

ABSTRACT: The stratigraphic architecture of aeolian sandstones is thought to record signals originating from both autogenic dune behavior and allogenic environmental boundary conditions within which the dune field evolves. Mapping of outcrop-scale surfaces and sets of cross-strata between these surfaces for the Jurassic Page Sandstone near Page, Arizona, USA, demonstrates that the stratigraphic signature of autogenic behavior is captured by variable scour depths and subsequent fillings, whereas the dominant signatures of allogenic boundary conditions are associated with antecedent surface topography and variable water-table elevations. At the study area, the Page Sandstone ranges from 55 to 65 m thick and is separated from the underlying Navajo Sandstone by the J-2 regional unconformity with meters of relief. Thin, climbing sets of cross-strata of the basal Page representing early dune-field accumulations fill J-2 depressions. In contrast, the overlying lower and middle Page consist of cross-strata ranging from less than 1 to 15 meters thick (average 2.44 m), and packaged between outcrop-scale bounding surfaces, though parts of the lower Page are bounded from beneath by the J-2. These bounding surfaces have been previously correlated to highstand deposits of the adjacent Carmel sea and at this site possess up to 13 meters of erosional relief produced by dune scour. Notably absent in packages of cross-strata bounded by these outcrop-scale surfaces are strata of early dune-field accumulations, any interdune deposits, and climbing-dune strata. Instead, these packages preserve a scour-and-fill architecture created by large dunes migrating in a dry, mature, dune field undergoing negligible bed aggradation. Any record of early phases of dune-field construction for the lower and middle Page are interpreted to have been cannibalized by the deepest scours of later, large dunes. Interpretations are independently supported by the relatively large coefficients of variation \( (c_v) \) in middle Page set thicknesses \( (c_v = 0.90) \), which are consistent with set production by successive deepest trough scours, the relatively low coefficient of variation for the depression-filling basal Page and lower Page sets consistent with a significant component of bed aggradation in J-2 depressions \( (c_v = 0.64 \text{ and } 0.49) \), and the fit of set thickness distributions to established theory. Numerical modeling presented here and more completely in the companion paper demonstrates how this cannibalization of early-phase stratigraphy is an expected outcome of autogenic dune-growth processes, and that early-phase strata can be preserved within antecedent depressions. Relative rise of the inland water table from basin subsidence and changing Carmel sea level forced preservation of 5–6 stacked packages composed of scour-and-fill architecture. Without these allogenic forcings, the Page would be little more than an erosional surface.

INTRODUCTION

Aeolian dune fields develop over time as a result of autogenic processes that occur in a set of environmental (allogenic) boundary conditions. Autogenic processes inherent to a field of migrating dunes include dune interactions (Werner 1995; Coleman and Melville 1996; Ewing and Kocurek 2010a; Kocurek et al. 2010; Gao et al. 2015a), dune deformation with migration (Pedersen et al. 2015; Swanson et al. 2016), and dune scour of the substrate (Paola and Borgman 1991; Bridge and Best 1997). Common allogenic boundary conditions for aeolian systems include the presence or absence of a near-surface water table (Crabaugh and Kocurek 1993; Kocurek and Havholm 1993), direction and magnitude of sediment-transporting winds (Rubin 1987; Rubin and Hunter 1987; Ping et al. 2014; Swanson et al. 2017), sediment availability (Courrech du Pont et al. 2014; Gao et al. 2015b), and geometry of the sediment source and basin (Ewing and Kocurek 2010b).

The general trend in dune-field development is for many, small, closely spaced dunes to coalesce into fewer, larger, widely spaced dunes over time and across space through constructive dune interactions (Ewing and Kocurek 2010a; Eastwood et al. 2012; Gao et al. 2015a; Day and Kocurek 2018). Aeolian strata record these interaction kinematics (Brothers et al.}
In the companion paper (Swanson et al. this issue), numerical modeling of aeolian dune-field development shows that the growth phase of a dune field is consistently associated with the reworking of older deposits. This reworking is due to the increase in depth and depth variability of scouring in dune troughs associated with autogenic dune growth. The resulting strata are relatively discontinuous and composed of the fills of a sequence of deepest scours to move through a particular location. This scour-and-fill architecture records the autogenically dominated phase of dune-field development. We examined the Jurassic Page Sandstone near Page, Arizona, USA (Figs. 1A, 2), with detailed field mapping and topographic measurements. Sedimentary structures, stratal architecture, apparent relief on bounding surfaces, and quantitative analysis of set-thickness distributions are used to test the hypothesis that the Page sets of cross strata are dominated by a scour-and-fill architecture constructed by relatively large, mature dunes. Moreover, these later-phase...
dunes cannibalized most strata that may have accumulated during earlier phases of dune-field development and even scoured into underlying strata from previous constructional events. In spite of this scouring, the deposits of two early dune fields with their distinct cross-strata were found preserved in local, pre-existing topographic lows. We demonstrate that antecedent topography and the depth to water table were subordinate allogenic controls on the overall stratigraphic architecture of the Page Sandstone. Interpretations were aided by the numerical model of the companion paper (Swanson et al. this issue), which couples dune morphodynamics, stratigraphy, and allogenic boundary conditions. The modeling work presented here is the product of some unique parameters not explored in the companion paper.

**Geologic Context and Previous Work**

Jurassic aeolian formations of the Colorado Plateau are among the most studied aeolian sandstones in the world (Blakey et al. 1983, 1988; Rodríguez-López et al. 2014), and literature discussing the Page Sandstone is extensive. The Page Sandstone preserves a time series of NE–SW-trending dune fields situated between the Monument Upwarp and the Carmel inland sea (Blakey et al. 1988; Riggs and Blakey 1993; Peterson 1994) (Fig. 1A) during the middle Jurassic, 171.5 Ma to 169.5 Ma (Blakey and Parnell 1995; Dickinson et al. 2010). The Carmel Formation preserves a record of shallow marine, sabkha, and fluvial settings that intertongue with aeolian Page accumulations across a belt ~75 km wide that runs parallel to the paleocoastline (Havholm et al. 1993; Blakey et al. 1996; Taggart et al. 2010). Intertonguing of the Carmel coastal complex with the western part of the Page Sandstone has been interpreted to represent the interplay between tectonic subsidence in the Utah–Idaho trough, and changes in sediment supply and sea level (Blakey et al. 1996).

The Page Sandstone is separated from the underlying Navajo Sandstone by the J-2 surface, one of six regional unconformities formed across the greater Colorado Plateau during the Jurassic (Pipirigos and O’Sullivan 1978). The J-2 surface near Page, Arizona, is characterized by large polygonal fractures, diagenetic chert nodules, and meters of erosional relief (Pipirigos and O’Sullivan 1978; Kocurek and Hunter 1986; Swezy 1991; Kocurek et al. 1991). The Page is overlain by the Carmel Formation, representing eastward migration of the Carmel fluvial and coastal complex (Blakey et al. 1996).

Previous work has produced hundreds of correlated vertical sections across the entirety of the Page Sandstone (Havholm 1991; Kocurek et al. 1991; Havholm et al. 1993; Jones and Blakey 1993; Havholm and Kocurek 1994; Blakey et al. 1996). The Page has been informally divided into a basal, lower, middle, and upper unit by Havholm et al. (1993), and these divisions correlate with formal stratigraphic names used by Blakey et al. (1996) (Fig. 1B). The informal units were defined using formation-scale, erosional bounding surfaces. These surfaces are characterized by polygonal fractures, interpreted as having developed in evaporite-cemented sand, and/or overlying wavy bedding interpreted as sabkha deposits (Kocurek and Hunter 1986; Havholm et al. 1993; Havholm and Kocurek 1994). Together these features have been used as proxies for the paleo-water table (i.e., “Stokes surfaces” of Fryberger et al. 1988; “super surfaces” of Kocurek 1988). Each of these surfaces can be traced westward to a point where they are overlain by transgressive tongues of Carmel strata (Havholm et al. 1993; Havholm and Kocurek 1994; Blakey et al. 1996) (Fig. 1B). Because these transgressive tongues represent relative high stands of the Carmel sea and their corrrelative inland surfaces are marked by features associated with the water table, the formation-scale surfaces are interpreted to define the elevation of the coastal water table, which rose in response to the adjacent sea-level rise (Havholm and Kocurek 1994; Blakey et al. 1996; Kocurek et al. 2001). The surfaces themselves are interpreted as having been formed by deflation down to the water table during relative high stands in sea level when sediment availability was limited. Conversely, the Page dune systems are thought to have developed during low stands in sea level that afforded greater availability to coastal sand. Each package of Page strata bounded by the interpreted deflationary surfaces is therefore inferred to represent an aeolian sand body accumulated during a low stand and preserved as a consequence of a rising continental water table that protected it from wind-blown deflation. The thickness of any preserved accumulation reflects the cumulative effects of subsidence and relative sea-level rise, as reflected in the continental water-table paleo-elevation (Havholm and Kocurek 1994; Blakey et al. 1996).

There is now consensus that episodic change in paleo–water table elevation represented a changing allogenic boundary condition of the Page dune fields (Havholm et al. 1993). What is not fully known, however, are the signatures of autogenic processes versus allogenic forcings recorded by the stacked sets of cross-strata housed between the major transgressive surfaces. Its well-documented paleo-environmental context, together with the excellent 3-D exposures accessible around Page, Arizona, make the Page Sandstone an ideal unit for the study of the autogenic processes and allogenic forcings encoded in aeolian stratigraphy.

**Aeolian Stratification Types**

Aeolian cross-strata are composed of grainfall, grainflow, and wind-ripple deposits (Hunter 1977). Grainfall deposits accumulate when a
significant fraction of saltating grains bypass the dune brink and rain down onto the lee faces of dunes. Grainfall deposits are typically thickest immediately downwind from the brink, and they thin with distance down the lee face. Because of this thickness distribution, the uppermost lee slope progressively steepens until the angle of initial yield is reached, triggering an avalanche, or grainflow (Allen 1970a; Hunter 1977; Kocurek and Dott 1981; McDonald and Anderson 1995; Nield et al. 2017) that redistributes sediment down the lee face of the dune. Grainflows and their deposits occur primarily along parts of the lee face aligned close to perpendicular to the sediment-transporting wind direction (Eastwood et al. 2012). Both grainflow and grainfall deposits are commonly reworked by wind-ripples that migrate along lee-face segments obliquely oriented to the regional wind direction (Eastwood et al. 2012) and in the process generate wind-ripple laminae (Hunter 1977).

Aeolian cross-strata are commonly composed of alternating packages of grainflow deposits and wind-ripple laminae, representing seasonal changes in wind direction and/or changes in dune shape and crest orientation (Hunter and Rubin 1983). Because aeolian sets of cross-strata typically represent only the basal parts of dune lee faces, grainfall deposits are less frequently preserved in sets representing large dunes (Kocurek and Dott 1981). Grainfall deposits are, however, common in cross-strata representing small dunes, where the grainfall apron extends to the bases of dunes (Kocurek and Dott 1981).

**Aeolian Set Architecture**

The architecture of aeolian sets of cross-strata present between outcrop-scale bounding surfaces preserve a record of dune-field kinematics. Schematic illustrations of set architectures are shown in Figure 3A–C (based on diagrams from Allen 1970b; Rubin and Hunter 1982). In cases where trains of migrating dunes climb over the accumulations of downwind dunes, set boundaries are expected to originate from a lower, outcrop-scale bounding surface and climb at some measurable angle (Fig. 3A). In cases where sets are migrating down into and in the process filling

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**Fig. 3**—Schematic showing A) climb, B) downlap, and C) scour-and-fill architectures of aeolian cross-sets. The black arrow at the top indicates that paleo-transport is from left to right in each case. Cross-strata, set boundaries, and outcrop-scale bounding surfaces are all indicated and consistent between diagrams. A moderate vertical exaggeration is used to accentuate boundary dips. Schematics are based on illustrations from Allen (1970b) and Rubin and Hunter (1982).

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**Fig. 4**.—Excerpt of the perpendicular-to-transport wall of the Ferry Swale cross section (Fig. S1). Location shown in Figure 2. There is no vertical exaggeration. Outcrop-scale bounding surfaces are represented by bold black lines separating outcrop-scale packages of cross-strata of different colors. Black lines in outcrop-scale packages represent cross-set bounding surfaces. Dipping gray lines represent the apparent dip direction of the mean Page transport direction. Colors are used to identify packages of cross-strata separated by outcrop-scale surfaces, and the colors do not necessarily represent correlations between outcrops. The major surfaces are S-up, S-rm, S-jh, and S-b from Havholm et al. (1993). Informal Page units are composed of one to several outcrop-scale packages separated by the outcrop-scale surfaces, and are labeled as in Havholm et al. (1993): PB (basal Page), PL (lower Page), PMm (middle middle Page), and PUI (lower upper Page). The PUI, colored peach, is composed of compound-dune deposits, and are not studied here. The basal Page (PB) is preserved above the J-2 at this location, and pinches out toward the east (Fig. 5). It is not uncommon for an outcrop-scale package to be composed of one to a few sets, and to vary in number of sets and set thickness laterally. Outcrop-scale bounding surfaces have meters of relief at this location. The width of a scallop in outcrop-scale bounding surface relief is demonstrated with white double-headed arrow.
pre-existing topographic lows, the architecture is defined by set boundaries
that originate from an upper, outcrop-scale bounding surface and descend,
ultimately downlapping onto a lower, outcrop-scale bounding surface that
hosts the antecedent topographic low (Fig. 3B). Finally, in cases where
variable depth of trough scouring creates space that is later filled by smaller
dunes in the train, sets boundaries persist for limited distances before being
cut out by other set boundaries rather than by outcrop-scale bounding
surfaces (Fig. 3C).

The architecture or geometries of set boundaries are not the only data
type used here to reconstruct the filling history. Distributions on set
thickness also contain information on how the stratification formed (Paola
and Borgman 1991; Bridge 1997; Bridge and Best 1997; Jerolmack and
Mohrig 2005; Ganti et al. 2013). In particular, distributions of cross-strata
produced by the scour-and-fill process (Fig. 3C) record an asymptotically
high value for the coefficient of variation (standard deviation divided by
the mean) of set thicknesses, while sets produced during net bed
aggradation (both the climbing and downlapping cases in Fig. 3A, B)
have distinctly smaller values for the coefficient of variation associated
with set-thickness distributions (Jerolmack and Mohrig 2005).

METHODS

Field Work

Three outcrops in and near Page, Arizona, were selected based on their
accessibility and orientation relative to the paleo-transport direction
determined from a measured distribution of cross-strata dip directions
(Fig. 2). The Ferry Swale outcrop was split into two sections, one segment
oriented perpendicular to the general dune migration direction and the
other oblique to the dune migration direction. The Manson Mesa and Golf
Course sections were oriented roughly parallel to the transport direction.
Cross-strata set boundaries and outcrop-scale bounding surfaces were
surveyed using a total station at each outcrop location. A coordinate was
recorded at each base station using GPS so that all surveyed points could
be converted to UTM coordinates. Each outcrop-scale erosional surface
was then correlated with vertical sections from Havholm (1991). In
addition to mapping surfaces, 90 measurements of foreset dip direction
were taken using a Brunton compass and averaged with the Circular
Statistics Toolbox in MATLAB (Berens 2009). Thicknesses of 124 cycles
of wind-ripple and stacked grainflow strata were collected from cross-
strata. All of these measurements were collected from the basal Page (PB),
lower Page (PL), and middle middle Page (PMm) intervals of the Page
Sandstone (Fig. 1B). For simplicity, we will refer to the middle middle
Page as the middle Page. These divisions make up the strata bounded by
the underlying J-2 and overlying S-rm surfaces (Fig. 1B). The upper Page,
unit PU1 of Figure 1, is composed of sets of compound-dune cross-strata
that are distinctively different from those of the underlying units and are
not part of this study.

Data Processing

Combining field maps with GPS datums and annotated total-station points,
a digital GIS project including all of the outcrop locations was
constructed. Continuous topographic surfaces were interpolated from point
data defining each outcrop-scale bounding surface and cross-strata set
boundary using a Kriging method that completely preserves input data.
The spatial resolution for resulting digital elevation models (DEMs) at
Manson Mesa, the Golf Course, and Ferry Swale was 0.55 m, 0.65 m, and
2 m, respectively.

Using the GIS, vertical stratigraphic sections were constructed at 20
m intervals across each outcrop. The 3-D mapping data allowed
surfaces in each cross section to be accurately correlated. Measure-
mments of set thickness and outcrop-scale bounding-surface relief were
made from the generated cross sections. Set geometry and its
relationship to the nearest bounding surface were also categorized
from the cross sections (Fig. 3).

Numerical Modeling

Swanson et al. (this issue) numerically model the production of cross
strata by coupling bed topography with bed shear stress and sediment
transport for long trains of aeolian dunes. Using this model, synthetic
stratigraphy hosting several outcrop-scale bounding surfaces has been
created in a 2-D panel. Observations from scenarios producing this
synthetic stratigraphy are compared to outcrop interpretations (model
parameters in Table S1.) To create the synthetic Page stratigraphy, a
Dune field and its accumulations are developed for a set period of time during which an initial rough surface develops into small, early-phase dunes, which develop into larger, more mature dunes. Following that time, the upwind sediment supply is cut off and erosion is limited to an elevation above the initial surface, causing a relatively flat outcrop-scale bounding surface to develop where the dune field had been. Re-establishment of the upwind sand supply promoted development of another dune field and its accumulations on top of this outcrop-scale bounding surface. In total, four episodes of aeolian accumulation are modeled in this scenario. This particular set of boundary conditions was...
set up to answer Page-specific questions not addressed in the companion paper (Swanson et al. this issue), demonstrating the flexibility of the numerical model.

RESULTS

Outcrop-Scale Architecture

At the three outcrops (Figs. 4, 5, S1–S3) the Page Sandstone is composed of packages of aeolian cross-strata partitioned by the formation-scale surfaces of Havholm et al. (1993). In the studied interval spanning from the J-2 to the S-rm surfaces (Fig. 1), the Page ranges from 25 to 45 m and is composed largely of meter-scale beds of cross strata in the lower and middle Page (Fig. 6A), with local preservation of thinner sets in the basal Page (Figs. 7A, 8A–D). The lower Page consists of a single coset that either sits above the basal Page or directly on the J-2 surface. It is observed primarily at the Ferry Swale outcrop (Figs. 4, 5, S1), with minimal exposure at Manson Mesa (Fig. S2) and no exposure at Golf Course (Fig. S3). In addition to the formation-scale surfaces that define the informal

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**Fig. 7.**—A) Close-up of the basal Page sets of cross-strata at the Golf Course outcrop. White arrows point to set-bounding surfaces. The black arrow points to a reactivation surface in the set, representing a period of lee-face erosion bounded by packages representing lee-face deposition. The deposit is composed of sets averaging 0.16 m in thickness with individual grainflow deposits separated by thin, tabular beds interpreted as grainfall deposits. The location of Part B is shown with the white box. Pencil for scale. B) A zoom in to part of Part A. Unlike the lower and middle Page sets, individual grainflow deposits are identifiable. Black arrows point to the bottoms of grainflow deposits featuring the characteristic blade shape. Finer-grained grainfall deposits are labeled between and at the bases of grainflows, and help distinguish the coarser-grained grainflow deposits. C) Plot comparing the means (circles) and the standard deviations (bars) of thicknesses of individual grainflow deposits in the basal Page with grainflow packages in the lower and middle Page. The standard deviation of individual grainflow deposits in the basal Page is below the size of the circle.
Page units, Havholm et al. (1993) identified less-continuous surfaces that are typically truncated laterally. For this study, the term "outcrop-scale bounding surface" refers to both the formation-scale and less-continuous super surfaces identified by Havholm et al. (1993).

**Outcrop-Scale Bounding Surfaces**

Figures 4, 5, and S1–S3 present the structure of the outcrop-scale bounding surfaces surveyed at the three outcrop locations (Fig. 2). The J-2 surface is characterized by wedge-shaped fractures into the underlying Navajo Formation, pebble-size, diagenetic chert nodules replacing evaporites in the uppermost Navajo strata, and up to 10 m of local erosional relief (e.g., Ferry Swale; Fig. S1). The outcrop-scale bounding surfaces in the lower and middle Page also preserve erosional relief that varies between 1.2 m and 13.5 m (Fig. 9A). On both walls of the Ferry Swale outcrop (Figs. 4, 5), this relief has a scalloped geometry. Horizontal distances from the adjacent high points on either side of a scallop were measured on the western, perpendicular-to-transport wall (Fig. 4). The widths of sets filling these scallops were measured on the same wall as the horizontal distance between pinchouts. Scallop widths (n = 23) have a mean value of 72 m and a standard deviation of 34 m. Sets filling these scallops (n = 33) have a similar mean width of 64 m and a greater standard deviation of 81 m.

Outcrop-scale bounding surfaces are commonly associated with two unique deposit types. Wavy-laminated sandstones with variable thicknesses ranging up to 0.4 m occur discontinuously along outcrop-scale bounding surfaces in the lower and middle Page (Fig. 10A–D). In the basal Page, the wavy-laminated sandstones were identified both overlying the J-2 surface and in between aeolian cross-sets, and these strata are generally thicker and more continuous than in the higher Page units. As a whole, the red, wavy-laminated strata have been interpreted as sabkha deposits that formed along surfaces deflated to the near-surface water table (Havholm et al. 1993; Havholm and Kocurek 1994). The second deposit type associated primarily with outcrop-scale bounding surfaces are prominent, wedge-shaped fracture fills. In exposures that provide cross-sectional views, the fractures crosscut sets of cross-stratified sandstone (Fig. 11A–C). These fractures narrow downward, although not always in a linear fashion. In plan view, the fracture fills take a more polygonal shape (Fig. 11A). Sandstone fill within the fractures is vertically laminated or structureless (Fig. 11B, C). The tops of the wedges end against outcrop-scale bounding surfaces. These sandstone wedges have been interpreted as sand-filled, evaporite-cemented thermal contraction polygonal fractures (Kocurek and Hunter 1986).

**Cross-Set Architecture**

The outcrop-scale bounding surfaces truncate and bound packages of cross-stratified beds, referred to hereafter as "outcrop-scale packages." In these packages, individual sets of cross-strata are defined by upper and lower set boundaries that are less continuous than the outcrop-scale...
surfaces. The architecture of outcrop-scale packages varies between the
basal, lower, and middle Page.

**Basal Page Architecture.**—The thin sets of cross-stratified sandstone
(Fig. 7A, B) are relatively uncommon and limited to the basal Page at the
outcrops studied. Set thicknesses range from 0.03 to 0.45 m with a mean of
0.16 m and a standard deviation of 0.10 m (Fig. 12A, B; n
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**Basal Page Architecture.**—The thin sets of cross-stratified sandstone
(Fig. 7A, B) are relatively uncommon and limited to the basal Page at the
outcrops studied. Set thicknesses range from 0.03 to 0.45 m with a mean of
0.16 m and a standard deviation of 0.10 m (Fig. 12A, B; n = 80). Individual
grainflow deposits are well defined by their characteristic blade shape and
are separated by millimeters-thick grainfall deposits (Fig. 7B). Alternating
grainflow and grainfall deposits characterize the cross-stratification in these
sets. The mean grainflow deposit thickness is 18 mm with a standard
deviation of 0.79 m (n = 36).

In contrast to the lower and middle Page, the sets of the basal Page are
stacked tens of sets high to form packages several meters thick. This
architecture occurs at Ferry Swale and north of the Golf Course outcrop
(Figs. 8A–D, 13). At the Ferry Swale outcrop, these thin sets are located
filling a local J-2 depression (Fig. S1 shows full J-2 topography at Ferry
Swale). North of the Golf Course outcrop, basal Page sets probably also fill
depressions of a few meters across the J-2 surface, but the contact with the Navajo is not
exposed. At both locations, these packages of stacked, thin sets are laterally
scoured and filled by thicker sets of the lower Page (Figs. 8A–D, 13). The
stacked, thin sets of the basal Page are the focus of our comparison
between the basal Page and the lower and middle Page. Parts of the basal
Page consisting of alternating sabkha and cross-set deposits (Havholm et
al. 1993) were not analyzed here.

**Lower and Middle Page Architecture.**—The predominant facies
composing the lower and middle Page at all three sites (Fig. 2) are thick
sets of cross-stratified sandstones (Fig. 6A) consisting of stacked grainflow
strata separated by intervals of wind-ripple laminae (Fig. 6B). Individual
grainflow deposits could not be distinguished, but rather amalgamations of
many grainflow deposits were observed. Where grainflow cross-strata do not
extend to the base of the set, lower-angle wind-ripple strata were found
(Fig. 6C). The lower Page has a mean set thickness of 1.61 m and a
standard deviation of 0.79 m (n = 59; Fig. 12A, C). Sets of cross-strata
from the middle Page are on average 2.44 mm thick, and occasionally exceed
10 m. The standard deviation of set thicknesses is 2.20 m (n = 402; Fig.
12A, D). In both the lower and middle Page, the thickness of individual
sets is laterally variable at the outcrop scale (Figs. 4, 5), because sets are
typically truncated by adjacent sets of cross-strata, limiting their lateral
continuity (Fig. 14A, B). The thicknesses of amalgamated grainflow
deposits were measured from several sets of these cross-strata (e.g., Fig.
6B), and range from 0.01 to 1.30 m with a mean and standard deviation
both equal to 0.19 m (n = 124; Fig. 7D). Ninety measurements of foreset
dip direction were taken from this facies and serve as a proxy measurement
of paleo-transport direction. The mean of these measurements is 143° with a
standard deviation of 42°.

The number of sets stacked between outcrop-scale surfaces at any
vertical section of the lower and middle Page ranges from 1 to 5 (Figs. 4, 5,
S1–S3). There is not a strong correlation between the number of stacked
sets and section thickness (Fig. 9B). There is, however, a strong correlation
between the thickness of an outcrop-scale package and the total relief

**Fig. 9.—A quantification of set architecture composing outcrop-scale packages.**
A) Total relief along an outcrop-scale bounding surface plotted against
the maximum thickness of the outcrop-scale package above the measured surface. The
linear fit is significant with a positive slope of
0.87, indicating that basal relief controls the
preserved thickness of the package. B) The
number of sets bounded by adjacent outcrop-scale
bounding surfaces at a given location plotted
against the thickness of the package at that same
location. The best-fit linear trend is not signifi-
cant, indicating that the number of sets does not
control the package thickness. C) Climb angle
plotted against the contribution of variable scour
to the mean set thickness based on the coefficient
of variation of dune height (\(c_{\text{DUNES}}\)). Colored
lines represent dune-height coefficients of varia-
tion. At low climb angles, variation in dune height
and the consequent variation in dune scour depths
are a dominant control on mean set thickness. An
increase in climb angle and/or a decrease in the
standard deviation of dune sizes decreases the
effect of variable scour on mean set thickness.
The fraction of set thicknesses attributed to variable
scour depth is calculated for White Sands based
on information in Baitis et al. (2014). Calculated
from Bridge and Best (1997) using mean height
and celerity values of dunes at White Sands
(Baitis et al. 2014).
FIG. 10.—A) Wavy-laminated to contorted sandstone beds interpreted as sabkha deposits. Pen for scale. B) Black arrow points to a thick sabkha deposit along an outcrop-scale bounding surface separating sets of cross-strata. Associated polygonal fractures are visible in the background (white arrows). C) An outcrop-scale bounding surface with variably thick sabkha deposits. White arrows show the locations with the thickest sabkha deposits. Thickness thins to zero at the person. Black arrows point to polygonal fractures associated with the outcrop-scale bounding surface. From the Ferry Swale outcrop. D) An outcrop-scale bounding surface with a laterally discontinuous set of cross-strata incorporated into a sabkha deposit (outlined in dashed white lines). White arrows point to the ends of the set of cross-strata. This is an unusual outcrop, and observed only at this location at the Ferry Swale outcrop. Yellow field book for scale.
Results of Numerical Modeling

Several observations provided by results from the numerical model are particularly relevant for interpreting the Page strata (Fig. 16). Firstly, the four episodes of aeolian accumulation modeled in this scenario produce four distinct packages of cross-sets separated by domain (outcrop)-scale bounding surfaces. Secondly, the relief along the modeled outcrop-scale bounding surfaces develops coevally via dune scouring with the development of the dune field during each phase of aeolian sedimentation. Thirdly, this relief is filled with the accumulations of the relatively late-phase dunes associated with the creation of the scour relief. Fourthly, except for antecedent topographic lows sequestering accumulations beneath the trough-scouring depths of late-stage dunes, there is almost no preservation of strata representing the early phases of the dune fields.

DISCUSSION

Interpretation of Cross-Strata

The thin sets of cross-strata of the basal Page are interpreted to represent dunes significantly smaller than those that gave rise to the sets of the lower and middle Page. The thin (mean = 0.16 m, n = 80) sets of the basal Page are characterized by thin grainflow strata (Fig. 7C; mean = 17.6 mm, n = 37) separated by grainfall deposits (Fig. 7B). Although the relationship between grainflow deposit thickness and dune height may be modified by factors other than dune height (McDonald and Anderson 1995; Nickling et al. 2002; Nield et al. 2017; Cornwall et al. 2018), consistently thin grainflow strata are characteristic of small dunes. Moreover, the common presence of grainfall deposits between grainflow strata indicates smaller dunes where grainfall deposits of observable thickness extended to the base of the set (Hunter 1977; Kocurek and Dott 1981).

Several observations indicate that the lower and middle Page sets are the deposits of much larger dunes. Firstly, these sets are on average an order of magnitude thicker (Fig. 12A–D; lower Page mean = 1.61 m, n = 59, middle Page mean = 2.44 m, n = 401) than those of the basal Page (0.16 m, n = 80). While we acknowledge that relationships between dune height and set thickness is complicated by dune deformation and kinematics (e.g., Ganti et al. 2013), numerical modeling that accounts for both has shown a correlation between set thickness and dune height (Jerolmack and Mohrig 2005). Secondly, the absence of grainfall deposits in the lower and middle Page sets (Fig. 6B, C) is suggestive of larger dunes where significant grainfall seldom reaches basal lee faces (Hunter 1977; Kocurek and Dott 1981). Thirdly, the sets of the lower and middle Page show alternating grainflow and wind-ripple strata (Fig. 6B, C), as described in detail in Kocurek et al. (1991). This alternation of stratification types is commonly interpreted as seasonal cycles reflecting varying wind directions (Hunter and Rubin 1983). Large dunes formed with an abundant sand supply are oriented to the gross bedform-normal transport direction over a year (e.g., Rubin and Hunter 1987; Swanson et al. 2016), such that not all seasonal winds are transverse to the long-term crestline orientation. Repetitive packaging characteristic of multiple transporting wind directions is absent in sets of the basal Page, which is interpreted to represent dunes small enough to completely reorient their crests with each seasonal change in the wind regime (e.g., bedform response time is shorter than wind-direction cycles; Rubin and Hunter 1987; Ewing et al. 2015). Of course, this
FIG. 12.—A) Comparison of the cumulative distribution functions (CDFs) of the basal, lower, and middle Page set thicknesses, along with statistical moments. Basal sets are much thinner, and middle Page sets cover a much wider range than the lower and basal Page. B–D) Probability density histograms showing set thickness distributions of the basal (Part B), lower (Part C), and middle (Part D) Page.

FIG. 13.—Location featuring a topographic depression in the J-2 surface at Ferry Swale, and a later partial scouring of early-phase basal Page accumulations (Fig. S1). The J-2 is mapped with a thick gray line, separating the Navajo from the basal Page. Scour surfaces bounding thick grainflow deposits are mapped with black lines. Black arrows show cross-strata dip directions. The stacked thin sets shown in Figure 8C and D are labeled, and are truncated by a scour into the S-b surface, which separates the basal and lower Page, dipping towards 120°, shown by the white arrow. Adjacent grainflow strata dip toward 70°. Wind-ripple strata dip towards 260° and 255°, nearly 180° different from the grainflow strata and over 100° different from the regional average transport direction. The center location is interpreted as the deepest part of a lower Page scour into the S-b surface that partially cannibalized early-phase basal Page.
comparison assumes that wind regimes were similar over the basal, lower, and middle Page dune fields, and that antecedent topography on the J-2 surface did not significantly steer winds.

Dune fields begin as collections of protodunes that interact during migration and grow into larger dunes (e.g., Werner 1995; Ewing and Kocurek 2010a; Swanson et al. 2017). Therefore, the relatively small dunes associated with the deposition of the basal Page sets are interpreted to represent an earlier phase of dune-field development when compared to the dune fields that produced the larger sets of the lower and middle Page. Significantly, there are no preserved strata from a comparably early phase of dune-field development in the lower and middle Page. This is consistent with modeling results from Swanson et al. (this issue) which predict the complete reworking of early-phase strata. An exception to this rule is early-phase strata sequestered in antecedent depressions (Fig. 16).

Stratigraphic Architecture and Outcrop-Scale Bounding-Surface Topography

Architecture Preserved in Antecedent J-2 Topography.—The J-2 regional surface represents regional erosion (Pipiringos and O’Sullivan 1978), and the relief on this surface in the Page area is not interpreted to be a product of dune scouring linked to the troughs of migrating Page dunes. Rather, J-2 topography is interpreted as antecedent to the development of the Page depositional system. Depressions along this surface had a measurable effect on the architecture of the Page Sandstone by providing local accommodation space for sabkha deposits, packages of wind-ripple strata (Kocurek et al. 1991; Havholm et al. 1993), and local, shallow-pond deposits (Swezey 1991). Antecedent J-2 depressions of up to 10 m are also filled by stacks of thin cross-sets of the basal Page (Fig. 8A–D). These deposits are thought to have aggraded there owing to local wind deceleration moving into the depression. At a location where the lower Page sits directly above the J-2 surface, the lower Page is observed to thin towards an antecedent topographic high, where it is composed of three to five stacked sets (Figs. 5, S1). Although these lower Page sets do not represent sedimentation by an early dune phase, we hypothesize that J-2 topography nonetheless controlled accumulation of the lower Page, as it did the basal Page. This hypothesis is quantitatively tested later in the Discussion section.

The antecedent relief of the J-2 surface prevented full reworking of the early-phase dune strata by later, deep-scouring larger dunes (Fig. 8A–D), as predicted by the numerical model (Fig. 16). Even so, packages of thin sets were partially scoured during reactivations of the Page dune fields and later filled by thicker sets of cross-strata. At Ferry Swale, scouring into the basal Page (Fig. 8C, D) formed a large depression that was later filled by strata from at least two sides (Fig. 13). Near the Golf Course outcrop, several meters of stacked, thin sets of the basal Page were laterally truncated by a thick set of lower Page (Fig. 8A, B). Although this section of basal Page was probably also formed in a J-2 depression, the J-2 surface is locally covered. Aggradation of early phases of Page dune fields may have occurred beyond any localized J-2 depressions, but ultimately, as dunes grew in size, these accumulations would have been completely cannibalized (Swanson et al. this issue).
Scour-and-Fill Architecture and Coeval Development of Relief on Outcrop-Scale Bounding Surfaces.—Several lines of evidence support a scour-and-fill type architecture (Fig. 3C) for the middle Page, including set geometry, set dimensions, outcrop-scale boundingsurface topography, and the distribution of set thicknesses. The most common set geometry is the scour-and-fill type (Fig. 15). This is confirmed with the lack of a predictive relationship between local outcrop-scale package thickness and the number of stacked sets (Fig. 9B). A better correlation is expected in an aggradational scenario (Fig. 3A, B). In the perpendicular-to-transport exposure at Ferry Swale (Fig. 4), the similarity in width of both aggradational scenario (Fig. 3A, B). The dominance of scour-and-fill set architecture and scoured outcrop-scale bounding surfaces throughout the middle Page Sandstone suggests very low climb angles such that the succession of deepest trough-scouring depths are the predominant control on set thickness (Fig. 9C; Paola and Borgman 1991; Bridge and Best 1997). This interpretation can be tested using relationships first established in Paola and Borgman (1991) and further generalized by Bridge and Best (1997) and Leclair et al. (1997). Mean set thickness, $s_m$, is a function of climb angle ($\delta$), dune spacing ($l$), mean dune height ($h_m$), and the standard deviation of dune heights ($h_s$): $s_m = l \tan(\delta) + 0.8225(h_s^2/h_m)$ (1)

In Equation 1, $l \tan(\delta)$ describes the part of mean set thickness due to climb (Allen 1970b; Rubin and Hunter 1982) and its associated net bed aggradation. The second term, $0.8225 (h_s^2/h_m)$, describes the part of mean set thickness produced by variability in dune size and thus, variability in scour depth as predicted by Paola and Borgman (1991). In the case of zero aggradation ($\delta = 0$), $s_m$ is only a function of variability in dune size: $s_m = 0.8225(h_s^2/h_m)$ (2)

Both Paola and Borgman (1991) and Bridge and Best (1997) note that with a climb angle of zero and gamma-distributed bedform heights, the standard deviation of set thicknesses ($s_m$) is: $s_m = 0.725(h_s^2/h_m)$ (3)

Equations 2 and 3 can both be rearranged to solve for $h_s^2/h_m$, yielding $s_m/s_m = c_{SETS} = 0.88$ (4)

where $c_{SETS}$ is the coefficient of variation for an exponential distribution of set thicknesses. Because we have connected the dominance of scour-and-fill style sedimentation with a lack of significant aggradation using other arguments, the hypothesis is that Equation 4 should hold true for the lower and middle Page Sandstone assuming that Page trough elevations were gamma distributed. It should be noted that Equation 4 is particularly useful in analyses of paleo-systems because it only requires measurements of set thicknesses that can be directly acquired in the field.

Using 402 measurements of thickness for sets of cross-strata preserved in the middle Page yield an $s_m = 2.44$ m and $s_s = 2.20$ m (Fig. 12). Their $c_{SETS}$ is 0.90, which is very close to the predicted 0.88 value of Equation 4. Importantly, the measured value is slightly greater than the predicted value, and within the bounds of a system dominated by variable trough depths (0.88 ± 0.3; Bridge 1997). Numerical experiments by Jerolmack and Mohrig (2005) revealed that a $c_{SETS}$ of 0.90 was associated with a climb angle of less than one-thousandth of a degree, essentially zero. Jerolmack and Mohrig (2005) also found that the incorporation of significant climb...
acted to reduce the $c_{v\text{-SETS}}$ value down to a point where it could be a small as $c_{v\text{-DUNES}}$, the coefficient of variation of formative dune heights ($h_r/h_m$). In contrast to the middle Page, the stacked sets of the basal Page have an $s_m = 0.16 \text{ m}$ and $s_r = 0.10 \text{ m}$, yielding a $c_{v\text{-SETS}}$ of 0.64. This value is consistent with numerical experiments that had a climb angle of 0.5 to 1$^\circ$ (Jerolmack and Mohrig 2005). The lower Page, which also sits directly above the J-2 in some locations (Fig. 5) has a $s_m = 1.61 \text{ m}$ and $s_r = 0.79$, with a $c_{v\text{-SETS}} = 0.49$. This $c_v$ has been found to be associated with climb angles that have ranged between 1 to 6$^\circ$ (Jerolmack and Mohrig 2005).

The theory of Paola and Borgman (1991), which has been subsequently built on by Bridge and Best (1997) and many others, takes as fact that the distribution of scouring topography can be accurately characterized using a two-parameter gamma distribution. While this distribution has been shown to hold for a variety of fields of bedform topography (e.g., Paola and Borgman 1991; van der Mark et al. 2008; Ganti et al. 2013), it is important to evaluate the likelihood of it being an accurate descriptor for the ancient Page system. Fortunately, the preserved strata directly provide data necessary to test the applicability of the stratification theory. Jerolmack and Mohrig (2005) demonstrated that as climb increases, the distribution of set thicknesses moved away from an exponential distribution characterizing set production by scouring only to unimodal, positively skewed gamma distributions with shapes inherited from the height distributions of the formative dunes. We can therefore use the structure of the set distributions themselves both to test the applicability of the modified theory and to test of the question of scour-and-fill versus aggradation. We have used the $\chi^2$ goodness-of-fit tests at a .05 significance level to test the best-fit exponential and two-parameter gamma distribution for the distribution of sets from the basal, lower, and middle Page. The data can be visually compared to fitted curves as cumulative distribution functions (CDFs) and probability distribution functions (PDFs) in Figure 18A and B. The basal Page is rejected as exponential ($p = 0.02$), but the gamma fit is not rejected ($p = 0.21$). Similarly, the lower Page is rejected as exponential ($p < 0.001$), but the gamma fit is not rejected ($p = 0.34$). Both of these results are consistent with sets being generated under the presence of net bed aggradation, which we have shown can be attributed to the filling of antecedent J-2 topography with basal (Fig. 8A–D) and lower Page strata.
similar set width and scour width (lower and middle Page) 

smaller set width than scour width (basal Page)

**FIG. 17.**—Schematic diagram showing the relationship between the scale of scour troughs (thicker lines) and the scale of filling sets (thinner lines). In the lower and middle Page, where scours are coeval with dune migration, set width and scour width are similar. In the basal Page, where scours pre-date the dune field, the scales are not similar. The circles with center dots show that both diagrams show perpendicular-to-transport views.

(Figs. 5, S1). In contrast, the best-fit exponential function is not rejected for the middle Page sets (p = 0.49), and, in fact, the exponential and gamma distributions are visually very similar, because at higher values for $c_v$-SETS the two-parameter gamma distribution yields an exponential shape. This exponential fit is taken as confirmation for the absence of climb in the middle Page, and the production of stratigraphy through successive scouring of the bed by migrating dunes.

To further demonstrate the universality of set thickness statistics in analyses of aeolian strata, the method was applied to set-thickness measurements from the nearby Jurassic Entrada Sandstone, a type example of an aggradational dune field with measurable positive climb angles (Crabaugh and Kocurek 1993; Kocurek and Day 2018). Thicknesses of 37 Entrada sets were taken from two vertical sections from Figure 2 of Kocurek and Day (2017, one characterized by downlapping sets filling a depression, and the other by climbing sets. For the Entrada, $s_m = 2.10$ m, $s_d = 0.96$ m, and $c_v$-SETS = 0.46. This ratio value suggests sufficient aggradation such that $c_v$-SETS more closely reflects $c_v$-DUNES (Jerolmack and Mohrig 2005) rather than Equation 4. This is again supported by the statistical rejection of an exponential fit (p < 0.001) and the non-rejection of a gamma fit (p = 0.16). Indeed, Kocurek and Day (2017) interpret the Entrada strata as including a component of alloegenically forced bed aggradation.

**Reconstruction of the Middle Page Dune Fields**

Reasonable approximations of a gamma distribution of bedform heights of the middle Page can be calculated using set-thickness measurements and a few simple assumptions about the formative dune field. The two parameters defining a gamma distribution, $\alpha$ and $\beta$, are functions of the mean ($h_m$) and standard deviation ($h_s$) of the population, in this case dune heights:

$$x = h_m^2/h_s$$

$$\beta = h_s^2/h_m$$

The numerical experiments of Jerolmack and Mohrig (2005) show that, in the zero bed aggradation case,

$$h_m = s_m/0.4$$

Although $h_m$ is not directly measurable with the available data, it can be estimated using assumptions about the coefficient of variation of middle Page dune heights ($c_v$-DUNES):

$$h_s = c_v$-DUNES * $h_m$$

We generate three distributions of middle Page dune heights using low, medium, and high estimates of the middle Page $c_v$-DUNES informed by modern dune fields. White Sands dune field has a $c_v$-DUNES of 0.28 (Baitis et al. 2014). Using Shuttle Radar Topography Mission elevation data (image number N32W116), we calculate a $c_v$-DUNES at Algodones dune field, California, of 0.45 (n = 52), and use this as a middle value. A high-end estimate is constructed with $c_v$-DUNES = 0.60, a value observed in fluvial dune fields (e.g., Trinity River, Texas: $c_v$-DUNES = 0.68: Mason and Mohrig in review).

The three gamma curves are compared to the exponential set-thickness curve in Figure 19. Note that the low-$c_v$-DUNES scenario rapidly approaches a probability density of 0 at 12 m, while the other distributions have longer tails. The low $c_v$-DUNES scenario is unlikely to create dunes higher than the thickest observed sets. The near-surface water table at White Sands (Kocurek et al. 2007) is likely preventing significant dune scour, thus limiting dune heights and $c_v$-DUNES. We hypothesize that a low $c_v$-DUNES is a common dune-field response to a near-surface water table. Assuming this hypothesis to be correct, the inconsistencies between the low-$c_v$-DUNES model and the observed set thicknesses are additional evidence of a lack of a near-surface water table in the middle Page dune fields.

**Role of Autogenic vs. Allogenic Controls on the Page Preserved Record**

Autogenic processes of dune scour-and-fill alone will not result in the preservation of stacked multiple dune constructional periods that represent the Page Sandstone. Indeed, without any additional forcing, the Page dune fields would be represented by an erosional surface and strata preserved just within depressions along the J-2 surface, as the analysis above shows that there was no significant climb during these periods. In agreement with previous work (Havholm and Kocurek 1994; Blakey et al. 1996) and model results (Fig. 16), preservation of Page accumulations is best attributed to allogenic forcing, which consisted of an episodic, but net progressive, rise of the continental water table as a function of sea level in the adjacent Carmel. The preserved accumulations capture those parts of the scour fill that were incorporated within the rising water table. Where scours were deeper, thicker sections were preserved (Fig. 9A). Field evidence argues that high stands of the Carmel sea were characterized inland not only by a limit to deflation of the aeolian accumulations, but also a diminished sand supply such that dune fields were replaced by extensive polygonally fractured surfaces and sabkha deposition (Figs. 10A–C, 11A–C). Later aeolian constructional
A. Set Thickness
Cumulative Distribution Functions

- Basal Page (n = 80)
- Exponential
- Gamma

B. Set Thickness
Probability Distribution Functions

- Basal Page (n = 80)
- Exponential
- Gamma

- Lower Page (n = 59)
- Exponential
- Gamma

- Middle Page (n = 402)
- Exponential
- Gamma
methods using rover and remote-sensing data. Interpretations of the Earth, aeolian sandstones on Mars could be characterized by similar associated ancient dune field. In addition to outcrops of sandstone on in understanding the formative environmental conditions of the Page strata largely through the analysis of cross-set the Page dune fields to shred their earlier accumulations. These processes conditions episodically or locally overcoming an autogenic tendency of periods during falling sea level and low stands were characterized by an influx of additional sand but also by scour into the surface, producing the compound erosional outcrop-scale surfaces. Broadly speaking, the preservation of any non-scour-and-fill-type architecture, as well as the stacking on multiple discrete scour-and-fill packages, represents an allogenic forcing overcoming the autogenic, signal-shredding tendencies of the ancient Page dune fields. This is consistent with much of the current theory regarding the recording of environmental signals in stratigraphy (Castelltort and Van Den Driessche 2003; Jerolmack and Paola 2010; Ganti et al. 2014; Romans et al. 2016; Paola et al. 2018), and framing future observations of aeolian stratigraphy in this manner will be informative of ancient environmental conditions on Earth and other planetary bodies with aeolian stratigraphic records, particularly Mars (e.g., Grotzinger et al. 2005; Milliken et al. 2014; Brothers et al. 2018; Banham et al. 2018; Day and Catling 2018; Anderson et al. 2018; Day and Catling 2019).

CONCLUSIONS

The Page Sandstone preserves a record of allogenic boundary conditions episodically or locally overcoming an autogenic tendency of the Page dune fields to shed their earlier accumulations. These processes are unraveled from Page strata largely through the analysis of cross-set thickness distributions coupled with geologic context, and interpretations are tested against results from the numerical model presented completely in the companion paper (Swanson et al. this issue). The methods used here to quantify the set architecture of the Page Sandstone are universal, and can be applied to any other aeolian sandstone where there is interest in understanding the formative environmental conditions of the associated ancient dune field. In addition to outcrops of sandstone on Earth, aeolian sandstones on Mars could be characterized by similar methods using rover and remote-sensing data. Interpretations of the unique influences on the development of other types of strata, such as fluvial or carbonate grainstone cross sets, will benefit from this type of analysis as well.

SUPPLEMENTAL MATERIAL

Supplemental materials are available from the SEPM archive: https://www.sepm.org/supplemental-materials.

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