Stratigraphic Evolution of the Eolian Navajo Sandstone, SE Utah*

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Abstract

The eolian Navajo Sandstone crops out extensively across southern Utah, and has been studied as a reservoir analogue, but sub-division and correlation between exposures is hindered by the paucity of non-eolian facies within the stacked dune deposits. The Navajo Sandstone was studied in detail in the Moab area of SE Utah, in order to reconstruct the depositional environments, characterise erg development and enable stratigraphic subdivision of the thick, dominantly cross-bedded succession. The results of previously unpublished logged sections, bounding surface mapping and dune reconstruction studies are presented here. In the Moab area, the Navajo Erg succeeded the Kayenta perennial fluvial system. This transition is commonly abrupt, with little interaction between the fluvial and eolian systems, but locally a more gradational transition zone exists, comprising ephemeral fluvial, extra-erg dunefield and playa environments, possibly reflecting the effects of underlying salt uplift and climatic fluctuation on the fluvial system. Above this, the Navajo succession is divided into three, locally four, stratigraphic units, separated by super bounding surfaces, indicating that it was formed by four separate phases of erg construction and demise. These sharp, laterally continuous surfaces record prolonged periods of deflation of the erg to the water table, and are characterised by reddening, polygonal fissures, root mottling, rhizoliths and lacustrine carbonates. Widespread horizons of soft sediment deformation occur at consistent stratigraphic levels, recording synchronous periods of sediment liquefaction. The individual stratigraphic units are characterised by different dune styles, showing a vertical change from simple to compound and back to simple dunes, together with a change in preserved set size and related interdune deposits. The character of the units appears to be consistent over a distance of at least 60km in the Moab region. These variations reflect differences in sand supply and relative water table elevation during successive erg phases. Reconnaissance mapping suggests that these divisions may be recognised up to 100km further west. Super surfaces are not apparent, however, within the thick Navajo successions in SW Utah, including Zion Canyon, suggesting a permanent erg in the west, which expanded and contracted eastwards. However, vertical evolution in dune style and preserved set thickness may provide a means of correlating between these areas.
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Introduction

The Lower Jurassic aeolian Navajo Sandstone crops out extensively over SE Utah, and while it has been the focus of detailed studies of various aspects of its sedimentology, such as carbonate interdune facies, vegetation, soft sediment deformation zones, vertebrate tracks and faulting, there have been few regional stratigraphic studies (e.g. Peterson and Piperigos 1979, Hintz 1988, Teasink 1989). This poster presents previously unpublished stratigraphic studies carried out in the 1980s and 90s which provide a model that may be used to place some of the more recent work in the context of the development of the Navajo erg, and allow lateral erg-margin to erg-centre changes to be distinguished from vertical temporal changes. The study presented here was centred on the Moab area (Fig. 1.1), where a consistent four-fold stratigraphic subdivision was recognised over a NW-SE (cross-palaeowind) distance of 65km. The Poison Spider Mesa locality west of Moab (Fig. 1.2) provides a type-section and demonstrates many of the characteristics of the stratigraphic succession in this area. The four subdivisions are defined on the basis of the character of the dune deposits, proportion and facies of non-aeolian deposits and the recognition of two Super Bounding Surfaces (SBS), recording deflation of the entire dunefield to a quasi-planar, water-tabled controlled surface. The extensive exposures allow the SBSs to be walked out over large distances and the distinctive characteristics of the intervening units permit this stratigraphic framework to be correlated over larger distances between discontinuous outcrops. Reconnaissance logging in other areas suggests that stratigraphic model may be extended further across southern Utah, but this requires further detailed work at these localities to verify the existence of super surfaces. The recognition of super surfaces implies that significant time may be missing within the Navajo succession and not just at the J2 Unconformity.

Stratigraphic units

The Navajo succession is divided into four stratigraphic units (Fig. 1.3), which have a characteristic topographic expression (Fig. 1.4) and can be correlated throughout the Moab area (Fig. 1.5). The underlying Kayenta Formation is characterised by ledgy cliff outcrops of multi-storey perennial channel deposits, with locally well-developed lateral accretion surfaces. The top Kayenta Formation typically forms a bench, and is picked at the base of the first aeolian deposits. A Transition Zone is variably developed above this, characterised by the interbedding of aeolian, ephemeral fluvial and lacustrine deposits (Fig. 1.6). In some places, the Transition Zone is absent and aeolian deposits of Lower Navajo Unit NI abruptly succeed perennial fluvial deposits with very little interdigitation. Unit NI forms layered, vertical cliffs (Figs. 1.6 & 1.7), dominated by extensive tabular aeolian cross-set deposits separated by wet and damp interdune deposits. SBS1 defines the top of Unit NI and commonly marks the transition to rounded cliffs and benches of Unit NII, which comprises large aeolian cosets with dry interdunes. SBS2 defines the top of Unit NII, and is commonly marked by large eroded recesses within the sheer cliffs that characterise the lower part of Unit NIII, which usually contains the thickest cosets in the succession (Fig. 1.7). The upper part of Unit NIII crops out as characteristic pale rounded domes, and is typified by thinner cosets and the sparse occurrence of damp and wet lacustrine interdune deposits. SBS3 further subdivides Unit NIII in the Poison Spider Mesa area. The regional J2 Unconformity defines the top of the Navajo Sandstone, and is mostly overlain by dark red, silty deposits of the Dewey Bridge Member of the Entrada Formation. However, locally, coarser-grained aeolian deposits with well developed fluctuating-cycle flows, not typical of the Navajo, are found above the J2 Unconformity, and interpreted as pockets of Page Sandstone.

Fig. 1.1 Study localities in the Moab area. PSM – Poison Spider Mesa.

Fig. 1.2 Navajo Sandstone outcrop on Poison Spider Mesa west of Moab with mapped super surfaces and carbonate lacustrine lenses overlaid.

Fig. 1.3 Stratigraphic scheme for the Navajo Sandstone in the Moab area.

Fig. 1.4 Outcrop of the Navajo sandstone in Courthouse Wash showing the typical topographic expression of the units.

Fig. 1.5 Correlation of sections measured in the Moab area, showing lateral continuity of SBS1 and SBS2 and more localized nature of SBS3 and the Transition Zone.

Fig. 1.6 Kayenta-Lower Navajo succession on the SE side of Poison Spider Mesa. The Transition Zone is c.30m thick. Note sharp base (exposure surface) of aeolian sandbody 1 (ASB1) and lateral pinch-out of ASB3. Note also the sharp base of Unit NI shown, marked by thick, discontinuous carbonate lenses, and the layered nature of the Lower Navajo Unit NI cliff exposures, with laterally continuous bounding surfaces and associated interdune deposits.

Fig. 1.7 Southeast face of Whitbeck Rock (WBR section in Fig. 1.5) clearly illustrating the divisions of the Navajo Sandstone in the Moab area. Note the continuity of first-order surfaces in the Lower Navajo Unit NI compared to the lack of tabular stratification and interdune deposits in the Upper Navajo Unit NII (c. 25m thick). Upper Navajo Unit NII is characterised by very large sets and complex cosets in the lower part, including a set and more continuous, tabular cosets in the upper part. The J2 Unconformity probably forms the flat top to this exposure.
Stratigraphic evolution of the Navajo Sandstone: 2 Transition Zone

Kayenta Formation and Kayenta-Navajo Transition Zone

The Kayenta Formation is composed primarily of perennial fluvial deposits, characterised by multi-storey channel bodies with locally well-developed lateral accretion surfaces (Fig. 2.1). Paleo-flow direction measured in these channels varies between NNE and SSE, somewhat divergent from the W and SW palaeoflow directions determined in SE Utah by Luttrel (1987), which may reflect the channel sinuosity implied by the presence of lateral accretion surfaces. In some locations, the boundary between the Kayenta and Navajo formations is clear, and Kayenta fluvial deposits are abruptly overlain by basal Navajo Unit NI aeolian deposits, with little or no fluvio-aeolian interaction. Kayenta fluvial deposits may pass upwards into more distal fluvial, sheetflood and playa deposits in the top few metres of the formation, and are typically capped by ponded mudstones (Fig. 2.2). In other areas, interbedding of dune and ponded sheetflood deposits occurs in the lower few metres of Unit N1, which can be attributed to the ponding of floods in wet interdune areas at the front of the advancing erg. In the centre of the study area, however, in sections between Bootlegger Canyon and the Windows, the top of the Kayenta Formation and the base of the Lower Navajo Unit N1 are separated by up to 30m of interbedded aeolian, ephemeral fluvial, sheetflood and playa deposits, here termed the Transition Zone (Figs. 1.3 & 1.6), which appear to record widespread temporal alternations between aeolian and fluvial environments, and the establishment and subsequent destruction of possible extra-erg dunefields, and the position of the Kayenta-Navajo boundary is debatable. The base of the Transition Zone lies at the base of a distinctive, dark orange aeolian unit (Fig. 2.3), termed aeolian sandbody 1 (ASB1), which contrasts markedly with the purple-grey fluvial Kayenta sandstones, and crops out in the slope below the Unit N1 cliffs over an area of at least 100km², from Amsa Back in the SW to the Windows in the NE, and along the length of the Moab salt collapse valley to the SE (Fig. 1.5).

Transition Zone Cycles

The Transition Zone was studied in detail at Poison Spider Mesa (PSM, Figs. 1.6 & 2.4), where aeolian, ephemeral fluvial, sheetflood and playa deposits are systematically arranged in three laterally-extensive wetting-upward cycles. A complete cycle consists of a flat-based aeolian sandbody (ASB1, 2 and 3), which is incised locally by sandy ephemeral fluvial channels that pass upwards into muddy sheetflood deposits capped by carbonate-rich lacustrine-playa deposits. However, two of the two cycle components may be missing and cycle boundaries can be difficult to define where the aeolian component is absent, due to scour by overlying channels. The basal cycle contains the most extensive aeolian sandbody ASB1, which is 10m thick and is rarely breached by younger fluvial deposits. ASB1 overlies a sharp deflation surface, termed the basal exposure surface (Fig. 2.5), that truncates the underlying Kayenta fluvial deposits and shows evidence of prolonged sub-aerial exposure, including fissuring and granule lags (Fig. 2.6). ASB1 is dominated by dm-scale wedge and trough cross-strata formed dominantly of low-angle wind ripple cross-strata, although sandflow strata are abundant in the larger sets (Fig. 2.7). Bounding surfaces are planar, curved and scalloped and reactivation surfaces are common, and ASB1 is interpreted as the deposits of cretaceous dunes laid down in a variable ESE-SEE wind regime (Fig. 2.8). The top of ASB1 is variably incised by ephemeral fluvial channels, characterised by low-angle cross-beded sandstones with plane current lineation, which pass up into trough cross-beded sandstones and massive mudstone deposits (Fig. 2.9). These channels deposited overbank and sheetflood deposits over the entire dunefield (Fig. 2.10), which were capped by thin, carbonate-rich playa deposits (Figs. 2.11 & 2.12). In the second cycle, another aeolian sandbody (ASB2) crops out intermittently over the same area as the first, and may have formed a continuous sheet, but appears to have been stabilised, with evidence of rooting, prior to erosion by a more sustained period of fluvial channel activity, which culminated in unconfined sheetflood and playa development. A third sandbody (ASB3) crops out over a smaller area, and apparently terminates at PSM, and is replaced to the east by dominantly sheetflood and playa deposits with minor fluvial channel deposits at sections PTL, CHW and WIN (Fig. 1.5). Sheetflood deposits at the top of cycle 3 are commonly overlain by thick, variably desiccated mudstone, which marks the top of the Transition Zone, and are sharply overlain by thick aeolian silt and muds at the base of Lower Navajo Unit N1 (Fig. 1.6). These mudstones are interpreted as recording ponding of fluvial sheetfloods by dunes at the front of the advancing erg.

Controls on Transition Zone Development

Transition Zone aeolian sandbodies are interpreted to represent extra-erg dunefields and show evidence of degradation, vegetation and consolidation prior to fluvial incision, which might suggest that the three cycles record arid-humid climatic fluctuations during an overall trend towards arid conditions at the end of Kayenta times. However, the cycles do not extend throughout the whole study area, and it is unclear whether the extra-erg dunefields did not form there, or whether subsequent fluvial erosion has removed them. Another possibility is that the Transition Zone dunefields formed in response to contemporaneous subsidence of the Gobal salt anticline, due to halokinetic movements in the underlying Paradox Basin salt deposits. This may have elevated areas of the Kayenta floodplain, allowing deflation and formation of dunefields, and locally modified the paleo-fluvial drainage system. Heavy mineral studies revealed a larger proportion of euhedral and subhedral zircons in the Transition Zone aeolian deposits compared to aeolian deposits in the main body of the Navajo Sandstone, suggesting that they were sourced by reworking of Kayenta fluvial deposits.

Fig. 2.1 The Kayenta-Navajo boundary at Seven Mile Canyon is typical of areas where the transition Zone is developed. Note sharp, planar base of basal aeolian set overlain by a thin cemented playa horizon (P).

Fig. 2.2 Position of the Kayenta-Navajo boundary is debatable. The base of the Transition Zone lies at the base of a distinctive, dark orange aeolian unit (Fig. 2.3), termed aeolian sandbody 1 (ASB1), which contrasts markedly with the purple-grey fluvial Kayenta sandstones, and crops out in the slope below the Unit N1 cliffs over an area of at least 100km², from Amsa Back in the SW to the Windows in the NE, and along the length of the Moab salt collapse valley to the SE (Fig. 1.5).

Fig. 2.3 ASB1 forms a distinctive orange unit overlain by perennial fluvial deposits of the Kayenta Formation above Bootlegger Canyon. The Transition Zone, N1 and N2 divisions are clearly outlined here.

Fig. 2.4 Correlation panel showing facies variation in the Transition Zone and Unit N1 at Poison Spider Mesa. Three cycles are defined by three sharp-based aeolian sandbodies. Sandbodies 2 and 3 are cut out by fluvial channels, and sandbody 3 was not observed in PSM. The large channel between sections 3 and 4 was the only channel observed which breached ASB1. Intense sheetflood, playa and mudstone lenses characterise the top of the Transition Zone.

Fig. 2.5 Base of ASB1, showing marked contrast between orange wind ripple deposits of ASB1 and grey fluvial bedform deposits of the Kayenta Formation across the sharp and planar basal exposure surface.

Fig. 2.6 Close-up of the basal exposure surface in SBS2 showing development of a thin granule-rich horizon at the base of ASB1 and orange sandstone desiccation features in the underlying fluvial sandstones.

Fig. 2.7 Exposure of ASB1 at Poison Spider Mesa, comprising dm-scale sets which appear tabular in the downwind direction and trough-shaped in the perpendicular direction.

Fig. 2.8 Rose plots and summary rose showing foreset dip of ASB1, which indicates mean foreset dip direction.

Fig. 2.9 Close-up view showing foreset dip of ASB1, which indicates mean foreset dip direction.

Fig. 2.10 Possible model for formation of ASB1 in areas of the Kayenta Formation that were elevated by growth of Paradox salt anticlines.

Fig. 2.11 Vertical section through a carbonate-rich playa deposit showing several horizons of desiccation cracks and associated chert nodules, indicating repeated recharge and drying.

Fig. 2.12 Polygonal desiccation features and chert nodules, which probably form in the surface of a carbonate playa deposit.

Fig. 2.13 Possible model for formation of ASB1 in areas of the Kayenta Formation that were elevated by growth of Paradox salt anticlines.
Lower Navajo, Unit NI

Unit NI also informally termed the Lower Navajo is 30-40m thick across the Moab region (Fig. 1.5). Aeolian dune deposits constitute 60-95% of the Lower Navajo succession, the remainder being composed of interdune, fluvially-flooded, and wet interdune deposits, which form laterally continuous horizons and give a conspicuous layered character in outcrop (Figs 1.6 & 1.7). The detailed geometry of dune and interdune deposits in Unit NI is shown in correlation panels from Poison Spider Mesa (Fig. 2.4) and Shafer Trail (Fig. 3.1).

Unit NI Interdune Deposits

Interdune deposits within Unit NI show a distinct vertical evolution throughout the study area, reflecting changing hydrological conditions during the deposition of the unit. Wet interdune deposits produced by surface flooding occur at the base of the succession, succeeded by dune deposits and bioturbation is limited, suggesting that biogenic activity was restricted by groundwater salinity, but well developed evaporite deposits recording pedogenic processes in vegetated interdunes. Notebook 20cm long.

Unit NI Aeolian Deposits

Aeolian cosets 2-12m thick are defined by planar, horizontal first-order bounding surfaces and are typically internally complex. Although detailed dune studies are hampered by the 2-dimensional nature of the outcrop. The middle of the succession is characterised by slightly better organised compound cosets, which are still dominated by wind-ripple strata, but may have a more regular pattern of compound wind-rippled toets overlain by more organised trough and wedge sets (Fig. 3.2a). Scalaordinated and asymmetrical trough sets are more common at this level, and indicate the development of lee-side scours, indicating both dry interdune conditions and along-crest sand transport. There is no uniform increase in coset thickness upwards in the Lower Navajo, although the upper two or three cosets tend to be larger, reaching 6-8m in thickness. The upper cosets are generally simpler, with a larger proportion of sandstone strata. Some cosets are composed locally of a single tabular or broad trough set, but compound cosets are most common at the top of Unit NI (Fig. 3.2b & c). Planar and concave-up second-order bounding surfaces define individual sets 0.5-2m thick that are up to 1m thick. Trough sets in cross-section and wedge shaped in longitudinal section, and represent the deposits of a draw with superimposed crescentic dunes which migrated in approximately the same direction as the main dune. Palaeocurrent measurements from the lower order bounding surfaces show a symmetrical plot with a mean of 129°, suggesting a variable wind regime in which northwesterly winds were dominant. This agrees well with the generally recognised southerly transport direction in the Navajo Sandstone of south-east Utah (Kocurek and Dott 1983, Peterson 1988), but compound bedforms and evidence for along-crest sediment transport suggest that the dunes were somewhat oblique and that wind directions were variable.
Upper Navajo Unit NII

Upper Navajo Unit NII lies between SBS1 and SBS2 (Fig. 1.3), and has a relatively constant thickness of 20-25m and a consistent depositional style throughout most of the study area (Fig. 1.5). Unit NII is composed entirely of aeolian dune deposits separated by sharp first-order surfaces indicating dry interdunes, and dune or wet interdune deposits are absent, although some surfaces are reddened. Soft sediment deformation of the top c.5m of NII is widespread at some localities. Cross-bedding styles were studied in detail at Poison Spider Mesa (Fig. 4.1) and the Portal. Two main cross-stratification styles, type 1 and type 2, can be identified and are interpreted to represent relatively simple and more complex compound dunes respectively.

Unit NII type 1 cross-stratification

Type 1 dune stratification represents the simplest of the cross-bedding styles seen in the Upper Navajo and comprises very large, symmetrical trough sets up to 15m thick and 120m wide. Sandflow strata 2-6cm thick constitute the dominant stratification type and wedge out into wind-ripple laminae, forming tangential foresets. Wind-ripple laminae are more abundant at the trough margins. Concordant fluctuating-flow cycles are well developed in some sets, but compound fluctuating-flow cycles with basal wind-ripple wedges are rare and superposition cycles are absent.

Exposures of Unit NII overlying a prominent lacustrine carbonate horizon at the top of Unit NI near the Portal exhibit type 1 stratification, characterised by very large, simple trough cross-sets (Fig. 4.2a). Fig. 4.2b is oriented NE-SW, perpendicular to the trough axes, which trend dominantly towards the SE (Fig. 4.2c). Sets are defined by concave-up bounding surfaces of limited extent and it is difficult to distinguish first-order bounding surfaces in this orientation. Fig. 4.2d is oriented NW-SE, parallel to the trough axes, and sets appear simple and tabular, with planar, more extensive bounding surfaces. Foresets are asymmetric, with few marked reactivation surfaces. Reddening of the lower part of the sets reflect the dominance of wind ripple lamination in the toezone. This exposure represents the deposits of large, crescentic dunes with simple slipfaces dominated by sandflow processes. The dominance of sandflow strata, with thin wind-ripple toesets, indicates that a wind-ripple apron or plinth was not strongly developed on the lee of these dunes and implies that the bedforms were transverse to the dominant wind direction and that any oblique winds were of insufficient strength to form significant lee-slope wind-ripple wedges (Kocurek 1991). The planar nature of the basalt bounding surfaces of these two sets, when viewed parallel to the trough axes, suggests that the elevation of the interdune trough remained constant as the bedforms migrated.

Figure 4.1 (bottom left) shows a large, simple trough set c.4m thick directly overlying SBS1 at the base of Unit NII near the Portal exhibit type 1 stratification, characterised by very large, simple trough cross-sets (Fig. 4.2a). Fig. 4.2b is oriented NE-SW, perpendicular to the trough axes, which trend dominantly towards the SE (Fig. 4.2c). Sets are defined by concave-up bounding surfaces of limited extent and it is difficult to distinguish first-order bounding surfaces in this orientation. Fig. 4.2d is oriented NW-SE, parallel to the trough axes, and sets appear simple and tabular, with planar, more extensive bounding surfaces. Foresets are asymmetric, with few marked reactivation surfaces. Reddening of the lower part of the sets reflect the dominance of wind ripple lamination in the toezone. This exposure represents the deposits of large, crescentic dunes with simple slipfaces dominated by sandflow processes. The dominance of sandflow strata, with thin wind-ripple toesets, indicates that a wind-ripple apron or plinth was not strongly developed on the lee of these dunes and implies that the bedforms were transverse to the dominant wind direction and that any oblique winds were of insufficient strength to form significant lee-slope wind-ripple wedges (Kocurek 1991). The planar nature of the basalt bounding surfaces of these two sets, when viewed parallel to the trough axes, suggests that the elevation of the interdune trough remained constant as the bedforms migrated.

The existence of lee-side spurs on some NII bedforms is supported by two exposures of zigzag cross-bedding (Hunter and Rubin 1983) on Poison Spider Mesa, within complex trough cosets with type 2 stratification (Figs. 4.6). Cross-bedding on either side of the zig-zag intersections is cyclic and deposition appears to have switched sides every few cycles. Data measured from these spurs show that bounding surfaces and foresets dip in the same direction on each side of each spur and that both spur crests pointed towards 140° (Fig. 4.6c).

Unit NII type 2 cross-stratification

Laterally and vertically, the Unit NII style 1 trough sets grade into the type 2 stratification style, characterised by more complex cosets composed of trough and wedge sets up to 10m thick and 50m wide. Sets may be internally complex, commonly showing asymmetrical fill, abundant reactivation surfaces and migration of trough axes within sets. Compound fluctuating-flow cycles are variably developed but regular superposition cycles are uncommon. Scalloped and zig-zag cross-bedding are seen occasionally.

Fig. 4.4 shows a typical exposure of type 2 cross-stratification, which comprises irregular trough, wedge and scalloped sets defined by curved bounding surfaces. Fluctuating-flow cycles are common, although relatively thin. However, in some sets it is difficult to distinguish reactivation and superposition surfaces or define set margins. It is therefore difficult to define the number of bedforms represented by this exposure and the outcrop may be the deposit of one large, complex dune. This style of coset shows some similarities to the simulation by Rubin (1987) of bedforms with pseudorandom along-crest migrating sinuosities (Fig. 4.5). This simulation produces asymmetrical trough sets with sharply defined axes which migrate laterally, reflecting the along-slope component of migration.

The types of cross-stratified sets on some NII bedforms are supported by two exposures of zigzag cross-bedding (Hunter and Rubin 1983) on Poison Spider Mesa, within complex trough cosets with type 2 stratification (Figs. 4.6). Cross-bedding on either side of the zig-zag intersections is cyclic and deposition appears to have switched sides every few cycles. Data measured from these spurs show that bounding surfaces and foresets dip in the same direction on each side of each spur and that both spur crests pointed towards 140° (Fig. 4.6c).
Upper Navajo Unit NIII

Upper Navajo Unit NIII is defined by SBS2 at the base and the J2 Unconformity at the top. It can be further sub-divided into a lower and upper part, based on thickness and complexity of cross-sets, bounding surface continuity and presence of interdune deposits. The lower part is c.30-50m thick and is characterised by very large cross-sets, up to 20m thick, which are the largest found in the Moab area. In the lower part, extensive planar bounding surfaces are uncommon and damb interdune deposits are absent, although some sets show preservation of thick dune aprons. The upper part is up to c.60m thick, but is deeply truncated by the J2 Unconformity in some sections. It is characterised by simpler, tabular, cosets defined by planar, extensive (first-order) bounding surfaces which may be overlain by carbonate lacustrine deposits or show evidence of rooting. This division is well illustrated at Whitebook Rock and Hawks Draw (Figs. 1.7 & 5.1), although there is no continuous surface separating the two styles of bedding and in some sections the division is more gradational. At Poison Spider Mesa, super-surface 3 (SBS3) lies just above the base of the upper part. Detailed cross-bed analysis was carried out at Poison Spider Mesa (Figs. 4.1 & 5.2), but was limited to the lower part of Unit NIII, due to the availability of accessible 3D outcrops. Three major cross-bedding styles were recognised in the lower NIII deposits.

Unit NIII type 1 cross-stratification

Unit NIII type 1 stratification comprises simple sets and more complex cosets of troughs (resembling style 1 NII deposits) 3-8m thick, separated by probable first-order bounding surfaces, which are planar or curved and extend for several hundreds of metres. Sets are dominated by 2-6cm thick sandflow strata with variable development of fluctuating flow cycles. Cross-bedding style shows a large variation both between and within cosets. Unit NIII is c.20m thick here.

Unit NIII type 2 cross-stratification

Unit NIII type 2 stratification comprises very-large scale, simple, broad, trough-sets up to 20m thick and up to 500m wide. Sandflow strata dominate the upper part of the set, wedging out in thick, wind-ripple laminated toesets of varying complexity. Fig. 5.4 shows a typical type 2 bedform, (Bedform 1 in Figs. 1.7 & 5.2), dominated by sandflow strata up to 5cm thick that wedge out in to a thick, dark wind-ripple pilet. Fig. 5.5a shows well-developed, regular fluctuating cross-beds, another type 2 dune outcrop (Bedform 2 in Fig. 5.2), which are discordant higher up the outcrop, possibly indicating the incipient development of superimposed bedforms. In the toe of this dune, interfering wedges of sandflow and wind ripple strata were placed on either side of asymmetric troughs (Fig. 5.5b), indicating alternating periods of sandflow deposition on the main dune slope during subordinate periods of oblique airflow. Bedform 2 also demonstrates the tendency of style 2 dunes to scour down into underlying style 1 deposits (Fig. 4.1). In some cases, the simple sets cut down through three or four style 1 cosets, to lie directly on SBS2 (e.g. Fig. 1.7 extreme right), which was presumably sufficiently cemented to resist further scour.

Unit NIII type 3 cross-stratification

Unit NIII style 3 stratification comprises medium to very-large scale compound cosets which reach similar magnitude to the simple style 2 sets, but show varying styles of superimposed bedform cycles. First-order bounding surfaces may be difficult to recognise in these deposits, due to the potential for irregular scour and the presence of bedforms in the interdune trough where superimposed bedforms are present. Bedform 3 (Figs. 4.1 & 5.2) appears simple on its NW-SE trending face (Fig. 5.6a), but is clearly composed on its NE-SW trending face, where second-order bounding surfaces, dipping towards the viewer, define sets c.5-10m thick, with foresets oriented towards the right (Fig. 5.6b & c). The geometry of this outcrop is very similar to Rubin’s (1987) computer simulation of a bedform with directly along-crest migrating, straight-crested superimposed bedforms (SBS3). Bedform 4 (Figs. 4.1 & 5.2) shows a different compound style, comprising tabular and wedge-shaped superimposed bedforms defined by inclined planar second-order bounding surfaces (Fig. 5.7a), interpreted to record superimposed dunes which migrated obliquely downslope (Fig. 5.7b).

Overall NIII dune pattern

The variety of cross-bedding styles and size of cross-stratified sets preserved in Unit NIII indicates that the dunes were large and three-dimensional and varied extremely in complexity, both spatially and temporally. Relatively simple slabs developed increasingly discordant fluctuating flow cycles which evolved into superimposed bedform cycles. Superimposed-bedform cycles with a component of along-crest migration are common, indicating that parts of many dras were oblique to the dominant sand transport direction to some extent. Nill dunes are interpreted to have initially developed as sinuous baranchid ridge dunes, which were aligned to be as transverse as possible to an average north-westly wind regime that varied between westerly and northerly (Fig. 5.8), resulting in dunes with along-crest migrating sinuous ridges and sandpits. These extended along several dune directions and that plferaotioa dii the dres increaded with time, cret segments that ranged in orientation from N to E-W, with a mean NE-SW trend (Fig. 5.9). Simple slabs developed on the most transverse segments, and grew by scouring down into older deposits, indicating that interdune areas were dry. Along-crest migrating superimposed dunes developed and migrated more towards the east on E-W oriented oblique segments and towards the south on N-S orientated segments. More complex patterns may have developed on convex-down wind segments that experienced migration in both directions. The extremely large sets in the lower part of Unit NIII appear to represent the period of maximum dune build-up and preservation in the Navajo succession in the Moab area and bedforms were probably as big as the largest modern dunes. Subsequent relative rise of the water table during the latter part of Unit NIII restricted the level of scour in interdune areas, producing planar, first order surfaces bounding tabular dune cosets with local lacustrine interdune deposits.
Stratigraphic evolution of the Navajo Sandstone: 6 Super Surfaces

Super Bounding Surfaces

Super bounding surfaces representing significant hiatuses in aeolian deposition have not previously been described from the Navajo Sandstone, although Kocurek (1988) suspected they might exist. Three super-surfaces, SBS1, 2 and 3, were identified and mapped out on Poison Spider Mesa (Fig. 1.2), and SBS1 and 2 were recognised in other localities in the Moab region (Fig. 1.3). These super-surfaces are parallel to first-order surfaces, but exhibit several diagnostic features:

1. Lateral extent (10s of km), which is an order of magnitude greater than first-order surfaces (up to 2km?).
2. They separate units with differing depositional styles.
3. They show features indicative of prolonged periods of subaerial exposure, such as deep fissuring and carbonate rhizoliths, which were not generally seen on first-order surfaces.

Super Bounding Surface 1 (SBS1)

Super bounding surface 1 (SBS1) truncates the top of Lower Navajo Unit NI and defines the base of the Upper Navajo Unit NII. It can be traced from the eastern edge of the study area as far west as Whitbeck Rock, but was not identified with confidence between there and Shafer Trail, although west of here, limestone lenses are present at approximately the level of SBS1. SBS1 covers a minimum area of 1500km², although reconnaissance studies suggest it extends over a much larger area (see section 8).

In the Moab area, SBS1 is slightly undulating and the super-surface zone characteristically contains lacustrine carbonate lenses, which are common in the top 5m of the underlying NI succession and on the surface itself (Fig. 6.2a). A particularly well-developed cryptalgal-laminated lacustrine dolomite, up to 1.8m thick and at least 800m wide occur below SBS1 at Poison Spider Mesa (Fig. 6.2b). The SBS1 zone exhibits up to two periods of dune stabilisation and vegetation. Massive sandstones and lenses of lacustrine carbonate were deposited shallows in the remnant aeolian topography. Muddy subaqueous deposits, suggest inflowing of lows by surface floods, but fluvial channels were not seen. Carbonate rhizoliths 1-4cm in diameter and up to 70cm long and nodules suggesting rooting of a remnant high. (c) Mounded aeolian topography below the surface zone is undeformed and of constant thickness. (d) Elongate mottles. Ruler is 90cm long.

The sharp, planar nature of SBS1 and lack of obvious topography on an outcrop scale suggest that this super-surface formed during a period of deflation to the water-table. Fluctuating water table conditions are evident, with a high relative water-table indicated by widespread zones of liquefied dune deposits below SBS1, which may be related to the presence of rare lace limestones, and more arid conditions indicated by subsequent fissuring of cemented areas and deflation to a smooth surface prior to deposition of the NII dunes.

Super Bounding Surface 2 (SBS2)

SBS2 was mapped out and studied in detail on Poison Spider Mesa (Figs. 1.2 & 6.1a) and at Seven Mile Canyon, CFg. 6.1b). In the Moab region, it has been interpreted from Whitbeck Rock in the west to Dewey Bridge in the east (Figs. 1.7 & 1.8), and possibly extends much further (see section 8). SBS2 can be more difficult to identify because it only locally exhibits a well-developed super-surface zone. For most of its extent, it resembles a sharp, planar, dry interdune surface, but it is conspicuous because it commonly marks a break in slope between Unit NII and Unit NIII and the underlying NII deposits are commonly deformed and pale buff in colour, in contrast to the darker orange colour of the lowest NII deposits (Fig. 6.6). The largest dune sets in any one succession generally either directly overlie SBS2, or occur just above it. SBS2 is most marked locally where the super-surface zone is reddened, massive, cemented and fissured (Figs. 6.7 & 6.8), over areas of several hundred square metres that fade laterally into a simple deflation surface. Little clear evidence of vegetation was observed on SBS2 and lacustrine carbonates are rare (Fig. 6.9).

Super Bounding Surface 3 (SBS3)

This is the least extensive super-surface and could only be recognised with confidence over an area of 11km² on Poison Spider Mesa, although it is tentatively traced as far as Courthouse Wash and Bootlegger Canyon (Fig. 1.5). SBS3 lies c.60m above SBS2 and is typically a sharp, planar surface, which truncates a super-surface zone characterised by mottling and root moulding (Fig. 6.11a) and severe soft-sediment deformation of underlying NII dune deposits (see section 7), although it locally constitutes a dry deflation surface. Vegetation clearly followed deformation and planation of the super-surface, since the reddened and mottled super-surface zone is undeformed and of constant thickness. Root or trunk casts, up to 15cm in diameter, in vertical growth position, and carbonate rhizoliths occur in areas where vegetation and subsequent fissuring are most intense, representing the wetted areas on the surface. Fissures up to 8cm wide and 1m deep, filled with aeolian sand (Fig. 6.11b), define irregular polygons 0.1m across which cross-cut root-mottles and clearly post-date rooting.

The restricted extent of SBS3 precludes its formation by a major contraction of the erg but it does lie just above the level where interdune deposits begin to appear in Unit NII, suggesting that an overall relative water-table rise was occurring regionally at this time. It is therefore suggested that SBS3 represents a Stakes-type deflation surface which formed within the erg as a response to decreased sand-supply caused by the development of slightly wetter conditions (Fig. 6.12).

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Stratigraphic evolution of the Navajo Sandstone: 7 Deformation and Carbonates

Deformation zones

Zones of widespread soft-sediment deformation are characteristic of the Upper Navajo Units NII and NIII in the Moab area (Figs. 3.6 & 5.2), but are less common in the Lower Navajo Unit NI. Soft-sediment deformation was also observed in the Navajo Sandstone in all the reconnaissance sections in SE Utah (see section 8) and is widely reported from other localities (Droe and Dott 1985; Hornowitz 1988; Marsolf 1983; Tusurik 1989; Bryant et al. 2006). Brittle deformation is uncommon, but rare examples of isolated zones of duplex-like stacking of packages of slipface strata above a lower slip horizon are seen, which are interpreted as localised slipface slumps. Soft-sediment deformation zones are tens to hundreds of metres wide and c.5-20m thick and are found in two settings. The most extensive zones lie directly below SB2 and SB3 (Figs. 7.1 & 7.2) and may affect several coasts, so that first-order bounding surfaces, sometimes involving cemented and carbonate interdune deposits, are deformed (Fig. 7.3). Smaller zones lie below, and are truncated by, first-order bounding surfaces in Unit NIII, indicating that deformation of these deposits occurred shortly after their deposition and prior to the deposition of the upwind dune. They are particularly common in the largest aeolian sets in the lower part of the unit, but are less common, in the upper part, where persistent bounding surfaces are developed. Within most zones, deformation increases progressively from the base to the top of the deformed deposits (Fig. 7.4) and passes gradationally laterally into undeformed dune deposits. The lower boundary of the deformation zone may be gradational or abrupt and commonly coincides with the transition from wind-ripple laminated to sandstone to sandflow deposits in the preserved sets, possibly reflecting the closer packing or possible early cementation of the wind-ripple deposits. Undeformed sets pass upward into a zone of folds which are either folded in the foreset dip direction, or resemble more upfolded sets with stratified lineations separating more massive antichains, recording the foundering of sediment packages between vertical dewatering features. Less common, large vertical dewatering pipes or injection features are seen (Fig. 7.5). These become broken and disconformal upwards and finally pass into completely structureless sandstone, which is truncated by the overlying bounding surface. More rarely, the top of the deformation zone is not sharply truncated but grades up into undeformed aeolian deposits. In the latter case it is rarely marked by a band of weakly parallel-laminated sandstone suggesting shearing.

Deformation is interpreted to be the result of liquefaction of dune deposits below the level of the water table, possibly triggered by seismicity. Bryant et al. (2006) proposed an elegant model of a contoured water table, that rose up within large dunes, to account for the truncation of deformation zones by first-order surfaces. This seems plausible given the very large size suggested for the Unit NIII dunes (see section 5). The deformation zones below SB5 may have formed in the same way, and may be linked to SBS formation and fluctuations in the water table. The association of deformation zones with dunes with generally dry interdunes suggests that water-table instability, rather than a permanently elevated water-table, was important in controlling deformation in the Navajo Sandstone.

Carbonate deposits

Carbonate deposits are a volumetrically minor but none the less important component of the Navajo Sandstone in the Moab region and across SE Utah. There is a spectrum of carbonate development ranging from early cementation of dune deposits, overlying bounding surface or precipitation of a few centimetres of silty limestone or micrite to tabular carbonate beds and lenses, particularly in the lower part of Unit NI, where a few metres to an over a kilometre in width. Both dolomitic and calcitic types were recorded, and the beds commonly developed geometrically from relict laminated to redissolved or reddened massive, fine-grained sandstones. They are interpreted as reflecting the influence of the water table on both interdune and regional deflation surfaces, ranging from early cementation at the capillary fringe of the water table in dune deposits to impounded areas of groundwater-fed interdune lakes and are important diagnostic indicators of palaeoclimatic and the state of the water table. Three main types of lacustrine carbonate have been distinguished, based on appearance in hand-specimen, and studies in the Moab area suggest that they are distributed systematically within the succession, being most prominent in the upper parts of Units NI and NII and on SB3 1 and 2, and absent within Unit NIII and the lower part of Unit NI.

Cryptically-Laminated dolomitic limestones were found only in the uppermost levels of Unit NI, reflecting the development of wetter conditions associated with the formation of SB3. The thickest development of this type is seen at the top of Unit NI at Poison Spider Mesa, where it forms a 1.8m wetting-upwards cycle (Kocurek 1981), which develops upwards from cm wavy-laminated calcareous sandstones to mm crinkly-laminated dolomitic mudstones (Fig. 7.6a, b). In thin section, laminae are comprise mm alternations of dense dolomicrite and quartz-silt laminae, with a few laminae consisting of small cracks or vugs, unfilled with dolomite, calcite or chert, and lath-shaped dolomite voids suggesting replacement of gypsum (Fig. 7.6d).

Lenses of yellow-brown dolomites are restricted to the upper part of Unit NII. These lenses are 40-75cm thick (Fig. 7.7a) and appear yellow on polished surfaces (Fig. 7.7b, d), although they weather to pale buff in the field. In this section, they show a either a clotted dolomitic fabric, similar to the above-described dolomitic lenses, or a sharply parallel-beded micritic fabric, which is not seen in either of the other carbonate types (Fig. 7.7c). Yellow limestones were not seen in association with super bounding surfaces and authigenic chert was found in only one sample. The fine bedding seen in some examples and the rarity of authigenic chert and desiccation horizons suggests that they were precipitated under stable conditions in which water depth and salinity did not fluctuate significantly. They are found only in interdune settings towards the top of the Navajo succession and may indicate a change in the groundwater conditions at that time.

Grey, wavy bedded limestones, generally less than 60cm thick and characterised by irregular cm bedding, may be dolomitic or calcitic (Fig. 7.8a, b). They are found throughout the Navajo succession (except within NI and lower part of NII), and are the dominant type associated with super surfaces. The lenses commonly have a sharp, irregular base, and horizons of angular limestone breccia are seen, suggesting desiccation and/or reworking by wave surface activity. In this section, the carbonates comprise massive, cloudy, heterogeneous or recrystallised groundmasses with seams of angular quartz silt (Fig. 7.8c, d). Chert nodules, sometimes forming bedding-parallel masses several decimetres long, are most common in this type of carbonate, and may locally constitute up to 80% of the lens (Fig. 7.8a, b). On bedding plane surfaces the chert appears rounded and globular and is rarely seen filling desiccation fissures (Fig. 7.9c). The chert appears to have formed early, as lamine are not bent around the nodules (Fig. 7.9d), and is interpreted to have been formed from a gelatinous, hydrous magadrite-type precursor, which crystallised into nodules composed of chalcedony spheres (Fig. 7.9e). These lenses indicate that the ponds fluctuated between alkaline conditions, when carbonates were precipitated, and acidic conditions, possibly brought about by the decay of plants or algae as ponds intermittently dried up, when silica gel was precipitated. A return to wetter, alkaline conditions resulted in the conversion of the gel to chert, and the resulting volume reduction formed cracks and vugs which were filled with phases of length slow and fast chalcedony and later calcite (Fig. 7.9f, g).

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Regional correlation

Reconnaissance logging carried out at a number of other sections suggests that it may be possible to extend the stratigraphic model outside the Moab area (Fig. 8.1). However, more work is required at these other locations to establish the depositional style and presence or absence of super surfaces, and the correlation remains speculative. All sections show an upward transition from a horizontally-stratified Lower Navajo, characterised by interbedded tabular aeolian cosets with dry or damp interdune deposits to an Upper Navajo characterised by very thick and complex cosets and extensive zones of soft sediment deformation. However, sections in the north and west (TMT, I70, WBR, PSM and CCR) show a thick development of the Transition Zone/Lower Navajo Unit NI (Fig. 8.2), with considerable interbedding of fluvial and aeolian deposits, whereas down-wind sections to the south and east (BTR, BHY, HDR, U95, BLUFF) show an abrupt transition from the Kayenta fluvial to Navajo aeolian deposits (Fig. 8.3). Correlations to the Moab sections are seen most convincingly at Hart’s Draw (HDR), 40km to the S of Moab (Fig. 8.1) and at Temple Mountain (TMT), 95km W. At TMT, the candidate SBS2 is generally a sharp deflation surface separating buff-white intensely deformed dune deposits below from more yellow-coloured sets above (Fig. 8.4 and 8.5), although up to 8m of heavily bioturbated, purple sandstones were seen at one location, indicating the development of moist conditions. The succession appears similar at BHY, with a candidate SBS1 capping a thin Unit NI and the candidate SBS2 lying at the base of very thick, darker coloured sets, which are overlain by thinner more tabular sets towards the top of the succession (Fig. 8.3). More unusual wet deposits, including tufa carbonate spring deposits displaying evidence of abundant vegetation and faunal activity, have been described from a number of locations in the Moab region. Silicified logs associated with circular carbonate build-ups (Fig. 8.6) were described from an “oasis” area at section TRC and silicified trees were also seen at 7MC by Sansom (1992), which appeared to lie at or above SBS2. It is tempting to associate these areas, which may correlate with outcrops of spring-fed lacustrine carbonates, some containing silicified conifer stumps, described just to the north by Parrish and Falcon-Lang (2007), Dorney et al. (2017) and Parrish et al. (2017), with the formation of SBS2, apparent only a few km to the east at WBR, but the stratigraphic level of the TRC and published examples was not clear, and they appear to show evidence of contemporaneous dune activity. The oases are evidence of prolonged aquifer-fed water supply, that possibly commenced around SBS2 and continued during the deposition of the Lower Unit NI. However, one example of a catastrophic flood that cut a channel around 2km wide through the Navajo Sandstone in Comb Ridge near Blanding (section 7MC) was again deflated down to a quasi-planar water table controlled surface (Fig. 8.7).

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Discussion

Reconnaissance studies suggest that the stratigraphic framework for the Navajo Sandstone established in the Moab region may be applicable over a larger area, providing a model for further challenge and testing. However, the interpretation that SBS1 and 2 record complete demise of the erg in the Moab area is open to challenge, as it is possible that large deflection surfaces developed in the dunefield when dunes were still active elsewhere. Further work is required to establish whether super surfaces, zones of soft sediment deformation and the occurrence of springs and lacustrine deposits represent related features that could establish a basin-wide stratigraphy for the Navajo Sandstone, and in particular how they relate to the Navajo Sandstone in SW Utah, where non-aeolian deposits are largely absent. Establishing a regional framework to sub-divide and correlate the Navajo Sandstone would allow more detailed studies of different aspects of the geology to be placed in context and facilitate interpretation of the relationship between super surfaces, water table fluctuations and dune/interdune style. This in turn will influence interpretations of the drivers and controls on Navajo deposition, such as climate, wind regime, sand supply and subsidence/accommodation space, and help to constrain the non-unique solutions produced by different combinations of these variables.

Summary of the evolution of the Navajo Erg

The Navajo Sandstone in the Moab area comprises four stratigraphic units, reflecting 5 stages in development of the erg. The Kayenta Navajo Transition Zone records cycles of localised deflation of the Kayenta fluvial floodplain and establishment of extra-erg dunefields, which included reworked Kayenta sand and were terminated by renewed fluvial activity. Lower Navajo Unit NI records the abrupt arrival of the Navajo erg front. Declining Kayenta fluvial systems only penetrated a short distance into the erg fringe, and interdune deposits evolved from low-energy surface flood-derived mudstones and muddy sandstones to damp or vegetated groundwater-sourced interdune deposits as a damper erg centre which bound tabular aeolian cosets. First order surfaces commonly truncate areas of deformed and liquified dune deposits, interpreted to record pulses of possibly seismically-triggered water table instability, and are overlain locally by carbonate lacustrine and damp, vegetated interdune deposits. At least one large, vegetated deflation surface, SBS3, developed during this time, but it is unclear whether this records a significant demise of the erg. The Navajo Erg was finally terminated and subsequently eroded at the J2 unconformity, which exhibits evidence of prolonged exposure, including polygonal fissuring, vegetation and chert lag formation (Fig. 8.7).

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