Outcrop Studies of Soft-sediment Deformation Features in the Navajo Sandstone

by

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2011 Ph.D. Thesis
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ABSTRACT

In contrast to early work establishing the importance of earthquake-induced liquefaction in producing soft-sediment deformation (SSD) of the Navajo Sandstone, this report advances the use of SSD analysis to: characterize wet climatic conditions and flood events during the depositional history of ancient eolianites; discriminate the signatures of multiple deformation events from those of complex deformation features formed in a single event; and to document the occurrence of liquefaction features unrepresented in modern Earth analogues. The diversity of deformation styles, presented here, is very unusual in a report from a single formation; yet the high resolution of interpreted time relationships between various processes of deposition, erosion, water table fluctuation, and deformation is even more notable. These exceptional features derive from the extraordinary outcrops of the Colorado Plateau, which expose many large-scale (tens of meters) features throughout their entire extent and reveal an extended history of episodic deformation through thick (hundreds of meters) sections of cross-bedded units, which frequently continue along several kilometers of cliff face.

Prior studies of fluid escape from unconsolidated sand that support the present work are outlined in Chapter II. These include laboratory simulations of liquefaction and fluidization as well as analyses of analogous deposits, both ancient and modern. Chapter III provides an overview of outcrop evidence, gathered during the course of this study, for dramatic alterations in the topography and sedimentation patterns of the Navajo erg. Interpreted perturbations include: the foundering of active dunes; sediment eruptions; and the subsidence of interdune surfaces. Chapter IV constitutes an example of the detailed
analyses that support the overview of Chapter III. Outcrop features from a site in West Canyon, Arizona provide the basis for interpreting the subsidence of a dry interdune surface to a position several meters below the contemporary water table, followed by the filling of this depression with a succession of mass flow, lacustrine, and eolian deposits. Chapter V outlines the implications of various outcrop features for the prevailing model of soft-sediment deformation in the Navajo Sandstone. Proposed modifications of this model accommodate a broader range of deformation dynamics and specifically incorporate the impact of wet climates.
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I. INTRODUCTION

Focus of this Study

Three decades have passed since a sweeping reinterpretation of the Jurassic Navajo Sandstone (Freeman and Visher, 1975) sparked intense debate, in the sedimentological community, over facies criteria for ancient eolian deposits. This debate prompted detailed investigations of Navajo Sandstone sedimentary structures and provoked a widespread interest in the depositional architecture of eolian accumulations. Questions about the source of systematic architectural variations led to the development of climbing bedform theory and a recognition of the important role played by interdunal moisture in sand sea development. These advances were followed by more than a decade of relative silence in Navajo Sandstone research, before the recent spate of activity. The current resurgence of interest in the Navajo Sandstone covers a broad range of topics; but includes particular emphases in two areas: the provenance of the eolian sand (e.g. Dickinson and Gehrels, 2003) and the environmental significance of the interdune deposits. It is the latter topic that gains the most support from the present work.

In modern eolian dune environments, local rainfall patterns often determine interdunal moisture conditions and, consequently, sedimentation patterns; however, in the ancient record, the effects of direct rainfall on a local water table cannot be systematically discriminated from the passive rise associated with fluvial incursions out of adjacent highlands. This study, as proposed, was aimed at developing new methods to distinguish these factors and to analyze ancient groundwater processes. The most productive methodology capitalized on the remarkable outcrop exposure of the Navajo Sandstone (Figure 1). Many kilometers of cliff face, throughout the Colorado Plateau, were surveyed and the comparison of distinctive architectures from various sites provided key insights into process/response associations in the ancient erg. Outcrop interpretation was aimed at characterizing those aspects of Navajo Sandstone architecture with direct paleohydrological implications. The starting points for these investigations are summarized below.
**Eolian Facies Architecture**

Kocurek and Havholm (1994) presented a conceptual framework for eolian sequence stratigraphy that features the role of autogenic mechanisms of dune migration and highlights the importance of dune/interdune dynamics in the development of facies architecture. They recognized a complex spectrum of eolian depositional systems extending between three distinct end members defined by moisture conditions at the interdune surface and the general mobility of the sandy substrate:

1. Dry systems do not produce interdune deposits except when unusual events, such as interdune flooding (Langford, 1989), deliver more sediment to the areally limited, interdune depressions than can be eroded before burial by an advancing dune.

2. In wet eolian systems, persistent moisture or free-standing water at the interdune surface traps eolian sediment and facilitates the production of evaporates and biogenic sediments. Through time, wet eolian systems are characterized by accumulation that proceeds in concert with a rising water table (Carr-Crabaugh and Kocurek, 1998)

3. Stabilized systems are active eolian systems broadly affected by vegetation (Pye and Tsoar, 1990), cements (Schenk and Fryberger, 1988), lag surfaces, mud drapes (Purvis, 1991), or other features that minimize erosion. Interdune deposits in these systems may vary widely and produce accumulations displaying irregular, discontinuous, and amalgamated units with numerous erosional surfaces.

As conceived, the mechanisms associated with each end member shape eolian architecture in response to whatever allogenic controls affect sediment supply, transport conditions, and hydrology. Blakey (1988) summarized the range of such extrinsic controls and their presumed effects on erg development. For Jurassic eolianites of the Colorado Plateau, the actual effects of specific allogenic controls on sequence development are being identified through facies analysis and the correlation of eolian supersurfaces across facies transitions. Several workers have examined the transitions between eolian deposits and the deposits of adjacent environments, identifying genetic packages defined by erg interactions with fluvial (Middleton and Blakey, 1983; Porter, 1987; Clemmenson et al, 1989; Langford and Chan, 1989; Herries, 1993; Jones and Blakey, 1997; Mountney and Jagger, 2004) and marine (Loope, 1985; Eschner and Kocurek, 1985; Carr-Crabaugh and Kocurek, 1998; Havholm et al, 1993; Blakey et al, 1996) systems.
Figure 1: Isopach map outlining the preserved extent of the Navajo Sandstone and its equivalents, from outcrop and borehole data. The dashed lines indicate regions of sparse data, primarily in the subsurface. (Adapted from Verlander, 1995) The various names assigned to this unit appear, in red letters, within the primary geographic range of their usage, as summarized in the associated table. Sites across the entire outcrop range of the formation were examined during the course of this study.
Though formation-scale supersurfaces have not been identified in the Navajo Sandstone, paleohydrological conditions apparently did vary, both spatially and temporally. The diverse sedimentary structures produced by penecontemporaneous soft-sediment deformation provide uniquely valuable indicators of these paleohydrological conditions and expand the range of discernible controls on facies architecture. This augmentation of paleohydrological criteria is especially useful in modeling erg dynamics in the pre-Cretaceous world, devoid of stabilizing grasses (Glennie and Evamie, 1968), which may have functioned in ways impenetrable to conventional wisdom based on experience in modern environments.

**Navajo Sandstone Paleohydrology**

No detailed and comprehensive synthesis of Navajo Sandstone paleohydrology has been attempted. Carbonate lenses (Gilland, 1979; Doelling et al., 1989; Stokes, 1991), interpreted as pond deposits (Driese, 1985), attest to the episodic intersection of the water table with the interdune surface. These lenses are most common in the eastern portion of the Navajo outcrop area (Bromley, 1992), and its lower stratigraphic levels (Marzolf, 1983), where interactions between the ancient erg and contemporaneous fluvial systems of the Kayenta Formation are well documented (Middleton and Blakey, 1983; Porter, 1987; Clemmenson et al., 1989; Herries, 1993). However, direct rainfall appears to have been an important factor in some episodes of interdune flooding. Loope and others (2001) attributed thick slump masses within large-scale dune cross-strata near the Utah-Arizona border to an annual monsoon pattern of precipitation. Loope and Rowe (2003) later argued, on the basis of trace fossil distributions in those same outcrops, that intervals of enhanced monsoonal rainfall supported the development and persistence of interdunal ecosystems. This scenario suggests a more varied hydrology in the Navajo erg than was previously imagined.

Extensive modern sand seas typically display compartmentalized groundwater regimes that are dissociated from regional base level, where water table configurations respond to local rainfall patterns (Maglione, 1976). High recharge rates can produce substantial topographic relief of the water table (Ahlbrandt and Fryberger, 1981). In the western region of the Nebraska Sand Hills, where textural parameters are comparable to
Navajo values (compare Uygur, 1980 and Swinehart, 2002), near-surface hydraulic flow occurs in localized patterns that include persistent lakes, with a variety of chemistries, but no regional surface drainage (Ahlbrandt and Fryberger, 1980). Sparse, variably intense precipitation in the region nevertheless supports meter-scale water table mounds (Winter, 1986; Gosselin et al., 1999).

Some evidence points to the existence of water table mounds in the Navajo erg. Bromley (1992) described water-table-controlled variations in permeability and induration associated with carbonate lenses at the eastern margin of the formation. The carbonates and a few meters of overlying sandstone were preserved as paleotopographic highs, subsequent to erosion of the J-2 unconformity, at the top of the Navajo. Bromley (1992) attributed preservation of the sandstone to a series of early diagenetic processes that derived from topographically contoured water tables, perched above the carbonate lenses.

This thesis research demonstrates how the architectural criteria developed in these previous studies can be used to characterize the configuration of the water table during individual soft-sediment deformation events. It also shows how the event characteristics of soft-sediment deformation features themselves can be used to better characterize the history of water table fluctuations in ancient ergs.

**Thesis Objectives**

The present report provides new perspectives on cause/effect relationships between primary controls, depositional processes, and the architecture of the Navajo Sandstone. Clarifying those relationships supports the development of predictive tools for petroleum exploration and other practical pursuits. It also contributes to the analysis of ancient climatic cyclicity, facilitating the conceptual integration of terrestrial and celestial processes and their changes through time.

This research addresses current questions regarding the impact, on Early Jurassic erg development, of contemporary hydrologic factors, including: rainfall abundance, pathways of fluid flow, water table variations, ponding, and stream activity. These questions represent more general issues regarding the importance of climatic controls on environmental changes represented in the Glen Canyon Group: from coeval fluvial and
eolian sedimentation that produced Moenave/Wingate deposits, through fluvial dominance during Kayenta deposition, to the Navajo eolian regime. Deciphering this succession in detail requires a thorough understanding of Early Jurassic hydrology.

Several sets of hypotheses, formulating fundamental interpretive issues, were tested by this research:

- Interdune ponds in the Navajo erg were fed by streams sourced in adjacent highlands to the south and to the east.
- Interdune ponds in the Navajo erg derived from deeply sourced springs that responded to regional groundwater controls.
- Interdune ponds in the Navajo erg were fed by a local, rainwater-dominated hydrology, superimposed upon a regional groundwater flow regime.
- Convoluted crossbedding in the Navajo Sandstone represents penecontemporaneous soft-sediment deformation of saturated sands below the level of dune troughs.
- Convoluted crossbedding in the Navajo Sandstone represents deformation in contemporaneous bedforms, above the level of dune troughs.

Examination of outcrop evidence provided some support for each of these non-mutually-exclusive hypotheses. However, the most notable contribution of the studies reported here was to establish, both observationally and theoretically, the contributions of rainwater-controlled hydrologies to the distinctive architectures of the Navajo Sandstone. Outcrop interpretation was enhanced by the contributions of several workers who accompanied me into the field on various occasions. The primary collaborations affecting the final thesis document are itemized below.

**Collaborations**

Giovanni Monegato, Ph.D. candidate at Padua University provided several weeks of field assistance and is recognized as a co-author of chapter IV in this report. He helped to measure and document sedimentological features in Red Rock Canyon and at the sinkhole site in West Canyon. He helped produce Figure 4A, in Chapter IV, and did most of the graphic work on Figure 11. Giovanni also facilitated a subsequent collaboration with a fellow graduate student at Padua, Ronaldo Nalin, which is described in the final chapter of this report.
The pre-publication (Bryant and Miall, 2010) editorial suggestions of Mads Huuse substantially improved Chapter III.

David Loope and Ron Blakey provided many useful insights during the course of various sedimentological discussions and field excursions into the Navajo. Their contributions are represented in the numerous citations of their publications.

Uli Wortmann, director of the Geobiology Stable Isotope Laboratory at the University of Toronto, field-checked several of the sites featured in this report and helped refine various lines of evidence on which my interpretations are founded.

Robert Cushman, palynologist and chair of Natural Sciences at Loma Linda University, supervised my Masters’ research in West Canyon, which provided some of the key observations presented in Chapter V. He will be listed as a co-author of that material when it is submitted for publication. Kevin Nick, also from LLU, accompanied me into the field on several occasions, during the course of my Masters’ research and during my Ph.D. research at the University of Toronto. Bob and Kevin found the protosuchid fossils, described in Chapter V, which were prepared by Larry Rhinehart, at the New Mexico Museum of Natural History.

Andrew Miall, Gordon Stollery Chair in Basin Analysis and Petroleum Geology at the University of Toronto, provided valuable advisement at every stage of this work, including personal visits to field sites, collaborative development of future work, and editorial advice. His contributions will be recognized in co-authorship of each part of this document that is submitted for publication.
II. BACKGROUND AND METHODS

Value of this Study

Much recent interest in soft-sediment deformation has been directed toward its role in petroleum reservoir partitioning (Hurst, 2007) or, in the case of eolianites, specifically, its value as an indicator of an extraordinary triggering event that affected erg deposits (Alvarez et al., 1998; Netoff, 2002; Obermeier, 1996b; Stromback, 2005). However, eolianite soft-sediment deformation studies also support less exotic paleoenvironmental interpretations (Loope et al., 2001; Loope, 2003) and the broader analysis of ancient climates, geography, and life forms - both terrestrial and extra-terrestrial (Mahaney, 2004). The success of all these applications depends upon the development of process/response models that explain the observed form and distribution of deformation features by linking them, through process explanations, to a discrete set of causative factors. Typically, problems of scale do not allow the comprehensive laboratory simulation of these processes, neither do modern environments represent the full range of conditions under which deformation has taken place; therefore, model development must often rely upon the study of ancient deposits to establish the extent of deformation variability and to identify specific pathways through which deformation processes have occurred. The present report responds to this need in at least three ways: it presents the outcrop details of unique deformation features, produced in an extraordinary system; it supplements and refines existing models for understanding eolianite deformation processes, generally, and the depositional environment of the Navajo Sandstone, specifically; and it exemplifies methods of outcrop interpretation with value for future research.

Scope of this Study

The deformation of unconsolidated sediment occurs in a wide variety of depositional settings, at a range of scales from millimeters to kilometers, and can be induced by such diverse triggering mechanisms as animal activity, flooding, and bolide impact. It often occurs in association with high instantaneous rates of deposition, rapid accumulation, and volatile pore-fluid pressures. Within non-marine deposits, it is most
common in loosely packed, water-saturated, fine sand subject to seismic shaking. In outcrop, it is recognized as the contortion of primary sedimentary structures within stratigraphically discrete intervals, most notably when the affected deposit shows signs of subsequent reworking; that is, when deformation can be seen to have episodically affected near-surface sediment during its accumulation history. Because of this linkage with ongoing deposition, it has often been referred to as penecontemporaneous or syn-sedimentary deformation.

The generality of the term, “soft-sediment deformation” (SSD) suits the present study; because it opens to consideration features with different forms, occurring at a variety of scales, which are linked by overlapping sets of environmental factors, but may be differentiated by association with distinct event characteristics. Thus, the distortion of interdune sediment by animal activity, the collapse of storm-wetted dune foresets, and the production of water-escape structures during consolidation of thick cross-stratified intervals will all receive attention. For the purposes of this study, no fine distinctions between various degrees of “softness” in the natural continuum from freshly deposited sediment to solid rock (Maltman, 1984) are required.

Though the occurrence of SSD is not diagnostic of a specific depositional environment, it does carry important process/response significance. Not all sediments are equally susceptible and otherwise highly susceptible sediments remain stable in the absence of a critical susceptibility factor or triggering mechanism. Also, the forms displayed by deformation features reflect the stress fields under which deformation occurred. So, the presence of SSD, its distribution, and its morphology all point back to factors in the environment, broadly construed. These may be factors, such as primary texture, that derive from depositional processes; they may be factors, such as differential cementation, that carry a diagenetic signature; or they may be factors linked more directly to allogetic controls, such as seismicity.

SSD in ancient eolianites has now been reported from widely separated deposits throughout the geologic record. Many of the early investigations, however, targeted features found in late Paleozoic and early Mesozoic deposits of the Colorado Plateau, especially the Navajo Sandstone. This is due in large part to the excellent outcrop exposure of these features, in the region, at scales corresponding to the maximum extent
of deformation. The present report focuses on those outcrops, exclusively, without attempting to illustrate the entire spectrum of eolianite SSD.

This chapter provides an overview, introducing the general principles of interpretation that were applied in various outcrop studies. Subsequent chapters present the results of those studies, focusing on the process implications of specific architectural relationships. These chapters also highlight the chronologic implications of SSD. Deformation processes proceeded very rapidly, relative to the accumulation history of the affected sediment, so their products mark discrete moments in that history. Since these features are often very large and form cross-cutting relationships with other chronologically significant architectural features, they are useful relative time markers; especially when they can be linked to depositional processes.

**Purpose of this Report**

The purpose of this report is to document Navajo Sandstone deformation features representing a wide range of event characteristics and to provide examples of how the interpretation of SSD can inform broader analyses. It is intended to revitalize and refine earlier discussions, to demonstrate the diverse potential of eolianite SSD for high-resolution paleoenvironmental analysis, and to provide an introduction to the remarkable record awaiting further investigation.

**Geologic Setting**

**Age**

Although Early Jurassic volcanics interfinger with eolian deposits towards the presumed southern limit of Navajo deposition, the radiometric dates obtained from this setting (Riggs et al., 1993) cannot be physically correlated into the main body of the formation. No age-diagnostic fossils have been recovered from Navajo deposits, either. The Early Jurassic age assignment of the entire Glen Canyon Group (Wingate, Moenave, Kayenta, and Navajo Formations) is bracketed by the biochronology of palynomorphs in Moenave fluvial deposits (Litwin, 1986) and zircon dates from bentonites in the Temple Cap Sandstone (Kowallis, 2001), which overlies the Navajo Sandstone across the J-1
conformity, in the vicinity of Zion National Park. From these reference horizons, and their relationships to Glen Canyon Group stratigraphy, a late Pliensbachian to Toarcian age for the Navajo Sandstone is generally assumed.

**Tectonic and Eustatic Context**

During the Early Jurassic, eolian depocenters lay 10°-20° north of the equator, as the supercontinent of Pangaea progressed through the early stages of its demise (Kocurek and Dott, 1983). Global sea levels had begun to pulse gradually upward, from lows at the end of the Triassic toward highs in the Cretaceous (Hallam, 2001). Eolian sediment accumulated in the southern part of the Western Interior Basin, which stretched from present-day Arizona and New Mexico north into Canada (Peterson, 1994a). These deposits, now exposed on the Colorado Plateau, lay east and north of a magmatic arc whose activity accompanied subduction along the complexly evolving margin of North America, from the Triassic to the Cretaceous (Dubiel, 1994). The trend of this arc is represented by the present-day Sierra-Nevada range (Blakey, 1988a). Episodic flexural downwarp of a retro-arc foreland basin, the Utah-Idaho trough, provided accommodation space for thick erg deposits in both the Lower and Middle Jurassic (Allen, 2000; Blakey, 1994b; Blakey, 1996; Huuse, 2005), including the Navajo Sandstone (Figure 1A).

Broader wavelength, northeastward tilting, probably from dynamic adjustments to mantle convection, also affected regional sedimentation patterns from late Triassic to early Cretaceous time (Blakey, 1994b; Heller et al., 2003). This produced a broad, flat plain with a depositional surface that remained close to sea level (Blakey, 1994b). Early Jurassic fluvial activity, represented in the Moenave and Kayenta Formations, consisted of low-gradient flow north from the eastward curving magmatic arc and east off of short-lived highlands in the region occupied by the present-day Rocky Mountains (Peterson, 1994a).

The extent to which paleocurrent patterns were influenced by forebulge migration east of the foreland basin has not been determined, as apparent inconsistencies between its relative positions through the Jurassic have yet to be resolved (Allen et al., 2000). Widespread, though moderate, seismic activity can be inferred from angular relationships at the bounding unconformities of the entirely non-marine, Early Jurassic sequence on the Colorado Plateau (Peterson, 1986; Peterson, 1994a). Deposits below the lower, J-0,
boundary display a slight eastward tilting; whereas erosion of the upper, J-2 boundary followed a slight westward tilting (Peterson, 1994). Structural relationships at the J-1 unconformity cannot be determined because it only occurs across a small area (Peterson, 1994). Blakey (1994) divides the Glen Canyon Group into two sequences, separated by the J-sub-k disconformity (Riggs, 1993), underlying the Kayenta Formation and the Springdale Sandstone Member of the Moenave Formation, which some recent workers reassign to the Kayenta Formation (Lucas, 2006).

**Paleoclimate**

In the Early Jurassic, widespread eolian deposition, with subsidiary fluvial interludes, followed dominantly fluvial deposition in the Triassic (Blakey, 1994b). This shift in depositional environments coincided with a phase of increased magmatism in the arc to the west and the continued northward drift of the continent, as North America broke away from Pangea (Peterson, 1994). Movement of the plates served both to remove Early Jurassic depocenters from the lower latitudes and to disrupt the extreme continentality of the Pangean landmass, both of which had previously favored monsoonal circulation patterns with abundant rainfall (Parrish, 1988). It appears that latitudinally zoned circulation - in particular the dry, subtropical convergence that accounts for most large, modern deserts - dominated the climate of this area by the Middle Jurassic, producing consistent transport winds that did not change direction, dramatically, with the seasons (Parrish, 1988). In addition to this, westerly winds from the paleo-Pacific Ocean would have lost their moisture across the elevated topography of the volcanic arc, leaving the foreland depression in an extensive rain shadow (Marzolf, 1988a; Peterson, 1994a). Mesozoic global warming (Fischer, 1977) may have offset the cooling effect of the northward drift of the continent, keeping the region dry and hot (Parrish, 1993).

Foreset dip directions within the deposits of large dunes provide a proxy for the dominant direction of the sand-transporting winds that shaped those dunes (Rubin and Hunter, 1983). The large number (>1000) of foreset dips that have been measured in the Navajo Sandstone indicate a dominance of northerly winds in the northern region of
Figure 1A: Current field relations, in the American Southwest, between major features produced during the early Jurassic (Blakey, 1994; Dickenson and Gehrels, 2003; Peterson, 1994). The arrows indicate surface airflow directions predicted by Early Jurassic paleoclimate models (Parrish and Peterson, 1988). The tadpole symbols plot paleocurrent measurements: the lines represent average foreset dip directions (generally from >10 measurements), in sections located at the positions indicated by the associated solid circles (Peterson, 1988c). Figure 1B presents a generalized cross-section across the thickest part of the preserved Navajo accumulation (Blakey, 1994b). The rose diagrams of 1C summarize paleocurrent measurements from the Kayenta Formation in southeastern Utah and northeastern Arizona (Luttrell, 1993).
Navajo deposition and northwesterly winds farther south (Peterson, 1994); though deviations from these norms are apparent in the summary data (resultants). The extent of the Navajo Sandstone is great enough to record major transitions between contemporaneous pressure cells and this has been proposed as an explanation for the bi-directionality of the primary trends. The westerly winds indicated by paleocurrent resultants from the southeastern portion of the Colorado Plateau have been attributed to the lingering influence of low pressure cells, which diverted surface air circulation to the east on a seasonal basis (Loope et al., 2001; Parrish, 1988). An alternative paleoclimatic reconstruction has been advanced, based on a more equatorial position for the region in the Early Jurassic (Loope, 2004); however, evidence for significant compaction flattening of the uncorrected paleomagnetic data that support that reconstruction (Dickinson, 2005) casts doubt on its conclusions (Loope, personal communication). Both reconstructions show less than ten degrees of rotation relative to the present continental alignment.

In addition to the limitations of current theory, problems with data acquisition contribute to anomalous divergences of the paleocurrent data (Figure 1A) from the predicted pattern of flow. The precision to which the sampled stratigraphic intervals of most paleocurrent measurements have been identified does not support sub-formation-level analysis. Furthermore, these measurements do not represent an evenly distributed sampling through space and time; so neither the temporal evolution of wind patterns nor the local effects of paleogeography are well-defined, and atypical horizons may be over-represented in the data set. This situation arises both from access limitations and from the random nature of sampling strategies (Peterson, 1988c), which rely upon statistical methods to smooth the effects of varying bedding styles and of non-systematic, local perturbations in dune symmetry. It is exacerbated by difficulties in correlation across the formation.

**Stratigraphy**

Fluvial deposits of the Kayenta Formation conformably underlie and intertongue with the Navajo Sandstone (Figure 1B). Modal analyses of detrital framework grains indicate that these sediments derived from tectonic highlands, to the east, and volcanic
highlands to the south (Dickinson, 2003; Luttrell, 1996a). As shown in Figure 1C, paleocurrent measurements indicate that fluvial flow generally opposed contemporaneous eolian transport (Luttrell, 1996), producing widespread recycling (Blakey, 1994b). Complex interactions between the fluvial and eolian systems are apparent in preserved lateral relationships at the southern margin of the Jurassic erg and in various vertical successions at other locations (Blakey, 1994b; Middleton and Blakey, 1983). The extent of ongoing fluvial influence on erg hydrology and interdune sedimentation has not been established, however, and recent studies (Loope et al., 2001; Loope, 2003) suggest that some sedimentary episodes were more heavily influenced by direct rainfall, even at locations near the upslope margins of the erg. Figure 2 presents six possible sequence interpretations of Navajo Sandstone architecture, as enumerated by Blakey (1994b).

In the vicinity of Zion National Park, the Navajo Sandstone is unconformably overlain by another eolianite, the Temple Cap Sandstone, across the J-1 regional unconformity (Peterson and Pipiringos, 1979; Pipiringos and O'Sullivan, 1978). Elsewhere in the field area, it is truncated directly by the J-2 surface, a major North American unconformity, which separates the Navajo from the eolian Page Sandstone and partially equivalent Carmel deposits (Figure 1B), representing various near-coastal environments (Blakey et al., 1988; Peterson and Pipiringos, 1979; Pipiringos and O'Sullivan, 1978). Erosional beveling below the J-2 has removed the original eastern limit of Navajo accumulation and accentuates depositional thinning in that direction (Blakey et al., 1988). A shortage of reliable data from the tectonically disrupted Basin and Range geomorphic province prevents an authoritative evaluation of depositional trends in a westerly direction. However, from well-established relations, it is clear that the preserved deposits are substantially less voluminous than the original accumulation. In spite of this erosional diminution, the preserved thickness of Navajo Sandstone, in southern Utah, still exceeds 650 m. Along with the equivalent Aztec and Nugget Sandstones, it currently extends across a region measuring nearly 1,000 km north to south and 400 km east to west.
Provenance

The thick, extensive deposits of the Lower Jurassic Navajo Sandstone and Middle Jurassic Entrada Sandstone of the southwest Colorado Plateau represent the culmination of voluminous eolian deposition that began in the late Paleozoic (Rubin and Hunter, 1988). Recent U/Pb analyses of detrital zircons (Dickinson, 2003; Rahl, 2003) support the speculation (Johansen, 1988; Marzolf, 1988b) that much of the sediment in these eolianites originated in basement rock on the eastern side of the continent, unroofed during the Appalachian orogeny. Those studies suggest that a trans-continental fluvial system persisted throughout the period of eolian deposition, transporting sediment to flood plains and strand lines north of the present-day Colorado Plateau. Persistent winds to the south redistributed these sediments into the observed array of mature sandstone bodies. Proximal highlands and detritus from the Ouachita System, in present-day southwest Texas, also contributed sediment to these ergs (Blakey, 1994b); though detrital zircon populations indicate that fluvial deposits along these transport pathways consisted mainly of recycled eolian sand (Dickinson, 2007).

The paleogeographic configuration implied by these studies raises the prospect of an additional level of complexity among primary controls on Navajo deposition: Climatic shifts and tectonic events far beyond the basin of deposition may have regulated the sand supply essential to erg expansion during the Early Jurassic.

Petrology

Sandstone lithologies within the Navajo plot (McBride, 1963) in a narrow range from subarkose to quartz arenite (Uygur and Picard, 1980). Subrounded, nearly equant, well-sorted, fine to medium quartz grains, including chert fragments, represent up to 98% of framework constituents (Doelling et al., 1989; Harshbarger et al., 1957; Riggs and Blakey, 1993a), with feldspars typically composing the remaining percentages. A minor fraction of heavy minerals is also present (Jennison, 1980; Riggs and Blakey, 1993a). Generally, the grains are weakly cemented with calcite; though hematite or authigenic quartz dominate locally (Jennison, 1980). Grain size, sorting, and roundness vary little in cross-stratified deposits composing the bulk of the formation (Uygur and Picard, 1980).
Figure 2: Navajo Sandstone facies architecture (from Blakey, 1994b). A) Cross-section showing stratigraphic relationships and generalized facies associations. B) Six alternative models, with inferred time lines for each, which plausibly explain the observed facies architecture.
Non-sandstone facies within the main body of the Navajo Formation make up a small, unevenly distributed proportion of the total mass. The most prominent of these are discontinuous beds of horizontally stratified, cherty limestone (Desborough and Poole, 1992; Gilland, 1979; Harshbarger et al., 1957), interpreted as interdune pond deposits (Driese, 1985). These typically occur within lenticular lithosomes, a few meters thick, dominated by horizontally stratified sandstone intercalated with thin horizons of mudstone. The apparent dimensions of the carbonates seldom exceed 1 m in thickness and 100 m in diameter (Stokes, 1991), though diameters over 1 km do occur (Doelling et al., 1989). Carbonate lenses occur more frequently in the southeastern portion of the Navajo outcrop area and its lower stratigraphic levels, than elsewhere (Bromley, 1992; Marzolf, 1983), a trend paralleling the association with fluvial facies (Blakey, 1994b).

**Previous Work**

**Early Descriptions of SSD in Colorado Plateau Eolianites**

General descriptions of SSD (Dana, 1849; Darwin, 1851; Lyell, 1841; Vanuxem, 1842) began circulating shortly before the Whipple expedition produced the first reconnaissance report (Marcou, 1856) on the geology of the Navajo country (Gregory, 1917; Van Loon, 1987). However, such curiosities did not illicit comment from researchers on the Colorado Plateau until Newsom (1903) drew attention to enigmatic breccia pipes in the Entrada Sandstone (Netoff, 2002). When Gregory (1917) proposed the name Navajo Sandstone for the eolian unit featured most prominently in outcrops across the Navajo Nation, he published a photograph (Plate XXII-A) of trough cross-beds in Glen Canyon that does include unnoted soft-sediment deformation features. Whether or not this particular example of SSD had already attracted his attention, it is clear that he eventually began tracking the features. In a later report, he (Gregory, 1950) referred to soft-sediment deformation in both the Wingate and Navajo Sandstones, depicting two different styles (Figure 45, p 81). He suggested, based on his comparison of “scores of photographs” (p 79), that the distribution of deformation features in the Wingate corresponds to a major, lateral facies transition at the margins of the ancient erg.

Kiersch (1950) was the first to pursue the possibilities of SSD as a tool for paleoenvironmental interpretation of the Navajo Sandstone. Applying Rettger’s (1935)
finding that dry or moist sand failed by faulting under conditions that caused saturated sand to flow and fold, he proposed that deformation structures in the Navajo Sandstone of the San Rafael Swell derived from intermittent episodes of sediment saturation and draining, tied to climatic cycles. He postulated that active dunes were saturated and undercut during episodes of groundwater resurgence, then slumped along oversteepened profiles as water drained from the bedforms. He concluded that a widespread zone of SSD occurring in his study area indicates frequent wet cycles and the more highly distorted and complexly configured deformations indicate seismic events. (p 941-942)

**Theoretical Milestones in Eolianite SSD Research**

Additional interest in the paleoenvironmental implications of eolianite SSD was stimulated by various environment-targeted experiments, observations, and genetic discussions that produced criteria useful for outcrop interpretation. Laboratory experiments on the deformation of unconsolidated sands under various conditions of water saturation (McKee et al., 1971; McKee et al., 1962a) produced distinct differences in style of deformation, extending previous findings (Rettger, 1935). These studies detailed the way that deformation structures vary in relationship to the cohesiveness of the sand and established that degree of cohesion was primarily a function of moisture content, providing a basis for interpreting moisture conditions in ancient eolian deposits. Field observations of small-scale structures on the lee side of dunes exposed to wet climatic conditions confirmed the laboratory findings (Bigarella, 1971; Bigarella et al., 1969; McKee, 1972). These developments were paralleled by a growing appreciation for the effect of groundwater cohesion in limiting the extent of deflation in eolian systems (Opdyke, 1960; Peirce, 1964; Stokes, 1968).

Allen and Banks (1972) strongly influenced the discussion of Navajo SSD with their physical interpretation and quantitative analysis of simple recumbent folding in soft sediments. They interpreted this style of soft-sediment deformation, which commonly occurs in fluvial deposits, as the result of current drag across a liquefied bed of sand. They showed that the geometry of the resultant deformation feature is determined by the initial shape of the cross-strata, the properties of the deformed sediment, and the forces responsible for the soft-sediment folding. Their report provided both a broad review of
SSD field relations and detailed analyses of genetic processes, developing a perspective that informed all manner of SSD research for the next decade. Subsequent workers both extended and modified their conclusions, as is notably exemplified by the work of Hendry and Stauffer (1975), who refined the kinematic hypotheses of Allen and Banks (1972) based on their analysis of recumbent folds in the trough-cross-bedded fluvial deposits of the Pleistocene Floral Formation.

Another notably influential, general report was that of Lowe (1975), who addressed a broad range of SSD originating in fluid escape from unconsolidated, coarse-grained sediments. He highlighted three processes that characterize the de-watering of these sediments: seepage, involving the upward movement of fluid through existing pore spaces; liquefaction (Seed, 1968), marked by fluid expulsion due to the sudden collapse of a grain framework into its interstitial pore spaces; and fluidization (Soo, 1967), where pore volume increases and grains in a framework are disassociated by the movement of pressurized fluid. He enumerated various types of fluid escape structures representing either the direct rearrangement of grains by escaping fluids or the deformation of hydroplastic, liquefied, or fluidized sediment in response to external stresses.

**Detailed Descriptions and Paleoenvironmental Applications of Navajo SSD**

Sanderson (1974) followed up Kiersch’s (1950) work in the San Rafael Swell with a more rigorous examination of the physical basis for, and the geometric relations between, SSD features at that location. He noticed a recurring relationship between deformation facies occurring within stratigraphically isolated units: Near the base of the interval, cross-bedding is undisturbed; this facies grades upward into contorted laminations, which give way to indistinct stratification that is truncated by a major subhorizontal bedding plane. The thickness of the affected area varies considerably, though the units containing deformation features are defined by parallel bounding surfaces. He noted two or three such intervals - some deformed across more than 30 m of thickness and extending laterally for hundreds of meters - within the Navajo sections that he examined. The absence of deformation zones indiscriminately cutting across major bedding planes he interpreted as evidence for repetitive episodes of deformation during the depositional history, as opposed to a single event that occurred after accumulation.
was complete. His microscopic and x-ray comparisons of samples from various
deformation facies established that the convolute structures derive from deformed
bedding, not liesegang banding, and revealed that all contain relict stratification. He
concluded that the transition from undeformed laminae to indistinct stratification
represents a transition towards increasingly greater amounts of intergranular
displacement. He also noted that zones of indistinct bedding are less porous and more
resistant to erosion than distinctly laminated zones. Based on comparisons of observed
high-angle asymmetric folds, flame structures, and drag folds to the much smaller-scale
deformation geometries produced by McKee and others (1971), he concluded that sand
flowage had occurred under water saturated conditions (Sanderson, 1974a).

Freeman and Visher (Freeman and Visher, 1975; Visher and Freeman, 1977) used
soft-sediment deformation features as evidence for shallow marine conditions, in their
reinterpretation of the Navajo Sandstone depositional environment. They pointed out that
none of the deformation structures described from modern eolian environments occur at a
comparable scale to the large Navajo structures, nor do they exhibit, overall, the same
deformation style - that characteristic of totally saturated sands with low cohesion. They
further asserted that the preservation of Navajo laminae indicates a slow deformation
process (Freeman and Visher, 1975). This time factor has not otherwise been addressed
in discussions of Navajo SSD, though mathematical models incorporating a term for
duration of the deformation event have been applied to SSD in other deposits (e.g.,

In response to Freeman and Visher (1975) and other critics of the eolian
interpretation of Navajo deposition (Jordan, 1965; Marzolf, 1969; Stanley, 1971; Visher,
1971), Doe and Dott (1980) provided what remains the most comprehensive discussion
of Navajo SSD. Incorporating observations from a uniquely broad range of outcrops,
they extrapolated from previous genetic discussions (Allen, 1972b; Anketell, 1970;
Bigarella, 1971; Bigarella et al., 1969; McKee et al., 1971; McKee et al., 1962b; McKee,
1972) to argue that characteristic patterns of SSD could be used to distinguish between
eolian and subaqueously deposited cross bedded sandstones. They pointed out that
avalanche foresets containing brecciated sand match those observed by Bigarella (1971)
in modern Brazilian dunes and could only have been produced in the presence of an air-
They also noted that the type of parabolically deformed crossbeds attributed by Allen and Banks (1972) to current shear across a liquefied substrate, are rare in the Navajo, preferentially occurring below abrupt shear zones overlain by a highly deformed interval with massive or indistinct bedding. They interpreted this relationship to indicate that remobilized sediment had flowed in a slurry across a liquefied substrate during a post-depositional liquefaction event (Allen, 1972b; Hendry, 1975). They joined other workers (Horowitz, 1979; Kiersch, 1950; Stokes, 1961) in emphasizing the importance of groundwater in the deformation process; but also speculated that atmospheric humidity may have played an important role in wetting the dune surfaces (p 809).

Horowitz (1982) proposed a general model for Navajo SSD, invoking earthquake-induced liquefaction and dune collapse (Figure 3). He based his analysis on detailed mapping of SSD in outcrops in Red Rock Canyon, Nevada, and along Highway 89, north of Kanab, Utah. He supported these architectural studies with petrographic characterizations of deformation fabrics, soil engineering analyses of liquefaction potential, and structural comparisons to features produced by the failure of the Lower San Fernando Dam in California (Seed, 1971). His simple model assumed a flat water table, situated below the interdune troughs, as may occur in hyper-arid desert regimes (Ahlbrandt and Fryberger, 1981). Horowitz (1982) argued that interdune areas, where saturated sands occur closer to the surface, were more susceptible to liquefaction than the more tightly confined, saturated sands below the dunes themselves; so there may have been a tendency for dunes to founder forward into subsurface liquefaction zones during a seismic event. He hypothesized that this movement produced the large-scale, non-cohesive folding in the direction of dune migration that occurred at his study sites and is represented in many other Navajo deposits (Rubin and Hunter, 1988). Horowitz (1982) used panoramic photos to document both SSD geometries and depositional architectures, and suggested that changes in depositional style were produced by a shift to drier climatic conditions. This, in turn, lowered the water table, reducing liquefaction susceptibility, and limiting the development of SSD to the lower part of the section (p 178).
Figure 3: Horowitz’ (1982) hypothesis to explain large-scale, directional deformation in ancient wind-blown sand deposits. (From Horowitz, 1982)

A. Earthquake motion liquefies saturated sand beneath an interdune low.
B. Steeper portion of the upwind dune collapses into the liquefied sand, resulting in lateral shifting of subsurface sand masses.
C. Preservation of only the lowest portion of the deformation after deflation.

The absence of bedforms in Part C of this diagram is not essential to the proposed model. Non-climbing dunes migrating across the upper surface of the accumulation would produce the same result, as Horowitz (1982) depicted in a separate figure.
Stephens (1985) returned to the Kiersch (1950) and Sanderson (1974) study area in the San Rafael Swell, working under Sanderson’s supervision. Her work emphasized the importance of sediment underconsolidation (Casagrande, 1936) in deformation dynamics. Along with previous analysts (Allen, 1972a; Doe and Dott, 1980; Finn, 1971; Fryberger, 1979; Horowitz, 1982) she pointed to the high depositional porosity of eolian avalanche deposits, in particular, as a key factor in developing liquefaction susceptibility and documented porosity differences between deformed and undeformed Navajo crossbeds. She found an average porosity of 30.5% in the undeformed facies and 18.7% within SSD (p 45), due to the tighter packing of framework grains produced during deformation and maintained through subsequent diagenetic changes. These findings have been corroborated by more recent studies (Net, 2003). Paralleling Fryberger’s (1979) observations in the Weber Sandstone, Stephens (1985) catalogued morphological differences between SSD in isolated units and those occurring in more extensive zones affecting multiple units. She observed that in single sets of affected cross-strata, fold hinges are generally parallel to the strike of adjacent undeformed cross-strata; whereas fold orientations are essentially random in the more extensive zones. She noted that three extensive zones, in particular, appear to correlate across distances greater than 125 km and hypothesized that variations in the form and continuity of deformation within these zones may derive from differences in location relative to surficial and water table topographies (p 112).

Peterson (1988a) suggested that an extensive zone of deformation, up to 7 m thick, near the top of the Navajo/Nugget Sandstone provides a crude means of correlation between widely separated outcrops; although his own detailed work showed that contorted strata are not precisely isochronous. Noting that this deformation zone is not present north of the Uintah mountains, where wet interdune facies are absent in this interval, he suggested that it represents a relatively brief episode of tectonic activity that affected the entire expanse of dune deposits; but did not produce deformation where low water tables limited sediment susceptibility (Peterson, 1988a). Peterson (1988a) also observed that the lack of contortions in lower parts of the formation that do present abundant evidence of high syndepositional water tables demonstrates that sediment saturation was not the only limiting factor on SSD during the Navajo depositional history.
Rubin and Hunter (1988) offered a brief review of Navajo SSD as part of their field guide to sedimentary structures in the Navajo and Entrada Sandstones. Following the lead of Horowitz (1982), they relegated large-scale deformation to a zone of susceptibility below the level of interdune troughs. They also highlighted the enigma of preferential folding parallel to crossbed dip, in this setting, and advanced an alternative explanation for the phenomenon: the sequential loading of large, migrating dunes, acting as giant rolling pins to preferentially deform sediment in the downwind direction (p 133).

Other Related Work on Eolianite SSD

Concurrent with the work on SSD in Colorado Plateau eolianites, other investigators (Glennie, 1972; Glennie, 1983; Peacock, 1966; van Veen, 1975) were grappling with the interpretation of similar structures in Europe, especially those encountered in Jurassic deposits of the North Sea region. At first they appealed to some form of marine reworking of eolian dune deposits to explain the observed SSD (Glennie, 1972; van Veen, 1975), but soon established that these features occurred within the eolian architectures themselves; though the timing of deformation corresponded to a rapid, widespread inundation, the Zechstein transgression (Glennie and Buller, 1983, p 50). Influenced by this catastrophic association, Bagnold’s (1941) observations regarding deformation in dry North African dunes, and a line of reasoning established by Peacock (1966) in his investigation of SSD in Scotland’s Hopeman Sandstone, these investigators pursued the idea that entrapped air was the interstitial fluid that mediated deformation. However, because the compressibility of air inhibits the development of high pore pressures and the low viscosity and density of air promotes efficient escape (Doe and Dott, 1980), this interpretation is no longer advanced to account for large-scale features (Glennie, 2007). Nevertheless, Glennie and Buller’s (1983) persuasive arguments regarding the triggering of Weissliegendes deformation by flooding raise a cautionary flag against the unconstrained use of large-scale SSD features as seismic indicators in other eolianites. SSD associated with ancient marine transgressions has since been identified in various Jurassic and Cretaceous eolianites, in both North and South America (Benan, 2000; Eschner and Kocurek, 1986; Stromback, 2005). Most recently, Glennie
and Hurst (2007) and Hurst and Glennie (2008) have discriminated a pluvial contribution to the triggering of Weissliegendes deformation, suggesting a very broad climatic control.

Working in the Pennsylvanian/Permian Weber Sandstone of the Colorado Plateau, Fryberger (1979) noted apparent inconsistencies in localized patterns of SSD. At some locations, features typical of water-saturated sand - complex overturned folds, horizontally extensive drag folds and shear zones, and large pods of undisturbed sand within zones of SSD – occurred alongside break-apart structures characteristic of cohesive damp sand. He proposed that some of the sediment displaying more brittle behavior may have undergone early cementation or that primary textural differences alone may have produced greater cohesion (p 18). He also observed that much of the large-scale plastic deformation affected multiple genetic units; but that some appeared to have developed within active bedforms, with internal foresets that were saturated at the time of deformation, even though deposited under dry conditions (p 23).

**Recent Work on Navajo Sandstone SSD**

In spite of the repeatedly published opinion that Navajo SSD merits further investigation (e.g. Rubin and Hunter, 1988), specific focus on the topic faded out in the mid-1980’s, along with debate over the Navajo Sandstone depositional environment. The recent use of cyclic lee-slope fluidization features (Loope et al., 2001) and trampled dune surfaces (Loope and Rowe, 2003) as indicators of monsoonal conditions during Navajo deposition constitute notable exceptions to this trend. These studies revive some familiar themes. Along with reports of giant stromatolites (Eisenberg, 2003), mass flow deposits (Eisenberg, 2003; Loope et al., 2001; Parrish, 2007), and stands of coniferous trees (Parrish, 2007; Stokes, 1991), associated with Navajo interdune deposits, they portray an ancient erg subject to complex paleohydrological controls, quite unlike the monotonous sea of blowing sand conjured up by traditional comparisons to the modern Sahara (Marzolf, 1988a). However, these applications of surficial SSD to paleoenvironmental interpretation of the Navajo Sandstone have not been accompanied by a revival of interest in the more typical and widespread, subsurface features. This, in spite of a general growth of interest in SSD, represented by the recent special volume, *Subsurface Sediment Mobilization*, produced by the Geological Society of London (van Rensbergen,
2003) and the appearance of AAPG Memoir 87, Sand Injectites: Implications for Hydrocarbon Exploration and Production (Hurst, 2007), which showcases the remarkable scale and diversity of elastic injection features, worldwide, and specifically highlights the spectrum of deformation features found in Colorado Plateau eolianites (Chan, 2007).

One study, by Mahaney and others (2004), did examine large-scale Navajo SSD in the San Rafael Swell, which had already been interpreted as originating in deep subsurface processes (Sanderson, 1973). These authors noted that differential erosion within broad zones of indistinct stratification resembles that observed within deep-rooted seepage and injection features of the Entrada Sandstone (Huuse, 2005; Netoff, 2002; Netoff, 2001). Unlike the Navajo features, the Entrada clastic pipes typically occur as discrete cylindrical features, abruptly truncating undeformed stratification; however, the authors postulated that preferential cementation of ancient pathways of fluid flow was produced by similar processes in both cases. Their report focused on the implications of these features for the search for evidence of wet conditions and microbial life on Mars and did not attempt to resolve any outstanding issues regarding the deformation processes, themselves.

The shift of interest away from large-scale SSD in the Navajo Sandstone occurred soon after actualistic process/response models emerged to replace environmentally specific indicators in paleoenvironmental interpretation, providing a basis for high-resolution genetic stratigraphies (Van Loon, 1987). In eolian studies, specifically, the development of robust criteria for the identification of ancient eolianites had just reached its climax (Brookfield, 1977; Hunter, 1976; Hunter, 1977; Kocurek, 1981b; Kocurek and Dott, 1981; Rubin and Hunter, 1982b). Debate still raged around the origin of extensive bounding surfaces in ancient eolian deposits (Brookfield, 1977; Hunter, 1977; Kocurek, 1981b; Kocurek, 1986; Loope, 1981; Loope, 1984a; Loope, 1985; Loope, 1984b; McKee and Moiola, 1975; Rubin and Hunter, 1982a; Simpson and Loope, 1985; Talbot, 1985). Systematic genetic frameworks for eolian stratigraphy (Fryberger, 1993; Fryberger et al., 1988; Havholm et al., 1993; Havholm and Kocurek, 1994; Kocurek and Havholm, 1991) had not yet been proposed and the “evolution in thinking regarding the relationships between processes in depositional environments” (Miall, 2000) had not yet occurred.
These later developments provide a relatively untapped interpretive context within which the paleoenvironmental implications of large-scale Navajo SSD may now be explored.

**Methods**

**Outcrop Selection**

The original data presented here derive from outcrop studies of the Navajo Sandstone and its stratigraphic equivalents. Study sites were selected for their excellent exposure of SSD relative to the outcrop quality criteria discussed below. The only marked exceptions to this were the outcrops in Red Rock Canyon, Nevada, which were targeted because of their significance to the development of a general model for Navajo SSD (See Horowitz, 1982). Following the practice of Doe and Dott (1980), we examined a very large number of outcrops, besides those referred to here, in order to develop a sense for the range of observable features and their typical field relations; and to identify locations where specific attributes were amenable to photographic representation. Additionally, much time and effort were devoted to the search for deformation features occurring in outcrops which preserve evidence for changes in surface processes of erosion and deposition (such as mass flow production and stoss slope preservation) induced by deformation events. These outcrops were targeted because of their more definitive ties to depositional chronology and for the better opportunities they present to establish process/response interpretations based on the convergence of multiple lines of evidence.

**Photographic Data Collection**

Along with most other investigators, we find that photographs are the best available instrument for documenting sedimentary structures in the Navajo Sandstone. As Gregory (1950) remarked: “These straight lines, curved lines, and truncate planes that characterize the Navajo cross bedding vary so widely in dimension, position, and arrangement that adequate detailed description seems impracticable. Even attempts to outline types of cross bedding have proved unsatisfactory. Fortunately, photographs record the features with fidelity and make leisurely study possible.” (p 84)
Not only do single photographs document the details of SSD, but photographic panoramas provide an excellent means to record the spatial relations between them, as demonstrated by Doe and Dott (1980) and Horowitz (1982). Significant features of depositional architecture can also be traced on these panoramas, providing essential temporal and paleoenvironmental context to SSD analysis. These effectively replace stratigraphic sections in high-resolution studies, since the frequent lateral changes in bedding thickness and stratification type that characterize Navajo Sandstone architecture limit the usefulness of one-dimensional sections. Furthermore, in cross-stratified deposits, the interpreted vector of time extends more continuously down the direction of paleocurrent flow than it does vertically, and less frequently encounters boundaries of highly speculative significance. Lateral relations therefore constitute the most reliable starting point for an analysis of depositional trends. This primary analysis can then be used to evaluate the significance of the vertical succession.

**Sampling and Laboratory Analyses**

The studies documented in this report focus on the implications of visibly defined architectural features of the Navajo Sandstone. However, in a few cases where samples were available and afforded the opportunity for useful petrologic distinctions that could not be made in the field, laboratory analyses also contributed to outcrop interpretation. These consisted, primarily, of petrographic evaluations of sandstone texture and trace mineralogy.

**Chronostratigraphic and Paleoenvironmental Interpretation**

Understanding the process implications of large-scale SSD in Navajo outcrops can greatly enhance the interpretation of outcrop architectures; even though these features typically do not carry a distinct depositional signature comparable to that of recumbent folds in fluvial deposits (Allen and Banks, 1972), for example. As noted in the previous section of this report, the presence of SSD generally indicates sediment saturation at the time of deformation. This process/response association can be very useful in reconstructing hydrogeological controls on the depositional history of the succession.
The analysis of SSD provides more specific benefits to the interpretation of those outcrops where cross-cutting relationships constitute a basis for event correlations between surface and sub-surface processes. This application is based on an assumption of the geologically instantaneous production of SSD (See subsequent chapters for field evidence justifying this assumption) and the evident truncation of depositional facies and chronostratigraphic boundaries by these features. Navajo deformation features resemble igneous dikes in the way they cut across depositional architecture, establishing relative time markers; though they provide no opportunity for direct dating. Unlike igneous intrusions, their development responds to controlling factors of the depositional environment and persists within a time frame limited by fluid loss, without significant influence from heat flow parameters. In this regard, they maintain a strong affinity to more protracted processes of early textural and mineralogical diagenesis, where controlling factors such as pore-fluid chemistry, groundwater flow patterns, and static loading may derive from the same climatic and tectonic controls as do ongoing depositional dynamics. This distinct, but parallel, relationship to primary controls provides a basis for using SSD in paleoenvironmental interpretation.

The extraordinary outcrop exposure of sedimentary structures in the Navajo Sandstone provides exceptional opportunities to observe, in detail, the strain produced by subsurface stress regimes in the ancient erg, at discrete moments in its depositional history. Each instance presents the visual record of a unique history, constrained by factors controlling load distribution, hydraulic pressure differentials, sediment susceptibility, and the localization of environmental triggers. However, deciphering this history requires the mitigation of several obscuring factors, as enumerated below.

**Interpretive Challenges**

1. **Poor Outcrop Quality**

As with any outcrop study, progress in Navajo soft-sediment deformation research is hampered by problems of outcrop quality, even in the extraordinary landscape of the Colorado Plateau. Exposure is fragmentary and incompletely extensive. Opportunities for three-dimensional analysis of large-scale SSD are relatively rare. Many outcrops do not display distinct sedimentary structures, because of faint or low-contrast coloration,
color patterns that do not follow sedimentary structures, and the obscuring presence of desert varnish, efflorescence, surface stains, etc. Such difficulties have played a prominent role in past misinterpretations of Navajo Sandstone facies – usually not, however, because field workers interpreted surficial features as primary structures; but because they failed to recognize subtly expressed features with critical interpretive significance. For example, Sanderson (1974) devoted much of his effort to establishing that contorted structures do represent deformed bedding, not liesegang banding, and that apparently massive sandstone facies also contain relict bedding, disrupted by deformation: “In surface exposures, indistinct-bedded sandstone appears to lack bedding of any kind, although grain characteristics are not different from those of the cross-bedded sandstones. Kiersch (1950) recognized the indistinct stratification and thought that it represented case hardening under the effect of weathering. Marzolf (1969) recognized it, considering it to be a primary sedimentary structure whose interpretation is environmentally significant, but he made no attempt to explain its origin . . . “(p 231). See comments by Gregory (1950) and Doe and Dott (1980) along similar lines.

Our primary mitigation strategy for this problem is to initially target outcrops with distinctly displayed structures. We find that this approach helps to define process/response dynamics that can then be applied to the interpretation of less completely or less vividly displayed SSD. Of course, not every obscurity can be circumvented in this manner. Some may eventually be penetrated through persistence and meticulous attention to detail; while others do not allow definitive interpretation and can only be accommodated by multiple working hypotheses.

2. Lack of Established Criteria for Interpreting Large-Scale SSD

As the study by Mahaney and others (2004) exemplifies, it is the recognition of slight differences in cementation and/or texture, marking ancient pathways of fluid flow, which often constitutes the most critical interpretive challenge. Visual effects produced by subtle differences in weathering characteristics across flow boundaries usually provide the most distinct evidence of these features; yet their identification is often constrained only by vague, qualitative comparisons or analogies to small-scale features with definitive expression at other locations. Subsequent chapters address this topic more
specifically; but an illustration of the dynamics of the problem merits consideration in the context of the current overview.

Figure 4A depicts an outcrop of the Entrada Sandstone where a very large-scale, upward spreading, pillar structure, defined by a distinctive fracture pattern and positive relief on the cliff face, underlies a lens of horizontally stratified deposits. In most respects, this feature resembles various arcuate structures commonly formed by stress propagation through eolian dune deposits, when undercut by erosion. This tendency toward conchoidal fracture patterns derives from the mechanical isotropy of the well-sorted, mineralogically homogenous, sandstone. However, that explanation does not adequately explain the field relations in this instance: this is not an abutment between alcoves, situated along an underlying discontinuity. Rather, pillar morphology matches the symmetry of the overlying deposits. Furthermore, multiple occurrences of a similar association, exemplified in the Wingate outcrop, shown in Figures 4B and 4C, suggest a genetic relationship rather than a merely fortuitous juxtaposition of fracture patterns and lithosomes. As is more readily apparent at the Wingate site, the pillar structure and lens of horizontal stratification are separated by a zone of convolute bedding that extends to limits closely approximating those of the other two elements. The mechanics of fluid escape (Lowe, 1975) provide a coherent explanation for these associations: deep-rooted seepage, near-surface fluidization, and surface deposition controlled by outflowing water. The morphology of the pillar structures is explicable in terms of fluidization dynamics in a localized flow of water, escaping through uncapped, permeable sand, which encounters decreasing magnitudes of confining pressure in the framework of grains as it approaches the ground surface. Sediment displacement is negligible in the lower part of the pillar, where horizontal stratification is apparently undisturbed. The flat-bottomed profile of the depression centered on the pillar structure and its abrupt occurrence along a broad interdune flat are not typical deflation features. They may derive from erosion by stream currents or mega-sand boils; though perhaps preferential compaction along the pathway of fluid flow better accounts for the observed architectural relations. As fluidized sediment settles, it re-packs in a tighter framework, representing a loss in original volume often exceeding 10% (Net, 2003; Stephens, 1985). This re-packing produces an amount
of water equal to the change in volume, augmenting the flow and enhancing the fluidization of successive regions of the deposit along the pathway of fluid escape.

The morphology of these large pillar structures strongly resembles that of small-scale fluid escape features described from non-eolian deposits (Ricci Lucchi, 1995). Comparably shaped small-scale features also occur in the Navajo Sandstone; though they are most distinctly developed at locations where fluid escape occurred across an impermeable boundary (for example, Figure 3 of Chapter III). However suggestive they may be, none of these ancient analogues yield definitive criteria for establishing the process/response significance of the Entrada feature. At this stage of the investigation, arcuate fracturing around the mechanical inhomogeneities introduced by the horizontal bedding is as plausible as any other hypothesis. A robust interpretation awaits a more comprehensive analysis of the feature, successfully placing this individual occurrence within a coherent regional pattern of fluid escape. Its proximity to comparably scaled pipe structures in the formation (Netoff, 2002) invites such an approach.

3. Lack of Lithofacies Indicators

Since recognizing the paleoenvironmental implications of SSD requires depositional context, any factor affecting the interpretation of primary architectural features impacts this process, as well. Several aspects of this relationship merit consideration in the present discussion, beginning with the problem presented by the lithological homogeneity of the formation.

Although varying depositional regimes in the Navajo Sandstone can be discriminated using formal methods of facies analysis (Miall, 1982), as demonstrated by Porter (Porter, 1985), at outcrop scale these methods provide less distinct characterizations of purely eolian accumulations than they do of other types of non-marine successions. Consider, for example, some key differences between eolian and fluvial facies, arising from the differing transport conditions in the two depositional environments. The channel and overbank facies associations encountered in fluvial systems correspond to conditions of confined and unconfined flow of a medium competent to erode and transport a broad spectrum of clast sizes. Since this flow naturally varies through time, it often produces deposits with wide textural variations and diverse stratigraphic successions, even at
outcrop scale. These fluvial parameters differ fundamentally from the far less competent transport medium and broadly effectuated flow conditions that characterize eolian systems. In large ergs, these produce a notably more efficient, strongly tri-modal sequestration of grain sizes. Source area lags may lie far upwind of saltated sand deposits, which lie upwind of the fines transported in atmospheric suspension. In the ancient record, loess deposits typically do not appear in the same outcrops as dune deposits. The interdune deposits that do appear, in some places, generally represent a sedimentary response to hydrologic controls that were superimposed upon the eolian transport regime (Havholm et al., 1993; Kocurek and Havholm, 1991), producing a broader range of facies variation and more extensive stratigraphic boundaries. This is why the most comprehensive genetic stratigraphies (Blakey et al., 1996; Kocurek, 1981a) have been developed from accumulations displaying mixed marine/eolian or fluvial/eolian influences. In a dry system, deflation surfaces typically constitute the only record of interdune processes.

The net effect of these unique qualities of eolian systems, for the interpretation of eolianite outcrops, is fewer lithofacies indicators. High resolution architectural studies (Miall, 1985) of eolian dune deposits must therefore rely more heavily on the analysis of bounding surface geometries and secondary structures, such as SSD features, with genetic ties to deposition and bounding surface formation.

4. Lack of Comprehensive Modern Analogues

Another class of difficulty in the use of Navajo SSD for paleoenvironmental interpretation is the shortage of appropriate modern analogues. This applies generally to Navajo deposition and accumulation and more specifically to the development of large-scale deformation features. No accumulations comparable in scale or depositional continuity are currently developing anywhere in the world. In the vast, dune-covered portions of the Sahara Desert, for example, few significant accumulations occur and large dunes typically migrate over the deposits of prior systems (Marzolf, 1988a). Present draa morphologies and erg patterns were inherited from more vigorous sand-transport regimes, associated with Pleistocene glacial maxima, and are not in equilibrium with current wind flow patterns (Kocurek, 1991). Modern deposits are thinner, architecturally
Figure 4: Large-scale (~100 m), upward-spreading, pillar structures centered below lenses of water-laid deposits within eolian successions. 4A: Entrada Sandstone along highway 89 south of Paria, Utah. 4B: Wingate Sandstone in Colorado National Monument. 4C: Indistinct stratification gives way to contorted stratification towards the periphery of the local zone of deformation.
dissimilar, and generally not accessible for examination in vertical cross-sections. Perhaps for these reasons, they have yielded no examples of large-scale SSD.

Some of the limitations imposed by disparities between modern and ancient eolian architectures can be overcome by extrapolations from downscaled natural examples or laboratory simulations. Others are more intractable. Perhaps the most important factor in the stabilization of modern dunes, for example, is climate. Precipitation has significant direct effects, but its greatest impact is the support it provides to dune-stabilizing vegetation (Marzolf, 1988a). In general, modern dunes experiencing high amounts of rainfall lose their mobility due to an invasion of highly adapted grasses and other forms of hardy vegetation that exercise a more persistent influence than the erosive winds promoting bedform migration. There is no evidence for dune stabilizing vegetation before the Cretaceous (Glennie, 1968; Loope, 1988; Marzolf, 1988a); so, in the instance of wet-climate dune processes, particularly, non-actualistic methods of investigation are required.

5. Diverging Theoretical Perspectives on Eolian Architecture

Besides limiting the development of specific process/response models, disparities between the depositional architectures of ancient eolianites and observable modern features also foster broader interpretive biases. Climbing bedform theory developed to its present state of detailed articulation (Allen, 1963; Brookfield, 1977; Kocurek and Havholm, 1994; Kocurek, 1980; Rubin and Hunter, 1982a) largely in response to the interpretive challenges presented by systematic architectural features of Colorado Plateau eolianites (Kocurek, 1991). The success of this perspective belies its lack of verification in full-scale modern systems. Workers with perspectives informed, primarily, by experience with modern systems tend to prefer outcrop interpretations representing less continuous processes of deposition and accumulation. Fryberger’s (1993) comments regarding the architectures of coastal eolian systems, ancient and modern, aptly illustrate this preference: “The author’s view of aeolian preservation, schematically outlined in Fig. 23, is of a world in which preservation of aeolian deposits is a highly fortuitous accident. In this view, a stack of aeolian sediments very often represents the bypassing or episodic deposition of considerable material; and seldom represents the product of
perfectly sequential large and small bedforms depositing well organized, neatly hierarchically arranged sets of bounding surfaces.” (p 180)

The potential complexity of interactions between sedimentary systems and primary controlling factors constitutes an interpretive challenge, even when the interval under scrutiny displays clear evidence of ongoing deposition. For example, interfingering of dune and interdune deposits in the Navajo Sandstone indicates that dune migration sometimes persisted under moist to flooded interdune conditions. Wet interdune facies may record fluvial input sourced from higher, wetter, locations; but it is also possible that Early Mesozoic ergs of the Colorado Plateau remained active in spite of high direct precipitation during wet climatic episodes, as is suggested by cycles of slumped foresets that have been described from northernmost Arizona (Loope et al., 2001). Large bodies of standing water would interrupt transport pathways; but dunes were not readily stabilized by vegetation during humid phases (Marzolf, 1988a). This increases the potential importance of autogenic factors in fluvial/eolian sedimentary cycles and renders the climatic interpretation of isolated sections problematical (Marzolf, 1988a). Does an increase in eolian facies toward the top of a specific section represent a drying upward climatic trend, opportunistic expansion of the erg when streams were diverted to another location by tectonics or by autogenic fluvial processes, or does it represent increasingly effective eolian diversion of fluvial systems as the erg relentlessly expanded?

Of course, differing perspectives on the development of eolian architectures are not, necessarily, mutually exclusive. However, the pragmatic demands of outcrop description almost inevitably elicit the organizational preferences of preconditioned biases: simplifying assumptions are required in order to reduce natural complexity to a manageable data set. To mitigate this type of bias, the studies reported here incorporated multiple working hypotheses and a research strategy that included follow-up visits to the study sites, at various stages of the interpretive process, in order to re-evaluate the outcrops with newly informed vision. Often, an emergent perspective indicated somewhat different priorities than were implemented in the original description of an outcrop, leading to additional data collection.
Complex Chronostratigraphic Relationships

The need to critically evaluate depositional continuity permeates any attempt to establish the chronostratigraphic distribution of SSD. This is particularly difficult in Navajo Sandstone depositional architecture, where diachronous erosional surfaces truncate laterally accreted cross-strata. No biostratigraphic divisions, chronostratigraphic markers, or through-going surfaces have been identified. Even the top and bottom of the formation represent diachronous processes: progressive erosional beveling and progressive erg development, respectively. Vertically successive diastems may originate from processes as direct as the migration of laterally successive dune troughs or as obscure as repetitive cycles of sediment accumulation followed by bypass and/or erosion. Evaluating the synchronicity of non-continuous SSD, therefore, depends upon the specific interpretation of depositional architecture. Under conditions of bedform climb, a single deformation event could have produced deformation features separated, vertically, by extensive diastems and laterally, by bedform periodicities exceeding a kilometer. It is also possible that multiple events could have affected the same body of sediment, though no systematic evidence for this type of complexity, among large-scale features, has yet been developed from ancient eolianites.

Useful criteria for establishing the event relationship of discontinuous SSD in individual outcrops of the Navajo Sandstone can be provided by high-resolution analyses (See Chapter IV); however the event correlation of widely separated features, in the absence of independent chronostratigraphic control, requires the development of more reliable genetic models (See Chapter V). This problem frustrated the attempts of previous workers to establish an event stratigraphy in the San Rafael Swell (Kiersch, 1950; Sanderson, 1974a; Stephens, 1985). These researchers recognized the occurrence of discrete intervals of SSD across very broad areas, which probably represent events or episodes of widespread soft-sediment deformation. Stephens (1985) even provided some interesting speculations on the influence of bedform spacing over the pattern of recurrence. Nevertheless, these studies did not establish any precise correlations nor did they demonstrate the impact of specific controls on lateral variations within these intervals. Peterson’s (1988a) pragmatic approach to using an interval of SSD as a means of approximate correlation suffers from the same limitations; though his work establishes...
the potential benefits of regional event correlation in the Navajo and the plausibility of his results tends to justify his simplifying assumptions.

The reported occurrence of regional supersurfaces (Kocurek, 1988) in easterly (Eisenberg, 2003; Verlander, 1994) and southerly (Blakey, 1994b) outcrops of the Navajo Sandstone raises the possibility of better opportunities for evaluating the chronostratigraphic significance of SSD. These extensive surfaces offer some degree of temporal control among the abundant deformation features in these regions. In the Echo Cliffs, for example, proposed supersurfaces representing episodes of enhanced fluvial activity (Blakey, 1994b) extend from a transition zone of alternating fluvial and eolian deposits into the main body of eolian deposits comprising the Navajo Sandstone in the Glen Canyon region. Ideally, these boundaries would represent a time when every part of the surface was simultaneously exposed: a paleotopography or an event horizon. However, even if they represent more diachronous processes, such as progressive erosion or sediment bypass above persistent water tables, they still hold chronostratigraphic significance, which can be developed through the accurate evaluation of their process implications. Perhaps the contrast between the temporal characteristics of SSD and such diachronous surfaces can itself be used to help characterize the regional architecture. For example, an extensive deformation feature, formed in a discrete event, may display various types of cross-cutting relationships with an erosional surface that developed progressively, over a protracted period of time: cross-cutting the surface in its older, buried reaches; deforming it, where concurrently exposed; and being truncated by it in areas subsequently exposed. Mapping out these relationships would reveal much about the nature of the accumulation history. The mere verification that such relationships do or do not occur will provide useful constraints on process interpretations of Navajo Sandstone architecture (See Figure 2).

6. Complex SSD Morphologies

The geometries of Navajo SSD are so complex and varied that mere description is a daunting task. Furthermore, even if the full range of morphologies could be catalogued, the interpretation of those features would not necessarily follow; because similar structures may originate along different process/response pathways: the progression of a
deformation event is affected by dynamic interactions between zones of liquefaction and surface loads, for example, as well as complexly defined initial conditions, such as the subtle permeability anisotropies constituted by every order of bounding surface in the depositional architecture (Lindquist, 1988; Sanderson, 1974a).

The primary strategy for dealing with morphological complexity, in the research reported here, was to reduce it by means of relatively simple process explanations. This approach requires the identification of important waypoints in the progression of each deformation event, starting with the depositional dynamics represented in the outcrop architecture, and proceeding along a pathway of causation defined by successive and cross-cutting relationships. Modeling of the process/response dynamics associated with each of those waypoints was achieved by postulating various interactions between key factors in the limited suite of probable controls. In essence, this approach simplifies the innumerable products of deformation into a manageable set of deformation processes, then searches for plausible pathways through which deformation dynamics may have proceeded to produce the specific morphologies evident in outcrop. This is an iterative process, which gradually tends to reveal the significance of deformation details, to uncover flaws in the theoretical framework of the analysis, and to identify important gaps in the evidentiary basis for interpretation provided by the outcrop.

Problems of scale limit the usefulness of laboratory simulations of SSD; however, numerical models may someday circumvent this limitation as well as those imposed by the lack of comprehensive depositional analogues and comparably scaled deformational analogues. The success of Rubin’s (1987a) approach to deciphering the complex depositional products of climbing bedforms provides encouragement in this direction. Ultimately, however, the usefulness of any such model depends upon the appropriateness of its simplifying assumptions, which themselves must derive from qualitative analyses of field relations, such as those presented here.
Interpretive Context

General Process Implications of Navajo SSD

In spite of the complexity of SSD in the Navajo Sandstone, fundamental theoretical considerations and commonly occurring field relations provide a basis for broadly characterizing certain aspects of their genesis, as enumerated below. These justified assumptions provide an interpretive context for the initial assessment of specific outcrops, enabling the efficient organization of diverse details into preliminary interpretations and testable genetic hypotheses. Not only do they help to focus attention on genetically significant characteristics of SSD, they provide a backdrop of explicit expectations against which the unusual aspects of individual features emerge more distinctly. The observations presented in subsequent chapters of this report exemplify these benefits.

1. Deformation occurred in distinct, geologically instantaneous events.

Deformation driven by fluid escape occurs during a finite history limited by the permeability of the sedimentary succession and the settling rate of the sedimentary particles composing the affected deposits. Except in cases where ongoing fluid flow is supported by regional groundwater input (See #3, below), active development of SSD cannot proceed on time scales of many years. Most subsurface features probably develop in hours or days (e.g. Chapter III, Figure 3). Surface deformations, such as footprints and small mass flows, can be completed in seconds.

2. Deformation events occurred episodically during the depositional history.

Erosional truncation of deformation features at numerous stratigraphic levels within the formation establishes the episodic nature of deformation events. Sanderson (1974) identified repetitive truncations of highly deformed intervals, represented by indistinct stratification; however, more definitive evidence appears in the less usual truncation of large-scale folds (Chapter III, Figure 4) and syn-sedimentary faults (Chapter III, Figure 5). Because of possible cryptic linkage between deformation features (See Chapter III, Figure 6), care must be taken to evaluate all available indicators to establish the stratigraphic limits of a deformation event.
3. Deformation affected saturated sediment and proceeded through processes of water escape.

Distinct evidence for all three processes of water escape from coarse-grained sediments, as summarized by Lowe (1975), appear in Navajo outcrops. Seepage can be inferred from the occurrence of stromatolites and tufa mounds (Eisenberg, 2003; Parrish, 2007); but fluid escape pillars (Chapter III, Figure 3; Chapter IV, Figure 17) provide more direct evidence. Unmistakable fluidization features appear at both small scales (Chapter III, Figure 3) and large (Chapter III, Figure 14). Liquefaction features, in the form of downwardly displaced passive markers, tens of meters below the surface of sedimentation (Chapter III, Figures 11-13), constitute some of the most enigmatic SSD in the Navajo Sandstone. Studies of cylindrical spring conduits in the eolian deposits of the Nebraska Sand Hills (Guhman, 1992) demonstrate that sand can be maintained in a fluid state for long periods of time, to depths up to 44 m, by concentrated groundwater movement (Terzaghi, 1967). However, the deformation pattern under consideration, here, does not conform to a sustainable fluidizing flow of upward-directed fluid escape; though it is apparent that a large volume of liquefied sediment must have maintained its fluid condition throughout the duration of the large displacements. In these instances, particularly, it appears that deformation was initiated by the collapse of underconsolidated sediment, at depth, followed by fluidization of associated sediment, within preferred pathways of fluid escape from the de-watering mass.

4. Deformation morphologies were influenced by the location of the affected deposit relative to dune topography in the ancient erg.

The deformation of bedform cross-strata by storm-induced slumping (Loope et al., 1999; Loope et al., 2001) represents a readily interpreted example of topographic control on deformation distribution. Previous workers generally agree that foresets preferentially deformed in the direction of dune migration also indicate the action of topographic control, though various opinions have been expressed on how this control may have operated (e.g., Kiersch, 1950; Horowitz, 1982; Rubin and Hunter, 1988). Chapter V of this report analyzes those different views relative to SSD in the Horowitz (1982) study.
area in Nevada. Chapters III and IV present new outcrop data regarding topographic controls on broader patterns of SSD distribution (Horowitz, 1982; Stephens, 1985) and their relationship to large-scale mass flow deposits (Chan, 2007; Eisenberg, 2003).

5. *The distribution of SSD in the Navajo Sandstone represents the overlapping influences of various susceptibility factors and triggering events.*

As noted previously, the loose packing of eolian dune deposits (Bagnold, 1954) make them particularly susceptible to liquefaction and fluidization (Allen and Banks, 1972). Natural packing arrangements typically produce void ratios in the 40-50% range, with the higher values occurring in grainflow deposits (Hunter, 1977; Pryor, 1971). This represents an unstable, underconsolidated condition (Casagrande, 1936) with respect to the various static loads and/or shear stresses that affected these sediments after deposition. Sediment saturation increases intergranular cohesion (Namikas, 1995); but it also provides a means for applying additional stress, through high pore pressures and directional pore fluid flow regimes. The grain size of Navajo dune deposits falls in the range most suitable for liquefaction/fluidization effects, as well (Lowe, 1975). The fine sand of the Navajo is coarse enough to maintain high void ratios, yet has low enough permeability to sustain high pore fluid pressures (Casagrande, 1936), especially since the minor amount of fine-textured material is concentrated along bedding surfaces (Sanderson, 1974). The relative density of sedimentary layers can also impact liquefaction susceptibility (Seed, 1978); however, the uniformity of Navajo petrology removes this factor from consideration in analyzing SSD distribution patterns.

Susceptibility factors, alone, can explain major trends in the distribution of SSD within the Navajo Sandstone, without recourse to the potential effects of various environmental triggers. The importance of sediment saturation is signaled by the preferential occurrence of deformation features in the vicinity of fluvial or lacustrine deposits. Following this association, they are commonly found at the base of the formation and towards the southern and eastern margins. The abundant deformation features of the Glen Canyon region, for example, can be explained on this basis; but the association also appears in locations such as Red Rock Canyon, Nevada, and Capitol Reef, and the San Rafael Swell, in Utah. Even the Navajo Sandstone of Zion National
Park, which is characterized by the regularity of its cross-bedding, shows some deformation, associated with interdune deposits in the lower part of the formation (Figure 5). The well-known SSD along Highway 89, north of Kanab, just east of Zion, is all associated with a zone of large-scale intertonguing between the Navajo and Kayenta formations. Significantly, however, fluvial deposits at these locations do not display large-scale SSD. Clearly, the combination of sediment saturation with sediment underconsolidation is required for large-scale features to develop. This is borne out, at outcrop scale, by the preferential occurrence of SSD in grainflow deposits, over the more densely packed climbing ripple and grainfall deposits, as observed by various workers (Allen, 1972a; Doe and Dott, 1980; Finn, 1971; Fryberger, 1979; Horowitz, 1982).

Other trends in distribution suggest that factors in addition to sediment saturation and underconsolidation must also have contributed to the development of deformation features. For example, SSD appears throughout the Navajo section on the Paria Plateau. It is more dramatic, more abundant, and more stratigraphically persistent there than it is to the southeast, in the Echo Cliffs, where a thick interval of fluvial/eolian transition, containing abundant, large-scale grainflow deposits, is continuously exposed for tens of kilometers. Doe and Dott (1980) argued that shear stresses developed by burial pressures or water table gradients may be sufficient to induce liquefaction; but neither of these factors appears to adequately account for contrasting trends in SSD occurrence between the Echo Cliffs and the Paria Plateau. Unevenly distributed, seismic triggering events could account for such anomalies; however, no correlation has yet been attempted between trends in the distribution of Navajo SSD and the location of Early Jurassic structural elements.

General Paleoenvironmental Implications of Navajo SSD

1. Water tables fluctuated dramatically in the Navajo erg(s).

As described in previous sections of this report, the intertonguing of fluvial and eolian deposits and the uneven distribution of interdune pond deposits, clearly indicate varying relationships between interdune surfaces and the water table in the Navajo erg(s). SSD extend this evidence beyond the limits of subaqueous deposition by providing evidence for successive dry and saturated sub-surface conditions during the depositional and early
diagenetic history of cross-stratified deposits. According to established criteria, avalanche strata could only have been deposited as dry sand (Hunter, 1976; Hunter, 1977), deformed while in a saturated condition (McKee et al., 1971; McKee et al., 1962a; McKee et al., 1962b; Rettger, 1935), and deflated while unsaturated (Opdyke, 1960; Peirce, 1964; Stokes, 1968). These small-scale water table fluctuations are mirrored by larger-scale patterns recorded in successive intervals of truncated deformation features, representing repetitive cycles of saturated and unsaturated conditions during an overall rise in the water table within the accumulation. Fluctuations at even larger scales are indicated by other architectural associations between deflation surfaces and saturated-sediment deformation features or subaqueous deposits: superscoops (Blakey, 1988b), for example, commonly contain sediment deposited in damp or wet environments; but they are initiated by localized deflation that often cuts tens of meters into the accumulation, which itself may exhibit signs of prior saturation. The paleohydrological implications of these features are explored in more detail in Chapter V of this report.

2. Seismic shaking episodically affected portions of the Navajo erg(s).

Previous workers generally agree that seismic triggering events were important in producing Navajo SSD. This is a key feature of the Horowitz (1982) model, for example. Doe and Dott (1980, p 799) observed that, “Although upward seepage of groundwater (Terzaghi and Peck, 1967) can cause liquefaction under unusual natural circumstances, the most commonly cited source for high pore pressures is cyclic loading. Seed and Lee (Seed, 1966) showed in triaxial tests of loose sand under undrained conditions that cyclic loading causes an incremental increase in pore pressure with each cycle, which eventually leads to failure.“

As noted earlier, the Navajo Sandstone was deposited in an active foreland basin (Allen et al., 2000) and various angular relationships at the unconformities defining the allostratigraphy of the Glen Canyon Group testify, generally, to a seismically active environment (Peterson, 1994). In addition, field evidence supporting the seismic triggering hypothesis for Navajo SSD can be seen in: the episodic nature of deformation events; their wide areal distribution; and the lack of deformation features in deposits of
Figure 5: Deformed Navajo strata along the Canyon Overlook Trail in Zion National Park. The upper photo shows an upturned interdune stratum and subsequently emplaced, climbing foresets. The lower photo shows much shorter wavelength compressional features.
comparable susceptibility at other locations. Furthermore, the occurrence of SSD whose extents surpass the likely wavelength of eolian bedforms, whose fold morphologies display diverse directionality, and whose upper transition into undeformed foresets occurs below the set boundary (See chapter V) clearly indicates that, at least in these instances, surface processes (static loading, flooding, impacts, etc.) did not trigger deformation. More specific seismic interpretations, regarding earthquake magnitude and epicenter proximity, are hampered by the lack of modern analogues for scale and permeability factors. Various sites examined during the reported research offer some relief from this limitation (Chapter III, Figure 3; Chapter IV, Figures 14-21) by focusing on meter-scale fluidization features occurring in interdune settings where sandstones underlie impermeable carbonate caps. These features are more directly comparable to those described from modern seismic zones (Obermeier, 1996b; Obermeier, 2004).

3. **Deformation events modified topography and altered depositional processes.**

The cyclic, lee-side storm deposits described by Loope and others (2001) provide evidence of small-scale interactions between deformation and deposition. Comparably distinct examples appear in other settings and at larger scales, as well. The association of liquefaction, fluidization, and clastic injection features, culminating in sand volcano production at the surface of an interdune pond deposit in Navajo Canyon (Chapter III, Figure 3), constitutes clear evidence of subsurface/surface interactions during a Navajo deformation event. More diverse features with less obvious connections appear in outcrops in West Canyon, Arizona, as described in Chapter V of this report. The impact of a well-constrained deformation event on interdune sedimentation, also represented in West Canyon outcrops, is detailed in Chapter IV. These instances provide extraordinarily distinct views of causal relationships between deformation and sedimentation, which are otherwise suggested by multiple occurrences of fluid escape features underlying water-laid sediments or mass flow deposits. Ongoing research along these lines is aimed at interpreting an unusually well-exposed complex of large-scale features, representing dramatic topographic alteration and catastrophic sedimentation, which can be viewed from the observation deck of the visitor’s center at Glen Canyon Dam (Chapter III, Figure 13).
Summary

As the petrologic record of sensitive responses to fast-acting processes of fluid escape, soft-sediment deformation features in the Navajo Sandstone provide temporal control for high-resolution event interpretation of individual outcrops. This function proves especially useful in outcrops where architectural relations indicate the involvement of surface processes in a deformation event. Navajo SSD also provides indications of sediment saturation and seismic activity during discrete episodes of the depositional history. These specific indications, not represented in other proxy data, can uniquely inform the reconstruction of contemporaneous climatic and tectonic controls.

This report does not exhaustively catalogue the author’s thesis research. It does provide useful applications of the methods and theoretical contexts developed in this chapter. Chapter III presents outcrop evidence supporting the generalizations about Navajo SSD, made here. Chapter IV presents an example of a detailed study of a specific deformation site. Chapter V applies observed field relationships and their process interpretations to the development of a general model for SSD in the Navajo Sandstone. Chapter VI briefly outlines the implications of this study for future work.
Abstract

The Navajo Sandstone of the Colorado Plateau, USA, displays a wide range of soft-sediment deformation features, including decameter-scale features that have not been found in any modern desert environment. Laboratory simulations and partial analogues from other depositional environments suggest that these features derived from episodic liquefaction and fluidization of unconsolidated dune deposits.

Outcrop details at many locations preserve the effects of fluid escape dynamics through porous, permeable, well sorted sand, which was partitioned by subtle textural changes at depositional boundaries between successive dune deposits and, less commonly, by distinct lithofacies changes marking the interface between wet and dry depositional environments. Extreme deformation and turbulent sediment flow have effaced primary structures in some zones of deformation; but other sites preserve the ductile modification of primary structures. Some outcrops preserve evidence of dramatic alterations in topography and sedimentation patterns due to localized compaction and large, subsurface, sediment displacements. Particularly notable among these extraordinary features are those representing the foundering of active dunes, sediment eruptions, and the subsidence of interdune surfaces in the ancient erg.

The distinctive patterns of deformation in the Navajo Sandstone, interpreted in the context of its primary sedimentary architecture, provide unique insights into environmental conditions in the region during the Early Jurassic. Widespread ductile deformation in the Navajo indicates extraordinarily wet conditions for an active dune environment. The truncation of successive deformation features by deflation surfaces establishes the episodic nature of deformation in the unit and also suggests climatic variability. The widespread, episodic occurrence of soft-sediment deformation features, viewed within the seismic context provided by paleotectonic reconstructions, strongly suggests that earthquake triggering of localized liquefaction controlled the distribution of deformation in this unit.
Introduction

Unconsolidated sedimentary deposits may be deformed, generating sedimentary structures by “soft-sediment deformation” (SSD). This commonly occurs due to weak, often transitory, stresses in the shallow subsurface deriving from gravity, seismic activity, and/or hydraulic pressure. SSD occurs at a broad range of scales and has affected sedimentary deposits of all ages and depositional environments. Newsom (1903) first reported evidence of subsurface sediment re-mobilization from ancient eolianites of the Colorado Plateau over a century ago (Newsom, 1903). His commentary on pipe structures in the Middle Jurassic Entrada Sandstone has been greatly supplemented by recent studies of those features (Netoff and Shroba, 1995; 2001; Netoff, 2002; Huuse et al., 2005) and reports of a broad range of other deformation structures, from a variety of Late Paleozoic to Jurassic eolian sandstones exposed in the region (Chan et al., 2007). The more recent studies benefited from numerous laboratory experiments with deformation processes that provided essential interpretive criteria; such as the critical role of saturation in the initiation of convolute deformation morphologies in sand (Rettger, 1935; McKee, et al., 1962a; b; McKee et al., 1971) and the pervasive influence of fluid escape on their development (Lowe, 1975). However, SSD in Colorado Plateau deposits frequently occurs at scales of tens to thousands of meters (Chan et al., 2007), so comprehensive simulation of deformation dynamics cannot be achieved in the laboratory. Furthermore, modern dune sediments have not provided analogues for any of the large-scale features, so interpretation of these ancient structures depends upon the reconstruction of fundamental processes and specific environmental conditions evidenced in subtle facies variations and complex stratification geometries. Fortunately, the outcrop record is very good. Structural deformation is minimal, and the rocks are exposed in sections tens of meters high along cliffs up to several kilometers in length, with little vegetation cover, providing ample opportunity for analysis.

Previous workers in the Navajo Sandstone emphasize the key role of liquefaction (Seed, 1968) in deformation of that eolian unit. That is, deformation was driven by ephemeral spikes in fluid pressure, derived from the rapid reorganization of loose sedimentary packing, under water-saturated conditions (Doe and Dott, 1980). Most large-scale deformation events were probably triggered by earthquakes (Horowitz, 1982); but
liquefaction was the initial stage in a suite of processes associated with de-watering. Subsequent stages included seepage (Lowe, 1975), involving the upward movement of fluid through existing pore spaces, and fluidization (Soo, 1967), which causes grain packing to loosen and pore volumes to increase by the movement of pressurized fluid. These processes have been conceived as working in concert to produce a succession of rapidly evolving stress fields, which interact with more stable elements of the depositional environment to produce unique deformation morphologies and topographic anomalies. The dynamics of sand deformation respond to local variations in sediment properties (such as mechanical strength, porosity, and permeability) and the distribution of static stresses. Because of the complexity of the interactions between these controls, the interpretation of deformation structure geometries must proceed in conjunction with the analysis of the sedimentary architecture of the host deposits.

Analysis of eolianite SSD yields information about the depositional environment that can greatly supplement the otherwise non-distinctive lithologic data available from these unusually homogenous deposits. Deformation structures may record the occurrence of earthquakes, storms, or other high-energy events. They may indicate the position of the water table at the time of deformation. Their event characteristics provide a means to evaluate the frequency of environmental triggers and may also facilitate correlation (Peterson, 1988a). Furthermore, the nature, size, and distribution of SSD constrain the reservoir characteristics of the host deposits, affecting the movement of both water and hydrocarbons (Net, 2003). However, the interpretive criteria necessary to extract environmental information from SSD and extrapolate those data throughout the reservoir are at present poorly developed. Because deformation morphologies vary widely and are typically very complex, their usefulness can only be fully realized when the effects of specific deformation mechanisms can be recognized as having acted within a particular configuration of environmental parameters. Current classification schemes, even those targeting a narrow range of deposits (Chan et al., 2007) are often too generic to provide guidance for a reliable process interpretation. More detailed criteria may not apply across formation boundaries, even between lithologically similar deposits. For instance, the primary author’s reconnaissance during the last ten years indicates that SSD structures in the eolian Navajo and Entrada Sandstones differ markedly in size, distribution, and
morphology in spite of the close affinities of their depositional environments. The overlap in deformation styles that is apparent can be attributed to common dynamics of fluid escape. The environmental significance of the disparities will only emerge by comparative analysis. In order to achieve this, the distribution of SSD must be mapped and a database of distinctive case examples developed for each unit.

The present work partially fulfills this need by providing a succinct primer on the interpretation of SSD in the Navajo Sandstone, which was episodically deformed at numerous locations as deposition proceeded in the Early Jurassic. The sites described in this report provide illustrative examples of the opportunities and challenges for the interpretation of SSD in eolianite outcrops of the Colorado Plateau. Site data are documented photographically and presented with interpretive labels, captions, and line drawings that exemplify the methods of process-based architectural analysis applied by the authors. They are presented, here, to provide a sample of the diverse remobilization features that occur in these deposits and to demonstrate the information potential of SSD in eolianites with good outcrop exposure.

**Geologic Setting**

The Navajo Sandstone, a formation of the Glen Canyon Group (Peterson, and Pipiringos, 1979), stretches some 1000 km, north to south, and 400 km, east to west. It is only an erosional remnant of the extensive eolian system that accumulated hundreds of meters of sand in a broad, shallow, retro-arc foreland basin (Figure 1) during the Early Jurassic. In comparison, dunes of the modern standard of large-scale eolian deposition, the Sahara Desert, extend over a comparable area, but typically occur above bedrock surfaces or meter-scale accumulations (Marzolf, 1988). Some of the sediment for the extraordinary Navajo deposits was delivered by streams flowing off of proximal highlands to the east and to the south (Luttrell, 1996). Gradational and intertonguing transitions between fluvial Kayenta and eolian Navajo deposits (Blakey, 1996) clearly indicate the local interplay of wet and dry systems; however, detrital zircon analyses suggest that the bulk of Navajo sand came from further east (Dickinson and Gehrels, 2003). Apparently, a trans-continental fluvial system transported enormous volumes of sand to
Figure 1 (Previous page): Figure 1A outlines current field relations, in the American Southwest, between major features produced during the early Jurassic (Blakey, 1994; Peterson, 1994; Dickinson and Gehrels, 2003). The tadpole symbols plot paleocurrent measurements: the lines represent average foreset dip directions (generally from > 10 measurements), in sections located at the positions indicated by the associated solid circles (Peterson, 1988b). Figure 1B presents a generalized cross-section across the thickest part of the preserved Navajo accumulation (Blakey et al., 1988). The Kayenta Formation, underlying the Navajo, is a predominantly fluvial deposit, with isolated eolian and lacustrine units. The overlying formations - separated from the Navajo by a major unconformity - encompass a broad range of nearshore facies, including extensive eolian units very similar to the Navajo. Figure 1C maps the locations of the detailed studies represented in this report. These sites all occur within a broad area preserving a gradual – and highly punctuated - transition from fluvial to eolian deposition. GPS coordinates for specific features at these sites appear within the figure captions.

Figure 2 (Next page): This outcrop in Zion National Park, Utah (N37.4020° W122.0803°), illustrates the most common depositional architecture of the Navajo Sandstone. It shows successive sets of distinct, large-scale, cross-strata with remarkably uniform dip directions. The larger foresets display tangential basal contacts and small plinths. Horizontal stratification indicative of interdune deposition is conspicuously absent along the deflationary bounding surfaces separating crossbed sets. The spindly pine tree in the middle foreground is about 20 m tall.

Figure 3 (Subsequent page): This sandstone section in Navajo Canyon, Arizona (N36.87458° W111.22645°), includes a 0.5 m thick carbonate lens, representing deposition in a persistent interdune pond. The carbonate horizon is underlain by pillar-like fluid-escape structures. Very distinct indications that sand was liquefied and injected into the overlying material appear in association with these features. These include a sandstone dike cutting through the entire thickness of the carbonate cap, culminating in a sand volcano at the paleo-surface (3B). Note the abundance of carbonate clasts within the sand volcano (3C). The low-angle dip of its flanks (3B) suggests an underwater eruption and the marked asymmetry of the feature indicates the action of currents, which may have been generated during the deformation event. Sand-through-sand clastic injection features are particularly well displayed at the site shown in 3D and 3E, which lies to the left of the field of view in 3A, within the same interval. Here, the color contrast between orange injected sand and the host bed of red sand provides an unusually distinct record of deformation processes. The color difference is due to a slight enrichment of fines in the red bed, apparently derived from eluviation of the underlying deposit. The size of features in 3B and 3E can be derived from the scaled fields of view in 3C and 3D.
flood plains and strand lines north of the present-day Colorado Plateau, from the late Paleozoic through middle Jurassic Appalachian orogen of eastern North America (Johansen, 1988; Marzolf, 1988). Persistent winds to the south redistributed these sediments into the extraordinary array of mature sandstone bodies that we see today (Parrish and Peterson, 1988; Peterson, 1994).

The lithology of Navajo dune deposits varies little from a quartz arenite composition and a well-rounded, well-sorted, fine-to-medium sand texture (Uygur and Picard, 1980). The typical stratigraphic architecture of the Navajo Sandstone, produced under dry interdunal conditions (Kocurek, 1981; Kocurek and Havholm, 1993; Havholm and Kocurek, 1994), consists of successive crossbeds separated by erosional bounding surfaces, as exemplified in the bulk of the Zion Canyon section (Figure 2). Such deposits are devoid of large-scale deformation structures. Outcrops displaying fluvial/eolian interactions or interdune deposits of any kind are those most likely to contain penecontemporaneous deformation features. This distribution accords with experimental indications that sediment saturation is a prerequisite for large-scale ductile deformation (Rettger, 1935; McKee et al., 1962a; b).

**Observations and Interpretations**

In general, the patterns of strain in soft-sediment deformation features of the Navajo Sandstone are very complex, representing the coupled responses of sediment and interstitial fluid to rapidly evolving stress fields (Lowe, 1975) initiated by seismic tremors (Horowitz, 1982) or other environmental triggers (Doe and Dott, 1980). Under favorable conditions, however, much can be learned about deformation dynamics from a close examination of their products. Figure 3 illustrates such circumstances at an outcrop in Navajo Canyon containing interdune pond deposits, which constitute exceptional permeability barriers in the well-sorted sandstone. At some sites, interdune deposits also provide persistent marker beds through volumes of rock where strain has effaced the more subtly defined cross-strata.

The outcrop details presented in Figure 3 represent rapidly evolving conditions of liquefaction and fluidization such as those produced in modern deposits by seismic tremors (Obermeier, 1996; Obermeier et al., 2004). In particular, the eruption of liquefied sand through an overlying horizon of impermeable mud, shown in 3B and 3C, represents a well-known association from the New Madrid Seismic Zone. The sand volcano produced in this event has very low-angle flanks, suggesting that the sediment eruption occurred underwater, while the
interdune was still flooded. Sand-through-sand clastic injection features are particularly well displayed at the site shown in 3D and 3E, within the same interval. The extraordinary color contrast between the host and injected materials in this outcrop supports a detailed interpretation of progressive fluidization. It appears that water from the injected body of sand escaped into the surrounding sediment, simultaneously consolidating the injected body and fluidizing the host sediment. This explains the brittle nature of the secondary deformation: one appendage of the injected body of sand was fractured off as the fluidized host sediment lost its cohesiveness.

Most deformation morphologies are not so readily interpreted as the meter-scale structures in Navajo Canyon; however, diverse patterns of strain may hold less significance than other, less complex aspects of these features. For example, convolute stratification is often truncated by a deflation surface (Figure 4). This cross-cutting relationship indicates fluctuating groundwater conditions in the ancient desert: The sand was dry when it was deposited (Hunter, 1976; 1977; 1980), saturated when it deformed (McKee et al., 1962a), and dry again when it was deflated, since wet sand is too cohesive to be eroded by the wind (Opdyke and Runcorn, 1960; Cornelis et al., 2004).

Brittle deformation features overlying zones of liquefaction indicate even more precisely the position of the water table during deformation events (Figure 5). Erosional truncation of both faults and folds establishes that deformation occurred episodically during the depositional history rather than simultaneously after accumulation was complete. These cross-cutting relationships can be used to establish the relative history of deformation events and hydrological conditions that characterizes a section. To arrive at valid interpretations of outcrops displaying SSD at multiple intervals, however, particular care must be taken to establish the limits of individual events (Figure 6). The three-dimensional intricacies of an injection complex are difficult to predict and cannot always be narrowly determined based on available evidence.

Not all deformation features are contained within individual sets. Some cut through successive boundaries; though it is clear that the subtle concentration of fines along bounding surfaces constrained fluid flow, affecting deformation morphologies (e.g., Figure 6). The involvement of multiple units in a single deformation event demonstrates the occurrence of deformation within the accumulation up to 80 m below the depositional surface and the base of overlying dunes. However, some of the deformation occurred across the depositional interface: in the shallow subsurface and within active bedforms. The Navajo Canyon features pictured in
Figure 4: At this site near Moab, Utah, the upper arc of contorted eolian dune foresets has been truncated by a planar deflation surface, where the field worker is seated. This relationship establishes that deformation occurred during the depositional history, in concert with water table fluctuations. Note also the abrupt transition between contorted and undeformed foresets in the lower right of the photograph, which testifies to a delicate balance between the forces driving deformation and susceptibility factors. This transition does not occur along a permeability barrier. It formed across the continuous deposits (crossbeds) of a single dune, responding to a stress field defined by event dynamics and influenced by a dunefield topography whose instantaneous specifications cannot be reconstructed in detail.
Production of Lower Deformation Features

1. Migrating Dune
   - Wind Direction
   - Accumulating Deposits

2. Deformation of Bounding Surface
   - Zone of Liquified Sand
   - Primary Fluidization

3. Dune Collapse
   - Secondary Fluidization

4. Subsequent Dune
   - Deflation ofCollapsed Dune
   - Ongoing Accumulation
Figure 5 (Previous page): Based on experimental studies of the role of saturation in the deformation mechanics of sand (Rettger, 1935; McKee et al., 1962a; b; McKee et al., 1971), the transition between ductile and brittle deformation evident in this outcrop at North Coyote Buttes, on the Utah/Arizona border (N37.00528° W112.00904°), may be understood as marking the water table that was contemporary with deformation. Note that the deflation surface that truncates the syn-sedimentary faults is planar, having formed after deformation of the underlying sand, then buried beyond the reach of the later deformation event that affected the sediments now exposed at the top of the outcrop.

Figure 6 (Next page): Within the field of view represented by the white rectangle, at North Coyote Buttes, Utah (N37.01035° W112.00945°), 5 successive sets of crossbeds contain apparently isolated deformation features. However, the larger perspective reveals that at least 4 of these units were affected by the same event. The continuity of the deformation features can be followed across set boundaries and through intervening zones of undeformed foresets, in the larger view. These cryptic connections not only indicate complex event dynamics; but also reveal the influence of subtle permeability barriers on deformation morphologies. This influence is specifically indicated by the attenuation of deformation features against a portion of one set boundary (inset), where the tighter packing of toset sedimentation, along with a slight concentration of fines, sufficed to inhibit peripheral fluidization.
Figure 3 provide clear examples of this, and various other features support that view. For example, differential compaction around bodies of injected sand, at a site in West Canyon, indicates that deformation occurred in the shallow subsurface, shortly after consolidation of carbonate muds, and before they were fully compacted (Figure 7). In an associated body of intraclast-rich sandstone, just above the carbonate lens, two protosuchids were found in close proximity. These primitive crocoddilians were apparently entombed during the deformation event that produced the matrix around their fossil remains. The close proximity of their occurrence, the preservation of delicate articulations (Figure 8) through turbulent sediment displacement, and the absence of other fossil fragments or extra-clasts suggest that these creatures died when trapped in sand that liquefied during the deformation event. Preservation of scute and gastralial arrangements during deformation indicates that soft tissues were present both during burial and during the deformation event that produced the intraclasts within their sandstone matrix. That two, similarly well-preserved fossils occur at the same location, within an intraclast-rich matrix, strongly suggests that death and burial occurred simultaneously during liquefaction of the underlying sand. This taphonomy of the fossils and the association of diverse features produced during the deformation event (Figure 9) enable a detailed reconstruction of topography and facies relationships, for a moment in time, at this location in the ancient erg (Figure 10).

Two kilometers away from the fossil locality, subsurface deformation produced a sinkhole, 20 m deep, which was filled by mass flow deposits, initially, then a succession of interdune deposits (Figure 11). Comparably scaled interdune subsidence explains the pattern of interrupted carbonate sedimentation depicted in Figure 12; though in this case it appears that the former interdune surface was covered with fluidized sediment as it subsided so that no major topographic depression formed. Mapping the architecture of these and other distinctive sites (Figure 13), provides detailed information about groundwater conditions and deformation dynamics at specific locations within the Navajo erg and reveals a broad range of relationships between deformation, sedimentation, and erosion (Figure 14).
Figure 7: At an outcrop in West Canyon, near the Utah/Arizona border (N36.98695° W11112716°), numerous, intraclast-rich, sandstone injectites occur within a 0.5 m carbonate lens. Differential compaction around the injection features indicates that they were emplaced in a near-surface environment, where the intraclast-producing carbonate mud was consolidated, but minimally compacted. Vugs within the sandstone body occur where soft intraclasts of shale and carbonate have been preferentially eroded.
Figure 8: Two Protosuchus fossils were found within a matrix of intraclast-rich sandstone at the West Canyon study site, about 200 m south (right in the photo) of the features pictured in Figure 9. The fossils consist of a well-preserved bed of articulated ventral scute impressions; numerous articulated and disarticulated scutes, all presented in the ventral aspect; several partially articulated vertebrae; a complete set of gastralia; and other material not pictured here. The taphonomy of these fossils indicates that death and burial occurred during the same event that produced the various deformation features at this location.

Figure 9: Downdropped beds, above and to the right of the 1.5 m stick, leaning against the same West Canyon outcrop featured in Figure 7, provide distinct definition to a vertical pathway that leads from an underlying pillar structure to contorted cross-strata, 6 m above. A similar association of pillar structures with vertical fluid escape pathways occurs in several places across this portion of the outcrop. Alcoves on either side of the pillars contain erosional remnants of deformed, shaly siltstone. The inset provides a schematic of postulated fluid flow pathways relative to the labeled features of the photo.
Figure 10: The event association of diverse features observed in the West Canyon outcrop enables an unusually detailed reconstruction of local facies relations and topography at a moment in the early Jurassic.

Figure 11 (Next page): Mapping the facies architecture of deformation features in the Navajo Sandstone provides a basis for detailed event interpretations, particularly when deformation can be seen to have affected depositional dynamics. This site in West Canyon, Utah (N36.99733° W111.13518°), exposes a record of decameter-scale subsidence, caused by subsurface liquefaction and fluidization, followed by a complex fill history.
1. Depositional surface conforming to underlying structure.
2. Foresets variously: a. contorted; b. effaced; c. oversteepened to 45 degrees; and d. flattened to as little as 10 degrees.
3. Initial mass flow deposit.
4. Successive mass flow deposits.
5. Lacustrine carbonate over finely bedded sandstone.
6. Eolian dune deposit.
7. Succession of sandstone and mudstone deposits.
8. Extensive, capping beds of sandstone and mudstone,
9. Large-scale dune foresets, dipping 27 degrees, to the SE.
Figure 12: This outcrop in Navajo Canyon, Arizona (N36.89619° W111.26348°), exposes a record of interrupted sedimentation in an interdune pond. The early formed carbonate lens subsided during a deformation event and was simultaneously covered by liquefied sand. Ongoing, post-deformation, carbonate deposition within the interdune pond is represented by the upper, undeformed lens, which joins the downdropped carbonate above undeformed sandstone to the right.
Figure 13: Dramatic deformation features below the bridge abutment on the east wall of the canyon, at Glen Canyon Dam, Arizona (N36.936620° W111.481993°), appear in distinct contrast to the undeformed architecture of the overlying section. The products of two distinct deformation events are prominently displayed in this section. The earlier event occurred during accumulation of the lower half of the scaled section. The later event appears to have partially effaced the prior deformation features and affected the entire 80 m section scaled in the photograph; though this represents an extremely unusual depth of liquefaction, based on theoretical expectations, modern analogues, or comparable outcrops. See 1-3 of Figure 13B (next page) for a detailed interpretation of the earlier event. Figure 13B-4 is a reconstruction of the sedimentary architecture prior to the later deformation event.
Figure 13B.

1. Wind Direction
   - Migrating Dune
   - Water Table
   - Accumulating Dune Deposits
   - Fine-grained Horizontally Stratified Interdune Deposits

2. Fluidization of Dune Interior
   - Eruption of Fluidized Sand
   - Fluid Escape through Aquitard
   - Liquifaction below Aquitard

3. Renewed Dune Migration
   - Sagged Bounding Surface

4. Area Affected by Later Deformation Event
   - Onlapping Sets of Crossbeds
   - Outflow Deposits
   - Indistinct Stratification
   - Sagged Bounding Surface
   - Subsequent Medium-Scale Crossbed Sets
Figure 14: The original volumes of most outflow deposits in the Navajo Sandstone are not preserved, due to subsequent wind erosion. The thickness of the fluidized zone in this outcrop in Glen Canyon, above Lake Powell, is about 20 m. Though distinct evidence for voluminous, upward-directed fluid movement is preserved, the impact on contemporaneous surface topography is not apparent.
Discussion
Among the products of SSD in the Navajo Sandstone, similar patterns of subsidence (Figures 11 and 12) and fluid escape (Figures 13 and 14), produced during different deformation events, point towards a relatively small set of deformation mechanisms, as suggested by other workers. The specific diversity of deformation products, on the other hand, suggests that deformation proceeded in sensitive response to subtle environmental variations. Clearly, sedimentary architecture exercised important controls (Figures 3, 6, 9, and 10), as did the configuration of the water table (Figures 5, 9, and 10). Topographic controls, specifically the modification of subsurface stress fields by differential dune loading, have been invoked by previous authors to explain the preferential deformation parallel to foreset dip that commonly occurs (Horowitz, 1982; Rubin and Hunter, 1988). The architectural evidence from North Coyote Buttes (Figure 5) corroborates this line of reasoning. Presumably, the depth, spacing, and relative timing of multiple centers of liquefaction, during single widespread events, also exercised important control on deformation morphologies. However, this can only be established by a more ambitious program of high-resolution studies, coupled with regional correlation of deformation features, than has been attempted to date. Until that takes place, the more apparent associations of liquefaction and fluidization (Figures 3D and 3E) may provide the best indicators of the possibilities for interaction between independently initiated liquefaction zones.

The process interpretation of SSD typically proceeds with less difficulty at sites where deformation was limited to the scale of the Navajo interdunes, up to about 1 km. Larger features are more difficult to map, especially since critical transitions more often descend into the subsurface or cannot be correlated with other products of the same event (Kiersch, 1950; Sanderson, 1974). Where larger deformation complexes are well exposed, the process implications of the preserved features are often more dramatic than could reasonably be extrapolated from smaller-scale exposures (Figure 13). Nevertheless, it is the comprehension of the more evident dynamics that provides a basis for extending process interpretation of SSD into new frontiers, just as small-scale laboratory experiments provided the criteria supporting the initial phase of SSD interpretation in the Navajo Sandstone.
The unique characteristics of deformation features at various sites can best be appreciated in contrast to the typical depositional architecture of the Navajo Sandstone (Figure 2), the more commonly observed patterns of deformation within the formation, and the limited range of deformation features in modern desert environments. For example, at the prominently exposed site next to the Glen Canyon Dam (Figure 13), the upper third of the section appears similar to the Zion outcrop (Figure 2); but the lower portion displays very different architectural characteristics. In the middle of the section, the thickness of one deformed interval approaches 80 m. At the top of this interval, a set of crossbeds was downwarped some 20 m. In an adjacent feature – apparently formed prior to this and partially effaced in the subsequent event - liquefied sand spread across an interdune expanse, preserving the lower portion of the downwind stoss surface (Figure 13B), a feature not seen in the typical architecture of the Navajo Sandstone and unusual even among deformation features representing comparable dynamics (Figure 14). Such deep-seated liquefaction and such a voluminous outflow of sand would be entirely unique in any modern desert environment on Earth. This aspect of Navajo Sandstone SSD may prove particularly useful in the context of planetary geology, especially in the exploration of Mars, where relict topographies, shaped by fluid flow, testify to exotic groundwater processes for which no comprehensive modern Earth analogues are available (Chapman, 2007). Perhaps the Navajo Sandstone will provide key insights into these extra-planetary features, as it did in the case of the Martian “blueberries”, which have been interpreted as iron concretions based on their similarity to “Moki marbles” in the Navajo (Chan et al., 2005).

Of more immediate interest, SSD in the Navajo Sandstone provides information of paleoenvironmental conditions on Earth that lie beyond the range of modern analogues. Three general implications of typical occurrences of SSD within the sedimentary architecture of the formation are particularly apparent:

1. **Water tables fluctuated dramatically in the Navajo erg(s).**

The intertonguing of fluvial and eolian deposits and the uneven distribution of interdune pond deposits clearly indicate varying relationships between interdune surfaces and the water table in the Navajo erg(s). SSD extends this evidence beyond the limits of
subaqueous deposition by providing evidence for successive dry and saturated sub-
surface conditions during the depositional and early diagenetic history of cross-stratified
deposits (Figure 4). Successive intervals of truncated deformation features represent
repetitive cycles of saturated and unsaturated conditions during an overall rise in the
water table within the accumulation. These data provide a basis for detailed
paleogeographies and high-resolution climatic reconstructions that would escape the
resolution of models based on modern environmental analogues. For example, modern
dunes experiencing high amounts of rainfall typically lose their mobility due to an
invasion of highly adapted grasses and other hardy vegetation that exercise a more
persistent influence than the erosive winds promoting bedform migration. There is no
direct evidence for dune stabilizing vegetation before the Cretaceous (Glennie and
Evamy, 1968; Loope, 1988; Marzolf, 1988); so, in the instance of wet-climate dune
processes, particularly, modern environments do not provide comprehensive analogues.
The near-equatorial latitude of the Navajo erg is associated today with tropical
rainforests. Wet interdune facies in Navajo deposits may record fluvial input sourced
from higher, wetter, locations; but it is also possible that Early Mesozoic ergs of the
Colorado Plateau remained active in spite of high direct precipitation during wet climatic
episodes, as is suggested by cycles of slumped foresets that have been described from
northernmost Arizona (Loope et al., 2001). Since dunes were not readily stabilized by
vegetation, autogenic factors were potentially more important, relative to climate, in
generating fluvial/eolian sedimentary cycles than is evident today: Does an increase in
eolian facies toward the top of a specific section represent a drying upward climatic
trend, opportunistic expansion of the erg when streams were diverted to another location
by tectonics or by autogenic fluvial processes; or does it represent increasingly effective
fluvial diversion as the erg relentlessly expanded?

2. Deformation events modified topography and altered depositional processes.

Distinct examples of small-scale interactions between deformation and deposition
appear in the association of liquefaction, fluidization, and clastic injection features,
culminating in a sand volcano at the surface of an interdune pond deposit, in Navajo
Canyon (Figure 3). Foundered foresets and truncated faults at N. Coyote Buttes (Figure
5) constitute further evidence of subsurface/surface interactions during a Navajo deformation event. More diverse features with less obvious connections appear in West Canyon outcrops (Figures 7-10). Linked together by an event interpretation of deformation dynamics, however, they provide a surprisingly coherent, extraordinarily detailed snapshot of erg conditions. These instances reveal causal relationships between deformation and sedimentation that provide tools for deciphering more complex features (Figures 11-14) that might otherwise remain enigmatic.

3. *Seismic shaking episodically affected portions of the Navajo erg(s).*

Previous workers generally agree that seismic triggering events were important in producing Navajo SSD. This is a key feature of the Horowitz (1982) model, in particular. The Navajo Sandstone was deposited in an active foreland basin (Allen et al., 2000) and subtle angular relationships at the unconformities defining the allostratigraphy of the Glen Canyon Group testify, generally, to a seismically active environment (Peterson, 1994). In addition, field evidence supporting the seismic triggering hypothesis for Navajo SSD can be seen in: the episodic nature of deformation events; the wide areal distribution of their products; and the lack of deformation features in related deposits of comparable susceptibility. More specific seismic interpretations regarding earthquake magnitude and epicenter proximity are hampered by the lack of modern analogues for scale and permeability factors. Perhaps this limitation can be partially overcome by a close examination of meter-scale fluidization features occurring in interdune settings where sandstones underlie impermeable carbonate caps (Figure 3), since these features are more directly comparable to those described from modern seismic zones (Obermeier, 1996; Obermeier et al., 2004).
Conclusions

Outcrop investigations of soft-sediment deformation features in the Navajo Sandstone provide a unique window on Early Jurassic events and paleoenvironmental conditions, both broadening the range and increasing the clarity of our perspective on ancient processes and system controls. Specifically, soft-sediment deformation features in the Navajo Sandstone:

- Indicate seismic activity in the Early Jurassic;
- Record water table fluctuations in the ancient erg;
- Constitute an event framework that links diverse outcrop features in time; and
- Provide information about processes at scales beyond those available to experimentation.

The record of penecontemporaneous deformation in the Navajo Sandstone indicates a succession of events in the ancient erg(s) unlike any reported from modern settings, including:

- Widespread liquefaction,
- Large-scale subsidence,
- Dune destabilization, and
- Sediment eruption

These events reshaped topography and modified depositional processes. The condition of persistent, near-surface sediment saturation implied by ductile deformation patterns and other fluid-escape features suggests an extraordinary set of hydrological conditions, as well. Navajo climates may have been quite humid. An abundant supply of sand in an absence of grass may have overwhelmed contemporaneous surface stabilization processes, producing landscapes quite different from any modern setting.

The information potential of soft-sediment deformation features in the Navajo Sandstone, and other ancient eolianites that are well-exposed on the Colorado Plateau, has not been exhausted. Further insights into eolian paleoenvironments, deformation dynamics, and reservoir characteristics may yet be revealed by studies targeting both the details of deformation dynamics and the distribution of features produced by individual events.
IV. TOPOGRAPHIC RESPONSES TO SOFT-SEDIMENT DEFORMATION IN AN ANCIENT ERG: THE LOWER JURASSIC NAVAJO SANDSTONE

Abstract

Extensive outcrops of Navajo Sandstone in the southwestern United States expose eolian dune deposits that are subdivided in a complex array of foresets and bounding surfaces. In the Glen Canyon region, and other places, this architecture is frequently disrupted by large-scale, soft-sediment deformation features. These features have been attributed to episodic liquefaction events that affected saturated sand below the level of the interdune surface. Though erosional truncation of deformation features indicates that liquefaction often occurred in the uppermost levels of Navajo dune deposits, very few paleotopographic disruptions due to subsurface deformation have been documented.

Navajo Sandstone outcrops in West Canyon, Utah, provide unusually comprehensive exposure of architectural details linking large-scale deformation features and subsequent interdune deposits, enabling a well constrained appraisal of their genesis. At this location, a 23 m succession of sandstone, mudstone, carbonate, and chert deposits overlies a zone of deformation that extends, laterally, for hundreds of meters. This horizontally stratified lens occupies an abrupt synform along a first-order bounding surface that otherwise appears as a featureless, sub-horizontal plane between successive crossbeds. Large-scale foresets below this bounding surface oversteepen at the margins of the synform and grade downdip into contorted stratification and structureless expanses.

The authors propose that liquefaction, in the Jurassic erg, initiated localized subsidence of a dry interdune surface to a position several meters below the contemporary water table. A succession of mass flow, lacustrine, and eolian deposits filled this depression prior to the advance of large dunes across the site. The process/response dynamics evident in this outcrop suggest that deformation may have exercised significant, non-systematic control over depositional architectures in areas of the erg prone to liquefaction.
Introduction

General Geologic Setting

The Navajo Sandstone (Figure 1) is a very extensive eolianite, spectacularly exposed on the Colorado Plateau, in the United States. It accumulated near sea level in the southern part of the Western Interior Basin during the initial stages of the break-up of Pangea, in the early Jurassic (Peterson, 1994b). This broad, back-arc area was the site of episodic eolian deposition from the late Paleozoic through the Jurassic (Blakey et al., 1988; Peterson, 1988c), prior to inundation by an epicontinental seaway, during eustatic highs in the Cretaceous (Hallam, 2001).

During the early Jurassic, the basin was centered some 10°-20° north of the equator (Kocurek and Dott, 1983) and experienced warm, mostly dry conditions from general global warming (Fischer and Arthur, 1977), latitudinally zoned circulation patterns modified by seasonal monsoons, and rain-shadow effects from the volcanic arc to the west (Parrish and Peterson, 1988). Foreland basin subsidence accommodated thick accumulations along a NE/SW trend (Allen et al., 2000; Blakey, 1994b). Both the general tectonic setting of the depositional basin and angular relationships at the bounding unconformities of the early Jurassic sequences indicate widespread, though moderate, seismic activity during the depositional history (Peterson, 1994b).

Stratigraphy

Fluvial deposits of the Kayenta Formation conformably underlie and intertongue with the Navajo Sandstone (Figure 1B). Modal analyses of detrital framework grains indicate that these sediments derived from tectonic highlands, to the east, and volcanic highlands to the south (Dickinson and Gehrels, 2003; Luttrell, 1996b). Paleocurrent measurements indicate that fluvial flow generally opposed contemporaneous eolian transport (Luttrell, 1996), producing widespread recycling (Blakey, 1994b). Complex interactions between the fluvial and eolian systems are apparent in preserved lateral relationships at the southern margin of the Jurassic erg and in various vertical successions at other locations (Blakey, 1994b; Middleton and Blakey, 1983). The extent of ongoing fluvial influence on erg hydrology and interdune sedimentation has not been established,
however, and some studies (Loope and Rowe, 2003; Loope et al., 2001) indicate that direct precipitation may have greatly influenced the configuration of local water tables, even at locations near the upslope margins of the erg.

In the vicinity of Zion National Park, the Navajo Sandstone is unconformably overlain by another eolianite, the Middle Jurassic Temple Cap Sandstone, across the J-1 regional unconformity (Peterson and Pipiringos, 1979; Pipiringos and O'Sullivan, 1978). Elsewhere, it is truncated directly by the J-2 surface (Blakey, 1994a), a major North American unconformity, which separates the Navajo from the eolian Page Sandstone and partially equivalent Carmel deposits (Figure 1B), representing various near-coastal, Middle Jurassic environments (Blakey et al., 1988; Peterson and Pipiringos, 1979; Pipiringos and O'Sullivan, 1978).

**Petrology**

Sandstone lithologies within the Navajo plot (McBride, 1963) in a narrow range from subarkose to quartz arenite (Uygur and Picard, 1980). Subrounded, nearly equant, well-sorted, fine to medium quartz grains, including chert fragments, represent up to 98% of framework constituents (Doelling et al., 1989; Harshbarger et al., 1957; Riggs and Blakey, 1993b). Generally, the grains are weakly cemented with calcite; although hematite or authigenic quartz dominate locally (Jennison, 1980). Grain size, sorting, and roundness vary little in the cross-stratified deposits that compose the bulk of the formation (Uygur and Picard, 1980). Non-sandstone facies within the main body of the Navajo Formation make up a small, unevenly distributed proportion of the total mass. The most prominent of these are discontinuous beds of horizontally stratified, cherty limestone (Desborough and Poole, 1992; Gilland, 1979; Harshbarger et al., 1957), interpreted as interdune pond deposits (Driese, 1985). These typically occur within lenticular lithosomes, a few meters thick, dominated by horizontally stratified sandstone intercalated with thin horizons of siltstone and, sometimes, shale. Carbonate lenses constitute a higher percentage of the total volume in the southeastern portion of the Navajo outcrop area and its lower stratigraphic levels, than elsewhere (Bromley, 1992; Marzolf, 1983). This trend parallels the association with fluvial facies (Blakey, 1994b); although fluvial deposits have not been documented from the carbonate-bearing interdune successions in Glen Canyon.
Figure 1A: Current field relations, in the American Southwest, between major features produced during the early Jurassic (Blakey, 1994b; Dickinson and Gehrels, 2003; Peterson, 1994b). The tadpole symbols plot eolian foreset dips (Peterson, 1988c). Figure 1B: A generalized cross-section across the thickest part of the preserved Navajo accumulation (Blakey et al., 1988). Figure 1C: A paleogeographic reconstruction by Ron Blakey ((Blakey). The arrows represent prevailing transport winds (Parrish and Peterson, 1988).
Typical Features of Soft-sediment Deformation in the Navajo Sandstone

In some parts of the formation, especially those associated with water-laid deposits, the cross bedding of the Navajo Sandstone is contorted in zones tens of meters thick and hundreds of meters in diameter (Harshbarger et al., 1957; Kiersch, 1950). These deformation structures typically occur as irregular folds, which are sometimes recumbent or even overturned, within isolated cross-bed sets (McKee, 1979a). Lateral and lower extents usually grade into undeformed cross-bedding. Upper terminations often abut a deflation surface, where deformed material was subaerially exposed. Many of the larger features display internal transitions from contorted bedding to structureless sandstone, representing lower to higher degrees of deformation (Sanderson, 1974b).

Factors Contributing to Navajo deformation

Large-scale deformation features in the Navajo Sandstone have been attributed to penecontemporaneous, soft-sediment deformation of saturated sand below the level of interdune troughs (Doe and Dott, 1980; Horowitz, 1982; Rubin and Hunter, 1988). The high depositional porosity of eolian sand, particularly avalanche deposits, produces underconsolidated conditions upon even shallow burial, rendering these deposits highly susceptible to liquefaction (Casagrande, 1936; Net, 2003; Stephens, 1985). General agreement on the saturation of the sediments at the time of deformation arises from the successful experimental production of similar features only under saturated conditions (McKee et al., 1962b; Rettger, 1935). Horowitz (1982) listed various explanations that have been offered for Navajo deformation features and argued persuasively that the chain of deformation events typically began with earthquake-induced liquefaction. He also presented a theoretical analysis of soil mechanics in the ancient erg, which indicates that liquefaction zones occurred preferentially beneath interdune troughs (See Figure 2).

Preserved Surface Effects of Large-scale Deformation Events

Common erosional truncation of deformation features clearly indicates that deformation often took place near the contemporary depositional surface; however, very little unambiguous evidence has been documented linking subsurface deformation to any
type of topographic alteration in the Navajo erg; though such a relationship has sometimes been inferred (Chan et al., 2007). In particular, the common occurrence of preferential folding in the direction of foreset dip has caused various workers to speculate about possible controls related to the direction of dune migration (Rubin and Hunter, 1988). Horowitz (1982) argued that interdune areas, where saturated sand occurred closer to the surface, were more susceptible to earthquake-induced liquefaction than the loaded (more tightly confined) sands beneath the dunes themselves; so there may have been a tendency for dunes to founder forward into subsurface liquefaction zones during a seismic event. Conversely, Rubin and Hunter (1988) suggested that the sequential loading of large, migrating dunes may have acted as giant rolling pins to preferentially deform consolidating sediment in the downwind direction. Deformation of large intraclasts and rafted blocks within mass flow deposits, identified at sites in southeastern Utah (Eisenberg, 2003; Parrish and Falcon-Lang, 2007), suggests process affinities with typical subsurface deformation features; but surficial processes such as catastrophic flooding (Eisenberg, 2003) and heavy rainfall (Loope et al., 2001) may have been the primary causative agents in those events. Outcrop details at several sites examined for this report do indicate various types of linkage between subsurface deformation and contemporary topographic disturbances. One such site, in particular, yields distinctive evidence of a depositional episode controlled by large-scale deformation processes. Those outcrops are the focus of this report.

**Purpose of this Report**

This report documents field relationships between depositional facies architecture and associated deformation features exposed in outcrops of the Navajo Sandstone in West Canyon, Utah. It provides an interpretation of these features emphasizing genetic links between large-scale soft-sediment deformation and a subsequent depositional episode. This documentation provides a window onto processes - unknown from modern eolian environments - that are not amenable to comprehensive laboratory simulation. Furthermore, it establishes a basis for the identification of similar types of features in less fortuitously exposed locations, enhancing our ability to recognize the interplay of allogenic controls on continental sedimentary systems.
Figure 2: Contoured liquefaction resistance profile beneath a 30 m high sand dune with a water table 3 m below the idealized depositional surface (defined by interpolation between interdune depressions). Lower values of liquefaction resistance indicate areas more prone to liquefy during earthquake shaking. Results show that liquefaction will occur most readily several meters below the water table and in topographically low areas, such as interdunal flats. (Horowitz, 1982, Fig. 26, p. 176)
Location and Methods

Location

Access to the study site at N 36.9973, W 111.13538 (Figure 3), requires an hour-long boat ride on Lake Powell, from the Antelope Point Marina, near Page, Arizona. Field work was conducted within Glen Canyon National Recreation Area, under NPS permit #GLCA-2006-SCI-0006, during the summer of 2006. At that time, the surface of the reservoir was at an elevation of 1100 m, 28 m below the full pool level targeted by the United States Bureau of Reclamation. This low lake level (due to several years of drought in the Colorado River drainage, prior to our field work) exposed the feature of interest, which occupies the entire interval between current lake level and full pool. The J-2 surface, defining the top of the formation, lies 120 m above the study interval, in a region with a reported section thickness of 357-375 m (Anderson et al., 2000).

Methods

A photomosaic, covering a 400 m extent of outcrop, provided a base on which to map the sedimentary architecture (Figure 4A). Because of the gentle structural dip (1-2° to the NW) in the area, the interval of interest rises in elevation in the upstream (SE) direction. A normal fault with an offset of 15 m, down to the southwest, follows the same trend as the canyon (120/300) and twice intersects the outcrop in the study area. Breaks in the steep topography, from preferential erosion along this fault, provide access onto ledgy, horizontally stratified deposits, along critical portions of panorama coverage.

The dips of foresets in cross-stratified units within the panorama were directly measured, where accessible, though some apparent dips were also noted, in one key area. The various lithologies of the study interval were sampled for petrographic analysis.

Results

Architectural Relations

Our investigations reveal a 23 m, horizontally stratified succession of sandstone, mudstone, chert, and carbonate beds, forming a lenticular deposit over a zone of plastic
Figure 3A: Location of the principal outcrops described in this report.
Figure 3B: Topographic map of the West Canyon study site.
Figure 4A: Generalized architecture of the West Canyon study site. NE view is dramatically foreshortened to the north and vertically exaggerated by 200%. 4B: Detailed architecture of interdune deposits at the West Canyon study site. View is to the east.
deformation (Figure 4). The strata occupy a steep-sided synform along a horizontal bounding surface that elsewhere separates successive units of large-scale cross-strata with a predominance of avalanche foresets dipping southward. Units occupying the uppermost 2 m of this succession extend across the entire study area. Alluvial cover and efflorescence obscure the details of transition as these beds gradually pinch out to the south. To the north, the ultimate lateral termination of horizontal stratification is poorly exposed because of changing outcrop orientation along a stream meander; however, bed boundaries can be seen to splay into overlying foresets in that direction, merging with reactivation surfaces in the dune architecture. In general, horizontal beds diminish in thickness and in number to the north. The total lateral extent of continuous horizontal stratification exceeds 500 m.

Foresets in the sandstone unit that underlies the horizontally stratified package oversteepen at the margins of the synform and grade, downdip, into a zone of convoluted bedding and structureless sandstone. Apparent foreset dips increase from 23 degrees to 45 degrees in proximity to the steep north end of the synform, then flatten to 10 degrees beneath its lowest point, so that the attitude of the foresets approximates the shape of the synform. A detachment zone accommodates the transition between packages of oversteepened and flattened foresets (Figure 5). A fluid escape structure, marked by an hourglass-shaped bundle of flow lines, connects a body of structureless sandstone below the deformed foresets with a wedge of intensely fractured sandstone (Figure 6), above. All but the topmost horizontally bedded units in the vicinity of this feature have been fractured. Structures beneath the south limb of the synform are obscured by alluvial cover, due to offset across the normal fault, so that the symmetry of the synclinal depression cannot be determined.

**Facies Succession**

We have divided the horizontally stratified succession within the synclinal depression into 6 genetic units (A-F), distinguished by bedding style, lateral extent, and petrology. The lowermost unit (Unit A), 6 m thick, is composed of massive, fine-grained sandstone. This concave-up bed terminates abruptly against the smoothly curving north side of the synform. Capped by a thin mudstone, it is overlain by a 9 m succession of
Figure 5: Zone of detachment between deformed foresets. View is to the northeast, at the location indicated in Figure 4.
Figure 6: Area of dense fractures above the detachment zone pictured in Figure 5. A closely spaced array of parallel fractures dips to the north, opposite the foreset dip. Field of view in the lower photo is approximately 10 m.
fine sandstone beds that pinch out above the north margin of the depression (Unit B). Individual beds, 0.1 m to 1 m thick, are separated by silty drapes. A break in the curvature of the synform occurs at the base of this unit, producing a more gently dipping surface. Above this package, a 0.3 m interval of finely bedded sandstone and a 0.6 m carbonate deposit constitute Unit C. The carbonate has a micritic texture, contains dark gray chert nodules, and is subdivided into alternating intervals of massive bedding and coarse laminae by silty parting surfaces. A zone of mottled reduction extends for several cm below its lower surface, throughout most of the underlying finely bedded sandstone. A polygonal pattern of sand-filled fractures dissects its upper surface to the north, where it rises and pinches out at the margin of the synform. The foresets of a 1.5 m cross-stratified sandstone unit (Unit D), dipping 25° to the south, lap down onto the carbonate to its lowest elevation. Above this lies a 4 m succession of massive, lenticular sandstone beds (Unit E), 5-50 cm thick, interspersed with mudstone beds up to 10 cm thick. This unit overlaps the underlying units on the north side of the synclinal depression. Individual beds are burrowed and fractured in diverse patterns. Many of the sandstone beds are preferentially cemented with calcite and weather out in clean ledges. This succession is capped by a 2 m interval of sandstone, silty mudstone, and chert deposits (Unit F) that extend well beyond the margins of the synform. The chert occurs as a 5 cm lens of black silica near the base of the capping deposits (Figure 7A). It is continuous with a rectilinear pattern of fracture fillings in the underlying sandstone bed (Figure 7B), part of the fracture network referred to in the previous section, and appears not to extend beyond that zone.

Above Unit F, horizontal stratification gives way to large-scale cross-stratification. Intertonguing relationships across this interface indicate that dune migration was contemporaneous with the final phases of interdune sedimentation.

Discussion

Sinkhole Interpretation

Because of the direct association of deformation structures and heterogenous deposits in this outcrop, along with the distinctive characteristics of those features, we propose that they represent the alteration of contemporary topography and depositional processes by sub-
Figure 7A: Black chert bed in Unit F. 7B: Chert-filled rectilinear fractures below bedded chert.
surface deformation. In support of this hypothesis, we discuss the significance of seven complementary sets of observations, in the following order:

1. The unusual depression in a $1^{\text{st}}$-order boundary;
2. Underlying deformation structures that parallel the depression boundary;
3. The depositional geometry of units filling the depression;
4. The initiation of horizontal stratification within the depression, rather than more generally along the bounding surface;
5. Sedimentological features in the fill succession which indicate:
   a. a transition from rapid to gradual deposition and
   b. a transition from wet to dry, then variably moist conditions at the depositional surface;
6. Capping of the fill by much more extensive horizontal beds; and
7. The interdigitation of horizontal stratification with overlying cross-strata.

The unusual depression in a $1^{\text{st}}$-order boundary

Most boundaries between cross-stratified sets in the Navajo Sandstone appear as smooth, nearly planar surfaces. Some of these boundaries are truncated, at outcrop scale, by more extensive surfaces; but many extend for indeterminable distances beyond the limits of the few kilometers of their outcrop exposure. Climbing bedform theory (Allen, 1963; Brookfield, 1977; Kocurek, 1981b; Kocurek and Havholm, 1994; Rubin and Hunter, 1982a) explains the more extensive (first-order) boundaries as erosional surfaces separating the deposits of successive dunes or dune complexes. This theory, developed in response to the interpretive challenges presented by systematic architectural features of Colorado Plateau eolianites (Kocurek, 1991), is supported by small-scale observations and laboratory simulations; but has not been verified in large-scale modern systems. Workers with perspectives informed, primarily, by experience with modern systems tend to prefer outcrop interpretations representing less continuous processes of deposition and accumulation (Fryberger, 1993). For the purposes of this study, no evaluation of the general significance of such boundaries, whether by simple bedform climb or by the operation of a more complex series of processes, is necessary, since critical environmental interpretations can be based directly on observable field relations.

The origin of the observed depression in the boundary under scrutiny, here, might be attributed by some observers to causes other than subsurface deformation. Comparable features, due to erosion, do occur in the Navajo Sandstone and other ancient
eolianites of the Colorado Plateau. Fluvial channels might reasonably be expected, based on regional stratigraphic relationships to Kayenta fluvial deposits; however, channel scour is not evident and no distinctly fluvial facies occur within the infilling succession. Superscoops (Blakey, 1988b) are another possibility, and a relatively common feature of eolian architecture. These large, deflationary features are typically filled with a sedimentary succession that differs in lithology and/or bedding style from the encasing deposits, as occurs at the West Canyon site. However, they generally present as broad, gentle, symmetrical hollows. The variably sloping north limb and flat bottom of the depression in the West Canyon bounding surface differ from this norm (See highlighted contour below “Mass Flow Deposits” in Figure 4A). The way this surface conforms to underlying deformation structures is even more distinctive.

Craterlets, produced by upward fluid escape from zones of liquefaction (Dutton, 1889; Kuhn, 2005; Obermeier, 1996a; Rajendran and Rajendran, 2003), may provide the closest available process analogue for the depression. These erosional pits and collapse features commonly occur at the surface of seismically disrupted sand deposits; though they have not been described from any modern desert dune environment, nor have any been documented that approach the large scale of the West Canyon feature. The stratigraphy of the infilling deposits of documented craterlets does not resemble the fill succession at this study site, either. Perhaps that is an issue of scale; but without more evident commonalities, there is no reason to assume similar modes of genesis.

**Deformation structures that parallel the depression boundary**

Typically, in Navajo dune deposits, scour features cut smoothly across primary sedimentary structures, except for centimeter-scale corrugation that occasionally occurs at upper crossbed boundaries, following foreset textural variations. No mechanism has been proposed that would explain the systematic control of surface erosion by contemporary deformation structures in the Navajo erg, nor have we found observational support for the existence of such a mechanism. Our survey of deformation features broadly distributed within the Navajo Sandstone has included many instances of deformation structures that are truncated by smooth erosional surfaces. Nowhere have we seen deformation structures controlling subsequent erosion of crossbeds; although
differential erosion of contrasting lithologies, exposed by deformation processes, has been observed.

We interpret the geometry of deformed foresets interspersed with zones of structureless sandstone, appearing in the West Canyon outcrop (Figure 4A), as the result of plastic displacement of primary sedimentary structures in water-saturated, near-surface deposits (Doe and Dott, 1980; McKee et al., 1962a; Rettger, 1935) accompanied by more turbulent fluidization (Lowe, 1975; Soo, 1967) along pathways of preferential fluid flow. Structureless sandstone occurs in those regions where intergranular displacements were greater than those where deformed and contorted foresets are preserved (Sanderson, 1974). Loss of support occasioned the downward deflection of foresets that now appear oversteepened. Their displacement was accommodated by the flow of fluidized sediment, appearing as structureless sandstone both behind and below the downcurved foresets. This oversteepening at the north edge of the depression gives way to flattening further down its north limb, a relationship accommodated by detachment between internally cohesive bundles of foresets (Plaziat et al., 2006) and further movement of liquefied sand. The wedge of intensely fractured sandstone updip and above these detached foresets (Figure 6) probably represent existing dune deposits that were partially fluidized by the escape of excess pore water along the shear zone, as well as mobilized sand that welled up to the surface along this structure. Fracturing occurred subsequent to stabilization of these sediments, during the fill history.

The depositional geometry of units filling the depression

Crucial to our deformation hypothesis is the observation that deposits overlying the deformed bounding surface were not themselves deformed during the liquefaction event. The upper surface of each deposit in the fill succession defines a more subdued expression of basin form than does its predecessor (See highlighted surfaces 3/4, 5, and 8 in Figure 4B). The lowermost deposits pinch out against the basin margin (See right side of Figure 4A). The upper deposits onlap or thin in that direction (See left side of Figure 4A). The capping beds (#8, Unit F, in Figure 4B) maintain a planar geometry across basin boundaries. In short, bedding geometries define an onlapping fill succession culminating in generalized deposition of horizontal strata above the bounding surface and
across the exposed margin of the mini-basin. Furthermore, basin form itself suggests the operation of consecutive processes of deformation, erosion, and deposition. The break in slope along the north limb of the synform can best be explained by erosion subsequent to deformation of the original bounding surface, making that surface peculiarly diachronous, from a climbing-bedform perspective (Brookfield, 1977; Rubin and Hunter, 1982a): Across this segment, it is younger in the paleo-upwind direction. As a consequence of ongoing erosion of the original surface, after subsidence, the 23 m of observable displacement represents the minimum that might have occurred.

Initiation of horizontal stratification within the depression

The capping deposits of the fill succession extend well beyond the margins of the depression itself. Their configuration to the north, in the paleo-upwind direction is complex, as they merge with overlying foresets and cap other isolated deposits that may be contemporary to part of the fill succession (Extreme left of Figure 4A). The increasing overlap of horizontally stratified deposits within the depression, however, indicates that deposition began, there, before it blanketed the interdune surface, generally. This localized commencement of horizontal stratification corresponds to the development of a topographic basin. The fill succession itself provides further clues to the nature of events in its subsequent history.

Sedimentology of the Fill Succession

Unit A (Figure 4B provides an outcrop diagram of the various units)

We interpret Unit A as a single mass flow deposit that occurred during the initial stages of sinkhole development, as near-surface sand was fluidized and subsidence destabilized the topography. The provenance of this sand cannot be precisely determined and it is likely that sediment transport included an indistinguishable component of movement perpendicular to the outcrop orientation; though it seems that a fairly passive process, simultaneous with deformation, would be required to preserve the steep slope of the synform. It appears that Unit B is continuous with the zone of structureless sandstone updip and above the flattened foresets of the deformed set that underlies it.
Subsidence appears to have taken place on an extensive interdune flat. There is no architectural evidence which indicates that sinkhole development occasioned the collapse of an adjacent dune. More specifically, we cannot correlate any disrupted foresets, above the deformed bounding surface, to the fill succession. Interfingering between fill units and overlying foresets only involves the uppermost strata and occurs tens of meters in the paleo-upwind direction from the depression margin. These foresets may not represent the deposits of the nearest, upwind dune at the time of deformation: the set’s lower boundary cuts down through a prior set, above the horizontal strata capping the fill succession.

Unit B

We interpret Unit B as an episodic succession of mass flow deposits. Episodicity may have derived from temporal separation of depositional events, spatial separation of sediment sources, or fluctuating flow conditions. The adjustment of local topography in response to oversteepening, produced by subsidence, is indicated by the change in basin slope, at the base of this package. The silty drapes coarsely separating individual units suggest the segregation of fines during turbulent flow.

Unit C

Unit C provides the first definitive indication of a prolonged history of sedimentation within a closed basin. The carbonate precipitated gradually, probably in an evaporative pond environment such as that modeled from similar, Paleozoic occurrences (Driese, 1985) and interpreted from many outcrops of the Navajo Sandstone (Desborough and Poole, 1992; Gilland, 1979; Harshbarger et al., 1957). Standing water was continuously present throughout deposition of this unit. Atmospheric dust trapped in the pond appears as thin silt stringers. The top of this bed, where it drapes up onto the north margin of the depression, represents the minimum water table level during carbonate production and may approximate the height of the water table at the time of deformation. The thin sandstone beds underlying the carbonate represent the distribution of sand within the pond before water chemistry reached saturation with carbonate ions. Sand-
filled fractures dissecting the top of the carbonate represent desiccation, occasioned by a drop in the water table, which allowed the eolian transport of sand across the basin.

Unit D

The fine structures of Unit D have been obscured by groundwater-mediated diagenesis along the carbonate aquitard, so they do not provide definitive environmental indicators. Nevertheless, the angle and direction of foreset dips in Unit D are concordant with the overall eolian trend and no fluvial indicators appear which would suggest the interpretation of this isolated set as anything but a product of eolian processes. Apparently, the initial dry period of this little basin’s history lasted long enough for a small dune to develop and migrate across the surface of the carbonate. This set begins within the basin, though there is no reason to suppose that the dune itself did not originate upwind from that point. The cessation of dune migration and preservation of its deposits were occasioned by the rise of groundwater level, which cut off sediment supply to the dune and established a lower limit of deflation.

Unit E

Unit E, though consisting predominately of sandstone beds separated by silty fines, as do Units A and B, provides several indications of a distinctly different genesis. Stratification is more coherent, desiccation cracks and bioturbation features appear, and preferential cementation has occurred at several intervals. In general, the sand to fines ratio is markedly lower. These features indicate that Unit E was deposited during an extended history, while the water table rose at a rate approximating that of sediment accumulation. When the water table was just below the depositional surface, capillary moisture trapped saltating sand grains and precipitated cements in near-surface sediments. During flooded surface conditions, saltation ceased at the pond margin, but trapping of atmospheric dust increased in efficiency, producing fine-grained deposits.

Unit F

The general rise in the water table continued until undeformed portions of the surface topography were moistened, halting deflation and providing a mechanism for
horizontal stratification to extend well beyond the limits of the original basin, producing Unit F. The lateral terminations of these capping deposits are not fully exposed; however, complex relationships with overlying toesets, comparable to those described from the Permian, Cedar Mesa Sandstone (Mountney, 2006; Mountney and Jagger, 2004), indicate that horizontal stratification developed upon a dune-bounded surface, at least in its latter stages. The deposits of Units C-F are in most ways identical to widely distributed interdune deposits previously described from the Navajo Sandstone (Desborough and Poole, 1992; Gilland, 1979; Harshbarger et al., 1957).

**Significance of Fracture Pattern**

The polygonal mudcracks in Unit C are common features in Navajo interdune deposits; however, the other fractures that appear in all but the uppermost bed of the fill succession do not typically occur. Contemporaneity of the fracturing with the depositional history is indicated by its localized occurrence and its relationship to soft-sediment deformation structures and is further established by the continuity between fracture fill and chert bedding (Figure 7). These patterns must represent some kind of ongoing instability in the vicinity of the sinkhole. This may have derived from localized groundwater flow (Guhman and Pederson, 1992) or residual instability in the deformed strata and/or initial fill deposits. Comparable evidence for ongoing instability does not appear in association with any other deformation feature we have examined. The association of chert precipitation with high density fracture patterns suggests that deep groundwater circulation may have been involved, especially since the black coloration of the chert, present as nodules in Unit C, fracture deposits in Unit E, and a discrete lens in Unit F, is also unusual in Navajo interdune deposits.

**Volumetric Considerations**

The development of such a large depression, without substantial erosion or prior removal of subsurface material, raises the question of how subsidence was accommodated. Perhaps the local subsidence was directly offset by the eruption of a similar volume of material at another location. Evidence for sediment outflow within
Figure 8: The original volumes of most outflow deposits in the Navajo Sandstone are not preserved, due to subsequent wind erosion. The thickness of the fluidized zone in this outcrop in West Canyon, above Lake Powell, is about 20 m. Though distinct evidence for voluminous, upward-directed fluid movement is preserved, the impact on contemporaneous surface topography is not apparent.

Figure 9 (Next page): The subsidence mechanism that produced the 20 m depression in an ancient interdune surface at the West Canyon study site involved various processes of liquefaction and fluid escape. A: Seismic loading triggered re-packing of loose, saturated, grainflow deposits. Reduction in pore space produced water escape toward the surface, constrained by subtle permeability variations in the cross-stratification. B: Fluidization in a preferred pathway of fluid escape concentrated flow along this pathway, mobilizing sediment and transporting it to the surface. As both water and sediment escaped from the subsurface, overlying deposits subsided into the vacated volume, producing a fluid-filled depression into which the expelled sediment settled. C: Subsequent to the deposition of locally expelled sediment, a more voluminous supply arrived from one or more vents, situated outside the limits of outcrop exposure. Emplacement of this succession above the initial deposit may indicate separation in space and/or time, from the local vent. The crude stratification that distinguishes these deposits from the locally expelled sand may derive from pulsating flow from a single vent or from sequential deposition from multiple vents.
deformed Navajo deposits is not very unusual (e.g. Figure 8) and this appears to be the source of the initial mass flow deposits within the fill succession. Even if this is true, however, observed mass flow deposits do not account for all the observed displacement.

Other workers have noted that avalanche foresets, such as those occurring in the deformed interval, are particularly susceptible to liquefaction, because their loose initial packing provides both a high void ratio and unstable grain-to-grain contacts (Hunter, 1977; Loope et al., 2001). The porosity of grainflow deposits is sometimes more than 10% higher than that of grainfall deposits in similar sediments (Hunter, 1977). The liquefaction process results in resedimentation and tighter packing of the granular framework, accommodated by the escape of excess pore fluid (Casagrande, 1936; Doe and Dott, 1980; Net, 2003; Sanderson, 1974b; Stephens, 1985). Surface displacement, in this context, may represent a cumulative effect, similar to the subsidence observed to occur when shallow aquifers are overpumped (Mousavi et al., 2001), except that focusing of the effect is facilitated by the displacement of fluidized sediment (Figure 9). Complex flow patterns may have developed due to migrating fluidization fronts, differential loading, and permeability inhomogeneities affecting local pressure gradients. The exposure of both sinkhole geometry and deformation extent, in this outcrop, is inadequate to constrain volumetric calculations based on consolidation in liquefaction zones; however, it is clear that substrate deformation was far more extensive than the surface depression, as suggested by Figure 4A.

**Implications for Future Studies**

Soft-sediment deformation features are not unusual in the Navajo Sandstone of the Glen Canyon region. These features are commonly truncated by subhorizontal bounding surfaces of the type commonly interpreted as interdune deflation (Brookfield, 1977) or hiatal erosion (Mountney and Thompson, 2002) features, indicating that deformation events occurred frequently during the depositional history, as opposed to rare events that affected entire sections (Sanderson, 1974b). If topographic disruptions on the scale of the West Canyon feature were commonly associated with these events, then they would have exercised a significant, non-systematic control over depositional architectures in the region. Ongoing studies are aimed at characterizing the frequency of
this association and identifying the variety of topographic disruptions recorded in the preserved architectural relations. Preliminary results indicate that the feature described in this report is neither unique nor particularly exotic among the identifiable topographic responses to large-scale deformation events in the Navajo erg. See Figure 10 for a comparable example from nearby Navajo Canyon. Architectural relationships at this site reveal carbonate sedimentation in an interdune pond, interrupted by deformation. Subsidence of the interdune surface did not produce a topographic depression, in this instance.

Conclusions
The architecture of the West Canyon, Utah, outcrop described in this report indicates the catastrophic development of a surface depression, due to subsurface liquefaction and deformation. This feature formed along a dry interdune surface, underlain by a shallow water table. Subsidence triggered mass flow deposition, from destabilized topography and/or sediment outflow, and initiated the development of an evaporative pond, where half a meter of carbonate precipitated. The bedding and petrology of the sedimentary succession overlying the carbonate horizon indicates fluctuating moisture conditions at the depositional surface, but an overall rise in the water table, before the eventual resumption of consistently dry interdune conditions across the infilled depression. Figure 11 outlines successive stages in the processes represented at the study site.

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Production of Two Carbonate Horizons

1. Interdune Deposition

2. Deformation

3. Renewed Deposition

Figure 10: Process interpretation of deformed interdune architecture in Navajo Canyon.
High water table, but dry interdune conditions, between large, migrating dunes.

Liquefaction and deformation of substrate, producing fluid-filled depression.

Carbonate deposition in evaporative pond, fed by groundwater (sinkhole detail).

Low water table and eolian deposition in sinkhole. (sinkhole detail)

Episodic resurgence of the water table, filling of sinkhole, and widespread interdune deposition.

Ongoing deposition by migrating dunes, under dry interdune conditions.

Figure 11: Process interpretation of sinkhole architecture in West Canyon
V. PALEOCLIMATIC CONTROLS ON SOFT-SEDIMENT DEFORMATION IN THE NAVAJO SANDSTONE

Abstract

Many workers have noted the presence of plastically deformed cross-strata in the Navajo Sandstone and other ancient eolianites. These have long been recognized as indicators of sediment saturation during the accumulation history. Horowitz (1982) proposed a general model for the production of such features, in ancient ergs, by episodic, seismically induced liquefaction of accumulated sand. A key feature of that model is the prevalence of a flat water table, characteristic of a hyper-arid climatic regime, during deformation. Under arid climatic conditions, the water table is established by regional flow and liquefaction is limited to the saturated regions below the level of interdune troughs. However, various paleohydrological indicators from Navajo Sandstone outcrops point toward wetter climatic conditions and a consequently broader range of water table configurations during the deformation history of that eolianite. This raises questions about the general applicability of the Horowitz model and provides impetus for revising some of its major tenets.

This report examines the implications of a wet climatic regime for the Horowitz deformation model. It demonstrates how a contoured water table, characteristic of humid climates, may have facilitated deformation within active bedforms, as well as in the accumulation, more parsimoniously explaining the frequent occurrence of erosionally truncated deformation structures in the Navajo Sandstone. It documents two contrasting styles of deformation that can be attributed to the interplay of tectonic and climatic controls on liquefaction in the ancient erg.
**Introduction**

**Purpose of this Report**

In 1982, Horowitz proposed a model for large-scale, soft-sediment deformation in ancient eolianites, based on an engineering analysis of liquefaction resistance in unconsolidated dune deposits and field observations of features in the Navajo Sandstone. He focused, primarily, on a mechanism to explain the parallel-to-bedding geometry of deformation zones and the preferential occurrence of folds with axes parallel to crossbed strike. The fundamental limitations of this model as a general theory of eolianite deformation are apparent in the light of more recent reports (Chan et al., 2007; Eschner and Kocurek, 1986; Glennie and Hurst, 2007; Netoff, 2002) revealing a broader range of large-scale deformation styles in ancient eolianites than that considered by Horowitz (1982). In the present report, we propose that less obvious limitations apply to its usefulness as a general model for large-scale soft-sediment deformation in the Navajo Sandstone, alone. Though it provides a very succinct representation encompassing many salient aspects of Navajo deformation dynamics, the Horowitz model does not explain the full range of deformation styles in the Navajo Sandstone. That is, it does not enable an adequate characterization of the history of penecontemporaneous deformation in the formation. That history can be an important source of information regarding fundamental controls on soft-sediment deformation - seismic, climatic, and sedimentological conditions that prevailed in the early Jurassic - if different deformation styles are recognized and their process/response significance accurately interpreted. Toward that end, we propose significant modifications to the Horowitz model, making it more generally applicable to the interpretation of soft-sediment deformation features in the Navajo Sandstone, and more informative to broader analyses, while maintaining its long-standing illustrative value.

**Geologic Setting**

**General**

The Navajo Sandstone accumulated in the southern part of the Western Interior Basin (Figure 1A), during the initial stages of the break-up of Pangea (Parrish and
Peterson, 1988; Peterson, 1994b). This expansive, back-arc area was the site of episodic eolian deposition, near sea level, from the late Paleozoic through the Jurassic (Blakey et al., 1988; Peterson, 1988c). Fed by a very broadly sourced sand supply (Dickinson and Gehrels, 2003; Dickinson et al., 2007; Rahl et al., 2003) and accommodated by foreland basin subsidence along a NE/SW trend (Allen et al., 2000; Blakey, 1994b), Navajo erg deposits accumulated to a thickness of at least 700 m. Both the general tectonic setting of the depositional basin and angular relationships at the bounding unconformities of the early Jurassic sequences indicate widespread, moderate, tectonic activity during the depositional history (Peterson, 1994b). The occurrence of fanglomerates and other orogenic sediments in the correlative Dunlap Formation, of Nevada, corroborates this view (Ludington et al., 1996; Stanley, 1971); although the only evidence of Jurassic seismic activity within Navajo deposits, themselves, is the widespread, stratigraphically intermittent occurrence of large-scale, soft-sediment deformation features.

_Paleoclimate_

In the Early Jurassic, widespread eolian deposition, with subsidiary fluvial interludes, followed dominantly fluvial deposition in the Triassic (Blakey, 1994b). This environmental shift coincided with a phase of increased magmatism in the arc to the west and the continued northward drift of the continent, as North America broke away from Pangea (Peterson, 1994). Movement of the plates removed Early Jurassic depocenters from the lower latitudes, placing them 10°-20° north of the equator (Kocurek and Dott, 1983), and disrupted the extreme continentality of the Pangean landmass, which had previously favored monsoonal circulation patterns with abundant rainfall (Parrish and Peterson, 1988). Previous analyses indicate that latitudinally zoned circulation - in particular the dry, subtropical convergence that accounts for most large, modern deserts - dominated the climate of this area by the Middle Jurassic, maintaining consistent transport winds from season to season (Parrish and Peterson, 1988). It has been postulated that westerly winds from the paleo-Pacific Ocean lost their moisture across the elevated topography of the volcanic arc, leaving the foreland depression in an extensive
Figure 1A: Current field relations, in the American Southwest, emphasizing major features produced during the early Jurassic (Blakey, 1994; Dickinson and Gehrels, 2003; Peterson, 1994). The tadpole symbols plot paleocurrent measurements: the lines represent average foreset dip directions (generally from >10 measurements), in sections located at the positions indicated by the associated solid circles (Peterson, 1988c). Figure 1B presents a generalized cross-section across the thickest part of the preserved Navajo accumulation (Blakey et al., 1988). Figure 1C is a paleogeographic reconstruction of the maximum extent of the Navajo Erg (Blakey, 2008). The arrows indicate surface airflow directions predicted by early Jurassic paleoclimate models (Parrish and Peterson, 1988).
rain shadow (Marzolf, 1988a; Peterson, 1994b) and that Mesozoic global warming
(Fischer and Arthur, 1977) offset the cooling effect of the northward drift of the
continent, keeping the region dry and hot throughout the Jurassic (Parrish, 1993).
Foreset dip directions within the deposits of large dunes provide a proxy for the dominant
direction of the sand-transporting winds that shaped those dunes (Rubin and Hunter,
1983). The large number (>1000) of foreset dips that have been measured in the Navajo
Sandstone indicate a dominance of northerly winds in the northern region of Navajo
deposition and northwesterly winds farther south (Peterson, 1994); though deviations
from these norms are apparent in the summary data (Figure 1A). The extent of the
Navajo Sandstone is great enough to record major transitions between contemporaneous
pressure cells and this has been proposed as an explanation for the bi-directionality of the
primary trends. The westerly winds indicated by paleocurrent resultants from the
southeastern portion of the Colorado Plateau have been attributed to the lingering
influence of low pressure cells, which diverted surface air circulation to the east on a
seasonal basis (Loope et al., 2001; Parrish and Peterson, 1988). An alternative
paleoclimate reconstruction has been advanced, based on a more equatorial position for
the region in the Early Jurassic (Loope et al., 2004); however, evidence for significant
compaction flattening of the uncorrected paleomagnetic data supporting that
reconstruction (Dickinson, 2005) casts doubt on its conclusions (Loope, personal
communication). Both reconstructions show less than ten degrees of rotation relative to
the present continental alignment.

Stratigraphy and Petrology

The Navajo Sandstone (Figure 1B) is the uppermost of three Lower Jurassic
formations known collectively as the Glen Canyon Group. Along with the underlying
Kayenta Formation and the basal Wingate Sandstone, it crops out above the Colorado
River in the walls of Glen Canyon, Utah. It is spectacularly exposed in its southern
range, across the Navajo Nation of northern Arizona, and remains a prominent
component of the landscape throughout most of the Colorado Plateau. Together with
correlative units, it forms an unusually homogenous clastic body stretching nearly 1000
km from north to south and 400 km east to west (Figure 1).
The initial interpretation of the Navajo Sandstone depositional environment recognized the homogeneity of the deposit, its large-scale cross bedding, and scarcity of other internal structures as evidence of eolian processes (Gregory, 1917). Later refinements of eolian criteria (Hunter, 1976; Brookfield, 1977; Hunter, 1977; Kocurek, 1981; Kocurek and Dott, 1981; Rubin and Hunter, 1982a) confirmed this view. In the Navajo, eolian bedform migration under paleohydrological conditions that maintained dry interdune corridors resulted in thick, cross-stratified sandstone units, separated by extensive diastems (Kocurek and Havholm, 1994). Episodes of interdune flooding produced intercalated, horizontally stratified deposits (Kocurek and Havholm, 1994), which often include carbonate lithologies.

Interdune pond carbonates in the Navajo (Driese, 1985; Gilland, 1979) consist of lenticular beds of horizontally stratified, cherty limestone and dolostone. They make up a small (<1%), unevenly distributed proportion of the Navajo Sandstone. Their dimensions seldom exceed 1 m (typically, 0.5 m) in thickness and 100 m in diameter (Stokes, 1991), though diameters over 1 km do occur (Doelling et al., 1989). Carbonate lenses constitute a higher percentage of the total volume in the eastern portion of the Navajo outcrop area (Bromley, 1992) and its lower stratigraphic levels (Marzolf, 1983), than elsewhere, a trend paralleling the association with fluvial facies of the Kayenta (Luttrell, 1996b).

**Soft-sediment Deformation in the Navajo Sandstone**

**Outcrop Features**

In many outcrops of the Navajo Sandstone, large-scale cross-bedding is deformed in zones tens to hundreds of meters in diameter (Harshbarger et al., 1957; Kiersch, 1950). Deformation structures occur as irregular folds, often within isolated cross-bed sets (McKee, 1979b), but also across thicker intervals comprising multiple sets. In some outcrops, zones of continuous deformation, tens of meters deep, extend for several kilometers (Kiersch, 1950; Sanderson, 1974b). Lateral and lower boundaries are usually gradational, into undeformed cross-bedding. Upward terminations appear gradational in some outcrops (Horowitz, 1982); but commonly there is an upward transition from less to more intensive deformation (contorted strata to indistinct bedding) terminated by erosional truncation at the upper bounding surface of a discrete crossbed set (Sanderson,
The orientation of shear folds at the base of deformation zones commonly appears in approximate alignment with cross-bed dip, suggesting that dune migration direction somehow controlled the direction of shearing (Rubin and Hunter, 1988). Though this appearance may partly be due to the tendency for the component of deformation along the vector of dune advance to be emphasized by crossbed geometries, the general observation is supported by detailed studies of the orientation of elongate grains in selected shear folds (Horowitz, 1982).

**Process Interpretations of Navajo Deformation Features**

Large-scale plastic deformation features in the Navajo Sandstone have been attributed to soft-sediment deformation of saturated sand below the level of eolian dune troughs, which occurred due to episodic seismic loading during the depositional history of the unit (Doe and Dott, 1980; Horowitz, 1982; Rubin and Hunter, 1988; Sanderson, 1974b). General agreement (Rubin and Hunter, 1988) on the saturation of the sediments at the time of deformation arises from the successful experimental production of similar features only under saturated conditions (McKee et al., 1962a; McKee et al., 1962b; Rettger, 1935) and is supported by small-scale observations in wet-climate dunefields of the Brazilian coast (Bigarella et al., 1969; McKee et al., 1971). The truncation of deformation features by erosional surfaces that separate successive sandstone units establishes that deformation events were dispersed within the depositional history, corresponding to the event characteristics of seismic triggers (Horowitz, 1982; Rubin and Hunter, 1988). Some local observations support the assignment of specific deformation processes to a location below the level of dune troughs; however, generalization of such interpretations (Horowitz, 1982) derives from the assumption that saturated intradunal conditions did not occur above the level of the interdunal water table (Figure 2). That is, such generalizations are based upon a Navajo paleohydrology featuring an essentially flat water table, which fluctuated in response to climatic variations in the recharge catchment and/or the vicissitudes of a regional base level, such as occurs, at much smaller scales, in hyper-arid modern analogs.
Inherent Weaknesses of the Current Deformation Model

Figure 2 (Horowitz, 1982) presents the most recent and widely favored model for soft-sediment deformation in the Navajo Sandstone. Its applicability as a general model is doubtful, however, because it does not account for: 1) the depth, upward attenuation, and lateral extent of deformation apparent in many outcrops of the Navajo Sandstone; and 2) deformation during aggradational episodes of dune migration. Furthermore, this model requires frequent, dramatic fluctuations of the regional water table to lower it between deformation and deflation of the sediments (saturated sand is not prone to deflation), then raise it before the next deformation event (dry sand is not prone to plastic deformation). These requirements apply to the lateral successions, in these cross-stratified deposits, as well as the vertical.

The first point highlights the limitations of a model dependent on dune loading to produce the deformation forces. It brings into consideration outcrops such as that represented in Figure 3, where the effects of upward-directed fluid escape, as opposed to gravity-driven dune foundering, is clearly exhibited both in the morphology of the deformation features and their attenuation at overlying permeability barriers. At the illustrated locality, a single deformation event affected a succession of at least 5 dune deposits, representing an accumulation of at least 20 m; but each set of crossbeds displays distinct deformation morphologies that are, typically, discontinuous with overlying features. Deformation features with an extent exceeding any reasonable estimate of dune wavelength, discussed later in this report, cast further doubt on the singular importance of dune loading on deformation morphologies.

The second point is more subtle, but no less significant to the general applicability of this model. The scenario depicted in Figure 2 could occur only during degradation of the accumulation, when there was a net decrease in the volume of the accumulated sediment, as the upper surface of the “previous dune deposits” dropped to the level of the water table. Therefore, where abundantly preserved, soft-sediment deformation features would belie the aggradational history represented in the hundreds of meters of accumulated sand in which they occur. Not only does Horowitz’ general model (1982, Figure 27) require a net degradation of the accumulation, each of his interpretations of specific features (Figures 28 and 29) do, as well.
Earthquake motion liquefies saturated sand beneath an interdune low. Steeper portion of the upwind dune collapses into the liquefied sand, resulting in lateral shifting of subsurface sand masses. Preservation of only the lowest portion of the deformation after deflation.

The absence of bedforms in Part C of this diagram is not essential to the proposed model. Non-climbing dunes migrating across the upper surface of the accumulation would produce the same result, as Horowitz (1982) depicted in a separate figure.
Figure 3: Deformation of multiple crossbed sets at North Coyote Buttes (N37 00.621 W112 00.6). A perspective limited to the white rectangle might prompt the interpretation of multiple events, rather than deformation in a single event, modulated by the permeability inhomogeneities of the stratigraphic architecture.
More specifically, the Horowitz model infers that the deposits of consecutive dunes are not preserved across any surface that truncates large-scale, soft-sediment deformation features. In Figure 2, the “previous dune deposits” may represent the accumulated deposits of the dune immediately downwind of the dune that is shown to founder; but, by deflation to the water table, some of this accumulation is removed. None of the foundered dune is preserved; it only serves to generate directional pressure to deform the underlying accumulation. Hypothetically, any number of bedforms could migrate across the field of view during the time that elapses between “B” and “C” of Figure 2. Therefore, when accumulation resumes, the bounding surface that truncates the deformation features will not separate the deposits of a direct succession of dunes. In other words, in those sections where successive deposits are separated by a boundary that truncates deformation features, accumulation did not proceed by bedform climb.

Such a constraint poses no obvious problems for many parts of the Navajo; but in places like the lower half of the Glen Canyon section, it would apply to most units in the succession. Without recourse to climbing bedform theory, the remarkably systematic architecture of these deposits is difficult to explain (Kocurek, 1991). The main problems lie in modeling an aggradational succession under these circumstances and explaining the selection process for those isolated bedforms whose deposits were preserved through multiple wavelengths of migration. In typical sections of Navajo Sandstone, the thickness of the succession, the thickness and continuity of individual crossbed sets, and the regular distribution of bounding surfaces between sets all suggest production by trains of climbing bedforms: Conditions of bedform climb affect a succession of bedforms simultaneously, not individual bedforms at random. Perhaps an accumulation produced by climbing bedforms can be eroded so that only the deposits of one or two bedforms are ultimately preserved. This process could be repeated over and over to produce a thick succession of deposits; however, it is difficult to imagine how the contingencies of extrinsic controls could produce such regular successions.

These caveats to the Horowitz model apply only to its general applicability. There is no problem with the Horowitz model as a special case: It adequately explains, in isolation from the context of the succession as a whole, the features he examined in Red Rock Canyon. Furthermore, the present report will document additional evidence for
dune foundering from other Navajo outcrops, corroborating Horowitz’ key hypothesis. The problem arises when this model is applied as a general case, which Horowitz (1982) may have encouraged by dubbing it a “hypothesis to explain deformation of aeolian dune deposits” (p 174). However, he clearly enumerated the characteristics (p 155) of the features he targeted: 1) planar zones of deformation that parallel the boundaries between crossbed sets; 2) zones of deformation scaled in meters of thickness and tens to hundreds of meters in lateral extent; 3) deformation zones generally not involving multiple sets; and 4) deformation morphologies characterized by simple to complex folds, drag folds, and minor faults. Focus on these features reflects Horowitz’ opinion that: “The key for developing a satisfactory hypothesis to explain the deformation of eolian dune deposits lies in identifying the driving mechanism accounting for the block-like translation of sand masses once liquefaction has occurred” (p 174).

Erg Hydrology and Soft-sediment Deformation

Though the paleoclimatic perspective featuring persistently hyper-arid conditions and a flat water table in the Navajo erg is consistent with the best available paleogeographic reconstructions (Kocurek and Dott, 1983; Parrish and Peterson, 1988; Peterson, 1994b), these do not exclude the possibility of monsoonal interludes. The dominance of the hyper-arid desert interpretation may derive more directly from several traditional arguments. First of all, the modern, arid, Sahara Desert has been presented as an analogue for the Navajo depositional environment ever since the unit was first described (Gregory, 1917); even though some serious limitations of this comparison have long been recognized (Marzolf, 1988a), as noted below. Secondly, modern dune fields subjected to high precipitation typically become stabilized by vegetation, so that the concept of a large, active, wet-climate dunefield is something of an oxymoron in paleoclimate interpretation. Thirdly, prior to the emergence of climbing bedform theory, extensive sub-horizontal boundaries in eolian dune deposits were considered to represent deflation to the lower limit established by a regional water table (Opdyke and Runcorn, 1960; Peirce, 1964; Stokes, 1968) and this dynamic does appear to predominate over bedform climb in modern eolian dune environments (Fryberger, 1993). Finally, Horowitz (1982) successfully modeled preferential shear folding in the direction of dune migration.
by showing that, under flat water table conditions, liquefaction susceptibility is higher in
the saturated sand below interdune lows than below the dunes themselves; so that dunes
would tend to founder forward into subsurface zones of liquefaction during a seismic
event.

The force of logic supporting the use of a featureless water table in the modeling
of Navajo paleohydrology is blunted by counter-arguments for each of its salient points:
Saharan groundwater systems are themselves quite localized (Mainguet, 1999); there are
modern examples of active, wet-climate dunefields, in coastal locations of high sediment
flux, such as the Oregon Dunes, on the west coast of the United States and Lencois
Marenhenses, on the northeast coast of Brazil; and the sedimentary architectures of
modern dunefields do not typically display the systematic bedding geometries seen in
Colorado Plateau eolianites (Fryberger, 1993). For example, though dune-covered
portions of the modern Sahara are similar in extent to the area occupied by preserved
Navajo deposits, there are few similarities between the accumulations. Most Saharan
dunes are perched on bedrock surfaces or minor sand accumulations (Marzolf, 1988b).
With regard to dune stabilization, there is no geologic evidence for efficient, dune-
stabilizing vegetation prior to the Cretaceous (Glennie and Evamy, 1968; Loope, 1988;
Marzolf, 1988b); so modern environments do not provide good analogues for this aspect
of dune dynamics in the early Jurassic. As for the foundering of dunes, the present study
will present architectural evidence in support of a more nuanced view of that process.

Though the meager fossil record in the Navajo Sandstone (Winkler et al., 1991) is
consistent with a continental environment of deposition, it provides few clues about
specific paleohydrological conditions. However, the distribution of plastic deformation
features and interdune deposits, in the context of well-exposed depositional architectures,
dramatically augments the available information regarding the saturation of near-surface
sediment at some locations in the ancient erg (Loope and Rowe, 2003; Loope et al., 2001;
Loope et al., 2004). Local rainfall, rather than fluvial input from wetter elevations, may
have produced some episodes of interdunal flooding: Loope and others (2001) attributed
thick slump masses within large-scale dune cross-strata at Coyote Buttes, near the Utah-
Arizona border, to an annual monsoon pattern of precipitation; Loope and Rowe (2003)
later argued, on the basis of trace fossil distributions in those same outcrops, that intervals
of enhanced monsoonal rainfall supported the development and persistence of interdune ecosystems. Bromley (1992) described water-table-controlled variations in permeability and induration associated with carbonate lenses at the eastern margin of the formation. The carbonates and a few meters of overlying sandstone were preserved as paleotopographic highs, subsequent to erosion of the J-2 unconformity, at the top of the Navajo. Bromley (1992) attributed the preservation of the sandstone hills to a series of early diagenetic processes that derived from highly localized water table contours, perched upon the carbonate lenses.

Modern, wet-climate dunes typically display localized hydrologic regimes and considerable topographic relief of the water table (Ahlbrandt and Fryberger, 1981). Small (meter-scale) water table mounds have been documented from a few places, such as the Nebraska Sand Hills (Winter, 1986; Gosselin et al., 1999); however, no systematic documentation of water table variations in unvegetated, wet-climate dunes has yet been published.

**Objectives of this Report**

The present report revises the hydrologic and topographic contexts of the current model for soft-sediment deformation in the Navajo Sandstone, while offering additional support for some of its other elements. The proposed revision is recommended both by theoretical considerations and by process interpretations of observed outcrop relationships between soft-sediment deformation features and the depositional architecture of the Navajo Sandstone.

Outcrop examples provide a basis for distinguishing two different general styles of large-scale, soft-sediment deformation, representing distinctly different combinations of paleoenvironmental controls. The first style is characterized by stratigraphically discrete and narrowly confined deformation zones, developed within volumes of sediment tens of meters in diameter. These isolated zones feature fold patterns concordant with original foreset dip directions, preferential folding above toe-set deposits, and common upper termination by erosional truncation. This is the style documented by Horowitz (1982), and addressed by his proposal for a general model. The second style occurs in large zones of continuous deformation that include several
successive sets of cross-strata and extend across areas hundreds to thousands of meters in
diameter. It encompasses complex deformation features with highly variable strain
patterns and often displays a gradational, upsection termination.
Both of these deformation styles are well represented in Navajo (Aztec) Sandstone
outcrops in Red Rock Canyon National Conservation Area, where Horowitz’ primary
study site is located. This report provides photo-documentation of these features, along
with comparable data from other, more fortuitously exposed outcrops.

Methods

Stratigraphic Signatures of Deformation Events
Because of its uniform petrology, lack of datable horizons, limited and
undiagnostic fossil content, and the discontinuity of its internal boundaries,
chronostratigraphic subdivision of the Navajo Sandstone has not been achieved.
Therefore, the relative timing of depositional events across the ancient erg cannot
currently be established. The event characteristics of the deformation features that are
widely distributed across Navajo outcrops do hold promise for chronostratigraphic
correlation (Peterson, 1988a); however, a lack of specificity in current deformation
models prevents the general use of deformation features as a correlation tool. A reliable
association between specific deformation styles and well-defined areal and stratigraphic
limits, susceptibility conditions, and triggering mechanisms has not been established; so
event linkage is often equivocal. There exists no independent record of Early Jurassic
triggering events by which to establish an event framework for the region; so
chronological relationships between various deformation features must be constructed
based on physical continuity and cross-cutting relationships to other elements of the
depositional architecture. This task is impeded by the complex time lines of these cross-
stratified deposits, cryptic linkage between apparently isolated features (Figure 3), and
the possibility of multiple events affecting the same body of sediment.

Difficulties with chronostratigraphic correlation impede paleohydrological
analysis and the interpretation of climatic controls, as well. Reconstructing the ancient
water table configurations across the Navajo erg requires more information than can
usually be obtained, even from the extraordinary outcrops of the Colorado Plateau. In
spite of the frequent occurrence of deformation features, indicating groundwater saturation of the affected sediments during a discrete interval of the depositional history, water table configurations at the moment of deformation can rarely be assessed because the reconstruction of paleotopographies from the preserved stratification is seldom possible. Without time linkage between a particular deformation feature and the nearest, contemporaneously exposed foreset or interdune surface, even broad characterizations of the position of the water table relative to bedforms is usually limited to those instances where moist to flooded interdunal conditions resulted in distinctive (horizontally stratified) deposits. These instances establish a lower limit for the water table inside the adjacent paleodunes, but reveal nothing regarding its contour.

Outside the areas affected by wet interdune processes, the internal architecture of the Navajo Sandstone appears as a complex array of foresets and higher-order bounding surfaces (Figure 4). These divide the remarkably homogeneous sandstone lithology into genetic packages of increasingly less certain significance as the scale is increased. That is, a lateral succession of foresets can readily be interpreted in terms of a dune advancing downwind; whereas a vertical succession of cross-strata may represent processes as direct as a climbing train of successive dunes or as obscure as repetitive cycles of sediment accumulation followed by bypass and erosion. Nevertheless, in outcrops where the effects of deformation on surface processes have been preserved, analysis of deformation features within the context of the depositional architecture may yield surprisingly detailed views of event characteristics. Such outcrops provide very useful constraints for the modeling of paleohydrology and the dynamics of soft-sediment deformation in the Navajo Sandstone. The exquisitely defined sedimentary structures exposed in many outcrops of the Navajo Sandstone provide exceptional opportunities to observe, in detail, the strain produced by transitory stress regimes in the ancient erg, at discrete moments in its depositional history. Each instance presents the visual record of a unique history, constrained by factors controlling load distribution, hydraulic pressure differentials, sediment susceptibility, and the localization of environmental triggers.
Figure 4: Depositional architecture of the upper Navajo Sandstone, in West Canyon, Arizona. Scalloped cross-bedding (Rubin, 1987b) is evident at this location; however, the large scale and complexity of stratification impede the recognition of regular patterns, even with excellent outcrop exposure. Note the opposing foreset dip directions between the bottom and the top of the outcrop. These indicate deposition in troughs along irregular dune crests, not fluctuating transport directions.
Data Collection

Photodocumentation

Along with most other investigators, we find that photographs are the best available instrument for documenting the sedimentary architecture of the Navajo Sandstone. As Gregory (1950) remarked: “These straight lines, curved lines, and truncate planes that characterize the Navajo cross bedding vary so widely in dimension, position, and arrangement that adequate detailed description seems impracticable. Even attempts to outline types of cross bedding have proved unsatisfactory. Fortunately, photographs record the features with fidelity and make leisurely study possible.” (p 84)

Not only do single photographs document the details of SSD, but photographic panoramas provide an excellent means to record the spatial relations between them, as demonstrated by Horowitz (1982). Significant features of depositional architecture can also be traced upon these panoramas, providing essential temporal and paleoenvironmental context to SSD analysis. These effectively replace stratigraphic sections in high-resolution studies. As Sanderson (1974) noted, “... the lateral changes in bedding type are sudden and varied between major bedding planes; thus a stratigraphic section is of limited value in describing the Navajo Sandstone. A cross section, however, shows lateral changes in detail.” (p 236) Furthermore, in cross-stratified deposits, the interpreted vector of time extends more continuously down the direction of paleocurrent flow than it does vertically, and less frequently encounters boundaries of highly speculative significance. Lateral relations therefore constitute the most reliable starting point for an analysis of depositional trends. This primary analysis can then be used to evaluate the significance of the vertical succession.

Sampling and Laboratory Analyses

The studies documented in this report focus on the implications of visibly defined architectural features of the Navajo Sandstone. However, in a few cases where samples were available and afforded the opportunity for petrologic distinctions that could not be made in the field, laboratory analyses also contributed to outcrop interpretation. These consisted, primarily, of petrographic evaluations of carbonate lithology and sandstone texture and trace mineralogy.
Observations And Interpretations

Study Site Locations

Figure 5 provides a regional view, showing the relative locations of the various study sites documented in this report. Separate figures and GPS coordinates, attached to specific descriptions, provide more detailed location information.

Extensive Deformation Zones

Temple Mountain, Utah

Extensive deformation of the Navajo Sandstone within the San Rafael Swell of Central Utah was reported by Kiersch (1950) and Sanderson (1974). Sanderson later supervised Master’s thesis research (Stephens, 1985) focused on exposures in the vicinity of Temple Mt., on the steep east limb of the asymmetrical anticline, where three, thick (15-35 m), stratigraphically isolated deformation zones are evident. These deformation zones can be traced in continuous outcrop for kilometers, both parallel and perpendicular to the dominant paleowind direction (NW to SE), indicated by foreset dip, and can be plausibly correlated across 125 km² of outcrops. Figure 6A shows the common association of massive sandstone with disturbed crossbedding that characterizes these extensive zones. Sanderson (1974) used x-ray analysis to demonstrate that what appears to be massive sandstone in outcrop actually contains relict sedimentary structures, dislocated incrementally between grains. These zones of indistinct stratification most commonly grade through deformed crossbedding into undisturbed foresets at their peripheries (Figure 6B); though, in some instances, the upper boundary appears abruptly at an erosional surface. A vertical succession of several sets of cross-strata has been deformed within each of these widespread zones. Fold orientations are, typically, highly variable relative to foreset dip, apparently responding to evolving pressure differentials in the liquefied mass at the time of deformation; though this did not preclude deformation in the direction of foreset dip (Figure 6B). Stephens (1985) contrasted this style of deformation with that observed in much more localized deformation zones confined within single sets of cross-strata. In that setting, fold hinges are typically aligned with foreset strike, such as the drag folds described by Horowitz (1982) from the Wilson Cliffs (Red Rock Canyon, Nevada).
Figure 5: Relative locations of primary study sites in this report. More detailed location maps for the Red Rock Canyon (N36 09.0 W115 27.0) and West Canyon (N36 59.2 W111 07.6) study sites are provided in Figures 7 and 14. Moenkopi Wash is readily accessible below the Hopi village of Moenkopi (N36 06.7 W111 13.3), which location is shown with sufficient precision on this map. North Coyote Buttes (N37 00.6 W112 00.6) is accessible only by special permit from the US Bureau of Land Management. The Temple Mt site is located at: N38 39.541 W110 39.833).
Figure 6: Deformation of the Navajo Sandstone at Temple Mt., Utah. 6A: Indistinct stratification associated with extensive zones of deformation. 6B: Drag folds at the bottom of a deformed set, indicating lateral motion of an overlying, liquefied mass of sand.
Calico Basin, Nevada

Approximately 6 km from Horowitz’ (1982) study site (Figure 7A) in the vicinity of Willow Spring, in the Red Rock Canyon National Conservation area, Nevada, the outcrops of Calico Hills and Calico Basin (Figure 7A) expose soft-sediment deformation structures comparable to the more extensive Temple Mt. features. Doe and Dott (1980) diagrammed overturned crossbeds in an outcrop at this location (Figure 11, p 802); otherwise, the literature is silent regarding these features. In an approximately 2 km x 3 km area of exposure (Figure 7A), these outcrops reveal a single extensive zone of deformation that cuts gently up to the northeast, through a succession of crossbed sets (Figure 7B), within a stratigraphic interval from 100 m to 135 m above the prominent break in slope defining the contact between predominantly eolian sandstones (Lower Jurassic “Aztec”) and underlying, undifferentiated fluvial deposits containing an abundance of fines. Deformation within this interval is more continuous in the northern outcrop, suggesting that the southern outcrop may represent a peripheral deformation facies. Post-lithification diagenetic processes have redistributed the interstitial iron oxides, producing color patterns that do not always correspond to sedimentary structures (Figure 8A); nevertheless, even a cursory examination reveals diverse orientations of fold axes within the deformation structures (Figure 8B). The upper boundary of this deformation zone displays a transition from plastic to brittle styles of deformation (Figure 9A), at a level approximating the ancient water table. In the main body of the deformation zone, fields of indistinct stratification, within deformed avalanche foresets, surround isolated blocks of more cohesive, ripple-laminated sandstone (Figure 9B) such as elsewhere occurs within the basal plinths of cross-stratified units. It appears that porosity differences between these two types of stratification constrained fluid flow patterns between successive sets, exercising significant control over deformation morphologies (See also Figure 3).

Deformation of Accumulated Deposits

Clearly, the bulk of deformation at both Temple Mt. and Calico Basin occurred in the developing accumulation, not within active bedforms since, typically, a succession of beds deformed as a unit. This contrasts markedly with the stratigraphically isolated
Figure 7A: Location of Nevada study sites, within the Red Rock Canyon National Conservation Area. 7B: Typical section in Calico Hills, showing gentle dip of deformation zone, relative to bedding.
Figure 8A: Concordant and discordant patterns of coloration, relative to stratification at Calico Hills. 8B: diverse orientations of deformed crossbeds in extensive deformation zone at Calico Hills.
Figure 9A: This transition from plastic to brittle styles of deformation appears to approximate the ancient water table at the time of deformation. 9B: Cohesive blocks of wind-ripple-stratified sand have been distribution of SSD features at many other locations, notably the West Canyon outcrops in Figures 14-19, as discussed later in this report.
distribution of SSD features at many other locations, notably the West Canyon outcrops in Figures 14-19, as discussed later in this report.

Diverse orientations of fold axes indicate that differential surface loading was not the primary controlling factor in stress field generation during deformation. The persistence of continuous deformation well beyond any reasonable estimate of the wavelength of contemporary bedforms supports this interpretation. Pressure generated by fluid escape from deep (tens of meters) liquefaction zones, accompanied by localized fluidization of overlying deposits, better accounts for the diverse patterns of strain. dispersed within a fluidized matrix derived from more porous, avalanche foresets. The contrasts in cohesiveness and permeability between these stratification types appear to have exercised various controls over deformation dynamics (See also Figure 3).

Localized, Large-scale, Deformation Features

Red Rock National Conservation Area, Nevada

Approximately 25 m below the extensive zone of deformation in Calico Hills, more isolated deformation features appear within individual crossbed sets (Figure 10). Fold axes in these features display preferential orientation parallel to foreset strike, similar to the features (Figure 11) described by Horowitz from the Willow Springs/Lost Creek outcrops of Red Rock Canyon National Conservation Area. Though precise correlation is not feasible, these features do occur within the interval, 65-90 m above the base of the Aztec/Navajo Sandstone, to which Horowitz assigned the deformation features from his study area. Their occurrence appears not to extend into the northern outcrop, above Calico Basin (Figure 7A). Upper boundaries are typically abrupt, occurring at discrete erosional surfaces that truncate contorted or indistinct stratification.

North Coyote Buttes, Arizona

Excellent examples of both styles of soft-sediment deformation appear in outcrops at North Coyote Buttes, along the border between Utah and Arizona. Here, sedimentary structures have been highlighted by patterns of diagenetic coloration, and further enhanced by differential erosion, to produce unusually explicit displays of sedimentary architecture. Figure 12 shows a distinctive example of a discrete feature that
Figure 10: The lower, less extensive deformation zone in Calico Hills (N 36.14508; W 115.42731) displays localized deformation features with slump structures (A) and/or fold axes parallel to crossbed strike (B), pointing toward gravity as the primary control over local stress fields.
Figure 11: Gravity control over deformation dynamics also characterizes the features described by Horowitz (1982) from his Lost Creek study site, in both the upper (A) and middle (B) deformation zones.
Figure 12: Erosionally truncated, foundered foresets at N Coyote Buttes (N37 00.317 W112 00.542).
demonstrates bounding surface relationships comparable to those postulated by Horowitz (1982) in his analysis of Lost Creek outcrops (Figure 2). Figure 13 shows an associated feature (same crossbed set) that indicates additional dynamics in operation during the deformation event. Interpretation of these features does not require an overhaul of the Horowitz model; however, the process is simplified by postulating intradunal deformation. Transitions between brittle and ductile deformation suggest that the interior of the foundered dune was moist, if not saturated. In this context, it must have been the interior of the dune, not the lee slope, that foundered. Diverse architectural relationships in a series of outcrops in West Canyon, Arizona, provide even greater impetus toward a model that incorporates intradunal deformation to explain localized, large-scale deformation features with coherent relationships to crossbed orientations.

West Canyon, Arizona

At a study site in West Canyon (Figures 14-21), several associated features provide remarkably fine resolution of the details of a deformation event and indicate fluidization of sand within an active bedform, during deposition of the Navajo Sandstone. The study area encompasses a 75 m x 750 m cross-section that includes two carbonate lenses measuring 575 m and 50 m in outcrop diameter. The overall trend of the canyon is NW/SE, which parallels the regional paleowind direction for the Navajo Sandstone (Anderson et al., 2000; Poole, 1964). West Canyon Creek flows to the northwest and meanders through two, broad, 90-degree turns (See Figure 14A), providing three-dimensional perspectives on the stratification geometries. The study section includes 5 successive sets of cross-stratified sandstone, each 10-20 m thick (Figure 14B). Every unit in this succession displays large-scale soft-sediment deformation features. None of the deformation features crosses unit boundaries. The carbonate lenses occur in lateral succession at the base of the section and are overlain by a thin siltstone followed by up to 6 m of horizontally stratified sandstone. These horizontal strata interfinger and merge with the southeast-dipping basal aprons of 18 m foresets, and the carbonate lithologies become increasingly sandy approaching these transitions. To the southeast, the carbonate lenses pinch out between successive sets of large-scale cross-strata.
Figure 13: Pipe structure within the same set of crossbeds featured in Figure 12, 50 m away, in the direction of foreset dip (SE). Concentric faults trending at an acute angle to crossbed dip have accommodated collapse of a cylinder with fluidized sand at its core. Total offset exceeds 1 m. No apparent rotation occurred during displacement. The nearest reactivation surface in this set occurs 150 m further down the paleo-wind direction, indicating that dune foundering did not occur at the dune/interdune junction.
In some places above the larger, older, carbonate lens, horizontal stratification is absent. Here, the interval is occupied by massive sandstone containing varying proportions of angular clasts of carbonate and siltstone in a matrix of fine sand (Figure 15A). Streamlined pendants and angular blocks of horizontally stratified sandstone also occur within this interval (Figure 15B) and sill-like bodies of the intraclast-bearing sandstone extend into overlying remnants of horizontally stratified sandstone (Figure 16). Lenses of intraclast-rich sandstone, up to 3 m in horizontal cross-section, truncate carbonate laminae at various locations. These cross-cutting relationships indicate that the horizontally stratified sand overlying the carbonate was remobilized after deposition. It developed intrastratally, as sand was liquefied and mobilized around the partially consolidated carbonate mud. More subtle features, delineating pathways of fluid escape (Figures 16B and 17), accompany the dramatic indicators of hydroplastic flow.

Event linkage provided by these features opens a unique window onto conditions in the ancient erg at the time of their genesis. The sill-like body of intraclast-rich sandstone pictured in Figure 16A tapers to the northwest into the lateral fluid-escape pathway of Figure 16B. The lateral pathway terminates in a vertical pipe, which broadens upward into a zone of soft-sediment deformation in the overlying, cross-stratified sandstone, 6 m above the top of the carbonate lens (Figure 17). These relationships indicate that a dune had advanced over at least a portion of the interdune deposits when deformation occurred. Undulations in the surface of northwesterly portions of the carbonate lens, accompanied by boudinage of the siltstone horizon, also suggest dune loading during liquefaction. A large-scale (18 m x 100 m) deformation feature appears in the first cross-stratified sandstone unit above, and towards the southeast end of, the larger carbonate lens (Figure 18). The deformation appears as a contorted mass of discontinuous flow features and structureless sandstone. Its northern boundary grades irregularly into undeformed foresets. The southern boundary is obscure, lying within a complexly stratified region in which sedimentary structures are indistinct. The lower boundary is defined by the top of the horizontally stratified sandstone, which displays only small-scale (cm) scour and no deformation. The upper boundary is the deflation surface marking the top of the first cross-stratified sandstone unit. It truncates the deformation. No linkage to the deformation of the carbonate interval is apparent.
Figure 14A: Detailed locations of the West Canyon outcrops described in this report. The base map is a composite of the USGS 7.5’ quadrangles for: Face Canyon, Arizona; West Canyon, Arizona; Cathedral Canyon, Utah; and Gregory Butte, Utah (See Figure 5 for general location map). Access is by boat only, via Lake Powell, and the study area crosses the boundary between Glen Canyon Recreation Area and the Navajo Nation, along the 3,720’ elevation contour. Research was conducted under permit #GLCA-2006-SCI-006 and various permits from the Navajo Nation, including a special collection permit for the fossil specimens, which are archived at the New Mexico Museum of Natural History (NMMNH P-33097 and P-33098).
Figure 14B: The study section in West Canyon. The stratigraphic succession includes: a lenticular, horizontally stratified interval in which a laminated carbonate deposit occurs; the cross-stratified sandstone that encases the lens; and the overlying, 75 m succession of cross-stratified sandstone units that are exposed in the cliff face. Each of the labeled set boundaries truncates a large-scale soft-sediment deformation feature within the study area. This view is to the northeast, near the north end of the study site.
Figure 15: Sandstone bodies in a variety of configurations within the carbonate interval. In Figure 15A, the upper surface of the carbonate is scoured and overlain by structureless sandstone containing angular clasts of carbonate and siltstone. Preferential weathering of these clasts has produced the distinctive, vuggy surface. Non-intraclast-bearing sandstone bodies (mudracks?) appear within the carbonate horizon. In Figure 15B, red intraclast-rich sandstone encases a streamlined pendant of gray, horizontally stratified sandstone. Another horizon of sandstone containing intraclasts appears as the vuggy white band within the overlying unit of gray sandstone.
Figure 16: Clastic injection and fluid escape features in horizontally stratified sandstone. In 16A, a well-defined body of intraclast-rich sandstone (~20 cm thick) cuts across both underlying and overlying sandstone laminae, 80 cm above the carbonate lens. This injection feature tapers to the northwest, into the fluid-escape pathway pictured in 16B. That pathway is defined by a 2 cm zone of eluviation and marked by erosional pockets in the weathered surface of the outcrop. Note that the fluid-escape pathway, like the clastic sill, gently cuts across the horizontal lamination of the sandstone.
Figure 17: Vertical fluid-escape pathway. Downdropped beds, above and to the right of the 1.5 m stick leaning against the outcrop, provide distinct definition to a vertical pathway that leads to contorted cross-strata, 6 m above. A similar association of pillar structures with vertical fluid escape pathways occurs in several places across this portion of the outcrop. Faint lineations within the pillars, paralleling their external morphology and continuing into the overlying, undeformed sandstone, further indicate their origin as pathways of fluid escape. Alcoves on either side of the pillars contain erosional remnants of siltstone. The arrow points to the lateral fluid-escape pathway pictured in Figure 16.
Two partially preserved crocodylomorph specimens were collected out of talus below the larger carbonate lens, 230 m south of the series of deformation features depicted in Figures 16-17 and 80 m northwest of the large-scale deformation feature in Figure 18 (See Figure 14A). In life, the larger of these may have approached 70 cm. The second specimen, recovered from within 2 m of the first, is about half that size. The fossils occur in two separate blocks and are encased in fine-grained, light red sandstone containing angular, elongate clasts of dark red shale and gray carbonate. This intraclast-bearing sandstone lithology matches that occurring in the horizontally stratified interval at this location, immediately above the carbonate horizon. The larger sample contains a portion of the carbonate horizon, displaying the lithologic transition immediately below the vertebrate remains. Together, the specimens consist of articulated ventral scute impressions, dorsal scutes, articulated vertebrae, a complete set of gastralia, a tooth, a manus, three partial pes, and unprepared material, representing the most complete protosuchid remains known from the Navajo Sandstone (Rinehart et al., 2000).

The taphonomy of these protosuchids indicates that deformation occurred during the initial burial of the interdune and establishes a downwind limit for the lee face of the prograding dune complex since, in life, the animals could not have been far removed from the land surface. The articulation of the specimens, coupled with an absence of other fossil fragments, suggests that death occurred locally. The presence of locally derived, angular clasts of carbonate and shale in the sandstone that encases them further supports this interpretation. Preservation of scute and gastralia arrangements, along with various articulations, indicates that soft tissues were present both during burial and during the deformation event that produced the intraclasts within their sandstone matrix. That two, similarly well-preserved fossils occur at the same location, within the disturbed interval, strongly suggests that death and burial occurred simultaneously during liquefaction of the surrounding sand. That is, these primitive crocodiles were engulfed in quicksand, probably as they sheltered in shallow burrows in the moist sand below the lee face of a large dune. Such burrowing behavior is not entirely conjectural: Figure 19 shows a suitably sized excavation that occurs slightly higher up within this same interdune succession. Figure 20 summarizes the observed architectural relationships.
Figure 18: Large-scale deformation feature. The 20-30 cm thick carbonate horizon tapers towards its southeast (right in the photo) termination across this portion of the outcrop. It is overlain by 5 m of horizontally stratified sandstone and 18 m of deformed, cross-stratified sandstone. This deformation feature postdates the event that entombed the protosuchids.
Figure 19: Anomalous, meter-scale, cut-and-fill structure in a N/S West Canyon section. Lens cap (under D) for scale. This feature appears within the same interdune succession that produced the protosuchid fossils; however, on the basis of architectural relationships, it post-dates those specimens.

The primary fill (A) consists of horizontally stratified sandstone. It occupies a 120 cm trough that cuts across 15 cm of low-angle stratification deposited in the basal plinths of southerly advancing dunes. To the north (left), the thickness of this fill tapers down to less than 1 cm, just beyond the boundary of the trough, and persists indefinitely as a uniform bed. The fill interval persists, to the south, as a narrow band overlying an irregular interval of disrupted stratification until both those units merge into uniform bedding, some 5 m further south along the outcrop. A subsidiary trough (B) occurs at the bottom of the primary trough. It is smaller (40 cm x 8 cm), and its sides are more steeply inclined. It, also, cuts across stratification. It is filled by indistinctly cross-laminated sandstone, dipping north, roughly parallel to the southern wall of the trough. Fill structures are discontinuous between the primary and subsidiary troughs. A small sand flow marks the north margin (C). Deformation, clastic injection, and fluid escape structures appear in the stratified sandstone beyond the south margin of the primary trough (D). Stratified, secondary fill units (E) taper into beds of uniform thickness beyond the extent of the primary fill. Units immediately overlying the secondary fill (F) are uniform in thickness across the trough, but deformed in that region, due to differential compaction between the fill material and the surrounding deposits.

The shape of the trough is consistent with excavation by a small (~1 m) animal, such as a protosuchid. In this scenario, the surface sand was moist, but not fully saturated, allowing the excavation to proceed. However, trampling of the perimeter south of the trough, during excavation, liquefied the sand below the water table and caused the fluidized material to erupt through the strained and fractured sand mass above. The extended zone of massive sandstone in this area represents a mixture of trampled surface and excavated material. The northern sandflow resulted from oversteepening of the excavation on that side. The north-dipping fill strata were produced as the animal back-filled that portion of the excavation.
Figure 20: Architecture of the West Canyon section (idealized N-S cross-section of 75m x 750m outcrop)
A. Large-scale, cross-stratified, eolian sandstone unit.
B. Superscoop, filled by large-scale foresets. The lower boundary of the scoured trough is marked by a zone of alteration.
C. Secondary deflation hollow, filled with horizontally stratified sandstone.
D. Silt deposit underlying the principal carbonate lens.
E. Partially dolomitized carbonate deposit displaying desiccation cracks, evaporate textures and pseudomorphs, and subdivided by stringers of silt and fine sand.
F. Silt deposit overlying the carbonate lens.
G. Horizontally stratified sandstone that grades into the carbonate facies, at the north end of the lens, and overlies the carbonate, elsewhere. The thickness of this unit varies dramatically.
H. Protosuchus fossils.
I. Large-scale, cross-stratified sandstone. Wind-rippled-laminated basal aprons interfinger with the underlying, horizontally stratified sandstone deposits.
J. Second, stratigraphically superior carbonate lens. The first-order bounding surface underlying this deposit can be traced back to its origin within the foresets of the overlying, cross-stratified unit.
K. Sandstone bodies (clastic injection features), within and above the carbonate horizon, containing intraclasts of carbonate and siltstone. The margins of these inclusions are marked by truncation and deformation of the carbonate laminae. The carbonate is deformed around these inclusions due to differential compaction.
L. A specific soft-sediment deformation feature (Figure 17) that is associated with an assemblage of liquefaction and fluid escape features in the vicinity of the primary carbonate lens.
M. The upper sandstone section, composed of large-scale, cross-stratified sandstone units, separated by deflation surfaces.
N. Large-scale, soft-sediment deformation features (e.g. Figure 18) in the upper sandstone section. Their upper surfaces are truncated by deflation surfaces.
O. A large trough in the upper sandstone section.
Deformation of an Active Dune

The deformation features in West Canyon provide a clear record of fast-acting processes of fluid escape. The entombment of the protosuchids constitutes particularly dramatic evidence of this. The deformation event recorded here occurred after the first interdune pond had dried up and during a period of variably moist conditions similar to those interpreted from the Helsby Sandstone (Mountney and Thompson, 2002). A large dune was actively advancing across the interdune area, prior to water table resurgence and the development of a second, smaller, pond at this site (Figure 21). Both inter-dune and intra-dune sediments were affected by deformation; though dramatic dune foundering is not apparent, nor have we found any mass flow deposits associated with this event.

Even if the large-scale deformation feature above the downwind portion of the first carbonate lens (Figure 18) represents dune collapse, the taphonomy of the fossils establishes that it occurred in a subsequent event. It remains an open question whether that event took place as the large dune continued its southeasterly march or whether it happened much later, when the dune deposits had joined the subsurface accumulation. Even with these ambiguities of timing, the tight lateral spacing of the SSD features from separate events points toward an extremely active deformation environment, characterized by frequent events.

Discussion

Implications of Observed Features for the Horowitz Model

Deep Deformation of the Accumulation

Widespread, deep deformation, involving successive sets of crossbeds and producing folds with diverse axial orientations, are documented in this report from the vicinity of Temple Mt. in the San Rafael Swell, Utah, and the Calico Hills, Nevada. Similar features have been observed by the authors at numerous other localities, as well. These are interpreted, here, as the products of liquefaction at depth and fluid escape through the overlying accumulation. Where a gradational upward transition is preserved, relatively low water table conditions may be postulated, and exceptionally vigorous seismic shaking deemed responsible for the greater depth and areal extent of deformation.
Figure 21: Diverse effects of a liquefaction event in the Navajo erg. Fine-grained, horizontally stratified sand liquefied where it lay in proximity to consolidated carbonate mud. Deformation affected interdune, intradune, and dune-buried sediment.

A. Protosuchids, sheltering in the moist interdunal sand below the lee slope of an advancing dune, died when the surrounding sediment suddenly liquefied, flowed turbulently, and quickly dewatered.
B. A zone of intraclastic sand was produced by turbulent flow within the liquefied, horizontally stratified sand. Angular clasts of carbonate and siliciclastic mud were produced from the underlying, partially consolidated sediments.
C. A silty horizon, draping the carbonate, deformed into thick mounds or lenses within the intraclastic sandstone when overburden pressure was redistributed consequent to liquefaction.
D. Vertically radiating pathways of fluid flow in mobilized sand between silt lenses.
E. A wedge of intraclastic sand, tapering in the upwind direction, was injected along preserved horizontal laminae, cutting gently across stratification.
F. The injection wedge followed a lateral fluid escape pathway along which eluviation and small-scale deformation occurred.
G. The lateral fluid escape pathway terminated in a vertical one that was a conduit for water from the underlying zone of liquefaction. This vertical pathway is marked in the outcrop by faint vertical lineations and a succession of synclinally deformed bounding surfaces.
H. Water rising under pressure fluidized cross-stratified sand within the dune. These deposits deformed in response to the redistribution of static loads and the
evolution of fluid pressures.
This style is not specifically addressed by the Horowitz model; however, directional deformation features attributable to differential loading sometimes do occur in conjunction with the more voluminous, deep-seated features. This may indicate the coincidence of high water table conditions and a high energy triggering event.

_Intradunal Deformation_

Cross-cutting relationships at North Coyote Buttes suggest foundering of a dune into an underlying zone of liquefaction, similar to that featured in the Horowitz model. Though no particular relationship to interdune topography is evident, the upward transition from plastic to brittle styles of deformation clearly indicates that the water table was not mounded very high within the bedform, if at all. Contrary to the Horowitz model, however, no appeal to subsequent deflation of the accumulation is necessary to accommodate the observed architectural relationships.

At the West Canyon study site, the evidence of saturated-sediment deformation within an active dune suggests the presence of a contoured water table, mounded within the bedform, during deformation. However, intradunal moisture was clearly augmented by fluid escape from the subsurface during the event that entombed the protosuchids. Perhaps that fluid, alone, mediated deformation. That is, the fluidization features may have occurred above the contemporaneous water table, much like the pipe structure at North Coyote Buttes (Figure 13). Such an interpretation is not strictly precluded by the outcrop evidence. Nevertheless, the definitive indications of intradunal deformation do provide impetus for a re-evaluation of groundwater conditions during Navajo deformation events and an examination of the potential impact of a contoured water table on deformation patterns.

_Near-Surface Stress Field Generation_

In the Horowitz model, directional deformation occurs in the shallow subsurface, due to stress propagation from dune collapse into underlying zones of liquefaction. In this scenario, gravity is the driving force and preferred directions of folding are produced by the tendency for liquefaction to occur below interdunes, so that dunes founder forward
(downwind). However, if deformation occurs within the bedform itself, there is no need to postulate the transmission of directional forces into the accumulation, since gravity would act directly to deform the bedform toward the steep free face (downwind) and along internal discontinuities. Within Navajo dune deposits, the only regular discontinuity in the homogenous lithology is the crossbedding, which dips in the preferred direction of deformation (downwind). The tendency for cryptic slippage along these surfaces, during a deformation event, has already been documented in other eolian dune deposits (Plaziat et al., 2006).

**Deformation during Aggradation of the Accumulation**

The possibility of large-scale, plastic deformation of intradunal sediment, during bedform migration, provides the means to model deformation under conditions of bedform climb and net aggradation of the accumulation, while simplifying the history of water table fluctuations necessary to explain the common occurrence of deflated deformation features (Figure 22). In a humid climate, water table mounds would migrate along with the host bedforms, so that any particular column of sediment could plausibly experience dry conditions during deposition followed by saturated conditions during deformation, and unsaturated conditions during subsequent deflation, without major fluctuations of a regional water table. The contoured water table may also have promoted accumulation by limiting the volume of intradunal sediment subject to deflation.

**Theoretical Implications of a Contoured Water Table Hypothesis**

If the water table of the Navajo erg was contoured and deformation did occur within the bedforms, certain other paleohydrological hypotheses readily follow:

1. *The high level of the water table inside the draa was not established by infiltration from an interdunal supply.*

   Otherwise, every episode of soft-sediment deformation should be laterally associated with interdune deposits. Such an association is not evident and the overwhelmingly greater frequency of soft- sediment deformation features than interdune deposits argues against such a scenario. The possibility that these deposits were
preferentially, and very efficiently, eliminated is unlikely, given the better preservation potential for deposits at the base of the lee slope than for crossbeds within an active bedform. Vestiges of eroded interdune deposits are not apparent, nor does the state of preservation of those that do occur suggest the operation of such a destructive mechanism. Systematic channel erosion and mass wasting of dunes has not been documented, except in basal transition zones (See Figure 22). Furthermore, a tremendous volume of interdunal water would be required since such a supply network could not raise the elevation of the water table at the interior of the dune (or draa) above that of the surface water level of the interdunal source. An elevated water table within the dune could only be established by interdunal flooding sufficiently prolonged to saturate the dune followed by interdunal drying that was sufficiently rapid to prevent equilibration of the water table surface by groundwater flow from the dune’s interior. Deformation would necessarily occur within that window of time when the sediments remained saturated.

2. The water table contour was established by a dynamic balance between local precipitation and evaporation.

Rainfall supplied water to the topographic surface, where it rapidly infiltrated the porous, permeable sediment. Because deposition generally occurred under dry interdunal conditions, the surface of the erg was dominated by dunes, rather than interdunal flats (Kocurek and Havholm, 1994), so that most of the influx of water took place where relief was positive, passing through the interior of the dune. Also, infiltration occurred preferentially towards the lee of the dune as textural variations within the cross-stratification favored percolation along bedding planes. That is, since the stoss side of the asymmetric dune form provides the majority of its surface area, and the inversely-graded stratification dipped at least 30° in a downwind direction from this surface, percolation tended to further concentrate water towards the interior of the dune. At the level of saturation within the dune, hydraulic head developed which directed flow towards the interdunes, where evaporation occurred. Of course such a dynamic balance would produce storm-induced and seasonal fluctuations in the intradunal water table.
3. *The elevation at which the water table (that is, its capillary fringe) intersected the stoss slope established a lower limit to the portion of the bedform that was incorporated into the accumulation.*

Evaporation along the stoss surface depressed the water table in that vicinity. When evaporation rates, aided by the capillarity of the sediment, exceeded groundwater flow rates, dry interdunal conditions could be maintained in spite of the existence of hydraulic potential between the dune interior and the interdunal lows. However, even under these conditions, deflation would be inhibited by moisture passing across the air/sediment interface. Moisture stabilization effected accumulation whenever this lower limit of deflation exceeded that established by basin dynamics (airflow expansion). The angle of bedform climb similarly depended on these same factors. Furthermore, every dune that migrated while the water table persistently intersected its stoss surface left a deposit, so that the upper boundary of the deposit was fixed by the deflation that occurred in the immediately trailing interdunal low, rather than in some successive interdune of extraordinary depth. In other words, deflation by a subsequent scour pit could only occur consequent to a shift in the internal hydrologic equilibrium of the dune coupled with a general lowering of the water table within the accumulation.

4. *The porous eolian sediments stored rainwater efficiently.*

Once percolating water passed below the zone of capillarity within a draa, only discharge into evaporative interdunal areas or a regional basin could remove it from the system – and initial percolation was efficient through the unstabilized, sandy surfaces. Evaporation of water stored in the accumulation, even during persistent dry conditions, was attenuated by the build-up of dunes, at the expense of interdunal areas, as scoured sand moved through the system (Kocurek and Havholm, 1994).
Conclusions

Patterns of localized, directional, soft-sediment deformation in the Navajo Sandstone suggest the operation of rainwater-controlled hydrologic regimes within its depositional history. During these episodes, water table mounds persisted below topographic highs. Deformation of cross-stratified sand commonly occurred both within and below the large bedforms, as well as beneath the interdune corridors.

By modifying Horowitz’ (1982) deformation model (Figure 2) to include a topographically contoured water table, as suggested by outcrop evidence, a more parsimonious explanatory context can be achieved (Figure 23). In such a setting, deformation could occur above the level of the interdune surfaces, within the dunes (or draas) themselves. Deflation of the deformed deposits could take place at the trailing edge of the same bedform, within an aggradational succession of dune deposits. The saturation level of a particular column of near-surface sand would vary as the water table contours migrated along with the bedforms, while the regional hydrology varied less dramatically. Table 2 summarizes salient features of Navajo Sandstone petrology, described in this report and integrated by this hydrological model.

The cross-cutting relationships established during individual deformation events support high-resolution temporal correlation of outcrop features in the Navajo Sandstone. Having formed very quickly relative to primary depositional structures of comparable extent, soft-sediment deformation features provide time markers for process interpretations of the sandstone architecture. This temporal control is especially useful when patterns of erosion and deposition were altered during the deformation event. In these instances, even the reconstruction of ancient topographies may be possible. At outcrop scale, event correlations open unique windows into the exotic process/response dynamics of the ancient erg and provide useful constraints for the modeling of tectonic, climatic, and autogenic controls.
Even though recycling of sand commonly occurred between fluvial and eolian depositional environments, minimizing lithological contrasts, each environment produced distinct facies assemblages. The cut-and-fill structures of 22A (N 36.1055; W 111.2006) typically are not found in association with Navajo interdune deposits.
Figure 23: Contoured water table hypothesis to explain the production of erosionally truncated, large-scale, soft sediment deformation features in the Navajo Sandstone.

Upper Diagram: Topographic relief of the water table in dunes migrating under dry interdunal conditions.
A. The water table (or its capillary fringe) intersects the stoss surface of the dune at its base. The deposits of this dune are not moisture-stabilized in spite of the saturated conditions inside the dune. No net deposition will occur except as facilitated by other basin dynamics.
B. The interdune occurs between A and B, where airflow detachment generally prevents the deflation of dry sediment. Under non-aggrading conditions, the water table is far enough below the interdune to prevent moisture-trapping of atmospheric fallout.
C. The zone most commonly affected by liquefaction and fluidization. This determination is based on: 1) the typical occurrence of soft-sediment deformation with gradational lateral contacts into undeformed crossbeds and truncation by an upper deflation surface; and 2) the location of maximum loading, below the dune crest. The distribution of sediments susceptible to liquefaction, such as loosely packed grainflow deposits or unusually fine-grained sand deposits, influences the placement of this zone in any particular circumstance.
D. The base of the stoss slope of the advancing dune occurs at the same stratigraphic level as that of the retreating dune, representing zero climb.

Lower Diagram: Topographic relief of the water table in dunes climbing under dry interdunal conditions.
A. The water table intersects the stoss surface of the retreating dune above its base, preserving the lower portion of the dune deposits.
B. Soft-sediment deformation that occurred in the retreating dune (when it was situated slightly in advance of the current position of the advancing dune) displays gradational lateral transitions and truncation by the overlying deflation surface.
C. Successive first-order bounding surfaces in the accumulation may represent the passage of successive dunes.
D. The base of the stoss slope of the advancing dune occurs at a higher stratigraphic level than that of the retreating dune, though elevations may be similar, depending on the attitude of the substrate and the angle at which the dunes climb.
<table>
<thead>
<tr>
<th>Feature</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Succession of large-scale cross-strata separated by featureless bounding surfaces</td>
<td>Primarily dry interdunal conditions during deposition</td>
</tr>
<tr>
<td>Isolated lenses of horizontally stratified deposits along some bounding surfaces</td>
<td>Episodic intersection of the water table with the interdunal surface</td>
</tr>
<tr>
<td>Large-scale, soft-sediment deformation structures</td>
<td>High (up to several meters deep) water table conditions during deposition</td>
</tr>
<tr>
<td>Soft-sediment deformation structures truncated by deflation surfaces</td>
<td>Water table fluctuations, so that sediment saturated with water was rendered susceptible to deflation</td>
</tr>
<tr>
<td>Succession of abundant soft-sediment deformation structures, commonly cut by erosional surfaces</td>
<td>Persistent high water table conditions: The rate of relative water table rise matched the rate of accumulation</td>
</tr>
<tr>
<td>Medium to large-scale deformation structures isolated within single sets, or co-sets, of crossbeds and recurring along section</td>
<td>Soft-sediment deformation that occurred within the dunes or draa themselves, rather than within the accumulated deposits</td>
</tr>
<tr>
<td>Extensive, deep zones of deformation, cutting vertically across multiple sets of crossbeds and, commonly, grading upward into undisturbed primary structures</td>
<td>Deformation of the accumulation, triggered by extrinsic events that mobilized saturated sediment in the deeper (tens of meters) subsurface</td>
</tr>
<tr>
<td>Upsection decrease in frequency and volume, first of interdune deposits, then of soft-sediment deformation structures</td>
<td>Long-term trend of increasingly dry conditions</td>
</tr>
</tbody>
</table>
VI. APPLICATIONS OF THESIS WORK

Introduction

General Applications

As indicated in previous chapters, soft-sediment deformation features constitute a uniquely useful element of Navajo Sandstone architecture:

1. They record water table fluctuations in the ancient ergs.
2. They provide insight into processes at scales beyond those available to modern observation and experimentation.
3. Their cross-cutting relationships establish an event framework that links diverse outcrop features in time.
4. They provide a basis for identifying extraordinary triggering events during the depositional history of the formation.
5. They offer clues about seismicity in the early Jurassic.
6. Their interpretation contributes to broader analyses of ancient climates and geographies.
7. Characterizing their occurrence contributes to the analysis of petroleum reservoir partitioning.

The thesis work reported here enhances the utility of soft-sediment deformation features in each of these areas by providing process/response models from the observed form and distribution of deformation features and linking them to discrete sets of causative factors. The specific value of this interpretive process is illustrated by the author’s own subsequent and proposed work, outlined in the rest of this chapter. Before reviewing those applications, however, it seems appropriate to emphasize one broad benefit of the interpretive process modeled in this research that has merely been mentioned, previously: its supplementary relationship to uniformitarian methodologies.
Non-uniformitarian Aspects of Navajo SSD Interpretation

Ever since (Gregory, 1917) first defied convention by attributing the widespread deposits of the Navajo Sandstone to non-marine processes (Stokes, 1991), this formation has frequently been the object of interpretations invoking processes without comprehensive modern analogues. Though preserved Navajo deposits represent a dune system similar in extent to dune-covered portions of the modern Sahara desert, comparably thick deposits are not accumulating in any modern eolian environment. No modern analogues to many of its architectural details (set thickness, cyclicity, bounding surface continuity, etc) have been documented, either. It is the most massive pile of sand known on Earth - and its nearest rivals are closely related ancient rocks, not surficial deposits. This uniqueness suggests that it represents not only extreme climatic conditions; but also other unfamiliar combinations of factors controlling sediment supply, accumulation, and preservation.

Modern desert environments appear to be irreversibly alienated from Navajo-like conditions by specific developments in the evolution of Earth systems. Certainly one milestone constitutes a major divide: the appearance of dune-stabilizing vegetation, in the Cretaceous. This produced a fundamental shift in the balance of extrinsic controls on dune dynamics in humid climates. In modern settings with abundant moisture, hardy grasses and other angiosperms exercise a more persistent influence than the erosive winds promoting bedform migration; so that dune stabilization predominates outside of narrow (typically, coastal) bands of high sediment flux. In the Jurassic ergs, wet-climate dune migration could more readily be sustained, and evidence that this occurred appears in the interfingering of dune and interdune deposits within the formation. In this instance, particularly, non-uniformitarian perspectives guide the way to plausible parameters for the depositional system.

The analysis of soft-sediment deformation features formed during the depositional history of the Navajo Sandstone requires strategic creativity. All modern environments taken together do not represent the full range of conditions under which deformation took place during the early Jurassic; though the diverse morphologies observed in the ancient rocks probably do represent a broad spectrum of responses to a smaller set of controls. Subtly diverse environmental triggers orchestrated deformation events through successive
stages, amid individualized patterns of sediment susceptibility, to produce an array of features without modern analogue. Typically, problems of scale do not allow the comprehensive laboratory simulation of these processes; therefore, model development must rely upon the study of ancient deposits to establish the extent of deformation variability and to identify specific pathways through which deformation processes occurred.

The present report helps alleviate the limitations of uniformitarian methodology in at least three ways:

1. It presents the outcrop details of unique deformation features, produced in an extraordinary system.
2. It supplements and refines existing models for understanding eolianite deformation processes, generally, and the depositional environment of the Navajo Sandstone, specifically.
3. It exemplifies methods of outcrop interpretation with value for future research.

Though, in both detail and dimension, the features described in this report defy categorization alongside the products of deformation within modern eolian environments, their forms are not totally enigmatic. Processes of liquefaction, fluidization, and fluid escape appear to have dominated the dynamics of deformation events, as illustrated in various outcrop details from different parts of the formation. The documentation of typical styles of disruption to the depositional architecture does provide a practical basis for discriminating between genetic processes at a broad range of scales and there is no ready substitute for the models produced in this manner. They provide the keys to resolve persistent enigmas of Earth’s ancient deposits and may someday provide the very analogues needed to decipher more patently other-worldly features on Mars - or even more exotic terrains, yet to be discovered.

**Professional Contributions**

The thesis research reported here provided the basis for the presentation of a subsequently published paper (Bryant and Miall, 2010) to the Geological Society of London, posters at the International Conference on Aeolian Research VI (Bryant et al., 2006a) and the Geological Society of America (Bryant et al., 2006b), as well as seminar
presentations at the University of Toronto, Loma Linda University, and Dixie State College. Subsequent collaborations have resulted in a presentation at the International Association of Sedimentologists (Bryant and Owen, 2010) and another poster presentation to the Geological Society of America (Nalin and Bryant, 2010). Of these, the study reported at GSA 2010 is particularly significant because it demonstrates the broader applicability of process/response studies in the Navajo Sandstone: the lateral spreading interpretation applied to deformation features in alluvial fan deposits of the Fountain Formation came from observations made at various deformed interdunes in the Navajo. This interpretation provides an alternative to the ice-wedging hypothesis advanced by other workers (Sweet and Soreghan, 2010; Sweet and Soreghan, 2008) in support of a broader interpretation invoking widespread Late Paleozoic glaciation.

**Future Studies**

As demonstrated in this report, the cross-cutting relationships established during individual deformation events support high-resolution event analyses of Navajo Sandstone outcrops. Having formed very quickly relative to primary depositional structures of comparable extent, soft-sediment deformation features provide time markers for process interpretations of the sandstone architecture. This temporal control is especially useful when patterns of erosion and deposition were altered during the deformation event. In these instances, even the reconstruction of ancient topographies may be possible. However, a lack of independent chronostratigraphic controls and specific deformation models impedes the general application of this correlation tool. At outcrop scale, deformation correlations open unique windows into the exotic process/response dynamics of the ancient erg and provide useful constraints for the modeling of tectonic, climatic, and autogenic controls. At a regional scale, progress awaits the characterization of broad episodes of deformation, the modeling of distinct styles of deformation, and the development of additional constraints on genetic stratigraphy. These are the areas to which the author is attempting to apply this thesis research most directly. A program of directed student research is being developed around the central goal of providing an internal stratigraphy and correlation methodology for the Navajo Sandstone, as detailed below.
CORRELATION STUDIES

Previous Attempts

Ever since Kiersch (1950) postulated both climatic and seismic controls on deformation events in the Navajo erg(s), various workers in the formation have been enticed by the possibility of using soft-sediment deformation (SSD) features for correlation. Sanderson (1974b), working in the same outcrops of Utah’s San Rafael Swell that Kiersch (1950) had studied, described two discrete intervals of discontinuous deformation features, which persist across many kilometers of outcrop and probably represent events or episodes of widespread SSD. Stephens (1985), following up these studies, under Sanderson’s supervision, even provided some interesting speculations on the influence of bedform spacing over the pattern of recurrence. However, the lack of independent chronostratigraphic control frustrated these workers’ attempts to establish precise correlations and to demonstrate the impact of specific controls on lateral variations within their study intervals.

In his study area around the Uintah Mountains, in northern Utah, Peterson (Peterson, 1988b) used extensive zones of deformation near the top of the Navajo/Nugget Sandstone as a means of approximate correlation between widely separated outcrops; although his own detailed work showed that the contorted strata are not precisely isochronous (Peterson, 1994b). His pragmatic approach assumed an event framework characterized by discrete episodes of widespread deformation in the late stages of the accumulation history. The results he obtained, supported by isopach trends and broad patterns of facies change, provided a convincing stratigraphic interpretation. This success tends to justify Peterson’s (1988a) simplifying assumptions; though it does not provide a specific basis for more precise correlations.

Problems

Three types of problem currently prevent the use of SSD for precise correlation within Navajo deposits:

1. There is no means, other than physical continuity, to identify the synchronous products of a deformation event.
2. Current deformation models do not support the differentiation of various genetic types of large-scale deformation.

3. We do not know the degree to which the preserved accumulation represents deposits affected by any particular deformation event.

These general obstacles to deformation event correlation each encompass several issues: The first category of problem stems from the fact that deformation features provide no means of absolute dating. Even though Navajo deformation features resemble igneous dikes in the way they cut across depositional architecture, establishing relative time markers, they only obtain a precise chronological significance when they can be seen to have affected depositional processes. In these instances, their event significance is established at a particular time in the depositional history. Unfortunately, as has been discussed earlier in this report, the lack of chronostratigraphic control within the formation prevents the dating of such events with a precision adequate for correlation purposes.

The second category of problem encompasses three main issues:

1. The need for deformation models that relate different styles of deformation to different event parameters.

2. The need to understand patterns of susceptibility in the ancient erg – whether, for example, conditions allowed deformation to initiate simultaneously at different locations or limited each occurrence to a single, continuous zone.

3. The need to identify spatial effects peculiar to a particular triggering mechanism, such as intensity variations in relationship to earthquake epicenters. If different styles of deformation could be tied to different sets of susceptibility conditions and different types of triggering events, then mapping the distribution of those styles would enable event correlation.

The third type of obstacle to using deformation features for correlation derives from the complexity of the patterns of deposition and accumulation in the formation. At its simplest, Navajo Sandstone architecture is composed of diachronous erosional surfaces
truncating laterally accreted cross-strata. Even the top and bottom of the formation represent non-synchronous processes: progressive erosional beveling and progressive erg development, respectively. Evaluating the synchronicity of non-continuous SSD, therefore, often depends upon the specific interpretation of depositional architecture. Under conditions of continuous bedform climb, a single deformation event could have produced features separated, vertically, by extensive diastems and laterally, by bedform periodicities exceeding a kilometer (See Figure 1). Furthermore, as implied by Figure 2B, each sequence model would be associated with a different set of event correlation possibilities. Model 3 of Figure 2B would limit these possibilities most severely and formation-wide correlation would probably not be possible. Deformed strata would have been removed by erosion in a patchwork pattern that juxtaposed deposits of very different ages. The recent deposits of active ergs would likely be more susceptible to deformation than the older deposits of stabilized ergs, further affecting deformation patterns.

Opportunities

In spite of these significant obstacles, parts of the formation, such as the Echo Cliffs/Glen Canyon region, appear favorably disposed to a variety of correlation methods. In the Echo Cliffs, prominent surfaces extend from an unusually diverse facies succession (fluvial/eolian transition) into a region of abundant deformation features (Glen Canyon). Extensive outcrops and thoroughly dissected, accessible topography provide extraordinary opportunities for high-resolution outcrop studies that may be correlated with some precision by means of a series of supersurfaces (Blakey, 1994b). Ideally, these boundaries represent a time when every part of the surface was simultaneously exposed: a paleotopography or an event horizon. However, even if they are not isochronous surfaces, the precision of the chronostratigraphic control they provide can be improved through the accurate evaluation of their process implications. Perhaps the contrast between the temporal characteristics of SSD and such surfaces can itself be used to help characterize the regional architecture. For example, an extensive deformation
Figure 1: Architectural relationships of deformation features formed in a single event under conditions of bedform climb. The top left diagram, depicting fundamental relationships between climbing dunes and depositional architecture, is adapted from (Kocurek, 1988).
Figure 2: Navajo Sandstone facies architecture (from Blakey, 1994). A) Cross-section showing stratigraphic relationships and generalized facies associations. B) Six alternative models, with inferred time lines for each, which plausibly explain the observed facies architecture.
feature, formed in a discrete event, may display various types of cross-cutting relationships with an erosional surface that developed progressively, over a protracted period of time (Figure 1): cross-cutting the surface in its older, buried reaches; deforming it, where concurrently exposed; and being truncated by it in those areas into which the surface extended after the deformation event. Mapping out these relationships would reveal much about the nature of the accumulation history. The mere verification that such relationships do occur would provide useful constraints on process interpretations of Navajo Sandstone architecture, such as those in Figure 2.

Educational Applications

General

A research proposal currently under development at Dixie State College of Utah, along with other institutional partners, would couple the refinement of Navajo stratigraphy with educational objectives at both the graduate and undergraduate levels. Undergraduate research would focus, primarily, on detailed outcrop studies at sites where Navajo successions containing both interdune deposits and soft-sediment deformation features are well exposed. Graduate research would address issues of stratigraphic correlation, paleoclimate interpretation, and allostratigraphic analysis, while integrating the detailed studies into a broader framework.

Undergraduate Student Research

Innumerable small projects can be generated for undergraduate research because, among the dune deposits of the Navajo Sandstone in the Glen Canyon region, both interdune carbonates and SSD frequently appear, often in intimate association. This is not surprising, since saturated-sediment deformation features (McKee et al., 1971; McKee et al., 1962a; McKee et al., 1962b; Rettger, 1935) suggest the presence of high water tables in the ancient erg (Doe and Dott, 1980; Kiersch, 1950; Peterson, 1994b) and the carbonates themselves must have been deposited when the interdunes were flooded with water (Driese, 1985). According to Horowitz (1982), interdune areas were sites of
preferential deformation, because this is where saturated sediment occurred closest to the surface and was least confined by static loads.

These sites hold particular significance to soft-sediment deformation studies because:

1. The interdune deposits provide independent constraints on the paleohydrology of the region during deformation episodes.
2. Horizontal lenses of cohesive carbonate mud served as excellent passive markers (Stephens, 1985) to record displacements during deformation events.
3. The carbonate horizons constituted unique permeability barriers, within these deposits, creating field relations similar to those encountered at well-known sites of modern seismic deformation. This correspondence to modern settings may prove particularly valuable, simply because such analogues have not been found for most SSD in the Navajo Sandstone.

The time-intensive, exploratory nature of these studies discourages the attention of experienced researchers. They are ideal for student projects, however, because they provide opportunities for complex analysis within a relatively simple, spatially limited field context: Participants are readily brought to consider a broad spectrum of processes, acting in multiple time frameworks, to produce the observed results. Additionally, every well-exposed outcrop containing soft-sediment deformation features presents new opportunities for event interpretation and the prospect of fresh glimpses into the dune dynamics that produced the most voluminous erg deposits preserved on Earth. This provides incentive to the investigation. Furthermore, there are many accessible sites open to investigation and the logistics of these outcrop studies are relatively simple, if the research project is limited to a single study site. Finally, SSD investigations establish an interpretive context for other types of analysis, providing a powerful springboard into more diverse investigations.

Among these more diverse investigations, two notable examples were actually accomplished in conjunction with the work reported here: Helen Macinnes and Antonia O’Dowd-Booth, exchange students from the University of Birmingham, provided field assistance for this thesis research during successive seasons. After they completed their
contract work, they both stayed on to accomplish field work, under my supervision, for their Masters’ year in England. Each of them successfully completed her plan of study. Two other Birmingham students also accompanied me on field trips across the Colorado Plateau, on separate occasions, providing additional opportunities to further develop logistical approaches and teaching skills.

**Ancillary Studies**

Not only do the proposed future studies provide opportunities for undergraduate research into Navajo paleoenvironments, they also set the stage for a much broader range of related studies, including laboratory investigations. Several complementary lines of investigation were explored during the course of this thesis work that now provide a basis for independent projects and student activities. Much of this work targeted provenance issues, exploring some novel applications of detrital zircon analysis in an attempt to discriminate populations of fluvial sand and to compare the provenance of saltated dune sand with that of silt transported in eolian suspension and trapped by interdune moisture. These studies, in conjunction with petrographic, palynological, and other geochemical analyses were designed to evaluate the persistence of fluvial influences on erg hydrology and interdune sedimentation; but each of them can also be applied to the proposed correlation research. Testable hypotheses generated from this work include:

1. The provenance of interdune loessite in the Navajo Sandstone differs measurably from that of contemporary sandstones, which represent transport, within the basin, by eolian saltation and/or stream processes.
2. Silt-sized particles trapped in interdune ponds within the Navajo erg included juvenile zircons produced by contemporaneous island-arc volcanism to the south and to the west.
3. Palynological criteria can be used to differentiate the deposits of stream-fed interdune ponds from those of groundwater-fed ponds in the Navajo erg.
4. Stable isotope ratios (oxygen, carbon, and strontium) in the organic and inorganic components of interdune carbonates from the Navajo Sandstone varied systematically in relation to the source of the ion-bearing waters of their depositional environments.

5. Ground penetrating radar can be used to discriminate between deformed and undeformed dune and interdune facies.

Acknowledgements

Among the broader research opportunities provided by my thesis work at the University of Toronto were several involving collaborations not represented elsewhere in this report. It pleases me to acknowledge, in particular, the contributions of these individuals:

Mike Hamilton, managing director of the Jack Satterly Geochronology Laboratory at the University of Toronto provided guidance on laboratory techniques and resources for mineral separation work preparatory to detrital zircon analysis of Navajo Sandstone samples. Provenance analysis of silt deposits proved impractical without direct access to an ion microprobe, which was not available locally. Correspondence with William Dickinson, at the University of Arizona, informed me of parallel work on the discrimination of fluvial and eolian provenance. The Arizona research team was well-staffed, well-equipped, and funded by the National Science Foundation. I sent them some of my samples, which were featured in an abstract presented to the Geological Society of America (Schmidt et al., 2005).

Oluwatosin Akinpelu, a fellow graduate student at the University of Toronto, carried out several ground penetrating radar (GPR) surveys on the Colorado Plateau, with my assistance. Some of these studies targeted Navajo interdune deposits and soft-sediment deformation features. Though none of them contributed to the present report, they did provide the basis for future student training in GPR techniques.
Omar Colmenares, post-doctoral researcher at the University of Toronto, helped with several maceration preparations of Navajo samples and provided palynological analyses of the residues. These results did not provide a basis for any interpretations featured in this report; but they did constitute a useful pilot for future work discriminating between riparian and lacustrine paleoenvironments.

Uli Wortmann, director of the Geobiology Stable Isotope Laboratory at the University of Toronto, provided support for a pilot study of carbon and oxygen isotopes in interdune carbonates from the Navajo Sandstone. Ultimately, we forwarded those results to Judy Parrish who included them in a paper presented to the Geological Society of America (Parrish and Dorney, 2009). This collaboration came out of my participation in some of Judy’s field investigations of Navajo interdune deposits, most notably the discovery and exploration of a site in Navajo Canyon featuring meter-scale carbonate mounds.
WORKS CITED


Marcou, J. 1856. Resume of a geological reconnaissance extending from Napoleon, at the junction of the Arkansas with the Mississippi, to the Pueblo de Los Angeles in California. U.S. Pacific Railroad Explorations, 3, 165-171.


Obermeier, S.F. (1996) Use of liquefaction-induced features for paleoseismic analysis - An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes. *Engineering Geology, 44*, 1-76.


Opdyke, N.D. and Runcorn, S.K. (1960) Wind Direction in the Western United States


