LATE PLEISTOCENE BEDROCK CHANNEL INCISION OF THE SUSQUEHANNA RIVER, HOLTWOOD GORGE, PENNSYLVANIA

A Masters Thesis Presented
by
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to
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of
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Presentation Outline

• Problem statement and background
• Dating river incision with $^{10}\text{Be}$
• Holtwood Gorge field area
• Timing and style of bedrock channel incision
• Potential drivers of incision
• Conclusions
• Future avenues of research
Cosmic ray bombardment \textit{in situ}

Quartz

5.2 atoms/g/yr

$^{26}$Al, $^{21}$Ne, $^3$He

$^{10}$Be, $^{14}$C, $^3$He
Model Age ~ Terrace Abandonment

High $^{10}\text{Be}$ Concentration
Older Model Age

Lower $^{10}\text{Be}$ Concentration
Younger Model Age
Significance of Research

• River incision through bedrock has important implications for landscape development.

• Recent efforts to directly measure or model rates of incision with numerical simulations may not capture the timing and/or nature of dominant erosional processes.

• Very little is known about how, when, or why passive margin rivers incise through bedrock.

• Age control is mandatory to decipher how passive margin rivers respond to glaciation, climate, land-level, and/or sea-level.
Goals of The Project:

• Estimate the age of bare-rock strath terraces within Holtwood Gorge.
• Investigate the spatial patterning of erosion.
• Determine the timing and rate of incision within the gorge.
• Consider potential drivers of incision.
• Refine this new application of cosmogenic dating.
Long-Profile of the Susquehanna

Oversteepening:
Flexural response to Offshore sediment loading
And Isostatic response to denudation

Holtwood Gorge

~0.5 m/km

~1.0 m/km
Holtwood Gorge Field Area

• Located approximately 50 km upstream from Chesapeake Bay and immediately below Holtwood Dam.

• Carved into the Wissahickon Schist of the Appalachian Piedmont.

• Harbors three distinct levels of bedrock terraces.

• Accessible by canoe.

• Abundant extractable quartz.
Bedrock Terrace Levels

Level 1: Strath

Level 2: Terrace

Level 3: Terrace

Level 4: Heavily Weathered High Point

KEY
- Incised Modern Strath
- Eroded High Points

80 Bedrock Samples
3 Well Preserved Terraces
Heavily Weathered High Points
Bedrock Terrace Levels
Nested Sampling Strategy

A

KEY
- Lowest strath incised by modern river
- Heavily weathered and eroded high points

1 2 Intermediate 3 4 Terrace Level

B

Schematic Example of a Nested Sampling Strategy

small-scale cross-sections longitudinal

13 23 22 16 2 Total Number of Samples Collected
Lab Work and Nuclide Measurement
(From Piles of Rocks to Piles of Numbers)

• Quartz Purification

• Chemical Isolation of $^{10}$Be (Jen’s Magic)

• Accelerator Mass Measurement at Lawrence Livermore National Laboratory
Spatial Patterning of Erosion in Holtwood Gorge
Does the Livermore Accelerator really work??

Laboratory and Measurement Replication

LR-04c  14.0 +/- 1.5 ka
LR-04cX  14.2 +/- 1.6 ka
 +/- 1.0 %

LR-37  17.4 +/- 1.9 ka
LR-37X  17.9 +/- 1.9 ka
 +/- 1.9 %
Does One Sample Represent the Age Of An Entire Bedrock Surface??

Level 3 small-scale variance

26.8 +/- 2.9 ka
25.0 +/- 2.7 ka
26.0 +/- 2.8 ka

+/- 3.8%
(geomorphically Identical)
Level 2 small-scale variance

17.5 ± 1.9 ka

18.6 ± 2.0 ka

18.2 ± 2.0 ka

+/- 3.3%
(geomorphically Identical)
Level 1 small-scale variance
(lowest bedrock terrace)

14.1 +/- 1.6 ka

16.4 +/- 1.8 ka

13.9 +/- 1.5 ka

+/- 8.5%
(Much more variable than surfaces higher in the gorge)
Terrace Level 3: Longitudinal Incision Rate

Highest, Well Preserved Strath Terrace

Inferred River Gradient = 2.0 m/km
$R^2 = 0.9$

No Relationship Between Distance and Model Age

14 Samples Over 4.5 km
Terrace Level 2: Longitudinal Incision Rate

Mid Level

Significant Age Gradient: 1.4 ky/km upstream

Older Ages Downstream
Knickpoint Retreat?

Inferred River Gradient = 1.5 m/km
R² = 0.9

20 Samples Over ~5 km
Terrace Level 1:

- Longitudinal Incision Rate
- Lowest Level
- Modern Strath
- 10 Samples
- Over ~2.5 km

Inferred River Gradient
- ~1.5 m/km
- $R^2 = 0.9$

No Relationship Between Distance And Model Age

10 Samples Over ~2.5 km
Timing and rate of bedrock incision within Holtwood Gorge
How Old Are The Holtwood Terraces??

Average Terrace Ages

- Lower Limiting Ages
  - Mean Age = 36 ± 7 ka
- Mean Age = 20 ± 3 ka
- Mean Age = 14 ± 1 ka
- Mean Age = 14 ± 1 ka

Height Above Riverbed (m)
When and How Quickly Did The Susquehanna River Incise??

- Incision Ceased ~14 Level 1 Mean Age
- Increase at ~20 ka Level 2 Abandonment
- Acceleration at ~35 ka Level 3 Abandonment
- Maximum Rate Since ~100 ka

Incision Rate (m/ka)

Model Age (ka)
Are Rates of Downcutting At Specific Locations Similar to Gorge Wide Averages?

Middle Gorge Cross-Section

- Incision Rate = 0.52 m/ka
- $R^2 = 0.72$

Model Age (ka)

Height above river bed (m)
Are Rates of Downcutting At Specific Locations Similar to Gorge Wide Averages?

Upper Gorge Cross-Section

- **Model Age (ka)**
- **n=13**
- **Incision Rate = 0.60 m/ka**
- **$R^2=0.96$**

- Green diamond = Upper Gorge
- Red circle = Middle Gorge

- Height above river bed (m)
- Model Age (ka)
Long- vs. Short-Term Rates of Incision along the Susquehanna River

Episodic Incision

Long-Term Rate
~12 m/My

Late Pleistocene Rate
20 X - 60 X Faster

Piedmont

GORGE
Rates in active regions measured with cosmogenic isotopes:
(Indus River, Himalayas)

1 to 12 m/ka
Driven primarily by uplift
An alternative approach to considering the timing of terrace abandonment:
(Probability Modeling: Balco et al., 2002)
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- **Level 1**: Mean = 14.4 ka, Peak = ~14 ka
- **Level 2**: Mean = 19.8 ka, Peak = ~18 ka
- **Level 3**: Mean = 36.1 ka, Peaks at 26, 32 and 45 ka

Rapid Incision From ~50 ka to ~10 ka
Potential Drivers of Rapid Late Pleistocene Incision
Similar Incision Histories

**Holtwood Gorge**

**Mather Gorge**

**Thousands of Years Before Present**

- **Rapid Incision From** ~50 to 10 ka
  - **At** 0.4 to 0.6 m/ka

- **Rapid Incision From** 37 to 13 ka
  - **At** 0.5 to 0.8 m/ka
What Caused this Pulse of Late Pleistocene Incision?

- Glaciated Susquehanna Basin
- Unglaciated Potomac Basin
  - Similar Timing
  - Similar Rate

- Regional Forcings:
  - Land-Level
  - Base-Level
  - Global and Regional Climate
Land Level Change…
(The Growing Glacial Forebulge)

Crustal Response to mantle displacement by advancing ice load

Timing and extent uncertain
Where was the ice front?
Probably didn’t initiate Incision, But likely helped maintain it

Increased River Gradients
Thousands of Years Before Present

Base Level Change...
(Global Sea-Level Through The Last Glacial Cycle)

Timing of Sea-Level Fall Uncertainties

Exposure Age Modeling Uncertainties

Rate and Process of Upstream Translation Through Bedrock Not Know
Thousands of Years Before Present

Base Level Change...
(Global Sea-Level Through The Last Glacial Cycle)

Paleo-Shorelines

Holtwood Gorge

~70 mbp
At 50 ka

~150 mbp
At ~20 ka

Continental shelf edge

Upstream effect uncertain

Mean Global Sea-Level
(Huon Peninsula)

Meters Below Present
Global Climate Change…
(GISP2 ice core records)

**Terrace formation and rate increase coincident with glacial Max in PA**

- **Holtwood Gorge:**
  - Rapid Incision From
  - ~50 ka to ~10 ka

- **Mather Gorge:**
  - Rapid Incision From
  - ~37 ka to ~13 ka

**Paleostorminess**
Storminess in Northeast Through Holocene
(Noren et al., 2003)

**Paleotemperature**
Temperature trends correlate To Florida (Grimm et al.), And Blue Ridge (Litwin et al., 2004)

- **Susquehanna River**
- **Potomac River**
What Do Temperature and Storminess Have to do with Bedrock Incision??

Floods

Incision Threshold...Critical Shear Stress

Frozen Ground...More Runoff??

Discharge Concentration:
  • Snow Melt Floods
  • Rain on Snow Events
  • Stormier Climate

Hurricane Isabel
October, 2003
Conclusions

Bedrock strath terraces record a pulse of rapid incision.

Downcutting increased between ~50 and ~35 ka; incision ceased near the Pleistocene/Holocene transition.

Influence of glacial retreat on Susquehanna River; but regional first order drivers for the initiation of incision on both rivers.

Correlation to GISP2 climate proxy records.
Implications and Future Research

$^{10}\text{Be}$ dating is a useful tool for investigating the tempo and style of bedrock channel incision around the globe.

The episode of incision measured in Holtwood Gorge represents one pulse in an ongoing period of river adjustment operating over geologic time scales.

This study just scratches the surface:

- Similar approach on other major Appalachian drainages
- Tributary response to changing boundary conditions and landscape connectivity
- Many questions regarding climate driven process rates still remain
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Hecras Modeling:

= Left and Right overbank locations
6 = Cross-Section Number
Hecras Modeling:

HECRAS Modeling of Holtwood Gorge

A

B

C
Hecras Modeling:

Modeled
Level 1 Samples

HEC-RAS Age Adjustments
- Original Data
- Adjusted Data

<10% average adjustment for water shielding
Hecras Modeling:

Modeling explains ~32% of the model Age variance between Level 1 samples.
Cosmic ray bombardment in situ

- Si
- O
- Ca, K, Cl
- $^{26}\text{Al}$, $^{21}\text{Ne}$, $^{3}\text{He}$
- $^{10}\text{Be}$, $^{14}\text{C}$, $^{3}\text{He}$
- $^{36}\text{Cl}$, $^{3}\text{He}$
Inferred Paleo River Gradients

Level 1 Gradient = 1.5 m/km

Level 2 Gradient = 1.5 m/km

Level 3 Gradient = 2.0 m/km
Residual Analysis:

Level 3 Residual Analysis

A: All Level 3 Samples

Residuals (m)

R² = 0.21

B: Upper Gorge Samples

Residuals (m)

R² = 0.71

C: Middle Gorge Samples

Residuals (m)

R² = 0.17
Boulders:

Surface: ~15 ka

Boulder: ~24 ka
Boulders:

- Late Pleistocene origin
- Ages may incorporate prior Periods of burial and exposure
- Two boulders alone don’t tell us much.
- Flood origin??
Title