The Role of Aeolian Sediment Transport in the Preservation of Archaeological Sites, Grand Canyon: Developing Criteria for Evaluating Effects of Dam Operations

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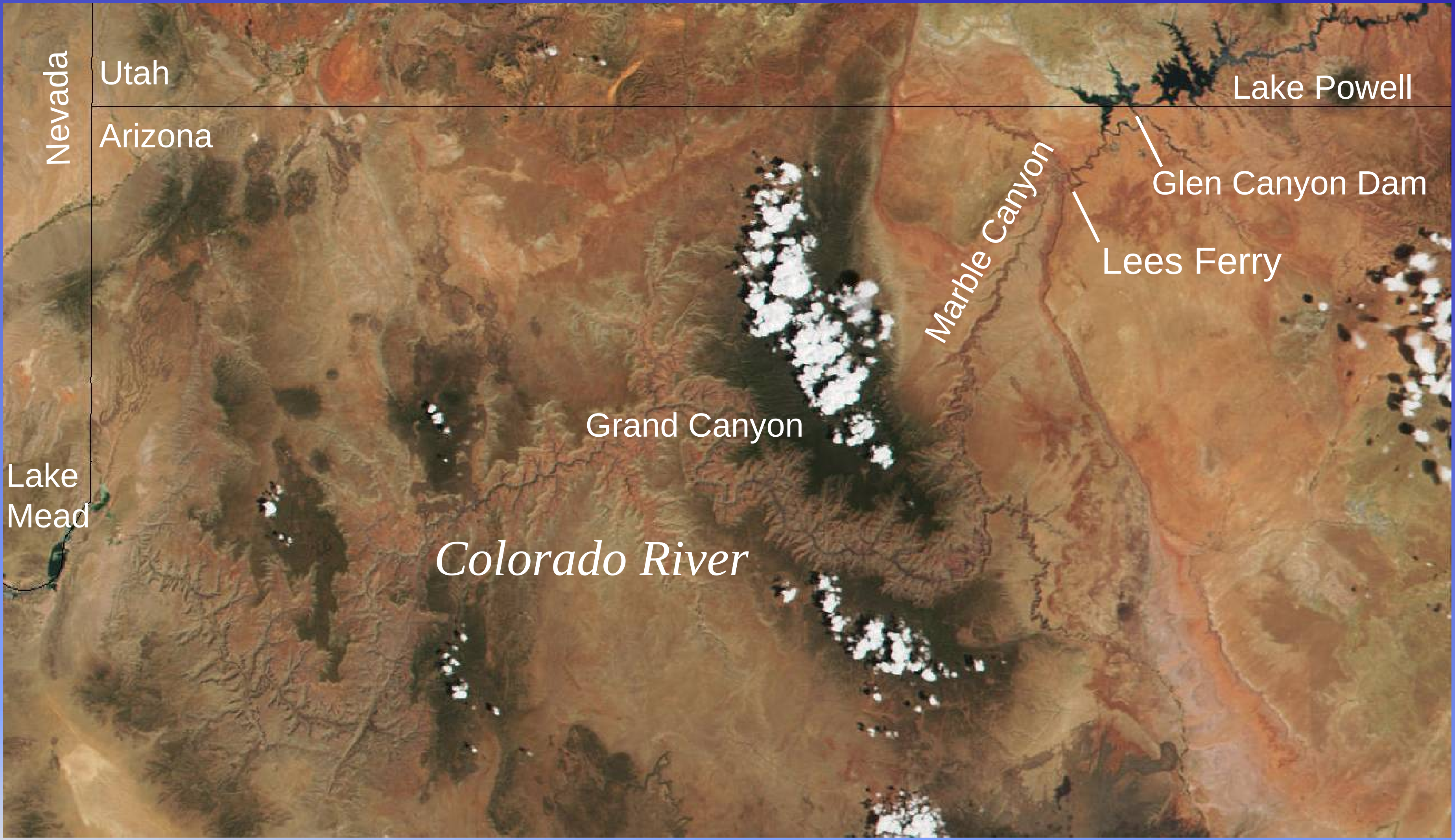
Outline

- Background… Aeolian sediment and archaeological-site preservation
- Instrument stations
- Criteria for evaluating limits of dam effects
- Three case studies

Grand Canyon area



Loss of river-level sand bar area and volume compared with pre-dam conditions

1952, photo by Kent Frost

1995, photo by USGS

Archaeological site erosion/ preservation

- Archaeological sites built on fluvial, aeolian, slope-wash deposits; many preserved by subsequent aeolian deposition
- Accelerated erosion of cultural features believed tied to reduced sediment sources (loss of open sand bar area → less sand supply for aeolian deposits → deflation/erosion by wind)

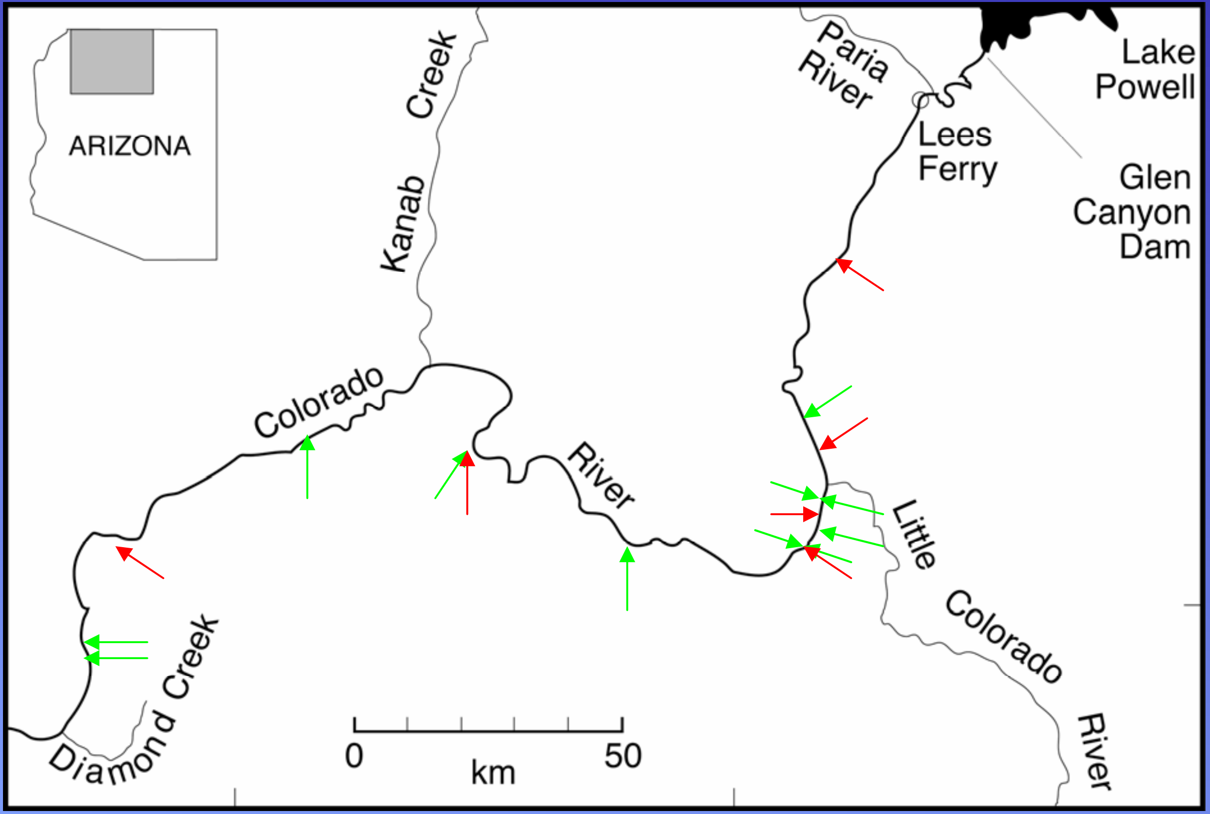
River-level sand bar

Sand dunes above river

Gully undercutting roasting feature

Potsherds exposed by wind deflation

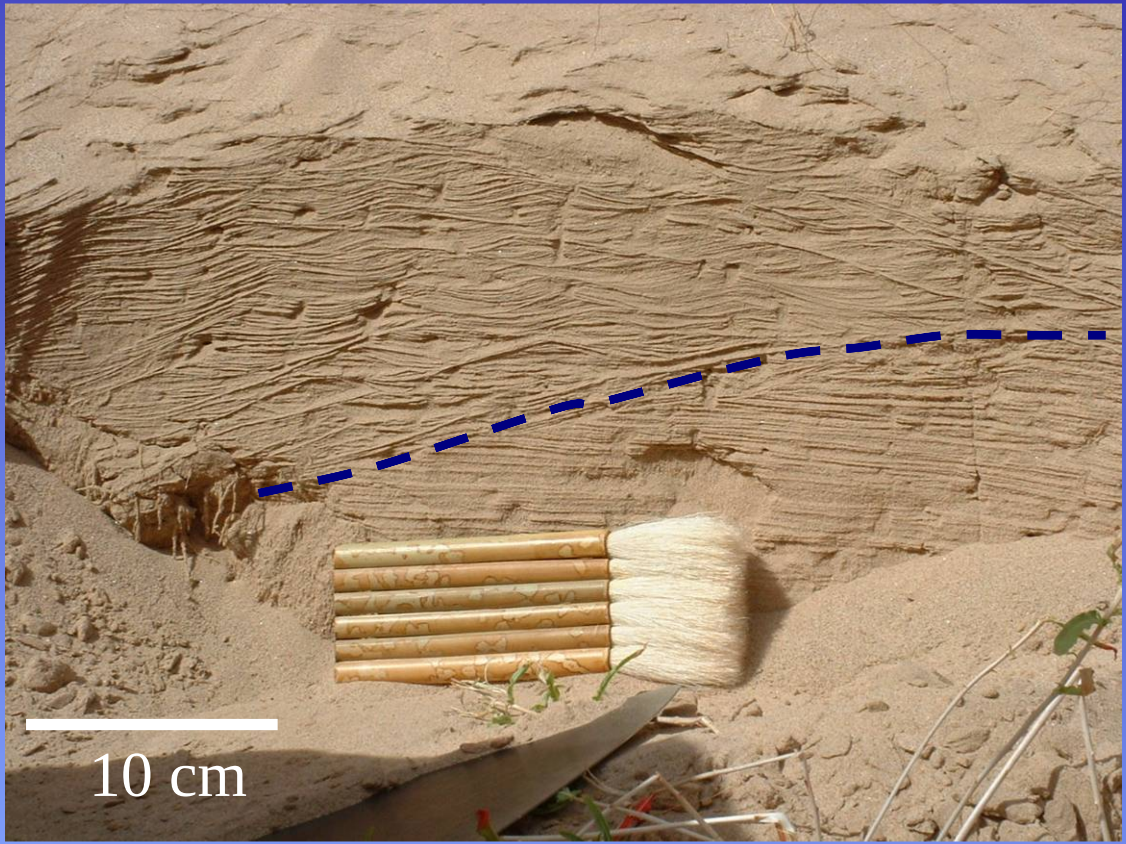
Studying aeolian sediment in the river corridor



Instrument station (anemometers, rain gages, sand traps)

Stratigraphic analysis

Stratigraphic interpretation

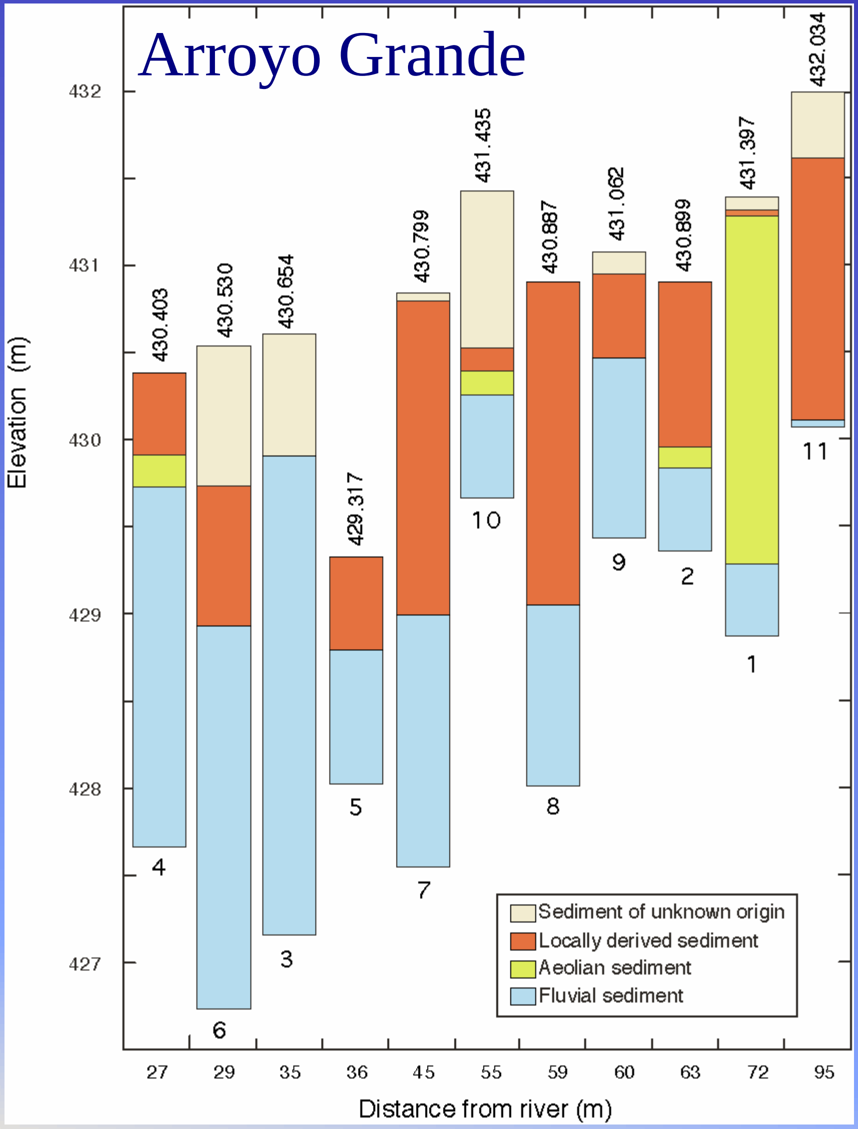


Fluvial

Aeolian

Sedimentary structures help identify depositional environments

Pre-dam depositional environments



- Thick Holocene fluvial terraces form substrate for many arch. sites
- Aeolian reworking of sediment on terrace surfaces
- Locally derived (slope-wash, debris-flow) sediment

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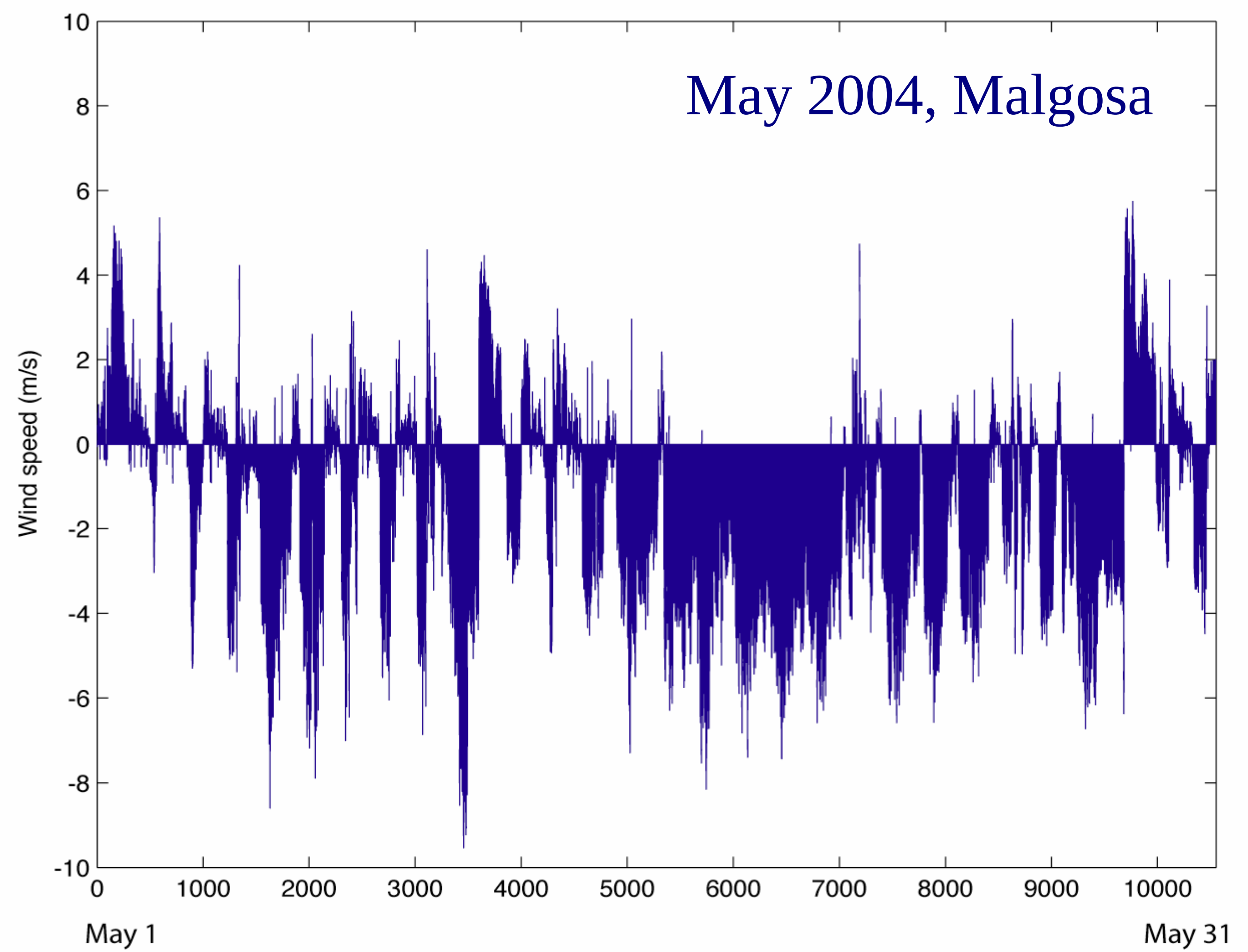
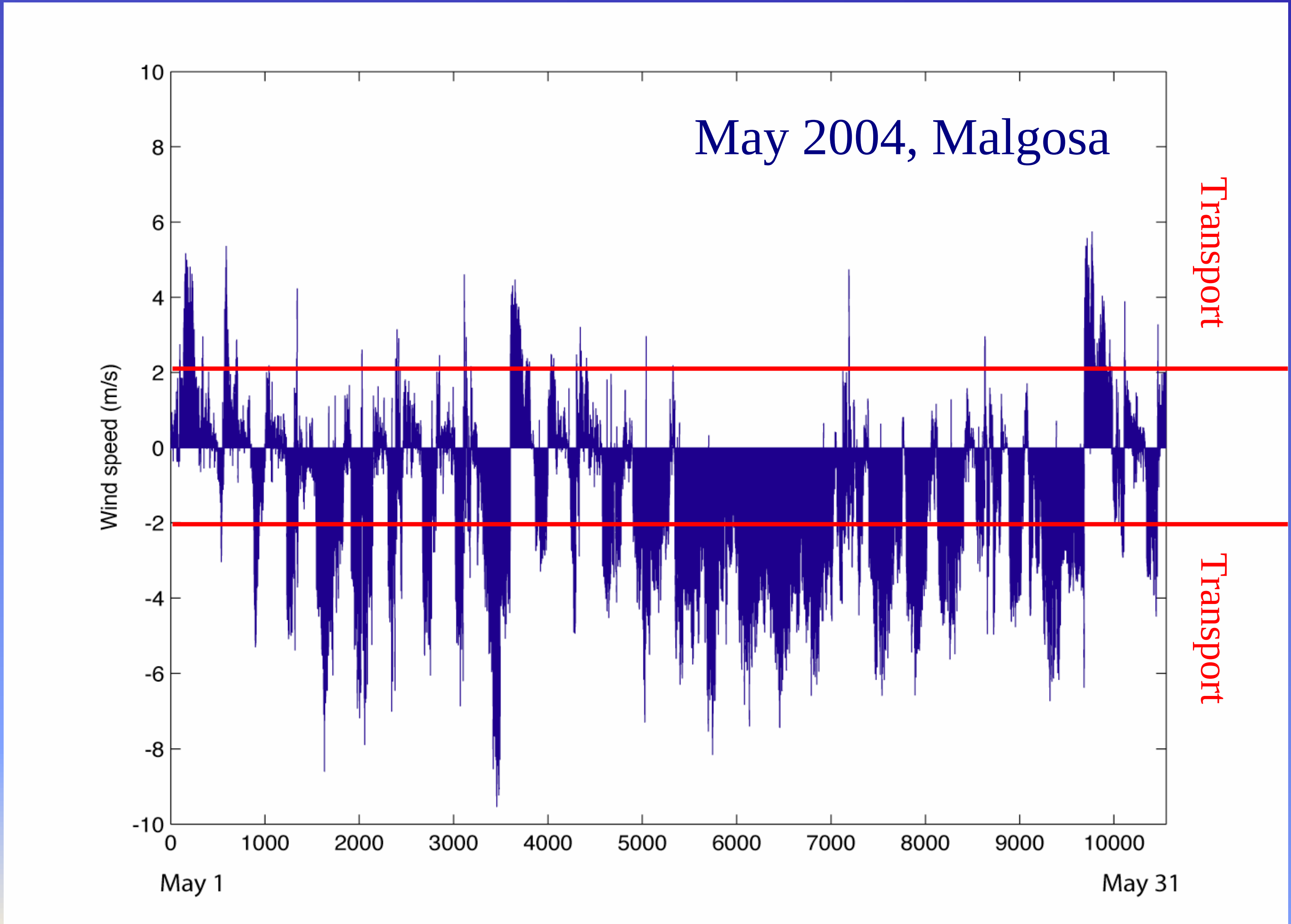
Measuring modern aeolian sediment transport

- Anemometers → wind speed and direction
- Sand traps → integrate total transport 0-1 m from the bed
- Rain gages → identify events causing gully incision / determine when sand too wet to transport

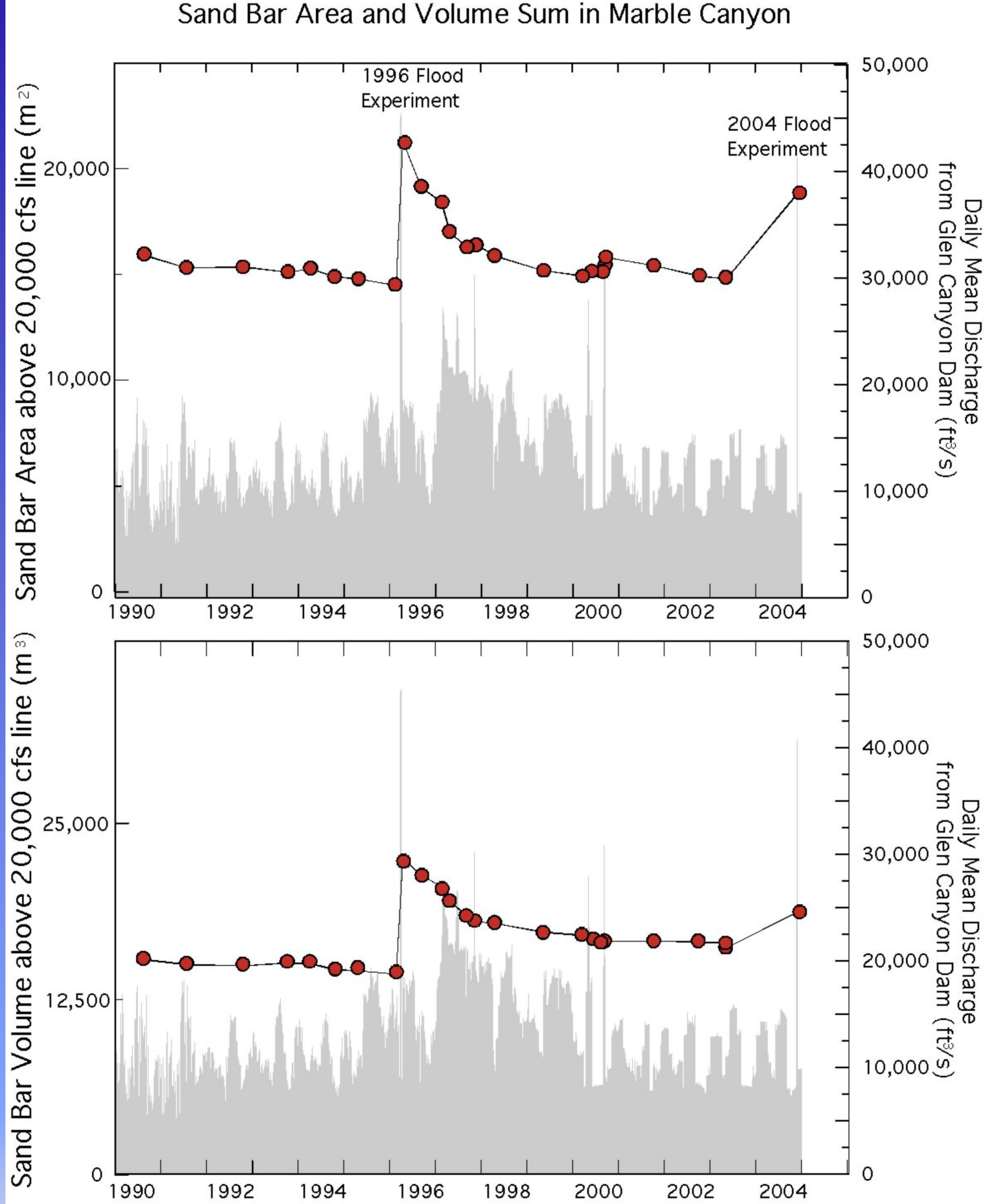
Wind patterns vary diurnally and seasonally



Wind patterns vary diurnally and seasonally



Sand-bar area & volume, Marble Canyon



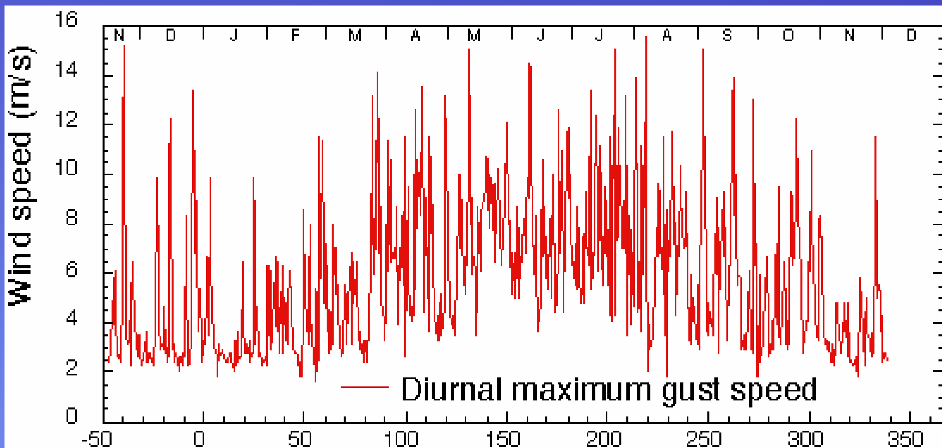
Source: Northern Arizona University

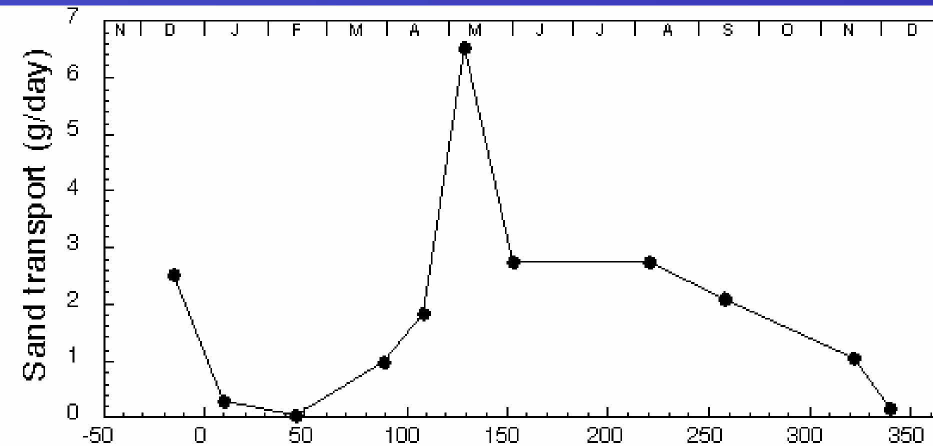
Instrument sites: 24.5 mile

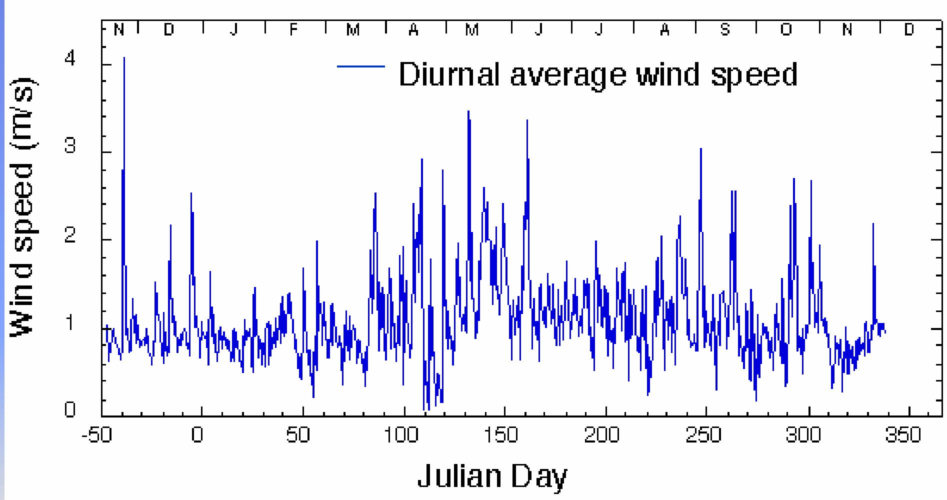
Pre-flood (November 17, 2004)

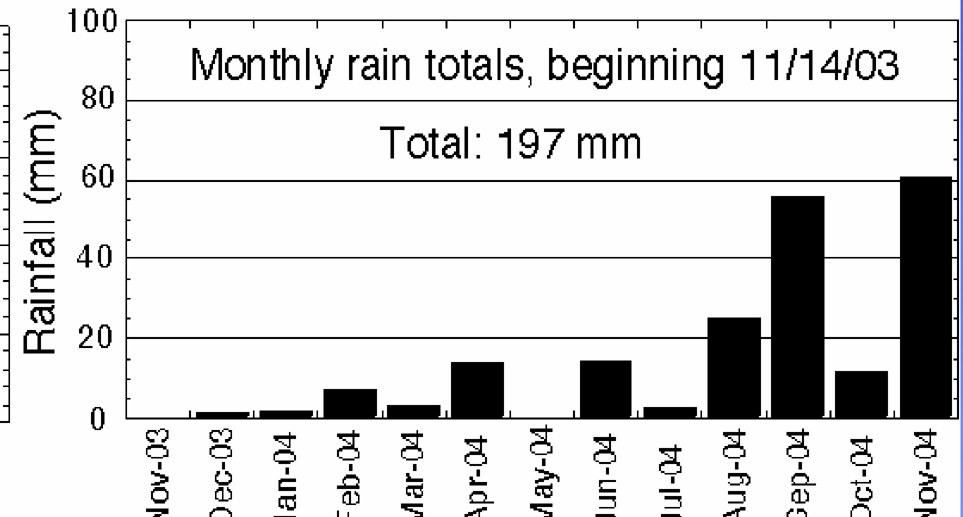
Post-flood (December 4, 2004)

24.5 mile: 12 months of pre-flood data

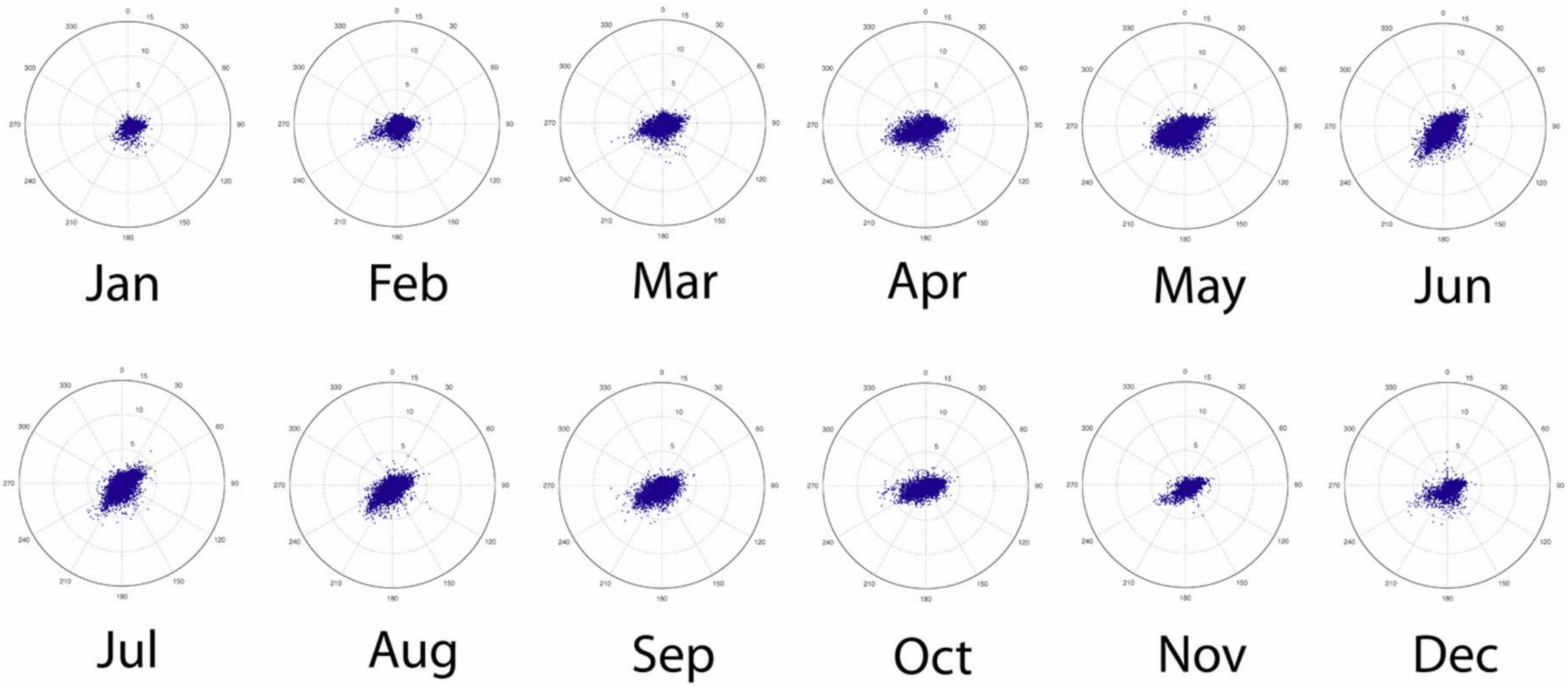




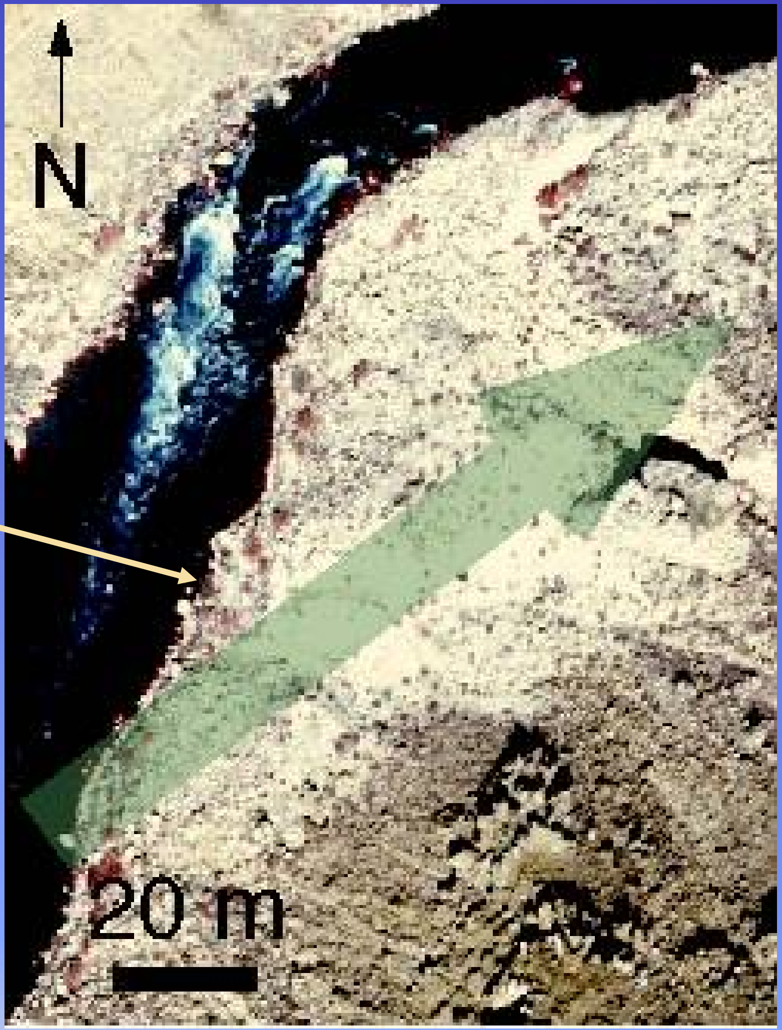




24.5 mile - 2004 wind data



24.5 mile: net sand transport



Sand deposit photographed

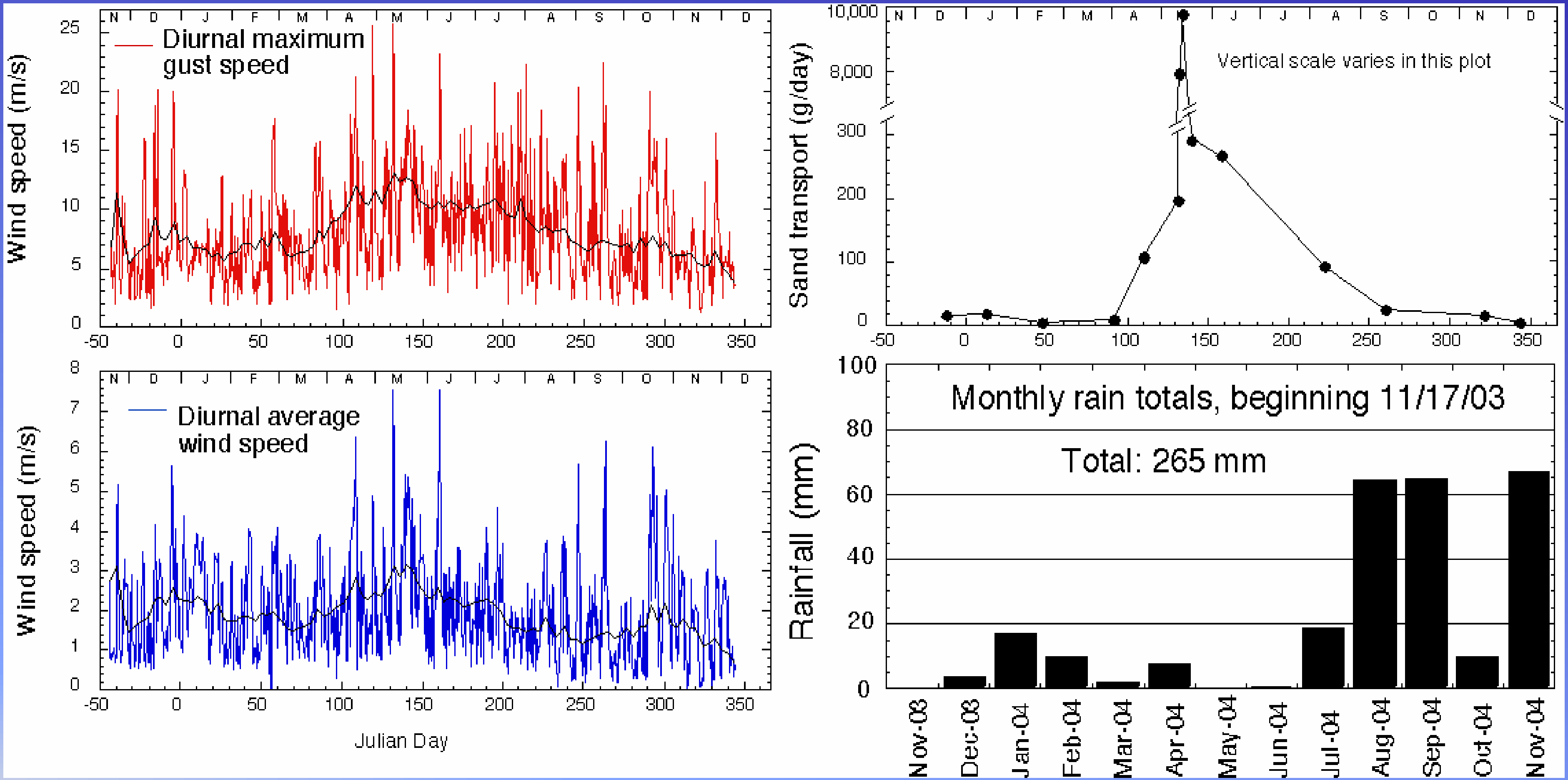
Net vector sum: Aeolian sand transport from 223º, from river-level sand bar across dune field

Instrument sites: Malgosa

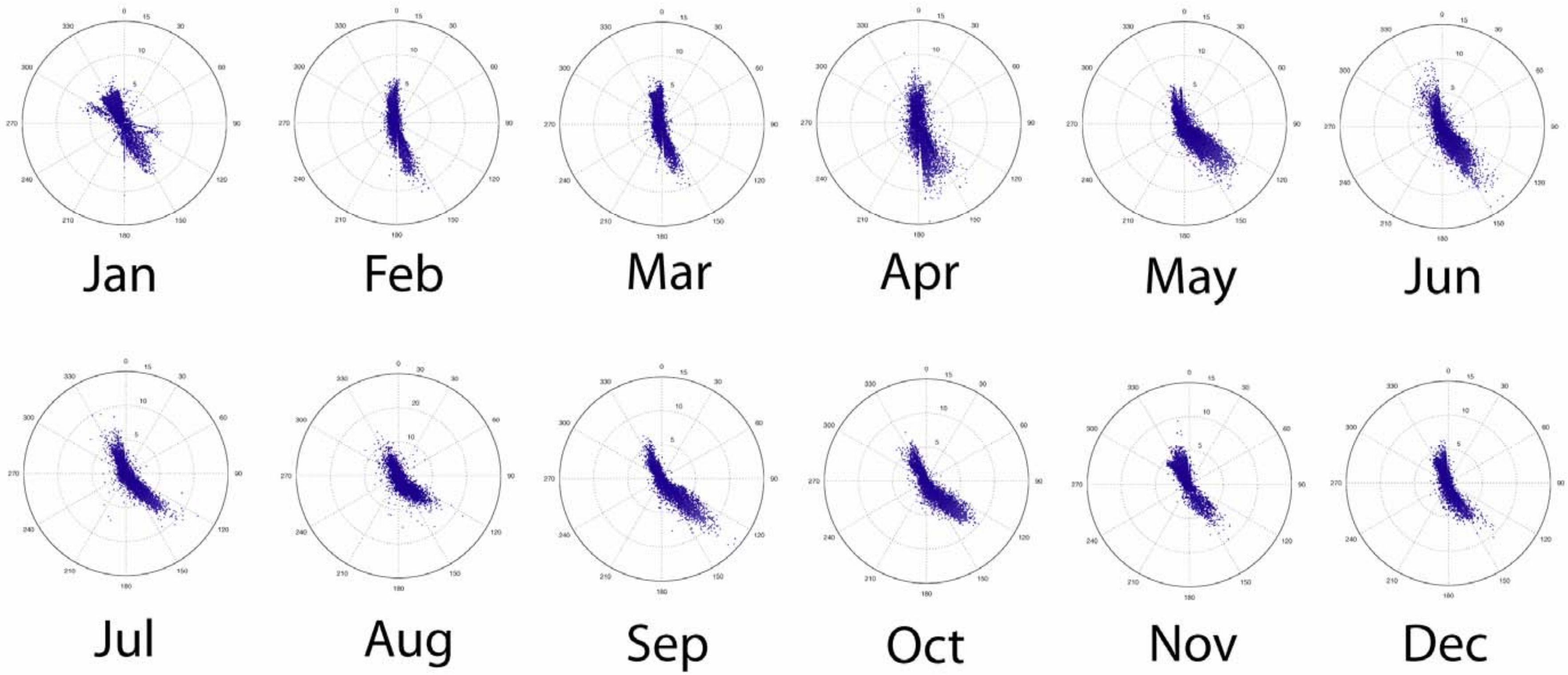
Pre-flood (November 17, 2004) at 8,000 cfs

Post-flood (December 9, 2004) at 8,000 cfs

Malgosa: 12 months of pre-flood data

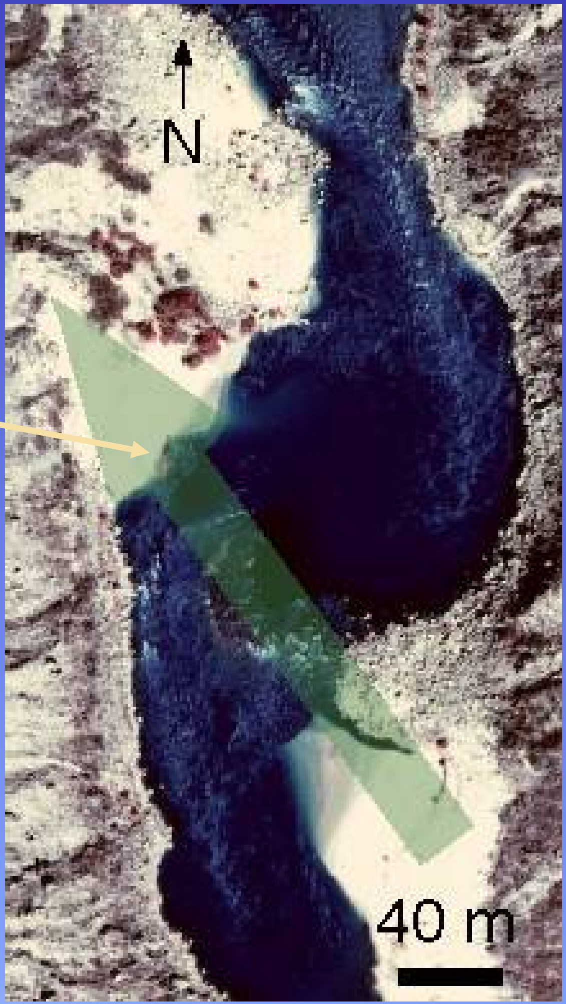


Malgosa - 2004 wind data



Malgosa: net sand transport

Sand deposit photographed



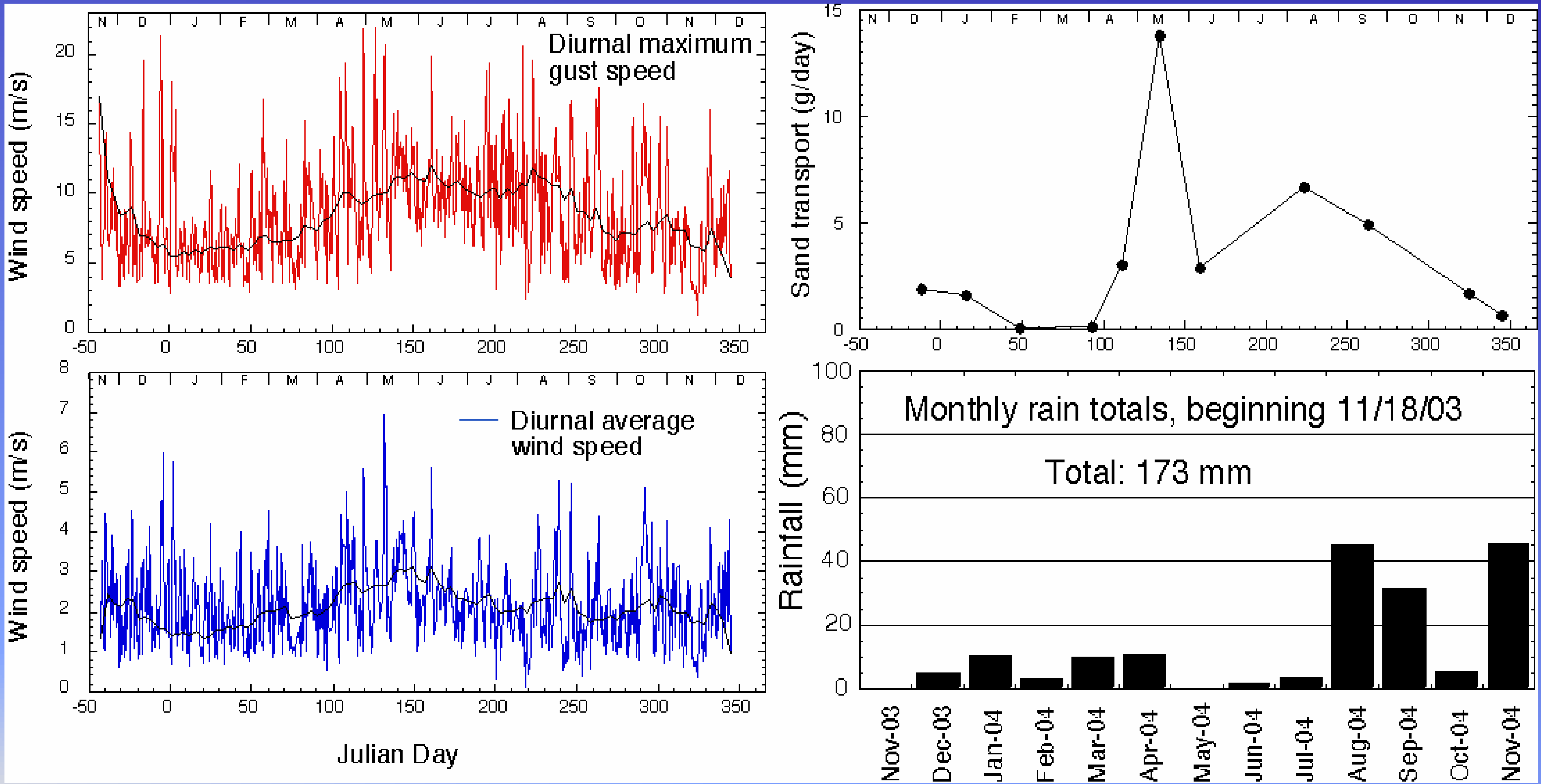
Net vector sum: Aeolian sand transport from 144º, from river-level sand bar(s) across dune field

Instrument sites: Palisades

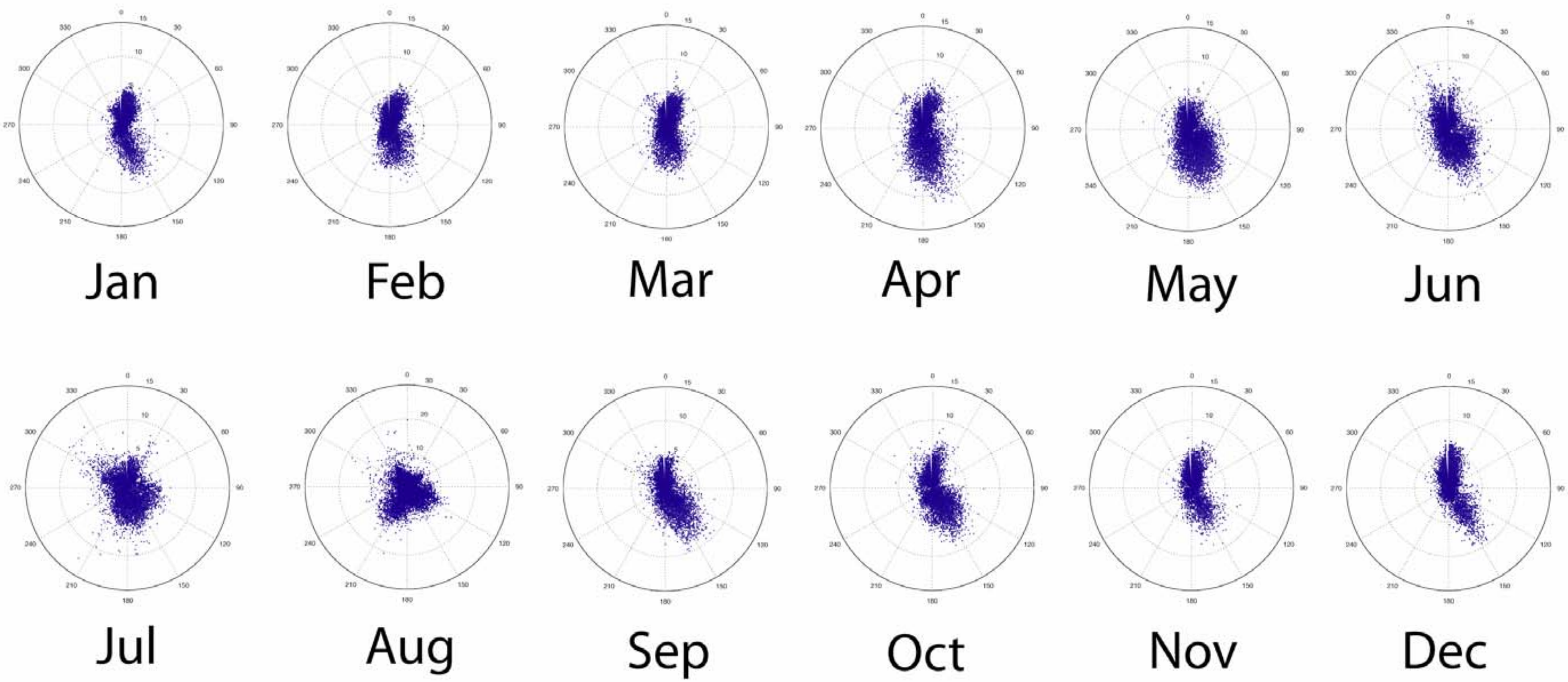
Pre-flood (November 19, 2004) at 8,000 cfs

Post-flood (December 10, 2004) at 10,000 cfs

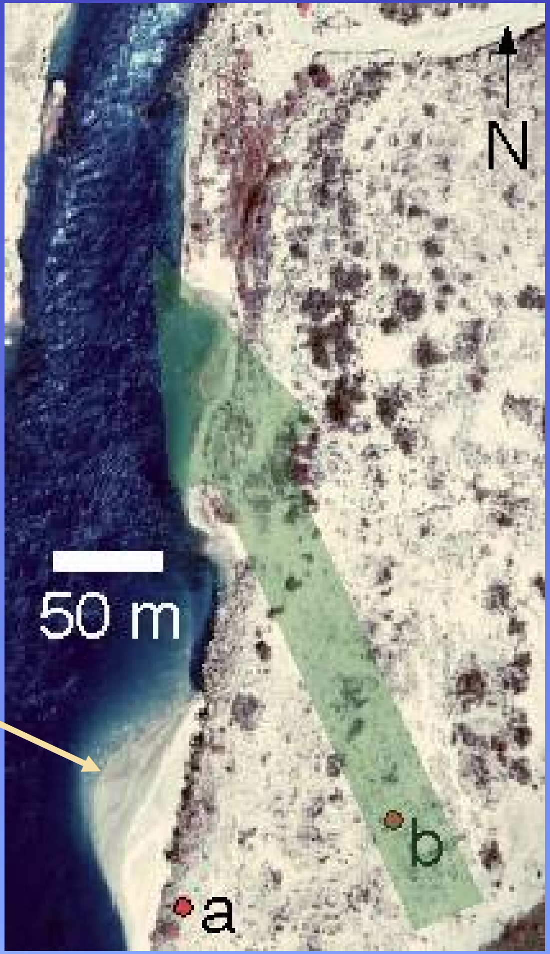
Palisades: 12 months of pre-flood data



Palisades - 2004 wind data



Palisades: net sand transport



Net vector sum: Aeolian sand transport from 156^{o}, upstream and somewhat away from dune field

(Ephemeral) sand deposit photographed

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Evaluating limits of dam effect on aeolian sediment transport

- Site-specific evaluation
- Multi-faceted data collection:
  - Surface geomorphology
  - Stratigraphic profiles
  - Document wind speeds/direction of sand transport
  - Aerial & ground photographs
  - Repeated total-station mapping

Series of questions to ask…

Evaluating dam influence on aeolian sediment transport related to archaeological site preservation

1. What is the **depositional context** of sediment on which the site is **built**?
2. What is the **depositional context** of sediment that has **buried**/protected the site?

If the answer to (2) is aeolian sediment:

3. Is there evidence for **loss** of aeolian sediment that previously covered the site?

4. What is the **source** of aeolian sediment that has buried the site?
5. Has there been a demonstrated **reduction in the source** surface area from which this aeolian sand is derived?
6. Could renewed deposition of aeolian sand have a substantial restorative effect on this site?

If the answer to (6) is yes,

7. How could this be accomplished (i.e., is there evidence that a dam operations could be used to help restore the source for aeolian sand at this site)?

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Case study: Site 1

1. What is the **depositional context** of sediment on which the site is **built**?

Aeolian (small dune field)

2. What is the **depositional context** of sediment that has **buried**/protected the site?

Aeolian (surface morphology; climbing wind ripples observed in small test pit)

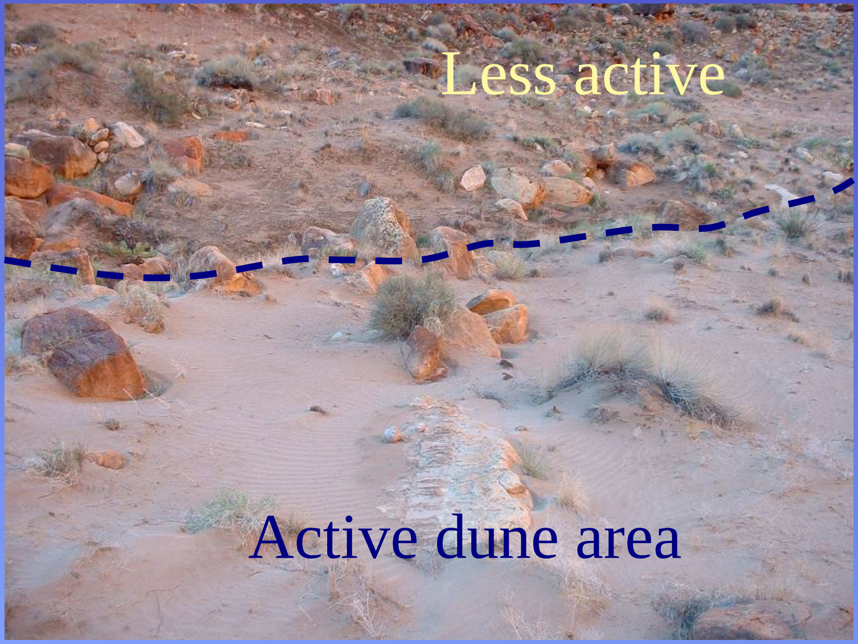
Case Study: Site 1

If the answer to (2) is aeolian sediment:

3. Is there evidence for **loss** of aeolian sediment that previously covered the site?

Yes:

- Deflated surface
- Cryptogamic crust
- Downslope movement of artifacts



Case study: Site 1

4. What is the **source** of aeolian sediment that has buried the site?

Fluvial sand bar located directly upwind of site
(based on measurements of wind speed/direction)

5. Has there been a demonstrated **reduction in the source** surface area from which this aeolian sand is derived?

Yes - 1923 vs. 1974 photos (Turner and Karpiscak, 1980) show decrease in volume of river-level sand bar at this location

Case study: Site 1

6. Could renewed deposition of aeolian sand have a substantial restorative effect on this site?

Yes - additional burial by wind-blown sand could aid preservation. No other factors threaten it (e.g., no gully incision, no visitation)

If the answer to (6) is yes,

7. How could this be accomplished (i.e., is there evidence that dam operations could be used to help restore the source for aeolian sand at this site)?

Yes - 1996 and 2004 flood experiments both caused substantial increase in sand volume here

Case study: Site 2

1. What is the **depositional context** of sediment on which the site is **built**?

Aeolian (tributary debris-flow sediment underlies aeolian dune area)

2320 – 2030 BP

2. What is the **depositional context** of sediment that has **buried**/protected the site?

Aeolian

Case Study: Site 2

If the answer to (2) is aeolian sediment:

3. Is there evidence for **loss** of aeolian sediment that previously covered the site?

Yes:

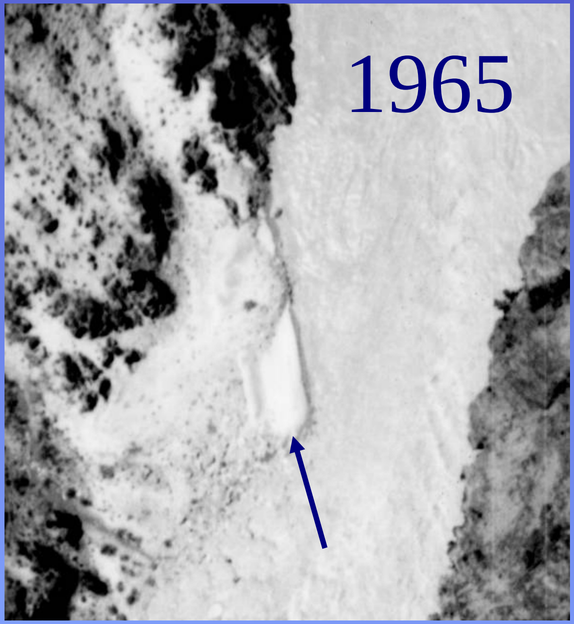
- Advanced deflation of upper dune-field surface
- Cryptogamic crust

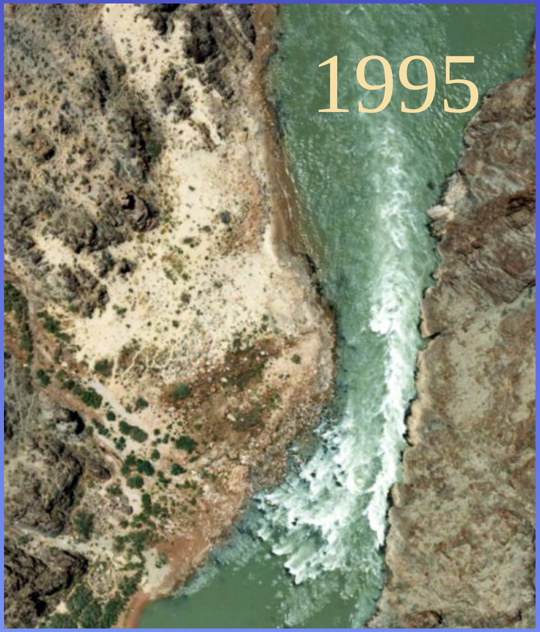
4. What is the **source** of aeolian sediment that has buried the site?

Fluvial sand bar located upwind of site (based on observations of dune slip faces, “sand shadow” morphology over multiple seasons)

Case study: Site 2

5. Has there been a demonstrated **reduction in the source** surface area from which this aeolian sand is derived?





Yes - comparing historical aerial photographs shows smaller river-level sand bar at this location, more vegetation on dune area than in the past

Case study: Site 2

6. Could renewed deposition of aeolian sand have a substantial restorative effect on this site?

Unlikely - additional burial by wind-blown sand would not facilitate preservation. Other factors (tributary incision) destabilize this site more quickly than aeolian deflation.

Case study: Site 3

1. What is the **depositional context** of sediment on which the site is **built**?

Aeolian (large dune field)

2. What is the **depositional context** of sediment that has **buried**/protected the site?

Aeolian

Case Study: Site 3

If the answer to (2) is aeolian sediment:

3. Is there evidence for **loss** of aeolian sediment that previously covered the site?

Yes:

- Some deflation of upper dune-field surface; dune migration
- Slumping, downslope movement of artifacts
- Minor cryptogamic crust

4. What is the **source** of aeolian sediment that has buried the site?

Channel-margin sand deposits at river level, upwind of sites (based on wind data measured)

Case study: Site 3

5. Has there been a demonstrated **reduction in the source** surface area from which this aeolian sand is derived?

Yes - comparing historical aerial photographs shows smaller channel-margin sand deposits now than in the past

6. Could renewed deposition of aeolian sand have a substantial restorative effect on this site?

Yes (aeolian processes are responsible for its exposure), but -

Case study: Site 3

Site exposed both by deflation, dune migration.

Dune migration is a natural process… over time scales of years-decades, expect artifacts to be covered again.

Will this happen? Time scales of observations, measurements must be long.

Summary

- Greatest potential for aeolian re-distribution of sand expected in April-May, transport rates 3-10x the non-windy season rates
- Direction, magnitude of aeolian transport vary with location
- In some areas, redistribution of flood sediment could benefit archaeological site preservation
- How will post-flood aeolian transport rates compare with pre-flood rates? And, ENSO conditions vs. weather recorded last year?
- Sites have different sensitivity (+ and -) to effects of dam operations


A few words about modeling…

Aeolian sediment transport presents a modeling challenge…

- Many sources of uncertainty: air flow around obstacles (vegetation, rocks, etc.), interstitial moisture, salt encrustation, cryptogamic soil, bedform irregularities, solar heating & convection, sand-source limitations (esp. in coastal dunes…)
- Bauer et al., 1996: “Accurate predictions of aeolian sediment flux may never be realized…”

- So… **eliminate as much uncertainty as possible.**

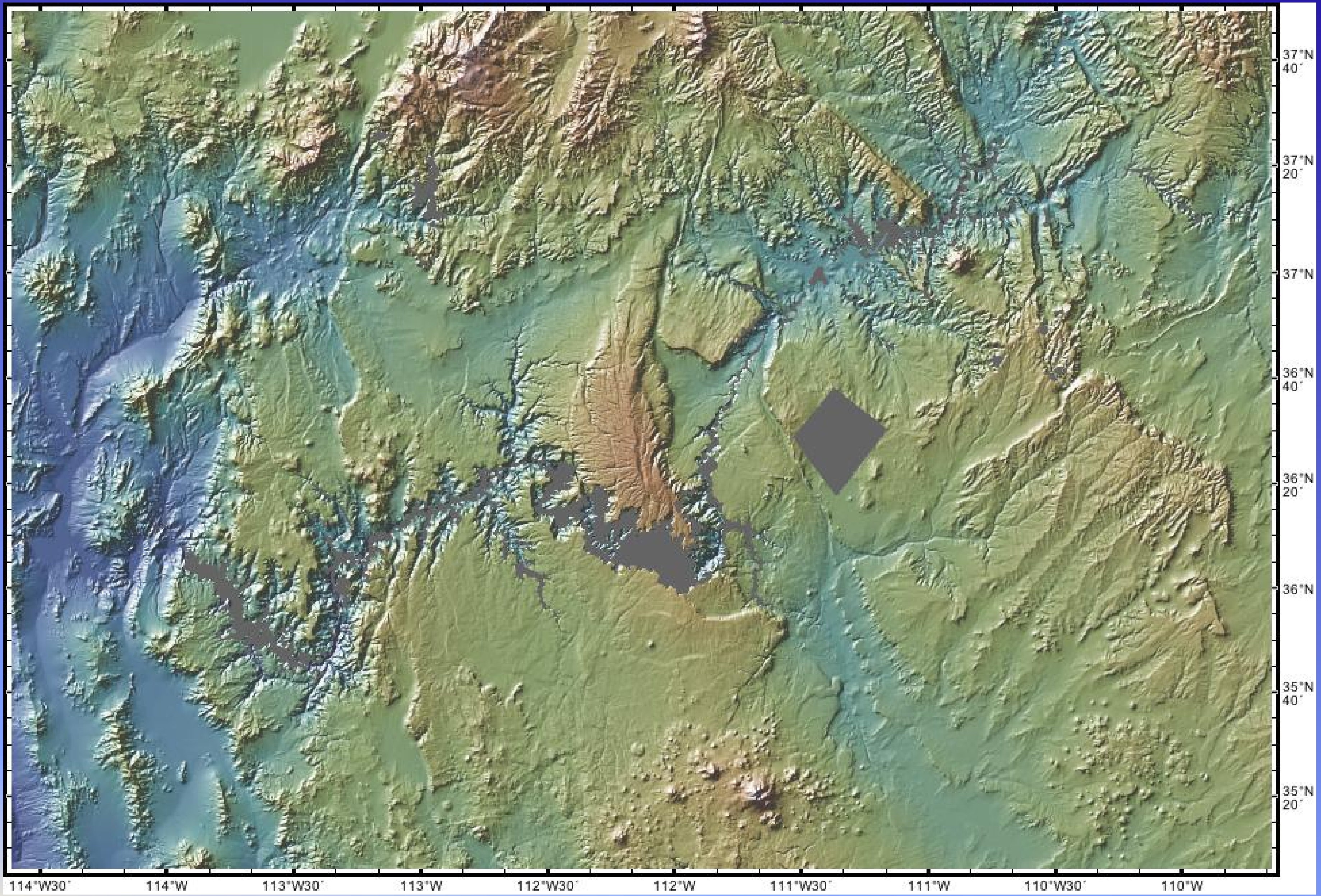
Testing transport models:

Bagnold (1941)	$q = 1.8\sqrt{\frac{d}{D}}\frac{\rho}{g}u_*^3$
Kawamura (1951)	$q = 2.78\frac{\rho}{g}(u_* - u_{*t})(u_* + u_{*t})^2$
Zingg (1953)	$q = 0.83\left(\frac{d}{D}\right)^{0.75}\frac{\rho}{g}u_*^3$
Williams (1964)	$q = 4.066\frac{\rho}{g}u_*$
Hsu (1971)	$q = 10^{-4}e^{4.79d - 0.47}\frac{u_*^3}{(gd)^{1.5}}$
Lettau and Lettau (1977)	$q = 4.2\sqrt{\frac{d}{D}}\frac{\rho}{g}(u_* - u_{*t})u_*^2$
White (1979)	$q = 2.61u_*^3\left(1 - \frac{u_{*t}}{u_*}\right)\left(1 + \frac{u_{*t}^2}{u_*^2}\right)\frac{\rho}{g}$
Sørensen (1991)	$q = 10^{-4}\rho u_*(u_* - u_{*t})(u_* + 7.6u_{*t} + 205)$

Results

Dumont Dunes	*Measured*	*105% Trap Efficiency*	*115% Trap Efficiency*
Measured transported sand (g)	61.8	58.9	53.7
Ratio of Predicted: Measured Flux			
Bagnold (1941)	1.47	1.54	1.69
Kawamura (1951)	0.856	0.898	0.985
Zingg (1953)	0.712	0.747	0.819
Williams (1964)	34.9	36.6	40.2
Hsu (1971)	2.29	2.41	2.64
Lettau and Lettau (1977)	0.430	0.452	0.495
White (1979)	0.406	0.426	0.467
Sørensen (1991)	0.241	0.253	0.277

Malgosa	*Measured*	*95% Trap Efficiency*	*115% Trap Efficiency*
Measured transported sand (g)	2770	2910	2400
Ratio of Predicted: Measured Flux			
Bagnold (1941)	1.82	1.73	2.09
Kawamura (1951)	2.58	2.45	2.96
Zingg (1953)	0.880	0.840	1.01
Williams (1964)	17.3	16.4	19.8
Hsu (1971)	2.85	2.70	3.27
Lettau and Lettau (1977)	1.99	1.89	2.29
White (1979)	1.38	1.31	1.59
Sørensen (1991)	0.620	0.590	0.710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