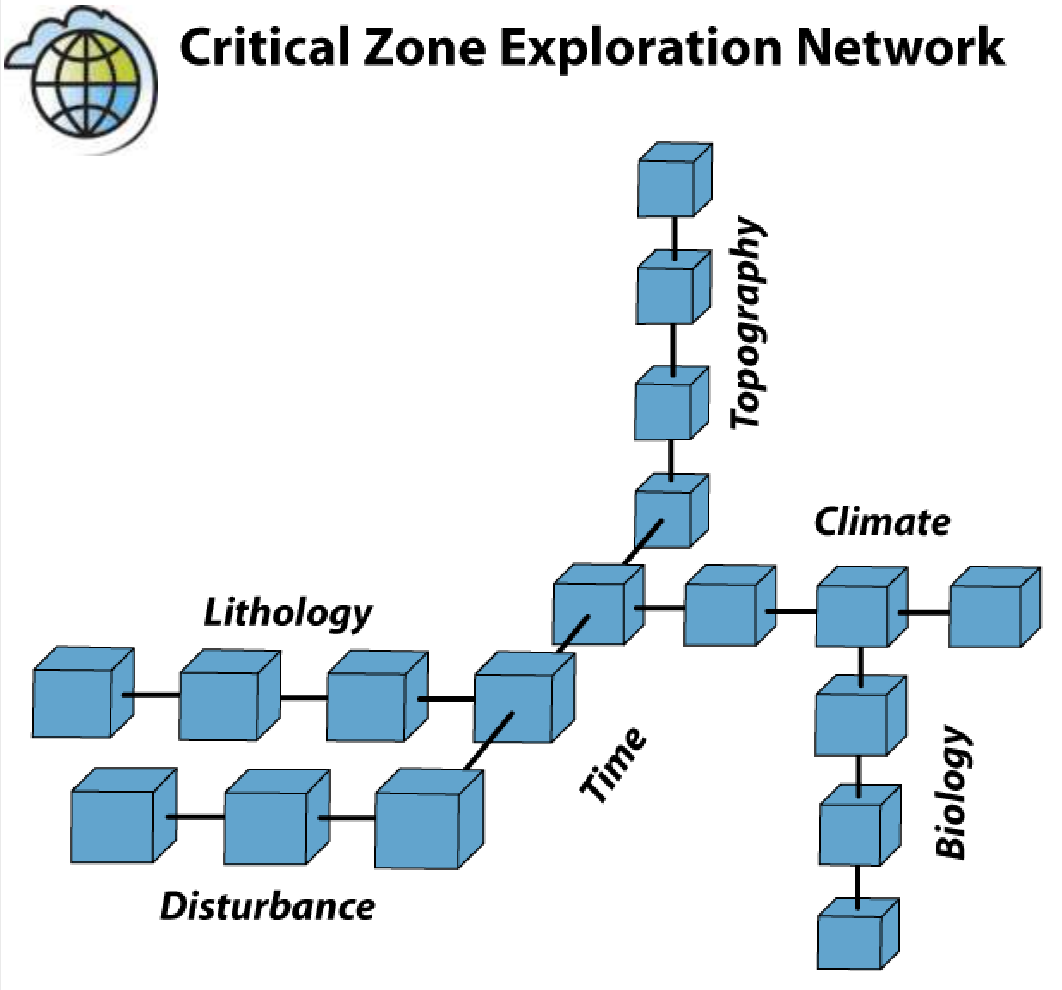
http://www.czen.org/



The Critical Zone Exploration Network (CZEN) is a network of people, sites, tools, and ideas to investigate processes within the Critical Zone. CZEN has been created by a consortium of researchers and educators drawn from the geosciences, hydrology, microbiology, ecology, soil science, and engineering who study the physical, chemical and biological processes shaping and transforming Earth’s outermost thin veneer.

The **Critical Zone Exploration Network** (CZEN) is a network of people, sites, tools, and ideas to **investigate processes within the Critical Zone**.

…..CZEN has been proposed by a consortium of researchers and educators drawn from the **geosciences, microbiology, ecology, soil science, and engineering** (Weathering System Science Consortium) to investigate the **physical, chemical and biological processes shaping and transforming Earth's outermost thin veneer**. …

Four outstanding scientific questions

1. How do processes in the Critical Zone control fluxes of carbon, particulates, and atmospherically reactive trace gases between the land surface and the atmosphere?

2. How do important biogeochemical processes and mechanisms at Critical Zone interfaces govern long-term sustainability of soil and water resources?

3. How do processes in the Critical Zone that nourish ecosystems change over geologic and human time scales?

4. How do weathering processes impact the establishment of the Critical Zone and how is this weathering engine perturbed by global environmental change?

International CZO Workshop – Delaware 2011, November

Design of Global Environmental Gradient Experiments using International CZO Networks

SEVENTH FRAMEWORK PROGRAMME

This event is supported by the National Science Foundation (USA) and the European Commission for strengthening international collaboration and interaction on critical zone science. The overarching goals of the workshop are to:

Encourage international collaboration in developing the agenda, vision, and execution of the next five years of critical zone science.

Promote core project proposals that seek to develop “satellite” NSF-funded CZO sites within the growing and emerging CZO network.

Encourage core project proposals that will take advantage in novel ways of the emerging CZO infrastructure

Promote cross-cutting research proposals that integrate the social sciences with the natural sciences in the global CZO network, something is prominent in the SoilTrEC program.

National Science Foundation
WHERE DISCOVERIES BEGIN

Program Title:

Critical Zone Observatories (CZO)

Synopsis of Program:

This solicitation calls for proposals to develop Critical Zone Observatories that will operate at the watershed scale and that will significantly advance our understanding of the integration and coupling of Earth surface processes as mediated by the presence and flux of fresh water. Successful proposals will be motivated and implemented by both field and theoretical approaches, each providing the impetus for advances in the other, and they will include substantial and novel plans for education, outreach and broader impacts.

National CZO Program

funded by NSF

CRITICAL ZONE OBSERVATORIES

studying the zone where rock meets life

- Boulder Creek (Colorado)
- Christina River Basin (Delaware)
- Jemez – Catalina (New Mexico / Arizona)
- Luquillo (Puerto Rico)
- Southern Sierra (California)
- Susquehanna Shale Hills (Pennsylvania)

NSF

National CZO Program

funded by NSF

CRITICAL ZONE OBSERVATORIES

studying the zone where rock meets life

- Boulder Creek (Colorado)

  We study how erosion and weathering control Critical Zone architecture and evolution, concentrating on slope, climate, ecosystems, and rock properties.

- Susquehanna Shale Hills (Pennsylvania)

  We emphasize quantitative prediction of Critical Zone creation and structure, focusing on pathways and rates of water, solutes, and sediments

- Christina River Basin (Delaware)

  We integrate knowledge of water, mineral and carbon cycles to quantify human impact on Critical Zone carbon sequestration - from uplands to coastal zone.

funded by NSF

National CZO Program CRITICAL ZONE OBSERVATORIES

studying the zone where rock meets life

- Southern Sierra (California)

  The Southern Sierra Critical Zone Observatory (CZO) is a platform and program for investigating how the water cycle drives Critical Zone processes, focusing on water balance, nutrient cycling, and weathering across the rain-snow transition.

- Jemez – Catalina (New Mexico / Arizona)

  We focus on Critical Zone interactions that help drive models of carbon/water cycling, arid/semi-arid ecohydrology, and landscape evolution.

- Luquillo (Puerto Rico)

  We study how Critical Zone processes and water balances differ in landscapes with contrasting bedrock but similar climatic and environmental histories.

related programms

NSF-CZO

CZEN

LTER

NEON

CUASHI

SoilTrEC (EU)

The influence of critical zone development on watershed hydrology and biogeochemistry

The Boulder Creek Critical Zone Observatory Team

INSTAAR
University of Colorado Boulder

Colorado
University of Colorado at Boulder

Williams

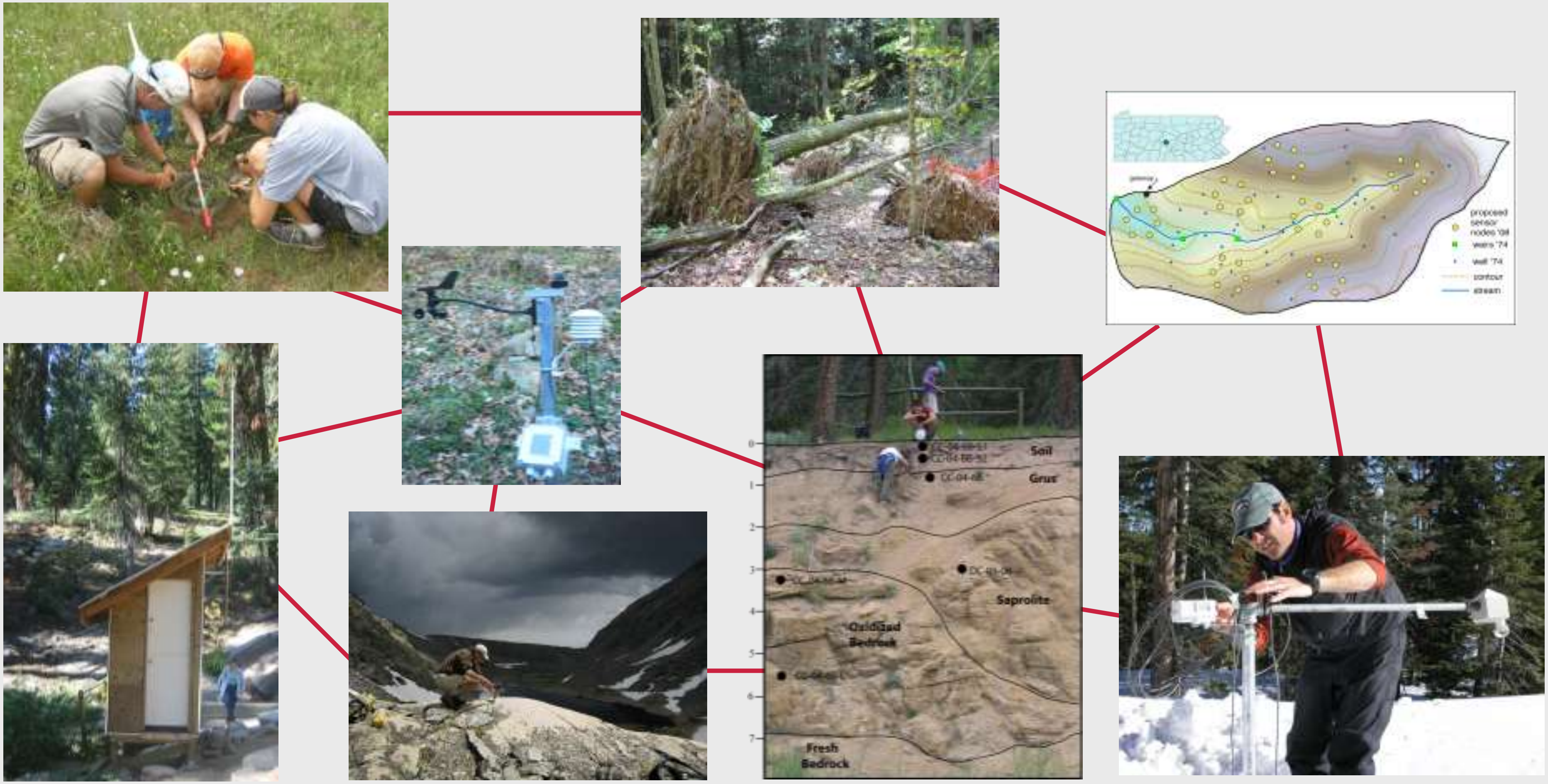
USGS
science for a changing world

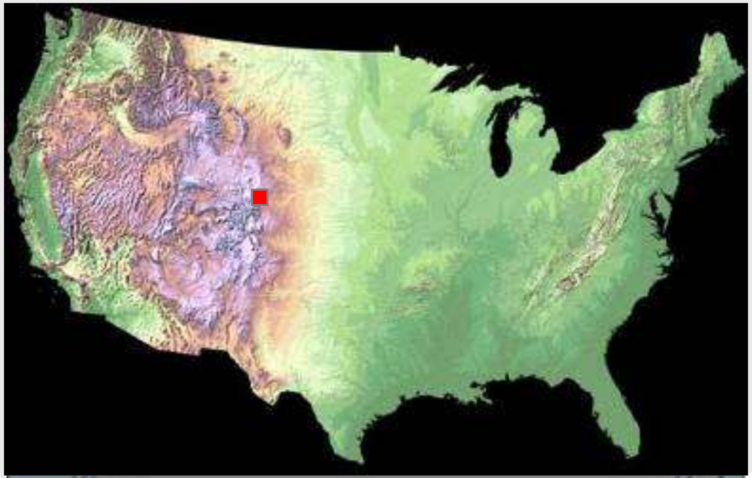
CIRES

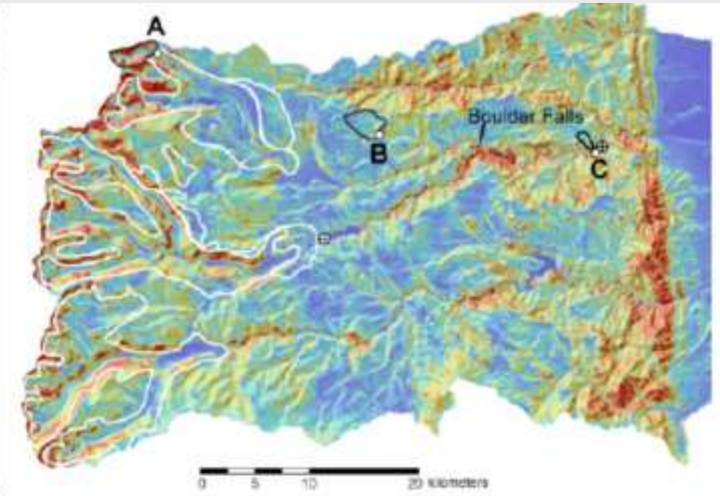
NSF

Who are we?

Building a network to advance interdisciplinary studies of Earth surface processes







Untersuchungsgebiete des Boulder Creek Critical Zone Observatory BcCZO
(U.S. National Science Foundation, Aktenzeichen: 0724960, Völkel / Leopold, 2007-2012)


National CZO Program
BOULDER CREEK CRITICAL ZONE OBSERVATORY


University of Colorado Boulder
NSF

Boulder CZO objectives

- **We study how erosion and weathering control Critical Zone architecture and evolution, concentrating on slope, climate, ecosystems, and rock properties.**

Tasks

- Document Critical Zone architecture across erosional and climate regimes
- Measure rates of denudation and model landscape evolution
- Document Critical Zone function within the context of CZ architecture

Seasonal fate of N

Snow melt

Wildfire

Water in vadose zone

Orographic precipitation

Glacier history

Hillslopes:
-rock weathering
-mechanical strength
-soil formation
-transport rates

DOM in soils & streams

Saprolite evolution

Landscape evolution

Didymo, streamflow & water quality

Groundwater dynamics

Chemical weathering & water

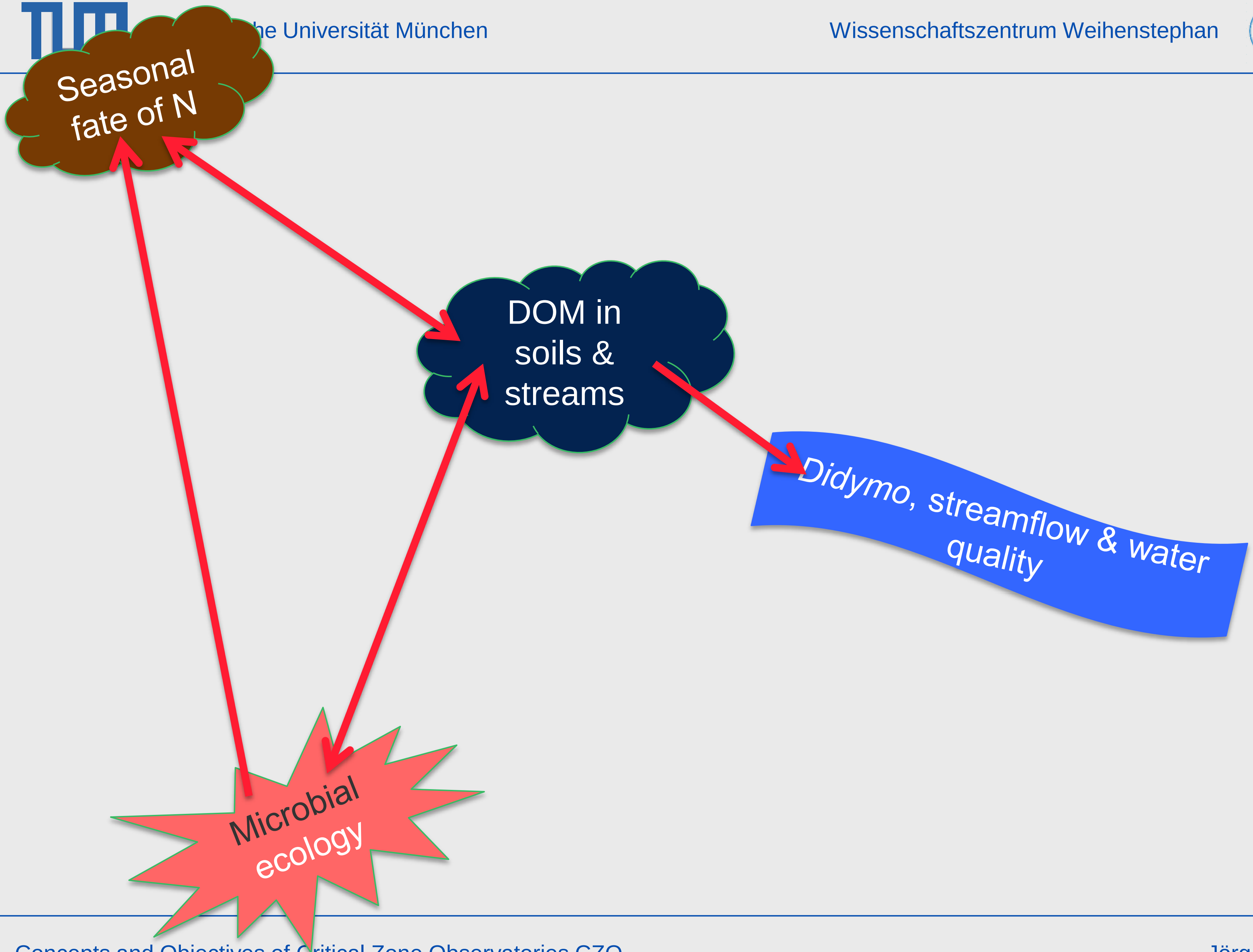
High Plains sedimentation & erosion

Gully erosion

Microbial ecology

Geophysical characterization of CZ

Trees:
snow,
water,
C,
erosion

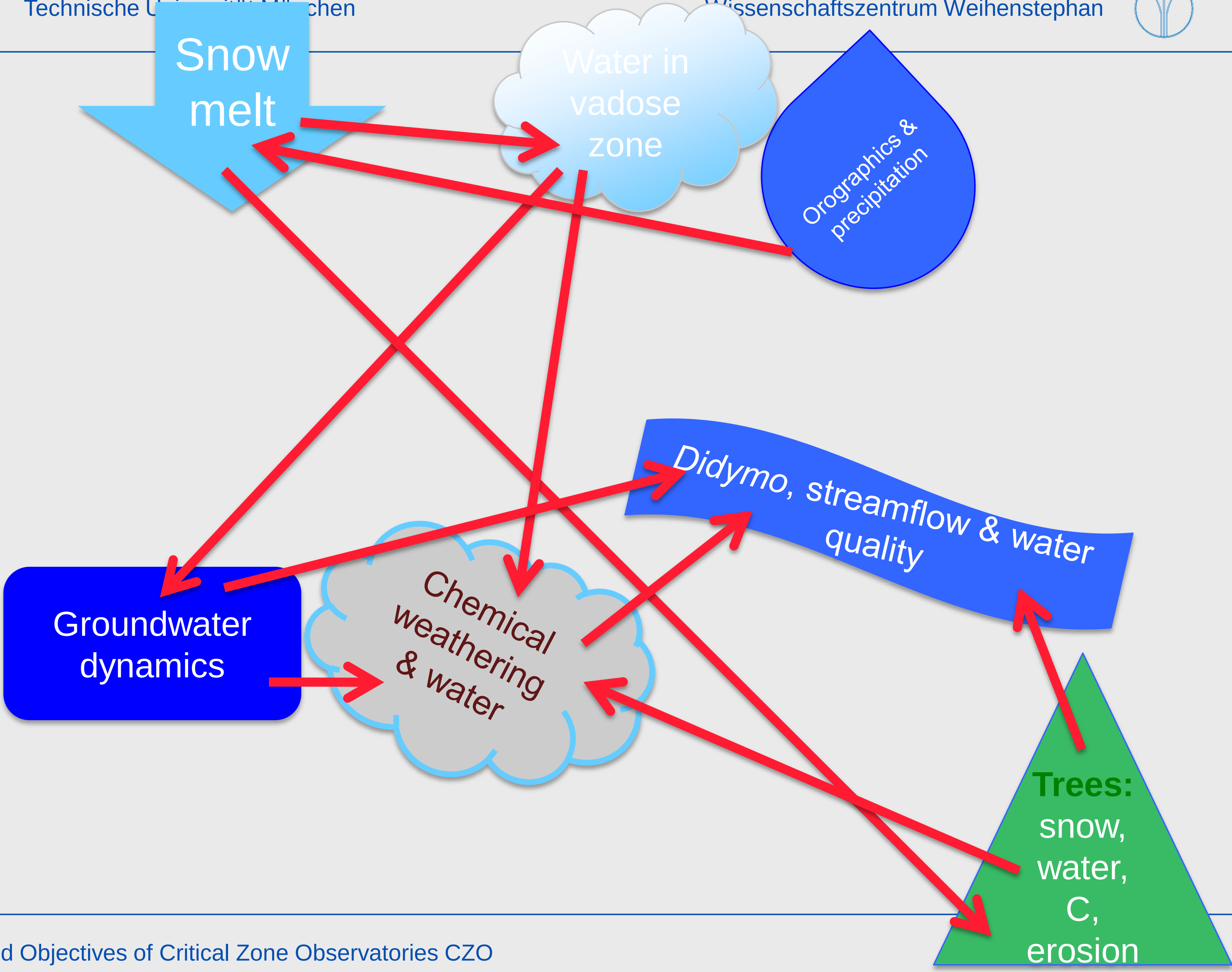


Seasonal fate of N

DOM in soils & streams

Didymo, streamflow & water quality

Microbial ecology



Snow melt

Water in vadose zone

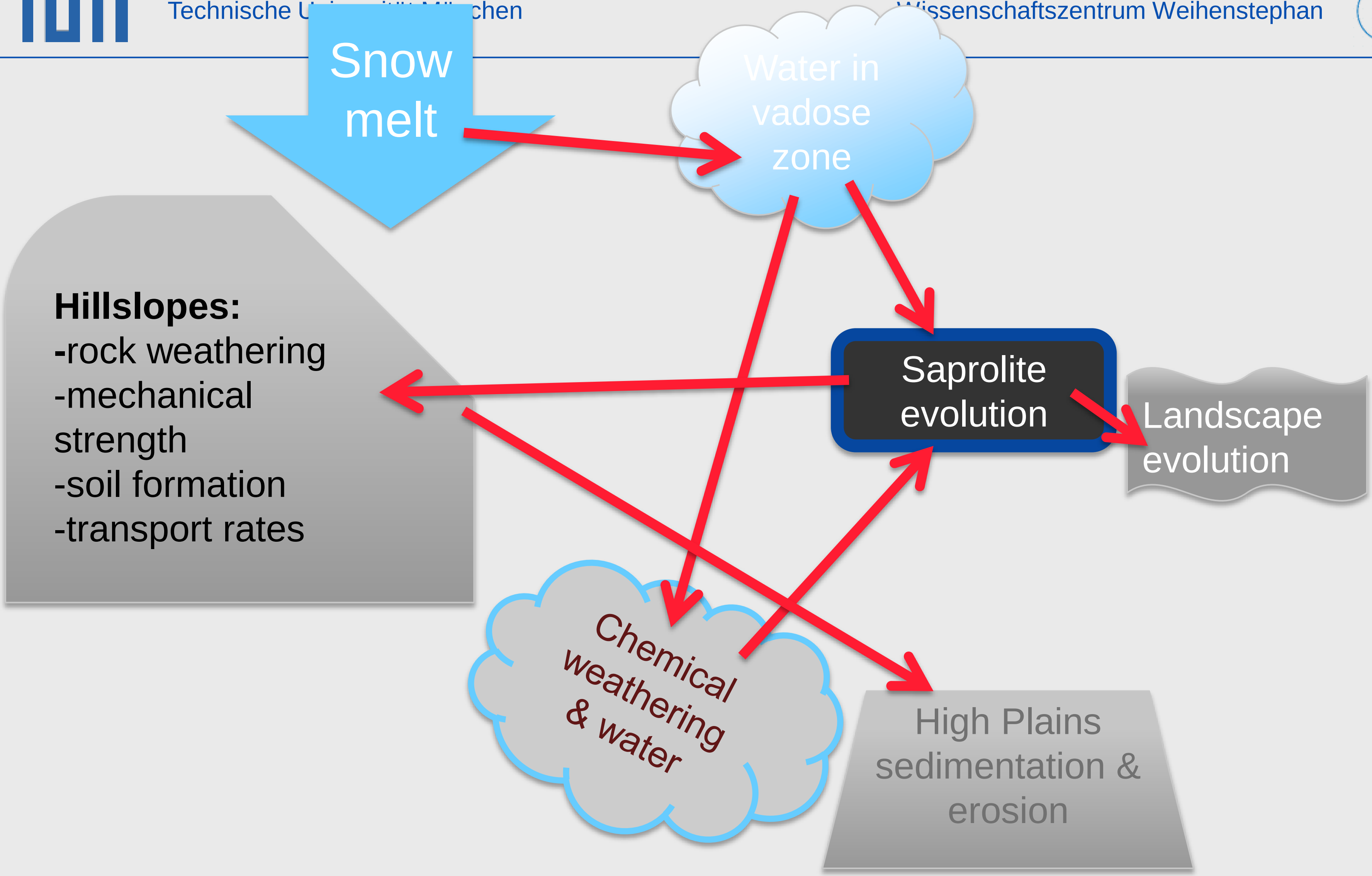
Orographics & precipitation

Didymo, streamflow & water quality

Groundwater dynamics

Chemical weathering & water

Trees: snow, water, C, erosion



Snow melt

Water in vadose zone

Hillslopes:
-rock weathering
-mechanical strength
-soil formation
-transport rates

Saprolite evolution

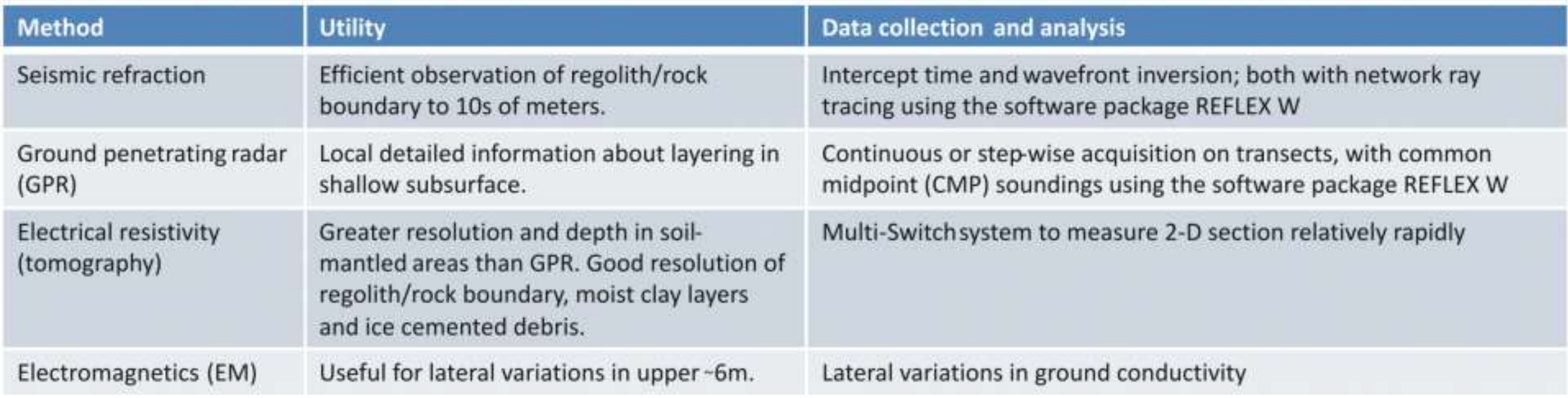
Landscape evolution

Chemical weathering & water

High Plains sedimentation & erosion

TUM Project: Geophysical Prospection of the CZ

- **CZ architecture**
- Rates of evolution
- CZ processes and function
- Modeling CZ evolution



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 ray tracing using the software package REFLEX W
Ground penetrating radar (GPR)	Local detailed information about layering in shallow subsurface.	Continuous or step-wise acquisition on transects, with common midpoint (CMP) soundings using the software package REFLEX W
Electrical resistivity (tomography)	Greater resolution and depth in soil-mantled areas than GPR. Good resolution of regolith/rock boundary, moist clay layers and ice cemented debris.	Multi-Switch system to measure 2-D section relatively rapidly
Electromagnetics (EM)	Useful for lateral variations in upper ~6m.	Lateral variations in ground conductivity

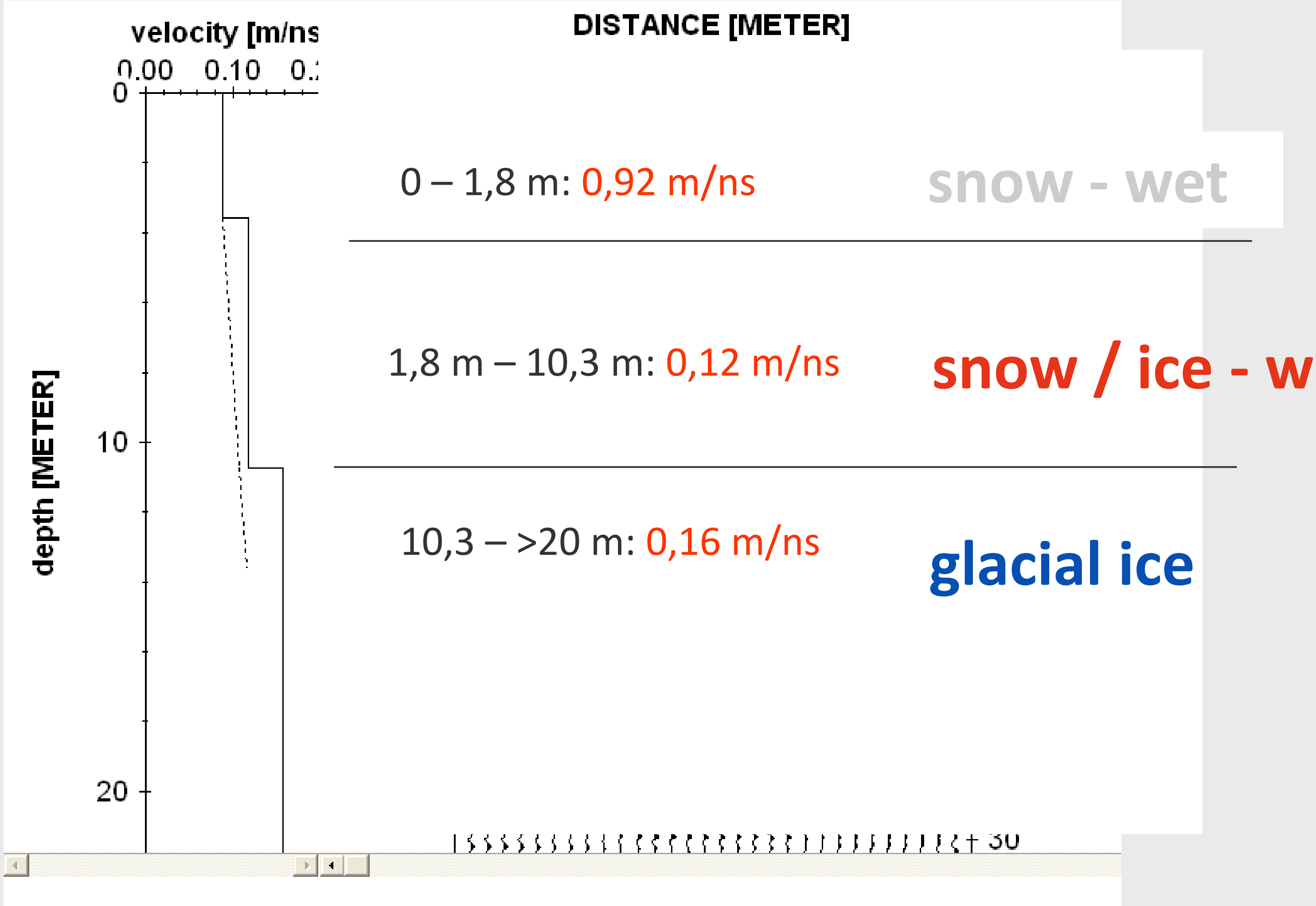
Ground Penetrating Radar GPR
electromagnetic waves: 25 – 200 MHz
penetration depth: 2 – 15 m
resolution: 10 – 50 cm
→ 2D information

Electro-Tomography ERT
subsurface electric resistivity: Ωm
penetration depth: 2 – 30 m
resolution: 50 – 100 cm
→ 2D information

Green Lakes watershed


CMP

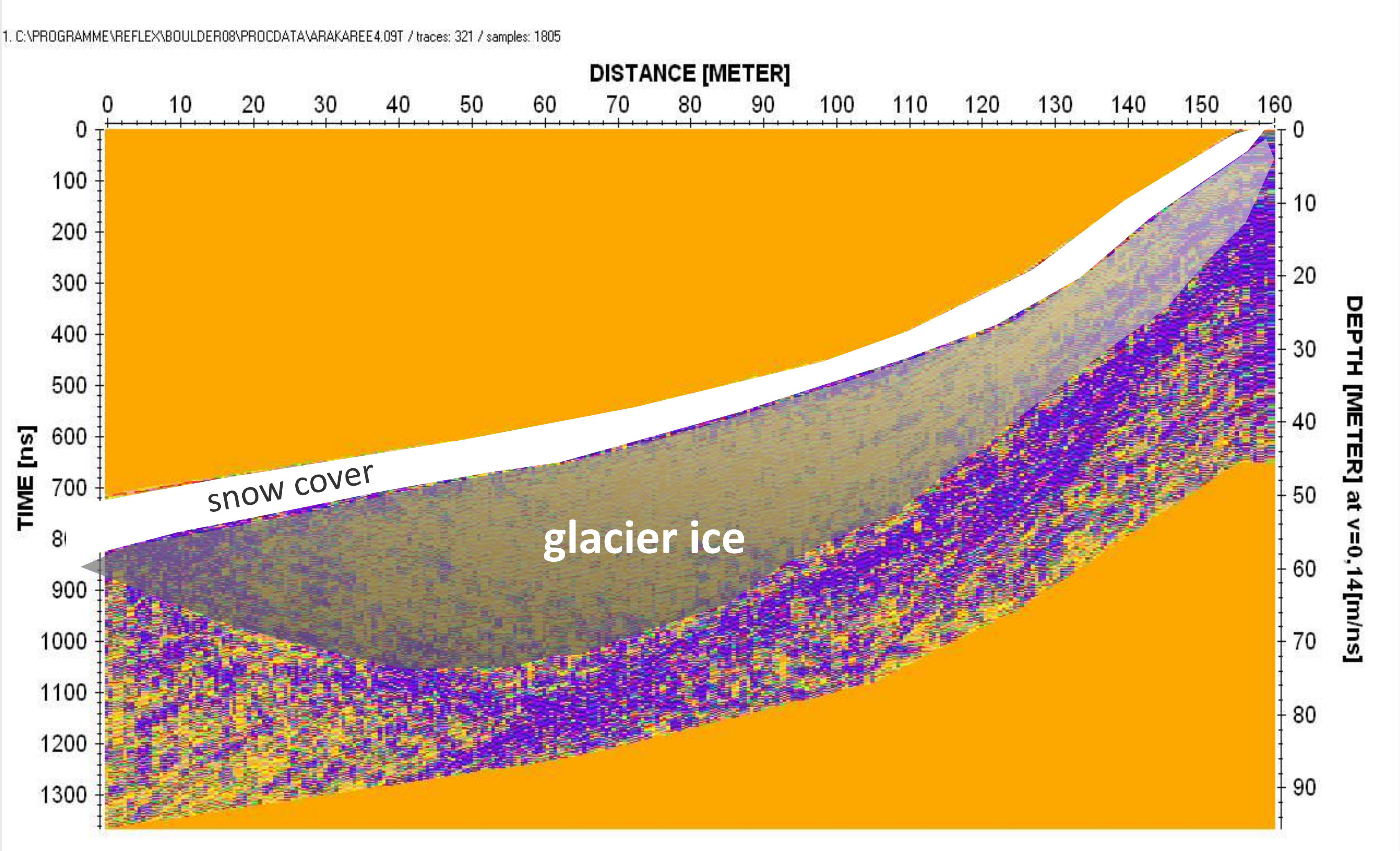
CMP – Common Midpoint Measurement: 1D-velocity analysis of the transmitted signal allows a conclusion on the material



0 – 1,8 m: 0,92 m/ns **snow - wet**

1,8 m – 10,3 m: 0,12 m/ns **snow / ice - wet**

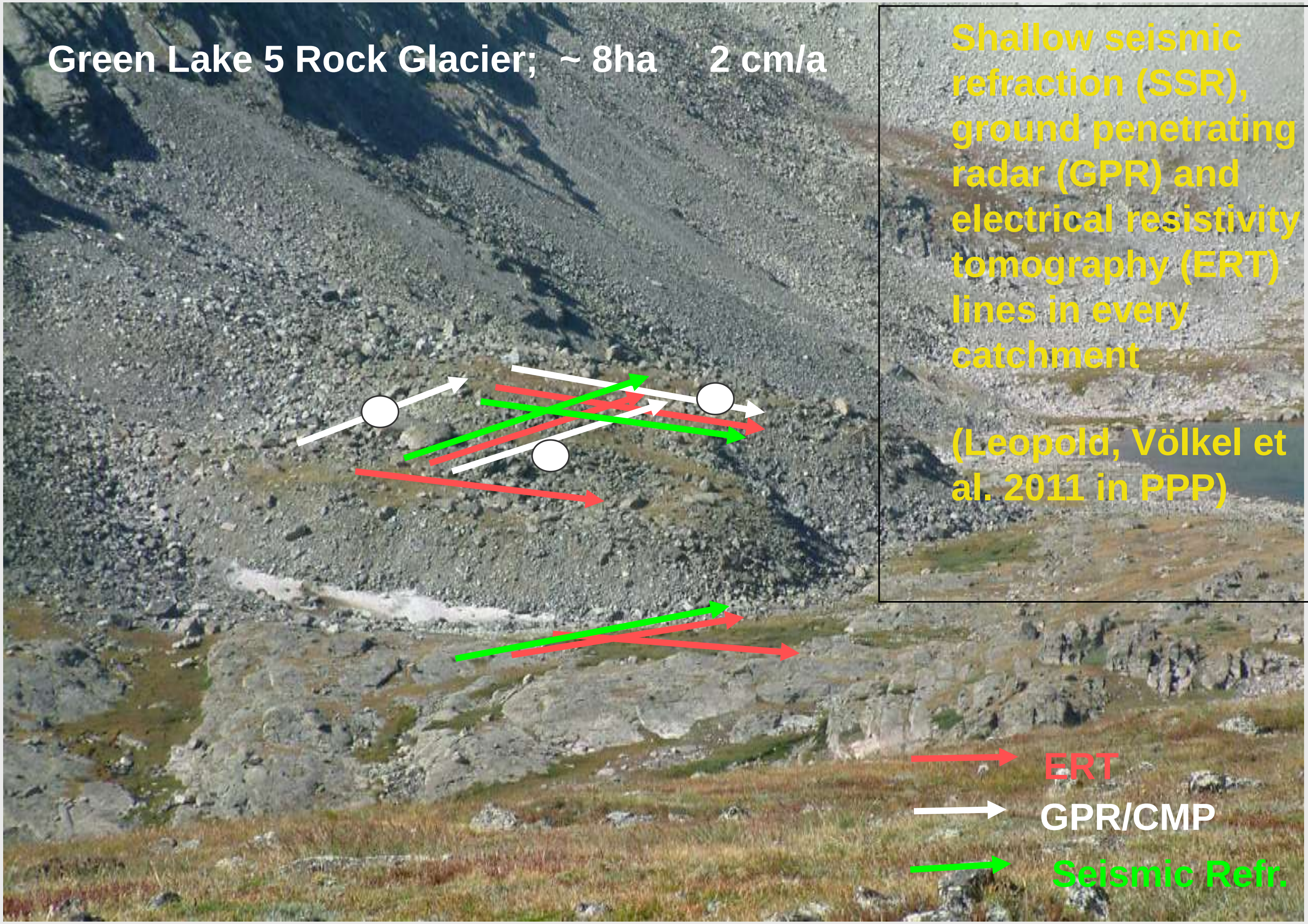
10,3 – >20 m: 0,16 m/ns **glacial ice**



1. C:\PROGRAMME\REFLEX\BOULDER08\PROCDATA\ARAKAREE4.09T / traces: 321 / samples: 1805

Mass balance of the Arikaree Glacier – an important source of water for CZO's studies

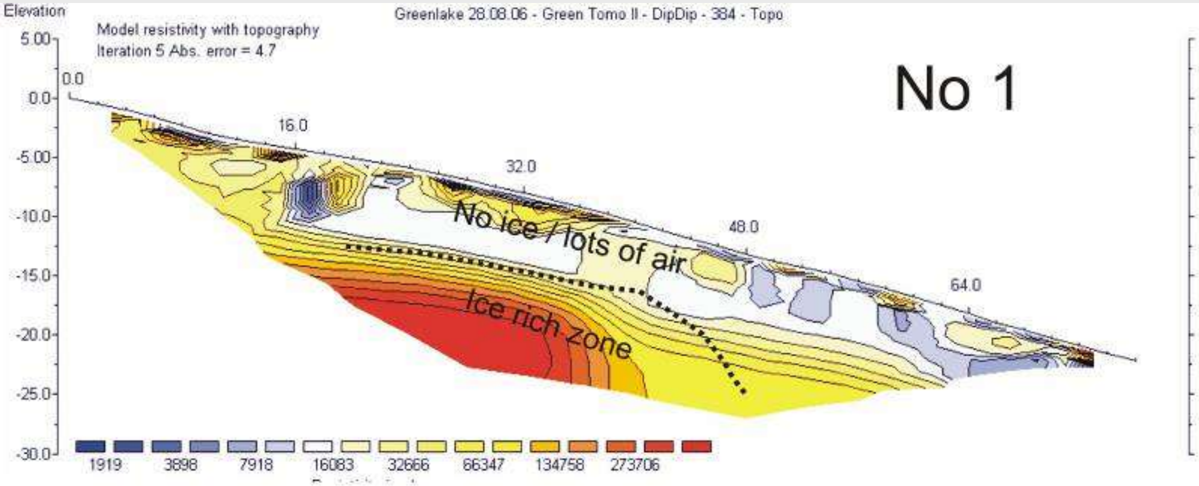
Green Lake 5 Rock Glacier; ~ 8ha 2 cm/a

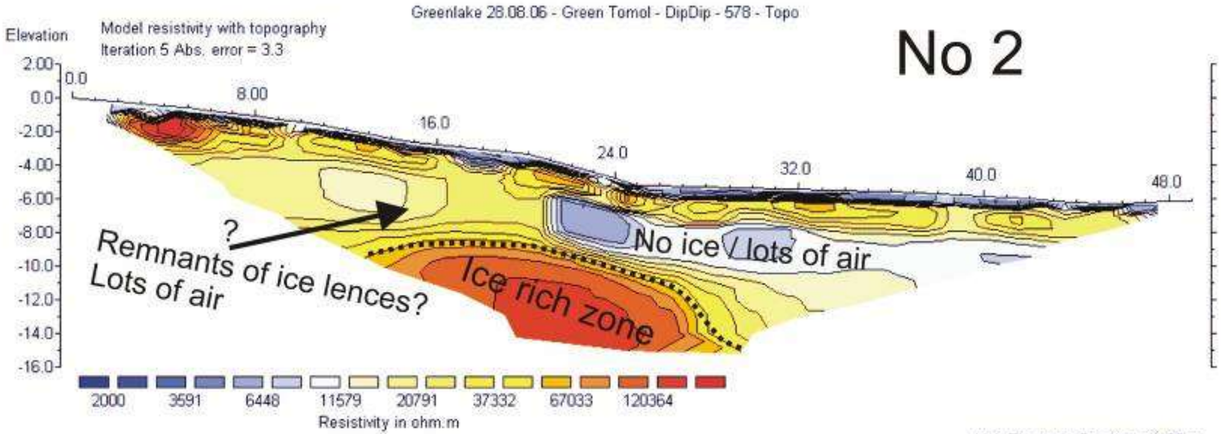


Shallow seismic refraction (SSR), ground penetrating radar (GPR) and electrical resistivity tomography (ERT) lines in every catchment

(Leopold, Völkel et al. 2011 in PPP)

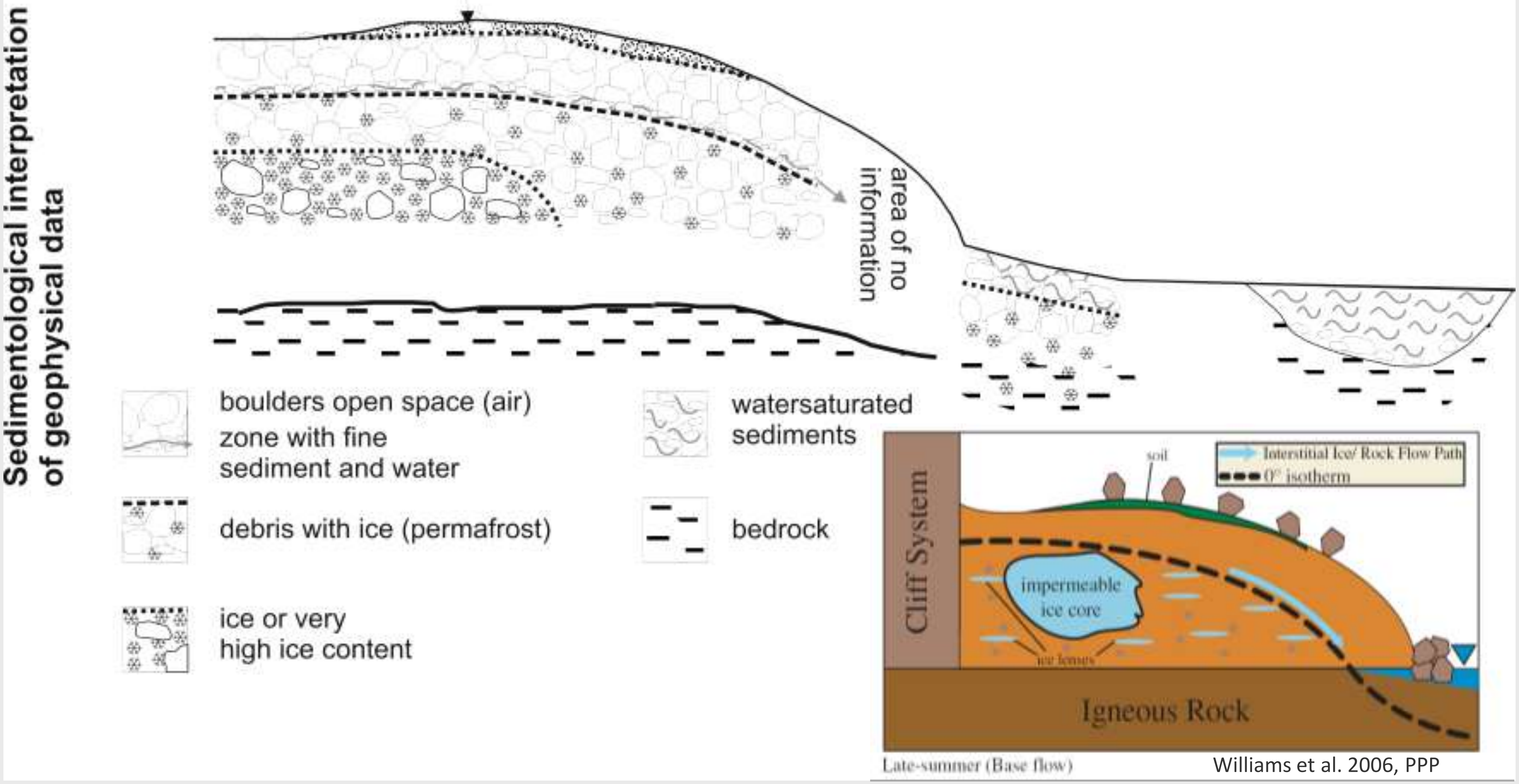
ERT-Messung auf dem Blockgletscher



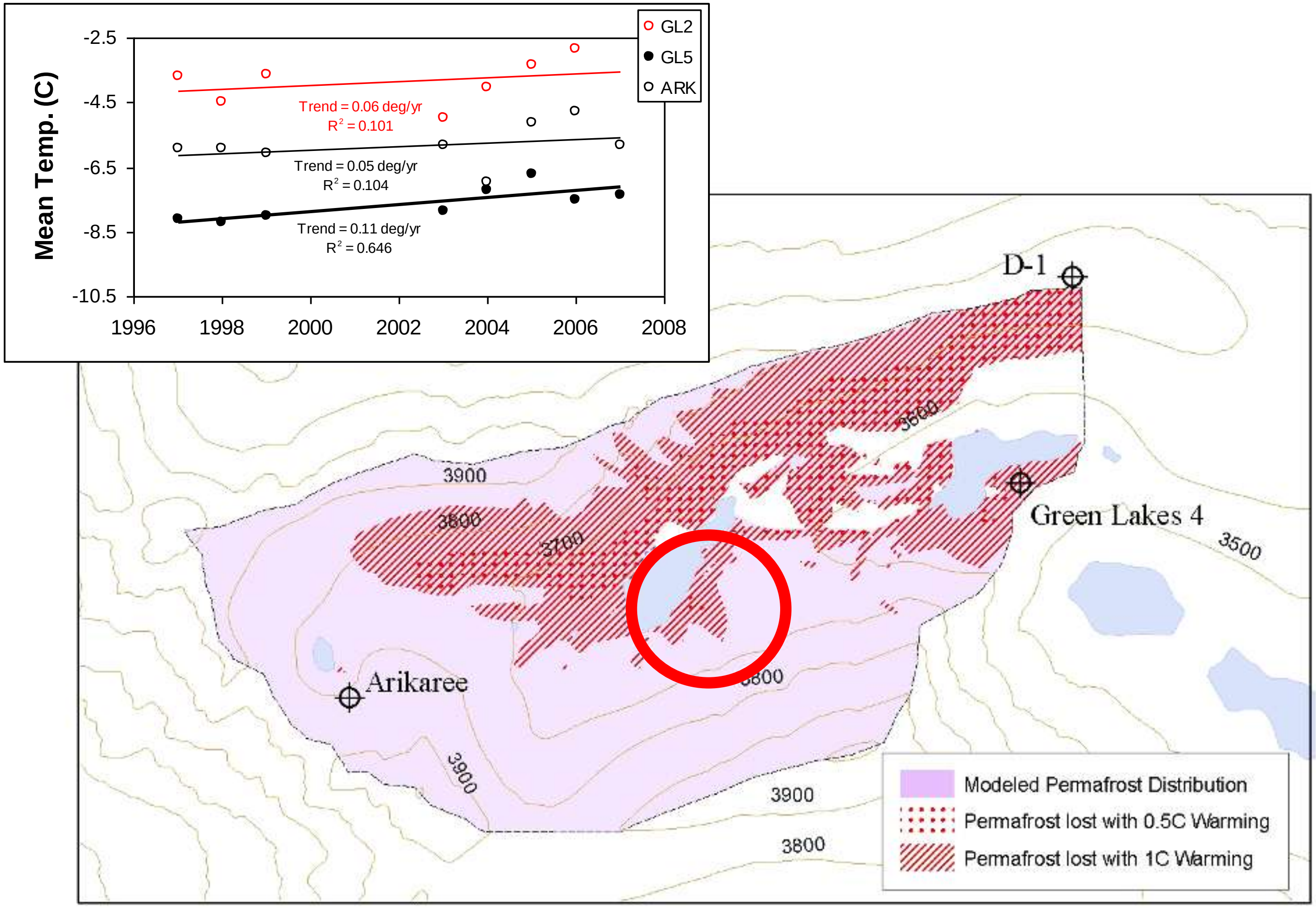


Geophysikalisch basiertes Modell zum Aufbau des Blockgletschers und seines Vorfeldes

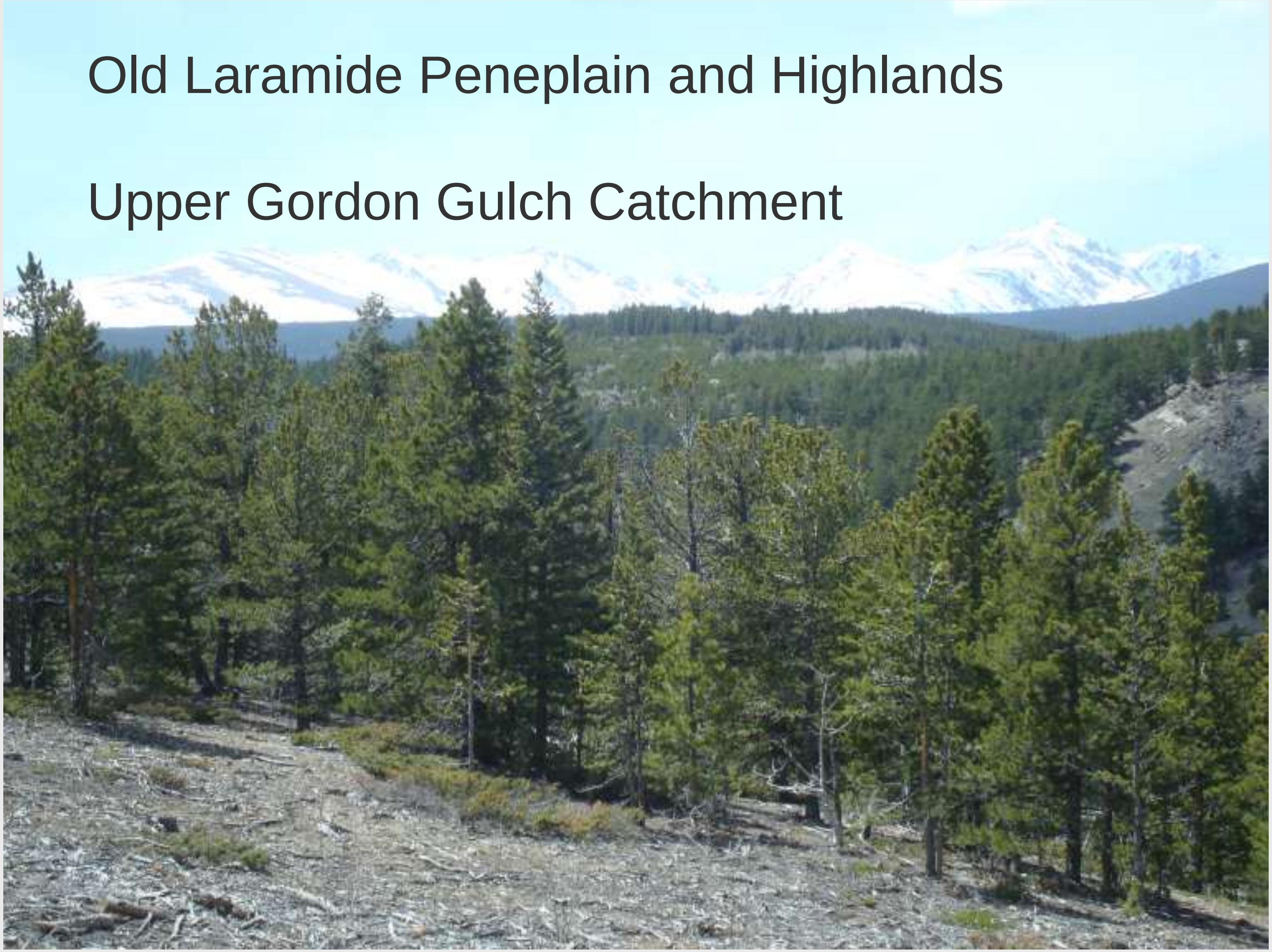
*Leopold, Völkel et al. 2011 in **P**ermafrost & **P**eriglacial **P**rocesses*



Williams et al. 2006, PPP

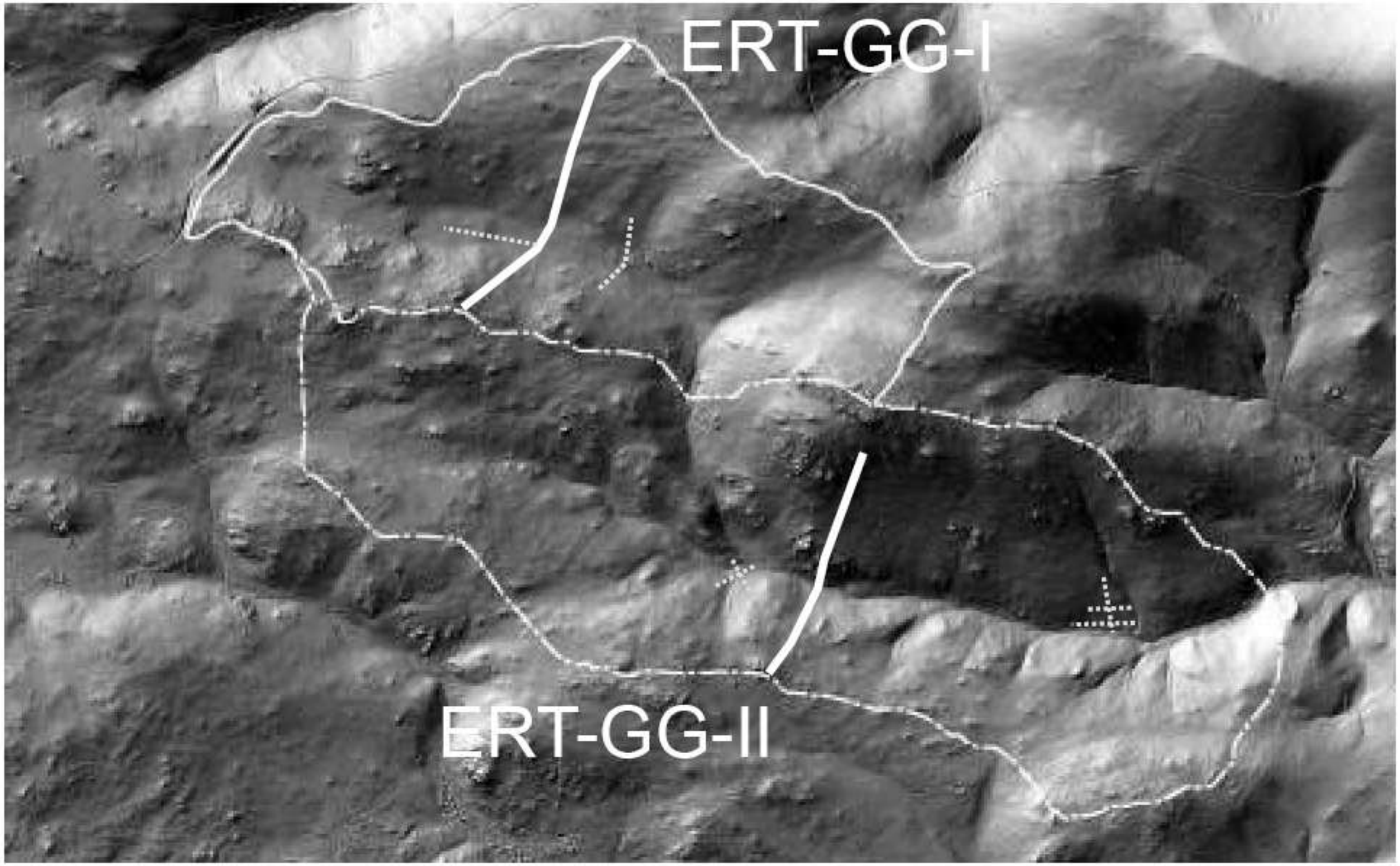


Leopold, Völkel et al. 2011, PPP



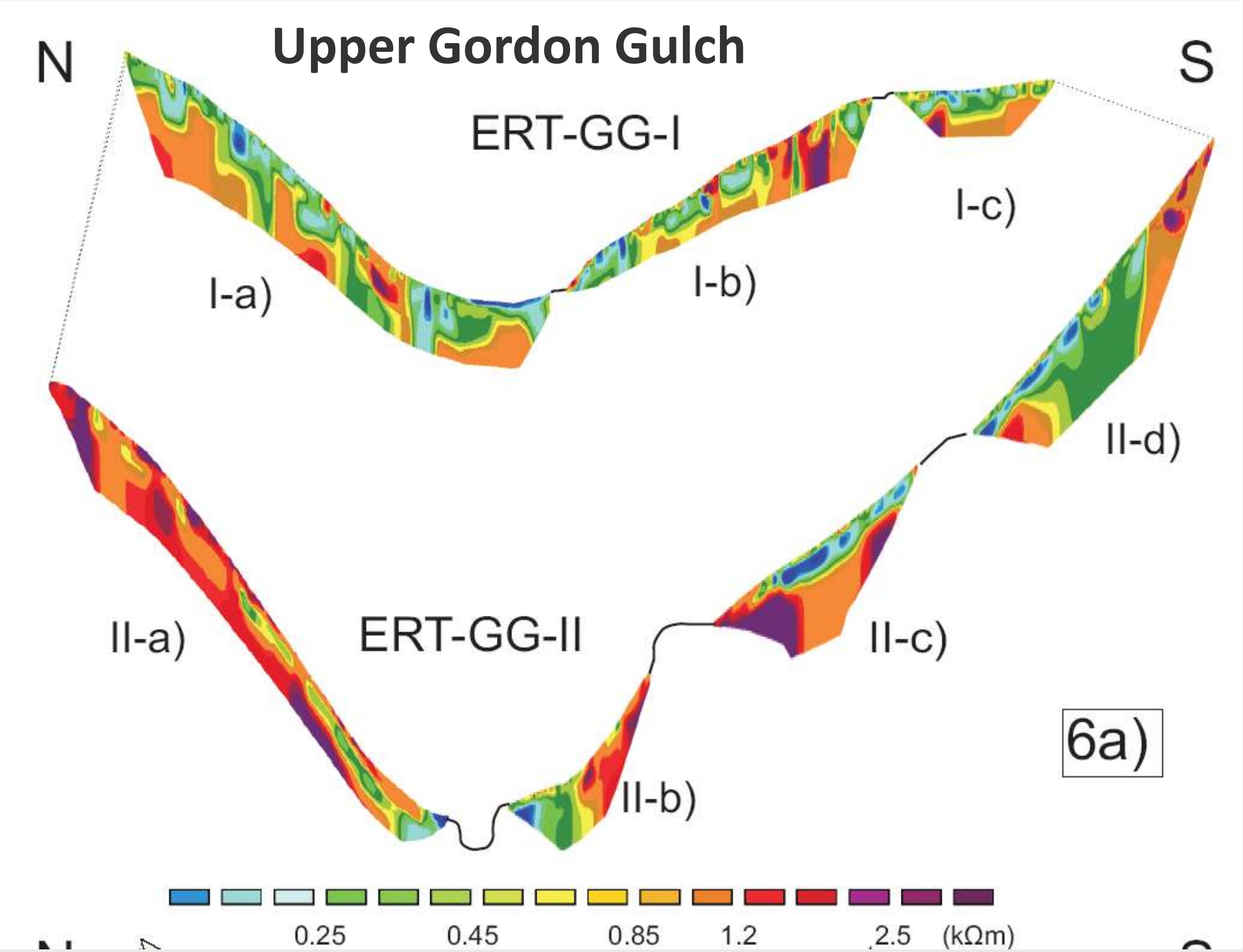
Old Laramide Peneplain and Highlands

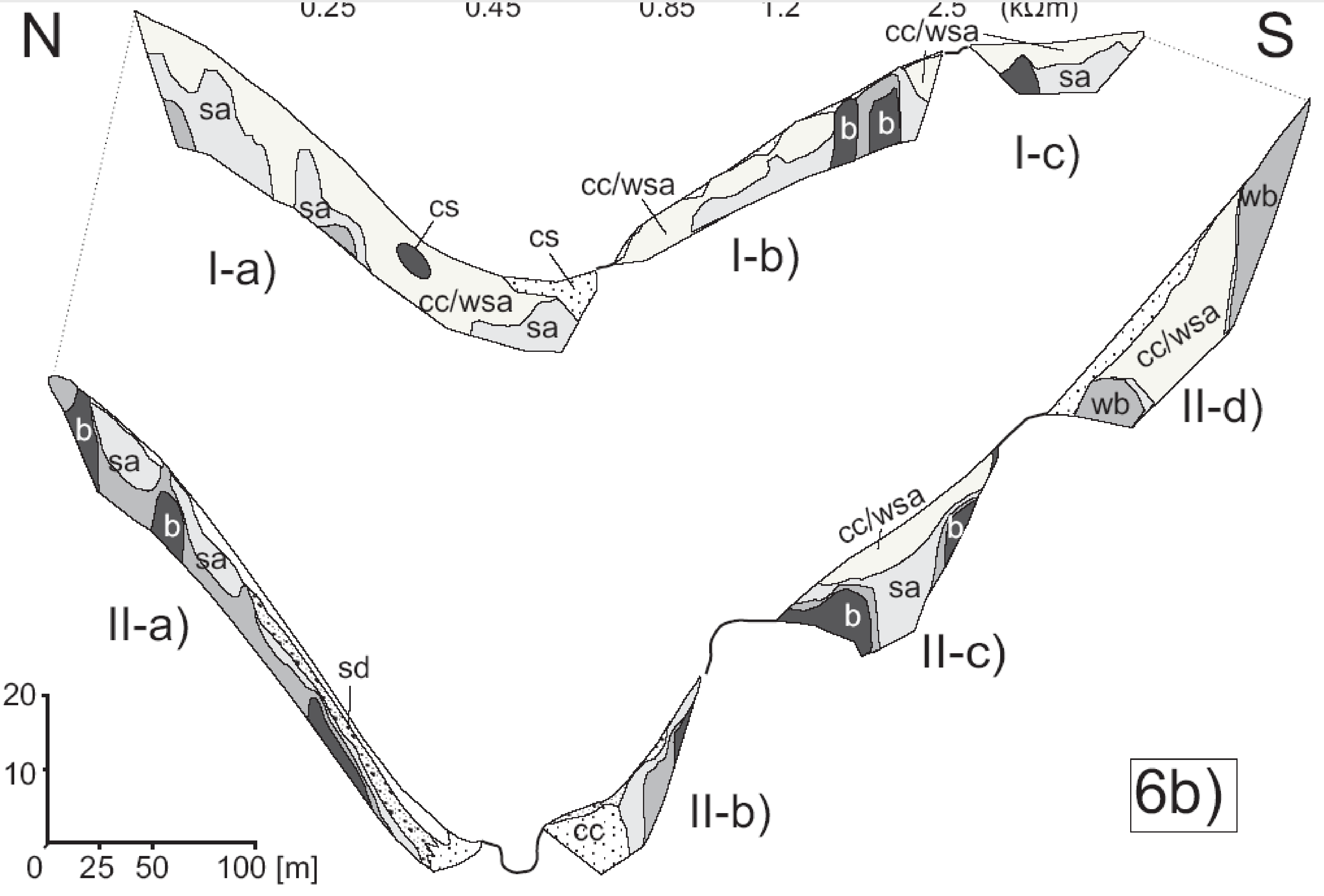
Upper Gordon Gulch Catchment



Gordon Gulch
2446-2737 m asl
$2.75\ km^2$

Auflösung Lidar: 12 Punkte / 1 m^2


Upper Gordon Gulch
N
S
ERT-GG-I
I-a)
I-b)
I-c)
ERT-GG-II
II-a)
II-b)
II-c)
II-d)
6a)
0.25
0.45
0.85
1.2
2.5
(kΩm)


0.25
0.45
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1.2
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(kΩm)
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sa
cc/wsa
b
b
I-a)
I-b)
I-c)
wb
cc/wsa
wb
II-d)
b
sa
b
sa
II-a)
sd
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sa
b
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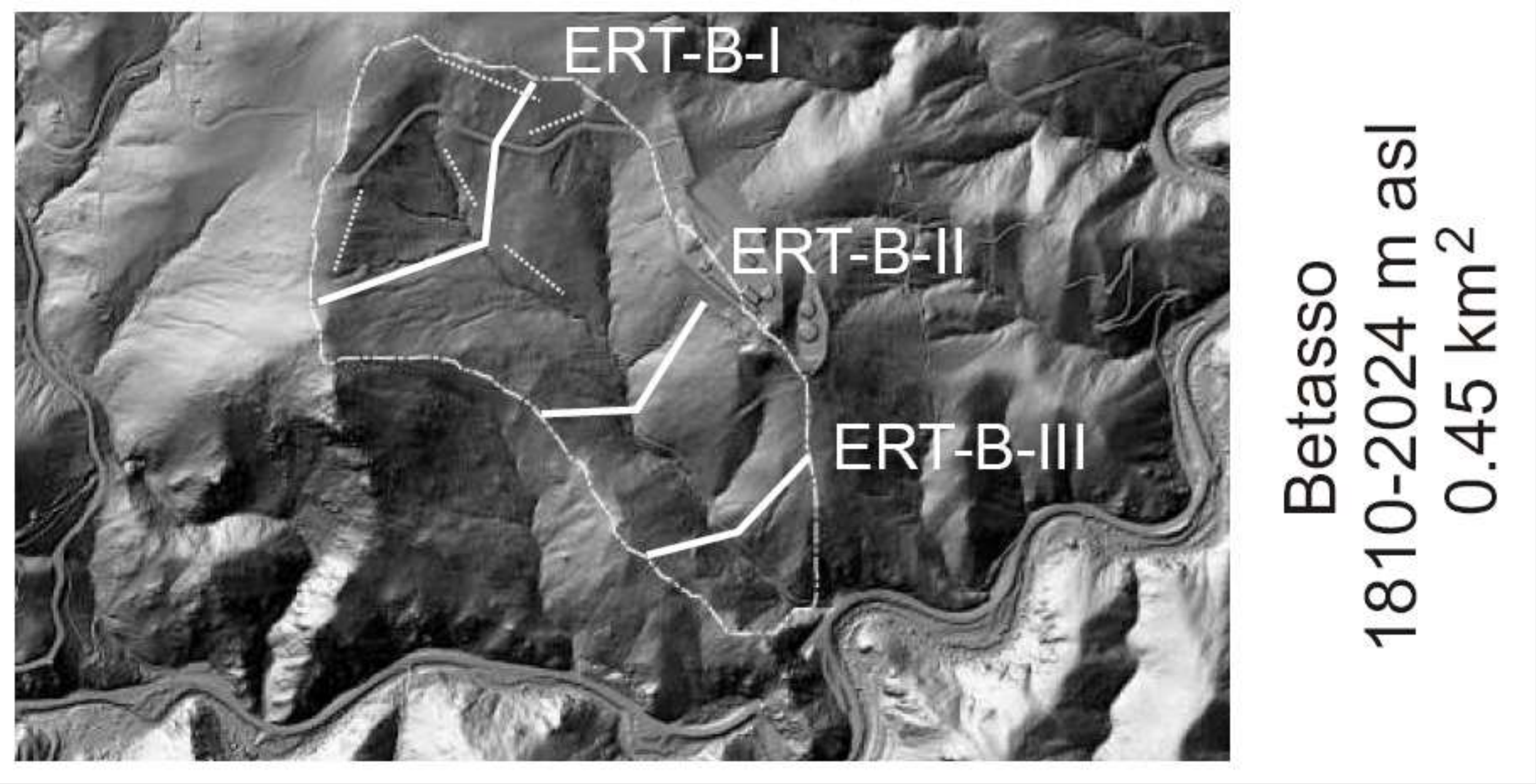
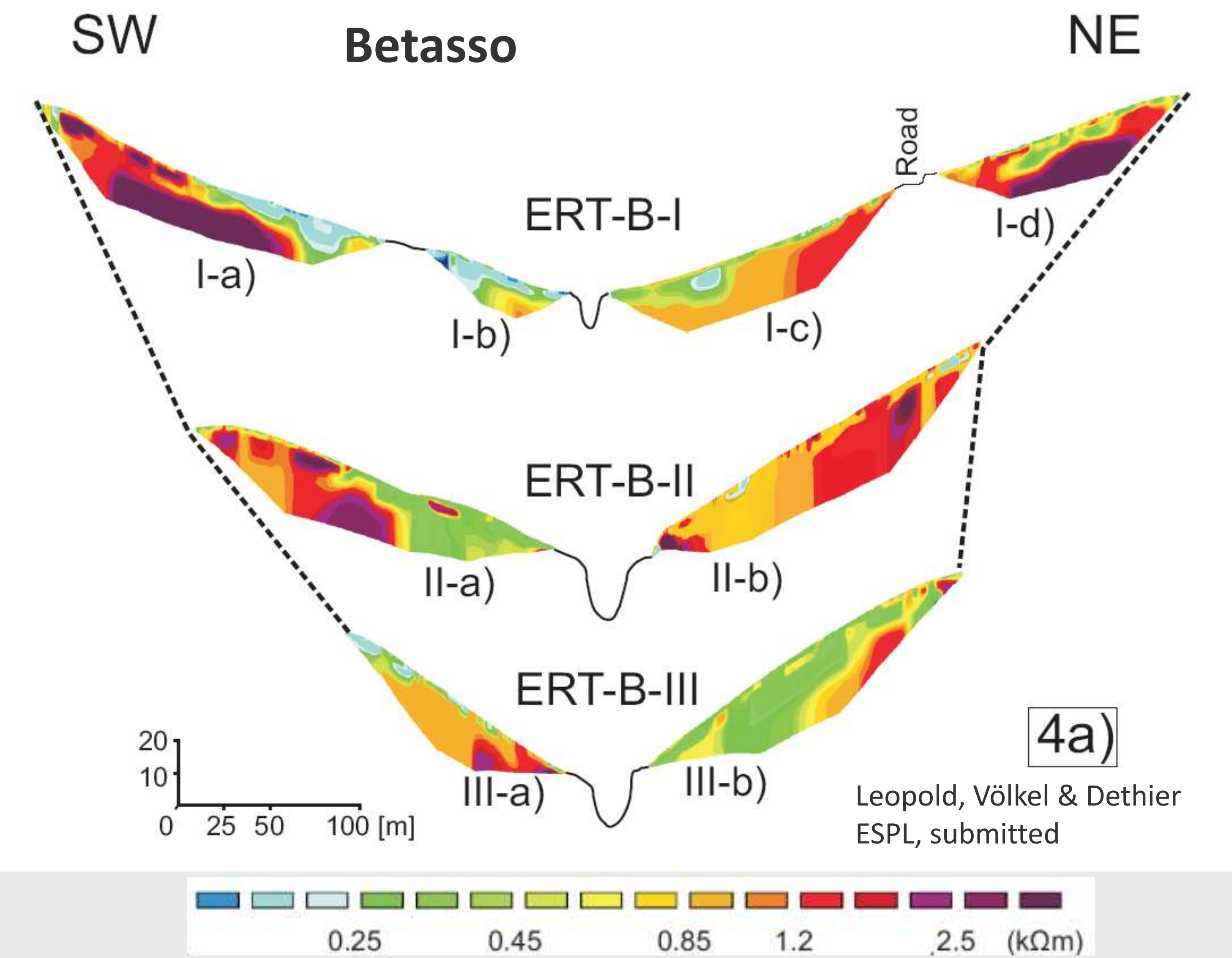
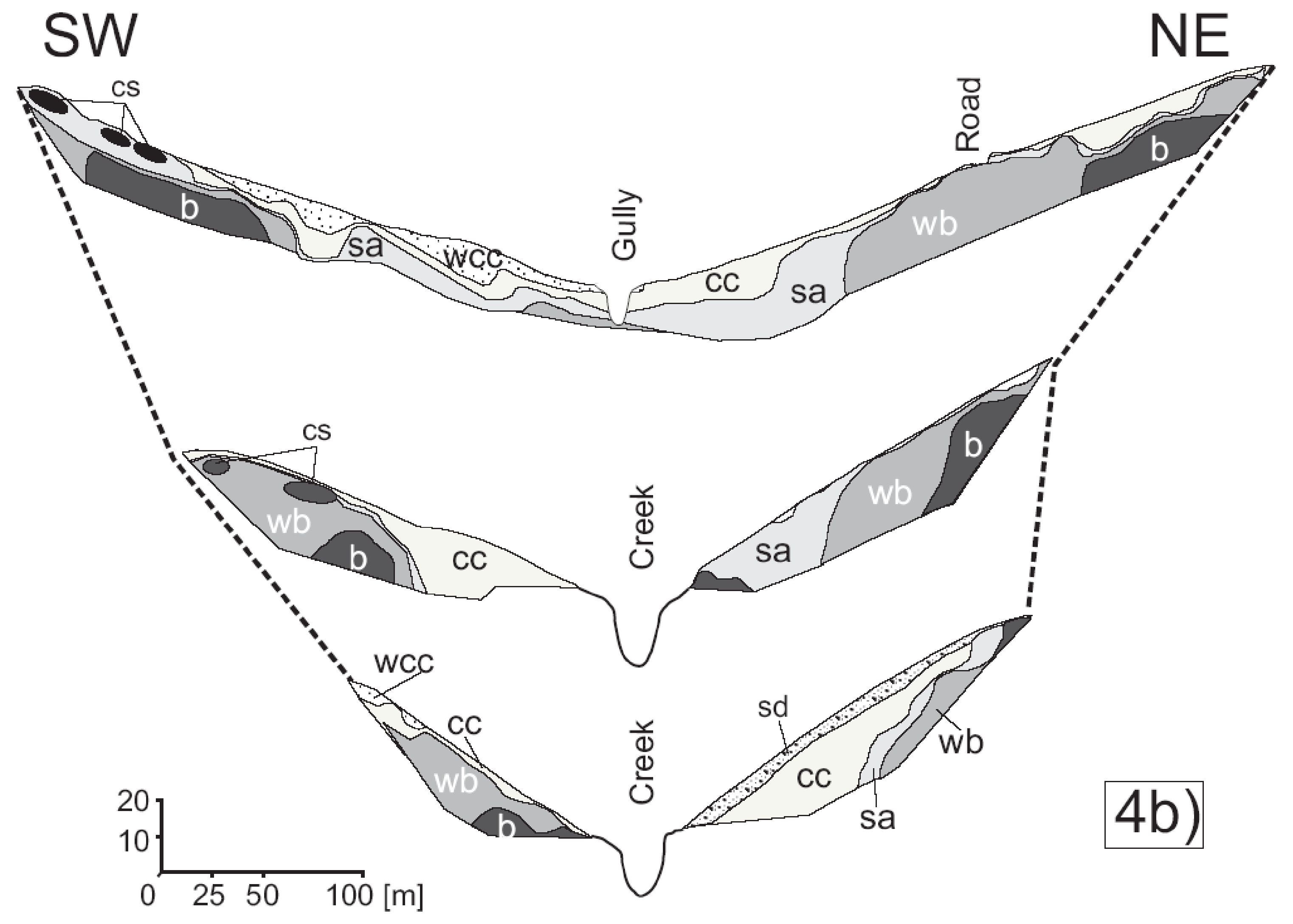
cc
II-b)
20
10
0
25
50
100 [m]
6b)



Auflösung Lidar: 12 Punkte / 1 m^2



Leopold, Völkel & Dethier
ESPL, submitted


SW
NE
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wcc
Gully
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Road
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Creek
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wb
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wcc
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Creek
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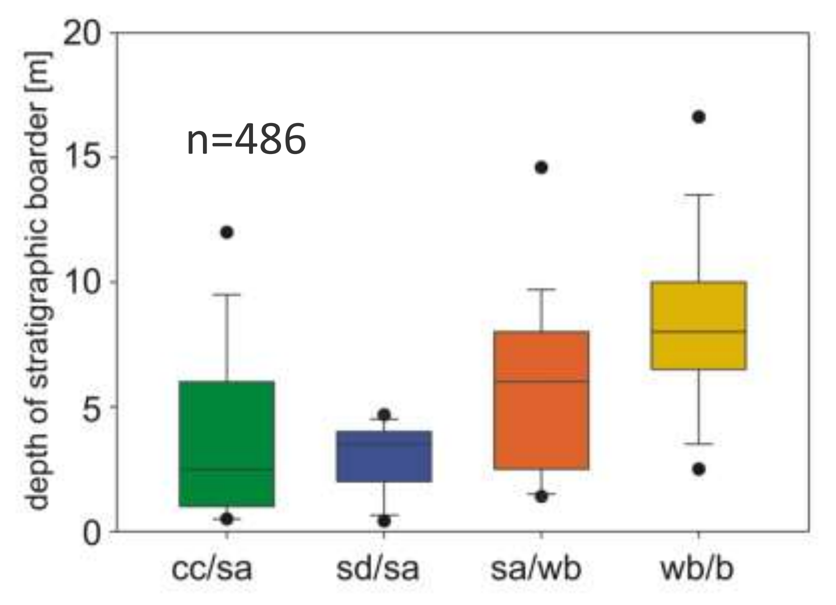
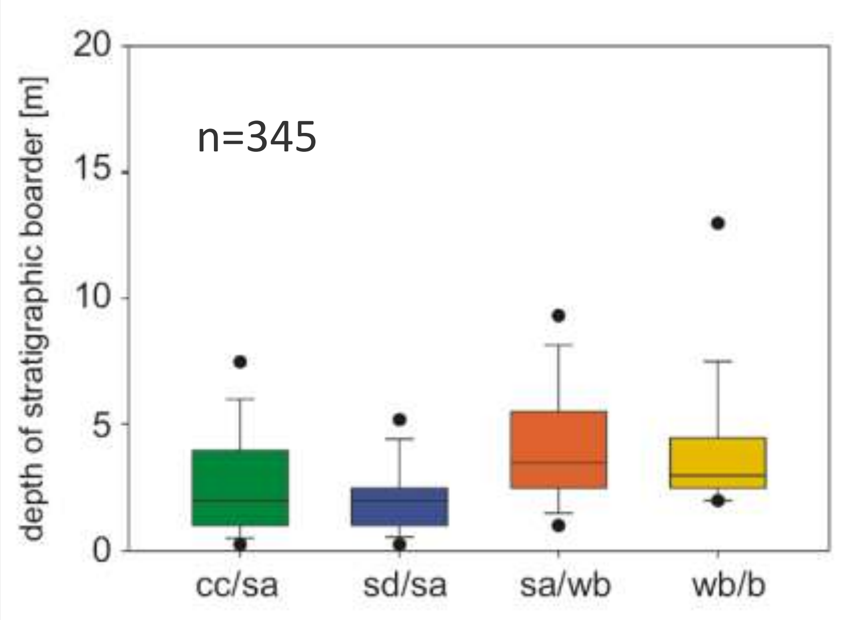
cc
sa
wb
20
10
0
25
50
100 [m]
4b)

Betasso



Upper Gordon Gulch



Tiefenlage der Schichtgrenzen in Metern
Median, 5, 10, 25, 75, 90, 95 %-Percentil

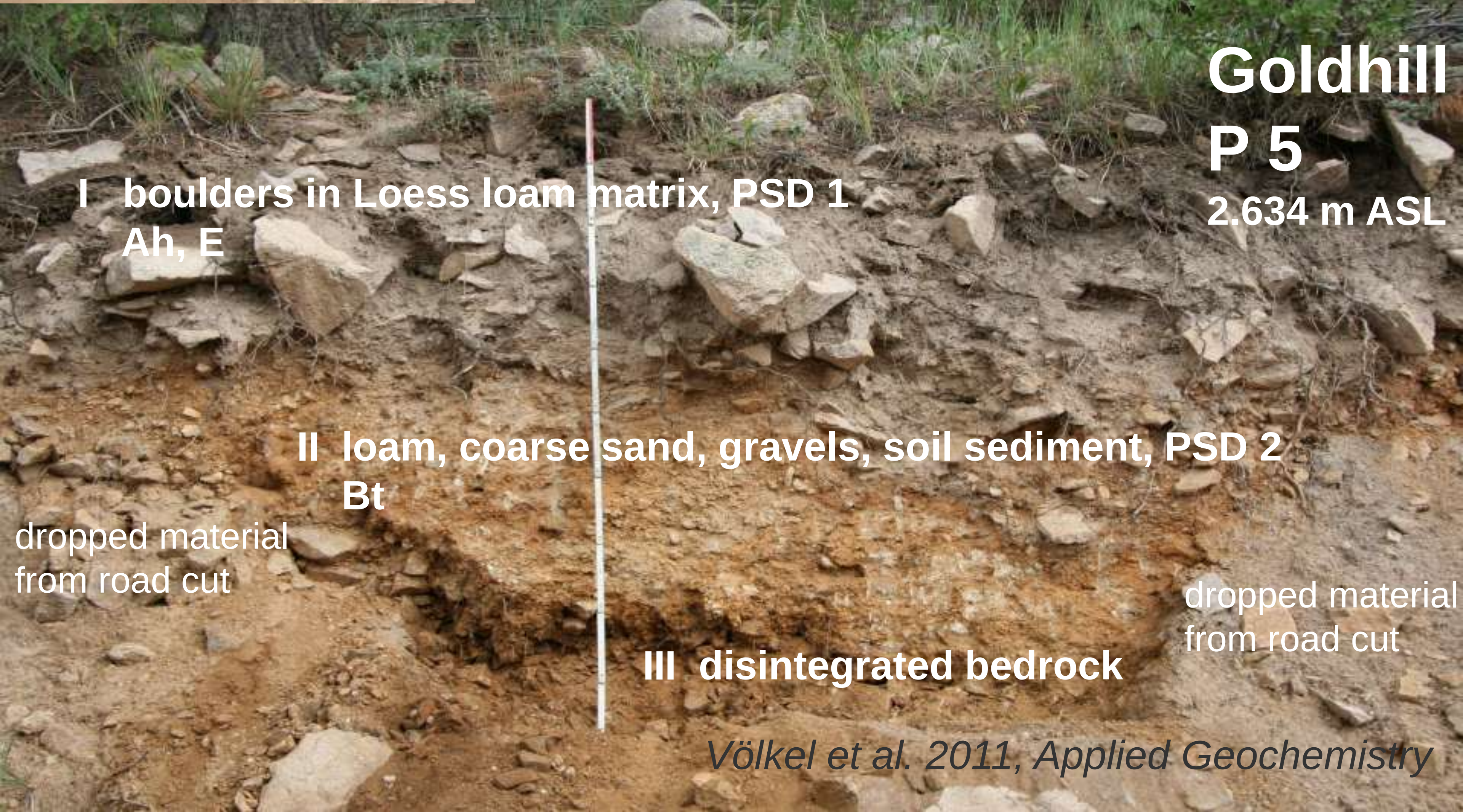
cc coarse colluvium (Holocene)
sd slope deposits (periglacial, Pinedale (= Würm))
sa saprolite
wb weathered bedrock (e.g. physically stressed)
b bedrock (solid)

Aufbau der *Critical Zone* im Hangbereich, montan und collin

Left Hand Canyon

Goldhill P 5

2.634 m ASL



Völkel et al. 2011, Applied Geochemistry

Goldhill
P 1

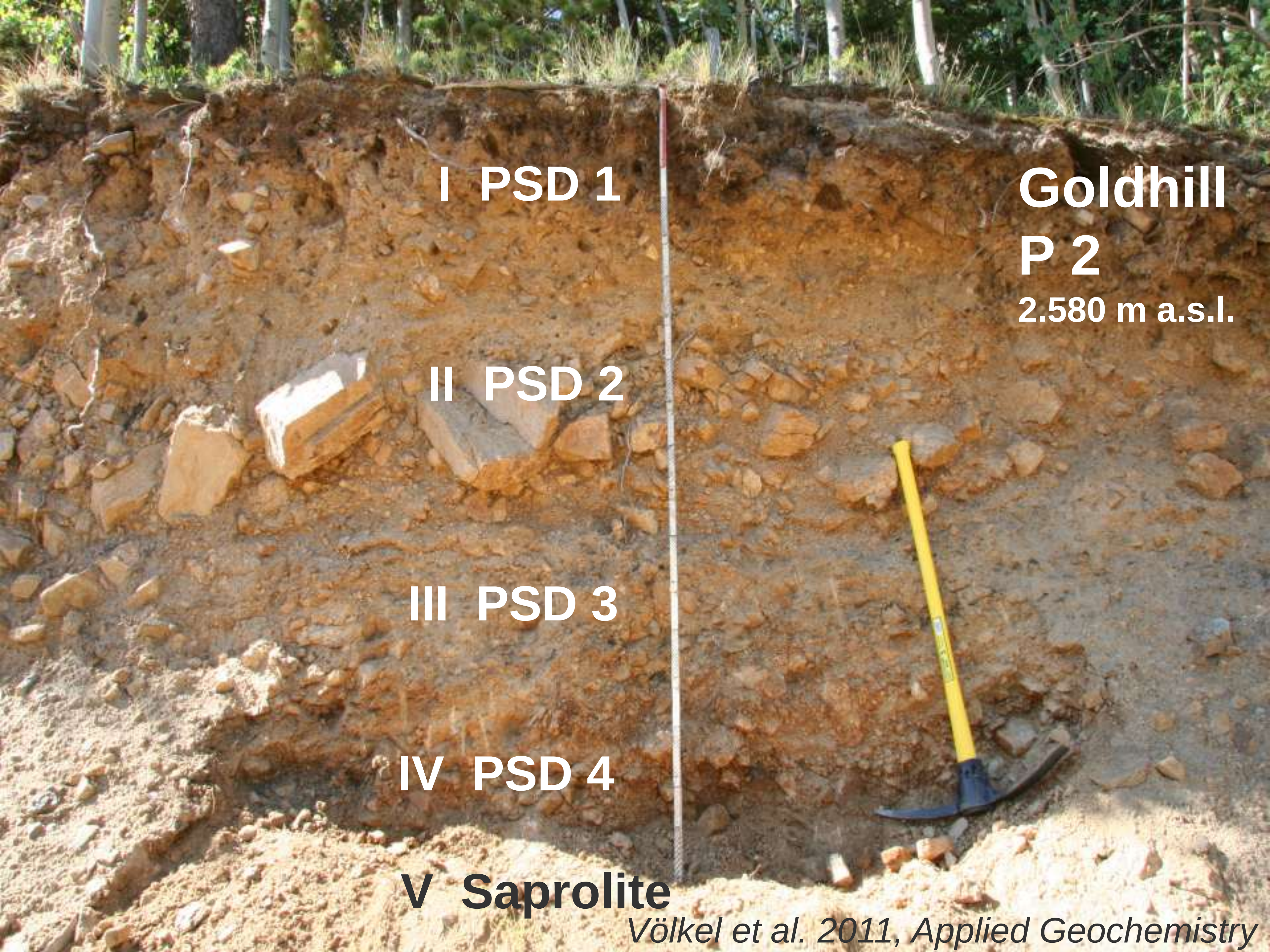
2.650 m a.s.l.

I colluvium caused by clear-cutting
Ah

II Loess loam with single boulders, PSD
Bv, cambic horizon

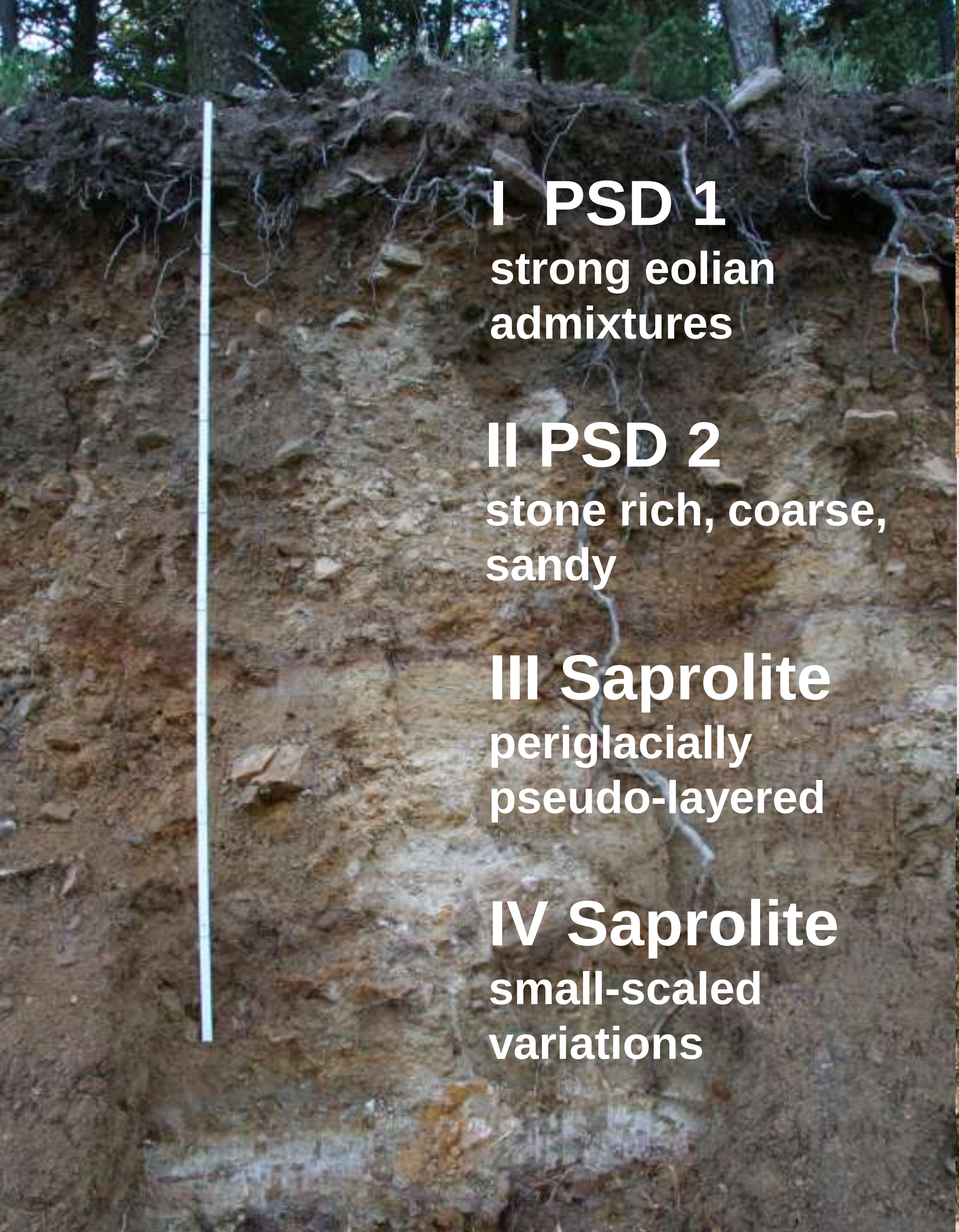
III bedrock

Völkel et al. 2011, Applied Geochemistry



Goldhill
P 2
2.580 m a.s.l.

Völkel et al. 2011, Applied Geochemistry



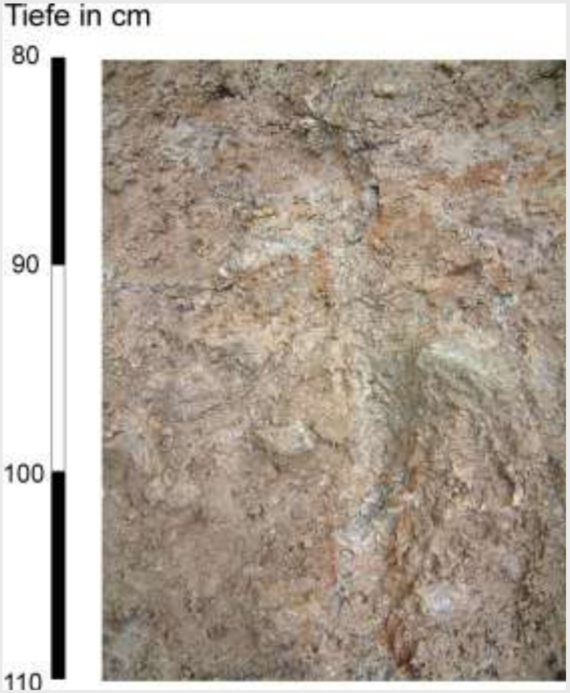
I PSD 1
strong eolian admixtures

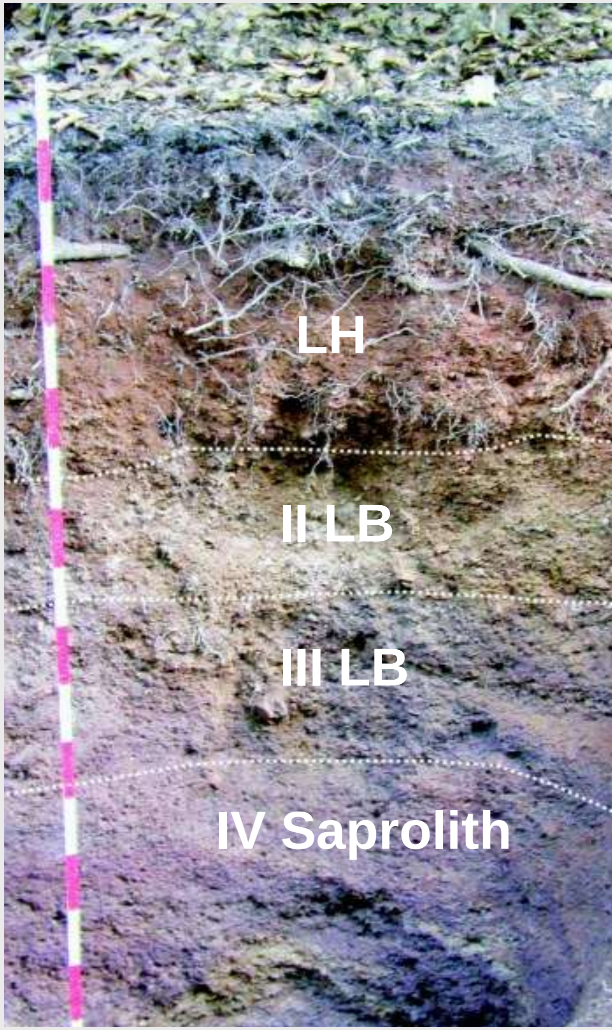
II PSD 2
stone rich, coarse, sandy

III Saprolite
periglacially pseudo-layered

IV Saprolite
small-scaled variations

Advent Gulch
Eldorado Springs P 1
2.016 m a.s.l.


Tiefe in cm
80
90
100
110

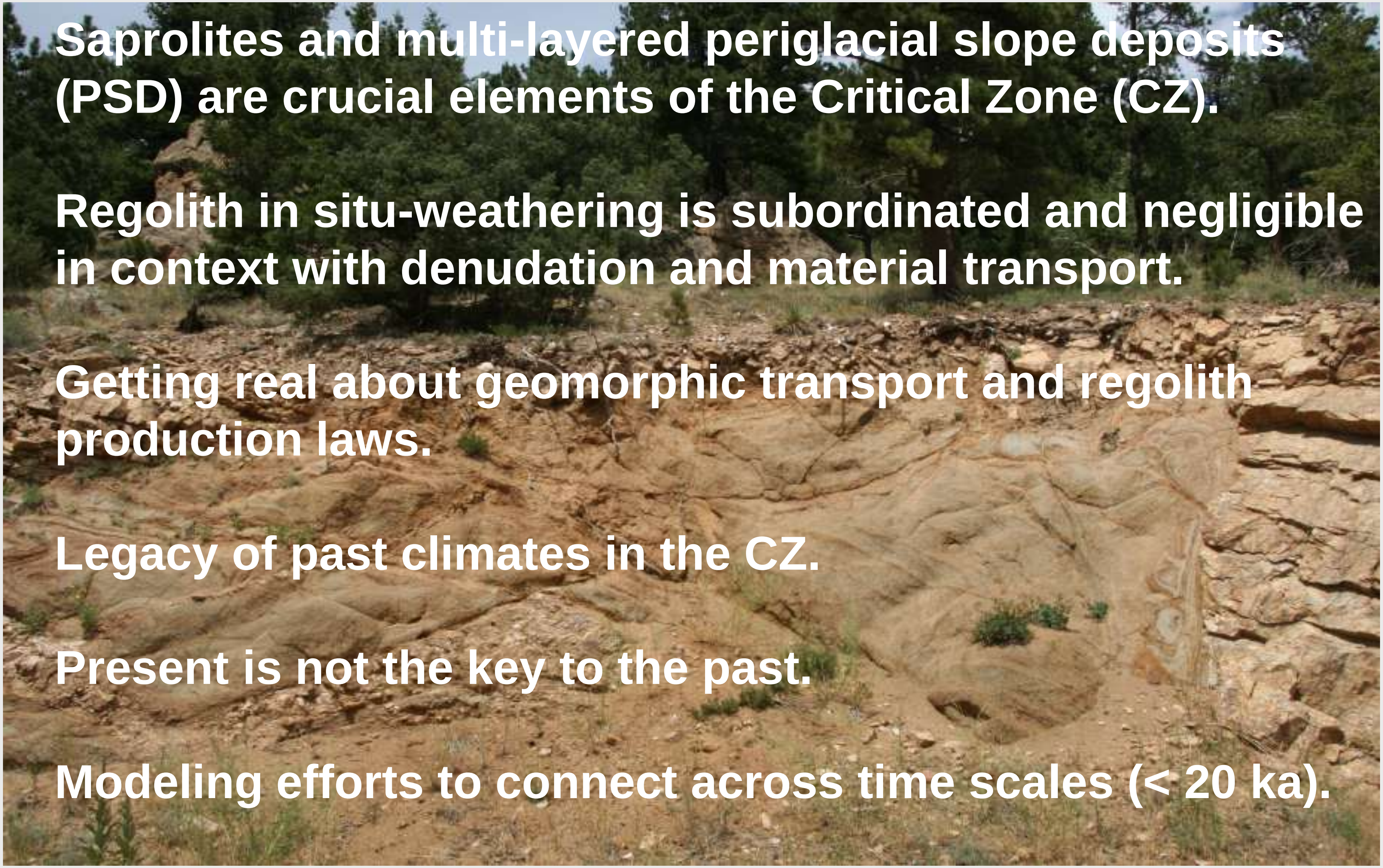

LH
II LB
III LB
IV Saprolith

Waterflow between different layers causing strong hydromorphic features

FP-RFA	Fe (in ppm)	Mn (in ppm)
Upper Layer	57.270	443
Red	103.429	697
Black	33.162	78.158
Saprolite	48.225	1.823

Fe and Mn enrichment between PSD and saprolite

Slope deposits should be part of the Critical Zone concept.



Saprolites and multi-layered periglacial slope deposits (PSD) are crucial elements of the Critical Zone (CZ).

Regolith in situ-weathering is subordinated and negligible in context with denudation and material transport.

Getting real about geomorphic transport and regolith production laws.

Legacy of past climates in the CZ.

Present is not the key to the past.

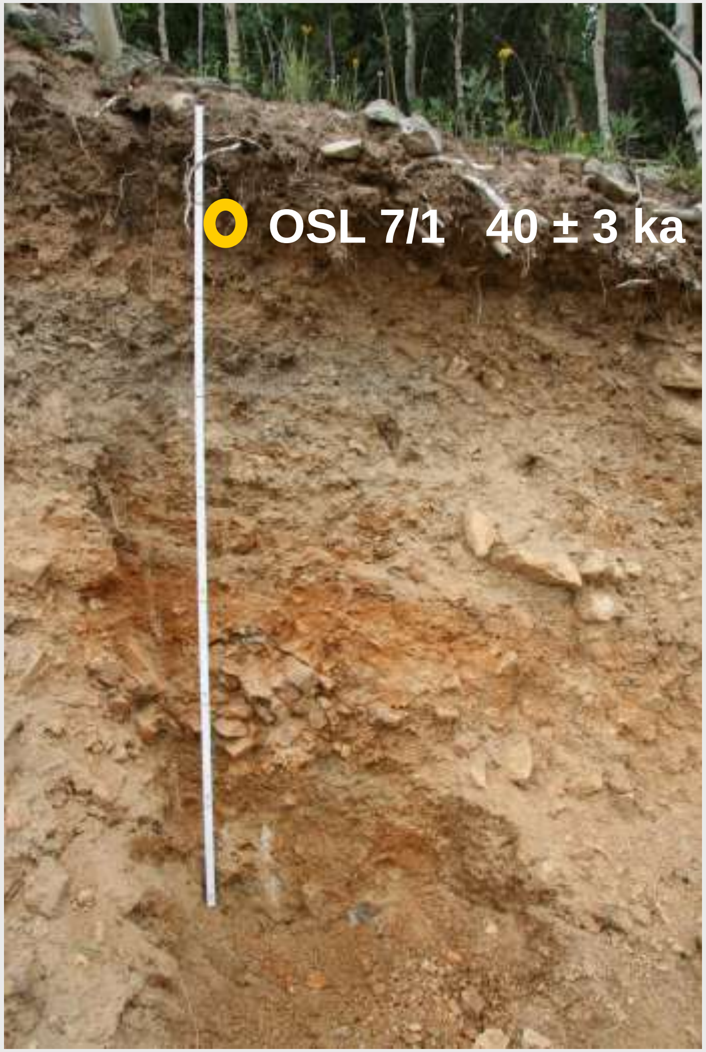
Modeling efforts to connect across time scales (< 20 ka).

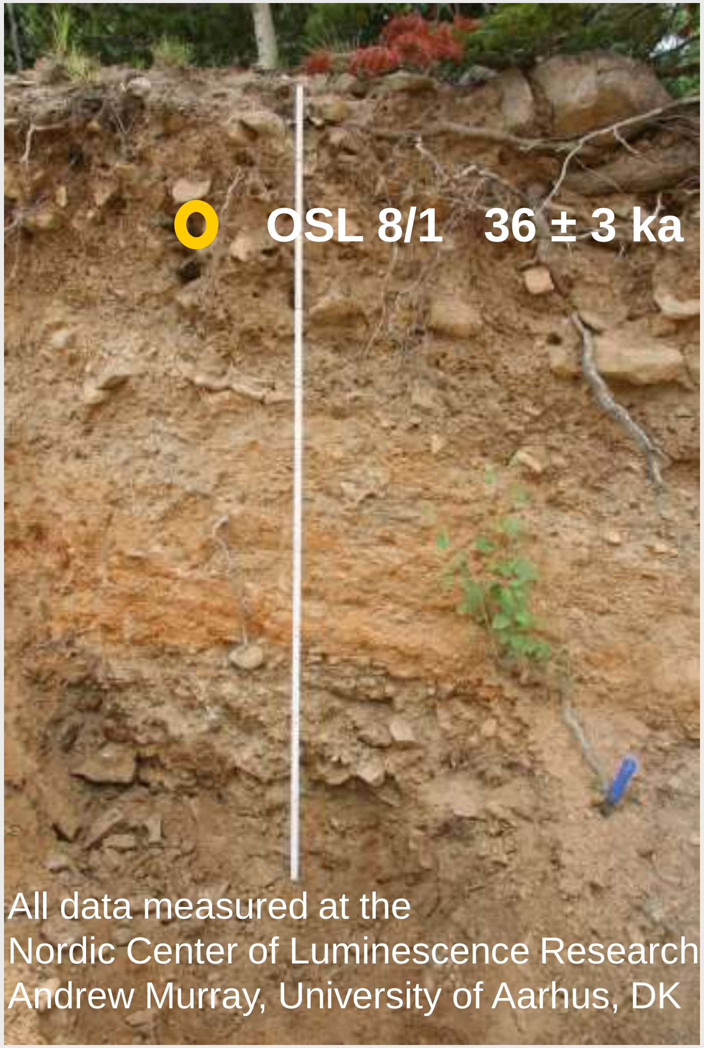
Ages ?

First Results …

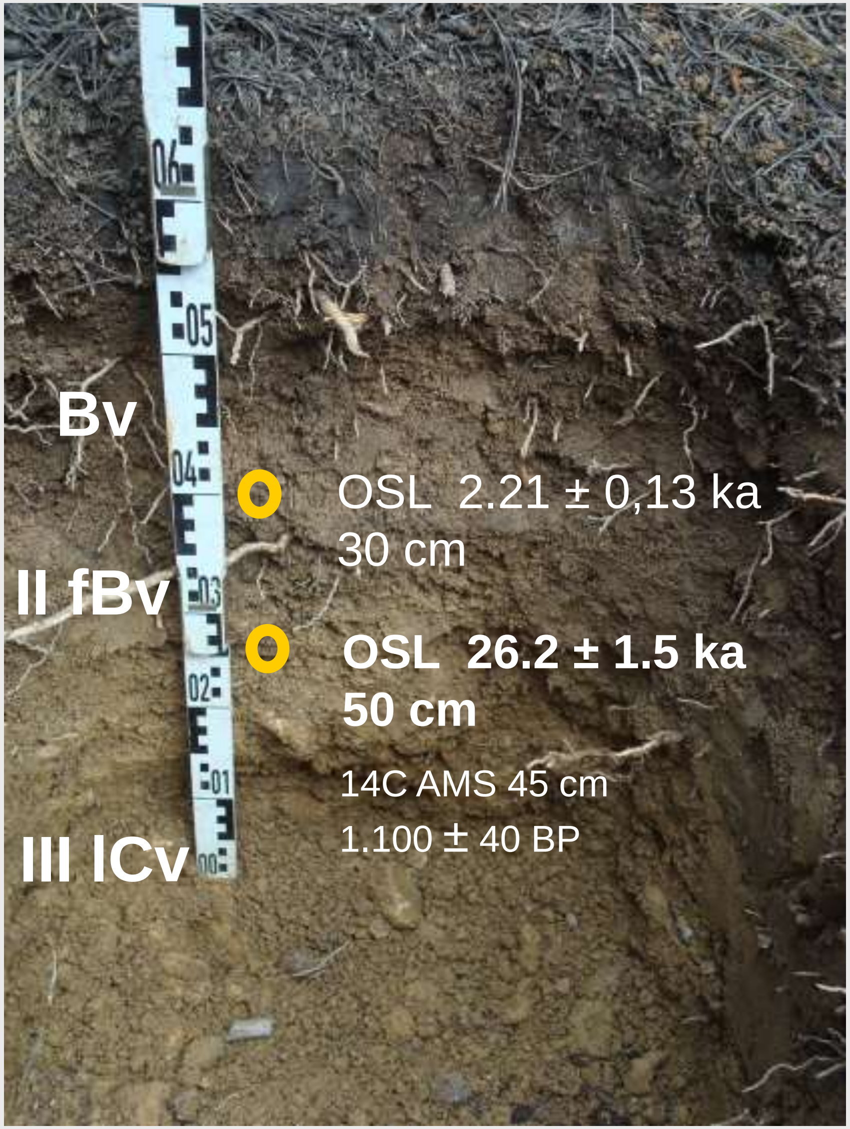
Funded by DFG Az VO 585/14-1

Gold Hill 4965 III SW 7 and 8 (Left Hand Canyon)





All data measured at the
Nordic Center of Luminescence Research
Andrew Murray, University of Aarhus, DK



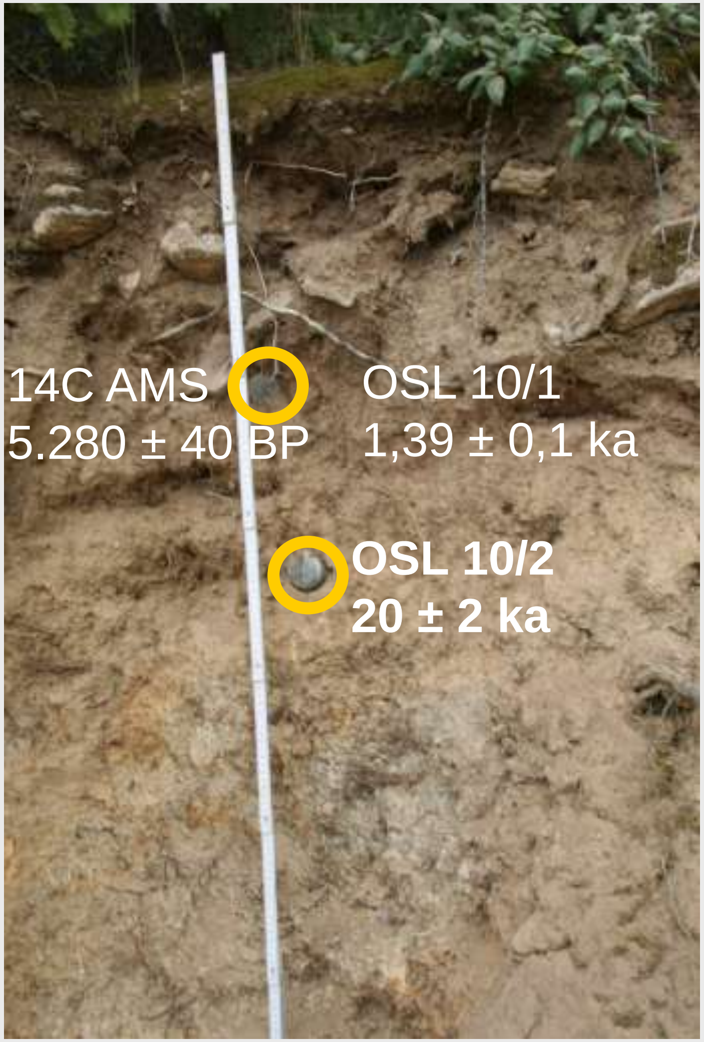
Upper Gordon Gulch

4965 III SW

N 40°01’23,5“ W105°28’36,6“

2.700 m a.s.l.

Gold Hill 4965 III SW 10 (Sunshine Canyon)



14C AMS
5.280 ± 40 BP

OSL 10/1
1,39 ± 0,1 ka

OSL 10/2
20 ± 2 ka

Eldorado Springs 4963 IV NE 1 (Advent Gulch)

GPS: N 39° 55’ 02,3”, W 105° 21’ 55,6”, 2405 ± 4 m

Deutsche Forschungsgemeinschaft DFG

Loess and Loess derived colluvium at Bummers Gulch

OSL 1 13.3 ± 0,8 ka
90 cm

OSL 2 16.4 ± 1.2 ka
320 cm

OSL ages (5) and radiocarbon (1)

5.4 ± 0.3 ka OSL 1 65 cm

6.2 ± 0.3 ka OSL 3 110 cm

9.000 - 8.640, 8.530 - 4.820 cal BP

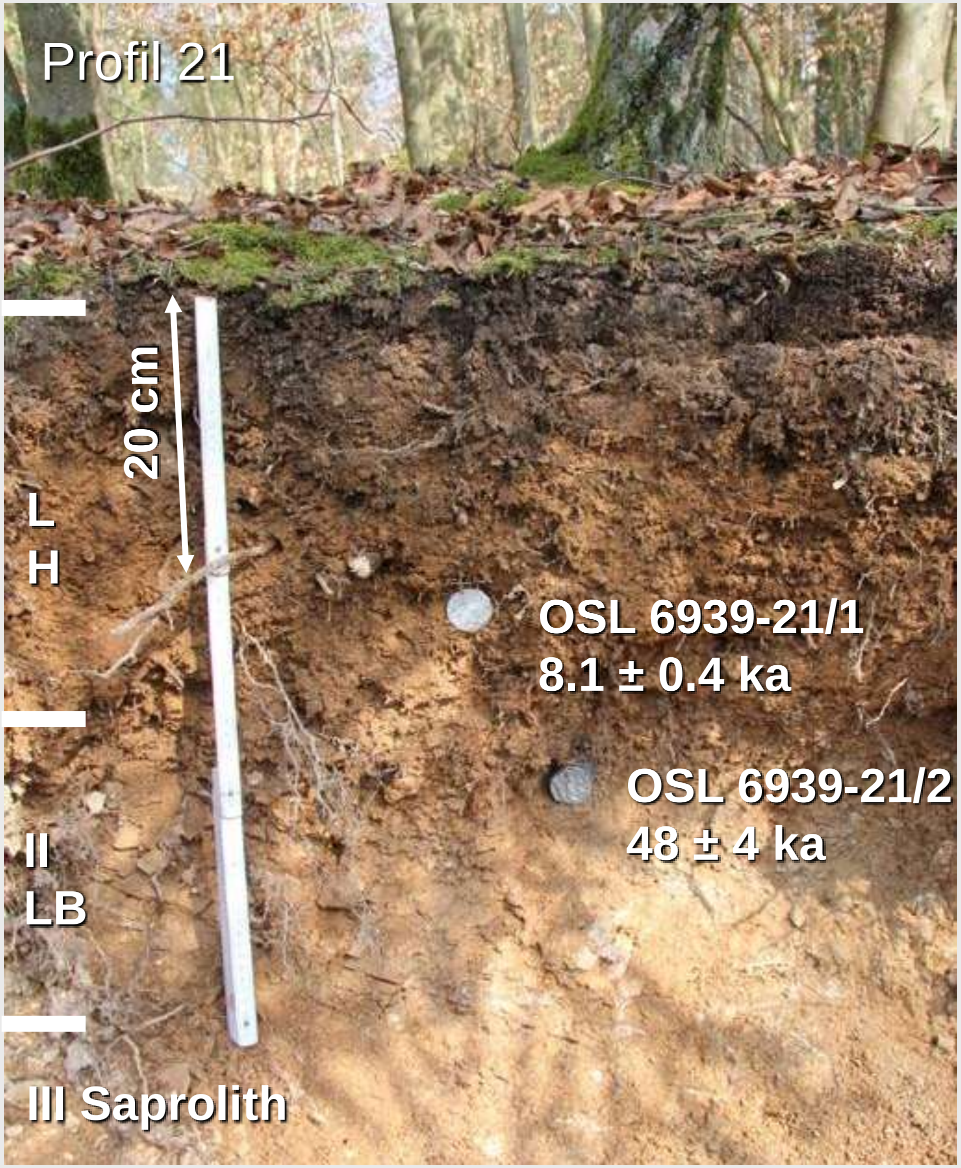
12.2 ± 0.7 ka OSL 2 200 cm

18.0 ± 1.1 ka OSL 4 270 cm

16.1 ± 1.1 ka OSL 5 410 cm

Deutsche Forschungsgemeinschaft DFG

Catena Hundshänge, Exposition West
Oberhang, Profil 6939-21



OSL-Datierungen
NLL Risoe, DK

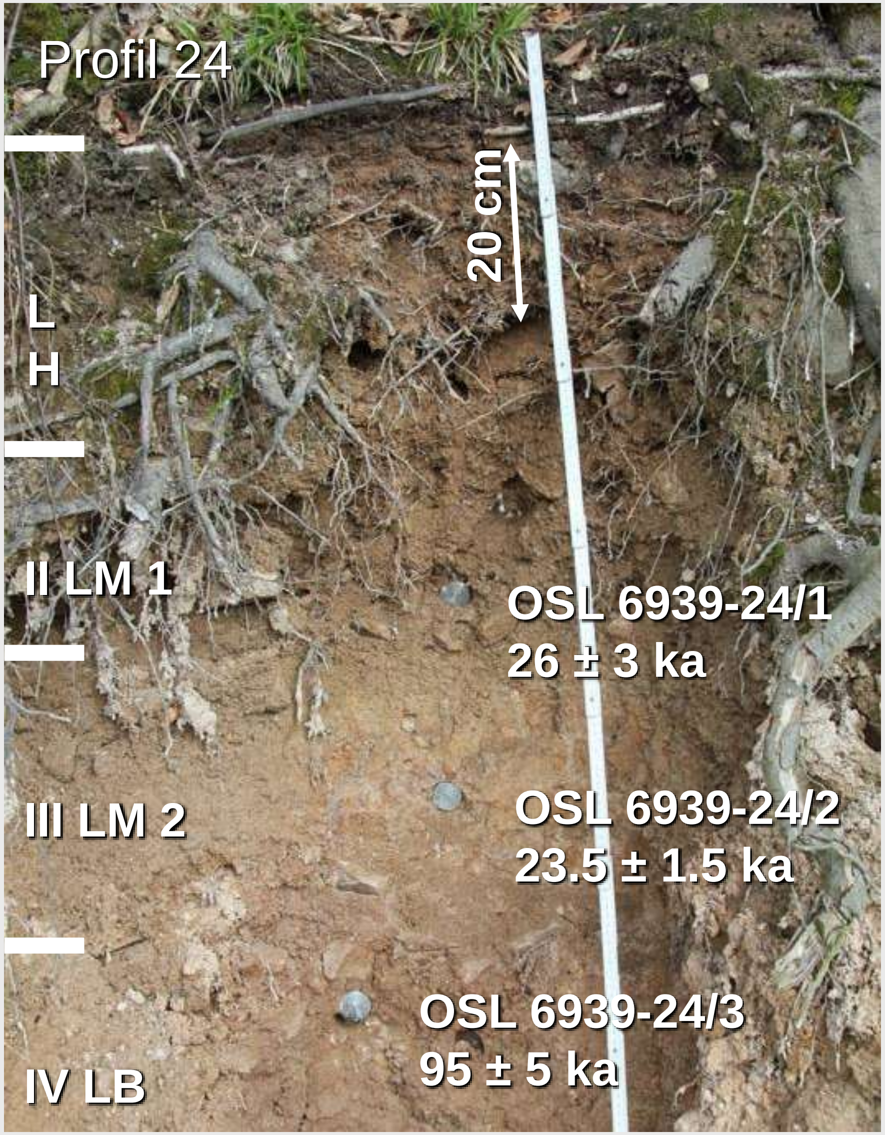
First Results …

Funded by DFG
Az VO 585/15-1

Deutsche Forschungsgemeinschaft DFG

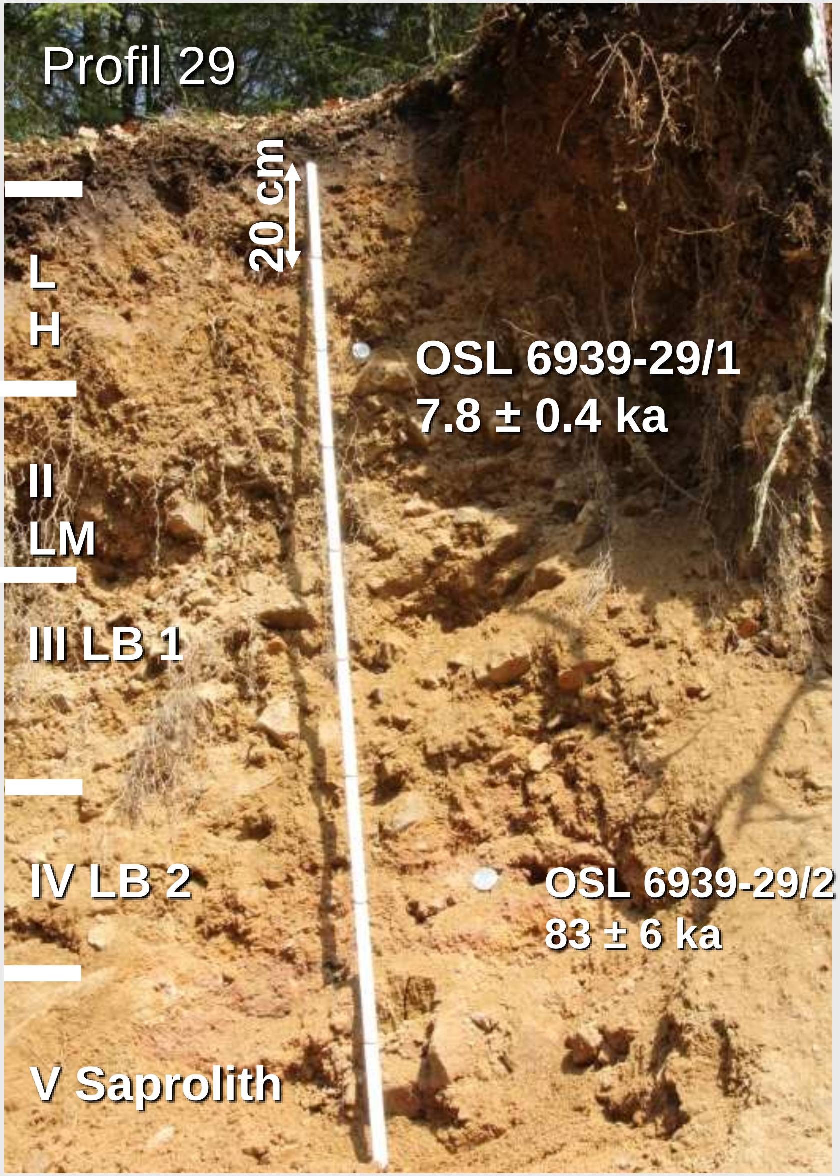
Catena Lindenschlag

Hangfuß Catena Hundshänge, Profil 6939-24, unmittelbar am Übertritt in die Aue des Otterbachs, Schwemmfächer im Hintergrund



OSL-Datierungen
NLL Risoe, DK
2011

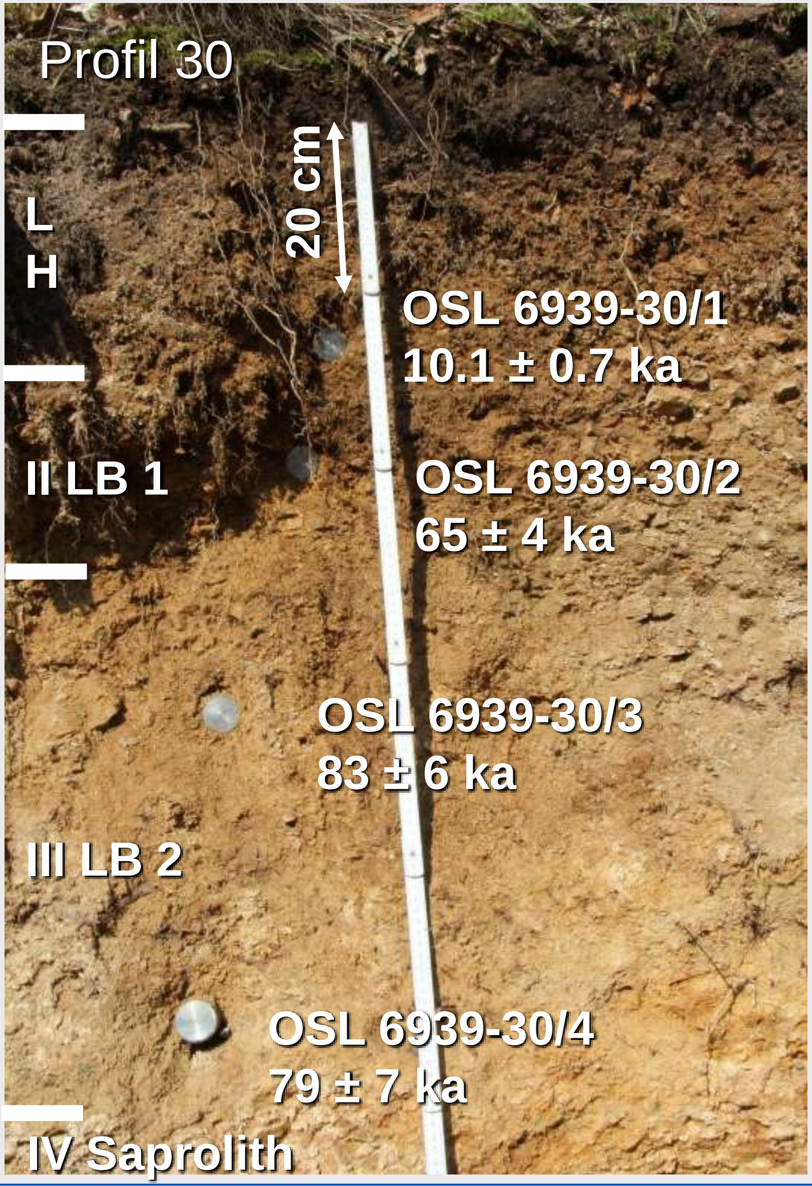
Catena Lindenschlag
Exposition Ost
Profil 6939-29, Umgebung



OSL-Datierungen
NLL Risoe, DK
2011

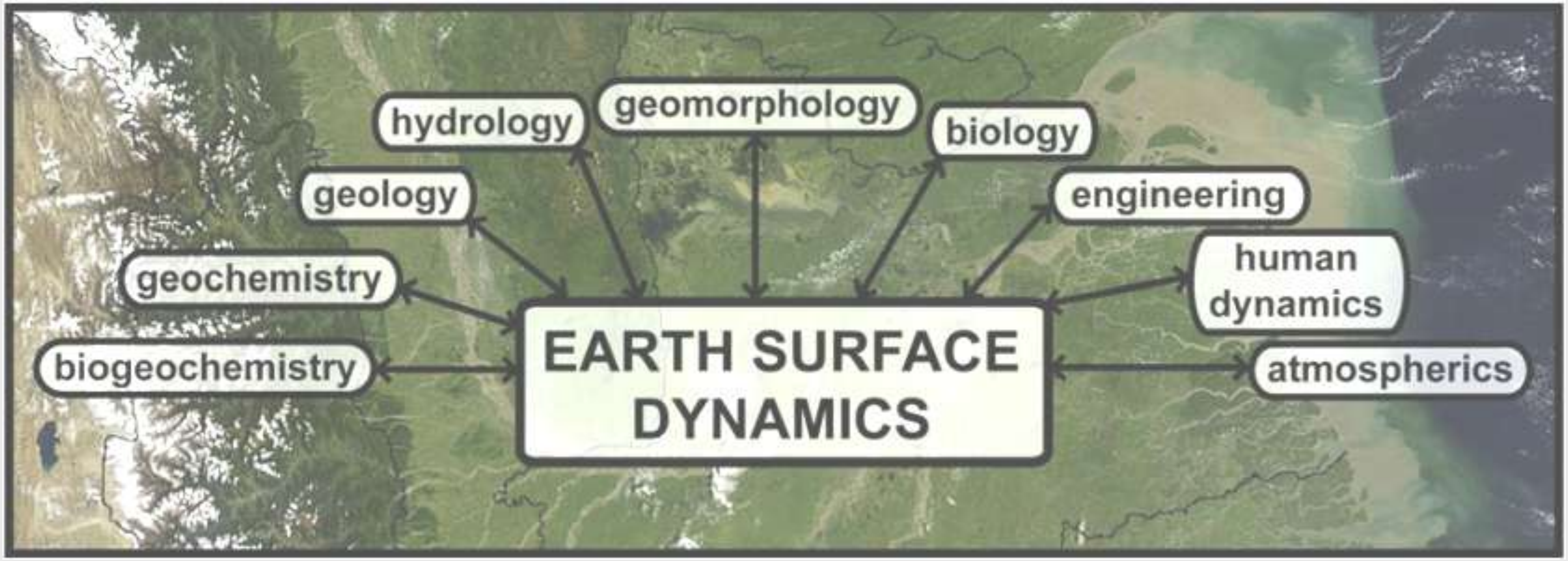
Deutsche Forschungsgemeinschaft DFG

Catena Lindenschlag
Exposition Ost
Profil 6939-30, Umgebung



OSL-Datierungen
NLL Risoe, DK
2011

Deutsche Forschungsgemeinschaft DFG



Geomorphology, the study of landscape change, thus stands in the center of a newly emerging science of the Earth's surface, where strong couplings link human dynamics, biology, biochemistry, geochemistry, geology, hydrology, geomorphology, and atmospheric dynamics, including climate change.

Murray et al. (2009), *Geomorphology* **103**: 496-505. – **White Book U.S. National Research Council**

Concepts and Objectives of Critical Zone Observatories

Soils and Geomorphology as Crucial Parts

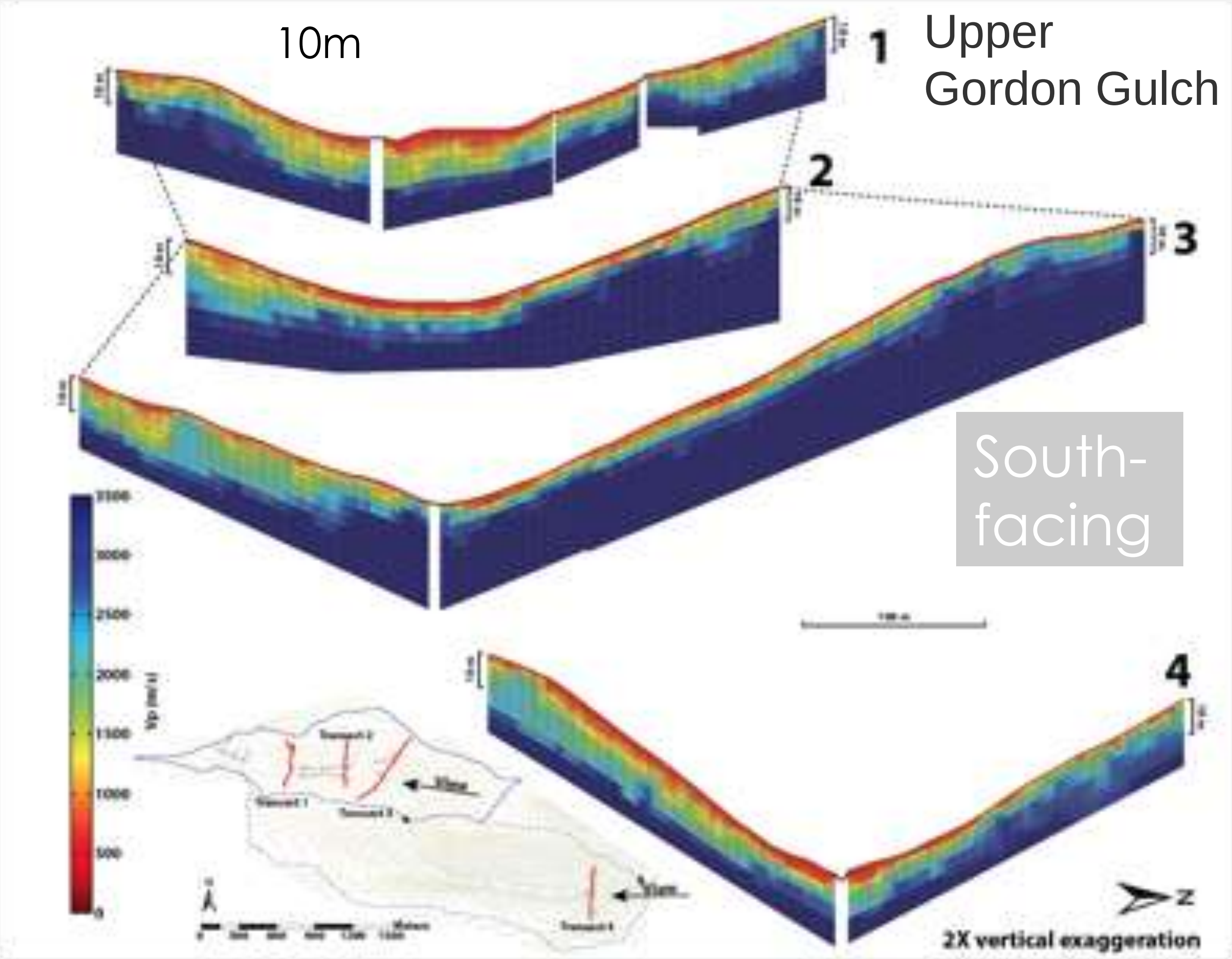
Examples from the Boulder Creek CZO, Colorado U.S.A.

Jörg Völkel

25. Januar 2012

Out of the dark, into the light…

North-facing Slope

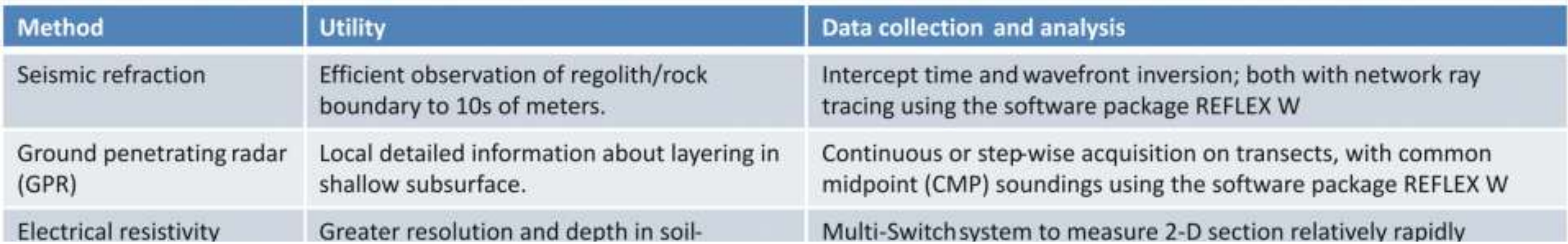


Upper Gordon Gulch

South-facing

Befus et al., 2011

Shallow seismic refraction (15 km)



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 ray tracing using the software package REFLEX W
Ground penetrating radar (GPR)	Local detailed information about layering in shallow subsurface.	Continuous or step-wise acquisition on transects, with common midpoint (CMP) soundings using the software package REFLEX W
Electrical resistivity	Greater resolution and depth in soil-	Multi-Switch system to measure 2-D section relatively rapidly

NOTE !

Geophysical methods develop a subsurface model which is based on the physical and chemical parameters of the CZ!

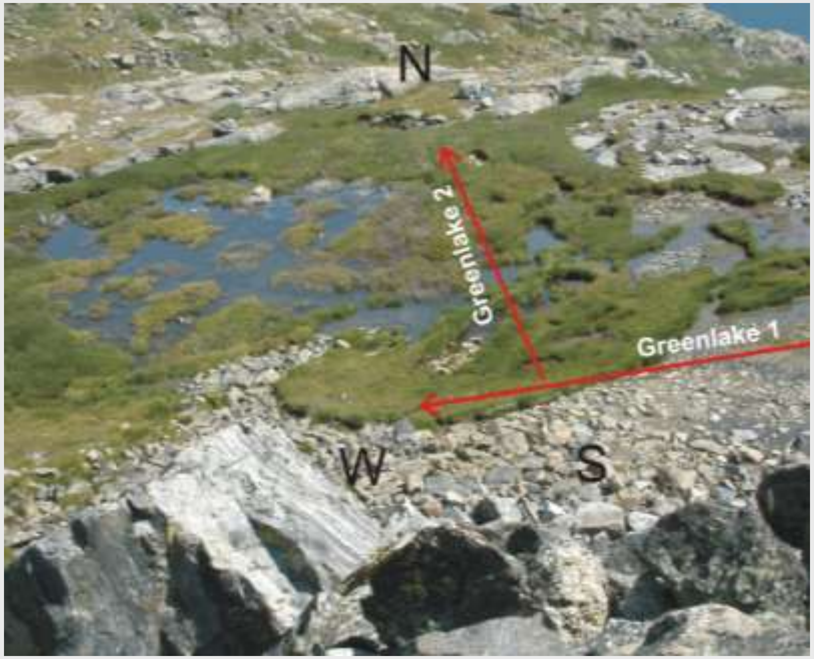
Any reliable interpretation needs both:

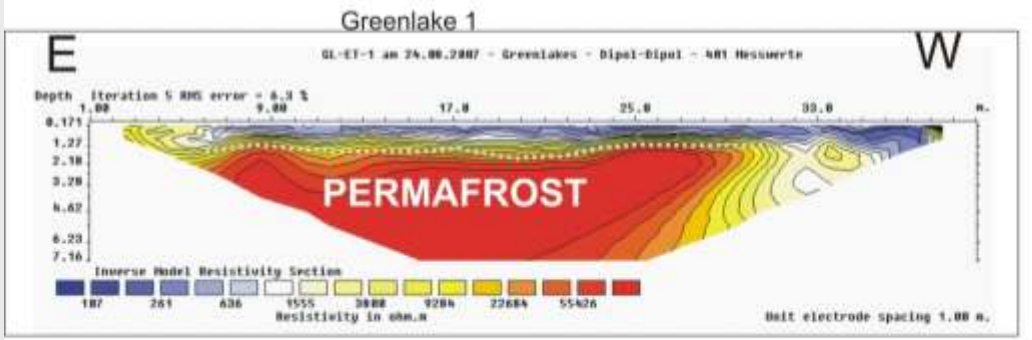
– experience and expertise of geoscientists;

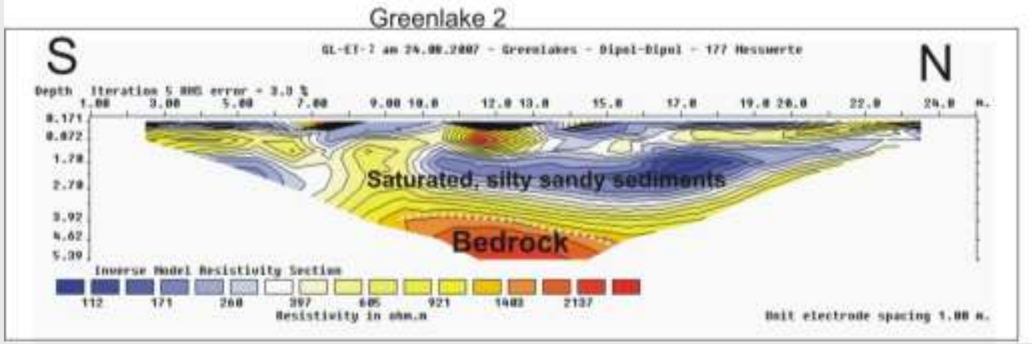
– ground truth (pits, profiles, drillings etc.)

to develop a realistic stratigraphic model.

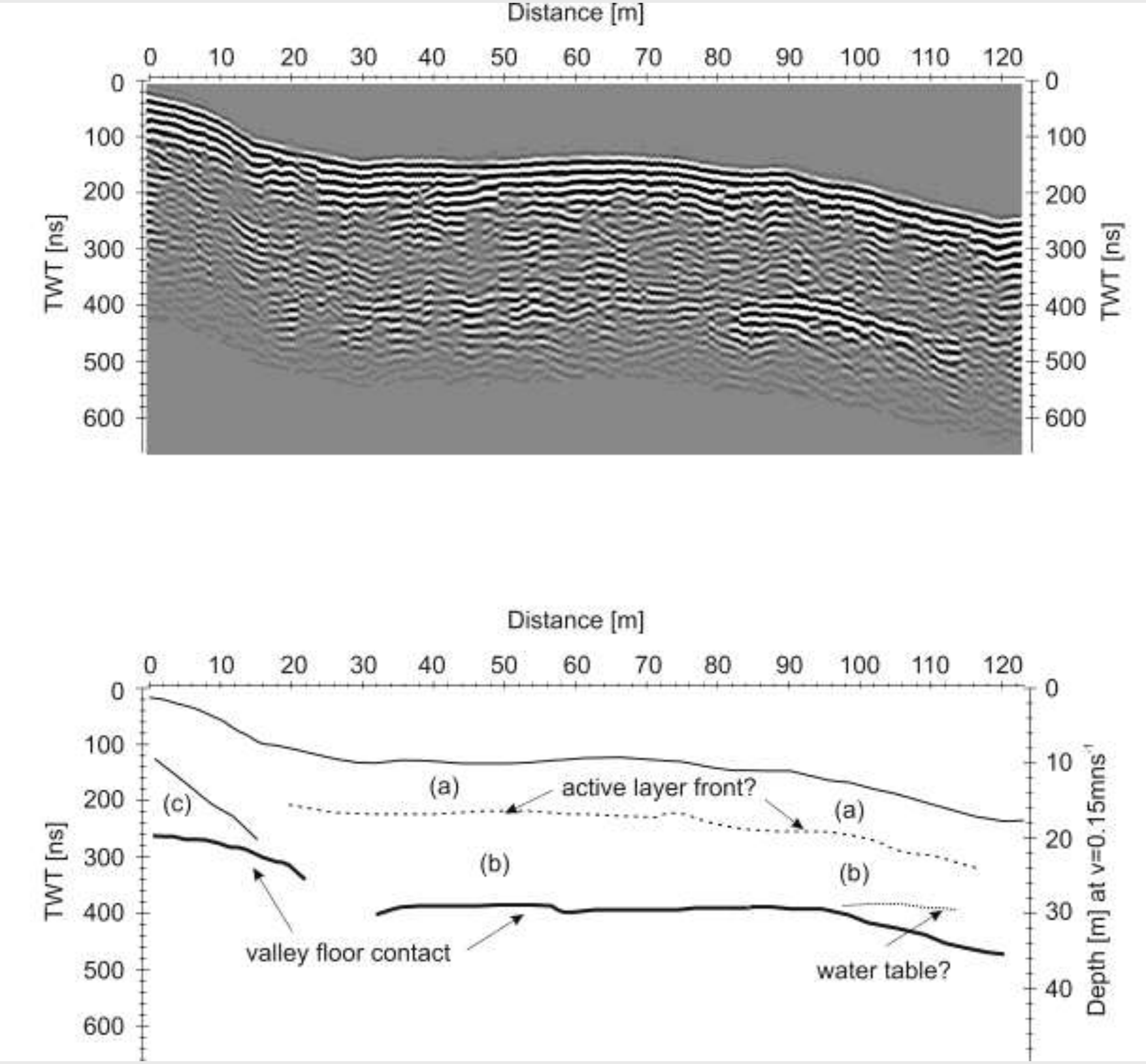
ERT-Messung im Vorfeld des Blockgletschers

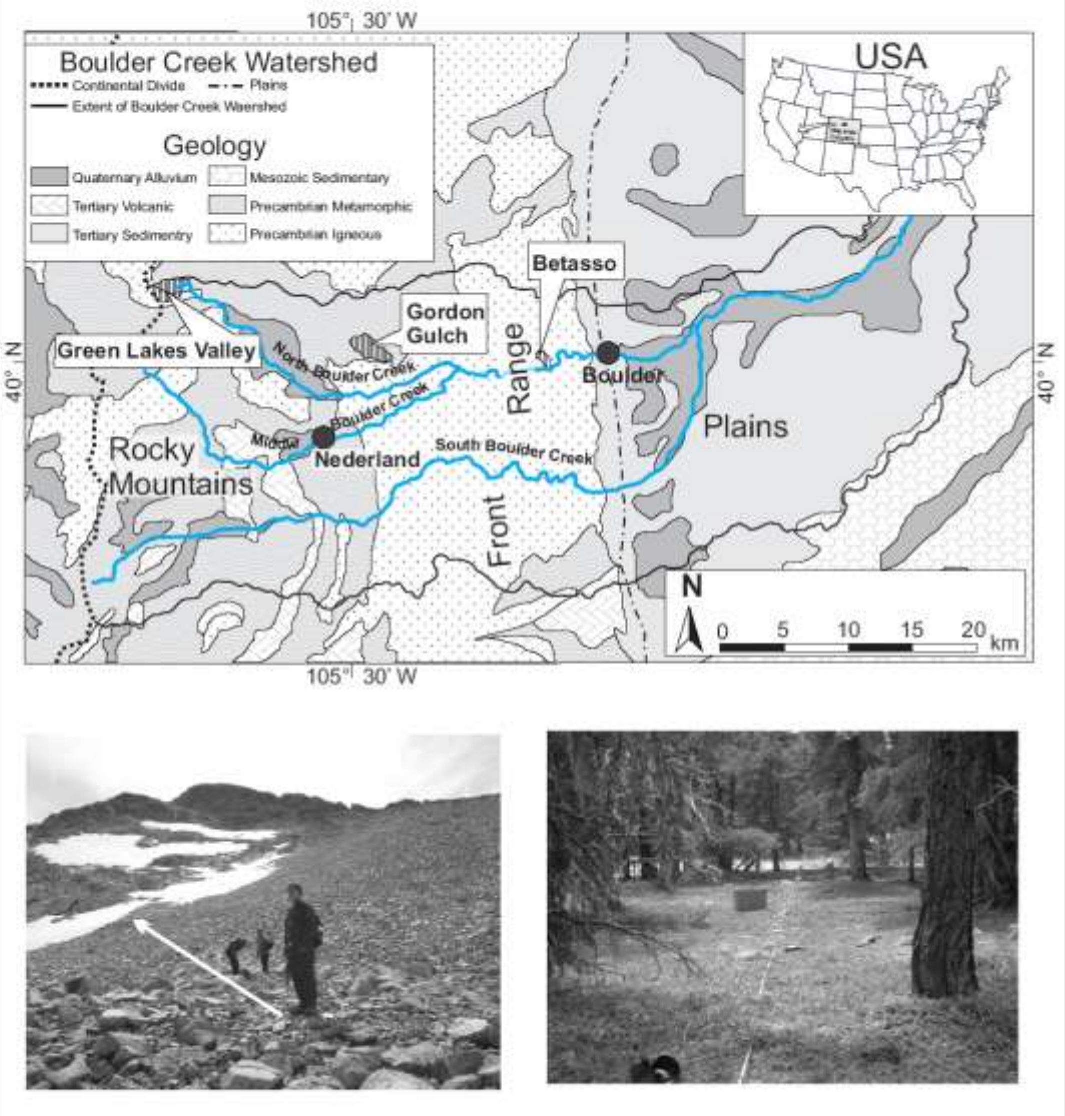



Greenlake 1


Greenlake 2

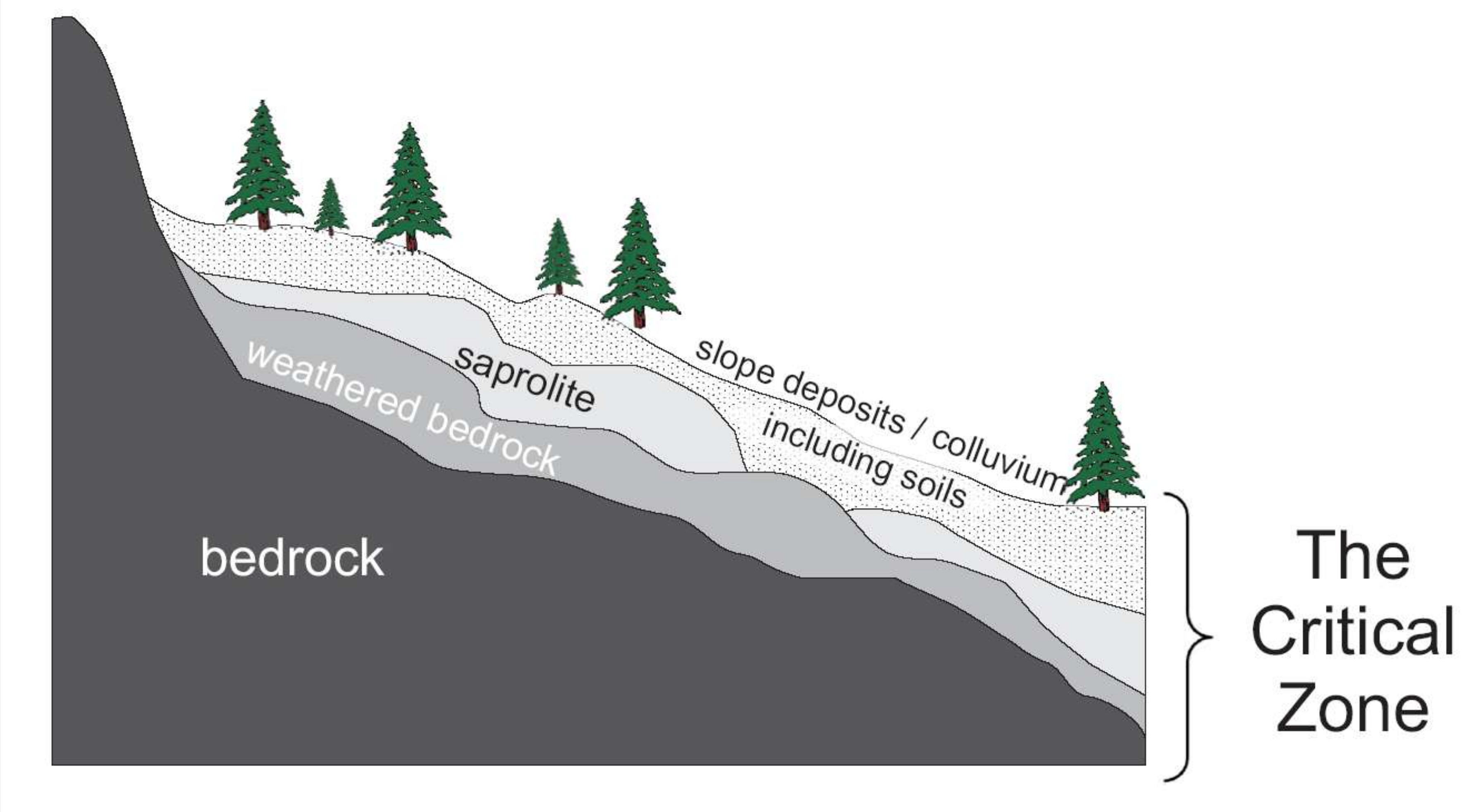
GPR-Messung auf dem Blockgletscher

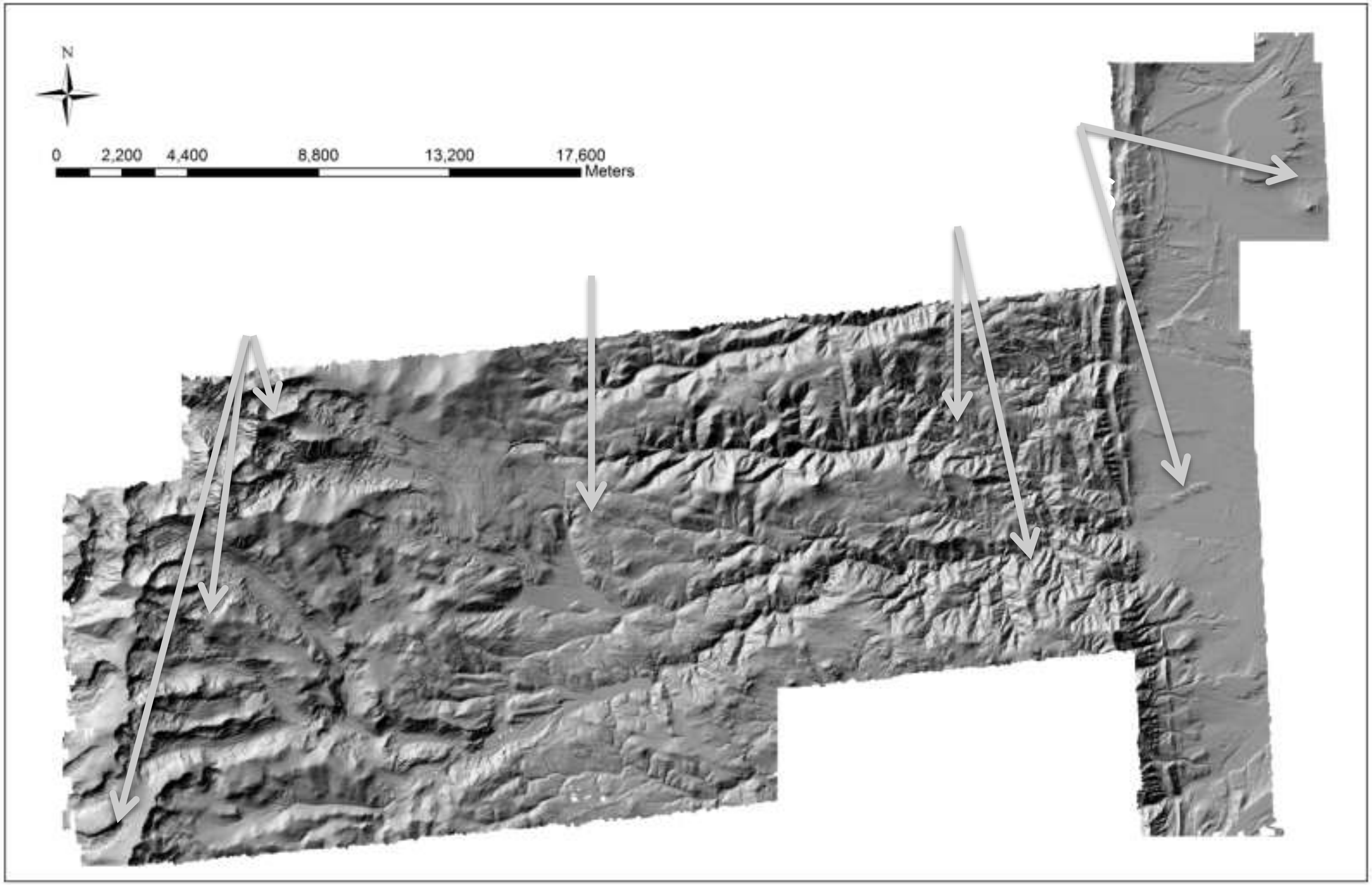



Boulder Creek Watershed
Continental Divide
Plains
Extent of Boulder Creek Waershed
Geology
Quaternary Alluvium
Mesozoic Sedimentary
Tertiary Volcanic
Precambrian Metamorphic
Tertiary Sedimentry
Precambrian Igneous
USA
105° 30' W
40° N
Green Lakes Valley
Gordon Gulch
Betasso
North Boulder Creek
Boulder Creek
Middle
South Boulder Creek
Boulder
Nederland
Rocky Mountains
Front Range
Plains
N
0 5 10 15 20 km

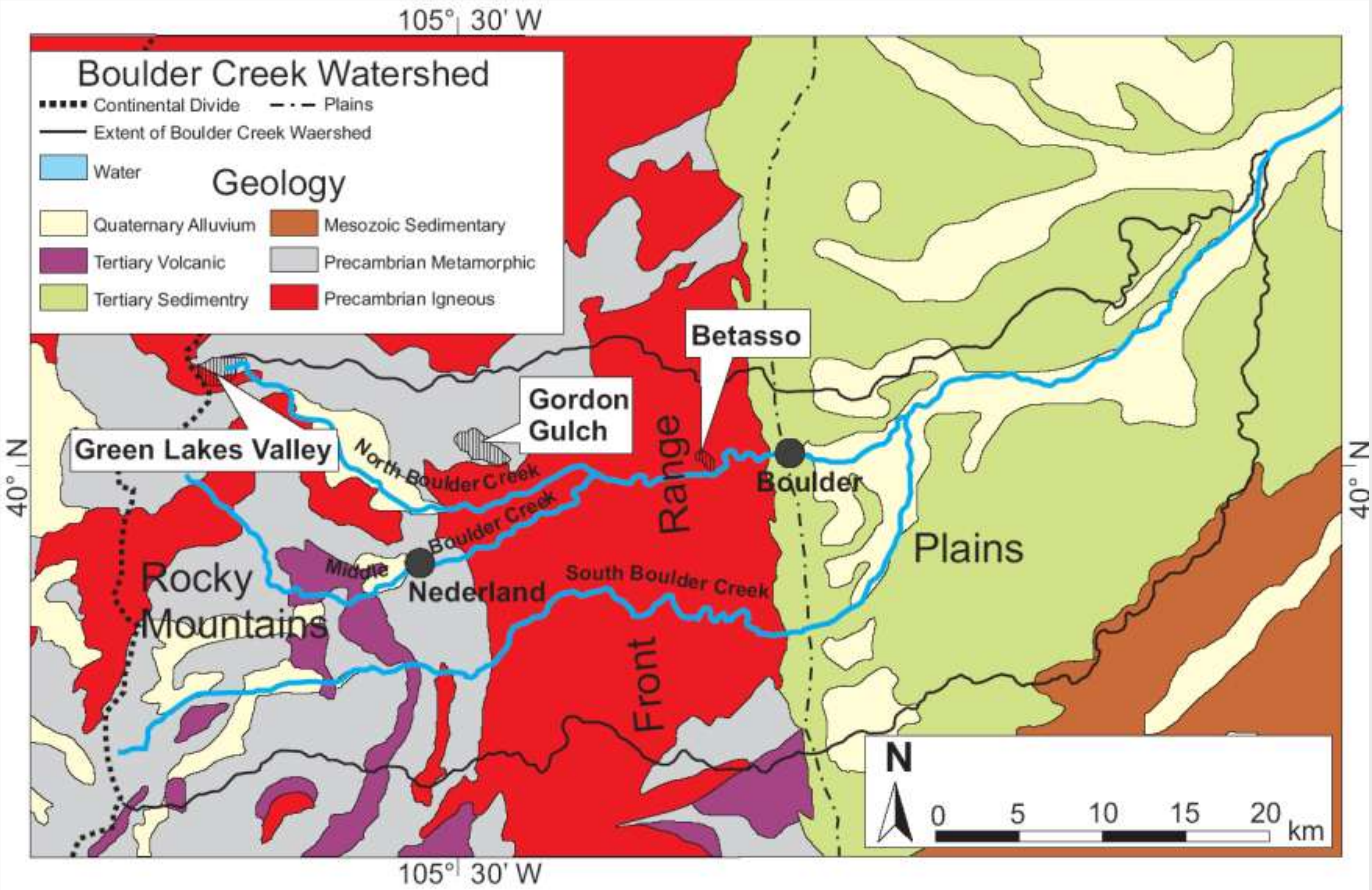
Boulder Cr. Catchment

Old Laramide Peneplain and Highlands


slope deposits / colluvium
including soils
saprolite
weathered bedrock
bedrock
The Critical Zone



LiDAR-based hillshade; data acquired Aug 2010


105° 30' W
Boulder Creek Watershed
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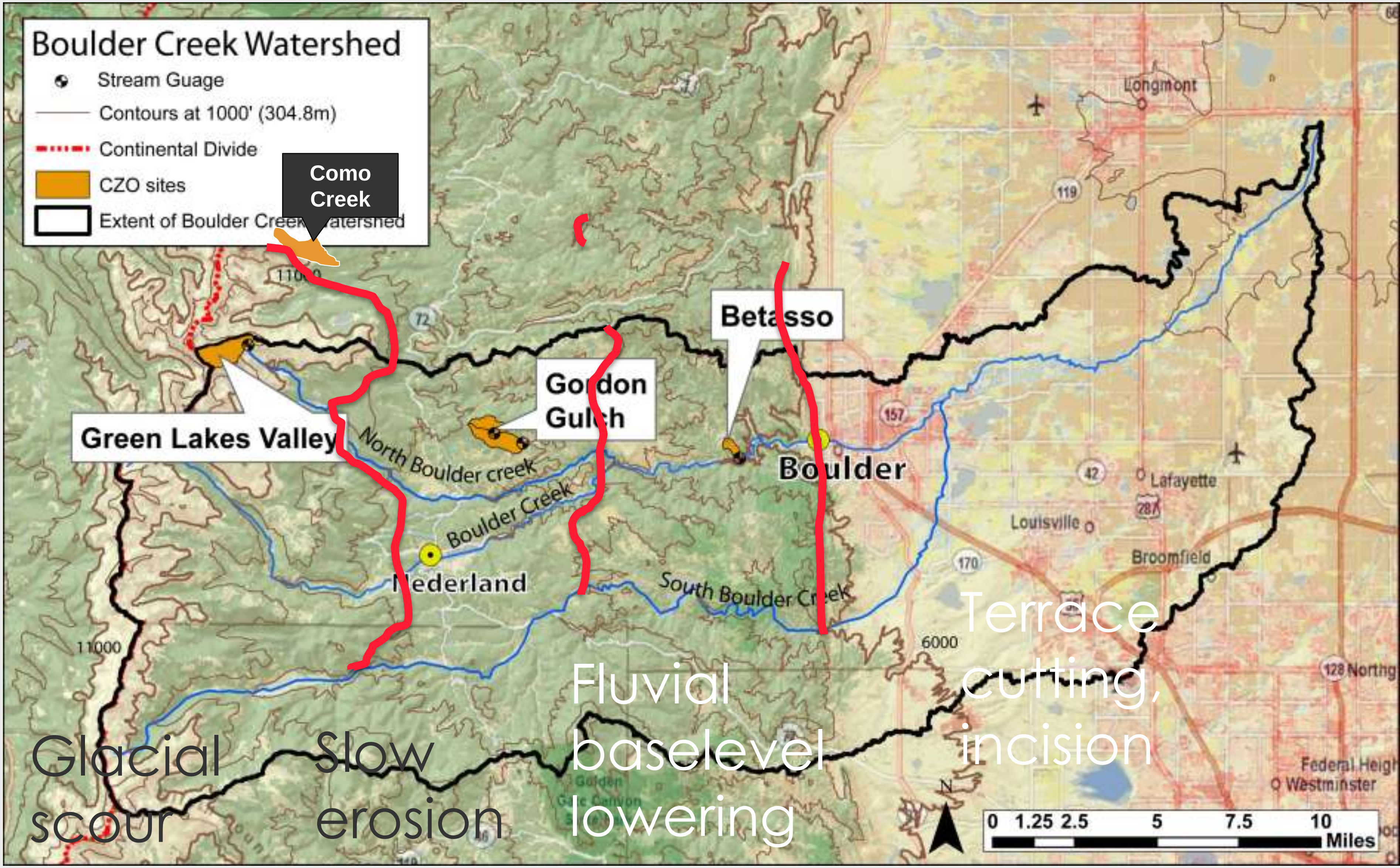
Green Lakes Valley
North Boulder Creek
Boulder Creek
Middle
Nederland
South Boulder Creek
Range
Front
Boulder
Plains
Rocky Mountains
40° N
40° N
N
0
5
10
15
20
km
105° 30' W



Glacial scour

Slow erosion

Fluvial baselevel lowering

Terrace cutting, incision