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The Role of Eolian Sediment in the Preservation of Archeologic Sites Along the Colorado River Corridor in Grand Canyon National Park, Arizona

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By Amy E. Draut and David M. Rubin

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COVER—Photograph taken in 2007 of eolian sedimentary deposits in the Palisades area of the Colorado River corridor, Grand Canyon, Ariz.

Contents

Executive Summary 1
Introduction....3
Overview of Wind, Precipitation, and Eolian-Sediment-Transport Measurements 4
Overview of Sedimentologic and Geomorphologic Investigations 6
Identifying Fluvial and Eolian Deposits by Using Sediment Grain Size....7
Two Types of Eolian Deposit Defined for the Colorado River Corridor 7
Sedimentary Environments—Implications for the Preservation of Archeologic Sites 14
Criteria for Identifying Site Sensitivity to Dam Operations 15
Three Case Studies....17
Effects of the November 2004 Controlled-Flood Experiment on Eolian Sediment Transport 19
Recommended Future Research....21
Conclusions....22
Acknowledgments....23
References Cited....24
Appendix 1. Site-Specific Observations 29
24.5 Mile....29
Malgosa....34
Palisades....39
Comanche 44
Forster 46
202.9 Mile....49
Arroyo Grande....51
Appendix 2. Evaluating the Predictive Power of Eolian-Sediment-Transport Models—
Can Sediment-Supply Limitation Be Discerned?....55
Introduction....55
Eolian-Sediment-Transport Models....55
Sediment-Supply Limitation 56
Model Testing 56
Experimental Methods....56
Results 58
Discussion....61
Potential Sources of Error....61
Performance of Tested Models....62
Relevance for Investigation of Sediment-Supply-Limited Systems 64
Conclusions....64
Appendix 3. Estimation of Historical Changes in Eolian Sand Sources....65
Introduction....65
Aerial Photographs Incorporated into a GIS Database Compiled by the Utah State University....65
Results and Interpretation....65

Figures

1. Colorado River corridor in Grand Canyon National Park, Ariz., showing locations of study sites....5

2. Aerial photographs of study area sites along the Colorado River corridor in Grand Canyon National Park, Ariz., with geomorphology shown in colored overlay....8
3. Grain-size distributions, obtained by using laser particle-size analysis, in fluvial and eolian deposits along the Colorado River corridor in Grand Canyon National Park, Ariz....11
4. Aerial photographs showing two types of eolian deposit defined for the Colorado River corridor in Grand Canyon National Park, Ariz....12
5. Sedimentary profiles at Palisades, Lower Comanche, and Arroyo Grande study sites in Grand Canyon National Park, Ariz. 13
6. Sedimentary material in area where a tributary channel erodes an eolian deposit containing cultural material (site 2) along Colorado River corridor in Grand Canyon National Park, Ariz....18
7. Study site at Malgosa (river mile 57.9) along the Colorado River corridor in Grand Canyon National Park, Ariz., showing effects of November 2004 flood and subsequent fluctuating flows. 20
8. Aerial photographs taken in May 1965 and May 2004 of 24.5 Mile, Colorado River corridor in Grand Canyon National Park, Ariz. 30
9. Rose diagrams of sand-transport potential calculated from 2 years of wind data collected at weather station 24.5 L along the Colorado River corridor in Grand Canyon National Park, Ariz....31
10. Rose diagram of sand-transport potential calculated from 2 years of wind data collected at weather station 24.5 U along the Colorado River corridor in Grand Canyon National Park, Ariz....31
11. Rainfall, wind, and sand-transport data collected at weather station 24.5 L along the Colorado River corridor in Grand Canyon National Park, Ariz., from November 2003 to January 2006....32
12. Rainfall, wind, and sand-transport data collected at weather station 24.5 U along the Colorado River corridor in Grand Canyon National Park, Ariz., from November 2003 to January 2006. 33
13. Aerial photographs taken in May 1965 and May 2004 of 23.5 Mile area along the Colorado River corridor, Grand Canyon National Park, Ariz....34
14. Aerial photographs taken in May 1965 and May 2004 of Malgosa area along the Colorado River corridor in Grand Canyon National Park, Ariz. 35
15. Rose diagrams of sand-transport potential calculated from 2 years of wind data collected at weather station Mal L along the Colorado River corridor in Grand Canyon National Park, Ariz....36
16. Rose diagrams of sand-transport potential calculated from 2 years of wind data collected at weather station Mal U along the Colorado River corridor in Grand Canyon National Park, Ariz. 36
17. Rainfall, wind, and sand-transport data collected at weather station Mal L along the Colorado River corridor in Grand Canyon National Park, Ariz., from November 2003 to January 2006....37
18. Rainfall, wind, and sand-transport data collected at weather station Mal U along the Colorado River corridor in Grand Canyon National Park, Ariz., from November 2003 to January 2006....38

19. Zones within dune field at Malgosa along the Colorado River corridor in Grand Canyon National Park, Ariz. 39
20. Aerial photographs taken in May 1965 and May 2004 of Palisades area along the Colorado River corridor in Grand Canyon National Park, Ariz. 40
21. Rose diagrams of sand-transport potential calculated from 2 years of wind data collected at weather station Pal L along the Colorado River corridor in Grand Canyon National Park, Ariz. 41
22. Rose diagrams of sand-transport potential calculated from 2 years of wind data collected at weather station Pal U along the Colorado River corridor in Grand Canyon National Park, Ariz. 41
23. Rainfall, wind, and sand-transport data collected at weather station Pal L along the Colorado River corridor in Grand Canyon National Park, Ariz., from November 2003 to January 2006. 42
24. Rainfall, wind, and sand-transport data collected at weather station Pal U along the Colorado River corridor in Grand Canyon National Park, Ariz., from November 2003 to January 2006 43
25. Aerial photographs taken in May 1965 and May 2004 of Comanche area along the Colorado River corridor in Grand Canyon National Park, Ariz. 45
26. Rose diagrams of sand-transport potential calculated from wind data collected at weather station Com along the Colorado River corridor in Grand Canyon National Park, Ariz., from April 2004 to January 2006 46
27. Rainfall, wind, and sand-transport data collected at weather station Com along the Colorado River corridor in Grand Canyon National Park, Ariz., from April 2004 to January 2006 47
28. Aerial photographs taken in May 1965, May 2004, and April 2004 of area by mouth of Forster Canyon along the Colorado River corridor in Grand Canyon National Park, Ariz. 48
29. Rose diagrams of sand-transport potential calculated from wind data collected at weather station For along the Colorado River corridor in Grand Canyon National Park, Ariz., from April 2004 to January 2006. 49
30. Rainfall, wind, and sand-transport data collected at weather station For along the Colorado River corridor in Grand Canyon National Park, Ariz., from April 2004 to January 2006. 50
31. Aerial photographs taken in May 1965 and May 2004 of 202.9 Mile area along the Colorado River corridor in Grand Canyon National Park, Ariz. 51
32. Rose diagrams of sand-transport potential calculated from wind data collected at weather station 202.9 along the Colorado River corridor in Grand Canyon National Park, Ariz., from April 2004 to January 2006 52
33. Rainfall and wind data collected at weather station 202.9 along the Colorado River corridor in Grand Canyon National Park, Ariz., from April 2004 to January 2006 53
34. Aerial photographs taken in May 1965 and May 2004 of Arroyo Grande area along the Colorado River corridor in Grand Canyon National Park, Ariz. 54
35. Study site at the Dumont Dunes in the Mojave Desert, southern Calif., showing location of experiment in late February 2004 58

36. Histograms of shear velocity (u_*) measured during experiment at the Dumont Dunes in the Mojave Desert, southern Calif., and two tests at Malgosa along the Colorado River corridor in Grand Canyon National Park, Ariz. 60
37. Sand flux (q) predicted for various shear velocities (u_*) by eight eolian-sediment-transport models. 62
38. Total area of various types of sedimentary deposits mapped from aerial photographs in the Glen Canyon reach of the Colorado River corridor in Grand Canyon National Park, Ariz. 67
39. Total area of various types of sedimentary deposit mapped from aerial photographs of the Lees Ferry reach of the Colorado River corridor in Grand Canyon National Park, Ariz. 68
40. Total area of various types of sedimentary deposit mapped from aerial photographs in the Redwall Gorge reach of the Colorado River corridor in Grand Canyon National Park, Ariz. 69
41. Total area of various types of sedimentary deposit mapped from aerial photographs of the Point Hansbrough reach of the Colorado River corridor in Grand Canyon National Park, Ariz. 70
42. Total area of various types of sedimentary deposits mapped from aerial photographs of the Little Colorado River reach of the Colorado River corridor in Grand Canyon National Park, Ariz. 71

Tables

1. Summary of sedimentary processes affecting archeologic sites at Palisades, Grand Canyon National Park, Ariz. 9
2. Summary of sedimentary processes affecting archeologic sites at Lower Comanche, Grand Canyon National Park, Ariz. 9
3. Summary of sedimentary processes affecting archeologic sites at Arroyo Grande, Grand Canyon National Park, Ariz. 10
4. Eolian-sediment-transport models tested in the Dumont Dunes in Death Valley, Calif., and the dune field at Malgosa at Grand Canyon National Park, Ariz. 57
5. Comparison of predicted sand flux with sand flux measured by using sand traps during experiments in the Dumont Dunes and the dune field at Malgosa. 59
6. Reaches of the Colorado River, with corresponding river miles, analyzed by using a GIS database compiled by the Utah State University. 66
7. Dates of and riverflow in aerial photographs included in the Utah State University's GIS database, with available mapped river reaches in each aerial photograph 66

Executive Summary

This report summarizes a 3-year study of eolian sedimentary processes in the Colorado River corridor, Grand Canyon National Park, Ariz., and discusses the relevance of those processes to the preservation of archeologic sites. The results reported here are based on detailed sedimentologic and geomorphologic investigations in three reaches of the river corridor, as well as continuous measurements of wind, rainfall, and sand transport at six sites for as long as 26 months, short-term field study at 35 other sites, examination of historical aerial photographs, and review of data collected and analyzed during previous studies. The data generated by this study, which involved collaboration with scientists of the U.S. Geological Survey (USGS) Grand Canyon Monitoring and Research Center, the National Park Service, Northern Arizona University, the Hopi Tribe, and GeoArch, Inc., were previously published by Draut and Rubin (2005, 2006, 2008) and Draut and others (2005, in press). This report, which supersedes that by Draut and Rubin (2007), provides an overview of the results and contains new conclusions regarding eolian sedimentary processes in the Colorado River ecosystem and their relevance to the preservation of archeologic sites.

At many of the study sites, eolian sediment serves as a substrate on which archeologic sites were formed (many sites were also built on fluvial and slopewash sediment) and, commonly, as a surficial deposit (cover) inferred to help preserve cultural materials. Over time, many cultural artifacts are exposed by wind deflation of the overlying sediment, forming a lag deposit on the land surface. Archeologic material also is vulnerable to erosion by gully incision. Incision of gullies and arroyos into sedimentary deposits during rainfall runoff is an erosive process counteracted by transport and deposition of eolian sediment because gullies are natural traps for windblown sand. The ability of eolian sediment transport to inhibit gully formation and to heal small gullies (<1 m wide or deep) is a major factor controlling the geomorphic evolution of Grand Canyon sedimentary deposits. Rainfall and sand-transport rates measured during this study showed that areas with heavy rainfall but abundant windblown sand may have no gullies (which form episodically but are quickly filled by eolian sediment), whereas areas of relatively low rainfall and low sand-transport rates can be substantially eroded by gullies and arroyos, destabilizing archeologic sites.

Many eolian dunes in Grand Canyon show evidence of reduced sand supply relative to some time in the past, with vegetation and biologic soil crust covering relict duneforms. Vegetation and soil crusts indicate an absence of eolian sedimentation and a decrease in dune mobility relative to past times when the supply and transport of eolian sediment were abundant enough to form dunes. Some dunes with substantially reduced sand supply (and with well-developed vegetation and soil crust) have insufficient active eolian sedimentation to counteract gully incision; where present, large gullies and arroyos erode and degrade such dune fields and many of the archeologic sites within them.

The availability and transport of eolian sediment has important implications for the management of Glen Canyon Dam operations, which regulate the flow of the Colorado River through Grand Canyon. Because fluvial sandbars now provide the greatest source of eolian sediment in the river corridor, the alongshore and cross-shore dimensions of unvegetated, dry fluvial sandbars directly affect the entrainment and transport of eolian sediment. Therefore, depending on location and wind direction, fluvial-sandbar area and dimensions also can substantially affect eolian sediment transport to dune fields in which archeologic sites are covered by windblown sand. This relation between fluvial sandbars and many of the eolian deposits in Grand Canyon implies that the availability of eolian sediment is affected by dam operations that increase or decrease the area of open, dry fluvial sedimentary deposits. An increase in sandbar area due to dam operations could increase eolian sediment transport to specific dune fields and associated archeologic sites in areas with an appropriate dominant wind direction. This report discusses criteria for evaluating the sensitivity of archeologic sites to dam operations with regard to eolian sedimentation.

We distinguish two types of eolian deposit in the Colorado River corridor: (1) modern fluvial-sourced (MFS) deposits, which formed as the wind transported sand inland from a river-level sandbar, creating an eolian dune field downwind; and (2) relict fluvial-sourced (RFS) deposits, which formed as the wind eroded and redistributed sediment of extensive predam flood deposits. MFS deposits generally are smaller and more common in Grand Canyon than are RFS deposits. In areas of RFS deposits, the dominant wind direction may or may not be appropriate to transport sand from the river (non-flood-stage fluvial sandbars) to local eolian dune fields. Archeologic material is known to occur in eolian deposits of both types.

Both MFS and RFS deposits are sensitive to dam operations for different reasons. MFS deposits, situated directly downwind from fluvial sandbars, receive an amount of windblown sand as a function of wind velocity, dimensions of exposed dry fluvial sandbars, and any barriers (such as vegetation) that exist between the fluvial sediment and its associated eolian deposits. Fluvial-sandbar area and riparian vegetation have been shown, by numerous studies, to respond to dam operations. Therefore, changes in either fluvial-sandbar area or riparian vegetation can affect the delivery of eolian sediment to MFS dune fields downwind. RFS deposits include eolian coppice dunes (vegetated sand mounds), which compose the uppermost, wind-reworked part of predam terraces. Predam terraces are largely alluvial in composition and contain sediment deposited by floods higher than any postdam floods have been (≥5,660 m^3/s). Because sediment-rich floods of that magnitude no longer occur in this regulated river, the fluvial deposits from which extensive RFS dune fields formed no longer constitute an active sand source; no substantial new deposition is likely to occur on those dune fields as long as no large sediment-rich floods occur. As vegetation and biologic soil crust colonize RFS coppice-dune fields over time, active

eolian sediment transport decreases within them, such that these areas become increasingly unable to compensate for precipitation-induced gully erosion. As a result, large gully and arroyo systems can form on predam terraces and associated RFS dune fields.

Analysis of the effects of the November 2004 controlled-flood experiment on eolian sediment transport indicates that in areas where sandbars are enlarged by floods, sediment-rich controlled floods can be an effective means to restore sediment deposition locally in eolian dune fields above the controlled-flood stage. Sandbar-building riverflows of about 1,270 m^3/s are much more likely to enhance eolian sedimentation on MFS than on RFS deposits because of the direct link between fluvial sandbars and MFS dune fields downwind.

Our data suggest that the restoration potential for archeologic sites in eolian deposits can be optimized by using dam operations (controlled floods and postflood flows) that maximize the open sand area on fluvial sandbars during the spring windy season (April through early June), when eolian sediment transport is greatest. To effect the greatest sand transport to eolian deposits and associated archeologic material, riverflows that follow sandbar-building high flows would need to be managed to retain and maximize high-elevation, open, dry sandbar area. In spring 2005, the first windy season after the November 2004 high flow, the one study site with a clear MFS-type link between a fluvial sandbar and eolian dunes and with substantial remaining flood sediment (not entirely eroded by high fluctuating flows, as at other study sites), sand-transport rates were significantly higher than in the spring 2004 windy season. At the same site, gully erosion was effectively counteracted by deposition of eolian sediment derived from the 2004 flood deposit. If controlled high flows were followed by low fluctuating flows (as defined in the 1996 Record of Decision signed by the Secretary of the Interior) or steady low flows rather than the experimental high daily flow fluctuations that occurred from January to March 2005, windblown sand would be more likely to be transported to and deposited in gullies, and erosion of eolian deposits and associated archeologic sites might be reduced. Operating Glen Canyon Dam under low fluctuating flows (or steady low flows) between the end of a controlled flood and the start of a spring windy season is predicted to maintain the postflood sandbar area longer than in winter 2005, leaving more sand available to be blown into higher elevation dune fields during the subsequent spring windy season.

Sedimentation patterns documented during this study indicate that eolian deposits above the riparian zone can respond to dam operations and that archeologic sites within these deposits can be consequently affected. The sensitivity of eolian deposits to dam operations could have either detrimental or restorative results. If reduction of open, dry fluvial-sandbar area causes a corresponding reduction in sand transport to and deposition on an eolian dune field downwind, then sand transport to and deposition on that same dune field can be enhanced by enlarging the area of the fluvial sandbar serving as a sand source for the dune field. As shown by this study, an increase in eolian sediment transport in the dune field as a result of dam operations can counteract deflation and gully incision there, potentially leading to greater preservation of associated archeologic sites. Protection of cultural artifacts in Grand Canyon on geologic time scales is unrealistic because of continual downcutting and backwasting of the bedrock canyon. However, preservation of archeologic sites likely could be enhanced on decadal to centennial time scales by restoring fluvial and eolian sedimentation that resembles more closely predam processes, including large, sediment-rich floods that once left fluvial deposits from which sediment was remobilized by wind.

The Role of Eolian Sediment in the Preservation of Archeologic Sites Along the Colorado River Corridor in Grand Canyon National Park, Arizona

By Amy E. Draut and David M. Rubin

Introduction

Since the closure of Glen Canyon Dam in 1963, the natural hydrologic and sedimentary systems along the Colorado River in the Grand Canyon reach have changed substantially (see, for example, Andrews, 1986; Johnson and Carothers, 1987; Webb and others, 1999b; Rubin and others, 2002; Topping and others, 2003; Wright and others, 2005; Hazel and others, 2006b). The dam has reduced the fluvial sediment supply at the upstream boundary of Grand Canyon National Park by about 95 percent. Regulation of river discharge by dam operations has important implications for the storage and redistribution of sediment in the Colorado River corridor. In the absence of floods, sediment is not deposited at elevations that regularly received sediment before dam closure. Riparian vegetation has colonized areas at lower elevations than in predam time when annual floods removed young vegetation (Turner and Karpiscak, 1980). Together, these factors have caused a systemwide decrease in the size and number of subaerially exposed fluvial sand deposits since the 1960s, punctuated by episodic aggradation during the exceptional high-flow intervals in 1983–84, 1996, and 2004 and by sediment input from occasional tributary floods (Beus and others, 1985; Schmidt and Graf, 1987; Kearsley and others, 1994; Hazel and others, 1999; Schmidt and others, 2004; Wright and others, 2005).

When the Bureau of Reclamation sponsored the creation of the Glen Canyon Environmental Studies (GCES) research initiative in 1982, research objectives included physical and biologic resources, whereas the effects of dam operations on cultural resources were not addressed (Fairley and others, 1994; Fairley, 2003). In the early 1980s, it was widely believed that because few archeologic sites were preserved within the river's annual-flood zone, cultural features would not be greatly affected by dam operations. Recent studies, however, indicate that alterations in the flow and sediment load of the Colorado River by Glen Canyon Dam operations may affect archeologic sites within the river corridor, even above the annual flood limit (Hereford and others, 1993, Yeatts, 1996, 1997; Thompson and Potochnik, 2000; Draut and others, 2005). (The annual-flood zone is defined here by the mean annual predam flood of 2,410 m^3/s; the "predam flood limit," the highest elevation at which fluvial deposits are present locally, was approximately equivalent to a rare, major flood of 8,500 m^3/s; Topping and others, 2003.) Of about 500 archeologic sites documented between Glen Canyon Dam and Separation Canyon (255 river miles), more than 330 are considered to be within the area of potential effect (APE) of dam operations (Fairley and others, 1994; Neal and others, 2000; Fairley, 2005). The APE was designated by the National Park Service (NPS) to include the area below the peak stage of the 1884 flood; though previously believed to have reached 8,490 m^3/s, this flood was shown by Topping and others (2003) to have peaked at 5,940 m^3/s.

Archeologic research and monitoring in Grand Canyon National Park focus increasingly on the potential effects of Glen Canyon Dam operations on the landscape in which these sites exist. Many archeologic sites in or on sedimentary deposits are being eroded, owing to eolian deflation and gully incision (Leap and others, 2000; Neal and others, 2000; Fairley, 2003, 2005). Hereford and others (1993) first suggested that gully incision of sedimentary deposits, and the base level to which small drainage systems respond, were linked to dam operations; they hypothesized that pronounced arroyo incision, which occurs during rainfall runoff, was caused by lowering of the effective base level at the mouths of ephemeral drainages to meet the new postdam elevation of high-flow sediment deposition, about 3 to 4 m below the lowest predam alluvial terraces. Thompson and Potochnik (2000) modified that hypothesis to include the restorative effects of fluvial deposition in the mouths of gullies and arroyos, presumed to raise effective base level at least temporarily, and new eolian deposition on predam alluvial deposits as wind reworks flood-deposited sand. Thompson and Potochnik (2000) concluded that sediment deprivation and fewer floods as a result of dam operations reduce the potential for new deposition that could heal gullies formed by rainfall runoff. Neal and others, following Lucchitta (I. Lucchitta, unpub. data, 1991), suggested that eolian deposition in incipient gullies is "one of the strongest restorative forces operating at archaeological sites." Repeated high-resolution mapping after the 1996 controlled-flood experiment (1,270 m^3/s; see Webb and others, 1999b; Schmidt and others, 2001) confirmed that high riverflows can deposit sediment in arroyo mouths and suggested that those deposits can be a source for windblown sand which accumulates at higher elevation, causing sediment accretion above the flood-stage elevation (Yeatts, 1997; Hazel and others, 2000, 2008).

This study began in 2003 as a collaborative effort between the USGS and the NPS, funded by the Bureau of Reclamation through the USGS Grand Canyon Monitoring and Research Center (GCMRC), to investigate the role of eolian sediment transport in the preservation of archeologic sites along the Colorado River corridor in Grand Canyon National Park and thereby to clarify the actual or potential effects of dam operations on eolian deposits and associated archeologic sites. Participants in this research included geologists and archeologists from the USGS (including the GCMRC), the NPS, Northern Arizona University, GeoArch, Inc., the Hopi Tribe, the Hualapai Nation, and the Western Area Power Administration.

Observations by this research group during reconnaissance in May 2003 formed the basis for more detailed sedimentologic and geomorphologic studies in the following year and led to the selection of sites at which weather stations were deployed to measure wind, precipitation, and eolian sediment transport continuously between late 2003 and early 2006. This report summarizes the results of that study and presents a final analysis and conclusions drawn from the data. Detailed discussions of data are omitted from this report but were presented by Draut and Rubin (2005, 2006, 2007, 2008) and Draut and others (2005).

Overview of Wind, Precipitation, and Eolian-Sediment-Transport Measurements

Wind, precipitation, and eolian-sediment-transport data, collected during this study at six sites, constitute the only continuous weather record available from the Colorado River corridor between November 2003 and January 2006, except for NPS temperature and rainfall measurements at Phantom Ranch (near river mile 88). Locations in the river corridor are commonly referred to by their distance (in miles) downstream from Lees Ferry, Ariz. (fig. 1); this report follows that convention and uses SI units for other measurements. River miles used here are those provided by the World Wide Web map server operated by the GCMRC (URL http://www.gcmrc.gov/products/ims/ims.htm, accessed Apr. 2, 2008).

This study provided the first measurements at this temporal and spatial resolution of seasonal and regional variations in wind speed and direction and resulting eolian sediment transport, as well as of rainfall patterns within the interior of Grand Canyon. High-resolution records from weather stations can be used to identify rainfall events that caused gully incision and to predict eolian sediment redistribution, thus aiding other sedimentologic and geomorphologic studies of sedimentary deposits in the river corridor. Quantifying wind magnitude and direction was essential for identifying eolian-sediment-transport pathways in the vicinity of the study sites. This information was used to evaluate the potential sensitivity of certain study sites to dam operations. Detailed discussions of the data collected at weather stations, as well as electronic datafiles, were presented by Draut and Rubin (2005, 2006; see appendix 1 for summaries of weather data from each study site).

A total of nine weather stations were deployed in the Colorado River corridor in Grand Canyon National Park (fig. 1) as part of this study: two weather stations at each of three sites in eastern Grand Canyon—an area known as “24.5 Mile” (river mile 24.8), Malgosa (river mile 57.9), and Palisades (river mile 66.1)—from November 2003 to January 2006; and one weather station at each of three study sites—Comanche (river mile 68.0) in eastern Grand Canyon, and Forster (river mile 123.0) and 202.9 Mile (river mile 202.9) in western Grand Canyon—from April 2004 to January 2006. The weather stations were deployed in areas known to contain cultural artifacts, but were located such that the presence and operation of the instruments would not disturb the archeologic sites. Analysis of aerial photographs indicated that a reduction in open sand area had occurred at all six study sites after Glen Canyon Dam was constructed and that new deposition had occurred as a result of the 1996 controlled-flood experiment (Webb and others, 1999a). These criteria were intended to allow monitoring of the effects of similar controlled-flood experiments in the event that any such releases occurred during the 2-year operation of the weather stations; thus, the effects of the November 2004 controlled-flood experiment were studied as part of this project. Wind and rainfall data were recorded digitally at 4-minute intervals at all weather stations; eolian sediment transport was measured on the basis of collection of sand in sand traps that were emptied during maintenance visits every 4–8 weeks (Draut and Rubin, 2005, 2006).

At all study sites, the most common incidence of high wind velocities and, thus, the greatest potential for eolian sediment transport (as well as actual measured sand-transport rates) occurred during the spring windy season. In 2004, seasonal sediment transport peaked in April and May; in 2005, the peak was later, in May and early June. During the spring 2004 and 2005 windy seasons, local maximum gusts were about 25 m/s, and daily local sand-transport rates were >100 g/cm. At all weather stations, sand-transport rates during the spring windy season generally were 5 to 15 times higher than at other times of the year (see appendix 1). High winds occur outside of the spring windy season but then are more commonly accompanied by rain, such as during the summer and early fall monsoon season, and so these high winds cause little or no sediment transport because wet sand is too cohesive to move.

Wind direction was observed to change radically over short time intervals; wind velocity and dominant wind direction commonly varied on a diurnal cycle, with maximum gusts typically in the afternoon. At 24.5 Mile, Malgosa, and Palisades, where two weather stations were deployed at each study site, wind velocities and sand-transport rates were consistently higher at the higher elevation weather station than at river level, attributable in part to the presence of vegetation near the river, which reduces wind velocity and, thus, eolian sediment entrainment. Sand transport has been shown in many studies to decrease approximately exponentially as vegetation cover increases (Olson, 1958; Bressolier and Thomas, 1977; Ash and Wasson, 1983; Wasson and Nanninga, 1986; Buckley, 1987; Bauer and others, 1996; King and others, 2005). Wind velocity also can increase at higher elevations, given the reduced interaction of airflow with the canyon walls, although local topography can cause significant local variations in wind speed and direction.

Variations in sand-transport rates between study sites are related not only to variations in wind velocity, but also to other local factors that affect sediment-entrainment potential. Sand transport is likely reduced near the river because the moist, cohesive sediment that composes fluvial sandbars limits sediment entrainment by wind as the sand becomes cohesive when damp (Svasek and Terwindt, 1974; Sarre, 1988, 1989; McKenna Neuman and Nickling, 1989; Namikas and Sherman, 1995; Selah and Fryrear, 1995; Wiggs and others, 2004). In Grand Canyon, sandbars inundated by daily fluctuating flows released from the dam for hydropower generation commonly do not dry thoroughly before being inundated again the following day. Although the sand traps used in this study did not allow resolution of sand transport on the daily scales of riverflow fluctuations (no automated sand traps are available commercially that record sand transport at that resolution), this study documented a local increase in eolian sediment transport adjacent to a new dry (subaerial) sandbar deposited during the 2004 controlled-flood experiment (Draut and Rubin, 2006).

The highest sand-transport rates were measured in "active" dune fields, that is, those with well-defined dune crests and sand shadows and with sparse or absent vegetation and biologic soil crust. On active dune fields, particularly at Malgosa and Forster (fig. 1), sand transport occurred by saltation and suspension at daily rates commonly of about 10 g/cm, but reached 100 to 1000 g/cm during the spring windy season. In contrast, less active eolian dune fields (those with substantial vegetation and soil crust, such as Palisades and Comanche) had daily sand-transport rates at least an order of magnitude lower (0.1–1 g/cm during the nonwindy season and 1–10 g/cm during the windy season). Those measured differences are consistent with the results of previous studies that demonstrated lower sand-transport rates over vegetated dunes and over soil crusted surfaces (Leys and Eldridge, 1998; Belnap, 2003; Goossens, 2004). The dune field at 24.5 Mile, which has both active and relatively inactive areas, had daily sand-transport rates more like those at Palisades and Comanche (about

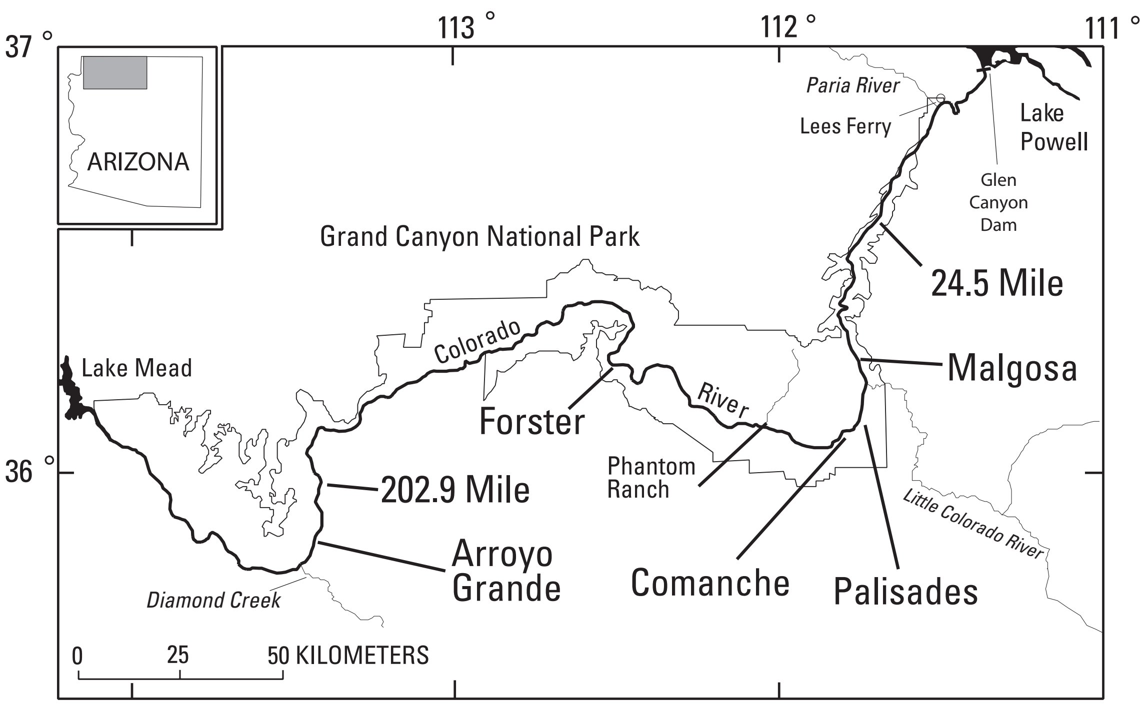

Figure 1. Colorado River corridor in Grand Canyon National Park, Ariz., showing locations of study sites. Data were collected from weather stations at 24.5 Mile, Malgosa, Palisades, Comanche, Forster, and 202.9 Mile; sedimentary profiles were studied at Palisades, Comanche, and Arroyo Grande. River reach between Lees Ferry and the Little Colorado River is known as Marble Canyon.

1 g/cm) than at active Malgosa and Forster (see appendix 1). The weather station near the river at Palisades (Pal L; see fig. 20 for location), on a relict fluvial cobble-boulderbar, typically recorded daily sand-transport rates of about 0.01 g/cm—the lowest of all the study sites—apparently owing to a low sand supply and not to low wind velocities (Draut and Rubin, 2006).

Rainfall data collected throughout the 26-month study interval indicate considerable spatial and seasonal variations (see appendix 1). Daily rainfall recorded by the upper and lower rain gages at a single study site commonly differed by several tenths of a millimeter, and daily rainfall totals by as much as several millimeters. Rain gages recorded strong, spatially isolated storms, particularly during the summer and early fall thunderstorm season. Total annual rainfall varied by a factor of >2 over distances of about 10 km in 2005 (Draut and Rubin, 2006), when the weather stations at Malgosa and Palisades (fig. 1) recorded the highest and lowest rainfall measured during this study, respectively—a difference attributable to local topographic influence on the movement of weather systems. During the unusually wet winter of 2005, weather stations at study sites in western Grand Canyon recorded approximately twice the average rainfall recorded by weather stations at study sites in eastern Grand Canyon and Marble Canyon. The measured spatial variation in rainfall indicates that future sedimentologic and geomorphologic studies in Grand Canyon would benefit substantially from continued or expanded data collection at multiple sites along the river corridor because the rainfall records collected by the NPS at Phantom Ranch (near river mile 88) evidently are not valid for other parts of the canyon.

Overview of Sedimentologic and Geomorphologic Investigations

In May 2003, reconnaissance along the Colorado River corridor in Grand Canyon National Park was performed by personnel from the USGS, the Hopi and Hualapai Tribes, GeoArch, Inc., and the Western Area Power Administration, led by NPS archeologists J.R. Balsom, J.L. Dierker, and L.M. Leap. This group visited 38 archeologic sites at which eolian sediment was believed to be important either as the material underlying the site or as material forming a protective cover. Depositional environments of the sediment around these archeologic sites were determined, where possible, through identification of sedimentary textures characteristic of water-lain (fluvial or tributary flow) or eolian deposition (for example, Walker, 1963; Hunter, 1977; Rubin and Hunter, 1982, 1987; Gladfelter, 1985; Rubin, 1987; Rubin and others, 1990; Schmidt, 1990; Southard and Boguchwal, 1990). The group performing this reconnaissance, while noting that the selected sites likely were not typical of all archeologic sites in the river corridor, determined (through digging shallow test pits into sediment to expose three-dimensional sedimentary structures) that much of the sediment beneath or above these particular archeologic sites had been transported by wind from fluvial deposits at the river margins (Draut and others, 2005). Several archeologic sites were built on or buried by sediment deposited directly by large floods of the Colorado River. Observations during the reconnaissance formed the basis for more detailed sedimentologic and geomorphologic investigations at a selected subset of the 38 archeologic sites the following year and for deployment of the weather stations discussed above.

The research group hypothesized that eolian sediment transport to archeologic sites apparently is limited largely by sand supply and vegetation cover rather than by wind. Reduction in open sand area on sandbars, and submergence of sandbars by daily riverflow fluctuations, can be expected to reduce eolian sediment transport to nearby dune fields with associated archeologic sites (Ash and Wasson, 1983; Buckley, 1987; Namikas and Sherman, 1995; Wiggs and others, 2004). Reduced eolian sediment transport, in turn, can be expected to facilitate the growth of existing arroyos and the establishment of new ones, as discussed by Thompson and Potochnik (2000). Erosion of archeologic sites by arroyo incision was apparent at many of the sites visited in May 2003; repeat photographic images at those sites, taken by NPS personnel since the late 1990s, support this observation (Leap and others, 2000). Some archeologic sites are affected by small drainages that might be repairable by modest increases in eolian sediment deposition. At some archeologic sites, filling of small (<1 m wide) gullies by eolian sediment would aid preservation of cultural features that have already been stabilized by construction of check dams; other areas are compromised by large drainages that could not reasonably be expected to fill with eolian sediment, given the current local geomorphology and observable sand supply.

Sedimentologic and geomorphologic investigations in May 2004 focused on the Palisades, Lower Comanche, and Arroyo Grande areas along the Colorado River corridor (figs. 1 and 2). These river reaches are all characterized by alluvial terraces that represent multiple episodes of floodplain aggradation within the pool-and-drop bedrock canyon. The highest alluvial terraces at each study site contain deposits left by predam floods of >5,660 m^3/s (Hereford and others, 1993; Topping and others, 2003). The terraces at all three study sites contain arroyo networks (Patton and Schumm, 1981; Waters and Haynes, 2001; Webb and Hereford, 2001), as much as several meters deep and wide, that result from incision by local rainfall runoff. Coppice dunes partly cover the terrace surfaces at all three study sites. Talus piles commonly are present at the base of bedrock walls, and debris fans occur at the mouths of side-canyon tributaries. The May 2004 investigations complemented several previous studies, particularly those at Palisades, where geomorphologic mapping by Hereford (1993, 1996) and Hereford and others (1993, 1996) generated detailed interpretations of the surficial geology and radiocarbon dates; the same area was visited by Hereford and others (1993) and Thompson and Potochnik (2000) to formulate the base-level hypotheses discussed above. Grams and Schmidt (1999) used historical photographs to document a reduction in the extent of surficial sand deposits at Palisades since 1890. High-resolution topographic surveys by Yeatts (1996) and Hazel and others (2000) indicated aggradation of fluvial sand deposits at Palisades as a result of the March 1996 controlled-flood experiment from Glen Canyon Dam, and inferred eolian migration of sediment to higher elevations during the following year. Topographic surveys documented about 25 m^3 of sediment deposition in an arroyo mouth at Palisades as a result of the November 2004 controlled-flood experiment; in the 6 months after that experiment, the raised arroyo base level was not observed to have affected the topography of higher terrace areas at Palisades (Hazel and others, 2008).

After viewing natural sedimentary exposures, the May 2004 research group chose to focus on those that were most complete vertically and that offered good spatial coverage throughout varying terrain. Data were obtained by detailed examination of sedimentary profiles and numerous shallow test pits in alluvial terraces, coppice-dune fields, and, at Palisades, near the distal margin of a debris fan from a tributary canyon (fig. 2). Although the sedimentary deposits studied during this investigation were in the vicinity of archeologic sites, no cultural artifacts were exposed or collected. The presence of arroyos facilitated the exposure of vertical faces; at Palisades and Lower Comanche (fig. 1), three of the sedimentary sections studied in detail were exposed by digging test pits into areas without cultural artifacts. Thicknesses of sedimentary units were measured, and sedimentary structures, clast lithology, and sediment color were described. At selected sites, sediment samples were collected for grain-size analysis, using a Coulter laser particle-size analyzer at the GCMRC laboratory in Flagstaff, Ariz. Sedimentary structures were used to identify the number and thickness of fluvial deposits, eolian reworking of fluvial sediment, and interaction of those processes with local runoff sedimentation. Geomorphic and sedimentary processes that affect each studied archeologic site are summarized for Palisades, Lower Comanche, and Arroyo Grande in tables 1, 2, and 3, respectively; detailed discussions of each site were presented by Draut and others (2005).

Identifying Fluvial and Eolian Deposits by Using Sediment Grain Size

In addition to describing depositional units by using sedimentary structures, we investigated the use of grain-size analysis to distinguish fluvial from eolian material. Previous studies have shown that grain size and moment statistics are of little use for identifying fluvial and eolian deposits when comparing samples from multiple geographic regions (Ahlbrandt, 1979; Tucker and Vacher, 1980; Gladfelter, 1985), owing to variations in clast composition and weathering conditions. We analyzed particle-size distributions in 100 sediment samples from predam fluvial deposits, postdam fluvial deposits, and eolian deposits collected only within the Colorado River corridor of Grand Canyon (fig. 3) to assess whether this sedimentary system is consistent enough to use grain size to classify samples of unknown origin collected within this reach of the river corridor. (We refer here only to fine-grained fluvial deposits at flood-stage elevation that are relevant to archeology; deeper in the river channel, fluvial deposits include sediment grain sizes as large as boulders to which this discussion does not apply.)

Although grain sizes within Colorado River fluvial deposits vary as a function of sand supply, riverflows, and proximity to flooding tributaries, this study found essentially no overlap between the textural characteristics of predam fluvial (fig. 3*A*) and mature eolian deposits (fig. 3*A*) in Grand Canyon; the finest eolian deposits are coarser than the coarsest predam fluvial units sampled (fig. 3*E*; see Burke and others, 2003). The absence of overlap indicates that although the mature eolian deposits are assumed to have been derived largely from predam fluvial deposits, enough finer fluvial sediment is removed by wind that the grain-size distribution of the remaining (winnowed) sand in mature eolian deposits is characteristically coarser than in the original fluvial deposit (see Rubin and others, 2006). Grain-size distributions of eolian samples overlap, however, with those from postdam high-flow deposits (fig. 3*F*). The postdam fluvial samples shown here (deposited by the November 2004 high flow) are coarser, as a population, than the predam flood deposits (fig. 3*D*). The presence of coarser postdam fluvial deposits is consistent with previous analyses of other postdam flood deposits and reflects the observation that the sediment transported and deposited by the Colorado River coarsened after the closure of Glen Canyon Dam in response to limitation of the upstream sediment supply and winnowing of the fine sediment already in the river channel (Rubin and others, 1998; Topping and others, 2000a,b).

Therefore, within the Colorado River corridor, grain size can be used to distinguish predam flood deposits (which underlie and overlie archeologic sites in Grand Canyon, unlike younger, lower-elevation postdam deposits) from mature eolian deposits if sedimentary structures are absent. Particle size as a diagnostic tool should still be used with caution even within one sedimentary system, unless the range of grain sizes for known eolian and fluvial deposits in that system is well defined. The difference in grain-size distribution between a fluvial deposit and its winnowed, eolian counterpart depends on the initial composition of the flood sediment and on the wind conditions affecting the sediment. Colorado River fluvial sediment that has undergone some wind reworking might not yet plot within the mature eolian field of figure 3*C*, limiting these diagnostic applications.

Two Types of Eolian Deposit Defined for the Colorado River Corridor

Results of the sedimentologic and geomorphologic investigations of 2004, in combination with quantified seasonal wind directions and sand-transport potential, indicate two types of eolian deposit in the Colorado River corridor—modern fluvial-sourced (MFS) and relict fluvial-sourced (RFS)—

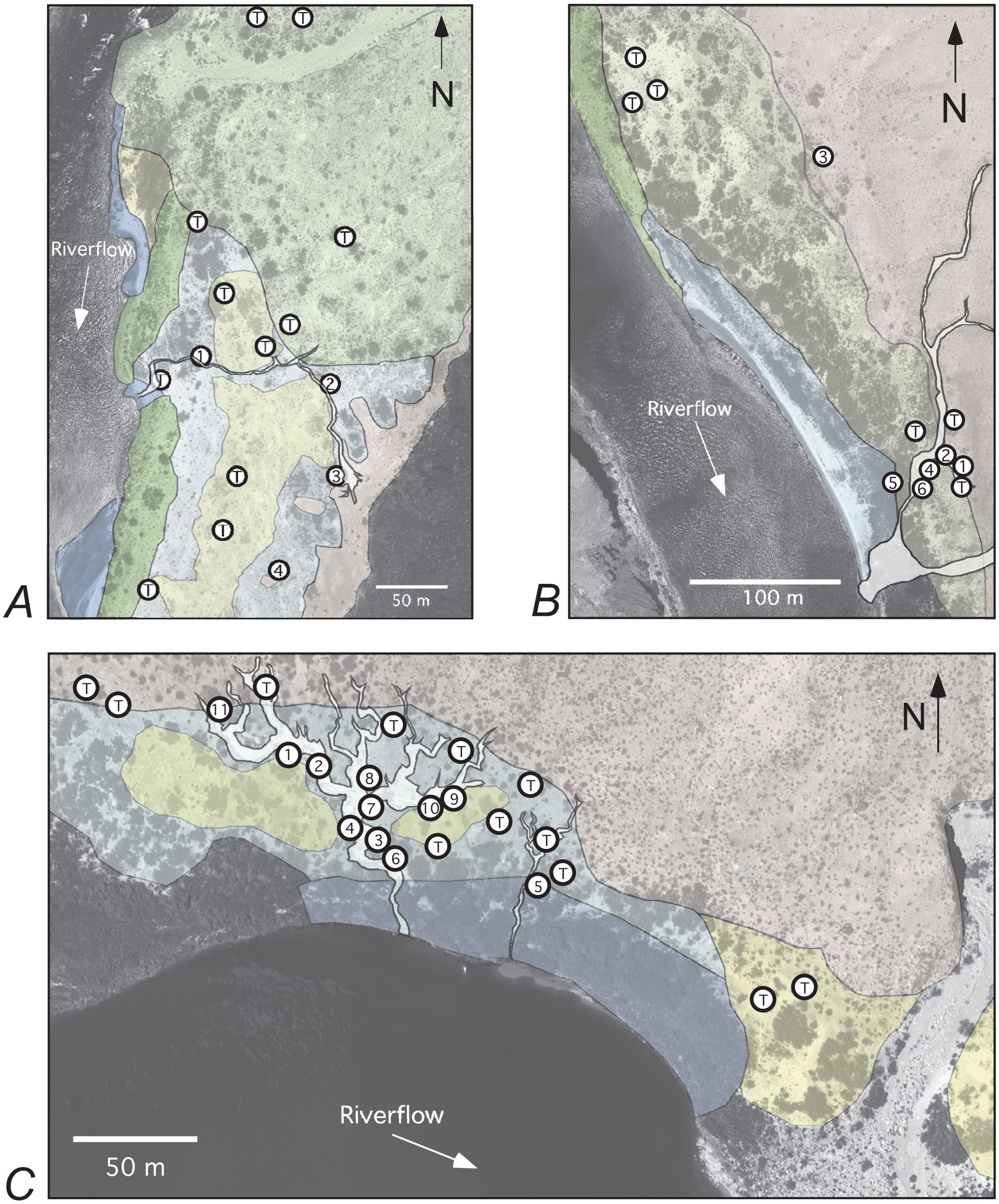

Figure 2. Aerial photographs of study area sites along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1), with geomorphology shown in colored overlays. Numbered circles, sedimentary profiles measured in detail; circled Ts, test pits studied in less detail and to shallower depth. Riverflow is 226 m^3/s in all photographs. *A*, Palisades. Geomorphic data from this study and Hereford and others (1993). Pale-green area in north is a debris fan; darker green strips along shoreline are a cobble bar, likely a reworked part of debris fan. Light-blue areas are relict (predam) terrace surfaces; darker blue areas are modern fluvial sandbars at an elevation within common dam-controlled flow fluctuations (<566 m^3/s). Yellow areas are coppice dunes. Orange area is a playalike surface where slopewash and colluvial sediment accumulate. Arroyo is outlined in white. *B*, Lower Comanche. Green area is a boulder bar. Blue area is fluvial deposits that form a narrow terrace. Yellow area is coppice dune. Orange area is a talus and colluvial slope drained by an arroyo outlined in white. *C*, Arroyo Grande. Light-blue and dark-blue areas are two terrace surfaces, one at higher and one at lower elevation, respectively. Yellow areas are eolian coppice dunes on the upper terrace and to east. Orange area is talus and colluvium with bedrock exposed. Arroyo is outlined in white.

Table 1. Summary of sedimentary processes affecting archeologic sites at Palisades, Grand Canyon National Park, Ariz.

[Site numbers assigned by the National Park Service. See Draut and others (2005) for detailed discussions of sedimentary processes in these areas. Prehistoric sites were dated by radiocarbon methods and artifact identification to the Pueblo I and Pueblo II (PI and PII) periods (Fairley and others, 1994; Hereford, 1996), although there is some evidence for Preformative occupation (Dierker and Downum, 2004). The historical site is associated with mining activity and was occupied from A.D. 1890 to 1910]

Site	Age and affiliation of site	Sediment on which site was originally built	Sediment overlying site	Sedimentary and geomorphic characteristics
C:13:033	Uncertain; probably Pueblo I–III	Debris-fan cobbles, gravel	Eolian (minor)	Dominated by debris-flow deposition
C:13:098	Historic	Debris-fan cobbles, gravel	None	Remains of 19th century cabin built on debris-fan sediment
C:13:099	Pueblo I–II	Fluvial; slopewash sand, gravel	Eolian; distal debris-flow material	Interbedding of fluvial, eolian, debris-flow and slopewash sediment
C:13:100	Pueblo I–II	Fluvial	Fluvial and eolian	Fluvial sediment modified by wind
C:13:101	Pueblo I–II	Rounded cobbles, likely fluvial	Eolian (minor)	Coppice dunes overlying rounded cobbles
C:13:272	Pueblo I–II	Debris-fan cobbles, gravel	Fluvial and eolian	Fluvial sediment modified by wind into coppice dunes; bioturbated
C:13:334	Pueblo I–II	Fluvial; ponded slopewash	Fluvial	Eroding out of apparent fluvial deposit
C:13:336	Pueblo I–II	Likely fluvial (artifacts not in original position)	Fluvial and eolian	Fluvial sediment reworked by wind into coppice dunes
C:13:355	Pueblo II	Fluvial; distal debris flow	Fluvial and eolian	Area dominated by debris fan, smaller volumes of fluvial and eolian sediment

Table 2. Summary of sedimentary processes affecting archeologic sites at Lower Comanche, Grand Canyon National Park, Ariz.

[Site numbers assigned by the National Park Service. Most cultural features in this area date to the Late PI–Early PII Formative period (about A.D. 900–1000; Fairley and others, 1994). At least one site contains artifacts related to late prehistoric and early historical use by the Hopi Tribe (Fairley and others, 1994). Early Formative age for site C:13:273 is based on radiocarbon ages obtained on a hearth feature by Yeatts (1998)]

Site	Age and affiliation of site	Sediment on which site was originally built	Sediment overlying site	Sedimentary and geomorphic characteristics
C:13:273	Early Formative (Basketmaker III)	Fluvial, eolian; colluvial	Eolian (minor)	Fluvial and eolian deposits interbedded with slopewash colluvium.
C:13:274	Pueblo I–II	Eolian	None	Eolian substrate overlies distal debris-fan sediment.
C:13:333	Pueblo I–II	Eolian	Eolian (minor)	Site destabilized by eolian deflation and dune migration.
C:13:335	Pueblo I–II	Eolian	Eolian	Exposed by eolian deflation.
C:13:337	Pueblo I–II	Eolian	None	Eolian dunes; site in interdune area.
C:13:373	Prehistoric to Early Historic Hopi	Eolian	Eolian	Site destabilized by eolian deflation and dune migration.

Table 3. Summary of sedimentary processes affecting archeologic sites at Arroyo Grande, Grand Canyon National Park, Ariz.

[Site G:03:064 includes 15 separate features, generally associated with the protohistoric and Early Historic-era Pai culture related to the Paiute and Hualapai Tribes. Many features were built on eolian sediment directly, but this relatively thin eolian substrate is underlain by volumetrically more substantial flood deposits. N.a., not assigned]

Site	Age and affiliation of site	Sediment on which site was originally built	Sediment overlying site	Sedimentary and geomorphic characteristics
G:03:064, F1	Protohistoric to Early Historic Pai	Eolian	Eolian (minor)	Coppice dunes on upper terrace surface
G:03:064, F2	Protohistoric to Early Historic Pai	Eolian	Eolian (minor)	Coppice dunes on upper-terrace surface
G:03:064, F3	Protohistoric to Early Historic Pai	Eolian	Eolian (minor)	Coppice dunes on upper-terrace surface
G:03:064, F4	Protohistoric to Early Historic Pai	Eolian	Eolian (minor)	Interdune area in coppice-dune field; arroyo incision affects feature stability
G:03:064, F5	Protohistoric to Early Historic Pai	Eolian	Eolian (minor)	Interdune area in coppice-dune field; affected by eolian deflation
G:03:064, F6	Protohistoric to Early Historic Pai	Terrace surface (dominantly fluvial)	None	Arroyo incision affects terrace surface in vicinity of this feature.
G:03:064, F7	Protohistoric to Early Historic Pai	Terrace surface (dominantly fluvial)	None	Surface of upper terrace
G:03:064, F8	Protohistoric to Early Historic Pai	Terrace surface (dominantly fluvial)	None	Surface of upper terrace
G:03:064, F9	Protohistoric to Early Historic Pai	Terrace surface (dominantly fluvial)	None	Surface of upper terrace
G:03:064, F10	Protohistoric to Early Historic Pai	Terrace surface (dominantly fluvial)	None	Surface of upper terrace
G:03:064, F11	Protohistoric to Early Historic Pai	Terrace surface (dominantly fluvial)	None	Surface of upper terrace
G:03:064, F12	Protohistoric to Early Historic Pai	Eolian	Eolian (partly covers feature)	Small coppice dunes on upper-terrace surface. Feature affected by arroyo incision.
G:03:064, F13	Protohistoric to Early Historic Pai	Eolian	None	Small coppice dunes on upper-terrace surface. Feature affected by arroyo incision.
G:03:064, F14	Protohistoric to Early Historic Pai	Interbedded fluvial/eolian/colluvial	Eolian	Exposed in small drainage within upper terrace
G:03:064, F15	Protohistoric to Early Historic Pai	Colluvium	None	Near landward edge of upper terrace, in area dominated by slopewash sedimentation
N.a.	Unknown	Slopewash colluvium and eolian	Fluvial, eolian, and colluvial	Hearth feature exposed in arroyo wall within upper terrace

distinguishable by the relative positions and orientations of eolian deposits and modern (<1,270 m^3/s) fluvial deposits and by the dominant wind directions causing eolian sediment transport in each setting.

MFS dune fields, directly downwind from recent (post-dam) fluvial deposits, formed as the wind transported sand inland from a river-level sandbar, creating the dune field downwind. An example of an MFS deposit, at the mouth of Forster Canyon (river mile 123.0), is shown in figure 4*A*. In this area, the dominant wind direction (as measured during this study) is from the north-northeast, dune configuration indicates net sand transport to the south-southwest, and high wind velocities (>20 m/s during the spring windy season) transport sediment away from a river-level sandbar to form a dune field downwind. Within this active dune field, daily sand-transport rates of about 100 g/cm were common in 2004 and 2005, and dune-surface elevations were observed to increase or decrease locally by tens of centimeters between equipment-maintenance visits every 6–8 weeks.

RFS deposits formed as the wind eroded and redeposited sediment that composed extensive predam flood deposits, generating eolian dunes essentially in place over parts of fluvial terraces. Whether or not RFS deposits are downwind of modern fluvial sandbars, their most substantial sediment

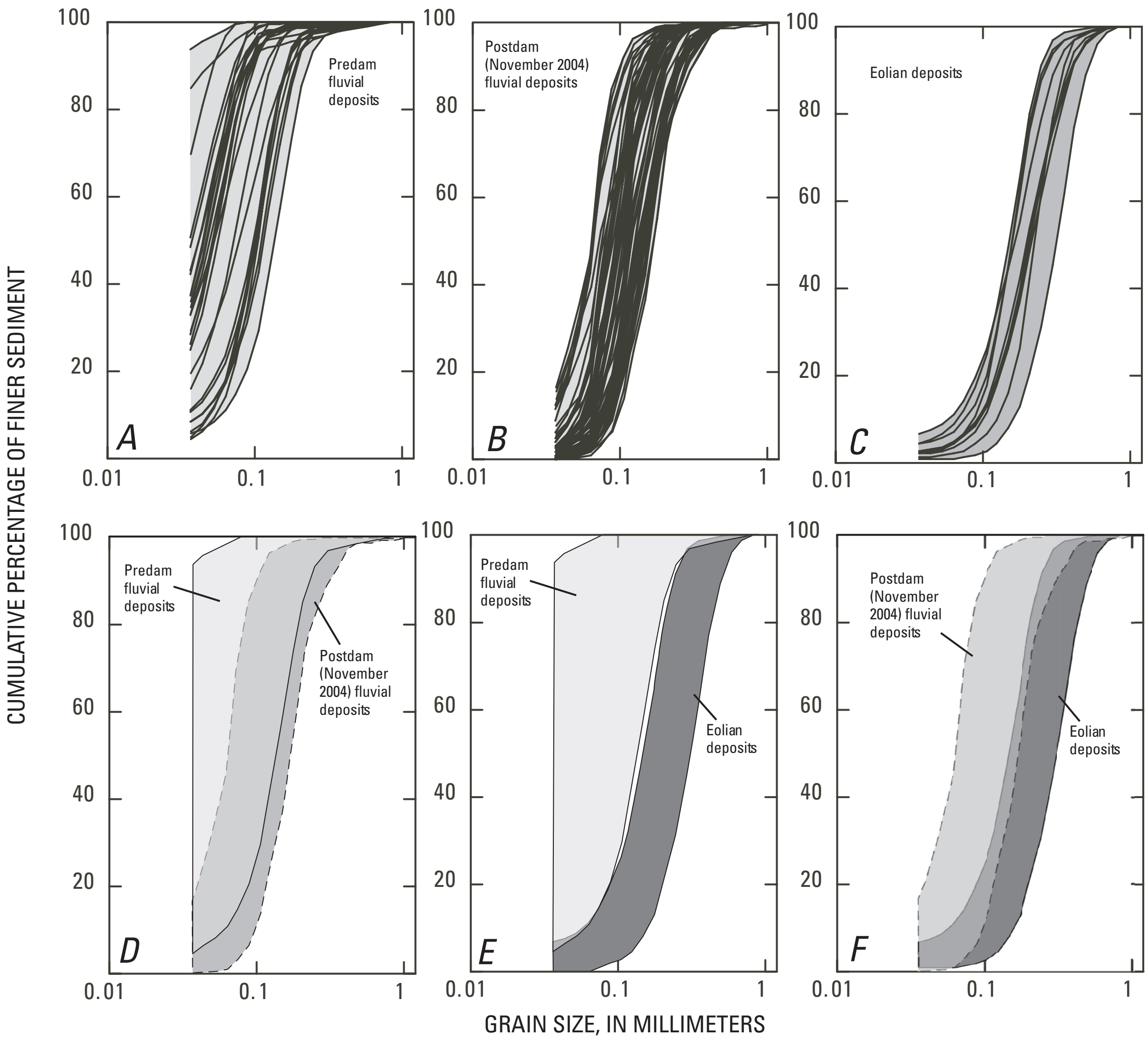

Figure 3. Grain-size distributions, obtained by using laser particle-size analysis, in fluvial and eolian deposits along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Cumulative percentage of the sediment sample that is finer than the corresponding grain diameter shown on the horizontal axes, ranging from 0.037 mm (coarse silt) to 1.000 mm (boundary between coarse and very coarse sand; Boggs, 1995). *A*, Grain-size distributions in 27 sediment samples from 10 different fluvial strata, all deposited by Colorado River floods that predated closure of Glen Canyon Dam. Samples were identified as fluvial deposits by presence of unequivocal sedimentary structures. Multiple samples were collected from some flood deposits because grain size commonly varies vertically within each deposit (Rubin and others, 1998). *B*, Grain-size distributions in 63 samples from 10 different sedimentary deposits from November 2004 experimental flood in Grand Canyon. *C*, Grain-size distributions in sediment from 10 eolian deposits in Grand Canyon. *D*, Comparison of predam fluvial deposits in figure 3*A* (solid-outlined light-gray field) with postdam (Nov. 2004) deposits in figure 3*B* (dashed-outlined darker gray field). Deposits of 2004 flood are coarser and show a tighter distribution than the predam deposits. *E*, Comparison of predam fluvial deposits in figure 3*A* (light-gray field) with eolian deposits in figure 3*C* (dark-gray field). *F*, Comparison of the postdam (Nov. 2004) flood deposits in figure 3*B* (dashed-outlined medium-gray field) with eolian deposits in figure *C* (dark-gray field).

source is not the modern, presently active sandbars (those containing fluvial sediment transported by riverflows at or below approximately 1,270 m^3/s), but larger predam flood deposits (see Burke and others, 2003), for example, the coppice-dune field at Palisades (fig. 4*B*). This study and those by Hereford and others (1993, 1996) showed that the Palisades area is underlain by extensive predam fluvial deposits; the eolian dune field lies atop part of the fluvial terrace. The dominant direction of sediment-transporting winds measured at Palisades over >2 years was from the south-southeast (Draut and Rubin, 2006). If that direction is representative of long-term local weather conditions, then only minor amounts of sediment are transported by wind from river-level sandbars to the eolian dune field at Palisades, where the dunes apparently formed from wind erosion and redeposition of sediment that composed the predam fluvial deposits. Although some migration of eolian dunes is apparent today in the northern part of the Palisades dune field, generally this dune field is inactive (relative to such study sites as Malgosa and Forster) and has well-established vegetation and biologic soil crust. Although some new sediment probably is occasionally transported into the dune field from river-level sandbars (Yeatts, 1996), given appropriate short-term wind conditions, the dominant direction of sand-transporting wind measured at Palisades in this study indicates that wind likely causes a net loss of sand from this dune field to the northwest (where it can be lost into the river) at daily rates of about 1 g/cm. Continued erosion of eolian and fluvial deposits by gullies causes substantial additional loss of sediment at Palisades. Because the mechanism of formation of this RFS deposit was linked inextricably with the deposition of fluvial sediment during large, sediment-rich predam floods, substantial new sediment will probably not be supplied to the Palisades dune field without similar large, sediment-rich floods in the future.

MFS deposits generally are smaller and more common in Grand Canyon than are RFS deposits. Eolian deposits of both types are known to contain archeologic material. For different reasons, both MFS and RFS dune fields should be considered sensitive to Glen Canyon Dam operations. Because they are directly downwind from fluvial sandbars, MFS deposits receive some windblown sand as a function of wind velocity, exposed dry fluvial-sandbar area, and sediment-trapping vegetation between the fluvial deposit and its associated eolian deposits. Fluvial-sandbar area and riparian vegetation have been shown in numerous studies to respond to dam operations, and so changes to either condition can affect the delivery of eolian sediment to MFS dune fields downwind.

The dimensions (length and width) of fluvial sandbars relative to the local wind direction control the supply of windblown sediment inland that forms MFS deposits and potentially covers local archeologic sites. For example, a 2-m-wide sandbar that extends 50 m along the riverbank will be able to supply more windblown sand inland and downwind to a longer strip of shoreline than will a 10-m-wide and 10-m-long sandbar, assuming that equilibrium sand transport is attained

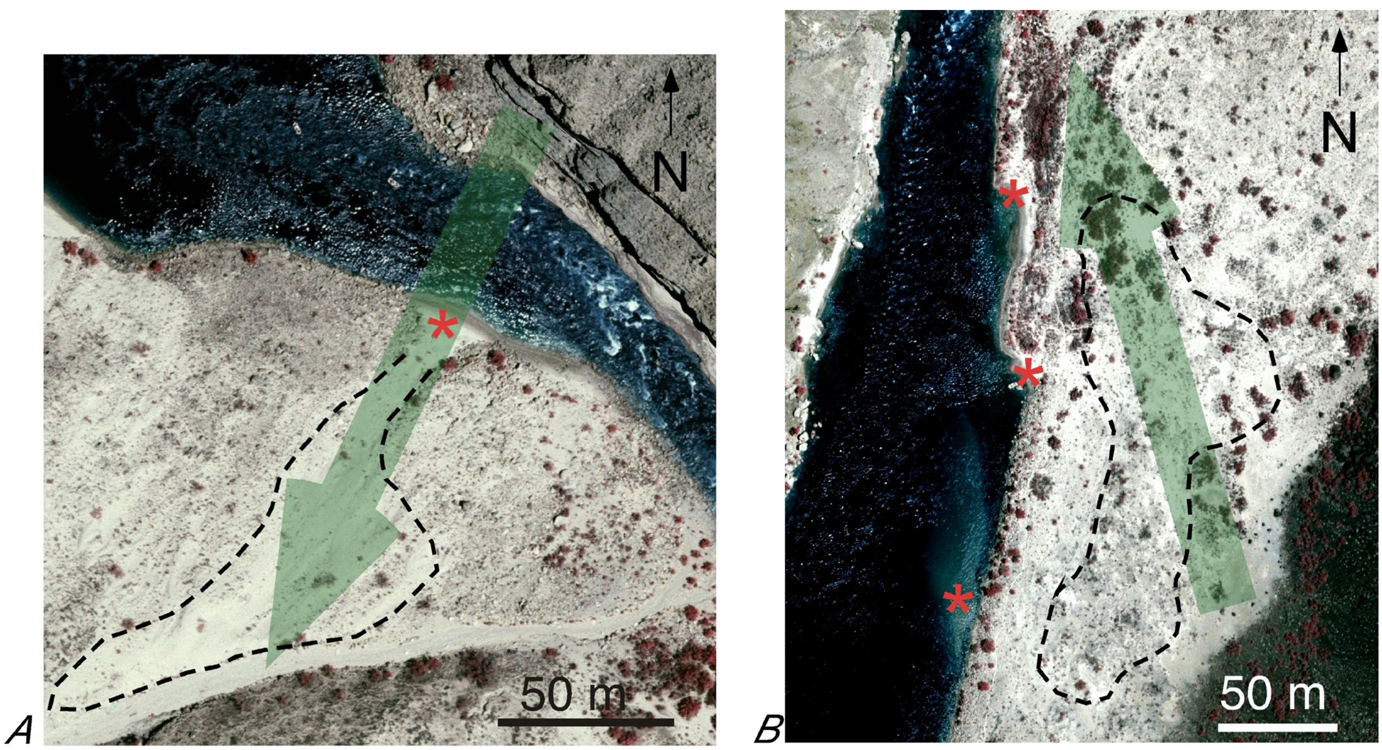

Figure 4. Aerial photographs showing two types of eolian deposit defined for the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Green arrows indicate dominant direction of local wind with high-enough velocity to transport sand (obtained from vector sums of 4-minute wind-velocity measurements collected over many months; see Draut and Rubin, 2005, 2006). Black dashed lines, edges of eolian dune fields; red asterisks, nearby modern fluvial sand deposits. *A*, Modern fluvial-sourced (MFS) deposits at the mouth of Forster Canyon (river mile 123.0, fig. 1) directly downwind from fluvial sand deposits. In this area, dominant wind direction is from north-northeast, transporting sand away from a river-level sandbar to form a dune field downwind. *B*, Relict fluvial-sourced (RFS) deposits at Palisades (river mile 66), formed as wind reworked sediment deposited by large predam floods, generating eolian dunes basically in place across parts of fluvial terraces. Dominant wind direction in this area is from south-southeast. Modern fluvial sand deposits are not directly upwind of eolian dune field, and so little sediment from those sandbars reaches dunes.

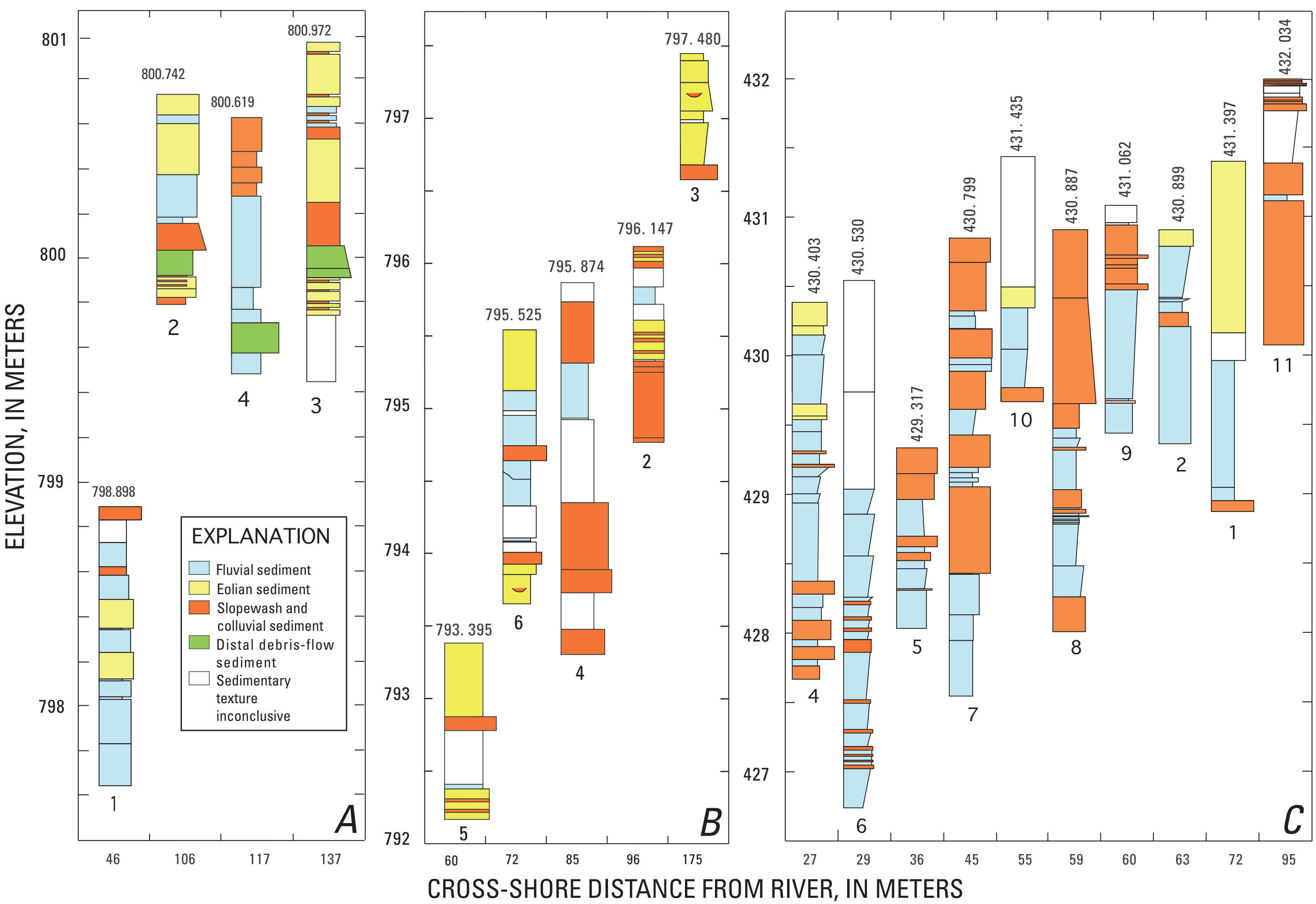

Figure 5. Sedimentary profiles at Palisades (*A*) Lower Comanche (*B*) Arroyo Grande (*C*) study sites in Grand Canyon National Park, Ariz. (fig. 1). Elevation is referenced to NAVD88 (1999) datum; numbers above each profile are elevation of land surface (in meters). 1,270-m^3/s flood stage is equivalent to elevations of 796 m at Palisades, 789 m at Comanche, and 425 m at Arroyo Grande. Stage-discharge relations for Palisades and Comanche from Hazel and others (2006a); values for Arroyo Grande are estimates only. Numbers below each profile indicate stratigraphic sections by which these profiles are identified in detailed discussion by Draut and others (2005). Colors of individual units within each profile correspond to inferred depositional environment (assigned on the basis of sedimentary structures, clast composition, and, for about 10 individual strata, grain-size distribution). Slopewash and colluvial sediments are derived from local bedrock and talus. White units are those for which a depositional setting was not assigned, either because sedimentary textures were inconclusive or because those parts of profiles were inaccessible. Width of each sedimentary unit is a schematic representation of its grain size (the wider the unit, the coarser the sediment); some units coarsen or fine upward. Grain-size properties were determined primarily by using grain-size-comparator charts.

during wind events over each sandbar, even though the two sandbars have identical area (100 m^2). Sensitivity of MFS deposits to dam operations is, therefore, a function not only of postdam changes in the area of fluvial sandbars but also of the dimensions of the remaining open, dry sandbar and its position relative to eolian deposits (and any archeologic sites) inland of the river.

RFS deposits include eolian coppice dunes that compose the uppermost, wind-reworked part of predam terraces that are largely alluvial in composition, containing sediment deposited by floods higher than any postdam floods (≥5,660 m^3/s). Sediment-rich floods of predam magnitude no longer occur in this regulated river, and so the relict fluvial deposits no longer constitute an active sediment source. Therefore, no substantial new deposition is likely to occur on RFS dune fields in the absence of large sediment-rich floods. As vegetation and biologic soil crust grow on RFS coppice-dune fields over time, active eolian sediment transport decreases within them, such that these areas become increasingly unable to compensate for precipitation-induced gully erosion. As a result, large gully and arroyo systems can form on predam terraces and associated RFS dune fields (figs. 2*A*, 2*C*).

Sedimentary Environments—Implications for the Preservation of Archeologic Sites

Fluvial deposits are the most common substrate underlying the archeologic sites at Palisades and Arroyo Grande (fig. 1). Fluvial deposition was observed generally to decrease with increased elevation and distance from the river as locally derived slopewash and colluvial sediment became more conspicuous (fig. 5). The abundance of fluvial sediment does not decrease regularly away from the river, however, partly because eolian modification can occur across much of an alluvial terrace almost irrespective of distance from the river (although wind velocities generally are lower at the river margin, where vegetation commonly is thick). In the Colorado River corridor, wind velocity (and eolian modification of fluvial sediment) typically peaks during the spring windy season, as discussed above. Although eolian dunes are present on terrace surfaces at Palisades and Arroyo Grande, eolian sediment was observed to be more important as a protective cover in those areas than as the substrate on which cultural features were formed. At Lower Comanche, in contrast, five of the six archeologic sites were formed on and are partly buried by eolian sediment; however, the largest and most extensive archeologic site at Lower Comanche is not in the eolian dune field but on a lower elevation terrace constructed of fluvial, eolian, and slopewash deposits. In all three areas, geomorphic processes that affect the condition of archeologic sites today include arroyo incision, wind action, and episodic local deposition of slopewash and debris-flow sediment. Arroyo incision and eolian deflation contribute to exposure and erosion of cultural artifacts in all three areas: eolian deflation exposes artifacts that may then be washed away by rainfall runoff, and dune migration (particularly at Lower Comanche) causes downslope movement of artifacts as the sand surface shifts underneath. Episodic deposition of flood sediment at Palisades and Arroyo Grande no longer occurs at elevations high enough to affect archeologic sites under the present dam-controlled flow regime of the Colorado River.

Many archeologic sites, including most of those at Palisades, Lower Comanche, and Arroyo Grande (fig. 1), were formed on terraces that consist largely of Colorado River alluvium. Many of those sites are preserved today by having been buried by flood deposits and eolian dunes. From prehistoric times until the closure of Glen Canyon Dam in 1963, the highest-elevation fluvial deposition in this river corridor occurred during spring snowmelt floods that regularly exceeded even the highest postdam riverflows: the highest postdam riverflow, 2,750 m^3/s, occurred in 1983, while the predam 8-year flood level was 3,540 m^3/s (Topping and others, 2003). Annual sediment-rich floods occurred concurrently with, or receded during, the spring windy season, when wind would have remobilized sand from recent flood deposits to form eolian dune fields. The modern absence of sediment-rich floods eliminates the mechanism for depositing sediment at the elevations of prehistoric alluvium, as well as the source of new sediment for eolian deposits. Dam operations have thus substantially altered the fluvial and eolian processes that acted on the prehistoric, inhabited landscape. This alteration potentially hinders the preservation of tens to hundreds of archeologic sites, including most of those visited in this study, by limiting the fluvial and eolian sediment available to bury and cover them. (The NPS lists several hundred archeologic sites as potentially affected by dam operations, but we refer only to those that were studied at this level of sedimentary detail for this project.) Therefore, preservation of archeologic sites might be enhanced by restoring fluvial and eolian deposition to resemble more closely those processes that occurred before the river was dammed—large, sediment-rich floods that left fluvial sand deposits from which sand was remobilized by wind.

Fluvial deposits form the most extensive base on which the archeologic sites at Palisades and Arroyo Grande (fig. 1) were formed, spanning hundreds of square meters in area (see Hereford and others, 1996). Moderate (about 1,270 m^3/s) controlled Colorado River high flows, as released in 1996 and 2004, can enlarge sandbars (at least temporarily) that supply sand to eolian deposits covering archeologic sites at higher elevations. To effect a large-scale restoration of fluvial terraces, however, a riverflow of >4,810 m^3/s would likely be needed, on the basis of stage-discharge relations developed for Palisades from historical-flood debris (Draut and others, 2005; Hazel and others, 2006b), although we recognize that stage-discharge curves can vary, owing to episodic constriction of the river channel by debris flows. To cause deposition instead of erosion, flood waters also would require high suspended-sediment concentrations (Hazel and others, 2006a; Topping and others, 2006). The suspended-sediment concentrations measured for predam riverflows >1,000 m^3/s were within an order of magnitude of 0.1 g/L (Topping and others, 2000b);

it is not known what the suspended-sediment concentration would be in a postdam flood of 4,810 m^3/s. In general, the average annual postdam sediment load is about 5–15 percent of average predam values (varying locally relative to tributaries). An experimental flow of the magnitude needed to inundate predam fluvial terraces at Palisades, about 4,810 m^3/s, would be nearly 4 times higher than the highest experimental flows currently under consideration by the Glen Canyon Dam Adaptive Management Program. Suspended-sediment concentrations also would probably be too low in such a high flow to have a substantial restorative effect unless the flood followed an exceptionally large input of tributary sediment or sediment were added artificially downstream of Glen Canyon Dam. If a sediment-rich, high-discharge dam release were to deposit a large volume of new high-elevation fluvial deposits, those deposits could then act as a source for windblown sediment, which could be transported to MFS dune fields and reworked to form or replenish RFS dune fields. Increased transport of eolian sediment to dune fields is expected to inhibit erosion by filling small gullies, which act as natural traps for windblown sand (documented in filled paleogullies by Thompson and Potochnik, 2000, and observed during this study in several paleogully exposures and in modern dune fields; Draut and Rubin, 2006), and by providing additional protective cover to archeologic sites.

Controlled dam releases of about 1,270 m^3/s in 1996 and 2004 deposited sand in arroyo mouths at Palisades and elsewhere (Yeatts, 1996; Topping and others, 2006; Hazel and others, 2008), possibly increasing the preservation potential of some archeologic sites by temporarily raising the effective base level to which arroyos incise (Hereford and others, 1993). This effect is likely short lived, however, because runoff from local rainstorms can quickly remove the new deposits in arroyo mouths and lower the effective base level once again. Relatively few data are available concerning the effects of sediment deposition during controlled floods and the ability of sediment deposition to control arroyo base level on various time scales; such data would definitively support or refute the still-debated hypotheses of Hereford and others (1993) and Thompson and Potochnik (2000). Local climate, drainage area, substrate composition, and river-related sediment and base-level effects all contribute to arroyo incision and healing (Waters and Haynes, 2001; Webb and Hereford, 2001), although arroyo incision remains incompletely understood. Arroyo-incision processes in the Colorado River ecosystem could be clarified by repeated high-resolution mapping of gullies and affected archeologic sites to measure local erosion and deposition rates, and by measuring rainfall and other climatic parameters that vary widely within the complex canyon topography. It is noteworthy that Palisades and Lower Comanche, where large arroyos erode multiple archeologic sites, were the two areas with the least rainfall of the six sites monitored during this 26-month study (Draut and Rubin, 2006). If our data are representative of longer term, regional variation in rainfall, then enhanced local precipitation might be eliminated as a possible cause of recent preferential arroyo formation at those sites.

In general, dam operations are less likely to affect deposition of slopewash and debris-flow sediment than to affect fluvial and eolian deposits. However, deposits resulting from local runoff will vary in their extent and location from predam condition if the base level onto which local sediment is delivered is lowered. For example, if the configuration of eolian dunes changes or if a new gully breaches the dune field (as at Palisades), slopewash events may cause additional gully incision that drains to the river instead of allowing slopewash and colluvial sediment to accumulate in ponded areas. Loss of slopewash sediment would have the greatest effect farthest from the river, where the proportion of such sediment is highest. At our study sites, slopewash and colluvial sediment composed only thin overlying layers relative to the thicker cover provided by fluvial and eolian deposits. However, multiple exposures that we observed in other areas of the river corridor include interbedded eolian and local sediment—a thin stratum of poorly sorted debris-flow sediment that can form a resistant cap protecting the underlying, more easily erodible eolian sediment. Therefore, reduction in the accumulation of cap-forming slopewash sediment (caused by a reconfiguration of local slopewash drainage) could lead to an increase in the erosion of eolian sediment.

Criteria for Identifying Site Sensitivity to Dam Operations

In this study, we combined analysis of prehistoric sedimentary and geomorphic environments with that of modern eolian processes to assess the sensitivity of specific archeologic sites to dam operations. Site-specific evaluation of archeologic sites is important because the relative roles of fluvial, eolian, and other sedimentation processes, as well as local wind and precipitation patterns, differ widely among sites in the same reach of the river corridor. We proposed a series of steps to determine the role of eolian sediment in preserving any given archeologic site, and then to assess the effect of dam operations on eolian sedimentation at that site (Draut and others, 2005); three case studies using those criteria were presented by Draut and Rubin (2008). Here, we summarize those site-evaluation criteria and case studies briefly. These guidelines were formulated specifically to apply to eolian sedimentation, although our approach could be modified to address a wider range of processes and their interaction with cultural features. We reiterate that although the guidelines below refer only to eolian sedimentation and, specifically, to MFS deposits, predam fluvial terraces with associated archeologic sites (as well as all RFS deposits, for the reasons outlined above) should be considered sensitive to dam operations because the absence of sediment-rich floods of about 2,830 m^3/s eliminates the mechanism by which those deposits formed and received significant amounts of new sediment.

An important first step in evaluating the factors that enhance preservation of archeologic sites is to determine the depositional context of the sediment on which the site was built and by which the site has been buried (covered). Depositional settings can be inferred by examining geomorphic features, sedimentary structures on the land surface, and sedimentary structures in the subsurface viewed in vertical section (sedimentary profiles). Field investigations can be supplemented by laboratory analyses of sediment particle-size distributions, as discussed above, and by radiocarbon dating of materials that contain organic matter or charcoal (whether cultural or noncultural). Radiocarbon dating not only provides information on the date of cultural occupation but also can be used to determine recurrence intervals of floods and debris flows in the study area, events that may have affected occupation by prehistoric cultures (for example, Hereford and others, 1996, 2000).

If field study of surface geomorphology and sedimentary horizons determines that eolian deposition has buried and (as is commonly inferred) preserved a given archeologic site, then the possible loss of some of the eolian sediment that previously covered the site needs to be determined. Recognizing whether eolian sediment cover has been lost, by wind deflation or gully incision, is a step in assessing the risk of impending archeologic site degradation, or the degree to which such degradation has already occurred. If no loss of eolian sediment is suspected at a particular site, that site may not be at immediate risk of artifact loss. Future loss of eolian sediment at an archeologic site could be documented most accurately by repeated high-resolution mapping to measure changes in the elevation of a deflating land surface, or in the depth and width of growing gullies. If quantitative survey methods are unavailable, loss of sediment can be qualitatively identified by repeated ground-based photography and geomorphic evidence of deflation, including winnowed lag deposits on the land surface, pedestal formation, especially around plants (although erosion by rainfall can also leave small-scale pedestal features), and exhumation of plant roots.

Deflation of eolian deposits represents a net loss of sediment from an area where net deposition has formerly occurred. Such a situation would arise from a change in the balance between the sediment supply and the sediment-transport capacity of local winds. If local wind conditions are assumed not to have changed significantly and a decrease in sediment supply is likely, the next step in this evaluation is to identify the source of the eolian sediment that buried the archeologic site. Source areas for eolian sediment are most readily identifiable by monitoring local wind conditions. The longer the time interval over which winds are monitored, the more accurate the resulting eolian-sediment-transport predictions will be. In Grand Canyon, the most important sources of new sediment from which wind can mobilize sand are fluvial sandbars. Records of wind speed and direction, such as those obtained during this study, can be used to generate vector sums that demonstrate the potential for eolian sediment transport over time (Draut and Rubin, 2005, 2006). If long-term weather monitoring is not feasible, recent local wind conditions can be inferred in the field from the orientation of ripple structures, sand shadows (which form in the lee of obstacles), and dune morphology (slipfaces).

The presence of biologic soil crusts also indicates that eolian deposits now receive little or no active sand deposition. Soil crusts, which are dark-colored microbiotic soils that compose ≤70 percent of desert soils in the Southwestern United States, are dominated by cyanobacteria that live symbiotically with mosses and lichens. The crusts begin to form in 6–24 months and require ≥5 years without disturbance to develop fully into a community. Although biologic soil crust may survive after being subjected to shallow burial, as the biota extend sheaths to the land surface to resume photosynthesis, deeper burial (>0.5 cm in quartz sands) will kill the crust (Belnap and Eldridge, 2003; J. Belnap, written comm., 2006). Therefore, if an area with eolian duneforms on the land surface also contains well-developed soil crust, this observation implies that although sediment accumulated there in the past (forming the dunes), it has been years since any substantial amount of windblown sand was last deposited on that surface. Similarly, abundant vegetation on the surfaces of eolian dunes implies that the duneforms are now relatively immobile and not undergoing rapid deposition or migration. Vegetation and biologic soil crust on dunes do not directly indicate deflation (loss of eolian sediment) but an absence, or near absence, of deposition in an area where it had formerly occurred. In an eolian dune field where sediment supply becomes limited, the land surface can first deflate (as wind transports more sediment out of than into the dune field), and then, after several years of limited sediment input and deposition, vegetation and biologic soil crust can colonize the deflated land surface and reduce additional deflation by armoring the relict duneforms (Leys, 1990; Leys and Eldridge, 1998; Belnap, 2003).

In a dune field where dunes become less mobile over time (and where vegetation and biologic soil crust have grown), dune “stability” should not be confused with the “stability” of archeologic sites. An archeologic site in a deflated, vegetated dune field can be eroded by gully incision, as is commonly observed in Grand Canyon dune fields (such as those at Palisades, Comanche, Tanner/Cardenas [about river mile 70], Arroyo Grande, and 202.9 Mile, fig. 1). In those areas, where dunes are relatively immobile, gully incision proceeds with little or no counteraction by eolian sediment deposition, thereby ultimately destabilizing dunes and associated archeologic sites.

After local wind conditions have been monitored to identify a sand source, possible decrease in the area of that sand source needs to be addressed. Aerial photography and repeated high-resolution mapping have been used to document historical changes in sandbar area and structure throughout the Colorado River corridor in Grand Canyon National Park (for example, Schmidt and others, 2004). Oblique, ground-based photography can effectively document other changes in source-area characteristics that might affect the ability of sandbars to serve as sources of eolian sediment. Important changes in sand-source quality might include a decrease in area due to sandbar erosion; growth of vegetation; increased moisture content of the open sand area (more frequent inundation by flow fluctuations); greater surface exposure of rocks, driftwood, or other obstacles that inhibit wind; or formation of soil crust on the land surface.

If the supply of windblown sediment to a particular site in an MFS dune field appears to have declined, the probability that renewed deposition of eolian sediment could enhance the preservation of associated archeologic sites needs to be determined. Sites at which increased eolian deposition would substantially protect cultural features are those at which the greatest degradation occurs owing to deflation of sediment cover by wind, or from incision by gullies that are small enough to be healed by windblown sand (<1 m wide or deep, judging by a few exposures of filled gullies observed during this study and by Thompson and Potochnik, 2000). Eolian sedimentation is unlikely to prevent the loss of cultural features that are threatened more immediately by incision of a major arroyo or side-canyon channel than by deflation or minor gullies.

These steps thus provide a method for evaluating the sensitivity of a particular MFS deposit (and any associated archeologic sites) to dam operations by assessing how closely the condition of the eolian deposit is linked to that of nearby fluvial sandbars, which, in turn, are greatly affected by the dam-controlled flow and sediment content of the river (for example, Wiele and others, 1996; Webb and others, 1999a; Schmidt and others, 2004; Topping and others, 2006). Archeologic sites can be preserved in several ways by using the increase in cover and gully-filling ability of additional eolian sediment. At some sites, erosion control by check dams can keep gullies small enough to be partially or fully healed by windblown sand. Localized mitigation efforts by the NPS and collaborating tribes might substantially restore site conditions in such areas (Leap and Coder, 1995; Balsom and others, 2005). In many areas, however, especially if a larger scale solution is desired, preservation of archeologic sites that rely on eolian sediment cover can be achieved only by restoring the source areas from which the eolian sediment is derived. Because Colorado River sand deposits constitute the largest source of new sediment mobilized by wind, increasing dry, open sandbar area is the most effective way to enhance the potential for transport to and deposition on MFS dune fields and associated archeologic sites. Restoring sandbars by using controlled high riverflows under sediment-enriched conditions could be the most effective way to restore eolian deposits and preserve archeologic sites above the flood stage (Yeatts, 1997; Fairley, 2005; Draut and Rubin, 2006).

Three Case Studies

This study identified archeologic sites at which (1) erosion apparently is linked to dam operations, (2) erosion is not linked to dam operations, and (3) the connection between dam operations and site degradation remains unclear. Case studies of these three situations are presented in this subsection. The locations of the studied archeologic sites cannot legally be disclosed, and so they are referred to here simply as sites 1 through 3.

Site 1 is considerably sensitive to dam operations. On the basis of geomorphologic observations and a shallow test pit dug into sediment near the site in May 2003, eolian sediment forms both the substrate on which this site was built and the cover that has kept the roasting feature and artifact scatter largely intact. Site 1, located near the land, upper-elevation end of an eolian dune field, has undergone loss of eolian sediment, as shown by downslope movement of artifacts as the land surface has deflated (determined by years of monitoring by the NPS). Although the dune field shows evidence of active sand transport in the vicinity of the site, much of the dune field has undergone pronounced deflation and soil-crust growth, indicating little or no active sand deposition at present. The source of the eolian sediment that partly covers site 1 is a fluvial sandbar about 80 m directly upwind of the site, identified on the basis of wind conditions monitored at a weather station near site 1 for >1 year. Therefore, the eolian deposit at site 1 is considered to be MFS. Comparison of oblique historical photographs indicates a major decrease in the area and volume of the site 1 river-level sandbar from predam (1920s) to postdam (1970s) time (Turner and Karpiscak, 1980), a trend confirmed by comparison of aerial photographs of the area taken in the 1960s and 1990s. This decrease in sandbar area and volume suggests that deflation and limited sand transport in the dune field are related to the loss, since dam closure, of the fluvial sandbar about 80 m upwind. Site 1 presently is intact enough that it could be better preserved, given additional eolian sediment cover. The archeologic site and its surroundings are not affected by gully incision, visitor trails, or any other degradation processes.

The apparent sensitivity of site 1 to dam operations implies that restoration of the fluvial sandbar could enhance windblown sediment delivery to the associated MFS dune field, helping to cover the cultural artifacts there. The site 1 sandbar received substantial new sediment during the 1996 and November 2004 controlled floods (on the basis of preflood and postflood aerial photographs and visits). Sand-transport rates measured at the site before and after the 2004 flood showed greater sand flux during the spring 2005 windy season than during the spring 2004 windy season, even though wind conditions in spring 2004 had a greater sand-transport potential than those in spring 2005. Therefore, site 1 provides an example of dam operations rebuilding a sandbar, thus enhancing sand transport to an archeologically important MFS deposit.

Site 2 shares many characteristics with site 1 in that it contains cultural features built on and buried by eolian sediment. A natural cross-section exposure reveals debris-flow sediment underlying the eolian dune field in the area of site 2. Advanced deflation and well-developed biologic soil crust are apparent throughout the upper part of the dune field. Although wind conditions were not monitored in the immediate area, the orientations of dunes and sand shadows in the lower, more active part of the dune field, which was photographed during four visits in multiple seasons, indicate that the source of the eolian sediment is a fluvial sandbar about 70 m upwind of the site. Aerial photographs show a pronounced decrease in open sand area on the sandbar between the 1960s and 1990s, as well as an increase in vegetation cover on the eolian dune field. Thus far, evidence suggests that deflation and reduced sand mobility on the dune field are linked to postdam shrinkage of the river-level sandbar which serves as the sand source for that MFS dune field. However, although the general condition of the dune field likely responds to dam operations, the rapid degradation of site 2 cannot be linked to Glen Canyon Dam because other factors unrelated to windblown sand affect the site on shorter time scales. A large tributary channel where major floods and debris flows are known to have occurred in historical time has incised into eolian sediment at the edge of the dune field (fig. 6). The cultural features at site 2 are eroded more substantially by episodic tributary activity than by processes that could be reduced or reversed with more windblown sand (eolian deflation or formation of small gullies).

In contrast to sites 1 and 2, where archeologic-site sensitivity to dam operations can be either confirmed or refuted, respectively, site 3 presents a situation in which the effect of dam operations remains unclear even after detailed study. Similar to sites 1 and 2, site 3 was built on and buried by eolian sediment; the site is situated in a large, sparsely vegetated dune field. Individual features show evidence of some loss of the eolian sediment that previously covered them, including deflation, slumping, and downslope movement of artifacts associated with dune migration. Some minor biologic soil crust is present, but most of the dune field appears to be undergoing active sand transport. The dominant local wind direction, measured near site 3 for >1 year, indicates that the most likely sand source for this dune field is a large, predam fluvial terrace upwind, making the dune field RFS type. The modern morphology of the fluvial terrace suggests a substantial loss of sediment from, as well as of eolian sediment-entrainment capacity in, this source area. The terrace is incised by an arroyo network several meters deep and wide, and its surface has been colonized by abundant vegetation and biologic soil crust, observations consistent with the fact that no postdam floods have reached the level of this terrace.

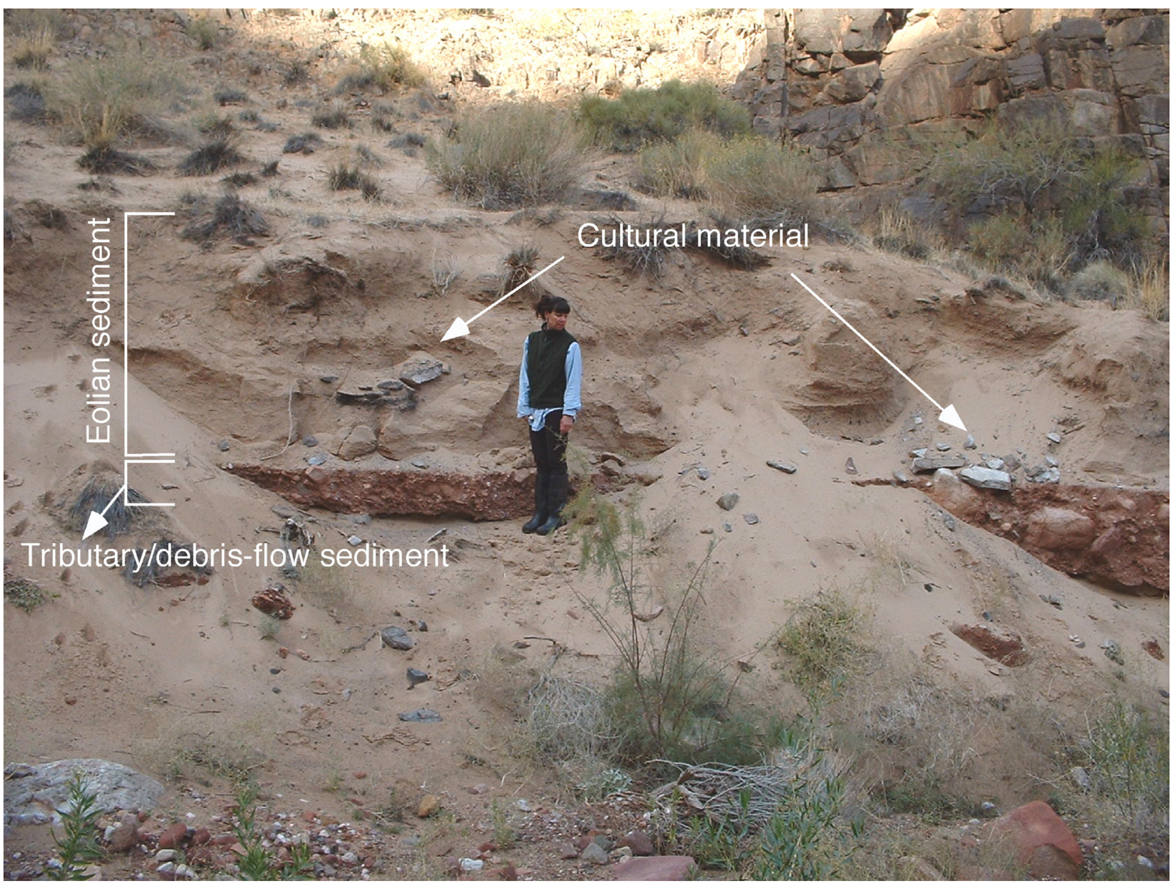

Figure 6. Sedimentary material in area where a tributary channel erodes an eolian deposit containing cultural material (site 2) along Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Poorly sorted sediment exposed in lower part of nearly vertical bank is interpreted as a deposit from a tributary debris flow. Fine, light-colored eolian sand was deposited later, overlying debris-flow sediment; formation of archeologic site apparently was synchronous with formation of eolian deposit, because cultural material is being eroded out at a level approximately halfway through eolian deposit thickness.

Although surface conditions in the eolian dunes may be related to postdam reduction of sediment from the fluvial terrace upwind, it is unclear whether or not site 3 would be better preserved if new deposition from a large, sediment-rich flood were to increase sand transport from the terrace to the RFS dune field. Eolian processes are responsible for the disturbance of artifacts at site 3, but the dune migration that affects them is a natural process endemic to active dune fields. In a natural system, continued dune migration would be expected eventually to cover the site. Over time scales of years to decades, migrating dunes in an unaltered eolian system would expose and cover any given part of the dune field repeatedly, and downslope movement of artifacts would be expected as the sand shifts under them. Dunes near the site would need to be surveyed repeatedly over decades to determine whether or not dune migration will continue as it would naturally with plentiful sediment, or whether the dune field will show signs of exacerbated sediment-supply limitation in the future (increases in vegetation, biologic soil crust, or winnowed lag deposits and decrease in the mobility of duneforms), which might indicate that sediment deprivation caused by dam operations had prolonged the exposure of these artifacts, thereby increasing the risk of their damage and loss.

As outlined above, we can determine in many cases through careful, site-specific field study whether and to what degree a particular archeologic site is sensitive to the effects of Glen Canyon Dam operations. Although in-place preservation of cultural artifacts on geologic time scales is unrealistic, owing to continual downcutting and backwasting in this bedrock canyon, preservation of archeologic sites could be enhanced on decadal to centennial time scales by restoring fluvial and eolian sedimentation to resemble more closely the processes that occurred before the river was regulated by upstream dams, including large, sediment-rich floods that left fluvial deposits from which sediment was remobilized by wind.

Effects of the November 2004 Controlled-Flood Experiment on Eolian Sediment Transport

Archeologic sites that depend on a supply of windblown sediment from fluvial sandbars for their continued preservation can receive an increase in eolian sediment after restoration of sandbars by high releases from Glen Canyon Dam. Sandbar restoration was the primary goal of the controlled-flood experiment on the Colorado River in November 2004, the second such experiment. To ensure a greater sand supply in the upstream reach than was available during the first controlled-flood experiment in March 1996 (Webb and others, 1999b; Patten and others, 2001; Schmidt and others, 2001), the 2004 controlled flood occurred after substantial amounts of sand had recently been supplied to upper Marble Canyon by the Paria River and other tributaries, and after an interval of lower dam releases designed to minimize sediment export. Conditions during the 2004 high flow therefore represented sediment enrichment in the river channel relative to conditions during the 1996 flood (Topping and others, 2006).

The design of the 2004 controlled-flood experiment included a 60-hour steady riverflow of 1,160 m^3/s released from Glen Canyon Dam on November 22 and 23. Postflood surveys indicated that the area and volume of sandbars in Marble Canyon above approximately river mile 40 were significantly greater than before this high flow and that approximately half of the surveyed sand deposits were much larger than immediately after the 1996 controlled flood (Hazel and others, 2005; Topping and others, 2006). Below approximately river mile 40, localized deposition and erosion were documented, and a consistent pattern of sandbar aggradation could not be demonstrated, implying that in future high-flow experiments, more sand must be present in the river channel to achieve deposition on sandbars throughout the canyon (Topping and others, 2006).

In addition to the sandbar surveys after the 2004 controlled-flood experiment (Hazel and others, 2005), fluvial sand deposits at our study sites were photographed immediately before and after the flood (in November and December 2004, respectively) and again at multiple times during 2005; preflood and postflood photographs were published by Draut and Rubin (2005, 2006). The duration of this study included 1 year of preflood data and >1 year of postflood data. Study sites were chosen partly because new fluvial sand deposition had occurred at them during the 1996 controlled-flood experiment. Therefore, similar deposition was predicted to occur at these sites during the November 2004 high flow. On the basis of wind conditions monitored in the year before the controlled-flood experiment (Draut and Rubin, 2005), the greatest potential for redistribution of new, flood-deposited sediment was predicted to occur during the spring 2005 windy season.

At all six weather-station sites (fig. 1), major deposition of new fluvial sand occurred as a result of the November 2004 controlled flood (Draut and Rubin, 2005, 2006). The substantial deposition in those areas during a sediment-rich Colorado River high flow implies that to the extent that such flows can restore the sandbars, controlled floods are also an effective management option to increase the availability of sediment to MFS deposits. In addition to depositing a substantial amount of new sand on many sandbars, the November 2004 high flow also facilitated eolian sediment entrainment because the new sediment covered vegetation, rocks, and driftwood, decreasing the roughness of the land surface and thereby promoting sediment entrainment by wind (Lettau, 1969; Marshall, 1971; Raupach and others, 1993; Gillies and others, 2000; King and others, 2005).

However, if maximizing eolian redistribution of sediment is one of the management goals of a controlled flood, riverflows that occur between the time of the flood and the next windy season must also be managed to maximize open, dry sandbar area during that windy season (April–early June). Much of the 2004 flood-deposited sand was eroded by high, daily flow fluctuations that ranged from 142 to 566 m^3/s from January to March 2005, before the spring windy season began (Draut and Rubin, 2006). For example, at Malgosa (river mile 57.9, fig. 1), a new sand deposit, 1.5 m thick and more than 10 m wide, formed during the flood but was eroded almost entirely during the next 4 months (fig. 7). Sites a short distance downstream of the Little Colorado River, such as Palisades and Comanche, 7.4 and 10.4 km, respectively, below the confluence with the main stem, showed a less pronounced loss of sand during January–March 2005 flow fluctuations than did Marble Canyon, presumably because flooding of the Little Colorado River in February 2005 (about 70 m^3/s) provided additional sand to these nearby areas.

At the study sites where flood deposits were entirely eroded before the 2005 windy season began, sand-transport rates measured during the spring 2005 windy season were comparable to or lower than those measured during the spring 2004 windy season, given similar wind conditions. At 24.5 Mile, however, where approximately half of the flood-deposited sand remained at the start of the spring 2005 windy season, sand-transport rates measured near the river during the spring 2005 windy season were approximately double those

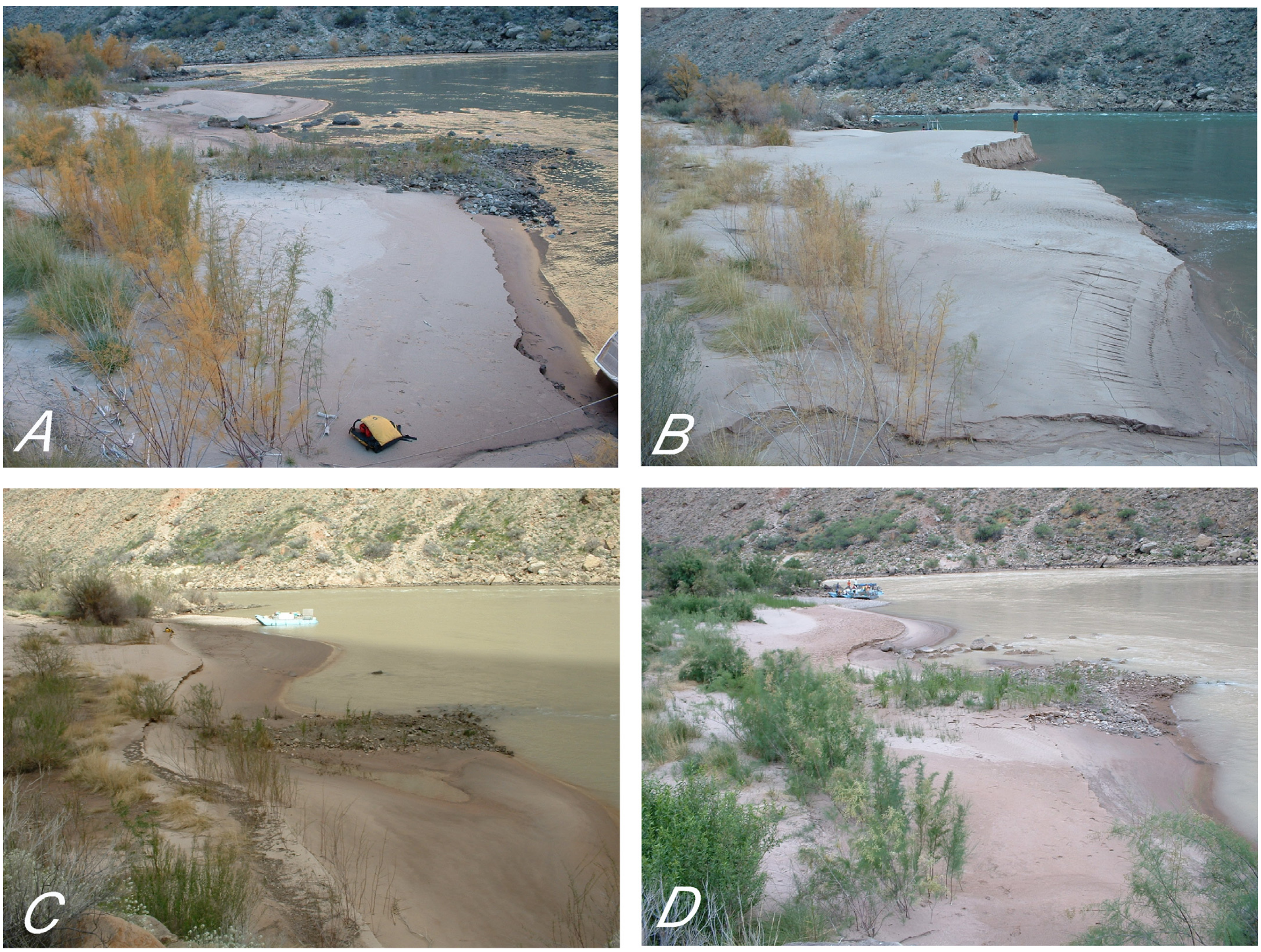

Figure 7. Study site at Malgosa (river mile 57.9) along the Colorado River corridor in Grand Canyon National Park, Ariz., showing effects of November 2004 flood and subsequent fluctuating flows. Study site is on river right, near weather station Mal L (see fig. 14 for location). Photographs from Draut and Rubin (2006). *A*, Preflood photograph taken November 17, 2004, at a riverflow of 226 m^3/s. *B*, Postflood photograph taken December 9, 2004, at a riverflow of about 226 m^3/s. New sand deposited at site during flood was approximately 2 m thick (note person for scale). *C*, After several months of 142 to 566-m^3/s daily flow fluctuations, flood deposit had been eroded substantially, exposing many rocks in center of beach that were present before flood. Photograph taken March 13, 2005, during riverflow of about 226 m^3/s. *D*, By late spring 2005, flood deposit had been almost entirely removed, and state of sandbar was nearly identical to preflood state. Photograph taken May 28, 2005, during riverflow of 226 m^3/s.

in spring 2004 (Draut and Rubin, 2006), even though wind conditions there in spring 2005 had less capacity to transport sediment than in spring 2004 (see appendix 1). The increase in sand transport near the river in spring 2005 relative to spring 2004 is interpreted as a result of an increase in the area of available sand upwind and a decrease in the roughness of the land surface where 2004 flood sediment was still present. No similar increase in sand flux relative to the previous year was measured at the upper-elevation station in the same dune field.

The dominant wind direction at 24.5 Mile transports sand from the west-southwest to the east-northeast (from river level to the upper part of the MFS dune field; see appendix 1). Sand-transport measurements at 24.5 Mile suggest that although the influence of the new flood sediment was measurable near river level (at the lower of the two weather stations) in spring 2005, its effects had not yet propagated to the upper part of the dune field. In many areas of the river corridor, new sand would need to reach the highest parts of eolian dune fields in order to increase sand transport to archeologic sites. Because the sand flux measured at the upper weather station at 24.5 Mile exceeded that measured at the lower station, even with the new flood sand present (Draut and Rubin, 2006), the net sand flux into the dune field was still negative even after the controlled-flood experiment. Had the sandbar near the lower station been as large during the spring 2005 windy season as it was immediately after the November 2004 controlled flood, the sand flux into the dune field might have balanced or exceeded that out of the dune field, resulting in net sediment gain. At this same site, the restorative function of eolian sediment derived from the flood deposit was still apparent >1 year after the controlled-flood experiment. In January 2006, a new gully that had recently begun to incise into the eolian dune field was photographed at 24.5 Mile. The orientation of the gully and of wind ripples in the sand indicated that sediment filling the lower part of the gully had blown inland from the November 2004 controlled-flood deposit, an observation consistent with the dominant wind direction recorded at 24.5 Mile during the preceding 26 months (Draut and Rubin, 2006). The ability of gullies to act as natural traps for windblown sand could contribute to slowing or cessation of erosional processes that affect the stability and preservation of archeologic sites in eolian deposits (for example, Thompson and Potochnik, 2000).

Effects of the November 2004 controlled-flood experiment on eolian sediment transport, therefore, indicate that increasing the area of sandbars can increase sediment deposition in eolian dune fields above the flood-stage elevation. Sandbar-building floods have a greater potential to enhance eolian sedimentation on MFS deposits than on RFS deposits, as defined above (fig. 4), because of the direct link between active fluvial sandbars (at or below the 1,270-m^3/s flood stage) and MFS dune fields downwind. To substantially restore RFS dune fields would require sediment-rich floods on the scale of predam spring snowmelt floods, at least several times as high as those conducted experimentally thus far and for a longer duration. Therefore, any future controlled high flows on the scale of the 2004 experiment would probably substantially enhance eolian deposition on MFS dune fields (provided that postflood flows are managed to maintain the size and condition of new fluvial deposits throughout the next windy season) but have little effect on eolian sediment transport into RFS dune fields.

The high daily flow-fluctuation schedule (142–566 m^3/s) of experimental flows was conducted during January–March 2003, 2004, and 2005 to suppress nonnative fish populations. Each of those high-fluctuating-flow intervals exported approximately twice as much fluvial sediment as under modified low fluctuating flow (MLFF) operations of Glen Canyon Dam for comparable-volume months and sediment influx (S.A. Wright, oral commun., 2006). Therefore, operation under low fluctuating flows (or steady low flow) between the end of a controlled flood and the start of spring high winds is predicted to maintain much more of the postflood sandbar area until the wind can redistribute flood sediment into higher elevation eolian deposits during the subsequent spring windy season.

Recommended Future Research

To evaluate the degree to which the presence and operation of Glen Canyon Dam may influence the preservation of archeologic sites in the Colorado River corridor (fig. 1), site-specific stratigraphic and geomorphic knowledge is needed. Establishment of the local importance of fluvial, eolian, and other processes in predam and postdam time is an important prerequisite for accurate assessments of dam effects, and archeologic-site sensitivity to dam operations must be evaluated on a site-by-site basis because the relative roles of various sedimentation processes differ widely between sites, even within the same river reach. Future sedimentologic and geomorphologic studies could assess the sensitivity to dam operations of additional archeologic sites not included in this study. It would be highly informative to include field analysis of vertical sediment profiles (identifying depositional environments by using sedimentary structures) in any future excavation of archeologic sites in the river corridor.

Wind, rainfall, and sand-transport data collected during the 26 months of this study span various weather conditions but still are probably not representative of long-term climate in the Grand Canyon region. A long-term weather-monitoring program would allow climate patterns and potential-sand-transport measurements to be refined with greater accuracy. To represent weather conditions at high spatial resolution over the entire Colorado River corridor in Grand Canyon National Park, many stations would be required. To represent spatial variation reasonably, at least five (preferably more) weather stations should be distributed between Lees Ferry and Diamond Creek (river miles 0–226, fig. 1). Although the stations used in this study monitored weather conditions that were directly relevant to archeologic sites (wind, rainfall, and sand transport), a longer term weather-monitoring program could use additional equipment to measure air temperature, relative humidity, barometric pressure, and other parameters to generate a broader scale climatic record in the Colorado River corridor that would be useful for physical, biologic, and cultural research. The measured broad spatial variation in rainfall documented during this study indicates that future sedimentologic and geomorphologic studies in the canyon would benefit substantially from continued or expanded weather monitoring at multiple sites along the Colorado River corridor because the rainfall records collected by the NPS at Phantom Ranch cannot be considered valid for other parts of the canyon.

As a step to realizing those objectives, new weather stations were installed in early 2007 to measure wind speed and direction, precipitation, sand transport, air temperature, relative humidity, and barometric pressure. These stations, at 24.5 Mile, 60 Mile, Palisades, 70 Mile, 136 Mile, 202.9 Mile, and 223 Mile (fig. 1), allowed monitoring of local effects of the March 2008 controlled-flood experiment on sand flux. Data from those weather stations are not yet available.

Recording climatic data in the Colorado River corridor is only one step to identifying the complex geomorphic processes that affect the condition of eolian deposits, and, by extension, of many archeologic sites. The information gathered and presented in this and our previous reports could form the basis for a wide array of future modeling studies. It is becoming increasingly clear that eolian transport and deposition of sediment affects the condition of archeologic sites in the river corridor and that the availability of sediment from open sand areas on fluvial sandbars is an integral component of these processes. Although eolian-sediment-transport modeling formed a component of this study (see appendix 2), we suggest three additional research initiatives to address these issues in more detail:

1. A detailed aerodynamic-modeling study of one or more sites that would involve numerical representation of airflow, including dynamic interactions with obstacles, slope, and irregular spatial boundaries.

2. Construction of a new sand-trap design that would allow higher temporal resolution of sand-transport response to specific, short-duration wind conditions. Future research in these two linked directions would lead to a better understanding of the eolian-sediment-transport systems that affect natural and cultural resources in Grand Canyon.

3. Because of the approximately exponential inverse relation between eolian sediment transport and vegetation cover (Bressolier and Thomas, 1977; Buckley, 1987), studying the response of eolian sediment transport to localized removal of riparian vegetation would be informative. Such areas as the sandbar downstream of 202.9 Mile or along the east bank of the river near Comanche are possible sites where vegetation removal could promote additional eolian sediment transport, given that eolian dune fields are nearby and vegetation cover is known to have increased locally in postdam time (see appendix 1). To promote sand transport effectively, near-complete removal of vegetation would be needed; nearbed wind velocities are negligible on surfaces with about 40-percent vegetation cover (Buckley, 1987), and in many riparian areas of Grand Canyon, the vegetative cover is much denser. We recommend that in future vegetation-removal projects, wind conditions and sand transport should be monitored at study sites for several months, ideally spanning a spring windy season before and a spring windy season after vegetation removal, to assess possible effects.

Conclusions

Eolian sediment serves as a substrate on which many archeologic sites in the Colorado River corridor were formed (in many areas also in association with fluvial and slopewash sediment), and, more commonly, as a surficial deposit covering archeologic material. Without sufficient eolian sediment, cultural artifacts are exposed by wind deflation of the overlying sediment, forming a lag deposit on the land surface. Many eolian dune fields in Grand Canyon show evidence of reduced sediment supply in the form of vegetation and biologic soil crust covering relict duneforms. The presence of well-developed microbiotic soil crusts and colonization by grasses indicates a lack of sediment deposition and a decrease in dune mobility relative to times in the past when the supply and transport of eolian sediment were great enough to generate dunes. Sand-transport rates on dune fields in Grand Canyon with well-developed vegetation and biologic soil crust are typically a tenth of those on dunes without vegetation or soil crust. Although vegetation and biologic soil crust limit the mobility (migration) of dunes relative to their earlier state of sediment abundance, this observation does not imply that dunes and associated archeologic sites cannot erode. Dunes with substantially reduced sand supply (and with vegetation and soil crust) are less likely to have sufficient sediment transport and deposition to counteract gully incision. In these vegetated, soil-crusted dunes, large gullies and arroyos are more likely to form and cause major erosion and degradation of dunes and archeologic sites.

Reduction in the source areas that provide windblown sand to eolian deposits is evident from comparison of aerial photographs taken in the 1960s with modern images. At the study sites (fig. 1), many fluvial sandbars are smaller, and riparian vegetation is more abundant, now than in 1965, consistent with the results of previous studies in many other areas of the Colorado River corridor (Turner and Karpiscak, 1980; Beus and others, 1985; Schmidt and Graf, 1987; Kearsley and others, 1994; Leschin and Schmidt, 1995; Hazel and others, 1999; Schmidt and others, 2004).

The problem of archeologic-site preservation in postdam time is essentially a competition between two processes—precipitation runoff, which creates gullies that erode sedimentary deposits (as well as overland flow that can wash artifacts into gullies); and eolian sediment transport, which fills in small gullies, inhibiting their growth (gullies act as natural traps for windblown sand). The ability of eolian sediment transport to counteract gully formation and heal small (<1 m wide and deep) gullies is a major factor controlling the geomorphic evolution of Grand Canyon sedimentary deposits. Areas where abundant rainfall and high sand-transport rates were measured during this study can lack gullies (which form episodically but are quickly filled by windblown sand), whereas areas where little rainfall and little sand transport were measured have been substantially eroded by gullies and arroyos, destabilizing archeologic sites. Although many factors (long-term climatic fluctuations, drainage-basin geometry, substrate composition, and effective base level) contribute to gully formation, we infer that the arroyo incision would not have progressed so far in some areas if eolian-sediment-transport rates were significantly higher. For example, several kilometers upstream of the deeply incised Palisades terrace, gullies typically are absent in the dune field at Malgosa—a study site that had twice the rainfall and 10 times the sand-transport rate of Palisades.

Two types of eolian deposit occur in the Colorado River corridor, defined by the relative positions of the deposits and nearby fluvial sandbars and the locally dominant direction of eolian sediment transport. Modern fluvial-sourced (MFS) deposits formed as the wind transported sand inland from a river-level sandbar, creating an eolian dune field downwind; and relict fluvial-sourced (RFS) deposits formed by in-place wind reworking of predam flood deposits. Both MFS and RFS deposits are known to contain archeologic material, and both types of deposits are sensitive to dam operations, but for different reasons. Changes in dry, open, fluvial-sandbar dimensions (a function of dam operations) affect eolian sediment transport to MFS dune fields downwind; we have defined criteria to judge the sensitivity to dam operations of particular archeologic sites within MFS deposits. RFS deposits compose the uppermost, wind-reworked part of predam terraces that are largely alluvial, containing sediment deposited by riverflows ≥5,000 m^3/s. Because sediment-rich floods of that magnitude do not occur in the regulated Colorado River, fluvial deposits from which RFS dune fields formed no longer constitute an active sand source, and so no substantial new deposition is likely to occur on RFS dune fields in the absence of large, sediment-rich floods.

Management of Glen Canyon Dam operations affects eolian sediment transport in the Colorado River corridor through Grand Canyon. If the size and number of the fluvial sandbars from which wind remobilizes sand can be increased by controlled, sediment-rich flows of about 1,270 m^3/s, then windblown sand transport can significantly increase in the vicinity of new flood deposits, and new flood sand can be transported by wind to elevations above the flood stage, replenishing sediment in MFS deposits. All of those processes were documented on seasonal time scales during this study after the November 2004 1,160-m^3/s controlled-flood experiment. Eolian sediment transport to eolian dune fields will be greatest if postflood dam operations maximize the area and number of fluvial sandbars during the spring windy season (between April and early June), when sand-transport rates are about 5 to 15 times higher than in other seasons. After the November 2004 controlled flood, newly deposited sandbars were eroded substantially by daily flow fluctuations of 142 to 566 m^3/s between January and March 2005, before the spring windy season began. Sandbar erosion by high daily flow fluctuations removed much of the sand that was potentially available for eolian redistribution, limiting the effects of the 2004 flood on archeologic sites. Because high fluctuating flows export approximately twice as much fluvial sand as is exported by modified low fluctuating flow (MLFF) operations of Glen Canyon Dam, more eolian sediment would be available to be blown inland (to MFS dune fields and the associated archeologic sites) if sandbar-building floods were followed by low fluctuating flows rather than by high daily fluctuations. Operating under low fluctuating flows or steady low flows between the end of a controlled flood and the start of the spring windy season is predicted to retain more of the post-flood sandbar area until the next spring windy season, when wind can transport sand into eolian deposits above flood-stage elevation. If sandbars could be rebuilt to the extent that they remained larger throughout the year, or retained sediment from one flood to the next, overall eolian sediment transport would be greater than under present conditions, even though sandbars would still be partially eroded between floods.

Preservation of archeologic sites along the Colorado River corridor in Grand Canyon National Park on geologic time scales is unrealistic, owing to continual downcutting and backwasting of the bedrock canyon. On decadal to centennial time scales, tens to hundreds of archeologic sites in Grand Canyon could be better preserved by restoring fluvial and eolian sedimentation to resemble more closely those processes that occurred before the river was regulated by upstream dams, including sediment-rich floods that left fluvial deposits from which sediment was remobilized by wind.

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Appendix 1. Site-Specific Observations

This appendix summarizes wind, rainfall, and sand-transport measurements at six study sites (nine weather stations) along the Colorado River corridor in Grand Canyon National Park between November 2003 and January 2006 and provides conclusions specific to each site. Technical specifications of instruments and data-processing methods were discussed by Draut and Rubin (2005) and are summarized briefly here.

Mean wind velocity, maximum gust, and mean wind direction were measured digitally at each weather station with a 4-minute sampling interval. Sand flux was monitored by using traps that were emptied during maintenance visits every 4–8 weeks. Sand-transport measurements are based on cumulative values representing the interval between maintenance visits.

The total mass of sand collected from each trap during each maintenance visit was weighed, and sand-transport rates were calculated for each interval between collections by integration from 0 to 1 m of a curve fitted to the mass-versus-height data. The amount of sediment transport represented by the lowermost 1 m generally accounts for more than 99 percent of the total sediment transport (Zobeck and Fryrear, 1986; Vories and Fryrear, 1991; Sterk and Raats, 1996; Zobeck and others, 2003). The curve-fitting procedure uses a five-parameter combined power-law and exponential function that has been shown to model vertical sand flux more accurately than either power-law (Zobeck and Fryrear, 1986; Fryrear and others, 1991) or exponential (Vories and Fryrear, 1991) fits alone (Sterk and Raats, 1996). The actual mass flux is considered to span an efficiency range of 70–130 percent in “big spring number eight” (BSNE) sand traps for grain sizes and wind velocities measured at the various study sites (Goossens and others, 2000).[1] This efficiency range was used to estimate error in the sand-transport data. Although this estimate constitutes a conservative treatment of the data, it is the best available for these bulk sand-transport data. (The exact correspondence between wind velocities and local sand-transport rate is unknown.)

Grain-size analyses were performed on surface-sand samples from each instrument tripod at the time of initial deployment. Median grain size (d_{50}), obtained by laser particle-size analysis (Draut and Rubin, 2006), allowed estimation of the critical threshold of motion (minimum wind velocity needed to mobilize and transport sand grains of a certain size) for sand at the study sites, taken to be about 2 m/s by using the formulation of Bagnold (1941; see appendix 2). In analyzing the wind data, we consider not only wind velocity but the sand-transport potential due to a given wind velocity. To represent this potential, we use a proxy variable, *Qp*, calculated for all the data points at which the wind velocity (u) exceeded the critical threshold of motion (u_{crit}), which is defined as the cube of the difference between the measured wind velocity and the critical threshold of motion:

$$Qp = (u - u_{\mathrm{crit}})^3 \, . \qquad (1)$$

This relation follows the convention used to construct eolian-sediment-transport models, such as those of Kawamura (1951) and Lettau and Lettau (1977), but substitutes wind velocity for shear velocity (see appendix 2). Although the units of *Qp* (m^3/s^3) do not directly translate to a sand flux, comparison of the spatial and temporal variations in relative *Qp* values yields useful information about sand-transport potential. For the data points at which $u<u_{crit}$, *Qp* was set equal to zero, indicating that no sand transport would occur. Dominant wind directions causing sand transport were then calculated by using vector sums of *Qp* values from the 4-minute wind measurements. Monthly vector sums of *Qp* values for each weather station were reported by Draut and Rubin (2005, 2006).

The error in each wind-direction measurement is estimated at ≤10° (5° for the manufacturer’s stated accuracy of the anemometer plus 5° for operational error). For the magnitude component of wind velocity, analyses include an error of 0.5 m/s at u <17 m/s and ±3 percent at u between 17 and 30 m/s (manufacturer’s stated accuracy). Measurement errors are not expected to affect net (dominant) wind-velocity calculations significantly, except where winds blew often from opposing directions, such as at 202.9 Mile (fig. 1). For all other study sites, wind directions were consistent enough that measurement errors would not significantly affect the reported dominant wind and sand-transport directions.

24.5 Mile

Two weather stations were deployed in an eolian dune field on the downstream side of a debris fan at 24.5 Mile (fig. 8)—one near river level (weather station 24.5 L, fig. 8B) and one at the upper end of the dune field (weather station 24.5 U; Draut and Rubin, 2005, 2006). The dune-field area between the two weather stations undergoes active sand transport and has little vegetation or biologic soil crust. An approximately equal area at the north (upstream) end of the dune field is relatively inactive, with a well-developed soil crust and evidence of deflation of the land surface. Comparison of aerial

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[1]Ideally, sand traps would be isokinetic (100-percent efficiency), meaning that the sand trap would not disrupt airflow around it and would capture 100 percent of the sediment in transport locally per unit width. No perfectly isokinetic sand traps have been designed. A sand trap operating at <100 percent efficiency diverts airflow away from the trap orifice, and the amount of captured sediment underrepresents the amount of sediment transport locally. A sand trap operating at >100 percent efficiency diverts air flow into the trap, thereby overrepresenting the amount of sediment transport locally per unit width.

photographs taken in 1965 and 2004 (fig. 8) shows a decrease in the area of river-level sandbars and an increase in riparian vegetation at 24.5 Mile in postdam time. Notably, a river-level sandbar at the west end of the eolian dune field (sandbar a, fig. 8) is clearly visible in 1965 photographs but much smaller or absent in recent photographs (see fig. 39 of Turner and Karpiscak, 1980). This sandbar was temporarily enlarged by the 1996 controlled-flood experiment (on the basis of aerial-photographic analysis) and again by the November 2004 controlled-flood experiment (Draut and Rubin, 2006), after which it was partially eroded by daily flow fluctuations. A second fluvial sand deposit (sandbar b, fig. 8) is now smaller than in 1965 and is partly covered by vegetation, and riparian vegetation is more abundant there today than in 1965.

Wind with velocity high enough to transport sediment consistently came from the west-southwest at 24.5 Mile (figs. 9, 10). Therefore, the eolian dune field is directly downwind of the river-level sandbar (a, fig. 8) and is defined as an MFS deposit.

Daily sand-transport rates were typically about 1 g/cm in the dune field at 24.5 Mile; daily sand-transport rates at the upper end of the dune field were consistently higher than those measured near river level by a factor of 2 to 4, consistent with the higher wind velocities measured at weather station 24.5 U (figs. 8*B*, 11, 12). Given the projected strong link between sediment composing the fluvial deposit (sandbar a, fig. 8) and the eolian dune field, it was not surprising that replenishment of sediment on this sandbar during the 2004 controlled flood was followed by a measured increase in eolian sediment transport near river level (recorded at weather station 24.5 L) in the spring 2005 windy season, relative to the spring 2004 windy season. The sand flux at weather station 24.5 L was higher in spring 2005 than in spring 2004, even though the sand-transport potential of wind measured there was about 30 percent lower in spring 2005 (total Qp=4,150 m^3/s^3 in April and May 2005, in comparison with 5,970 m^3/s^3 in April and May 2004). No similar increase in sand flux relative to the previous year was measured at weather station 24.5 U (fig. 12), where the sand-transport potential of wind was similar in spring 2004 and spring 2005. Because the sand flux measured at weather station 24.5 U in spring 2005 exceeded that measured at weather station 24.5 L, even with the new flood deposit present, the net sand flux into this dune field was still negative, indicating deflation of its land surface. Given wind conditions similar to those measured in 2005, the sand flux at weather station 24.5 L would need to be about 50 percent higher than that measured in 2005 to equal that at weather station 24.5 U, indicating that the dune field underwent no net gain or loss of sediment. We speculate that if the sandbar near weather station 24.5 L had been as large

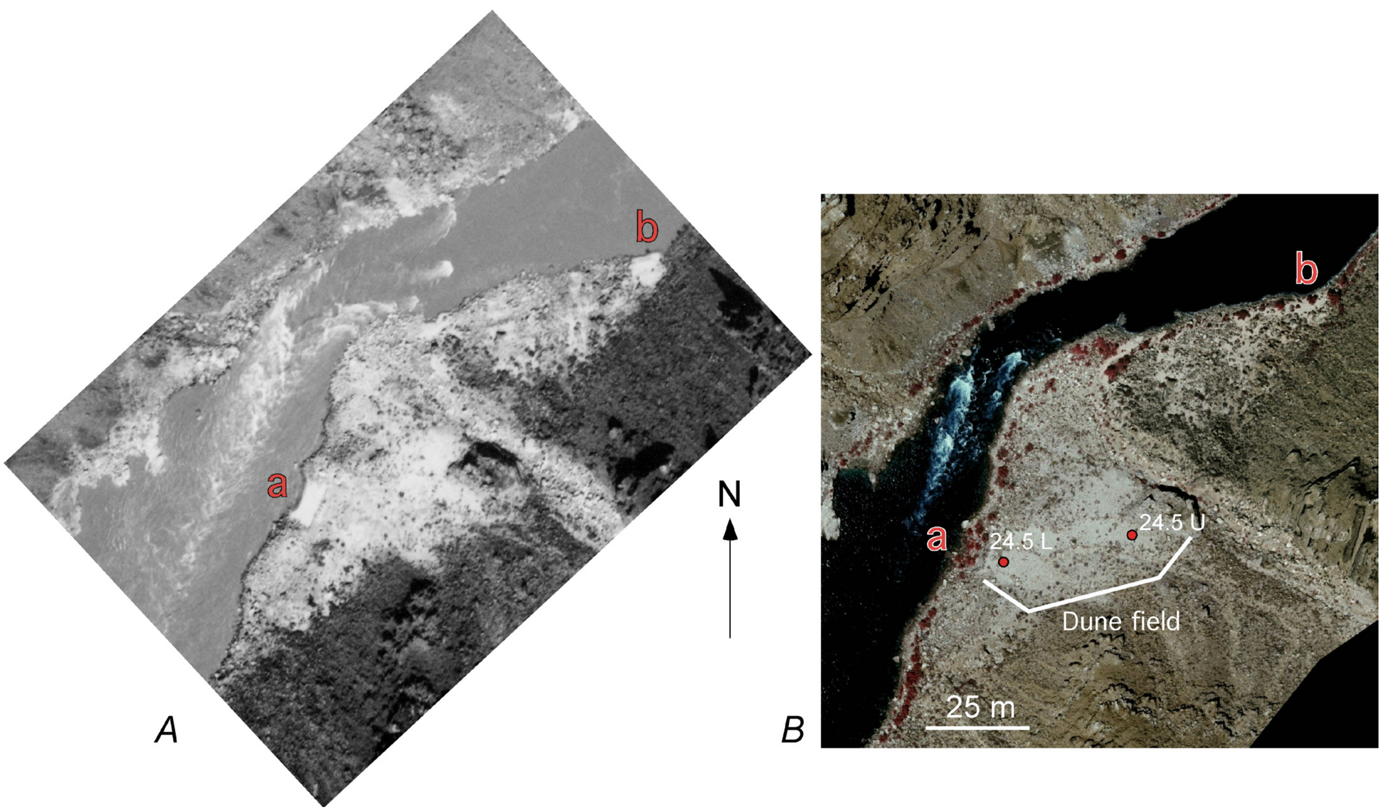

Figure 8. Aerial photographs taken in May 1965 (*A*) and May 2004 (*B*) of 24.5 Mile area along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Riverflow in May 1965 was between 680 and 792 m^3/s, and in May 2004 was 226 m^3/s. Fluvial sand deposits (a and b). Modern extent of eolian dune field is indicated in figure 8*B*. Red dots, weather stations 24.5 L (lower) and 24.5 U (upper). Note the increase in riparian vegetation and decrease in open sand area since 1965.

during the spring 2005 windy season as it was immediately after the November 2004 flood (having been reduced to half its postflood area by high daily flow fluctuations between January and March 2005), the sand flux into the dune field might have equaled or exceeded that measured at weather station 24.5 U, resulting in net sediment gain in the dune field.

Archeologic sites built on and buried by eolian sediment are known to occur in the vicinity of 24.5 Mile. Because this area is an MFS dune field in which an eolian deposit receives sediment from a fluvial sandbar directly upwind, changes in the amount of fluvial sediment available from this sandbar can be expected to affect the preservation of archeologic sites in the eolian deposit to which this fluvial sediment is linked. The relatively inactive northern part of the dune field at 24.5 Mile has probably undergone deflation as a result of the decrease in sand source upwind (sandbar a, fig. 8) since the 1960s. The growth of the same fluvial sand deposit during the 2004

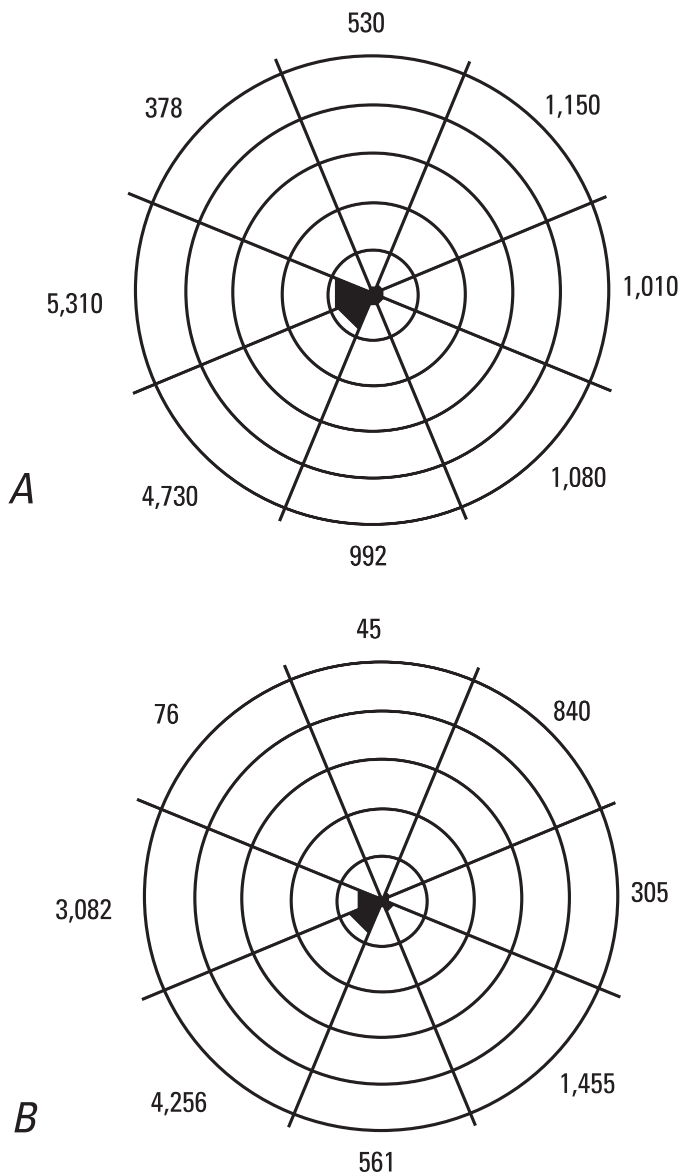

Figure 9. Rose diagrams of sand-transport potential calculated from 2 years of wind data collected at weather station 24.5 L (fig. 8*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Numbers for 2004 (*A*) and 2005 (*B*) are total values of proxy variable *Qp* for each of eight directional half-quadrants, indicating total potential for eolian sediment transport from each compass sector. Vector sum of 2004 data yields a net *Qp* value of 7,350 m^3/s^3 from a direction of 244°; vector sum of 2005 data yields a net *Qp* value of 5,974 m^3/s^3 from a direction of 244°.

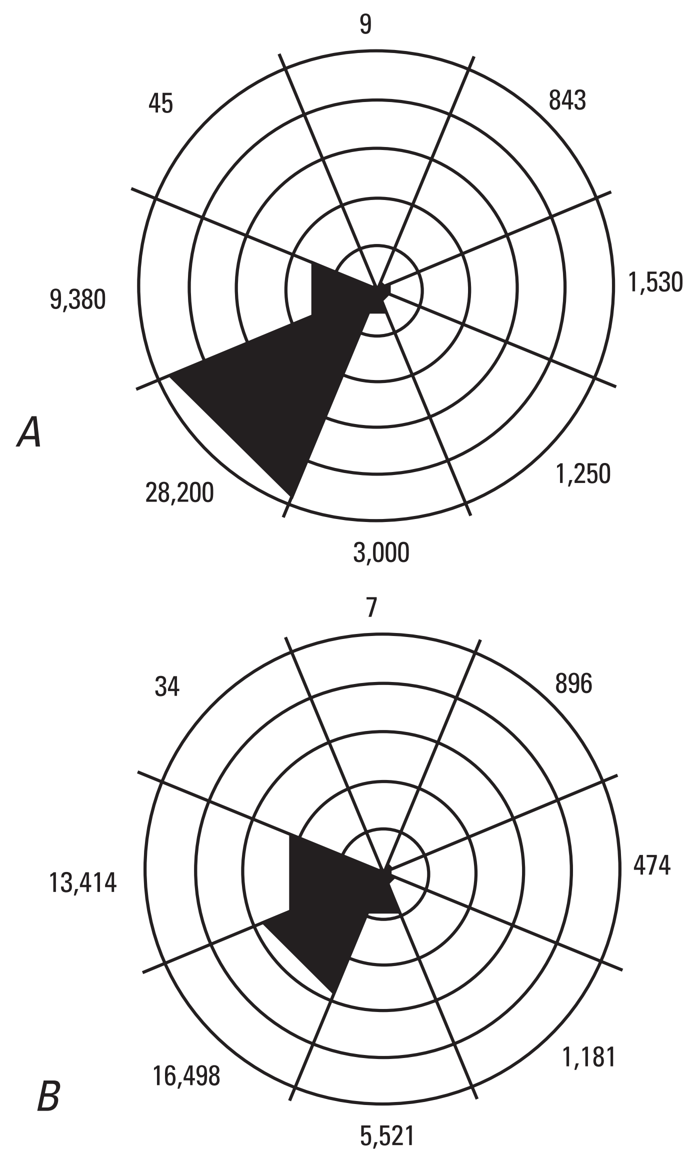

Figure 10. Rose diagrams of sand-transport potential calculated from 2 years of wind data collected at weather station 24.5 U (fig. 8*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Numbers are values of proxy variable *Qp* for each of eight directional half-quadrants, indicating total potential for eolian sediment transport from each compass sector. Vector sum of 2004 data yields a net *Qp* value of 35,800 m^3/s^3 from a direction of 229°; vector sum of 2005 data yields a net *Qp* value of 23,607 m^3/s^3 from a direction of 244°.

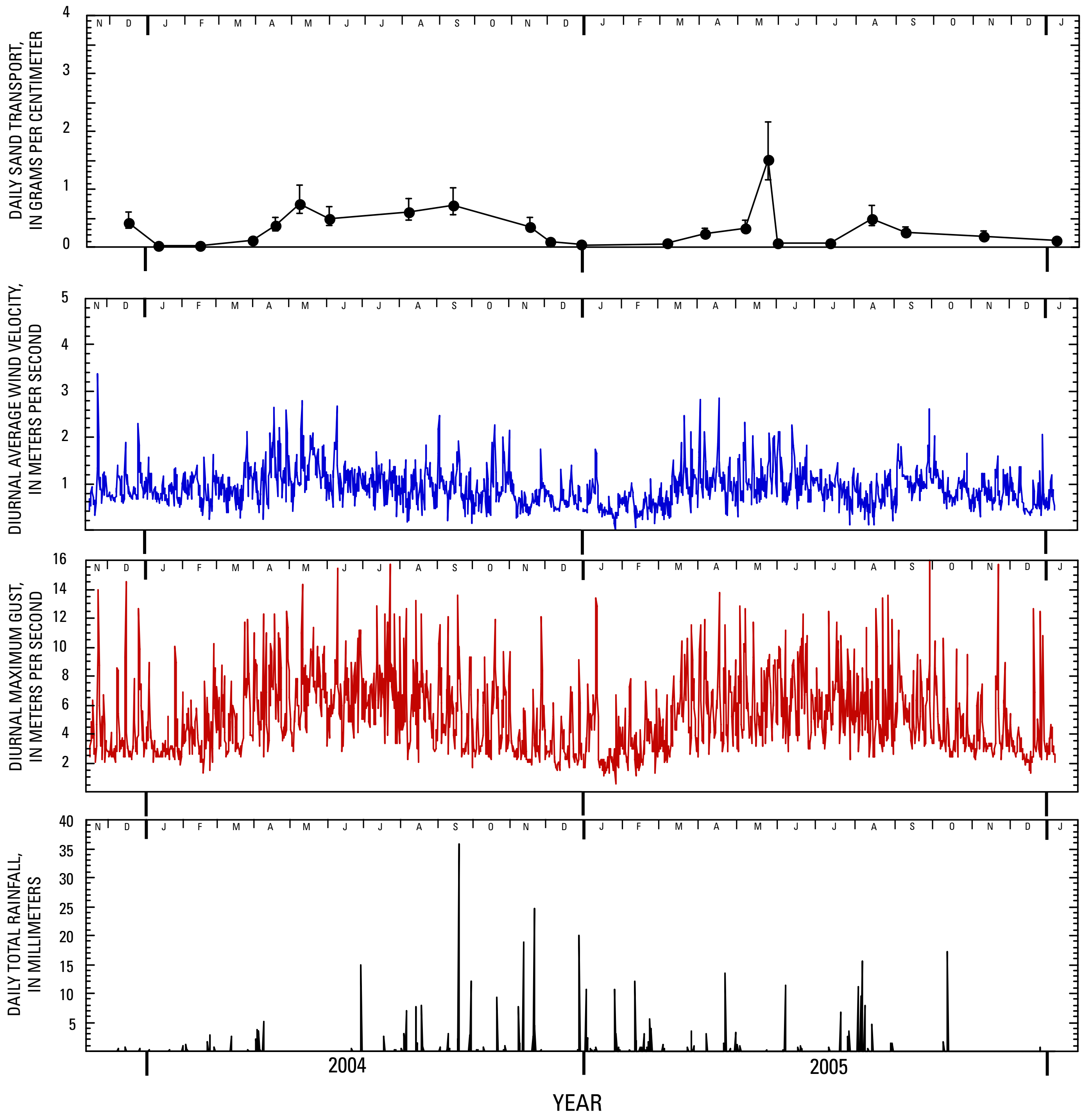

Figure 11. Rainfall, wind, and sand-transport data collected at weather station 24.5 L (fig. 8*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1), from November 2003 to January 2006. Daily sand transport is plotted in grams per day between ground surface and a height of 1 m (elevation of uppermost sand trap), normalized to a width of 1 cm. To obtain these values, sand mass collected from four traps during each maintenance visit was integrated over a width of 1 m and divided by number of days since traps had last been emptied. Wind data from upper (2.0-m height) anemometer only are presented as diurnal average wind velocity and diurnal maximum gust, using daytime (0600–1800 h) and nighttime (1800–0600 h) averages of data collected at 4-minute intervals. Daily total rainfall is summed over 24-hour intervals.

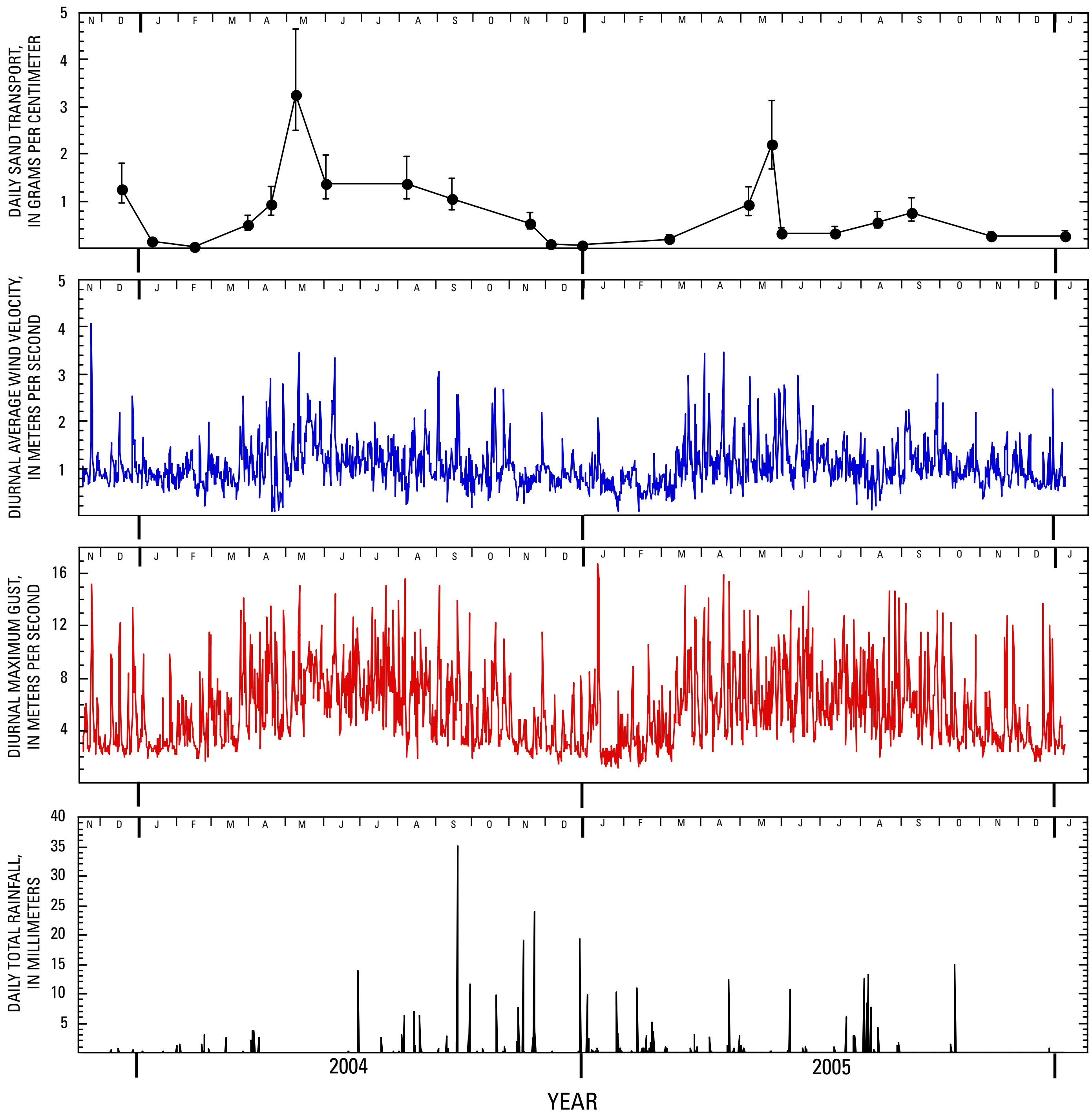

Figure 12. Rainfall, wind, and sand-transport data collected at weather station 24.5 U (fig. 8*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1) from November 2003 to January 2006. Daily sand transport is plotted in grams per day between ground surface and a height of 1 m (elevation of uppermost sand trap), normalized to a width of 1 cm. To obtain these values, sand mass collected from four traps during each maintenance visit was integrated over a width of 1 m and divided by number of days since traps had last been emptied. Wind data from upper (2.0-m height) anemometer only are presented as diurnal average wind velocity and diurnal maximum gust, using daytime (0600–1800 h) and nighttime (1800–0600 h) averages of data collected at 4-minute intervals. Daily total rainfall is summed over 24-hour intervals. Sand-transport data collected on November 15, 2005, were underestimated by an unknown amount, and those collected on January 12, 2006, correspondingly overestimated, because a mouse had contaminated lowermost (0.1-m height) sand trap at study site.

controlled flood, the resulting increase in sand flux into the dune field, and the filling of a small gully by windblown sand derived from the 2004 flood deposit (Draut and Rubin, 2006) all indicate that an increase in sandbar area can result in an increase in eolian sediment transport to, and deposition on, MFS deposits and associated archeologic sites.

The west-southwest dominant wind direction (and the same projected net sand-transport direction) measured at 24.5 Mile may be extrapolatable for some short distance upstream and downstream. Because wind conditions vary with local topography, however, extrapolation of these results for greater distances is not recommended, and any such extrapolation should be considered only speculative. However, because the orientation of the canyon around 24.5 Mile remains approximately constant (trending northeast and varying by ≤10° between river miles 22.5 and 25.0), similar net eolian sediment transport could be anticipated for other sedimentary deposits between river miles 22.5 and 25.0. Aerial photographs of the largest fluvial sandbar presently in that river reach (at river mile 23.5) indicate that this sandbar is now smaller and that vegetation in the area has increased since 1965 (fig. 13), similar to the changes apparent at 24.5 Mile. If a west-southwest dominant wind direction is assumed for 23.5 Mile, the small eolian deposit immediately northeast of the fluvial sandbar also is likely an MFS deposit in which sedimentation is linked to sand supply from the fluvial sandbar at 23.5 Mile. The eolian dune field at 23.5 Mile, which is approximately half the size of that at 24.5 Mile, was not investigated during this study.

The weather stations at 24.5 Mile from which data are reported here were removed in January 2006, and new weather stations were deployed in February 2007 at the same locations (24.5 L and 24.5 U, fig. 8) to monitor wind speed and direction, precipitation, temperature, relative humidity, barometric pressure, and eolian sand transport. Data from these new weather stations are not yet available.

Malgosa

The eolian dune field on the downstream, south side of the Malgosa Canyon debris fan (river mile 57.9, fig. 14) was one of the most active observed during this study. Wind direction there is most commonly aligned with the main canyon, from either the south-southeast or the north-northwest (figs. 15, 16). Wind records from Malgosa commonly show daily fluctuations in wind velocity, with higher-velocity, more consistently from the south-southeast in the afternoons (Draut and Rubin, 2005, 2006). Wind gusts >20 m/s were frequent during 2004 and 2005 in the upper part of the dune field (figs. 17, 18); daily sand-transport rates of about 10 to 100 g/cm were typical, and in May 2004 a 2-day event was recorded during which daily sand-transport rates were >4 kg/cm. Wind velocities

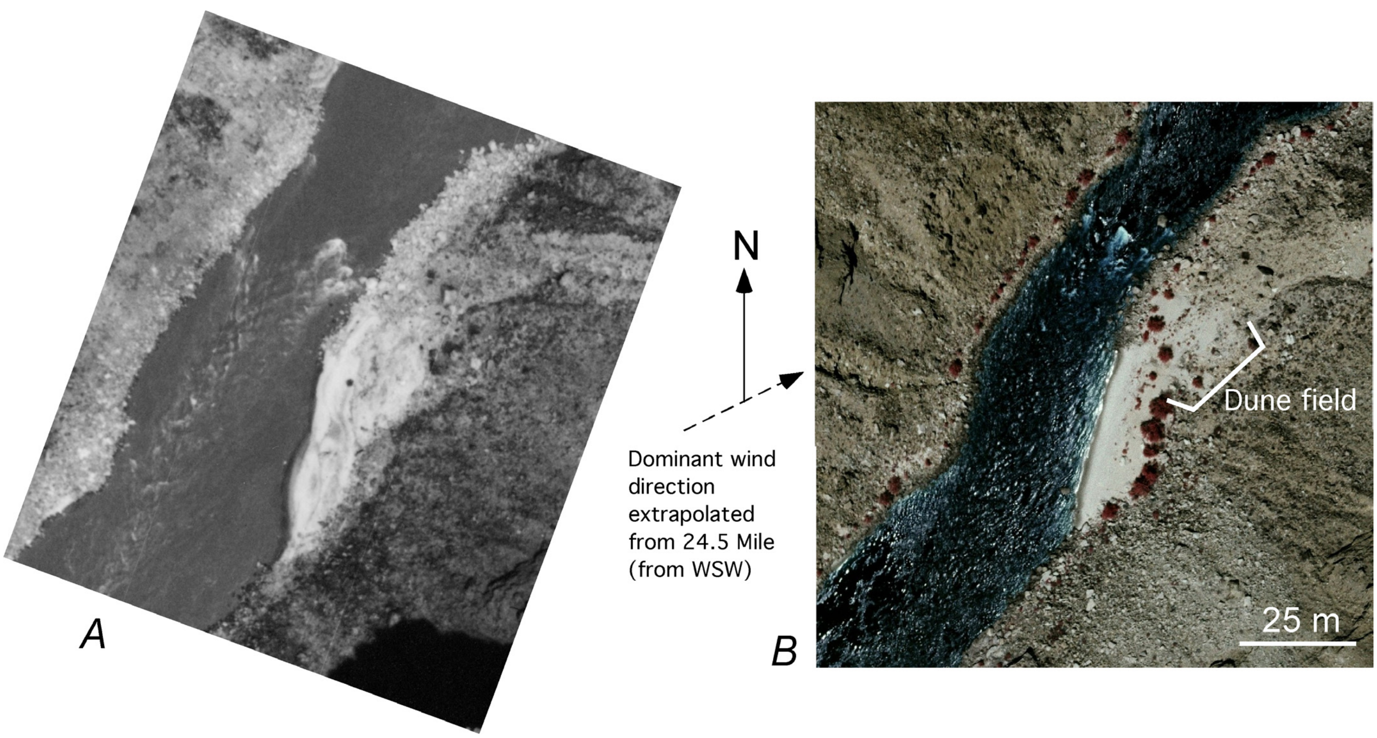

Figure 13. Aerial photographs taken in May 1965 (*A*) and May 2004 (*B*) of 23.5 Mile area along the Colorado River corridor, Grand Canyon National Park, Ariz. (fig. 1). Riverflow in May 1965 was between 680 and 792 m³/s, and in May 2004 was 226 m³/s. Small eolian dune field shown in figure 13*B*. If dominant wind direction is assumed to be the same at both 23.5 Mile and 24.5 Mile, then eolian dune field is directly downwind from a fluvial sandbar.

high enough to transport sediment of the grain size found in the dune field at Malgosa (>2 m/s) blow dominantly from the south-southeast, such that the net sand transport direction is upstream with respect to the Colorado River. This dominant wind direction is consistent with the dune morphology on the south side of the Malgosa debris fan, which has north-facing slipfaces that indicate north dune migration. Therefore, the primary sediment source for this dune field is the fluvial sandbar immediately upwind of the dune field (sandbar a, fig. 14). A second sandbar, across the river and about 200 m downstream (sandbar b, fig. 14), also occasionally provides a minor amount of sediment to the dune field. (In May 2004, sand was observed to blow from sandbar b across the river into the dune field upstream of sandbar a.) The orientation of the eolian dunes with respect to fluvial sandbars, together with the dominant wind direction measured from November 2003 to January 2006, implies that the dune field at Malgosa is an MFS deposit in which eolian sedimentation is directly linked to sediment supply from one or more fluvial sandbars upwind.

The higher riverflow in 1965 aerial photographs relative to those taken since the mid-1990s, and the generally low elevation of sandbars a and b today, make it difficult to compare fluvial-sandbar area between the two sets of photographs shown in figure 14. Aerial photographs do, however, show an increase in vegetation along the riparian zone and in the dune field at Malgosa itself in 2004 relative to 1965 (fig. 14). The increase in vegetation in the dune field since the 1960s suggests that the dunes have become less mobile. Dunes on the north side of Malgosa Creek (a tributary of the Colorado River that is dry except after recent heavy rain) can be considered inactive relative to those on the south side of Malgosa Canyon and have well-developed vegetation and biologic soil crust. The differences in dune surfaces between the north and south sides of Malgosa Creek are illustrated in figure 19. These differences are attributable to the trapping of eolian sand in the Malgosa Canyon channel between the two parts of the dune field—the southern dunes migrate north, but their sand is removed by episodic runoff in Malgosa Canyon before signifi-

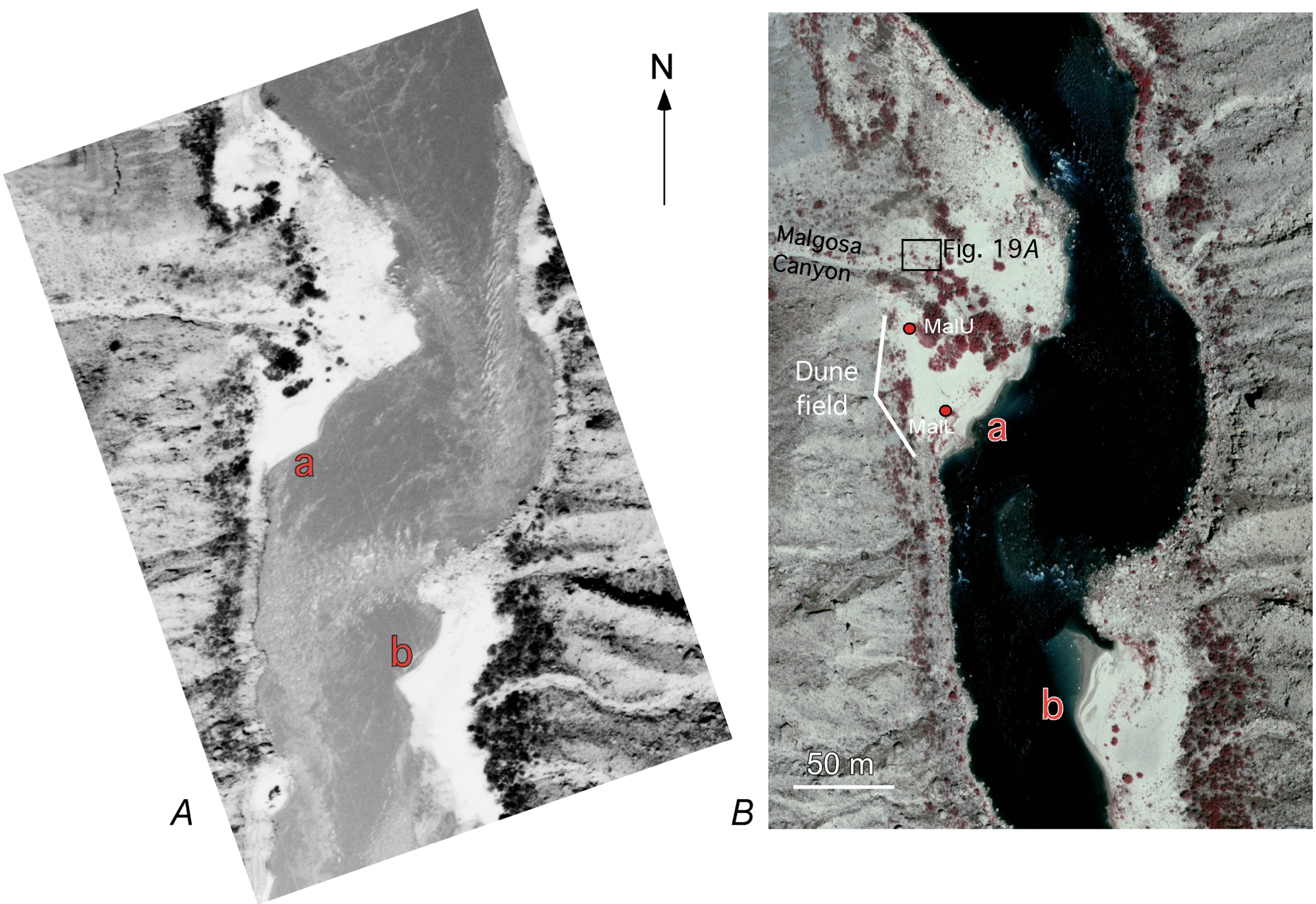

Figure 14. Aerial photographs taken in May 1965 (*A*) and May 2004 (*B*) of Malgosa area along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Riverflow in May 1965 was from 680 to 792 m^3/s, and in May 2004 was 226 m^3/s. Fluvial sand deposits (a and b). Red dots, weather stations Mal L (lower) and Mal U (upper). Most active area of eolian dune field on downstream side of Malgosa Canyon debris fan is indicated in figure 14*B*. Box in figure 14*B* indicates area of photograph in figure 19*A*. Note increase in riparian vegetation since 1965.

cant amounts of sand can reach the northern part of the dune field. Only sediment carried in suspension during high winds can be expected to reach the northern part of the dune field; sand carried north by saltation or reptation will be trapped in the tributary drainage and unavailable to the northern part of the dune field. Sand-transport rates were not measured in the dunes north of Malgosa Canyon during this study. The presence of substantial sand dunes on the northern part of the Malgosa debris fan, although they are now fairly inactive, suggests a greater sediment supply to the northern part of the dune field in the past than today.

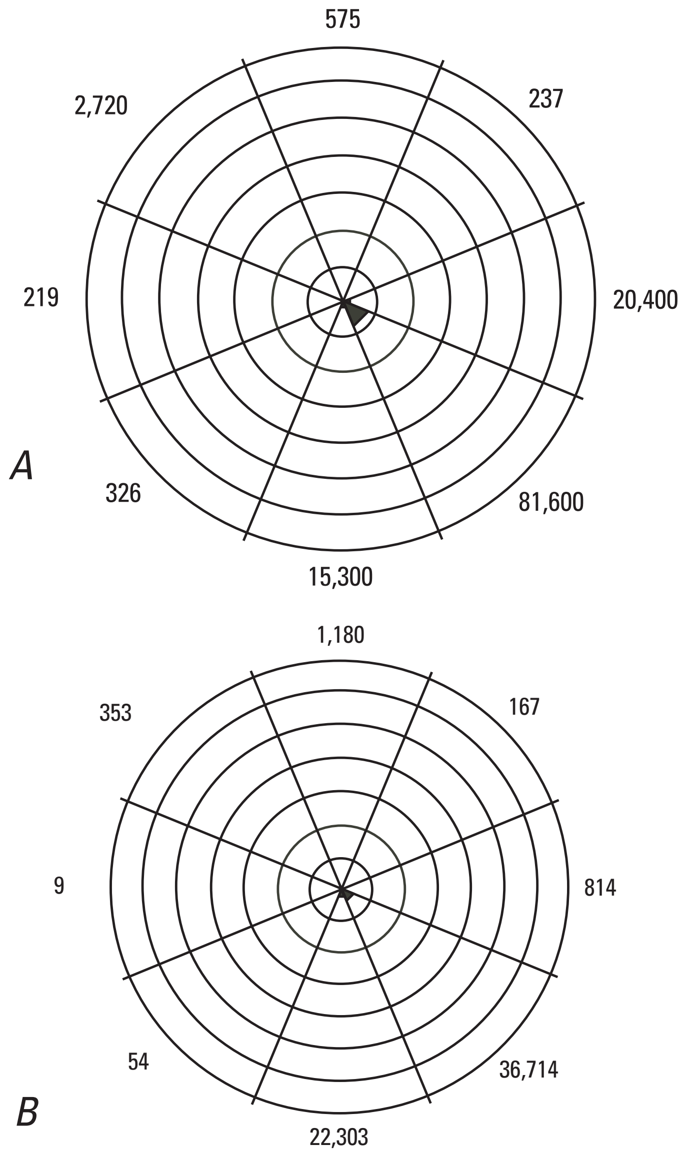

Figure 15. Rose diagrams of sand-transport potential calculated from 2 years of wind data collected at weather station Mal L (fig. 14*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Numbers for 2004 (*A*) and 2005 (*B*) are values of proxy variable *Qp* for each of eight directional half-quadrants, indicating total potential for eolian sediment transport from each compass sector. Vector sum of 2004 data, excluding period of inactivity from November 17, 2004, to December 9, 2004, when weather station was temporarily dismantled and stored on higher ground during and shortly after November 2004 high-flow experiment, yields a net *Qp* value of 107,000 m^3/s^3 from a direction of 132°; vector sum of 2005 data, ending when datalogger failed on September 19, 2005, yields a net *Qp* value of 56,148 m^3/s^3 from a direction of 154°.

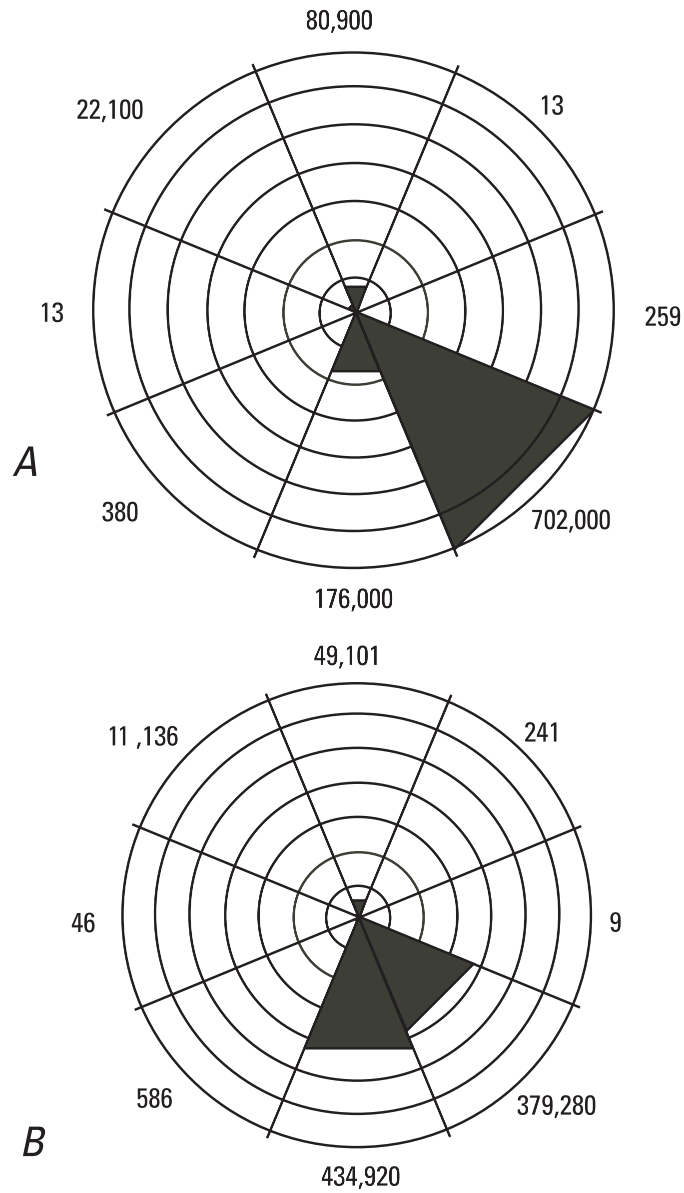

Figure 16. Rose diagrams of sand-transport potential calculated from 2 years of wind data collected at weather station Mal U (fig. 14*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Numbers for 2004 (*A*) and 2005 (*B*) are values of proxy variable *Qp* for each of eight directional half-quadrants, indicating total potential for eolian sediment transport from each compass sector. Vector sum of 2004 data yields a net *Qp* value of 757,000 m^3/s^3 from a direction of 143°; vector sum of 2005 data yields a net *Qp* value of 725,880 m^3/s^3 from a direction of 156°.

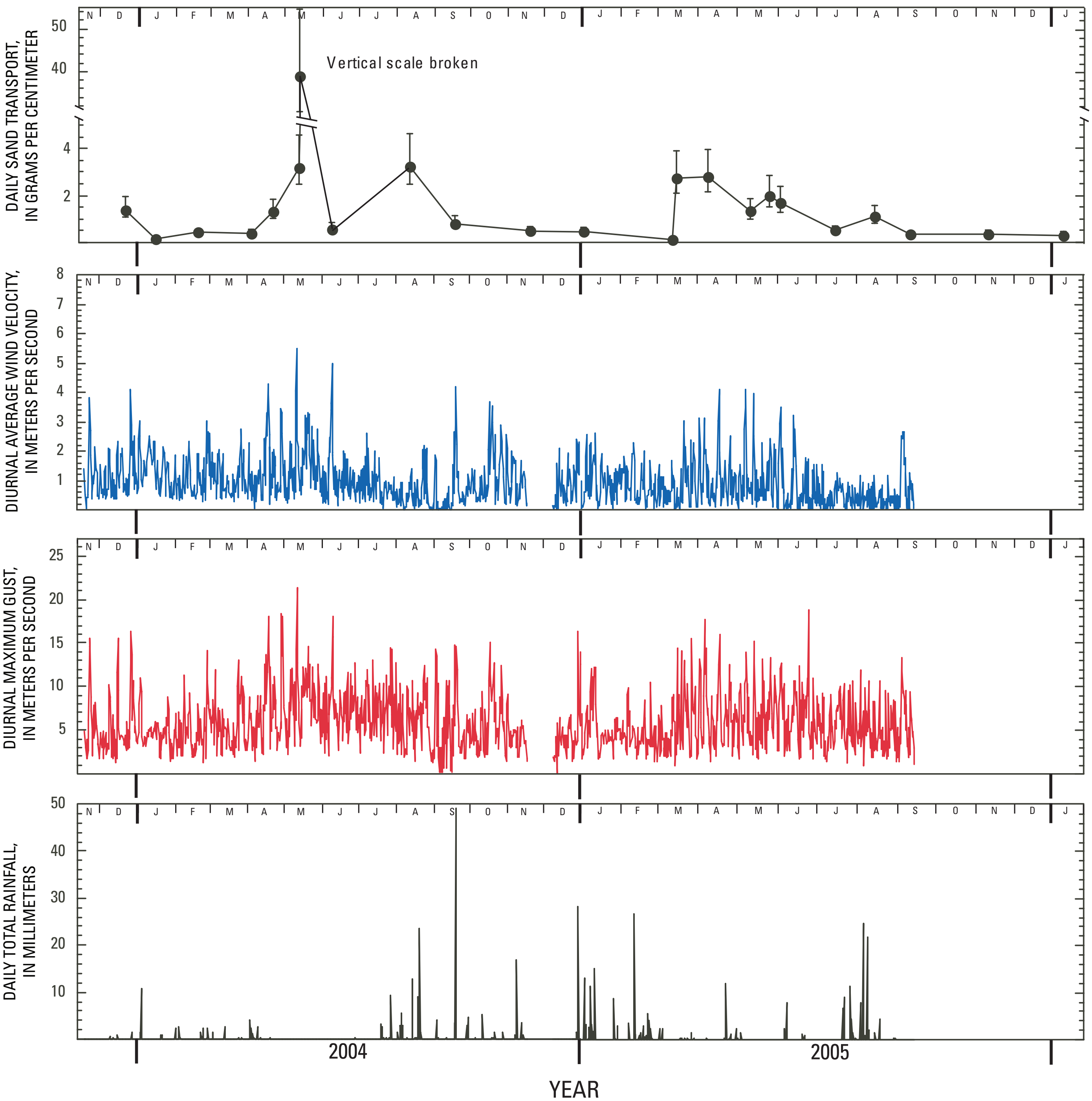

Figure 17. Rainfall, wind, and sand-transport data collected at weather station Mal L (fig. 14*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1) from November 2003 to January 2006. Record ended on September 19, 2005, when datalogger ceased to function. Daily sand transport is plotted in grams per day between ground surface and a height of 1 m (elevation of uppermost sand trap), normalized to a width of 1 cm. To obtain these values, sand mass collected from four traps during each maintenance visit was integrated over a width of 1 m and divided by number of days since traps had last been emptied. Wind data from upper (2.0-m height) anemometer only are presented as diurnal average wind velocity and diurnal maximum gust, using daytime (0600–1800 h) and nighttime (1800–0600 h) averages of data collected at 4-minute intervals. Daily total rainfall is summed over 24-hour intervals.

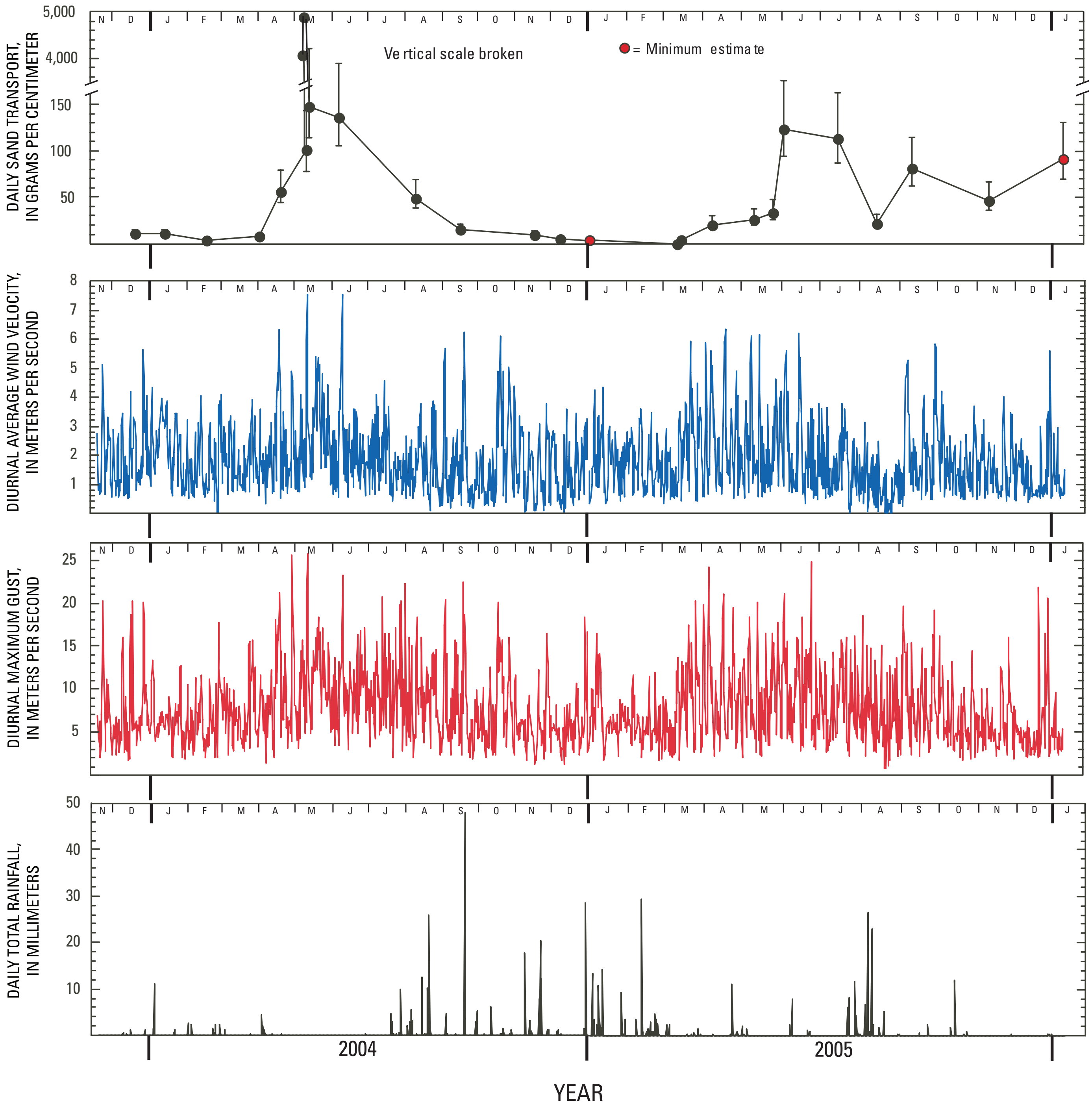

Figure 18. Rainfall, wind, and sand-transport data collected at weather station Mal U (fig. 14*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1) from November 2003 to January 2006. Daily sand transport is plotted in grams per day between ground surface and a height of 1 m (elevation of uppermost sand trap), normalized to a width of 1 cm. To obtain these values, sand mass collected from four traps during each maintenance visit was integrated over a width of 1 m and divided by number of days since traps had last been emptied. Wind data from upper (2.0-m height) anemometer only are presented as diurnal average wind velocity and diurnal maximum gust, using daytime (0600–1800 h) and nighttime (1800–0600 h) averages of data collected at 4-minute intervals. Daily total rainfall is summed over 24-hour intervals. Sand-transport data collected in January 2005 and January 2006 (red circles) are minimum estimates because one or more sand traps had been deployed incorrectly.

Malgosa had not only the highest daily sand-transport rates measured at any study site but also the heaviest rainfall (figs. 17, 18). Annual rainfall at Malgosa totaled 270 mm in 2005, twice that measured at the next-nearest study site (Palisades, 12 km downstream). Heavy rainfall at Malgosa relative to other sites was common on an event-by-event basis. The marked differences between the rainfall at Malgosa and elsewhere are attributable to local topography, although this interpretation is poorly constrained, and only 26 months of rainfall data are available from this study, possibly not accurately representing long-term conditions. The Malgosa Canyon tributary trends northeast and drains the east side of the Walhalla Plateau, southeast of the main Kaibab monocline. The orientation of Malgosa Canyon and the drainage-basin geometry may affect movement of local weather systems, possibly funneling east-moving storms in a way that could account for the significantly heavier rainfall recorded near river level at Malgosa relative to other study sites (Draut and Rubin, 2006).

Although Malgosa received more rainfall than other areas of Grand and Marble Canyons during this study, the active dune field there is not incised by gullies. A few small ephemeral gullies were observed there that were rapidly filled by windblown sand, but they did not grow large enough to cause substantial erosion. This relation among precipitation, gully incision, and the restorative effects of eolian sand contrasts with the conditions at Palisades, as discussed in detail below, where major gullies occur in an area that received less rainfall than other study sites. Eolian sediment transport at Palisades, however, was no more than a tenth of that at Malgosa and so is apparently unable to heal gullies of the size now there.

The November 2004 controlled-flood experiment resulted in deposition of a major new sandbar at Malgosa (a, fig. 14) ≤2 m thick and >10 m wide. High daily flow fluctuations for the first 3 months of 2005 eroded this sand deposit almost entirely. By May 2005, the new sandbar's condition appeared almost identical to its preflood condition (fig. 7). Because the sandbar had eroded so significantly before the spring 2005 windy season began, it was not surprising that sand-transport rates measured at the weather stations in the Malgosa area in spring 2005 were no higher than in spring 2004 (figs. 17, 18).

A

B

Figure 19. Zones within dune field at Malgosa along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). *A*, Duneforms in background, north of the Malgosa Creek tributary (in midground), are covered with abundant grass and other vegetation; biologic soil crust also occurs there, indicating little active eolian sediment deposition. View northward (upstream with respect to the Colorado River) from top of a dune crest just south of tributary. *B*, Southern part of dune field (south of Malgosa Creek), where vegetation is much sparser than in area of figure 19*A* and daily sand-transport rates reach hundreds of grams per centimeter.

Palisades

We analyzed sedimentary profiles at Palisades (Palisades of the Desert), near river mile 66, in addition to deploying two weather stations there that measured wind velocity, rainfall, and sand transport from November 2003 to January 2006. Detailed discussions of these data (figs. 2*A*, 5*A*; table 1) were presented by Draut and others (2005).

The Palisades area forms the upstream part of the geomorphic reach of the canyon described by Schmidt and Graf (1987) as the Furnace Flats reach. As discussed in the section above entitled "Overview of Sedimentologic and Geomorphologic Investigations," the alluvial terraces in this river reach represent multiple episodes of floodplain aggradation in predam time, by distinct fluvial sedimentary structures in the studied profiles. The areal extent of fluvial deposits indicates that the entire terraced area at Palisades was submerged episodically during predam high flows (see Hereford and others, 1993, 1996; Hereford, 1996). No postdam flows (since 1963) have inundated most of the terrace. A stage-discharge relation determined from driftwood deposits indicated that the terraced area was almost entirely inundated by a riverflow of about 5,940 m^3/s (Draut and others, 2005; Hazel and others, 2006a), a flood level reached most recently in 1884. Reworking of fluvial sediment by wind was common in predam time, as evidenced by eolian deposits interbedded with fluvial deposits; eolian material was also observed interbedded with "ponded," playalike sediment deposits where slopewash runoff had formed small, isolated pools on the east side of the terrace. Aerial photographs indicate that vegetation in the terraced area has increased somewhat since 1965, while that in the riparian zone has increased substantially (fig. 20). Deepening of the now-substantial arroyo at Palisades (fig. 2*A*) since the 1960s is believed to have occurred after this local drainage breached predam alluvium exposures and eolian dunes in the late 1970s or early 1980s and began to drain directly to the Colorado River (Hereford and others, 1993; Thompson and Potochnik, 2000).

Six of the nine archeologic sites at Palisades were formed in or on fluvial sediment, some of which had been reworked by wind (table 1; see Draut and others, 2005). Five of these nine archeologic sites are preserved at least partly by a cover of eolian sediment, with minor contributions from eolian sedimentary cover at two additional sites. Erosion associated with arroyo incision affects two of the archeologic sites. Exposure of cultural artifacts is attributable at least partly to eolian deflation at five of the archeologic sites at Palisades.

The greater abundance of fluvial relative to eolian sediment in vertical profiles indicates that the eolian coppice dunes on the terrace surface apparently formed by wind reworking of the extensive predam flood deposits which underlie the Palisades area, and so the dune there is defined as an RFS deposit (fig. 4*B*; Hereford, 1996). Wind directions generally align with the north-south orientation of the river in this area, with winds blowing from either the north or the south, although the dominant wind direction at Palisades (at velocities great enough to transport sand) is from the south-southeast (figs. 21, 22; Draut and Rubin, 2005, 2006). Daily sand-transport rates were about 1 g/cm within the coppice dunes but only about 0.1 g/cm on a cobble deposit at the river edge (figs. 23, 24). Given the dominant wind direction from the south-southeast, significant amounts of sediment are probably not transported by wind from river-level sandbars (see fig. 20 for locations) into the

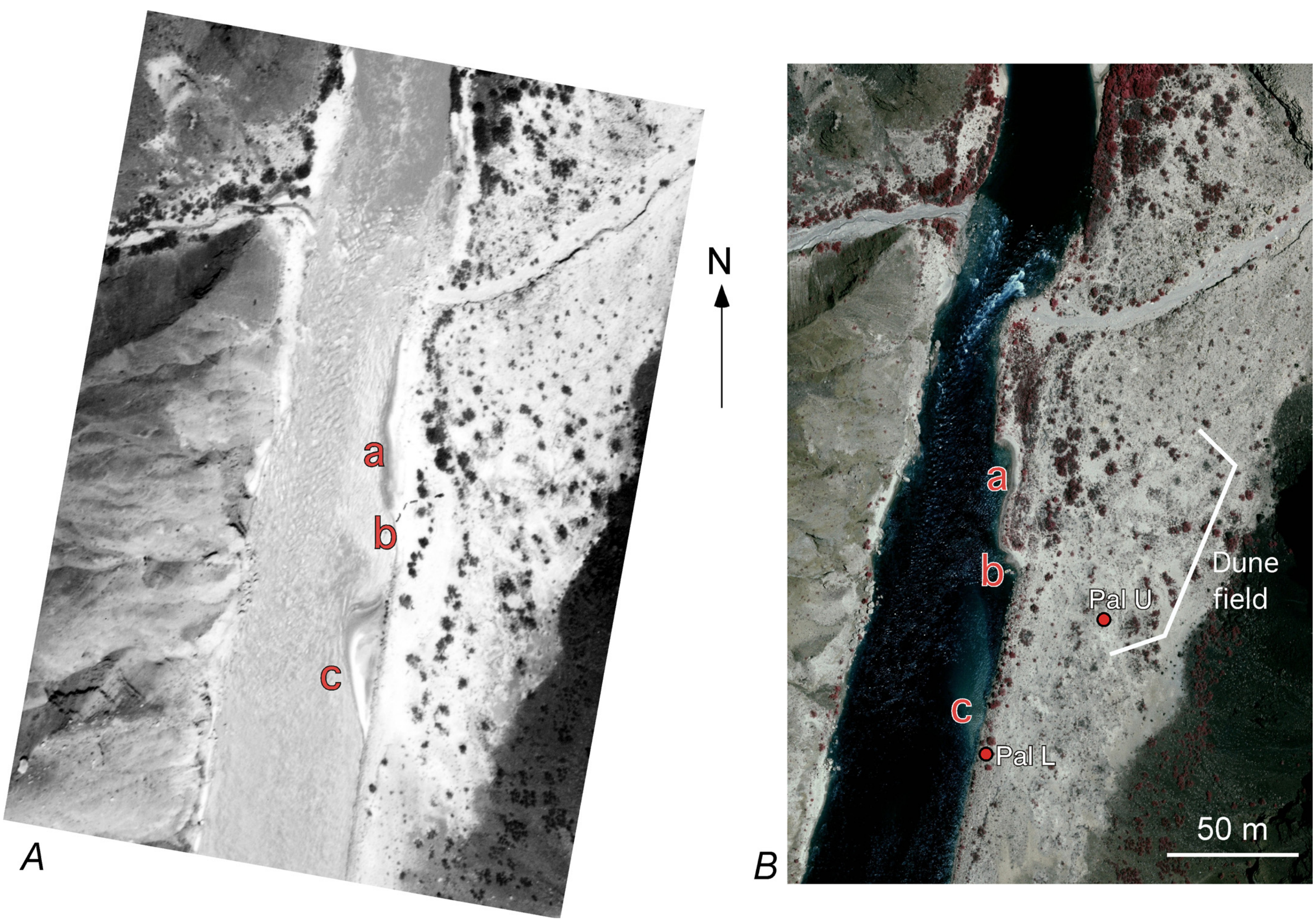

Figure 20. Aerial photographs taken in May 1965 (*A*) and May 2004 (*B*) of Palisades area along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Riverflow in May 1965 was between 680 and 792 m^3/s, and in May 2004 was 226 m^3/s. Fluvial sand deposits (a, b, and c). Red dots, weather stations Pal L (lower) and Pal U (upper). Most-active area of eolian dune field is indicated in figure 20*B*. Note increase in riparian vegetation and decrease in open sand area since 1965.

coppice dunes at Palisades. Although some migration of eolian dunes is apparent today in the northern part of the dune field, generally these dunes are relatively inactive, and vegetation and biologic soil crust are well established.

Some new sediment probably is occasionally transported into the dune field from river-level sandbars (Yeatts, 1996); however, the net wind direction measured during this study indicates a probable net loss of sediment from this dune field northwest (where it can be lost into the river). As discussed above, gully and arroyo incision causes episodic additional erosion of eolian sediment at Palisades. Because the formation of this RFS deposit was linked to deposition of fluvial sediment during large, sediment-rich predam floods, substantial new sediment will probably not be supplied to the dune field at Palisades without similar large, sediment-rich floods in

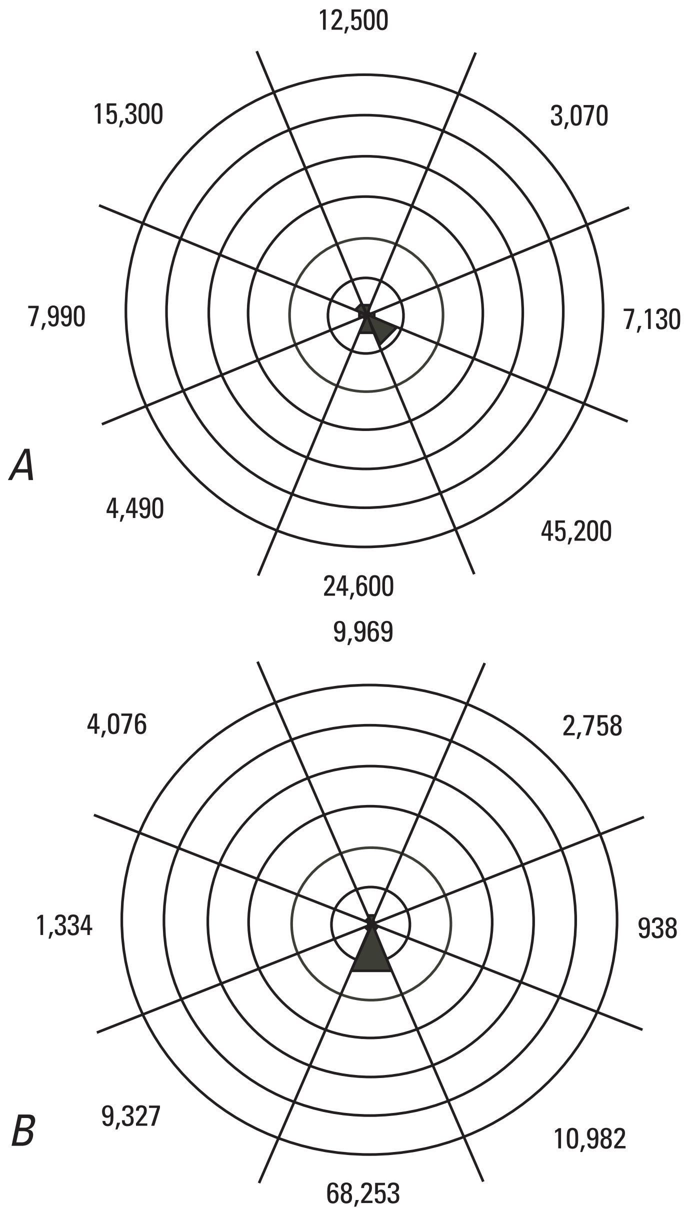

Figure 21. Rose diagrams of sand-transport potential calculated from 2 years of wind data collected at weather station Pal L (fig. 20*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Numbers for 2004 (*A*) and 2005 (*B*) are values of proxy variable *Qp* for each of eight directional half-quadrants, indicating total potential for eolian sediment transport from each compass sector. Vector sum of 2004 data yields a net *Qp* value of 38,800 m^3/s^3 from a direction of 149°; vector sum of 2005 data yields a net *Qp* value of 68,171 m^3/s^3 from a direction of 179°.

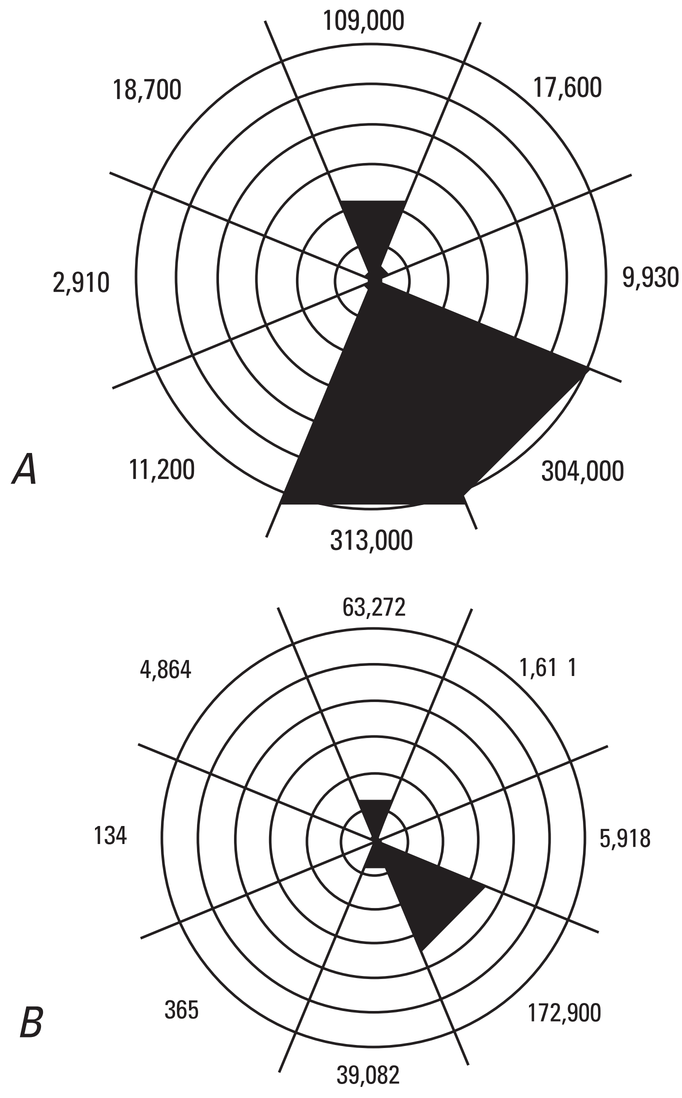

Figure 22. Rose diagrams of sand-transport potential calculated from 2 years of wind data collected at weather station Pal U (fig. 20*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Numbers for 2004 (*A*) and 2005 (*B*) are values of proxy variable *Qp* for each of eight directional half-quadrants, indicating total potential for eolian sediment transport from each compass sector. Vector sum of 2004 data yields a net *Qp* value of 467,000 m^3/s^3 from a direction of 155°; vector sum of 2005 data, collected while datalogger used a 4-minute sampling interval (Jan. 1, 2005–Apr. 2, 2005, and Sept.18, 2005–Jan. 14, 2006), yields a net *Qp* value of 154,890 m^3/s^3 from a direction of 132°.

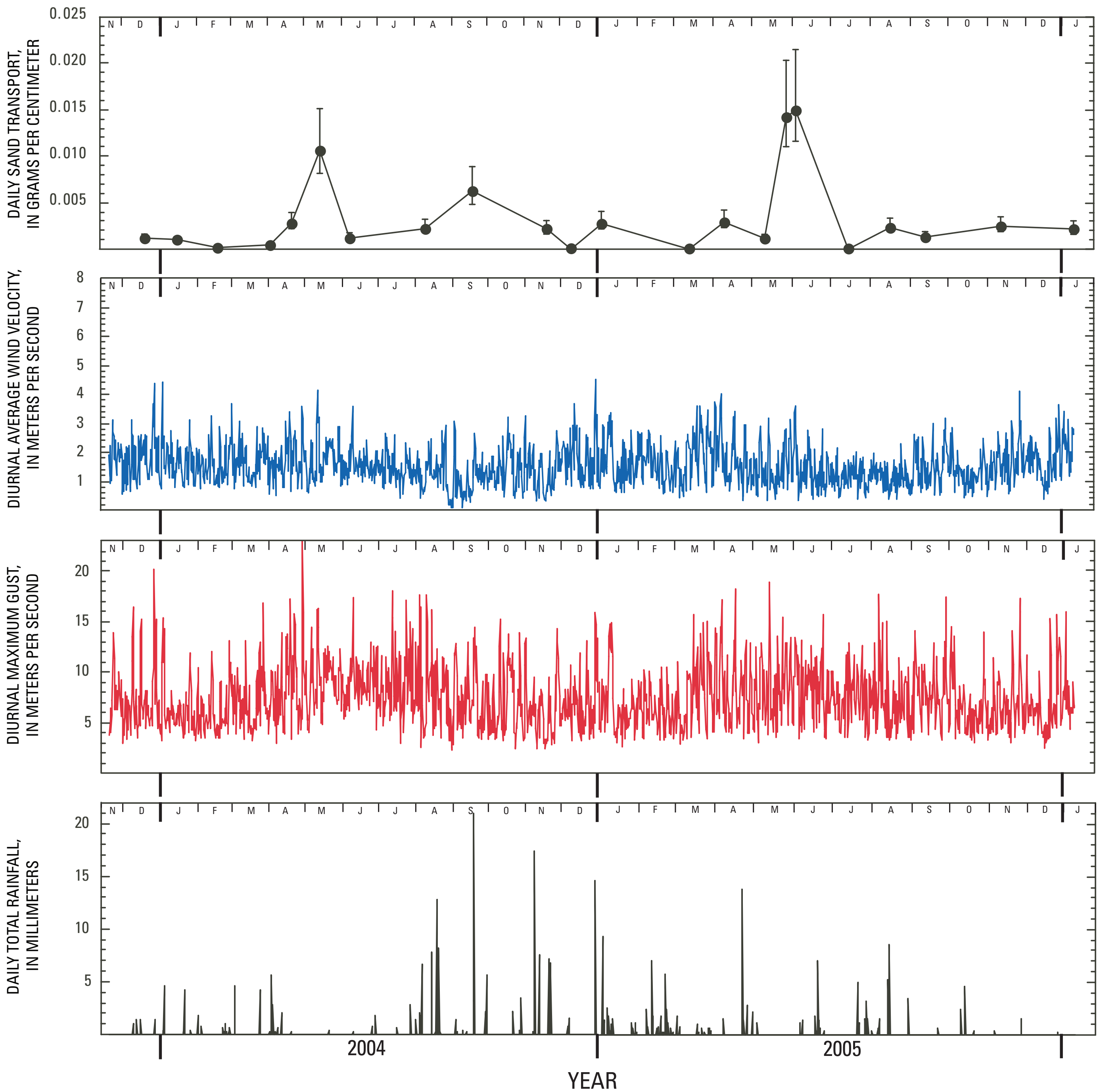

Figure 23. Rainfall, wind, and sand-transport data collected at weather station Pal L (fig. 20*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1) from November 2003 to January 2006. Daily sand transport is plotted in grams per day between ground surface and a height of 1 m (elevation of uppermost sand trap), normalized to a width of 1 cm. To obtain these values, sand mass collected from four traps during each maintenance visit was integrated over a width of 1 m and divided by number of days since traps had last been emptied. Wind data from upper (2.0-m height) anemometer only are presented as diurnal average wind velocity and diurnal maximum gust, using daytime (0600–1800 h) and nighttime (1800–0600 h) averages of data collected at 4-minute intervals. Daily total rainfall is summed over 24-hour intervals.

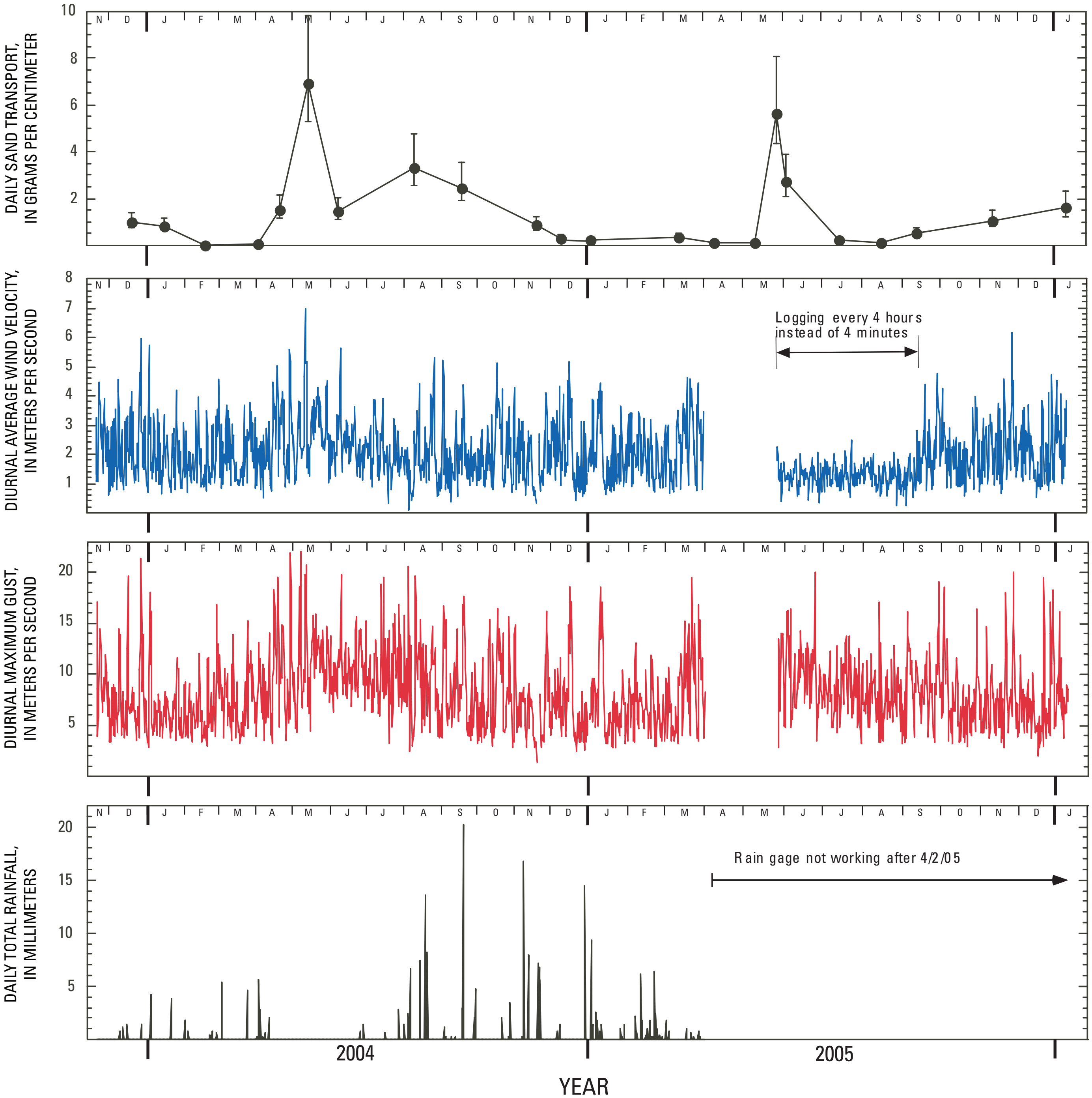

Figure 24. Rainfall, wind, and sand-transport data collected at weather station Pal U (fig. 20*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1) from November 2003 to January 2006. In April 2005, datalogger began to malfunction, and rain gage ceased to function. Operation resumed on May 30, 2005, but with datalogger incorrectly programmed to record data every 4 hours instead of every 4 minutes. Datalogger was reprogrammed to record at 4-minute intervals on September 18, 2005, after which operation proceeded normally but without a functioning rain gage, until weather station was removed on January 14, 2006. Daily sand transport is plotted in grams per day between ground surface and a height of 1 m (elevation of uppermost sand trap), normalized to a width of 1 cm. To obtain these values, sand mass collected from four traps during each maintenance visit was integrated over a width of 1 m and divided by number of days since traps had last been emptied. Wind data from upper (2.0-m height) anemometer only are presented as diurnal average wind velocity and diurnal maximum gust, using daytime (0600–1800 h) and nighttime (1800–0600 h) averages of data collected at 4-minute intervals. Daily total rainfall is summed over 24-hour intervals.

the future. Controlled, sediment-rich Colorado Riverflows of about 1,270 m^3/s can enlarge the fluvial sand deposits shown in figure 20 at least temporarily, and substantial deposition on sandbars (and in arroyo mouths) was documented at Palisades after high flows in 1996 (Yeatts, 1996) and 2004 (Draut and Rubin, 2006; Hazel and others, 2008). However, flows of that magnitude are unlikely to promote substantial eolian sediment transport into the dune field, given the dominant wind direction measured during this study and the positions of sandbars a through c (fig. 20) relative to the eolian dunes.

As mentioned above, during this study the annual rainfall measured at Palisades was significantly less than that measured 12 km upstream at Malgosa (in 2005, the 135 mm recorded at Palisades was less than half that measured at Malgosa; figs. 23, 24). Palisades had the least total annual rainfall of any study site, though similar to that measured nearby at Comanche (river mile 68, where 138 mm of rain fell in 2005). The much-studied arroyo at Palisades has, therefore, reached its advanced state of terrace incision despite its position in a reach of the Colorado River with relatively little rainfall, at least as measured during this 26-month study. Although many factors contribute to gully incision (including long-term climate, drainage-basin geometry, substrate composition, and effective base level), we infer that arroyo incision would not have progressed so far if eolian sediment transport within the Palisades terrace area were an order of magnitude greater than today. A short distance upstream, gullies are typically absent from the dune field at Malgosa—a site with twice the rainfall but 10 times the sand-transport rate at Palisades. Active eolian sediment transport at Malgosa more than accommodates the episodic gully incision there, and gullies (which act as natural traps for windblown sand) are quickly healed, similar to the situation observed at 24.5 Mile in January 2006 (Draut and Rubin, 2006).

The weather stations at Palisades from which data are reported here were removed in January 2006. In February 2007, a new weather station was deployed at Palisades dune field (Pal U, fig. 20) to monitor wind speed and direction, rainfall, temperature, relative humidity, barometric pressure, and sand transport. Data from this new weather station are not yet available.

Comanche

As discussed above, we analyzed sedimentary profiles at Lower Comanche (near river miles 68–69) in May 2004 (fig. 5*B*). One weather station (Com; see Draut and Rubin, 2005, 2006) measured wind velocity, precipitation, and sand transport in the northern part of the Lower Comanche area between April 2004 and January 2006. Detailed discussions of these data were presented by Draut and others (2005) (see figs. 2*B* and 5*B* and table 2).

The stratigraphy of the southern, arroyo-incised part of the Comanche area (that is, Lower Comanche) indicated multiple episodes of fluvial sedimentation, followed by reworking at the land surface by wind and local rainfall runoff. Eolian climbing ripples were present in some sedimentary deposits; much of the silt and fine sand did not contain preserved, diagnostic sedimentary structures. Colluvium (recognized by sandstone and shale clasts derived from local bedrock) was present in all six of the sedimentary profiles studied at Lower Comanche. Five of the six archeologic sites in the vicinity are within eolian dunes (table 2), of which four were originally on eolian sediment and the fifth was built on an interdune, playalike surface. Four archeologic sites were at least partly buried by eolian sediment, two of which have only minor sediment cover (<10 cm thick). Three of the five archeologic sites within the dune field are affected by active eolian deflation and dune migration. The one cultural site not in or among the large coppice dunes at Lower Comanche (site C:13:273, table 2) was constructed on a terrace that contained slopewash sediment interbedded with lighter colored, better sorted fine sand and silt with poorly preserved sedimentary structures that appeared to grade laterally into both fluvial and eolian deposits.

On the basis of field relations between fluvial and eolian deposits, the eolian dunes in the Comanche area most likely originated from reworking of large, predam flood deposits—some in place and some immediately southeast (upwind) of the dune area—similarly to those at Palisades. Therefore, the large eolian dune field at Comanche is defined primarily as an RFS deposit. The dominant wind direction (net potential sand-transport direction) identified for Comanche in 2004 and 2005 is from the southeast, directed upstream (fig. 26). A substantial component of potential sediment transport is from the south, however, implying that some sediment from non-flood-stage fluvial deposits may reach the eolian dunes. If sand is indeed blown from river-margin sandbars (a, fig. 25), this sediment supply has probably diminished since the 1960s because the open sand area has decreased and riparian vegetation has increased between the sandbar and eolian dunes in postdam time (fig. 25). A decrease in open sand area and an increase in vegetation are similarly apparent at sandbar b (fig. 25), several hundred meters downstream and to the south-southeast of sandbar a, where the November 2004 controlled flood substantially increased the open sand area. The new flood sand was eroded so rapidly by high daily flow fluctuations in early 2005 that 6 months after the flood, the state of the beach was virtually identical to that before the flood (Draut and Rubin, 2006). Postflood daily sand-transport rates during the spring 2005 windy season were higher, however, than in spring 2004, by a factor of ≤2 (daily sand-transport rates in this dune field are typically about 0.1 g/cm, reaching >1 g/cm during spring winds; fig. 27).

Given the proximity of Palisades to Comanche (about 5 km apart), the consistent north-south orientation of the main canyon between them, and the similar south-southeast dominant wind direction measured in both areas, we can reasonably extrapolate similar net eolian-sediment-transport pathways for the reach of the Colorado River corridor between these two areas. Few fluvial sandbars occur on river right (west bank) in that reach, except for a small deposit at the Lava-Chuar campsite (river mile 65.3). Open sand area is greater on river left (east bank), with some fluvial deposits from which sand is likely remobilized and transported predominantly north-northwest. The dominant sand-transport direction calculated for both Palisades and Comanche is such that new fluvial deposits left by riverflows of about 1,270 m^3/s will probably not act as major sand sources for adjacent dune fields on river left. Instead, in those areas and presumably along the intervening approximate 5 km of the Colorado River corridor, the net sand-transport direction from fluvial sandbars on river left is upstream and to the river, where windblown sand would become entrained in the water.

Immediately downstream of Lower Comanche, the canyon widens and makes several tight bends in the Tanner area (river miles 69–71). Given the substantial topographic variations between Comanche and Tanner, we cannot reasonably extrapolate a similar north-northwest dominant sand-transport direction downstream of Lower Comanche, where wind conditions would need to be measured independently to identify eolian-sediment-transport pathways in that area. Data from two weather stations deployed at river mile 70 in early 2007 should clarify sand-transport rates and directions in that reach of the Colorado River corridor.

Because many of the archeologic sites in the Comanche area are associated with eolian sediment that locally is apparently sourced from predam and, to a lesser extent, postdam fluvial deposits, the occurrence or nonoccurrence of sediment-rich floods is linked to sedimentary processes in the dune field, likely affecting the preservation of archeologic

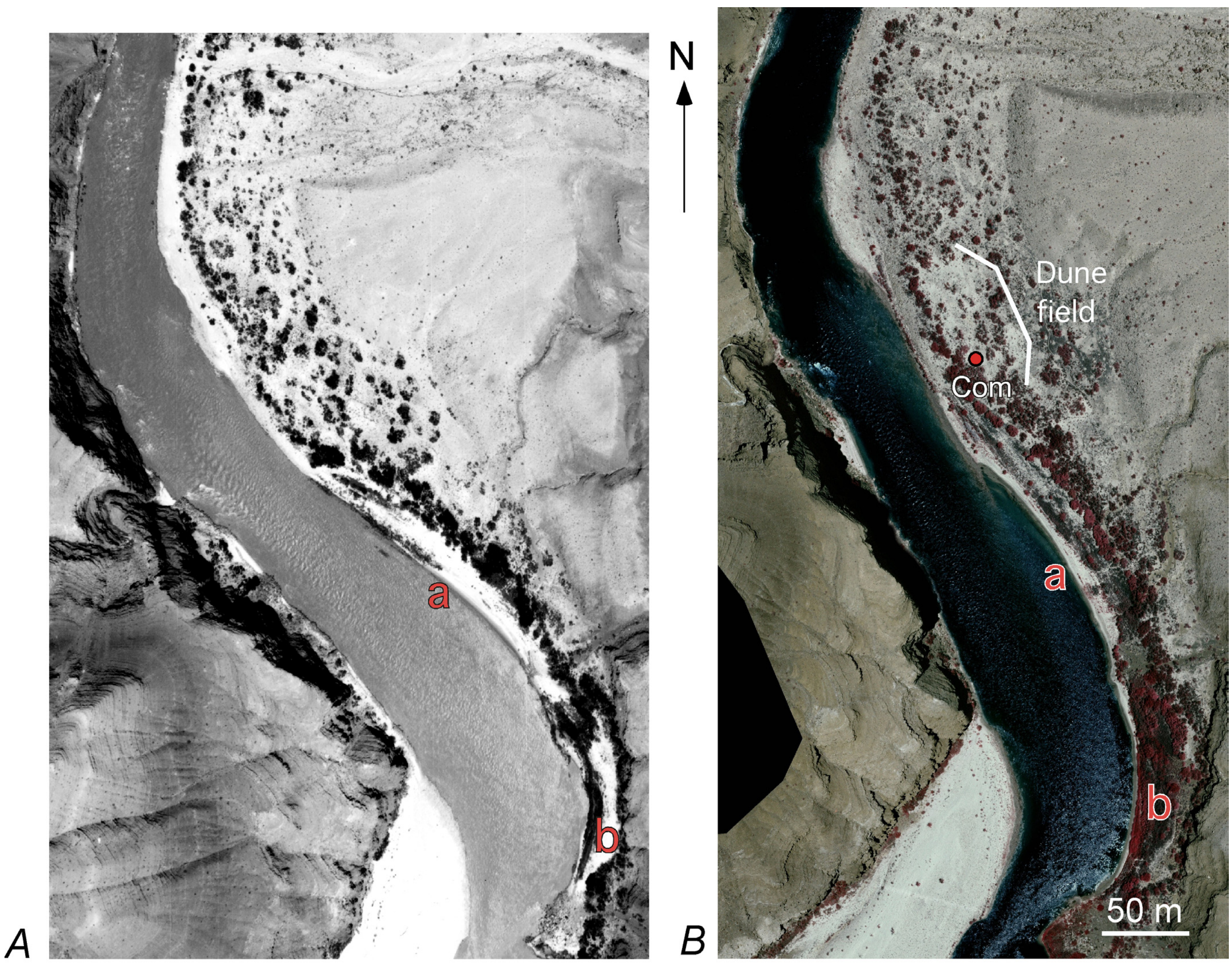

Figure 25. Aerial photographs taken in May 1965 (*A*) and May 2004 (*B*) of Comanche area along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Riverflow in May 1965 was between 680 and 792 m^3/s, and in May 2004 was 226 m^3/s. Fluvial sand deposits (a and b) red dot, weather station Com. Modern extent of eolian dune field is indicated in figure 25*B*. Note increase in riparian vegetation and decrease in open sand area since 1965.

sites there. As with several other large eolian dune fields in Grand Canyon, however (see discussion of site 3 in the subsection above entitled "Three Case Studies"), it is uncertain whether the archeologic sites at Comanche would be better preserved if new flood sediment were available to be blown into the dune field, because many of these sites are naturally exposed by dune migration over time. If the dune field at Comanche is significantly affected by sediment-supply limitation in the future (that is, by the effects of dam operations), vegetation and biologic soil crust will increase in this dune field, indicating a decrease in mobility of the eolian sediment composing the dunes. Continued monitoring and topographic surveys of dunes by the National Park Service would indicate whether, and how rapidly, dune migration and sand transport occur. As eolian sediment transport decreases in a sediment-supply-limited dune field and dune-migration rates correspondingly decrease, the risk of archeologic-site destabilization by dune migration is diminished. However, although cultural artifacts then will less likely be disturbed by dune migration, the risk of site erosion by gully incision will increase because with less sand transport, gullies that form during rain runoff will have less opportunity to be filled by eolian sand.

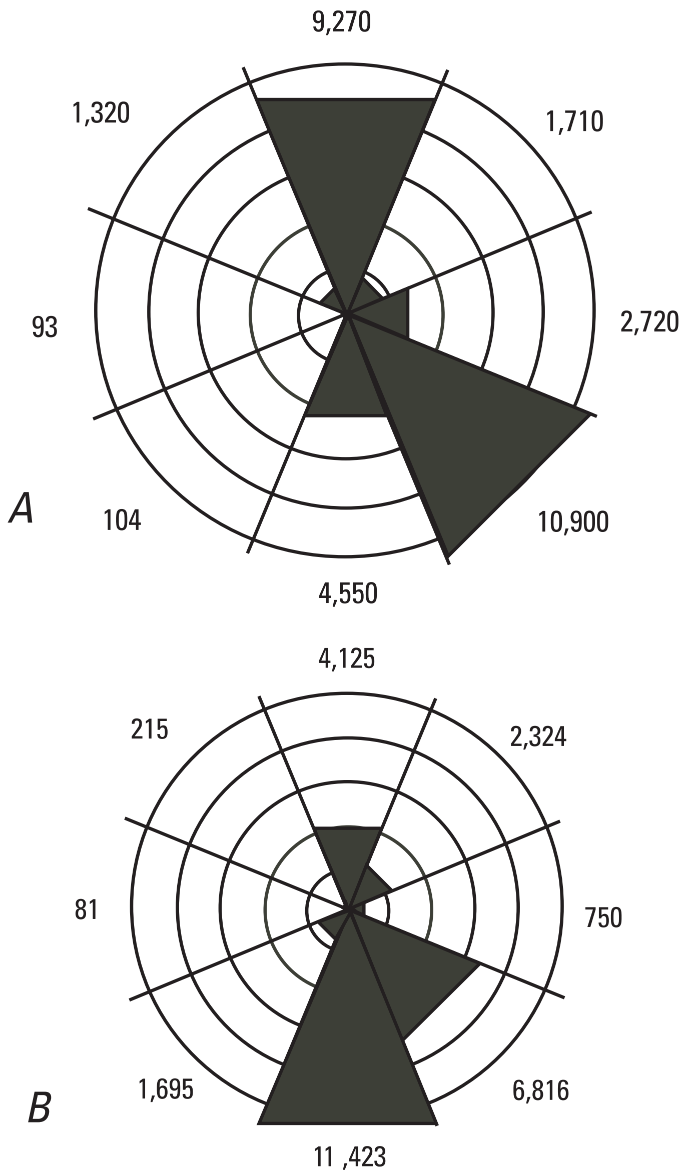

Figure 26. Rose diagrams of sand-transport potential calculated from wind data collected at weather station Com (fig. 20B) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1) from April 2004 to January 2006. Numbers for 2004 (*A*) and 2005 (*B*) are values of proxy variable *Qp* for each of eight directional half-quadrants, indicating total potential for eolian sediment transport from each compass sector. Vector sum of April–December 2004 data yields a net *Qp* value of 10,200 m^3/s^3 from a direction of 98°; vector sum of 2005 data yields a net *Qp* value of 13,308 m^3/s^3 from a direction of 153°.

Forster

The study site at the mouth of Forster Canyon (river mile 123.0) is in an eolian dune field south-southwest of a small fluvial sand deposit opposite the tail waves of Forster rapid (sandbar a, fig. 28). Higher riverflow in aerial photographs taken in 1965 relative to those taken in the 1990s and 2000s makes it difficult to determine accurately changes in the area of the sandbars at Forster (a–c, fig. 28), although the more recent photographs clearly show an increase in riparian vegetation covering a formerly open sand area.

One weather station deployed in the eolian dune field at Forster from April 2004 to January 2006 had multiple equipment failures related to adverse conditions caused by high winds and abundant windblown sand. During its operation, however, the station recorded wind directions almost exclusively from the north and northeast (oriented up the axis of Forster Canyon, perpendicular to the trend of the Colorado River in this area), with a dominant wind direction from the north-northeast (fig. 29). Therefore, the eolian dune field at Forster (figs. 5*A* and 28*B*) is directly downwind of the fluvial sand deposit (sandbar a, fig. 28) and is defined as an MFS deposit. Daily sand-transport rates within this dune field were among the highest measured during this study (commonly >100 g/cm, fig. 30), and the sand surface was observed to aggrade and deflate repeatedly at the weather station by tens of centimeters on a time scale of weeks. Forster was the site of the highest wind speed measured during this study, a gust in July 2004 of 29 m/s. Aside from the main dune field at Forster, eolian sediment also occurs at elevations tens of meters above the river, where the sediment is deposited on a steep, vegetated, sloping canyon wall on the south side (left bank) of the river. These eolian slope deposits, which are visible at the bottoms of figures 28*A* and 28*B* and shown obliquely in figure 28*C*, are downwind of the sandbars (a–c, fig. 28) and assumed to have been sourced from them. If those three fluvial deposits serving as sand

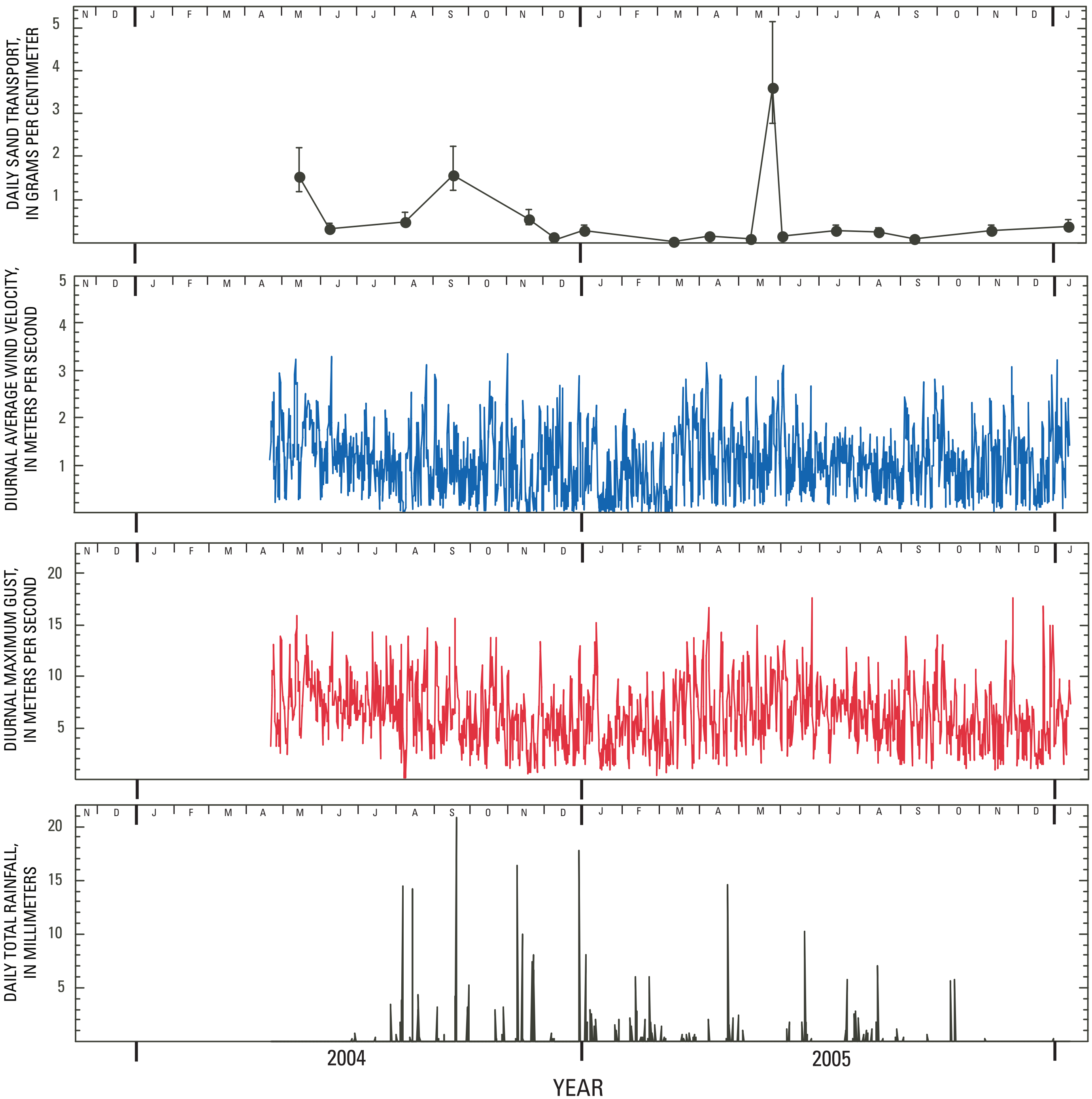

Figure 27. Rainfall, wind, and sand-transport data collected at weather station Com (fig. 20*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1) from April 2004 to January 2006. Daily sand transport is plotted in grams per day between ground surface and a height of 1 m (elevation of uppermost sand trap), normalized to a width of 1 cm. To obtain these values, sand mass collected from four traps during each maintenance visit was integrated over a width of 1 m and divided by number of days since traps had last been emptied. Wind data from upper (2.0-m height) anemometer only are presented as diurnal average wind velocity and diurnal maximum gust, using daytime (0600–1800 h) and nighttime (1800–0600 h) averages of data collected at 4-minute intervals. Daily total rainfall is summed over 24-hour intervals.

sources were enlarged, it is probable that new eolian sediment in turn also would accumulate in the dune field and on eolian deposits of the adjacent canyon-wall slope.

Aerial photographs taken before and after the 1996 controlled-flood experiment show an increase in the area of one sandbar (a, fig. 28) at the upstream end of the dune field at Forster. Although the schedule of flood-related fieldwork did not permit this beach to be photographed immediately before or after the November 2004 controlled flood, visual observations, including a shallow sedimentary profile dug in early 2005, indicated that new sand was deposited there as a result of this flood. High daily flow fluctuations from January to March 2005 caused partial erosion of the new flood deposit, such that tamarisk roots were exposed in March 2005 that had not been visible before the November 2004 flood. Sand-transport rates measured during the spring 2005 windy season were significantly higher than those measured in spring 2004 (fig. 30), but sand-trap malfunctions during spring 2004 and anemometer malfunctions in spring 2005 prevented thorough comparison of preflood and postflood spring wind conditions and sand transport at Forster.

Known archeologic sites in the Forster area include several sites built on and buried by eolian sediment. Dune migration causes many cultural artifacts to be exposed and covered repeatedly. Because this MFS deposit is unusually active, with frequent high winds that move significant

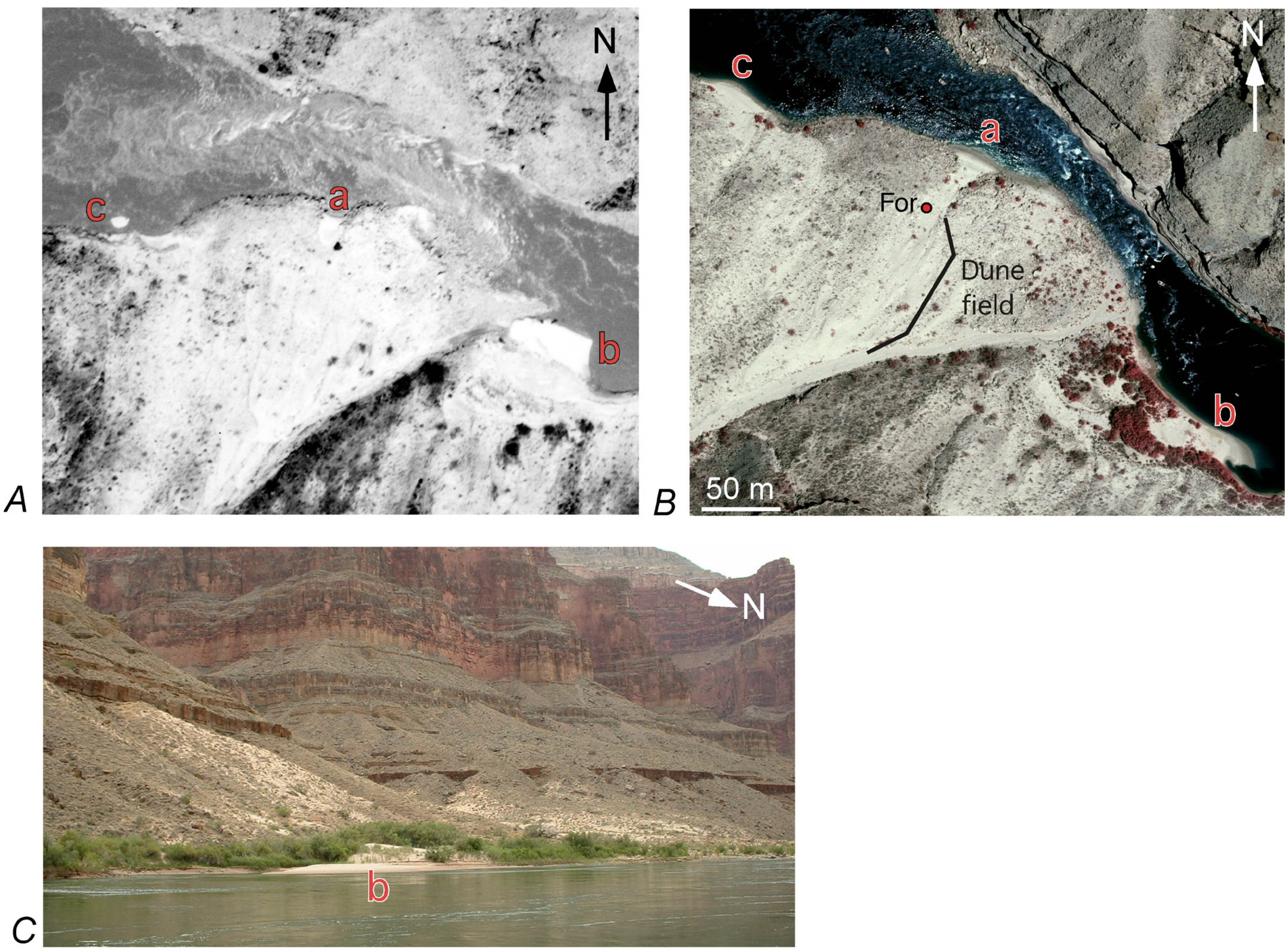

Figure 28. Aerial photographs taken in May 1965 (*A*), May 2004 (*B*), and April 2004 (*C*) of area by mouth of Forster Canyon along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Riverflow in May 1965 was between 680 and 792 m^3/s, and in May 2004 was 226 m^3/s. Fluvial sand deposits (a, b, and c; sandbar c is mostly obscured by high flow in 1965 photograph). Red dot, weather station For. Modern extent of eolian dune field is indicated in figure 28*B*. In figure 28*C*, light-colored eolian deposits on slopes above river, downwind from fluvial sand deposits. (Dominant wind direction at Forster is from north-northwest.) View southwestward toward river left near sandbar b. Note increase in riparian vegetation and decrease in open sand area since 1965.

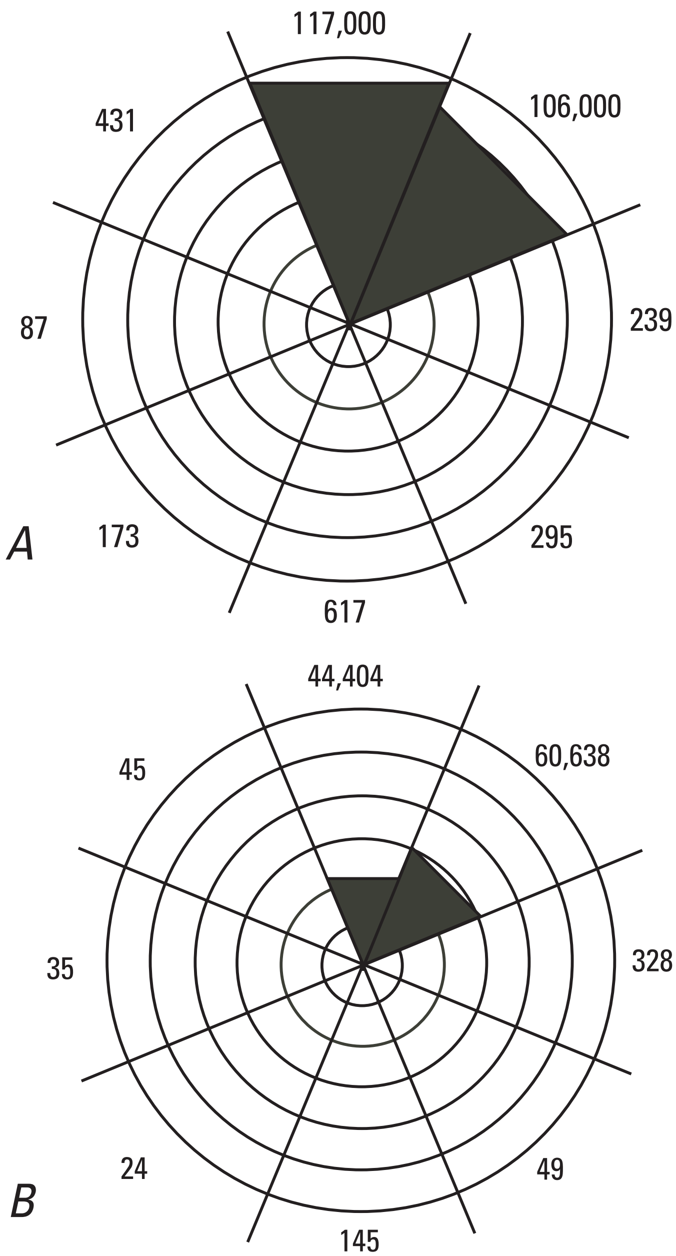

Figure 29. Rose diagrams of sand-transport potential calculated from wind data collected at weather station For (fig. 28*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1) from April 2004 to January 2006. High winds caused repeated problems during weather-station operation, resulting in data gaps of several hours to months (see fig. 30). Numbers for 2004 (*A*) and 2005 (*B*) are values of proxy variable *Qp* for each of eight directional half-quadrants, indicating total potential for eolian sediment transport from each compass sector. Vector sum of 2004 data yields a net *Qp* value of 219,000 m^3/s^3 from a direction of 21°; vector sum of data for two extensive intervals of normal operation during 2005 (Jan. 1, 2005–Apr. 3, 2005, and Sept. 20, 2005–Dec. 31, 2005) yields a net *Qp* value of 101,070 m^3/s^3 from a direction of 26°.

amounts of sand, sediment supply to the dune field at Forster is strongly linked to the amount of sediment available at the upstream sandbar (a, fig. 28). Forster is an area of Grand Canyon where the canyon orientation changes substantially within several kilometers of the study site; therefore, a dominant north-northeast wind direction should not be assumed for other areas upstream and downstream.

202.9 Mile

One weather station on river right (west bank, river mile 202.9) operated from April 2004 to January 2006. The study site (fig. 1) includes an eolian dune field near river level that is covered by trees and abundant other vegetation. The heavy vegetation has grown on the dune field and on a large river-level sandbar (a, fig. 31) just downstream from the dune field since the 1960s and now covers much of what was previously an open sand area. Immediately upstream of the weather station, an eolian dune field shows evidence of erosion by deflation, some biologic soil crust, and gully incision. The purpose of monitoring this site was to identify the sand source for the eroding, high-elevation dune field by measuring the dominant wind direction that could cause sand transport. Identifying the sand source could establish the degree to which vegetation encroachment downstream of the site may have affected the condition of the upper dune field by limiting eolian sediment transport from its sand source.

Data collected from April to December 2004 at 202.9 Mile indicated that the dominant sand-transport direction was north (from downstream, fig. 32). Those initial data supported the hypothesis that the large sandbar (a, fig. 31) formerly provided a sand source to the dune field on the debris fan, implying, in turn, that reduction in sand-entrainment potential from the newly vegetated sandbar had affected or could affect the condition of the eolian deposits downwind (upstream) of this sandbar. Wind conditions there in 2005, however, indicated a more complex situation. Although upstream and downstream winds nearly balanced each other at the study site in 2005, a tertiary component from the northwest yielded a vector sum showing net sand flux to the river (figs. 32, 33). Thus, the longer record now available from 202.9 Mile suggests that although the loss of a potential sand source (the now-vegetated sandbar) downstream from this site may affect the condition of the dune field, the sediment supply from other sources could also affect eolian deposition and erosion processes there. The net vector sums of *Qp* values from 2005 wind data (1,286 m^3/s^3 from 283°) indicated a weaker sand-transport potential to the east, however, than to the north, as implied by the net vector sum of *Qp* values from 2004 wind data (2,160 m^3/s^3 from 194°). Deployment of a new weather station at 202.9 Mile in March 2007 could clarify the eolian-sediment-transport regime at this site by providing longer-term wind data.

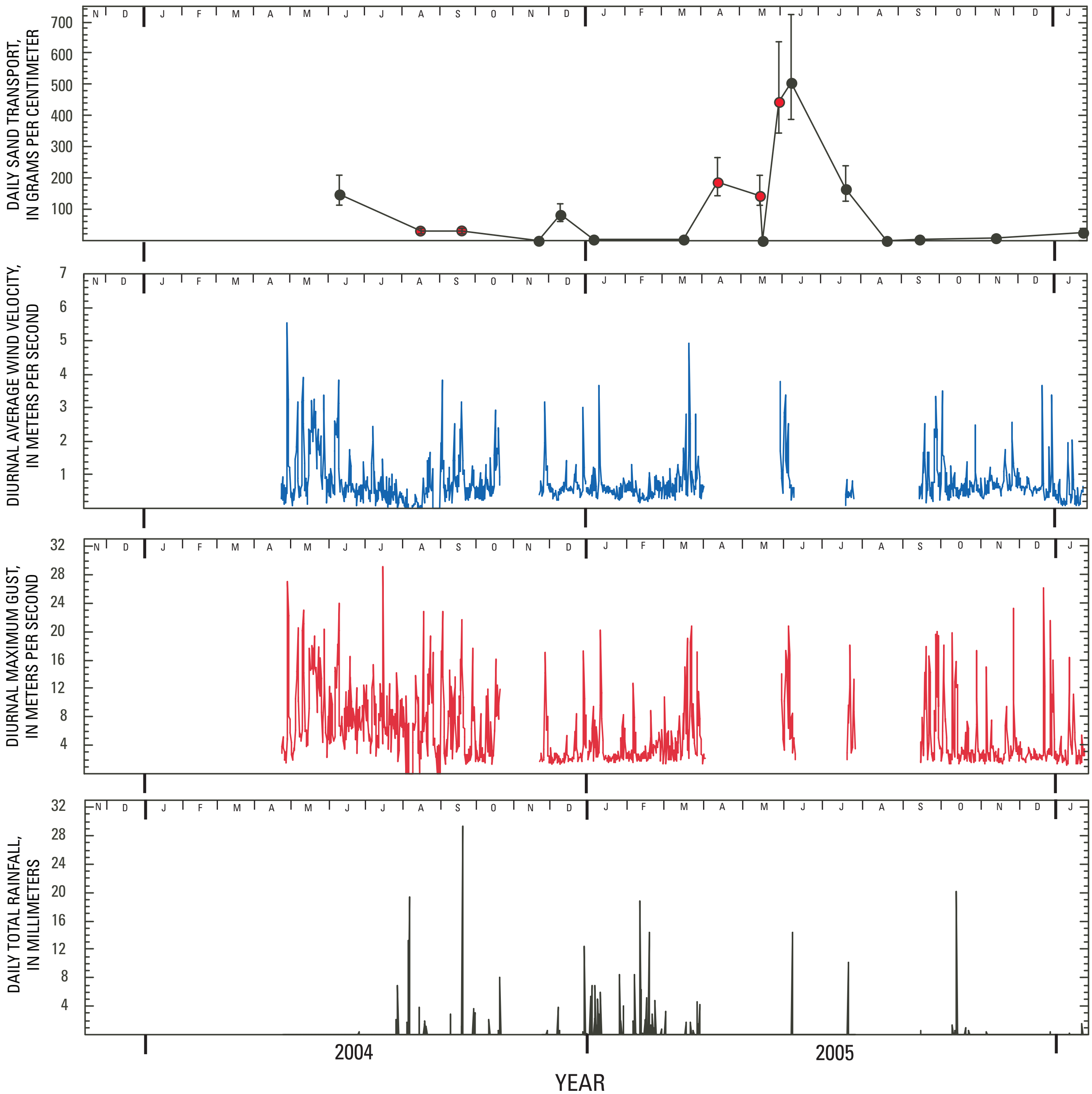

Figure 30. Rainfall, wind, and sand-transport data collected at weather station For (fig. 28*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1) from April 2004 to January 2006. High winds caused repeated problems during weather-station operation, resulting in data gaps of several hours to months. Red dots, sand-trap data points that are only minimum estimates of sand transport because during those maintenance visits, lowermost trap was completely filled with sand. Daily sand transport is plotted in grams per day between ground surface and a height of 1 m (elevation of uppermost sand trap), normalized to a width of 1 cm. To obtain these values, sand mass collected from four traps during each maintenance visit was integrated over a width of 1 m and divided by number of days since traps had last been emptied. Wind data from upper (2.0-m height) anemometer only are presented as diurnal average wind velocity and diurnal maximum gust, using daytime (0600–1800 h) and nighttime (1800–0600 h) averages of data collected at 4-minute intervals. Daily total rainfall is summed over 24-hour intervals.

Arroyo Grande

Arroyo Grande is on land managed jointly by the Hualapai Nation and the National Park Service. The study site covered an area of about 250 m by 70 m; the nearest side-canyon tributaries enter the Colorado River >1 km upstream and 300 m downstream of the study site (fig. 2*C*). A large eddy is present on river left (north bank) in the Arroyo Grande area even at nonflood stage. An arroyo network, ≤5 m deep, has incised two levels of predam alluvial terraces in this area (fig. 2*C*; white arrow, fig. 34). Eolian coppice dunes, most of which are now relatively inactive, with sparse vegetation and biologic soil crust, are present on the terraces. Terrace surfaces are deflated, as indicated by exposed plant roots and the formation of pedestals containing pebbles and cultural artifacts ≤5 cm above the surrounding land surface. Four archeologic-site complexes are present in alluvial-terrace and tributary-delta parts of the Arroyo Grande area, the largest of which (site G:03:064, table 3) is affected by the arroyo. The study site contains 15 documented cultural features on the land surface and several additional features exposed within the arroyo walls (table 3).

Colorado River flood deposits dominate the stratigraphic record around the largest archeologic site complex (site G:03:064, table 3) at Arroyo Grande. Sedimentary profiles within the upper terrace (fig. 2*C*) indicated that the proportion of fluvial sediment generally increases to the river. The record of flood deposition is best preserved in sedimentary profiles nearest to the river, with 15 individual flood events evident in one profile (Draut and others, 2005). All the profiles showed evidence of subaerial reworking and incorporation of colluvial and slopewash sediment between floods. The repeated occurrence of fluvial deposits overlain by subaerial sediment led to the description of a "flood couplet" facies consisting of a lower fluvial and an upper subaerial member (Draut and others, 2005, 2008). Bioturbation

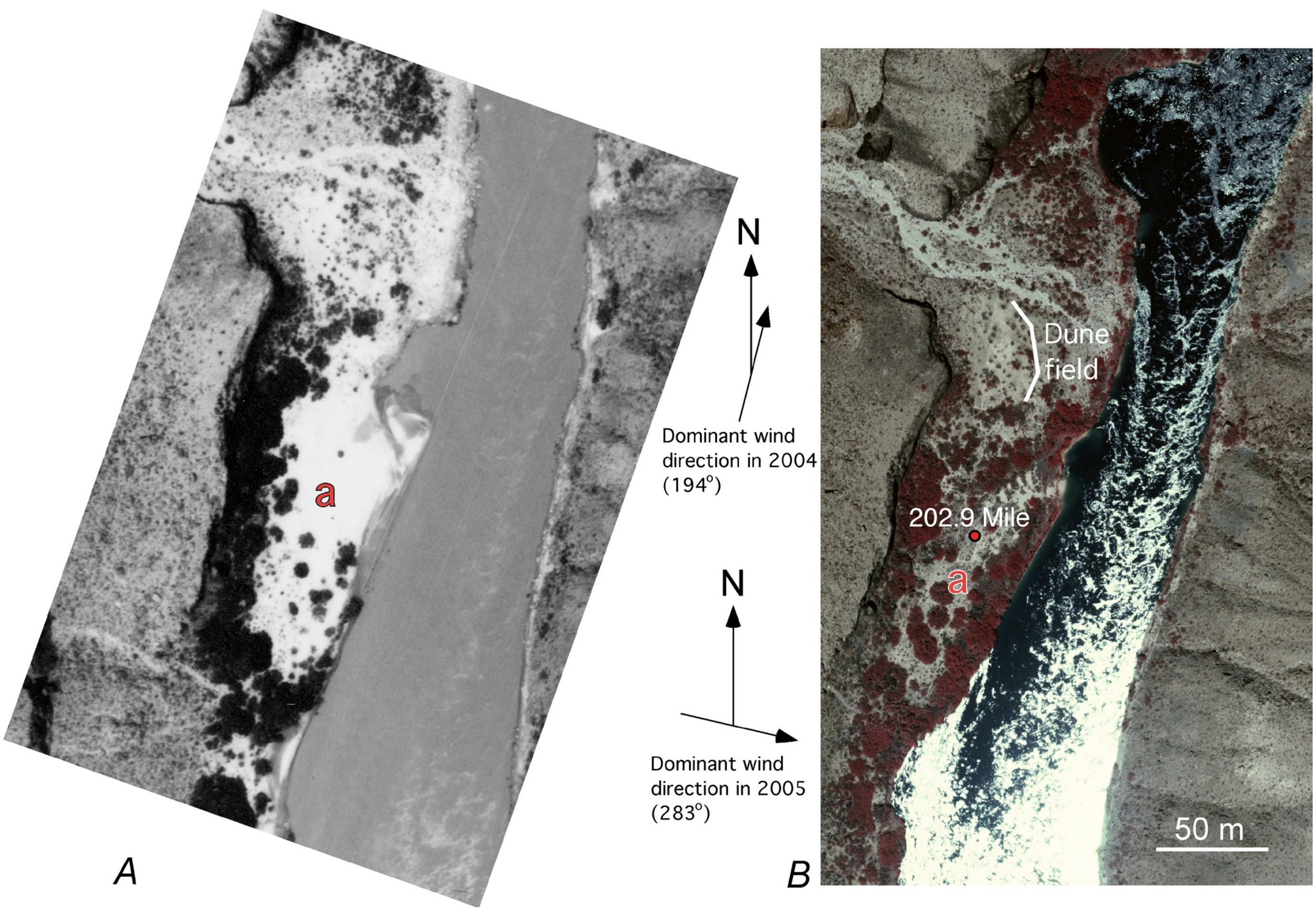

Figure 31. Aerial photographs taken in May 1965 (*A*) and May 2004 (*B*) of 202.9 Mile area along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Riverflow in May 1965 was between 680 and 792 m^3/s, and in May 2004 was 226 m^3/s. Large fluvial sand deposit (a); red dot, weather station 202.9. Modern extent of eolian dune field, on downstream (south) side of a small debris fan, is shown is figure 31*B*. Dominant wind direction varies widely at 202.9 Mile, with calculations yielding a net potential for eolian sediment transport from the south-southwest in 2004 and from the west in 2005. Note increase in riparian vegetation and decrease in open sand area since 1965.

and the presence of lithic clasts in the upper parts of flood couplets (derived from local gneissic bedrock) indicated reworking of flood sediment at the land surface. Similar to the Lower Comanche site, the channel-fill deposits exposed at Arroyo Grande indicate multiple episodes of gully formation and filling during past subaerial exposure. Eolian sediment constituted a relatively minor volume in the measured sections. The most likely sediment source for the small, deflated coppice dunes visible on the land surface today is from reworking of the extensive fluvial deposits that created the terrace morphology in the area. Therefore, the eolian dunes at Arroyo Grande, as at Palisades, can be considered relict features that formed by in-place eolian reworking of large, predam flood deposits, and so this dune field is defined as an RFS deposit.

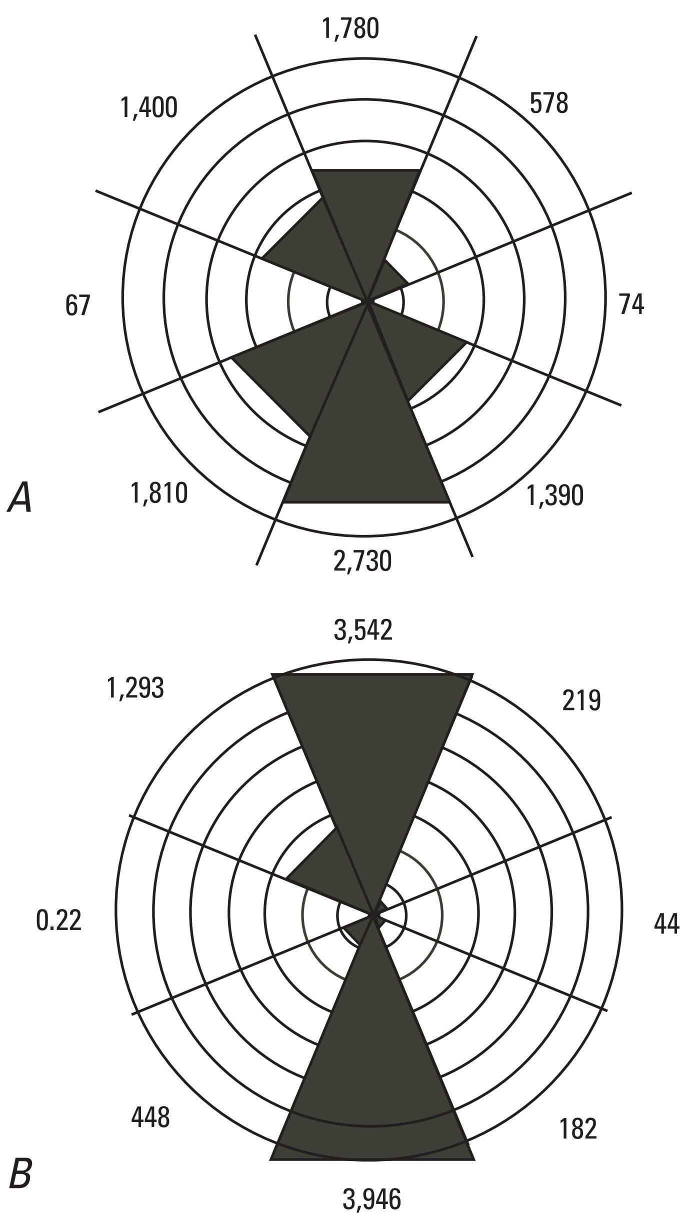

Figure 32. Rose diagrams of sand-transport potential calculated from wind data collected at weather station 202.9 (fig. 31*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1) from April 2004 to January 2006. Numbers for 2004 (*A*) and 2005 (*B*) are values of proxy variable *Qp* for each of eight directional half-quadrants, indicating total potential for eolian sediment transport from each compass sector. Vector sum of 2004 data, excluding data gaps from September to November 2004 (see fig. 33), yields a net *Qp* value of 2,160 m^3/s^3 from a direction of 194°; vector sum of 2005 data yields a net *Qp* value of 1,286 m^3/s^3 from a direction of 283°.

The abundance of charcoal and ash material in many strata at Arroyo Grande is attributable to grass fires during times of subaerial exposure, which probably were deliberately set by the inhabitants in the area, although lightning strikes could also have caused occasional fires. The Hualapai and Southern Paiute Tribes, both with ancestral ties to the Arroyo Grande area, have cultural traditions that include the deliberate setting of grass fires to initiate seed germination and to prevent other, larger fires from starting (Jackson and Bullets, oral communs., 2004). The setting of grass fires was practiced at prescribed times of the year and continues today. Other possible reasons for deliberately set grass fires include hunting and warfare (Powell, 1878; Kelly and Fowler, 1986; Boyd, 1999).

Of the 16 cultural features that we examined at Arroyo Grande, 15 are exposed at the land surface (table 3); 14 features were formed on the upper terrace surface, of which 7 are within coppice dunes on the terrace surface and the rest partly covered by eolian sediment. Of the two cultural features not formed on the upper-terrace surface, one was built on colluvium near the land edge of the terrace, and the other (an unnamed site) was exposed within an arroyo wall.

Comparison of aerial photographs taken in 1965 and 2004 shows a substantial decrease in open sand area along several hundred meters of river left (north bank) in postdam time (even though the 2004 photographs were taken during a much lower riverflow; fig. 34), as well as a substantial increase in riparian vegetation. Although we did not derive a stage-discharge relation for the Arroyo Grande area, we estimate that a riverflow of about 5,660 m^3/s, a flood level last reached in 1884, would probably inundate the upper terrace (recognizing that stage-discharge relations are episodically altered when debris flows constrict the river channel and cause water to pool upstream of the constriction). Because the eolian dune field at Arroyo Grande is apparently an RFS deposit, on the basis of sedimentary profiles through the dunes and underlying terrace, the postdam absence of sediment supply to this terrace by floods has removed the major source of sediment to the eolian dunes as well. Although we do not know the extent to which lower-elevation fluvial sandbars (≤1,270-m^3/s stage) contributed windblown sand to the dunes in predam time, any eolian sediment probably does not reach the dune field from the small river-level sandbars still present in this area because thick riparian vegetation now separates the fluvial sandbars from the eolian dune field. Therefore, a riverflow of 1,270 m^3/s would probably not deposit new sediment that would blow into the dune field (although the dominant wind direction at Arroyo Grande was not measured during this study) because such dense vegetation separates the dune field from the river in almost every direction. The dominant direction of winds capable of transporting sand is likely from the east on the basis of the slipface orientation of a large, active dune at the east edge of the study site (Draut and others, 2005).

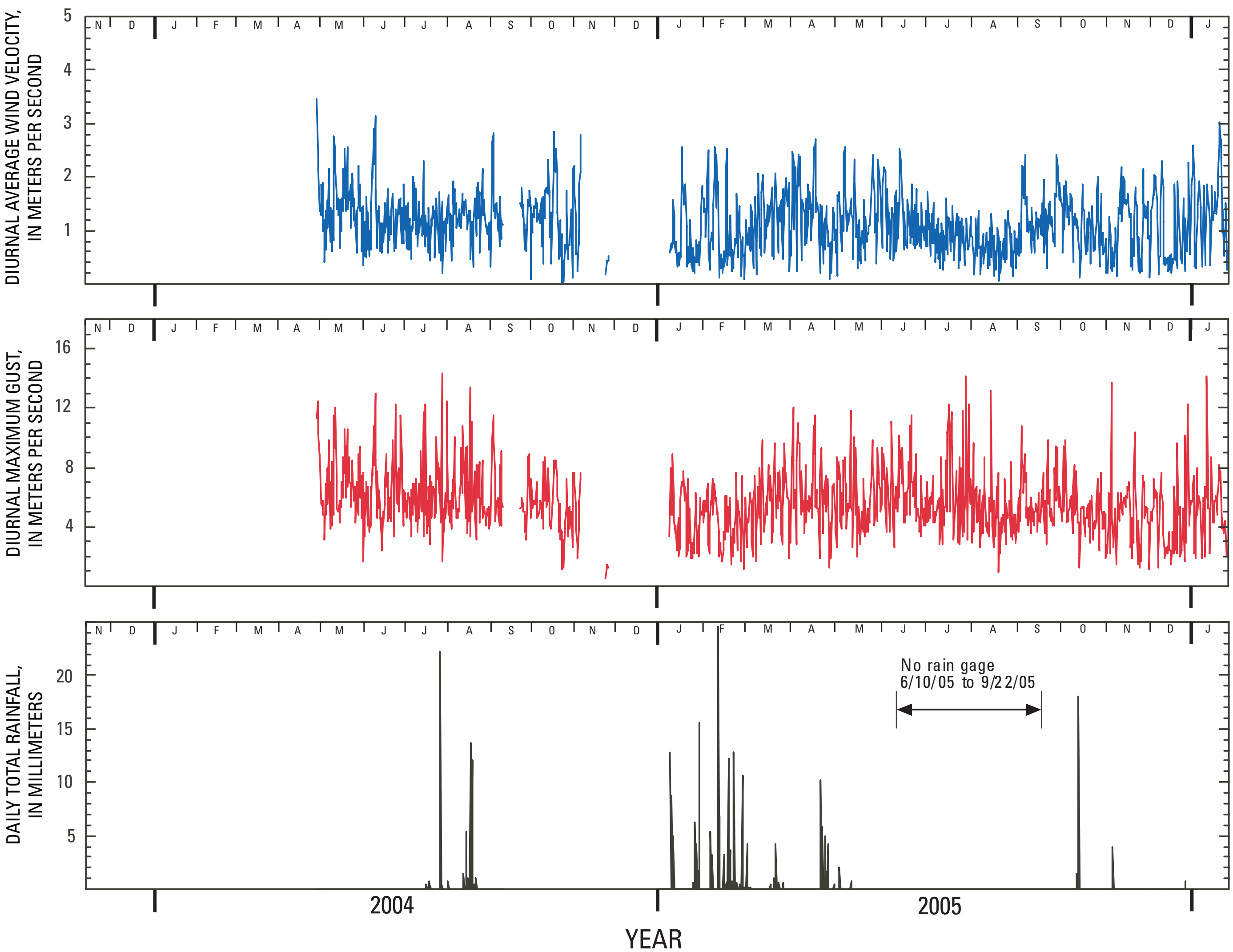

Figure 33. Rainfall and wind data collected at weather station 202.9 (fig. 31*B*) along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1) from April 2004 to January 2006. Data gaps were caused by animals chewing through cables and short-circuiting datalogger. No sand traps were used, and rain gage was not operational from June 10, 2005, to September 22, 2005. Daily sand transport is plotted in grams per day between ground surface and a height of 1 m (elevation of uppermost sand trap), normalized to a width of 1 cm. To obtain these values, sand mass collected from four traps during each maintenance visit was integrated over a width of 1 m and divided by number of days since traps had last been emptied. Wind data from upper (2.0-m height) anemometer only are presented as diurnal average wind velocity and diurnal maximum gust, using daytime (0600–1800 h) and nighttime (1800–0600 h) averages of data collected at 4-minute intervals. Daily total rainfall is summed over 24-hour intervals.

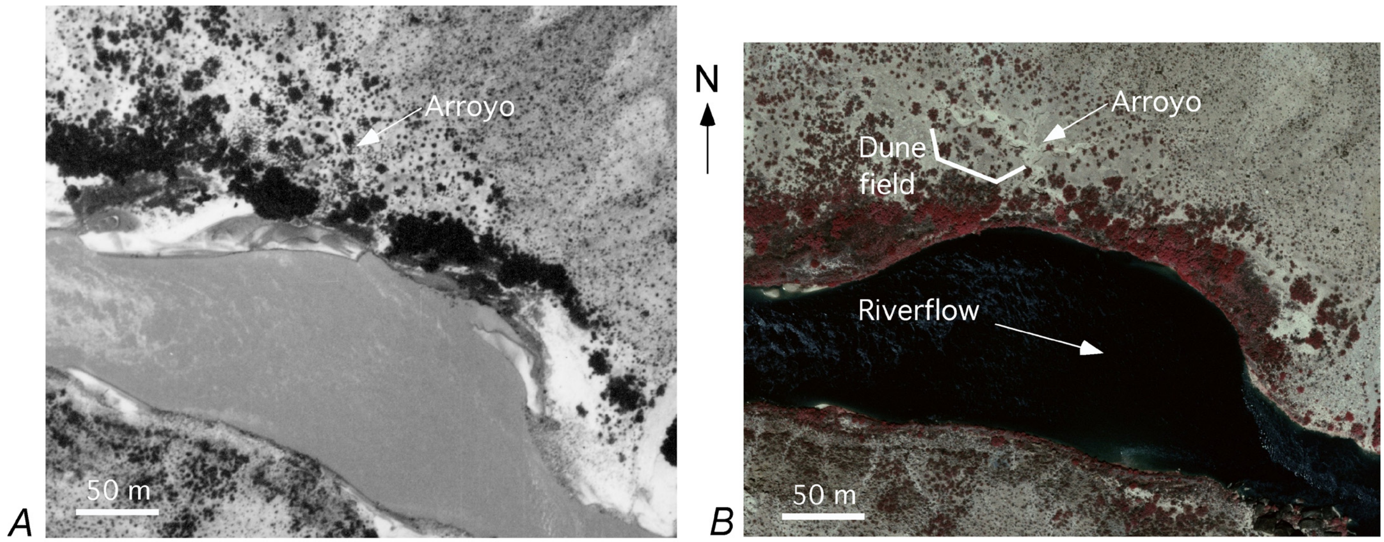

Figure 34. Aerial photographs taken in May 1965 (*A*) and May 2004 (*B*) of Arroyo Grande area along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). Riverflow in May 1965 was between 680 and 792 m^3/s and in May 2004 was 226 m^3/s. Modern extent of eolian dune field, on downstream (south) side of a small debris fan, is indicated in figure 34*B*, along with location of arroyo (see fig. 2*C*). Note great increase in riparian vegetation since 1965; extensive fluvial sand deposits visible in riparian zone in 1965 were no longer present as open sand areas in 2004, despite lower riverflow.

Appendix 2. Evaluating the Predictive Power of Eolian-Sediment-Transport Models—Can Sediment-Supply Limitation Be Discerned?

Introduction

A question remains regarding the evolution of eolian deposits along the Colorado River corridor in Grand Canyon National Park: to what extent has the sediment supply to individual sand deposits been limited by Glen Canyon Dam operations? Eolian sediment transport has always been somewhat restricted by confinement within this bedrock canyon—dune fields can become only so large before reaching canyon walls, the river, large talus piles, and other spatial limitations. This study indicates, however, that eolian sediment transport is now more limited than in predam time because the supply of windblown sand to some eolian deposits (particularly MFS deposits) increases or decreases in response to changes in fluvial-sandbar area upwind. Dam operations are known to have reduced the area, volume, and number of fluvial sandbars overall.

We have investigated whether eolian-sediment-transport models (based empirically on field and wind-tunnel experiments) can be used to discern sediment-supply limitation from field measurements of wind velocity and sand transport. If the sand flux predicted under given wind conditions closely matches that measured under the same conditions in the field, where sediment supply is not limited by sand availability, soil crusts, vegetation, or bed roughness, then sediment-supply limitation might be inferable in other field settings where the same models consistently overpredict measured sand flux. Thus, the inferred sediment-supply limitation could be caused by one or more factors (unavailability of sand, presence of vegetation or soil crusts, bed roughness), and further study would be needed to identify which possible causes were relevant. The experiments discussed here were conducted as part of the Grand Canyon eolian-sedimentation study but involved fieldwork in the Dumont Dunes of southern Death Valley, Calif., as well as in Grand Canyon National Park, Ariz.

We tested eight eolian-sediment-transport models (table 4) in an experiment in the Dumont Dunes, a desert environment with essentially unlimited open sand area and without vegetation or soil moisture, factors that commonly affect comparable studies conducted in coastal sand dunes. Comparison of the measured sand flux with those predicted by the various models indicates that although these eight models may perform better in this field setting, where sources of uncertainty have been minimized, generally the models did not yield results accurate enough to suggest their use in discerning sediment-supply limitation, likely partly owing to the limited range of wind velocities measured during the experiment. Subsequent high-resolution tests in the dune field at Malgosa (river mile 57.9, fig. 1) provided a greater range of wind velocities, but the physically more complex setting (canyon walls, vegetation, steeply sloping dune face) were such that the data were not obtained under simple, supply-unlimited conditions, as at the Dumont Dunes. Thus, the use of eolian-sediment-transport models to discern sediment-supply limitation needs further study; multiple avenues of environmental management could benefit from such deterministic models, through which the effects of sediment-supply limitation could be quantified.

Eolian-Sediment-Transport Models

Measurement and prediction of eolian sediment transport is a primary focus of many geologic and agricultural studies. An accurate understanding of the movement of sand and dust by wind has widespread practical implications for predicting landform evolution and erosion in agricultural areas and for guiding environmental management of coastal and desert regions. Numerous studies, beginning with that by Bagnold (1941), have devised empirical relations between wind conditions and resulting sediment motion; Bagnold's and other transport equations have been applied and tested in wind-tunnel and field settings with the goal of being utilized as predictive models.

Many comparative studies have indicated, however, that the application of commonly cited eolian-sediment-transport models in the field is problematic and that measured sand flux may deviate substantially from that predicted by models (Hunter and others, 1983; Berg, 1983; Sarre, 1988, 1989; Bauer and others, 1990, 1996; Goldsmith and others, 1990; Sherman and Hotta, 1990; Sherman and others, 1998; Craig, 2000). Assessment of the discrepancies between predicted and measured sand fluxes prompted Chapman (1990) and Bauer and others (1996) to suggest that field-based eolian-sediment-transport investigations involve serious uncertainties owing to the large number of physical factors affecting such complex systems relative to the number of variables represented in existing transport equations. Studies of sand transport on coastal dunes have identified such complexities as vegetative cover, soil moisture, topographic slope, variations in sediment composition and grain size, presence of salt crystals in sand, and variations in sand-source area due to tidal fluctuations and runnel formation. As a result, testing of eolian-sediment-transport models in coastal-dune settings is inherently complicated by spatiotemporal factors in such a setting (Baas and Sherman, 2006).

One approach to field studies in a discipline prone to serious uncertainties, as proposed by Bauer and others (1996), is to minimize uncertainty by focusing on maximally simplified systems. By minimizing or eliminating the variables that are known to exacerbate uncertainties in eolian-sediment-transport investigations, the predictive power of standard transport equations can be evaluated more accurately. Recognizing that sources of uncertainty probably cannot be entirely eliminated, we tested eight eolian-sediment-transport models in a desert sand-sheet environment where the above-mentioned complexities are minimal or absent. In so doing, we evaluated whether the predictive power of these models is sufficient to discern sediment-supply limitation.

Sediment-Supply Limitation

Existing transport equations were developed under the assumption that sand flux is limited by wind conditions (wind velocity and, therefore, bed shear stress required to mobilize sediment). Eolian sediment transport and erosion are commonly affected by sediment-supply limitations; however, this factor is not incorporated into current models (Leys, 1999). As a result, (1) the predictive power of current eolian-sediment-transport models will decrease as a given sand source is diminished by erosion over time, (2) discrepancies between predicted and measured sand flux may in some places be attributable to limited availability of sediment for transport, and (3) identification and quantification of sediment-supply limitation may be possible from analyzing those discrepancies. This investigation was particularly motivated by implications 2 and 3. By first evaluating the predictive power of existing eolian-sediment-transport models in a supply-unlimited desert setting unaffected by variables that can influence sand fluxes measured elsewhere, we evaluated the usefulness of these models for discerning sediment-supply limitation.

Model Testing

Most of the commonly used eolian-sediment-transport models incorporate a shear velocity term, u_*, which is defined as a function of shear stress [$u_* = \sqrt{(\tau / \rho)}$, where τ is the boundary shear stress and ρ is the fluid density]. Shear velocities are typically calculated from wind profiles by using the Karman-Prandtl equation, or "law of the wall":

$$u(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0}\ , \qquad (2)$$

where $u(z)$ is the wind velocity (in meters per second) at height z, κ is von Karman's constant (taken to be 0.4), and z_0 is the roughness length (in meters) of the sand surface. Shear velocity is considered relative to a critical threshold of motion or threshold shear velocity u_{*_t}, given by Bagnold (1941) as

$$u_{*_t} = A_t \sqrt{\frac{\rho_s - \rho}{\rho} gd}\,, \qquad (3)$$

where A_t is a dimensionless constant equal to 0.1 for the initiation of saltation (Bagnold's fluid threshold), ρ_s and ρ are the densities of quartz sediment and air (2,650 and 1.2 kg/m^3, respectively), g is the gravitational acceleration (9.8 m/s^2), and d is the sediment grain size (in meters).

The eight eolian-sediment-transport models tested in this study are listed in table 4. The empirical models of Bagnold (1941) and Zingg (1953), based on wind-tunnel experiments, are of the same form but differ in the dimensionless constant and exponent. Kawamura's (1951) model, also based on wind-tunnel experiments, first incorporated the threshold shear velocity u_{*_t} into an eolian-sediment-transport model. Lettau and Lettau's (1977) and White's (1979) models, as well as Sørensen's (1991) equation, the derivation of which incorporates sand-grain trajectories and grain-bed collision processes, also use threshold shear-velocity terms. Except for Lettau and Lettau's (1977) models, equations of this form do not require a separate term for grain size because u_{*_t} is itself a function of particle diameter. Hsu (1971, 1973) used a modified Froude number (of the form $u/(gd)^n$) to express eolian-sediment-transport rate. Among these eight models, Williams' (1964) model alone describes sand flux, q, as a linear function of u_*. Several models exist that do not depend on shear velocity, for example, Kadib's (1965) model, which uses a normally distributed transport-intensity function, and O'Brien and Rindlaub's (1936) model, which does not include a grain-size term but depends solely on the cube of wind velocity measured at 1.52-m height. We restricted our analysis to the models listed in table 4 because Kadib's (1965) model has been found to be less reliable than equations that rely on u_*, particularly at high wind velocities (Sarre, 1988; Sherman and others, 1998), and because u_* represents flow characteristics (that is, shear affecting the bed, which determines sediment motion) independent of the height of measurement.

Experimental Methods

We conducted an experiment in the Dumont Dunes at the south end of Death Valley in the Mojave Desert, Calif., in late February 2004. The dune field occupies an area of about 20 km^2 and contains central star dunes, >100 m tall, with lower barchan and linear dunes at its margins (McDonald, 1970; Nielson and Kocurek, 1987). A sand sheet at its north edge provided an ideal site to collect sand-transport data in an area unaffected by vegetation or other bed-roughness elements (other than wind ripples, footprints, and vehicle tracks, all

Table 4. Eolian-sediment-transport models tested in the Dumont Dunes in Death Valley, Calif., and the dune field at Malgosa at Grand Canyon National Park, Ariz. (fig. 1).

[u_*, shear velocity for which the equations were derived. *d*, grain size (in meters); D, reference grain size (in meters); for 250 μm-diameter sand; u_{*_t}, threshold shear velocity for motion of grain size considered; ρ_s and ρ, densities of quartz sediment and air, respectively (taken to be 2,650 and 1.2 kg/m^3; *g*, gravitational acceleration (9.8 m/s^2). In Williams' (1964) model, the constant is represented as the multiple of two constants obtained for 330 μm-diameter sand, slightly coarser than the 306 μm-diameter sand in this study. q value is expressed in all models as a mass of sand passing through a unit width in unit time (in kilograms per meter per second). For comparison with field data, q values were adjusted to reflect the 10-s averaging interval of wind data, and the 0.02-m width of the sand traps used. Bagnold's (1941) model was based on wind-tunnel data and tested in desert dunes. Kawamura's (1951), Zingg's (1953), Williams' (1964), and White's (1979) models were based on wind-tunnel data. Hsu's (1971) and Lettau and Lettau's (1977) models were based on field studies. Sørensen's (1991) model was analytically derived and tested in wind-tunnel experiments]

Reference	Equation for calculating sand flux (*q*)	u_* (m/s)
Bagnold (1941)	$q = 1.8\left(\frac{d}{D}\right)^{0.5}\frac{\rho}{g}u_*^3$	0.6–1.8
Kawamura (1951)	$q = 2.78\frac{\rho}{g}(u_* - u_{*_t})(u_* + u_{*_t})^2$	N/A
Zingg (1953)	$q = 0.83\left(\frac{d}{D}\right)^{0.75}\frac{\rho}{g}u_*^3$	0.35–1.06
Williams (1964)	$q = 4.066\frac{\rho}{g}u_*$	0.4–1.35
Hsu (1971)	$q = 10^{-4}e^{4.79d-0.47}\frac{u_*^3}{(gd)^{1.5}}$	0.05–0.8
Lettau and Lettau (1977)	$q = 4.2\sqrt{\frac{d}{D}}\frac{\rho}{g}(u_* - u_{*_t})u_*^2$	<0.32
White (1979)	$q = 2.61u_*^3\left(1 - \frac{u_{*_t}}{u_*}\right)\left(1 + \frac{u_{*_t}^2}{u_*^2}\right)\frac{\rho}{g}$	0.9–1.7
Sørensen (1991)	$q = 10^{-4}\rho u_*(u_* - u_{*_t})(u_* + 7.6u_{*_t} + 205)$	0.2–0.6

<10 cm high). Instruments were deployed in a relatively flat area to minimize the effect of surface slope on wind velocity. Soil moisture was not detected in the surface sediment and is generally negligible in this arid environment.

The experiment at the Dumont Dunes was conducted during a 16-hour interval. Wind velocity was measured by using three spinning-cup anemometers mounted on an instrument tripod at heights of 2.0, 1.0, and 0.3 m and connected to a datalogger (fig. 35). Mean wind velocity, maximum gust velocity, and mean wind direction were measured at a 1-Hz sampling interval and recorded as 10-s averages. This sampling strategy used the shortest averaging interval over which the statistical reliability of shear-velocity measurements can be retained (Namikas and others, 2003; see Anderson and others, 1991).

An array of sand traps was set up 5 m from the anemometer tripod to collect windblown sand (see Zobeck and others, 2003). Four "big spring number eight" (BSNE) sand traps (Fryrear, 1986) were mounted on a vertical pole; these sand traps are equipped with vanes to turn them into the wind. Sand traps were deployed with their orifice bases at heights of 1.0, 0.7, 0.4, and 0.1 m (fig. 35). Air temperature was measured at heights of 2.0 and 0.3 m to evaluate local atmospheric instabilities caused by insolation heating, which may affect wind-velocity profiles (Rasmussen and others, 1985; Lancaster and others, 1991; Frank and Kocurek, 1994). The measured temperature gradient was minor because thick cloud cover limited direct solar heating during the experiment. Because vertical motion of air due to solar instabilities is negligible relative to lateral motion at wind speeds high enough to generate sand transport (G. Kocurek, written commun., 2004; N. Lancaster, written commun., 2004), this factor is not considered further here.

The total sand mass collected from each trap during the experiment was weighed, and sand-transport rates were calculated by integrating a curve fitted to the mass-versus-height data. The curve-fitting procedure used a five-parameter combined power-law and exponential function, which has been shown to model vertical sand flux more accurately than either power-law or exponential fits alone (Sterk and Raats, 1996). Grain-size analysis of surface sand at the Dumont Dunes on a Coulter LS100Q laser diffraction particle-size analyzer yielded a d_{50} value of 305.8 μm (average of six analyses), which (from eq. 3) gives u_{*_t}=0.257.

In May 2004, we conducted a similar experiment during 2 days of high winds on the dune field at Malgosa (river mile 57.9, fig. 1). One of the weather stations deployed at that site (Mal U; Draut and Rubin, 2005, 2006) was refitted to match the configuration used in the experiment at the Dumont Dunes, with anemometers at heights of 2.0, 1.0, and 0.3 m, BSNE sand traps at 1.0, 0.7, 0.4, and 0.1 m, and the datalogger recording with a 1-Hz sampling interval and a 10-s averaging interval (as opposed to the 4-minute averaging interval used during normal operation of that weather station). Two tests were performed at Malgosa, on May 11 and 12, 2004; sand traps were emptied at the end of each test. Sand in the dune field at Malgosa has a d_{50} value of 312.9 μm (average of four analyses), and the u_{*_t} value is calculated to be 0.260. Using u_{*_t} values, cumulative sand fluxes at the Dumont Dunes and Malgosa were predicted from wind data, using the eight models listed in table 4, and then compared with the sand fluxes measured at both study sites.

Results

The sand fluxes measured in the experiment at the Dumont Dunes and in both tests at Malgosa are compared with those predicted by each of the eight eolian-sediment-transport models (table 4) in table 5. In the 16-hour experiment at the Dumont Dunes, the mean sustained wind velocities recorded at 2.0-m height (averaged over 10-s intervals) were 3.6±1.6 m/s, with gusts of ≤10.8 m/s. At those wind velocities, the efficiency range of BSNE sand traps is 105–115 percent

Figure 35. Study site at the Dumont Dunes in the Mojave Desert, southern Calif., showing location of experiment in late February 2004. At left is a tripod on which three anemometers (at heights of 2.0, 1.0, and 0.3 m) and a datalogger were mounted; at right are four sand traps (at heights 1.0, 0.7, 0.4, and 0.1 m). Surrounding sand sheet was free of vegetation and nonerodible obstacles, such as rocks, and had little slope for tens of meters in any direction. Tire tracks and footprints created surface-roughness elements <10 cm high.

Table 5. Comparison of predicted sand flux with sand flux measured by using sand traps during experiments in the Dumont Dunes and the dune field at Malgosa.

[Measured sand flux is given for each test as an integrated value for a height of 0 to 1 m, along with sand flux predicted from wind data measured at 10-s intervals. Modeled sand fluxes have been adjusted to account for the 10-s interval and 0.02-m width of sand trap orifices. Values are indicated for the possible range of measured sand fluxes, given the efficiency range of the sand traps used (105–115 percent during the study experiment in the Dumont Dunes and 95–115 percent for the tests in the dune field at Malgosa, Goossens and others, 2000)]

Sand flux (kg/m per second)			
Dumont Dunes	*Measured*	*105-pct trap efficiency*	*115-pct trap efficiency*
Measured transported sand (g)	61.8	58.9	53.7
Ratio of predicted to measured sand 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, test 1	*Measured*	*95-pct trap efficiency*	*115-pct trap efficiency*
Measured transported sand (g)	2,770	2,910	2,400
Ratio of predicted to measured sand 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

Malgosa, test 2	*Measured*	*95-pct trap efficiency*	*115-pct trap efficiency*
Measured transported sand (g)	183	193	160.0
Ratio of predicted to measured sand flux			
Bagnold (1941)	48.6	46.2	55.9
Kawamura (1951)	63.0	59.8	72.4
Zingg (1953)	23.6	22.4	87.5
Williams (1964)	603	574	694
Hsu (1971)	76.1	72.3	87.5
Lettau and Lettau (1977)	42.6	40.5	49.0
White (1979)	32.0	30.4	36.8
Sørensen (1991)	16.3	15.5	18.7

(Goossens and others, 2000). In the first test at Malgosa, which lasted 7 hours, mean sustained wind velocities recorded at 2.0-m height were 5.8±3.2 m/s, with gusts of ≤20.8 m/s; in the second test at Malgosa, which lasted 14.5 hours, mean sustained wind velocities at 2.0-m height were 3.1±1.9 m/s with gusts of ≤13.7 m/s. BSNE sand trap efficiency during both high-resolution experiments at Malgosa was considered to span an efficiency range of 95–115 percent (Goossens and others, 2000). Histograms of the u_* values calculated for the duration of each experiment are shown in figure 36.

Kawamura's (1951) model predicted a cumulative sand flux that most closely approximates the measured sand flux in the experiment at the Dumont Dunes. Three other models overpredicted the sand flux: Bagnold's (1941) model by a factor of about 1.5 to 1.7 (given the sand-trap-efficiency range), Hsu's (1971) model (which uses a modified Froude number) by a factor of >2, and Williams' (1964) model by a factor of >30; and four other models underpredicted the observed sediment flux: Zingg's (1953) model by about 18–25 percent, both Lettau and Lettau's (1977) and White's (1979) models by 50–57 percent, and Sørensen's (1991) model by 72–75 percent.

In the first test at Malgosa, during which the total sand transport was nearly two orders of magnitude greater than in the experiment at the Dumont Dunes, all the models generally performed similarly, though with a greater tendency to overprediction (table 5). The model that most closely approximated the measured sand flux in the first test at Malgosa was Zingg's (1953), which predicted about 84–101 percent of the measured value, given a sand-trap efficiency of 95–115 per-

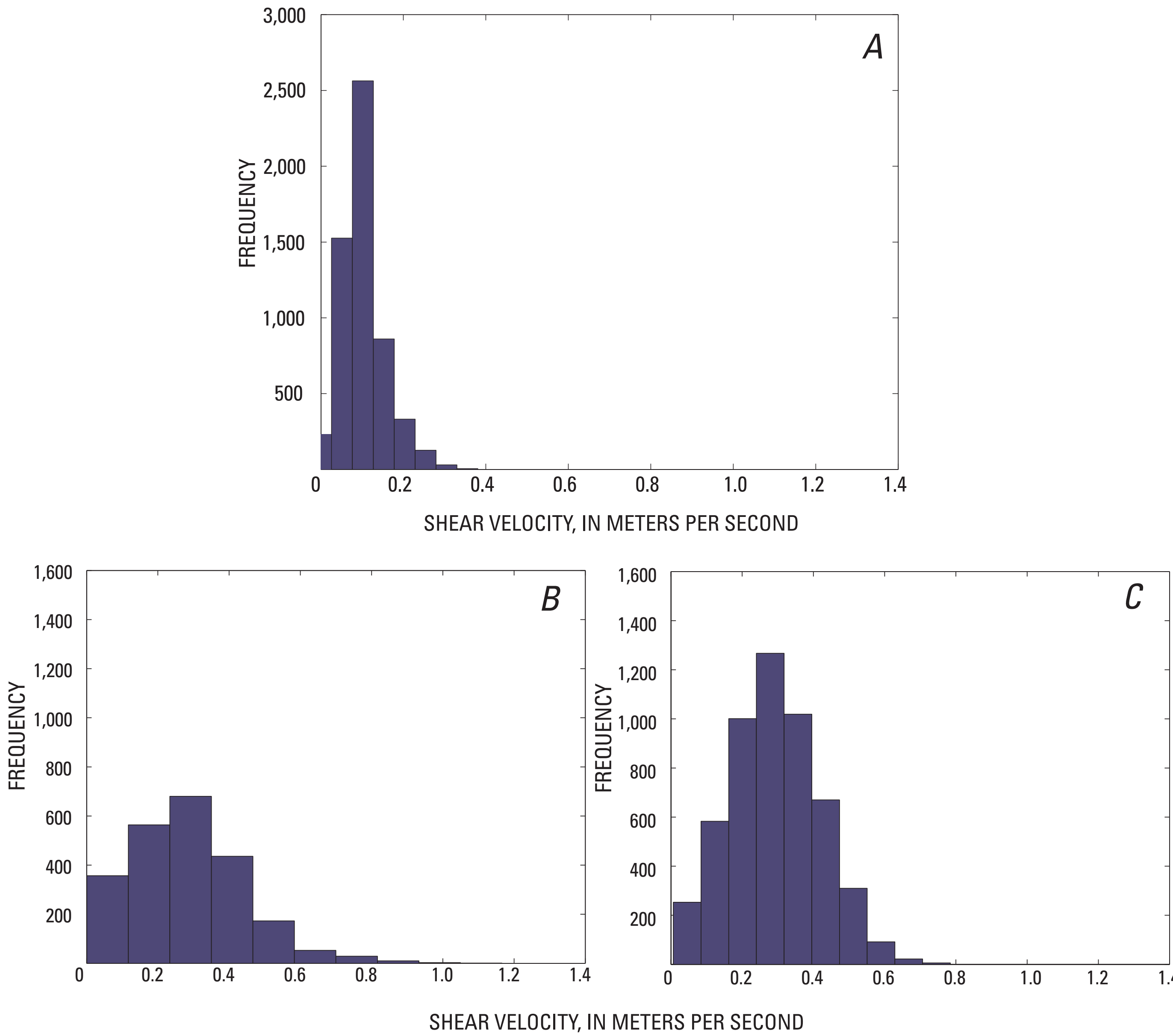

Figure 36. Histograms of shear velocity (u_*) measured during experiment at the Dumont Dunes in the Mojave Desert, southern Calif., and two tests at Malgosa along the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). *A*, Shear velocity during 16-hour experiment at the Dumont Dunes from February 29 to March 1, 2004, in which mean sustained wind velocities recorded at 2.0-m height (averaged over 10-s intervals) were 3.6±1.6 m/s (1σ), with gusts to 10.8 m/s. Shear velocity was calculated by using equation 2. *B*, Shear velocity during first test at Malgosa, which lasted for 7 hours on May 11, 2004. Mean sustained wind velocities recorded at 2.0-m height were 5.8±3.2 m/s with gusts to 20.8 m/s. *C*, Shear velocity during second test at Malgosa, which lasted 14.5 hours on May 12, 2004. Mean sustained wind velocities recorded at 2.0-m height were 3.1±1.9 m/s with gusts to 13.7 m/s.

cent. Kawamura's (1951) model, which had best predicted the measured sand flux in the experiment at the Dumont Dunes, overpredicted the measured value in the first test at Malgosa by a factor of 2.5 to 3. In the second test at Malgosa, during which the cumulative sand flux was intermediate between the values measured in the experiment at the Dumont Dunes and in the first test at Malgosa (about 100 *g*), all the models greatly overpredicted the measured value.

Discussion

Potential Sources of Error

Calibration of sand-trap efficiency plays an important role in measuring sand transport and can be a substantial source of error in field studies if not well established (McEwan and Willets, 1993; Sherman and others, 1998). The BSNE sand-trap design used in this study (Fryrear, 1986; Stout and Fryrear, 1989) is one of the most widely applied in agricultural and sedimentologic studies (Zobeck and others, 2003). Its efficiency has been determined by multiple wind-tunnel and field studies over wide ranges of sediment grain size and wind velocity (Fryrear, 1986; Shao and others, 1993; Goossens and Offer, 2000; Goossens and others, 2000, 2001). The widespread use of this design also allows comparison between studies. BSNE sand traps were chosen for this study because existing calibrations suggest that an efficiency range of 95–115 percent for the grain sizes and wind velocities in our experiments can be reasonably assumed.

The accuracy of shear-velocity estimates is affected by the number of anemometers used to generate wind velocity profiles. In this experiment, u_* values at each 10-s data point were generated from three measurements of wind velocity. Although increasing the number of anemometers would decrease the uncertainty associated with calculations of u_*, the accuracy of results would not necessarily increase (Namikas and others, 2003; see comparison of four- versus eight-anemometer u_* estimates by Namikas, 1999).

Bed-roughness elements are not believed to have affected data collection significantly during the experiment at the Dumont Dunes. Location of the instrument tripod at the study site was selected on the basis of absence of vegetation, large bedforms, or pebbles on the sand surface. Values of the roughness length, z_0, obtained from wind-velocity profiles, generally are within an order of magnitude of twice the Nikuradse roughness for the grain size at the study site ($2d_{50}/30$), and their departure from this value is attributable to the influence of saltation and/or ripple development. The low apparent roughnesses obtained at the Dumont Dunes indicate that form drag on the bed was negligible during the experiment. With unobstructed sand on an approximately flat surface for distances of >20 m around the instrument tripod and sand traps in all directions, we are reasonably confident that eolian sand transport measured at the Dumont Dunes reached equilibrium conditions (Anderson and Haff, 1988; Anderson and others, 1991; Raupach and others, 1993; King and others, 2005; R.S. Anderson, written commun., 2006).

In contrast to the Dumont Dunes, bed-roughness elements in the dune field at Malgosa are problematic. Even though Malgosa has among the sparsest vegetation of any Grand Canyon eolian deposit, vegetation and, possibly, a nearby talus slope generated measurably more roughness than in the Dumont Dunes; the wind data obtained at Malgosa yielded z_0 values five to six orders of magnitude above the Nikuradse roughness. Sand transport measured at Malgosa also was probably affected by variations in wind velocity caused by the approximate 20° slope of the stoss side of the dune on which the weather station was located (see Lancaster, 1985; Mulligan, 1988). Previous studies have shown that wind-velocity profiles on the stoss sides of dunes are not log-linear as on flat surfaces, such as the sand sheet in our experiment at the Dumont dunes, complicating the use of the Karman-Prandtl equation (2) to calculate shear velocity (Frank and Kocurek, 1996; Lancaster and others, 1996). The height of the lowermost anemometer used in our study (0.3 m) also was likely not low enough to measure wind velocity in the part of the boundary layer where much of the sand transport occurred (Lancaster and others, 1996).

Using spinning-cup anemometers under conditions of abundant windblown sand introduces an additional source of error because sand can clog the instruments and interfere with movement of the cups. Lower anemometers in a vertical array are preferentially affected by this problem, causing the wind velocities recorded to be erroneously low. If the lower anemometers are preferentially slowed by windblown sand, wind velocity profiles appear artificially steep, and the u_* values calculated from them will lead to artificially high predictions of sand flux q. This condition can be a source of significant error in experiments of this type where anemometers are used for an extended time, and was probably the reason why all the models greatly overpredicted sand flux in the second test at Malgosa (table 5), which was conducted after the anemometers had been subjected to sustained high winds and abundant sand transport for several days. Although the anemometers were cleaned between the two high-resolution tests at Malgosa (and during every maintenance visit throughout the 2-year Grand Canyon study), windblown sand continued to slow the function of the lower anemometer there (and at the Forster study site at river mile 123.0, fig. 1, where the lower anemometer was eventually disabled by windblown sand). This same problem probably affected the first test at Malgosa, especially to the end of the 7-hour interval, possibly explaining why all the eolian-sediment-transport models tended more to overprediction in the first test at Malgosa relative to the experiment at the Dumont Dunes (table 5). The anemometers used at the Dumont Dunes had never been deployed in the field before, suggesting that sand clogging was only a minimal factor there, whereas those at Malgosa had been in use (with regular cleaning and maintenance) for 6 months before the two high-resolution tests in May 2004.

Performance of Tested Models

Predicted sand flux is plotted against shear velocity in figure 37. Differences in the performance of the eight eolian-sediment-transport models become much more apparent at higher shear velocities (higher wind velocities) than those measured in either the experiment at the Dumont Dunes or the two tests at Malgosa. Values of u_* represented in our datasets (fig. 36) were <0.5 m/s at the Dumont Dunes (clustering around 0.1 m/s) and <1 m/s at Malgosa (clustering around 0.3 m/s). Wind velocities during the field studies were low enough that the models being tested would not necessarily show significant differences in predicted sand fluxes, except for the linear Williams (1964) model, because most of the divergence in their predicted sand fluxes occurs at $u_* > 1$ m/s (fig. 37).

Several of the models tested in this study showed somewhat greater predictive power in the simplified desert setting at the Dumont Dunes than had been indicated in previous studies conducted in coastal-dune environments, where some transport rates are commonly overpredicted and others

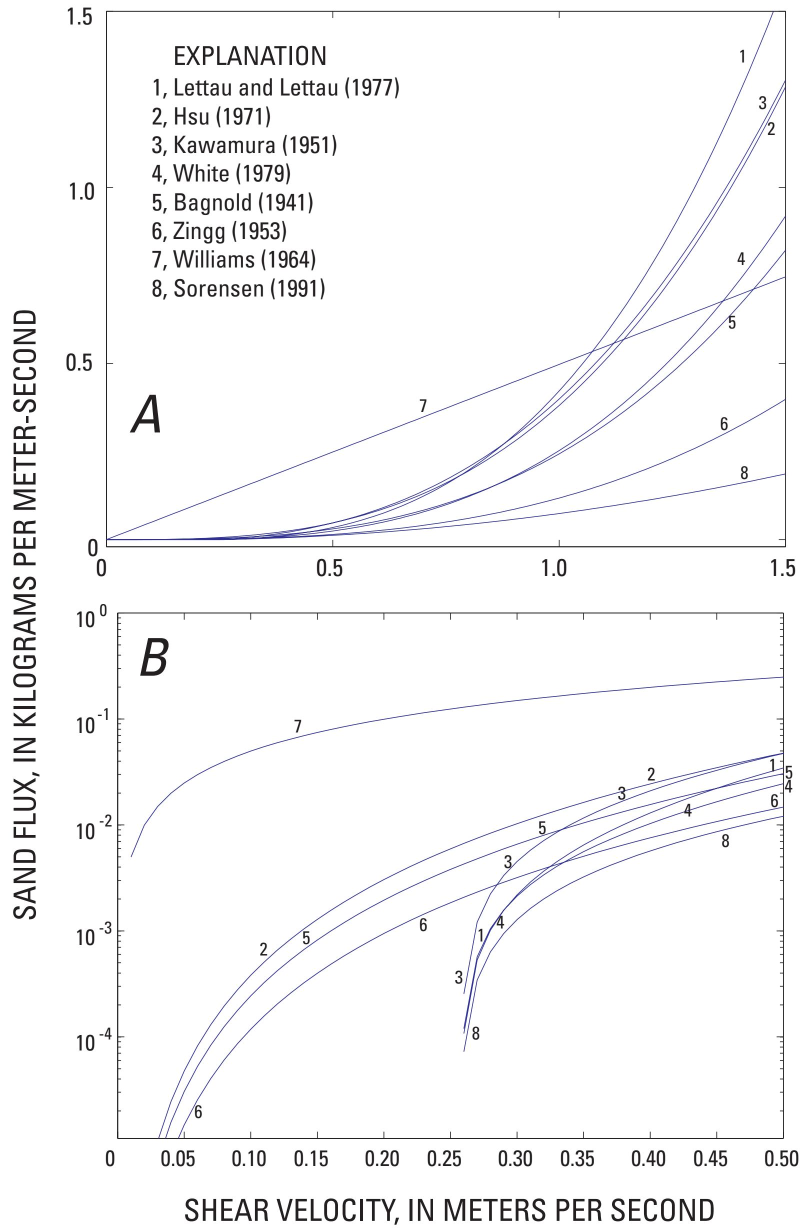

Figure 37. Sand flux (q) predicted for various shear velocities (u_*) by eight eolian-sediment-transport models. Most divergence in predicted sand flux occurs when $u_*>1.0$, such that predicted shear velocities substantially exceed those calculated from wind-velocity data obtained in this study.

underpredicted. Using Lettau and Lettau's (1977) model, Bauer and others (1996) reported that predicted transport rates exceeded those measured by factors of 1.9 to 5.6 on a sparsely vegetated foredune beach. Hunter and others (1983) reported that Bagnold's (1941) model overpredicted the transport rates measured from bedform migration of coastal dunes by a factor of 3.6. Overprediction factors of 5 and about 50 were obtained by Goldsmith and others (1990) and Bauer and others (1990), respectively, in applying Bagnold's (1941) equation to wind and sand-transport data on coastal beaches. Sherman and others (1998) reported overprediction of sand transport on a beach by factors of ≥2 when using Bagnold's (1941), Kawamura's (1951), and Lettau and Lettau's (1977) models, whereas Zingg's (1953) model underpredicted sand transport. Coastal studies by Sarre (1988) indicated that the predictive value of most tested equations can vary with shear velocity, with Bagnold's (1941) equation overpredicting sand transport at shear velocities comparable to those calculated in this study ($u_* < 0.5$ m/s). Sarre (1989) reported that White's (1979) model substantially overpredicted sand transport on foredunes in an intertidal zone.

The improvement in the predictive power of transport equations in a highly simplified field setting, such as the Dumont Dunes, would be expected (for example, Sherman and Hotta, 1990). Eolian sediment transport in coastal or other more complex sand systems can be influenced by multiple factors that did not affect the Dumont Dunes: vegetation (Olson, 1958; Bressolier and Thomas, 1977; Ash and Wasson, 1983; Wasson and Nanninga, 1986; Buckley, 1987; Bauer and others, 1996; King and others, 2005), soil moisture (Svasek and Terwindt, 1974; Sarre, 1988, 1989; McKenna Neuman and Nickling, 1989; Namikas and Sherman, 1995; Selah and Fryrear, 1995; Wiggs and others, 2004; Baas and Sherman, 2006), salt encrustation on sediment (Nickling, 1984; Sarre, 1989), fetch limitation due to nearby dune crests (Bauer and others, 1990) and tidal fluctuations (Sarre, 1988; Nordstrom and Jackson, 1992), trapping of sand by runnels and tidal channels (Bauer and others, 1996), nonerodible surface objects such as rocks (Gillette and Stockton, 1989; Raupach and others, 1993; King and others, 2005), biologic soil crusts (Leys and Eldridge, 1998; Belnap, 2003; Goossens, 2004), and perturbation of the wind-velocity profile by waves breaking near shore (Bauer and others, 1996).

Kawamura's (1951) model, one of the four listed in table 4 that incorporates threshold shear velocity into its expression for sand-transport rate, most closely represented the measured sand flux at the Dumont Dunes. Although the actual transport was slightly underpredicted, the range of values obtained indicates that Kawamura's model might have predicted up to 98.5 percent of the actual transport if the BSNE sand traps had performed at the upper limit of their known efficiency range for this grain size. The efficiency range for which Kawamura's (1951) model most closely approximates the measured sand flux occurs for BSNE sand traps collecting medium sand at wind velocities less than approximately 7 m/s (Goossens and others, 2000). Kawamura's (1951) model overpredicted the sand flux in the first test at Malgosa by a factor of 2.5 to 3; however, the performance of the models at the Dumont Dunes is considered a more accurate reflection of their predictive value, given that the second and, possibly, also the first test at Malgosa were apparently affected by sand-clogged lower anemometers, leading to erroneously high shear-velocity estimates.

The other three tested models that incorporate a threshold shear velocity yielded less accurate predictions of the sand flux at the Dumont Dunes. Lettau and Lettau's (1977) and White's (1979) models predicted 40–50 percent of the measured sand fluxes, whereas Sørensen's (1991) model predicted just over 25 percent of the measured value.

In his study of eolian sediment transport on coastal dunes in an intertidal zone, Sarre (1988) reported a close agreement between measured sand flux and that predicted by Kawamura's (1951) model, although the agreement improved when a constant of 2.4 was used in place of Kawamura's value of 2.78. Sarre (1988) reported that, in general, equations using the cube of u_* and a u_{*t} term provided the closest approximation to the measured sand flux, with White's (1979) model performing best. Svasek and Terwindt (1974) attributed the poor performance of Bagnold's (1941) and Kawamura's (1951) models when tested on a beach to capillary forces of moisture in the beach sand. Sherman and others (1998), studying coastal dunes in Ireland, reported that Kawamura's (1951) model overpredicted sand flux by a factor of 2 to 3 after corrections for soil moisture and surface slope. Lettau and Lettau's (1977) model yielded ratios of predicted to measured sand flux that ranged from 1.0 to 1.2 after such corrections in one coastal area (Sherman and others, 1998), and from 1.9 to nearly 6 in another coastal area (Bauer and others, 1996). Hsu's (1971) model overpredicted sand flux in this study by a factor of >2. This behavior is similar to that reported by Sarre (1988), in which Hsu's (1971) model overpredicted sand flux at low to moderate u_* values, much like Bagnold's model.

Arguably the most commonly used eolian-sediment-transport model, that of Bagnold (1941), which depends on the cube of u_*, overpredicted sand flux in this study by a factor of ≥1.5, comparable to the result of Sarre's (1988) study, which showed the overpredictive behavior of Bagnold's model for shear velocities in the range measured during this study (<0.5 m/s, generally <0.4 m/s). Bagnold's model yielded a closer fit to our data when the constant in this transport equation was decreased from 1.8 to 1.2. Zingg's (1953) model, which is of the same form as Bagnold's but differs in its constant and exponent, predicted about 75–82 percent of the measured sand flux at the Dumont Dunes, similar to the upper end of this model's predictive value as evaluated by Sherman and others (1998) after corrections to remove the effects of soil moisture and slope. Sarre (1988) also reported that Zingg's (1953) model reasonably predicted sand flux within the range of shear velocities considered here, although at higher u_* values Zingg's model underpredicted sand flux.

Williams' (1964) model, the only one tested in this study that considers sand-transport rate to be a linear function of shear velocity, performed poorly. Williams' model overpredicted sand flux in the experiment at the Dumont Dunes by more than an order of magnitude; his model also overpredicted the sand flux in both tests at Malgosa to a much greater degree than did the other models (table 5). A direct comparison between this study and the wind-tunnel experiments on which Williams' model is based may not be possible, however, because the constant terms in his equation apply to a specific grain size (330 µm), slightly coarser than that of the sand collected at the Dumont Dunes. Furthermore, using sand of a similar grain size to that required by Williams' model, Sarre (1988) obtained sand-transport rates that differed substantially from those predicted by Williams' model.

Relevance for Investigation of Sediment-Supply-Limited Systems

Testing of the eight eolian-sediment-transport models (table 4) at the Dumont Dunes, where sediment supply is nearly unlimited, indicates that Kawamura's (1951) model appears to be the most potentially useful for discerning sediment-supply limitation, considering the limited range of wind velocities available in the experiment at the Dumont Dunes and the more divergent performance of the models at higher shear velocities (fig. 37). To be useful for discerning sediment-supply limitation, an eolian-sediment-transport model would need to predict sand flux to within 5–10 percent in a sediment-supply-unlimited setting. Kawamura's (1951) model predictions fall within this boundary for the upper end of the sand-trap-efficiency range. Given that BSNE sand-trap efficiency decreases with increasing wind velocity, this result suggests that Kawamura's model is most applicable at lower wind velocities, where sand fluxes are low. This suggestion is consistent with the result of Sarre's (1988) study, in which Kawamura's model predicted sand flux most closely at the lowest shear velocities considered (<0.35 m/s); Sarre's (1988) field data also agreed well with Lettau and Lettau's (1977) and White's (1979) models. The wide variation in model applicability among different field areas and at different shear velocities indicates that the use of this or any other eolian-sediment-transport model to discern sediment-supply limitation warrants caution; therefore, we did not pursue similar model applications extensively as a means of discerning sediment-supply limitation in Grand Canyon dune fields, which are much more complex environments than that in our highly simplified experiment at the Dumont Dunes. More research is needed to determine the reliability of such models in sediment-supply-unlimited areas with, for example, different grain sizes, variation in sorting, and higher wind velocities than those represented here.

Although construction of a new eolian-sediment-transport model specifically for sediment-supply-limited systems is beyond the scope of this report, the practical applications of such a model would be extensive (Leys, 1999). Quantification of agricultural erosion processes would benefit from modeling capabilities that include adjustment for diminished sediment supply as erosion proceeds. Environmental-management problems that concern sediment availability could be more fully addressed if it were possible to determine the degree to which a system undergoing eolian sediment transport is supply limited. Examples include sediment mobilization on subaerial sandbars in dam-controlled rivers, such as the Colorado River in Grand Canyon, and the condition of beaches used for recreation on eroding coastlines. We recommend the construction of eolian-sediment-transport models that can be used for such purposes as a future research direction.

Conclusions

Testing of eight eolian sediment-transport models in a desert setting considered to have an unlimited sediment supply indicates that Kawamura's (1951) model most closely predicted the cumulative sand flux measured during a 16-hour experiment at the Dumont Dunes in Death Valley, Calif. This model appears to be the most potentially useful for discerning sediment-supply limitation, although at higher wind velocities than were measured during this study the predictive value of the tested models could vary substantially. Additional testing of this and other eolian-sediment-transport models in supply-unlimited settings is advisable as a future direction of research, as is construction of an eolian-sediment-transport model that could quantify the expected reduction in sand flux as sediment supply becomes progressively more limited. The ability to quantify the influence of sediment-supply limitation on eolian erosion, transport, and deposition would be advantageous for many environmental-management initiatives.

Appendix 3. Estimation of Historical Changes in Eolian Sand Sources

Introduction

This appendix catalogs our effort to evaluate changes in the availability of sand involved in eolian-sediment-transport systems within the Colorado River corridor on decadal scales. For this purpose, we used a geographic information system (GIS) database compiled by the Fluvial Geomorphology Laboratory of the Department of Watershed Sciences at the Utah State University (USU) that is based on aerial photographs taken from 1935 to 1996 between Glen Canyon Dam and the Unkar area (river mile 73, fig. 1). The aerial photographs and GIS resources discussed below were part of the dataset used by Schmidt and others (2004) to document decreased fine sediment in the river corridor between the dam and Bright Angel Creek (river mile 88). For the purposes of this study, although site-by-site changes are apparent, widespread decadal trends in eolian deposits and sand-source areas were not readily apparent. We believe that this observation is partly due to the great differences in riverflow represented in early aerial photographs relative to those taken in the 1990s, when all aerial photographic missions were flown during a steady 226-m^3/s riverflow. The absence of regional decadal trends likely is also due to difficulties of interpreting sedimentary features on the land surface by using only aerial photographs without the benefit of supplemental information, such as oblique photographs and direct field observations.

Aerial Photographs Incorporated into a GIS Database Compiled by the Utah State University

Aerial photographs of five river reaches between Glen Canyon Dam and approximately river mile 73 (fig. 1) were studied by a team of Fluvial Geomorphology Laboratory scientists led by J.C. Schmidt of USU's Department of Watershed Sciences. USU scientists interpreted the geomorphology shown in multiple sets of aerial photographs taken from 1935 to 1996, identified geomorphic units and mapped their boundaries as polygons, and stored the layers of polygons as shapefiles in a GIS database.

By using the polygons in those shapefiles that represent previously interpreted geomorphic units, the total area of sedimentary deposits considered relevant to eolian-sediment-transport systems was summed for each river reach in each set of available aerial photographs. Geomorphic features (for example, debris fans, channel-margin sand deposits, eolian deposits, and eddy sandbars) interpreted by USU scientists were not reinterpreted during this study, but representative areas were checked by independently studying the original aerial photographs from which the features had been mapped. The river reaches for which USU scientists compiled shapefiles of geomorphic features, and the dates of available aerial photographs used for each reach, are listed in table 6; and the dates of aerial photographs included in the USU GIS database, and the available mapped river reaches in each set of aerial photographs, are listed in table 7.

Categories of geomorphic features that together indicate eolian deposits were grouped together and their areas summed for each river reach and set of aerial photographs. Polygons designated as "eolian sand" in the GIS database were those that USU scientists interpreted to be "fine-grained sand deposits, often with dunelike features visible, commonly found on high terrace deposits and large, high-relief gravelbars. Reworking of a deposit between times of photography was considered to be good evidence of eolian sand if the deposit was topographically higher than any level reached by riverflows during the intervening years" (description excerpted from USU laboratory-procedure notes). In numerous polygons, the exact geomorphic feature was not identified exclusively but was listed under a combined heading, such as "eolian sand/channel margin" deposit, or "eolian sand/gravel." Predam sedimentary deposits formed above the 2,700-m^3/s flood stage (reached by the postdam flood of 1983) were assigned categories of "upper terrace" or "high terrace" deposits. Also summed for this exercise were areas of polygons representing fluvial sand deposits in eddies: separation bars, reattachment bars, and, where the distinction between separation and reattachment bars could not be made, simply eddy bars (Rubin and others, 1990; Schmidt, 1990).

Results and Interpretation

Bar graphs of the summed areas of different types of sedimentary deposit, by year, for each of the five river reaches listed in table 6 are shown in figures 38 through 42. The total mapped areas occupied by various types of sand deposit vary substantially between sets of aerial photographs for each river reach. This variation is believed to be largely an artifact of the different riverflows represented in each set of aerial photo-

Table 6. Reaches of the Colorado River, with corresponding river miles, analyzed by using a GIS database compiled by the Utah State University.

[River miles, which are those given by the U.S. Geological Survey's Grand Canyon Monitoring and Research Center (URL http://www.gcmrc.gov/products/ims/ims.htm) are measured downstream from Lees Ferry (fig. 1), with negative values indicating distances upstream from Lees Ferry. The same river reaches were used in the aerial-photographic analyses by Leschin and Schmidt (1995) and Schmidt and others (2004)]

River reach	River miles (fig. 1)
Glen Canyon (GL)	−15.2(dam)–0
Lees Ferry (LF)	–0.4–8.3
Redwall Gorge (RW)	29.2–35.3
Point Hansbrough (PH)	42.3–48.9
Little Colorado River (LCR)	60.0–72.8

graphs until it became customary, in the 1990s, to conduct overflights only during a steady 226-m^3/s discharge. Differences in riverflow between sets of photographs should not have affected the mapped area of "upper terrace" or "high terrace" deposits, however, because those deposits lie above the stage of any riverflows that appear in aerial photographs, and largely represent the 2,700-m^3/s flood stage reached in 1983.

Schmidt and others (2004) used changes in the area of the eddy sandbars visible in these aerial photographs, in combination with oblique photography and site-specific field study, to estimate that the open sand area in the predam and postdam flood zone was 1–20 percent less in the 1990s than in predam time. Schmidt and others' (2004) analysis did not distinguish between sand deposits that were strictly fluvial and those that had undergone (or were available for) wind reworking. From the aerial photographs, particularly in the upstream (GL and LF, table 6) reaches, eddy sandbar area apparently decreased as a result of the 1996 controlled flood, an observation consistent with the more widely documented pattern of accretion and growth of sandbars farther downstream in Grand Canyon at the expense of sandbars that had been eroded from Marble Canyon. This decrease in sandbar area was a primary reason why the 2004 controlled flood was designed to follow recent substantial input of sediment from the Paria River (Topping and others, 2006). (Note that because the Paria River joins the Colorado at Lees Ferry, sandbars in the Glen Canyon reach [GL, table 6] still could have been sediment starved and eroded during the 2004 flood.)

Table 7. Dates of and riverflow in aerial photographs included in the Utah State University's GIS database, with available mapped river reaches in each aerial photograph.

[March and April 1996 sets of aerial photographs were taken before and after the first controlled-flood experiment (Webb and others, 1999a; Schmidt and others, 2001). Riverflow is based on instantaneous discharge measured at the Lees Ferry stream gage on date of photographs (Topping and others, 2003)]

Date	Riverflow (m^3/s)	Reaches (table 6)
Mid-1930s	Unknown; apparently about 142–226	LF, RW, PH, LCR (partial)
1951	Unknown	LF
1952	252–380 on Sept. 24–25, about 175 on Oct. 8.	GL (Sept.), LF (Sept.–Oct.), RW (Sept.), PH (Sept.)
1954	119–156	LCR
1958	186–201	LCR
1965	680–792	LF, RW, PH, LCR
1973	76–396	LF, RW, PH, LCR
1984	144–226	GL, LF, RW, PH, LCR
1990	142	GL, LF, RW, PH, LCR
1992	226	GL, PH, LCR
1996 (Mar.)	226	GL, LF, RW, PH, LCR
1996 (Apr.)	About 226	GL, LF, RW, PH, LCR
1996 (Sept.)	226	LF, RW
1997 (Aug.)	226	RW

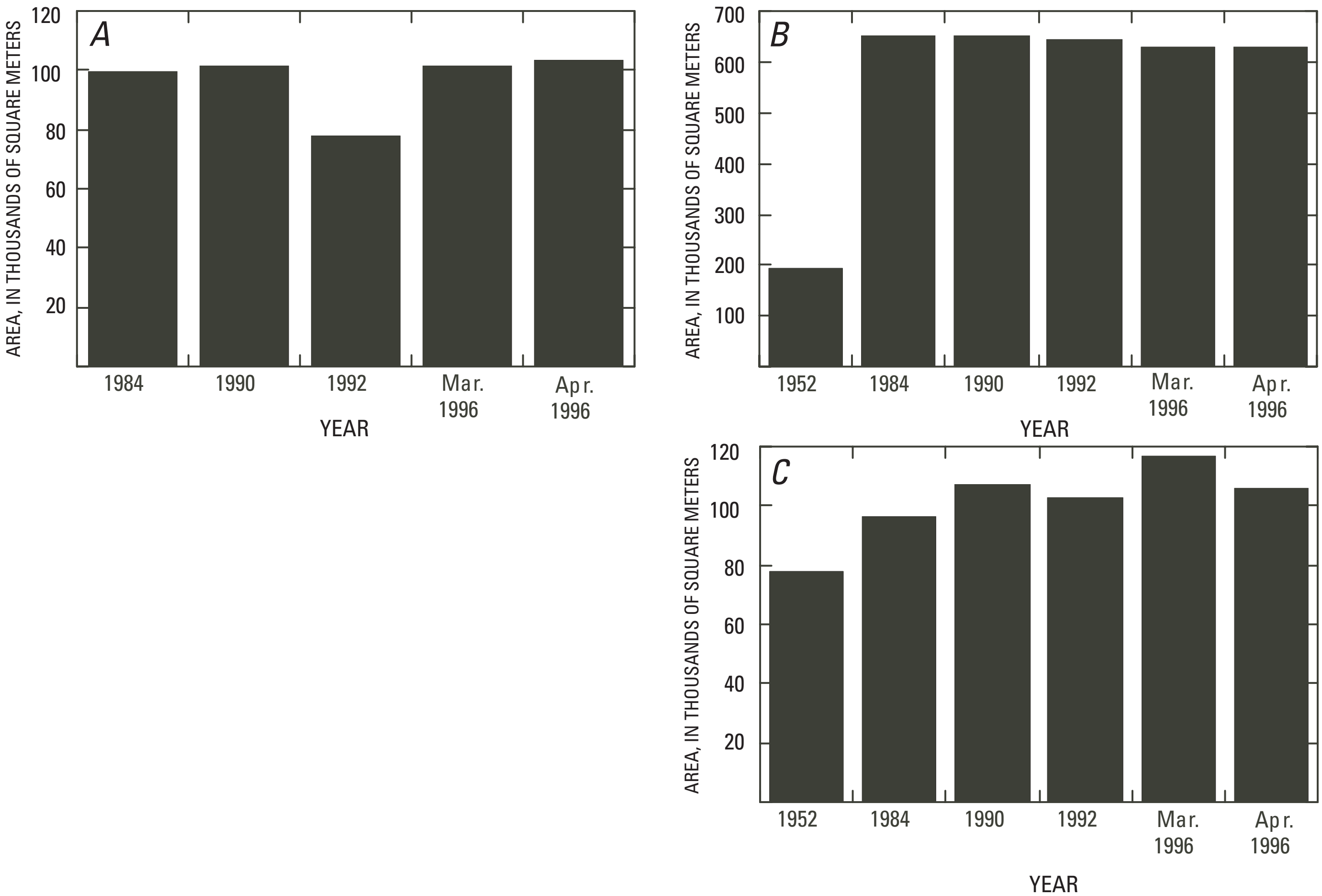

Figure 38. Total area of various types of sedimentary deposits mapped from aerial photographs in the Glen Canyon (GL, table 6) reach of the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). *A*, Total area of polygons mapped by Utah State University scientists as containing eolian sand, either alone or in combination with another geomorphic category. *B*, Total area of polygons containing sediment mapped as "upper terrace" or "high terrace" deposits (predam deposits formed above 2,700-m^3/s flood stage). Though not transported by wind, "upper terrace" or "high terrace" deposits contain sediment available for remobilization by wind. *C*, Total area of polygons containing fluvial sand deposits in eddies, including "separation bars," "reattachment bars," and, when separation and reattachment bars were not distinguishable as separate categories, "eddy bars." Fluvial sand deposits in eddies, where exposed subaerially, indicate source areas from which sand could be reworked and transported by wind. March and April 1996 sets of aerial photographs were taken just before and after first controlled-flood release from Glen Canyon Dam (Schmidt and others, 2001). Note decrease in area of eddy sandbars in the Glen Canyon reach (between dam and Lees Ferry) during time of 1996 flood; sandbars downstream in Grand Canyon that accreted during 1996 flood were built by sand eroded from eddy bars upstream in Glen Canyon and adjacent reaches.

The absence of apparent regional decadal trends in eolian deposits is partly due to difficulties of interpreting sedimentary features on the land surface by using only aerial photographs without the benefit of such supplemental information as oblique photographs and field groundtruthing (using sedimentary structures, for example, to determine more accurately the depositional history of sediment by examining it in three dimensions). Particularly in the earlier sets of aerial photographs, poor quality (commonly overexposure), shadows, and large scale also complicate detailed interpretation. Error is also introduced into geomorphic mapping methods by subjective decisions by the interpreter—whether in one set of aerial photographs a sedimentary deposit should be considered to contain eolian sand, while in another set of aerial photographs the same sedimentary deposit may look ambiguous or appear to have no geomorphic features suggesting wind reworking of sediment. These complexities would be amplified substantially as more people become responsible for interpretation and polygon naming, but this source of error was reduced in the USU laboratory by having the same personnel interpret most or all of the sets of aerial photographs, and was determined to be minimal when the interpretations by different scientists were compared (Schmidt and others, 2004).

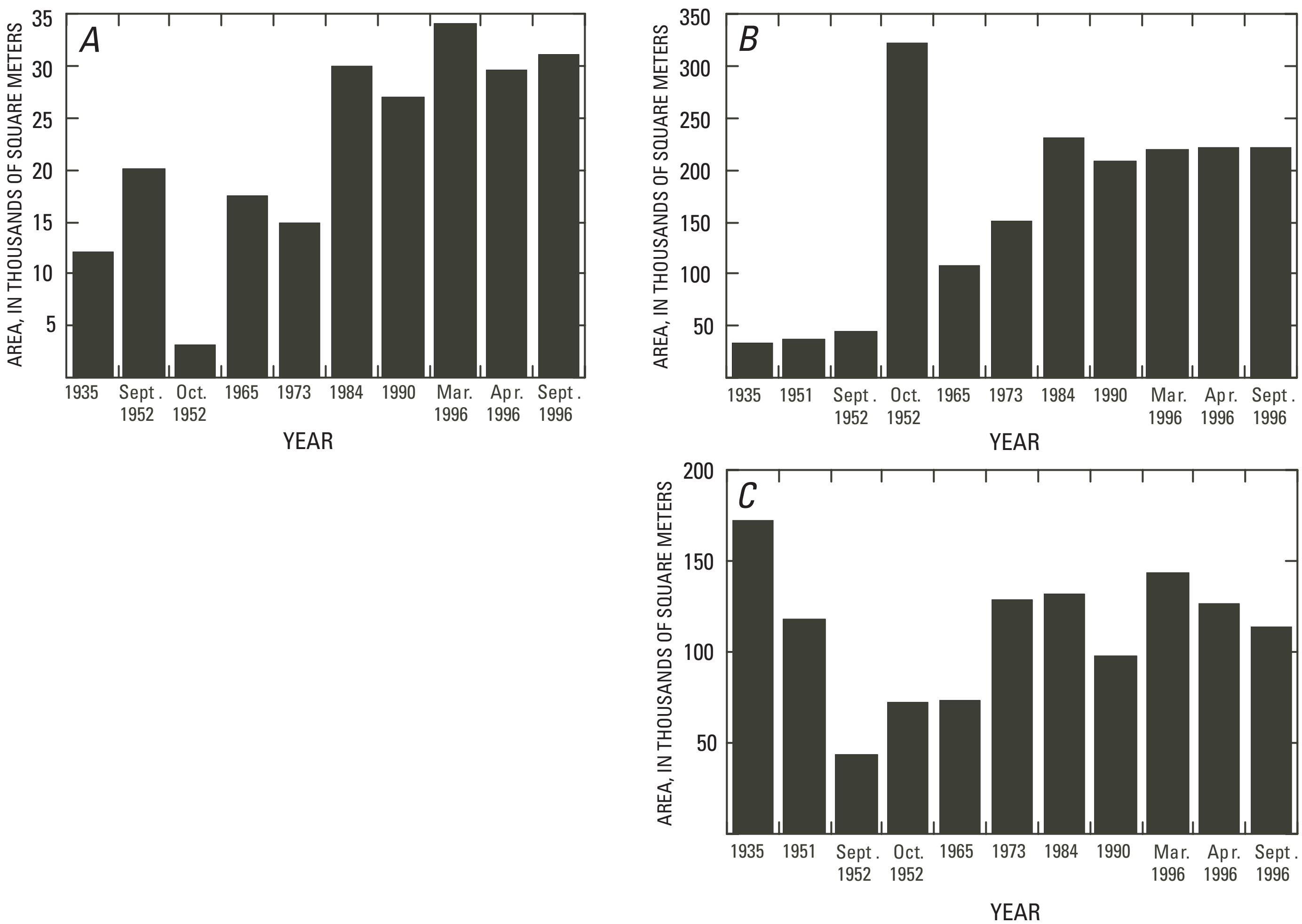

Figure 39. Total area of various types of sedimentary deposit mapped from aerial photographs of the Lees Ferry (LF, table 6) reach of the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). *A*, Total area of polygons mapped by Utah State University scientists as containing eolian sand, either alone or in combination with another geomorphic category. *B*, Total area of polygons containing sediment mapped as "upper terrace" or "high terrace" deposits (predam deposits formed above the 2,700-m^3/s flood stage). Though not transported by wind, "upper terrace" and "high terrace" deposits contain sediment available for remobilization by wind. *C*, Total area of polygons containing fluvial sand deposits in eddies, including "separation bars," "reattachment bars," and, when separation and reattachment bars were not distinguishable as separate categories, "eddy bars." Fluvial sand deposits in eddies, where exposed subaerially, indicate source areas from which sand could be reworked and transported by wind. March and April 1996 sets of aerial photographs were taken just before and after first controlled-flood release from Glen Canyon Dam (Schmidt and others, 2001). As in the Glen Canyon reach immediately upstream, area of eddy bars in the Lees Ferry reach appears to have decreased slightly between March and April 1996 as a result of controlled flood, and to have decreased farther between April and September 1996. Decrease in area of deposits containing eolian sand from March to April 1996 may have been related to loss of subaerial sandbars in eddies; if so, it is not known why area of deposits containing eolian sand apparently increased between April and September 1996, while area of eddy bars declined.

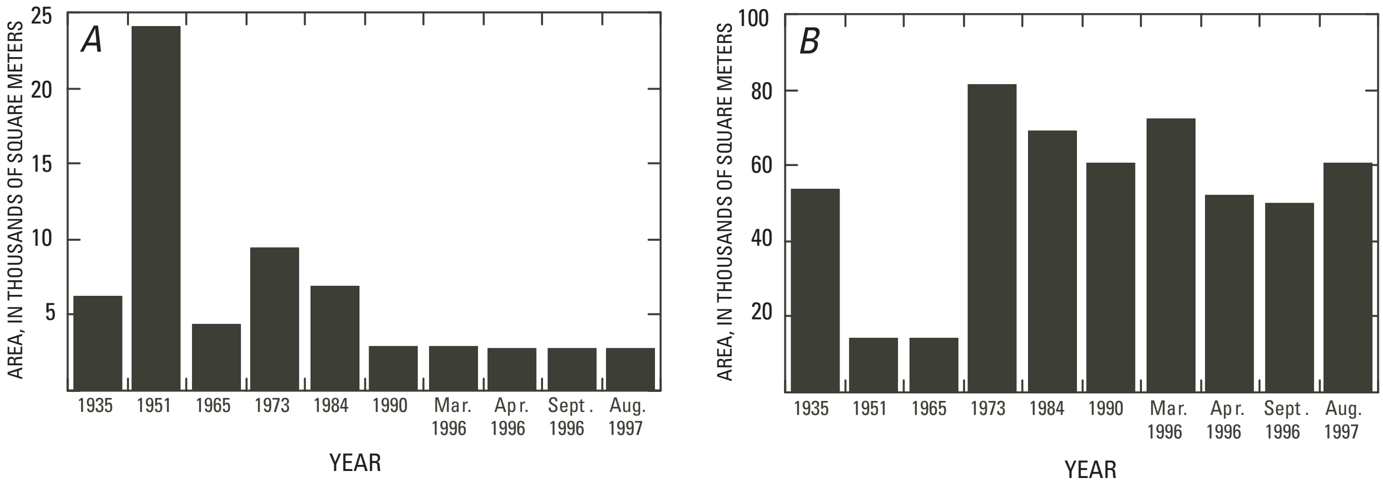

Figure 40. Total area of various types of sedimentary deposit mapped from aerial photographs in the Redwall Gorge (RW, table 6) reach of the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). *A*, Total area of polygons mapped by Utah State University scientists as containing “upper terrace” or “high terrace” deposits (predam deposits formed above the 2,700-m^3/s flood stage). Though not transported by wind, the “upper terrace” and “high terrace” deposits contain sediment available for remobilization by wind. *B*, Total area of polygons containing fluvial sand deposits in eddies, including “separation bars,” “reattachment bars,” and, when separation and reattachment bars were not distinguishable as separate categories, “eddy bars.” Fluvial sand deposits in eddies, where exposed subaerially, indicate source areas from which sand could be reworked and transported by wind. Eolian sediment was not mapped as a separate category for the Redwall Gorge reach, where eolian deposits are now rare and those that do occur are small relative to those in other river reaches.

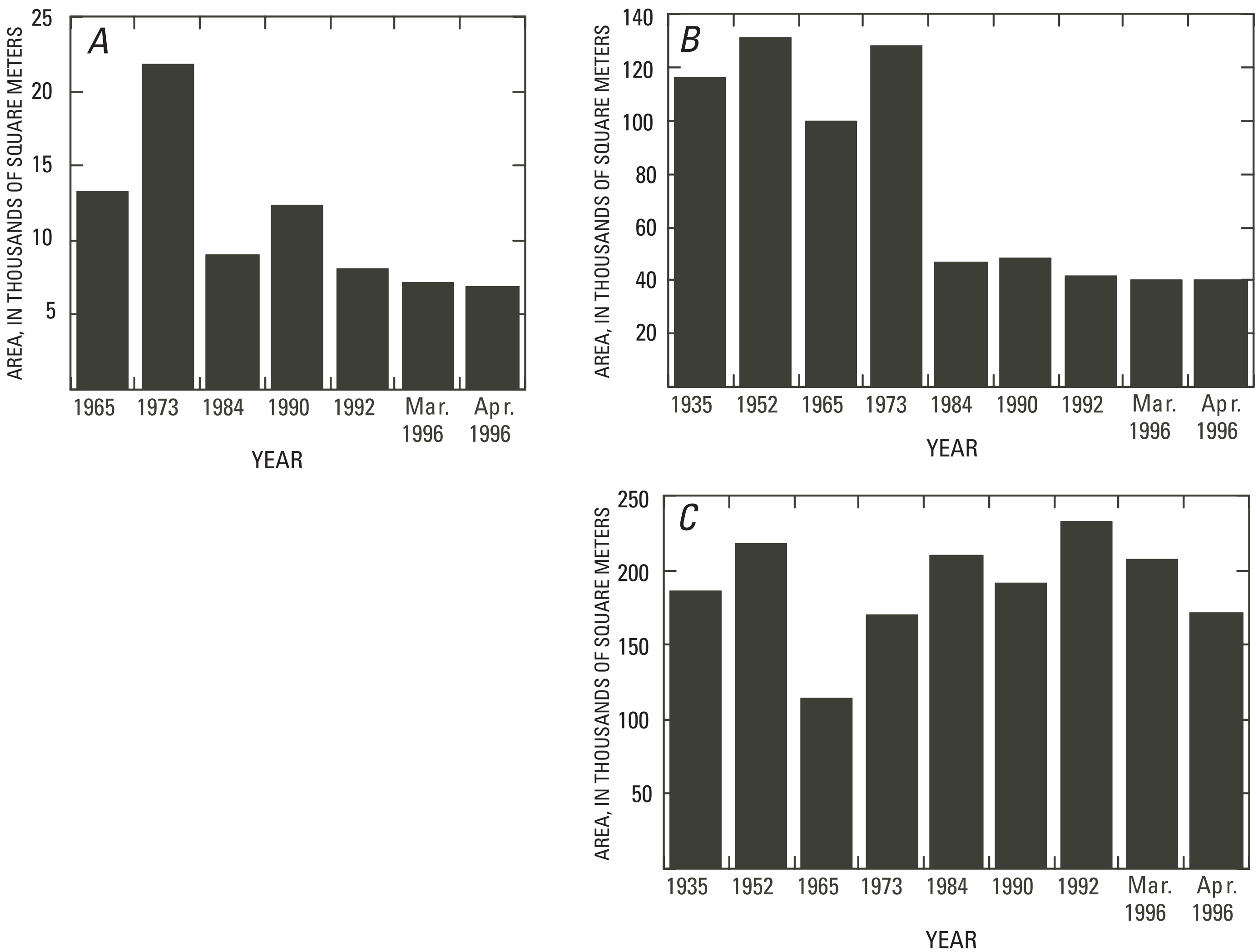

Figure 41. Total area of various types of sedimentary deposit mapped from aerial photographs of the Point Hansbrough (PH, table 6) reach of the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). *A*, Total area of polygons mapped by Utah State University scientists as containing eolian sand, either alone or in combination with another geomorphic category. Eolian deposits were not mapped as separate categories on 1935 or 1952 sets of aerial photographs for the PH reach. *B*, Total area of polygons containing sediment mapped as "upper terrace" or "high terrace" deposits (predam deposits formed above the 2,700-m^3/s flood stage). Though not transported by wind, "upper terrace" and "high terrace" deposits contain sediment available for remobilization by wind. *C*, Total area of polygons containing fluvial sand deposits in eddies, including "separation bars," "reattachment bars," and, when separation and reattachment bars were not distinguishable as separate categories, "eddy bars." Fluvial sand deposits in eddies, where exposed subaerially, indicate source areas from which sand could be reworked and transported by wind. March and April 1996 sets of aerial photographs were taken just before and after first controlled-flood release from Glen Canyon Dam (Schmidt and others, 2001). Note decrease in area of eddy bars as a result of 1996 flood.

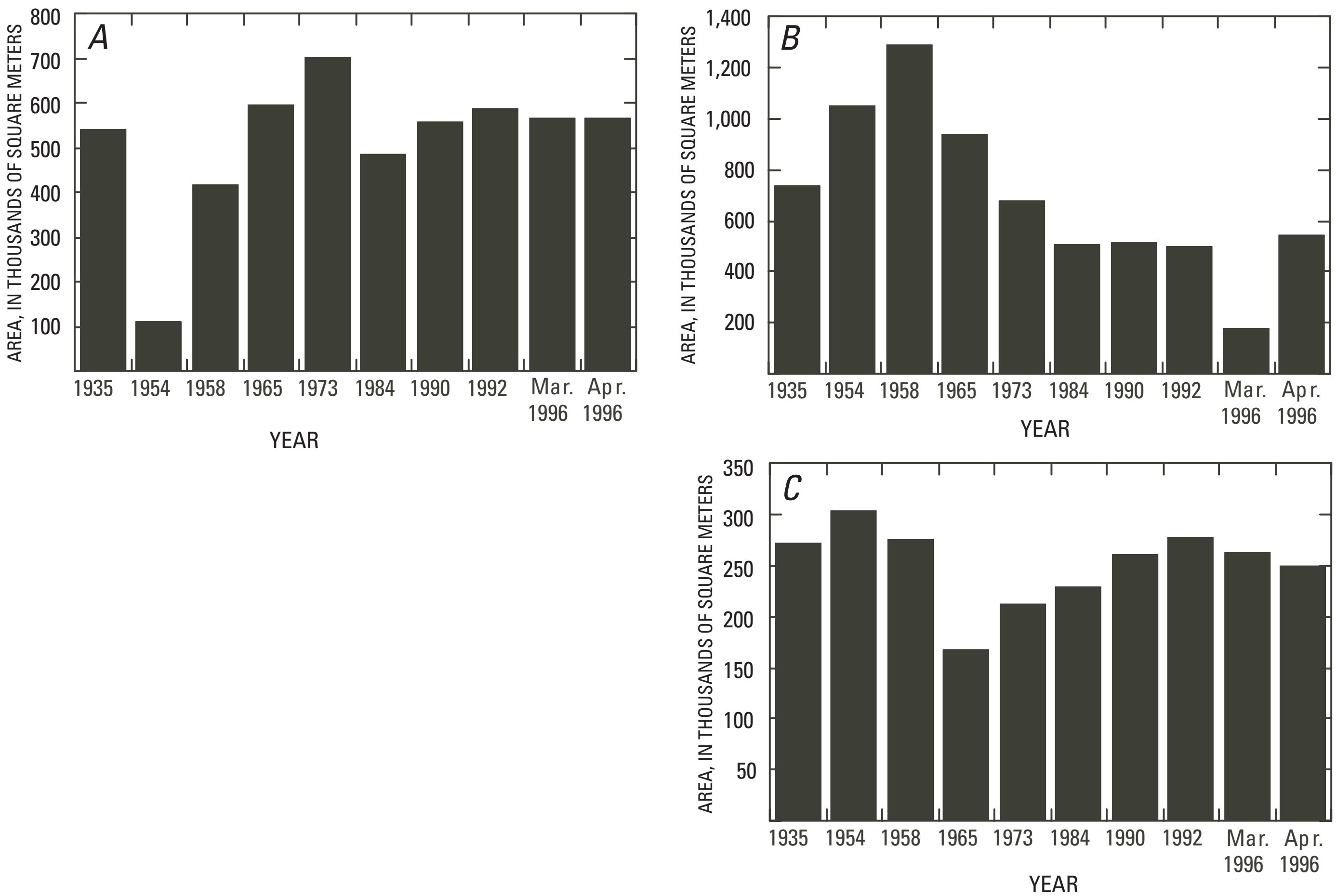

Figure 42. Total area of various types of sedimentary deposits mapped from aerial photographs of the Little Colorado River (LCR, table 6) reach of the Colorado River corridor in Grand Canyon National Park, Ariz. (fig. 1). *A*, Total area of polygons mapped by Utah State University scientists as containing eolian sand, either alone or in combination with another geomorphic category. *B*, Total area of polygons containing sediment mapped as "upper terrace" or "high terrace" deposits (predam deposits formed above 2,700-m^3/s flood stage). Though not transported by wind, "upper terrace" and "high terrace" deposits contain sediment available for remobilization by wind. *C*, Total area of polygons containing fluvial sand deposits in eddies, including "separation bars," "reattachment bars," and, when separation and reattachment bars were not distinguishable as separate categories, "eddy bars." Fluvial sand deposits in eddies, where exposed subaerially, indicate source areas from which sand could be reworked and transported by wind. March and April 1996 sets of aerial photographs were taken just before and after first controlled-flood release from Glen Canyon Dam (Schmidt and others, 2001).