Controls on soil erosion, soil production, and chemical weathering on hillslopes over a climate gradient

Lesego Khomo	University of the Witwatersrand
Tony Hartshorn	UC Santa Barbara
Oliver Chadwick	UC Santa Barbara
Kevin Rogers	University of the Witwatersrand
Arjun Heimsath	Dartmouth College

Andrew W. Mellon Foundation

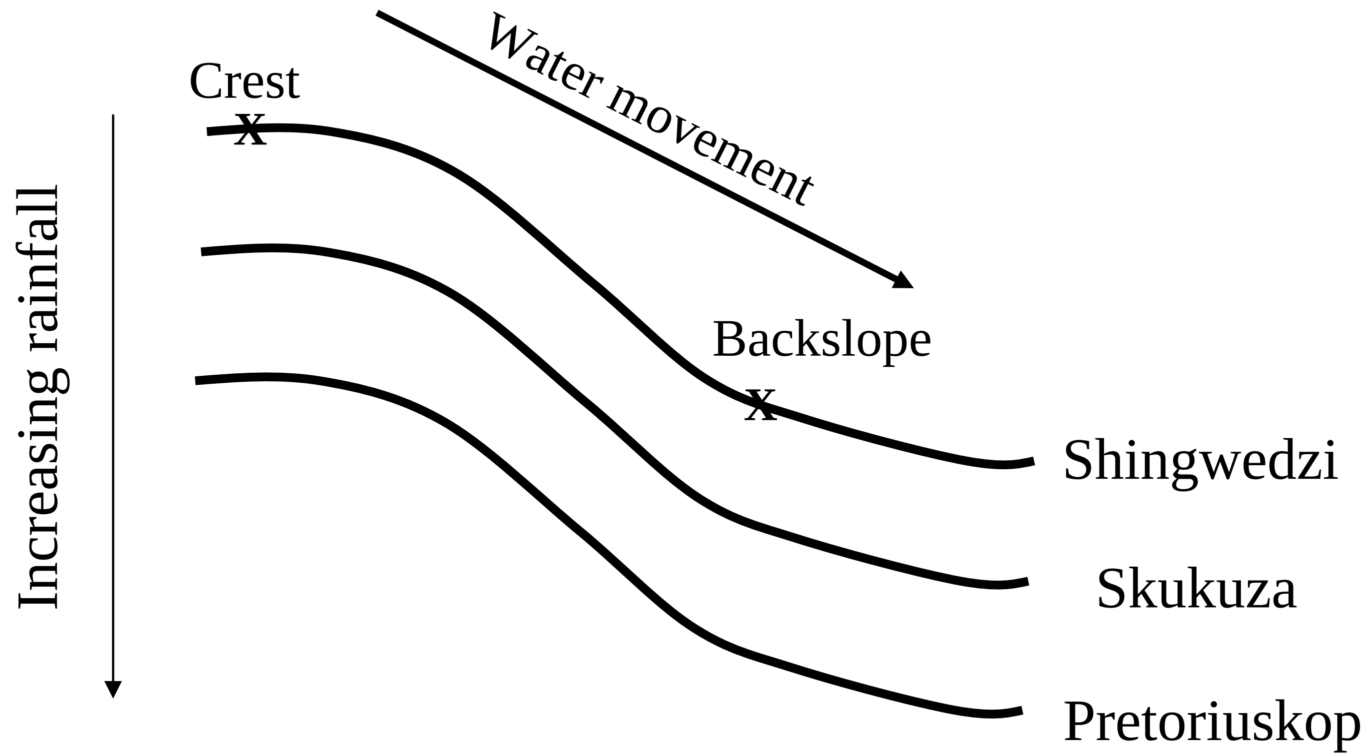
South African National Parks

Erosion, soil production, and chemical weathering on hillslopes over a climate gradient

Motivation

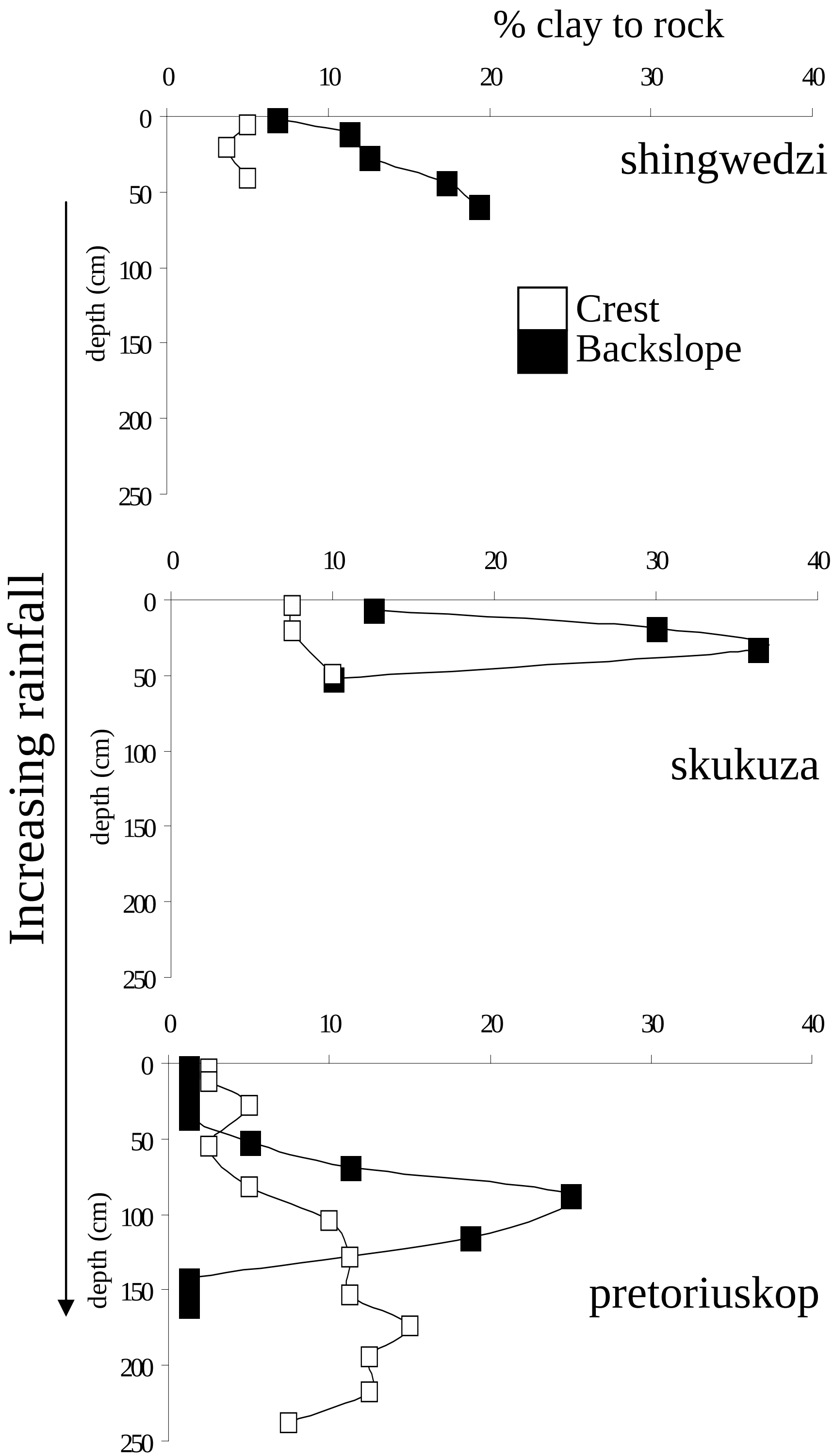
- What soil patterns do we see?
  - On hillslopes from crest to valley
  - Over climate
  - On different geologies
- Build on basis provided by Venter (1990)
  - Investigate mechanisms that account for the patterns
  - The soil geomorphic landscape is a template for ecological dynamics (Venter et al 2003)
- What sets the pace for soil landscape evolution on the Kruger granites?

Study design



- Patterns on a hillslopes from crest to backslope
  - Soil production, chemical weathering
- Patterns over a climate gradient from north to south
  - Catchment erosion rates

Properties of study hillslopes



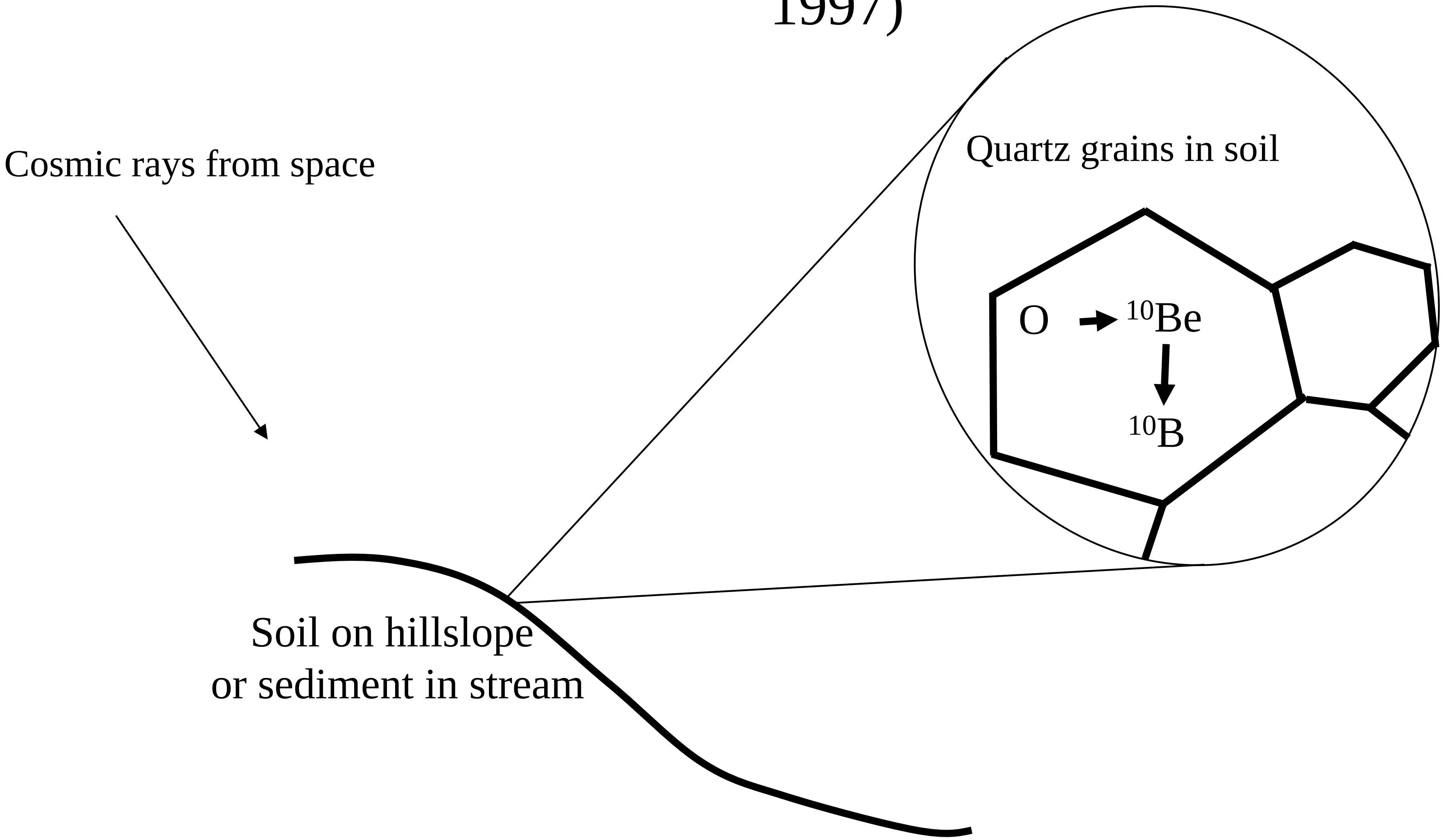
The soils get deeper ~ 40 cm – 250cm

Backslopes have more clay

Questions and analytical framework

- What is the pattern of erosion, soil production and chemical weathering on Kruger granites over the north-south climate gradient?
    - Erosion and soil production rates using cosmogenic isotopes
    - Geochemical mass balance to measure chemical weathering
- What mechanisms or processes account for the pattern?
    - Leaching power and soil fabric

Methods – Measuring erosion and soil production rates with cosmogenic isotopes (Heimsath et al 1997)



- Production rate of ^{10}Be from decay rate (half-life = 1.5 Ma)
- Concentration of ^{10}Be, attenuation length of cosmic rays, altitude, latitude
- Calculate erosion rate in river sediment or soil production rate in soil profile

Methods – Geochemical mass balance (Brimhall et al 1991)

•Fractional net loss or gain of a mobile element (e.g. Silicon) in soil relative to immobile element Zirconium (Zr)

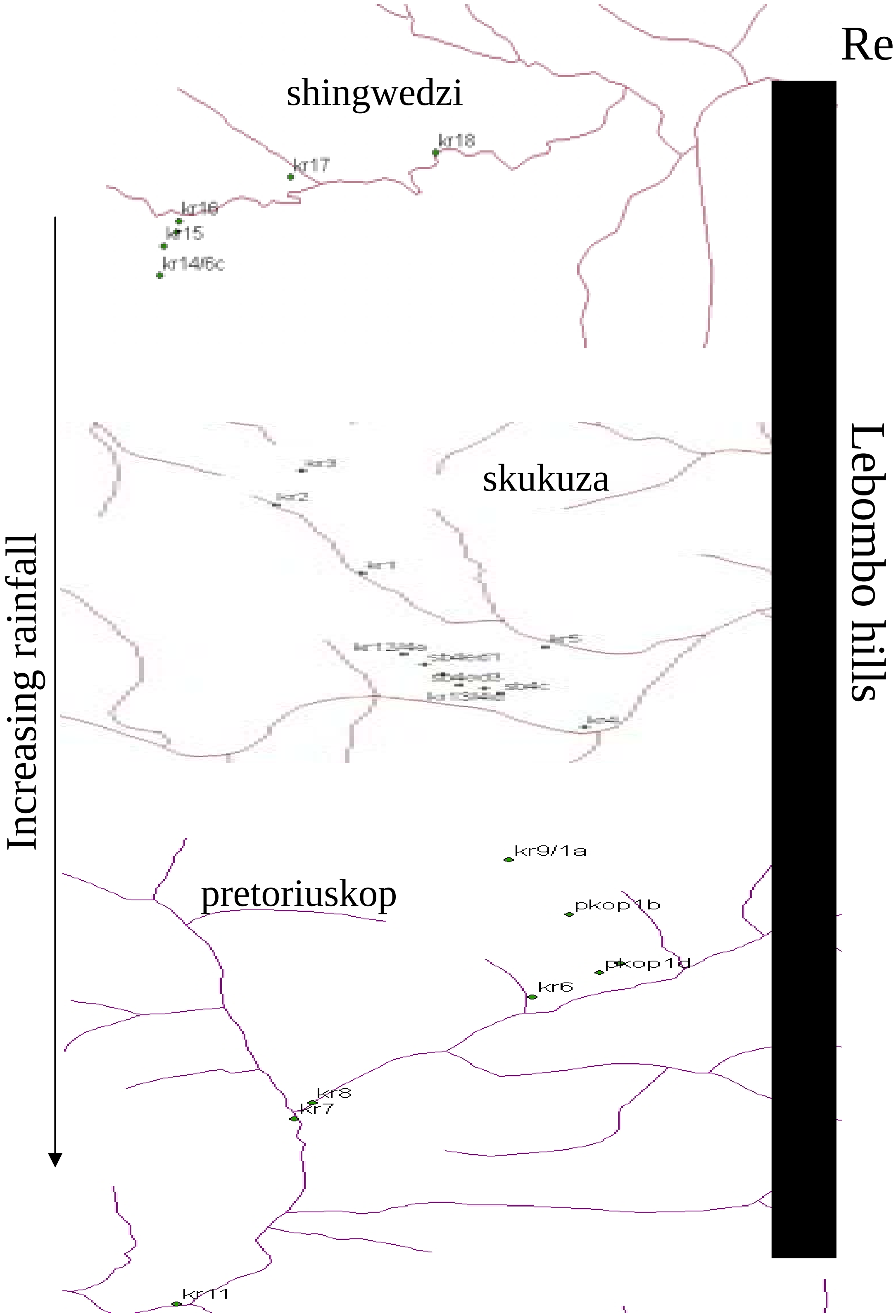
•Standardized by element and Zr concentrations in rock

$$gain/loss_{element,soil} = \left(\frac{Element, soil}{Zr, soil} \div \frac{Element, rock}{Zr, rock} \right) - 1$$

•Also measure Chemical Depletion Fraction (CDF) – average loss/ gain of elements using the conservation of Zr in soil

$$CDF = \left(1 - \frac{[Zr]_{rock}}{[Zr]_{soil}} \right)$$ (Riebe et al 2002)

Results – Range in catchment erosion rates



3.6 – 4.2 mm/ Ka

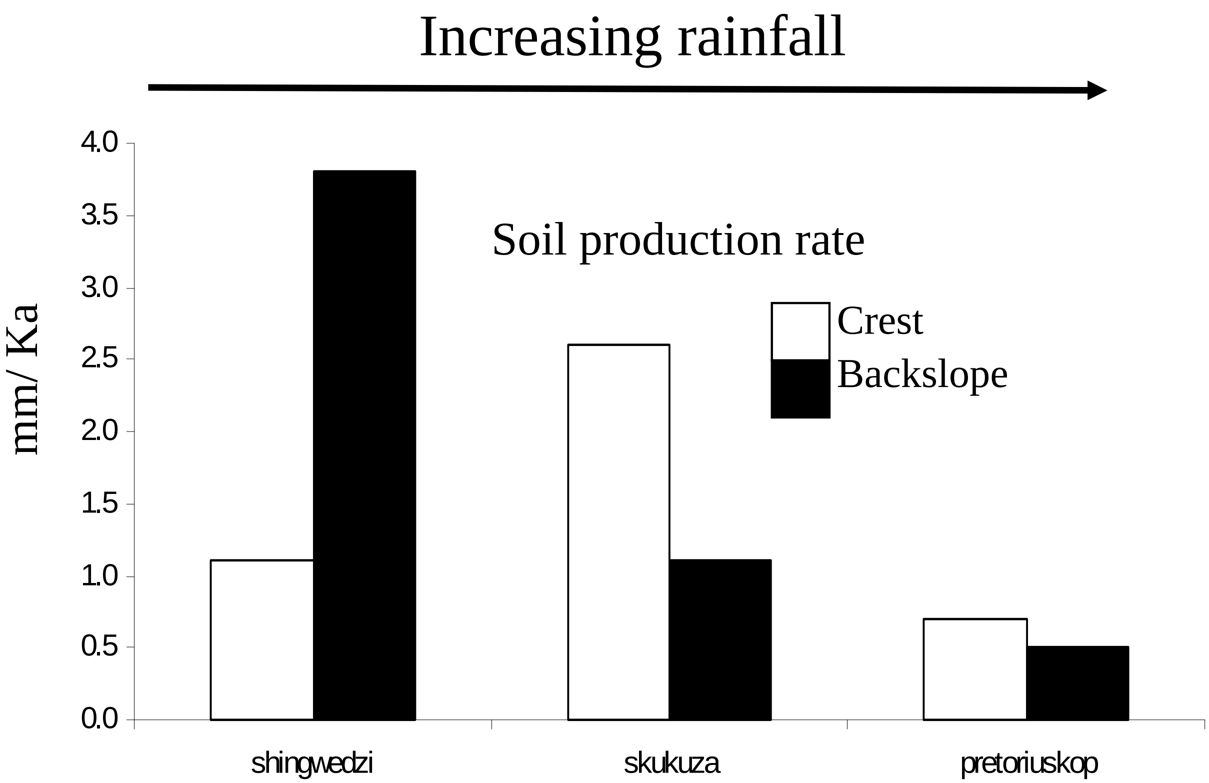
2.0 – 4.9 mm/ Ka

2.4 – 3.3 mm/ Ka

- Very low rates against global values – about 3 mm per 1000 years = 300 000 yrs for a 1m soil
- Catchment erosion rates are uniform across the climate gradient
- Patterns over climate not due to variation in erosion

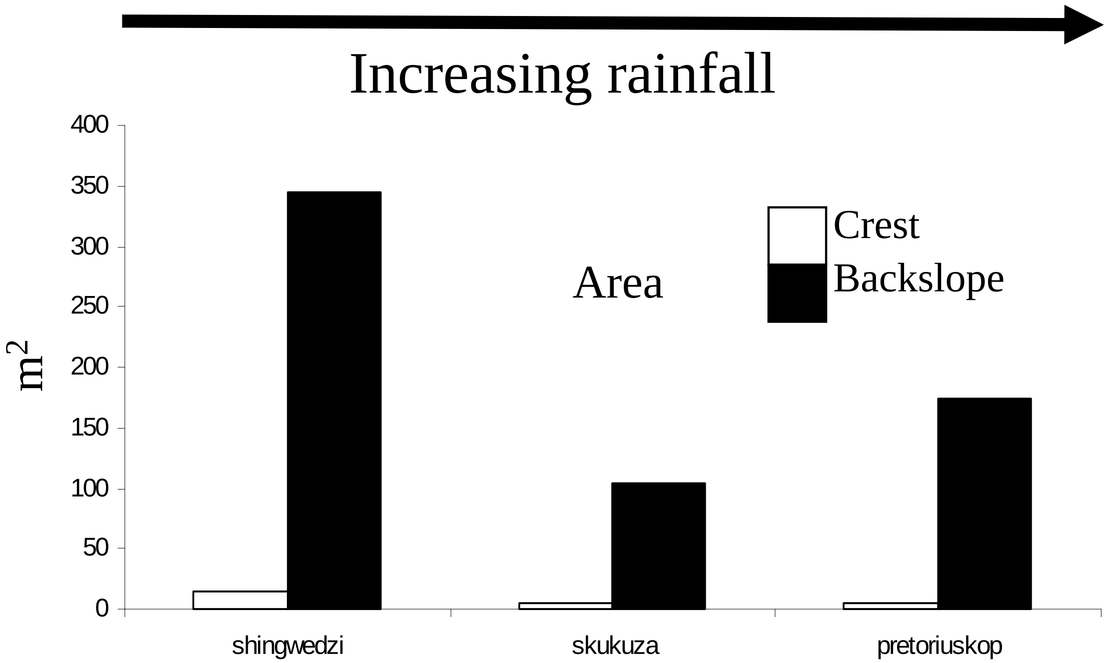
Results – soil production rate

- •Since erosion is constant something else must be leading to the patterns
- •Soil production?
- •Rate at which bedrock is converted into soil

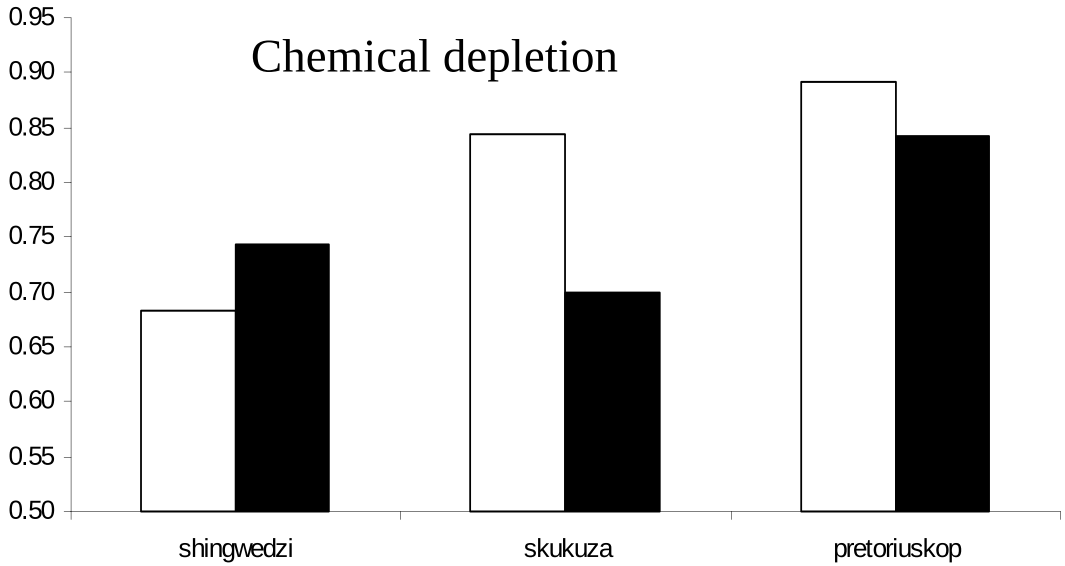


- •Peak in crest soil production at intermediate rainfall
- •Backslope soil production decreases with rainfall
- •Increase in soil production from crest to backslope in dry site
- •Decrease in soil production from crest to backslope on wet sites

Results – chemical depletion – loss of rock elements by leaching



- Contributing area increases from crest to backslope
- More water downslope



- Greater crest depletion with increased rainfall
- Backslope more depleted in dry site, less depleted in wet sites

Results – individual element losses/ gains

Increasing rainfall ↓

Shingwedzi

element	% depletion crest	element	% depletion backslope
Si	-69	[illegible]	[illegible]
Al	-69	[illegible]	[illegible]
Fe	20	[illegible]	[illegible]
Ca	-33	[illegible]	[illegible]
Na	-65	[illegible]	[illegible]
K	-92	[illegible]	[illegible]

Skukuza

element	% depletion crest	element	% depletion backslope
Si	-84	[illegible]	[illegible]
Al	-86	[illegible]	[illegible]
Fe	-81	[illegible]	[illegible]
Ca	-88	[illegible]	[illegible]
Na	-89	[illegible]	[illegible]
K	-87	[illegible]	[illegible]

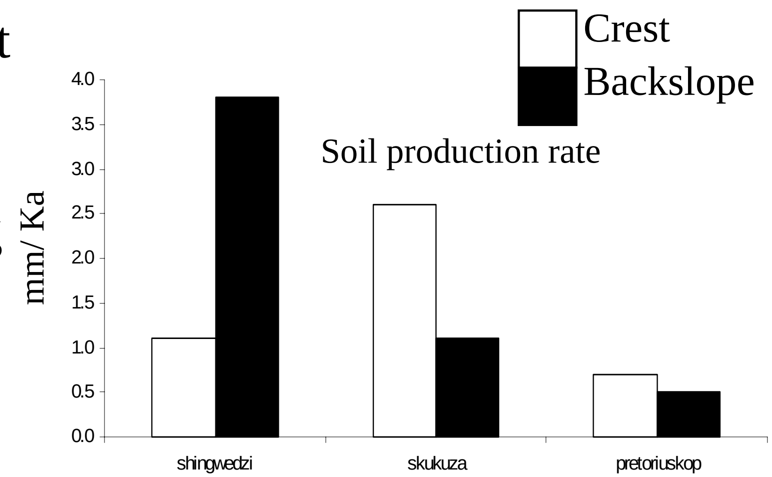
Pretoriuskop

element	% depletion crest	element	% depletion backslope
Si	-88	[illegible]	[illegible]
Al	-93	[illegible]	[illegible]
Fe	-73	[illegible]	[illegible]
Ca	-92	[illegible]	[illegible]
Na	-95	[illegible]	[illegible]
K	-95	[illegible]	[illegible]

- Most elements lost in soil relative to concentrations in rock
- More depletion in dry backslope relative to crest
- Chemical weathering increases with rainfall
- Wet backslopes less depleted than the crests

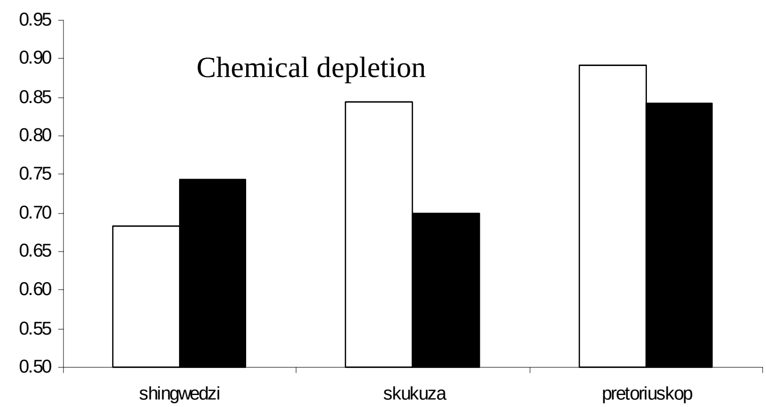
Recap, Problems and Resolution

- Why does crest soil production peak at intermediate rainfall?
  - Intermediate soil depth in Skukuza → (1) deep enough to preempt removal by erosion (2) shallow enough to maintain bioturbation and (3) not too dry to severely limit chemical weathering

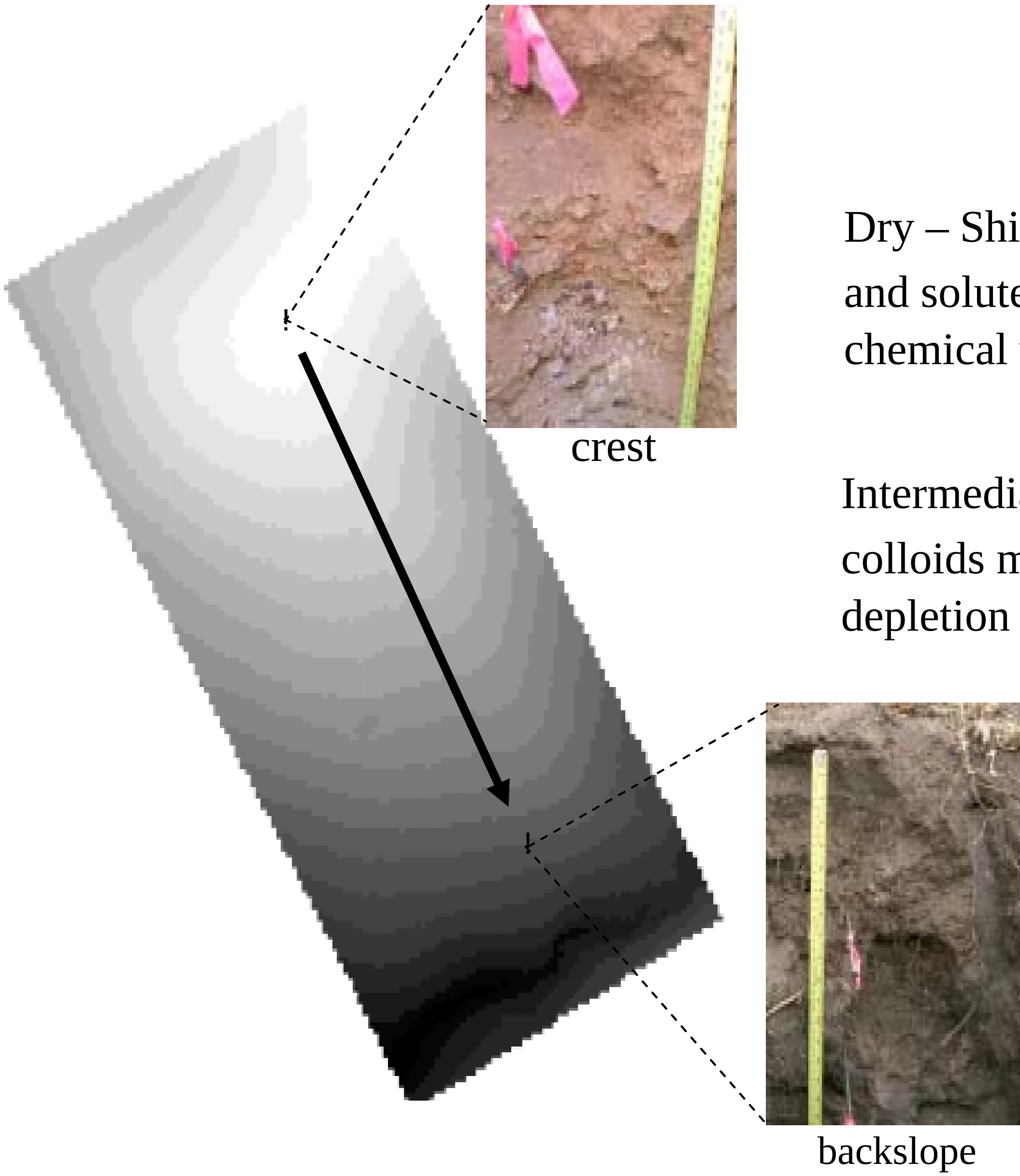


- Why does backslope soil production decrease with increasing rainfall?
  - Increasing leaching power over the hillslopes leads to material addition and backslopes have more clay

- Why does chemical depletion increase from crests to backslopes in Shingwedzi, but decreases in Skukuza-Pretoriuskop?
  - Contributing area
  - Additions



Mechanisms/ processes for soil landscape patterns on hillslopes across climate



Dry – Shingwedzi – not enough water to move colloids and solutes → backslopes have more soil production and chemical weathering

Intermediate rainfall – Skukuza – water with solutes and colloids moves downslope → material added → chemical depletion lower on backslopes

Wet – Pretoriuskop – same process as in Skukuza, but chemical weathering much more → deep soils → less soil production

The soil patterns on Kruger granites are due to:

- Low and uniform erosion across the park ~ 3 mm/ 1000 yrs
- Long residence time > 100 000 yrs
- Water has left a chemical imprint
- The imprint varies with position on hillslope and climate

The End

What does it all mean?

- Different processes lead to textural contrast on backslopes
    - Contributing area in Shingwedzi
    - Material translocation in Skukuza-Pretoriuskop
- Threshold in soil production in Skukuza

Mechanism – Soil profile scale

Crest

Footslope

Clay trap

Clay traps quartz grains from which we measure the erosion for much longer → longer residence of the quartz and lower soil production rates

Current understanding

Geochemical Mass Balance

(Brimhall et al., 1991, Science)

Parent Material
=
Weatherable
+
Non-weatherable
(eg., zircon)

[Zr]=100 ppm

Weathering
(dissolution & leaching)

Half of mass is lost.
But!
No Zr is lost

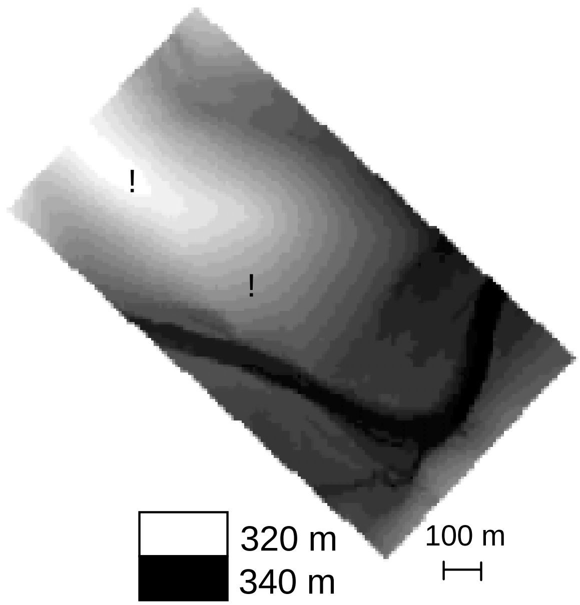
Soil Formed

[Zr]=200 ppm

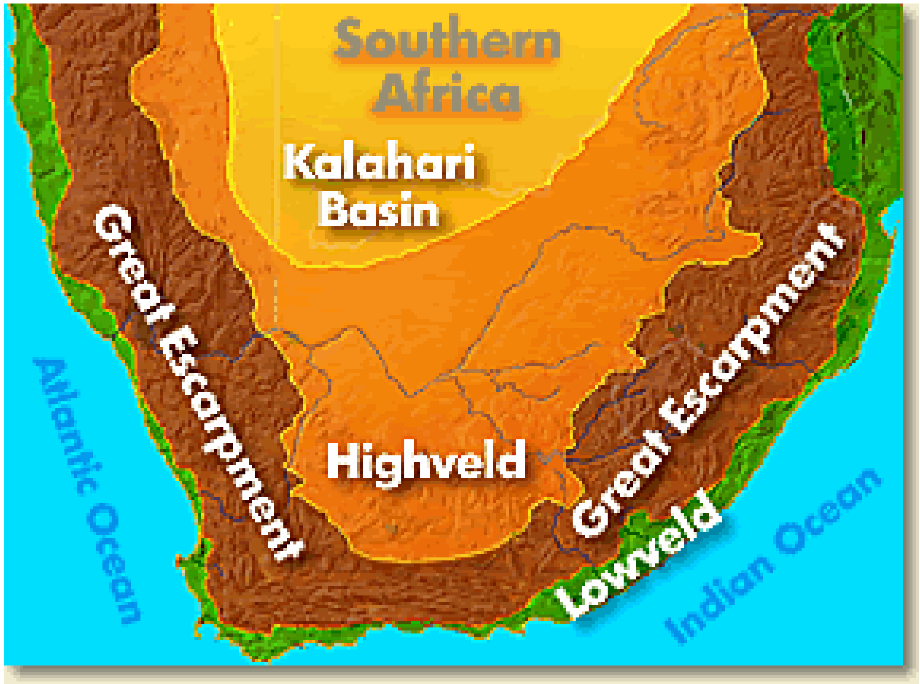
Zr enrichment

The amount of mass loss : (mass per area)

$$\Delta = \left(\frac{[Zr]_{soil}}{[Zr]_{parent\ material}} - 1\right) \times Mass\ of\ soil$$



!
!
320 m
340 m
100 m


Southern Africa
Kalahari Basin
Great Escarpment
Highveld
Great Escarpment
Lowveld
Atlantic Ocean
Indian Ocean

Caveat emptor