Cosmogenic nuclide-based perspectives on long-term landscape evolution models and short-term soil erosion rates in southern Africa

J.E. Decker¹*, S. Niedermann², M.J. de Wit³

1. AEON and Department of Geological Sciences, University of Cape Town, Rondebosch 7700, South Africa, geojedenator@gmail.com
2. Deutsches GeoForschungsZentrum, 14473 Potsdam, Germany, nied@gfz-potsdam.de
3. AEON and Department of Geological Sciences, University of Cape Town, Rondebosch 7700, South Africa, Maarten.DeWit@uct.ac.za

*Present address: Petroleum Agency SA, 7 Mispel Road, Tygerpoort Building, Bellville 7789, South Africa, deckerj@petroleumagencylsa.com

7TH Inkaba yeAfrika Workshop
November 2010
Southern Africa’s anomalous topography

A high plateau (elevation > 1,000 m) bound by escarpments and extensional continental margins.

*Elevation and bathymetry: ETOPO2*
Traditional models of landscape evolution

- Rely on King’s (1953) theory of pediplanation.
- Cyclic landscape evolution through backwearing (scarp retreat), following isostatic uplift after a threshold amount of denudation.
- Implies theoretical erosion surfaces (pediplains).
- Local relative ages inferred from varying elevation.
- Approximate stratigraphic ages of surfaces generally inferred from lithostratigraphic correlation of exposed weathering profiles with buried unconformities.

[Diagram showing cyclic landscape evolution with time markers A, B, C, D, illustrating initial and terminal ages.]
Example: Erosion surface map of Partridge and Maud (1987)

"Ar/Ar weathering age = 12-15 Ma (van Niekerk et al., 1999)

Digitised: C. Mielke
Constraints from denudation thermochronology:

**Higher** denudation rates in the **Mesozoic**

1) Cretaceous, late Jurassic and early Tertiary

- 130 - 36 Ma: 40 m/Myr (Cockburn et al., 2000)
- 115 - 90 Ma: <40 m/Myr (Kounov et al., 2009)
- 152 - 113 Ma: 41 - 82 m/Myr (Rust and Summerfield, 1990)
- 120 - 85 Ma: 15 m/Myr (Hanson et al., 2009)
- 91 - 69 Ma: 95 ± 43 m/Myr (Brown et al., 2002)
- 100 - 80 Ma: 125 -175 m/Myr (Tinker et al., 2008a)
Constraints from denudation thermochronology:

**Lower** denudation rates in the **Cenozoic**

2) Cenozoic and late Cretaceous

36 - 0 Ma:
5 m/Myr
(Cockburn *et al.*, 2000)

37 - 0 Ma:
7 - 9 m/Myr
(Rust and Summerfield, 1990)

65 - 0 Ma:
11-14 m/Myr
(Flowers and Schoene, in press)

85 - 0 Ma:
10 m/Myr
(Hanson *et al.*, 2009)

87 - 0 Ma:
3.4 m/Myr
(Partridge and Maud, 1987; and references therein)

80 - 0 Ma:
10 - 15 m/Myr
(Tinker *et al.*, 2008a)

78 - 0 Ma:
15 - 28 m/Myr
(Brown *et al.*, 2002)
Cosmogenic nuclides

• Form through the interaction between cosmic ray particles and target nuclei.

• Terrestrial cosmogenic nuclides are produced *in situ* in rocks at Earth’s surface.

• Production rates attenuate (approximately) exponentially with depth (e.g. production at 0.5 m depth is approximately 37 % that at the surface for a horizontal dolerite surface).
Cosmogenic nuclides

- Cosmogenic nuclide abundances thus provide quantitative constraints on the surface exposure history of a rock, on a timescale of $10^3$-$10^6$ yr.

But, there are TWO UNKNOWNS - Surface erosion rate & Surface exposure age

- Therefore, the nuclide abundance may be interpreted either as a **minimum exposure age**, $T$ (assuming instant exposure and zero subsequent erosion) or a **maximum erosion rate**, $\varepsilon$ (assuming a constant rate of erosion over an infinite period of exposure).
Previous cosmogenic nuclide study areas in southern Africa:
This study: the cosmogenic noble gases ($^{3}\text{He}$, $^{21}\text{Ne}$ & $^{38}\text{Ar}$)

- Stable nuclides (useful for long exposure histories).

- Analysed pyroxenes from dolerites of the Karoo Large Igneous Province (183 Ma). Reasons:
  - Pyroxene retains noble gases;
  - Karoo dolerites found across southern Africa;
  - Dolerites are topographically significant.

- Noble gas nuclide production rates depend on pyroxene mineral chemistry, as well as sample site altitude and latitude.
Distribution of Karoo dolerites

Karoo dolerite

National boundaries

SRTM Elevation (m)
- 0 - 200
- 201 - 400
- 401 - 600
- 601 - 800
- 801 - 1,000
- 1,001 - 1,200
- 1,201 - 1,400
- 1,401 - 1,600
- 1,601 - 1,800
- 1,801 - 2,000
- 2,001 - 2,200
- 2,201 - 2,400
- 2,401 - 2,600
- 2,601 - 2,800
- 2,801 - 3,000
- 3,001 - 3,200
- 3,201 - 3,400
- 3,401 - 3,473
Sampling sites

- Sample sites (n = 22)
- Karoo dolerite
- National boundaries

SRTM Elevation (m)
- 0 - 200
- 201 - 400
- 401 - 600
- 601 - 800
- 801 - 1,000
- 1,001 - 1,200
- 1,201 - 1,400
- 1,401 - 1,600
- 1,601 - 1,800
- 1,801 - 2,000
- 2,001 - 2,200
- 2,201 - 2,400
- 2,401 - 2,600
- 2,601 - 2,800
- 2,801 - 3,000
- 3,001 - 3,200
- 3,201 - 3,400
- 3,401 - 3,473

Kilometers
**Results:** Maximum erosion rates ~0.5 - 4 m/Myr for 19 of the 22 samples

Example: *Koppie* near Gariep Dam (1494 m)

- $2.33 \pm 0.17$ m/Myr
- $1.82 \pm 0.10$ m/Myr
- $0.929 \pm 0.057$ m/Myr

$^{3}$He maximum erosion rate $\varepsilon$, Dunai (2000) scaling

(Minimum exposure age $T = 219 \pm 13$ ka; $248 \pm 18$ ka; $315 \pm 17$ ka)
Another example:
Cliff overlooking incised meanders of the Pongola River valley, 1632 m.

$0.530 \pm 0.056 \text{ m/Myr}$

$^{21}\text{Ne}\ \epsilon$, Dunai (2000) scaling
$(T = 348 \pm 41 \text{ ka})$
1632 m south of Colesberg

1121 m east of Beaufort West

1187 m north of Graaf-Reinet

3 exceptions where there is field evidence of active exfoliation (minimum exposure age more appropriate)

20.3 +5.6/-5.2 ka

33 +16/-12 ka

67 +17/-14 ka

$^{3}$He minimum exposure age $T$, Dunai (2000) scaling

(Maximum erosion rate $\varepsilon = 18.9 +4.8/-5.2$ m/Myr; 6.2 +2.3/-3.0 m/Myr; 8.0 +1.6/-2.1 m/Myr)
Landscape evolution models from a cosmogenic nuclide perspective

- Rates are too slow to have created the present landscape over a geologically reasonable period of time.

- This implies a significant decrease in denudation rates over time (consistent with the thermochronology record).

- However, even recent denudation rates are high enough to destroy theoretical “pediplains”, making their continued existence and successful recognition today unlikely.
Comparison with model chemical weathering rates ($f_w$), based on Dessert et al.’s climate dependent basaltic rock weathering model:

Values in the same ballpark!

However:

Lower measured values than model values in more humid east, and higher values than model in more arid west

Clues to Pleistocene palaeoclimate?
Take home message so far:

- Consistently low maximum erosion rates for most samples (< 4 m/Myr), and similarity with model basalt weathering rates, strongly suggests that Karoo dolerite maximum erosion rates may be interpreted as approximating dolerite weathering rates at these sites.
Further support from the Holocene sedimentary record:

- Low maximum erosion rates are also similar to Holocene denudation rates determined stratigraphically for the Orange River catchment (~3-4 m/Myr; calculated after Compton *et al.*, 2010), suggesting that:
  - Denudation in southern Africa has been weathering limited over this time period (weathering is the rate determining step).
  - Karoo dolerite *weathering* rates are probably similar to those of the Karoo sedimentary country rocks in the same catchment.

- This means that dolerite maximum erosion rates < 4m/Myr = dolerite weathering rates = soil production rates from dolerites

- Dolerite areas are also known to yield the most productive soils in the Karoo.
Comparisons between Karoo dolerite weathering rates (soil production rates) with various 20th Century soil erosion rate estimates at the same sites:
Variations in sculpturing rates:

**Today:** 1-3 m/Myr

(1mm per millennium)

**Last 60 Million Years:** 10-15 m/Myr

1mm per century?

100-80 Million years ago: 50-175 m/Myr

Anthropocene denudation rates (> 50 m/Myr)

05-2 mm per decade
Conclusions

• Rates of soil loss are higher than rates of soil production at all sites, by up to 2 orders of magnitude.

• Different rates measured on different timescales, but suggests that the present land use practices are unsustainable under the prevailing climatic and tectonic regime.

• Anthropocene denudation rates (> 50 m/Myr) are unknown from the region since the Cretaceous.

• Modern agri-business mimics the Kalahari epeirogeny’s impact on southern Africa’s landscape?
Thank you