Eolian and Subaqueous Sedimentary Structures of the Devils Island Sandstone, Sand Island, Wisconsin (U.S.A.)

Zachary W. Stewart
Senior Integrative Exercise
August 11, 2011

Advisors:
Dr. Clinton A. Cowan, Carleton College
Anthony C. Runkel, Minnesota Geological Survey

Submitted in partial fulfillment of the requirements for a Bachelor of Arts degree from Carleton College, Northfield, Minnesota
Abstract

The Devils Island Sandstone, Northern Wisconsin, U. S. A., is a super-mature quartz arenite (99% quartz) that has been correlated to the Mesoproterozoic Hinckley Sandstone of Minnesota. The depositional environments of rift sediments like the Devils Island Sandstone are not well understood. This study describes sedimentary structures in a ~5 m thick interval of outcrop observed on Sand Island, Wisconsin. The observed sedimentary structures are dune-scale sets of eolian cross-strata, mm pinstripe-lamination, grain flows, adhesion structures, subaqueous ripples, a pustular algal mat, m-scale trough cross-stratification, pinstriped intraclasts, and soft sediment deformation. The studied interval within the Devils Island Sandstone is dominated by eolian strata, but exhibits at least one subaqueous stratigraphic layer. These two types of deposits are interpreted to represent a depositional environment in a barchan dune field subject to occasional flooding and reworking by ephemeral braided streams. These aqueous environments, called wadis, formed under the influence of possibly complex climatic factors operating across a range of timescales, likely including fluctuations in rainfall, atmospheric moisture, and water table elevation.

Keywords: Mesoproterozoic, Mid-Continent Rift, eolian, barchan dunes, adhesion structures, pinstripe lamination, braided streams, wadi
Table of Contents

Abstract

Table of Contents

Introduction........................................................................................................................................1
Geologic Setting...................................................................................................................................2
Facies of the Devils Island Sandstone at Sand Island.................................................................7
Sedimentary Structures of Facies 1.................................................................................................8
  Pin-stripe Lamination
  Grainflows
  Adhesion Structures
  Subaqueous Ripples
  Pustular Algal Mat
Interpretation of Facies 1.................................................................................................................17
Sedimentary Structures of Facies 2.................................................................................................20
  Trough Cross-stratification
  Intraclasts
  Soft/firm Sediment Deformation
Interpretation of Facies 2.................................................................................................................24
Discussion of Paleo-environment.................................................................................................25
Conclusions.......................................................................................................................................29
Acknowledgements.........................................................................................................................30
References.........................................................................................................................................31
Introduction

Raindrop imprints or terrestrial animal tracks are useful for identifying subaerial sediment, but they rarely occur (Hunter, 1977). In formations without these key eolian features, distinguishing between eolian and subaqueous deposits can be challenging. Characterization of macroscopic eolian sedimentary structures by Hunter (1974; 1977) and others has led to improved methods of identifying eolian deposits in the field. The Devils Island Sandstone, Northern Wisconsin, U. S. A., has been interpreted as lacustrine in origin, composed of reworked material from the underlying Orienta Sandstone (Tryhorn and Ojakangas, 1972; Morey and Ojakangas, 1982). Recently, recognition of eolian stratification types in the Devils Island and correlative Hinckley Sandstone has led to reinterpretation of those units as mixed eolian and braided stream deposits (Johnson et al., 2002; Galston et al., 2008; Havholm et al., in preparation).

The age of the Devils Island Sandstone is subject to debate. Some workers consider the unit to be Cambrian in age because it resembles nearby Paleozoic strata (Hamblin, 1958; Ostrom, 1967), while others (Morey and Ojakangas, 1982; Johnson et al., 2002) argue for a Mesoproterozoic age due to its integral position in the Midcontinent Rift System (Fig. 1). Galston et al. (2008) discovered possible trace fossils in the Devils Island Sandstone, which would either suggest a Cambrian age for the formation, or provide rare evidence of Mesoproterozoic multicellular life (Galston et al., 2008; Han and Runnegar, 1992).

The Devils Island Sandstone depositional environment is poorly understood, although it has been petrologically and mineralogically well described (Adamson, 1997;
Morey and Ojakangas, 1982; Tryhorn and Ojakangas, 1972). Better understanding of the depositional environment may be key to understanding the potential trace fossils and unraveling their implications. The purpose of this study is to determine the paleoenvironment(s) of the Devils Island Sandstone. Toward this goal, I observed, documented, and interpreted sedimentary structures in a 150 m long 2 – 5 m high outcrop of the Devils Island Sandstone at Sand Island, Wisconsin, U. S. A. (Fig. 2). This rare 150 m long interval of continuous outcrop provides a unique opportunity to observe sedimentary structures because it includes exposure on three faces due to the curvature of the shoreline of Sand Island.

**Geologic Setting**

The Precambrian Mid-continent Rift System began to develop ~1,100 Ma, ultimately resulting in formation of marginal basins, and emplacement of three distinct rock suites (Fig. 1; Cullers and Berendsen, 1998). Alternating basalts and rhyolites were extruded during rift formation, and the Oronto Group volcaniclastic sedimentary rocks were subsequently deposited in a subsiding axial basin (Ojakangas et al., 2001; Adamson, 1997; Cannon, 2005). The ~2100 m thick Bayfield Group overlies the Oronto Group and consists of quartzose and subarkosic sandstones with little volcaniclastic material (Cullers and Berendsen, 1998). The Bayfield Group is divided, in ascending order, into the Orienta Sandstone, Devils Island Sandstone, and Chequamegan Sandstone (Fig. 3; Morey and Ojakangas, 1982). The Devils Island Sandstone, an approximately 100 m thick mature quartz arenite (99% quartz), contains only rare fines or
Figure 1. Geologic map of the Mid-Continent Rift System, showing the distribution of volcanic and sedimentary rock broadly. Study area is designated with a red circle. Modified from Ojakangas et al. (2001).
volcaniclastics in the Sand Island study area (Myers, 1971). The Devils Island Sandstone has been subject to various paleoenvironmental interpretations, including lacustrine, fluvial, eolian, and braided stream deposits (Johnson et al., 2001; Galston et al., 2008; Ojakangas and Morey, 1982).

The provenance of underlying Oronto Group sediments is Mid-Continent Rift volcanics, whereas Bayfield Group sediments, including the Devils Island Sandstone, are quartzose, poor in feldspars and volcanic fragments, and contain a granitoid assembly of trace elements. The Bayfield Group is interpreted, based on composition as well as analysis and comparison of trace elements, to be derived from Precambrian granites on the edges of the Mid-Continent Rift (Cullers and Berendsen, 1998). Morey and Ojakangas (1982) suggest that the change in sedimentation from the volcaniclastic Oronto group to the granite-derived Bayfield group is due to a vertical tectonic regime taking the place of primarily extensional processes. The source area at the flanks of the rift is composed of felsic rocks, so Morey and Ojakangas (1982) propose that after uplift, streams carrying sediment from the rift flanks to the rift basin may have eroded through rift basalts and begun to cut down into older granitic rocks, causing the change in sediment supply from volcanic to granitic material. The wedge-like cross sectional geometry of the Bayfield Group implies that it was likely deposited in a half-graben basin bounded by the recently uplifted St. Croix Horst (Ojakangas et al., 2001).
Figure 2. The narrow belt of Devils Island Sandstone outcrop is shaded in orange. Black arrow points to study area. Modified from Adamson (1997).
Figure 3: Regional stratigraphy of the Bayfield and Oronto Groups along an East-West transect from Duluth, MN to Washburn, WI.

Adapted from Morey and Ojakangas (1982).

Distance (Kilometers)

Elevation (Meters)

Devils Island

Chequamegon

Pleistocene

Upper Oronto Group

Middle Oronto Group

Lower Oronto Group

Bayfield Group

Devlo Group

Lower

Middle

Upper
Facies of the Devils Island Sandstone at Sand Island

I differentiate two Facies in the stratigraphic interval of the Devils Island Sandstone exposed along the shoreline of Sand Island. These Facies vary both stratigraphically and laterally across the study area. Both Facies 1 and Facies 2 consist of well-sorted, fine to medium size, subrounded quartz grains, but they contain two different assemblages of sedimentary structures.

Facies 1 is a succession of decimeter to meter-scale sets of cross-strata: these sets are lenticular to wedge-shaped, the foresets range in dip angle from subhorizontal to ~24˚ and approach lower bounding surfaces tangentially (Fig. A1). These sets lap onto one another in varying orientations, truncating the underlying sets at low angles. The average set size is 10 – 30 m long by 1 - 2 m tall. Facies 1 contains a suite of sedimentary structures indicative of eolian dune and inter-dune deposition (described in detail below).

Facies 2 is a channel-shaped deposit that forms a distinct layer within Facies 1. This layer occurs at the bottom of the outcrop (the water line) in the southern part of the study area, and ranges from 10 cm to 1.5 m thick. It contains intraclasts (derived from Facies 1), is trough cross-stratified, and truncates underlying sets of Facies 1 sharply, with the underlying bounding surface showing up to 1 meter of erosional relief. Facies 2 is laterally extensive: it fills an erosional scour tens of meters wide, which wedges out into Facies 1 to the Northeast (Fig. A1).
Sedimentary Structures of Facies 1

The foresets that make up the decimeter to meter-scale sets of Facies 1 are themselves composed of smaller scale sedimentary structures, which indicate paleo-bedforms that existed on the surfaces of the larger-scale dune bedforms. These sedimentary structures are distributed widely across the study area, and are interpreted to represent deposition in wet (subaqueous), damp, and dry (eolian) conditions.

Pinstripe-lamination

The bulk of Facies 1 is composed of sets of mm-scale laminated sand, which is identified as pinstripe lamination (Fig. 4A; Hunter, 1977). Pinstripe-lamination is the stratification formed by mm-scale wind-driven bedforms called wind ripples. Bagnold (1941) called the process by which pinstripe-lamination arises tractional deposition. Ralph Hunter (1977) refined this terminology, calling the pinstripe-lamination left behind by wind ripples climbing translatent strata.

Unlike subaqueous ripples, which form in response to the shear stress exerted on sand grains by moving water, wind ripples form due to the repeated impacts of saltating, or airborne, sand grains against the sand surface. Some sand grains are too large to be lifted and moved by the wind, so they roll or creep slowly downwind along the depositional surface in a process called reptation (Hunter, 1977). When small grains (saltons) are lifted by the wind they travel at very high velocities, eventually falling to strike the depositional surface with much kinetic energy. This impact ejects several larger grains (reptons), pushing them out of place enough that they roll or reptate to a new resting place a few to hundreds of grain-diameters downwind from their initial
Figure 4. Photograph A is pinstripe lamination with finger for scale. B depicts the process of forming pinstripe lamination through climbing wind ripple migration. In time 1, saltating grains impact reptating grains, forming microtopography in time 2. In 3 grains start to organize into ripples due to fewer impacts on lee surfaces. In time 4 and 5, wind ripples migrate downwind, saltons tending to deposit in ripple troughs while reptons deposit on crests. 6 is the pinstripe lamination left behind wind ripples (compare to A).
position (Fig. 4B; Forrest and Haff, 1991). The cumulative effect of these impacts soon causes the initially flat sand surface to self organize into micro-ridges, leading to an increased probability of saltation impact on upwind inclined slopes and a decreased probability of impacts on downwind inclined slopes. If wind conditions continue to cause saltation during a net-depositional regime, the cumulative effect causes small ridges or low amplitude ripples to form and migrate downwind due to the impact-driven erosion on stoss slopes and the net deposition on lee slopes (which experience fewer impacts than stoss slopes) (Fig. 4B; Forrest and Haff, 1991). Individual foresets within wind ripples are generally too small to observe, but the set created by one migrating wind ripple is a single lamina. One wind ripple lamina appears in outcrop as a millimeter-scale dark-light couplet (Fig. 4).

Climbing translatent strata are often characterized by an inverse grading pattern, with the coarsest grains depositing on the ripple crest, or the top of the foreset. I have not been able to confidently identify inverse grading in outcrop, probably due to the small scale of the laminations, and the homogeneity of sand and lack of fines in the Devils Island Sandstone. Petrographic analysis could reveal inverse grading, but is outside the scope of this study. However, the chemically stained foreset surfaces which make pinstripe lamination visible in outcrop suggest some grain scale permeability difference between the top and bottom part of a single climbing translatent strata foreset (Fig. 4A). This permeability difference is likely the result of inverse grading.

Hunter (1977) indicates that climbing translatent strata, or wind ripple laminations, occur on the stoss sides of dunes, on the downwind trailing horns of crescent-shaped barchanoid dunes, and on lee slopes that are inclined less steeply than the
angle of repose. Net deposition occurs most often on lee slopes, so these pinstripe-laminae were probably deposited on the lower lee slope of dunes, as a gently dipping “apron” (Hunter, 1977).

*Grainflows*

In the Sand Island study area, tongues or wedges of unstratified sand are commonly interbedded at the centimeter scale with subcritically climbing translatent strata. These tongue-shaped bodies of unstratified sand are identified as grainflow strata (Hunter, 1977). Two different types of grainflow deposits are observed in Facies 1: slump degeneration and scarp recession. Slump degeneration occurs when a body of dry sand at or near the angle of repose (~34°) gives way, gradually losing cohesion between grains, and sliding down a slipface on the lee side of a dune. This avalanching action destroys any pre-existing stratification and results in the deposition of a tongue or wedge of unstratified sand (Fig. 5). Scarp recession grainflow begins at a “breakaway scarp” and recedes upslope and outward along slope by the gradual fall of individual grains or tiny masses of sand until the scarp ascends to a cohesive area of sand or the crest of the dune. Repeated scarp recession events deposit series of unstratified tongues that commonly stack onto each other, forming a rhomboid cross-section parallel to transport direction. This rhomboid cross-sectional profile was observed at one location in the Sand Island study area. Grainflows only occur on the steep parts of the dune slipface, and the migration of dunes is caused by sequential grainflows triggered by wind-blown deposition on the lee slope (Kocurek and Dott, 1981).
Adhesion structures

Irregular mm-scale bumpy, ridged, or wart-like surfaces are visible on bedding plane exposures of some foresets in Facies 1 (Fig. 6). Where cross-sections are exposed, mm-scale laminations, similar to pinstripe lamination, are visible. These bumpy surfaces and mm-scale laminations are interpreted as adhesion structures, described by Kocurek and Fielder (1982). They experimentally investigated differences in adhesion structure morphology using a wind tunnel, and concluded that adhesion structures form on damp or wet sand surfaces when wind blows dry sand across the moist depositional surface (Kocurek and Fielder, 1982).

Similar to climbing translatent strata, adhesion structure genesis is dominated by the development of relief by saltating grains impacting upwind sides of microtopography or small bumps on the depositional bed. When saltating grains impact a wet or damp surface they stick to the site of impact (usually on the upwind side of a bump or ridge), trapped by the cohesive forces of water. Accumulations of small saltating grains soon adhere to form upwind climbing protuberances, which in turn trap larger reptating grains in their valleys, resulting in cohesion-driven upwind-migrating deposition. Variability of wind direction, wind strength, moisture content of sand base, and pre-existing microbial features or topography were identified as the main variables that influence adhesion structure morphology, which can range from well developed “ripples” to amorphous “warts” (Kocurek and Fielder, 1982). Adhesion structures indicate that moisture was present (at least occasionally) in the Devils Island depositional environment represented by Facies 1.
Figure 5. Cartoon illustrating the deposition of unstratified sand wedges. In panel 2, the lee face of the dune steepens past the angle of repose. The sand near the top of the lee is unstable and prone to avalanching. Panel 3 shows the resultant grainflow in darker brown. In panel 4 downwind dune migration and steepening of the lee face continue as climbing translatent strata are deposited over the unstratified grainflow. Panel 5 shows another grainflow avalanche, and depicts the interbedded tongues of unstratified sand (brown) and pinstripe lamination (tan) deposited by Devils Island Formation dunes.
**Subaqueous ripples**

Cm-scale rippleforms are observable both on bedding plane exposures and in cross-section. Three types of subaqueous ripples occur in the study area: symmetrical bifurcating wave ripples (Fig. 7A), climbing wave ripples, and asymmetrical current or current-modified ripples (Fig. 7B). These three ripple types imply at least two different types of subaqueous depositional environment: wave dominated and current dominated bodies of water. Wave ripples and climbing wave ripples form in standing bodies of water without significant current, while asymmetrical current ripples form by downstream migration of sand under shear stress from flowing water (Reineck and Singh, 1980). Climbing subaqueous ripple structures are indicative of rapid net sedimentation in an underwater depositional environment (McKee, 1965).

**Pustular algal mat**

The bedding plane surface in at least one location in Facies 1 exhibits irregular bumpy relief (Fig. 7C). Schieber (1997) explains that “upper bed surfaces with pustular and/or wrinkled appearance” are a characteristic feature in sandstones indicating microbial binding of sediment in shallow water to episodically emergent environments. The pustular texture arises when communities of microorganisms colonize sediment to such a degree that their bodies and metabolic wastes create a sticky physical layer strong enough to resist erosion. As successive generations of microbes live and die while deposition continues, the mat traps and incorporates grains of sand in irregular bumpy patterns. Microbial mats inhabited many terrigenous sandstones during the Proterozoic, and were capable of exploiting a diverse range of environmental conditions (Schieber,
The observed pustular surface is interpreted as evidence of microbial binding of the sand under ephemeral damp to wet conditions.
Figure 6. Adhesion structures are visible on multiple bedding plane surfaces in A. Hand for scale. The irregular adhesion surface visible close-up in B is accentuated by preferential weathering and chemical staining.
Figure 7. Subaqueous ripples exposed on bedding planes. A shows bifurcating wave oscillation ripples. B shows current-modified ripples with multiple orientations. Vermiform relief, or bumpy surfaces in C are interpreted as a fossil pustular microbial mat. Microbial communities physically bound sand grains into a mat under damp to wet conditions.
Interpretation of Facies 1

Taken as a suite, the sedimentary structures described above indicate an eolian dune to interdune depositional setting for Facies 1. Pinstripe-laminations or climbing translatent strata formed in dry environments where wind transport causes the saltation and reptation of sand grains (Hunter, 1977). Similarly, dry blowing sand is necessary for the formation of upwind climbing adhesion structures, including warts and ripples (Kocurek, 1982). The occasional presence of subaqueous features like ripples, a pustular algal mat and damp sand adhesion structures occurring along foresets formed by eolian processes (grainflows and pinstripe-lamination) show that damp and wet conditions must have existed sporadically in the Devils Island depositional environment. Formation of the climbing subaqueous ripples observed in Facies 1 requires abundant sediment supply, probably provided in this environment by wind-transported sand that became trapped on contact with the water surface of ephemeral pools or streams in which the climbing ripples formed (cf. Glennie, 1987). The presence of both current and wave ripples shows that both still and flowing water occasionally occupied the interdune areas of the Devils Island depositional environment.

Pinstripe-lamination and eolian grainflows form on different parts of a mature dune, so their distribution in preserved cross-strata can be used to understand the geometry of the ancient dunes that left them. Although grainflows are locally observed, pinstripe lamination is by far the most abundant structure in Facies 1. Pinstripe lamination forms around the base of a dunes lee side, while grainflows, according to Kocurek and Dott (1981), occur in the zone of flow separation near the top of the
concave downwind slope of a dune, often near the dune crests and on the steepest slopes (Fig. 8). The relative abundance of pinstripe-lamination shows that usually only the bottom gently-dipping portion or “toes” of dunes were preserved. The upper fraction of the dunes, where grainflows form, was rarely preserved. Much of the upper lee face is commonly eroded as the dune stoss slope and interdune area migrate downwind.

Changes in the water table and distribution of moisture throughout the system were likely major controls on what fraction of original dune height was preserved: capillary rise or a locally rising water table could saturate the sand, making it cohesive enough to resist eolian erosion (cf. Paim, 2007; Mountney and Thompson, 2002). Crabaugh and Kocurek (1993) suggest that sediment accumulation in a wet eolian system is often controlled by water table height, and that the presence of both dune and interdune-flat deposits are classic of wet eolian environments.
Figure 8. Morphology of a barchan dune (A). B shows the distribution of climbing translational strata in brown versus grainflow strata in orange. Note that the wind ripples which deposit climbing translational strata in the brown areas can occur in any orientation and migrate in any direction depending on the direction of small scale interdune wind currents and vortices. Modified from Duran et al. (2010) and Kocurek and Dott (1981).
**Sedimentary Structures of Facies 2**

*Scoured channel-form*

Facies 2 occurs in a scoured channel-form that shows up to 1 m of erosion into the underlying Facies 1. Facies 2 is trough cross-stratified (Fig. 8), but case hardening of the outcrop prevents good measurement of trough size. The only fully exposed trough structure measured 2 m long by 30 cm high. Trough cross-stratification and scour structures are present in a thin but laterally extensive lenticular sheet that pinches out, then re-occurs as a small lens at the same stratigraphic level (Fig. A1). Scoured channel-forms and trough cross-strata indicate erosion into underlying material accompanied by deposition into the erosional scour (McKee, 1957).

*Pinstripe-laminated intraclasts*

Intraclasts 1-3 cm long and less than 1 cm thick are present throughout Facies 2 (Fig. 9A, Fig. 10A). Intraclasts exhibit pinstripe-lamination, implying that pinstripe-lamination from Facies 1 must have been firm or partially lithified at the time of Facies 2 deposition. These intraclasts are visible as angular pieces that decrease in size with increasing distance from the margin of the Facies 2 scoured channel-form.

*Soft to firm sediment deformation*

The top surface of Facies 2 is irregular to wavy at the dm to m-scale, forming depressions meters wide in plan view and up to 20 cm deep in cross section (Fig. 9B, Fig. 10B). Surfaces like these can be difficult to interpret, but may indicate soft sediment
Figure 9. Unaltered photographs of intraclasts (A) and soft to firm sediment deformation (B). See figure 10.
Figure 10. Intraclasts in A average 1-3cm long, and exhibit pinstripe lamination. Hand for scale. B shows the gently deformed surface of element 2 where it is exposed by preferential erosion of Facies 1. Yellow camera case for scale is 15cm long.
deformation. McKee (1971) studied deformation of sand bodies in modern eolian environments, finding that “warps or gentle folds” were a common soft sediment deformation structure. These surfaces form most commonly in very wet to saturated sand, which has little cohesion. Fully developed “graviturbation” soft to firm sediment deformation in the form of flame structures and fluid escape structures were observed in the Devils Island Sandstone immediately outside the study area: along with the less extreme soft sediment deformation inside the study area these structures are interpreted to be the result of heavy eolian sand dunes migrating across soft to firm, still-saturated, subaqueous inter-dune deposits (van Loon, 1992).

**Interpretation of Facies 2**

Trough cross-stratification, intraclasts, soft to firm sediment deformation structures, and the erosional channel-like geometry of Facies 2 show that this lens of sand was deposited in a fluvial environment like an ephemeral stream. This environment probably formed during a flood, rainfall event, or wet season in the Devils Island Sandstone depositional environment. Temporary surface water and an elevated water table is consistent with the preservation of dune “toes” in Facies 1 due to cohesion in the damp sand. This transient flowing water eroded and re-deposited eolian sediments, forming the erosional scouring, intraclasts, and trough cross-stratification observed in Facies 2. The mm-scale laminated intraclasts in this fluvial bed indicate that some subcritically climbing translatent strata must have been firm or partially lithified at the time of fluvial reworking and deposition. In the Devils Island environment, intraclasts could have been partially lithified by evaporite minerals or bound by microbial mats.
before being broken apart by flowing water (Pflueger and Gesse, 1996). The erosional margin, where eolian climbing translatic strata of Facies 1 are preserved as intraclasts within Facies 2, is further evidence that ephemeral streams scoured into Facies 1 before depositing reworked sediment into the erosional scour.

**Discussion of the Paleo-environment**

The two observed facies that lap onto one another laterally indicate that two types of depositional process occurred in close proximity to one another during Devils Island Sandstone time.

Eolian subcritically climbing translatic strata, grainflow deposits, and adhesion structures make up most of the study area outcrop, so the majority of Devils Island Sandstone deposition must have occurred in dry to damp conditions. These cm- to dm-scale eolian structures were formed on the surfaces of large m-scale eolian dunes, which migrated across the landscape with the prevailing winds. “Horns” of sand that extend outward and downwind from the center of many preserved eolian dunes in the study area indicate that the Devils Island dunes were probably crescentic or barchanoid in shape (Fig. 8; Duran, 2010; Hunter, 1997).

Subaqueous features such as wave and current ripples, intraclasts, and trough cross-stratification were deposited in ephemeral ponds, pools, and stream channels that formed in interdune areas when water was introduced to the system. In these short-lived pools, wind caused ripples and small waves on the water surface, whose effects organized the sand into symmetrical wave ripples. The small size of observed subaqueous wave
ripples (ranging from 0.5 - 3 cm height and 2 - 15 cm in wavelength), lack of deformation or erosion caused by larger storm waves, and the relatively small amount of total subaqueous sediment point to exclusively small ephemeral pools of water as the source of Devils Island wave ripples. The channel structures and trough cross-stratification of Facies 2 were formed under flowing water conditions, as ephemeral braided streams or *wadis* flowed through interdune areas (Fig. 11). Flow in these temporary channels caused erosional scouring into the eolian landscape, followed by deposition of asymmetrical current-modified subaqueous ripples and trough cross-stratified, intraclast-bearing, *wadi* deposits.

The amount of water present must have determined depositional processes, and could have fluctuated on multiple timescales due to the complex interplay of many factors. Water in the Devils Island system could have varied depending on rainfall events, fog or atmospheric moisture, fluctuations in the water table, autocyclic changes in stream flow, seasonal variance in precipitation, annual weather changes (el Niño), or long term climatic changes. Larger volumes of water were required to form flowing *wadis* and pools of water large enough to form ripples, but adhesion structures and small subaqueous features could have formed on sand moistened by dew or light rain in an otherwise dry setting. Adhesion structures likely also formed after ponds or *wadis* dried, exposing damp surfaces to wind-blown sand. Under dry conditions, eolian dunes would have dominated the landscape, leaving behind a trail of pinstripe-lamination and grainflow deposits which record a small fraction of the original barchan dune height (Fig. 11). Where eolian dunes migrated over still-soft subaqueous sediment, soft sediment deformation occurred.
The conspicuous lack of fines, mud-cracks, desiccation structures, and pebbles in these *wadi* deposits can be attributed to the high degree of maturity and eolian reworking of the sediment. Dalrymple et al. (1985) explain the lack of mud, dust, or fines in ancient desert environments by the vigorous pre-vegetation eolian transport of these small particles off Laurentia into the sea.

Stratigraphic scale interpretation of the study area also supports an eolian dune and *wadi* depositional environment. Glennie (1970) calls interbedded layers of eolian and *wadi* deposits classic of a desert environment, explaining that eolian processes dominate in between periods of *wadi* deposition, and that flow in ephemeral *wadis* usually erodes only a small portion of eolian strata leaving variable sized stratigraphic sequences of eolian features to separate *wadi* channels and pond deposits (Fig. A1).

In light of the eolian reinterpretation of the Devils Island Sandstone, a shift in wind-driven erosion and transport could be another factor that influenced changing provenance. Tectonic versus eolian control of sedimentary processes deserves further investigation, because linking tectonic and sedimentary events temporally may settle age-debates and other questions about the geologic history of the region.
Figure 11. 3-D block diagram of the Devils Island Sandstone paleoenvironment. A series of barchan dunes is migrating downwind, leaving subaerial features in stream or pond environments. Occasionally, wadis (illustrated here in blue) flow through the interdune area, forming behind the colluvial sets visible in cross section. Barchan dunes are illustrated in brown.
Conclusions

The two Facies observed in the Devils Island Sandstone exhibit dune-scale sets of eolian cross-strata, mm-scale pinstripe-lamination, grain flows, adhesion structures, subaqueous ripples, a pustular algal mat, m-scale trough cross-stratification, pinstriped intraclasts, and soft sediment deformation. These sedimentary structures record two depositional environments, which vary both spatially and temporally: eolian dune and wadi. This limited study supports interpretation of the Devils Island Sandstone as eolian dune and interdune deposits interbedded with ephemeral braided stream sediments. The Devils Island barchan dune field was occasionally inundated by wadis and ephemeral pools that formed under the influence of variable timescale fluctuations in rainfall, atmospheric moisture, and water table height.

Galston et al. (2008) discovered potential trace fossils in a silt facies not present in the study area, but do not propose an origin for the potential traces. If the sinuous meandering forms observed by Galston et al. (2008) are Proterozoic metazoan trace fossils, then they formed in an obligate marine environment (Pemberton et al., 1992). There is no evidence of marine sedimentation recognized in this study, but the proposed traces may occur in a marine facies that crops out elsewhere in the Devils Island Sandstone. Alternatively, the sinuous forms could be evidence of microbial mats that bound the sand in ephemeral pools and were wrinkled or deformed by flow before preservation.
Acknowledgements

I sincerely thank Clint Cowan, Tony Runkel, and Karen Havholm, for taking time to guide, instruct, and assist me during fieldwork. Thanks especially to Clint for making multiple visits to the outcrop, guiding me through fieldwork, research, and writing, and for helping me design and revise this study. I also thank the Carleton College Geology Department for funding my project, John Anderson for taking us to Sand Island in his boat, to Living Adventure Inc. for accommodating my summer fieldwork schedule, and to all the Carleton Geology faculty and staff for cheerful help and advice on many aspects of the study.
References


Hesse, R., 2009, Do swarms of migrating barchan dunes record paleoenvironmental changes? -- A case study spanning the middle to late Holocene in the Pampa de Jaguay, southern Peru: Geomorphology, v. 104, no. 3-4, p. 185-190.


